The Clarendon block forms the central part of the island and contains Early to Late Cretaceous rocks that range in age from pre-Barremian to possible late Maastrichtian. The rocks are exposed in five main inliers (Lazaretto, Benbow, Central, St. Ann's Great River, and the Maldon and Calton Hill) and several minor ones (the Above Rocks, Sunderland, and Marchmont). Amphibolites occur in the Lazaretto inlier of the extreme southeastern part of the Clarendon block. The Benbow inlier contains the oldest sedimentary rocks in the island including over 4000 meters (13,100 feet) of volcanogenic conglomerates, sandstones, volcanic flows, and rudistid limestone. The Central inlier contains the most complete sequence of the Clarendon block and contains Upper Cretaceous igneous rocks and volcaniclastic deposits intercalated with rudistid limestone layers. The oldest rocks are volcaniclastic conglomerates, overlain by intercalated limestones and shales. Volcanic formations containing epiclastic sandstones and conglomerates interbedded with andesite flows unconformably overlie the shales. Volcanically derived siltstones overlie the volcanic formations and are interbedded with limestones. The top of the sequence consists of red volcanogenic and fluvial deposits, some containing pumice fragments in addition to ignimbrite flows. The Above Rocks inlier, the eastern part of the Central inlier, is dominated by granitoid rocks intruded into siliceous sedimentary rocks. The St. Ann's Great River, Sunderland, Calton Hill, Maldon, and Marchmont inliers are in the northern and northwestern parts of the Clarendon block and, unlike the eastern inliers, are devoid of the volcanic rocks. The St. Ann's Great River inlier contains shales, sandstones, and conglomerates of early Coniacian to late Campanian age that are unconformably overlain by Eocene sediments. The Sunderland, Calton Hill, and Marchmont inliers contain conglomerates and shales of the Sunderland Formation (Santonian to Campanian age). Red Maastrichtian sandstones and conglomerates occur in the southern region of these inliers (Reference 217).

The Blue Mountain block, consisting of the Blue Mountain and Sunning Hill inliers, occupies the eastern third of the island and contains Campanian to Maastrichtian volcanic rock and volcanogenic sedimentary rocks with major limestone horizons (Figures 2.5.1-302 and 2.5.1-303). The Blue Mountain inlier contains a thick sequence of interbedded andesitic tuff, flows, and volcanogenic conglomerates as well as contemporaneous pelagic limestones underlain by a chert-basalt-gabbro ophiolitic complex, granitoid intrusives, and regionally metamorphosed rocks, including mafic blueschists, greenschists, and amphibolite-facies rocks (References 217 and 806).

The younger Montpelier-Newmarket zone, Wagwater belt, and North Coast belt consist of Paleocene clastic rocks, later Tertiary carbonate rocks, and late Tertiary

to Quaternary carbonate rocks that are occasionally intercalated with clastic sequences. From oldest to youngest, the three belts include the Wagwater, Yellow Limestone, White Limestone, and Coastal Groups (Figures 2.5.1-302 and 2.5.1-303). Each group consists of shallow water facies (lagoonal to shelf edge) and deep-water faces. The Wagwater Group consists of a lower section of red conglomerates, a middle section of interbedded conglomerates and thinly bedded sandstones and shales, and an upper section of dacitic volcanics and minor basalts, interbedded with clastic rocks. The Wagwater Group strata range in age from Early Paleocene to lower Eocene and attain a total thickness of approximately 7000 meters (23,000 feet) (Reference 217). Gypsum occurs at several places and reaches a maximum thickness of 60 meters (200 feet). The Yellow Limestone Group is Lower to Middle Eocene in age and the White Limestone Group is Middle Eocene to Late Miocene in age. Together the Yellow and White Limestone Groups represent over 2750 meters (9000 feet) of lagoonal, shelf edge, and deep-water carbonates. The overlying Coastal Group is Pliocene to Pleistocene in age and consists of shallow water lagoonal and patch reef sediments with some subaerial to submarine fanglomerates.

According to Westcott and Etheridge (Reference 561) in Lewis and Draper (Reference 217), the clastic rocks of the Wagwater Group represent fan-delta and proximal to distal submarine-fan deposits. Erosion of the Cretaceous volcanic rocks supplied source material to several fan systems, which developed at the steep margin of the Wagwater belt basin. By late Early Eocene time, a general marine transgression submerged the entire island and led to the deposition of thick limestones. Volcanic activity concluded by the early Middle Eocene and was followed by a period of relative tectonic quiescence until the Middle Miocene. During this time, thicknesses of up to 2750 meters (9000 feet) of the Yellow and White Limestone Groups accumulated. The depositional environments of the Yellow and White Limestone Groups have been determined from a combined study of fauna and lithology to indicate that from Paleocene to middle Eocene time Jamaica experienced an island-wide marine transgression, with rapid subsidence of the North Coast, Wagwater, and Montpelier-Newmarket belts and the southern Hanover block (Reference 217). The Blue Mountain and Clarendon blocks subsided more slowly. North and east of the Wagwater fault bounding the western margin of the Wagwater belt, Coastal Group sediments consist of deep-water facies. In the Late Miocene to Pliocene, emergence occurred to subaerially expose both shallow-water and deep-water limestones. Some of this emergence was probably due to a eustatic sea-level drop, although much of it may have been due to tectonic causes (Reference 217). After the Aftonian interglacial, most sediments are neritic and the late Pleistocene geology is

expressed mainly as a series of raised marine terraces (Reference 217). Alluvium is confined to interior valleys, river floodplains, and the coastal margins.

Structures of Jamaica

The island of Jamaica occupies the northeastern tip of the Nicaraguan Rise, the eastern part of the Chortis block. Lewis and Draper (Reference 217) discuss structures seen on Jamaica in terms of the tectonic development of the island. The oldest rocks on the island are in the Blue Mountains province and are attributed to an early to mid-Cretaceous west-dipping island arc. By the late Cretaceous, subduction had shifted southeast of the island and magmatism for the most part ceased.

During the Paleocene to middle Eocene, the presently observed northwest-southeast oriented block-and-graben structures were created. The northwest-striking faults shown in Figure 2.5.1-300 initiated during this time period. These include the Montpelier-New Market fault zone, Santa Cruz fault, and Spur Tree fault. Several hypotheses have been presented to explain the northeast-southwest extension that gives rise to these rift structures, but none are conclusive (Reference 217).

After a 30 m.y. period of quiescence and submersion, the left-lateral transcurrent regime active today was established in the late Miocene. The role of Jamaica as a restraining bend in the Caribbean-Gonâve plate boundary was initiated at this time, and west-northwest- to east-southeast-striking left-lateral faults overprinted the earlier fault pattern. Mapped faults on the island are shown in Figure 2.5.1-300. To the north, the Duanvale fault zone extends from the north-central part of the island to the west through Montego Bay and connects to the Walton fault (Figure 2.5.1-202). To the east, the Plantain Garden fault extends to the east and connects to the Enriquillo fault in and west of Haiti. In the center of the island this deformation zone is expressed as the Rio Minho-Crawle River fault zone. The South Coast fault along the southwest coast also reflects the current stress regime.

Lewis and Draper (Reference 217) point out that some of Jamaica's early Tertiary normal faults may be reactivated as thrust faults, a prime example being the Blue Mountains fault. Oblique folding and tilting of beds has accompanied the current compressional stress field, along generally north-south-trending axes. Mann and Burke (Reference 859) describe the Wagwater belt, which comprises the western part of the Blue Mountains physiographic province, as an intra-arc inverted basin structure. They suggest the belt initially formed as a basin parallel to, and along

the axis of, the Greater Antilles Arc in the early Paleocene through early Eocene. With initiation of the Cayman Trough, the stress regime changed to transpressive, as the region became a restraining bend in a strike-slip system. The basin was thus uplifted (inverted) to form the present-day physiography, and normal faults originally associated with basin development are reactivated as thrust faults (Reference 849).

Seismicity of Jamaica

Jamaica has experienced 13 earthquakes of MMI VII and greater since the mid 1600s. The most severe was the {M_w 7.75 (Phase 2 earthquake catalog)} 1692 Port Royal earthquake near Kingston (Figure 2.5.2-214), which submerged the town and killed a quarter of its inhabitants. A MMI IX event in 1907 {(Phase 2 earthquake catalog M_w 6.64)} in the same region caused 1000 fatalities (Reference 563). The pattern of present-day microseismicity indicates the most intense activity is in the Blue Mountains region, the topographically highest region of the island. Focal mechanisms show a mixture of thrust and strike-slip mechanisms, consistent with transpression due to northeast-southwest compression (Reference 503). Aside from the Blue Mountains region, associations between seismicity and faults are not clear (Figure 2.5.1-267).

SOF 2.5.1-2

SOF 2.5.1-2

2.5.1.1.2.2.2.2 Geology of Hispaniola

Physiography of Hispaniola

Hispaniola is a mountainous island about 660 kilometers (410 miles) long and 260 kilometers (160 miles) wide. Haiti occupies the western part of the island and the Dominican Republic the eastern part. Hispaniola has many features in common with the islands of Cuba and Jamaica to the west and Puerto Rico to the east. Hispaniola is the second largest island of the Greater Antilles Deformed Belt, a Cretaceous-early Tertiary island arc that stretches from Cuba to Puerto Rico and the British Virgin Islands. Hispaniola is separated from Cuba to the northwest by the Windward Passage, 4000 meters (13,100 feet) deep; from Jamaica to the west-southwest by the Jamaica Passage, 3000 meters (9800 feet) deep; to the east from Puerto Rico by the Mona Passage, 460 meters (1500 feet) deep; and to the north from the Bahama Banks by the Old Bahama Channel (coincident with the northwestern portion of the Puerto Rico trench) 4300 meters (14,000 feet) deep.

Hispaniola is located at the convergence of five physiographic-structural trends in the northern Caribbean: the main axis of the Greater Antilles Deformed Belt, the Cayman Trench, the Nicaraguan Rise, the Beata Ridge, and the Bahamas-Cuba

intersection (Reference 217) (Figures 2.5.1-202 and 2.5.1-210). The significance of Hispaniola's location with respect to these trends is discussed later in this subsection.

Hispaniola has four nearly parallel west-northwest-trending mountain ranges, separated by three relatively narrow, alluvial-filled, longitudinal structural depressions (Reference 796) (Figure 2.5.1-304). At the northeastern end of the island, the Cordillera Septentrional is bounded on the southwest by the Cibao Valley. Southwest of the Cibao Valley lies the Massif du Nord-Cordillera Central and the Sierra de Seibo. These, in turn, are separated on the southwest by the Central Plateau-San Juan Valley. Southwest of the Central Plateau-San Juan Valley lies the Montagnes Noire and the Sierra de Neiba and its northwest extension, the Matheaux-Trou d'Eau. These central mountainous regions are bordered on the southwest by the Enriquillo Graben. South and east of the Enriquillo Graben lies the Sierra de Bahoruco trending west into the Massif de la Selle and continuing into the Massif de la Hotte. In general, the mountain ranges in the northern part of Hispaniola trend about N 40-50° W, oblique to the main axis of the island. This trend is parallel to the structural grain of central and eastern Cuba. However, the mountains ranges in the southwestern part of the island (the Massif de la Hotte and the Massif de la Selle of the Southern Peninsula) have an east-west trend, which is parallel to the axis of Hispaniola and the Greater Antilles as a whole (Reference 217).

Coastal plains also occur on the island of Hispaniola and are most extensive on the southeast coast of the Dominican Republic. In Haiti, where the mountains frequently stretch to the shoreline, the area of coastal plain is relatively small. Raised coral reef terraces, all of Quaternary age, are found in a number of localities along the coast, indicating that local uplift of up to several hundred meters continued at least well into the Pleistocene (Reference 796).

Stratigraphy of Hispaniola

Hispaniola consists of an agglomeration of twelve tectonic terranes or zones as indicated on Figure 2.5.1-305 and Table 2.5.1-206, namely:

1. Samaná

2. Puerto Plata-Pedro Garicía-Río San Juan

3. Altamira

4. Oro

5. Seibo

6. Tortue-Amina-Maimon

7. Loma Caribe-Tavera

8. Duarte

9. Tireo

10. Triois Rivières-Peralta

11. Presqu'île du North-Ouest-Neiba

12. Selle-Hotte-Bahoruco

One of the terranes (Selle-Hotte-Bahoruco) is a fragment of oceanic plateau terrane that crops out over the southern one-third of the island. As described in Subsection 2.5.1.1, the buoyancy of oceanic plateau crust makes it unlikely that this crustal fragment was accreted to Hispaniola during the development of the island-arc terranes. Eleven of the terranes are fragments of island-arc terranes that crop out over the northern two-thirds of the island. The eleven island-arc terranes, which range in age from Early Cretaceous to late Eocene, can be classified on the basis of lithologic associations, geochemistry, and structure as: (a) fragments of oceanic crust on which the island arcs were built, (b) fragments of the forearc/accretionary prism of an island arc, (c) fragments of the volcano-plutonic part of an island arc, and (d) a fragment of a back-arc basin (Reference 566) (Table 2.5.1-206). All twelve tectonic terranes generally have elongated shapes and are bounded by high angle strike-slip or reverse faults (Figure 2.5.1-302). Several of the terrane boundaries are either completely or partially covered by 1- to 6-kilometer (0.6- to 3.7-mile) thick, late Miocene to Recent clastic and carbonate sedimentary basins (Reference 564). The carbonates of the Seibo terrane began to form in the Early Cretaceous (Aptian to Albian) (Reference 566) while carbonates of the Selle-Hotte-Bahoruco terrane formed in a gradually deepening marine environment in the Paleocene to Miocene. The clastic sedimentary basins formed and filled during a transpressional phase of terrane docking (References 217 and 566).

The tectonic terranes of Hispaniola can also be divided on the basis of their deformational characteristics, as indicated in Table 2.5.1-206. Three types of terranes are identified:

- Stratigraphic terrane
- Metamorphic terrane
- Disrupted terrane

Seven of the twelve island-arc terranes are stratigraphic terranes, which are characterized by coherent sequences of strata in which depositional relations between successive lithologic units can be demonstrated (Reference 566). These seven stratigraphic terranes can be further subdivided into: (a) five fragments of the volcano-plutonic part of an island (these fragments are composed dominantly of volcanic and associated sedimentary rocks and the underlying plutonic roots of the island arc), (Tireo, Seibo, Oro, Presqu'île du Nord-Ouest-Neiba, Altamira); (b) one fragment of a back-arc basin characterized by mainly deep-marine turbiditic rocks of submarine fan facies (Trois Rivières-Peralta); and (c) one fragment of an oceanic plateau characterized by thick sequences of pillow basalts and gabbros with overlying deep-sea sedimentary deposits (Selle-Hotte-Bahoruco) (Reference 566) (Table 2.5.1-206).

Three of the twelve terranes are metamorphic terranes, characterized by rocks metamorphosed to a high enough grade that original minerals, stratigraphic features, and stratigraphic relationships are obscured. The Samaná metamorphic terrane is a fragment of the forearc/accretionary prism of an island arc, the Duarte metamorphic terrane is a fragment of ocean floor including seamounts, and the Tortue-Amina-Maimon metamorphic terrane is a fragment of a volcano-plutonic part of an island arc (Reference 566) (Table 2.5.1-206).

Two of the twelve terranes, the Puerto Plata-Pedro García-Río San Juan and Loma Caribe-Tavera terranes, are disrupted terranes. Disrupted terranes are characterized by brittle deformation that obscures the depositional relations between successive lithologic units. The Puerto Plata-Pedro García-Río San Juan terrane consists of blocks of heterogeneous lithology and age set in a matrix of serpentinite (Reference 566) (Table 2.5.1-206).

These various basement terranes of Hispaniola were left-laterally translated from points of origin to the west along faults associated with the Cayman spreading center. Mann et al. (Reference 566) note that translation of terranes along strike-slip faults can act to disperse terranes or to accrete them. In Hispaniola, Mann et al. (Reference 566) propose that the numerous terranes accreted over time because of offsets, or "restraining bends," in the controlling faults since the Miocene. Furthermore, the effect of deformation within the restraining bend in

Hispaniola was absorbed by: (a) uplift and erosion of lower crustal rocks (e.g., Duarte, Loma Caribe-Tavera, and Tortue-Amina-Maimon terranes of central Hispaniola); (b) large-scale rotation of terranes about vertical axes (e.g., post-Eocene counterclockwise rotation of Tireo terrane); (c) large-scale underthrusting of one terrane beneath another (e.g., Selle-Hotte-Bahoruco terrane beneath island-arc terranes of central Hispaniola); and (d) splaying of the strike-slip fault into several different strands at the restraining bends (e.g., the Oriente fault splays into the Bahamas Channel, Camu, and Septentrional faults in northern Hispaniola) (Reference 219). The end result is the geologic history of adjacent terranes is often quite distinct and difficult to unravel (Reference 904).

