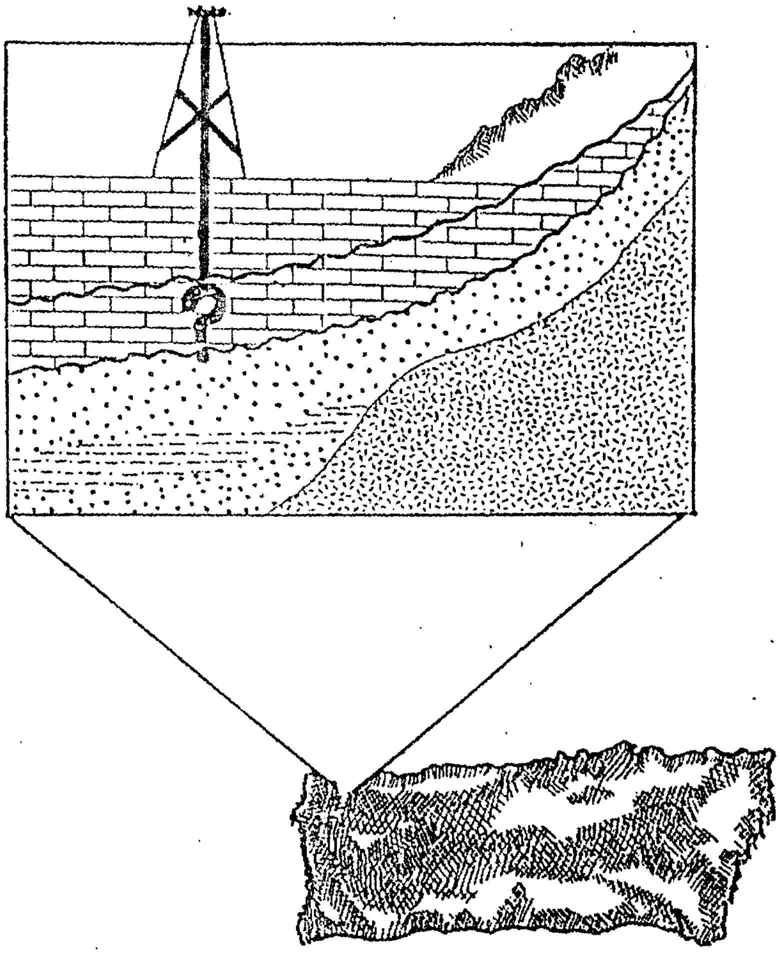
FIELD GUIDE

7th ANNUAL SYMPOSIUM ON CARIBBEAN GEOLOGY

TECTONICS AND PETROLEUM POTENTIAL OF THE CARIBBEAN REGION



FEBRUARY 24-28 1988
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BY: D.K. LARUE

Geology of Puerto Rico: An Overview

Introduction

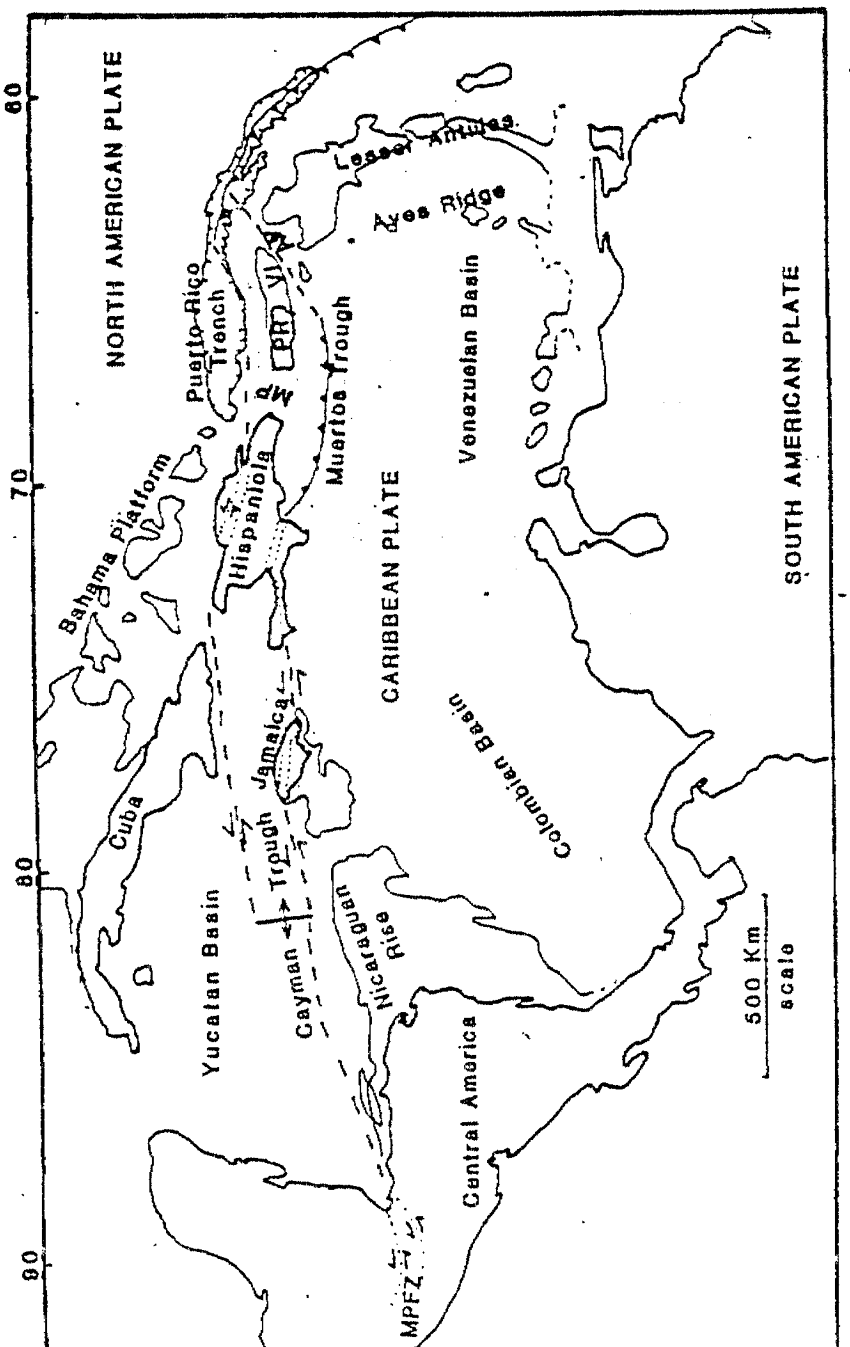
The geology of Puerto Rico (Fig. 1) is presented in terms of its three stage evolutionary history. The oldest rocks exposed on Puerto Rico, of Jurassic to middle Cretaceous age, are referred to as basement rocks (Figs. 2, 3). This basement assemblage is unconformably and structurally overlain by a Late Cretaceous to Early Tertiary island arc assemblage, which is in turn unconformably overlain by a Middle to Late Tertiary and younger sequence of little-deformed terrigenous sediments and carbonates.

The physiography of Puerto Rico is characterized by a central mountain belt and northern and southern coastal plains (Fig. 4). The central mountain belt consists of deformed island arc rocks of Cretaceous to Eocene age, cut by a multitude of faults, the largest of which form two through-going fault zones (Fig. 2). These two through-going fault zones, the Great Northern Fault Zone and the Great Southern Fault Zone, divide Puerto Rico into the northeastern, central and southwestern blocks. A belt of early Tertiary volcanic and sedimentary rocks is located along the Great Southern Fault Zone. Early Tertiary rocks are only exposed locally elsewhere on the island.

Puerto Rico is presently bound on the north by the Puerto Rico trench,which is characterized by oblique subduction, and on the south by the Muertos trough, which is characterized by extremely slow subduction. The Puerto Rico trench fades into a zone of strike-slip displacement to the west, and to the east, bends around and becomes the subduction zone of the Lesser Antilles arc.

Basement Rocks

Two types of basement rock assemblages are found on Puerto Rico. In southwest Puerto Rico, the basement is an odd mixture of ophiolitic materials, forming perhaps a melange in the sense of present day workers. This ophiolitic sequence, referred to as the Bermeja complex, consists of serpentinite, amphibolite and chert. The best age constraints come from radiolarians in the chert. Two ages have been reported by Mattson and Pessagno (1979), late Jurassic (Tithonian) and middle Cretaceous (Albian). Presumably, the chert was originally deposited atop pillow basalts (though pillow basalts are nowhere observed in the Bermeja Complex) , and represents deposition below the Carbonate Compensation Depth on oceanic crust. K-Ar studies of the amphibolite give an age of 125 to 85 m.y., or Hauterivian, thus younger than some of the cherts. The K-Ar dates probably were reset by some later event, assuming that the Bermeja complex represents a single disrupted sequence of oceanic crust. The serpentinite was

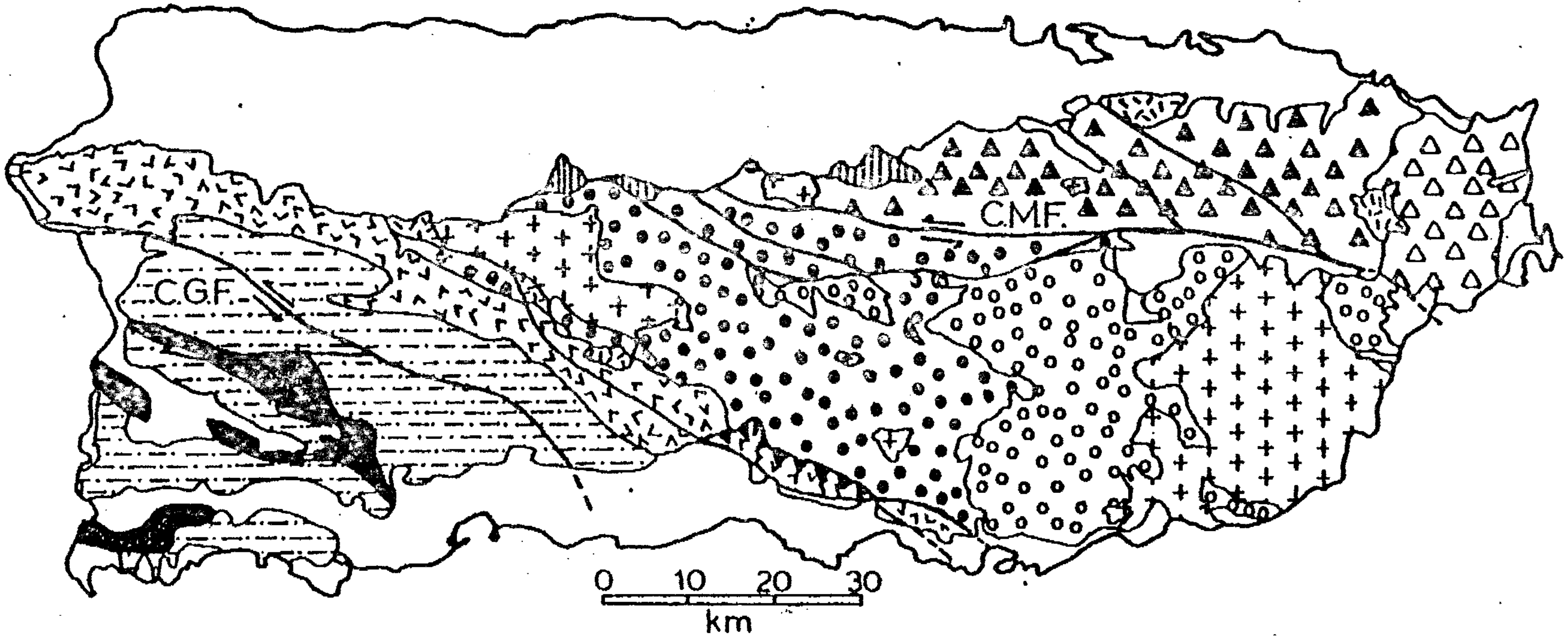


MP - Mona Passage

AP - Anegada Passage

MPFZ - Motagua-Polochic Fault Zone

Fig. 1 Location map of the Caribbean



SOUTHWEST IGNEOUS PROVINCE

- Bermeja Complex
- Late Cretaceous–Eocene volcanic–sedimentary rocks

CENTRAL IGNEOUS PROVINCE

- Early Cretaceous volcanic–sedimentary rocks
- Late Cretaceous volcanic–sedimentary rocks

NORTHEAST IGNEOUS PROVINCE

- Early Cretaceous volcanic–sedimentary rocks
- Late Cretaceous volcanic–sedimentary rocks

EARLY TERTIARY ROCKS

- "Eocene Belt" volcanic and sedimentary rocks
- Other volcanic and sedimentary rocks

IGNEOUS INTRUSIONS

- Cretaceous
- Early Tertiary

- Holocene–Oligocene sediments and sedimentary rocks

C.M.F. Cerro Mula Fault
C.G.F. Cerro Goden Fault
▼▼▼ Thrust Fault
—— Fault

Fig. 2 Geologic map of Puerto Rico

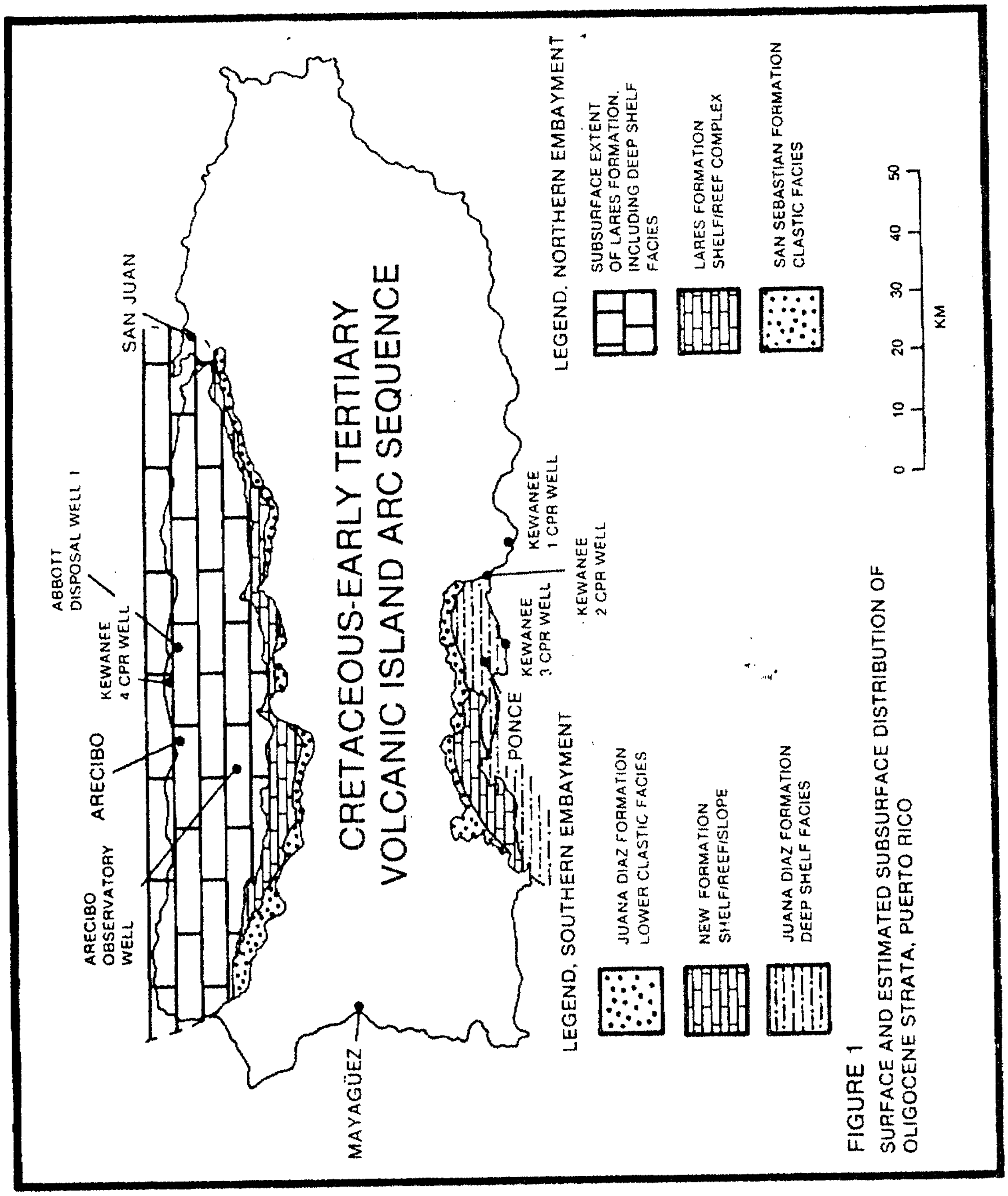


FIGURE 1
SURFACE AND ESTIMATED SUBSURFACE DISTRIBUTION OF
OLIGOCENE STRATA, PUERTO RICO

Fig. 3 Geologic map of Tertiary rocks of Puerto Rico.
(From Frost and others, 1983)

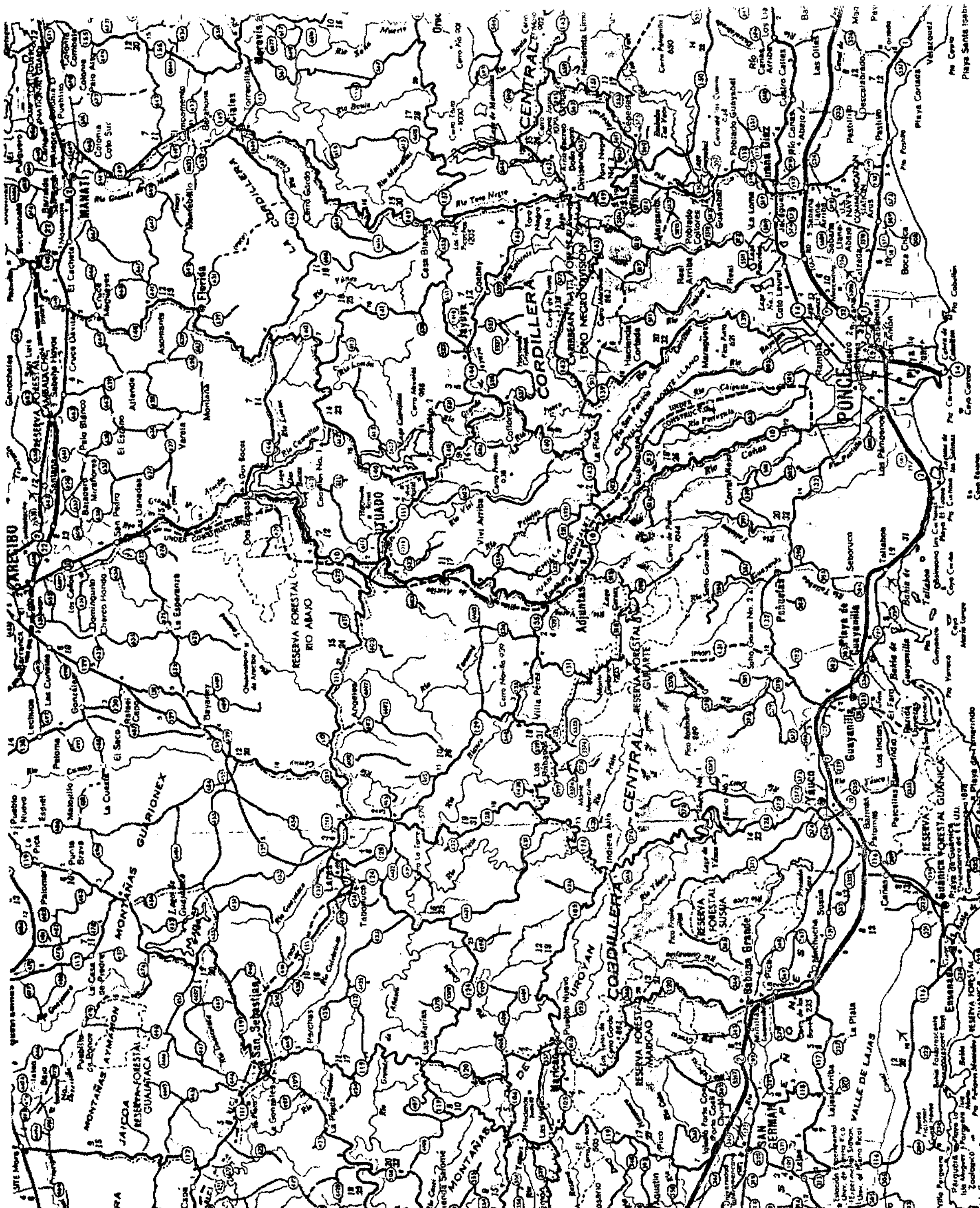


Fig. 4 Highway map, Western Puerto Rico

probably formed by the metamorphism of ultramafic rocks from the mantle underlying the oceanic crustal section. Note that the crystallization ages of the serpentinite and amphibolite are unknown, and are perhaps at least Jurassic, based on the hypothetical reconstruction of stratigraphy.

