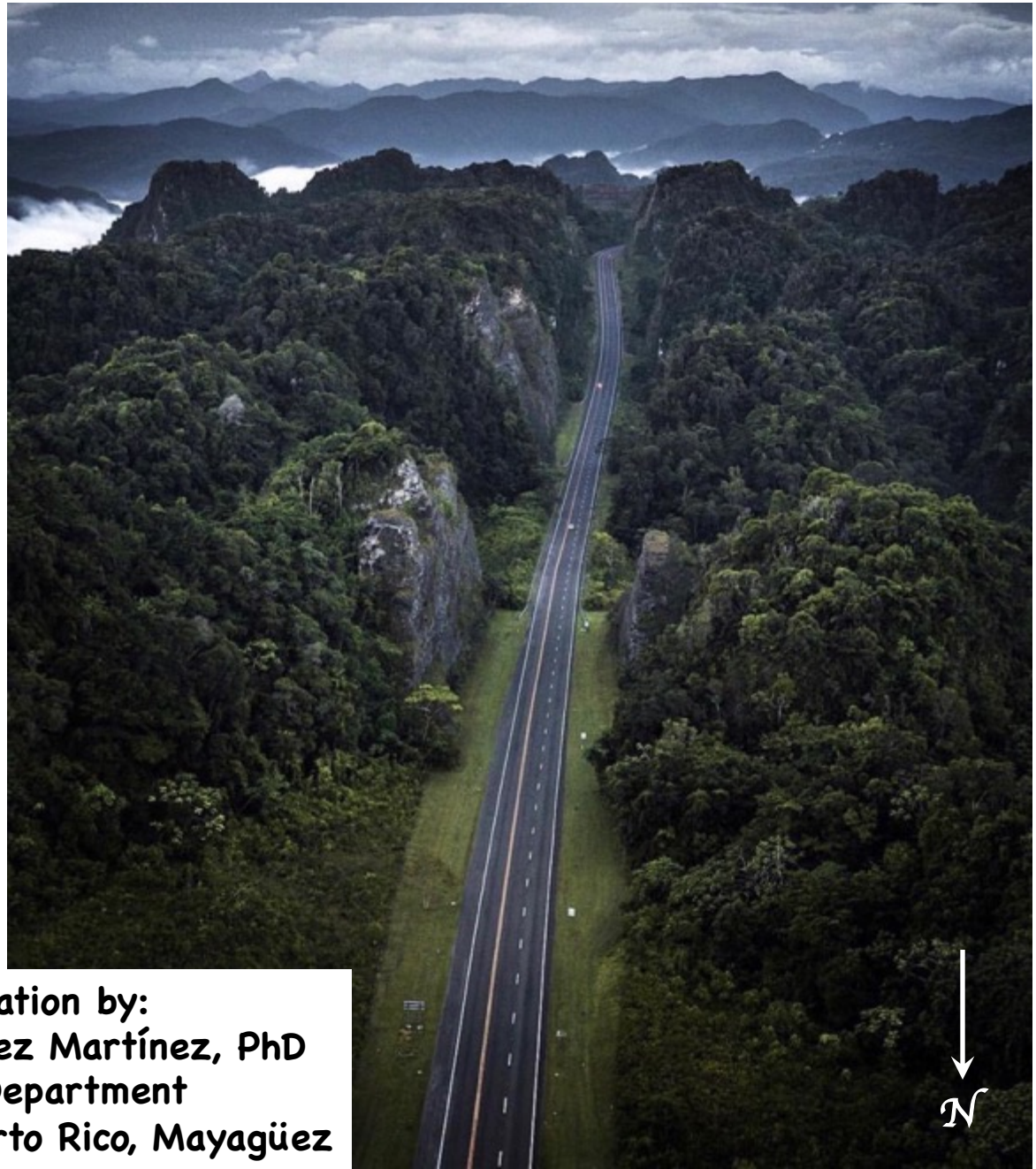
Puerto Rico North Coast Limestones at PR10

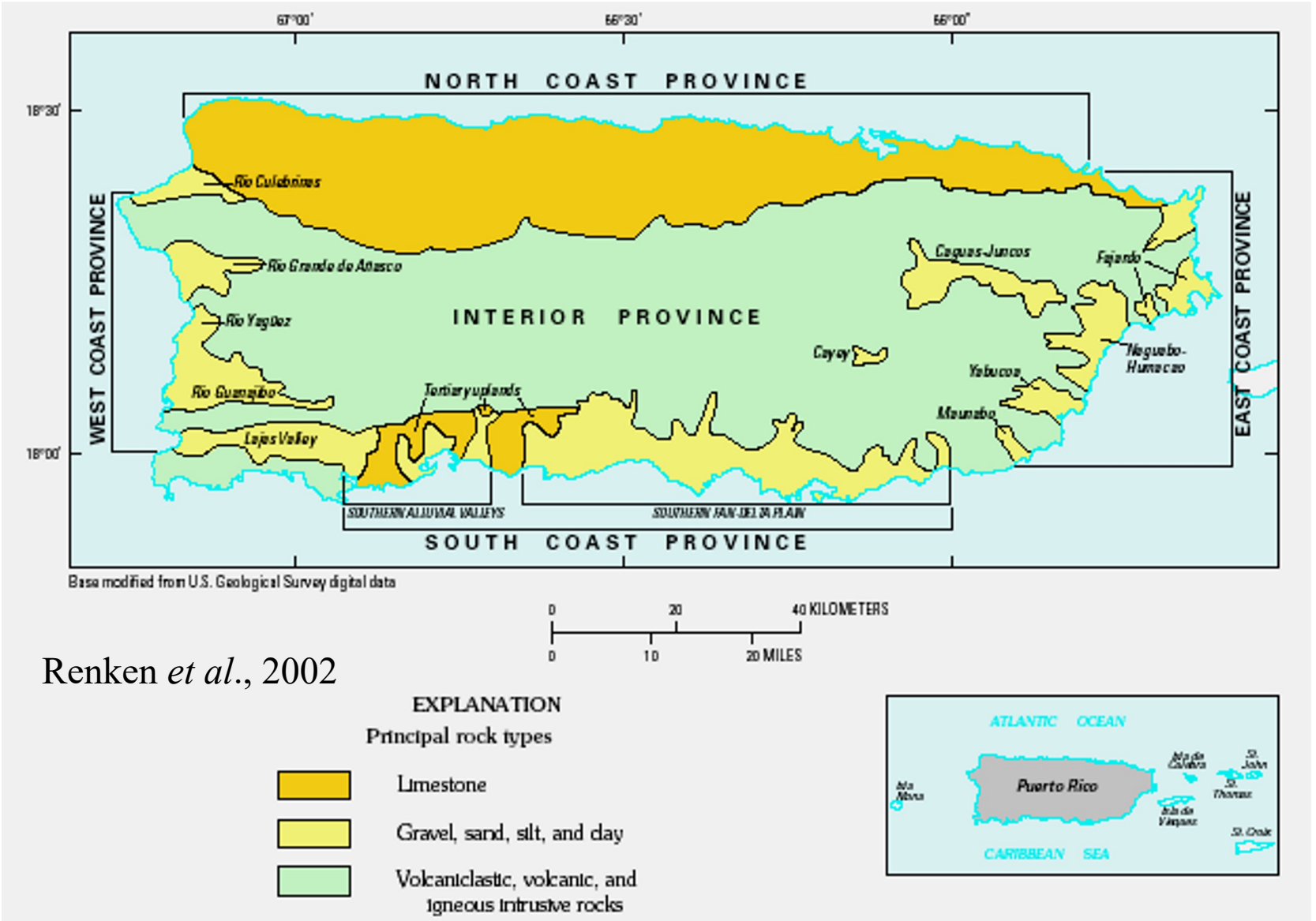


Simposio #34

9-12 Marzo 2023

Presentation by:
Wilson R. Ramírez Martínez, PhD
Geology Department
University of Puerto Rico, Mayagüez

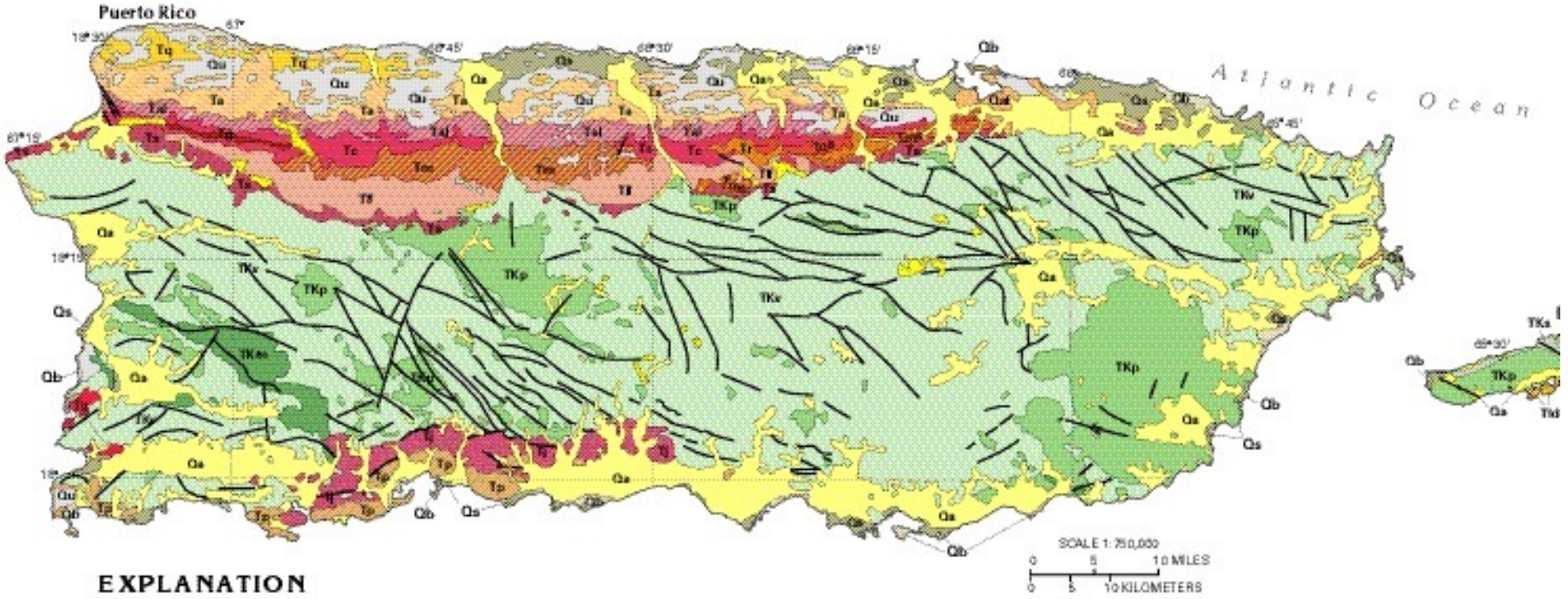
Cenozoic Limestones in Puerto Rico



Renken *et al.*, 2002

FIGURE 2.—Ground-water provinces of Puerto Rico (modified from McGuinness, 1948).

Mapa Geológico de Puerto Rico



EXPLANATION

Quaternary deposits

- Qa — Alluvium
- Ql — Landslide deposits
- Qb — Beach deposits
- Qs — Swamp and marsh deposits
- Qaf — Artificial fill
- Qu — Undifferentiated surficial deposits

Pliocene and Miocene rocks

- Tq — Quebradillas Limestone
- Tp — Ponce Limestone

Miocene rocks

- Ta — Aymamón Limestone
- Tal — Aguada (Los Puertos) Limestone
- Tg — Guanajibo Formation
- Tc — Cibao Formation
- Tms — Montebello Limestone Member
- Tqa — Quebrada Arenas Limestone Member—Includes Miranda Sand Member
- Tr — Río Indio Limestone Member—Includes Almirante Sur Lentil
- Tsg — Guajataca Member

Miocene and Oligocene deposits

- Tmas — Mucarabones Sand
- Tj — Juana Díaz Formation
- Tlf — Lares Formation
- Ts — San Sebastián Formation

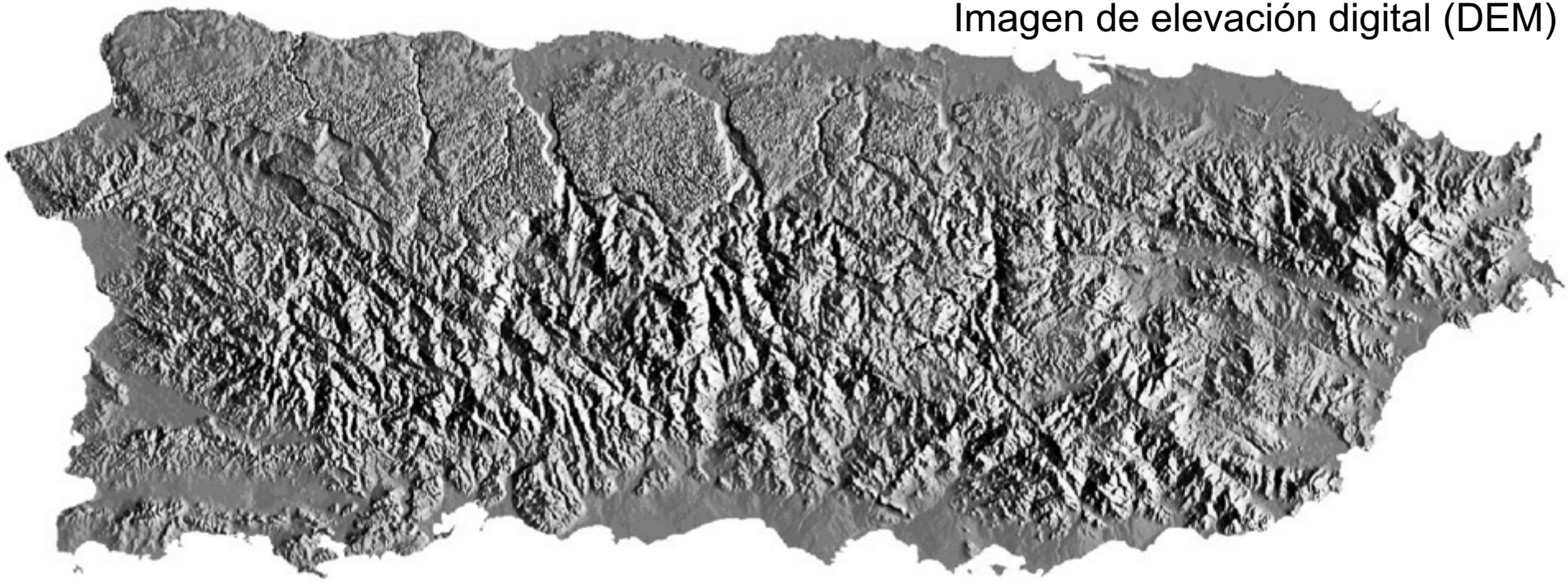
Eocene, Paleocene, and Cretaceous rocks

- TKv — Volcanic and sedimentary rocks
- TKp — Plutonic rocks—Mostly quartz diorite and granodiorite
- TKm — Metamorphic (serpentinite), sedimentary, and igneous rocks

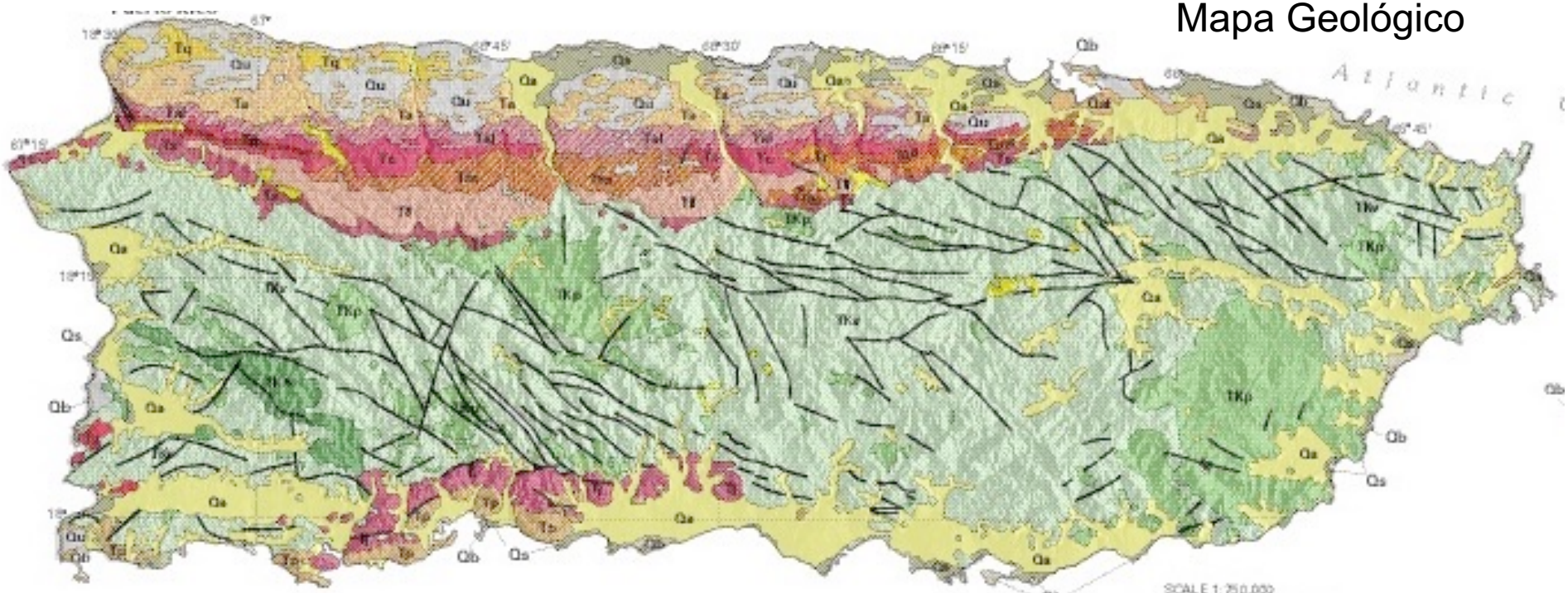
——— Fault

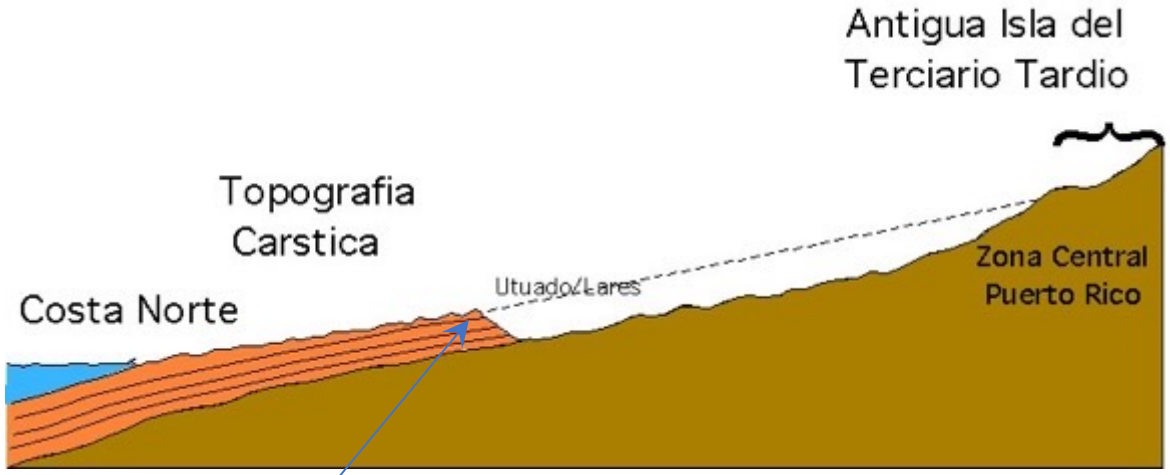
Renken *et al*., 2002

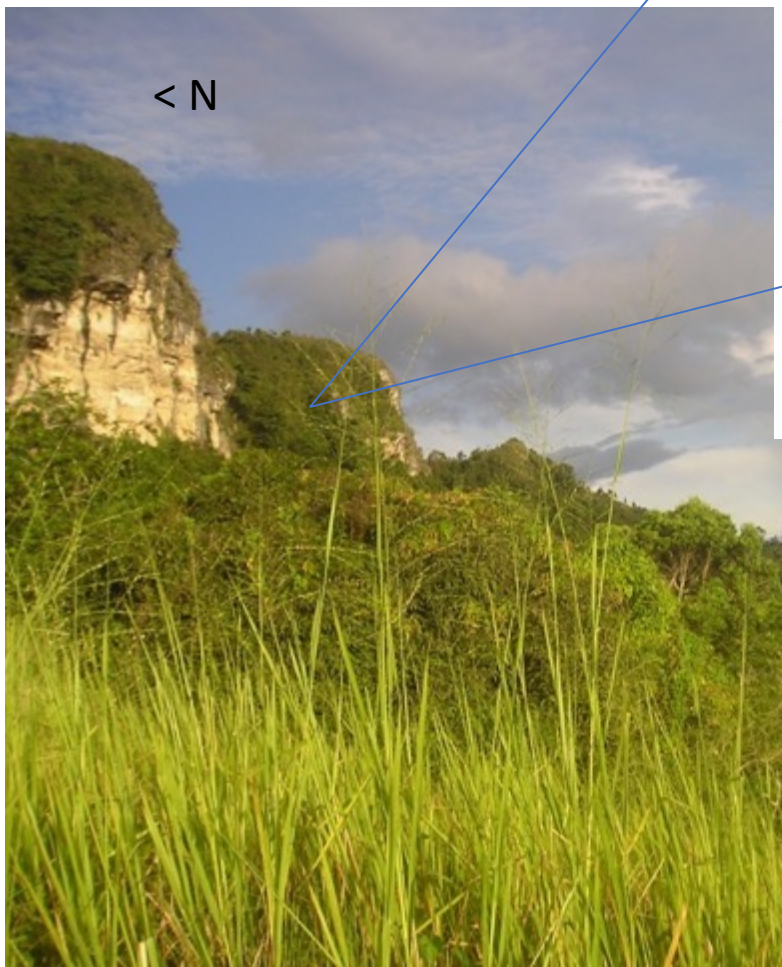
Imagen de elevación digital (DEM)



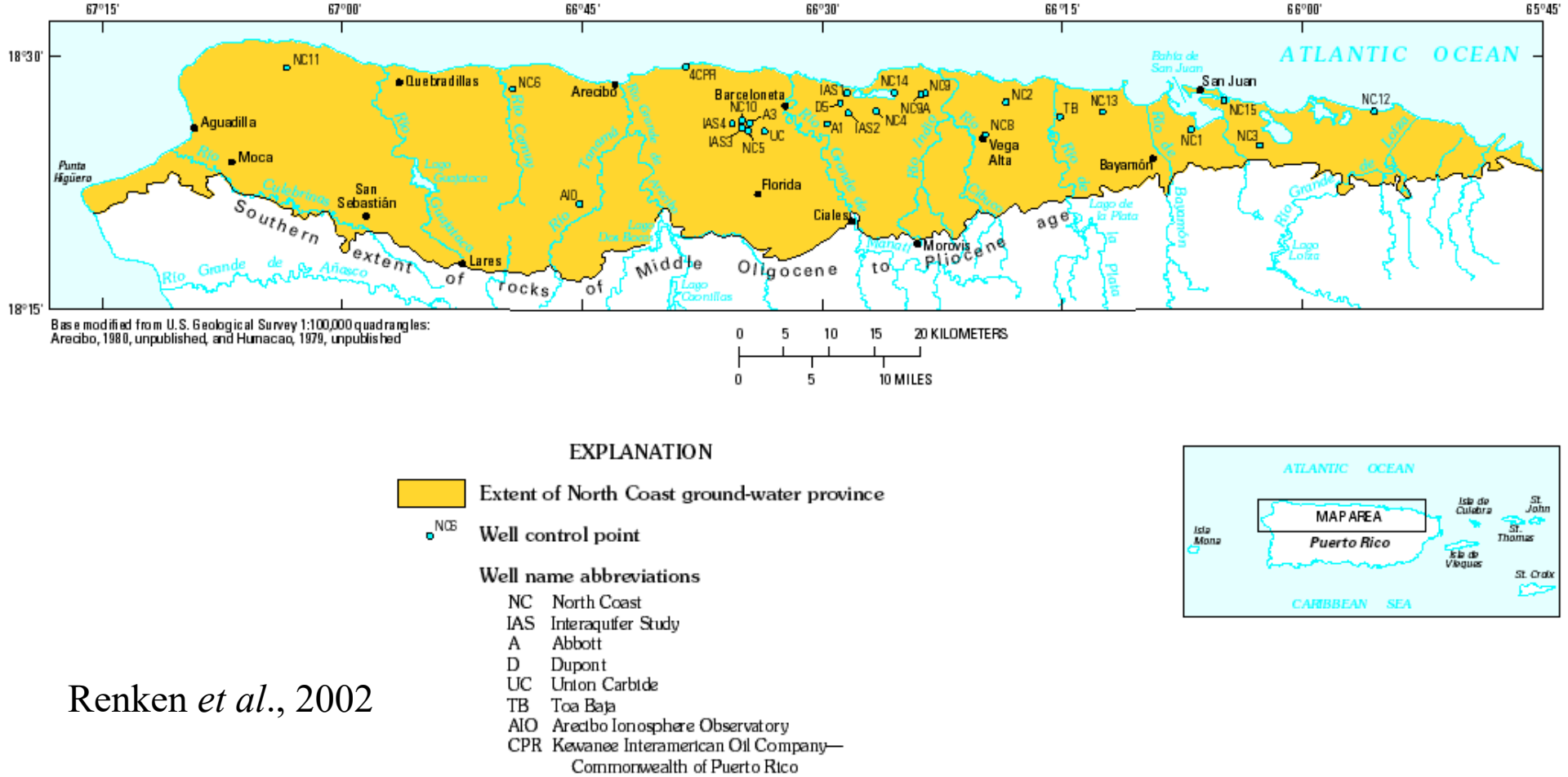
Mapa Geológico







Escarpado de las calizas (depósitos marinos) en los pueblos de Aguadilla, Lares hasta Bayamón.



EXPLANATION

Extent of North Coast ground-water province

NC6 Well control point

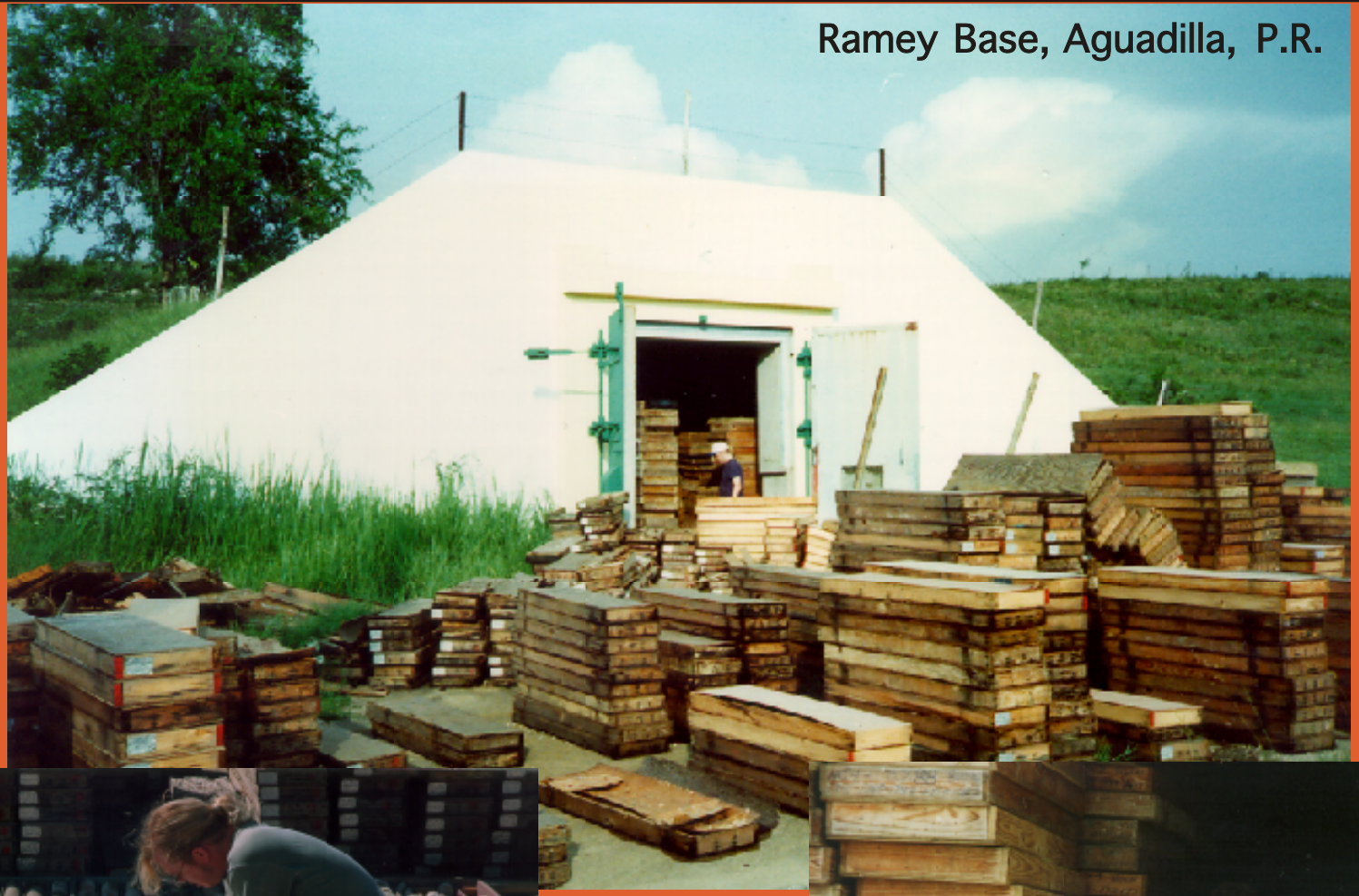
Well name abbreviations

NC	North Coast
IAS	Interaquifer Study
A	Abbott
D	Dupont
UC	Union Carbide
TB	Toa Baja
AIO	Arecibo Ionosphere Observatory
CPR	Kewanee Interamerican Oil Company—Commonwealth of Puerto Rico

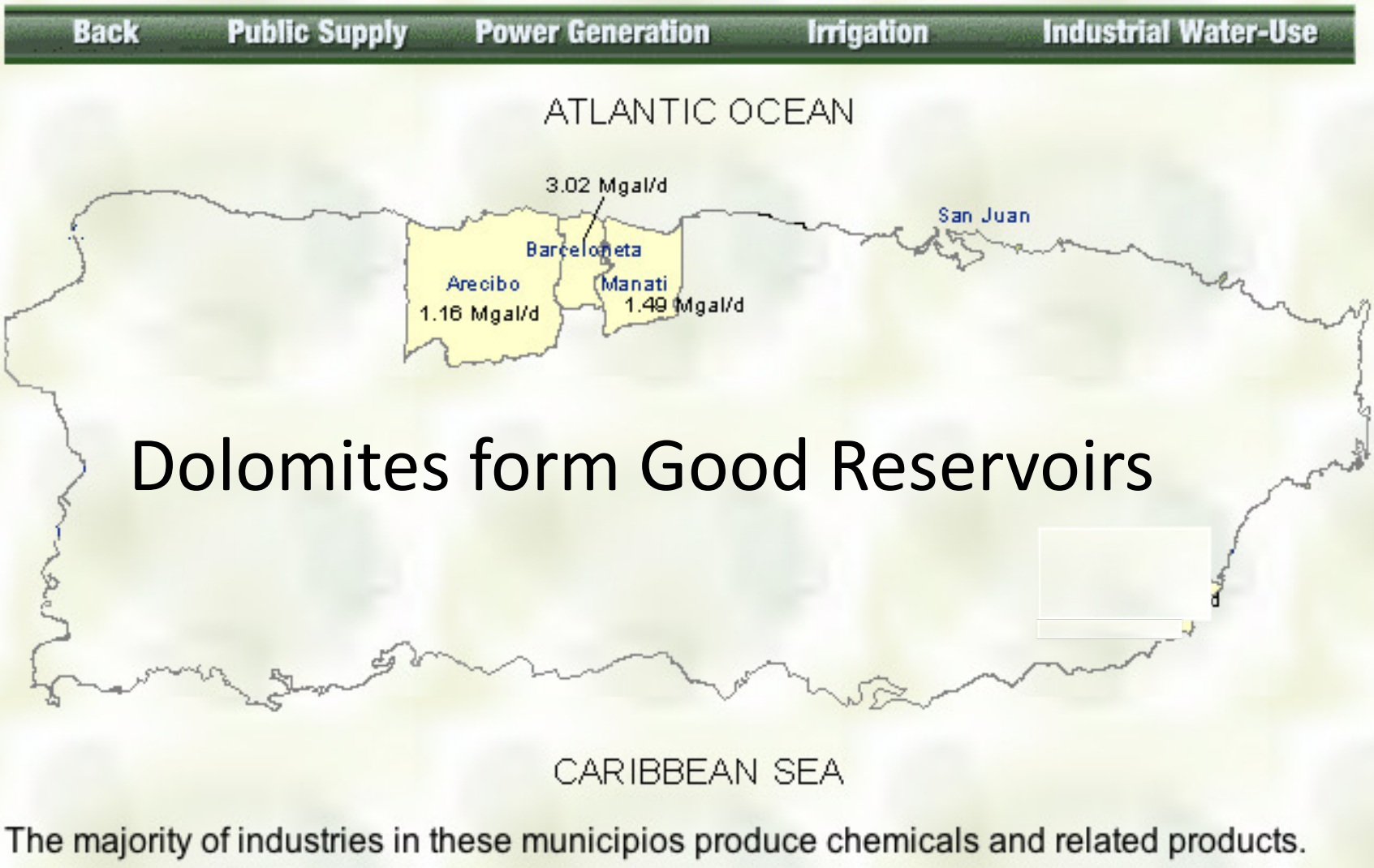
Renken *et al.*, 2002

FIGURE 21.—Location of cored test holes and other wells that penetrate Tertiary rocks beneath the North Coast ground-water province of Puerto Rico.

