VOLUME AND DENSITY APPROXIMATIONS OF MATERIAL INVOLVED IN A DEBRIS AVALANCHE ON THE SOUTH SLOPE OF THE PUERTO RICO TRENCH

A Report to the Puerto Rico Civil Defense
and the University of Puerto Rico Sea Grant College Program

by

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Project Summary

Analysis of recently collected bathymetric, sidescan sonar and single-channel seismic reflection data, together with onshore well and outcrop data are used to estimate the volume and density of material involved in a debris avalanche that generated the 57 km wide amphitheater-shaped scarp centered at approximately 66¡40ÕW on the northern insular slope of Puerto Rico. It is believed that the Oligocene-Pliocene megasequence of carbonates (PR1) was the major unit involved in the debris avalanche. Studies indicate that this unit, which extends across the entire north coast of Puerto Rico, has a relatively uniform thickness and ranges from 1500-1300 km in the vicinity of the landslide headwall scarp. Measurements of surface area assuming a pre-failure morphology of a straight, slope-parallel shelf break rather than the observed scalloped morphology, estimate that ~700 km2 of material was involved in the failure. On the basis of onshore well logs the density of this unit is estimated to be approximately 2.2 g/cm3. Assuming that the failure was catastrophic, volume estimates of material involved in the landslide range from 910 km3 to 1050 km3.

Project Description

A recent marine geophysical expedition (Grindlay et al., 1997) of the Puerto Rico trench and northern insular margin of Puerto Rico and the Virgins Islands was conducted to investigate the seismogenic potential of the region. The Puerto Rico trench represents a tectonically active plate boundary zone, where the north American plate is being subducted obliquely beneath the Caribbean plate. Grindlay et al., (1997) identified several active fault zones within the trench, including one on the south slope of the trench which lies within 60-100 km of the north coast of Puerto Rico. In addition, Grindlay et al., (1997) corroborated the existence of a major submarine slide first reported by Scanlon et al., (1988) and Schwab et al., (1991) on the south slope of the Puerto Rico trench, located about 37 km north of the city of Arecibo on the island of Puerto Rico (Figure 1). Although rarely documented directly, earthquakes are often inferred to be the triggering mechanisms of submarine slides (Hampton and Lee, 1996) and that under certain circumstances submarine slides can be accompanied by large and destructive tsunamis (Moore and Moore, 1984; von Huene et al., 1989; Jiang and Le Blond, 1992; Hampton and Lee, 1996). The presence of active fault zones in the Puerto Rico trench implies that there is a potential threat of repeat submarine slides and accompanying tsunamis.

In this study, geophysical data collected during the June-July 1996 cruise on board the R/V Maurice Ewing (Chief Scientist Grindlay, Co-Chiefs Paul Mann and James Dolan) and existing onshore well and outcrop data are used to provide estimates of the volume and density of material involved in the debris avalanche that formed the large amphitheater-shaped scarp. These data include sidescan sonar imagery (HMR1-system) which provides information about the reflectivity

and nature of seafloor material and structures. High-resolution multibeam sonar bathymetric data (Krupps-Atlas Hydrosweep system) provide vertical depth resolutions on the order of 10-15m and swath widths up to 2.5 the water depth. Accurate bathymetric maps are used to estimate the surface area of the material involved in the slide. Single-channel seismic (SCS) profiles provide information about the subsurface structures, including location of headwall scarps and extent and thickness of units that pre- and post-date the slide. Onshore well data from CPR-4 (Briggs, 1961) and Toa Baja wells (Anderson, 1991) are used to make lithologic and age correlations of seismic reflection data and determine physical properties of these units. The volume and density estimates of the material involved in the submarine landslide provided in this report will be used in numerical models to estimate potential tsunami propagation and runup.

Results

Classification and morphologic description of submarine landslide

On the basis of the geophysical data the landslide that generated the amphitheater-shaped scarp on the south slope of Puerto Rico trench was most likely a debris avalanche. Varnes (1978) define a debris avalanche as a landslide that involves the failure of hundreds to thousands of cubic kilometers of rock and sediment that have disintegrated into relatively smaller pieces (compared to the large slump blocks but can include blocks of many cubic kilometers) and have clearly moved rapidly. Each debris avalanche is thought to represent a single episode of catastrophic slope failure. The bathymetric and sidescan imagery clearly show a giant amphitheater-shaped scarp that is approximately 57 km across (Figures 2 A, B, and 3). The crown of the headwall scarp lies at depths of 2500 m to 3500 m. The debris deposit shown as dark, highly reflective material in the sidescan imagery extends more than 25 km down the slope to depths of approximately 7000 m (Figures 2A &B). The seismic profile 20 shows a thin layer characterized by chaotic returns and a hummocky surface that is the uppermost unit on the amphitheater-shaped scarp (Figure 4).

