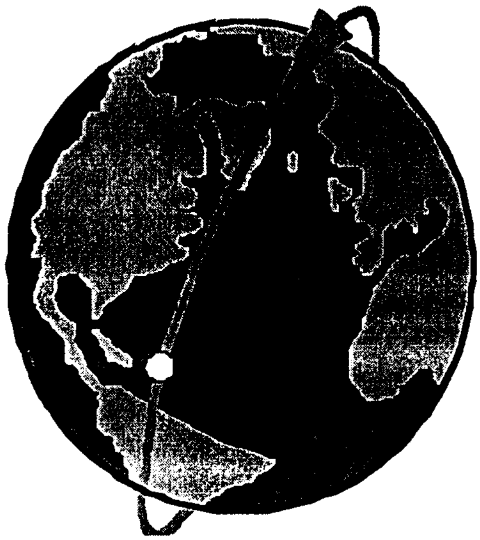
# 16th Annual Symposium on Caribbean Geology



## Remote sensing in the Earth Sciences

## Field Guide

Hernán Santos
James Joyce

Department of Geology
University of Puerto Rico
Mayagüez Campus

February 22-March 1, 1997

## Acknowledgments

This field guide was put together by Hernan Santos and James Joyce , but it could not have been made without the basis laid by previous field guides, which contained contributions by J.H. Schellekens, and E.G. Kauffman (Schellekens et al., 1989, 1993 1994, Kauffman, 1990). Research of Santos and Joyce, which part of this field guide is based, was supported by several grants from the Faculty of Arts and Sciences of the University of Puerto Rico at Mayagüez (SEED Money) and EPSCoR Grant (RII-85-13533), and two MRCE grants (RII 88-02961 and HRD-9353549).

## Introduction

Puerto Rico is localized in the northeastern boundary of the Caribbean plate (Fig. 1). Along with the northern Virgin Islands, it represent the subaerially exposed parts of the Puerto Rico-Virgin Islands Microplate (Byrne et al., 1985, Schellekens 1993, Schellekens et al., 1993) that lies between the seismically active Caribbean-North American Plate boundary zone. This microplate is defined to the north by the Puerto Rico Trench, and to the south by the Muertos Trough where Caribbean oceanic crust is subducted beneath the microplate (Byrne et al., 1985). To the west the microplate is separated from the Hispaniola block by extension in the Mona Canyon forming a graben that connect southward with the Muertos Trough (Gardner et al., 1980, Larue et al., 1990). To the southeast the Anegada Trough separates the microplate from the Lesser Antilles.

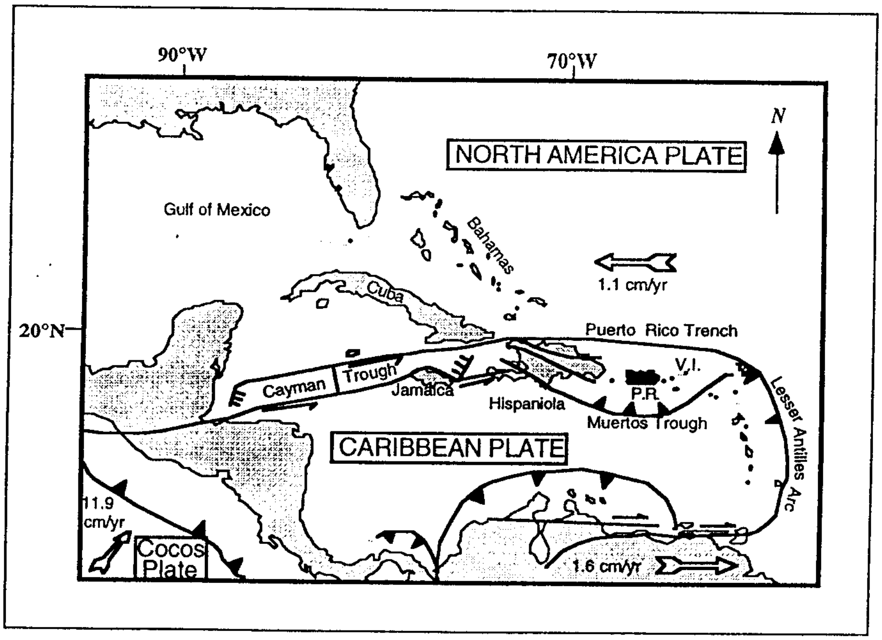



Figure 1- Tectonic map of the Caribbean region. Plate motion and velocities are after Mann et al (1991).

*General geology of Puerto Rico.*

Puerto Rico is a complex arc island with accreted terrains having a geologic record of about 195 My, initiating in the Pliensbachian. The island is composed of Early Jurassic to Early Cretaceous ophiolites, Early Cretaceous to Eocene island arc volcanic and sedimentary rocks, and two large felsic plutons, the Utuado and San Lorenzo batholits (Schellekens 1991, Schellekens 1993, Schellekens et al., 1993, Joyce et al., 1987). Middle Oligocene to Pliocene terrigenous clastics and limestones unconformably overly the older rocks along the north and south coasts. The pre-Oligocene rocks are divided into the Southwest , Central, and Northeast Igneous Province (Figure 2), each with a distinctive geology and petrology (Schellekens et al., 1993, 1989, Schellekens 1993, 1991, Cox and Briggs, 1973).

The paleogeographic setting of the earliest island arc volcanism differed in each of the three igneous provinces. The Southwest Igneous Province containg volcanic rocks associated with bathyal cherts indicating a deep submarine environment (Schellekens 1993, Schellekens et al., 1993, Montgomery and others, 1994). The Central Igneous Province volcanism was also submarine but limestone fragments suggest that the volcanic edifices were substantially higher, and by Albian time had formed a carbonate platform represented by the Aguas Buenas Limestone member and other limestone lenses of the Torrecillas Breccia, and the Rio Maton Limestone (Schellekens 1993, Schellekens and others, 1993). The Northeast Igneous Province island arc volcanism occurred in a subsiding basin and did not become exposed to subaerial conditions until the beginig of the Late Cretaceous (Schellekens 1993, Schellekens and others 1993). Chemical analysis of Las Palmas Hornblende Gneiss and Amphibolite, and Las Mesas Greenstone suggest that during the Lower Cretaceous rocks of the Sothwest Igneouis Province correspond to forearc environments, formatioins A, B, and C, the Rio Abajo Formation, the Torrecillas Breccia, the Pitahaya of the Central Igneous Province correspond to arc, and the rocks in the Northeast Igneous Terrain correspond to backarc environments. The formation of an acretionary prism due to subduction of the Caribbean Plate beneath the North America Plate by Cenomanian time resulted in exposures of neritic cherts and

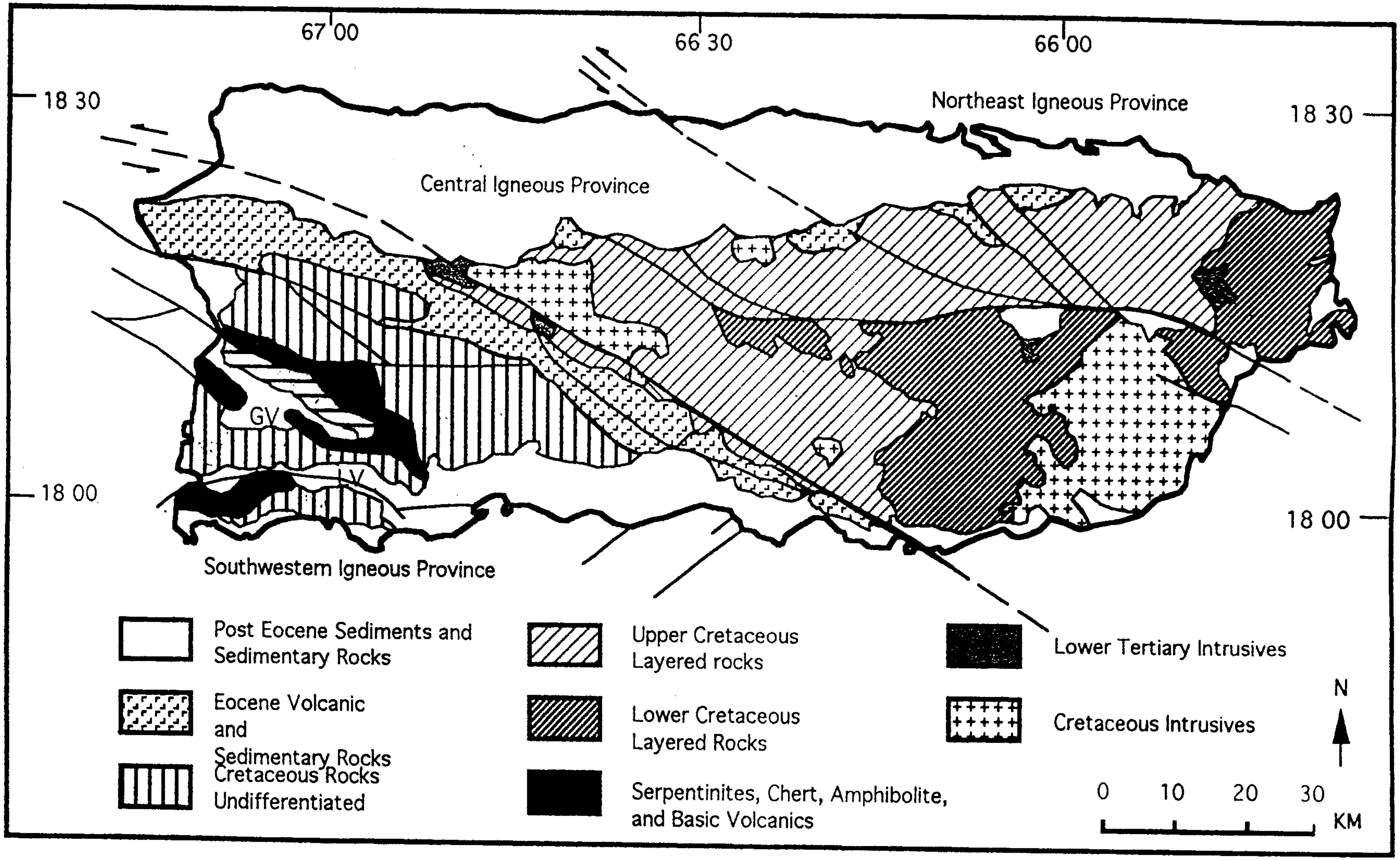



Figure 2. Geologic map of Puerto Rico showing the Northeast, Central, and Southwestern Igneous provinces. GV-Guanajibo Valley; LV- Lajas Valley

serpentinites in the Southwest Igneous Province. Thickening of the volcanic arc crust in the Central Igneous Province is evidenced by the first intrusive rocks and the extrusion of lavas in shallow water and possibly subaerial conditions (Schellekens 1993, Schellekens et al., 1993).

Burke (1978), and later Schellekens (1993) proposed that a flip in subduction direction, form west-verging to east-verging, occurred when buoyant thickened Caribbean crust clogged the subduction zone by the end of the Campanian (see also Matson, 1973, Burke et al., 1978, Mattson and P essagno, 1979). The changes on subduction direction resulted in the uplift of the Northeast Igneous Province as evidenced by a mayor unconformity at the end of the Campanian, and in the Central Igneous Province where subaerial conditions prevailed during the Maastrichtian. As a result of the change in subduction polarity, the Southwest Igneous Province (the former fore-arc basin) became the back-arc. Chemical characteristics of the volcanic rocks of the Monte Grande and El Rayo formations deposited in the Southwest Igneous Province during Late Campanian to Maastrichtian time suggest that they were deposited in a barck-arc tectonic setting (Schellekens 1991, 1993).

## FIELD TRIP 1
**Thursday February 27, 1997**

### *Geology of the Southwestern Igneous Province*

The Southwestern Igneous Province is a structurally and environmentally complex area separated from the rest of the island by the Great Southern Puerto Rico Fault Zone (Figure 2) . It contains a basal "Bermeja Complex", characterized by linear bodies of serpentinite, blocks of mafic metamorphic rocks, and cherts of Pliensbachian to Aptian age (Schellekens et al., 1993; Montgomery et al., 1994). This older sequence is unconformably overlain by a thick sequence of interbedded limestone, mudstone, and volcanic rocks of Cenomanian to Eocene age.

Bermeja Complex

The Bermeja Complex (Mattson, 1960), crops out in three serpentinite belts in southwest Puerto Rico (Figs.2 and 3). Suspended in the serpentinite occur the other rock types assigned to the Bermeja Complex: the Las Palmas Hornblende Gneiss and Amphibolite, the Las Mesas Greenstone, the Mariquita Chert, and the Cajul Basalt.

The serpentinite in outcrop is usually a blackish green to bluish green highly sheared rock with well developed slicken-sides. The deformation is often concentrated in distinct zones of pervasively sheared serpentinite, with less sheared intervening zones, in which original textures, such as bastite pseudomorphous after orthopyroxenes are visible. Locally decimeter thick dikes of rodingite cut the serpentinite.

The northernmost belt, consisting predominantly of serpentinite, stretches for more than 30 km ESE from the city of Mayagüez (Fig.3) (Mattson, 1960; McIntyre, 1975; Curet, 1986). Just east of Mayagüez, greenstone and amphibolite occur within the serpentinite (Mattson, 1960; Curet, 1981, 1986). McIntyre (1975) reports a "diatreme", consisting of amphibolite breccia in serpentinite, about 3 km. ESE of Maricao.

A second belt in which rocks are predominantly serpentinite, but of a more discontinuous nature, extends from Punta Guanajibo on the west coast, eastward through San German, until it merges with the northern belt (Mattson, 1960; Krushensky and Monroe, 1979; Volckmann, 1984c). This serpentinite is intruded by several dikes and small intrusions. Near SanGerman a large outcrop of Mariquita Chert has been mapped (Volckmann, 1984c) (Fig.4).

The southernmost outcropping belt of the Bermeja Complex trends discontinuously from Punta Melones in the west across the Sierra Bermeja (Fig.3) (Mattson, 1960, 1973; Volckmann, 1984 b,d). East of the Sierra Bermeja, only a few patchy exposures of the Bermeja Complex are encountered at Cerro Vertero (Volckmann, 1984b), and in Media Quijada (Krushensky and Monroe, 1979). At the Punta Melones occurrence, chert overlies serpentinite with

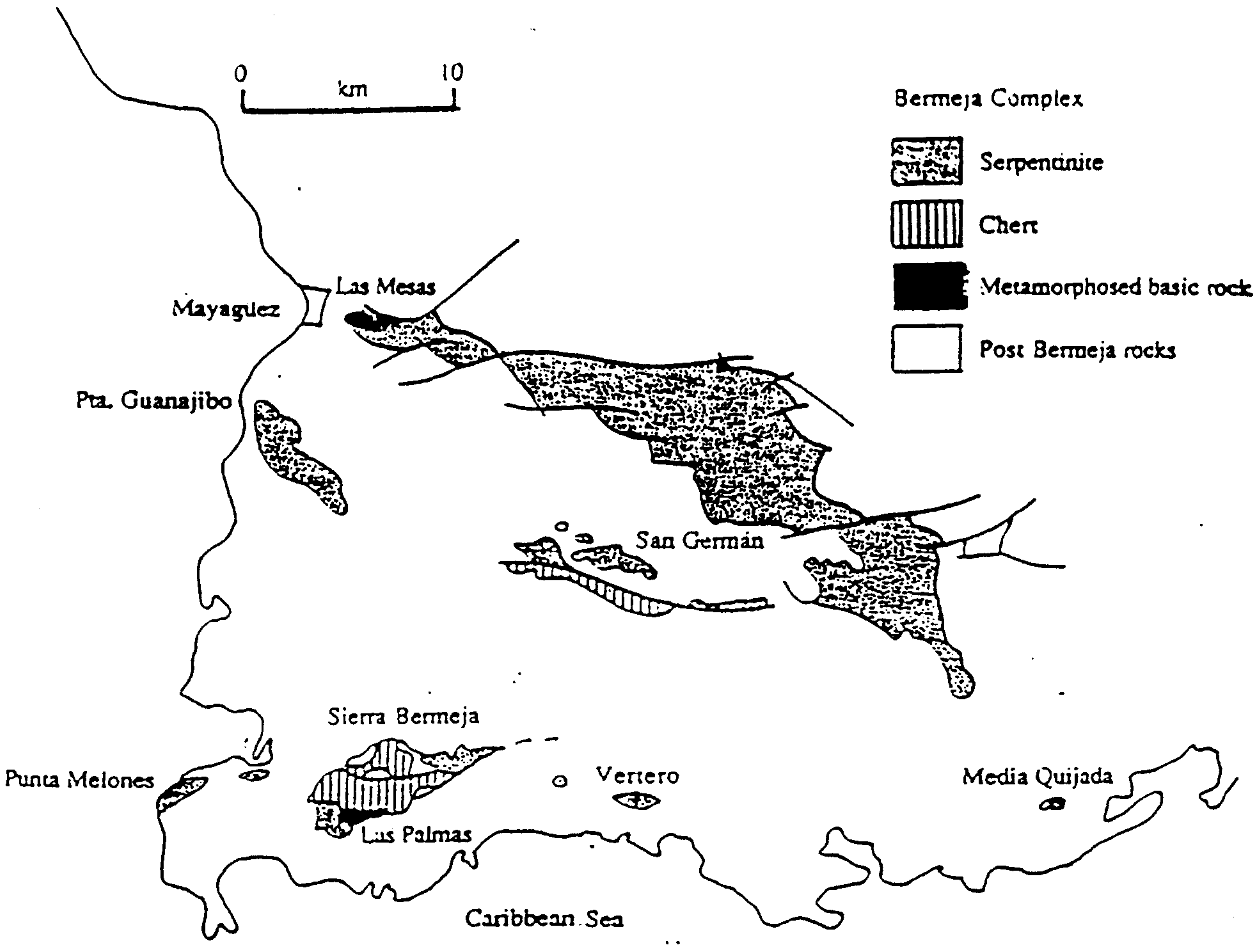



Figure 3. Location map of the Bermerja Complex with rock types and locations mentioned in the text.(Schellekens et al. ,1990)

amphibolite blocks (Volckmann, 1984b). In the Sierra Bermeja, the serpentinite encloses large blocks of amphibolite (Mattson, 1960; Renz and Verspyck, 1962; Tobisch, 1968), chert ( Mariquita Chert) (Mattson, 1973), and greenstones. The small occurrence in the east, near Media Quijada, exposes chert and amphibolite, with serpentinite and volcanic rocks (Krushensky and Monroe, 1979). The serpentinite of the southern belt is intruded by a Late Cretaceous diorite stock (Maguayo Porphyry) and related intrusives. The serpentinite belts have many characteristics of a tectonic melange.