Basement rocks of central Puerto Rico are dissimilar to those of southwest Puerto Rico, though ages overlap (Joyce, 1985). In central Puerto Rico, lower Cretaceous rocks are tuffs and volcanic rocks of clear island arc volcanic affinity. That is, while cherts were being deposited in southwest Puerto Rico in an environment far from any significant source of volcanism, in deep water below the CCD, in central Puerto Rico, turbidites derived from a nearby island arc were deposited. This strongly suggests that some topographic/sedimentation barrier existed between southwest and central Puerto Rico, or that the two basement rock assemblages were later juxtaposed by tectonism. We believe that between southwest and central Puerto Rico, there lies a suture between these two fundamentally different basement rock assemblages. The location of this suture may be in one of two principal locations, or may be a zone of distributed deformation spread between southwest and central Puerto Rico (Joyce, 1985). The general range in positioning of this suture or sutures is the Great Southern Puerto Rico Fault zone, and the easternmost exposures of serpentinite in southwest Puerto Rico.

Late Cretaceous to Early Tertiary Island Arc

The nature of the contact between the Bermeja complex and overlying limestones and volcanics of the Late Cretaceous island arc is not clear. There have been reported sightings of pebbles of Bermeja complex in the overlying Late Cretaceous Parguera limestone (Mattson, 1960; Almy, 1965), but upon reexamination of these critical sites, we see little indisputable evidence that reworked Bermeja Complex clasts are present in the Parguera Limestone. Therefore, we do not believe it can be easily shown in outcrop that the contact boundary is an angular unconformity and not a structural contact.

On the other hand, the presence of andesitic dikes and sills cutting the Bermeja complex, which are of similar composition and metamorphic state to volcanic rocks in the overlying island arc sequence, suggests that the Bermeja complex was indeed basement beneath the Late Cretaceous and Early Tertiary island arc. We have not as of yet been able to study the alleged unconformity that lies between Lower and Upper Cretaceous rocks of the central block, which is presumably of a similar age.

This hiatus is indeed drastic in the southwest, separating cherts which were probably deposited below the CCD on oceanic crust, and limestones which, as is discussed below, were deposited in a shelf/slope environment on an island arc platform. That is, on the order of 2 to 4 km of uplift probably occurred in the area, in the Santonian.

Late Cretaceous rocks of southwest Puerto Rico include both limestones and andesitic volcanics. The most volumetrically important limestone unit is the Parguera limestone, locally as thick as 400m representing deposition in a shelf/slope environment. Limestones equivalent in age to the Parguera were deposited mostly in shelfal conditions, and are interstratified with volcanic flows, some of which may be sills. The Parguera limestone is notable because it records relatively continuous deposition from the Santonian to Maestrichtian, and thus contains a nearly complete history of sedimentation on and near an island arc platform.

Almy (1965) divided the Parguera limestone into 3 units. The lowermost unit represents deposition in shallow to deep water, whereas cherty limestone of the second unit represents base-of-slope deposition. Overlying the cherty unit are limestones deposited in a slope apron facies in the third unit. This sequence thus records changes in relative sea level. Age equivalent rocks a few miles to the north of the Parguera limestone exposures are exclusively shallow water deposits of limestones and interstratified volcanics. This demonstrates that local topography existed on the arc platform during limestone deposition. Actual positions of depocenters and shelf/slope breaks are difficult to assess because of possible structural complications.

An extremely important stratigraphic problem exists in southwest Puerto Rico. The Late Cretaceous Parguera limestone is in part age equivalent to the Yauco Formation, consisting of turbiditic materials derived from an island arc. The Yauco consists of great amounts of volcaniclastic detritus, yet the Parguera contains essentially none. The coexistence of the two drastically different formations over such a great period of time (perhaps at least all of the Maestrichtian), suggests either a long-lived topographic barrier, which seems unlikely, or the two units have been juxtaposed by faults with kms of displacement. We are trying to isolate the exact position of this change in the Upper Cretaceous stratigraphy, to see if it can be related to a major tectonic feature. We believe at present that the northernmost and easternmost exposures of serpentinite may be the location of this tectonic boundary.

A complete continuum of turbidite facies in Late Cretaceous rocks can be traced from the Yauco Formation eastward, from basinal deposits near the towns of Yauco and Peñuelas, to inner fan facies near Coamo, and subaerial facies near Orocovis. This suggests that there has not been significant tectonic translation of these strata since the Late Cretaceous, or that tectonic translations have fortuitously juxtaposed similar stratigraphic units. To summarize then, apart from the clean limestones of southwest Puerto Rico, Late Cretaceous strata of the Southwest block, Central and Northeast blocks are mostly volcaniclastic turbidites indicating deposition in basin plain, submarine fan, slope. Locally shelfal facies rocks occur interstratifed with welded tuffs near Orocovis. Although limestone bodies occur locally, they are of uncertain origin (for example, deep water deposits, slide blocks, fault blocks?).

There was an apparent break in sedimentation between the Late Cretaceous and the Early Tertiary. Paleocene to Eocene rocks are dominated by volcaniclastic turbidites, volcanic flows and intrusives, and many occur in the "Eocene belt", which is contained within the Great Southern Puerto Rico Fault Zone, and is perhaps genetically related to it. Although ostensibly similar to the Late Cretaceous volcaniclastic strata, the Early Tertiary rocks seem in many places to be less reworked, that is, probably had a shorter residence time in a shelf setting before being redeposited into deep water. Whether the Early Tertiary turbidite deposition occurred in an intra-arc basin or basin flanking the arc platform is unknown. Near the contact between the Eocene belt and the overlapping Middle Tertiary strata, Middle Eocene strata are locally composed of reworked materials including blocks of Late Cretaceous limestones. This indicates uplift in this period.

The change in the nature of sedimentation between the Eocene and Late Cretaceous strata occurred at a period in time when the Caribbean plate was moving from a bottleneck between North and South America (in the latest Cretaceous) , into relatively clear sailing in the Paleocene followed by collision in the Eocene (Fig. 5). Perhaps this accounts for the change in nature of sedimentation near the arc platform.

Contact With Middle Tertiary Strata and Significance

The contact between the Late Cretaceous and Early Tertiary island arc rocks and the Middle Tertiary strata (the oldest ages documented are Middle Oligocene) is clearly an angular unconformity. Locally, some normal displacement on this contact may have occurred, but for the most part, it is a simple unconformable contact. The unconformity is profound, and records the transition from arc volcanism and collisional tectonism to virtual tectonic quiescence.

Plate reconstructions attribute this drastic change in geologic activity to the collision of the Bahamas and the Greater Antilles volcanic arc (Pindell and Dewey, 1982). Such an event explains the termination of volcanism on Puerto Rico, as well as the contrasting style of deformation between the highly deformed island arc sequence to the mildly deformed Middle Tertiary overlap sequence.

Middle Tertiary Overlap Sequence

Exposures on land on Puerto Rico indicate that the overlap sequence consists of a sequence of terrigenous sediments overlain by interstratified terrigenous and carbonate sediments (Figs. 6, 7). Ages range from Middle Oligocene to Recent. Terrigenous sediments are dominant in the lowermost part of

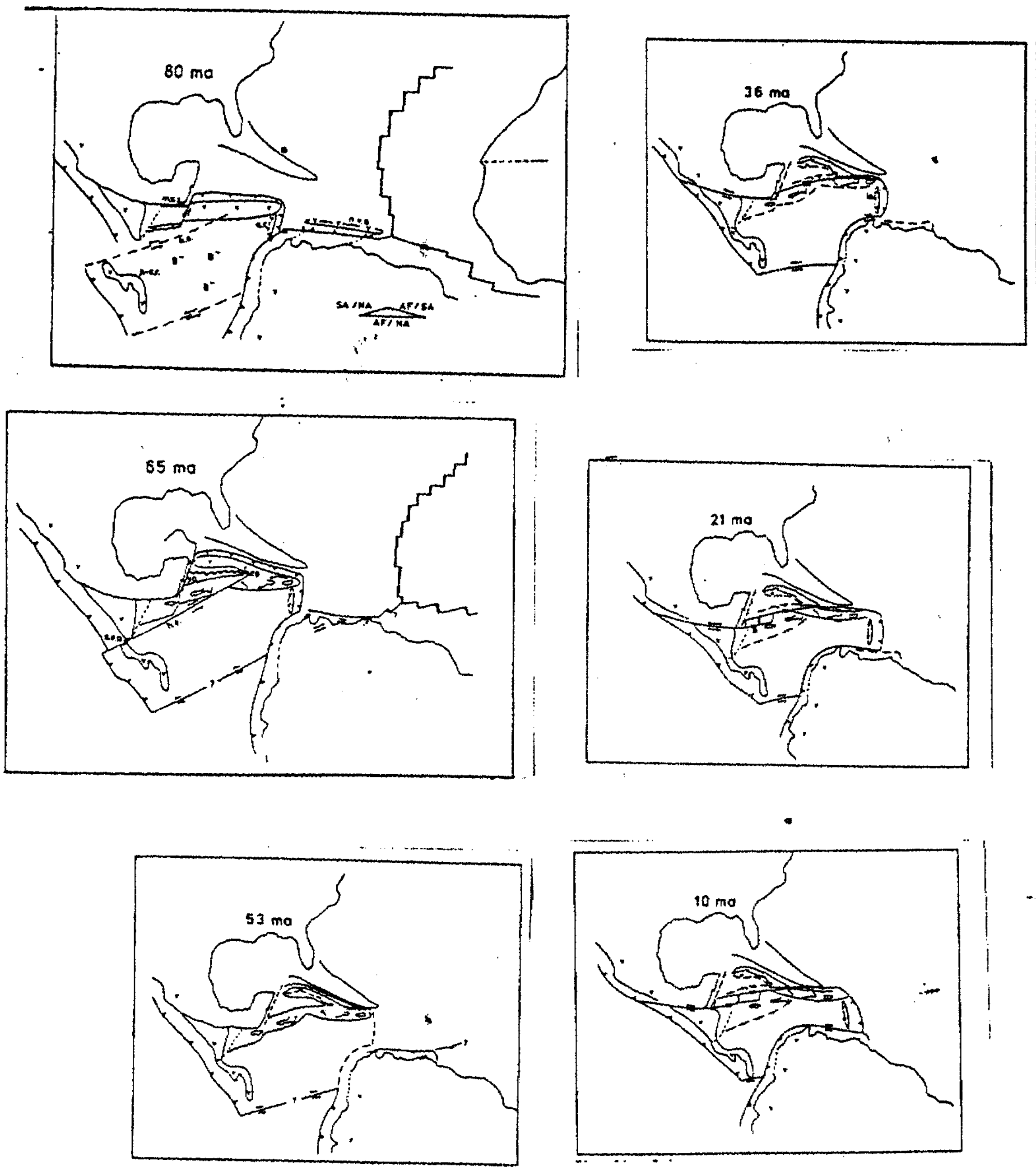


Fig. 5 The Pindell and Dewey (1982) interpretation of Caribbean tectonics.

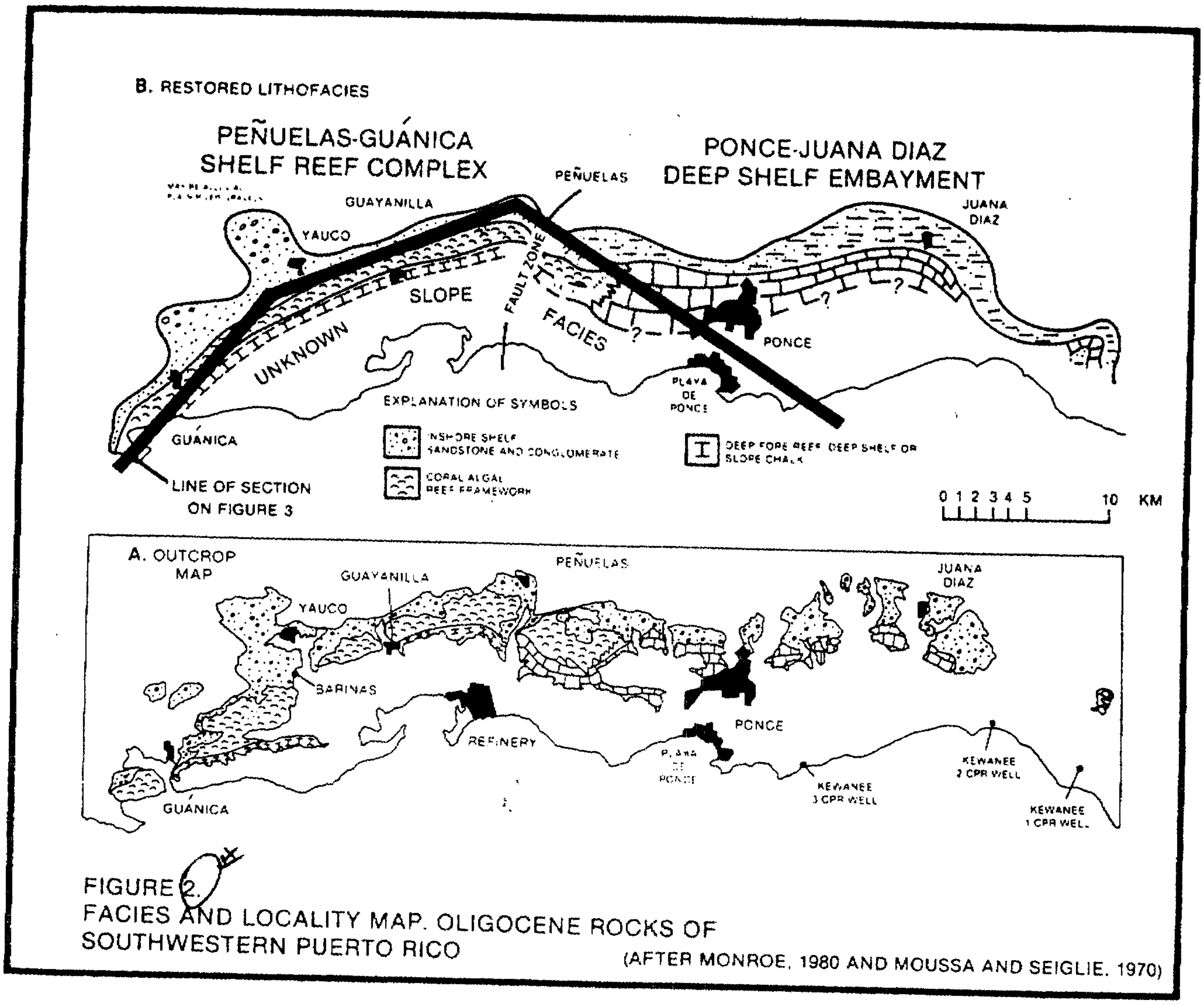


Fig. 6. Cartoon diagram showing interpretation of sedimentary facies in southern Puerto Rico Tertiary. From Frost and others (1983)

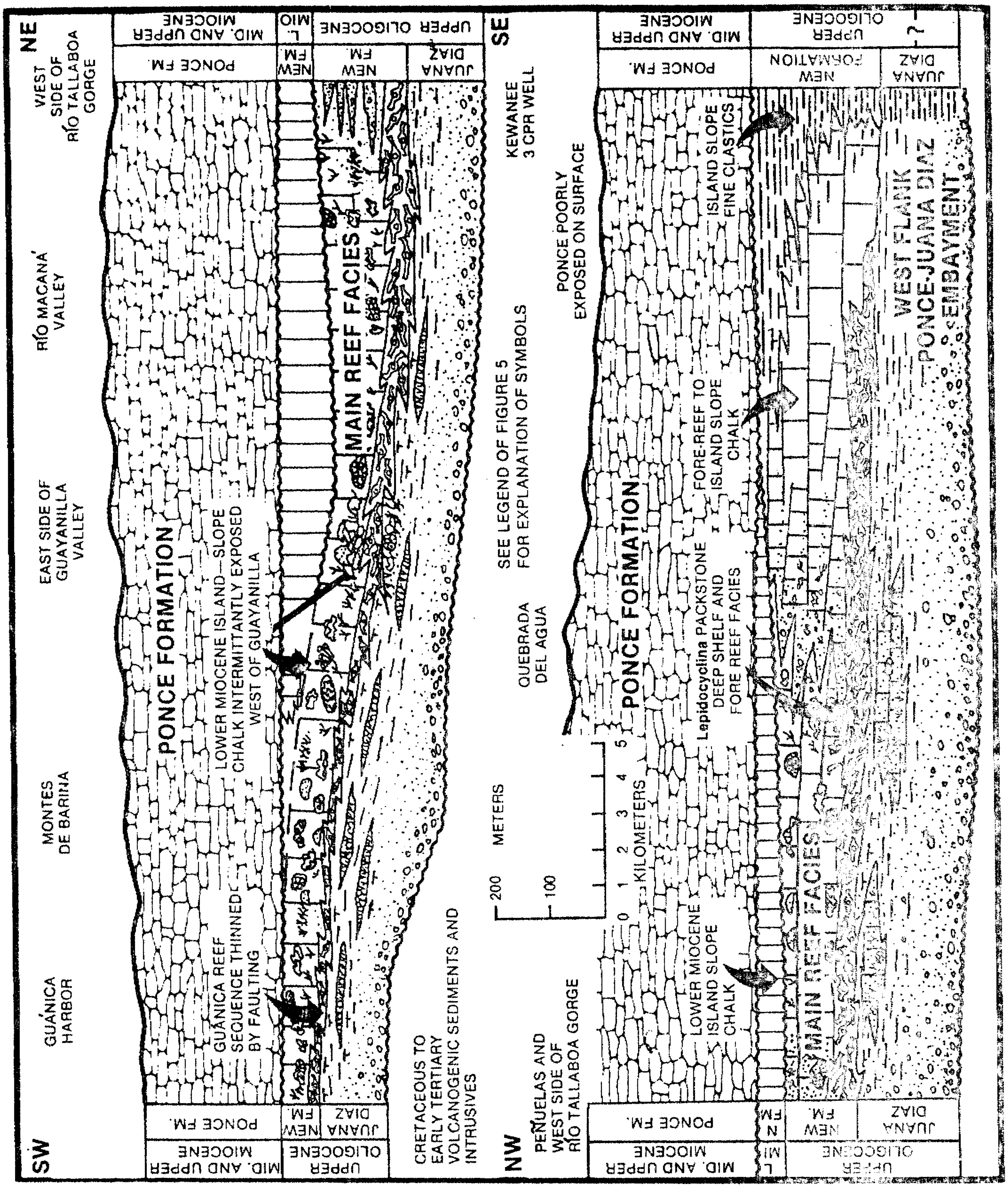
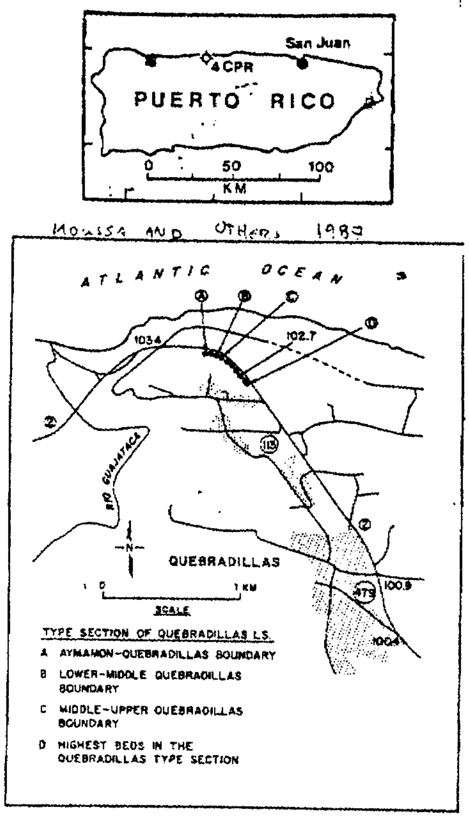
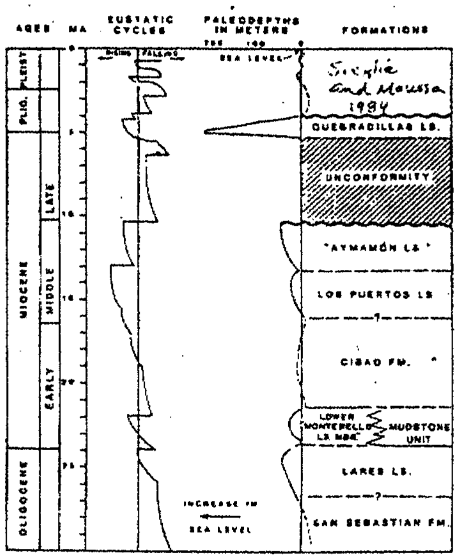


Fig. 7. Stratigraphic relations, South Coast Tertiary basin. (From Frost and others, 1983).