Description of the stratigraphic units on the south slope of the PR trench

Seismic profiles that extend across the northern insular margin of Puerto Rico show that the offshore stratigraphy of the platform can be divided into three megasequences (Meyerhoff et al., 1983; van Gestel et al., in review)(Figure 4, SCS profile 20). On the basis of well data from CPR-4 and Toa Baja wells these sequences can be correlated with lithologic units of defined ages (Figure 5) (Meyerhoff et al., 1983; van Gestel et al., in review). The lowest unit, PR1 consists of island arc basement rocks which based on subaerial exposures and samples dredged offshore (Fox and Heezen, 1975; Perfit et al. 1980) are of Cretaceous to Eocene age. The middle unit, PR2, does not correlate to any major formation or group of formations on Puerto Rico (Meyerhoff et al., 1983) but is speculated to be of Eocene age and formed as a basinal fill in a deep marine setting. Meyerhoff et al., (1983) and van Gestel et al., (in review) note that this unit is offset by large normal faults that extend upward into the overlying unit. It is possible that reactivation of these faults due to recent tectonic activity has resulted in their growth into the overlying unit PR3. The uppermost unit, PR3, consists of Oligocene-Pliocence shallow marine limestones deposited during a tectonically

quiescence period (Moussa et al, 1987; Meyerhoff et al., 1983, Reflectors within PR3 can be subdivided in five individual sequences that are conformable with reflectors in the underlying PR2 (van Gestal et al., in review) (Figure 5). Overall, unit PR3 is characterized by continuous parallel reflectors, constant thickness and constant dip that persists through the offshore units. During the past 2.5 m.y. the submarine part of PR3 has subsided more than 4000 m generating a 4.5¡ regional slope (Birch, 1986).

At the base of south slope SCS profile 20 shows thick onlapping deposits of stratified material characteristic of turbidites. Core and dredge samples show the top portion of this unit to consist of turbidites (Conolly and Ewing, 1967; Fox and Hezzen 1975, Perfit et al. 1980). The source of these deposits is unknown, although it is likely that some portion consists of sediments transported across the shelf and down the scarp face through the submarine canyons. These deposits have been offset vertically and most likely laterally by the South Puerto Rico slope fault. In addition a small, lower headwall scarp is observed cutting these deposits at 7500m.

Estimates of volume and density of material involved in the landslide

SCS Profile 20 suggests that only unit PR3 was involved in the submarine landslide, as it is the only unit to be truncated abruptly at the upper headwall scarp (Figure 5). Unit PR2 appears to vary little in thickness, although the seismic data do not provide enough penetration to clearly delineate the interface between units PR2 and PR1. On the basis of systematically collected SCS profiles over the platform, van Gestel et al., in press, estimate that the thickness of unit PR3 ranges from 1500 km to 1300 km (assuming a velocity of 2.75 km/s) at the upper headwall scarp. Given the surface area of failure calculated to be ~ 700 km2 (Figure 6) a volume of ~ 910-1050 km3 material is estimated to be involved in the landslide. Geophysical logs from the Toa Baja well (Anderson, 1991) indicate that unit PR3 has a density of 2.2 g/cm3.

Figures

Figure 1. Shaded relief of regional bathymetry (1 min grid interval). Contour interval is 500m. Box indicates location of study area. The location of CPR-4 and Toa Baja wells on the north coast of Puerto Rico are indicated by filled white circles.

Figure 2A. Side scan sonar imagery (HMR1) of amphitheater-shaped scarp cut into the northern Puerto Rico insular margin and debris deposit downslope. Highly reflective areas such as fault scarps, bare rock surfaces, appear as dark gray to black; areas with limited backscatter such as heavily sedimented surfaces and shadowed areas appear as light gray. Also identified: a possible lower headwall scarp at the base of the slope, the South Puerto Rico Slope Fault Zone and submarine canyons cut into the Oligocene-Miocene carbonate platform. The north coast of Puerto Rico is shown in black, areas of no data are in white. Location of seismic profile shown in Figure 5 is marked by dashed white line.

