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PLATE TECTONICS OF THE NORTHEASTERN CARIBBEAN SEA REGION

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ABSTRACT

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Previous geologic literature and the results of the Puerto Rico Seismic Network are synthesized into a plate tectonic model of the northeastern Caribbean Sea region. The Puerto Rico Seismic Network has detected earthquakes which form a well defined zone of seismicity dipping 45 to 50 degrees from the Puerto Rico Trench to a depth of about 150 km under Puerto Rico. This inclined zone of seismicity is interpreted to represent a lithospheric plate. However, focal mechanism solutions have shown that plate motion along the Puerto Rico Trench is directed in an east-to-west sense similar to that expected in a transform fault zone. A plate tectonic model is developed which shows that a portion of the North American plate, originally subducted under the northern Lesser Antilles, underrides the northern edge of the Caribbean plate. When this underriding plate reaches the Hispaniola subduction zone it sinks deeper taking on a plow-shaped configuration.

The Puerto Rico type of 'transform' trench is not unique to the Caribbean, but also occurs in the western Aleutian Trench, Puysegur Trench, northern Sunda Trench, and possibly the Scotia Sea region.

INTRODUCTION

The northeastern Caribbean plate boundary in the Puerto Rico-Virgin Island region has been an enigma with respect to the plate tectonic framework of the Caribbean and even to plate tectonic theory itself. On one hand, the Puerto Rico Trench is a well-developed oceanic trench and plate tectonic theory postulates that such trenches are areas of lithospheric consumption. The presence of large gravity anomalies and intermediate-depth earthquakes in the trench region supports the argument for a subduction zone. On the other hand, alternate lines of evidence commonly used to establish plate tectonic models, notably volcanic activity and earthquake-focal-mechanism solutions, indicate that this area is not a subduction zone.

Although the general nature of plate-tectonic interactions in this area have been widely discussed in several regional syntheses, a comprehensive model of how the plate motion changes from underthrusting in the Lesser Antilles to 'transform' motion in the Puerto Rico Trench has never been possible due to inadequate seismicity information. The results of the recently established Puerto Rico Seismic Network (PRSN) have shed new light on the tectonics of the northeastern Caribbean region by firmly establishing the existence and configuration of a lithospheric plate below the Puerto Rico-Virgin Island block. The following discussion integrates PRSN data with previously published data, and a comprehensive plate tectonic model of the northeastern boundary of the Caribbean plate is proposed.

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EVOLUTION OF THE CARIBBEAN PLATE

The Caribbean plate is bounded on the north by the Cayman Trough and the Puerto Rico Trench; on the east by the Lesser Antilles subduction zone; on the south by South America; and on the west by the Middle America subduction zone. Although differing in details, most palaeotectonic reconstructions suggest that the Caribbean plate originated in the Pacific Ocean (for example, DIETZ & HOLDEN, 1970; EDGAR ET AL., 1971; MALFAIT & DINKELMAN, 1972). The collision of the northeastward moving ancestral Caribbean plate with the Bahama Platform-North American continent between middle Cretaceous and Eocene times resulted in a change in relative motion between the two plates and welding of the Yucatan Basin portion of the ancestral Caribbean plate to the North American plate (MALFAIT & DINKELMAN, 1972; MATTSON, 1973). The Caribbean plate subsequently decoupled from the parent Pacific plate and presently is being underthrust on the west by the Pacific plate and the east by the North and South American plates. JORDAN (1975) has suggested that at the present time the Caribbean plate is stationary relative to mantle hot spots and that the relative plate motion across the northern boundary of about 2 cm/year is contributed predominantly by westward migration of the North American plate.