8B (Sieglie and Moussa, 1984)

Moussa and others, 1987

8A

Fig. 8A. Location map of Quebradillas outcrops, north coast of Puerto Rico.

Fig. 8B. Suggested relation between sea level curves and Tertiary sedimentation on North Coast Tertiary basin.

the sequence, and these sediments were apparently derived from the erosion of the underlying sequence of island arc rocks. Overlap strata exposured on the north and south coasts of Puerto Rico dip gently, about 5 to 10° seaward. Previous studies of these rocks indicated occurrence of facies changes, but the significance of these facies changes has not been addressed in detail.

Onshore seismic data has shown that the overlap strata were not simply deposited on homoclinal seaward-dipping surfaces, but rather, filled Late Eocene (?) through Oligocene basins (Birch,1985; Moussa and others, 1987). Several basins have been proposed to exist on the North Coast of Puerto Rico, and are subdivisions of what is generally called the North Coast Tertiary basin. Only the southern margin of this larger basin is recognized, the northern margin may lie on the Puerto Rico shelf, or may in fact be truncated by faults of the Puerto Rico Trench. The age and lithology of these basinal sediments can only be inferred at present, by studying outcrops exposed on Puerto Rico. These basin filling sediments are probably Oligocene (perhaps as old at Late Eocene) and younger, and consist of carbonate and terrigenous strata.

On the South Coast of Puerto Rico, an Oligocene basin is exposed in outcrop. The evidence for this basin is a facies change from southwest to northeast. In the southwest, the sequence consists of the Eocene unconformity, overlain by coastal and shallow-marine facies strata, overlain by a chalk unit, and capped by Miocene reefal facies. East of Ponce, near the town of Juana Diaz, the basal shallow water sequence is overlain by a thick turbidite sequence, consisting of terrigenous mudstones representing hemipelagic sedimentation, and sandy and conglomeratic carbonate materials deposited by turbidity currents. Locally slide blocks of reefal materials are found enclosed in the terrigenous mudstones (Moussa, 1975). Further to the east, fluvatile strata are observed, but there stratigraphic position is indeterminate.

Sedimentation in the Middle and Late Tertiary basins was influenced by basin subsidence and sea level changes (Fig. 8). Basin subsidence seems to have decreased with time, and probably individual basins ceased differential subsidence by Miocene time. That is, the small basins on the North and South Coasts probably formed in the Late Eocene (?) and Oligocene, and the basins were completely filled by the Miocene. Miocene and younger sediments were then deposited in the broader North and South Coast basins.

Seiglie and Moussa (1982) have made detailed studies of sea level fluctuations based on paleontologic studies of North Coast strata(Fig. 8). They concluded that sea level fluctuations can be recognized in Middle Tertiary strata. These fluctuations correlate well with the sea level curve of Vail and others (1977). However, in the Pliocene, the Quebradillas limestone was deposited in water deeper than

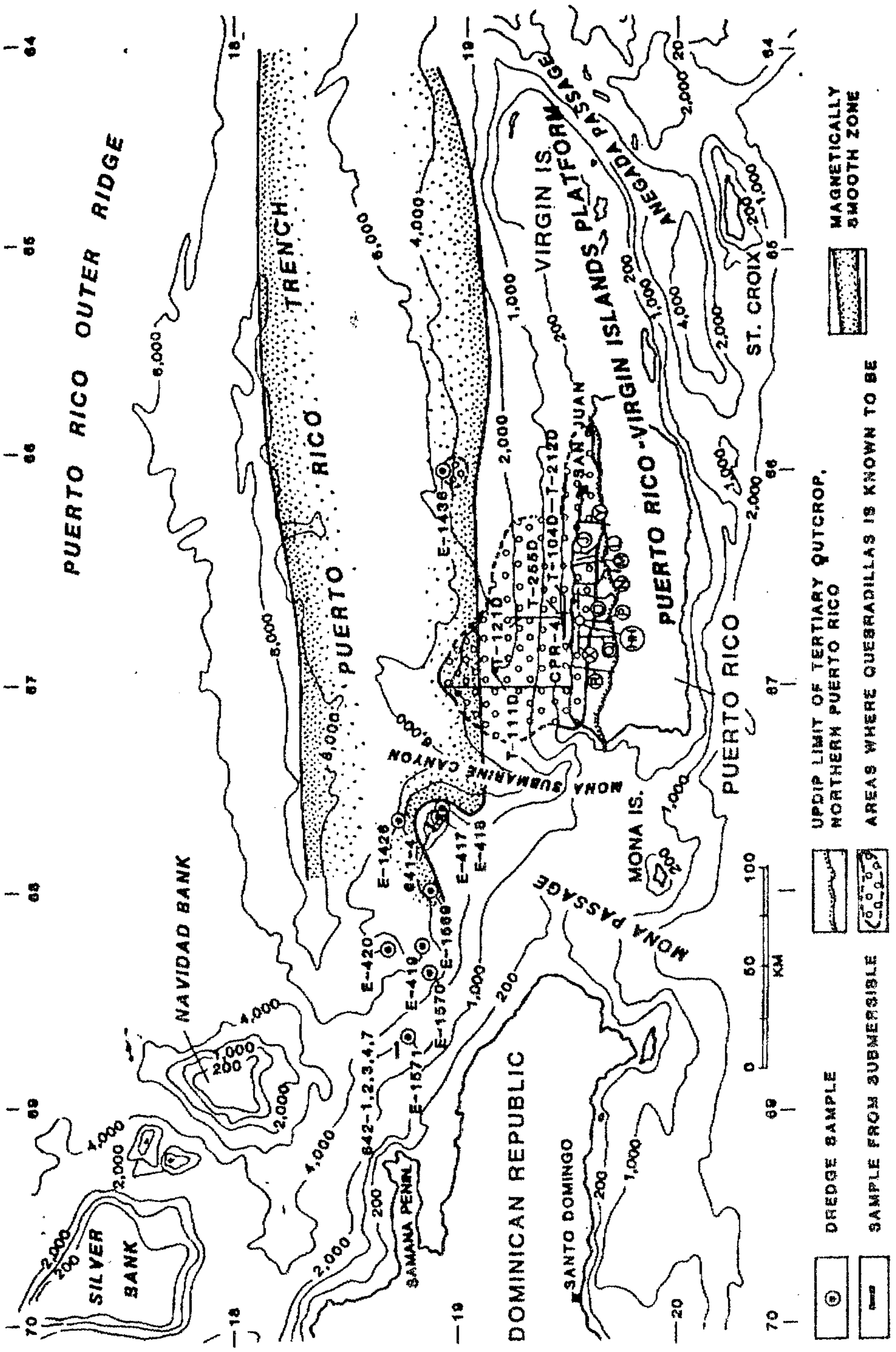


Fig. 9 Offshore geology of Puerto Rico. From Moussa and others, 1987

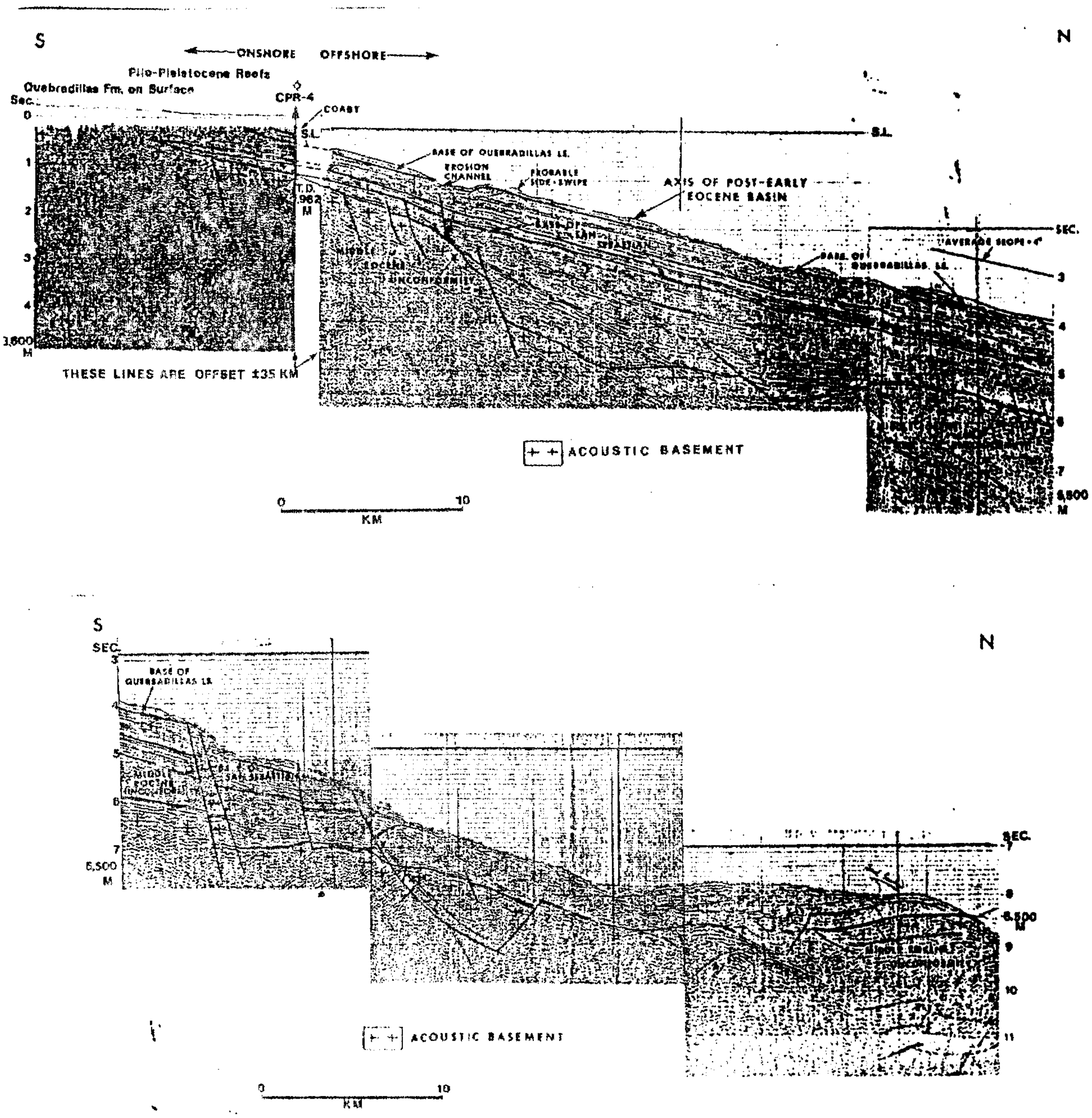


Fig. 10. Onshore to offshore transition, north coast Puerto Rico. From Moussa and others, 1987.

predicted by the Vail curve. Furthermore, Moussa, Seiglie and Meyerhoff (1987) have noted that Quebradillas equivalent strata can be traced into the offshore multichannel seismic records, and that the Quebradillas-equivalent formation is present at water depth of about 4 km (Fig. 8A). They argue that an intense tectonic event, sometime in the post-Late Miocene resulted in the subsidence of the Puerto Rico slope of over 4 km. Such subsidence probably is related to some tectonic event in the Puerto Rico trench, such as tectonic erosion, or subduction of anomalous crust (Fig. 9, 10).

Petroleum Potential

Based on plate reconstruction of the Garibbean (for example, Pindell and Dewey, 1982), Puerto Rico was part of the "Black Arc" in the Caribbean, that ring of petroleum production that rims northern South America to eastern Mexico. Thus, it is possible that Late Cretaceous rocks on Puerto Rico have considerable petroleum potential. Studies by Hayes and others (1985) confirm that Late Cretaceous turbiditic mudstones contain significant amounts of organic carbon, but vitrinite reflectance data indicate that most samples are in or below the Oil Window, and thus subsurface prospects are not great except for gas. On the other hand, the only known seeps of petroliferous materials are in Cretaceous rocks, of the southcentral portion of Puerto Rico.

Because the nature of the Middle Tertiary basins on Puerto Rico was poorly understood up to the present time, most workers concluded that these strata had not undergone sufficient maturation to produce hydrocarbons. However, with the discovery that the Tertiary basins may contain more than ten thousand feet of strata (Moussa and others, 1987; Birch, 1986), this prejudice must be reconsidered. Based on: 1) the observation that the Middle Tertiary strata are of significant thickness; 2) outcrop studies of the organic matter; 3) available data on heat flow; 4) Lopatin diagrams using the above information, we believe that there is a significant possibility that gas and some oil is trapped in the subsurface of the North and South Coasts of Puerto Rico, although it is somewhat problematic that no petroleum seeps have been observed in these areas. There is no evidence that the Atlantic Ocean in the vicinity of Puerto Rico was highly productive in the Middle Tertiary, therefore we do not expect to find extensive development of facies associated with upwelling, including anoxic facies, or the preservation of oil-prone organic matter.

Purpose of the Field Trip

These two and a half days of field trips attempt to describe some of the features of the geology of Puerto Rico, and their relationship to the petroleum potential and tectonic evolution of the region. The first half day field trip looks at geologic features of southwest Puerto Rico, including the Bermeja Complex, the Parguera Limestone, and the contact between the two assemblages. The second field trip lasts the whole day, and considers the geology of the South Coast of Puerto Rico. On this field trip we will examine cross sections through the Middle Tertiary section that help define the basin on the South Coast. We will also see deformed Late Cretaceous volcaniclastic turbidites. On the third day of field trips we will examine the stratigraphy of the North Coast of Puerto Rico, including Cretaceous rocks, the Middle Tertiary section, and the infamous Quebradillas limestone recording Pliocene tectonic subsidence.

DAY 1 FIELD TRIP:
SOUTHWEST PUERTO RICO (Fig. 11)

STOP 1: Bermeja Complex (Ramal 303 SW of intersection with 305, near Dump)

As mentioned above, the Bermeja Complex of Jurassic through middle Cretaceous age consists of serpentinite, amphibolite and chert. It is cut by intrusions of Late Cretaceous age. Outcrop 1 exposes foliated serpentinite melange with blocks of chert and silicified volcanic rocks. Silicification is believed to be related to a nearby intrusion. From the hilltop we can see the Parguera hills to the south. To the north the Lajas Valley separates the Bermeja and Parguera hills form highlands composed of Cretaceous basement rocks.

STOP 2: Parguera Limestone (Punta Papayo, off 324 near La Parguera)

In his 1965 M.S. thesis, Almy divided the Parguera Limestone into three members. The lowermost member is a fining upward sequence, consisting of possible shallow water facies deposits overlain by chalks. The second unit contains laminated fine-grained calcilutites and chert. The third unit contains fine-grained carbonate mudstones and turbidites.

At stop 2, we see the second and the third members: the cherty facies and overlying turbiditic limestones. The cherty facies is interesting for two reasons. First of all, what is the origin of the silica? In thin sections we see the occasional radiolarian test, suggesting that we are dealing with biogenic silica from radiolarians. Diatoms could also have been contributors, but when diatoms diagentically alter, they usually lose their distinctive morphologies. We suspect that all of the silica in the cherty layers is from radiolaria, with minor contributions from siliceous sponges.