Figure 2B. Bathymetric map (250m grid-interval) of the study area at the same scale as the side scan sonar imagery. Contour interval is 100 m. The crown of the amphitheater-shaped scarp ranges from 2500-3500m. The base of the upper scarp lies at approximately 7000m water depth. Location of the seismic profile 20 shown in Figure 4 is indicated by the dashed white line. The north coast of Puerto Rico is shown in black; areas of no data are in white.

Figure 3. A three-dimensional perspective view of the amphitheater-shaped scarp. View from the northeast. Modified from Grindlay et al., in prep.

Figure 4. Interpretation of main seismic megasequences of the northern margin of Puerto Rico from EW96-05 SCS line 20. This line is considered representative of several lines which extend across the margin. This figure shows the head-wall scarp of the amphitheater-shape scarp, debris deposits associated with scarp, the location of South Puerto Rico Slope Fault Zone, recent turbidite deposits within the trench and the lower-head wall scarp and associated debris deposit at the base of the slope.

Figure 5. CPR-4 and Toa Baja well logs from Briggs (1961) and (Anderson, 1991) and correlation of seismic sequences PR1 and PR3 identified in SCS profile 20 (Figure 5). Eustatic sea level curve of Haq et al., (1987) also shown. After van Gestel et al., in review.

Figure 6. Shaded surface area ~700 km2 of estimated material involved in submarine slide assuming a slope-parallel shelf break rather than the observed scalloped morphology. Contour interval is 100 m.