DESCRIPTION OF THE PUERTO RICO TRENCH

The large gravity anomalies in the Puerto Rico area generally conform to a pattern which is observed in subduction zones elsewhere in the world and are one of the most difficult characteristics of the Puerto Rico Trench to explain without invoking a subduction model. These anomalies possibly could be due to the presence of a relict pre-Eocene subducted slab under the Puerto Rico-Virgin Island block much like that envisioned by MALFAIT & DINKELMAN (1972), but it seems that the 40 million years that have elapsed since subduction ceased (Eocene) is too long a time to maintain these anomalies without active subduction or some similar mechanism. Furthermore, there is no volcanic activity in Puerto Rico or the Virgin Islands. Although there are a few exceptions, volcanism is generally associated with subduction. Even in the segments of subduction zones where volcanoes are not presently active (notably, the Peru-Chile Trench between 5° and 15°S latitude), the geologic record shows that volcanism has occurred within the last few million years. The absence of volcanism in the Puerto Rico Trench area for about 40 million years is difficult to rationalize in any model that proposes active subduction in the Puerto Rico Trench.

Geophysical surveys indicate that the Puerto Rico Trench is a zone of faulting up to 145 km wide. Seismic reflection and refraction profiles (TALWANI ET AL., 1959; BUNCE & FAHLQUIST, 1962; PUERTO RICO WATER RESOURCES AUTHORITY, 1974) and bathymetric profiles (MALEY ET AL., 1974) indicate that both walls of the Puerto Rico Trench contain high-angle faults. Dredged rock samples and underwater photographs BOWIN ET AL., 1966; PERFIT ET AL., 1974) indicate that oceanic crust is exposed in the walls of the Trench. Cross-sections based on seismic refraction and gravity data yield a structural configuration suggestive of a downdropped block (see TALWANI ET AL., 1959; BUNCE & FAHLQUIST, 1962).

Although gravity anomaly and seismicity trends continue along the whole length of the northern and eastern plate boundary without any obvious large discontinuities, there is a marked change in the bathymetric and faulting characteristics between the Puerto Rico segment of the plate boundary and the Lesser Antilles segment. MARLOW ET AL. (1974) have postulated that the under-thrusting along the Lesser Antilles changes to normal faulting just east of the Anegada Trough and that the change may be somehow related to the Anegada Trough.

The Trench deepens markedly westward from the Anegada Trough and both the abyssal plain surface and the stratified trench fill change attitude from one end of the trench to the other. At the eastern end the floor dips slightly north and at the west end near Hispaniola, where the trench is deepest and trench fill thickest, both the abyssal-plain surface and trench fill dip slightly south (BUNCE ET AL., 1974). This attitude of the trench fill and floor may be a direct reflection of the underlying basement configuration.

SEISMICITY

The seismicity in the northeastern Caribbean region forms a band of epicenters along the Atlantic side of the Lesser and Greater Antilles island arcs. The seismicity detected prior to the establishment of the PRSN shows that there are intermediate-depth earthquakes (<70 km depth) in the Puerto Rico area (Fig. 1), but cross-sections of these events do not show any strong alignments or clustering of events. East-west cross-sections do show a significant increase in the number and depth of events under Mona Passage and eastern Hispaniola.

The PRSN was established in 1974 by the Puerto Rico Water Resources Authority and the U.S. Geological Survey in order to develop definitive data regarding the seismicity and tectonics of Puerto Rico. The PRSN is presently recording an average of about 10 earthquakes per day with an accuracy previously unobtainable. The crustal seismicity within the island of Puerto Rico is typified by small-magnitude events of generally less than duration-magnitude 3 which do not show any major alignments suggestive of active faulting. The relationships of this seismicity to regional faults in the Puerto Rico area are discussed by SCHELL (1977). Aligned epicenters just south of the island suggest active faulting on the insular shelf but there is no appreciable seismicity in Muertos Trough. Intermediate-depth earthquakes detected by the PRSN form a prominent Benioff zone dipping about 45°-50° from the Puerto Rico Trench to a depth of about 150 km under the island (Fig. 2) (CARVER & TARR, 1976). This southward-dipping zone of seismicity is interpreted to represent a slab of the North American lithospheric plate. The upper surface of the slab, based on both U.S. National Oceanic and Atmospheric Agency data (NOAA) and PRSN data, is depicted by the contour lines drawn on figure 1.