Secondly, why is the cherty unit laminated? Sediments underlying oxygenated waters are bioturbated by benthic communities unless rapidly deposited. These sediments, however, do not appear to have been rapidly deposited. Alternatively, if the overlying waters were anoxic, a benthic community would not be well developed. A problem with this idea is that organic carbon is usually preserved in great

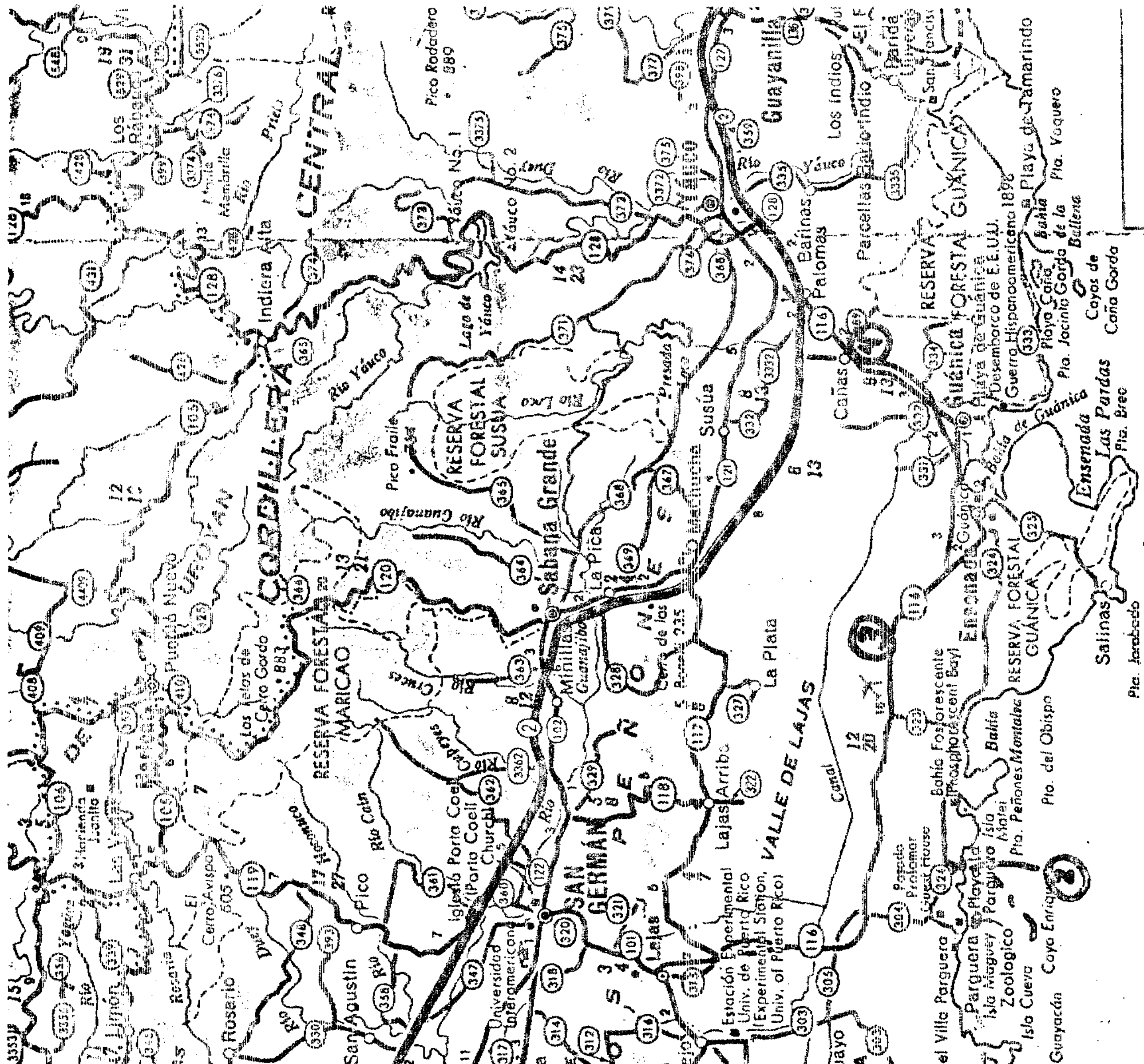


Fig. 11. Highway map, First Day Field Trip

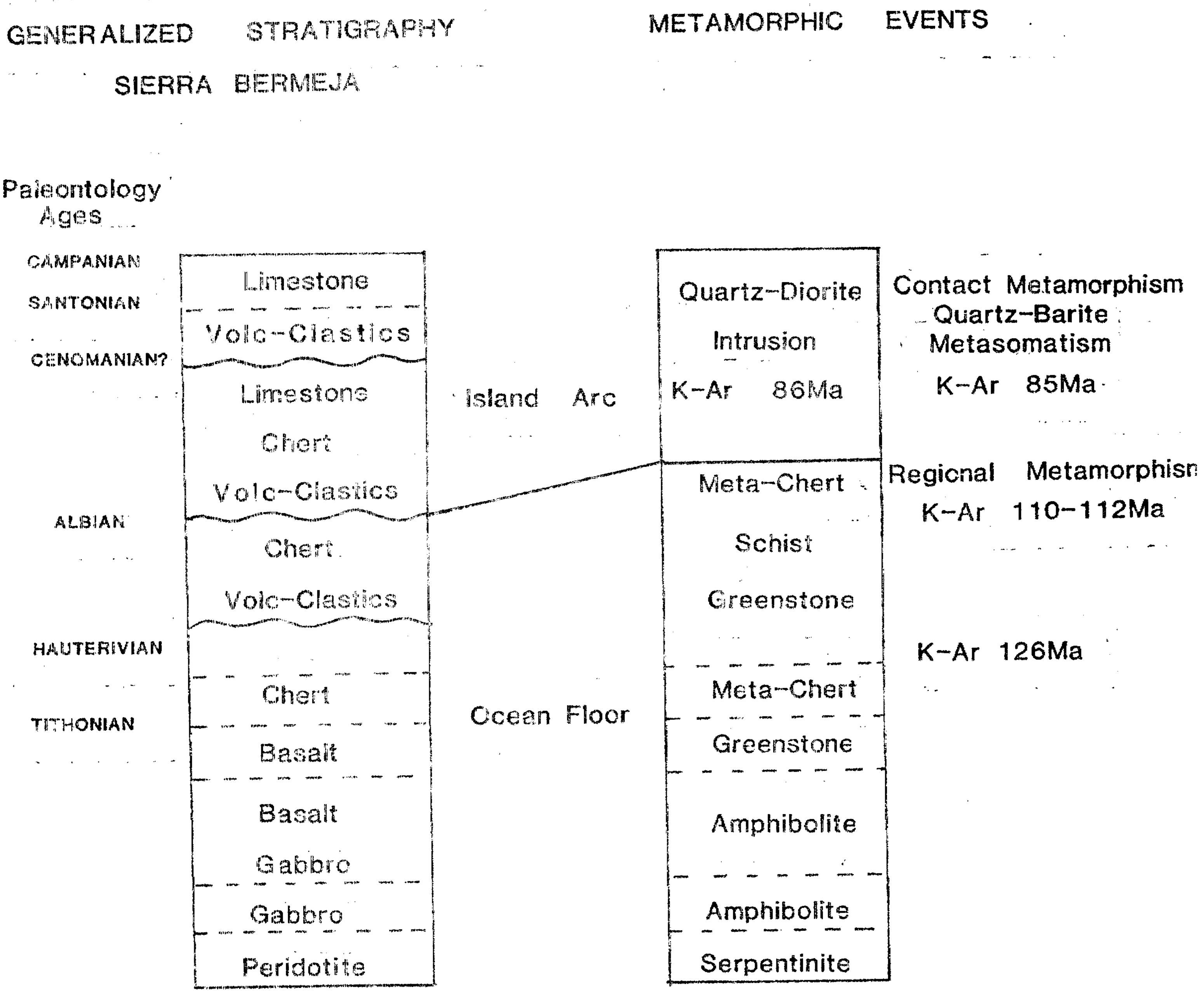


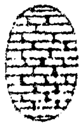
Fig. 11 Insert.
Bermeja Complex studies by Joyce
(work in progress)

Serpentinite Melange

Greenish to greenish gray fine grained, well foliated and blocky serpentinite;unit contains blocks of amphibolite, green and black, fine to medium grained ranging in site from the cne to the m scale.containing plagioclase and green-hornablende. The Amphiobolite blocks are non-foliated to highly foliated including a gneissic Amphicbolite, bluish green with altered layers of hornablende and plagioclase.

Greenstone

Gray brown green and yellowish green greenstone. The unit outcrops as metamorphosed pillow basalts in the arroyo cajul. Highly fractured and epidotized.

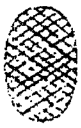


Chert

Black, red, white, and bluish grren, massive, thickly to medium bedded chert. Belts are commonly faulted, fractured and folded (a small syncline was recognized on a valley east of Rancho Cabassa).

Volcaniclastics and Cherts

Interbedded sequence of purple and grayish brown feldspathic sandstones and cherty conglomerates sandstones are medium to course grained commonly composed of feldspars (50%) and amphiboles in a silicious matrix.



Hydrothermally Altered Rocks

This unit is composed of metabasalts cherts and blocks of metalimeston. Blocks of recrystallized limestone, red brown to gray black in color range in size from 10 cm to 2m. Metabasalts are mappable units, purple to reddish brown in color and cut by calcite veins. Cherts are laterally continous bodies with bedding thicknesses of z-10cm. The cherts are bleached red to grayish white in color.

Volcanics

Volcanics are basaltic andesites, basalts and andesites, ranging in color from gray to purple and green. Some small mappable volcanic units clearly are tabular discordant intrusive bodies, that is dikes.

Porphyritic Intrusive Complex

Consists of two separate mapable elliptical discordant bodies one rhyolite (one east) and one dacite (one west).

Fig. 11 Insert

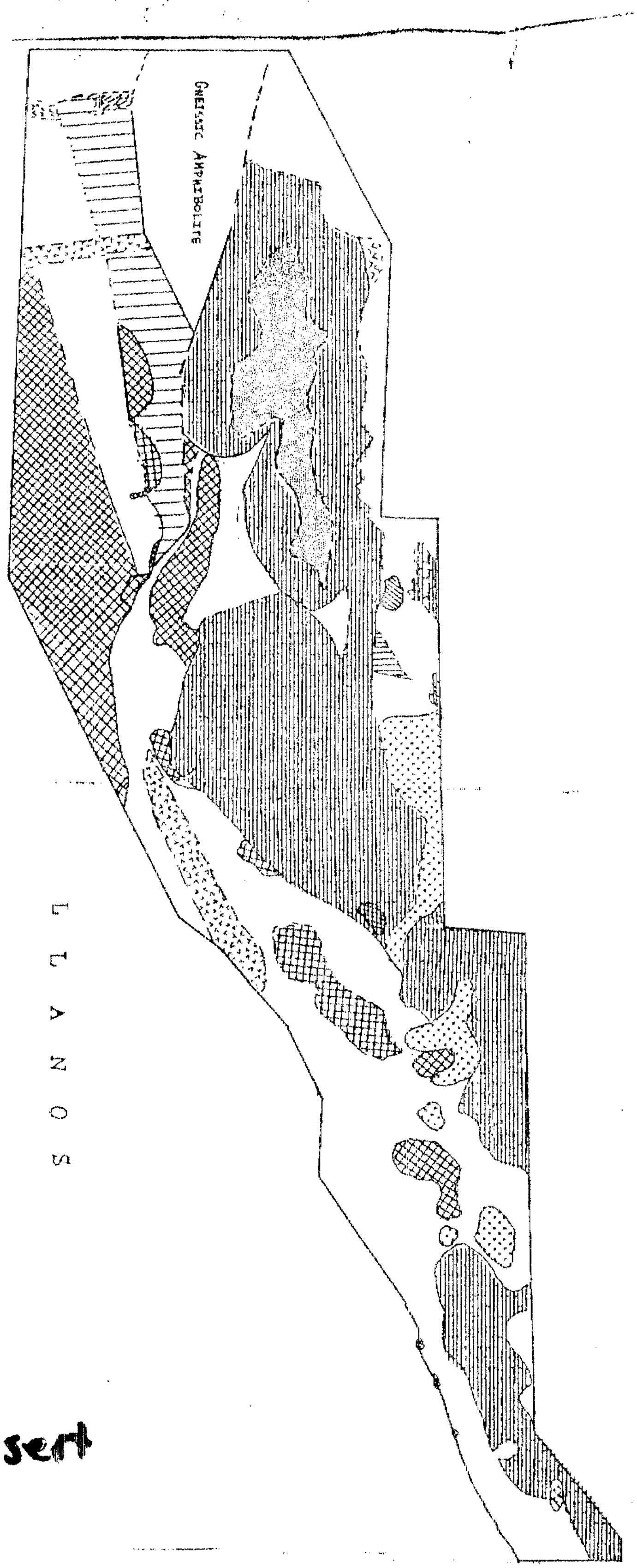


Fig. 11 Insert

quantities in anoxic facies: usually greater than 1.0%, rarely up to 30%. Rock-Eval studies of these rocks show that organic carbon is lacking (less than 0.5%). Thus, the answer to this problem remains unresolved.

The turbiditic facies of the Parguera Limestone is beautifully developed. Graded beds, Bouma sequences are all present, as are associated features such as slump folds and slump scars. Note the abundance of bioturbation structures.

Deformation of these rocks includes open folds with NW-trending axes, and a weakly developed pressure-solution cleavage.

A general model for deposition of the Parguera Limestone is based upon recent concepts of carbonate slope aprons. Carbonate slopes rarely develop submarine fans because carbonate sediments are commonly derived from a line source such as a barrier reef rather than a point source such as a river. Slope facies on carbonate aprons include fine-grained carbonate muds draping the slope, and turbidites and slump folds at the base of slope.

STOP 3: Glauconitic Facies of the Parguera Limestone (take 324 E to cross over road near salt pits to 116 E 2 miles to green rock)

In the lower member of the Parguera limestone is a glauconitic unit. Glauconite is a mixed-layer clay mineral, composed of Fe-rich smectite layers and illite layers. As you can see at this outcrop, there is a great quantity of glauconite present in this member. Locally, diagenesis of this galuconite has produced jasper beds. This is presumably because the Fe-rich smectite breaks down to illite upon heating and burial over time, and produces probably illite and chlorite, or biotite at higher temperatures. With diagenesis, the glauconite loses its Fe and Si, and this is used in the formation of the jasper.

STOP 4: Paleocene of Southwest Puerto Rico: Between Guanica and Route 2

Paleocene rocks occur in southwest Puerto Rico, and the nature of the contact between them and the underlying Cretaceous rocks is interpreted to be an unconformity, however it is nowhere exposed (Mattson, 1966).

The Paleocene rocks consists of fine- to coarse-grained volcaniclastic sediment. It has been suggested by Mattson (1969) that in the offshore realm, this unit would make an admirable reflector, and is probably the origin of Horizon A" in the Caribbean. (Horizon A" being a highly reflective unit seen in most single- and multi-channel seismic lines in the Caribbean basin and also in the North and South Atlantic basins.)

OPTIONAL STOP: Contact between the Parguera limestone and underlying serpentinite, Highway 2

This is an exposure showing the contact between the serpentinite of the Bermeja complex and the overlying Parguera limestone. It has been argued, mostly by Mattson (1960), that the serpentinite is diapiric, and this contact therefore represents the margin of the diapiric body.

FIELD TRIP NUMBER 2 (Fig. 12)

STOP 1: Juana Diaz Formation near Yauco (on 2 0.6 mi E. of intersection with 116)

This stop shows some of the clastics near the base of the Middle Tertiary sequence, and some examples of normal faults. The clastics are mostly massively bedded fine "grained" deposits. Carbonate concretions locally contain shelly material, indicating marine or possibly estuarine deposition. The environment of deposition was probably offshore, in relatively quiet waters. The local gravel deposits indicate abrupt incursions of flow. If the setting was indeed offshore, this might indicate sediment gravity flows into the offshore setting. On the other hand, if fossil studies indicate a more brackish water environment (no such studies have yet been made), then perhaps we are dealing with an estuarine environment with periodic incursions from nearby streams.

The pebble composition indicates a mostly volcanic provenance, probably the hills behind Yauco. Do you see any pebbles of chert, serpentinite or sedimentary rock?

The style of faulting is interesting. Obviously, the faults are normal faults. Slickenside striations indicate mostly dip-slip motion. The draping effect of the fault with greater displacement is probably a function of drag on the fault wall.

A general model for deposition of the Juana Diaz Formation may be a fan-delta, or an alluvial fan prograding into a marine basin. This would fit the style of tectonics thought to have been present during this time, as well as the sedimentary facies.

STOP 2: Basal Juana Diaz Clastics (First exit to Yauco, on right)

At this second stop, a well-exposed section of these basal clastics can be seen. Near the top of the

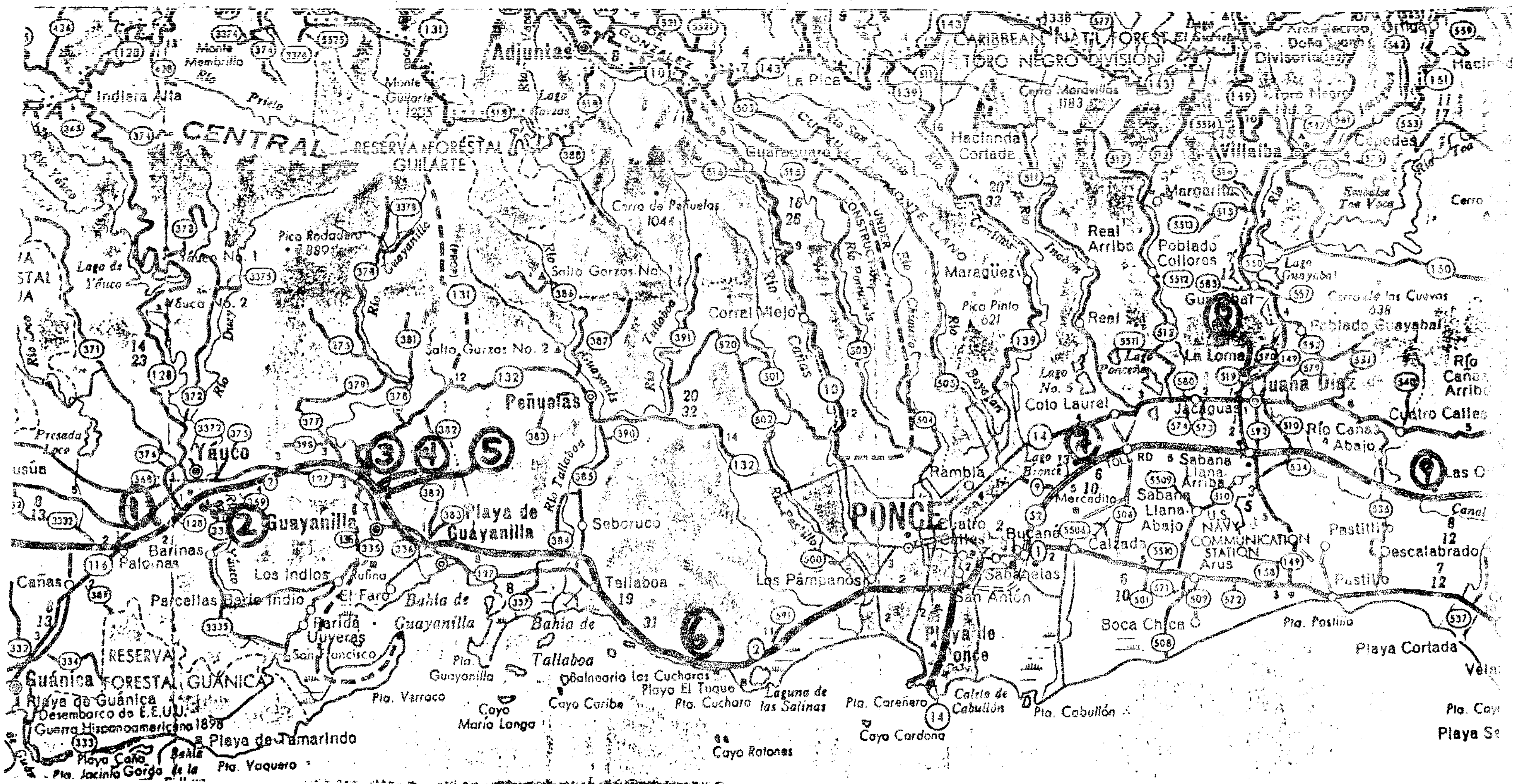


Fig. 12. Field trip locations, Second Day Field trip.

section, the transition from clastics into a carbonate reefal facies complete with attached coral heads is observed.

Interesting features of this outcrop include the local presence of organic rich layers (the most organic-rich layer is laced with gypsum veins oriented quasi-vertically to the bed), and various beds indicating offshore deposition (bioturbated, shell-rich). Conglomerate beds representing channel fills are present near the base of the section. Fine-grained sandstones are locally plane-laminated and bioturbated.

The transition from clastic to carbonate may be due to a proximal to distal transition (note the outcrop in general fines upward), or, possibly, due to a sea level change. The age of the Juana Diaz Formation is poorly constrained, but is mostly upper Oligocene. There is a huge sea level drop in the Upper Oligocene, followed by a gradual rise. I believe that this clastic to carbonate transition may actually be unconformable, with the clastic deposited below or during the sea level drop, and the carbonates deposited during the transgression.

STOP 3: Reefal Cycles in the Juana Diaz Formation (int. 132 and 2, N. side of road)

Overlying the basal clastics of the Juana Diaz Formation are a series of reef cycles (Figs. 13, 14, 15). Frost (1978) has recognized four principal reef cycles in these outcrops, each cycle indicating shallowing upward.

It is important just to state the basic facts about these outcrops. The best way to look at the reefal and other debris in outcrop if you don't know the names of the various organisms is to describe their shapes, and whether they are in growth position or not (Fig. 13). Coral types include finger corals, massive head corals, branching corals, tabular corals and encrusting corals. In general, the order of occurrence of coral types on a reef is a function of their durability. Encrusting corals can withstand any wave attach, then head corals, followed by branching corals in deeper water, and tabular corals in deeper water still. Tabular corals are trying to make the most of the light in the deeper waters.

On the Oligocene slopes, the dominate fossil type was a large foraminifera known as Lepidocyclina. Slope facies are made almost wholly of this fossil type.