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Figure 1

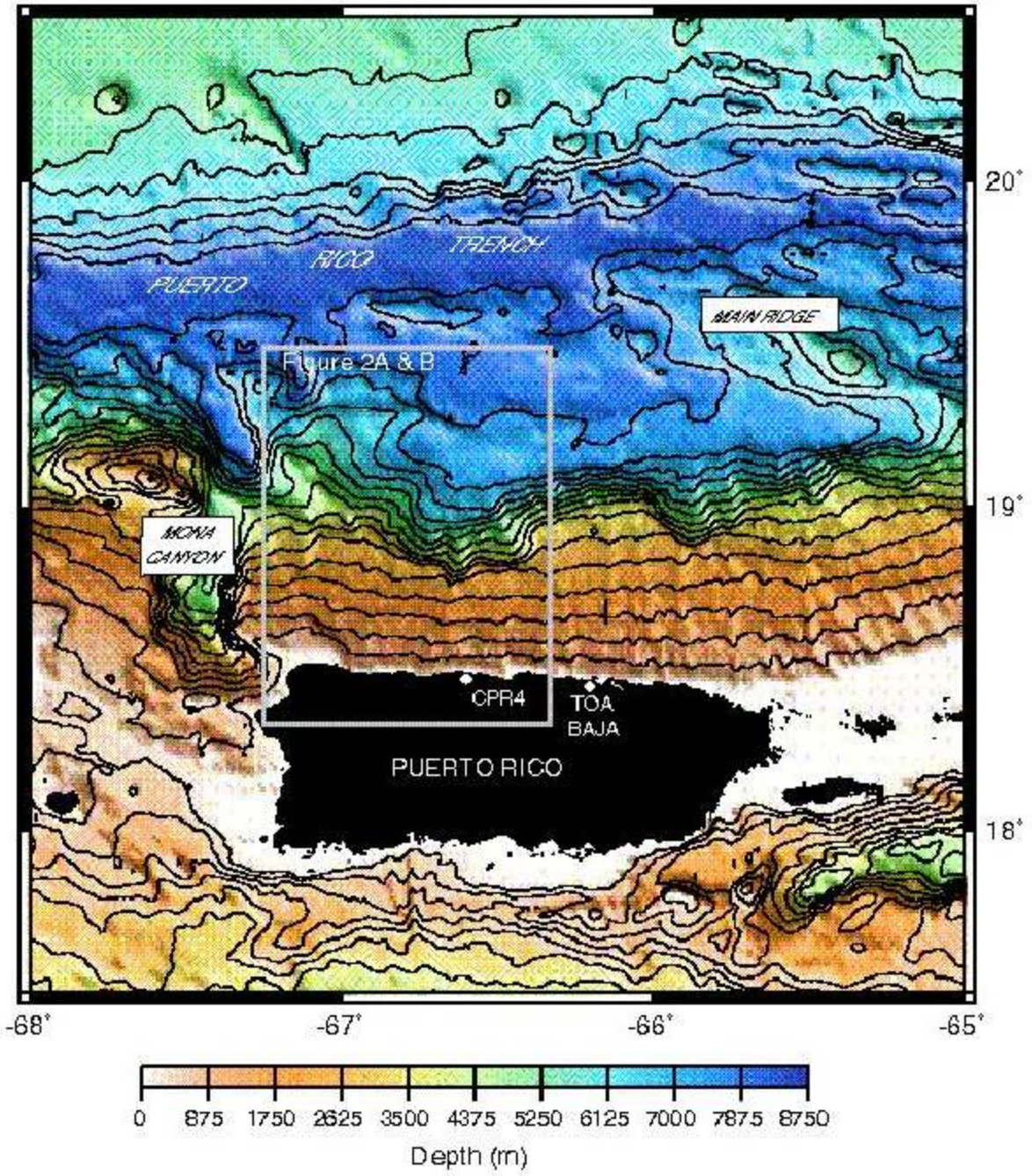
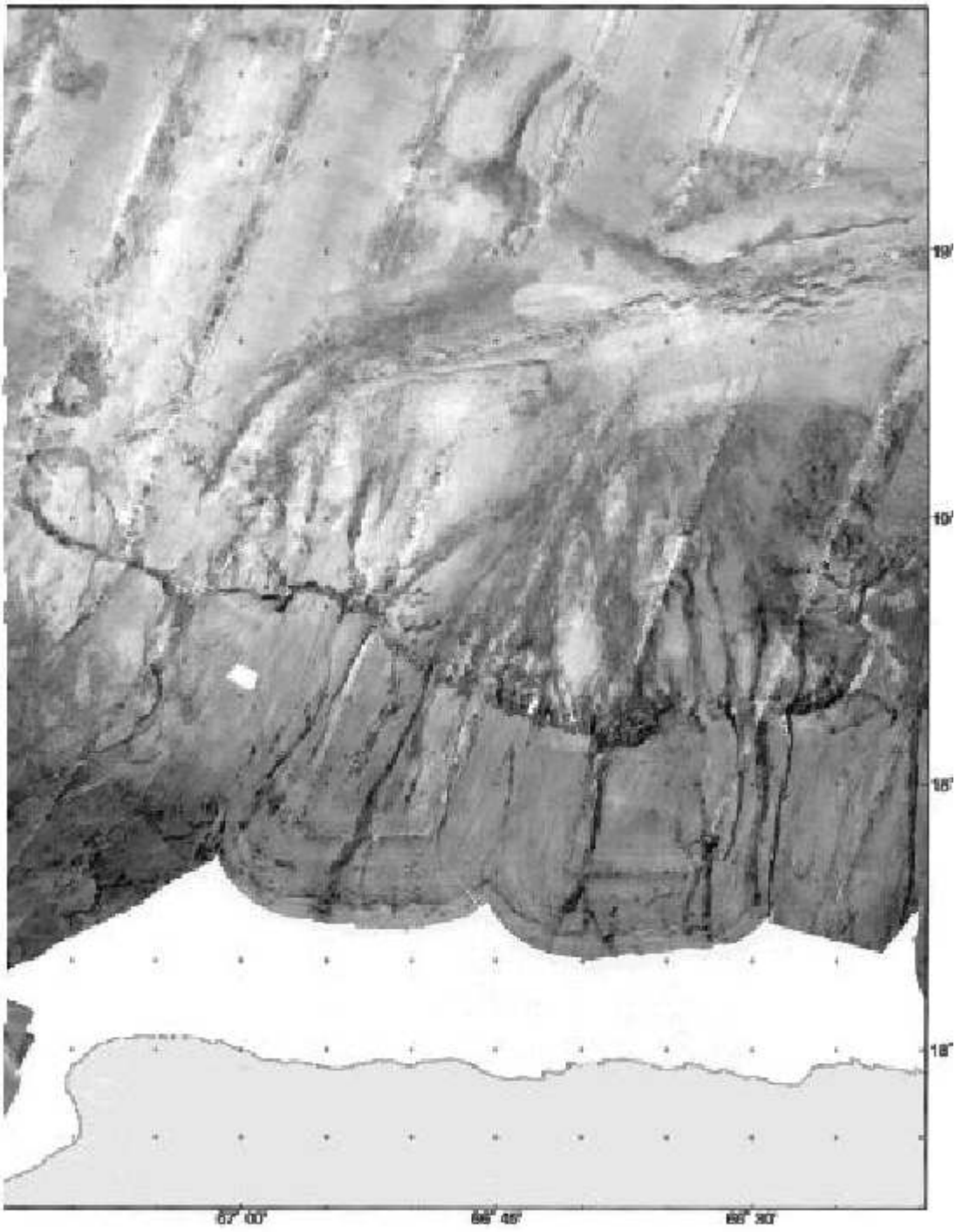