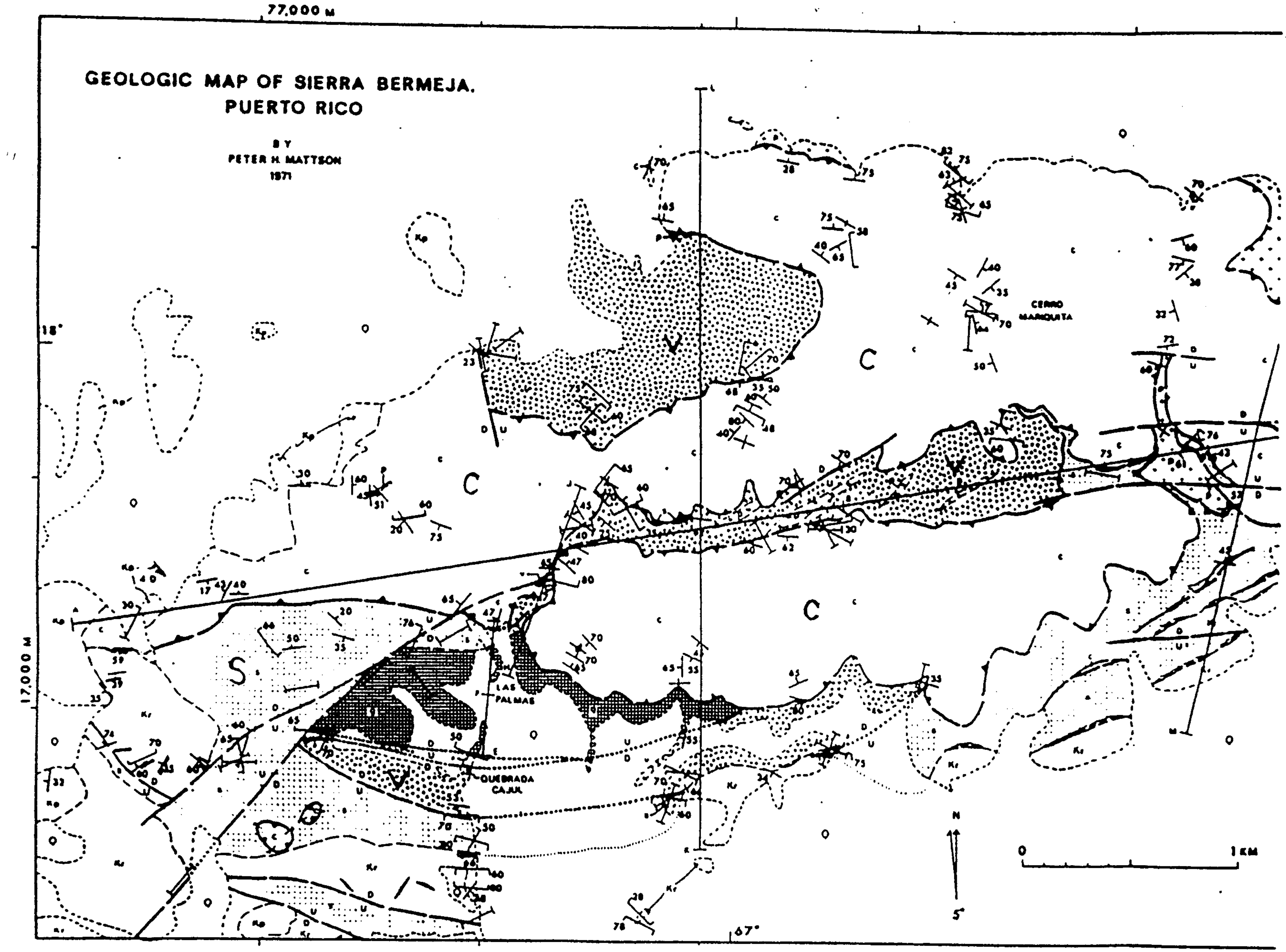



Figure 4- Geologic map of Sierra Bermeja. V (dashed pattern) Cajul Basalt. s (fine stippled ) serpentinite, C (no pattern) Mariquita Chert. g (crosshatched) Las Palmas Amphibolite-Hornblende Gneiss. (from Mattson, 1973)

## Petrography

"Amphibolites" as described by previous workers have been separated on the basis of their mineral content, texture, and metamorphic grade, into the following groups by Schellekens (1993):

1) Foliated amphibolite without clinopyroxene: Outcrops of these rocks occur in the largest block of amphibolites, that crops out in the Arroyo Cajul near Las Palmas.

2) Foliated amphibolite with clinopyroxene: This rock type is found in outcrops in Punta Melones, Las Palmas, near the "vertedero" at the Cabo Rojo-Lajas boundary, and in Media Quijada. The presence of relict phenocrysts of pyroxene and plagioclase, as well as the chemical composition, suggests a basaltic volcanic protolith.

3) Massive amphibolites with clinopyroxene: This rock type occurs as blocks suspended in the southern serpentinite belt from Punta Melones to the east end of the Sierra Bermeja, and on Cerro Las Mesas associated with the greenstone. At Cerro Las Mesas, plagioclase of the amphibolites is albitized, and the rock is veined by prehnite; in addition, it contains rarely patches of prehnite and radial aggregates of chlorite replacing hornblende.

4) Hornblende Two Pyroxene Gabbro: McIntyre (1975) describes a breccia in a "diatreme" cutting serpentinite near the town of Maricao. The breccia consists chiefly of serpentinite fragments, but also includes amphibolite fragments. McIntyre considers the presence of hydrogrossular and brown amphibole in the amphibolite as caused by reaction of the rock with fluids from the serpentinite. The brown hornblende from this breccia was dated by K-Ar method at 112 $\pm$ 15 Ma (Cox and others, 1977).

Other rocks within the serpentinite include:

1) Metabasaltic dikes: Metabasaltic dikes cross-cutting the foliation of the amphibolites occur in the Arroyo Cajul near Las Palmas (Tobisch, 1968). The dikes, which are usually light green with obvious phenocrysts, may have been faulted with small off-sets.

2) Las Mesas Greenstone (Schellekens et al., 1990): These rocks are described from two quarries near Mayaguez. In the northern quarry

the greenstones show bedding ranging from 20 cm to several meters, and include basaltic flow rocks and volcaniclastic conglomerates and sandstones, making up a sequence of non-foliated greenstones. In the southern quarry volcaniclastic sandstones are veined by epidote, calcite, actinolite, and prehnite, and occur in association with non-foliated amphibolite.

3) Cajul Basalt (Mattson, 1973; Volckman, 1984d): Volcanic and volcaniclstic rocks of basaltic composition. The presence of epidote, chlorite, and calcite suggests a low grade of metamorphism and the rocks can be called greenstones, locally iron metasomatosis has colored the rocks deep-red. The Cajul Basalt is occasionally intercalated with the cherts (Volčkman, 1984d), with radiolarian ages of Hauterivian to Aptian (Mattson and Pessagno, 1979; Schellekens et al., 1990).

## Metamorphism

Rocks of the Bermeja Complex include the highest grade metamorphosed rocks of Puerto Rico. (For locations see figure 3 and 4). Based on the mineral paragenesis present in the thin sections Schellekens (1993) distinguished the following grades of metamorphism:

The lowest grade metamorphism is present in the two-pyroxene gabbro, where a metamorphic paragenesis of prehnite, chlorite, and hydrogrossular is present. Although the rocks were originally described as amphibolites (McIntyre, 1975), the rock is not foliated and the paragenesis of orthopyroxene, clinopyroxene, and brown hornblende was interpreted later as the original igneous paragenesis (Schellekens et al., 1990).

The Las Mesas Greenstone contains phenocrysts of clinopyroxene (augite) in a groundmass composed of interstitial clinopyroxene, chlorite, and albitized plagioclase laths. Rare chlorite filled amygdules and chlorite pseudomorphs after olivine occur. The paragenesis is characteristic of the greenschist facies (Yardley, 1989).

The Las Palmas Hornblende Gneiss and Amphibolite is intruded by metabasaltic porphyry dikes. These dikes cross the foliation and show a metamorphic paragenesis in which the plagioclase is altered to albite, and clinopyroxene relicts are replaced by acicular actinolite and rimmed by green hornblende. Some chlorite is also present. The presence of green hornblende rimming actinolite aggregates and the associated albite and chlorite would place this rock at the boundary between greenschist and amphibolite facies (Yardley, 1989).

A slightly higher grade of metamorphism is represented by the non-foliated amphibolites associated with the greenstone in Las Mesas and as blocks in the southernmost serpentinite belt (Melones, Cerro Vertero), and by some of the foliated amphibolites (Media Quijada). In these rocks hornblende, which is brownish green in color, encloses clinopyroxene relicts, plagioclase composition ranges from oligoclase to bytownite, and sphene occurs as an accessory mineral. The paragenesis of plagioclase with brown-green hornblende and accessory sphene suggest conditions of the lower amphibolite facies. In the Las Mesas amphibolite the occurrence of veins of epidote, replacement of hornblende by chlorite, and albitized plagioclase provide evidence for retrograde metamorphism to greenschist facies conditions.

The highest grade of metamorphism is recorded in the rocks near Las Palmas (Las Palmas Hornblende Gneiss and Amphibolite). In these rocks hornblende occurs associated with labradorite, quartz, and accessory sphene.

Amphiboles have been used as pressure and temperature indicators by a number of workers (eg. Raase, 1974; Laird and Albee, 1981, 1982; Nabelek and Lindsley, 1985). Amphiboles from selected samples were analyzed and amphibole compositions from various metabasites of the Bermeja Complex were plotted on diagrams showing increase in metamorphic grade (Fig. 4)(Schellekens, 1993). Amphibole compositions fall into three different groups with some overlap in samples where hornblende mantles a core of actinolite. For comparison, the fields of the biotite, garnet, and staurolite-kyanite zones determined for pelitic rocks enclosing metabasites in Vermont (Laird and Albee, 1981) were superimposed on the diagram. The metabasaltic dikes in Las Palmas show

the lowest grade of metamorphism, overlapping, but with slightly higher grade are the non-foliated amphibolites of Las Mesas and the foliated amphibolites of Media Quijada. The highest grade is recorded in the amphibolites and gneisses of the Las Palmas area.

Amphibole compositions also appear to be dependent upon the facies series (Laird and Albee, 1981). For a given value of Aliv the (Alvi+Fe3++Ti) will be higher for amphiboles from higher pressure terranes. The amphibole compositions compared to the facies series of different pressure regimes: a high-pressure facies series of the Sanbagawa (Japan) and Franciscan (California) terrane, a medium facies series of the Dalradian (Scotland) and the Haast River (NewZealand), and the low pressure facies series of the Abukuma (Japan) terrane. The Bermeja metabasites have most in common with the medium and low pressure series (Schellekens, 1993)

On the basis of petrography and mineral chemistry the Bermeja Complex rocks bear evidence of different degrees of metamorphism and retrograde metamorphism. Greenschist facies conditions are present in the Las Mesas Greenstones, the metabasalt porphyry dikes, and in the retrograde assemblage of the amphibolite in Las Mesas. Amphibolite facies conditions are recorded in the metabasite blocks of the southern serpentinite belt and in the amphibolites in Las Mesas. In some rocks the metamorphism was less pervasive as shown in the presence of clinopyroxene relicts and lower pressure of formation as deduced from amphibole compositions. The metabasalt porphyry dikes show possible prograde amphibolite conditions in the same pressure regime as the amphibolites with pyroxene relicts, superimposed on greenschist facies conditions. The Las Palmas Hornblende Gneisses and Amphibolites show the highest pressure amphibolite conditions. Some replacement of the amphiboles by chlorite suggests that retrograde greenschist facies conditions also affected these rocks.

The metamorphic paragenesis suggests that the Las Palmas Hornblende Gneisses and Amphibolites were subjected to medium pressure and temperature conditions, in which metamorphic differentiation and isoclinal folding occurred. None of the other meta-basites studied showed such a high grade metamorphism, suggesting that this metamorphism probably took place before the juxtaposition of this block with the other meta-basites. The basalt porphyries and the other amphibolites were then subjected to prograde metamorphism into the lower amphibolite facies. Temperatures and pressure remained lower than the foliated amphibolite, as shown in the common absence of foliations, the amphibole compositions, the persistence of pyroxene relicts, and evidence for the prograde greenschist facies in the dikes. The latter were probably less susceptible to metamorphism due to their intrusion into the higher grade amphibolites.

## Mariquita Chert

The Mariquita Chert (Mattson, 1973) is a fine-grained greenish-gray or black radiolarian bearing rock, consisting of fine recrystallized quartz with minor iron oxides, named after Cerro Mariquita, the highest peak of the Sierra Bermeja. In the Sierra Bermeja, in the southern serpentinite belt, the chert overlies serpentinite with amphibolite rafts. Chert associated with serpentinite, near Punta Melones (El Combate), Media Quijada, and San German was also mapped as Mariquita Chert (Krushensky and Monroe, 1979, Volckmann, 1984a,b,c).

On the basis of ages of radiolaria chronostratigraphy in the cherts (Mattson and Pessagno, 1974, 1979, Pessagno written comm. in Volckmann, 1984c; Schellekens and others, 1990; Montgomery et al., 1994, and in prep.) four chert forming episodes can be distinguished (Fig. 5): An oldest episode with red ribbon chert with Lower Jurassic radiolarian was found in the northern Sierra Bermeja (Montgomery et al. 1994: Montgomery et al., and in press). A second episode with Kimmeridgian to Tithonian age radiolarians in the central northern Sierra Bermeja. The association was interpreted as deposited in an abyssal environment, at paleolatitudes of about 22$^{o}$ north or south (Montgomery et al, in press).

A third episode of Hauterivian to lower Albian age, suggesting bathyal depositional environments, was distinguished based on radiolarian in the southern Sierra Bermeja. Mattson and Pessagno (1979) described radiolarians of this age from a sequence, where the cherts are intercalated with volcanic and volcaniclastic rocks of the Cajul Basalts.

A fourth episode of chert formation occurred in the Late Cretaceous, as Cenomanian ages were determined for radiolaria in the cherts overlying the serpentinite conglomerate in Media Quijada, Campanian ages for the cherts overlying the serpentinite near El Combate (Schellekens et al., 1990), and Turonian ages for the cherts

Cajul Basalt

The Cajul Volcanic Rocks were first described by Mattson (1973, p.22-23) as: " purplish red and red-brown, rapidly weathering volcanic rocks" in the western Sierra Bermeja. The unit was named after Quebrada Cajul, with a type locality (77,890 mE; 16,680 mW) about 150 m south of the bridge of the route 303 over the arroyo. Mattson (1978) describes the rocks at the type locality as feldspathic finely crystalline lava, with well defined pillow structures. Elsewhere the unit consists of coarse tuff and highly amygdular lava.