Focal mechanism solutions along the Lesser Antilles island arc indicate that the relative motion between the Caribbean and American plates is directed in an east-west direction (Fig. 1) (MOLNAR & SYKES, 1969; see also JORDAN, 1975). Focal-mechanism solutions along the northern plate boundary near

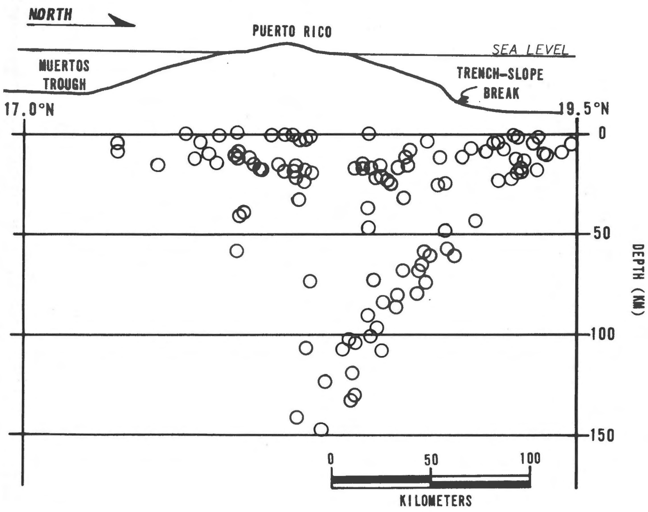


Fig. 2
North-south cross-section through the Puerto Rico-Virgin Island block onto which earthquake hypocenters have been projected. Data is from the Puerto Rico Seismic Network and represents events occurring from November 1975 through June 1977 which were detected by 10 or more PRSN seismograph stations.

Puerto Rico show this same general direction of motion but are less well constrained than the Lesser Antilles solutions; the azimuths of the slip vectors could probably vary up to 10 degrees either northward or southward of that shown on figure 1. These focal mechanism solutions seem to represent a peculiar type of sideways horizontal thrusting along nearly horizontal fault planes (MOLNAR & SYKES, 1969).

The distribution of earthquakes in the Hispaniola region (both NOAA data and PRSN data) show a concentration of shallow- to intermediate-depth earthquakes along the northeastern coast of Hispaniola, but these events do not form a well-defined Benioff zone. Focal mechanism solutions in the Hispaniola region support a general east-west direction of relative movement between plates, but their slip vectors trend more southerly and in some cases seem inconsistent with those in the Lesser Antilles.