About 80 species of corals have been observed in these rocks: less than 30 coral species have been observed in Miocene reef limestones.

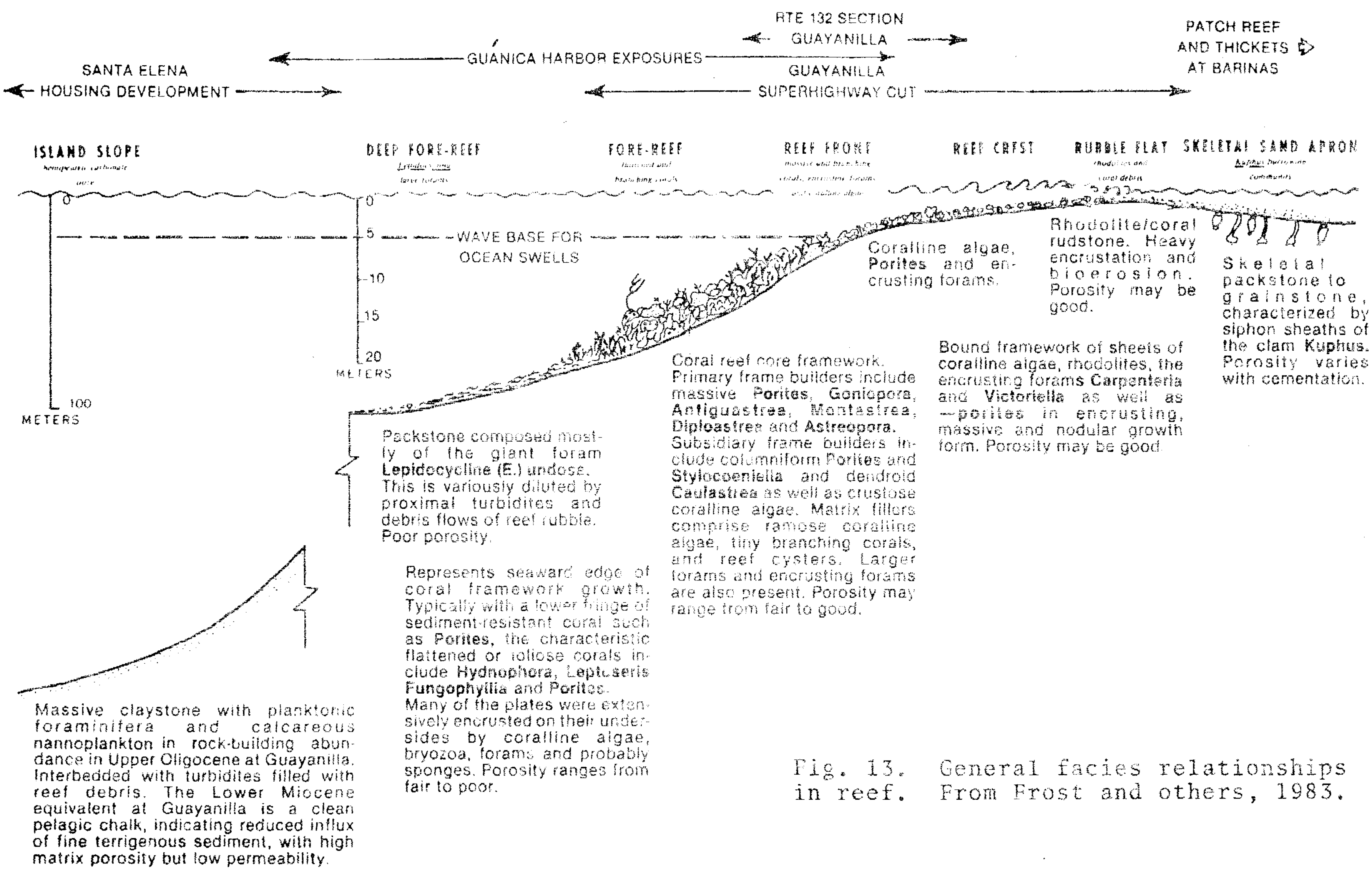


Fig. 13. General facies relationships in reef. From Frost and others, 1983.

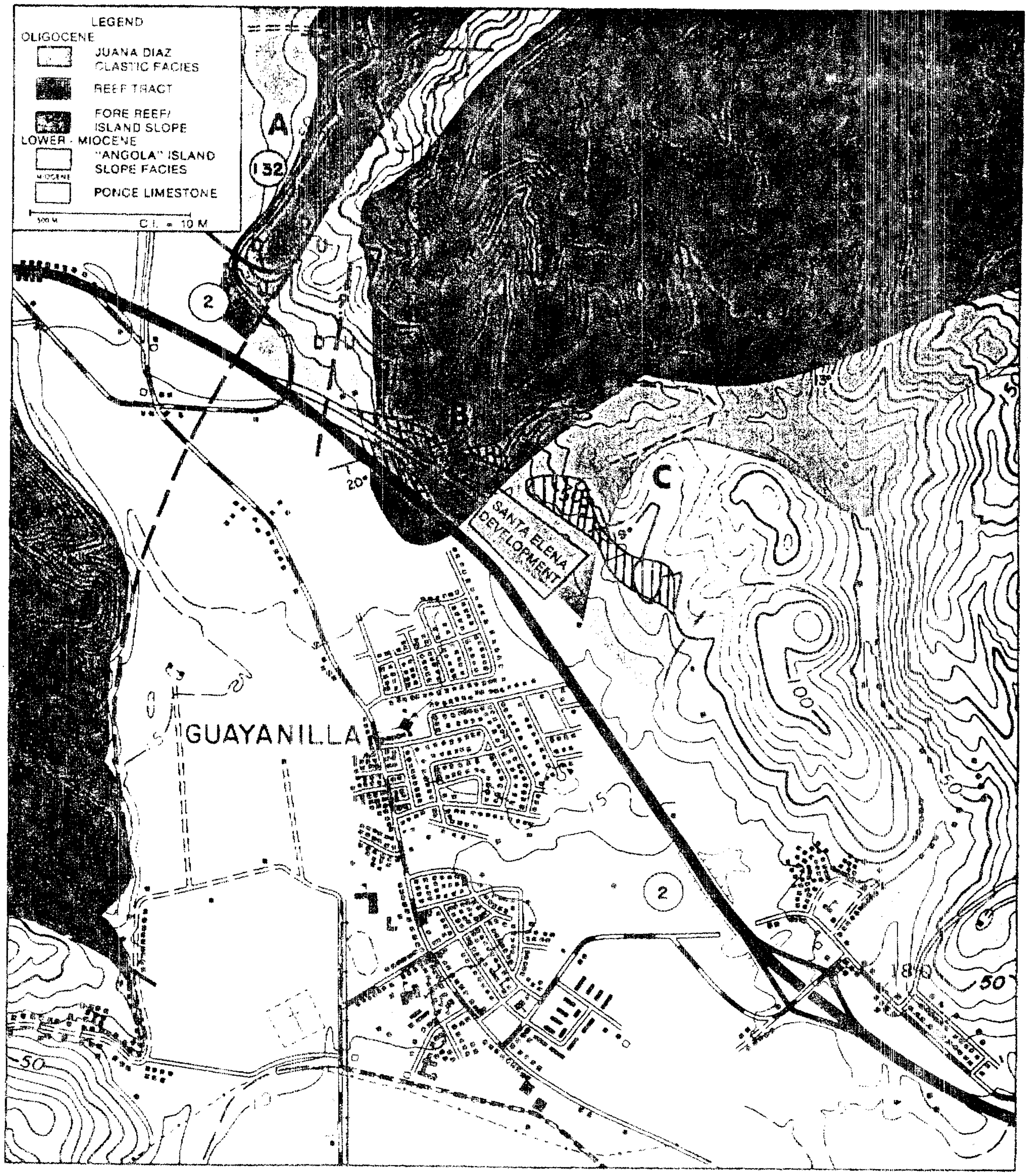


Fig. 14 Field trip stops in Guayanilla area. From Frost and others, 1983. A is stop 3, B is stop 4, and C is stop 5.

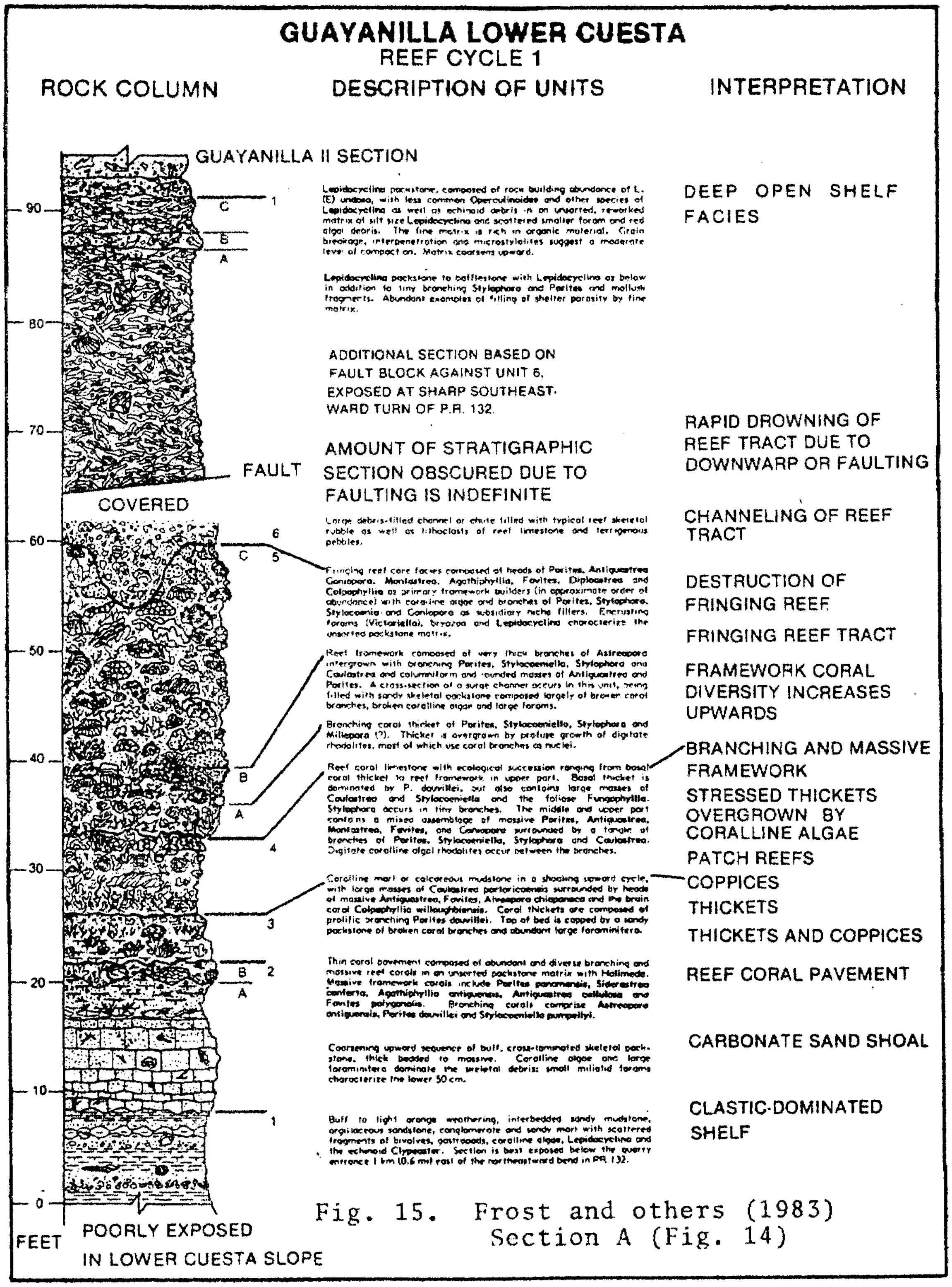


Fig. 15. Frost and others (1983) Section A (Fig. 14)

STOP 4: Reefal cycles (cuesta on 2 at intersection with 132)

Stop 4 is a continuation of the cycles seen at Stop 3 (Figs. 16, 17).

STOP 5: Santa Elena Chalks: The Angola Limestone (continue on road from stop 4 into development) (Fig. 18)

With continued sea level rise in the latest Oligocene and Early Miocene time, growth of the coral reef facies could not keep pace with the rising sea and subsiding land (probably both were occurring together). As a result, the coral reefal facies pass vertically upward into chalk facies of the Angola Limestone.

Here at the Sta. Elena housing development, we can see exposures of the chalks, unfortunately they are difficult to get to.

The section is divided into a lower, more marly calcareous mudstone, and an upper, creamy chalk.

These calcareous mudstones and chalks consist of calcareous nannofossils (mostly large coccoliths), planktonic foraminifera and detrital clay. The fossil assemblages in the lower half of the section indicate a late Oligocene age corresponding to an absolute age of about 26 m.y. The upper part of the section, consisting of creamy chalks, is of early Miocene age, and is separated from the lower part of the section by an unconformity with a hiatus of perhaps 1 to 2 m.y.

Based on faunal evidence, deposition occurred at bathyal depths for both lower and upper units. Locally, bioturbation is pronounced, and the beds are only coarsely layered, suggesting deposition in an oxidizing water column not prone to preservation of organic matter. If it had not been for this lack of organic matter, this unit could have made a great source-rock and/or reservoir.

STOP 6: Ponce Limestone (Rt. 2, km 217.7, Peñon de Ponce)

Outcrop of middle to upper Miocene Ponce Limestone. The section is composed of four units. Unit 1 is composed of large coral heads in a muddy fossiliferous matrix. Unit 2 is composed of columnar and finger coral accumulations of a single species of Porites. Unit 3 is a laminated mud layer which is burrowed but lacks macrofossils. Unit 4 is like unit 1 but lacks coral heads. A large foraminifera Miosorites is present throughout this unit. On the west end of the outcrop, coral heads are found in Unit 4. The four units represent changes in the environment of deposition. The change of coral types from Unit 1 to 2 may be