Because the composition of the volcanic rocks in all the outcrops in the Puerto Real, San German, Cabo Rojo, and Parguera quadrangles is basaltic, Volckmann (1984d) redefined the unit as the Cajul Basalt. He concludes that the Cajul Basalt is in part interbedded with the Mariquita Chert. Radiolarian chronostratigraphy (Mattson and Pessagne, 1979) assignes an age of Hauterivian to Aptian to the cherts intercalated with volcanic derived material, suggesting that the age of the Cajul Basalt is Hauterivian to Aptian (Volckman, 1984d).

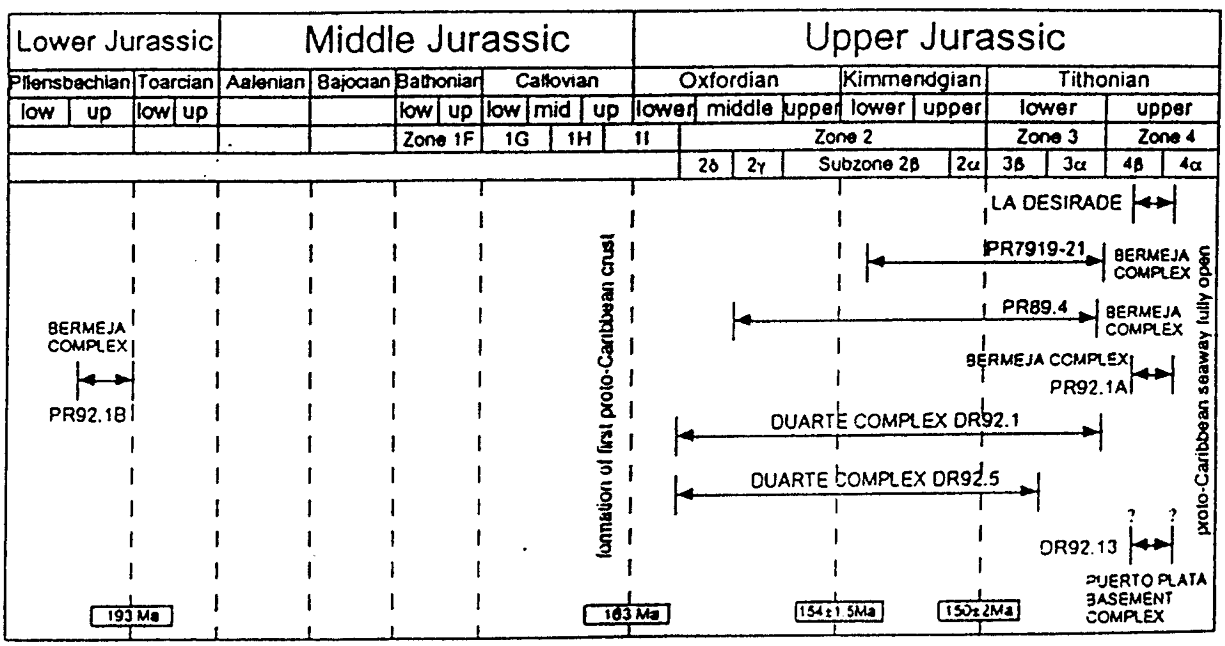



Figure 5 Schematic diagram of radiolarian ages in the northern Caribbean (from Montgomery et al. 1994).

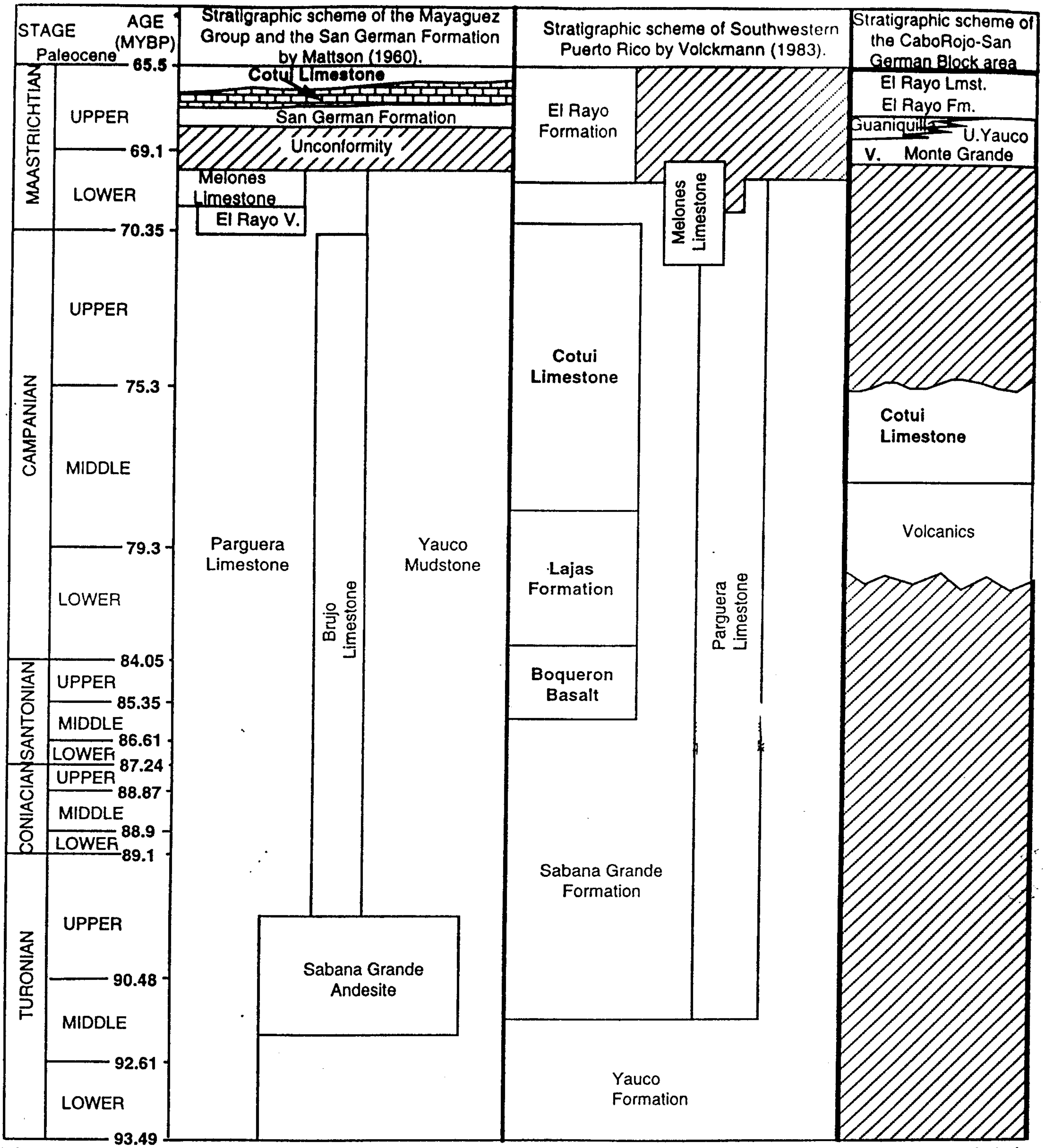
Radiometric ages for rocks associated with the Bermeja Complex

Radiometric and biostratigraphic age determinations are summarized in figure 5. The oldest radiometric age of 126 $\pm$ 3 Ma K-Ar on hornblende in the amphibolites of the NE Sierra Bermeja (Cox and others, 1977) is interpreted as an age of metamorphism, the other reported ages for the amphibolites, 110 $\pm$ 3.3 Ma (Mattson, 1964), and 86.3 $\pm$ 8.6 and 84.9 $\pm$ 8.5 Ma (Tobisch, 1968) are considered reset, possibly by the intrusion of the Maguayo Porphyry at 86.1 $\pm$ 2.1 Ma (K-Ar: Cox and others, 1977), and 83 Ma (Ar-Ar: Schellekens, unpubl.). The 112 $\pm$15 Ma K-Ar age on hornblende from the "diatreme" near Maricao (Cox and others, 1977) was reinterpreted as a magmatic age. The massive amphibolite of Cerro Las Mesas was dated by Ar-Ar at 123.1 $\pm$ 2.6 Ma, with a second plateau age of 80 Ma (Schellekens, unpublished).

## Volcano-sedimentary cycles of the Post-Bermeja rocks

This basal complex is unconformably overlain by a thick sequence of Cenomanian to Maastrichtian limestones and mudstones interbedded with volcanic rocks and cut by numerous small, high level, intermediate igneous intrusions (Mattson, 1973, Almy, 1969, McIntire, 1975, Krushensky and Monroe, 1979, Krushensky and Curet, 1984, Curet, 1980, Volkmann, 1983, 1984, Schellekens, 1989).

The Southwestern Igneous Province of Puerto Rico is divided into three major structural blocks by the Guanajibo and Lajas valleys (Figure 2) which occupy the trends of major normal faults, forming linear half-grabens. Mattson (1960) described the Guanajibo Valley as a breached anticline. The Lajas Valley has been described by Lobeck (1922) as a breached anticline and by Slodowsky (1956) as a syncline underlain by Paleocene strata. Thus the structural relationships of these areas are not yet clear. The blocks resemble half-graben structures with high topographic relief on the upthrown northern face of each block, decreasing gradually toward the south into the valleys or to the coast line. The middle Cabo Rojo-San German block and the southern Bermeja block are characterized at present by steep north-facing slopes rising above the Guanajibo and Lajas valleys, respectively. These escarpments are probably of




* Cretaceous time scale from Western Interior Cretaceous Basin (Kauffman, Obradovitch, and Cobban, 1992; Obradovitch, in mauscrid).

Figure 6- Stratigraphic scheme of Mattson (1960), Volckmann (1983), and Santos.

tectonic origin, marking high-angle fault planes. The northern Mayagüez-Sabana Grande block is in fault contact with the Las Mesas serpentinite mountain belt to the north. Shallow water carbonates representing shelf and slope environments of deposition occur on the west side of these blocks. These form the Hormigueros Syncline in the Mayagüez-Sabana Grande block, the Cotui Anticline in the Cabo Rojo-San German block, and the Parguera Syncline in the Parguera-Ensenada block.

Cretaceous exposures extend from Mayagüez to Parguera across the Southwestern Puerto Rico Province. These are characterized by several depositional cycles of: (a) intense volcanism and volcaniclastic sedimentation, followed by; (b), volcanic quiescence, erosion, planation and submergence of the island platform, and; (c) widespread but short-term development of carbonate platforms during the Cretaceous.

Previous stratigraphic studies of the Mayagüez area include Mattson (1956, 1960) and Volckmann (1983). Mattson (1960) described the sequences, in stratigraphic order, as: (1) A basal complex of amphibolite, serpentinites, spillite, and silicified volcanic rocks, the Bermeja Complex; (2) Andesitic lavas of the Rio Loco Formation which unconformably overlie the Bermeja Complex; (3) An interbedded sequence of lithofacies comprising the Mayagüez Group; and (4) the San German Formation (Fig. 6). The Cretaceous Mayagüez Group was considered by Mattson (1960) to be of Cenomanian through Early Maastrichtian age. It was composed of seven lithofacies, in ascending order: the Yauco Mudstone, Sabana Grande Andesite, Brujo Limestone, Parguera Limestone, El Rayo Volcanics, and the Melones Limestone. The San German Formation was described as a thick sequence of andesitic volcanic rocks with a distinctive lower member, the Cabo Rojo Agglomerate, and a middle member the Cotui Limestone (Figure 3).

Volckmann (1983) studied the geology of the Mayagüez area during the preparation of the San German, Cabo Rojo, and Puerto Real quadrangles for the U.S. Geological Survey, and made major revisions in the Cretaceous stratigraphy: Volckmann indicated that: (1) the San German Formation is composed of three lithologically distinctive and mappable units. For this reason he abandoned the name San German Formation and its Cabo Rojo Agglomerate Member. He renamed the basal member the Lajas Formation, raised the Cotui Limestone

Member to formation rank, and correlated the volcanic rocks both overlying the Cotui Limestone, and underlying the Lajas Formation with the Sabana Grande Formation of Slodowsky (1956). (2) He abandoned the name Brujo Limestone and described these rocks as lithologically and temporally identical to the Cotui Limestone. (3) Volckmann renamed the El Rayo Volcanics as the El Rayo Formation and restricted the term to exclude limestone interbedded throughout this unit from the Melones Limestone. (4) He restricted the term Parguera Limestone to limestone exposed south of the Lajas Valley. (5) He abandoned the term Mayagüez Group (Figure 3). These major stratigraphic revisions have already confused the relationship of individual carbonate and clastic units to each other, and to the rest of Puerto Rico.

## Cotui Limestone

The Cotui Limestone represents a carbonate platform developed during Middle Campanian time. The limestone was deposited during two marine cycles with maximum flooding and stabilization of the carbonate platform by the end of the Middle Campanian. This suggest primarily eustatic causes for flooding and stabilization of the platform despite its arc island setting.

Cretaceous rocks of southwestern Puerto Rico are dominated by volcanic and volcaniclastic facies, reflecting the backarc setting of this depositional basin, and proximity to active Cretaceous volcanic centers. Large scale tectonic activity and rapid volcaniclastic sedimentation prohibited stabilization of structural platforms and carbonate sedimentation during much of the island history. But relative short intervals of carbonate platform and slope development occurred episodically, commonly associated with limited reef growth. The first of these carbonate depositional episodes during the middle Cretaceous of southwestern Puerto Rico resulted in the deposition of the Cotui Limestone. The Cotui Limestone is now preserved as a carbonate platform approximately 4 Km wide in a north-south direction and 12 Km long in a west-northwest to east-southeast direction within the study area. The distribution of the facies presents a north-south thickening and environmental gradient. The thickness ranges from 30 meters in the south to 80 meters in the north. The thickness of the platform changes rapidly within 2 Km, from 80 meters in the type section to 40 meters in the middle of the platform reflecting a lower slope to platform margin facies transect. Toward the south, across the remaining 2 Km of the platform, the formation decreases gradually from 40 to 30 meters in the southernmost exposure (Santos, 1990).

The Cotui Limestone persisted for about 5 My and was characterized, during maximum development, by intertidal to shallow subtidal, shelf, shelf edge, foreslope, and slope carbonate facies (Santos, 1990). The shelf facies occur widely across the Cotui area and is divided in inner and outer lagoon subfacies with occasional rudistid bioherms as patch reef. The shelf edge, foreslope, and slope facies are only distributed in the north part of the area while the shelf facies covers the central and southern portion. These regional distribution patterns indicate two distinctive suites of environments in the northern and southern part of the platform. The northern part of the platform show characteristics of having been deposited under normal marine conditions in an outer platform-slope environmental setting. As the facies transgressed south, the diversity of facies (paleoenvironments) decreased, and the facies became gradually dominated by inner lagoon, possibly hyper saline facies that contain rudistid bivalves biostromes, and nerineid and actaeonellid gastropods in intertidal to shallow subtidal paleoenvironments. The detailed study of this platform (Santos, 1990) provides the best known example of a Caribbean arc island carbonate sequence, sea level history, sequence stratigraphy, and tectonic influence on carbonate platform development and termination in arc-island setting.

## Depositional history of the Cotui carbonate platform/slope complex.

The Cotui Limestone represents a carbonate platform facies sequence deposited over a volcanic/tectonic surface during a Late Santonian to Early Campanian transgressive event. This event can be divided into four stages of deposition: (1) deposition of the lower Cotui during the initial stage of transgression up the slope and across the outer platform; (2) flooding of the southern inner portion of the platform; (3) a minor regression and progradation of the platform; and (4) continued southward transgression associated with increased development and onlap of the shelf edge facies, forming a more effective barrier to the platform, and leading to development of more restricted environments in the inner platform facies (Fig.7).

1) The lower Cotui Limestone in the north of the area was probably deposited on an original slope of a volcanic island during a rapid stage of a Late Santonian to Early Campanian transgression. This is corroborated by thick sedimentary units and rapid vertical changes between facies. The Cotui Limestone lies in sharp (transgressive disconformity) contact with the lower Lajas Formation, with little or no transitional facies between volcanics and limestones. Sedimentary structures, grain textures, and other paleoenvironmental data suggest moderate water energy, and normal marine conditions for the facies deposited during this stage. The thickness of the limestone deposited during this stage is approximately 40 meters in the north of the platform.

2) The second stage of deposition is represented by erosion of the pre-existing tectonic/volcanic surface, and occurred at peak eustatic highstand, when the rate of transgression or sea-level rise reached its peak and begun to slow. This change in the rate of transgression resulted in the flooding of the southern two kilometers of the platform. This transgression is characterized in the south by a transition zone, 8-12 meters thick, between the Lajas Formation and the type Cotui Limestone that is composed of stacked interbedded sequences of volcaniclastic and limestone lenses with stabilization of sea level at highstand. During this second stage, the composition of foreslope facies 1 in the northern part of the study area consisted of up to 40% volcaniclastic grains transported downslope from the southern part of the platform.