Ramey Base, Aguadilla, P.R.



Municipios where Industrial direct withdrawals of ground water is greater than 1.0 Mgal/d (1995)



Dolomites form Good Reservoirs

The majority of industries in these municipios produce chemicals and related products.

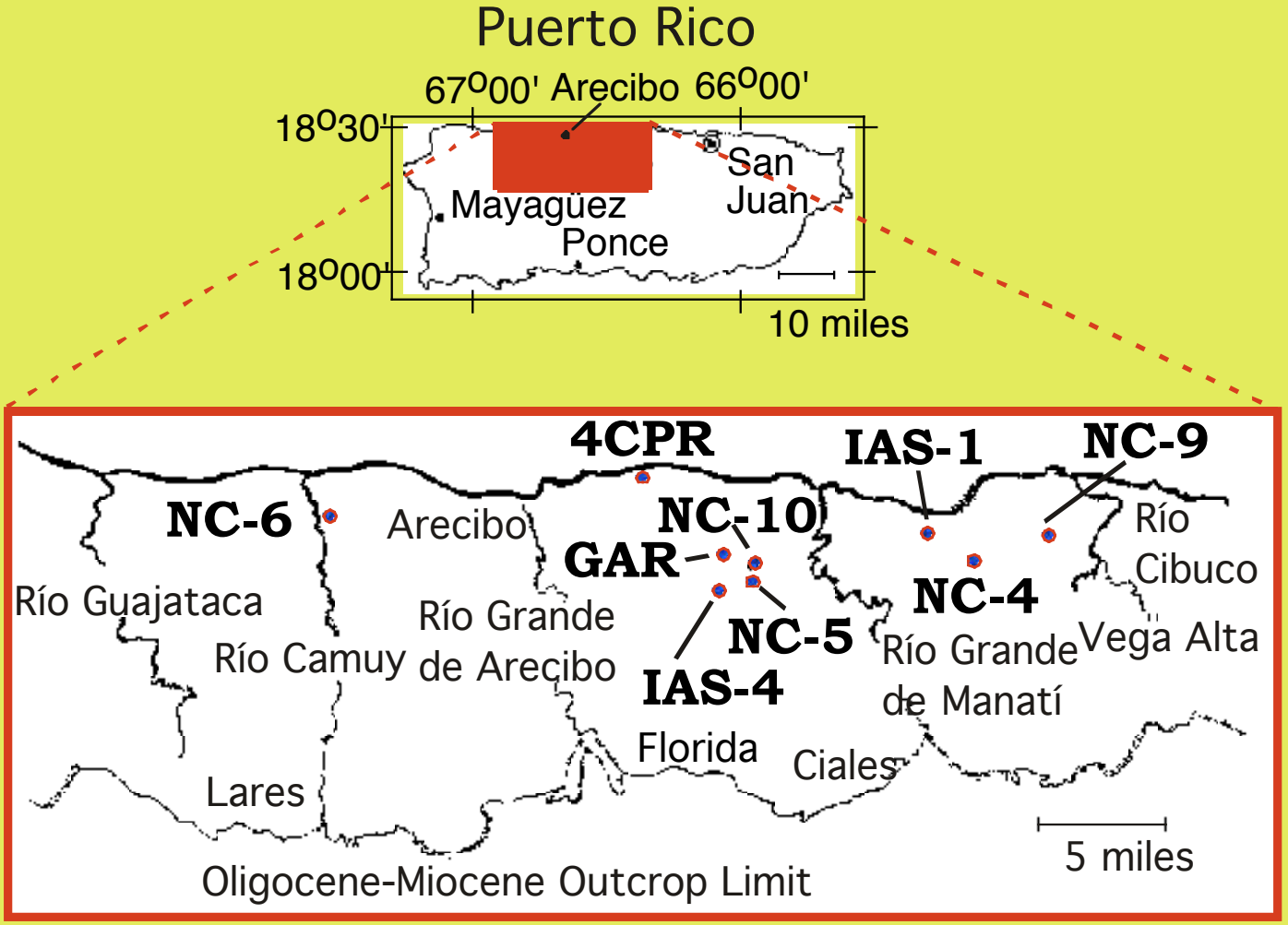
http://pr.water.usgs.gov/public/water_use/groundwater/

Industria farmacéutica en Puerto Rico

- Abbot Barceloneta Box 278- **Barceloneta**, P.R.-00617 846-3500
- Bristol Myers Box 657- **Barceloneta**, P.R.-00617 846-3800
- Merck Sharp & Dohme Box 601- **Barceloneta**, P.R.-00617 846-4100
- Pfizer Pharmaceuticals Box 628- **Barceloneta**, P.R.-00617 846-4300
- Searle Ltd. Box11247- **Barceloneta**, P.R.-00617 846-5000
- Up-John Caribe Box 11307- **Barceloneta**, P.R.-00617 846-4900
- Frito Lay Box 11517- **Barceloneta**, P.R.-00617 846-6060
- Playtex Box 188- **Barceloneta**, P.R.-00617 846-2260
- PSG (Planta Tratamiento) Box 2087- **Barceloneta**, P.R.-00617 846-1126
- Air Master Box 2097- **Barceloneta**, P.R.-00617 846-1800
- StarCom Calle Tomás Dávila #9 **Barceloneta**, P.R.-00617 846-4000

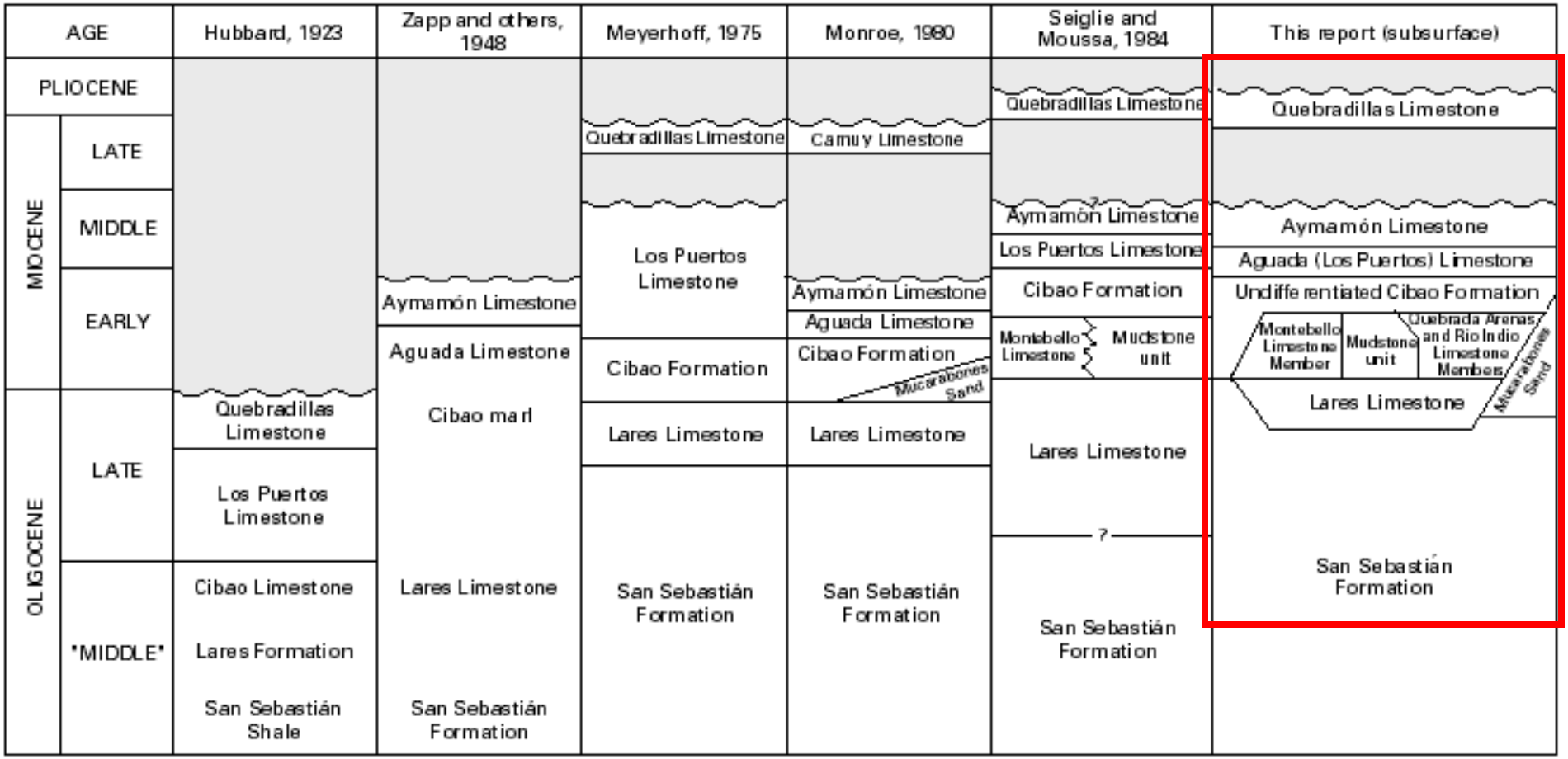
North Coast Confined Aquifer System

http://www.geocities.com/Heartland/Flats/6766/industrias/farmaceuticas.html

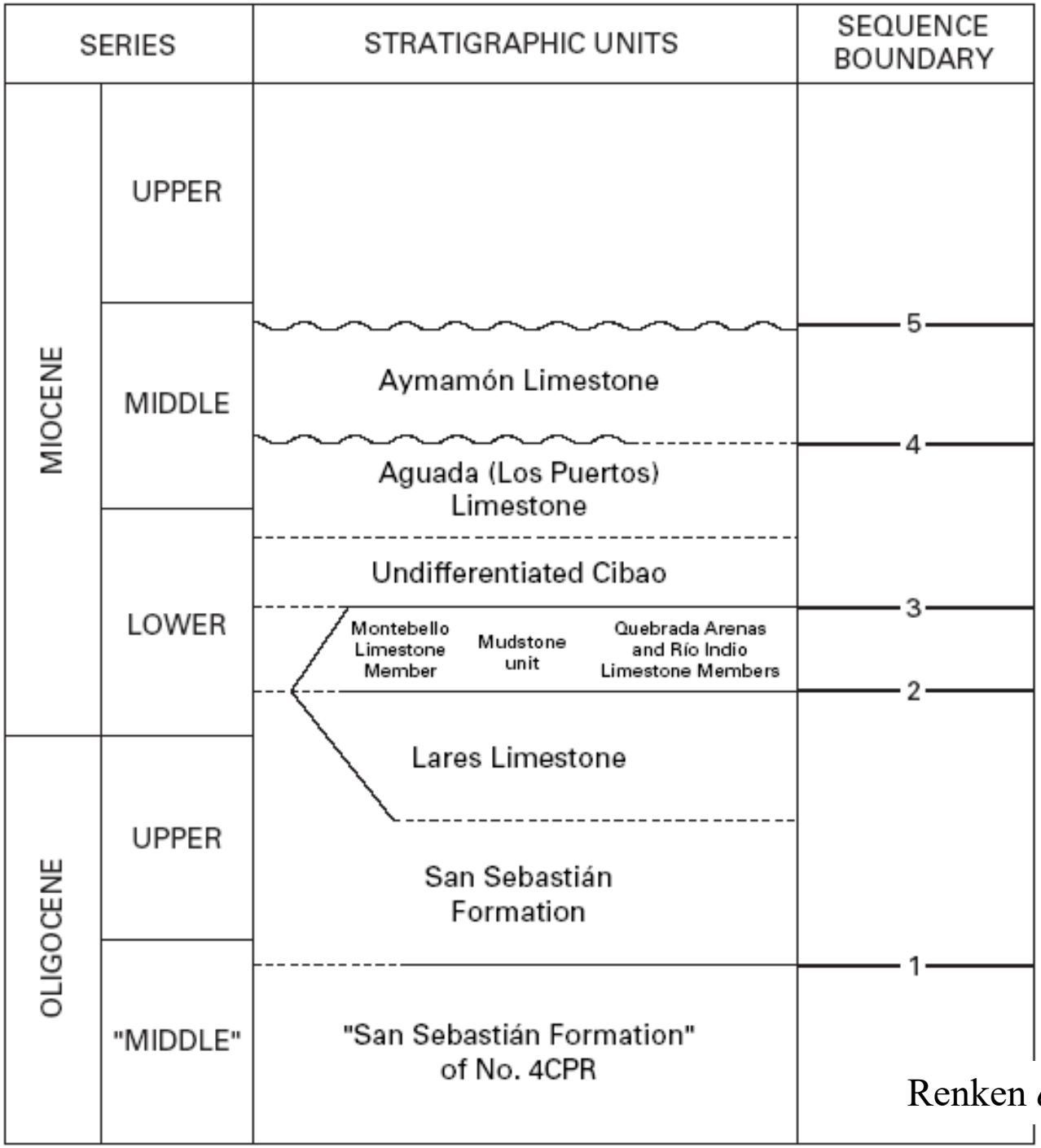


Ramírez, W., 2000

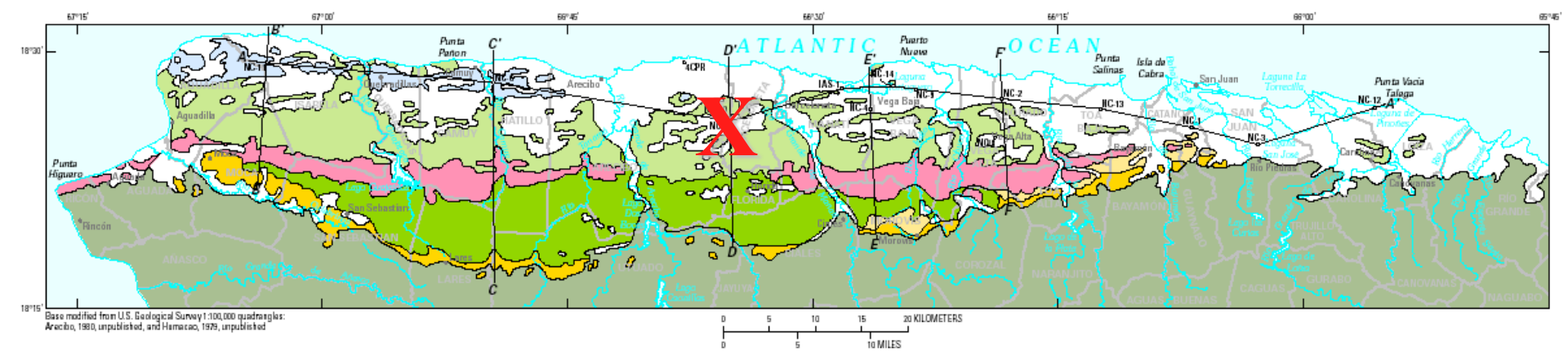
Stratigraphy of the Puerto Rico North Coast Province

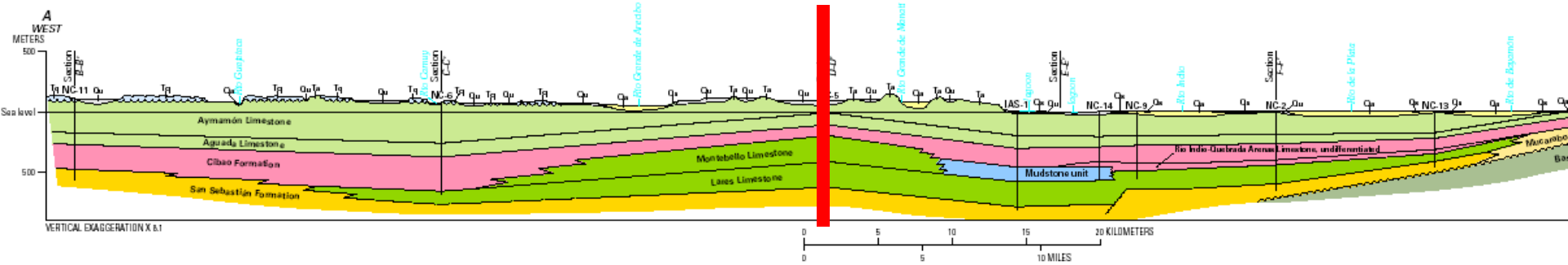


Renken *et al.*, 2002



Renken *et al*., 2002

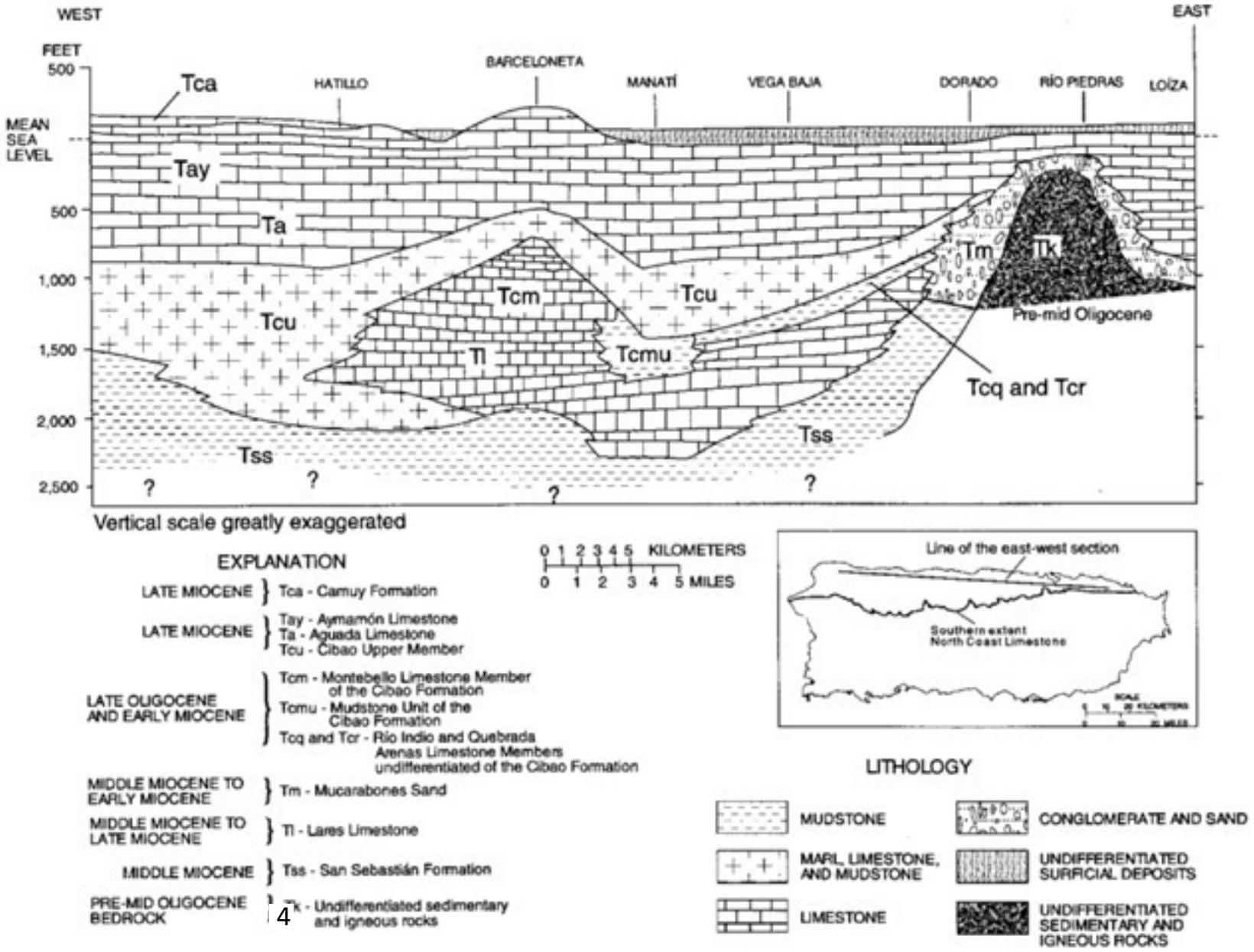




USGS
science for a changing world
USGS Water Resources of the Caribbean
Puerto Rico Water-Use Science and Information Program

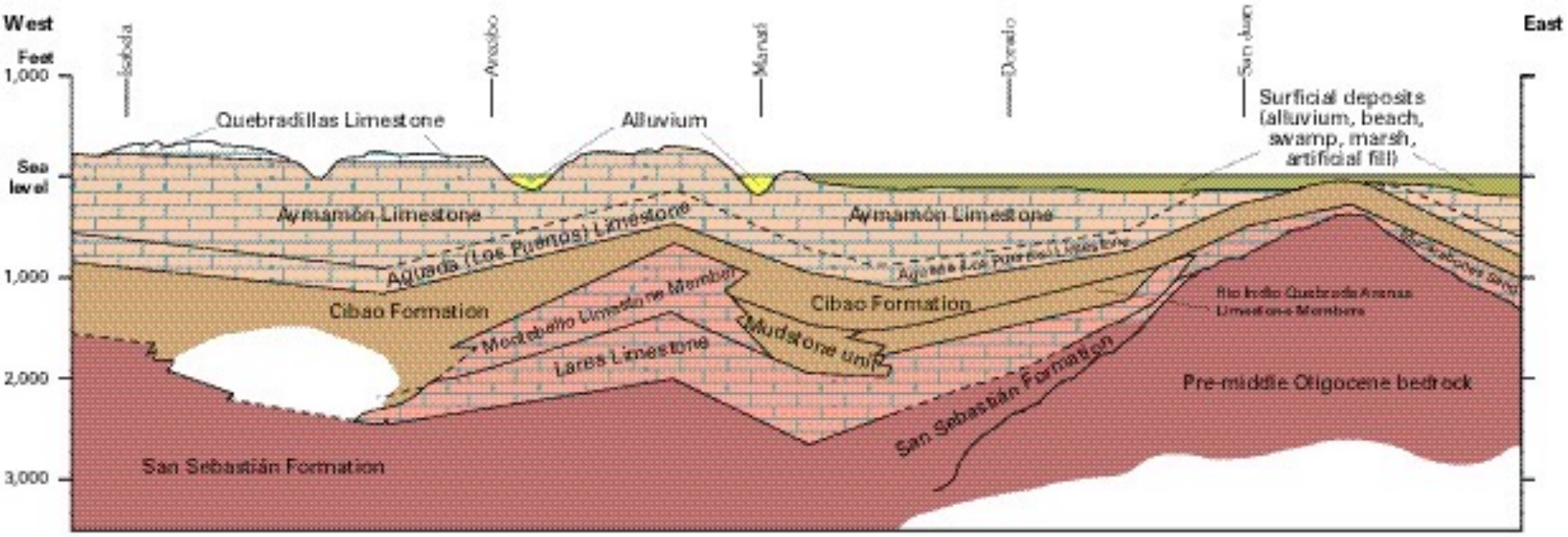
http://pr.water.usgs.gov

Age	EXPLANATION Depositional environments and lithofacies
PLIOCENE	Outer to middle neritic limestone
MIDDLE MIOCENE	Inner to middle neritic limestone and dolomite
EARLY MIOCENE	Inner to middle neritic mixed siliciclastic and carbonate rocks
LATE OLIGOCENE	Inner to middle neritic limestone and dolomite
"MIDDLE" OLIGOCENE	Nonmarine to inner neritic siliciclastic sandstone, mudstone, conglomerate with limestone
EARLY TERTIARY-CRETACEOUS	Volcanic rock, volcaniclastic sandstone and conglomerate, metavolcanic rock, sedimentary rocks
	Middle- to outer-neritic mudstone
	Marine and non-marine siliciclastic sandstone, mudstone and conglomerate
	Middle to inner neritic clays, sandstone, marl



East-west geologic cross section of northern Puerto Rico (from Rodríguez-Martínez, 1995).

East-west geologic cross section of northern Puerto Rico
(from Rodríguez-Martínez, 1995).



Rodríguez-Martínez, 1995

EXPLANATION

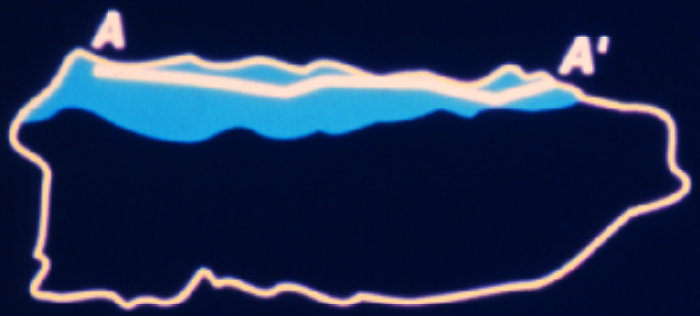
- Alluvial valley aquifer
- Local confining unit
- Unsaturated (nonaquifer)
- North Coast Limestone aquifer system
  - Upper aquifer
  - Confining unit
  - Lower aquifer
  - Basal confining unit

Geology modified from:

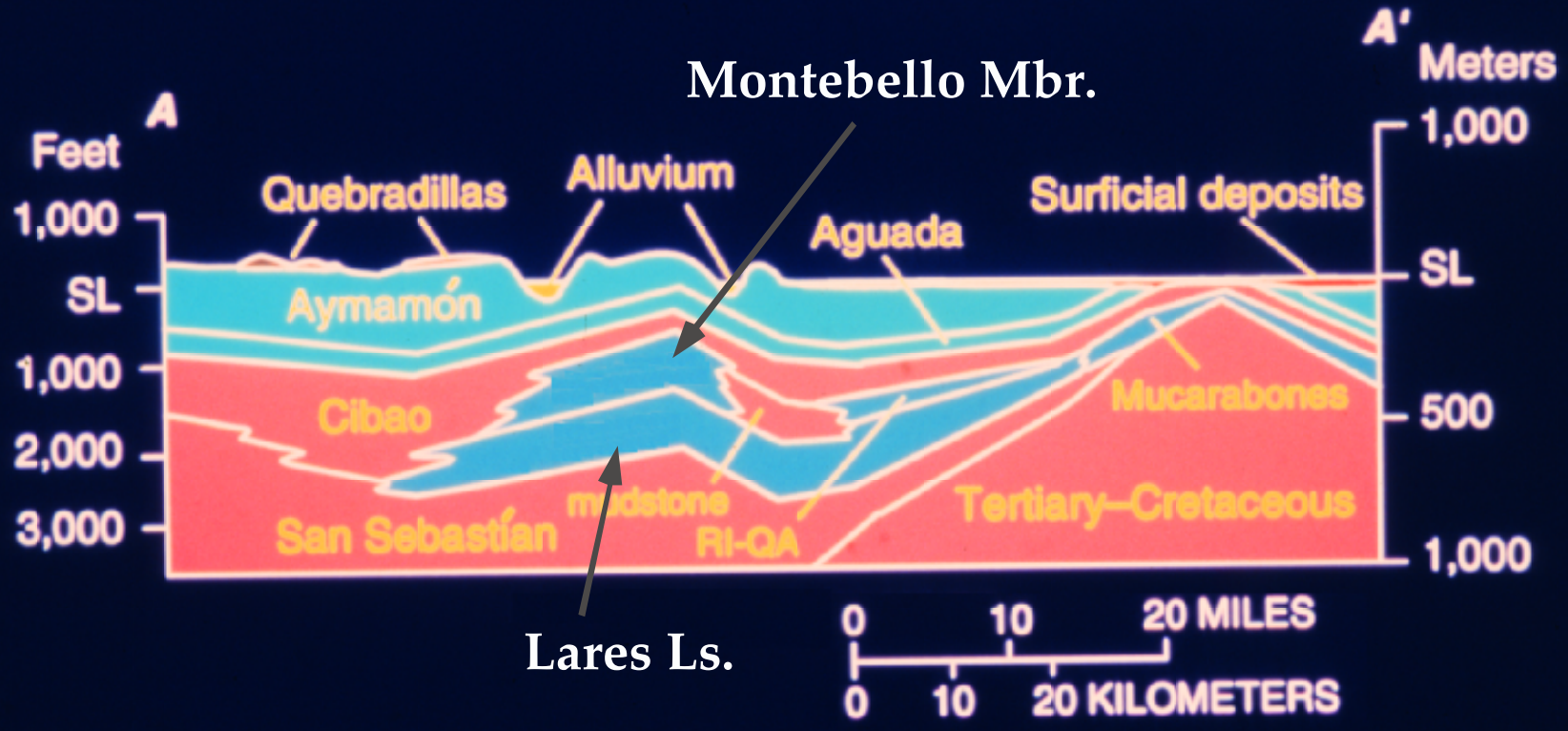
Ward, W.C., Scharlach, R.A., and Hartley, J.R., 1991, Controls on porosity and permeability in subsurface Tertiary carbonate rocks of northern Puerto Rico, in Gómez-Gómez, Fernando, Quiñones-Aponte, Vincente, and Johnson, A.I., eds., Regional aquifer systems of the United States—Aquifers of the Caribbean Islands: American Water Resources Association Monograph 15, p. 17–23;

Ward, W.C., Scharlach, R.A., and Hartley, J.R., in press, Geology of the North Coast ground-water province of Puerto Rico, in Renken, R.A., Ward, W.C., Gill, I.P., Rodríguez-Martínez, Jesús, and Gómez-Gómez, Fernando, Geology and hydrogeology of the Caribbean Islands aquifer system of Puerto Rico and the U.S. Virgin Islands: U.S. Geological Survey professional Paper 1419.