Mann et al. (Reference 566) postulate that many of the terrane boundaries separating island-arc and oceanic plateau terranes were reactivated as oblique-slip faults after active subduction ceased following the collision between Hispaniola and the Bahama Platform. Based on the complex structural relations found in the field, Mann et al. (Reference 566) conclude that Early Miocene to Recent transpression at the Hispaniola restraining bend (or convergent segment of the east-west-striking North America-Caribbean strike-slip plate boundary) produced ten morphotectonic zones that correspond to the major mountain ranges and intervening clastic sedimentary basins of Hispaniola (References 566 and 217). The boundaries of each of the zones are generally well-defined topographic escarpments or lineaments, and each zone has geologic characteristics that distinguish it from its neighboring zones. In general, morphologic boundaries between the ten morphotectonic zones correspond well to major differences in the rock types of tectonic terranes because of Neogene reactivation of major crustal faults separating tectonic terranes (Reference 566). Correlation between the ten morphotectonic zones and the twelve tectonic terranes of Hispaniola is described in Table 2.5.1-205.

Structures of Hispaniola

Hispaniola comprises an amalgamation of several terranes, reflecting a long and complex geologic and tectonic history. Present-day structures have been imprinted on these terranes that reflect the current role of Hispaniola as a microplate between the North America plate to the north and the Caribbean Plate to the south. In addition, this microplate has been proposed to consist of two parts: the Gonâve microplate to the west of central Hispaniola, and the El Seibo microplate to the east (Figure 2.5.1-202).

Because the major tectonic structures associated with Hispaniola have been described elsewhere, brief descriptions are provided below with cross-references

to more detailed descriptions elsewhere. These features are shown in Figure 2.5.2-214.

1. Septentrional fault: Described in detail in Subsection 2.5.1.1.2.3.2.1. This left-lateral strike-slip fault is the dominant plate boundary between Hispaniola and the North America Plate, and separates the Cordillera Septentrional-Samana Peninsula from the Cibao Valley (Figure 2.5.1-202). Slip rates from trenching and GPS studies range from 6 to 12 millimeters/year in the Cibao Valley region, decreasing to the east.

2. North Hispaniola subduction zone (NHSZ): Described in detail in Subsection 2.5.1.1.2.3.2.2. This south-dipping thrust fault merges with the Puerto Rico Trench (subduction zone) in the Mona Passage region to the east of the island (Figure 2.5.1-202).

3. Enriquillo-Plantain Garden fault zone: Described in detail in Subsection 2.5.1.1.2.3.2.3. This left-lateral strike-slip fault forms the boundary between Hispaniola and the Caribbean Plate in the western part of the island (Figure 2.5.1-202). The slip rate has been estimated to be about 8 millimeters/year.

4. Muertos Trough: Described in detail in Subsection 2.5.1.1.2.3.3. This north-dipping subduction zone accommodates north-south compression between Hispaniola and the Caribbean Plate (Figures 2.5.2-214 and 2.5.1-202).

5. Mona Passage extensional zone: Described in detail in Subsection 2.5.1.1.2.3.3. This is a zone of about 5 millimeter/year of east-west extension between Hispaniola and Puerto Rico (Figures 2.5.1-210 and 2.5.1-202).

Seismicity of Hispaniola

Descriptions of the historically significant and largest earthquakes associated with the active structural features of Hispaniola are briefly described below, along with cross-references to more detailed descriptions.

- Septentrional fault (Subsection 2.5.1.1.2.3.2.1). The {1842 M_w 8.20 (Phase 2 earthquake catalog)} earthquake occurred on the western part of the fault. Farther east in the Cibao Valley, paleoseismic trenching studies on the Septentrional fault indicate that the most recent surface faulting event SOF 2.5.1-2

occurred about 1200 A.D. (Reference 570). Damaging historic earthquakes also occurred in the vicinity in 1562, 1783, 1887, and 1897 {(Phase 2 earthquake catalog M_w 7.23, 6.13, 7.93, and 7.03, respectively).} (There is some uncertainty regarding the date of the 16th century earthquake. {The Phase 2 earthquake catalog indicates that it occurred in 1562,} whereas Scherer [Reference 571] indicates 1564). Due to the proximity of the Northern Hispaniola subduction zone, however, some or all of these may have occurred on that feature. SOF 2.5.1-2 SOF 2.5.1-2

- Northern Hispaniola subduction zone (Subsection 2.5.1.1.2.3.2.2). {Large earthquakes occurred on this feature in 1946, 1948, and 1953. The largest of these occurred in 1946, approached magnitude 8 (Phase 2 earthquake catalog M_w 7.90), and caused loss of life and extensive damage.} As discussed in the previous paragraph, it is possible that four other large historic earthquakes occurred on this feature. SOF 2.5.1-2

- Enriquillo-Plantain Garden fault (Subsection 2.5.1.1.2.3.2.3). {Large, damaging earthquakes occurred on the Enriquillo-Plantain Garden fault in 1751, 1770, and 2010. Magnitudes of the 1751 and 1770 earthquakes are M_w 6.83 and 7.53, respectively (Phase 2 earthquake catalog).} The destructive January 12, 2010, M_w 7.0 (Reference 572) earthquake near Port-au-Prince, Haiti occurred after completion of the Phase 2 catalog and is therefore not included. Subsection 2.5.1.1.2.3.2.3 provides additional information regarding the January 12, 2010, earthquake. SOF 2.5.1-2

- Muertos Trough (Subsection 2.5.1.1.2.3.3). A M_w 7.28 earthquake near the western end of the Muertos Trough occurred in 1751 (Figure 2.5.2-214).

- Mona Passage extensional zone (MPEZ) (Subsection 2.5.1.1.2.3.3). In 1918, a M_w 7.30 earthquake located in the Mona Passage generated a tsunami and ground shaking that caused extensive damage to coastal communities of northwest Puerto Rico. Abundant low to moderate magnitude seismicity is currently occurring in the Passage (Reference 573).

2.5.1.1.2.2.2.3 Geology of Puerto Rico

Physiography of Puerto Rico

The island of Puerto Rico is the smallest and easternmost island of the Greater Antilles. In addition to the principal island, the Commonwealth of Puerto Rico includes the islands of Vieques, Culebra, Culebrita, Palomino (the Spanish Virgin

Islands), Mona, Monito, and various other isolated islands. Deep ocean waters fringe Puerto Rico. The Mona Passage, which separates the island from Hispaniola to the west, is about 75 miles (120 kilometers) wide and more that 3300 feet (1000 meters) deep. The 28,000-foot (8500-meter) deep Puerto Rico Trench parallels the north coast of Puerto Rico. The Muertos Trough, more than 18,000 feet (5500 meters) deep, parallels the south coast of Puerto Rico.

Puerto Rico can be divided into three major physiographic provinces (Reference 881):

- The Upland province
- The Northern Karst province
- The Coastal Plains province

The topography of the Upland (or Interior) province reflects primarily the effects of erosion on a structurally complex sequence of many kinds of igneous and sedimentary rocks. The Northern Karst province shows the effects of limestone dissolution. The Coastal Plains province is an area predominantly of deposition (Reference 881).

The Upland province is formed by a central mountain chain commonly known as the Cordillera Central, extending across the interior of the island from east to west. This mountain chain includes the La Cordillera Central, La Sierra de Cayey, La Sierra de Luquillo, and La Sierra Bermeja. These rocks of the Upland province have been uplifted and erosionally dissected to form an asymmetric mountain range in which the southern slopes dip more steeply than the northern slopes. The mountains of the Cordillera Central in this province rise to more than 1300 meters (4300 feet) above sea level (Reference 574).

The Northern Karst province is a limestone region that reflects an advanced stage of limestone dissolution and contains extensive zones of mogotes (also known as haystack hills), sinkholes, caves, limestone cliffs, and other karst features.

The Coastal Lowlands province extends 13 to 19 kilometers (8 to 12 miles) toward the south from the northern coast and 3 to 13 kilometers (2 to 8 miles) toward the north from the southern coast of Puerto Rico. A series of smaller Coastal Lowlands valleys lie perpendicular to the western and eastern coasts of Puerto Rico. This area was originally formed by the erosion of the interior mountains.

Stratigraphy of Puerto Rico

Puerto Rico can be divided into three east-west-trending terranes: a Central Igneous Zone of island arc volcanic strata flanked to the north and south by younger carbonate strata covered by alluvium (the Northern Carbonate and Southern Carbonate Zones) (Figure 2.5.1-307). The most prominent feature of the three geologic terranes in the Puerto Rico-Virgin Islands area is a large, east-west-trending arch. The generally undeformed carbonate strata in the northern limb of the arch exhibit a smoother, more uniform dip than the folded and faulted carbonate strata exposed in the steeper, southern limb. The volcanic island arc basement rocks on Puerto Rico are exposed in the core of the arch (Reference 809).

The three terranes are discussed in the following paragraphs.

Central Igneous Zone of Island Arc Strata

The Central Igneous Zone of island arc volcanic strata in Puerto Rico, with rocks ranging in age from Early Cretaceous (Aptian) to Eocene and dating from about 120 to 45 Ma, represents one of the longest oceanic arc sequences preserved in the world (Reference 809). The strata rest on an unusually thick crust, reaching a maximum in the northeast of about 30 kilometers (Reference 809). Donnelly et al. (Reference 568) suggest that much of this represents underplating by arc-related plutonic bodies, rather than accumulations of material produced through volcanism.

Detailed, systematic geologic mapping indicates that post-volcanic sedimentary platform deposits consisting of limestone and detrital materials ring the island and cover extensive parts of the arc platform. However, representative strata of the entire volcanic arc sequence are exposed. Based on over 50 years of detailed stratigraphic study by the USGS and others, various researchers (References 217, 809, and 880) recognize three distinct igneous provinces across the island. The provinces are (a) a northeast igneous (or volcanic) province, separated from the central province by the Cerro Mula fault (shown as the North fault zone in Figure 2.5.1-307); (b) a central igneous (or volcanic) province, dominated by volcanic debris accumulated during sequential development of five east-west-oriented volcanic belts; and (c) a southwestern igneous (or volcanic) province, with a northwest-southeast-trending boundary of uncertain origin, containing remnants of two sequential island arc volcanic belts of Late Cretaceous (Campanian-Maastrichtian) and Eocene age.

In addition to the island arc volcanics, the oceanic Sierra Bermeja Complex crops out in the southwestern corner of the island. This complex consists of a tectonic mélange of partly serpentinized ultramafic rocks representing the lithospheric upper mantle originally composed of spinel-bearing peridotites (References 809 and 836). The mélange incorporates rafts, blocks, and boulder-sized clasts of Early Jurassic to Late Cretaceous pelagic sediments (Mariquita Chert), including radiolarian chert of Pacific provenance (References 804 and 820). The mélange also contains later volcanogenic strata (Cajul Basalt) and amphibolites (Las Palmas amphibolite mélange) of probable Early Jurassic age, representing pre-island arc oceanic crust (Reference 880).

Volcanic strata preserved in the central igneous province are subdivided into five major volcanic phases on the basis of stratigraphic and geochemical relations. Basalts evolved progressively from early primitive island arc tholeiites, to calc-alkaline basalts, and finally to incompatible element-enriched shoshonite basalts. Following a hiatus, calc-alkaline volcanism resumed. Correlative strata in the northeast province display a more restricted compositional range from early island arc tholeiites to calc-alkaline basalts. Volcanic strata of dominantly calc-alkaline affinities in the last phases of volcanism in both the northeastern and central provinces are chemically identical. Jolly et al. (Reference 809) infer that, by the mid-Late Cretaceous (mid-Santonian), the northeast and central blocks were tectonically juxtaposed by strike-slip movement along the Cerro Mula fault, the principal strand of the North Puerto Rico fault zone. The last phases of volcanism are represented in the west by a sequential pair of subparallel island arc belts of Campanian-Maastrichtian and late Paleocene–Eocene age, accompanied by extensive flanking sedimentary basins. A hiatus between the last two phases of volcanism, representing both a period of erosion and a nonvolcanic interval, persisted across the entire island from uppermost Late Cretaceous (Maastrichtian) through the Early Paleocene (Reference 809).

In the southwestern igneous province, island arc strata date from about 85 Ma (mid-Late Cretaceous), and the basement is inferred to have been transported into the active volcanic zone of the island arc simultaneously with left-lateral displacement along the Cerro Mula fault (Reference 809).

Jolly et al. (Reference 809) indicate that no consensus has developed regarding the polarity and tectonic history of subduction during generation of the Greater Antilles Arc. As discussed in Subsection 2.5.1.1.2.2.2, Mattson (Reference 804) and Pindell and Barrett (Reference 219) propose that Cretaceous igneous rocks of the Greater Antilles islands of Cuba, the Cayman Ridge, Hispaniola, and Puerto Rico originated in an intra-oceanic island arc, with northeast-dipping subduction,

bounding one edge of a proto-Caribbean Sea (Figure 2.5.1-347, part B). Structural fabric data from central Hispaniola suggest a reversal from east- to west-dipping subduction occurred early in arc history during the mid-Cretaceous (Aptian to Albian time). It has been suggested that initial subduction was from the west until arrival of a buoyant oceanic basalt plateau, the Caribbean Plateau, which developed in the Pacific basin at about 88 Ma, forcing a reversal in polarity of subduction between 105 and 55 Ma (Reference 833). Alternatively, the early arc might have formed along the margin of the Caribbean Plateau and advanced eastward locked with the plateau accompanied by west-dipping subduction of the proto-Caribbean (Atlantic) plate throughout arc history (Reference 809).

Northern Zone Carbonate Zone

In northern and western Puerto Rico, the siliciclastic San Sebastian Formation forms the base for the lower Oligocene to lower Pliocene Puerto Rico-Virgin Islands carbonate platform. Based on single-channel and multichannel seismic reflection lines, van Gestel et al. (Reference 670) evaluated the regional stratigraphy and structure of the platform. The platform covers an area of 18,000 kilometers^2 and extends from the eastern Dominican Republic on the island of Hispaniola, west of Puerto Rico, to the Virgin Islands, east of Puerto Rico. The continuity and similarity of facies across the platform indicate a remarkable stability over this area for a period of almost 35 million years (Reference 670). Where onshore platform rocks have been studied in detail in northern Puerto Rico (Reference 881) and southern Puerto Rico (Reference 882), they indicate deposition at sea level with minor periods of subsidence in the early Pliocene (Reference 670).

The carbonate strata in northern Puerto Rico include an uninterrupted sequence of generally undeformed Late Oligocene to Middle Miocene Lares, Cibao, Los Puertos, and Aymamon Formations. The carbonate lithologies reflect a general shallowing of sea level, punctuated by two rapid episodes of deepening near the Oligocene/Miocene boundary and two more in the Middle Miocene. An erosional unconformity breaks the sequence from the Middle to Late Miocene, after which carbonate deposition continued from Late Miocene to Late Paleocene with the Quebradillas Formation (Reference 881). Outcrop data for the northern Puerto Rico carbonates show a 4° dipping package of homogeneous carbonate layers unconformably overlying Cretaceous-Eocene arc basement rocks (Reference 670). Alluvium is sparsely intercalated with the shallow carbonate strata and overlies the carbonate strata exposed at the surface on the northeastern side of the island.

Two amphitheater-shaped escarpments, A and B, are seen in the GLORIA images on the lower slope north of Puerto Rico. Amphitheater A is about 60 kilometers (37 miles) across and up to 2250 meters (7380 feet) deeper than the surrounding seafloor; amphitheater B is smaller and is about 30 kilometers (19 miles) across and 1500 meters (5000 feet) deep. Based on seismic reflection profiles, an estimated 1500 kilometers^3 of sedimentary section have been removed from the larger amphitheater, and a system of canyons has formed. The interior of amphitheater B appears to have an irregular, high backscatter surface with no canyons; more recent slumping may have occurred in the smaller amphitheater. The implication is that modification of the amphitheaters may be an ongoing, presently active process (Reference 576).

Southern Carbonate Zone

The carbonate strata in southern Puerto Rico are about the same age as the carbonate units in northern Puerto Rico. The Ponce and the Juana Diaz Formations, Early Oligocene to Early Miocene and Middle to Late Miocene, respectively, have been mapped in southern Puerto Rico (References 809 and 881). The carbonate section of southern Puerto Rico has a maximum thickness of 500 meters (1600 feet) (Reference 670). The strata generally dip more steeply (10°) southward toward the Muertos Trough and show more faulting and folding both in outcrops (Reference 882) and in seismic reflection profiles than the carbonate strata on the north coast (Reference 670). Alluvium is sparsely intercalated with the shallow carbonate strata and overlies the carbonate strata exposed at the surface on the southeastern side of the island.

Structures of Puerto Rico

As described in the preceding section, Puerto Rico can be divided into three terranes: the Central Igneous zone and the Northern and Southern Carbonate zones (Figure 2.5.1-307). Whereas the Northern Carbonate zone is essentially undeformed, the Southern Carbonate zone contains steeply dipping faults. Folding is prominent only in the southwest Igneous province (Reference 217). The Central Igneous zone (Figure 2.5.1-307) is separated by major northwest-striking faults as seen in Figure 2.5.1-307. The island is also traversed by the North fault zone to the north, and the South fault zone to the south (also referred to as the Great North Puerto Rico fault zone and Great South Puerto Rico fault zone). Both North and South fault zones exhibit unknown but large amounts of left-lateral slip. Based on unfaulted Oligocene to Miocene age strata that overlie these structures, activity on these features apparently occurred before the Middle Miocene (Reference 217), and they are not considered to be seismogenic (Reference 577).