3) A minor regression or relative fall of sea level, and progradation of the platform, is suggested by the repetition of the shelf edge facies above foreslope facies-1 in the northern part of the area. In the type section (north) volcaniclastics comprises up to 20% of the grains in Shelf Edge Facies-2. The progradation of the platform margin to normal wave base during stabilization of sea level rise at highstand with progradation driven by continual production of bioclastic material. Evidence for progradation is the inverse repetition of the cf. *Antillosarcolites* sp., and *Durania* n. sp., aff. *D. curasavica* biofacies, and associated lithofacies suites.

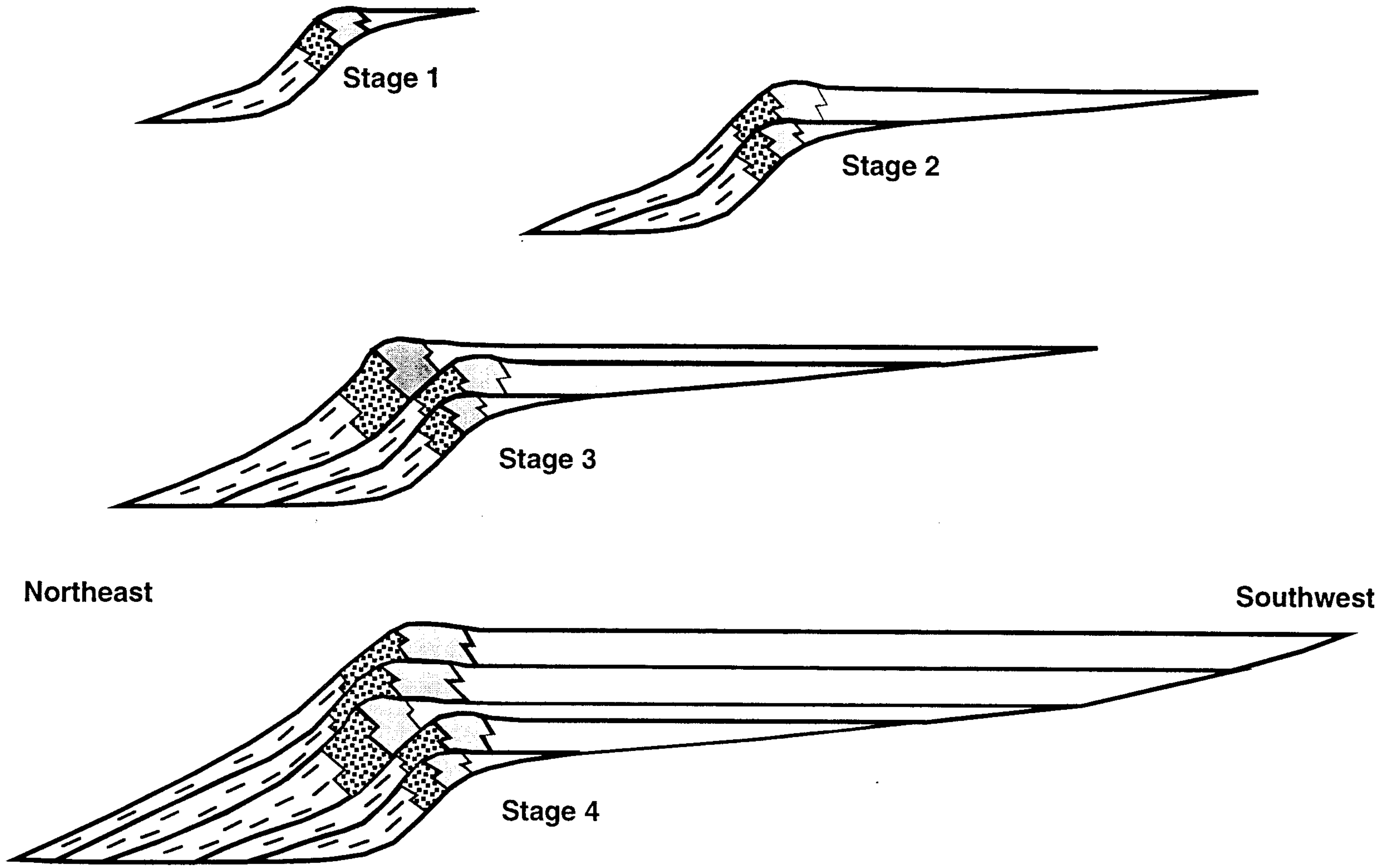



Figure 7. Cotui Limestone stages of deposition: (1) deposition of the lower Cotui during the initial stage of transgression up the slope and across the outer platform; (2) flooding of the southern inner portion of the platform; (3) a minor regression and progradation of the platform; and (4) continued southward transgression associated with increased development and onlap of the shelf edge facies, forming a more effective barrier to the platform, and leading to development of more restricted environments in the inner platform facies

4) In the fourth and final stage of Cotui Limestone deposition, sea level rise was accelerated, and the major transgression resumed. Shelf edge facies onlapped lagoonal facies toward the center of the platform as slope facies onlapped shelf edge facies in the north. The platform facies deposited under normal marine conditions in the northern part of the study area changed gradually southward into those representing more restricted hypersaline environments, as the shelf edge built up and created a barrier to circulation across the platform. North of the shelf edge margin, foreslope and slope facies continued to be deposited under normal marine conditions with little or no influx of volcaniclastic; most volcaniclastic sediment would have been trapped on and landward of the platform as a result of continued sea level rise.

The deposition of Cotui Limestone was terminated by an extremely rapid flooding of the ramp with volcaniclastic sediments of the Monte Grande Formation. The lower part of the Monte Grande Formation is composed of coarse limestone and volcanic breccias commonly encased in chaotic bedded sandstone, with clasts reaching sized of several meters in diameter. In many areas this beds show mass flow characteristic. This is probably the result of major tectonic/volcanic event during the late Upper Campanian. Santos and Kauffman (1989) described two stages of contemporaneous half-graben development, with mass flow infilling, at the Cotui-Monte Grande contact in the Padre Rufo area.

## The Monte Grande Formation

The Monte Grande Formation was first described by Slodowski (1956) as an heterogeneous assemblage of andesitic lava flows and calcareous mudstones. He broadly assigned a type area to road exposures that occur north and northeast of Sabana Grande town. He proposed an age for the type Sabana Grande as Turonian to probably Lower Santonian. Mattson (1956, 1960) redefined this formation as the Sabana Grande Andesite and traced the formation to the west-southwest into the Mayagüez area where it was mapped as occurring below the Hormigueros Syncline, below and laterally interfingering with the basal Parguera Limestone. It was also mapped in the base of the Tea Syncline and Guanajibo Anticline. Mattson (1956, 1960) extended the age range of the formation to be Turonian to Campanian based on the age of the underlying and laterally equivalent Yauco Mudstone, and the age of the overlying Parguera Limestone.

The "Sabana Grande Formation" of this study was first mapped by Mattson (1956) as the upper unit of the San German Formation composed of 150 meters of andesitic volcanic rock, shale, and conglomerate. This unit overlay the Cotui Limestone (the middle unit of the San German Formation) in the Buena Vista area, southeast of Cabo Rojo. Volckmann (1983) abandoned the name San German Formation and indicated that it is composed of three lithologically distinctive and mappable units. He named the basal units the Lajas Formation, elevated the overlying Cotui Limestone Member to formation rank, and correlated the rocks overlying the Cotui Limestone with the upper part of the Sabana Grande Formation. This created a major problem since the type Sabana Grande is pre-Cotui in age (Turonian to Campanian). Further, no maps show vertical stratigraphic continuity between pre- and post-Cotui units called "Sabana Grande", nor any lateral facies relationships of intervening rocks with facies characteristic of the type Sabana Grande or the Buena Vista area "Sabana Grande" Formation (Sampayo, 1992).

Sampayo (1992) described the rocks above the Cotui Limestone called "upper Sabana Grande formation" by Volckmann (1985) as a chaotic basal breccia, with boulder- to cobble-size clasts of volcanic rocks, limestone, sandstone, and mudstone. Stratigraphically higher are limestone conglomerates, individual limestone lenses, and sequences of interbedded sandstone and mudstone. Sampayo related these sediments to gravity flows during a major volcanic/tectonic event and redifined these rocks as the Monte Grande Formation. A Late Campanian to Maastrichtian age was assignet to the formation based on the presence of the rudistid <u>Barretia gigas</u>. Recent $K^{40}$- $Ar^{40}$ dating of a lava flow at the base of the formation resulted in dates of 68.8± 1.8 Ma, a lower Upper Maastrichtian age.

Geologic History of the Monte Grande Formation

During the end of the Cotui time (Middle Campanian), tectonic/volcanic activity was initiated in Southwest Puerto Rico. The Cotui platform was largely exposed and a short-term unconformity developed, as represented by a low-level karst topography. Following karstification, a period of volcanism was initiated and lava flows were extruded and covered parts of the exposed Cotui Limestone platform. The volcanic activity was accompanied by extensional forces and development of a half graben system to the east. This active period terminated deposition of the Cotui carbonate platform and drowned the platform. A relative rise in sea level occurred, accompanied by deposition of the Monte Grande Formation. Deposition of the Monte Grande Formation was characterized by an increase in volcaniclastic material into the basin. The major period of volcanic activity was short, but deposition of the Monte Grande Formation continued with local sources supplying different types of sediments. As deposition of the Monte Grande Formation continued, the enviromental setting was in progressively deeper water. The depositional setting during Cotui time was a shallow marine carbonate platform and upper slope environment and, during Monte Grande time a steeper slope-basin environment developed Sampayo, 1992). The deepening trend was mostly controlled by increase in relative sea level probably due to subsidence in the back-arc basin. Finally, a gradational transition occurred and the Monte Grande was overlain by the basinal mudstone of the Yauco Formation. This gradual change probably represents the transition to another period of tectonic quiescence expressed in basinal sedimentation and the development of the Guaniquilla carbonate ramp to the west.

## Lajas Formation and Boqueron Basalt

The Boqueron Basalt and the Lajas Formation were originaly mapped by Mattson (1956, 1960) as part of the San German Formation and undiferentiated Cretaceous volcanic rocks (Fig. 3). The Boqueron Basalt is exposed north of the Lajas Valley and consists of dark-gray porphyritic, locally amygdular, basaltic lava togheter with minor breccia and tuff (Volckmann, 1983). The Boquron Basalt, as descrived by Volckmann, is overlain by epiclastic sandstone which are interbedded with grayish-purple porphyritic lava flows of the Lajas Formation. These rocks are interpreted by Volckmann (1983) to represent subaerial deposition.

However this formation represents one of the most problematic rocks in the Southwestern Igneous Province. The classification of volcanic rocks under the Lajas Formation is based on texture and its characteristic color. As a consequence all the grayish-red to grayish-purple lavas exposed in the Cabo Rojo-San German structural block are mapped as Lajas Formation. Stratigraphically it is described as occurring below the Cotui Limestone and the age of the formation was based on this stratigraphic position as middle Campanian or older (Volckmann, 1983). Recent $K^{40}$- $Ar^{40}$ dating of the Lajas Formation at the type section (intersection of roads PR-116 and PR-315) and at road PR-314, produced ages of 53.4 ± 1.4 Ma, and 51.6 ± 1.3 Ma respectively, a Lower Eocene age. As a result the purple volcanics below the Cotui Limestone and the volcanics associated with the Monte Grande event need to be mapped and describe as different formations.

## The Parguera Limestone

The Parguera Limestone is exposed south of the Lajas Valley in the Parguera-Ensenada Block. This limestone was first identified by Mitchell (1922) as the Ensenada Shale and San German Limestone and later was renamed as the Ensenada Formation by Slodowsky (1956). In 1960 Mattson mapped the unit as part of the Mayagüez Group. Detailed stratigraphic work in the Parguera Limestone was carried out by Almy (1965). He divided the formation into three members: the lower Bahia Fosforesente Member, the middle Punta Papayo Member, and the upper Isla Magueyes Member with a total thickness of 1150 meters in the Parguera area (Figure 3).

Throughout its outcrop belt, the Parguera Limestone lies unconformably on serpentinites, cherts and amphibolites of the Bermeja Complex, and locally on andesites of the Rio Loco Formation, or the Sabana Grande Andesites Almy 1969). The basal Bahia Fosforesente Member consists of medium-grained volcaniclastics derived from the underlaying sources, in a calcarenite matrix. The member grades upward to a medium-grained glauconitic calcarenite, and subsequently to a fine-grained bioclastic calcarenite with algae, echinoids, molluscs and foraminifera (Almy, 1969). The bioclastic calcarenite is interbedded with foraminiferal mudstones up-section, forming a gradational contact with the Punta Papayo Member. The Bahia Fosforescente Member was defined by Almy (1969) as a basal transgressive deposit, with a glauconitic zone indicating a time of slow clastic sedimentation and condensation. Calcarenite toward the top of the member interbedded with mudstones signaled a gradual deepening of the Parguera Basin. The Bahia Fosforescente Member was assigned a Santonian to Maastrichtian age by Pessagno (personal communication in Almy, 1965) based on foraminifera, and a Campanian to Maastrichtian age by Perkins (personal communication in Almy, 1965), based on rudistids bivalves. Almy (1965) defined the age of this member as Late Santonian to Early Campanian based on foraminiferal and rudistid bivalve assemblages.

The Punta Papayo Member consists of interbedded clay-rich mudstone containing radiolarians, foraminifera, sponge spicules, echinoid spines, and medium- to coarse-grained bioclastic limestone at the base and upper part of the member. Locally, cyclically bedded conglomeratic packstones with abundant trace fossils (<u>Planolites</u>, <u>Rhizocorallium</u>, and <u>Thalassinoides</u>) represent a turbidite sequence and exhibits soft sediment transport and deformation (Kauffman and Johnson, 1988, Kauffman et al., 1990). The Punta Papayo Member was interpreted by Almy (1965) to have been deposited in slightly deeper, quieter water, probably on the outer shelf or shallow slope, with periodic gravity injection of coarser bioclastic material and rare volcaniclastics. Almy (1969) assigned a Early to Late Campanian age range to this member based on microfaunal dates by Pessagno (personal communication in Almy, 1965). An erosional unconformity separates the Punta Papayo Member from the basal Isla Magueyes Member.

The Isla Magueyes Member contains informal basal, middle and upper divisions. The basal portion is composed of non-calcareous, poorly sorted, volcanic conglomerate. The middle portion is not exposed (Almy, 1969). The upper portion is exposed in the Isla Magueyes and consists of coarse-grained volcaniclastic sandstones interbedded with thin bioclastic limestones containing larger foraminifera and coarse bioclastic debris in the lower one-third. This is overlain by an andesitic flow which is then overlain by cyclically bedded bioclastic limestone with volcanic clasts in the lower part, clusters and isolated specimens of rudistid bivalves (Barrettia gigas) in the middle, and with sponges and rare rudistids near the top. Almy (1965) assigned to the member a Late Campanian to Maastrichtian age range based on foraminifera identification by Pessagno (personal communication in Almy, 1965), and rudistid content. A detailed stratigraphic section was measured in the type area by Kauffman and Johnson (1990).

**Itinerary**

Leave the Mayagüez Campus through the main gate and go south in road PR#2 to the intersection with road PR#100, towards the town of Cabo Rojo. On both sides of the road hydrothermally altered Yauco Formation is exposed.

STOP 1: At Km 3.0 serpentinites of the Bermeja Complex are exposed. Serpentinites are here overlaid by nickel laterite of the Guanajibo deposit.