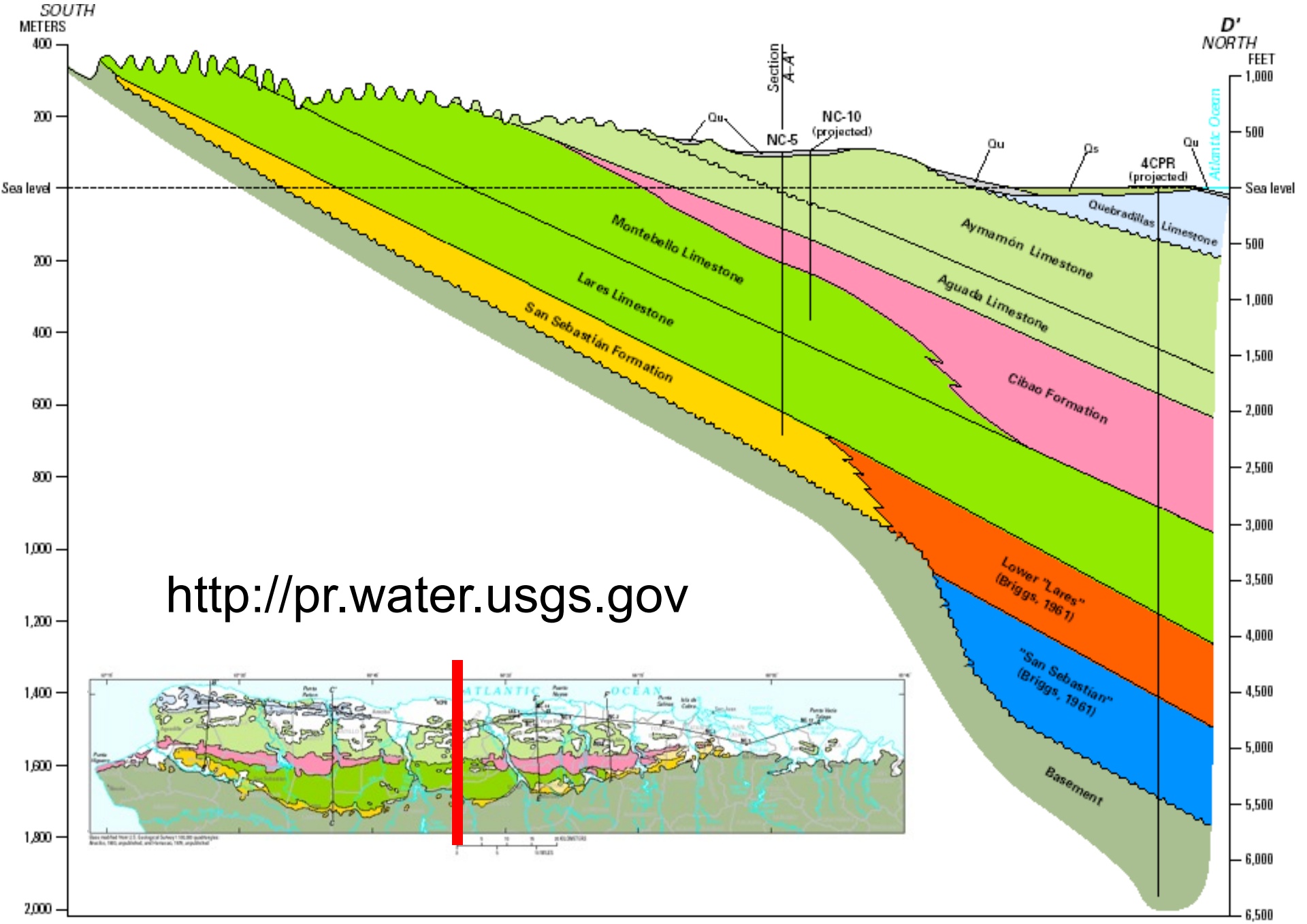
Hydrogeology modified from Renken, R.A., and Gómez-

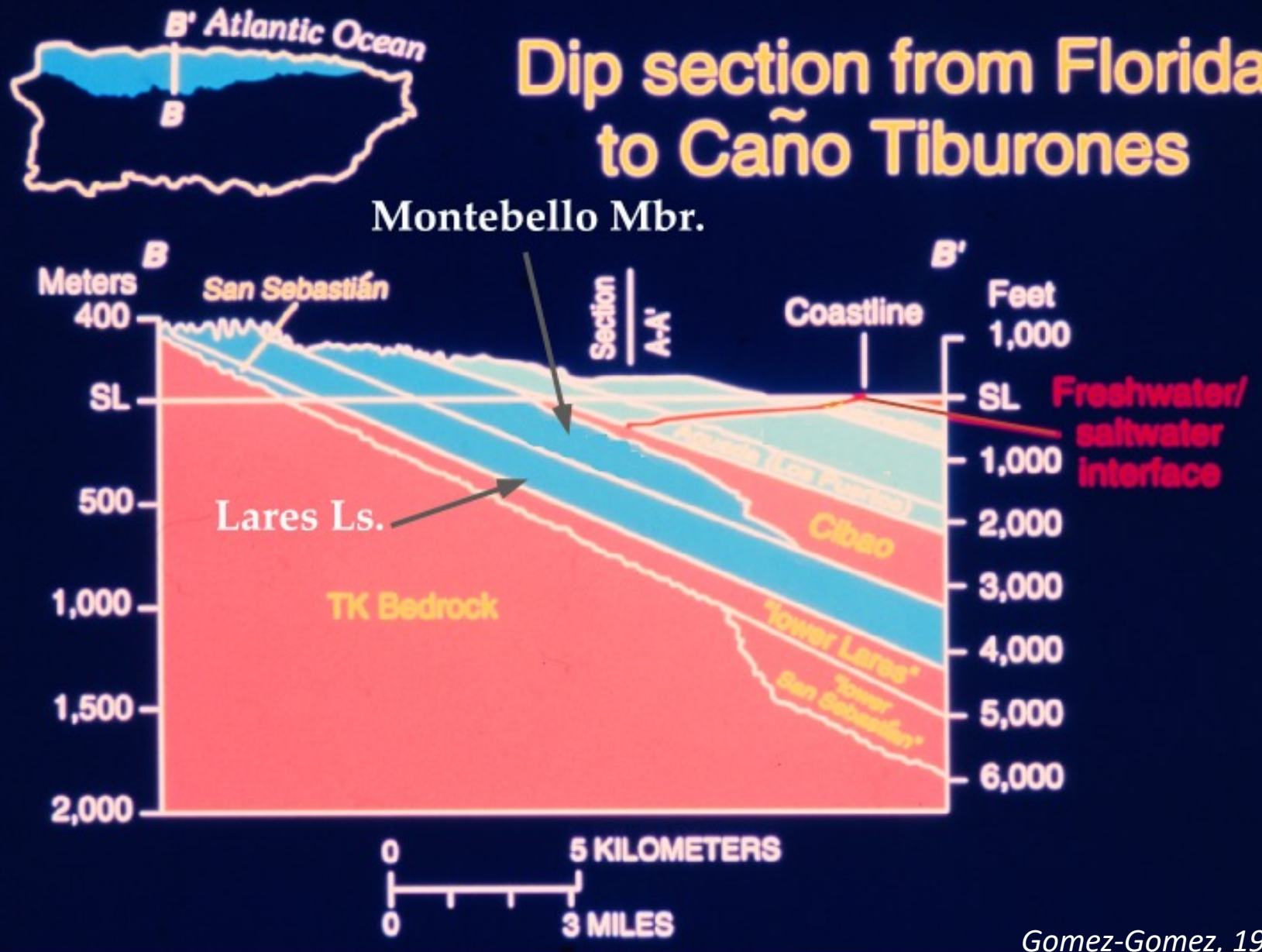


HYDROGEOLOGIC SECTION
North Coast Limestone aquifer system



Gomez-Gomez, 1995

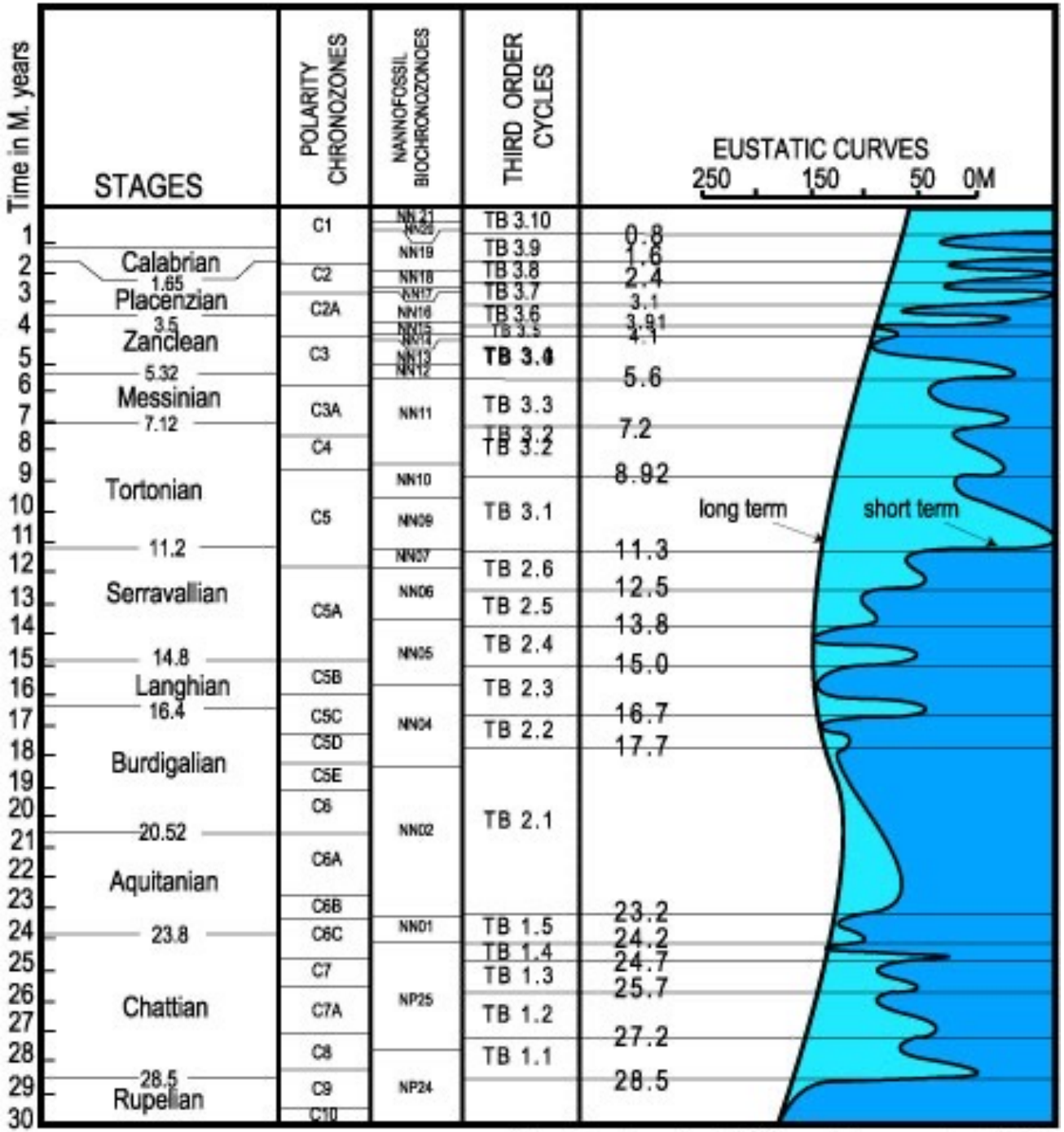

SOUTH
METERS
D'
NORTH
FEET
Section A-A'
NC-5
NC-10 (projected)
4CPR (projected)
Qu
Qs
Atlantic Ocean
Sea level
Montebello Limestone
Lares Limestone
San Sebastián Formation
Aymamón Limestone
Aguada Limestone
Cibao Formation
Quebradillas Limestone
Lower "Lares" (Briggs, 1961)
"San Sebastian" (Briggs, 1961)
Basement
http://pr.water.usgs.gov



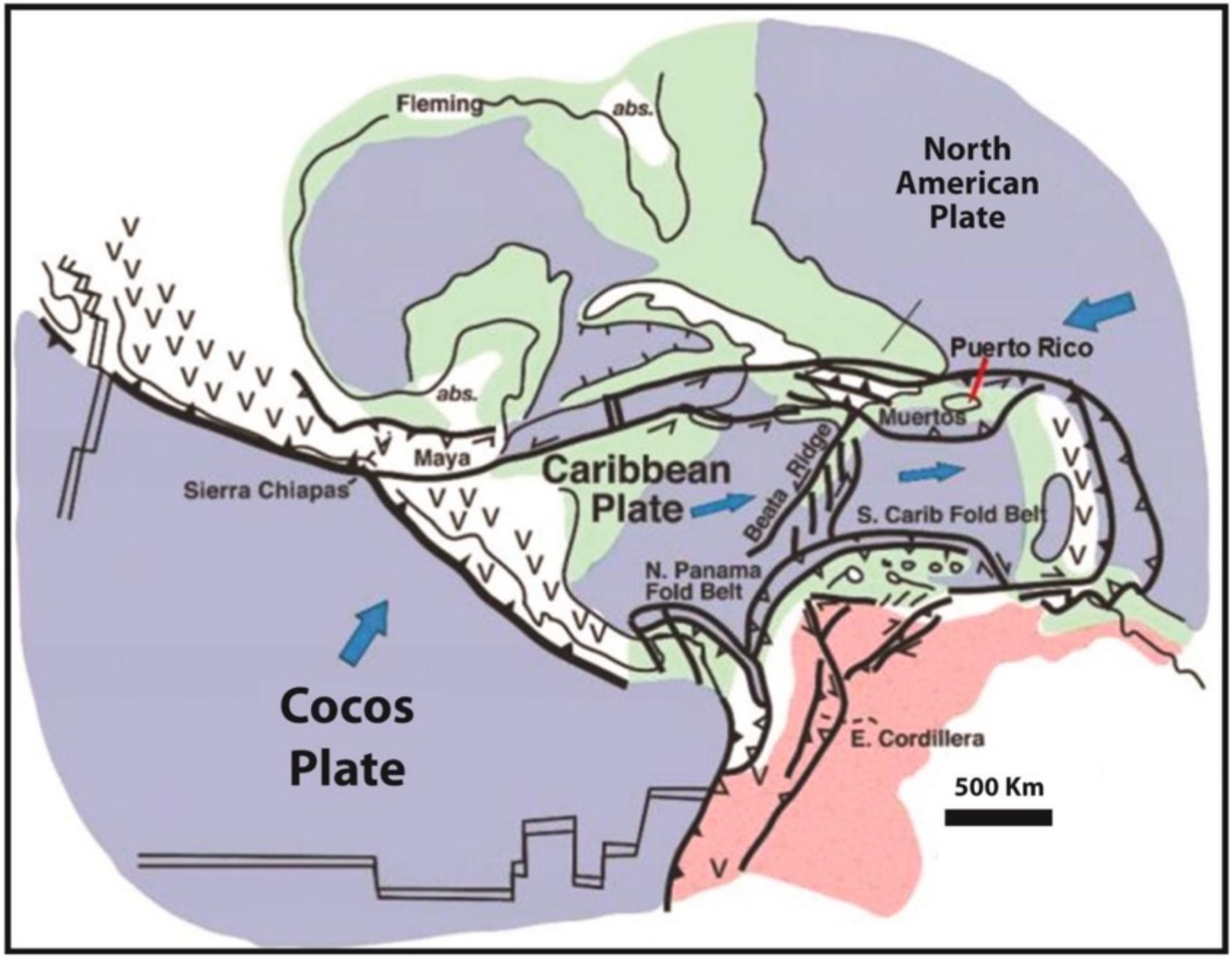
Gomez-Gomez, 1995


South

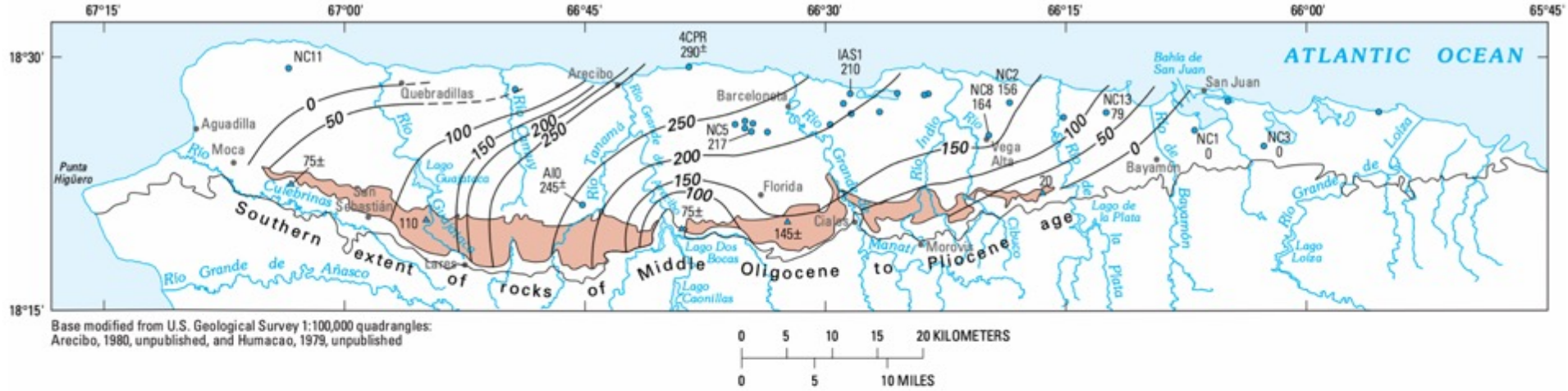

South
7 2'97



(Based on Haq et. al. 1987 and Berggren et. al. 1995)



Late Miocene tectonic setting of the Caribbean plate at approximately 10 Ma (modified from Pindell,1994).



EXPLANATION

Area of outcrop of Lares Limestone

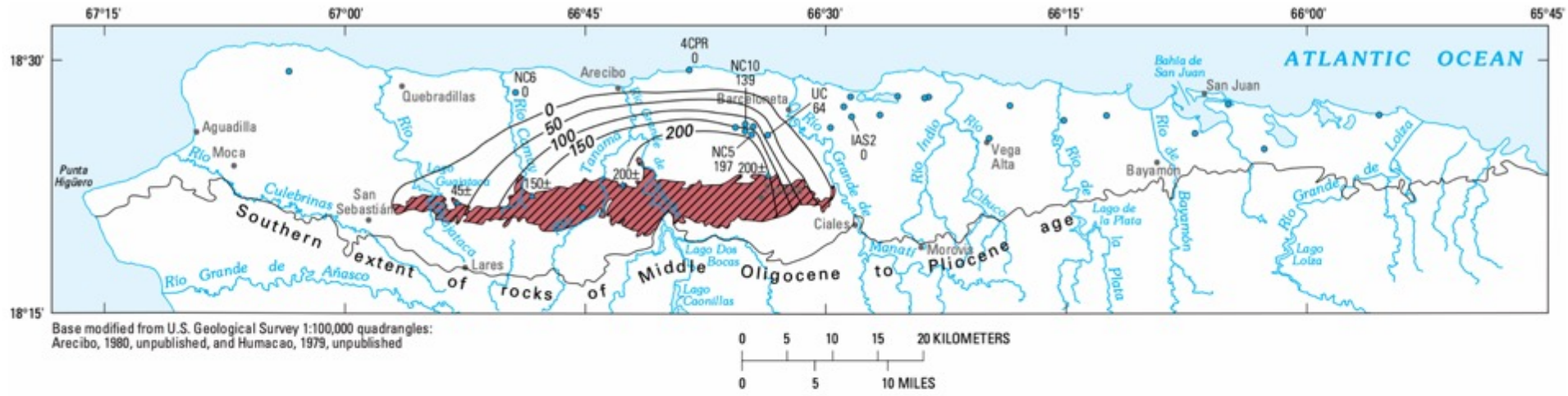
—100– – **Line of equal thickness of Lares Limestone**—Interval 50 meters. Dashed where approximately located

4CPR 290± **Well control point**—Thickness in meters (well name abbreviations on figure 21)

▲75± **Outcrop**—Thickness in meters

FIGURE 23.—Thickness of Lares Limestone, northern Puerto Rico (outcrop extent modified from Monroe, 1980).

Renken et al., 2002

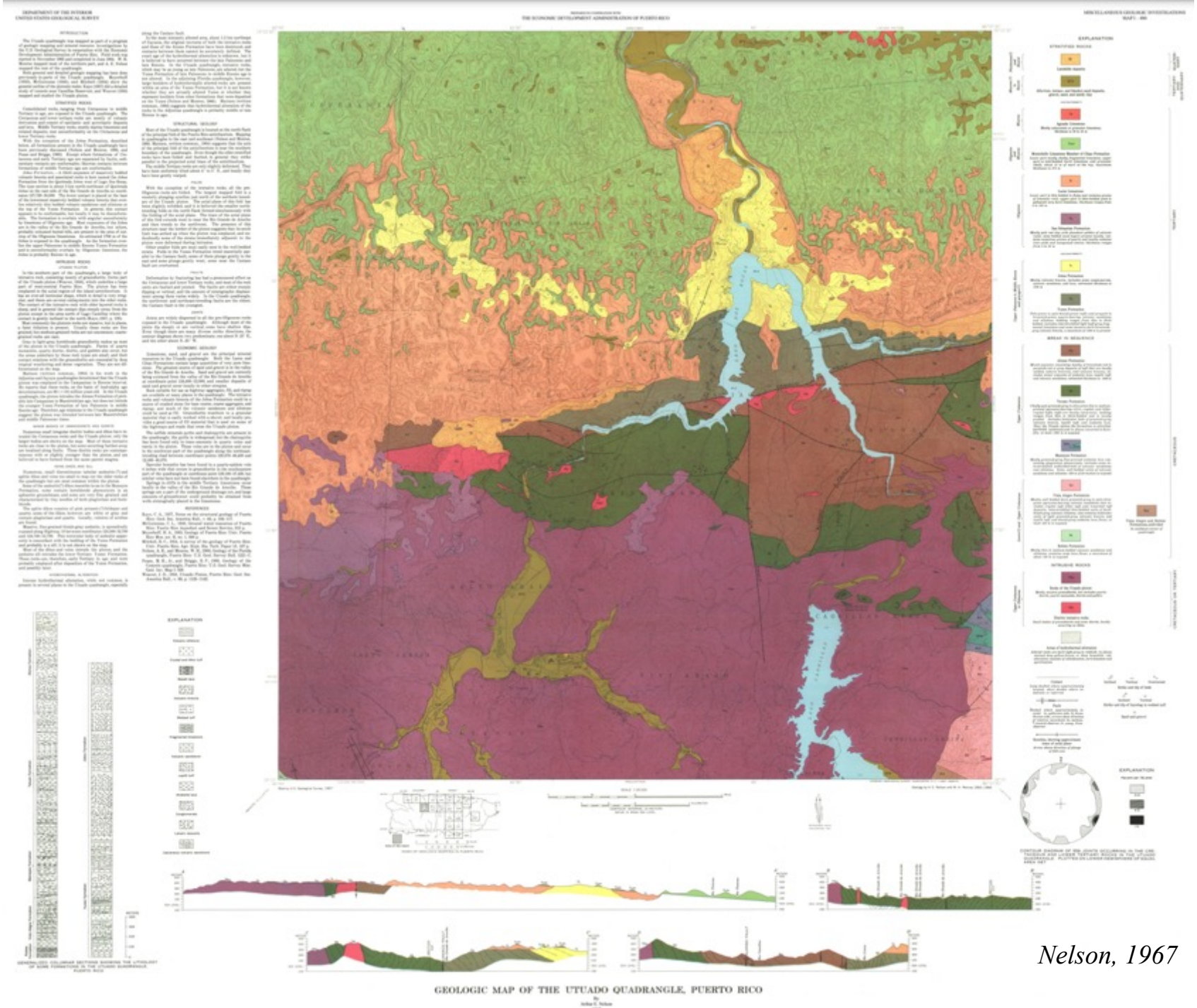


EXPLANATION

- **Area of outcrop of Montebello Limestone**
- —100— **Line of equal thickness of Montebello Limestone Member**—Interval 50 meters
- NC5 197 **Well control point**—Thickness in meters (well name abbreviations on figure 21)
- 200± **Outcrop**—Thickness in meters

FIGURE 25.—Thickness of Montebello Limestone, northern Puerto Rico (outcrop extent modified from Monroe, 1980).

Renken et al., 2002



Nelson, 1967

Fig. 17: PR10 Higway section from Arecibo to Utuado plotted in the U.S.G.S. Utuado Quadrangle Geologic Map

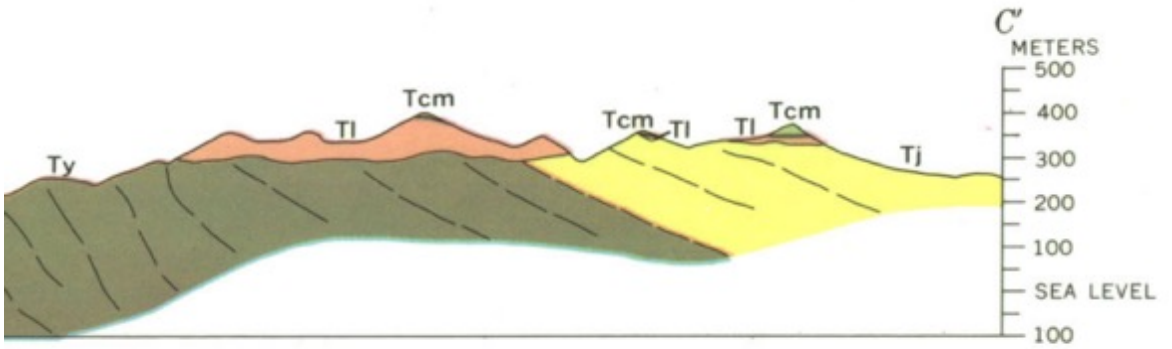
Nelson, 1967


Fig. 17: PR10 Higway section from Arecibo to Utuado plotted in the U.S.G.S. Utuado Quadrangle Geologic Map
Stop 11
Stop 10
Stop 9
Stop 8
Stop 7
Stop 6
Stop 5
Stop 4
Stop 3
Stop 2
Stop 1
CARRERAS
LAGO DOS BOCAS

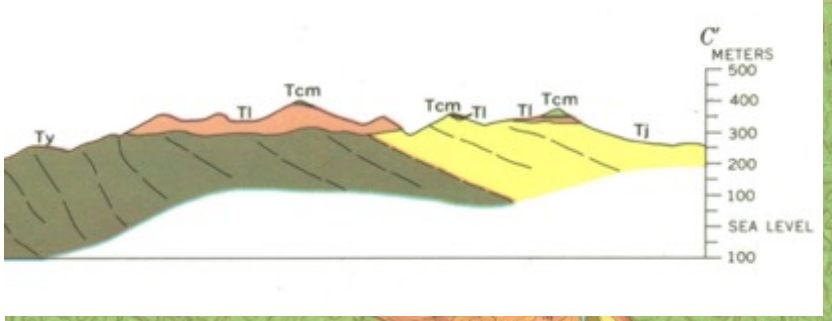
Nelson, 1967

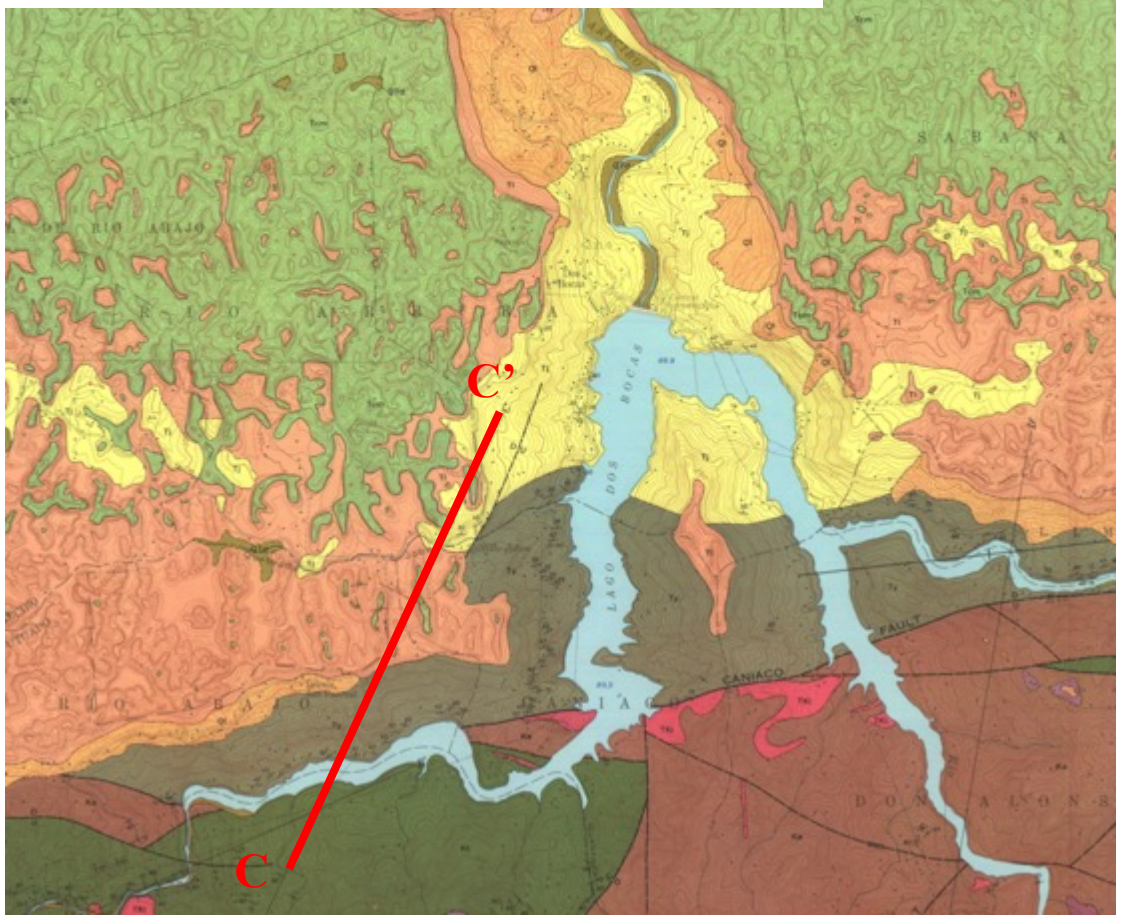
Fig. 17: PR10 Higway section from Arecibo to Utuado plotted in the U.S.G.S. Utuado Quadrangle Geologic Map

Nelson, 1967

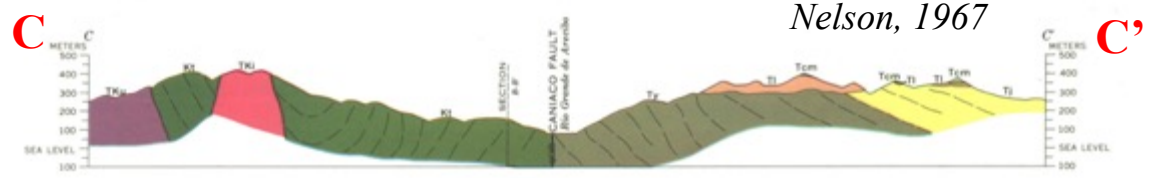


Stop #1:
San Sebastián Formation-Lares Limestone Contact





Nelson, 1967



Oligocene and Miocene

Tcm

Montebello Limestone Member of Cibao Formation

Lower part mostly chalky fragmental limestone; upper part is interbedded hard limestone and granular chalk; about 10 m of marl at the top; maximum thickness is 275 m

Oligocene

Tl

Lares Limestone

Lower part is thin bedded to flaky and contains grains of limonitic rock; upper part is thin-bedded pink to yellowish very hard limestone; thickness ranges from 0 to 180 m

Ts

San Sebastián Formation

Mostly pale red clay with abundant pebbles of volcanic rocks; some bedded sand layers present locally; contains numerous grains of quartz and locally contains iron oxide and manganese stains; thickness ranges from 0 to 50 m

UNCONFORMITY

Upper Paleocene to Middle Eocene and younger(?)

Tj

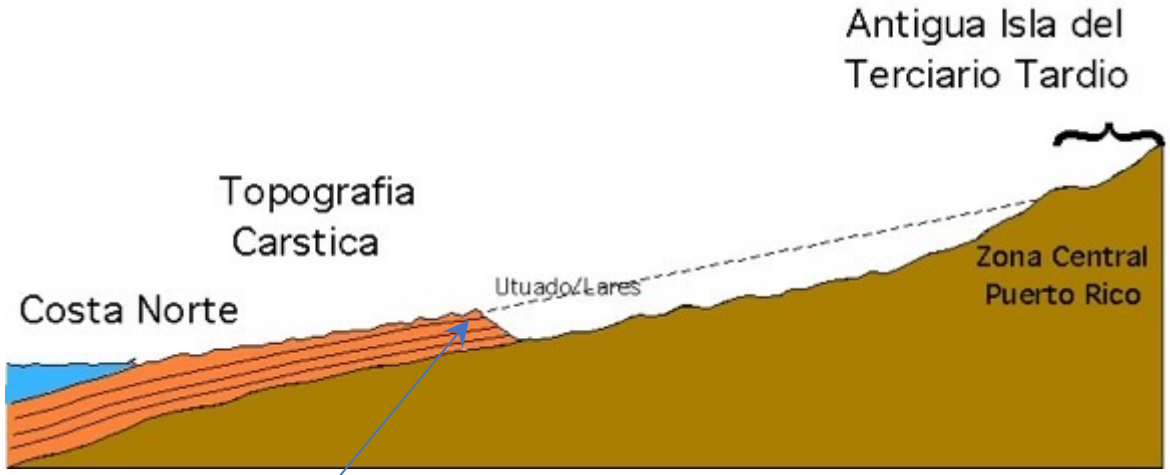
Jobos Formation

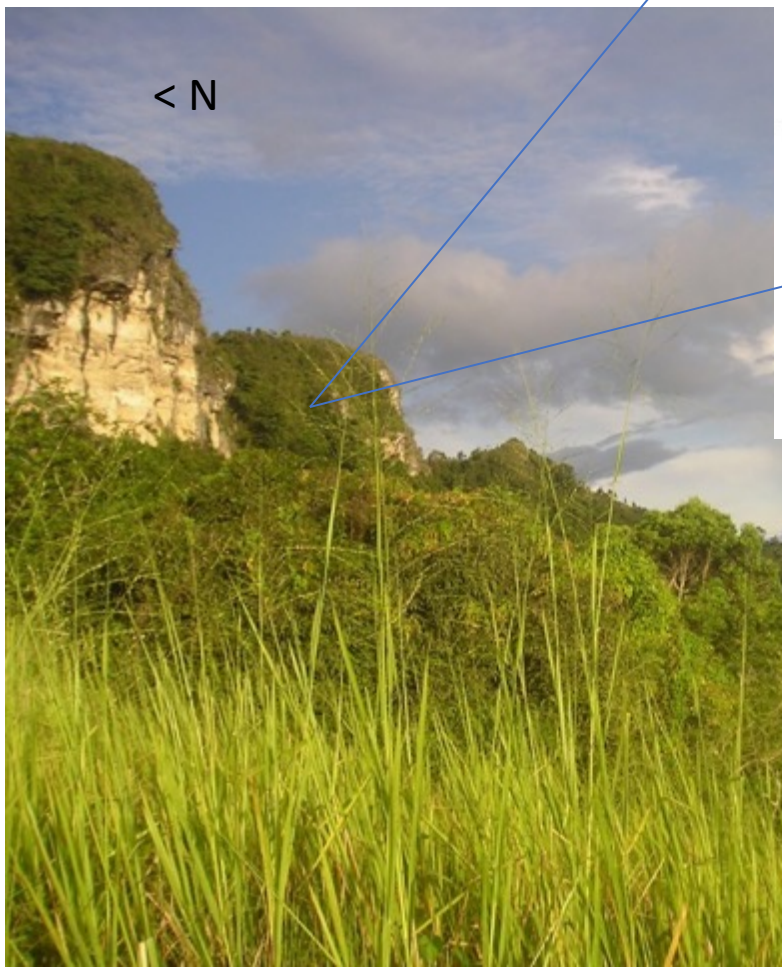
Mostly volcanic breccia, includes some conglomerate, volcanic sandstone, and lava; estimated thickness is 1700 m

Ty

Yunes Formation

Pale-green to pale-bluish-green tuffs and grayish to brownish-green quartz-bearing volcanic sandstone and siltstone; bedding ranges from thin to thick bedded; includes interstratified light buff-gray fragmental limestone and some massive dark brownish-gray volcanic breccia; a maximum of 1200 m is present

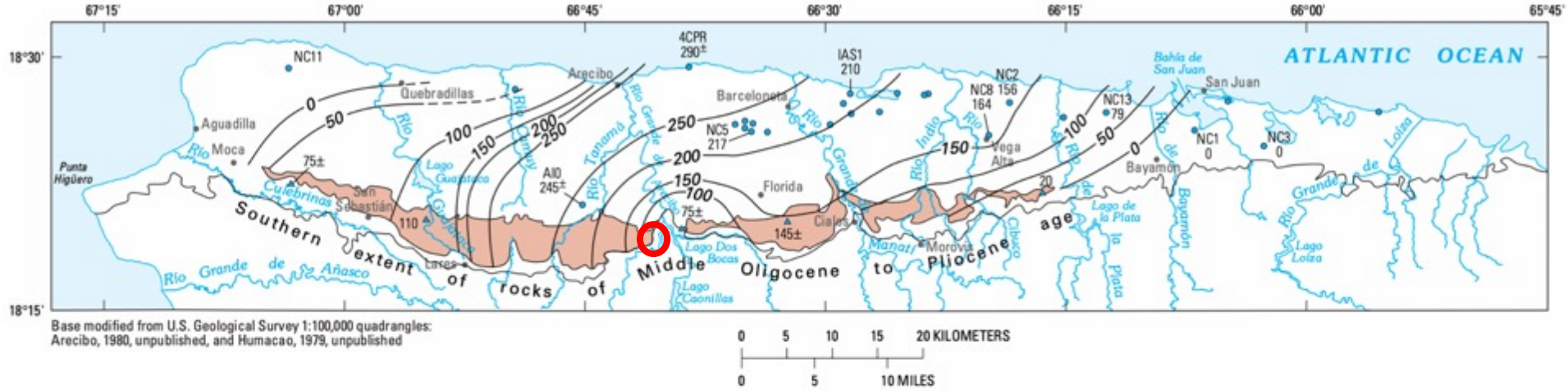




Escarpado de las calizas (depósitos marinos) en los pueblos de Aguadilla, Lares hasta Bayamón.