Trenching studies on the South Lajas fault, a 30-kilometer (19-mile) long east-west-striking fault in southwestern Puerto Rico, revealed two surface faulting events in the past 7000 years (Reference 578). This is the only Holocene fault currently documented on the island.

Seismicity of Puerto Rico

Local seismograph networks have been operated in Puerto Rico since the mid-1970s. Early results (Reference 587) show shallow seismicity beneath the island, and a south-dipping plane of seismicity associated with the subducting North America Plate extending to depths of about 150 kilometers (93 miles) (Figure 2.5.1-309). Later studies confirm this pattern (e.g., Reference 588). Crustal seismicity on the island of Puerto Rico is sparse, consisting of low- to moderate-magnitude (magnitude ≤5) activity (References 573 and 577). Seismicity appears to be more dense in the southwestern part of the island, where Huerfano et al. (Reference 573) interpret a pattern of northwest-southeast transtension. Relocations of seismicity in this area suggest that most of this seismic activity is associated with the Muertos subduction zone (Reference 569). An earthquake of approximately magnitude 6 was felt in southwest Puerto Rico in 1670 (Reference 579). This event may have occurred on one of the MPEZ faults (Subsection 2.5.1.1.2.2.4) to the west, on the Muertos subduction zone, or an unidentified fault in western Puerto Rico.

The island of Puerto Rico is surrounded and underlain by seismogenic features that have caused damaging earthquakes in historical times. Because these are described elsewhere, only cross-references are provided below:

- Puerto Rico Trench (Subsection 2.5.1.1.2.2.3). {In 1787, a M_w 8.03 (Phase 2 earthquake catalog) earthquake occurred in the vicinity of the Puerto Rico Trench. SOF 2.5.1-2
- Muertos Trough (Subsection 2.5.1.1.2.2.4). A M_w 7.28 earthquake near the western end of the Muertos Trough in 1751 (Figure 2.5.2-214).
- Mona Passage (Subsection 2.5.1.1.2.2.4). In 1918, a M_w 7.30 earthquake located in the Mona Passage (Phase 2 earthquake catalog)} generated a tsunami and ground shaking that caused extensive damage to coastal communities of northwest Puerto Rico. Abundant low to moderate magnitude seismicity is currently seen in the Passage (Reference 573).

2.5.1.1.2.2.3 Geology of the Puerto Rico Trench

Physiography of the Puerto Rico Trench

The Puerto Rico Trench is the surface manifestation of the Puerto Rico subduction zone (PRSZ). The trench itself is an unusual feature, being the deepest point in the Atlantic Ocean (>8 kilometers or >5 miles deep) and exhibiting the lowest free-air gravity anomaly on earth (Reference 581). It lies about 120 kilometers (75 miles) north of Puerto Rico and is about 1750 kilometers (5700 feet) long and 100 kilometers (62 miles) wide. It is located where the North America Plate is subducting under the Caribbean Plate. The subduction is highly oblique (10 to 20°) to the trench axis with a large component of left-lateral strike-slip motion. The trench is also characterized by a large negative free-air gravity anomaly, -380 mGal, which indicates the presence of an active downward force (Reference 581). This gravity anomaly is located 50 kilometers (31 miles) south of the trench with a water depth of 7950 meters (26,000 feet). A carbonate platform that is tilted strongly to the north provides evidence for extreme vertical tectonism in the region. Starting in the Late Oligocene, the platform strata were deposited as a thick, flat-lying sequence on top of Cretaceous to Paleocene arc rocks. At 3.5 Ma, the carbonate platform was tilted by 4° toward the trench over a period of less than 40,000 years (Reference 582). The northern edge of the carbonate platform is at a depth of 4000 meters (13,000 feet), and its reconstructed elevation on land in Puerto Rico is at +1300 meters (4300 feet) (Reference 582).

The physiographic and structural features of the trench were imaged in 2002 to 2003 using the SeaBeam 2112 multibeam system by the National Oceanic and Atmospheric Administration (NOAA). Backscatter mosaic images derived from the multibeam bathymetry data aided in interpretation (Reference 582). The bathymetric data obtained by NOAA illustrate in great detail the northern edge of tilted carbonate platform and southern edge on land. The images also show thrust faults, normal faults, strike-slip faults, the head scarp of slope failures, debris toes, fissures in the seafloor, a pull-apart basin, and the location of a probable extinct mud volcano. In addition, photographic images of the sea floor, obtained by the USGS, show that slabs of limestone (70 kilometers or 43 miles wide) have broken off and slid into the trench (Reference 582) (Subsection 2.5.1.1.5 contains a discussion of submarine landslides associated with the Puerto Rico Trench).

Stratigraphy of the Puerto Rico Trench

The Puerto Rico Trench can be divided into a western and eastern part at about 65 to 66° W. The western part includes the deepest part of the trench and is associated with the most oblique convergence. This part is 10- to 15-kilometers (6 to 10 miles) wide and 8300- to 8340-meters (27,200- to 27,400-feet) deep relative to mean sea level. The trench floor is flat and covered by pelagic sediments. Seismic profiles show the western part of the trench to be underlain by rotated blocks of the North America Plate that indicate trench subsidence (Reference 582). The trench floor narrows to the west and abruptly shallows to 4700 meters (15,400 feet) as it turns into the Hispaniola Trench, where convergence is more perpendicular. The eastern part of the trench is shallower by 700 meters (2300 feet) and more rugged than the deep western part. In the eastern section, the subducting North America Plate is observed in seismic lines to be broken into blocks that are not rotated (Reference 582).

The basin plain in the floor of the Puerto Rico Trench provides an example of a turbidite deposit resulting from a gravity flow event of regional derivation (Reference 583). The largest correlatable coarse layer within piston coring range on this basin plain extends for at least 300 kilometers (190 miles) with maximum thicknesses of close to 200 centimeters (6.6 feet). Although small by Hatteras or Sohm Abyssal Plain standards (see discussion of megasedimentary events in Subsection 2.5.1.1), this turbidite represents a sizeable volume of material to be derived from relatively small source areas. The volume of this flow, called the Giant Turbidite, was first estimated by Connolly and Ewing (Reference 584) to be 30 kilometers^3 (7.2 miles^3), but much more detailed coring reveals a more likely volume of 2 kilometers^3 (0.5 miles^3) (Reference 583). Apparently a turbidity current was produced by a very large seismic event, perhaps affecting the islands of Puerto Rico and Hispaniola and the Virgin Platform simultaneously. Material flowing into the western end of the trench most likely was derived from Hispaniola, and material at the eastern end of the trench came from the slope of the Virgin Platform. However, the bulk of the sediment of the Giant Turbidite almost certainly was derived from the insular margin of Puerto Rico (Reference 315).

Structures of the Puerto Rico Trench

The island of Puerto Rico is located within an approximately 250-kilometer wide deformation zone associated with the northern Caribbean-North America plate boundary. Deformation within this zone largely is controlled by left-lateral strike-slip faulting (Reference 858). A 535-kilometer (330-mile) long fault is located 10 to 15 kilometers (6 to 10 miles) south of the Puerto Rico trench and

passes through rounded hills that form the accretionary prism. The fault is interpreted to accommodate left-lateral motion because it is apparently associated with a left-stepping pull-apart depression. Seismic reflection data show that the steeply dipping fault penetrates 5 kilometers (3 miles) through the accretionary sediments before terminating in the subduction interface. Part of this fault trace was first identified as a weak lineament on a GLORIA backscatter image and was named the Northern Puerto Rico Slope fault zone (NPRSFZ) (or "Bunce fault") (Reference 670) (Figure 2.5.1-308). The NPRSFZ ends at the western end of the Puerto Rico Trench in several splays and appears to be the only active strike-slip fault. Its proximity to the trench suggests that slip along the subduction interface is oblique. Another fault closer to Puerto Rico, the South Puerto Rico Slope fault zone (SPRSFZ), has no clear bathymetric expression (Reference 582).

The NPRSFZ is deflected southward at 65° W, perhaps due to stress by the oblique subduction of a localized topographic ridge on the North America Plate known as the Main Ridge (Figure 2.5.1-308). Ten Brink et al. (Reference 582) suggest that the Main Ridge is underlain by a subducted ridge of seamounts because its axis is perpendicular to the observed abyssal-hill grain of the subducting North America Plate. Ten Brink et al. (Reference 582) also suggest that the resistance to subduction of the buoyant Main Ridge has resulted in the formation of local tectonic structures, including thrust and strike-slip faults and a reentrant in the trench axis.

A fault trace at the western edge of the Puerto Rico Trench is interpreted by ten Brink et al. (Reference 582) to be the eastern end of the Septentrional fault (Figure 2.5.1-308). The fault ends abruptly in a 1000-meter- (3280-feet-) deep circular depression 25 kilometers (15 miles) west of the Mona Rift. The Mona Rift consists of three en echelon depressions with depths that range from 5000 to 8150 meters (16,400, to 26,700 feet), which cut the carbonate platform and extend almost to the NPRSFZ (labeled "Bunce fault" in Figure 2.5.1-308) (References 582 and 585). The rift accommodates east-west extension between Hispaniola and Puerto Rico (Reference 585). A large slump failure along the western wall of the upper rift basin may be related to the 1918 earthquake and tsunami (References 319 and 580).

New multibeam bathymetry of the entire Puerto Rico trench reveals numerous retrograde slope failures at various scales at the edge of the carbonate platform north of Puerto Rico and the Virgin Islands (Reference 887). This, together with the fact that the edge of the carbonate platform is steeper than most continental slopes, indicates a higher potential for run-up, possibly as much as 20 meters (66 feet), than along many other U.S. coasts (Reference 887). The tilted carbonate

platform of Puerto Rico provides evidence for extreme vertical tectonism in the region. The carbonates were horizontally deposited over Cretaceous to Paleocene arc rocks starting in the Late Oligocene. Then, at 3.5 million years before present, the carbonate platform was tilted by 4° toward the trench over a time period of less than 40,000 years (Reference 582), such that its northern edge is at a depth of 4000 meters (13,100 feet) and its reconstructed elevation on land in Puerto Rico is at +1300 meters (+4300 feet) (Reference 887). The precariously perched carbonate platform contributes slumped material made of carbonate blocks that fail, at least in initial stages, as a coherent rock mass.

Two semicircular escarpments, 30 to 50 kilometers (20 to 30 miles) across are mapped along the northern edge of the carbonate platform at a distance of 35 to 50 kilometers north of Puerto Rico. The bathymetry and side-scan images indicated that the semicircular escarpments were shaped by continuous retrograde slumping of smaller segments. Fissures near the edge of the carbonate platform indicate that the slumping process is ongoing (Reference 582).

Seismicity of the Puerto Rico Trench

LaForge and McCann (Reference 577) model the PRSZ as two segments: (a) a shallowly dipping segment that ranges in depth from 10 to 40 kilometers (6 to 25 miles) and (b) a steeper portion extending to 130 kilometers (80 miles) depth (Figure 2.5.1-310). LaForge and McCann (Reference 577) also distinguish between an eastern and western Puerto Rico subduction zone based on the location of the impingement of the Bahama Bank on the trench at about 66.8° W longitude (Figure 2.5.1-310). This is due to denser seismicity in the western part, likely related to resistance of the buoyant Bahama Bank to subduction and therefore tighter seismic coupling in this area. Similarly, Mueller et al. (Reference 589) divide the Puerto Rico subduction zone into eastern and western portions, and model magnitude 7.9 earthquakes in the eastern section with return periods of 190 years, and magnitude 8.0 events in the western section with return periods of 200 years. LaForge and McCann (Reference 577) use both maximum moment and exponential models in the two zones, allowing for a wider range of magnitudes. However, the rates of the largest magnitude events are similar to Mueller et al. (Reference 589), on the order of several hundred years.

Seismicity of magnitude <7 is abundant in the Puerto Rico subduction zone, but only two events have exceeded magnitude 7 in the 500-year historical record. McCann (Reference 600) suggests that a magnitude 8 to 8.25 interface earthquake occurred on this segment in 1787 {(Phase 2 catalog M_w 8.03),} SOF 2.5.1-2

rupturing from roughly Mona Canyon on the west to the Main Ridge on the east. This earthquake caused widespread damage on the island. In 1943, a magnitude 7.8 earthquake {(Phase 2 catalog M_w 7.60)} ruptured an approximately 80-kilometer (50-mile) wide section of the subduction zone across Mona Canyon, and on the basis of a focal mechanism, it was judged to have occurred on the shallow interface (Reference 591). SOF 2.5.1-2

2.5.1.1.2.2.4 Geology of the Muertos Trough/Mona Passage

Physiography of the Muertos Trough/Mona Passage

The Muertos Trough is an east-west-trending depression, which is slightly concave to the north. The trough is 650 kilometers (400 miles) long and runs from the Beata Ridge in the west to the insular slope of the Aves Ridge in the east (Figures 2.5.1-202 and 2.5.1-311). The water depths of the trough are greater than -5550 meters (-18,000 feet). The Muertos Trough consists of elongated, narrow, sub-parallel ridges with the seaward slope steeper than the landward slope. The accreted pelagic sediments are from the foreland region and the turbiditic sediments are mostly derived from Hispaniola and Puerto Rico. The turbidity currents may form the deep canyons whereas the rivers carry the suspended material from onshore areas to the Muertos Margin (Reference 592).

Stratigraphy of the Muertos Trough/Mona Passage

The A" and B" seismic reflector horizons of the Venezuelan Basin gently dip to the north beneath the turbidite fill of the Muertos Trough and continue beneath the insular slope of the Muertos Trough. The insular slope that runs parallel to the trough is formed by an east-west deformed belt (Reference 592).

The axial slope of the Muertos Trough becomes deeper from east to west with a maximum depth of about -5580 meters. The trough is marked by a smooth seafloor with approximately 0° slope. The trough is characterized by a series of wedges of smooth, closely spaced, and subparallel reflectors with high seismic reflectivity. Core samples taken in 2005 indicate that the trough seafloor comprise different sources of sediments, including interbedded turbiditic and pelagic sediments, that are underlain by homogeneous carbonate pelagic mudstones and siltstones from the Venezuelan Basin. The turbidite wedge is separated from the Venezuelan Basin layers by a basal unconformity (Reference 592).

The toe of the insular slope, which runs parallel to the east-west deformed belt, defines the northern boundary of the Muertos Trough. In the northern boundary between the Venezuelan Basin and the toe of the insular slope, there is high

lateral variability in morphological features such as turbidite trough fill, onlap, detachment, deformation front, basal unconformity, anticlinal ridge, and incipient slope basin that appear located forward of the main deformation front. In the eastern part of the northern boundary there is no distinct morphological trough, which might possibly be due to higher sediment supply. In this eastern part of this boundary, the turbidite wedge is wider and thicker and continues southwards. Fault escarpments that separate the flat seafloor of the trough wedge and the northward slope of the Venezuelan Basin are located where the insular slope meets the Venezuelan Basin at the southern margin of the Muertos Trough (Reference 592).

The western segment is an elongated flat area that is the deepest part of the Muertos Trough. It is confined to the south by escarpments that are subparallel to the deformation front, which forms a structural ponded basin. The width of the confined trough is variable; however, it becomes narrower and shallower eastward. The eastern segment is a smooth, gentle bathymetric undulation without a distinct morphological trough (as seen in the western segment). The eastern trough segment does not consist of normal faults in the outer wall of the trough (Reference 592).

The escarpments in the western segment of the Muertos Trough are the result of normal faults that affect the sedimentary cover of the A" and B" reflector horizons. From seismic reflection profiles, at least 20 of these normal fault scarps are observable in the Venezuelan Basin near the trough and beneath the turbidite wedge in the western segment. In the eastern segment of the Muertos Trough, the single anticline located in the main deformation front is forming a small ridge that is sub-parallel to the front. This anticline has an elongated shape due to the activity of a propagating blind thrust that is folding the trough fill material. This thrust is the result of the propagation of the detachment surface toward the turbidite wedge; however, horizontal turbidite layers bury the thrust, which is interpreted to suggest a low rate of recent activity (Reference 592).

Granja-Bruña et al. (Reference 592) divide the Muertos Trough into three east-west-trending provinces: the lower slope, the middle slope, and the upper slope. The lower slope is at the base of the insular slope from the toe of the deformation front to the convex slope break. The middle slope is from the convex slope break to the concave slope break; however, in many places the concave slope break is not well defined in the bathymetry data due to a higher sedimentation rate and lower deformation rate (thrusting activity). When the sedimentation rate is faster than the thrusting activity, slope basins are completely filled, which then forms the terraces. This is seen as a smooth bathymetric profile

with shallower horizontal and smooth downward-dipping sedimentary reflectors. Another characteristic of the middle slope is the imbricate structure, which is similar to the lower slope, but extended slope deposits bury the structure. The upper slope is located between the concave slope break and the edge of the carbonate platform (at the top of the island arc consisting of Hispaniola and Puerto Rico). It is characterized by talus, the steeply sloping area between the carbonate platform and the terrace deposits located at the base of the steep slope (the material is derived from the carbonate platform), and by the presence of terraces with gentle seaward slopes. Important sedimentary processes such as mass movement, gravity flows, slumping, and sliding define the talus area. The mass movement and gravity flows show a smoother bathymetry. The slumped areas are sometimes aligned with the escarpment and ridges (Reference 592).