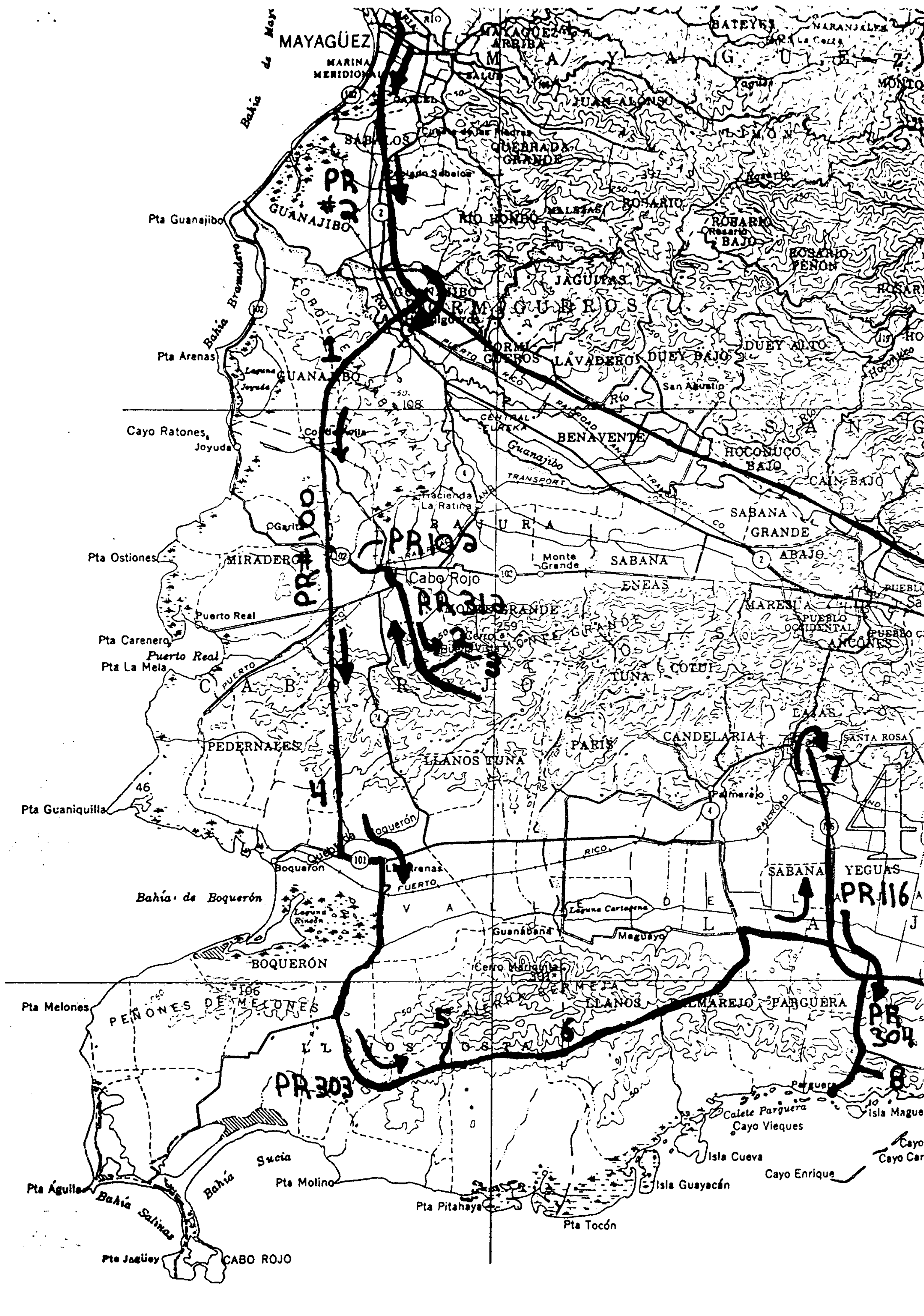
Continue south in road PR#100 to intersection with road PR#102, turn left. This road goes across the town of Cabo Rojo where we will take a right turn at the intersection with road PR#312. Continue this road to KM 9.8. Turn left in the rural road that goes north toward the Buena Vista area.

STOP 2: At the end of the rural road (top of the hill) a view of the Mayagüez-Sabana Grande structural block, the Guanajibo and Lajas valleys, and the Sierra Bermeja range can be observed.

Turn left (east) and continue to the dead end of the road.

STOP 3: The contact between the middle Campanian Cotui Limestone and the lower Upper Maastrichtian Monte Grande Formation is exposed in the farm at the end of the road.

Return to road PR#100 and continue south. The Guaniguilla Limestone is here exposed at Km11.9. This limestone was previously map as cotui Limestone and later redescribed by Santos (1990) and



MAYAGÜEZ
MARINA MERIDIONAL
Bahía de Mayagüez
PR #2
GUANAJIBO
Pta Guanajibo
Bahía Bramadero
Pta Arenas
Laguna Joyuda
HORMIGUEROS
JAGUITAS
LAVADEROS
DUEY BAJO
DUEY ALTO
San Agustín
BENAVENTE
HOCONUCO BAJO
CAIN BAJO
SABANA GRANDE
SABANA ENEAS
Cayo Ratones
Joyuda
Hacienda La Ratina
PR100
PR102
PR312
Cabo Rojo
MIRADERO
Pta Ostiones
Monte Grande
Puerto Real
Pta Carenero
Pta La Mela
CABO ROJO
PEDERNALES
LLANOS TUNA
TUNA
COTUI
PARIS
CANDELARIA
MARESUA
PUEBLO OCCIDENTAL
ANCONES
LAJAS
SANTA ROSA
Palmarejo
Pta Guaniquilla
Boquerón
Bahía de Boquerón
Laguna Rincón
BOQUERÓN
SABANA YEGUAS
PR116
Guanábana
Maguayo
Laguna Cartagena
Cerro Mariquita
SIERRA BERMEJA
LLANOS
PALMAREJO
PARGUERA
Pta Melones
PEÑONES DE MELONES
LLANOS COSTA
PR 303
PR 304
Parguera
Caleta Parguera
Cayo Vieques
Isla Cueva
Isla Guayacán
Cayo Enrique
Bahía Sucia
Pta Molino
Pta Pitahaya
Pta Tocón
Pta Águila
Bahía Salinas
Pta Jagüey
CABO ROJO
1
2
3
4
5
6
7
8

Rodríguez (1995) based on fosil content. Purple volcanics previously assigned to the Lajas Formation underlies the limestone.

STOP 4: The Boqueron Basalt is exposed at road PR#100 at Km 13.3. This formation was described by Mattson (1960) as Santonian to Lower Campanian based in its stratigraphic position below the Cotui Limestone. Recent $K^{40}$- $Ar^{40}$ dating produced a date of 68.8 ± 1.8 Ma. This date is stratigraphically higher than the Cotui Limestone and correlates the Boqueron Basalt with the Monte Grande event.

**Lunch Break**

Continue to the end of road PR#100 and turn left in road PR#101. Turn right at the intersection with road PR#301. Continue in this road until you reach the intersection with road PR#303 toward Las Palmas in the Sierra Bermeja.

Stop 5: A dirt road goes north from road PR#303 in Las Palmas area. Follow this road until the exposures of bedded chert.

Return to road PR#303 and continue this road (it becomes a dirt road) toward the east along the foothill of the Sierra Bermeja until Km 7.8.

STOP 6: A road outcrop here shows serpentinites, amphibolites, and andesite in what is an example of the nature of the outcrop in the Bermeja Complex.

Continue east in road PR#303 to the intersection with the road PR#305. Continue this road to the T-junction with the PR#116 and turn left.

STOP 7: Road PR#116, Km 0.5. The type section of the Lajas Formation is here exposed.

Turn back toward the south in road PR#116. Turn in the intersection with road PR#304 toward the Parguera Village.

STOP 8: Outcrop of the Parguera Limestone in the Mirador at Parguera.

## SELECTED REFERENCES

Almy, C.C., Jr., 1965, Parquera Limestone, Upper Cretaceous Mayaqüez Group, southwest Puerto Rico: Houston, Texas; Rice University; unpublished Ph.D. thesis, 203 p.

Almy, C.C., Jr. 1969, Sedimentation, tectonism in the Upper Cretaceous Puerto Rican portion of the Caribbean Island Arc: Transc. Gulf Assoc. Geol. Sci., v. XIX, p. 269-279.

Burke, K. Fox, P.J., and Sengor, A.M.C., 1978, Buoyant ocean floor and the evolution of the Caribbean, Journal of Geophysic Research, vol. 83, p. 3949-3954.

Cox, D.P., Marvin, R.F., M"Gonigle, J.W., McIntire, D.H., and Rogers, C.L., 1977, Potassium-argon geochronology of some metamorphic, igneous, and hydrothermal events in Puerto Rico and the Virgin Islands, U.S. Geological Survey Journal of research, 5, 689-703.

Curet, A.F., 1986, Geologic map of the Mayagüez and Rosario Quadrangles, Puerto Rico: U.S. Geological Survey Miscellaneous Investigation Series, Map I-1657, scale 1:20,000.

________, 1981, The geology of a Cretaceous-Tertiary volcano-sedimentary sequence in the Mayagüez and Rosario quadrangles in west-central Puerto Rico: unpublish Ph.D. thesis, University of California at Santa Barbara.

Dommelen, H. van, 1971, Ontogenic, phylogenic and taxonomic studies of the American species of Pseudovaccinites and of Torreites and the multiple fold Hippuritids: Ph.D. thesis; 125p..

Johnson, C.C., and Kauffman, E.G. 1990, Parguera Limestone in Kauffman, E.G. editor, Field Guide to the Cretaceous-Cenozoic carbonate platform and reefs of western Puerto Rico: Department of Geology, University of Puerto Rico and the University of Colorado.

Joyce, J., Smith, A.L., Schellekens, J.H., and Johnson, C.C., 1987, Field guide to the Sixth Annual Symposium of Caribbean Geology; Department of Geology, University of Puerto Rico.

Kauffman, E.G., 1977, The evolution and ecology of Caribbean Mesozoic reefs: Eighth Caribbean Geological Congress, Curacao, Supplemental Abstract Volume, pp. 1-2.

Kauffman, E.G., 1965, The Upper Cretaceous Inoceramus of Puerto Rico: 4th Caribbean Geological Conferences, Trinidad, p. 203-218.

Kauffman, E. G., and Johnson, C., 1988, The morphological and ecological evolution of Middle and Upper Cretaceous reef-building rudistids: Palaois, Reefs issue, v.3, p. 194-216.

Kauffman, E.G. and Sohl, N.F., 1979, Rudistids, in The Encyclopedia of Paleontology, Fairbridge, Rhodes, and Jablonski, eds., Dowdon, Hutchinson & Ross, Inc., p. 723-737.

Krushensky, R.D., and Monroe, W.H., 1979, Geologic map of the Yauco and Punta Verraco Quadrangle; Puerto Rico: U.S. Geological Survey investigations Map I-1147, scale 1:20,000.

———, and Curet, A.F., 1980, Geologic map of the Monte Guilarte quadrangle; Puerto Rico: U.S. Geol. Surv. Miss. Inv. Series Map I-1556, scale 1:20,000.

Mattson, P.H., 1973, Middle Cretaceous nappe structure in Puerto Rico ophiolites and their relation to the tectonic history of the Greatter Antilles: Geological Society of America Bulletin, vol. 84, p. 21-38.

———, 1956, Geology of the Mayagüez area, Puerto Rico: unpublished P.H.D. thesis, Princeton University, 166 p.

———, 1960, Geology of the Mayagüez area, Puerto Rico: Geological Society of America Bulletin, v. 71, no. 3, p. 319-362.

Mattson, P.H., Pessagno, E.A., Jr., and Helsley, C.E., 1972, Outcropping layer A and A" correlation in the Greater Antilles: Geological Society of America Memoir 132, p. 57-66.

Mattson, P.H., and Pessagnon, E.A., 1974, Tectonic significance of Late Jurassic-Early Cretaceous radiolarian chert from Püerto Rico ophiolite [Abst]: Geological Society of America Abstracts with programs, v. 6 (7), p. 859.

Mattson, P.H., and Pessagno, E.A., 1979, Jurassic and Early Cretaceous radiolarians in Puerto Rico ophiolite-Tectonic implications: Geology, v.7, p.440-444.

Mitchell, G.J., 1922, Geology of the Ponce district, Porto Rico: New York Academy of Sciences, Scientific Survey of Porto Rico and the Virgin Islands, v. 1, pt.3, p. 229-300.

Montgomery, H.M., Pessagno, E.A., Lewis, J.F., and Schellekens, J.H., in prep., Paleogeographical history of Jurassic terrains in Puerto Rico and Hispaniola.

Montgomery, H.M., Pessagno, E.A., and Pindel J.L., 1994, A 195 Ma Terraine in a 165 Ma Sea: Pacific Origen of the Caribbean Plate: GSA Today, vol. 4, No. 1, pp. 1-6.

Muños, I.M., 1990, Biostratigraphy and paleoecology of the radiolarian-rich interval, Parguera Limestone, El Combate and Punta Papayo, Puerto Rico; Unpublish undergraduate thesis, 22 p..

McIntyre, D.H., 1975, Geologic Map of the Maricao quadrangle Puerto Rico: U.S. Geol. Survey Misc. Geol. Inv. Map I-918...

Santos, Hernan, 1990, The stratigraphy, paleoenvironments, and biofacies of the Cotui Limestone: Cretaceous of Southwestern Puerto Rico; unpublish Masters thesis, University of Colorado.

Santos, H. and Kauffman, E.G., 1989, Regional structural and volcanic events associated with the Cotui Limestone-Sabana Grande contact interval (Late Campanian) of Southwestern Puerto Rico: 12Th Caribbean Geological Conference, San Croix, U.S. Virgen Island; Abstract.

Schellekens, J.H., 1991, Late Jurassic to Eocene geochemical evolution of volcanic rocks of Puerto Rico: Geophisical Research Letters vol. 18 (3), p. 533-556.

Schellekens, J.H., Montgomery, H., Joyce, J., and Smith, A.L., 1989, Petrology and paleontology of the Bermeja Complex, Puerto Rico, Questions about the origin of basal terrains of the northern Caribbean (Abstr): Abstract with programs Geol. Soc. America. v. 21 (1) p. 40.

Schellekens, J.H., Montgomery, H., Joyce, J., and Smith, A.L., 1990, late Jurassic to Late Cretaceous development of island arc crust in southwestern Puerto Rico: Transaction of the 12th Caribbean Geological Conference, St. Croix, U.S. Virgin Island, Aug. 1989, edited by Larue, D.K., Draper,G., p. 268-281.

Schellekens, J.H., Santos,H., Almy,C.C., and Jansma, P., 1993, Field Guide to the 12th Symposium on Caribbean Geology, University of Puerto Rico, Mayaguez, 65p..

Slodowski, T.R., 1956, Geology of the Yauco area, Puerto Rico: Princeton University, unpublished Ph.D. thesis, p. 84-92.

Sohl, N.F., and Kollman, H.A., 1985, Cretaceous actaeonellid gastropods from the Western Hemisphere: U.S. Geological Survey Professional Paper 1304.

Trechmann, C.T., 1922, The Barretia beds of Jamaica: Geological Mgasine, vol. 59, p. 501-514.

Volckmann, R.P., 1984a, Geologic map of the Puerto Real Quadrangle, southwest Puerto Rico: U.S. Geological Survey, Miscellaneous Investigations Series, Map I-1559, scale 1:20,000.

______1984b, Geologic map of the San Germán Quadrangle, southwest Puerto Rico: U.S. Geological Survey, Miscellaneous Investigation Series, Map I-1558, scale 1:20,000.

______1984c, Geologic map of the Cabo Rojo and Parguera Quadrangles, southwest Puerto Rico: U.S. Geological Survey Miscellaneous Investigation Series Map I-1557, scale 1:20,000.

______1983, Upper Cretaceous stratigraphy of southwest Puerto Rico: U.S. Geological Survey Bulletin 1537-a, p. A73-A83.

Woodward, S.P., 1862, Some accounts of Barretia, a new and remarkable fossil shell from the Hippurite Limestone of Jamaica: Geologist, vol. 5, p. 372-377.

# 16th Annual Symposium on Caribbean Geology

## Remote sensing in the Earth Sciences

## Field Guide
## DAY 2

James Joyce
Hernán Santos

Department of Geology
University of Puerto Rico
Mayagüez Campus

## Day 2 Geomorphic Provinces of Northwestern Puerto Rico

The purpose of today's trip is to see the geomorphic features that define the provinces we can see on the radar and topographic maps. The material used in the guide has been taken from Bruce Taggert's Ph.D. thesis, Stanley Frost's book on the Oligocene Reef Tracts in Puerto Rico and USGS maps and publications. We appreciate the work of these geologist and are grateful for being able to use their figures.