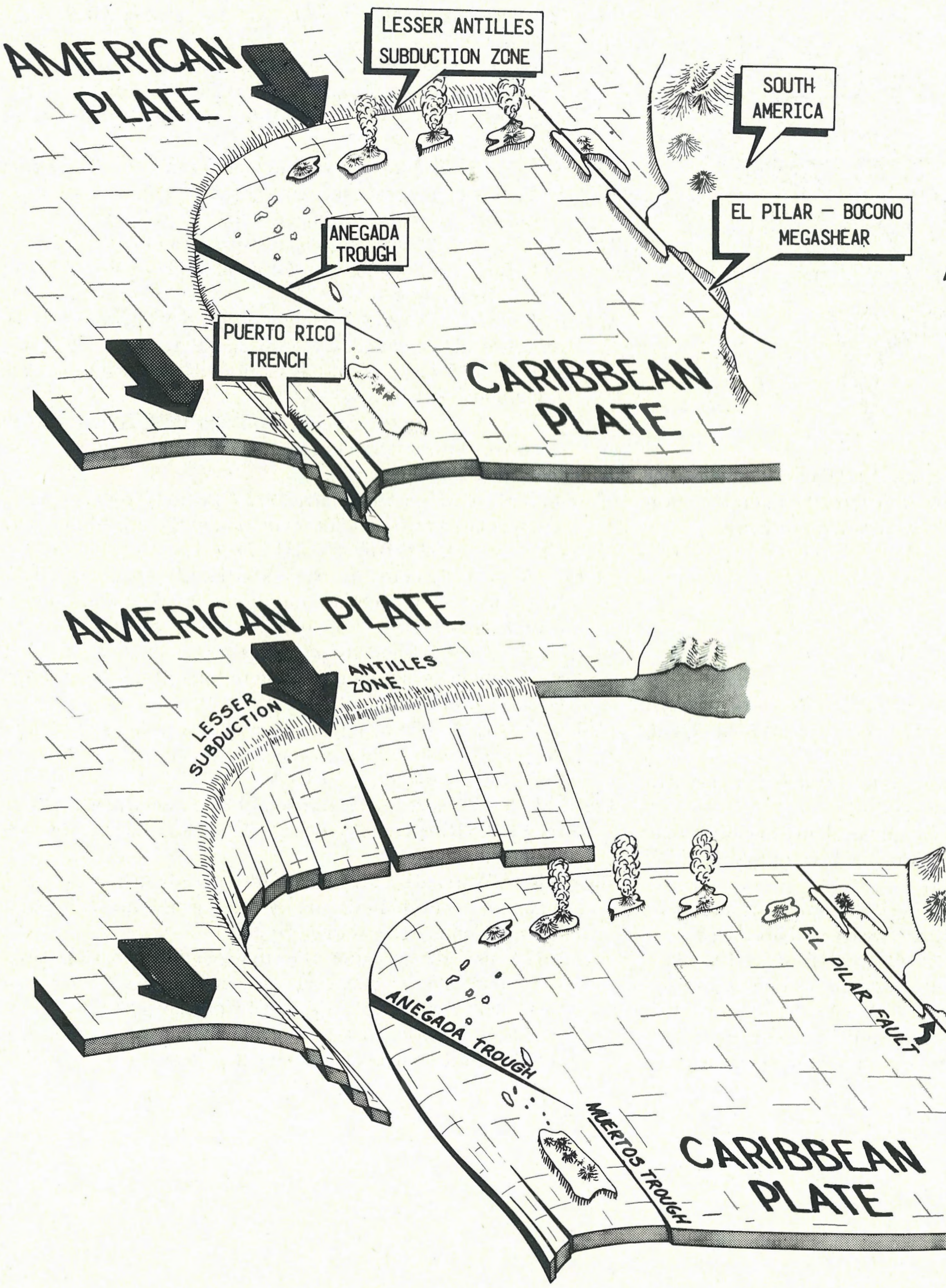
PLATE TECTONIC MODEL

Figure 3 is a conceptual model of the plate configuration along the northeastern Caribbean-North American plate boundary (refer also to figure 1). Note the protrusion of the North American plate under Puerto Rico in figure 3A. This configuration is suggested by the seismicity shown in figures 1 and 2. In figure 3B the plates are pulled apart to show the subsurface configuration more clearly. As the American plate is subducted under the Lesser Antilles the deeper portion of the plate is melted and is either extruded as molten material through the volcanoes of the Lesser Antilles island arc or assimilated into the asthenosphere. At the northeastern corner of the Caribbean plate, however, the portion of the plate above the critical melting depth is carried along with the rest of the American plate beneath the edge of the Caribbean plate. The stresses exerted on the American plate as it is bent and twisted probably cause fracturing into segments and blocks and reactivation of existing zones of weakness such as oceanic fracture zones which originated near the Mid-Atlantic Ridge during initial rifting. This block-like segmentation and interaction of the blocks may explain why the Puerto Rico Trench appears block-faulted on the surface but yields focal mechanism solutions, suggestive of horizontal thrusting and normal faulting; that is, many of the earthquakes are caused by shifting and grinding of subsurface blocks as the American plate breaks up, and others by movement between the Caribbean and American plates.