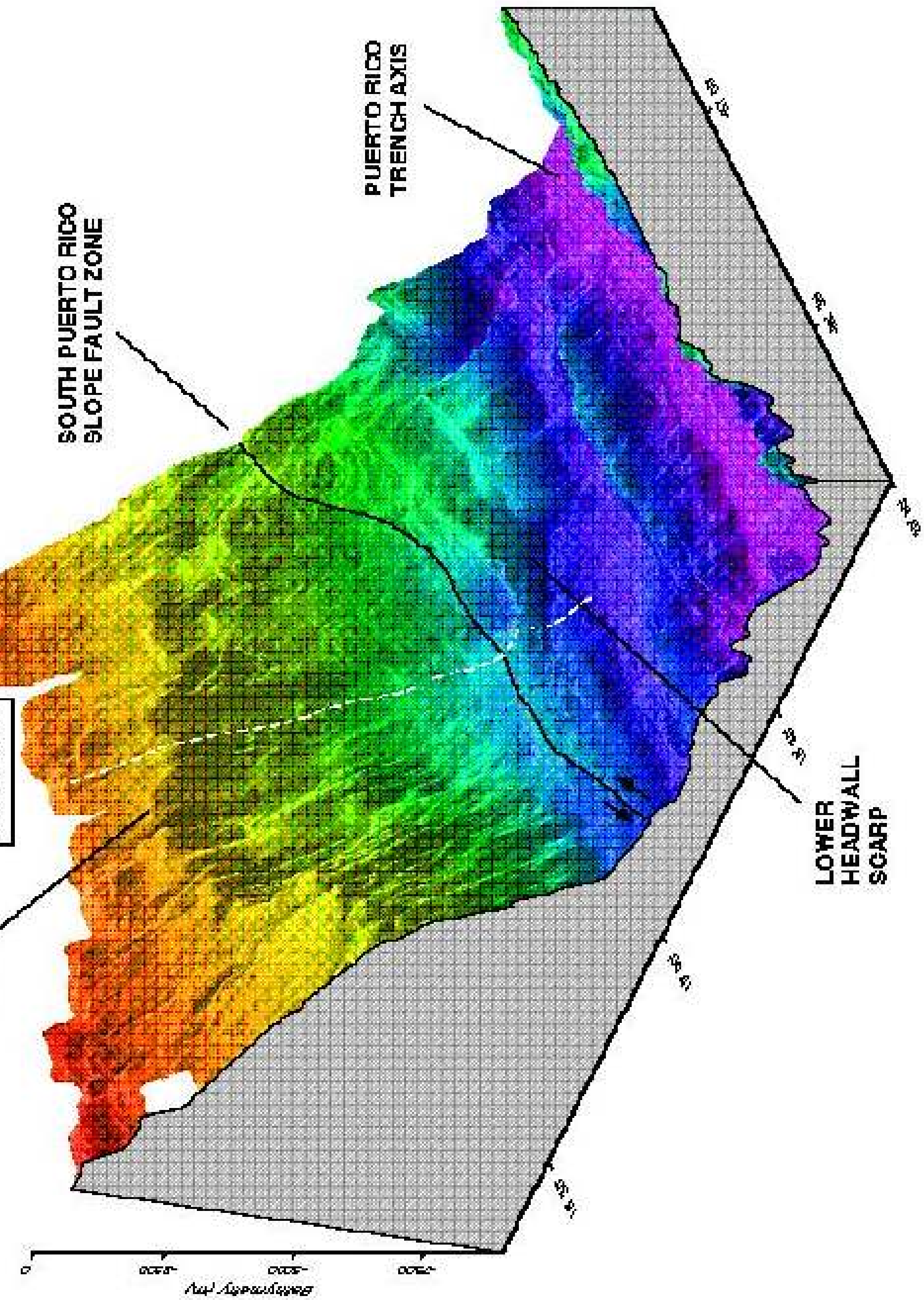
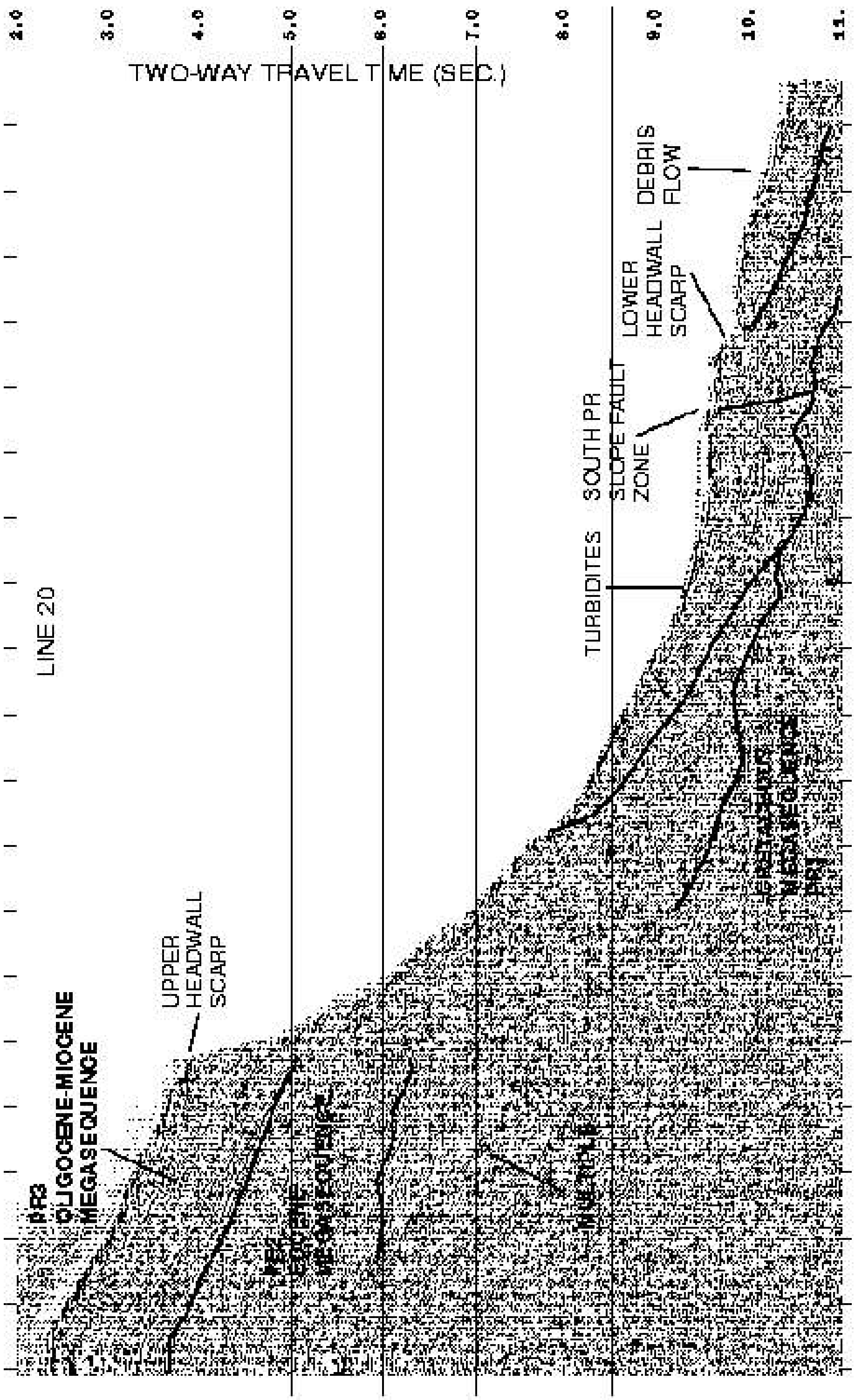