Structures of the Muertos Trough/Mona Passage

The Muertos Trough forms the boundary between the Caribbean Plate to the south, the Hispaniola microplate to the northwest, and the Puerto Rico-Virgin Islands (PRVC) microplate to the northeast. These two microplates are separated by the MPEZ, a region of east-west extension (Figure 2.5.1-202).

South of the island of Puerto Rico, the North Caribbean deformed belt comprises two primary features: the Muertos thrust belt (labeled "LMDB" on Figure 2.5.1-327) and the Anegada passage (Figures 2.5.1-210, 2.5.1-308, and 2.5.1-328). The Muertos Trough is the ocean floor manifestation of the Muertos subduction zone. It is about 5 kilometers (about 3 miles) deep near central Hispaniola, becoming shallower toward the east, reaching a depth of 4 kilometers (2.5 miles) at the longitude of eastern Puerto Rico, where the bathymetric feature disappears. The Muertos thrust belt (Figure 2.5.1-311) appears to be an accretionary wedge structure (Reference 593). Based on GPS measurements, Jansma et al. (Reference 594) calculate an average compressive relative motion of 2.4 millimeters/year between southwestern Puerto Rico and stable Caribbean Plate, in a west-southwest direction. This plate boundary thus accommodates largely left-lateral relative motion, with a north-south compressive component (Figure 2.5.1-311).

Seismicity of the Muertos Trough/Mona Passage

Seismicity in the vicinity of the Muertos Trough appears to be more dense to the west (Reference 595). A great earthquake of estimated magnitude 8.0 {(Phase 2 earthquake catalog M_w 7.28)} occurred on the Muertos thrust belt in 1751 (Reference 596) (Figure 2.5.2-214). A M_S (surface-wave magnitude) 6.7 {(Phase SOF 2.5.1-2 SOF 2.5.1-2

2 earthquake catalog M_w 6.70)} earthquake that occurred in 1984 in the western Muertos thrust belt displays a thrust mechanism consistent with the direction of relative plate motion and location of the subducting Caribbean Plate (Reference 595). However, no moderate to large earthquakes recorded in the historical record appear on the Muertos subduction zone east of Hispaniola. A possible exception is an event of approximately magnitude 6 that was felt in southwest Puerto Rico in 1670 (Reference 579). However, an origin of this earthquake on one of the MPEZ faults or an unidentified fault in western Puerto Rico is equally likely.

LaForge and McCann (Reference 577) assigned slip rates to the Muertos thrust belt of 1.2 and 0.6 millimeters/year to sections west and east of 67° W, respectively, based on constraints from GPS measurements and historic seismicity. This corresponds to return periods of a few thousand years for earthquakes in the M_w 7.8 to 8.2 range, and should be considered conservative values. Mueller et al. (Reference 589) does not consider the Muertos thrust belt to be an active feature, citing lack of positive evidence. However, McCann (Reference 597) performed a joint hypocenter-velocity model inversion using local earthquakes and identifies well-defined active seismicity on the Muertos thrust belt beneath Puerto Rico. The sense of motion on the Muertos thrust belt beneath Puerto Rico is a subject of controversy. Despite the highly oblique relative plate motion, no strike-slip faults are seen on land or in the accretionary prism, which are typical of such plate boundary environments (e.g., the Septentrional fault of northern Hispaniola). On this basis ten Brink et al. (Reference 593) suggest that all motion on the Muertos thrust belt is due to compressive stresses transmitted from the Puerto Rico thrust belt to the north. Until focal mechanisms from well-located earthquakes on the Muertos thrust belt are available, this question will remain unanswered. In summary, while the Muertos subduction zone appears to be an active feature beneath Puerto Rico, its seismic potential remains enigmatic.

At about 65° W, bathymetric expression of the Muertos Trough disappears, and the North Caribbean deformed belt is expressed as the Anegada Passage (Figures 2.5.1-210, 2.5.1-308, and 2.5.1-328). The Anegada Passage is underlain by a late Neogene complex of extensional basins and intervening ridges in the northeastern Caribbean. It cuts the older Antillean Arc Platform, from the Puerto Rico-Lesser Antilles Trench in the northeast to the Muertos Trough in the southwest. It is an east-northeast-striking extensional zone approximately 50 kilometers (31 miles) wide, which separates the Puerto Rico-Virgin Islands microplate from the Caribbean Plate to the south (Reference 598). Several deep

basins, including the Virgin Islands and Whiting Basin (Figures 2.5.1-312 and 2.5.1-313), were formed between 11 and 4.5 Ma as the Puerto Rico-Virgin Islands microplate underwent approximately 20° of counterclockwise rotation. This rotation is postulated to be due to the impingement of the Bahama Bank on the northwest corner of Puerto Rico (e.g., Reference 599). Although no rotation has been noted during the last few million years, active deformation in the Anegada Passage basins is indicated by abundant seismicity, including a tsunamigenic event with an estimated magnitude of 7.3 {(Phase 2 earthquake catalog M_W 7.50)} that occurred in 1867 (Reference 600). SOF 2.5.1-2

The Investigator fault (Figure 2.5.1-312) cuts the slope between the Puerto Rico Island Platform and the Muertos Trough, and exhibits north-south extension that increases from west to east. Based on orientation and bathymetric expression, LaForge and McCann (Reference 577) divide the Investigator fault into west and east segments (Figure 2.5.1-312). They estimate slip rates of 0.8 and 1.5 millimeters/year on the west and east segments, respectively.

2.5.1.1.2.2.5 Geology of the Nicaraguan Rise

The Nicaraguan Rise (or Plateau) is a major submarine crustal feature that extends northeast across the Caribbean Sea from the coast of Honduras and Nicaragua to northeast of Jamaica, where it intersects the southwestern part of the Southern Peninsula of Haiti. The Nicaraguan Rise covers an area of some 413,000 kilometers^2 (159,500 miles^2) (Figure 2.5.1-210). Little is known about its structure and lithological composition, and it is probably the least understood major crustal feature in the Caribbean (References 810 and 811).

The broad shelf area of the Nicaraguan Rise to the northeast of the land areas of Honduras and Nicaragua and extending to Jamaica (the upper Nicaraguan Rise of Reference 526) is here termed the northern Nicaragua Rise (Figure 2.5.1-210). The southern boundary of the northern Nicaraguan Rise is the Pedro fault (or Fracture) zone. The southern Nicaraguan Rise extends from the Pedro fault (or Fracture) zone to the Hess Escarpment (Figure 2.5.1-319).

Morphologically the northern Nicaraguan Rise is characterized by a series of carbonate banks and shelves separated by channels and basins that have evolved from a continuous carbonate "megabank" established over basement highs (References 300, 864, and 601). In essence, the submarine shelf area of the northern Nicaraguan Rise is a topographic extension of the Precambrian-Paleozoic continental Chortis block (References 850, 851, 852, and 319). For this reason Meyerhof (Reference 853) and others maintained that a

considerable part of the Nicaraguan Rise must be underlain by Pre-Mesozoic continental crust. New information, however, indicates that the Chortis block is not compositionally homogeneous (Reference 812) and that most of the basement rock of the northern Nicaraguan Rise is not of continental composition but consists of island arc crust and is likely to be of similar composition to the island of Jamaica near the northern end of the rise (References 601, 528, 811, and 217). With the exception of the northern Honduran borderlands, no rocks older than Cretaceous in age are known on Jamaica or have been reported from any part of the Nicaraguan Rise (Reference 812).

The Nicaraguan Rise represents a broad carbonate platform that formed over an calc-alkaline island arc basement to the north and over block-faulted oceanic plateau crust to the south (Reference 219). The San Pedro fracture zone (Figure 2.5.1-319) represents the boundary between these two basement types, separating the northern Nicaraguan Rise and the southern Nicaraguan Rise. The area underlain by calc-alkaline island arc includes Jamaica, the shallow banks, and the intervening deeps of the northern Nicaraguan Rise, and is bounded on the north by the Cayman Trough. The southern Nicaraguan Rise is separated from the Colombian Basin to the southeast by the Hess Escarpment (Reference 219) (Figure 2.5.1-319).

The carbonate platform of the northern and southern Nicaraguan Rise was drowned by the Miocene carbonate crash (see discussion of carbonate platforms: growth, shut downs, and crashes in Subsection 2.5.1.1.1.1.1.2). Typical sediments found in the middle/upper Miocene carbonate crash interval (9.6 to 13.5 Ma) are micritic nannofossil chalk and clayey nannofossil chalk. The drowning interval is equivalent to the lithologic Unit I found at Site 1000 of ODP Leg 165 (Reference 299). The Unit I carbonate platform sediments display the high sedimentation and accumulation rates averaging 47.0 meters/m.y. (4.5 to 7.5 $g/cm^2/k.y.$), the mass accumulation rates were calculated from the sedimentation rates. The mass accumulation rates results for the noncarbonated portion increased steadily from the bottom of the section to a peak at approximately 380 meters below sea floor (mbsf) (approximately 11 Ma) and then declined upsection to a low at approximately 230 mbsf (approximately 6.5 Ma). Carbonate mass accumulation rates basically parallel the noncarbonated mass accumulation rates record except at approximately 450 and 380 mbsf (12.8 to 10.8 Ma) where the mass accumulation rates converge, a sharp peak centered at approximately 180 mbsf in the uppermost Miocene section (approximately 5.5 Ma) and a broader peak in the Pliocene centered at 100 mbsf (approximately 3.5 Ma). The bulk mass

accumulation rate record is dominated by the carbonate component and mostly follows the trends of carbonate mass accumulation rates (Reference 299).

The high-carbonate mass accumulation rates at Site 1000 generally indicate the proximity to a periplatform environment, where pelagic settling is mixed with other fine sediments derived from the surrounding banks. The highest carbonate mass accumulation rates are out of sync with turbidite occurrence, which can be interpreted to reflect increased pelagic input during the lower middle Miocene; it is also consistent with an increase in primary productivity. Non-carbonate mass accumulation rates at Site 1000 show an increase from the base of the cored interval throughout the late middle Miocene with peaks in the lower and middle Miocene (Reference 300).

2.5.1.1.2.2.5.1 Geology of the Northern Nicaraguan Rise

Physiography of the Northern Nicaraguan Rise

The carbonate banks and reef shoals that are part of the northern Nicaraguan Rise are the Pedro Bank, Thunder Knoll, Rosalind Bank, Serranilla Bank, and Alice Shoal (Figure 2.5.1-314). These carbonate banks, knolls, and shoals are separated by four northeast-trending channels or troughs that range in depth from less than 400 meters to 1500 meters (from less than 1300 feet to 4900 feet). The channels deepen towards their ends but in most cases merge with canyons that lead down to the Pedro Escarpment or down into the Cayman Trough. Between the southern end of the Cayman Trough and the northern part of the northern Nicaraguan Rise, there is a broad boundary that rises to 500 meters (1640 feet). South of the Pedro Bank, the channel is floored by a plain at 1300 to 1400 meters (4300 to 4600 feet) depth. Linear depressions occur along the base of the Pedro Escarpment. The Jamaican Plain occupies one of these depressions. The line of the Pedro Escarpment and the Jamaican Plain is interrupted by the Banco Nuevo Ridge (References 555, 526, 558, 499, and 300).

Stratigraphy of the Northern Nicaraguan Rise

The rocks recovered from the north side of the northern Nicaraguan Rise are similar to those from the Cayman Ridge. Schistose metamorphics and plutonic rocks are absent from the stratigraphic section or might not have been sampled. However, breccias, wackes, and arenites contain detrital material indicative of granitic and metamorphic sources. Most of the metamorphics are low-grade greenschists. Shearing and cataclasis are evident in the rocks. An example is a quartzite that was composed of fragmental, recrystallized quartz in a

polycrystalline quartz groundmass with minor opaque bands and degrees of recrystallization of fossiliferous micritic carbonates (Reference 528).

Interbedded arenites and graywackes with lesser amounts of argillite and carbonates are the most abundant sedimentary rock types along the northern Nicaraguan Rise. A reddish brown color on some of the breccias and wackes is due to oxidation of iron oxides and red-brown clay (Reference 252) (see discussion of marine red beds associated with LIPs in Subsection 2.5.1.1). Clastic carbonates and sedimentary rocks with carbonate cement and tuffs and tuffaceous clastic rocks were also recovered (Reference 528).

Dredging on the Walton Basin; the Pedro, Rosalind, and Diriangen Channels; and the northern part of Rosalind Bank recovered neritic limestone samples (consisting mostly of corals [*Montastrea costata*, *Stylophora* cf. *imperatoris*, and *Porites trinitatis*], green algae, and the benthic foraminifer, *Miogypsina gunteri*). The fossiliferous assemblages yielded an early Miocene age (22 to 20 Ma). High resolution seismic profiles in the interbank channels across the northern Nicaraguan Rise reveal that the basin and channel subseafloor consists of a series of foundered, faulted, and folded shallow carbonate banks and barrier reefs. These carbonate banks and barrier reef materials, possibly as young as Early/Middle (?) Miocene, were buried under a relatively recent periplatform sedimentary cover. The top of the neritic carbonate layer is marked by a major unconformity (Reference 236).

The northern Nicaraguan Rise was continuously covered by shallow carbonate banks and barrier reefs. Partial foundering of these banks and reefs occurred during the Middle Miocene and possibly as early as late Early Miocene (References 236 and 853). Foundering of the reefs and banks of the northern Nicaraguan Rise might have been the direct consequence of the initiation of the Caribbean Current and the development and strengthening of the North Atlantic Western Boundary Current (Figure 2.5.1-213) in the middle Miocene. (Reference 236).

Structures of the Northern Nicaraguan Rise

The Nicaraguan Rise is bounded by the Cayman Trough to the north and by the Hess Escarpment to the south (References 601 and 602) (Figure 2.5.1-314). The Hess Escarpment extends for 1000 kilometers (620 miles) in a southwesterly direction and forms a divide between the Colombian Basin to the south and the Nicaraguan Rise to the north. It is a linear northeast-trending escarpment of highly variable relief (100 to 3000 meters (330 to 9800 feet), facing the Colombian Basin

(Reference 526). Locally, an undeformed onlap sequence is seen over the escarpment and has a possible age of Late Cretaceous to Recent. The Hess Escarpment appears to form a major crustal boundary that separates blocks with different Neogene fault styles and basement characteristics. To the north of the southwestern end of the escarpment Neogene and possibly Quaternary north-south striking normal faults form a series of horsts and grabens (Reference 493).

The Pedro fault zone (Figure 2.5.1-317) divides the northern Nicaraguan Rise from the southern Nicaraguan Rise. Arden (Reference 601) describes oil industry wells from the Nicaraguan Rise that encountered plutonic rocks of Late Cretaceous and early Cenozoic age that are unconformably overlain by Cenozoic carbonate banks of the Nicaraguan Rise.

The western half of the northern Nicaraguan Rise is dominated by complex basement structural rises and normal faults compiled by Case and Holcombe (Reference 480) from private industry data. These faults have no consistent direction and range from <20 kilometers (<12 miles) to approximately 100 kilometers (62 miles) long. Rogers et al. (Reference 603) relate this faulting to the Colon fold-thrust belt of eastern Honduras, which records a Late Cretaceous shortening event due in part to the suturing of the Siuna terrane to the eastern Chortis terrane in the Late Cretaceous. They recognize thrust faulting and normal faulting in this area of the northern Nicaraguan Rise as starting in the late Cretaceous (post-80 Ma) and continuing into the Eocene, but ending by the beginning of the Oligocene.

The Eastern half of the northern Nicaraguan Rise contains many fewer identified faults, with the majority of these faults concentrated on the north near the Cayman Ridge province and in the south near the Pedro fault zone (Reference 480).

Seismicity of the Northern Nicaraguan Rise

{The Phase 2 earthquake catalog (Subsection 2.5.2.1.3) indicates moderately sparse seismicity in the northern Nicaragua Rise. Magnitudes of these events range from approximately M_w 3 to 7, with all but one event less than M_w 6.0 (Phase 2 earthquake catalog)} (Figure 2.5.1-267). The majority of the events are located proximal to the Cayman Ridge. Earthquakes south of the Cayman Ridge may have occurred on the Cayman Ridge, but are mislocated, or may be correctly located and are due to stress effects near the Cayman Ridge. The Phase 2 earthquake catalog extends south to 15° N latitude (Figure 2.5.2-201) and does not cover the southern half of the northern Nicaraguan Rise. SOF 2.5.1-2

2.5.1.1.2.2.5.2 Geology of the Southern Nicaraguan Rise

Physiography of the Southern Nicaraguan Rise

The southern (or lower) Nicaraguan Rise appears to be a thickened oceanic crustal block bounded on the northwest by the Pedro Escarpment, on the southeast by the Hess Escarpment, on the northeast by the Morant Trough, and on the southwest by the San Andres Trough. The Hess Escarpment and other rift valleys and escarpments with the same northeast trend, occur across the southern Nicaraguan Rise (Figure 2.5.1-319). Scattered volcanic cones rise above the floor of the rise (e.g., La Providencia and San Andres Islands). Overall, the rise lies at a water depth of 2000 to 4000 meters (6500 to 13,100 feet), with depth increasing generally to the southeast. Based on multichannel seismic refraction data, the crust has been regarded as oceanic in origin, similar to the crust in the Colombian Basin to the south (References 526 and 604).