Stop #1:

San Sebastián Formation-Lares Limestone Contact



EXPLANATION

Area of outcrop of Lares Limestone

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▲75± **Outcrop**—Thickness in meters

FIGURE 23.—Thickness of Lares Limestone, northern Puerto Rico (outcrop extent modified from Monroe, 1980).

Renken et al., 2002

Stop #1:
San Sebastián Formation-Lares Limestone Contact

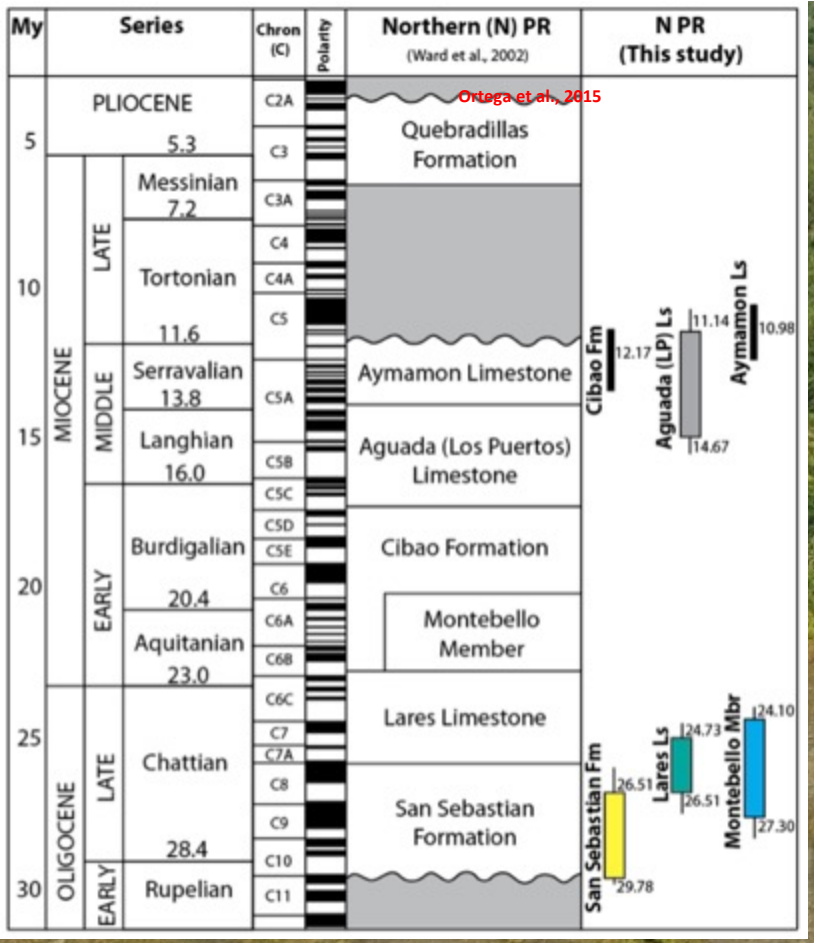

Ortega et al., 2015
Lares Lm.
San Sebastián Fm.

ANALYTICAL RESULTS OF LOW-Mg CALCITE *KUPHUS INCRASSATUS* BIVALVES AND DERIVED NUMERICAL AGES FROM PUERTO RICO (PR) AND THE DOMINICAN REPUBLIC (DR)

Lithologic unit, locality/Sample ID	Raw value $^{87}Sr/^{86}Sr$	Corrected value $^{87}Sr/^{86}Sr$	$\delta^{13}C$ (PDB)	$\delta^{18}O$ (PDB)	Sr (ppm)	Mg (ppm)	Fe (ppm)	Mn (ppm)	Age min (Ma)	Age mean (Ma)	Age max (Ma)
				-1.82	455	2956	139	4	9.12	**9.84**	10.49
				-1.77	496	3222	115	17	9.46	**10.09**	10.77
				-1.74	747	3545	39	3	9.77	**10.41**	11.14
				-1.80	518	2708	62	7	10.10	**10.80**	11.85
				-1.60	514	1554	44	5	10.10	**10.80**	11.85
				-2.10	538	4055	68	1	10.37	**11.14**	12.29
				-1.60	932	4478	75	4	10.44	**11.20**	12.37
				-2.47	657	2367	25	4	10.59	**11.39**	12.54
				-1.82	585	6032	72	5	10.79	**11.81**	12.80
				-2.38	523	3249	58	2	11.21	**12.37**	13.36
				-0.19	988	4747	44	1	11.43	**12.58**	13.86
				-2.51	510	3255	99	9	12.05	**13.02**	14.69
				-2.55	515	2146	120	4	12.10	**13.07**	14.72
				-1.50	673	2731	**455**	10	12.20	**13.18**	14.78
				-2.09	699	4164	57	2	12.20	**13.18**	14.78
				-1.91	700	4255	39	1	12.35	**13.36**	13.71
				-1.94	789	4100	54	2	12.40	**13.43**	14.88
				-2.05	623	4694	110	11	12.72	**14.33**	15.04
				-2.43	714	5197	62	8	13.13	**14.74**	15.23
				-1.59	882	3794	34	3	13.44	**14.87**	15.31
Lares Ls, Lares, PR/12 PR111 PS8	0.708147	0.708145	2.74	-2.47	1497	9165	62	1	24.63	**25.26**	25.97
Lares Ls, Lares, PR/11-1 PR111 PS6	0.708132	0.708130	-0.52	-2.38	1602	6984	199	6	25.01	**25.70**	26.53
Lares Ls, Lares, PR/6 PR448	0.708123	0.708121	0.09	-1.85	1450	5256	**794**	27	25.27	**25.97**	26.83
Lares Ls-San Sebastian Fm, Lares, PR/9 PR111	0.708109	0.708107	-0.48	-3.56	1683	5981	**306**	14	25.68	**26.51**	27.27
San Sebastian Fm, Lares, PR/A27 RG	0.708015	0.708013	**-2.02**	-2.80	916	5992	**632**	**1019**	28.59	**29.17**	29.77
San Sebastian Fm, Lares, PR/A29 RG	0.707991	0.707989	-1.11	-2.47	1094	6537	43	**167**	29.19	**29.78**	30.51
Cercado Fm, AB, DR/A4 AB1	0.709003	0.709001	-0.56	-2.11	1076	6159	40	2	5.52	**5.88**	6.16
Cercado Fm, AB, DR/A24 AB2	0.708998	0.708996	0.03	-1.73	1189	12286	66	16	5.63	**5.96**	6.27
Cercado Fm, AB, DR/A1-9 AB1	0.708986	0.708984	1.15	-1.42	1308	5410	119	7	5.87	**6.15**	6.59
Cercado Fm, AB, DR/A2 AB1 4-7	0.708979	0.708977	**-4.39**	-2.46	958	5253	31	6	5.98	**6.31**	6.85
Yanigua-Los Haitises Fms, DR/14 DR7 Km124	0.708826	0.708824	**-6.18**	-3.68	462	3099	**659**	**272**	11.43	**12.58**	13.86
Yanigua-Los Haitises Fms, DR/A26 DR7 Km87	0.708770	0.708768	**-5.75**	-2.50	591	1725	51	2	14.78	**15.25**	15.57
Yanigua-Los Haitises Fms, DR/15 DR7 Km87	0.708738	0.708736	**-6.90**	-2.35	**231**	1455	67	6	15.41	**15.75**	16.07

Ortega-Ariza, 2016

Table 2.1: Raw Sr data corrected to NIST 987 value of 0.710248 to use the McArthur et al. (2001) look-up curve. Error results from 2 SEs of mean Sr isotope value and confidence limits of the seawater Sr isotope curve. Estimated age resolution: Ponce Limestone, ~0.7-1.3 m.yr.; Lares Limestone, ~0.6-0.8 m.yr.;San Sebastian Formation, ~0.6 m.yr.; Cercado Formation, ~0.3 m.yr.; and Yanigua-Los Haitises, ~0.3-1.3 m.yr. Bold analytical data indicate samples outside the accepted ranges (see "Materials and Methods" and "Results").AB = Arroyo Bellaco; PDB = Pee Dee belemnite; PQ = Ponce Quarry. * Indicates samples collected from *Ostrea haitensis* bivalve.



Lares Lm.

26.51 Ma

San Sebastián Fm.

June 1997

June 1997

June 1997

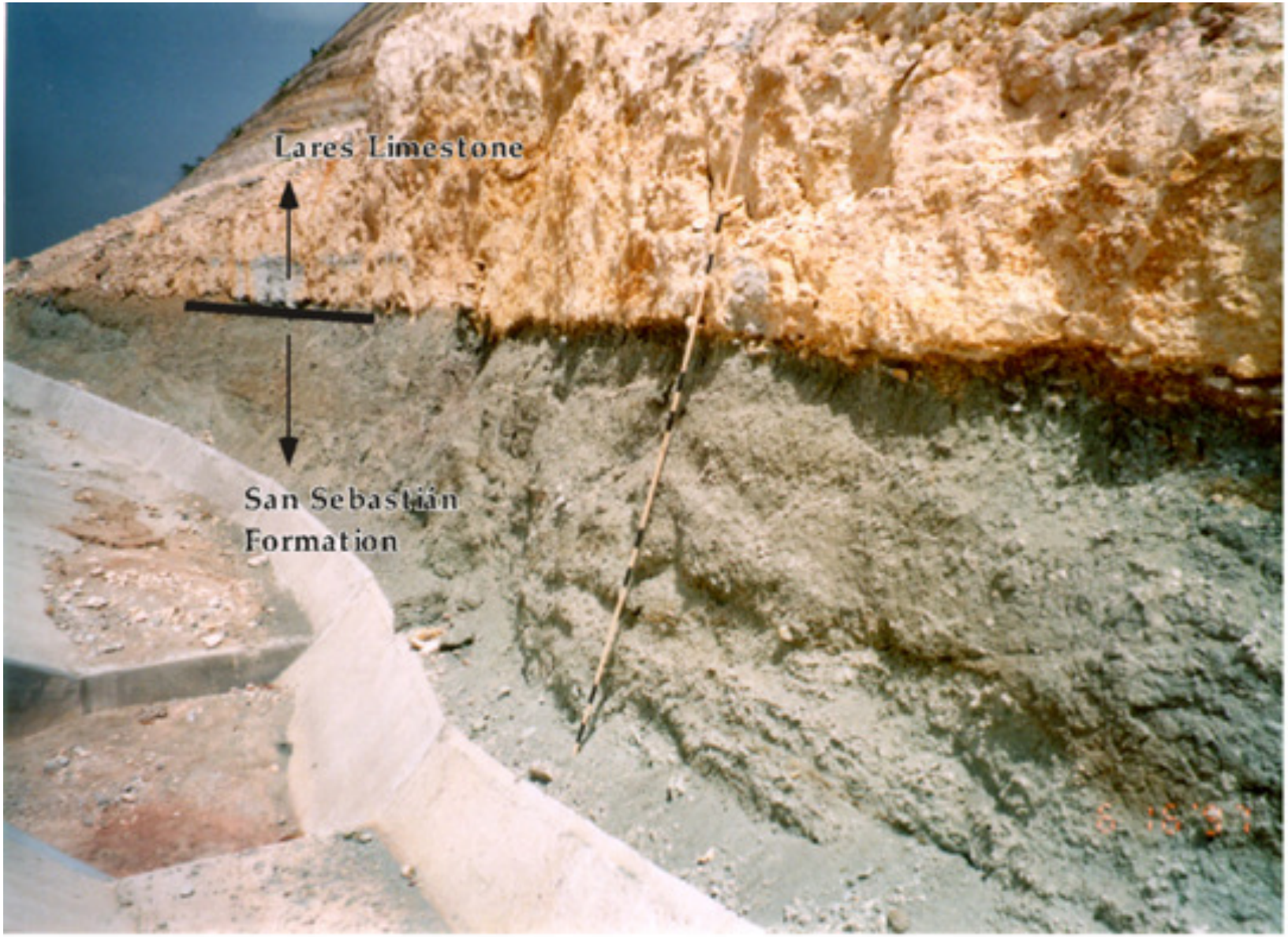


Fig. 6: The base of the Lares Limestone and its contact with the San Sebastián Formation exposed at the PR10-PR6621 intersection (N18°18'52", W66°41'05").

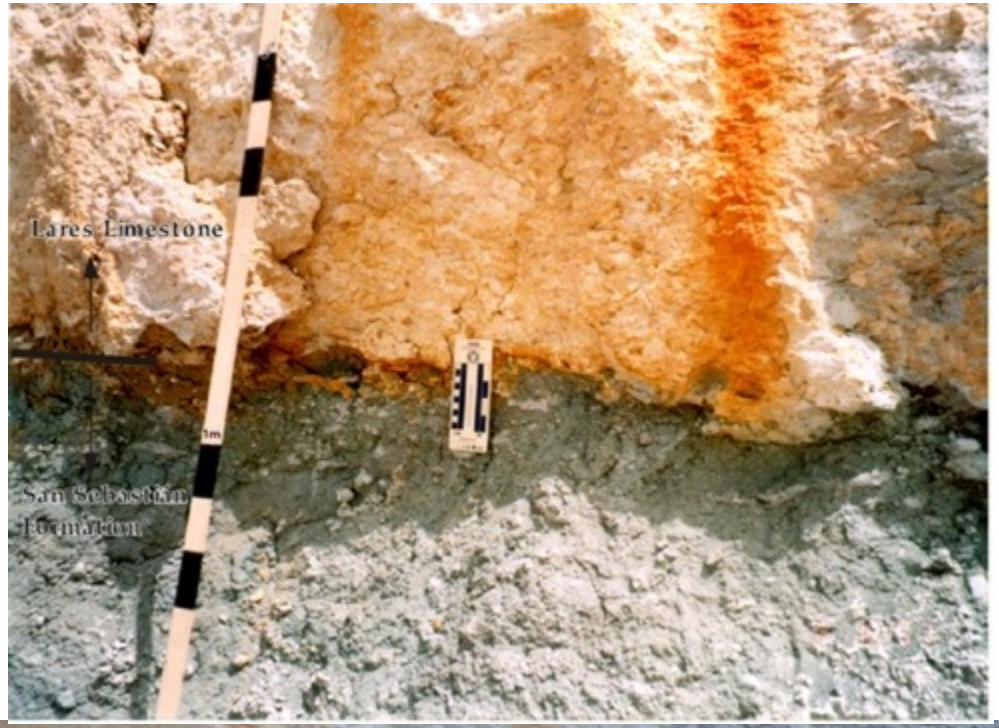
Stop #1:
San Sebastián Formation - Lares Limestone Contact

Top of San Sebastián Formation

- poorly consolidated sandstone, siltstone, & conglomerate
- well-rounded pebbles to cobbles
- beds of lignite or carbonaceous clays
- abundant trace fossils (burrows) filled with the Lares Limestone material

Stop #1:
San Sebastián Formation - Lares Limestone Contact

- **Contact**
  - Sharp
  - Undulatory



Stop #1:
San Sebastián Formation-Lares Limestone Contact

- **Base of Lares Limestone**
  - grainstone dominate (some packstone)
  - abundant fine to medium sand composed of quartz & weathered volcanic lithoclasts
  - layer of cobbles (weathered/oxidized volcanic rocks) aligned 0.6 m above the contact that follow the apparent dip of the unit
  - fossiliferous limestone with forams (Lepidocyclina undulosa), red algae (rhodolites) and echinoderms (regular & irregular urchins)
  - Lares Lm is 17.8 m thick in this exposure (310 m in the Bayaney Quadrangle)
  - topographic high in the area (basement Cretaceous & San Sebastián Fm rocks) created a thin L Lm unit

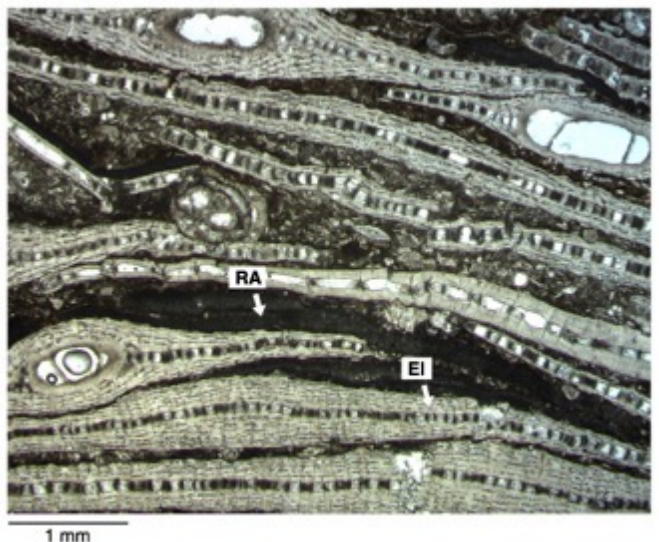
Fig. 8: The base of the Lares Limestone and its contact with the San Sebastián Formation exposed at the PR10-PR6621 intersection. Lines of cobbles composed of weathered (oxidized) volcanic rocks follow the apparent dip of the strata.

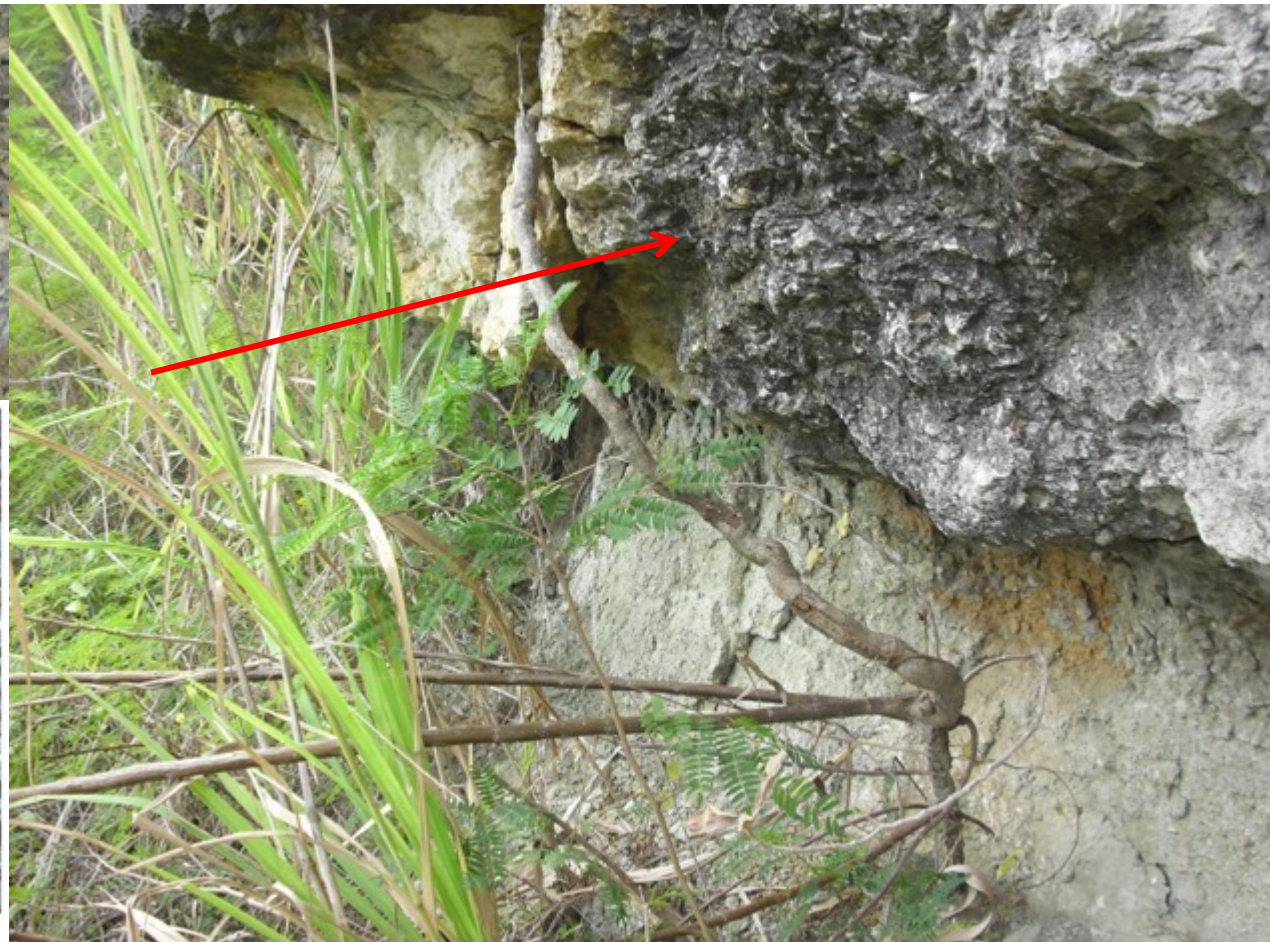
Layer of cobbles (weathered/oxidized volcanic rocks) aligned 0.6 m above the contact that follow the apparent dip of the unit

2010

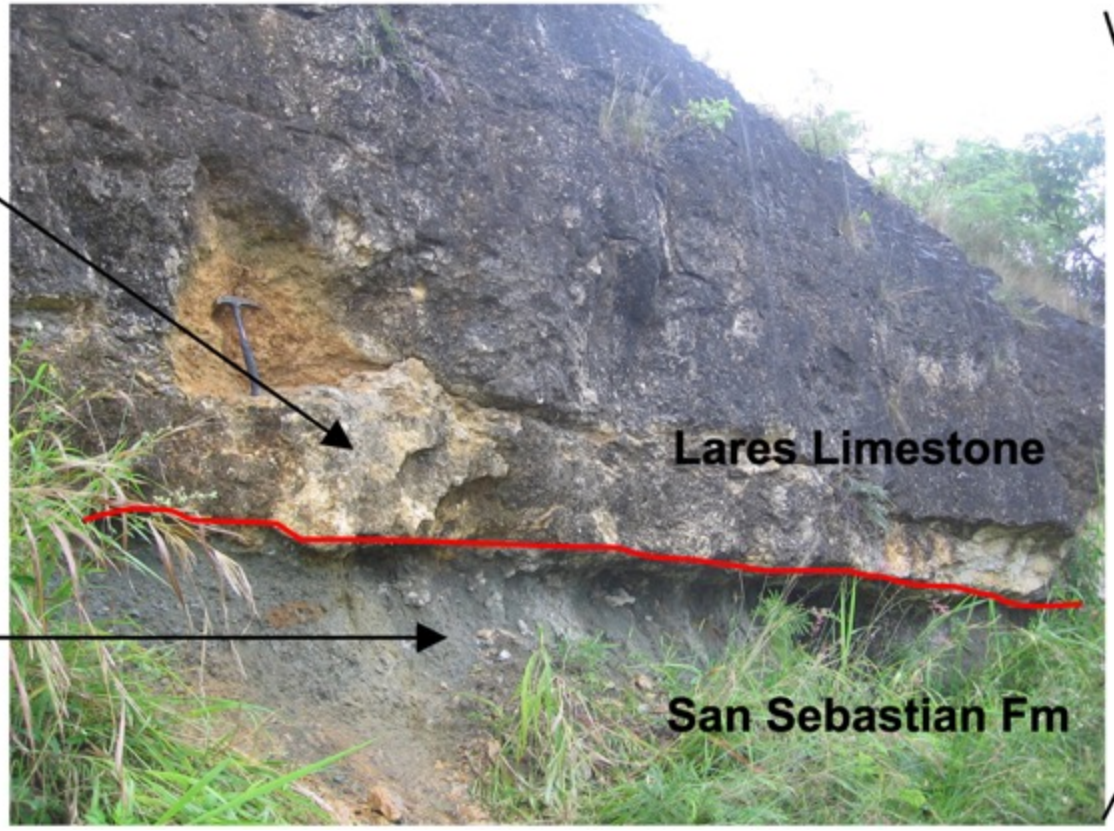
Stop #1:
San Sebastián Formation-Lares Limestone Contact

- **Base of Lares Limestone**
  - grainstone dominate (some packstone)
  - abundant fine to medium sand composed of quartz & weathered volcanic lithoclasts
  - layer of cobbles (weathered/oxidized volcanic rocks) aligned 0.6 m above the contact that follow the apparent dip of the unit
  - fossiliferous limestone with forams (Lepidocyclina undulosa), red algae (rhodolites) and echinoderms (regular & irregular urchins)
  - Lares Lm is 17.8 m thick in this exposure (310 m in the Bayaney Quadrangle)
  - topographic high in the area (basement Cretaceous & San Sebastián Fm rocks) created a thin L Lm unit



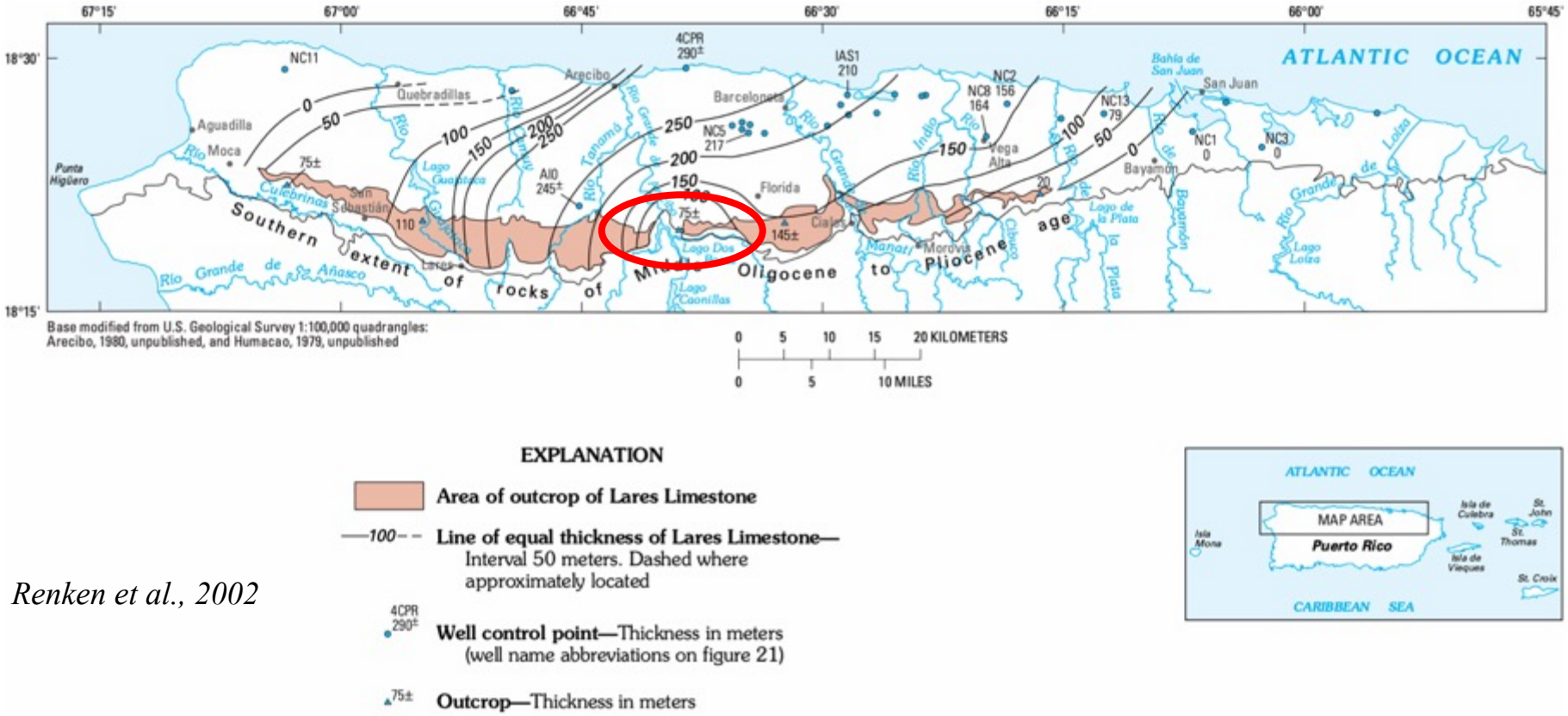


Fossiliferous limestone with forams (Lepidocyclina undulosa), red algae (rhodolites) and echinoderms (regular & irregular urchins)



Stop #1:
San Sebastián Formation-Lares Limestone Contact

- **Base of Lares Limestone**
  - grainstone dominate (some packstone)
  - abundant fine to medium sand composed of quartz & weathered volcanic lithoclasts
  - layer of cobbles (weathered/oxidized volcanic rocks) aligned 0.6 m above the contact that follow the apparent dip of the unit
  - fossiliferous limestone with forams (Lepidocyclina undulosa), red algae (rhodolites) and echinoderms (regular & irregular urchins)
  - Lares Limestone is 17.8 m thick in this exposure (310 m in the Bayaney Quadrangle)
  - topographic high in the area (basement Cretaceous & San Sebastián Fm rocks) created a thin L Lm unit



Renken et al., 2002

FIGURE 23.—Thickness of Lares Limestone, northern Puerto Rico (outcrop extent modified from Monroe, 1980).