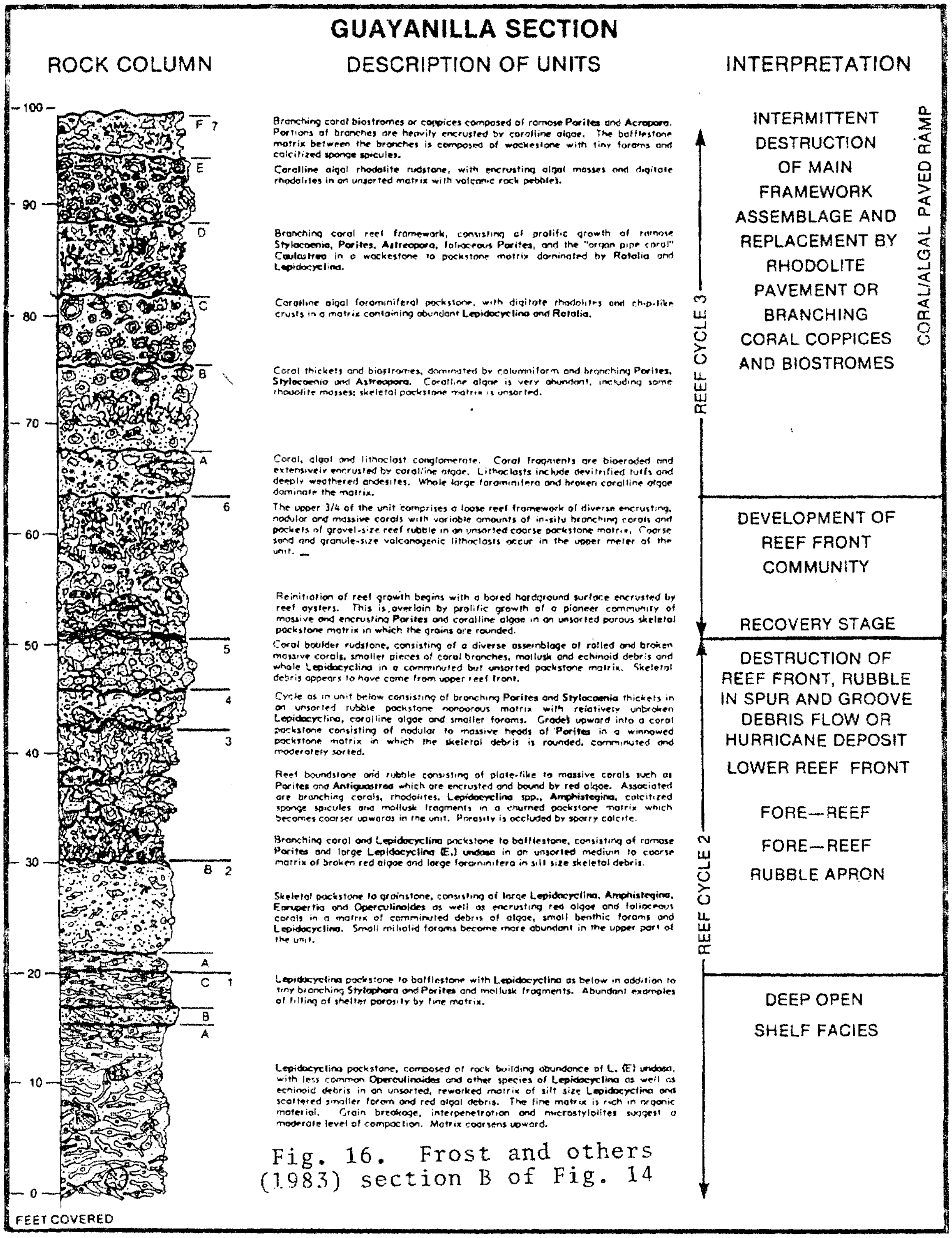


Fig. 16. Frost and others (1983) section B of Fig. 14

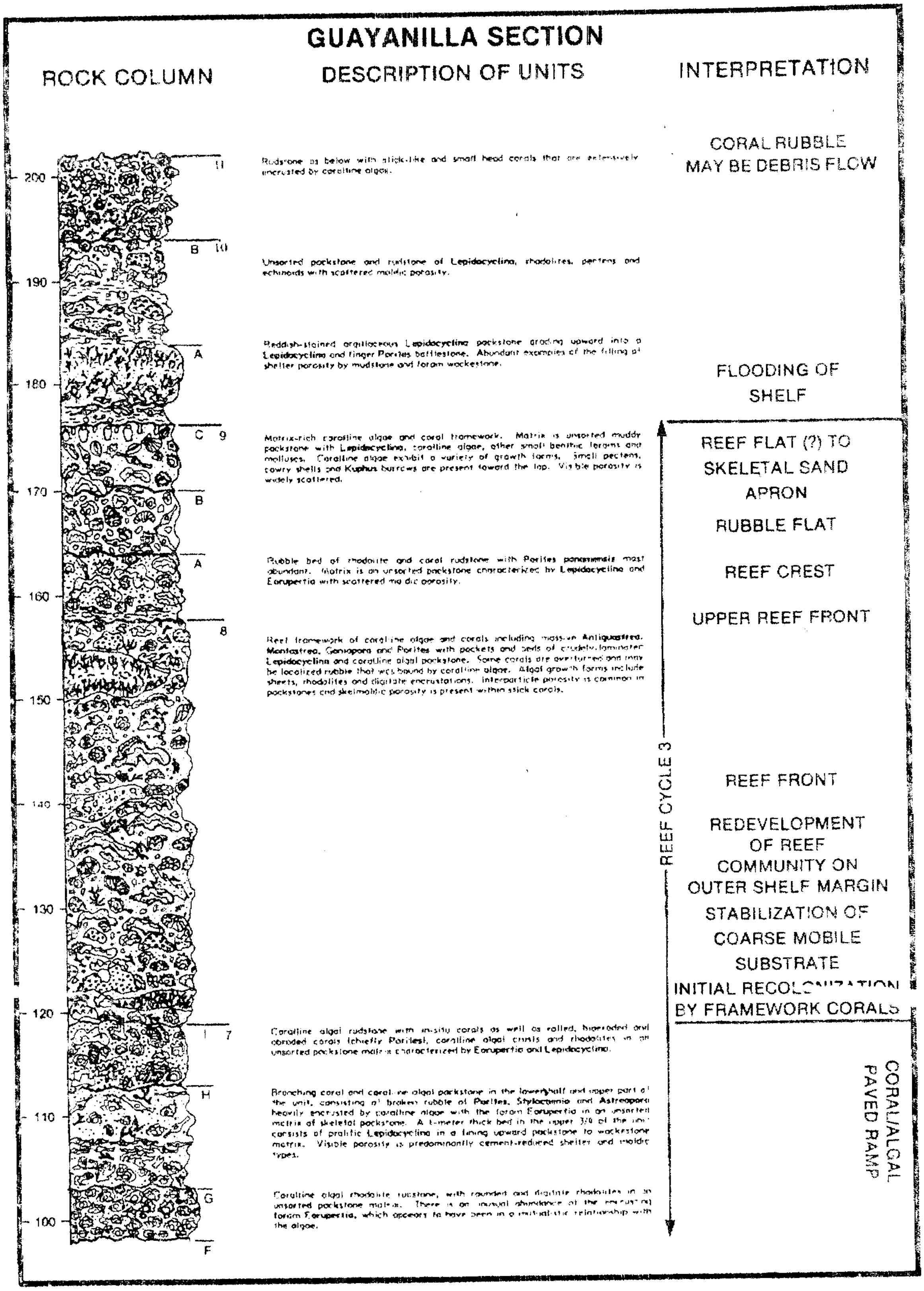
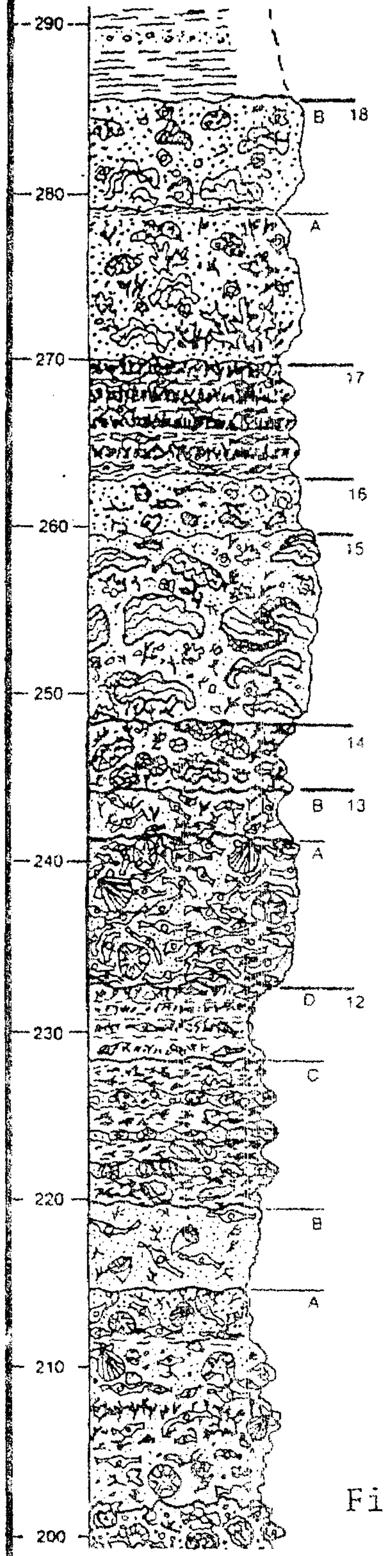

GUAYANILLA SECTION
ROCK COLUMN
DESCRIPTION OF UNITS
INTERPRETATION
200
190
180
170
160
150
140
130
120
110
100
11
B 10
A
C 9
B
A
8
I 7
H
G
F
Rudstone as below with stick-like and small head corals that are extensively encrusted by coralline algae.
Unsorted packstone and rudstone of Lepidocyclina, rhodolites, pectens and echinoids with scattered moldic porosity.
Reddish-stained argillaceous Lepidocyclina packstone grading upward into a Lepidocyclina and finger Porites bafflestone. Abundant examples of the filling of shelter porosity by mudstone and foram wackestone.
Matrix-rich coralline algae and coral framework. Matrix is unsorted muddy packstone with Lepidocyclina, coralline algae, other small benthic forams and molluscs. Coralline algae exhibit a variety of growth forms. Small pectens, cowry shells and Kuphus burrows are present toward the top. Visible porosity is widely scattered.
Rubble bed of rhodolite and coral rudstone with Porites panamensis most abundant. Matrix is an unsorted packstone characterized by Lepidocyclina and Eorupertia with scattered moldic porosity.
Reef framework of coralline algae and corals including massive Antiguastrea, Montastrea, Goniopora and Porites with pockets and beds of crudely-laminated Lepidocyclina and coralline algal packstone. Some corals are overturned and may be localized rubble that was bound by coralline algae. Algal growth forms include sheets, rhodolites and digitate encrustations. Interparticle porosity is common in packstones and skelmoldic porosity is present within stick corals.
Coralline algal rudstone with in-situ corals as well as rolled, bioeroded and corroded corals (chiefly Porites), coralline algal crusts and rhodolites in an unsorted packstone matrix characterized by Eorupertia and Lepidocyclina.
Branching coral and coralline algal packstone in the lower half and upper part of the unit, consisting of broken rubble of Porites, Stylocoenia and Astreopora heavily encrusted by coralline algae with the foram Eorupertia in an unsorted matrix of skeletal packstone. A 1-meter thick bed in the upper 3/4 of the unit consists of prolific Lepidocyclina in a fining upward packstone to wackestone matrix. Visible porosity is predominantly cement-reduced shelter and moldic types.
Coralline algal rhodolite rudstone, with rounded and digitate rhodolites in an unsorted packstone matrix. There is an unusual abundance of the encrusting foram Eorupertia, which appears to have been in a mutualistic relationship with the algae.
CORAL RUBBLE
MAY BE DEBRIS FLOW
FLOODING OF
SHELF
REEF FLAT (?) TO
SKELETAL SAND
APRON
RUBBLE FLAT
REEF CREST
UPPER REEF FRONT
REEF FRONT
REDEVELOPMENT
OF REEF
COMMUNITY ON
OUTER SHELF MARGIN
STABILIZATION OF
COARSE MOBILE
SUBSTRATE
INITIAL RECOLONIZATION
BY FRAMEWORK CORALS
REEF CYCLE 3
CORAL/ALGAL
PAVED RAMP

Fig. 16 cont.

GUAYANILLA SECTION



DESCRIPTION OF UNITS

POORLY EXPOSED.

18 B — Grainstone with scattered in-place massive Stylocoenia colonies and Antiquastrea. Top of unit is marked by thin clay layer.

18 A — Coralline grainstone with scattered in-place massive coral heads.

17 — Porites thickets and Lepidocyclina packstone alternating with mudstone.

16 — Well-sorted coarse grainstone of large benthic forams, coralline algae and coral.

15 — Reef framework composed of large heads of Porites panamensis.

14 — Packstone of Lepidocyclina, branching coralline algae and Porites with scattered heads of Montastrea intermedia, Porites panamensis and Hydnophora.

13 B — Lepidocyclina and Porites packstone. Porites occurs in thin branches.

13 A — Lepidocyclina packstone, locally a bafflestone, with minor coral rubble and echinoids. Becomes a Lepidocyclina and coralline algae grainstone toward the top.

12 D — Lepidocyclina and finger Porites marl alternating with calcareous mudstone.

12 C — Coralline limestone interbedded with calcareous mudstone and marl containing lenses of Porites. The Porites occurs as massive, twigs or thin plates that are aligned parallel to bedding.

12 B — Rubbly wackestone with scattered Lepidocyclina, casts and molds of solitary corals and delicate branches of Porites.

12 A — Lepidocyclina wackestone and packstone with rolled Porites and other corals as rubble. One white to tan bed of calcareous clay with small broken Porites twigs in lenses.

OFFSET MEASURED SECTION 200 FEET TO EAST

Well-sorted foram grainstone and packstone with scattered pectens, echinoids and Lepidocyclina. Matrix is muddier where Lepidocyclina are abundant.

INTERPRETATION

DEEP FORE—REEF TO ISLAND SLOPE MUDSTONE

REEF CYCLE 4

SHALLOW SHELFAL PATCH REEFS AND THICKETS

CYCLES OF SEDIMENT SMOTHERING AND REGROWTH OF BRANCHING PORITES THICKETS

PORITES REEF FRAMEWORK

REEF DEVELOPMENT

SUBSTRATE STABILIZATION

SHALLOWING CYCLE

FORE—REEF LEPIDOCYCLINA COQUINITE

MAXIMUM DEPTH 50 M.

SLOWLY DEEPENING SHELF

CORAL RUBBLE MAY BE DEBRIS FLOW

Fig. 16 cont.

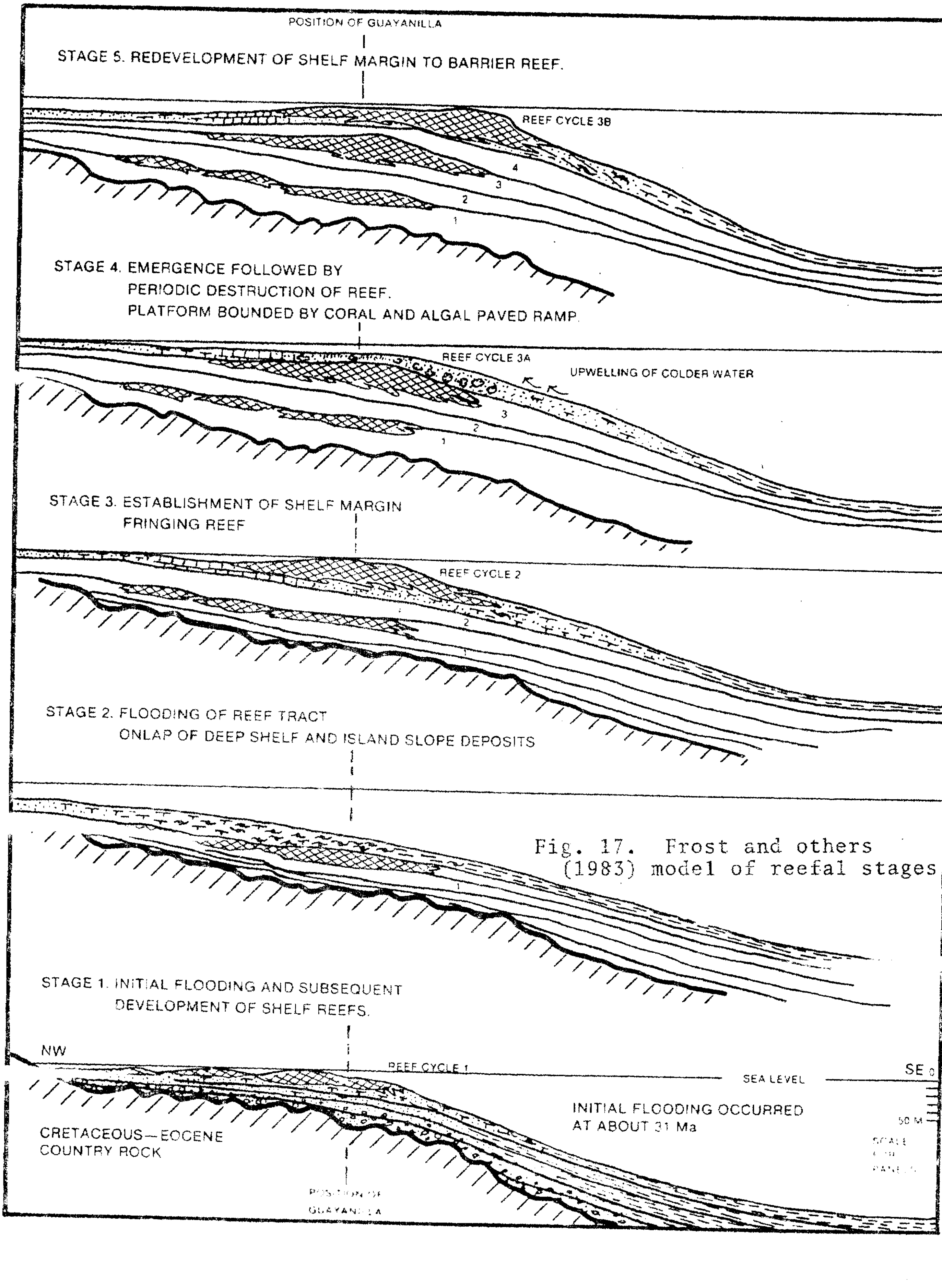
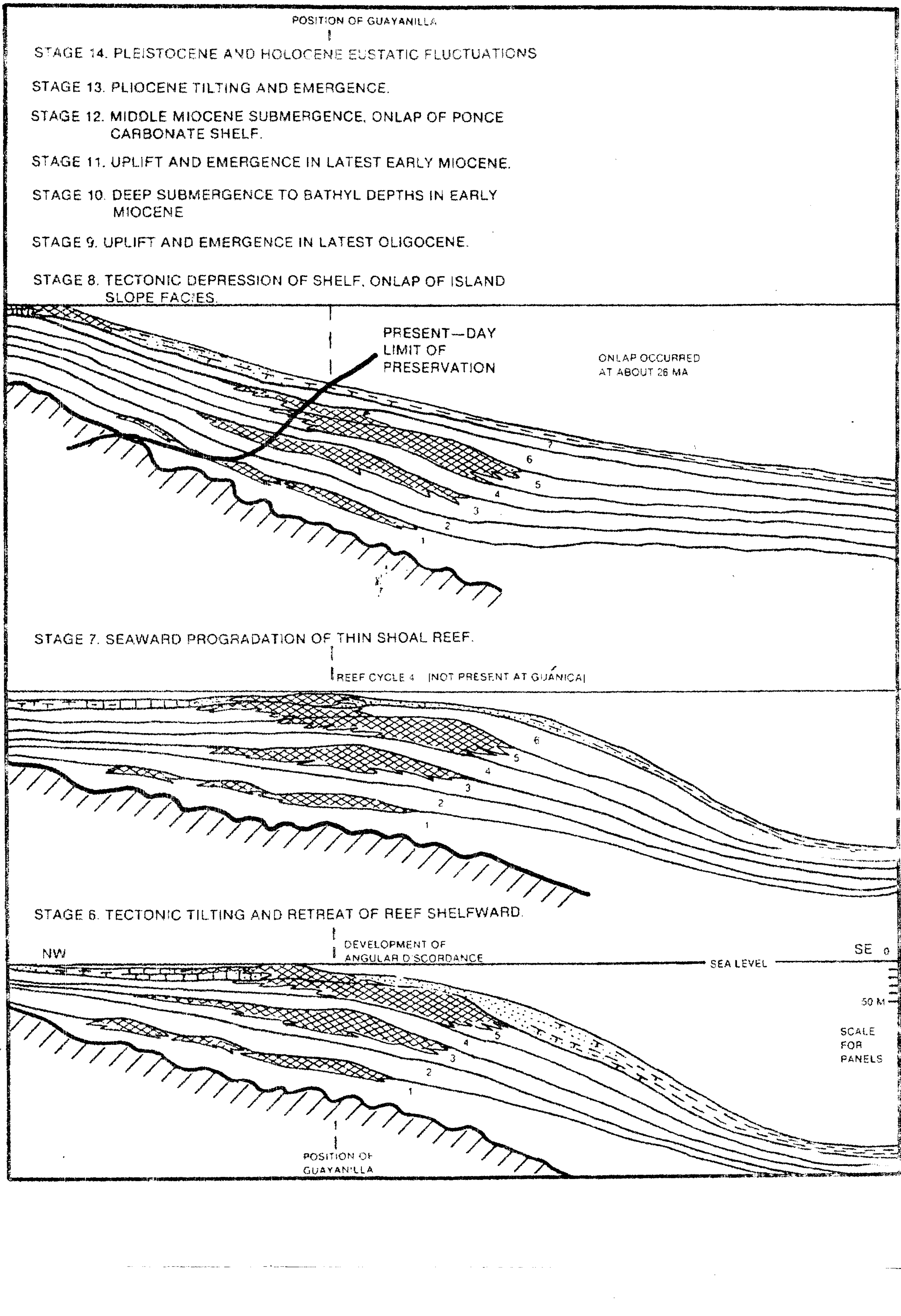


Fig. 17. Frost and others (1983) model of reefal stages


POSITION OF GUAYANILLA
STAGE 14. PLEISTOCENE AND HOLOCENE EUSTATIC FLUCTUATIONS
STAGE 13. PLIOCENE TILTING AND EMERGENCE.
STAGE 12. MIDDLE MIOCENE SUBMERGENCE, ONLAP OF PONCE CARBONATE SHELF.
STAGE 11. UPLIFT AND EMERGENCE IN LATEST EARLY MIOCENE.
STAGE 10. DEEP SUBMERGENCE TO BATHYL DEPTHS IN EARLY MIOCENE
STAGE 9. UPLIFT AND EMERGENCE IN LATEST OLIGOCENE.
STAGE 8. TECTONIC DEPRESSION OF SHELF, ONLAP OF ISLAND SLOPE FACIES.
PRESENT—DAY LIMIT OF PRESERVATION
ONLAP OCCURRED AT ABOUT 26 MA
7
6
5
4
3
2
1
STAGE 7. SEAWARD PROGRADATION OF THIN SHOAL REEF.
REEF CYCLE 4 (NOT PRESENT AT GUÁNICA)
6
5
4
3
2
1
STAGE 6. TECTONIC TILTING AND RETREAT OF REEF SHELFWARD.
NW
DEVELOPMENT OF ANGULAR DISCORDANCE
SE 0
SEA LEVEL
50 M
SCALE FOR PANELS
5
4
3
2
1
POSITION OF GUAYANILLA