A small subduction zone has been postulated (BRACEY & VOGT, 1970) west of Puerto Rico along the northeast coast of Hispaniola. As the segmented American plate reaches this region it sinks deeper (to about 250 km) under the lithospheric root of the island acquiring a plow-like configuration (Fig. 4). The Quaternary volcanism in Hispaniola may be a result of the melting of the deeper portions of this plate. This hypothesis is supported by the location of the Quaternary volcanic rocks directly west of the deepest portion of the subducted plate (Fig. 1). The already-fragmented nature of the North American plate readily lends itself to further splintering, and the diversion of the blocks in various directions gives rise to the variation in slip-vector azimuths of the focal-mechanism solutions in the Hispaniola area. The poor definition of the Hispaniola Benioff zone can be attributed to the complexity of the North American plate's subsurface configuration.

The presence of the postulated east-to-west moving underriding slab offers a plausible explanation for the hitherto seemingly anomalous data such as intermediate-depth seismicity, focal mechanism solutions, and gravity anomalies. Furthermore, this east-to-west movement (rather than north-to-south) does not actively supply crustal material to the asthenosphere; thus there is no volcanism on the Puerto Rico-Virgin Island block. The oblique subduction and plow-shaped slab under Hispaniola explain the deepening of the floor of the Puerto Rico Trench and the seismicity westward near Hispaniola, and also explain the southerly dip of the trench floor and fill in that region. The active consumption of crustal material subducted under Hispaniola is reflected in the Quaternary volcanic activity on Hispaniola. The infrequency of this volcanic activity is most likely due to the slow rate of subduction (about 2 cm/year) and consequent small volume of material reaching pressures and temperatures sufficient to produce melting. One may also speculate that the collision of the North American plate with Hispaniola may cause anticlockwise rotation of Hispaniola setting up the tension required to explain the extensional nature of the Mona Canyon and Anegada Trough. This rotation may also cause compression in the western Muertos Trough.

The Puerto Rico Type of 'transform' trench is not unique to



A. View is toward the southeast with American and Caribbean plates intact.

B. Plates pulled apart to allow visualization of subsurface configuration.

Fig. 3
Plate configuration in the eastern Caribbean Sea region. The crustal thickness and relative depths of the subducted plate are diagrammatic and not drawn to scale.

the Caribbean region. The western Aleutian Trench is nearly a mirror image of the Puerto Rico area and has the same general plate motion, seismicity, gravity, and non-volcanic characteristics (CORMIER, 1975). Other areas where Puerto Rico-type 'transform' trenches may occur are in the Andaman Island portion of the Sunda Arc (CURRAY & MOORE, 1974), the Puysegur Trench of the Macquarie Ridge complex south of New Zealand (CHRISTOFFEL & VAN DER LINDEN, 1972), and possibly along the edges of the Scotia Sea plate.