Stop #1:
San Sebastián Formation-Lares Limestone Contact

Interpretations:

- **Top of San Sebastián Formation**
  - fluvial influences and shallow water
  - fossils of marine or estuarine environments not present
  - beds of lignite or carbonaceous clays
    - 5 beds of lignite (21m bellow contact) in Highway 111 (southwest of the PR10) reported pollen from *Rhizophora sp.* (Graham & Jarzen, 1969)
    - other lignites from the same area showed dicotyledons (flowering angiosperms) of tropical environments that live near lagoons or estuaries with brackish water (Hollick, 1928)
- **Base of Lares Limestone**
  - grainstones dominance suggest deposition in shallow water
  - lignite beds suggest deposition close to the shore

Stop #1:
San Sebastián Formation-Lares Limestone Contact

Interpretations:

- **Top of San Sebastián Formation**
  - fluvial influences and shallow water
  - fossils of marine or estuarine environments not present
  - beds of **lignite** or carbonaceous clays
    - 5 beds of lignite (21m bellow contact) in Highway 111 (southwest of the PR10) reported pollen from mangrove (*Rhizophora sp.)* (Graham & Jarzen, 1969)
    - other lignites from the same area showed dicotyledons (flowering angiosperms) of tropical environments that live near lagoons or estuaries with brackish water (Hollick, 1928)
- **Base of Lares Limestone**
  - grainstones dominance suggest deposition in shallow water
  - **lignite** beds suggest deposition close to the shore

July 1997

Stop #1:
Lares Limestone - Montebello Member Contact

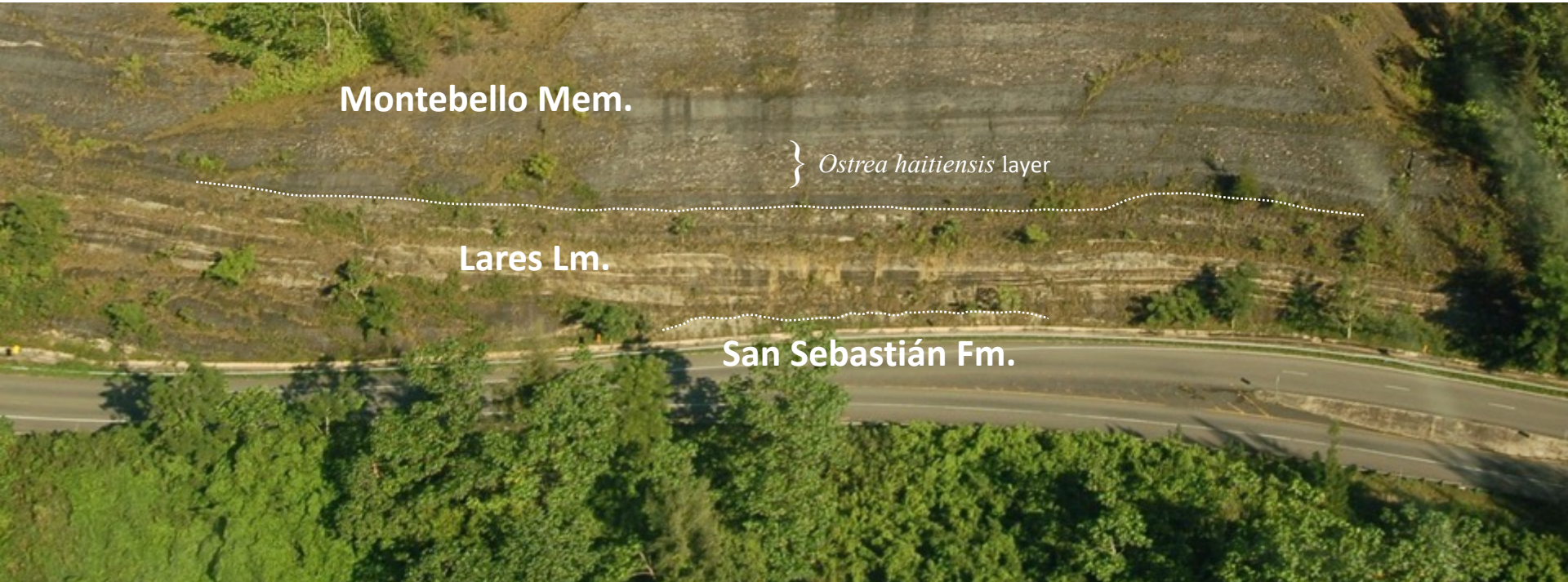
- **Lares Limestone**
  - Lares Lmst is 17.8 m thick in this exposure (310 m in the Bayaney Quadrangle)
  - Topographic high in the area (basement Cretaceous & San Sebastián Fm rocks) created a thin Lares Limestone unit at this location
  - A change in lithologic character between the Lares Limestone and Montebello Member units is visible at the contact

The Lares Limestone

- Composed predominantly of thickly bedded, fine-to medium-grained calcarenite.
- Gradational or sharp contact with the underlying San Sebastián.
- In some areas the formation rests directly on the basement (transgression).
- Crops out in a continuos belt of limestone in the northern coast of the island.
- Outcrop thickness ranges from 270-301 m (Bayaney Quadrangle). Subsurface thickness ranges from 0 to 500 m.
- Pinches out in the western and eastern edges of the outcrop belt.
- Deposited on a broad 25-km-wide shelf rich in marine organisms similar to those living in modern reef environments.
- Main mass developed as tongues of limestone projecting laterally into clastic beds (not massive). Western and eastern boundaries dominated by fluvial deposits.
- Interpretations suggest several cycles of reef growth (P.R. 129) composed of framestones (massive corals) and fringing-reef growth terminated by erosion (exposure), all developed under tectonically stable conditions. Progradation with backreef material and skeletal-sand shoals capping the sequence.

Stop #1:
Lares Limestone - Montebello Member Contact

- **Contact**
  - The division between strata's was defined by the presence of a bed 1 to 3 m thick with abundant *Ostrea haitensis* (oysters of 5 to 10 cm).
  - This oyster layer, at the basal Montebello Member, is present in the unit through the PR north coast and therefore is used to define the Lares Limestone-Montebello Member contact.



Ostrea haitiensis layer is present at the basal Montebello Member at many locations through the PR north coast and therefore is used to define the Lares Limestone-Montebello Member of the Cibao Formation contact

PR129

Ostrea haitiensis layer is present at the basal Montebello Member at many locations through the PR north coast and therefore is used to define the Lares Limestone-Montebello Member of the Cibao Formation contact


Ostrea haitiensis layer at PR10

Ostrea haitiensis layer at PR10

Ostrea haitiensis layer at PR10

Ostrea haitiensis layer at PR129

Stop #2:

Montebello Member of the Cibao Formation

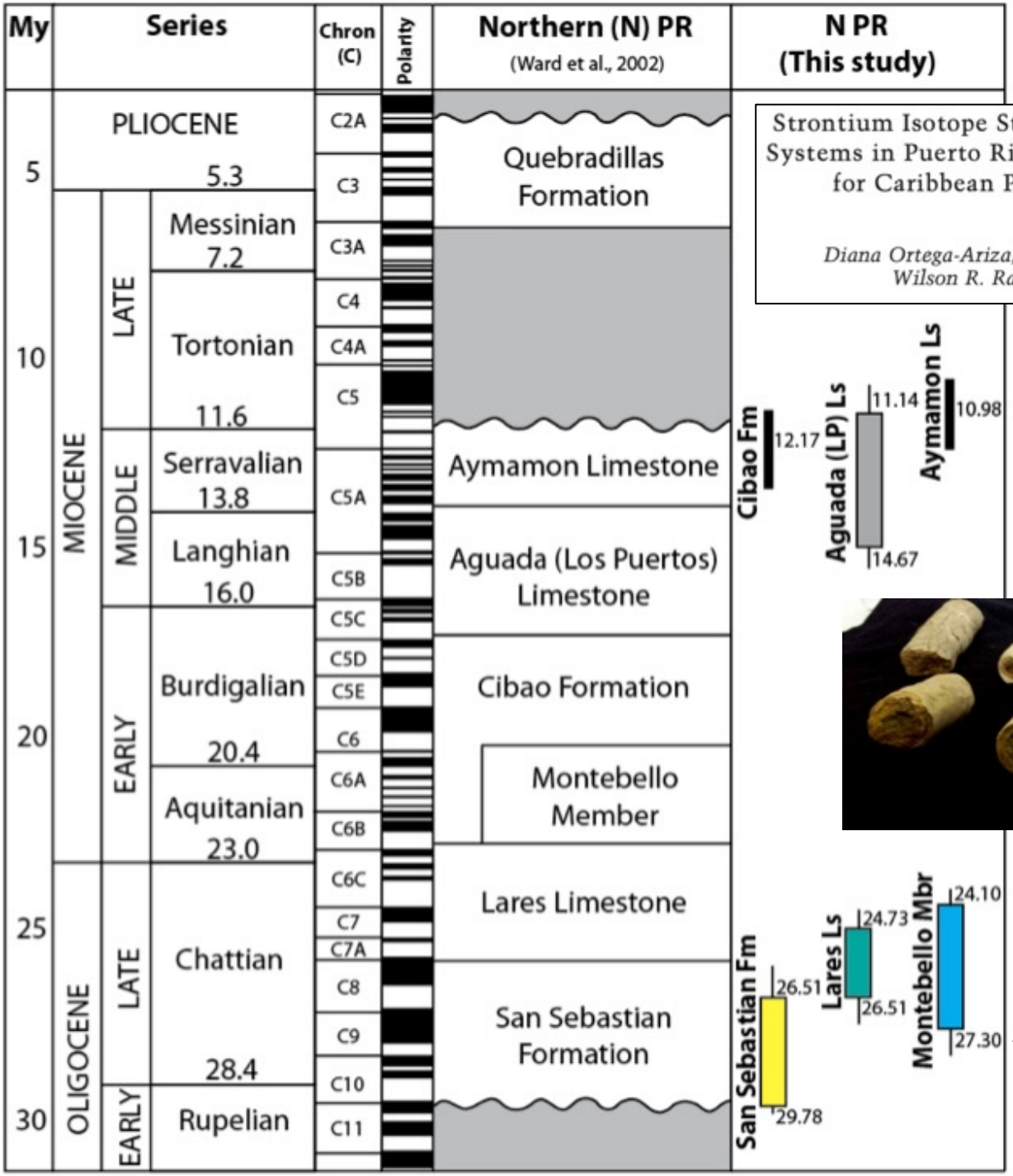
Exposure at the TOP of the outcrop of PR10 / PR6612 Intersection (N18°18’52”, W66°41’05”)

Stop #2:
Montebello Member

- 305 m thick along PR10 (Ramírez-Martínez, 2000)
- mostly of repetitions of coral-dominated boundstones (framestones) and foraminifer-, mollusks-, red algae- and rhodolite-dominated packstones (Ramírez-Martínez, 2000).
- lithofacies indicate deposition in shallow-marine environment (middle shelf or ramp)
- variations in fossil assemblages (and lithology) produced by either progradation or changes in water depth

Stop #2:
Montebello Member of the Cibao Formation

Exposure at the TOP of the outcrop of PR10 / PR6612 Intersection (N18°18’52”, W66°41’05”)



Strontium Isotope Stratigraphy for Oligocene-Miocene Carbonate Systems in Puerto Rico and the Dominican Republic: Implications for Caribbean Processes Affecting Depositional History

2015

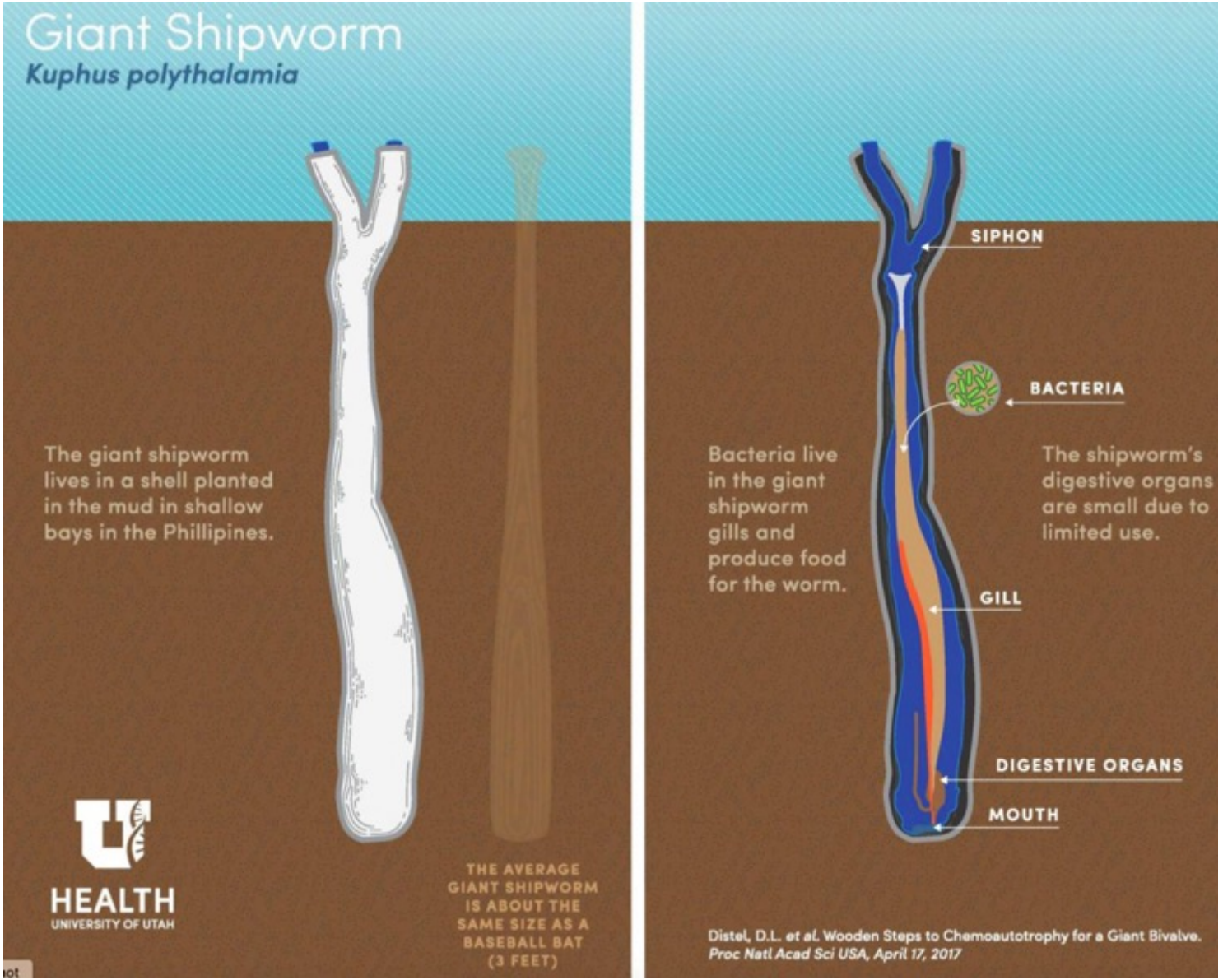
Diana Ortega-Ariza,[1,2,] Evan K. Franseen,[1,2] Hernán Santos-Mercado,[3] Wilson R. Ramírez-Martínez,[3] and Elson E. Core-Suárez[3]*

← 27.30 Ma
(average)

- Bivalves

Kuphus incrassatus

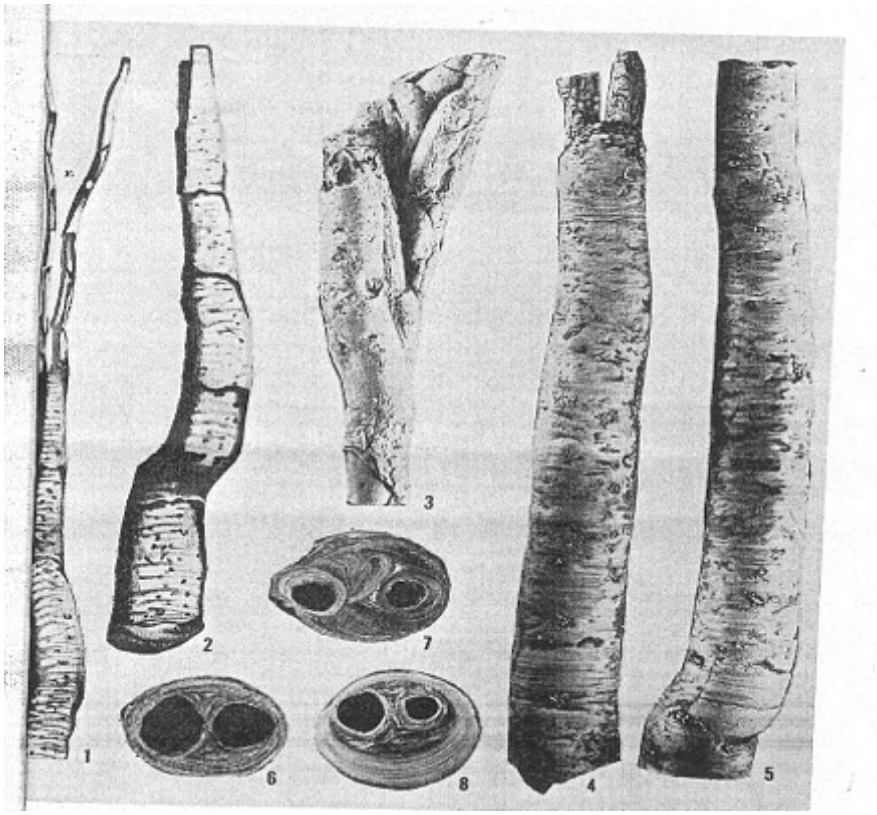
- Elongated calcareous tubes – Low Magnesium Calcite



Kuphus incrassatus

- Bivalves
- Elongated tubes composed of Low Magnesium Calcite
- Abundant in PR North Coast Neogene Limestones

photo/classification by Emily Vokes, Tulane University




PR10
6 23'97

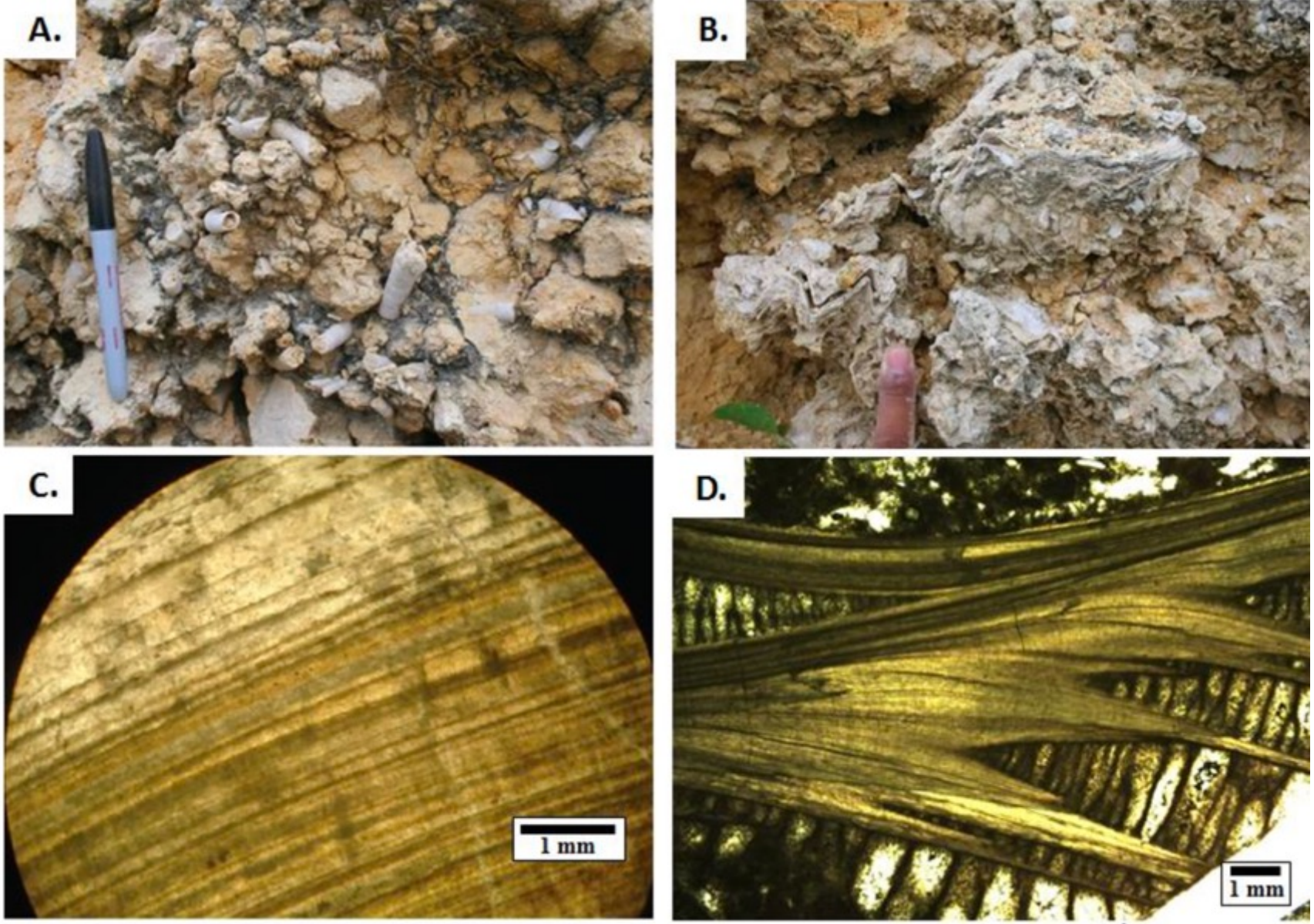


Figure 2.4: Low-Mg calcite *Kuphus incrassatus* and *Ostrea haitensis* bivalves. A-B) *Kuphus incrassatus* (A) and *Ostrea haitensis* (B) in outcrop. C) *Kuphus incrassatus* in thin section. Most inner layers (dark brown) of *Kuphus* preserve original internal shell texture, whereas outer layers (light yellow) are mostly recrystallized. D) *Ostrea haitensis* in thin section showing alternating constructional layers of lamellae (dark brown, non-recrystallized) and vesicular shell structure partly recrystallized (light yellow).

Dating (Strontium Isotopes from *Kuphus incrasatus)*

…and *Ostrea sp.*

$CaCO_3$

Sr

Four naturally ocurrring Strontium Isotopes

^{88}Sr (82.53%)

^{87}Sr (7.04%)

^{86}Sr (9.87%)

^{84}Sr (0.56%)

Four naturally ocurrring Strontium Isotopes

^{88}Sr (82.53%)

^{87}Sr (7.04%) - radiogenic

^{86}Sr (9.87%) - non radiogenic

^{84}Sr (0.56%)

Four naturally ocurrring Strontium Isotopes

^{88}Sr (82.53%)

^{87}Sr (7.04%) - radiogenic

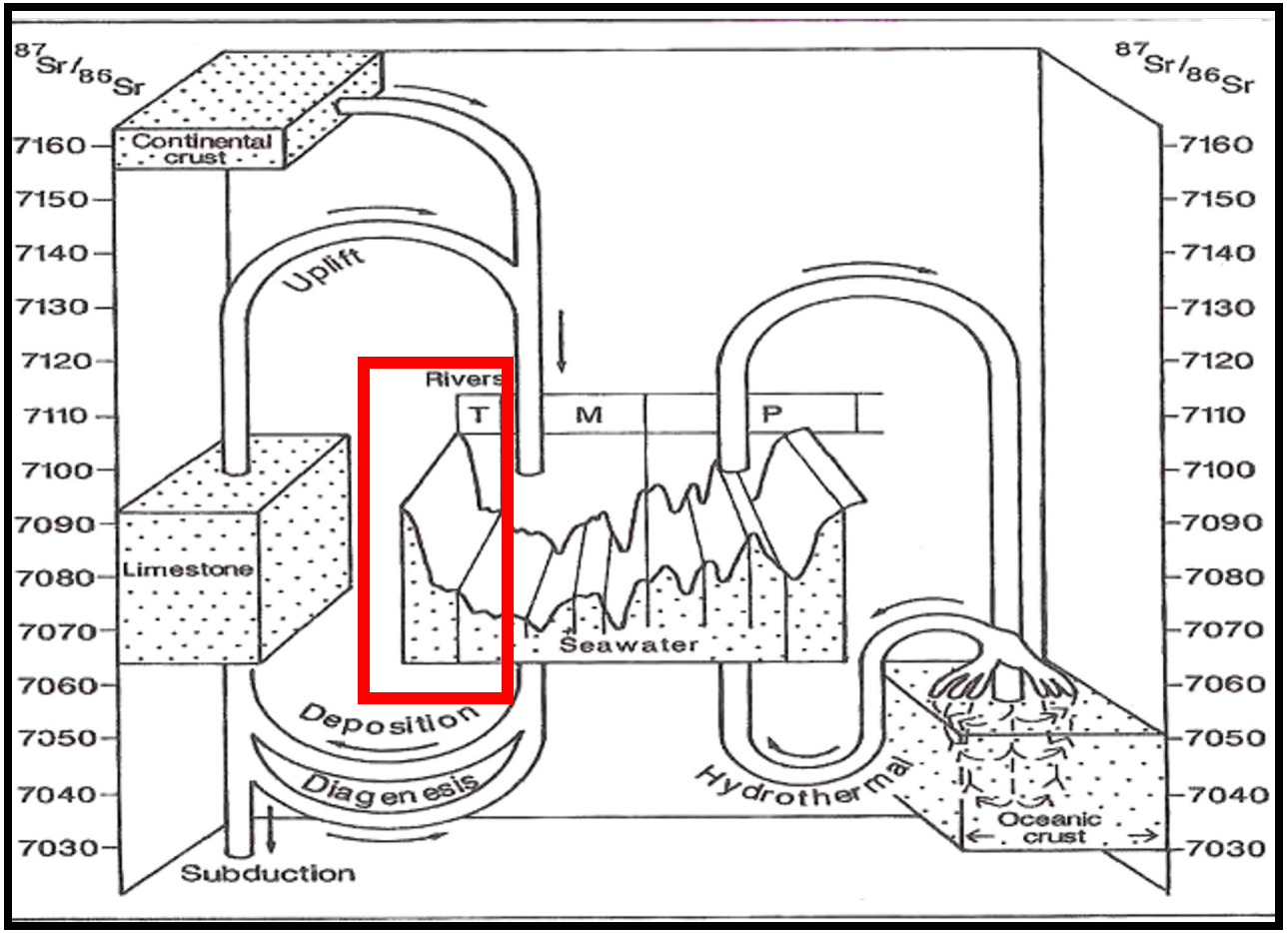
^{86}Sr (9.87%) - non radiogenic

^{84}Sr (0.56%)

Produced Radiogenically (= increase)

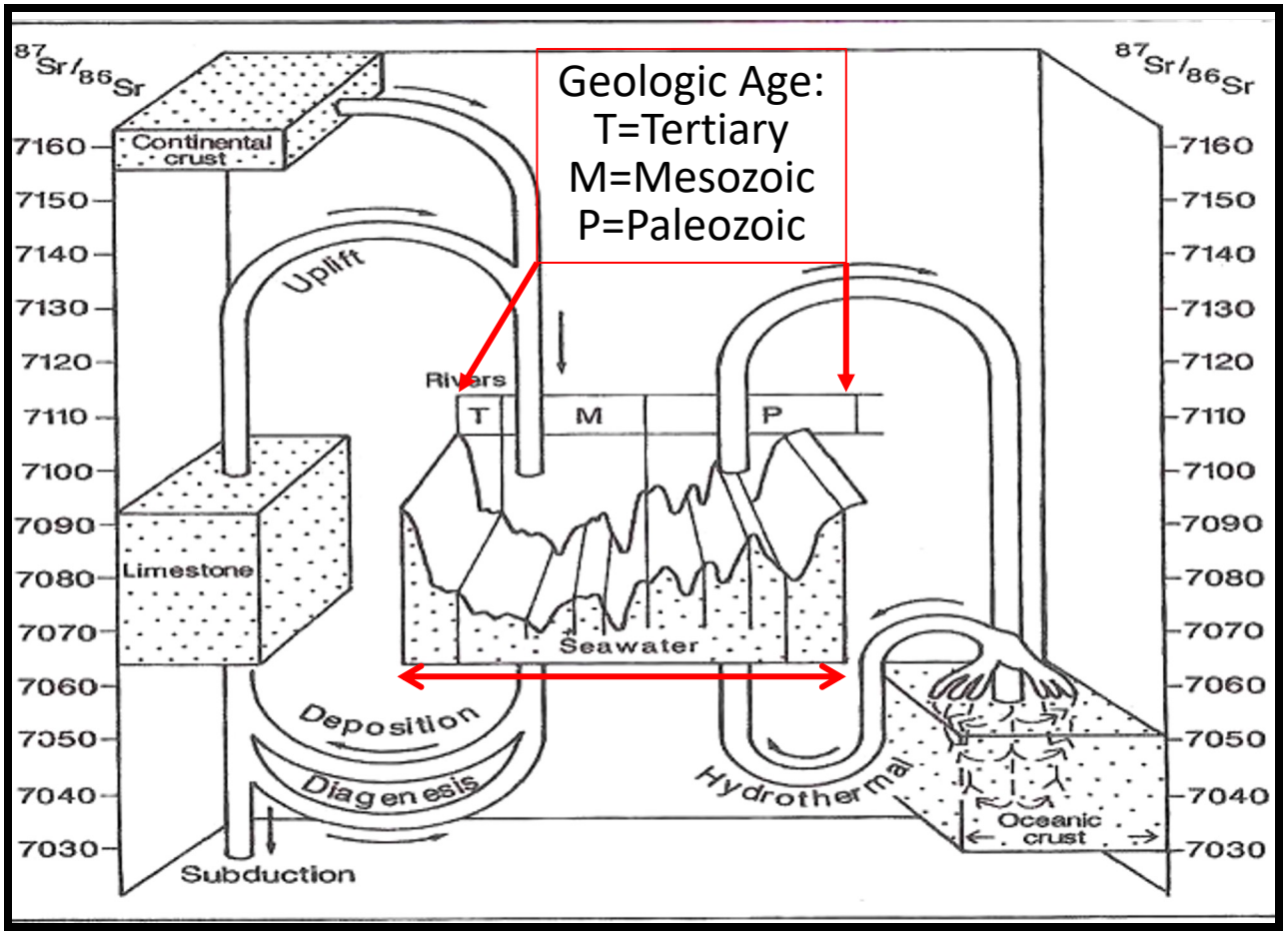
$$\frac{^{87}Sr}{^{86}Sr}$$

Always the same amount.



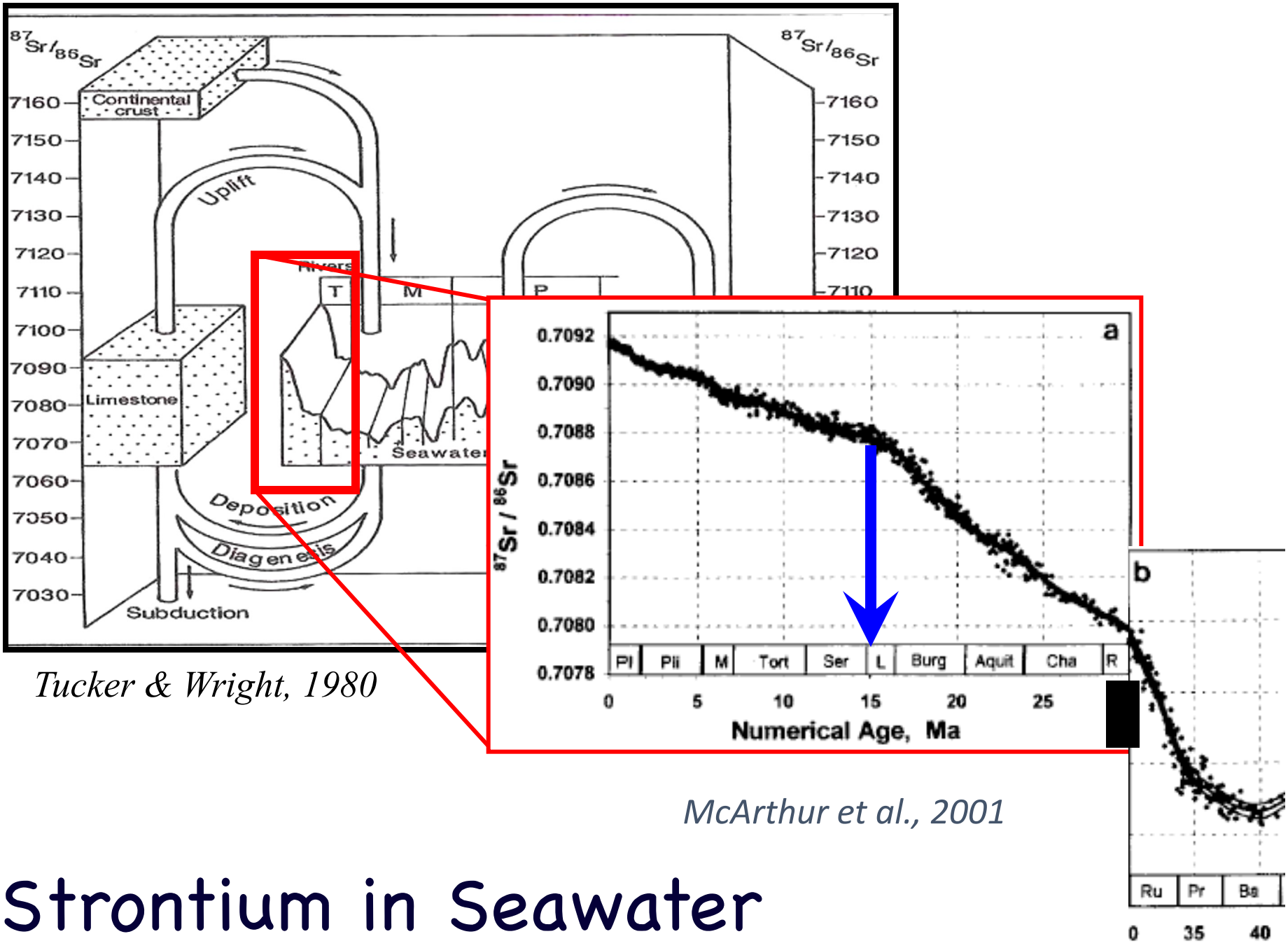
Tucker & Wright, 1980

Strontium in Seawater



Tucker & Wright, 1980

Strontium in Seawater



Tucker & Wright, 1980

McArthur et al., 2001

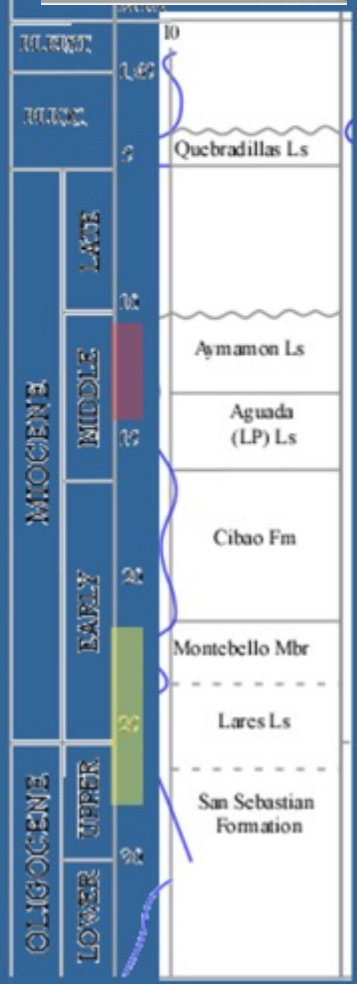
Strontium in Seawater

Strontium Isotope Stratigraphy (SIS)

- $^{87}Sr/^{86}Sr$ conversion to numerical ages (McArthur, 2001)