Stratigraphy of the Southern Nicaraguan Rise

The Caribbean crust in the southern Nicaraguan Rise area has been penetrated by drilling during DSDP Leg 15 (Site 152) and ODP Leg 165 (Site 1001) (Figure 2.5.1-211). ODP Site 1001 is located on the Hess Escarpment and is approximately 40 kilometers (25 miles) west-southwest of DSDP Site 152 (Figure 2.5.1-211). Seismic reflection data obtained from DSDP Leg 15 suggest that most of the deposits of the southern Nicaraguan Rise are uniformly pelagic and not characteristic of shallow-water deposits. Detailed lithologic descriptions are available for drill cores from both DSDP Site 152 and ODP Site 1001 (e.g., References 299, 604, and 606). The following provides a representative description of lithologies from ODP Site 1001.

According to Sigurdsson et al. (Reference 299), core recovered at ODP Site 1001 consists of four lithologic units. The basaltic basement (Unit IV) is radiometrically dated at about 77 Ma (mid-Campanian). Unit IV consists of a succession of 12 formations that likely represent individual pillow lavas and sheet flows. The margins are often highly vesiculated and glassy. The igneous basement is overlain by three sedimentary units. Based on fossil assemblages, the lowermost sedimentary unit, Unit III, is a Late Cretaceous sedimentary section of calcareous limestone and claystone with interbedded foraminiferal rich sand layers and ash layers that are thicker and more frequent in the lower part of Unit III. Unit II generally consists of calcareous chalk with foraminifers to mixed sedimentary rock with clay, and is interbedded with chert and volcanic ash layers and, near the bottom, is more clay rich with thin interbeds of foraminiferal rich sand layers.

Based on fossil assemblages, Unit II corresponds with the Paleocene-Eocene section. The uppermost sedimentary unit, Unit I, generally consists of clayey nannofossil sediment to clayey nannofossil ooze with foraminifers, showing highly variable carbonate contents and magnetic susceptibility throughout the column (Reference 299). Based on fossil assemblages, Unit 1 corresponds to the Miocene-Pleistocene section.

The Cretaceous/Tertiary boundary interval was recognized in core recovered at ODP Site 1001 (Holes A and B); several clay rich units between the basal Paleocene and upper Maastrichtian limestones were also recovered. A 1.7- to 4.0-centimeter (0.7- to 1.6-inch) thick light gray, highly indurated limestone of earliest Paleocene age overlies the clay rich strata constituting the bulk of the recovered boundary deposit. The topmost layer of the boundary deposits is a 3.5-centimeter (1.4-inch) thick massive clay. This unit contains rare grains of shocked quartz and overlies a 3.5-centimeter (1.4-inch) thick smectitic claystone with dark green spherules. The base of the boundary deposit is a 1- to 2-centimeter (0.4- to 0.8-inch) thick smectitic clay layer with shaly cleavage. In addition to these three clay layers, two pieces of polymict micro-breccia were recovered consisting of angular clasts (<6 millimeters [<0.2 inches]) of claystone and limestone in an unconsolidated matrix of smectitic clay. The total boundary deposit has an inferred thickness of approximately 25 centimeters (9.8 inches) (Reference 299).

According to Sinton et al. (Reference 606), ^{40}Ar-^{39}Ar incremental heating experiments of the basalts recovered on the southern Nicaraguan Rise in the vicinity of ODP Site 1001 and DSDP Site 152 indicate that the youngest period of volcanism occurred at about 81 Ma. Electron microprobe analyses show that the basalts are tholeiitic and generally similar to mid-ocean ridge basalts in composition. The comparatively low incompatible element concentrations (at the same MgO concentrations) in the ODP Site 1001 glass may signify derivation from either a more depleted mantle source or higher degrees of partial melting. The volcanism at this site is part of the continuing widespread submarine volcanism in the region that postdates the initial 90-Ma eruptions of the Caribbean oceanic plateau.

Structures of the Southern Nicaraguan Rise

The southern Nicaraguan Rise is a deep region of highly variable relief with rare scattered small carbonate banks, separated from the Colombian Basin in the south by the Hess Escarpment and separated from the northern Nicaraguan Rise by the Pedro fault zone (Reference 300) (Figure 2.5.1-317). Faulting in the

southern Nicaraguan Rise ranges from <20 kilometers (<12.4 miles) to over 100 kilometers (62 miles) long and is dominated by a general west-southwest to east-northeast direction. It is comprised primarily of normal faults (Reference 480). Holcombe et al. (Reference 526) describe evidence for young faulting and volcanism within seismically active rifts imaged by marine seismic reflection profiles from the southern Nicaraguan Rise, and propose that diffuse east-to-west rifting of the rise occurs in response to sinistral shear along its bounding escarpments.

Seismicity of the Southern Nicaraguan Rise

{The Phase 2 earthquake catalog (Subsection 2.5.2.1.3) indicates sparse seismicity within the southern Nicaraguan Rise, all of which are $M_w \leq 5.5$.} These earthquakes are primarily located in the northern portion of the southern Nicaraguan Rise near the Cayman Ridge, the Cayman Trough, and the southernmost extent of the Greater Antilles deformed belt. This seismicity, therefore, is likely related to its proximity to these active tectonic features. The Phase 2 earthquake catalog extends south to 15° N latitude (Figure 2.5.2-201) and does not cover the southern one-third of the southern Nicaraguan Rise. SOF 2.5.1-2

2.5.1.1.2.2.6 Geology of the Colombian Basin

Physiography of the Colombian Basin

The center of the Caribbean Plate is divided into the Colombian and Venezuelan Basins separated by a north-south topographic high, the Beata Ridge (Figure 2.5.1-210) (Subsection 2.5.1.1.2.2.8). The basins are covered by flat-lying sediments and irregularities in the topography of the basement are attributed to volcanic features. The Colombian Basin is bounded by the southern Caribbean deformed belt to the south, the North Panama deformed belt to the west, and the Hess Escarpment to the north, a prominent, 1000 kilometers (620 miles) long bathymetric lineament. The southern Nicaraguan Rise (Subsection 2.5.1.1.2.2.5.2) and the Cayman Trough (Subsection 2.5.1.1.2.2.1) are located to the northwest of the Hess Escarpment (Reference 606). The North Panama and the South Caribbean deformed belts are underlain by thick sections of folded Cretaceous and Cenozoic sedimentary deposits. The deformed belts merge in the Gulf of Uraba where they form a V-shaped embayment. The western margin of the Colombian Basin is a narrow (10 to 20 kilometers or 6 to 12 miles) continental shelf offshore of Costa Rica and Panama. The eastern margin of the basin is defined by scarps related to normal- or oblique-slip faulting on the western side of the Beata Ridge (Reference 607).

Stratigraphy of the Colombian Basin

In the Colombian Basin, recent faults strike northwest and bound the Mono Rise. A major unconformity suggests that uplift along current active northwest striking fault zones bounding the Mono Rise began in middle Miocene time (Reference 493).

The Magdalena Fan and the Colombian Plain dominate the sea-bottom morphology of the eastern half of the 3000 to 4000 meters (9800 to 13,100 feet) deep Colombian Basin. The Costa Rica Fan and Panama Plain occupy the southwestern extremity of the basin. Relief ranges from about zero to a few tens of meters; higher relief is associated with the Mono Rise, uplifted fault blocks, and channels on the fans. The dominant sediment source for the Colombian Plain and Magdalena Fan is the Rio Magdalena that drains from the Colombian Andes. The Costa Rica Fan's sediment source is from the rivers of eastern Honduras and the Central American mountains. The Panama Plain's sediment source is from the west in addition to the Rio Atrato in Colombia. Channels that are from the Panama Plain that lead into the Colombian Plain provide a pathway for Central American sediments to reach the center of the Colombian Basin (Reference 526).

Only the upper Miocene-Recent sediments have been drilled in the Colombian Basin. DSDP Site 154 (11° 0.5.11'N, 80° 22.75'W) was drilled on the Panama Outer Ridge (Figure 2.5.1-211). Sediments consisted of 153 meters (500 feet) of Pliocene and younger pelagic deposits that had constituents mainly composed of foram-bearing nanno-fossil marl. These pelagic deposits overlie a Pliocene and Miocene terrigenous sequence of deposits, which have calcareous, ash-bearing clay interspersed with black beds of pyrite and ash, containing turbidites. DSDP Site 502, Mono Rise (11° 29.42'N, 79° 22.78'W), consisted of cored material that was similar to Site 154; however, no turbidites were present in the calcareous clays of the lower unit (Reference 526) (Figure 2.5.1-211).

Seismic reflection records show that 1 to 3 seconds or about 1 to 4 kilometers (0.6 to 2.5 miles) of strata overlie an irregular oceanic crust in the central and western parts of the Colombian Basin; the strata consists of turbidite sequences, pelagic and hemipelagic deposits. There are two main reflector horizons, the A" and the B". The A" reflector horizon coincides with the top of the Upper Cretaceous-middle Eocene siliceous pelagic carbonates, whereas the B" reflector horizon correlates with the top of the Upper Cretaceous basalt sill/flow complex. In the northeastern most Colombian Basin, the A" and B" reflectors extend beneath the Colombian Plain turbidites that are adjacent to the Beata Ridge and Hess Escarpment and

are locally present around basement structural highs and within the central part of the basin (Reference 526).

Bowland (Reference 607) delineates five seismic stratigraphic units; they are from CB5 (oldest) to CB1 (youngest). Unit CB5 is mostly a sheet-drape deposit consisting of pelagic limestones, chalks, and clays (deposited in an open marine environment) that lies directly on igneous basement and is restricted to structural high areas of the oceanic plateau. The sequence is about 0.3 seconds or 0.5 kilometers (0.3 mile) thick over the Mono Rise and regionally thins to basement lows adjacent to the rise. Thinning of the unit to the west is caused most likely by transition through the carbonate compensation depth and/or erosion in a strong bottom current regime (References 607 and 526).

Unit CB4 is restricted to the highest areas of the Colombian Plateau and has a maximum thickness of about 0.8 seconds or 0.9 kilometers (0.6 mile) in the depression next to the North Panama deformed belt and at the crest of the Mono Rise. The seismic facies are hummocky-mounded to chaotic. This might be due to internal deformation of unconsolidated sediment. The sediments consist of upper Miocene siliceous microfossils and calcareous clay composed of poorly crystallized montmorillonite-smectite that might have a southern Central American province (References 607 and 526).

Units CB3 and CB2 are mid-Eocene to late Miocene in age and consist of unconfined turbidity-flow deposits interbedded with hemipelagic and pelagic layers. The turbidites are probably volcaniclastic related to volcanism north and west of the Colombian Basin during the Tertiary. Eocene and Oligocene limestone and marl occur on the Nicaraguan Rise, which suggests that carbonate-clast turbidites may also be present (References 607 and 526).

Unit CB1 consists of a pelagic sequence on the Mono Rise and on the uplifted Site 154 fault block and gravity-flow deposits elsewhere. The unit includes the younger sediment wedge beneath the Panama Plain and the younger fan sequence underlying the Costa Rica Fan (late Miocene to Holocene in age) (Reference 607).

The crustal layers within the western Colombian Basin have velocities within the range of normal oceanic crust; however, the crustal thickness varies from near normal to more than twice the average for typical oceanic crust. Typical ocean crustal thickness is about 7 kilometers (4 miles). The top of the crust consists of ridges and basins and is at least 18 kilometers (11 miles) below the Mono Rise. Compressional wave velocities within the uppermost basement average about 4.6

kilometers/second. The basement of the western Colombian Basin, including the Mono Rise, exhibits a smooth upper surface and occasionally is stratified as indicated by well defined internal reflectors. Farther east towards the Magdalena Fan the reflectors are absent and the oceanic crustal thickness is about 8.5 kilometers (5.3 miles). Reflectors within the eastern foundation of the Mono Rise overlap the rough basement which indicates that the rise may be younger. Heat flow unit (hfu) averages 1.57 hfu in the western basin but only 1.6 hfu east of the rise (Reference 526).

In an effort to explain the thickness of oceanic plateau crust and corresponding greater depth to the Moho (up to 16 kilometers or 10 miles below sea level), various researchers proposed that the Caribbean was an area of extensive intrusion by primary basaltic magma (Reference 608). The A" and B" reflector horizons show up on seismic profiles in the Colombian and Venezuelan Basins, and samples can be obtained from on land sections in Costa Rica, Colombia, and Curaçao. On DSDP Leg 15, reflector horizon B" was sampled at five drill sites with recovery of only about 15 meters (50 feet) of basement. The samples consist of basalt and diabase whose mineralogy and geochemical characteristics are distinct from those of the typical mid-ocean ridge basalt (Reference 605). This discovery led to the recognition of a Coniacian to early Campanian flood basalt event within the Caribbean. The flood basalt extends for 600,000 kilometers^2 (232,000 miles^2) and is exceptionally thick (up to 20 kilometers or 12 miles). The top of the plateau is the widespread smooth B' seismic reflector (Reference 609).

Radiometric ages indicate that the Caribbean Plateau formed during at least two major magmatic events, the first at about 90 to 88 Ma and the second at about 76 to 72 Ma (Reference 610). Revillon et al. (Reference 611) uses petrographic and geochemical data to demonstrate that the magmas produced during the different episodes have very similar petrological and chemical compositions. These data indicate that all the magmas came from a mantle source of similar composition and that the conditions under which they formed were reproduced at least three times from the Cretaceous into the Tertiary. Evidence to support fractional melts (in the spinel stability field) is the uniform, flat rare earth element patterns found in the gabbros and dolerites that were derived from an isotopically depleted source (Reference 611).

Revillon et al. (Reference 611) dated several samples by the $^{40}Ar/^{39}Ar$ method, either on whole rocks or separated plagioclases. Most samples have ages between 80 and 75 Ma, which are consistent with previous ages within the province, but a subordinate intrusive phase occurred at about 55 Ma (Reference 611).

Structures of the Colombian Basin

The Colombian Basin primarily comprises a depositional basin, with sediments ranging in age from Late Cretaceous to Eocene (Reference 607). The Colombian Basin is underlain by the oceanic plateau type crust, which has been dated to 69 to 139 Ma (Reference 245). This 70 m.y. period of continuous igneous activity is in sharp contrast to other data that indicate two major pulses (at 92 to 88 Ma and 76 to 72 Ma) of igneous activity created the Caribbean oceanic plateau (see CLIP discussion in Subsection 2.5.1.1). It is recognized as normal oceanic crust in thickness but the crust is overlain by nearly 2 kilometers (1.2 miles) of sediment (Reference 612). Bowland and Rosencrantz (Reference 613) used seismic reflection data to interpret that the eastern margin of the Colombian Basin is defined by scarps related to normal- or oblique-slip faults associated with the western Beata Ridge.

Bowland (Reference 607) describes a fault-bounded block adjacent to the Hess Escarpment and west of the Mono Rise, likely uplifted in Miocene to Holocene time. This block has a positive free-air gravity signature (Reference 614) and is aligned with several faults that extend to the southwest and displace basement and overlying sediments (References 766 and 613).

Bowland and Rosencrantz (Reference 613) recognize a zone of closely spaced normal faults and faults associated with a horst that displaces basement at least 500 meters (1600 feet) in the Colombian Basin. They also recognize a zone of normal faults that disrupts basement where the Mono Rise encounters the North Panama deformed belt and small-offset normal faults that displace basement on the southwestern flank of Mono Rise. Normal faults on the Colombian Plateau may be the result of thermal contraction and differential subsidence of laterally heterogeneous crust.

Seismicity of the Colombian Basin

{The Phase 2 earthquake catalog (Subsection 2.5.2.1.3) indicates sparse seismicity within the Colombian Basin with $M_w < 6$.} These earthquakes are located in the northeastern portion of the Colombian Basin near the Beata Ridge and the southern extension of the Greater Antilles deformed belt. The Phase 2 earthquake catalog does not cover the southern two-thirds to three-quarters of the Colombian Basin province. SOF 2.5.1-2

2.5.1.1.2.2.7 Geology of the Venezuelan Basin

Physiography of the Venezuelan Basin

The southern portion of the Caribbean Plate includes the Colombian and Venezuelan Basins separated by a north-south topographic high, the Beata Ridge (Figures 2.5.1-202 and 2.5.1-210) (Subsection 2.5.1.1.2.2.8). The basins are covered by flat-lying sediments. Irregularities in the topography of the basement are attributed to volcanic features and structural offsets. The Venezuelan Basin is bounded on the west by the Beata Ridge, on the north by the Muertos Trough (Subsection 2.5.1.1.2.2.4), on the east by the Aves Ridge, and on the south by the south Caribbean marginal fault. At the south Caribbean marginal fault, the Venezuelan Basin is obliquely subducted to the east-southeast beneath the continental South America Plate (Reference 615).