## Western Puerto Rico Ridge and Valley Province

Leaving Mayagüez we cross into the Añasco Valley. 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. The Añasco Valley is considered to be a south side down, half graben and the on land 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 lava 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

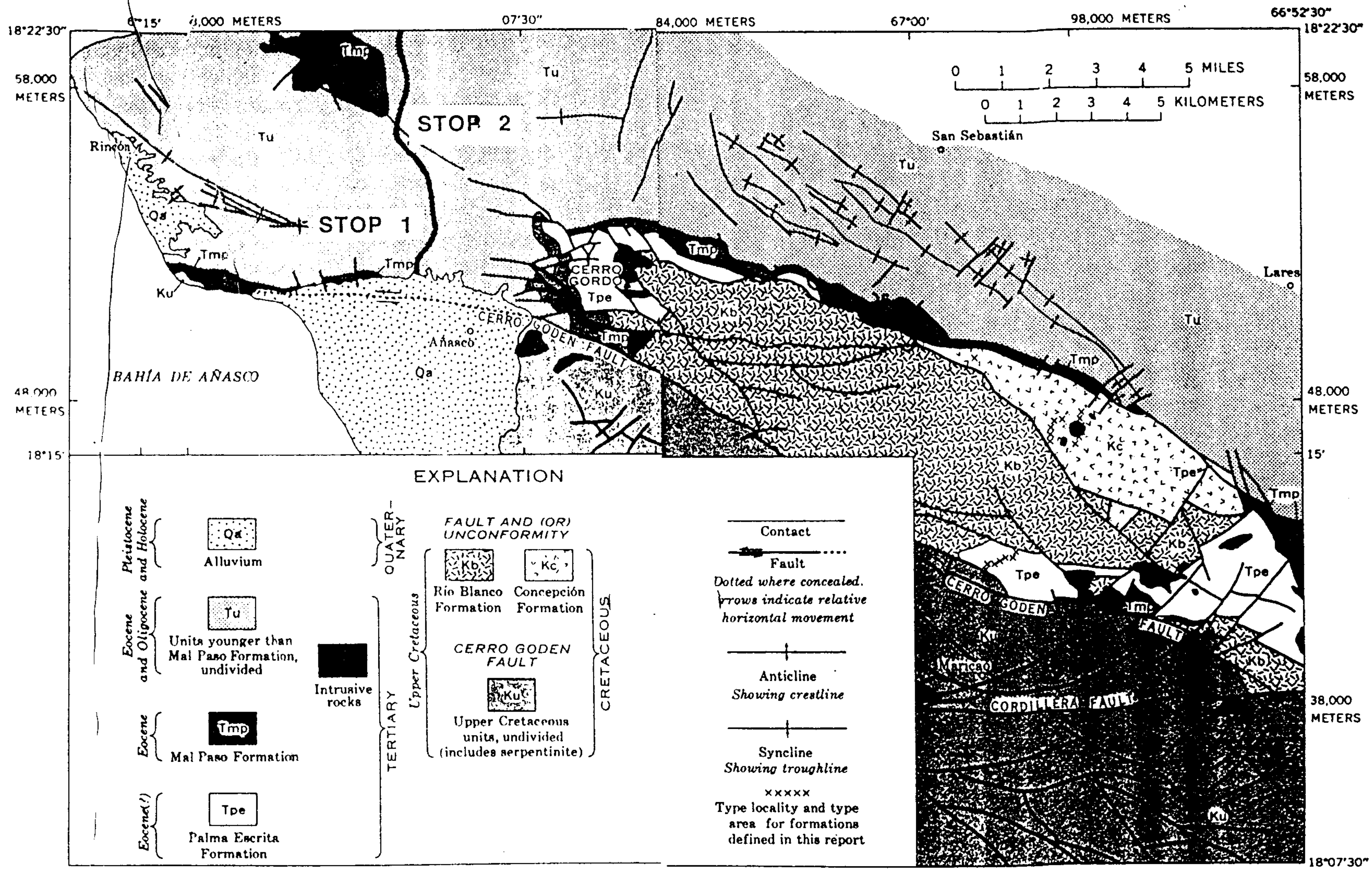
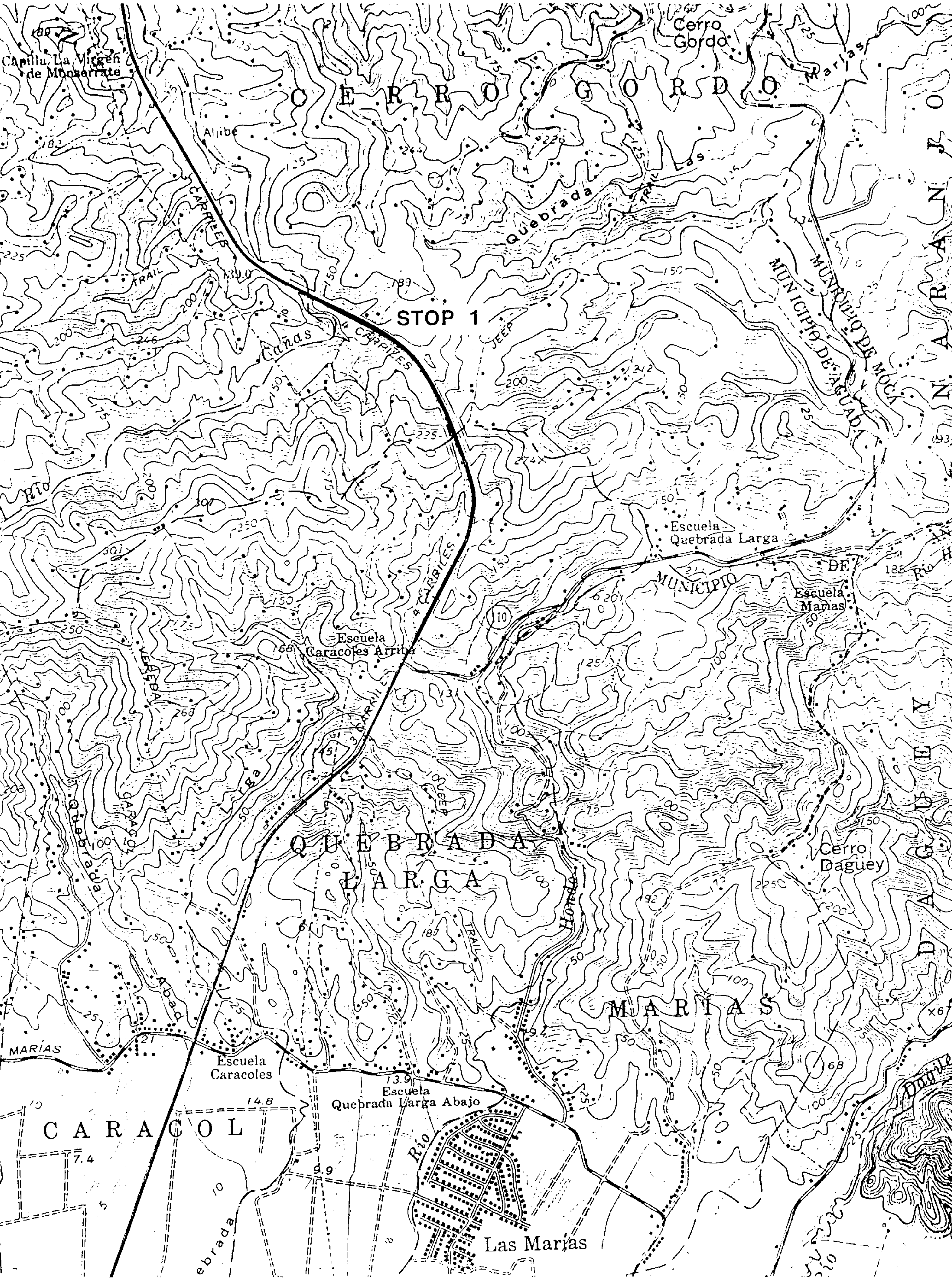



FIGURE 2.—Generalized geologic map of part of western Puerto Rico showing stratigraphic units cited in text. Generalized from J.M. Aaron (unpub. data, Rincón quadrangle), McIntyre (1971, 1973), and Tobisch and Turner (1971).


STOP 1
CERRO GORDO
Cerro Gordo
Capilla La Virgen de Monserrate
Aljibe
Quebrada Las Marías
TRAIL
CARRILES
4 CARRILES
JEEP
Río Cañas
MUNICIPIO DE MOCA
MUNICIPIO DE AGUADA
Escuela Quebrada Larga
MUNICIPIO DE
Escuela Marías
Escuela Caracoles Arriba
VEREDA
Quebrada Larga
QUEBRADA LARGA
Cerro Dagüey
Hondo
Quebrada Abad
MARÍAS
Escuela Caracoles
Escuela Quebrada Larga Abajo
CARACOL
Río
Las Marías

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 spheriodal weathering of coarser grained layers and intense fracturing of the thinner bedded, fine grained layers.

**Stop 1 Hydrothermally Altered and Chemically weathered intrusive rocks**

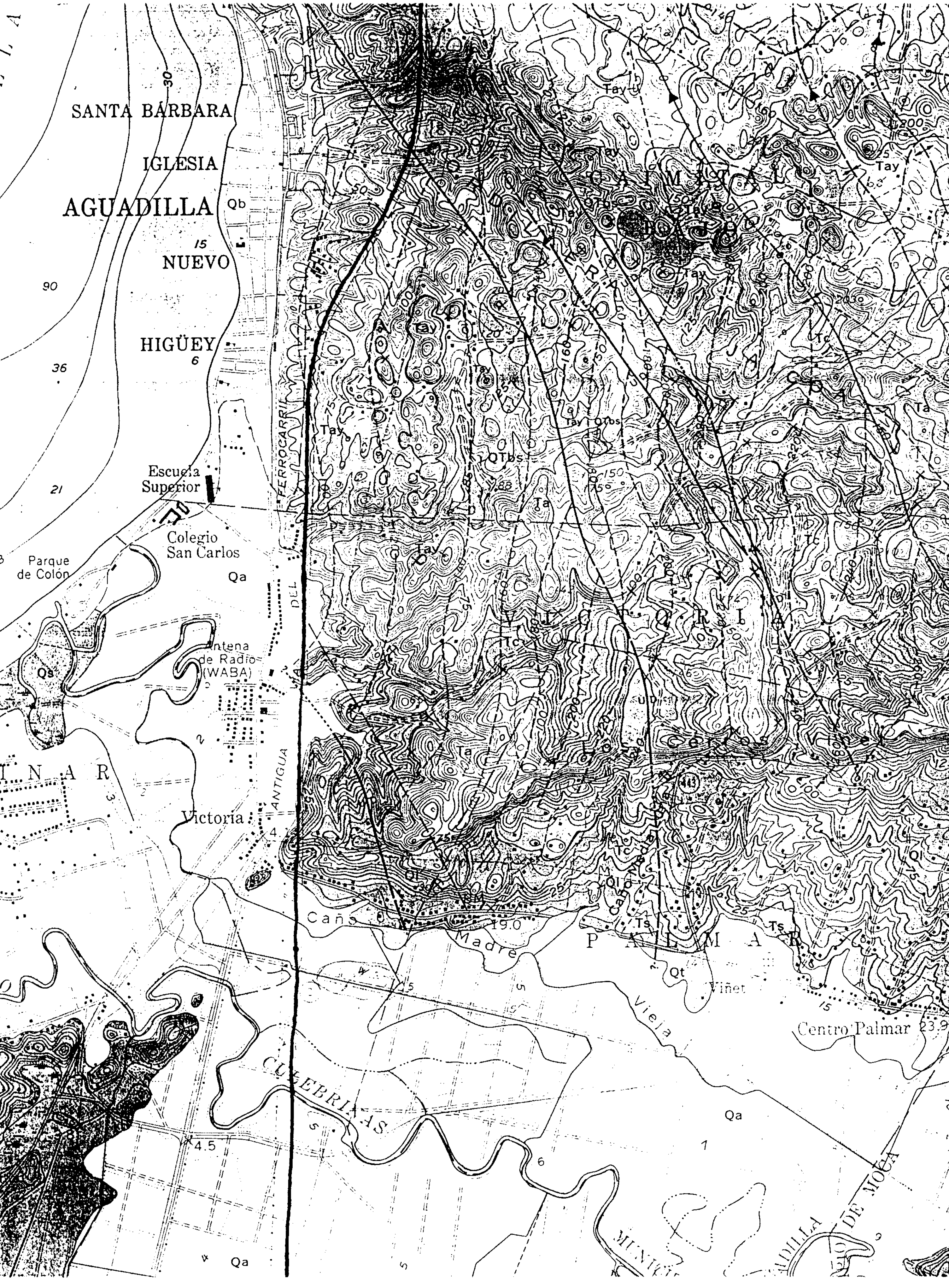
Hydrothermal alteration and deep chemical weathering of intrusive rock have lead to the erosion of a valley in the La Cadena Ridge. Numerous quartz veins evidence the hydrothermal activity. Only the intrusive rocks show the development of thick red laterite and saprolite soil.

**Stop 2 Culebrinas Formation Mega Conglomerate and sandy turbidites.**

Coarser grained facies of the turbidite sequence are exposed in new rock cuts. Notably the degree of weathering and erosion is much less than in the intrusive rocks. Most of the clasts are volcanic porphyry indicating a volcanic source land for the deposits

From here we continue into the Rio Culebrinas Valley which is also interpreted as a half graben and an on land continuation of the Mona Canyon fault system. Very little seismicity is associated with valley. The last large earthquake to affect Puerto Rico however, did occur offshore in the Mona Canyon. 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.

The Rio Culebrinas was probably one of the great Quaternary river systems of Puerto Rico that continued eastward into the Rio


SANTA BÁRBARA
IGLESIA
AGUADILLA
NUEVO
HIGÜEY
Qb
Escuela Superior
Colegio San Carlos
Parque de Colón
Qa
Antena de Radio (WABA)
Qs
Victoria
FERROCARRIL
DEL
ANTIGUA
Tay
Ta
Tc
QTbs
Ql
Ts
Qt
Caño
Madre
PALMAR
Viñet
Centro Palmar
Vieja
CULEBRINAS

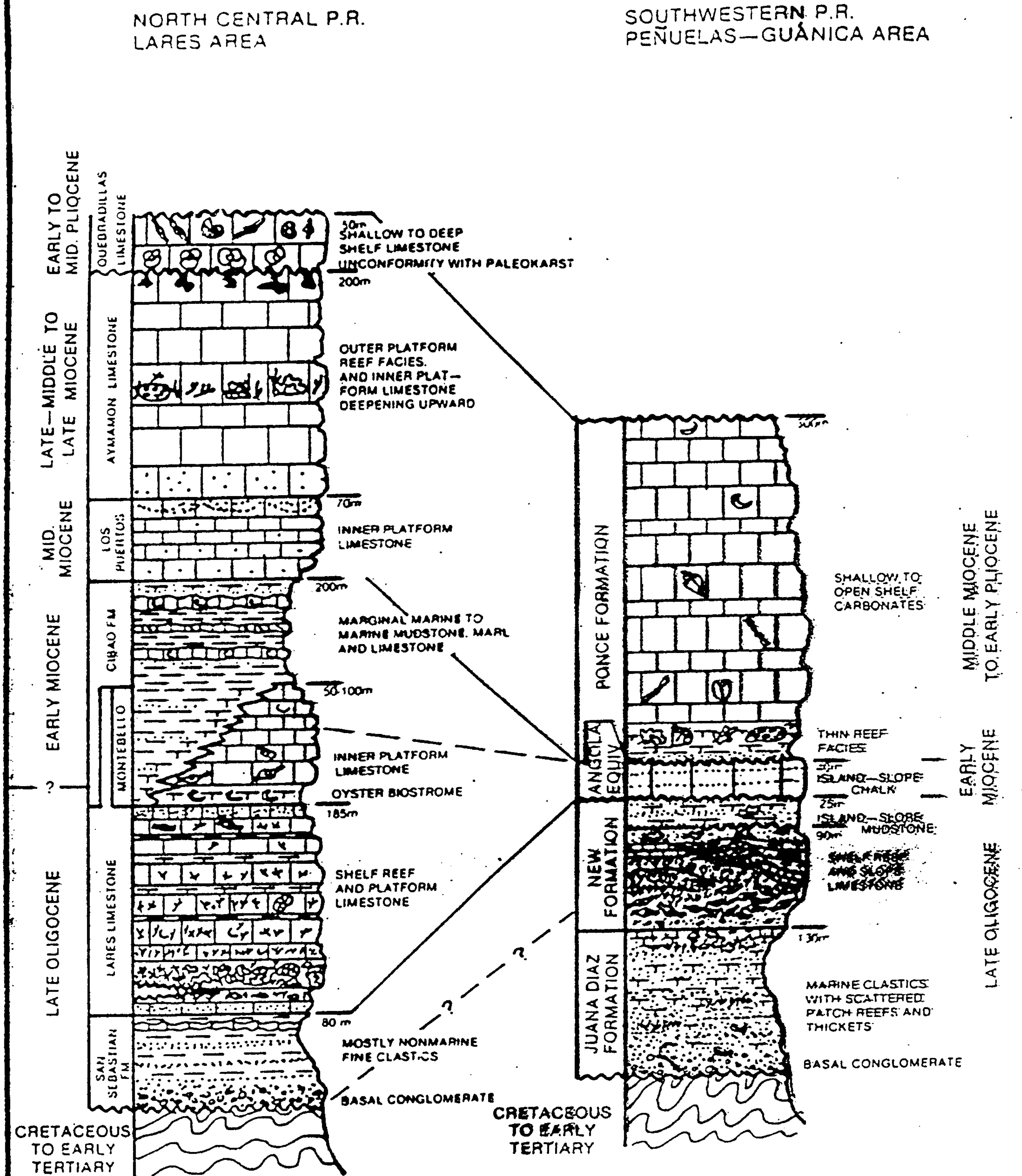



FIGURE . OLIGOCENE TO PLIOCENE STRATIGRAPHIC SEQUENCE, NORTH CENTRAL AND SOUTHWESTERN PUERTO RICO.