95% confidence limit

Sample ID	Lithologic unit	$^{87}Sr/^{86}Sr$	Age (Mya)
NC 13-526	Aymamón Ls	0.708858 +/- 0.000015	10.91+/-0.34
NC-11 1145-2	Aguada Ls	0.708854 +/- 0.000015	11.06+/-0.37
NC 11-1145-1	Aguada Ls	0.708851 +/- 0.000015	11.18+/-0.46
NC 11-1149-46	Aguada Ls	0.708845 +/- 0.000015	11.45+/-0.54
NC 11-1165-4	Aguada Ls	0.708843 +/- 0.000015	11.59+/-0.51
NC-6 LP 1380-77 -1	Aguada Ls	0.708795 +/- 0.000015	14.60+/-0.89
NC-11 1181-2	Cibao Fm	0.708835 +/- 0.000015	12.07+/-0.53
PR-10 10 3M2	Montebello Mbr	0.708198 +/- 0.000015	24.07+/-0.16
PR-10 2K1-4	Montebello Mbr	0.708128 +/- 0.000015	25.76+/-0.28
PR-10KM67.6 #3	Lares-Montebello	0.708109 +/- 0.000015	26.43+/-0.34
PR-10KM67.6 #2	Lares-Montebello	0.708085 +/- 0.000015	27.24+/-0.29
PR111OL-3	Lares Ls	0.708146 +/- 0.000015	25.23+/-0.26
PR 111-OL-2	Lares Ls	0.708171 +/- 0.000015	24.60+/-0.21
PR111-GPS	Lares Ls	0.708167 +/- 0.000015	24.69+/-0.22
PR-111 T1	Lares Ls	0.708162 +/- 0.000015	24.81+/-0.22
PR-111 M2	Lares Ls	0.708130 +/- 0.000015	25.70+/-0.27
PR-111 M8	Lares Ls	0.708121 +/- 0.000015	25.97+/-0.32



Ortega-Ariza, 2009

Stop #2:

Montebello Member of the Cibao Formation

Exposure at the TOP of the outcrop of PR10 / PR6612 Intersection (N18°18’52”, W66°41’05”)

Stop #1 and #2:

San Sebastián Formation - Lares Limestone Contact
Lares Limestone – Montebello Member Contact

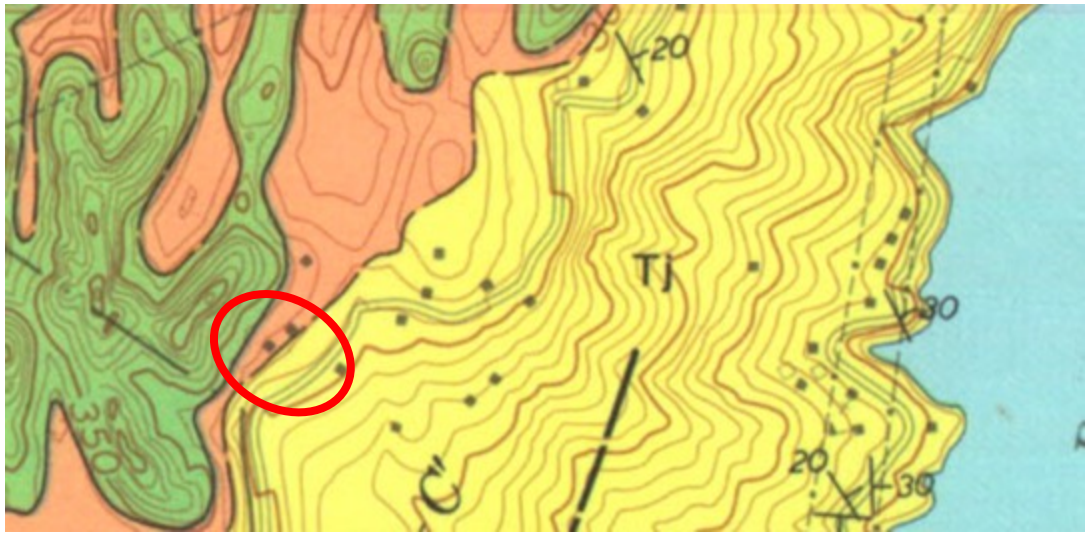
Parasequences: PR-10 Stop #1

Ortega-Ariza, 2009

General Characteristics of the Montebello Member of the Cibao Formation

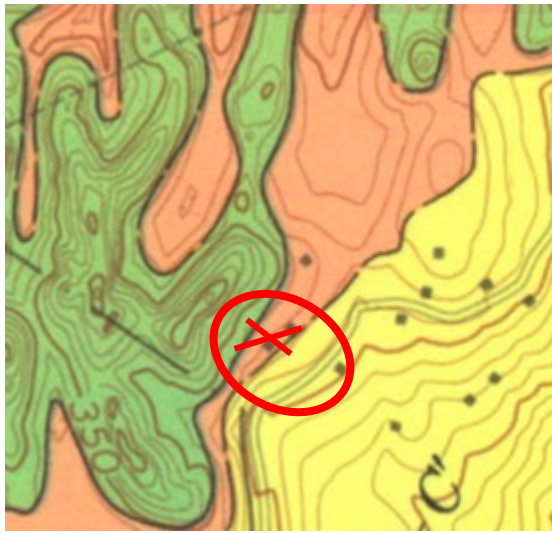
- Composed largely of foraminifers & fragments of molluskan shells
- The most laterally and stratigraphically extensive member unit of the Cibao Formation
- Grades to the west and east into the marly limestones of the undifferentiated Cibao Formation
- Type locality is in the Florida quadrangle where it is composed of pure calcium carbonate
- Subsurface - composed of shoaling-upward sequences with basal units dominantly shallow middle-to-inner shelf deposits and upper units showing high-energy near-shore environments
- The oyster layer marker probably pinches out downdip because it has not been found in the subsurface

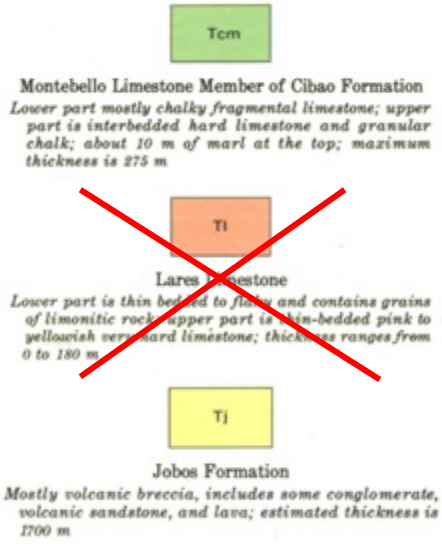
Intersection of the Highway PR10 and road PR621
(N18°19'58"; W66°40'42")



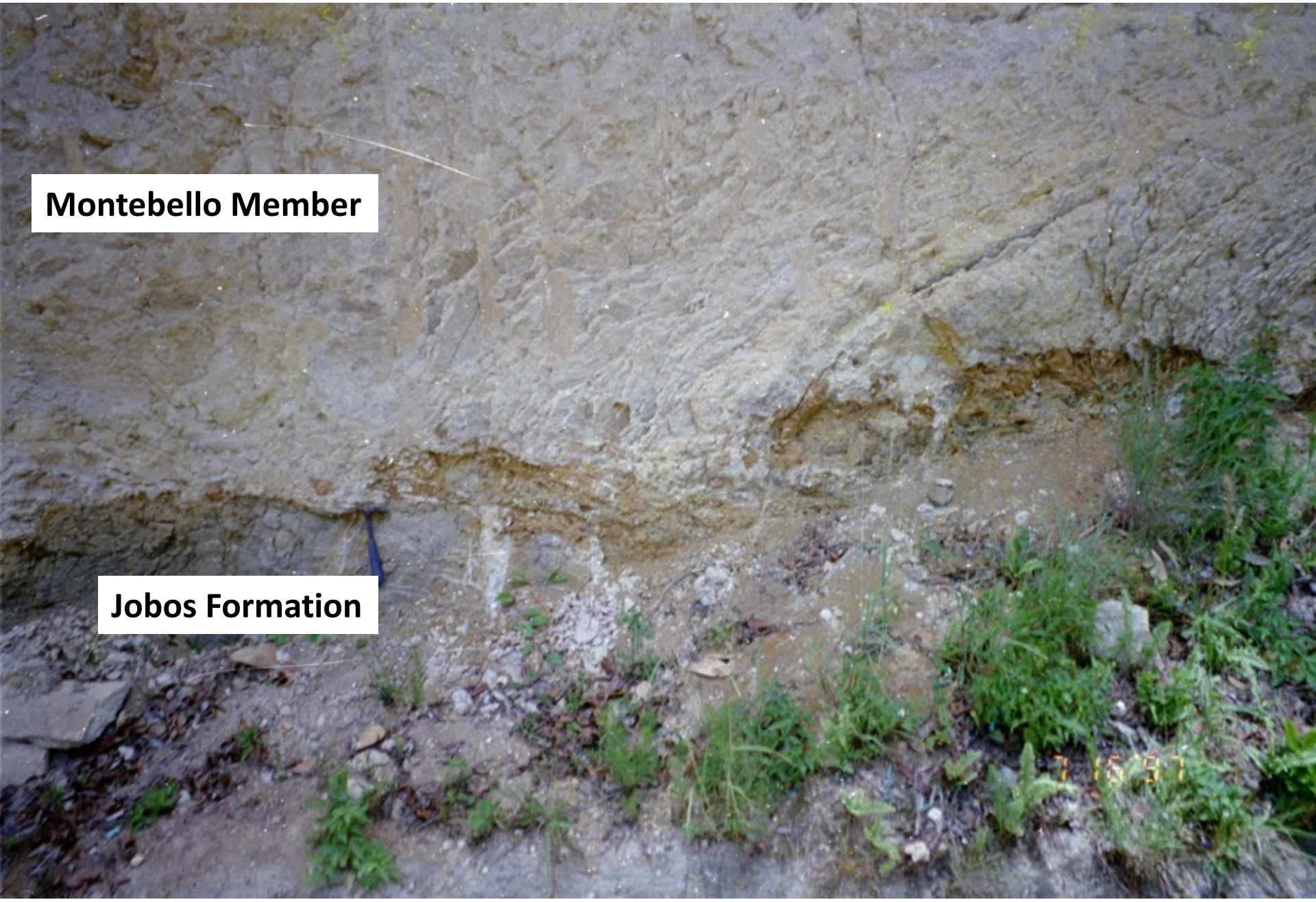
Stop #3:
Montebello Member- Jobos Formation Contact

Stop #3:
Montebello Member – Jobos Formation Contact



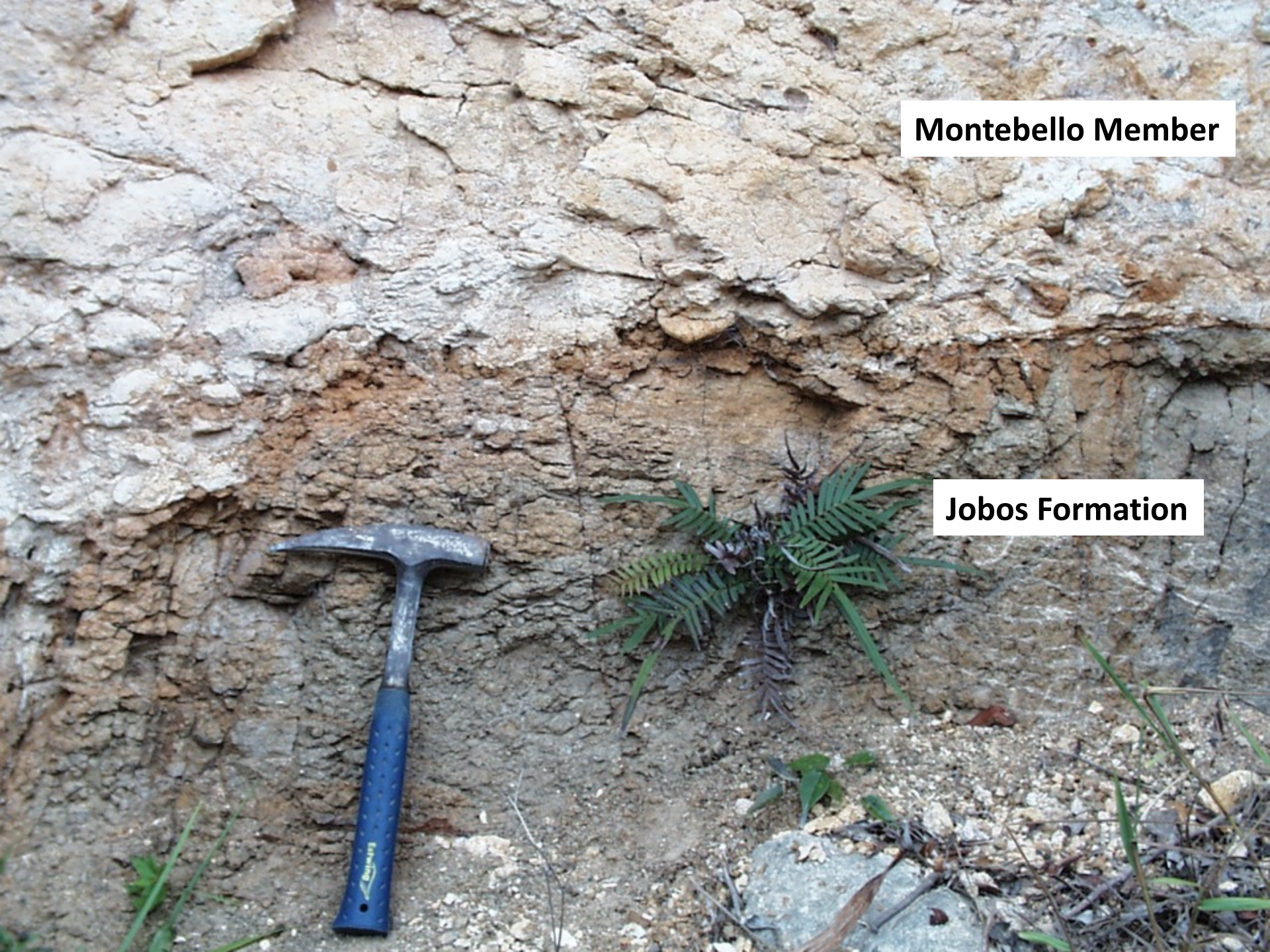


- Jobos Formation (Tj)
  - Upper Paleocene (59 Ma) to Middle Eocene (41 Ma)
  - mostly volcanic breccia
  - some conglomerate, volcanic sandstone, and lava
  - 1,700m thick (cores)
- Contact
  - undulatory with multiple truncations
- Montebello Member
  - 26 – 24 Ma (*Kuphus incrasatus*)
  - Packstone/ grainstone with scarce forams (*Miocerites sp.)* and Mollusks (mostly gastropods)
- Lares Limestone absent
  - former presence of a topographic high in the area composed of basement rocks of Cretaceous age (145 – 66 Ma)


Montebello Member
Jobos Formation

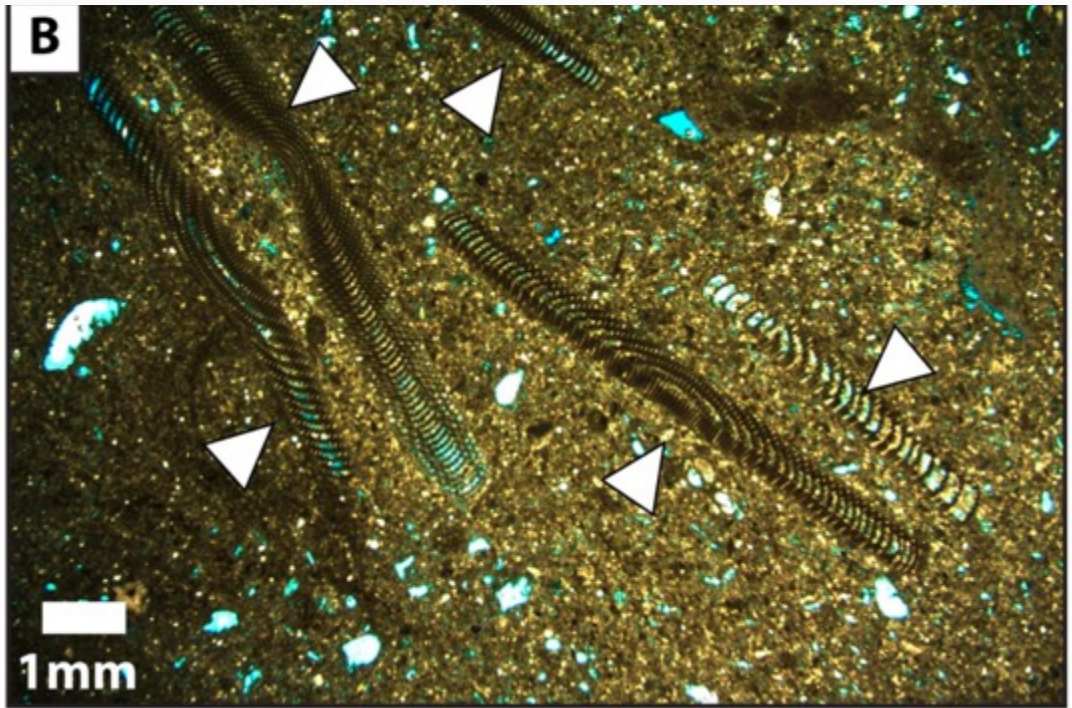

Montebello Member
Jobos Formation


Montebello Member
Jobos Formation

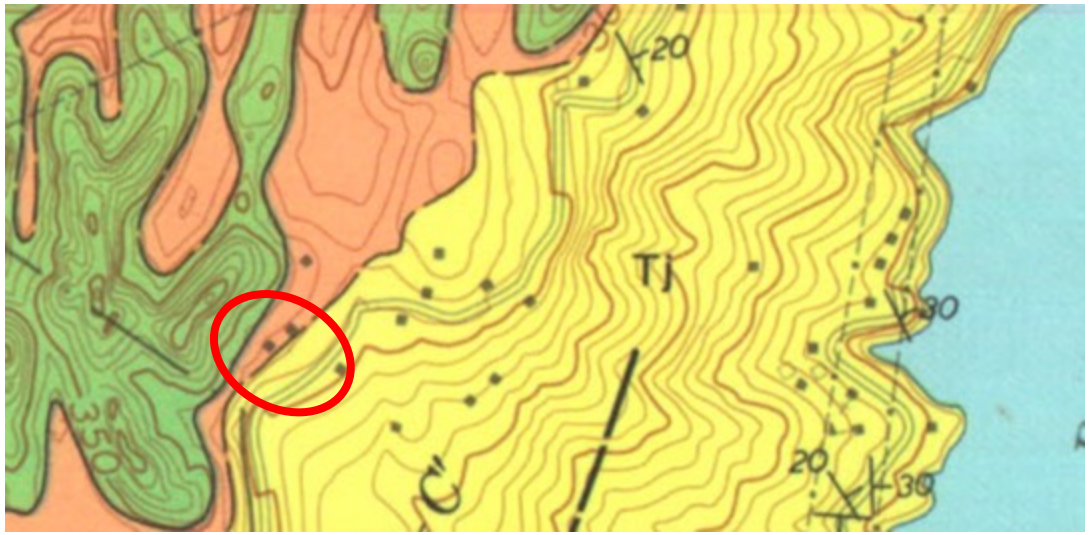

Montebello Member
Jobos Formation


Montebello Member
Jobos Formation

Photos showing soritid-rich packstone F2a facies in outcrop (A) and thin section (B). Finger and white arrow in A pointing at soritids. Yellow arrow points to preserved filled burrow. White arrows in photomicrograph (B) point to soritids.



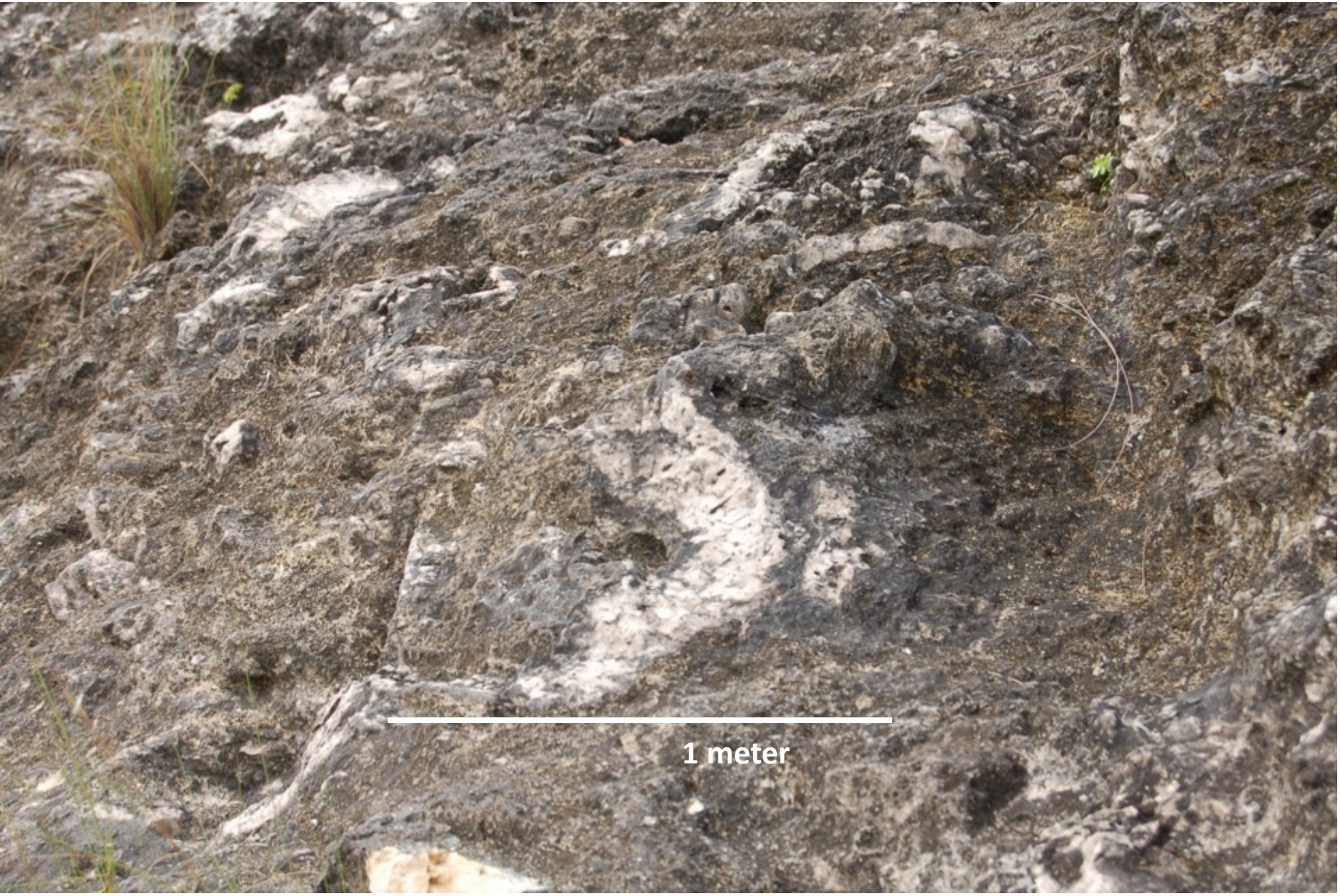
Intersection of the Highway PR10 and road PR621
(N18°19’58”; W66°40’42”)

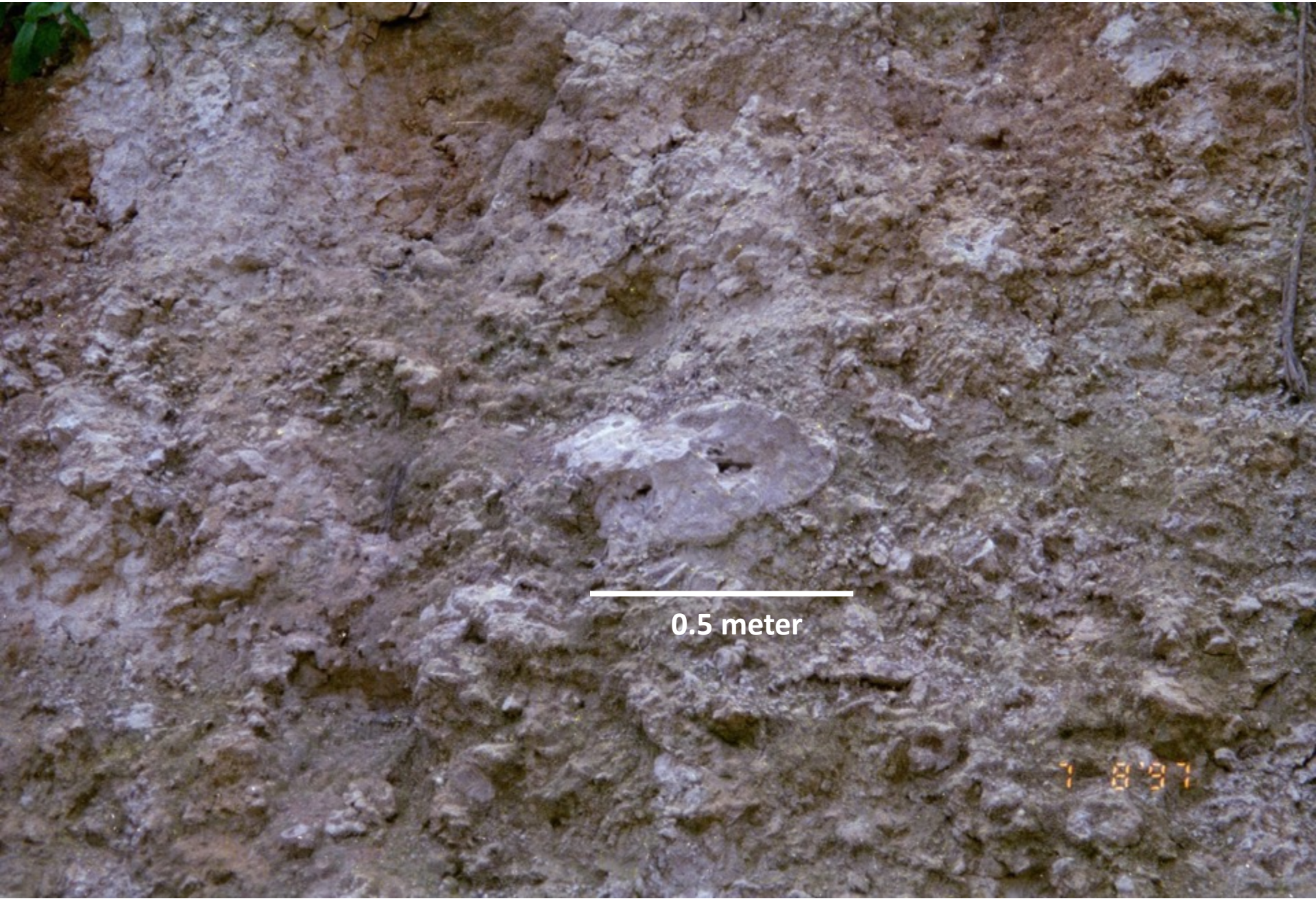


Stop #4:
Montebello Member – Coral Boundstone

Stop #4
Montebello Member / Coral Boundstone

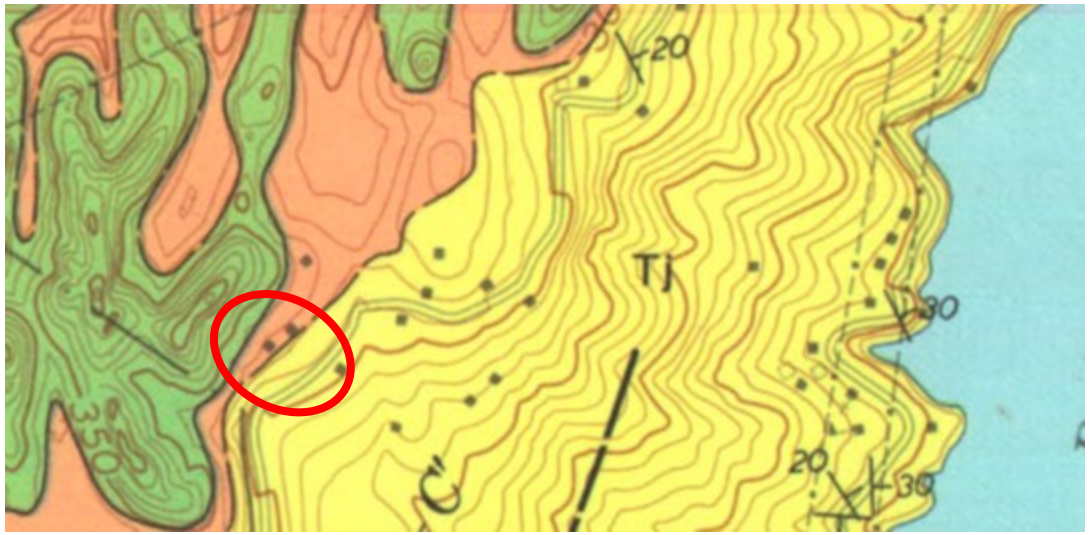
- observation Mogote at PR10 - PR621 road intersection (N18°19’58”, W66°40’42”)
- recrystallized corals in growth position with a wackestones matrix
- part of the repetitions of coral-dominated boundstones (framestones) and foraminifer-, mollusks-, red algae- and rhodolite-dominated packstones discussed at the top of the outcrop visited in Stop 1


1 meter


0.5 meter
7 8'97


3 14 97

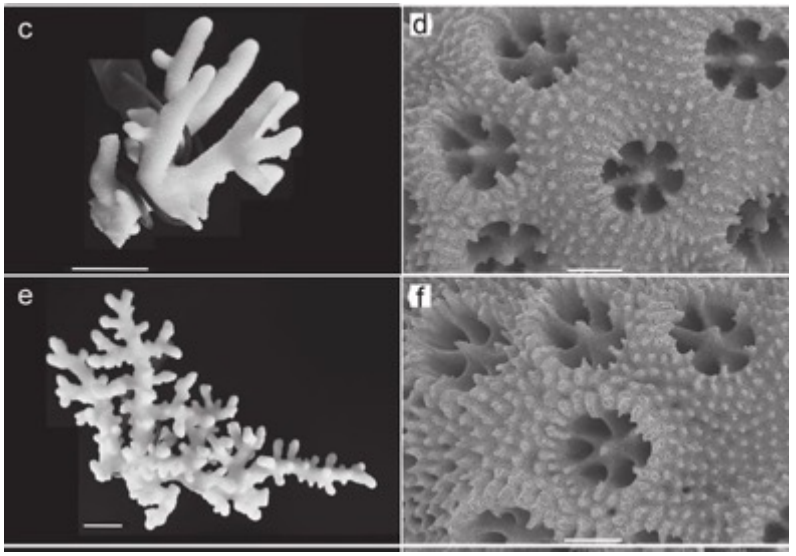
Intersection of the Highway PR10 and road PR621
(N18°19’58”; W66°40’42”)



Stop #5:
Montebello Member – *Stylophora sp*. Mound

Stop #5
Montebello Member / *Stylophora sp.* Mound/Bioherm (Boundstone/Framestone)

- 0.5 km north and across the street from PR10 - PR621 road intersection (N18°20’15”, W66°40’35”)
- lens-like structure of *Stylophora sp.* (branching coral)
- feature surrounded by red algal packstones and grainstones




WARNING-WEAR SAFETY GOGGLES

Stop #6

Montebello Member / *Porites* Boundstone
PR10 Km 70.5

The branching coral *Porites* is extremely abundant and seems to be in growth position. This unit is equivalent stratigraphically to the Branching Coral-Boundstone present at the top of the outcrop visited at Stop 1.

Stop #7

Montebello Member / *Miocerites* Packstone
N18º21'06", W66º41'12"

The study of the exposed section of the Montebello Member of the Cibao Formation in the new PR10 Highway from Arecibo to Utuado revealed cyclicity in the distribution patterns of coral-dominated, mollusks-dominated, foraminifers-dominated, and red algae/rhodolite-dominated units (Galluzzo and Ramírez, 1998). Here we have one of the multiple foraminifers-dominated packstones present in the section. The foram genus *Miocerites* is dominant. Oysters and equinodems are also common.

Stop #8

Montebello Member / Grainstone – Submarine Hardground.

N18°21'12", W66°41'12"

A 0.5 meter thick grainstone unit with abundant rhodolites, equinoderm fragments and spicules forms a sharp, linear, well defined bed in this area. The geometry of the bed, texture, and petrography suggest that this unit could have been a submarine hardground at some moment during the deposition of these rocks.

Fig. 22: A 0.5 meter thick grainstone bed interpreted as a submarine hardground.

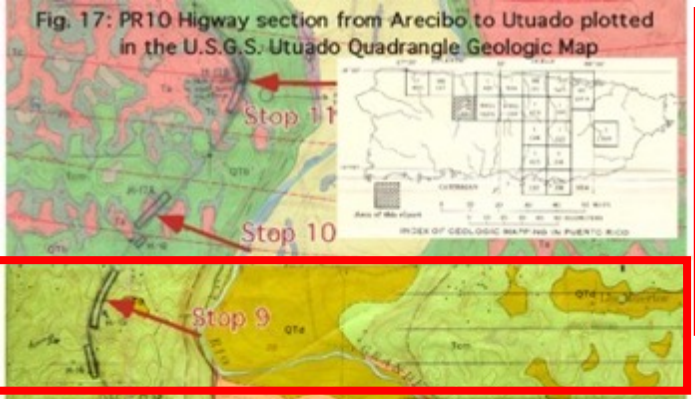

7 17'97


7 17'97

Stop #9

Montebello Member / Ancient Water Table or Exposure ?
N18º22'17", W66º41'39"

A bed of carbonaceous clays is present in between the fossiliferous limestones in this outcrop. This highly undulatory bed is not associated with calishe layers, brackish or freshwater fossils, nor it has any other feature that would suggest that it was formed by subaerial exposure. Several possible explanations could be suggested to explain the formation of this atypical bed in the area. Diagenetical explanations seem more feasible than depositional. One possibility is that this layer could have mark the position of the air-water interface (water table) present in the area at some moment in time.