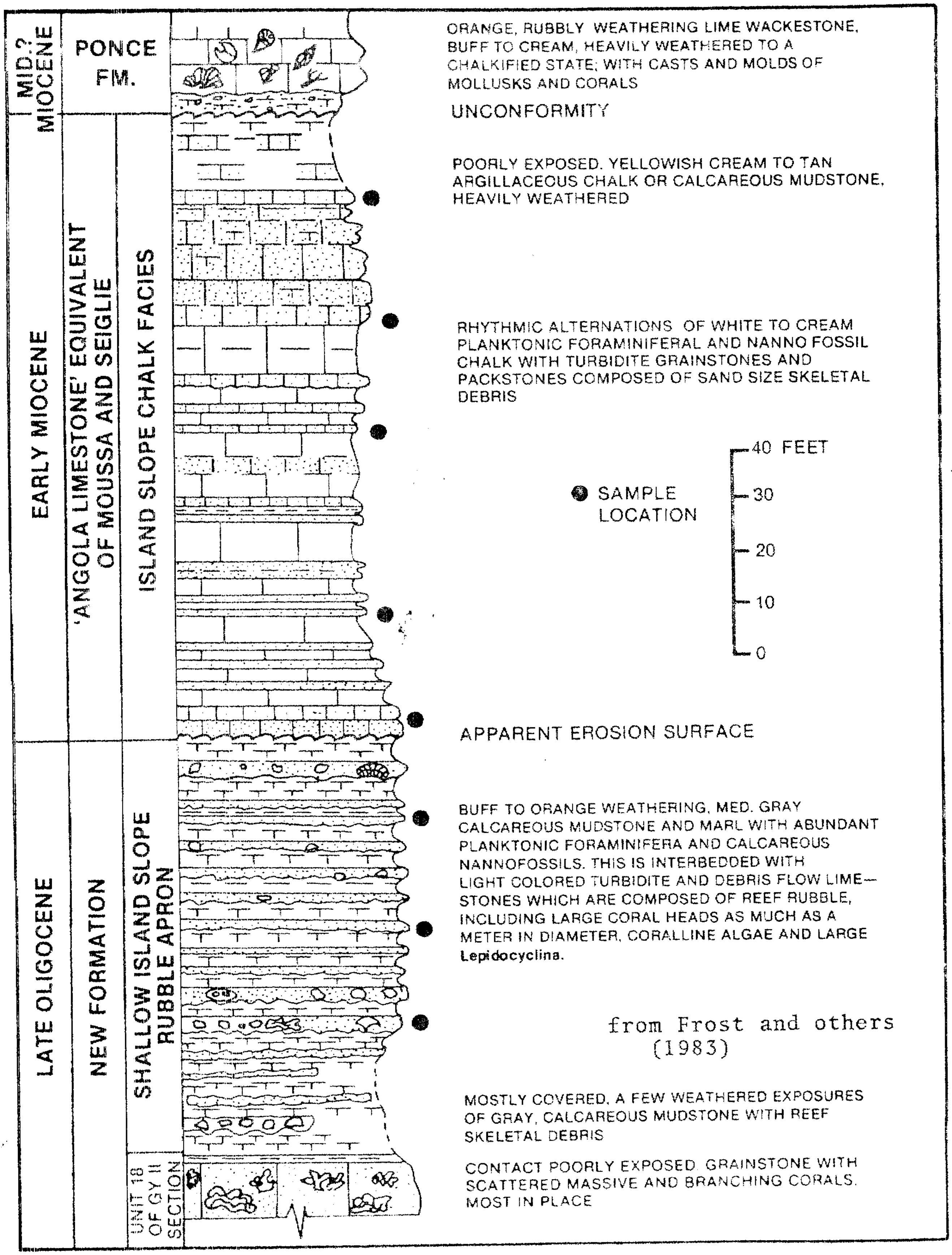

MID.? MIOCENE
PONCE FM.
ORANGE, RUBBLY WEATHERING LIME WACKESTONE, BUFF TO CREAM, HEAVILY WEATHERED TO A CHALKIFIED STATE; WITH CASTS AND MOLDS OF MOLLUSKS AND CORALS
UNCONFORMITY
EARLY MIOCENE
'ANGOLA LIMESTONE' EQUIVALENT OF MOUSSA AND SEIGLIE
ISLAND SLOPE CHALK FACIES
POORLY EXPOSED. YELLOWISH CREAM TO TAN ARGILLACEOUS CHALK OR CALCAREOUS MUDSTONE, HEAVILY WEATHERED
RHYTHMIC ALTERNATIONS OF WHITE TO CREAM PLANKTONIC FORAMINIFERAL AND NANNO FOSSIL CHALK WITH TURBIDITE GRAINSTONES AND PACKSTONES COMPOSED OF SAND SIZE SKELETAL DEBRIS
SAMPLE LOCATION
40 FEET
30
20
10
0
APPARENT EROSION SURFACE
LATE OLIGOCENE
NEW FORMATION
SHALLOW ISLAND SLOPE RUBBLE APRON
BUFF TO ORANGE WEATHERING, MED. GRAY CALCAREOUS MUDSTONE AND MARL WITH ABUNDANT PLANKTONIC FORAMINIFERA AND CALCAREOUS NANNOFOSSILS. THIS IS INTERBEDDED WITH LIGHT COLORED TURBIDITE AND DEBRIS FLOW LIME-STONES WHICH ARE COMPOSED OF REEF RUBBLE, INCLUDING LARGE CORAL HEADS AS MUCH AS A METER IN DIAMETER, CORALLINE ALGAE AND LARGE Lepidocyclina.
from Frost and others (1983)
MOSTLY COVERED. A FEW WEATHERED EXPOSURES OF GRAY, CALCAREOUS MUDSTONE WITH REEF SKELETAL DEBRIS
UNIT 18 OF GY II SECTION
CONTACT POORLY EXPOSED. GRAINSTONE WITH SCATTERED MASSIVE AND BRANCHING CORALS, MOST IN PLACE

Fig. 18.

caused by a change in wave energy or sedimentation rate. Both units were probably deposited in a shallow shelf environment. The mud in Unit 3 was probably deposited during a storm event. The lack of corals in Unit 4 may have resulted from this influx of mud that ended reef development.

STOP 7: Deep-water clastics in the Juana Diaz Formation (2.1 miles E. of start of 52)

As we proceed to the eastern part of the exposed Middle Tertiary basin of the South Coast of Puerto Rico, we note an amazing change in the nature of the basal clastic sediments. Whereas the basal clastics of Stops 1 and 2 were predominantly shallow water facies, toward the east, a great thickness of deep water (bathyal) sediments are observed. Unfortunately, the basal contact between the Juana Diaz Formation and the underlying basement is everywhere a fault, so we cannot easily correlate across the basin.

At Stop 7, we see a slide block of shallow water reefal material that has slid into thin to medium bedded sandstones and mudstones that contain foraminifera indicative of bathyal deposition. Based on what little is known about the paleogeography, we might guess that the direction of the slide was from the north or northwest, down a regional paleoslope (see Moussa, 1976).

STOP 8: Type section of the Juana Diaz (0.4 mi N of 14N out of Juana Diaz)

Exposed in the Jacaguas River valley are a sequence of turbidites. Notice that bedding dips to the north, opposite the regional dip, owing undoubtably to listric faulting.

This section of turbidites consists of sandy beds rich in Lepidocyclina, and massive silty beds, locally bearing concretions. Bedding is extremely tabular, indicating deposition of the turbidites in non-channelized facies. Foraminifera in the silty and muddy units indicate bathyal deposition.

STOP 9: Conglomeratic Fluvial Red Bed Facies (52 several miles E of stop 7)

In the extreme eastern area of deposition of Middle Tertiary sediments is an outcrop of conglomeratic materials, indicating deposition in a fluvial environment. This unit is extremely difficult to assign to the basin stratigraphy. Is this the missing basal unit of the turbiditic Juana Diaz Formation? Or is this the other side of the basin? We can't be sure until some good seismic reflection evidence is available.

GENERAL THOUGHTS ON FIELD TRIP NUMBER 2

On Field Trip Number 2, we have defined as best we can the South Coast Tertiary basin. We have shown something about the nature of its fill, how the stratigraphy relates to global eustacy, and the deformation of the sediments in the basin, but we still know very little about the basin itself. What were the margins of the basins? Was the flank of the Central Mountains of Puerto Rico one margin, such that the basin strikes East-West? What caused the basin to form? We have seen widespread evidence of normal faulting, yet the tectonics people tell us that the tectonic environment was one of strike-slip deformation.

To the south of Puerto Rico is the Muertos Trough subduction system, a subduction system that some people argue started in Middle Tertiary time. If this is so, is the South Coast Tertiary Basin a "forearc" basin (sans arc, of course, since the subduction is avolcanic)? If this is a forearc basin, what is the significance of all the evidence of normal faulting? And so on.

OPTIONAL STOP, TIME PERMITTING: A drive up Highway 139 to see the Eocene Belt

FIELD TRIP NUMBER 3:
North Coast Middle Tertiary

STOP I: Basal clastic facies of the San Sebastian Formation (Hwy 111, Lares, behind Mr. Special supermarket) (Fig. 19)

Exposed at this outcrop are fluvial-deltaic sediments of the San Sebastian Formation. The San Sebastian Formation is the North Coast equivalent of the Juana Diaz Formation on the South Coast.

At this outcrop, we can see mostly fine-grained facies, with a few prominent sandstone beds standing out. Within the fine-grained facies are at least three traceable coaly layers, filled with plant fragments. Locally these organic rich beds show evidence of being reworked by currents, as the organic matter is present in plane-laminated and rippled beds.

Concretions are also relatively common, and are typically a pale orange yellow in color. The carbon in these concretions we suspect was derived from the oxidation of methane during early diagenesis of the coaly materials. (Fig. 20)

STOP 2: San Sebastian Formation (129, at int. with 111)

At this outcrop, we observe a channel facies of the San Sebastian clastics, overlain by an overbank facies (inter-distributary?). Coaly sediments are also present at the top of the overbank facies.