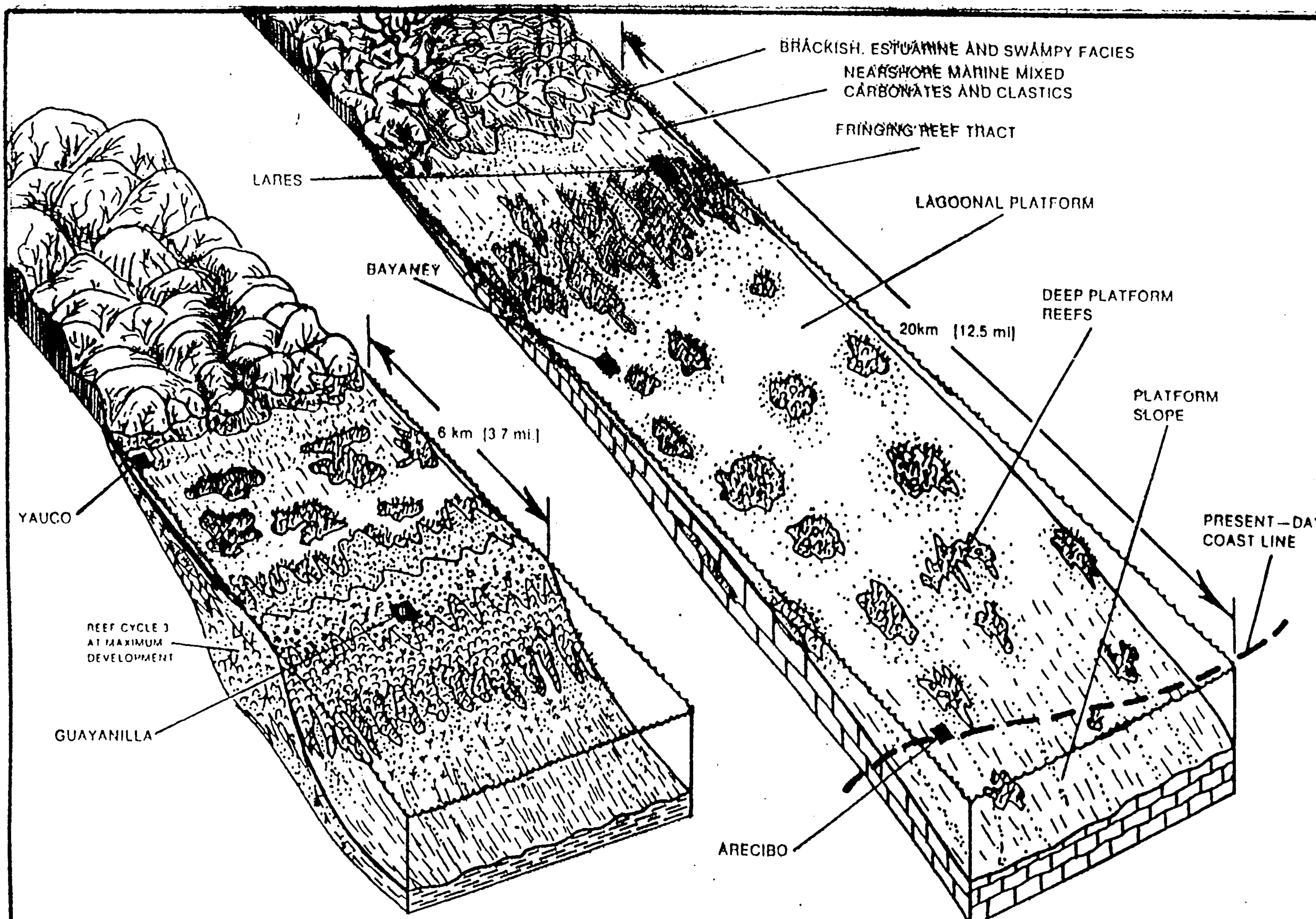



FIGURE . COMPARISON OF THE PEÑUELAS—GUÁNICA AND LARES CARBONATE BUILDUPS.

Blanco valley as far east as Adjuntas. Stream piracy of the Rio Blanco-Culebrinas River system by El Rio Grande de Añasco y de Arecibo diverted most of its water into the Añasco and Arecibo valleys. Low lying and thick fluvial deposits of the Oligocene San Sebastian Formation underlie the valley floor from San Sebastian to Moca. The low elevations and extent of these deposits suggest the Culebrinas and Rio Blanco valleys were the site an important river system in Oligocene.

**Northern Limestone Plateau Karst Province**

Deposition of the north coast limestone formations began in the Oligocene following the end of volcanism and a period of intense deformation in the Eocene. Limestone deposition was continuous up to the late Miocene and began again in the Pliocene. The presence of and erosional unconformity between Miocene and Pliocene limestones and deeper water character of the Pliocene deposits suggest a tectonic event in the Late Miocene.

As the we rise above Aguadilla on to the Tertiary limestone plateau, we pass along the edge of cock pit karst terrain developed on the Aguada and Aymamón Limestone. Linear patterns in the karst are due to NNW trending faults and folds. Presumably these deformational features are related to Quaternary faulting along the eastern margin of the Mona Canyon.

**Northwestern Limestone Plateau Marine Terrace Province**

North of Borinquen, cock pit karst features are lost due to Quaternary wave cut terraces that beveled this terrain into low hills and plains. Passing through Quajataca, Quaternary uplift of the northern limestone plateau is evidenced by the Rio Quajataca canyon that is deeply entrenched through the Camuy (Quebradillas) and Aymamón Limestones

At Quebradillas we turn north on PR-485 and cut across the Quaternary wave cut terraces and marine deposits to Puerto Hermina and the canyon of Quebrada Bellaca.

**Stop 3 San Jose Quaternary Beach Sandstone and Eolianite.**

These marine terrace deposits occur on the Aymamón Limestone at an elevation of 50 meters above present sea level. Fine grained lithic grainstones with little bedding occur along the base of

T I C
O C E
STOP 4
STOP 3
Qb
Qab
QTbs
FERROCARRIL
Tay
Tca
Tierra
S A N J O S E
Quebrada
Bellaca
Pozo del Rey
BM 137
Escuela Segunda Unidad Rivera
MUNICIPIO DE QUEBRADILLAS
MUNICIPIO DE CAMUY

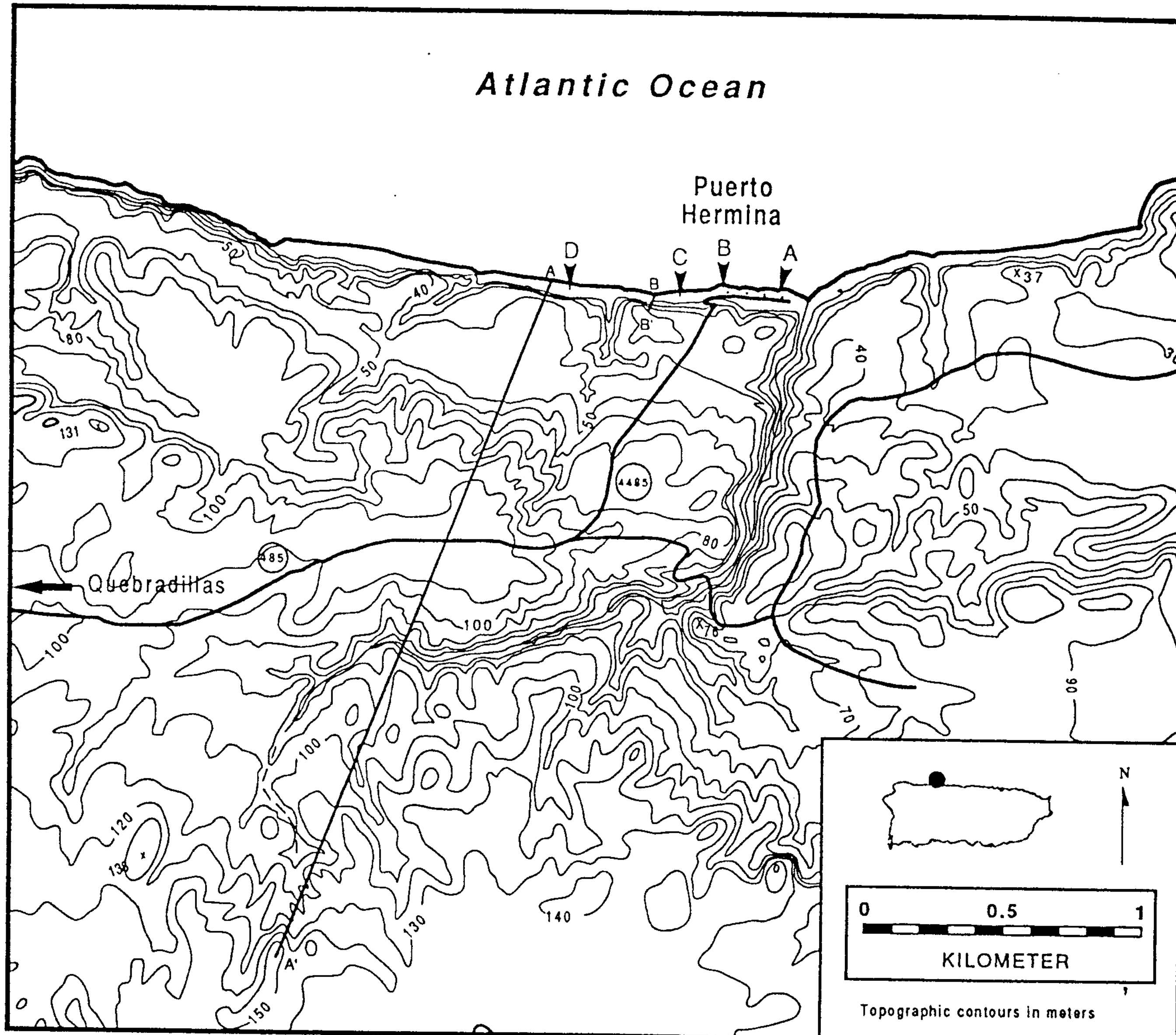



**FIGURE** Location map for the Quebradillas Region.

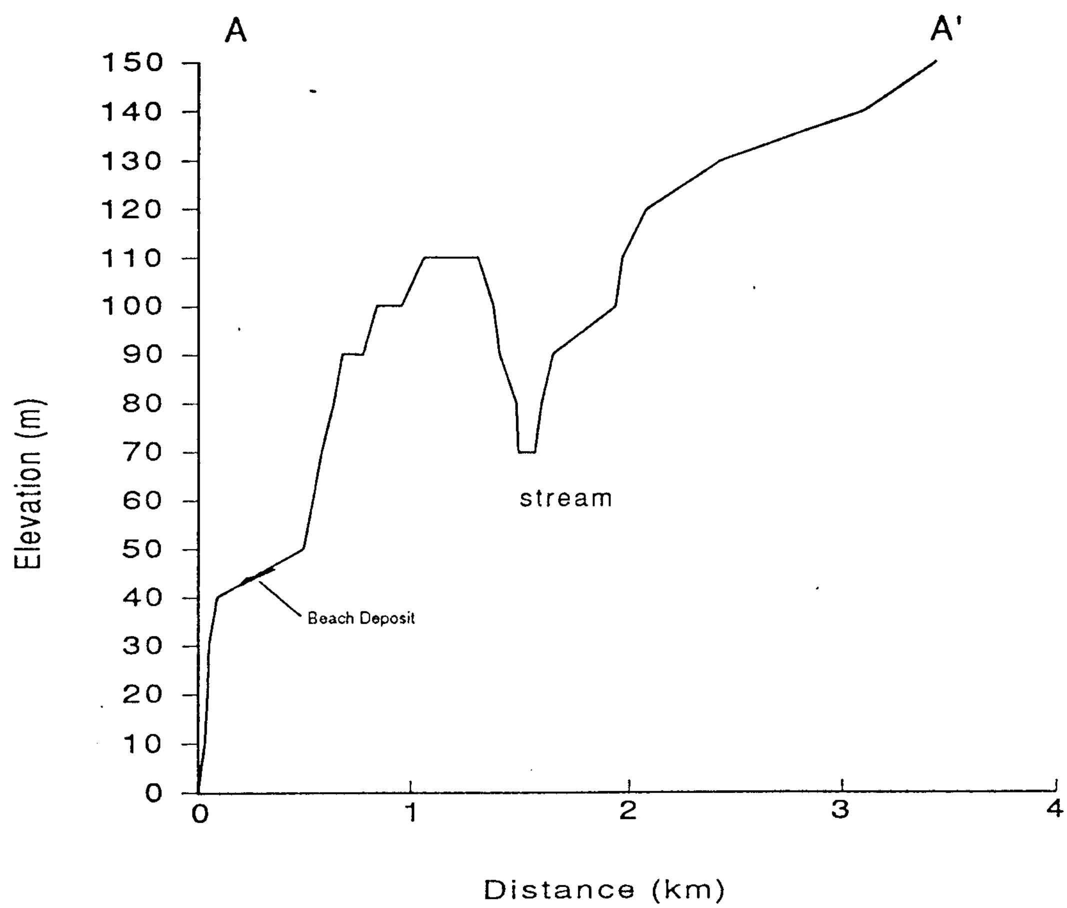



FIGURE . Topographic profile showing the higher marine terrace surfaces in the Puerto Hermina hinterland. Designated as A-A' in Figure

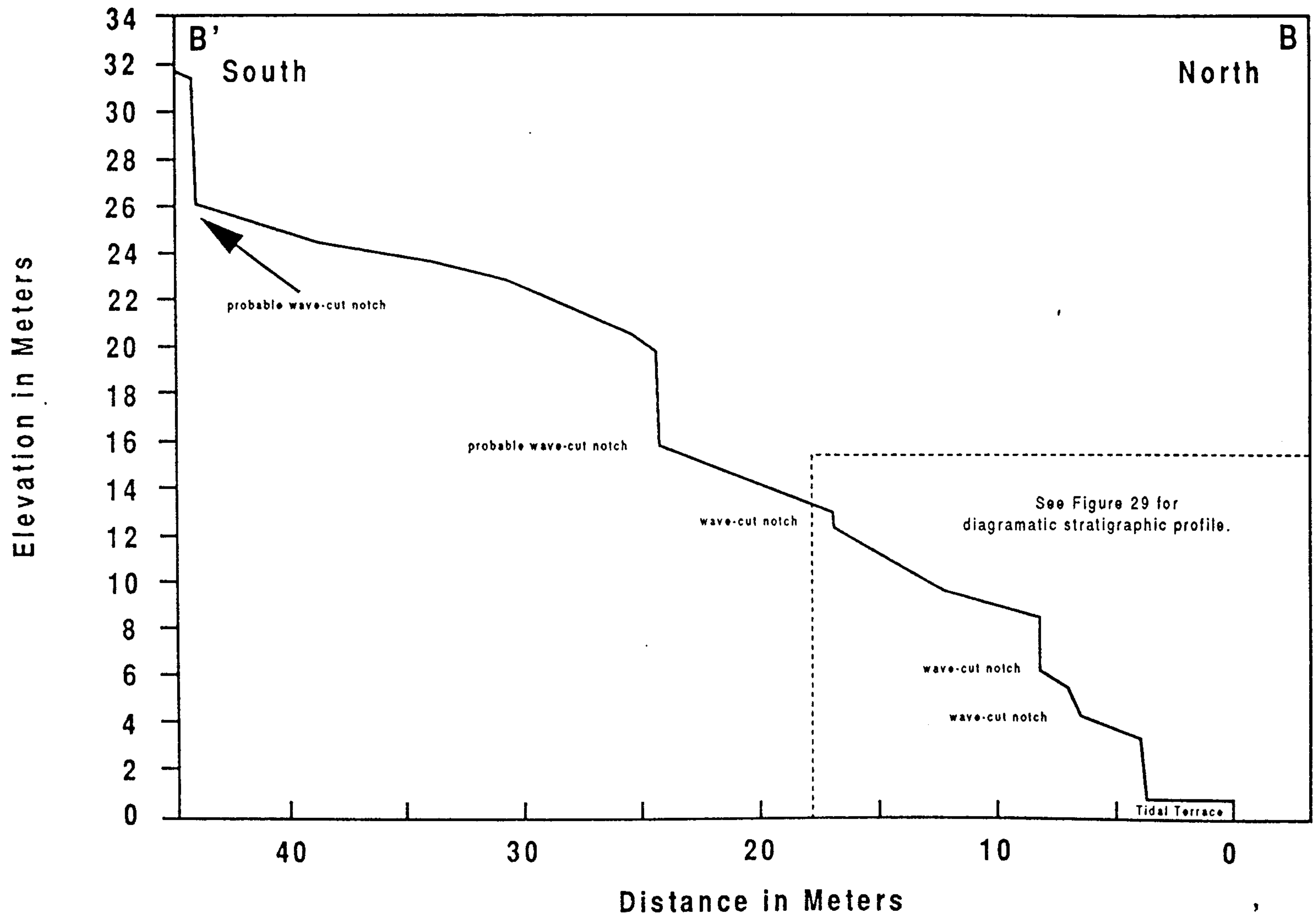



FIGURE Topographic profile through the Puerto Hermina site. Designated as B-B' in Figure