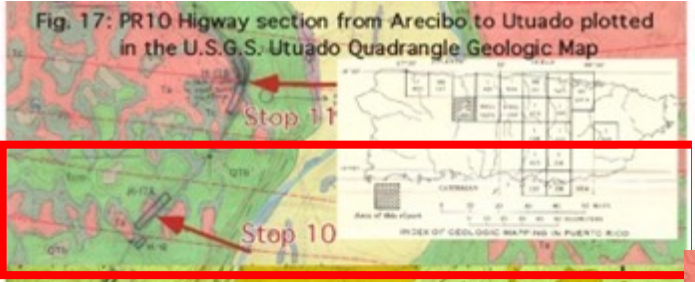
Stop #9 Water Table Effects ?

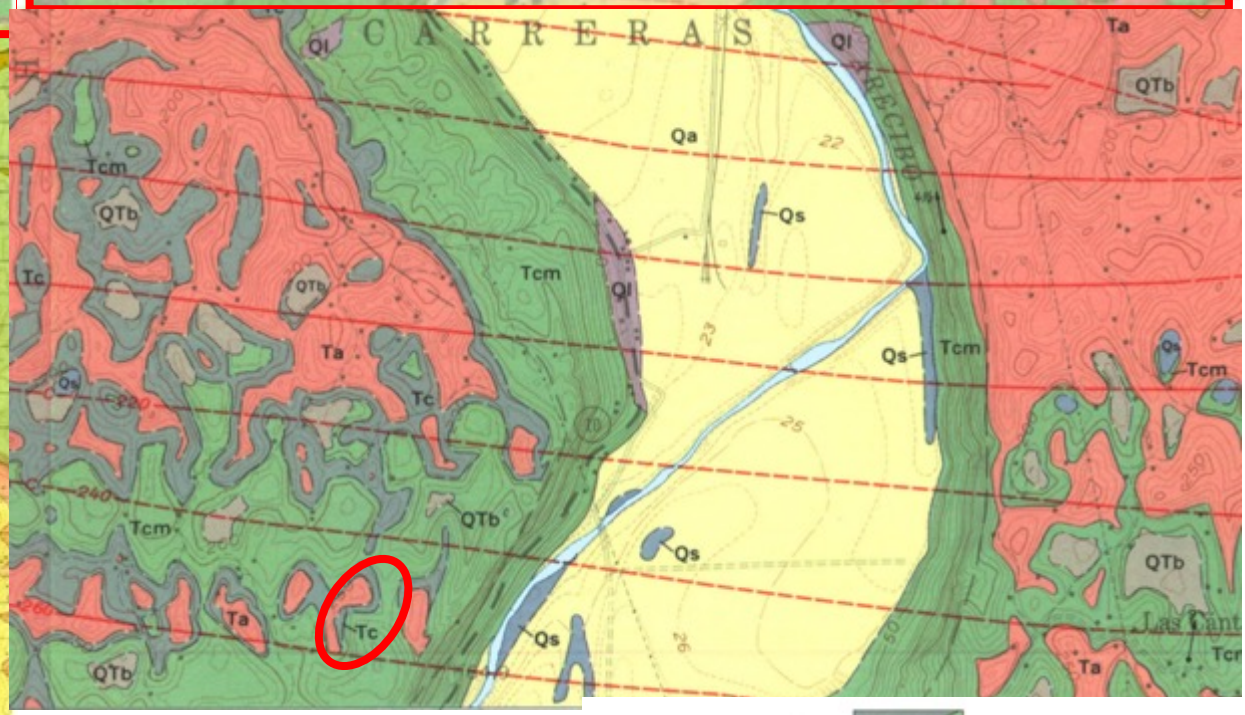

Evidence of SUBAREAL EXPOSURE absent
7 19 '97


Evidence of SUBAREAL EXPOSURE absent


Evidence of SUBAREAL EXPOSURE absent

Fig. 17: PR10 Higway section from Arecibo to Utuado plotted in the U.S.G.S. Utuado Quadrangle Geologic Map





Ta

Aguada Limestone

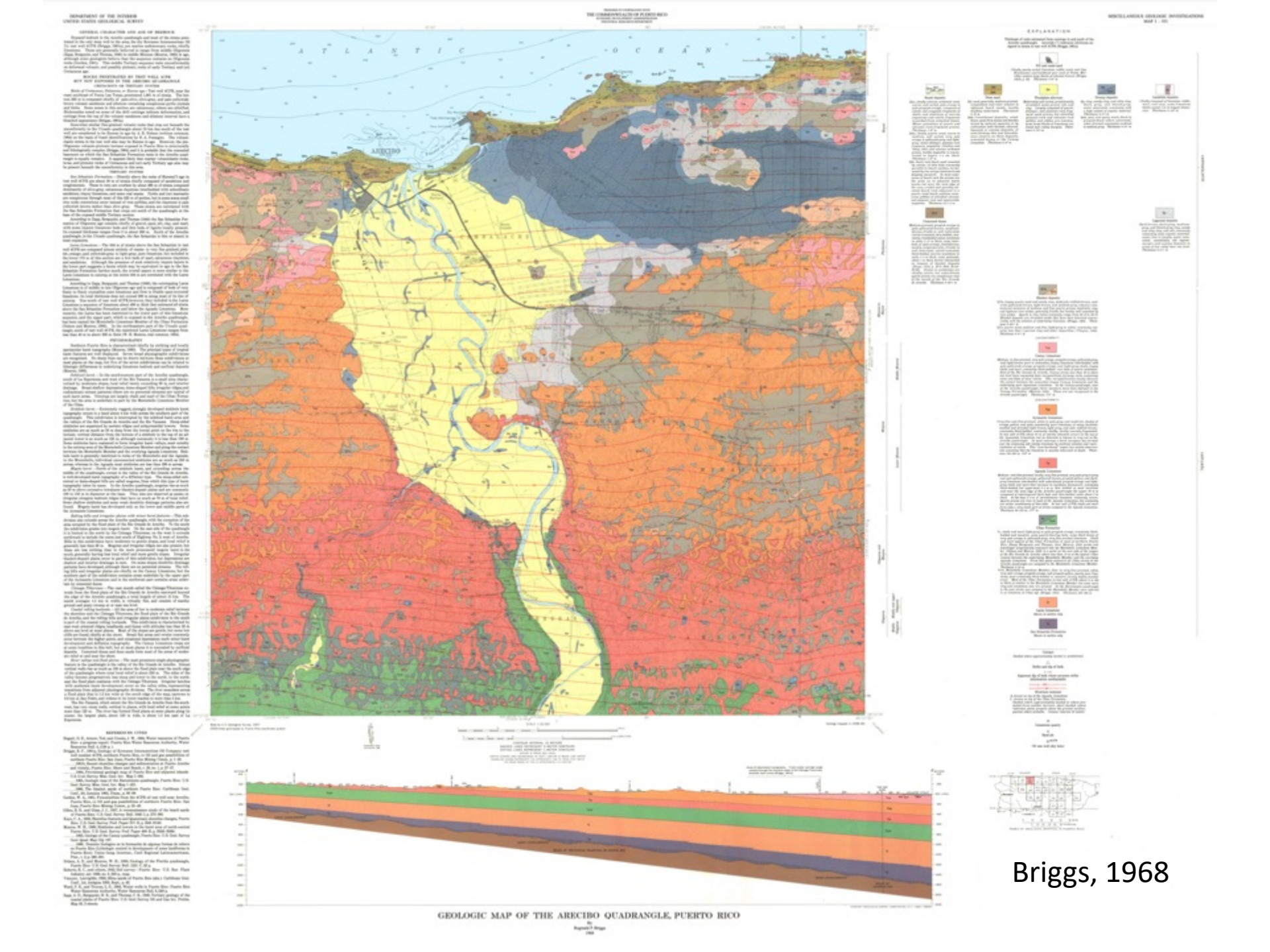
Medium- and fine-grained, locally very fine grained, very pale gray to gray and pale-yellowish-orange, yellowish-brown, grayish-yellow, and dark-gray limestone interbedded with subordinate grayish-orange and light-gray chalk and marl that increase in incidence downward; commonly thick-bedded, but uppermost 2-5 m is thin bedded at most localities and near the west edge of the Arecibo quadrangle the upper 30 m is composed of interlayered thick beds and thin-bedded units about 3 m thick. At the base 2-3 m of porcelaneous limestone commonly occurs. Quartz grains are rare in most of the Aguada Limestone, but commonly are minor constituents of thin beds. In test well 4CPR, chalk and marl form only a very small part of strata assigned to the Aguada Limestone. Thickness 90-150 m; 177 m*

Tc Tcm

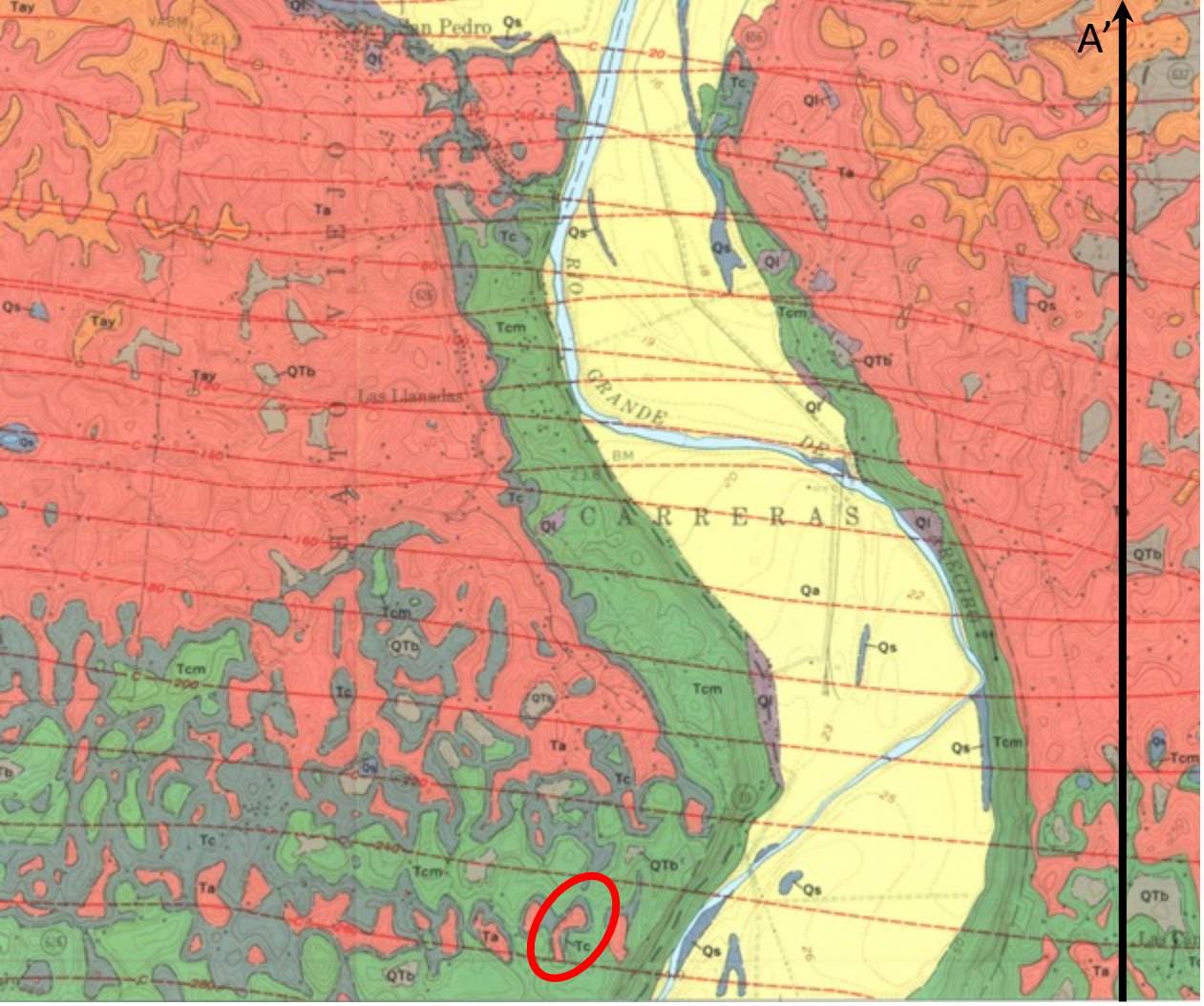
Cibao Formation

Tc, *chalk and marl, light-gray to pale-grayish-orange, commonly thick-bedded and massive; some quartz-bearing beds; some thick lenses of very pale orange to yellowish-gray, very fine grained limestone. Chalk and marl typical of the Cibao Formation in most of northern Puerto Rico (Zapp, Bergquist, and Thomas, 1948; Monroe, 1963) grade and interfinger progressively eastward into the Montebello Limestone Member (Nelson and Monroe, 1966) to a point on the east side of the canyon of the Río Grande de Arecibo where less than 10 m of the typical Cibao remain between the underlying Montebello Member and the overlying Aguada Limestone. From this point eastward all Cibao strata in the Arecibo quadrangle are assigned to the Montebello Limestone Member. Thickness 0-50 m*

Tcm, *Montebello Limestone Member; fine- to very fine grained, white, very pale orange, grayish-orange, and grayish-yellow nearly pure limestone, most commonly thick-bedded or massive, locally highly fossiliferous. Most of the Cibao Formation in test well 4CPR, where it is 305 m thick, is similar to the Montebello Limestone Member, but some marl, clay, and sandstone also are present. In the Barceloneta quadrangle to the east, strata now assigned to the Montebello Member were referred to as limestone of Cibao age (Briggs, 1965). Thickness 200-260 m*

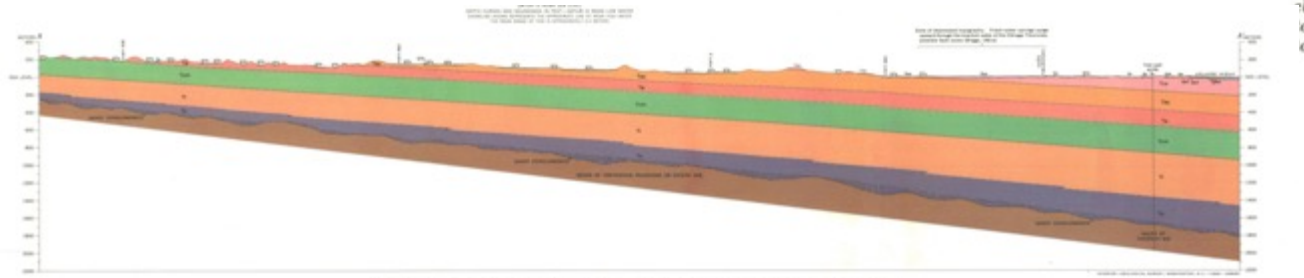

ATLANTIC OCEAN
ARECIBO
EXPLANATION
GEOLOGIC MAP OF THE ARECIBO QUADRANGLE, PUERTO RICO

Briggs, 1968



Briggs, 1968

A



A

GEOLOGIC MAP OF THE ARECIBO QUADRANGLE, PUERTO RICO

A'

Tay

Aymamón Limestone

Very fine and fine-grained, white to pale-gray and moderate shades of orange, yellow, and pink, essentially pure limestone, at many localities mottled and streaked light brown, light gray, and pale reddish brown; commonly thick-bedded; commonly chalky; locally coarsely fragmental. In test well 4CPR, about 67 m of calcitic dolomite occurs in the top of the Aymamón Limestone, but no dolomite is known to crop out in the Arecibo quadrangle. In most outcrops a hard carapace has formed over the commonly soft chalky limestone by surficial solution and reprecipitation of calcite. This "case-hardened" aspect has misled observers into assuming that the limestone is equally indurated at depth. Thickness 190-205 m; 216 m*

Ta

Aguada Limestone

Medium- and fine-grained, locally very fine grained, very pale gray to gray and pale-yellowish-orange, yellowish-brown, grayish-yellow, and dark-gray limestone interbedded with subordinate grayish-orange and light-gray chalk and marl that increase in incidence downward; commonly thick-bedded, but uppermost 2-5 m is thin bedded at most localities and near the west edge of the Arecibo quadrangle the upper 30 m is composed of interlayered thick beds and thin-bedded units about 3 m thick. At the base 2-3 m of porcelaneous limestone commonly occurs. Quartz grains are rare in most of the Aguada Limestone, but commonly are minor constituents of thin beds. In test well 4CPR, chalk and marl form only a very small part of strata assigned to the Aguada Limestone. Thickness 90-150 m; 177 m*

Tc | Tcm

Cibao Formation

Tc, *chalk and marl, light-gray to pale-grayish-orange, commonly thick-bedded and massive; some quartz-bearing beds; some thick lenses of very pale orange to yellowish-gray, very fine grained limestone. Chalk and marl typical of the Cibao Formation in most of northern Puerto Rico (Zapp, Bergquist, and Thomas, 1948; Monroe, 1963) grade and interfinger progressively eastward into the Montebello Limestone Member (Nelson and Monroe, 1966) to a point on the east side of the canyon of the Río Grande de Arecibo where less than 10 m of the typical Cibao remain between the underlying Montebello Member and the overlying Aguada Limestone. From this point eastward all Cibao strata in the Arecibo quadrangle are assigned to the Montebello Limestone Member. Thickness 0-50 m*

Tcm, *Montebello Limestone Member; fine- to very fine grained, white, very pale orange, grayish-orange, and grayish-yellow nearly pure limestone, most commonly thick-bedded or massive, locally highly fossiliferous. Most of the Cibao Formation in test well 4CPR, where it is 305 m thick, is similar to the Montebello Limestone Member, but some marl, clay, and sandstone also are present. In the Barceloneta quadrangle to the east, strata now assigned to the Montebello Member were referred to as limestone of Cibao age (Briggs, 1965). Thickness 200-260 m*

Tl

Lares Limestone

Shown in section only

Ts

San Sebastián Formation

Shown in section only

Stop #10

Grainstone layer with abundant *Kupus incrassatus* in growth position N18°22'47", W66°41'56"

The *Kuphus* belong to the super family *Pholadacea*, suborden, *Dufinae*, Orden *Myoida*, suborden *Proladina*, familia *Teredinidae*, subfamilia *Kuphinae* (Moore, Editor (n) Mollusca, 6^{2003} 1969). The *Kuphus* have an elongated tube that is mostly composed of low magnesian calcite (Fig. 27). The animal produces secretions of calcite for the protection of depredators. Most characteristic is the presence, in the upper smaller end of the tube, of two small tubes, one slightly larger than the other, that are encased in an extensive development of supplementary calcareous deposit (Vokes Tulane University). The smaller tubes house the inhalant and exhalent siphons of the animal, the one for the inhalant siphon being somewhat larger diameter than that for the exhalent one (Vokes Tulane University). Kuphus tubes are common in the North Coast Limestones and are composed of low magnesian calcite (high potential preservation). Sr isotopes have been used to obtain dates of fossils shells composed of low magnesium calcite based on well documented variations of Sr isotopes in marine water through geologic time. The former method can be applied to the *Kuphus incrasautus* tubes since they are made of low magnesium calcite. "Absolute ages" of the Kuphus tubes can help approximate the "absolute age" when a Limestone was being formed. This "absolute age" information can probably help to establish a better stratigraphic chronology of the Puerto Rico Tertiary Limestones providing that the Kuphus tubes have not being altered. Ramírez-Martínez et al. (2006 and 2008) has demonstrated they are a promising prospect to establish absolute dates along the North Coast Limestones.


T20'97

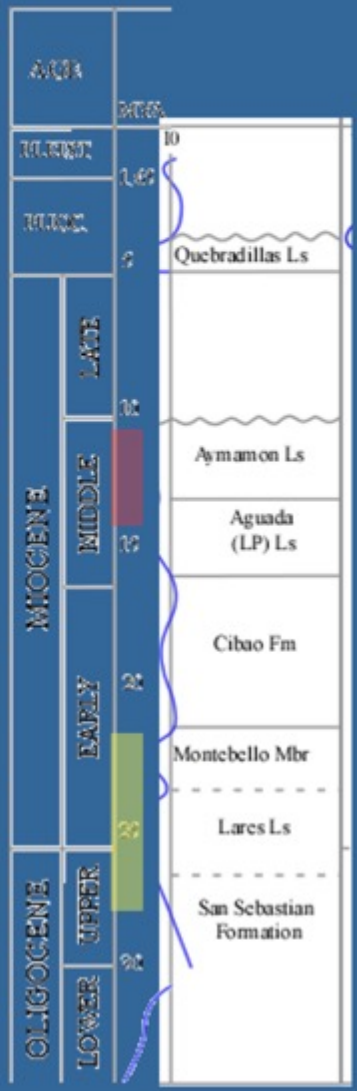
Fig. 24: The red arrow points to a layer could mark the position of the air-water interface (water table) present in the area at some moment in time. The blue arrow points to a grainstone surface with a high abundance of Kuphus fossils in growth position. N 18o22'17", W 66o41'39"

Strontium Isotope Stratigraphy (SIS)

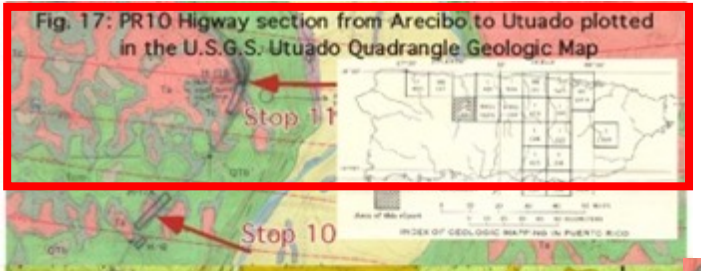
- $^{87}Sr/^{86}Sr$ conversion to numerical ages (McArthur, 2001)

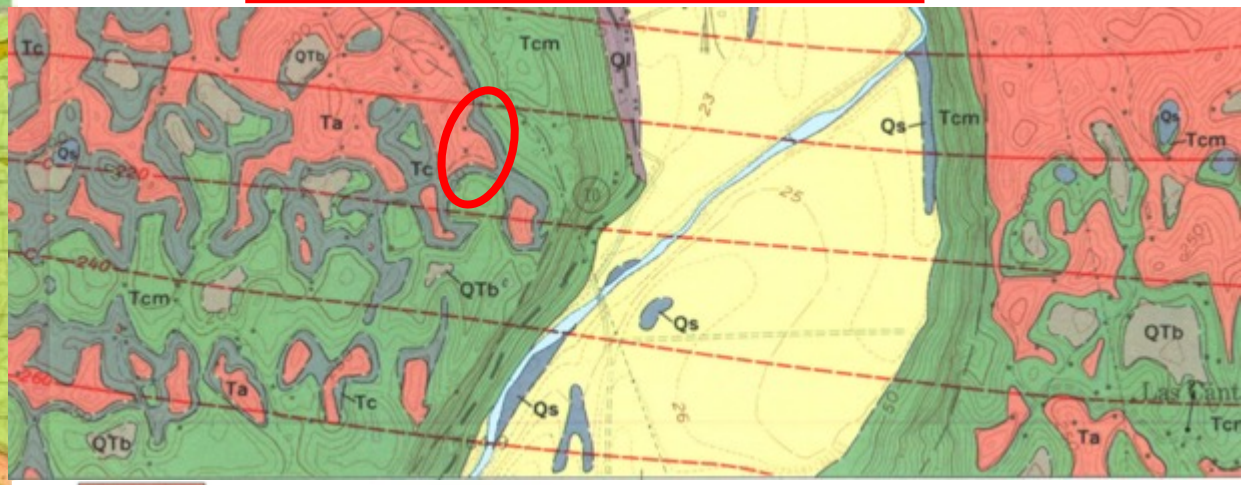
95% confidence limit

Sample ID	Lithologic unit	$^{87}Sr/^{86}Sr$	Age (Mya)
NC 13-526	Aymamón Ls	0.708858 +/- 0.000015	10.91+/-0.34
NC-11 1145-2	Aguada Ls	0.708854 +/- 0.000015	11.06+/-0.37
NC 11-1145-1	Aguada Ls	0.708851 +/- 0.000015	11.18+/-0.46
NC 11-1149-46	Aguada Ls	0.708845 +/- 0.000015	11.45+/-0.54
NC 11-1165-4	Aguada Ls	0.708843 +/- 0.000015	11.59+/-0.51
NC-6 LP 1380-77 -1	Aguada Ls	0.708795 +/- 0.000015	14.60+/-0.89
NC-11 1181-2	Cibao Fm	0.708835 +/- 0.000015	12.07+/-0.53
PR-10 10 3M2	Montebello Mbr	0.708198 +/- 0.000015	24.07+/-0.16
PR-10 2K1-4	Montebello Mbr	0.708128 +/- 0.000015	25.76+/-0.28
PR-10KM67.6 #3	Lares-Montebello	0.708109 +/- 0.000015	26.43+/-0.34
PR-10KM67.6 #2	Lares-Montebello	0.708085 +/- 0.000015	27.24+/-0.29
PR111OL-3	Lares Ls	0.708146 +/- 0.000015	25.23+/-0.26
PR 111-OL-2	Lares Ls	0.708171 +/- 0.000015	24.60+/-0.21
PR111-GPS	Lares Ls	0.708167 +/- 0.000015	24.69+/-0.22
PR-111 T1	Lares Ls	0.708162 +/- 0.000015	24.81+/-0.22
PR-111 M2	Lares Ls	0.708130 +/- 0.000015	25.70+/-0.27
PR-111 M8	Lares Ls	0.708121 +/- 0.000015	25.97+/-0.32



Ortega-Ariza, 2009





Ta

Aguada Limestone

Tc / Tcm

Cibao Formation

Tc, *chalk and marl, light-gray to pale-grayish-orange, commonly thick-bedded and massive; some quartz-bearing beds; some thick lenses of very pale orange to yellowish-gray, very fine grained limestone. Chalk and marl typical of the Cibao Formation in most of northern Puerto Rico (Zapp, Bergquist, and Thomas, 1948; Monroe, 1963) grade and interfinger progressively eastward into the Montebello Limestone Member (Nelson and Monroe, 1966) to a point on the east side of the canyon of the Río Grande de Arecibo where less than 10 m of the typical Cibao remain between the underlying Montebello Member and the overlying Aguada Limestone. From this point eastward all Cibao strata in the Arecibo quadrangle are assigned to the Montebello Limestone Member. Thickness 0–50 m*

Tcm, *Montebello Limestone Member; fine- to very fine grained, white, very pale orange, grayish-orange, and grayish-yellow nearly pure limestone, most commonly thick-bedded or massive, locally highly fossiliferous. Most of the Cibao Formation in test well 4CPR, where it is 305 m thick, is similar to the Montebello Limestone Member, but some marl, clay, and sandstone also are present. In the Barceloneta quadrangle to the east, strata now assigned to the Montebello Member were referred to as limestone of Cibao age (Briggs, 1965).* *Thickness 200–260 m*

Measurement of Montebello Member at PR10 = 305 m thick (Ramírez-Martínez, 2000).

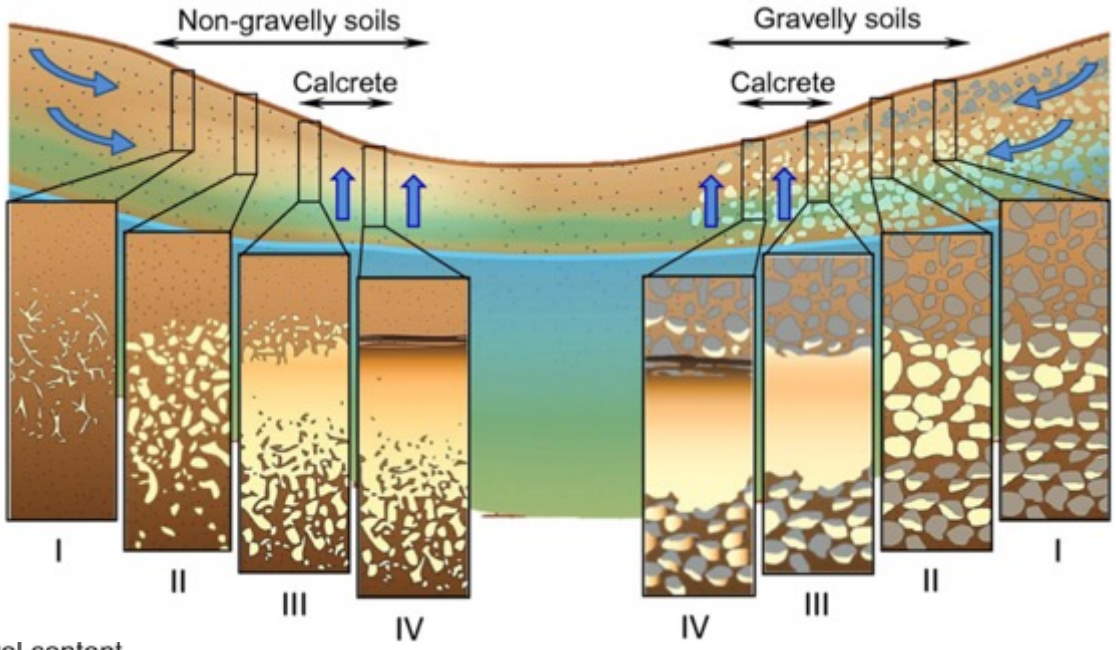
Stop #11

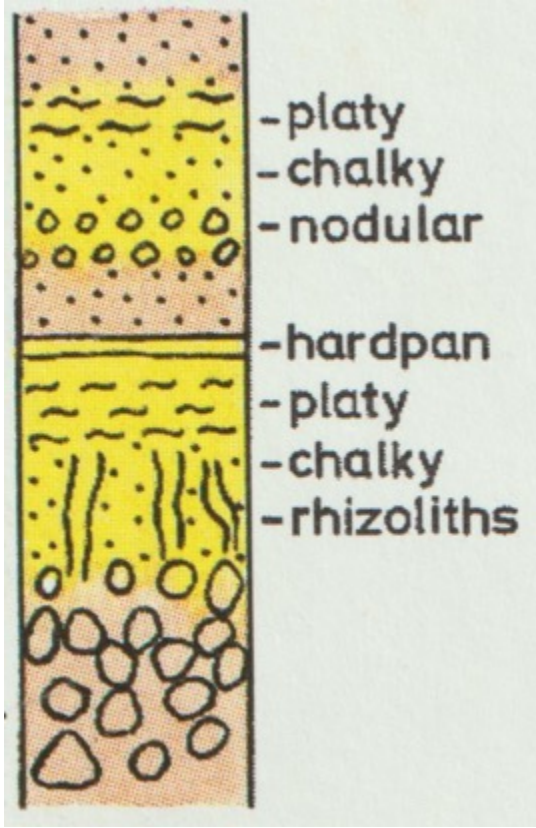
Stratigraphic Top of Montebello Member Exposure at PR10

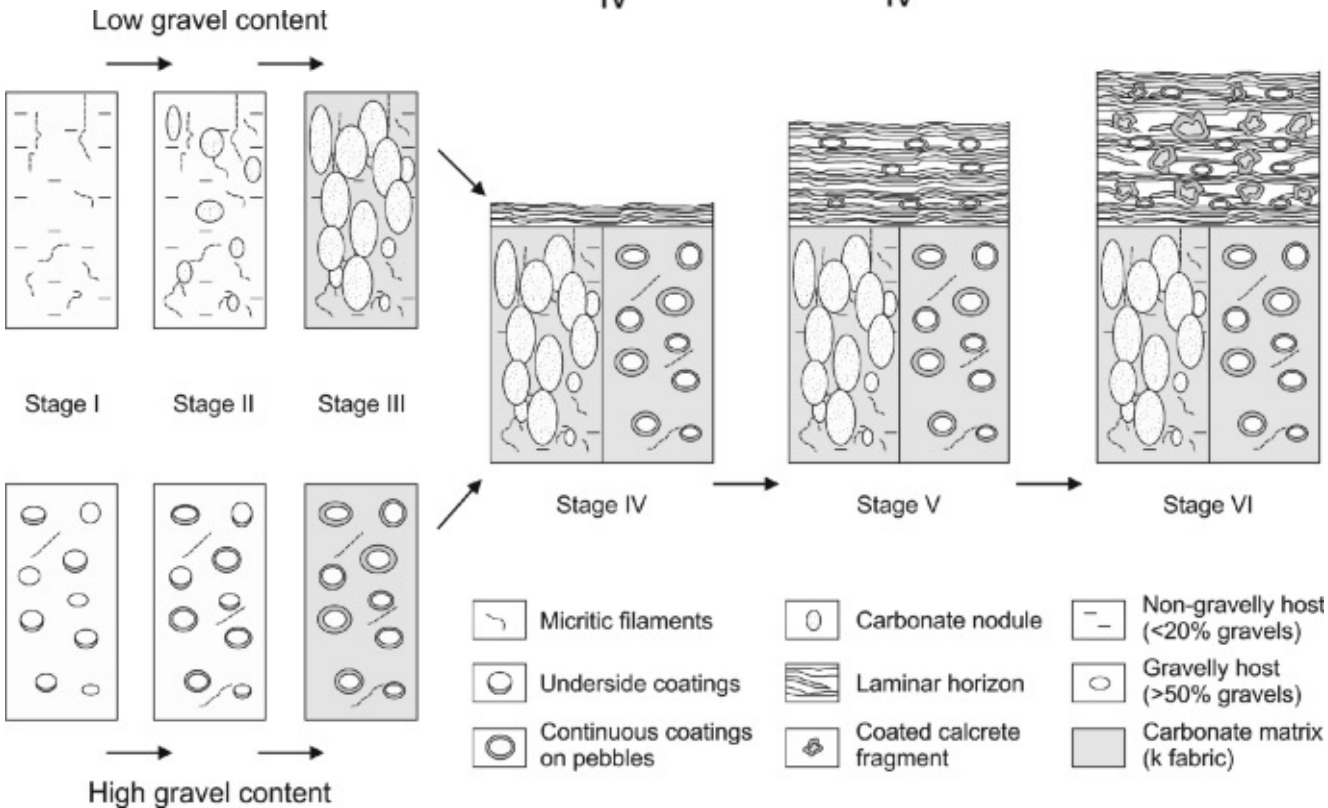
Sequence Boundary evidenced by: paleosoils/roots/paleokarst/freshwater gastropods

- N18º22'52", W66º41'16" - across the highway from the first scenic overlook at PR10 (northward direction)
- **Stratigraphic Unit 1 (base)** - pedogenetic calcrete profile
- **Strat. Unit 2** - carbonaceous clays intercalated with brecciated units, separated by undulatory contacts with pinching out beds. These units reach meter-scale circular cavities at some places and are filled with fine carbonaceous mud and carbonate breccias
  - solution collapse associated with subaerial exposure
- **Strat. Unit 3** - elongate structures that suggest rhizoliths
- **Strat. Unit 4** - bed 0.5 m thick composed of carbonate mud with abundant *Pomacea sp.* and *Physa sp.* gastropods
  - both genera are freshwater taxa with no tolerance for salinity and are very common in freshwater units of Tertiary age throughout the Caribbean
- Strat. Units 1 to 4 – Tip of the Montebello Member (Sequence Boundary)
- Strat. Unit 5 – Undifferentiated Cibao Formation


Stratigraphic Unit 1 (BASE)
Pedogenetic Calcrete Profile







Pedogenetic-Calcrete-Profiles.