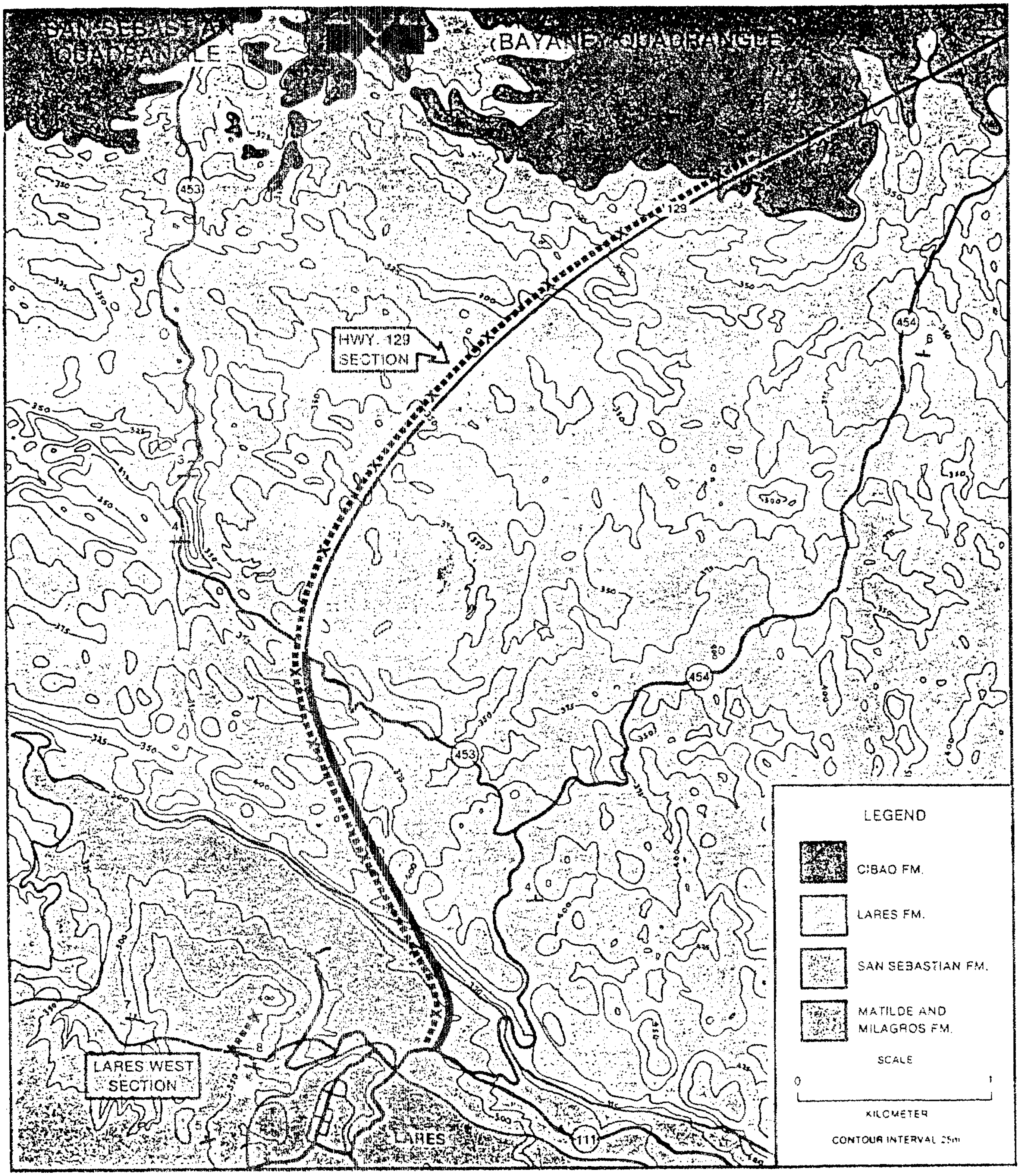


Fig. 19. Frost and others (1983) geologic location map of the Lares region

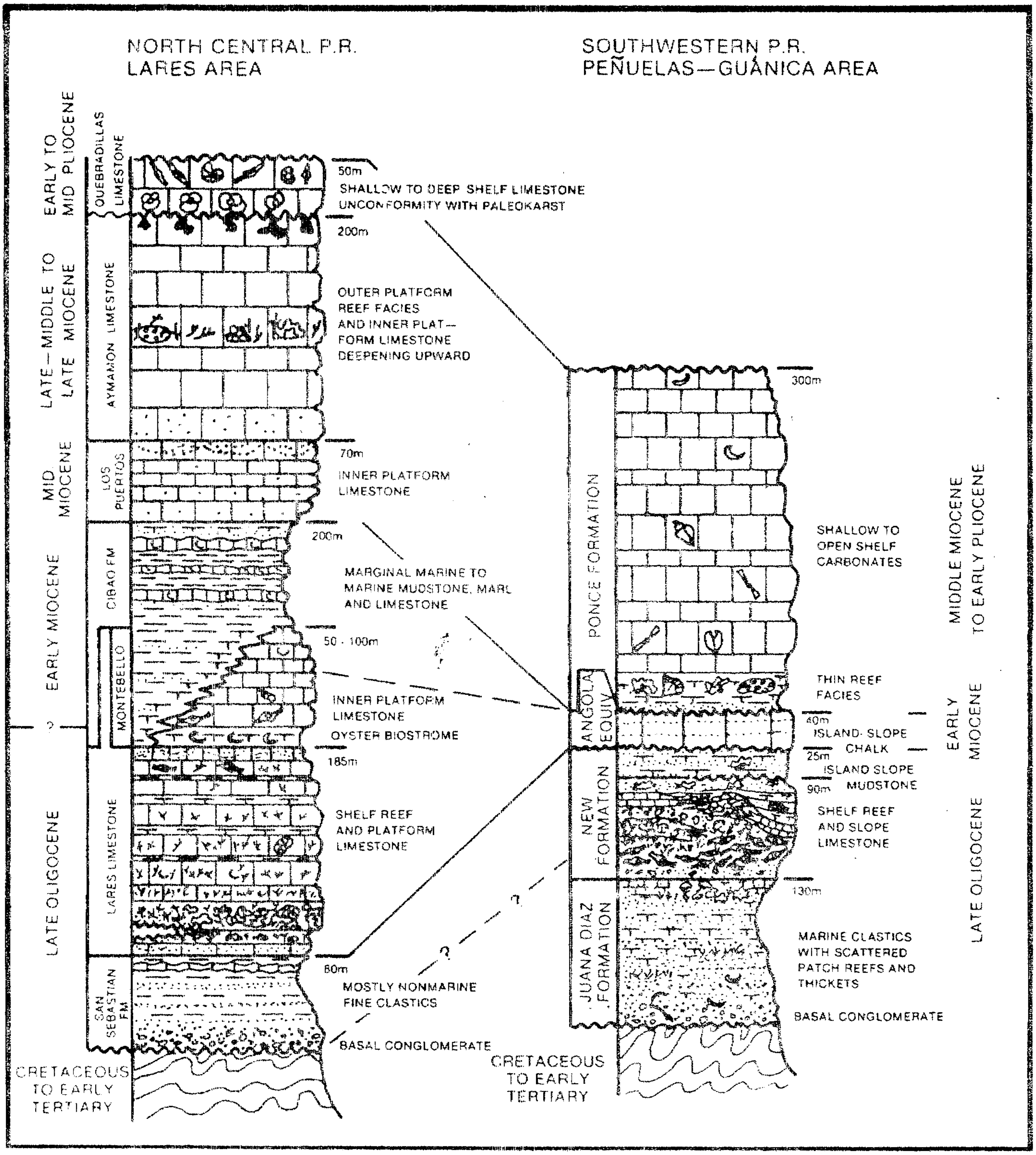


Fig. 20. Frost and others (1983) Stratigraphic correlations

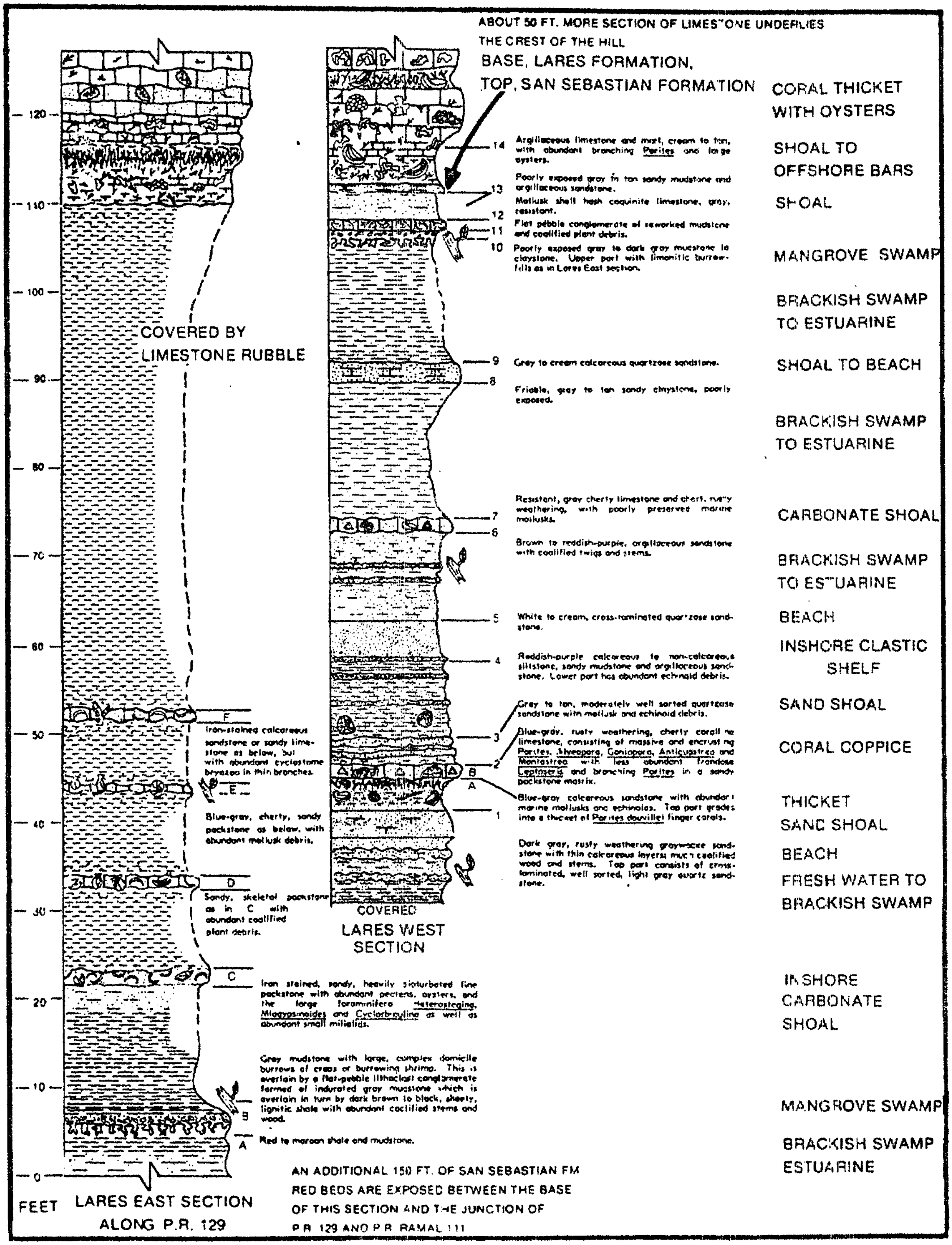


Fig. 21. Frost and others (1983) section in Lares area

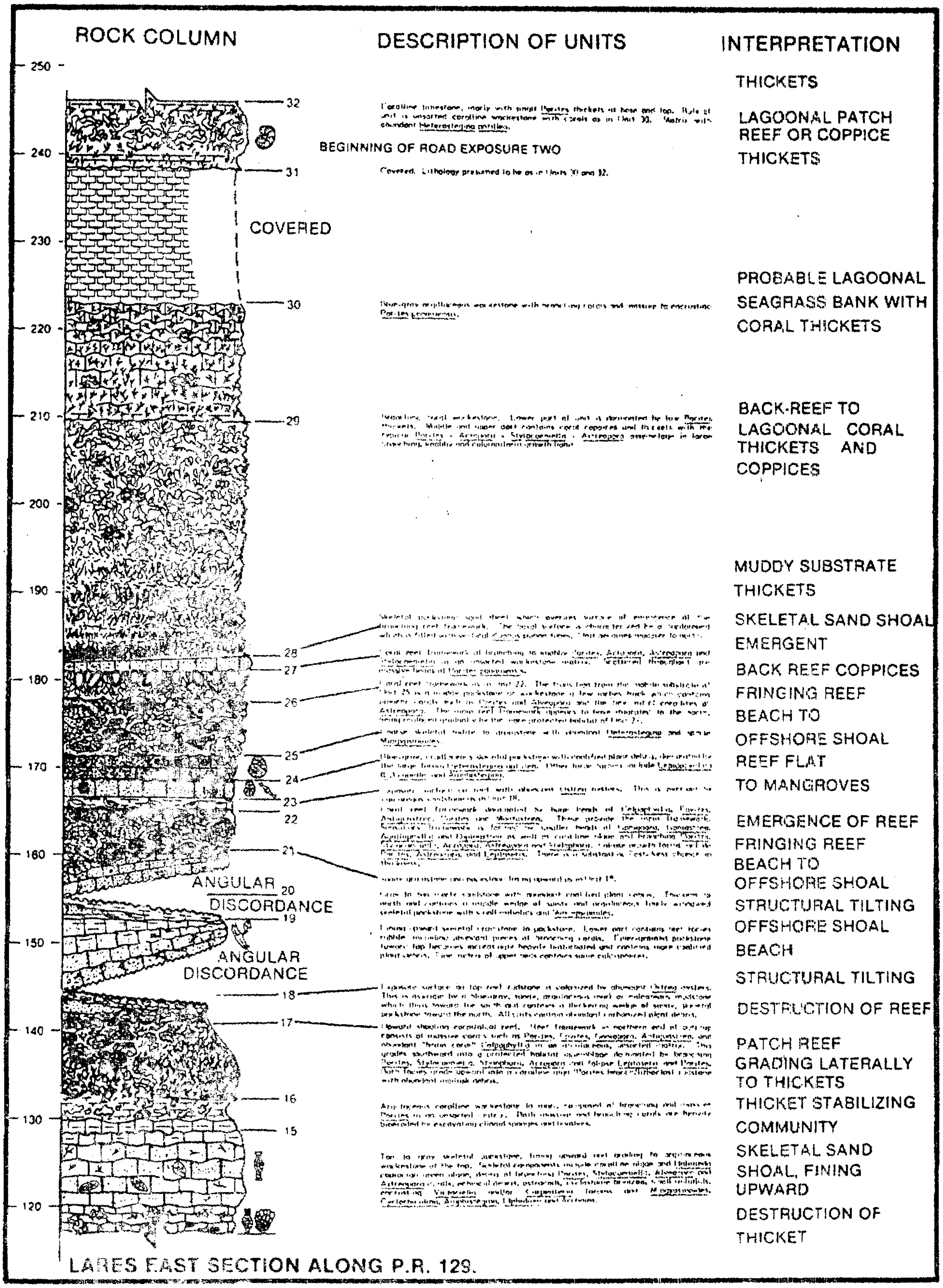

ROCK COLUMN
DESCRIPTION OF UNITS
INTERPRETATION
250
240
230
220
210
200
190
180
170
160
150
140
130
120
32
31
30
29
28
27
26
25
24
23
22
21
20
19
18
17
16
15
BEGINNING OF ROAD EXPOSURE TWO
COVERED
ANGULAR DISCORDANCE
ANGULAR DISCORDANCE
THICKETS
LAGOONAL PATCH REEF OR COPPICE
THICKETS
PROBABLE LAGOONAL SEAGRASS BANK WITH CORAL THICKETS
BACK-REEF TO LAGOONAL CORAL THICKETS AND COPPICES
MUDDY SUBSTRATE THICKETS
SKELETAL SAND SHOAL
EMERGENT
BACK REEF COPPICES
FRINGING REEF
BEACH TO OFFSHORE SHOAL
REEF FLAT TO MANGROVES
EMERGENCE OF REEF
FRINGING REEF
BEACH TO OFFSHORE SHOAL
STRUCTURAL TILTING
OFFSHORE SHOAL
BEACH
STRUCTURAL TILTING
DESTRUCTION OF REEF
PATCH REEF GRADING LATERALLY TO THICKETS
THICKET STABILIZING COMMUNITY
SKELETAL SAND SHOAL, FINING UPWARD
DESTRUCTION OF THICKET
LARES EAST SECTION ALONG P.R. 129.

Fig. 21 Cont

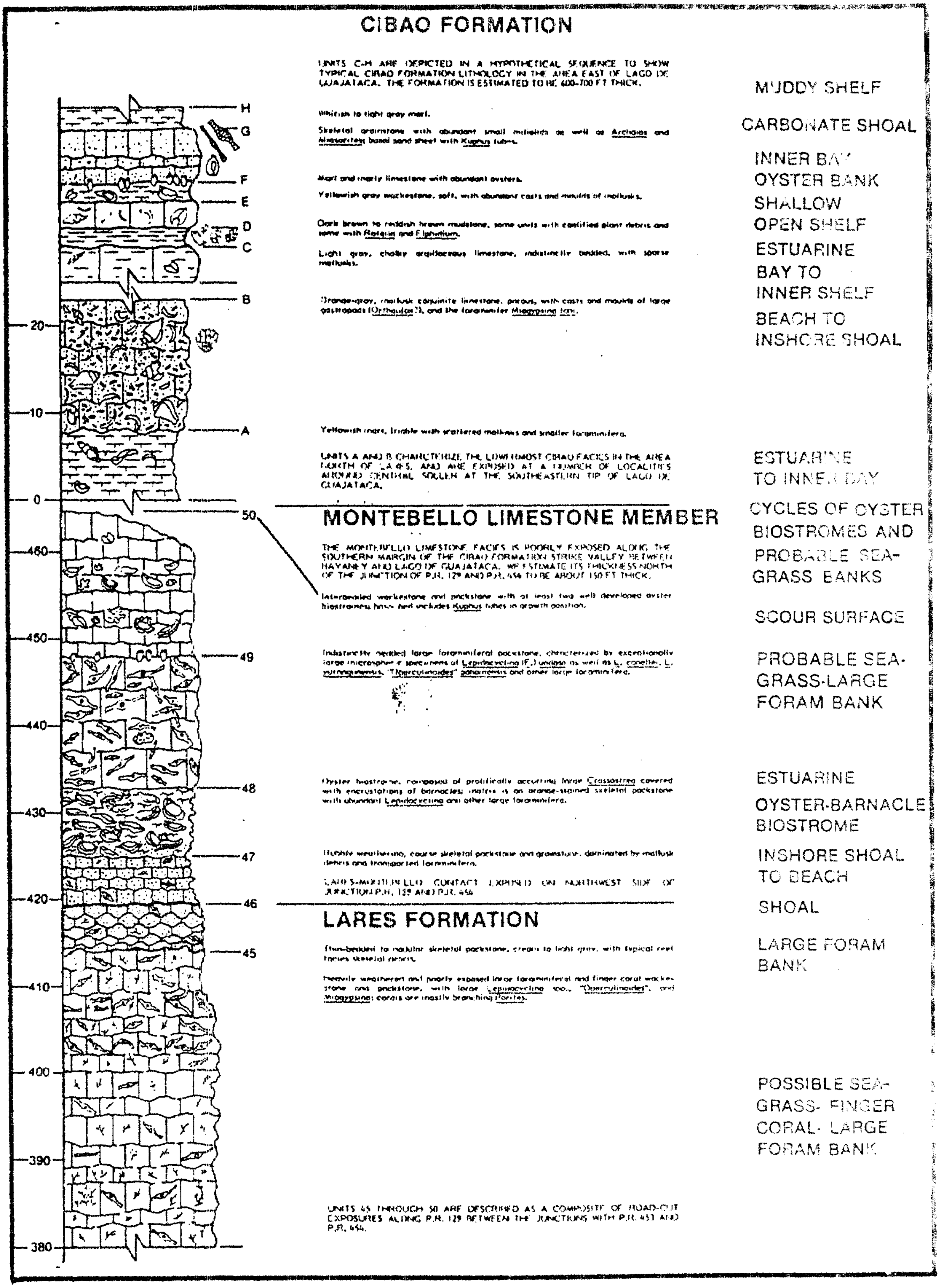

CIBAO FORMATION
UNITS C-H ARE DEPICTED IN A HYPOTHETICAL SEQUENCE TO SHOW TYPICAL CIBAO FORMATION LITHOLOGY IN THE AREA EAST OF LAGO DE GUAJATACA. THE FORMATION IS ESTIMATED TO BE 600-700 FT THICK.
H
Whitish to light gray marl.
MUDDY SHELF
G
Skeletal grainstone with abundant small miliolids as well as Archaias and Amphistegina basal sand sheet with Kuphus tubes.
CARBONATE SHOAL
F
Marl and marly limestone with abundant oysters.
INNER BAY
OYSTER BANK
E
Yellowish gray wackestone, soft, with abundant casts and moulds of mollusks.
SHALLOW
OPEN SHELF
D
Dark brown to reddish brown mudstone, some units with carbonized plant debris and some with Rotalia and Elphidium.
ESTUARINE
BAY TO
INNER SHELF
C
Light gray, chalky argillaceous limestone, indistinctly bedded, with sparse mollusks.
B
Orange-gray, mollusk coquinite limestone, porous, with casts and moulds of large gastropods (Orthaulax?), and the foraminifer Miogypsina sp.
BEACH TO
INSHORE SHOAL
20
10
A
Yellowish marl, friable with scattered mollusks and smaller foraminifera.
UNITS A AND B CHARACTERIZE THE LOWERMOST CIBAO FACIES IN THE AREA NORTH OF LARES, AND ARE EXPOSED AT A NUMBER OF LOCALITIES AROUND CENTRAL SOLLER AT THE SOUTHEASTERN TIP OF LAGO DE GUAJATACA.
ESTUARINE
TO INNER BAY
0
50
MONTEBELLO LIMESTONE MEMBER
THE MONTEBELLO LIMESTONE FACIES IS POORLY EXPOSED ALONG THE SOUTHERN MARGIN OF THE CIBAO FORMATION STRIKE VALLEY BETWEEN HAYANEY AND LAGO DE GUAJATACA. WE ESTIMATE ITS THICKNESS NORTH OF THE JUNCTION OF P.R. 129 AND P.R. 454 TO BE ABOUT 150 FT THICK.
CYCLES OF OYSTER
BIOSTROMES AND
PROBABLE SEA-
GRASS BANKS
460
Interbedded wackestone and packstone with at least two well developed oyster biostromes; basal bed includes Kuphus tubes in growth position.
SCOUR SURFACE
450
49
Indistinctly bedded large foraminiferal packstone, characterized by exceptionally large microspheric specimens of Lepidocyclina (E.) undosa as well as L. canellei, L. yurnagunensis, "Operculinoides" panamensis and other large foraminifera.
PROBABLE SEA-
GRASS-LARGE
FORAM BANK
440
48
Oyster biostrome, composed of prolifically occurring large Crassostrea covered with encrustations of barnacles; matrix is an orange-stained skeletal packstone with abundant Lepidocyclina and other large foraminifera.
ESTUARINE
OYSTER-BARNACLE
BIOSTROME
430
47
Rubble weathering, coarse skeletal packstone and grainstone, dominated by mollusk debris and transported foraminifera.
INSHORE SHOAL
TO BEACH
LARES-MONTEBELLO CONTACT EXPOSED ON NORTHWEST SIDE OF JUNCTION P.R. 129 AND P.R. 454
420
46
SHOAL
LARES FORMATION
45
Thin-bedded to nodular skeletal packstone, cream to light gray, with typical reef facies skeletal debris.
LARGE FORAM
BANK
410
Heavily weathered and poorly exposed large foraminiferal and finger coral wackestone and packstone, with large Lepidocyclina spp., "Operculinoides", and Miogypsina; corals are mostly branching Porites.
400
POSSIBLE SEA-
GRASS- FINGER
CORAL- LARGE
FORAM BANK
390
UNITS 45 THROUGH 50 ARE DESCRIBED AS A COMPOSITE OF ROAD-CUT EXPOSURES ALONG P.R. 129 BETWEEN THE JUNCTIONS WITH P.R. 453 AND P.R. 454.
380

Fig. 21 Cont.

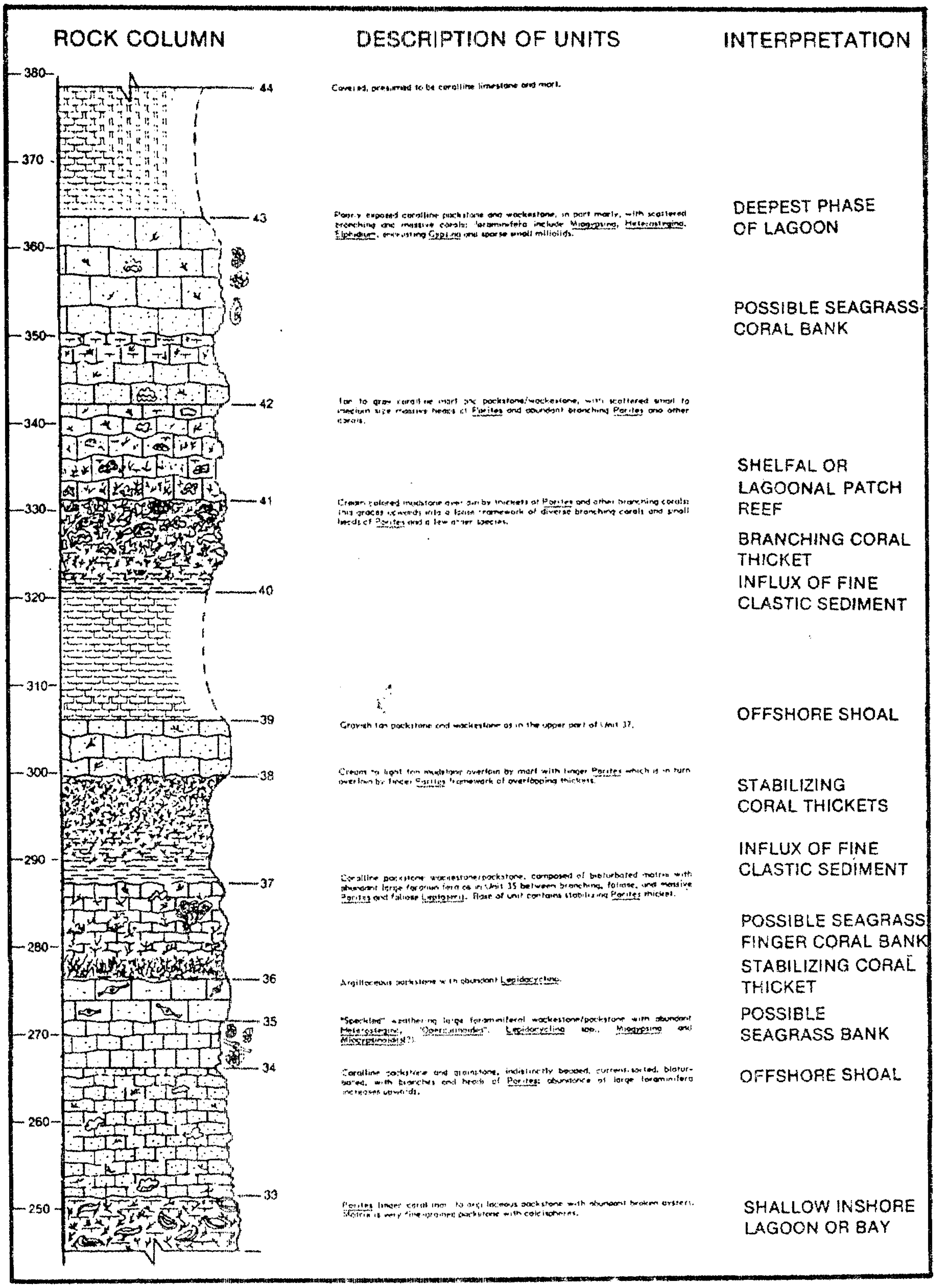

ROCK COLUMN
DESCRIPTION OF UNITS
INTERPRETATION
380
370
360
350
340
330
320
310
300
290
280
270
260
250
44
43
42
41
40
39
38
37
36
35
34
33
Covered, presumed to be coralline limestone and marl.
Poorly exposed coralline packstone and wackestone, in part marly, with scattered branching and massive corals; foraminifera include Miogypsina, Heterostegina, Elphidium, encrusting Gypsina and sparse small miliolids.
Tan to gray coralline marl and packstone/wackestone, with scattered small to medium size massive heads of Porites and abundant branching Porites and other corals.
Cream colored mudstone overlain by thickets of Porites and other branching corals; this grades upwards into a loose framework of diverse branching corals and small heads of Porites and a few other species.
Grayish tan packstone and wackestone as in the upper part of Unit 37.
Cream to light tan mudstone overlain by marl with finger Porites which is in turn overlain by finger Porites framework of overlapping thickets.
Coralline packstone wackestone/packstone, composed of bioturbated matrix with abundant large foraminifera as in Unit 35 between branching, foliose, and massive Porites and foliose Leptoseris. Base of unit contains stabilizing Porites thicket.
Argillaceous packstone with abundant Lepidocyclina.
"Speckled" weathering large foraminiferal wackestone/packstone with abundant Heterostegina, "Operculinoides", Lepidocyclina spp., Miogypsina and Miogypsinoides(?).
Coralline packstone and grainstone, indistinctly bedded, current-sorted, bioturbated, with branches and heads of Porites; abundance of large foraminifera increases upwards.
Porites finger coral mat in argillaceous packstone with abundant broken oysters. Matrix is very fine-grained packstone with calcispheres.
DEEPEST PHASE OF LAGOON
POSSIBLE SEAGRASS-CORAL BANK
SHELFAL OR LAGOONAL PATCH REEF
BRANCHING CORAL THICKET
INFLUX OF FINE CLASTIC SEDIMENT
OFFSHORE SHOAL
STABILIZING CORAL THICKETS
INFLUX OF FINE CLASTIC SEDIMENT
POSSIBLE SEAGRASS FINGER CORAL BANK
STABILIZING CORAL THICKET
POSSIBLE SEAGRASS BANK
OFFSHORE SHOAL
SHALLOW INSHORE LAGOON OR BAY

Fig. 21 Cont.

The channelized deposits contain abundant corse grained materials, and beautiful examples of trough cross-bedding are observed.

STOP 3: Middle Tertiary Carbonates (Taken From Frost, 1983) (Hwy 129, proceeding N)

See accompanying figures (Fig. 21).

STOP 4: Pliocene Quebradillas Limestone (Rt 2, Quebradillas)

The Quebradillas Limestone is of great importance because it records the Pliocene subsidence of the Puerto Rican shelf to become the Puerto Rican slope. The Quebradillas limestone was deposited at about 200 m water depth, much too deep to related to a Pliocene global sea level change. It has therefore been concluded by Birch (1986) that a massive flexuring event of northern Puerto Rico occurred at this time, uplifting Puerto Rico and submerging the slope. Such a flexure my be related to tectonic erosion in the Puerto Rico trench, according to Birch.

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