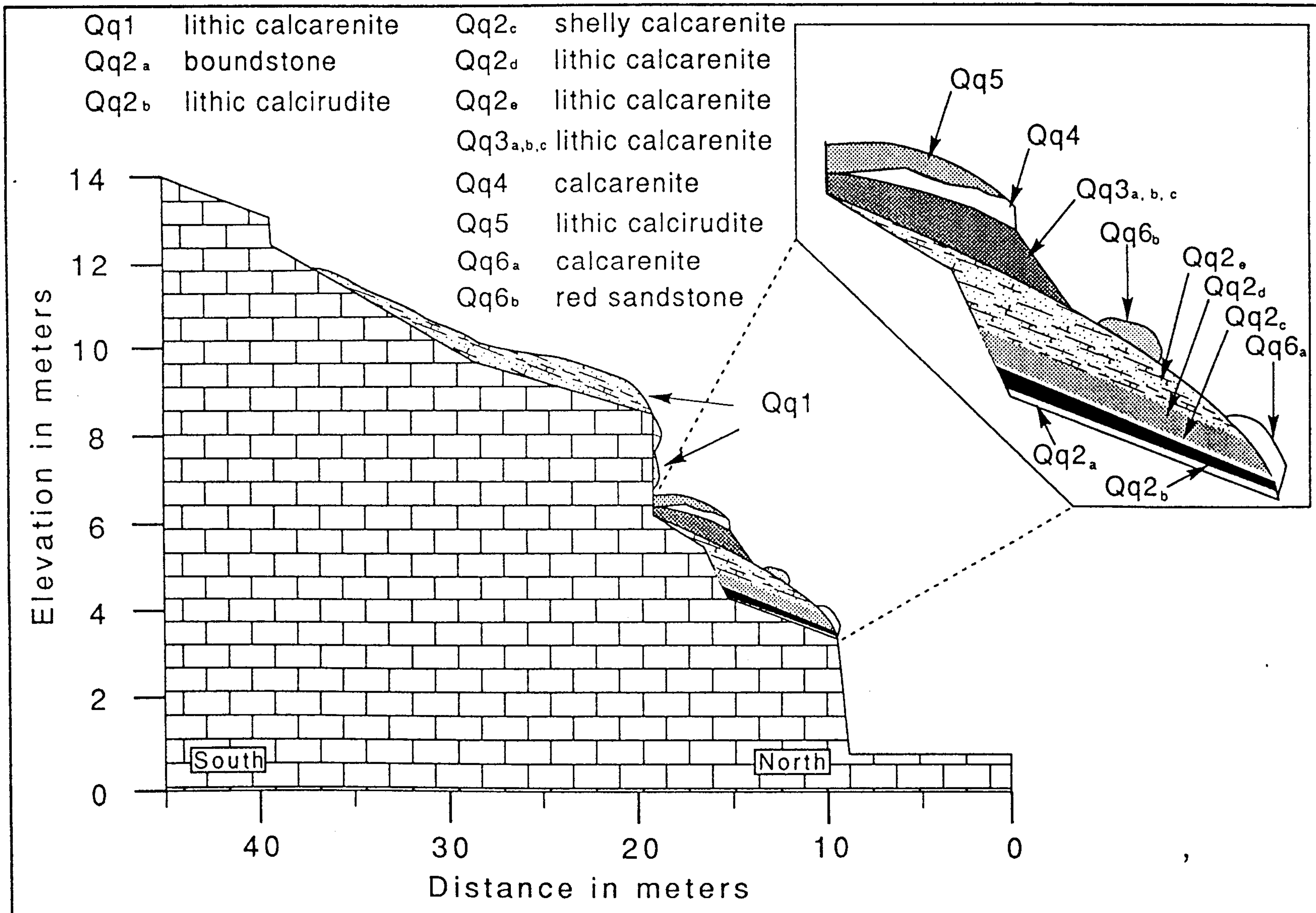



**FIGURE** Diagramatic stratigraphic profile of Quaternary marine terrace deposits at Puerto Hermina at site of Topographic Profile B-B' from 0-14 m. No marine terrace deposits are found above 14 m the urbanization and were probably formed along the shoreline. Thin bedded and inclined layers of fine grained lithic grainstone are seen in cuts made for the construction of the urbanization. These deposits are preserved coastal wind dunes.

**Stop 4 Puerto Hermina-Canyon de Quebrada Bellaca**

This site shows a variety of shoreline erosional and depositional features including sea cliffs, sea caves, wave cut notches, wave cut terraces, coral bearing basal conglomerates, marine sandstones and limestone colluvial breccias. This area formed an important part of Bruce Taggert's (USGS, San Juan) Ph.D. thesis (UPRM-Marine Sciences). We have included figures from Bruce's thesis that show topographic and stratigraphic profiles for the area. Taggert retrieved corals from a basal conglomerate that produced $^{230}Th/^{234}U$ radiometric ages of 133 and 132 thousand years before present. Somewhat younger ages of 120 thousand years were obtained for corals in an overlying conglomerate unit. These ages were consistent with his coral age studies for other terrace deposits at similar elevations from locations from Rincon to Bayamón. Comparison of the maximum elevations (12 meters) of the 120-133 thousand year old marine terrace deposits with the world wide sea levels for that time of 6 meters above present sea level suggests Puerto Rico has an uplift rate of about 5 meters per 100 thousand years. This uplift rate suggests the deposits at the previous stop are 900 thousand to 1 million years old.

From Quebradillas we continue east along PR-2 through the limestone terrain. Cock pit karst dominates the hilly terrain to south. Numerous solution features can be seen in the new road cuts between Camuy and Hatillo. Sinkholes in the limestone have been filled with red clayey laterite soils and quarts rich blanket sand deposits. We continue on to PR-22 to the intersection of PR-10 and the Rio Grande de Arecibo canyon.

**Northern Limestone Plateau Canyon**

**Stop 5 Rio Grande de Arecibo Canyon**

The meandering Rio Grande has been entrenched by late Tertiary and Quaternary uplift of the limestone plateau. In the lower valley features like abandoned caves and hanging valleys attest to the down cutting of the river system and lowering of the ground water table. Undercutting by the river and rock falls on extension fractures maintain the vertical walls of the canyon. The northward tilt of the limestone layers is also evident. In the upper part of the canyon we can see entrenched meanders with erosion notches at the cliff base and a karstified abandoned meander terrace (la parada verde).

### Northern Limestone Plateau Margin Landslide Province

We rise up from the valley through the limestone onto the newly completed section of PR-10. This new section of PR 10 crosses from the northern Puerto Rico limestone karst terrain into the late Cretaceous volcanic rocks that lie along the margin of the Utuado granodiorite pluton. The new road runs along the north slopes of the Caguana River valley before reaching the new bridge that crosses this river. The lower portions of these slopes are formed on Late Cretaceous and Early Tertiary volcanic rocks. The upper slopes are formed on middle Tertiary (Oligocene) limestone and underlying terrigenous deposits. Most of the middle slopes are formed on landslide deposits that overly the contact between the older volcanic rocks and younger limestones. Land sliding along these middle slopes are largely controlled by two major factors. Weaker clayey layers in the San Sebastian and underlying volcanic rocks lie below hard crystalline limestone of the Lares Formation. Ground water collected over an extensive area of karst in the Rio Abajo Forest drains out along the platform margin through these weaker deposits below the limestone. Construction of the highway along this landslide zone has required very expensive remediation design.

### Stop 6 Landslide PR-10, Rio Caguana

This is the last of the landslides that have plagued the construction of the new road. Following excavation of the road cuts on the north side collapsed in a large landslide and ground water burst forth from the ruptured slope. Continuous failure of this material required remediation to prevent enlargement of the landslide and allow for the construction of the roadway. Nicholson Construction Company designed and constructed Insert Walls that essentially pin the landslide to the underlying stable volcanic rock. Unfortunately after their construction, inclinometer data indicated that the landslide and the Insert walls continued down slope motion. Motion of few inches occurred during periods of heavy rainfall and during Hurricane Hortense these down slope motions ruptured parts of the Insert Wall. The reason the Insert walls initially failed to stop the landslide was that basal rupture surface of the landslide was located much deeper in the volcanic rock basement than previous geotechnical studies had indicated. The landslide mass and thus the driving force were actually much greater than the what the Insert Walls were originally designed for. More detailed studies have been and are being undertaken of the landslide and the Insert walls are being fortified and pinned deeper into the volcanic rock basement. Slope and drainage improvements have also been made to reduce the mass and ground water pressure in the landslide. The following descriptionsa and explanations are taken from a study supported by Nicholson Construction Company.

The Utuado Quadrangle map shows the approximate location of PR 10 in the area of study and the extensive landslide deposits that cover this area. The volcanic rocks that make the base of the roadway and landslide are largely of the Alonzo Formation (Ka) which is composed of purplish to brownish red or gray, tuffs, volcanic breccias and andesite lava. The Alonzo volcanic rocks in this area are noted, on the geologic map (Figure 1) and descriptions, to have suffered the most intense hydrothermal alteration in the quadrangle. Unconformably overlying the Alonzo Formation is the San Sebastian Formation (Ts) which is described as mostly red clay with abundant pebbles of volcanic rocks and local bedded sand layers. Directly overlying the San Sebastian Formation is the Lares Formation (Tl) which is composed of a lower thin bedded to flaky limestone with grains of limonitic rock and an upper thin bedded pink to yellowish very hard limestone. The landslide deposits (Ql) are neither described nor discussed on the quadrangle map.

Roadway excavations have exposed the volcanic rocks of the Alonzo Formation , the unconformity and basal sediments of the San Sebastian Formation and the pre-existing Quaternary landslide deposits. The Lares Limestone is exposed in cliffs on the upper slopes above the site. The upper San Sebastian Formation and the contact with the Lares Formation are covered by limestone colluvium and vegetation. The Alonso Formation is composed of three major rock types: Purple and reddish black feldspar porphyries and breccias: Gray and bluish gray feldspar porphyries and hydrothermally altered rocks. The color difference between the first two is probably due to hydrothermal alteration as their boundaries are usually transitional and show no structural organization. The gray rocks dominate the exposures on the east side of the site , where as the reddish rocks occur mostly on the west side of the site . Hydrothermal alteration of the gray andesite porphyries produced disseminated quartz, pyrite and sericite or other clay minerals. Locally intense hydrothermal alteration of these rocks has produced gray and occasionally reddish pyrite-clay veins and zones composed of angular rocks fragments in a pyrite-clay matrix . Hydrothermal alteration of the reddish colored volcanic rocks produced mostly Fe and other oxides. Locally the alteration formed green malachite rich zones and veins of red phyllitic claystones . Pyrite crystals were not observed in the reddish colored volcanic rocks.

The San Sebastian Formation is composed of inter layered sandy gravels, sands and silty clays. Most of the sand and gravels are clayey as a result of saprolitic weathering of their volcanic grains. Upper slope San Sebastian exposures are oxidized and reddish in color while sandy clays and gravels directly above the unconformity over the gray Alonzo Formation volcanic rocks are usually green to gray in color. Several lignitic layers were observed with the gray-green gravels and clays. No pyrite crystals or other evidence of hydrothermal alteration were observed in the San Sebastian sediments.

The Lares limestone occurs only as colluvium at the site. The limestone clasts are mostly fossliferous sandy limestones with some crystalline hard limestone and coarsely crystalline calcite.

The Quaternary landslide deposit is well exposed on excavated slopes on the south side of the roadway . The deposit is composed of three different geologic units: the coarse grained, cream colored Limestone colluvium on top, deformed and disrupted reddish San Sebastian sediments in the middle and rupture zone-fault bounded blocks of blue-gray Alonzo volcanic rocks. The contacts between the three units are marked by foliated clay and interpreted as ancient landslide rupture or slip surfaces.

The internal structure of the ancient landslide deposit is highly complex and composed of two major sections of thick colluvium over thin disrupted San Sebastian units that are separated by a section of thin Limestone Colluvium over thicker, folded and faulted San Sebastian sediments. The contacts between the disrupted San Sebastian sediments and the Alonzo volcanic rocks are very irregular and marked by foliated pyrite-clay rupture-slip surfaces that continue down into the volcanic rocks. These rupture slip surfaces also continue upward through the San Sebastian sediments and break up the deposit into discrete structural sections . While some of these sections may have had simultaneous sliding or slipping during their ancient movements, others show truncation of surfaces indicating sequential motion of the structural sections.

On the far eastern end of the ancient landslide deposit the basal volcanic unit is transitional from gray to reddish volcanic rock. The ancient rupture-slip surface observed here is mostly composed of fractured, flaked and sheared rock with only a minor amount of foliated pyrite-clay. The ancient rupture-slip surfaces that cut through both the San Sebastian sediments and the underlying volcanic rock show normal and thrust slip components in the plane of the exposure (east-west). Certainly their major component of motion was perpendicular to the plane of the exposure and down slope towards the south. This is clearly indicated by down dip slickensides on clay shear planes. It is these normal fault slip components that yield the very irregular contact between the disrupted San Sebastian and Alonzo Formations within the landslide deposit . Vertical foliation, folded layers and inclusions of the underlying blue-gray clay and volcanic rocks in the San Sebastian sediments suggest upward internal flow in this unit during ancient sliding.

On the western end of the landslide deposit most of the bright gray pyrite-clay rupture slip surfaces dip westward and continue down into the hydrothermally altered volcanic rock of the Alonzo Formation . No evidence for an upward curving detachment slip surface below these surfaces has been observed. A vertical bright gray pyrite-clay rupture-slip surface can be seen cutting through the west dipping surfaces at the west end of the out crop. It appears that slip along this surface has allowed for the downward and down slope movement of the San Sebastian Formation on the east or right hand side of this vertical surface. Although the west dipping rupture slip surfaces intersect this vertical surface they are not truncated by this surface but continue down into the volcanic rocks beyond this surface to the west. Further to the west on the road cuts, both west dipping and vertical bright gray pyrite-clay rupture-slip surfaces were observed to have contributed to smaller cut slope failures.

Cut slopes on the north side of the roadway, west of the active landslide, are also cut by bright gray clay rupture slip surfaces. These surfaces are either east dipping or vertical. Notably these slip surfaces have also allowed for downward movement of the San Sebastian Sediments and contribute to slope instability. The continuation of the bright gray pyrite-clay rupture slip surfaces down into the hydrothermally altered volcanic rocks, west of the ancient three formation landslide deposits suggests the unstable mass is or was considerably larger than the extent of these deposits. It is likely that the west dipping rupture-slip surfaces seen eastern road cuts intersect the east dipping surfaces seen western road cuts to form large sliding wedges in the volcanic rocks. The vertical rupture-slip surfaces have allowed for segmentation and differential movement of the sliding mass. Greater down slope movements of material in some segments have brought down the higher standing

San Sebastian sediments and Limestone Colluvium especially in the area of the active landslide.

## Caguana Peneplain-Tertiary Erosion Surface

If we look westward to the top of the slopes above the new bridge over the Rio Caguana we can see the edge of the Caguana Peneplain. This is the Tertiary erosion surface that flanks and underlies the limestone plateau. The erosion surface shows up as relatively smooth surface with gentle slopes and few topographic lines on the shaded topographic map. It is bound on the north by typical karst topography and on the south by rough, steep, and deeply dissected terrain.

## Utuado Pluton Erosional Basin and Deeply Dissected Volcanic Rock Provinces

If we look southward towards Utuado and Jayuya we can see the deeply eroded lowlands formed in the Utuado Pluton and the surrounding steep sloped high mountains of the deeply dissected metamorphosed volcanic rocks. We continue across the new bridge over the Rio Caguana. The first road cuts are composed of hornfels metamorphic rocks that form the contact aureole around the pluton.

## Stop 7 Granite of the Utuado Pluton

The road cut exposes granitic rock of the northern margin of the pluton. The granite here is hard and only slightly weathered and is cut by numerous pink dikes. The pink color of the dikes comes from orthoclase feldspar. Most of the pluton is composed of granodiorite and lacks the pink potassium feldspar seen in these rocks and in the dikes. Road cuts further south along the highway show increasing degree of weathering into grus. This is caused by the chemical decomposition of the mafic minerals, amphibole and biotite. The decay of the mafic mineral breaks the rock down into sand size fragments of quarts and feldspar (granular weathering). Sand size material is more easily eroded than clay and silt. Therefore the chemically weathered rocks of the pluton are more easily and rapidly eroded than the surrounding volcanic rocks that chemically weather into clay and silt rich laterite and saprolitic residual soils.


MUNICIPIO DE
C A C A N A
Cayucos
622
A T O B