Strat. Unit 2 - carbonaceous clays intercalated with brecciated units, separated by undulatory contacts with pinching out beds. These units reach meter-scale circular cavities at some places and are filled with fine carbonaceous mud and carbonate breccias. Solution collapse associated with subaerial exposure present.

Strat. Unit 2 - carbonaceous clays intercalated with brecciated units, separated by undulatory contacts with pinching out beds. These units reach meter-scale circular cavities at some places and are filled with fine carbonaceous mud and carbonate breccias. Solution collapse associated with subaerial exposure present.

Strat. Unit 2 - carbonaceous clays intercalated with brecciated units, separated by undulatory contacts with pinching out beds. These units reach meter-scale circular cavities at some places and are filled with fine carbonaceous mud and carbonate breccias. Solution collapse associated with subaerial exposure present.

Strat. Unit 2 - carbonaceous clays intercalated with brecciated units, separated by undulatory contacts with pinching out beds. These units reach meter-scale circular cavities at some places and are filled with fine carbonaceous mud and carbonate breccias. Solution collapse associated with subaerial exposure present.

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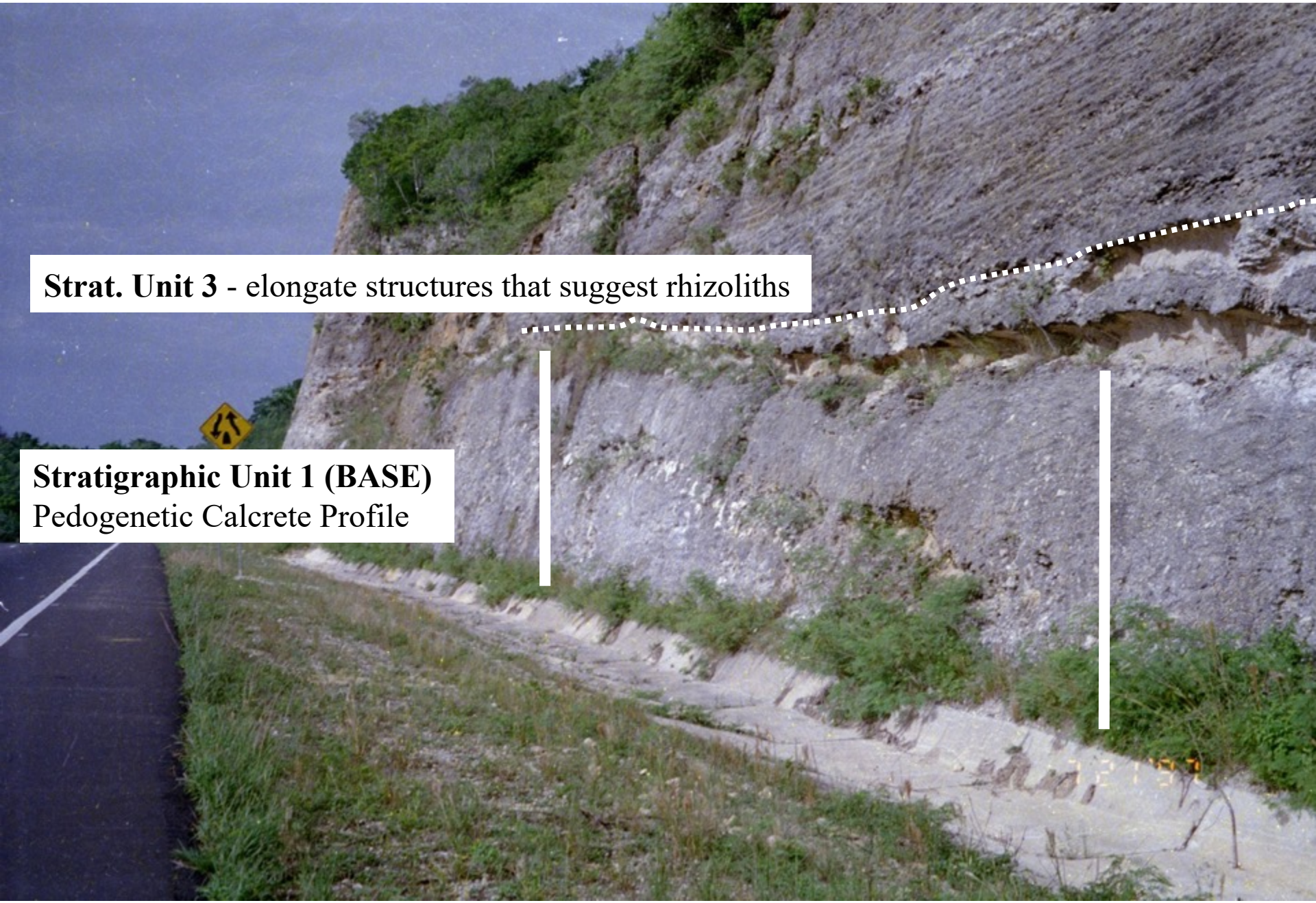
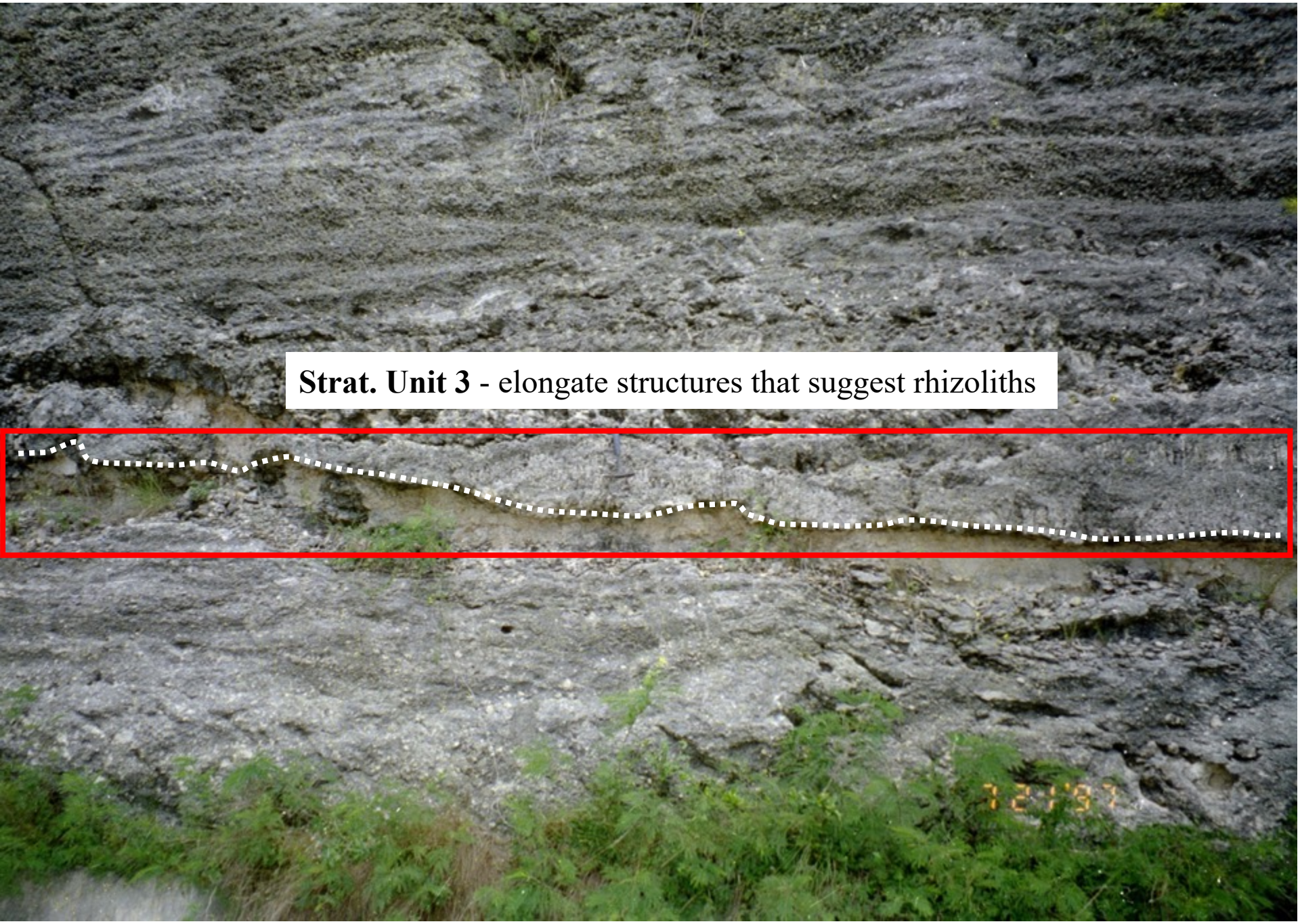
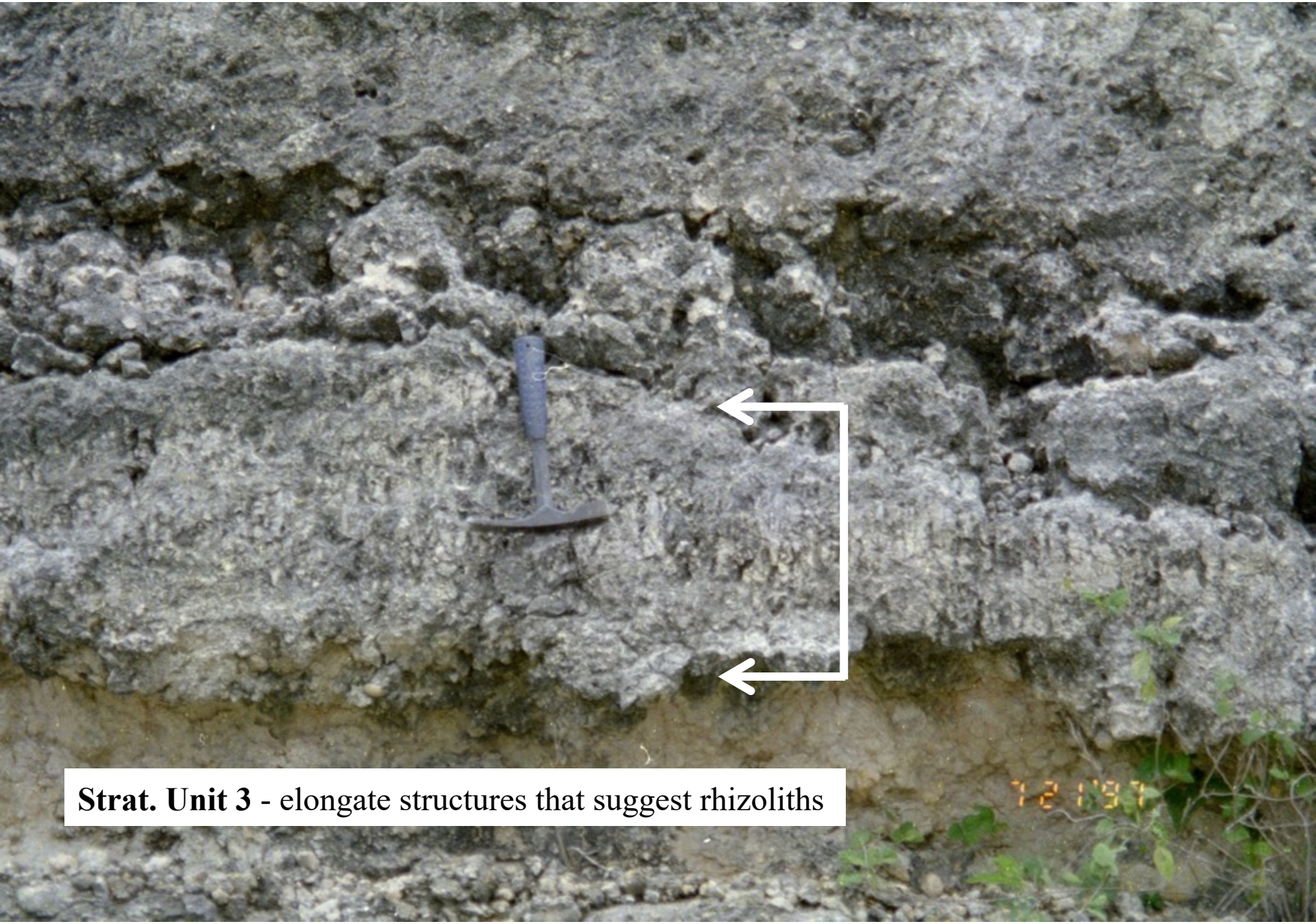
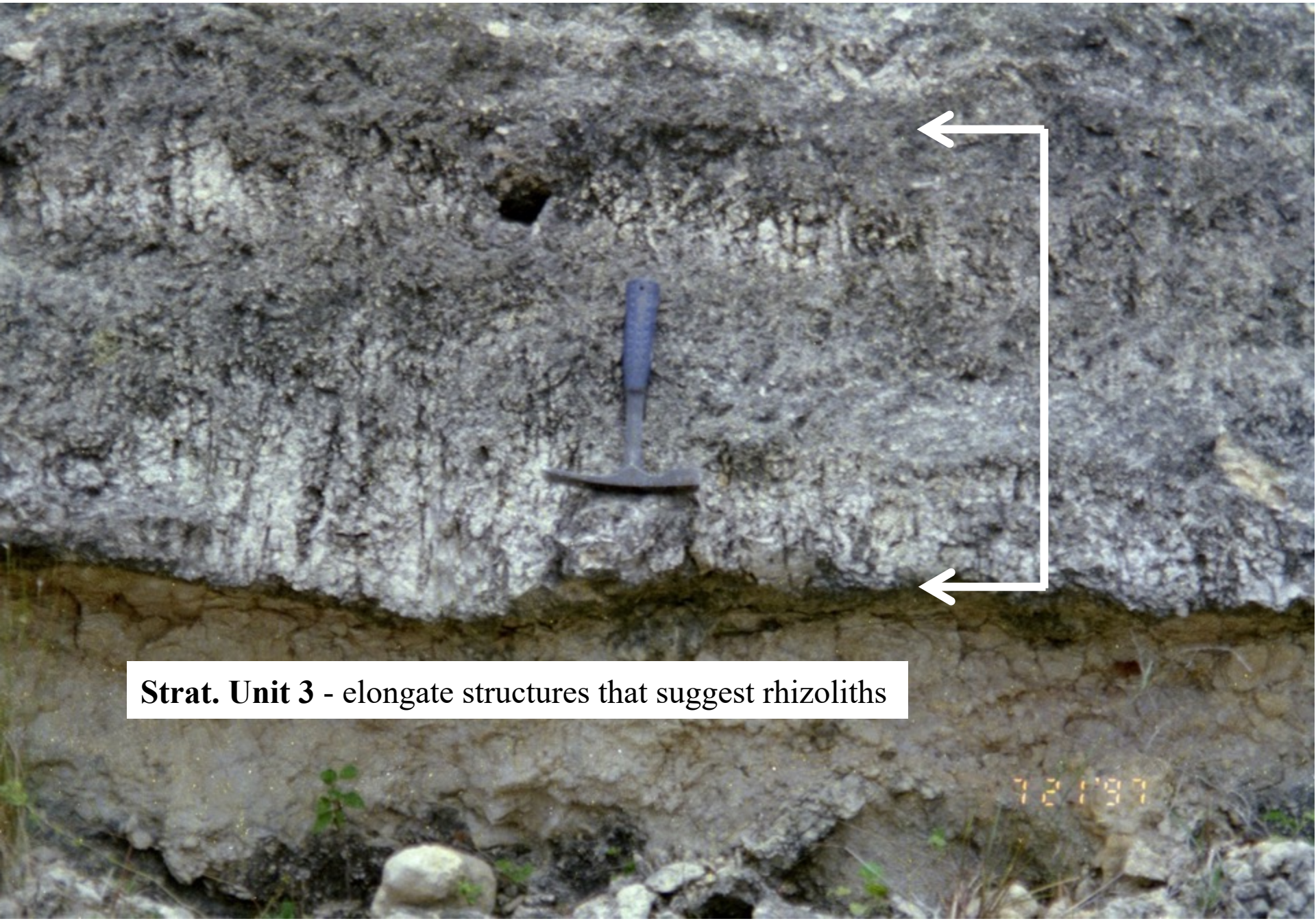
Strat. Unit 2 - carbonaceous clays intercalated with brecciated units, separated by undulatory contacts with pinching out beds. These units reach meter-scale circular cavities at some places and are filled with fine carbonaceous mud and carbonate breccias. Solution collapse associated with subaerial exposure present.


Strat. Unit 3 - elongate structures that suggest rhizoliths
Stratigraphic Unit 1 (BASE)
Pedogenetic Calcrete Profile


Strat. Unit 3 - elongate structures that suggest rhizoliths

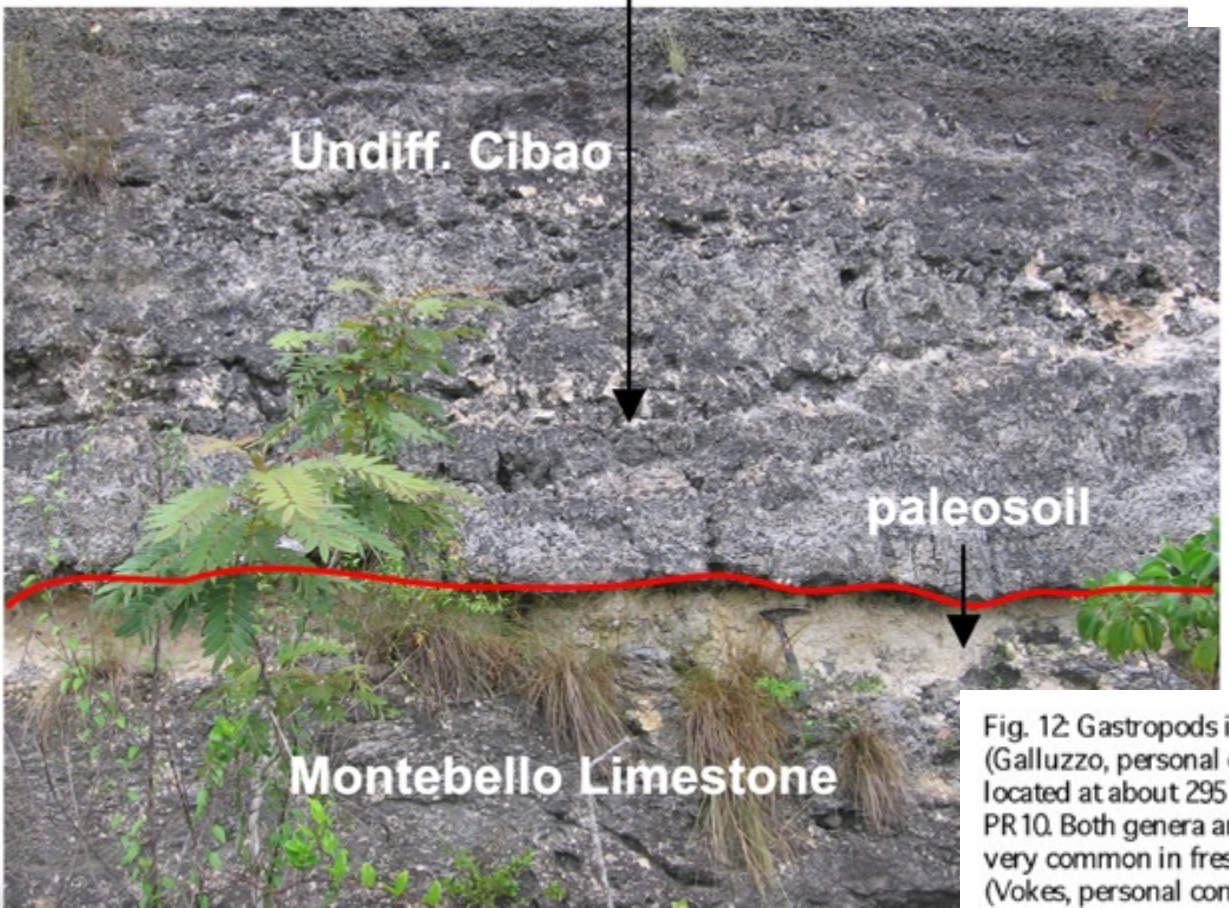


Strat. Unit 3 - elongate structures that suggest rhizoliths

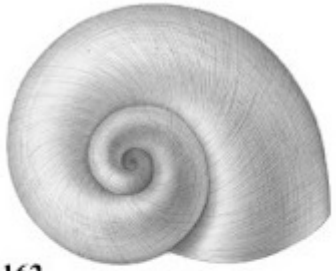


Strat. Unit 3 - elongate structures that suggest rhizoliths

Strat. Unit 4 - bed 0.5 m thick composed of carbonate mud with abundant *Pomacea sp.* and *Physa sp.* Gastropods. Both genera are freshwater taxa with no tolerance for salinity and are very common in freshwater units of Tertiary age throughout the Caribbean.

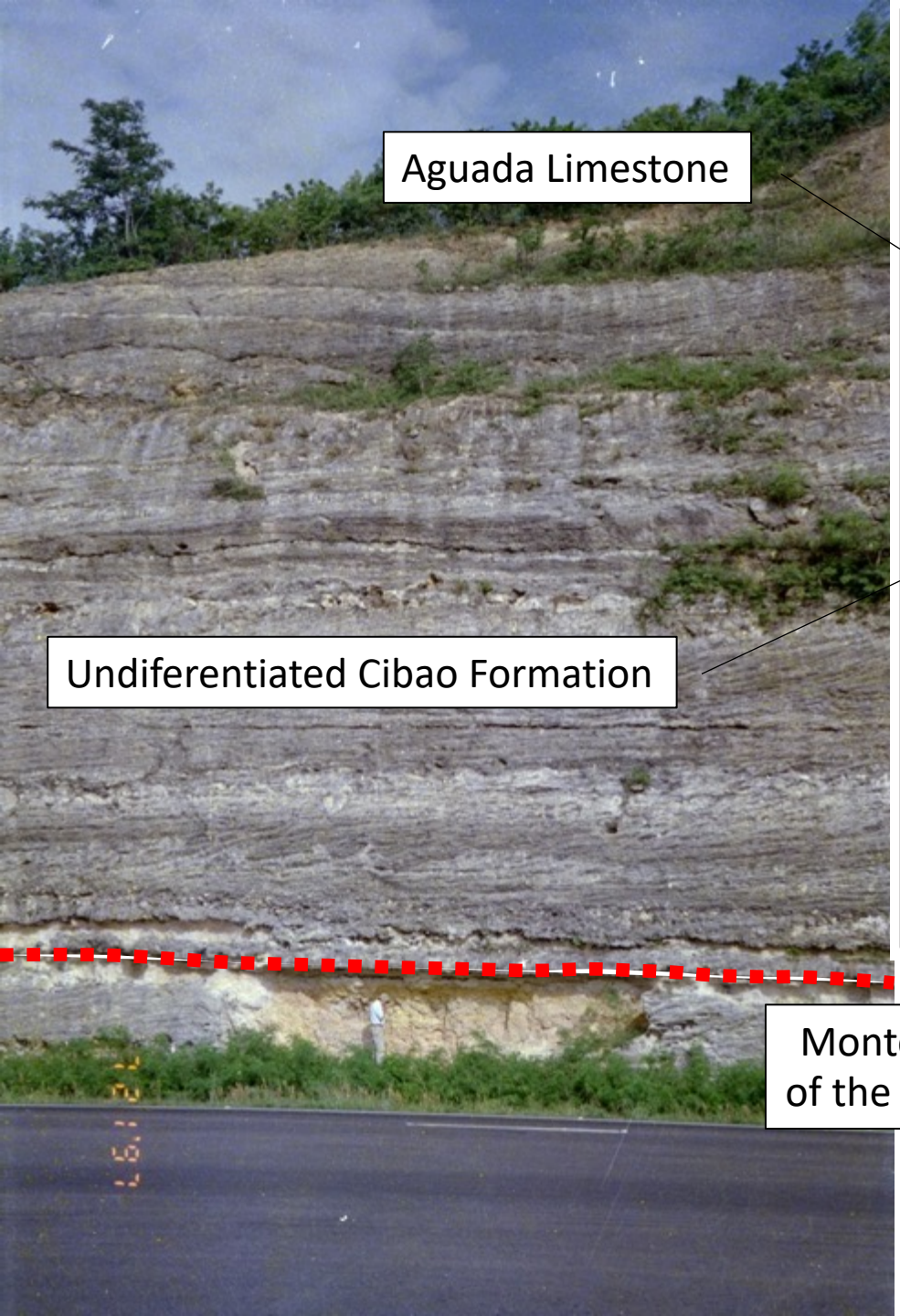


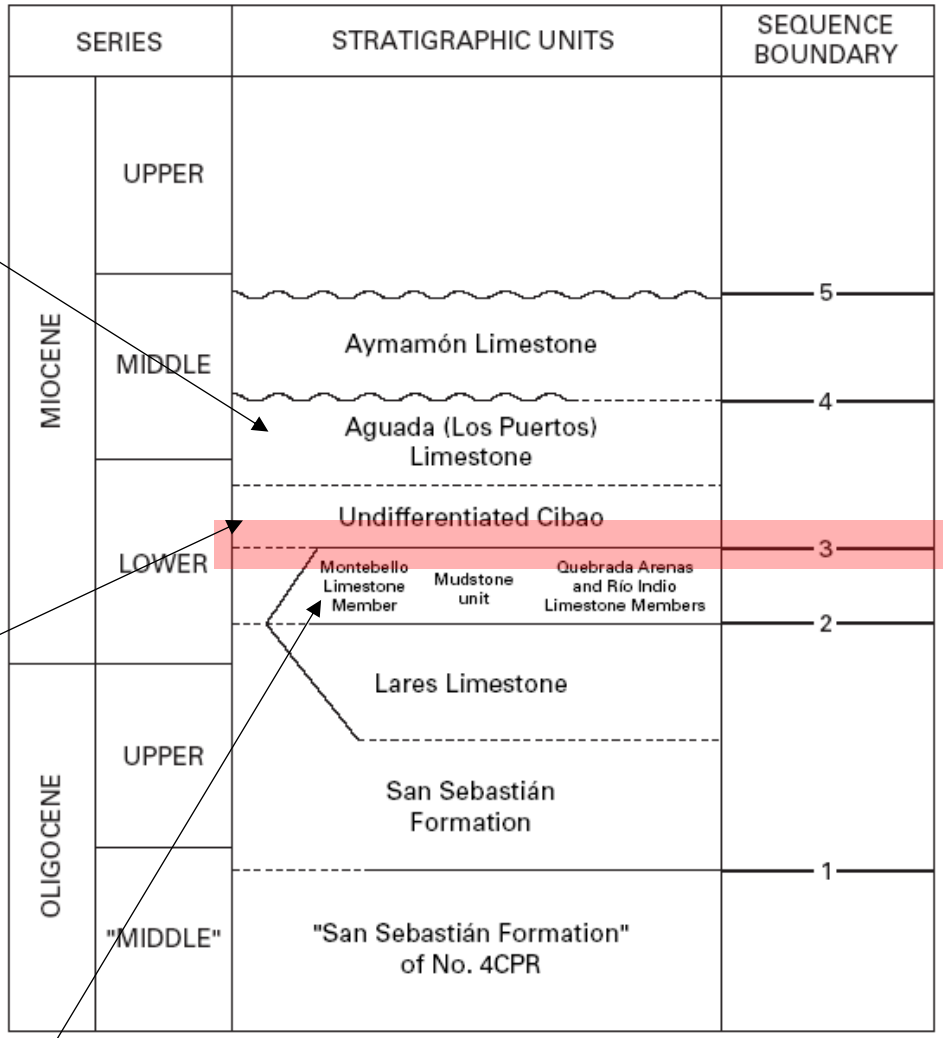
Physa sp.



Pomacea sp.

Fig. 12: Gastropods identified as belonging to the genera Pomacea and Physa (Galluzzo, personal communication, 1998) present above an erosional surface located at about 295 meters from the base of Montebello Member section on PR10. Both genera are freshwater taxa with no tolerance for salinity and are very common in freshwater units of Tertiary age throughout the Caribbean (Vokes, personal communication, 1998).


Aguada Limestone
Undiferentiated Cibao Formation
Montebello Member
of the Cibao Formation


SERIES
STRATIGRAPHIC UNITS
SEQUENCE BOUNDARY
MIOCENE
OLIGOCENE
UPPER
MIDDLE
LOWER
UPPER
"MIDDLE"
Aymamón Limestone
Aguada (Los Puertos) Limestone
Undifferentiated Cibao
Montebello Limestone Member
Mudstone unit
Quebrada Arenas and Río Indio Limestone Members
Lares Limestone
San Sebastián Formation
"San Sebastián Formation" of No. 4CPR
5
4
3
2
1

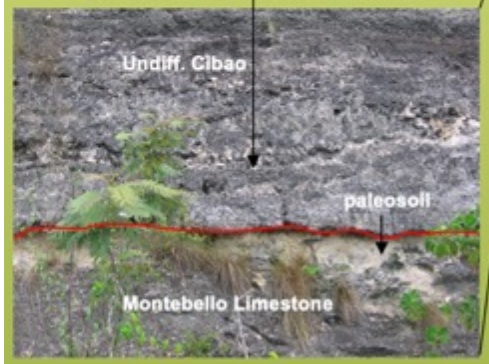
Sequence Stratigraphy

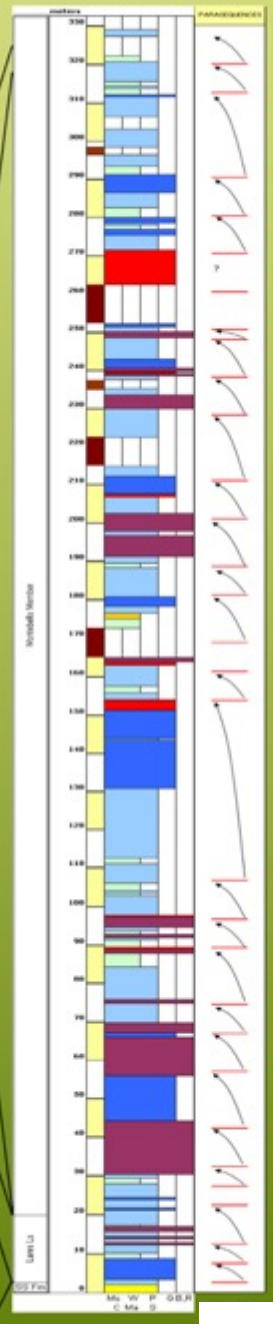
Ortega-Ariza, 2009

Legend

- mudstone
- wackestone
- wackestone to packstone
- packstone
- packstone to grainstone
- grainstone
- rudstone
- boundstone
- marls
- clay/ shale
- sand

Ms - mudstone
W - wackestone
P - packstone
G - grainstone
B,R - boundstone & rudstone
Ma - marls
C - clay
S - sand
lignite, black intraclasts





SERIES		STRATIGRAPHIC UNITS	SEQUENCE BOUNDARY
MIOCENE	UPPER		
	MIDDLE	Aymamón Limestone	5
		Aguada (Los Puertos) Limestone	4
	LOWER	Undifferentiated Cibao	
		Montebello Limestone Member / Mudstone unit / Quebrada Arenas and Rio Indio Limestone Members	3
			2
OLIGOCENE	UPPER	Lares Limestone	1
		San Sebastián Formation	
	"MIDDLE"	"San Sebastián Formation" of No. 4CPR	


The End