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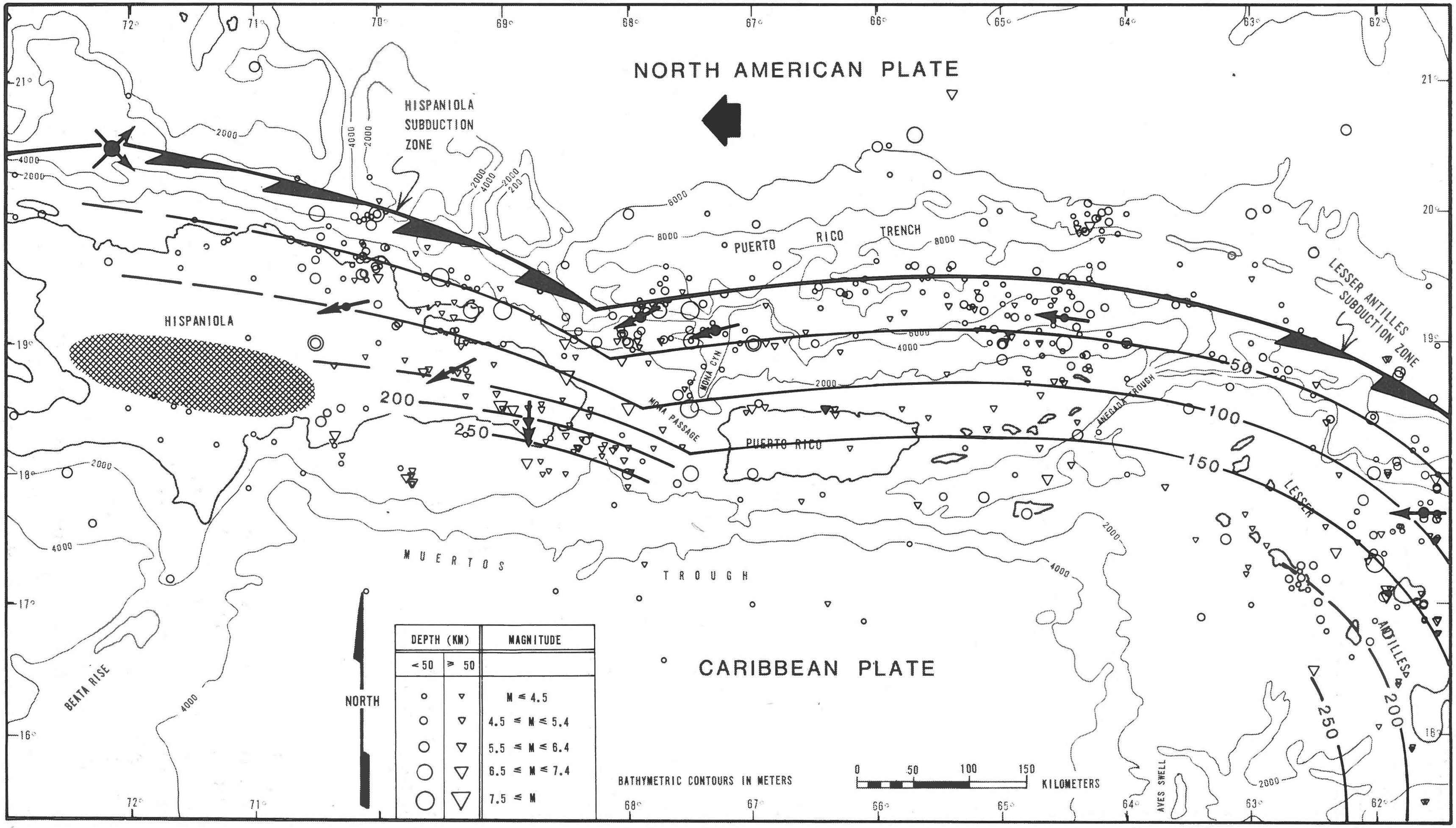
Fig. 1
Major plate-tectonic features and seismicity in the northeastern Caribbean Sea region. The seismicity data covers the years 1906 through 1976 as tabulated by NOAA. Solid symbols with arrows represent azimuths of slip vectors from thrust-fault focal-mechanism solutions; solid triangle without an arrow is a normal-fault solution; from Molnar & Sykes, 1969. Thick lines are contour lines approximating the upper surface of the underriding North American plate; contour interval is 50 km. Shaded area in Hispaniola marks the area of Quaternary volcanism.



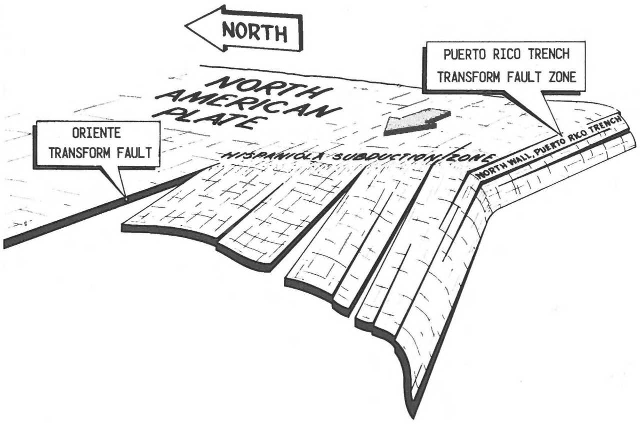


Fig. 4
Plate configuration in the Hispaniola region. Diagramatic drawing with Caribbean plate removed to show the sub-surface configuration of the North American plate. View is toward the northeast.

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