PUERTO RICO TRENCH
MAIN RIDGE
Figure 2A & B
MONA CANYON
CPR4
TOA BAJA
PUERTO RICO
20°
19°
18°
-68°
-67°
-66°
-65°
0 875 1750 2625 3500 4375 5250 6125 7000 7875 8750
Depth (m)

Figure 2




UPPER HEADWALL SCARP
PROFILE 20
SOUTH PUERTO RICO SLOPE FAULT ZONE
PUERTO RICO TRENCH AXIS
LOWER HEADWALL SCARP


2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.
11.
TWO-WAY TRAVEL TIME (SEC.)
LINE 20
PR3
OLIGOCENE-MIOCENE
MEGASEQUENCE
UPPER
HEADWALL
SCARP
TURBIDITES
SOUTH PR
SLOPE FAULT
ZONE
LOWER
HEADWALL
SCARP
DEBRIS
FLOW

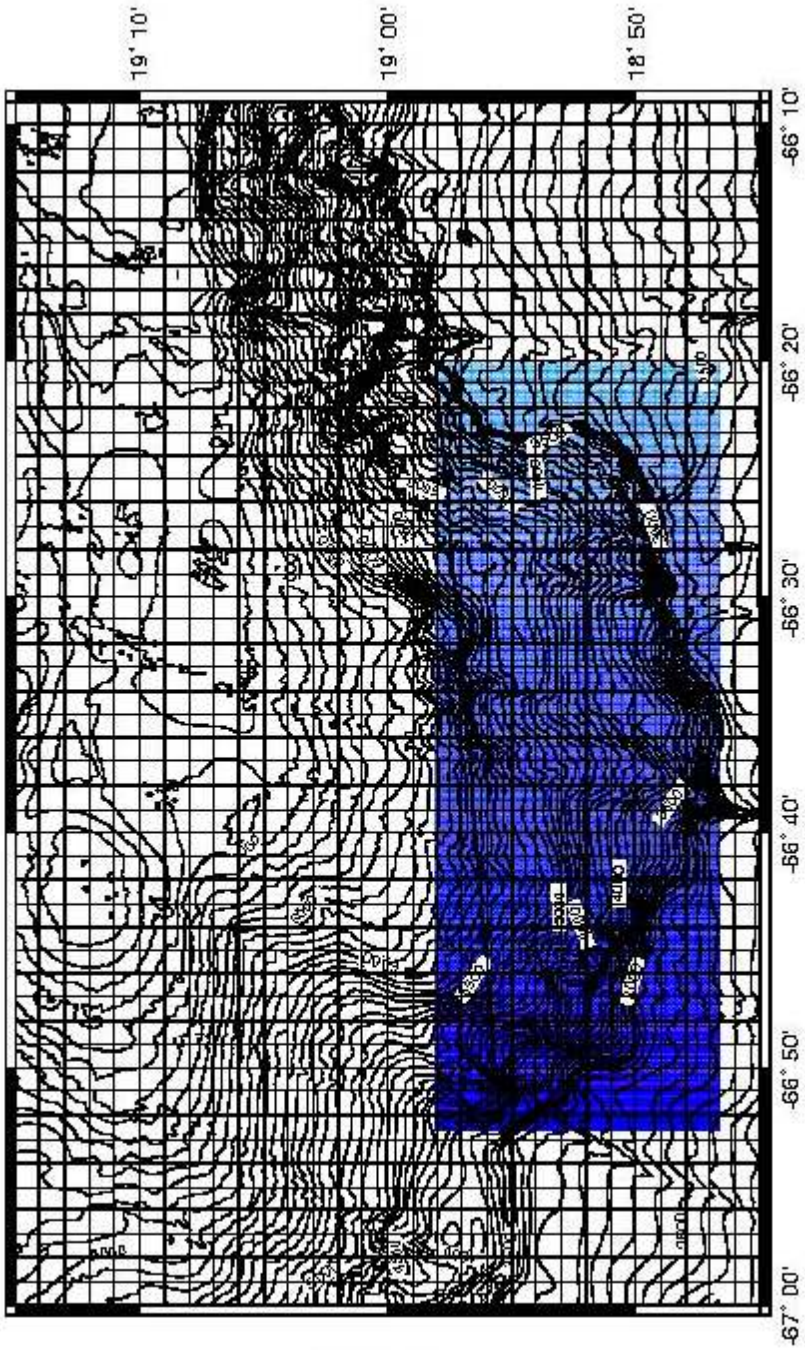
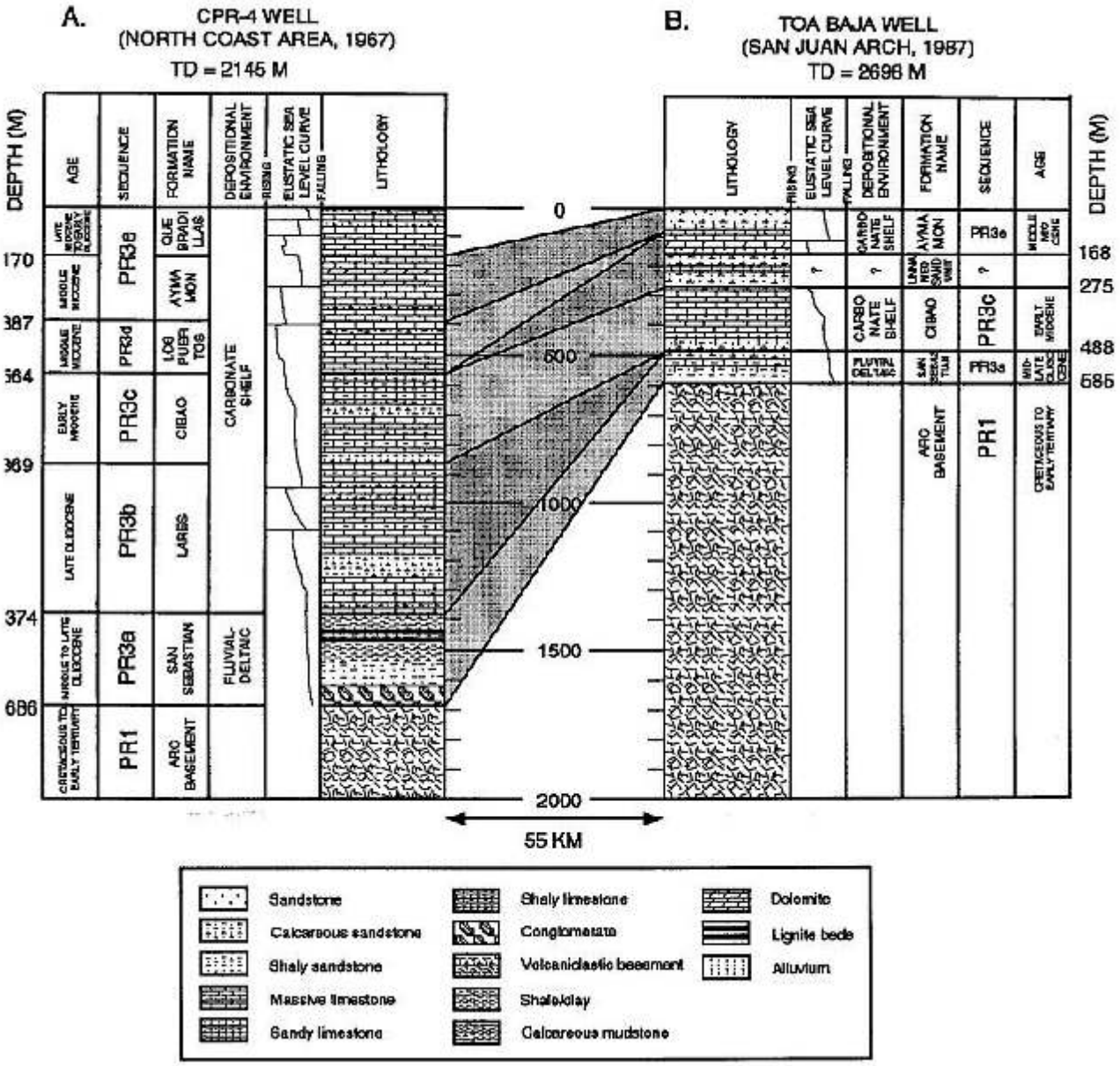


FIGURE 6


A.
CPR-4 WELL
(NORTH COAST AREA, 1967)
TD = 2145 M
B.
TOA BAJA WELL
(SAN JUAN ARCH, 1987)
TD = 2696 M
DEPTH (M)
AGE
SEQUENCE
FORMATION NAME
DEPOSITIONAL ENVIRONMENT
EUSTATIC SEA LEVEL CURVE
RISING
FALLING
LITHOLOGY
PR3e
PR3d
PR3c
PR3b
PR3a
PR1
QUEBRADILLAS
AYMAMON
LOS PUERTOS
CIBAO
LARES
SAN SEBASTIAN
ARC BASEMENT
CARBONATE SHELF
FLUVIAL-DELTAIC
170
387
564
969
374
686
0
500
1000
1500
2000
55 KM
168
275
488
585
Sandstone
Calcareous sandstone
Shaly sandstone
Massive limestone
Sandy limestone
Shaly limestone
Conglomerate
Volcaniclastic basement
Shale/clay
Calcareous mudstone
Dolomite
Lignite beds
Alluvium