The Venezuelan Basin is floored by oceanic crust that lies at water depths of between 3 and 5 kilometers (2 and 3 miles). The topography of the basin is subdued.

Stratigraphy of the Venezuelan Basin

Venezuelan Basin is underlain by igneous oceanic crust throughout, marked by the B" seismic horizon. The seismic stratigraphy to the level of B" is derived from data collected at DSDP Sites 146 and 149 (Figure 2.5.1-211) and later data collected at ODP Site 165. In the western region, the B" horizon is a smooth surface, whereas in the eastern part the B" horizon has the rough surface (References 616 and 617). Northeast-trending magnetic anomalies in the basin have been interpreted as reflecting crustal accretion at a spreading ridge, between Late Jurassic and mid-Early Cretaceous (127 and 155 Ma) (Reference 618). Prior to the mid-Late Cretaceous (Senonian at ~88 Ma), widespread and rapid eruption of basaltic flows began in concert with extensional deformation of the Caribbean crust. Thick volcanic wedges characterized by divergent reflectors that are observed along the boundary that separates rough from smooth oceanic crust are coincident with an abrupt shallowing of the Moho and appear to be bounded by a large, northwest-dipping fault system (Reference 255).

The outer margins of the basin are dominated by thick, turbidite-filled abyssal plains, which have not been penetrated by deep-sea drilling (Reference 526). On the other hand, DSDP drill sites in the interior of the basin have recovered a thick succession of pelagic sediments (DSDP Sites 29, 146, 149, and 150) (References 619 and 620). Upper Cretaceous limestone and marls containing

basaltic ash overlie the igneous basement, but at DSDP Site 153 the Upper Cretaceous sediments include carbonaceous clays, which imply euxinic conditions and restricted circulation during early evolution of the basin. Paleocene limestones and clays are overlain by lower Eocene cherts and hard siliceous limestone, which mark seismic horizon A". Miocene to Oligocene deposits are foraminiferal-nannofossil chalks and clays. Holocene to Miocene deposits are foraminiferal-nannofossil chalk oozes, marl oozes, and clays.

The stratigraphy to the level of B" reflector horizon of the Venezuelan Basin is derived from data collected at DSDP Sites 146 and 149 (Figure 2.5.1-211). The holes were nearly continuously cored and provide a 762-meter (2500-feet) composite section that represents pelagic sediments. No major unconformities were found and, as a result, most of the foraminiferal and nannofossil biostratigraphic zones and several of the radiolarian zones were identified. Recent to lower Miocene deposits are foraminiferal-nannofossil chalk oozes, marl oozes, and clays. Lower Miocene to lower Eocene deposits are radiolarian-nannofossil chalks and oozes thick in volcanic material. Underlying the middle Tertiary sediments is a lower Eocene (?)-Paleocene (?) section of chert associated with limestone (Reference 526).

In the deepest part of the Venezuelan Basin, the B" surface is rough compared to areas where the B" surface is smooth, requiring the distinction between rough B" and smooth B". The smooth B" may represent the older proto-Atlantic Plate. The overlying finely laminated sequence was designated A," corresponding to older than Middle Eocene (approximately 50 Ma) and younger than Senonian (approximately 88 Ma) consolidated cherts and chalks. The A" to B" sequence varies in thickness across the Caribbean, up to a maximum of 600 to 800 meters (2000 to 2600 feet), with the thickest sequence roughly coincident with areas of rough basement in the Venezuelan A" to B" for rough B" areas (Reference 253). Similarly, Driscoll and Diebold (Reference 253) note that the hemipelagic-pelagic sediment sequence above A" displays a pronounced increase in thickness across the rough-smooth B" boundary in the Venezuelan Basin. This increase thickness is interpreted to have been caused by a hiatus or non-deposition toward the northwest and away from the depositional center of the Venezuelan Basin.

Using multi-channel seismic reflection data, other maker horizons were identified. Leroy and Mauffret (Reference 621) recognized that B" is sometimes overlain by a thin layer, 2V, interpreted to be original oceanic crust overlain by a thin volcanic layer. Below B", an intra basement reflector (sub-B?) marks the top of original oceanic crust that is sandwiched between an upper volcanic layer and lower underplated material. This underplated layer that forms a very thick layer, 3V,

beneath the Beata and Nicaragua volcanic plateaus, is attributed to the presence of magnesian-rich rocks (picrites or ultramafic cumulates). The upper part of layer 3V is gabbroic and outcrops on the Beata Ridge. A highly reflective horizon (R) is located at the top of this layer.

Horizon A" was shown to be overlain by reflector eM, with Horizon A" representing the boundary between unconsolidated Early Miocene to Eocene oozes and consolidated Lower Eocene cherts and chalks-ooze and Early to Middle Miocene calcareous ooze. According to James (Reference 608), DSDP/ODP drilling showed that A" marks the top of a middle-Eocene chert-limestone section below unconsolidated sediments.

Horizon B" is smooth over the Caribbean Plateau and rough in areas of the Caribbean underlain by normal oceanic crust. Smooth B" ties to 90 to 88 Ma basalts sampled by drilling (Reference 605) and these are interpreted to indicate voluminous plateau volcanism over a short period. As discussed in Subsection 2.5.1.1.2.2.6, radiometric ages have identified at least two major magmatic events responsible for the production of the Caribbean Plateau, the first and largest at about 90 to 88 Ma and the second at about 76 to 72 Ma (Reference 610). Rough B" has never been penetrated by drilling. The rough B" profile is seen in the southeastern Venezuelan and western Colombian Basins (References 613 and 255) and is thought to represent "normal" thickness of the proto-Atlantic oceanic crust.

Structures of the Venezuelan Basin

The Venezuelan Basin consists of thicker than normal oceanic crust of Jurassic age that was thickened by emplacement of dikes and sills in Jurassic to early Cretaceous time, and then intruded by sills and flows in the mid- to late-Cretaceous (References 623 and 624). Faults and monoclines of Miocene and younger age are seen in the basin interior, indicative of minor internal deformation (References 623 and 625).

Seismicity of the Venezuelan Basin

{The Phase 2 earthquake catalog (Subsection 2.5.2.1.3) shows scattered, sparse seismicity of $M_W \leq 4$ in the northwestern part of the Venezuelan Basin.} The Phase 2 earthquake catalog extends south to 15° N latitude (Figure 2.5.2-201) and does not cover the southern one-half portion of the Venezuelan Basin. SOF 2.5.1-2

2.5.1.1.2.2.8 Geology of the Beata Ridge

Physiography of the Beata Ridge

The 2000-meter (6600-feet) deep Beata Ridge is a prominent topographic structure that trends south southwest from Cape Beata in Hispaniola and divides the 4000- to 5000-meter (13,100- to 16,400-foot) deep Colombian and Venezuelan Basins (Figure 2.5.1-210). It is 450 kilometers (280 miles) long and up to 300 kilometers (186 miles) wide, with a highly asymmetrical east-west profile due to a steep (15 to 25°) escarpment to the west that rises 2500 meters (8200 feet) above the Colombia Abyssal Plain, and a gentler slope to the east to the Venezuelan Basin (References 625, 778, and 628).

Stratigraphy of the Beata Ridge

In general, dredge material from the Beata Ridge consists of igneous rocks, holocrystalline basalts, and dolerites (Reference 626). Three discrete units are identified at DSDP Site 151 (Figure 2.5.1-211). Unit I consists of Tertiary pelagic sediments rich in carbonate faunal assemblages. Only fragments of the Paleocene and Eocene sequence are present. Three meters (10 feet) of basalt were recovered, but the contact with the overlying sediments was not recovered. Unit II is the hard ground that marks an unconformity between the Paleocene sediments and the overlying Santonian age sediments. Unit III is characterized by foraminiferal sands, volcanics, and carbonaceous clays of Santonian age and is capped by a siliceous hard ground (Reference 605). Magmatic samples that were collected during 12 selected dives (NB-04 to NB-16) that were distributed from north to south of the ridge. The samples consist of gabbro and dolerite that formed relatively continuous massive outcrops or boulders up to a few tens of centimeters across in talus. Based on subtle differences in structure, these rock units are interpreted as a sequence of sills. Some of the outcrops show concentric spheroidal forms; this alteration was superimposed on an earlier phase of sea floor alteration. Volcanic rocks are rare, but where present always formed pillowed lava flows. Basalts were observed at the base of the escarpment below outcrops of gabbro and dolerite (Reference 611).

The deepest dredge located at the base of the escarpment, 4100 meters (13,450 feet), contains deeply weathered rocks that are completely altered to clay, zeolite, and limonite phases. Nine dredge hauls contain igneous rocks in various states of weathering. They were distributed at depths ranging from 4000 meters to 2300 meters (13,100 to 7550 feet). The majority of the samples in all nine dredges are holocrystalline with textures ranging from ophitic to glomeroporphyritic. Several

samples found in dredge hauls 10, 12, and 31 have a porphyritic texture but the groundmass has a hemihyaline texture and is composed of a mixture of palagonite, acicular plagioclase, and opaque oxides (Reference 626).

Numerous dredged samples of basalt from the Beata Ridge were radiometrically dated (feldspars and whole rock) at 64 to 65 Ma. Several samples contain olivine or pseudomorphs after olivine, which might represent the eruption of linear intrusive bodies associated with block faulting of the Beata Ridge. The correlation of these bodies to reflectors A" and B" east and west of Site 151 (located off the Beata Ridge) would indicate a date of at least late Cretaceous (Reference 629).

Structures of the Beata Ridge

The Beata Ridge (Figure 2.5.1-210) extends from south-central Hispaniola on the north to the Aruba Gap at about 14° N to the south (Figure 2.5.1-316). It is a roughly triangular shaped region, about 200 kilometers (124 miles) north to south, and about 200 kilometers east to west at 14° N. The northern tip of the triangle is on land and comprises the Bahoruco Peninsula (for location, see morphotectonic zone 7 of Figure 2.5.1-305) of south-central Hispaniola, the southwestern corner of the triangle is DSDP Site 151 Ridge (a north-south ridge northwest of the Aruba Gap), and the southeastern corner of the triangle is the Beata Plateau (Figures 2.5.1-210 and 2.5.1-316). Relief generally decreases from the north, which is above sea level, to 4 kilometers (2.5 miles) below sea level to the south where it ends in the Aruba Gap. The northern termination also coincides with the eastern end of the Enriquillo-Plantain Garden fault and the western end of the Muertos Trough.

Mauffret and Leroy (Reference 630) present a detailed tectonic analysis of this feature, based on multi-channel seismic surveys, DSDP results, bathymetry from a Seabeam (SEACARIB I) survey, and focal mechanism studies of one earthquake. Because this reference appears to be the most comprehensive analysis to date, it provides the source for the summary below, unless otherwise stated.

The Beata Ridge consists of unusually thick oceanic crust (about 20 kilometers or 12 miles), formed by underplating of normal oceanic crust in the late Cretaceous, creating an oceanic volcanic plateau with subsequent transpression and uplift in the mid-Miocene. A petrologic analysis of dredged rocks identified three episodes of emplacement, one at 80 Ma, one at 76 Ma, and the last at 55 Ma (Reference 611). These authors propose that the first two episodes are related to original formation of the CLIP (see discussion of "Large Igneous Province (LIP)

Events" in Subsection 2.5.1.1) over probably more than one hotspot in the Pacific, and the third is due to later localized crustal thinning with contemporaneous magma emplacement.

Sub-elements within the Beata Ridge are (from north to south): the Tairona Ridge, the DSDP Site 151 Ridge, the Taino Ridge, and the Beata Plateau (Figure 2.5.1-316). It is bordered by the Colombian Basin and Haiti subbasin to the west, the Dominican subbasin and Venezuelan Basin to the east, and the Aruba Gap to the south. The west side of the Beata Ridge forms a relatively steep escarpment, with northeast-southwest oriented right-lateral strike-slip faults strongly suggested between Tairona Ridge and the Bahoruco Peninsula, and between DSDP 151 Ridge and Tairona Ridge. The Beata Ridge decreases in elevation from west to east, with the east side showing evidence for west-verging thrust faults. This indicates that the ridge is overriding the Venezuelan Basin. An east-west seismic line across the Taino Ridge shows evidence for initial east-west normal faulting, followed by later thrust faulting in the opposite direction on the same feature (Reference 630).

A tectonic model for the Beata Ridge and its relationship to surrounding elements of the Caribbean region is shown in Figure 2.5.1-317. Sheet 1 shows the proposed configuration in the early Miocene. The role of the Beata Ridge then was to accommodate differential motion between the Colombia and Venezuela microplates via southwest-dipping thrust faults. Sheet 2 shows proposed relations at present. The ridge still accommodates Colombia-Venezuela microplate differential motion (the Colombia microplate moving eastward faster than the Venezuela microplate), but due to the counterclockwise rotation of the Venezuela microplate, the deformation is partitioned into strong transpression (manifested largely as northeast-southwest strike-slip faults) on the west side and thrust faulting, as the Venezuela microplate is being overridden, on the east side. Since the early Miocene, closure between the North and South America plates has caused the north end of Beata Ridge to collide with the Hispaniola microplate. On the south end, the 40-kilometer (25-mile) wide Aruba Gap accommodates the differential motion via the Pecos fault zone, a transpressive zone exhibiting strike-slip and reverse faulting. The Euler pole for this system is placed just south of the south end of Beata Ridge (Figure 2.5.1-317), consistent with the increasing deformation, and topography, of the Ridge from south to north (Reference 630).

Seismicity of the Beata Ridge

{The Phase 2 earthquake catalog (Subsection 2.5.2.1.3) indicates sparse seismicity in the vicinity of the Beata Ridge, the largest earthquake having M_W SOF 2.5.1-2

4.8.} Seismicity from 1900 to 1994 (Reference 631) shows one earthquake near the southern end of the Bahoruco Peninsula (see morphotectonic zone 7 of Figure 2.5.1-305) of a magnitude M_w 4, and a M_w 5.8 earthquake (Reference 632) near the south end of the Taino Ridge. A focal mechanism for this earthquake (Reference 633) shows northeast-southwest directed thrust faulting, consistent with the tectonic model shown in Figure 2.5.1-317. The Beata Ridge is believed to be an oceanic spreading ridge that was active 80 to 55 Ma comprising unusually thick (20 kilometers or 12 miles) oceanic crust (Reference 611). As such, it may provide a zone of weakness in the crust and thus generate small to moderate earthquakes. {The extent of the Phase 2 earthquake catalog is south to 15° N latitude (Figure 2.5.2-201),} and does not cover the southern one-third to three-quarters of the Beata Ridge. SOF 2.5.1-2

2.5.1.1.2.3 Active Tectonic Structures of the Northern Caribbean Plate

Active tectonic structures on the southeastern North America Plate are described in Subsections 2.5.1.1.1.3 and 2.5.1.1.2.1. This subsection describes the active tectonic structure of the northern Caribbean Plate. The structures are grouped as single faults, fault systems, or spreading centers. Some faults and fault systems are transforms and one is a subduction zone. This following discussion emphasizes tectonic elements that are either (a) capable of generating large to great earthquakes (i.e., M [magnitude] approximately 7.5 or greater) and/or (b) within the 200-mile radius site region.

The Caribbean Plate is presently moving relative to the North America Plate at a rate of approximately 20 millimeters/year along an azimuth of roughly 075° (References 502, 635, and 636). Cuba was transferred to the North America Plate in the early to mid-Tertiary, and thus is not directly involved in the plate boundary tectonics, except along its southern coast. In the Caribbean-North America Plate boundary region, the relative plate motion is accommodated by the mid-Cayman spreading center and several subvertical, left-lateral transform faults extending from offshore of the northern coast of Honduras eastward through the Cayman Trough and through Jamaica and Hispaniola. The Cayman spreading center is located southwest of the Cayman Islands and is characterized by a north-south-trending axis of spreading with an average rate of approximately 15 millimeters/year since approximately 25 to 30 Ma (Reference 222). West of the Cayman Trough, Caribbean-North America Plate motion is accommodated offshore on the left-lateral Swan Islands fault (Figure 2.5.1-202). East of the Cayman Trough, on Hispaniola, the orientation of the plate-bounding structures changes and motion is partitioned between strike-slip faults (e.g., Septentrional and Enriquillo faults), minor oblique-reverse faults, and subduction on thrust faults

(e.g., Northern Hispaniola thrust fault) (References 637, 638, and 639). East of Hispaniola, the Caribbean-North America Plate boundary becomes an oblique subduction zone or zones at the Puerto Rico Trench and Muertos Trough, and finally a more pure dip-slip west-dipping subduction zone in the Lesser Antilles.

The kinematics of crustal deformation and faulting in Cuba are poorly understood. Geodetic data show that the current plate boundary is mostly south of Cuba along the Oriente and Enriquillo-Plantain Garden faults and that modern deformation rates across Cuba are likely <0.1 inch (3 millimeters) per year relative to North America (References 502 and 503). Some strike-slip faults have been mapped on Cuba, but none are adequately characterized with late Quaternary slip rates or timing or recurrence of large earthquakes (Reference 494). The Oriente and Enriquillo-Plantain Garden faults are active left-lateral strike-slip faults associated with the North America-Caribbean Plate boundary.

The Oriente fault zone is a left-lateral transform fault extending from the northern tip of the Mid-Cayman spreading center 500 miles (800 kilometers) to the southeastern tip of Cuba. The remainder of North America-Caribbean Plate motion that is not accommodated along the southern Cayman Trough boundary, or approximately 8 to 13 millimeters/year, is attributed to this fault. Again, variation in historical seismicity and geometry of the Oriente fault warrants its division into eastern and western segments. The largest historical earthquakes on the western Oriente fault are the 1992 M_w 6.8 to 7.0 event {(Phase 2 earthquake catalog M_w 6.80)} and a magnitude 7.0 to 7.1 {(Phase 2 earthquake catalog M_w 7.20)} earthquake that occurred off of the southwestern tip of Cuba (References 640, 489, and 641). The eastern Oriente fault along southern Cuba is characterized by more intense seismic activity and focal mechanisms indicating strike-slip, oblique, and reverse mechanisms (References 504 and 640). The largest historical earthquake on the eastern Oriente fault is the June 1766 M_w 7.53 earthquake (Subsection 2.5.2.1.3).

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SOF 2.5.1-2

The Septentrional fault is a left-lateral strike-slip fault that extends for roughly 400 miles (640 kilometers) west from the Mona Passage to the Windward Passage, where it merges with the Oriente fault (References 840 and 637). Strain is partitioned on this structure and on the gently south-dipping Northern Hispaniola thrust fault (References 591 and 643). The best estimate of a slip rate for the fault is 6 to 12 millimeters/year (References 636, 570, and 643), and it has been suggested that large historical earthquakes (M_w 7.75 to 8.0) occurred on this structure (Reference 641).

The Northern Hispaniola fault is an east-west-striking, north-directed thrust system. Geodetic data indicate a deformation rate of 5 millimeters/year on this structure (Reference 358). Historical seismic events of up to M_s 8.1 {(Phase 2 earthquake catalog M_w 7.90)} have been attributed to a shallowly south-dipping thrust fault plane (Reference 591). Variations in seismicity and crustal structure along strike indicate the fault is segmented and best described by a more seismically active eastern segment and a quieter western segment that roots at the Septentrional fault. SOF 2.5.1-2

The Swan Islands, Walton-Duanvale, and Enriquillo-Plantain Garden fault systems are left-lateral strike-slip faults associated with the mid-Cayman spreading center, which collectively form the southern margin of the Cayman Trough. The estimated slip rate for the system is approximately 8 millimeters/year (References 503 and 502). Slip is transferred more than 600 miles (970 kilometers) across these structures (causing a restraining bend in Jamaica) and eventually feeds into the Muertos Trough. The Jamaican restraining bend is interpreted as a boundary between a western portion of the system (the Walton-Duanvale fault) and an eastern portion (Enriquillo-Plantain Garden fault). Multiple historical events of magnitude approximately 7.5 have ruptured on the Enriquillo fault (Reference 641). The Swan Islands fault system is a left-lateral oceanic transform extending 450 miles (720 kilometers) west of the mid-Cayman spreading center. Geodetic data indicate that essentially the entire 18 to 20 millimeters/year Caribbean-North America Plate motion is accommodated on the Swan Islands fault system (References 502 and 635). An historical earthquake with an estimated magnitude of 8.3 {(Phase 2 earthquake catalog M_w 7.69)} is attributed to the western portion of the Swan Islands fault system (Reference 641). SOF 2.5.1-2

2.5.1.1.2.3.1 Cayman Trough Tectonic Structures

The Cayman Trough comprises a central north-northwest-trending spreading axis, with strike-slip faults extending both east and west from its southern terminus and a strike-slip fault extending east from its northern terminus (Figure 2.5.1-202). Extending east from the northern end of the spreading axis is the left-lateral Oriente fault, which connects with the Septentrional fault on the island of Hispaniola. From the southern end of the spreading axis, the Swan Islands fault extends to the west, eventually linking with the Motagua fault in Honduras. To the east of the southern end of the spreading axis, Walton fault, Duanvale fault and Enriquillo-Plantain garden fault extend eastward through Jamaica to Hispaniola. The submarine portions of these structures were mapped with a sidescan instrument (Reference 559). The spreading axis itself is offset by a short

discontinuity. Seismicity indicates this is a left-lateral strike-slip fault (Reference 499). The Oriente fault is described in detail in Subsections 2.5.1.1.1.3.2.4 and 2.5.1.1.2.3.1.2.

The Cayman Trough tectonic structures include two major fault systems, the western and eastern segments of the Swan Islands fault and the western and eastern segments of the Oriente fault. The two fault systems are described in the following subsections.

2.5.1.1.2.3.1.1 Swan Islands Fault

The Swan Islands fault is a left-lateral oceanic transform fault that extends from the southern tip of the mid-Cayman spreading center westward for roughly 450 miles (720 kilometers) where it merges with the onshore Polochic-Motagua fault system of Central America (Figure 2.5.1-202). West of the mid-Cayman spreading center, the northern margin of the Cayman Trough does not appear to accommodate significant left lateral relative plate motion; essentially the entire 18 to 20 millimeters/year North America-Caribbean Plate motion is accommodated on the Swan Islands fault (Reference 502).

Interpretation of high-resolution sea-floor bathymetry suggests the Swan Islands fault consists of several faults that locally form restraining and releasing geometries (References 563 and 655). West of the Swan Islands, the Swan Islands fault is expressed on the sea floor as a relatively continuous lineament. The thickened crust associated with the emergent Swan Islands is associated with a roughly 20-mile (32-kilometer) wide right step-over that forms a restraining geometry and a probable segmentation point for rupture propagation. Surrounding and east of the Swan Islands, the fault consists of one or more sections of about 60 to 120 miles (100 to 200 kilometers) in length to the eastern termination at the mid-Cayman Trough. Here, the crust of the mid-Cayman Trough that bounds the fault to the north is about 3.5 miles (5.5 kilometers) thick based on gravity (Reference 635).

McCann and Pennington (Reference 560) and McCann (Reference 641) note a large earthquake that occurred in August 1856 off the northern coast of Honduras may have ruptured the western portion of the Swan Islands fault. The estimated magnitude for this event is about M 8.3 (Reference 641), based on descriptions of the event summarized by Osiecki (Reference 645) {(Table 2.5.2-221)}. Earlier accounts of a similar great event off the northern Honduran coast suggest the possibility of a prior magnitude of approximately 8 {(Phase 2 earthquake catalog M_W 7.69)} earthquake on the western Swan Islands fault in 1539 (Reference 641). SOF 2.5.1-3 SOF 2.5.1-2

The probability of at least one great historical earthquake on the western Swan Islands fault suggests the fault is fully coupled. The eastern section of the fault between the Swan Islands and the mid-Cayman spreading center is not associated with large historical earthquakes.

2.5.1.1.2.3.1.2 Oriente Fault

The Oriente fault is a left-lateral transform fault that forms the northern boundary of the Gonâve microplate and extends for more than 500 miles (800 kilometers) from the southeastern tip of Cuba westward to the northern tip of the mid-Cayman spreading center (References 632, 840, 559, and 844) (Figure 2.5.2-214). To the east, the Oriente fault connects with the Septentrional fault in the Windward Passage. Slip-rate on the Oriente fault is estimated at 8 and 13 millimeters/year, with a best estimate of 11 millimeters/year. This estimate is based upon subtracting the approximate 7 to 11 millimeters/year rate of Gonâve-Caribbean relative motion measured in Jamaica (Reference 503) and Haiti from the entire 18 to 20 millimeters/year North America-Caribbean Plate motion (Reference 502).

The structural complexity and historical seismicity of the Oriente fault changes character along strike and forms the basis of a division into western and eastern sections (Figure 2.5.2-214). The western Oriente fault extends from the mid-Cayman spreading center to the southern tip of Cuba and the offshore Cabo Cruz Basin. This section of the fault is characterized by a simple, linearly continuous expression on the seafloor trending almost exactly parallel to relative Caribbean-North America Plate motion (References 840, 502, and 559). Seismicity on the western Oriente fault is less frequent than on other areas of the plate boundary, including on the eastern Oriente fault. Most seismicity has been localized in the Cabo Cruz pull-apart basin, which is associated with left-lateral strike-slip-normal oblique motion (References 504 and 640). The largest historical earthquakes on the western Oriente fault are the May 1992 magnitude 6.8 to 7.0 {(Phase 2 earthquake catalog M_w 6.80)} earthquake on the Cabo Cruz Basin and the February 1917 M 7.0 to 7.1 {(Phase 2 earthquake catalog M_w 7.20)} earthquake that occurred offshore the southern tip of Cuba (References 640, 641, and 489). A magnitude 6.2 earthquake in 1962 {(Phase 2 earthquake catalog M_w 6.29)} on the western Oriente fault adjacent to the Cayman spreading center is the largest historical event west of the Cabo Cruz Basin and reveals pure left-lateral strike-slip motion (Reference 640). It is unclear if the low seismicity rate on the western Oriente fault west of the Cabo Cruz Basin indicates it is fully locked, or if it is mostly unlocked and sliding at a relatively uniform rate. As mentioned previously, the crust of the Cayman Trough that constitutes the southern block of the Oriente fault is anomalously thin (2 to 6 kilometers or 1 to 4

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miles) for distances up to 200 miles (320 kilometers) or more from the mid-Cayman spreading center (Reference 844), which probably limits the seismogenic thickness of the western Oriente fault. A low coupling of the western Oriente fault west of the Cabo Cruz Basin would be consistent with oceanic transform faults worldwide, for which up to 95 percent of total slip is released aseismically (Reference 843).

The eastern Oriente fault extends along southern Cuba and is characterized by a zone that includes: (a) segmented, discontinuous, and probably vertical strike-slip faults and (b) more continuous, steeply north-dipping faults of the Santiago deformed belt south of the strike-slip faults (Reference 840). The eastern Oriente fault is characterized by more intense seismic activity than the western Oriente fault (Figure 2.5.2-215), with focal mechanisms indicating strike-slip, oblique, and reverse mechanisms (References 504 and 640). Seismicity depths reach 70 kilometers (45 miles) beneath southern Cuba associated with the Santiago deformed belt, indicating a thick seismogenic crust that contrasts with the thin crust of the western Oriente fault (Reference 504). The seismic moment release of historical large earthquakes is consistent with the approximately 11 millimeters/year slip rate on the Oriente fault determined by GPS (References 840 and 843), indicating that the plate interface there is fully locked (Reference 643).

2.5.1.1.2.3.2 Greater Antilles Deformed Belt Faults

While the previous sections describe tectonics of individual components of the Greater Antilles deformed belt, a number of recent studies have attempted to use GPS and other geophysical information to infer seismic hazards for the region as a whole by integrating these observations into a regional, self-consistent model.

Dixon et al. (Reference 780), using campaign GPS measurements over a ten year period (1986 to 1995), find that the North America-Caribbean relative motion was about 21 millimeters/year, twice the NUVEL-1A rate deduced from global plate rate inversions (References 649 and 650). Using elastic strain accumulation models for the Northern Hispaniola fault, Septentrional fault, and Enriquillo fault, they inverted for slip on these features. Their results indicate 4 ± 3 millimeters/year on the Northern Hispaniola fault, 8 ± 3 millimeters/year on the Septentrional fault, and 8 ± 3 millimeters/year on the Enriquillo fault. It is important to note that they assumed no aseismic slip and neglected any postseismic deformation effects, which may have affected northeast Hispaniola after the 1946 earthquake. These effects, however, are unlikely to perturb the results by more than 1 to 2 millimeters/year (Reference 651). These results were found to be consistent with a broader study encompassing the northern North America-Caribbean plate

boundary region (Reference 502). Calais et al. (Reference 358) performed a similar study for Hispaniola and calculate 5.2 ± 2 millimeters/year for the Northern Hispaniola fault, 12.8 ± 2.5 millimeters/year for the Septentrional fault, and 9.0 ± 9.0 millimeters/year for the Enriquillo fault.

An update of this analysis, expanded to the northeastern Caribbean from western Hispaniola to the central Lesser Antilles, was presented by Manaker et al. (Reference 643). They also modeled coupling ratios (if a fault slips aseismically this is 0, if fully locked it is 1), which estimate how much motion is translated into earthquakes. Fault slip rates are shown in (Figure 2.5.1-318). Rates on the Northern Hispaniola fault are 5 to 6 millimeters/year, 8 ± 5 millimeters/year on the Septentrional fault, and 7 ± 2 millimeters/year on the Enriquillo fault. These are consistent with the estimates mentioned above. The coupling ratios (Figure 2.5.1-318) show the Septentrional fault to be tightly coupled to the west, with a decrease to the east. This is consistent with the concept that the impingement of the Bahama Bank on the Caribbean Plate gives rise to high coupling and high seismicity, and that to the east subduction of normal oceanic crust decreases coupling and consequently reduces the seismic hazard (e.g., Reference 577).

Ali et al. (Reference 652) modeled Coulomb stress changes in the northeastern Caribbean due to the occurrence of 12 historic earthquakes, including effects of postseismic viscoelastic relaxation. These stress changes were then interpolated to three-dimensional representations of the major faults. The authors suggest that the 1751 event on the eastern Enriquillo fault was "encouraged" by the >0.1 MPa stress increase caused by the 1751 Muertos Trough earthquake, and that the east-to-west progression of earthquakes on the Northern Hispaniola fault was "encouraged" by loading resulting from each previous large event. The results quantify the concept of stress building up on a fault over time, and that stresses were high on the Enriquillo fault prior to the January 12, 2010, earthquake.

2.5.1.1.2.3.2.1 Septentrional Fault

The Septentrional fault extends approximately 600 kilometers (370 miles), from the Mona Passage on the east, to the northwestern tip of Hispaniola (Figure 2.5.1-202). On the west side it merges with the Oriente fault at about 74° W, where the plate boundary changes orientation from west-northwest to east-northeast. On the east side it has been observed to end in a circular depression about 25 kilometers (15.5 miles) west of Mona Canyon (Reference 582). This location is shown in Figure 2.5.1-320. As global plate motions were developed and those in the Caribbean became known (e.g.,

References 653 and 654), the importance of the Septentrional fault as a major plate boundary component was recognized (e.g., References 655 and 493).

Mann et al. (Reference 779) present results of paleoseismic and geomorphic studies of the Septentrional fault. As shown in Figure 2.5.1-321, they divide the fault into three sections, the western Septentrional fault system (identified as "western SFS" in Figure 2.5.1-321), the central Septentrional fault system, and the eastern Septentrional fault system. In the eastern area the fault parallels the southern shore of the Samana Peninsula, with the submarine trace of the fault lying about 2 kilometers (1.2 miles) south of the mountain front to the north (Reference 657). The central portion lies within the heavily populated Cibao Valley, and is marked by a 100-kilometer (62-mile) long trace on the valley floor. The scarp relief ranges from 1.1 to 11.3 meters (3.6 to 37 feet), with alternating facing directions. In the western section the fault bifurcates, with the southern section continuing through the western Cibao Valley and intersecting the coastline at the town of Pepillo Salcedo, and the northern section cutting through the northern Cordillera and intersecting the coastline at the town of Monte Cristi. The northern section is well exposed, but exhibits no evidence of Quaternary activity. The southern section, which is probably the more active trace (because it merges with the Oriente fault offshore to the west), is largely obscured due to recent fluvial sedimentation and erosion.

Early trenching studies near Santiago in the Cibao Valley (Reference 658) concluded that the most recent surface faulting event in this part of the fault occurred at least 430 years ago, as of 1993, and probably more than 730 years before 1993. Prentice et al. (Reference 658) estimate a slip rate of between 5 and 9 millimeters/year, based on estimates of the total plate boundary rate estimates at the time, which ranged from 12 to 37 millimeters/year (References 649 and 660, respectively). They conclude that about 3.5 meters (11.5 feet) of strain had accumulated on the fault since the last rupture.

Prentice et al. (Reference 570) present results and interpretations of all geomorphic and paleoseismic investigations of the Septentrional fault. They conclude that the slip rate on the central Septentrional fault is 6 to 12 millimeters/year, and that the last surface faulting event occurred about 800 years ago. This equates to strain accumulation between 5 and 10 meters, implying a potential earthquake in the magnitude 7.5 to 8 range (Reference 662).

Large historic events in northern Hispaniola occurred in 1564, 1783, 1842, 1887, and 1897 (Reference 571): all produced strong shaking in the Cibao Valley. The fact that all surface rupture identified by Prentice et al. (Reference 570) predated

these events means that either: (a) any or all occurred on the Northern Hispaniola fault or unidentified structures in the northern Hispaniola region, or (b) any or all occurred on the Septentrional fault, but were deep enough not to produce surface rupture. The latter is a distinct possibility, given the lack of surface rupture during the recent highly destructive M_w 7.0 Haiti earthquake (Reference 572) and the lack of knowledge regarding how deep the Septentrional fault extends.

2.5.1.1.2.3.2.2 Northern Hispaniola Fault

The North Hispaniola fault is the south-dipping plate boundary between the North America Plate and the island of Hispaniola. The left-lateral strike-slip Septentrional fault forms the other component of this boundary, and is discussed in Subsection 2.5.1.1.2.3.2.1. The eastern boundary of the North Hispaniola fault coincides with the western end of the Puerto Rico Trench and the eastern boundary of the contact between the Bahama Platform and Hispaniola (Figure 2.5.1-322). The western boundary is not as clear, but appears to be between 73° W and 74° W (Figures 2.5.2-202 and 2.5.1-323), where it merges with the Nortecubana fault and ceases to function as the modern plate boundary.

Early results from GPS measurements indicated 21 ± 1 millimeters/year relative motion between southern Hispaniola and stable North America, about twice the estimate from global plate motion models (Reference 780). A southward decrease in velocities was noted, and combined with elastic strain models, results in estimates of 4.3 ± 3 millimeters/year on the North Hispaniola fault (Figure 2.5.1-324). Other estimates are 4 millimeters/year (Reference 663), 5.2 ± millimeters/year (Reference 358) (Figure 2.5.1-311), 12.8 millimeters/year (Reference 664), and 5 to 6 millimeters/year (Reference 643). The relative motion is highly oblique, almost parallel, to the North Hispaniola fault.

Because the Septentrional fault is estimated to slip at a rate of 6 to 12 millimeters/year (Reference 570), most of the North America–Hispaniola relative plate motion is taken up on that feature. Figure 2.5.1-325 shows a kinematic diagram of the relationship between the two structures.

A number of significant historical earthquakes have occurred on the North Hispaniola fault, including the 1943, 1946, 1953, and 2003 earthquakes (Figure 2.5.1-326). All had thrust mechanisms consistent with subduction of the North America Plate beneath Hispaniola. These earthquakes are described below.

The 1943 event has been studied by a number of authors, and magnitude estimates range from M_S 7.5 to M_S 7.8 {(Phase 2 earthquake catalog M_w 7.60).} It has been associated with postulated high friction on the North Hispaniola fault due to the presence of the Mona block, the subducted southeast portion of the Bahama Bank (Reference 591). SOF 2.5.1-2

The August 4, 1946, earthquake ruptured an approximately 195 by 95 kilometer (121 by 69 mile) section of the Northern Hispaniola fault near northeastern Hispaniola (References 591 and 638) (Figure 2.5.1-326). Dolan and Wald's body-waveform inversions (Reference 591) yield a focal mechanism for the 1946 earthquake that indicates rupture occurred either on a shallowly south-dipping plane that strikes 085°, or a steeply northeast-dipping plane that strikes 110°. Dolan and Wald (Reference 591) prefer the shallowly south-dipping plane, which is consistent with subduction of the North America Plate. Magnitude estimates range from M_s 7.8 (Reference 666) to M_s 8.1 (Reference 665) {(Phase 2 earthquake catalog M_w 7.90)}. A tsunami generated by this event was responsible for about 100 deaths (Reference 857). An aftershock of approximately M_s 7.3 in 1948 appears to extend the 1946 rupture zone downdip and to the northwest (Reference 638) (Figure 2.5.1-326). An additional earthquake of approximately M_s 7.3 in 1953 (Phase 2 earthquake M_w 6.93) extended the 1946 earthquake rupture zone to the northwest. SOF 2.5.1-2

The rupture area of the 2003 M_w 6.4 Puerto Plata earthquake {(Phase 2 earthquake catalog M_w 6.40)} is shown in Figure 2.5.1-326 as the green area adjacent to the 1953 rupture area. The orange and blue stars and green circle denote epicentral locations from three different agencies. This event and its aftershocks were judged to have occurred on the North Hispaniola fault (Reference 638) (Figure 2.5.1-325). SOF 2.5.1-2

Large destructive earthquakes in northern Hispaniola appear in the earlier historic record in 1564, 1842, and 1887. The 1564 event destroyed the towns of Santiago and La Vega (Reference 571). The causative structures of these earthquakes are not known, but the most likely candidates are the North Hispaniola fault and the Septentrional fault. The 1842 event has been associated with the Septentrional fault (Figure 2.5.1-327), but association with the North Hispaniola fault cannot be ruled out. This earthquake was probably in the magnitude 8 range {(Phase 2 earthquake catalog M_w 8.23),} caused several thousand deaths, and generated a tsunami (References 571 and 666). SOF 2.5.1-2

2.5.1.1.2.3.2.3 Walton-Duanvale and Enriquillo-Plantain Garden Strike-Slip Fault System

The Walton-Duanvale, Plantain Garden, and Enriquillo faults are left-lateral strike-slip faults that collectively, from west to east, form the southern margin of the Cayman Trough and Gonâve microplate (Figure 2.5.1-202). The Walton fault extends for about 185 miles (300 kilometers) eastward from the southern end of the mid-Cayman spreading center to northwestern Jamaica (Reference 766). Slip is transferred from the Walton fault across the island of Jamaica through a broad restraining bend that includes the east-west striking Duanvale, Rio Minho-Crawle River, South Coast, and Plantain Garden faults (Reference 503). The Plantain Garden fault continues eastward and connects with the Enriquillo fault offshore southwestern Haiti. The Enriquillo-Plantain Garden strike-slip fault zone extends for about 375 miles (600 kilometers) from southeastern Jamaica to south-central Hispaniola and terminates eastward in the southern Dominican Republic east of Lake Enriquillo (Reference 383). There, slip apparently is transferred in a complex manner onto the Muertos Trough.

Several large earthquakes (magnitude 6.5 and greater) have struck the Port-au-Prince region of Haiti in the past {(Table 2.5.2-221).} These earthquakes are attributed to movement on the east-west oriented Enriquillo fault (Figure 2.5.2-214), a major tectonic element with a long history of deformation and slip (Subsection 2.5.2.4.4.3.2.10). The 1751 M 7.5 earthquake occurred near Port-au-Prince, Haiti, and the 1770 M 7.5 earthquake was located further to the west of Port-au-Prince on the Enriquillo fault. The Enriquillo fault ruptured again in a large earthquake still farther west in April 1860 (M 6.7) was accompanied by a tsunami. SOF 2.5.1-3

On January 12, 2010, the M_W 7.0 Haiti earthquake struck the Port-au-Prince region of Haiti causing significant damage and many casualties throughout the city. The earthquake epicenter set by USGS was 18.457° N, 72.533° W, which places the earthquake 25 kilometers (15 miles) west south-west of Port-au-Prince on or near the Enriquillo fault and 1125 kilometers (700 miles) southwest of Miami, Florida. Although the lack of local seismograph station data makes the precise earthquake location and depth somewhat uncertain, the focal depth has been estimated to be 13 kilometers (8 miles). The focal mechanism solution for the main shock indicates a left-lateral oblique-slip motion on an east-west oriented fault, which is consistent with the earthquakes that have occurred as left-lateral strike-slip faulting within the Enriquillo fault zone. This active fault accommodates a slip rate (and weights, as used in the estimate of its contribution to the PSHA of Subsection 2.5.2.4) of 6 [0.2], 8 [0.6], and 10 [0.2] millimeters/year, accounting for

nearly half the overall movement between the Caribbean and North America plates {(Table 2.5.2-217).} SOF 2.5.1-3

The USGS finite-fault model for the M_w 7.0 Haiti earthquake (Reference 667) shows the surface area of the causative fault that ruptured is quite compact with a down-dip extent of approximately 20 kilometers (12 miles) and a length of approximately 50 kilometers (31 miles). Therefore, the implied fault-surface area available for seismogenic rupture of the causative fault is about 1000 kilometers^2. For an average slip rate of approximately 8 millimeters/year and assumed shear modulus of 3.0×10^{11} dyne-cm, the rate of increase in the seismic moment (M_0) is about 2.4×10^{24} dyne-cm/year. The seismic moment deficit that has accumulated since the 1770 earthquake (240 years) is 5.8×10^{26} dyne-cm, equivalent to an unrelieved elastic strain that could release in a moment magnitude of about M 7.1 to 7.2 based on a standard moment-magnitude relation (Reference 668). Thus, the Port-au-Prince region of Haiti has a well-documented history of large earthquakes, and the historical pattern of earthquakes indicates that an earthquake of magnitude 7.0 or larger could strike southern Haiti near Port-au-Prince at any time.

The maximum magnitude (Mmax) probability distribution [and weights] for the Enriquillo fault for the PSHA described in Subsection 2.5.2.4 was considered to be M_w 7.5 [0.2], 7.7 [0.6], and 7.9 [0.2] {(Table 2.5.2-217).} These values are based on rupture dimensions of about 120 to 250 kilometers (75 to 155 miles) long (from mapping described in Subsection 2.5.2.4.4.3.2.10) and 15 to about 18 kilometers (9 to about 11 miles) wide. Thus, the Mmax distribution used in the PSHA is comparable to the upper estimates of historical earthquakes attributed to this fault source. Based on these interpretations of magnitudes, the Mmax probability distribution was used to capture the uncertainty in the magnitude range of the largest historical earthquakes. The highest weight was given to M_w 7.7 to support a source model whereby the Enriquillo-Plantain Garden strike-slip fault zone is fully coupled. This information shows that the 2010 M_w 7.0 Haiti earthquake was expectable and completely within the magnitude and recurrence assessments incorporated in the PSHA. SOF 2.5.1-3

2.5.1.1.2.3.3 Muertos Trough and Mona Passage Extensional Zone

Muertos Trough

The Muertos Trough is a 300-mile (480-kilometer) long linear feature defined prominently in the bathymetry off the southern shores of the Dominican Republic and Puerto Rico (Figure 2.5.1-202) and a prominent north-dipping trend in

seismicity (References 669 and 595). The structure accommodates underthrusting of the Caribbean Plate beneath the Puerto Rico microplate, which is situated between the Muertos Trough and the Puerto Rico-Northern Hispaniola subduction zone. The Muertos Trough ruptured in October 1751 in a great earthquake with an estimated magnitude 8.0 (Reference 596) {(Phase 2 earthquake catalog M_w 7.28).} SOF 2.5.1-2

Mona Passage

Mona Passage is the oceanic geographic feature that separates the islands of Puerto Rico and Hispaniola, and is about 150 kilometers 92-miles) east-west, and 50 kilometers (31 miles) north-south. The Mona Passage extensional zone (MPEZ) incorporates this oceanic part and extends about 50 kilometers (31 miles) into eastern Hispaniola, and is thought to include the southwestern corner of Puerto Rico (Figure 2.5.1-210, sheet 2). Structurally, the MPEZ is part of the Puerto Rico-Virgin Islands microplate. Van Gestel et al. (Reference 670) describe it as a symmetric arch of the carbonate platform, with gently dipping north and south flanks superimposed by mainly north striking, but also northwest-southeast-striking, oriented normal faults.

Figure 2.5.1-328 shows a more detailed view of the bathymetry of the MPEZ. Three rift features can be seen: Mona Canyon on the north limb, and Yuma Basin and Cabo Rojo Rifts on the south limb. Mona Canyon was the site of a M_w 7.2 earthquake in 1918 {(M_w 7.30 in the Phase 2 earthquake catalog)} that caused severe ground shaking and a tsunami that affected northwest Puerto Rico. One hundred and sixteen deaths were recorded, and damage estimates approach $25,000,000 (Reference 671). Reid and Taber (Reference 672) postulated that Mona Canyon was associated with the earthquake. Tsunami modeling by McCann (Reference 671) successfully matched the observed effects on land with the rupture of a fault on the eastern wall of the canyon. Later studies (Reference 673) present evidence that the tsunami was caused by a landslide, located within the canyon, which was triggered by the earthquake. SOF 2.5.1-2

Based on seven years of GPS measurements in Hispaniola and Puerto Rico, Calais et al. (Reference 358) measured 5 ± 3 millimeters/year of extension oriented east-northeast to west-southwest across the MPEZ. They postulate this was due to the impingement of Hispaniola on the Bahama Bank. The Puerto Rico-Virgin Islands microplate, being less impeded, moves to the east (relative to fixed North America) at a faster rate, which causes extension in the MPEZ. LaForge and McCann (Reference 577) identify 26 faults in the MPEZ, including two faults in western Puerto Rico (Cerro Goden and South Lajas faults), and two

faults associated with Mona Canyon (Figure 2.5.1-320). Slip rates are estimated by projecting the above horizontal extension rate onto these faults. Mondziel et al. (Reference 585) estimate a late Pliocene to Present extension rate of 0.4 millimeters/year across Mona Canyon. Assuming a fault dip of 64°, this agrees with the LaForge and McCann (Reference 577) estimate of 0.92 millimeters/year. This equates to a return period of 1900 years for a M_w 7.2 event, which is the largest magnitude postulated by Mondziel et al. (Reference 585) for the MPEZ faults.

The South Lajas fault in southwest Puerto Rico (Figure 2.5.1-320) is considered to be part of the MPEZ. Paleoseismic investigations reveal the occurrence of two surface-faulting events in the past 7000 years (References 570 and 578). LaForge and McCann (Reference 577) estimate a slip rate of 0.51 millimeters/ year for this fault.

Mueller et al. (Reference 589) model the MPEZ hazard by uniformly distributing the 5 millimeters/year extension throughout the zone. Their maximum magnitude estimate for the MPEZ is M_w 7.2 to 7.4.

The NPRSFZ and Bowin fault (Figure 2.5.1-320) are not well expressed in the seafloor bathymetry, but are considered to be strike-slip faults taking up some portion of the near arc-parallel plate motion (Reference 581). The NPRSFZ has a width of only a few kilometers due to its proximity to the Puerto Rico Trench (Reference 591), and therefore is not considered by LaForge and McCann (Reference 577) and Mueller et al. (Reference 589) to be a seismic source. The Bowin fault appears to be a possible eastward extension of the Septentrional fault. LaForge and McCann (Reference 577) and Mueller et al. (Reference 589) assign it a rate of 1 millimeters/year. LaForge and McCann (Reference 577) estimate a maximum magnitude of M_w 7.3; Mueller et al. (Reference 589) estimate M_w 7.6.

2.5.1.1.2.3.4 Puerto Rico Trench

The Puerto Rico Trench is the bathymetric manifestation of the Puerto Rico subduction zone (PRSZ). The trench itself is an unusual feature, being the deepest point in the Atlantic Ocean (8+ kilometers or 5+ miles deep) and exhibiting the highest negative free-air gravity anomaly on earth (Reference 675). With the advent of plate tectonics in the 1960s, it was recognized as a plate boundary, and early attempts were made to estimate the relative plate motion between Puerto Rico and the North America Plate (References 676 and 632).

Figure 2.5.1-322 shows the regional tectonic elements associated with the Puerto Rico Trench. The North America Plate is colliding with the Puerto Rico-Virgin Islands microplate at a highly oblique angle. Although relative plate motions were first deduced from global plate motion models, the deployment of GPS networks has permitted refined estimates. Recent GPS studies indicate a relative convergence between the North America Plate and the Puerto Rico microplate of 16.9 ± 1 millimeters/year in a west southwest direction (References 594 and 358). This is intermediate between values of 11 millimeters/year (Reference 649) and 37 millimeters/year (Reference 660), which were previously estimated on the bases of global plate motion models and the length of the downgoing slab, respectively.

Local seismograph networks have been operated in Puerto Rico since the mid-1970s. Early results (Reference 587) showed shallow seismicity beneath the island and a north-dipping plane of seismicity associated with the subducting North America Plate extending to depths of about 150 kilometers (90 miles) (Figure 2.5.1-309). Later studies confirm this pattern (Reference 573).

Seismicity on the deeper portion of the subduction zone is persistent. Shepherd et al. (Reference 677) list two magnitude 6 events that occurred between 64° W and 67° W, deeper than 50 kilometers (31 miles), from 1900 to 2001. An earthquake in 1844 {(Phase 2 earthquake catalog M_w 6.40)} may have been a moderate to large intra-slab event, with moderate shaking and low-level damage reported uniformly throughout the central-eastern part of the island. The event was not reported to have been felt in Hispaniola, but was claimed to have been felt in St. Thomas and Guadeloupe (Reference 641). Based on the 1900 to 2001 observations, LaForge and McCann (Reference 577) estimate a return period of 84 years for M_w 6.0 and above, with an upper bound of M_w 7.5. SOF 2.5.1-2

LaForge and McCann (Reference 577) distinguish between an eastern and western PRSZ based on the location of the impingement of the Bahama Bank on the trench at about 66.8° W longitude (Figure 2.5.1-310). This is due to denser seismicity in the western part, which likely results from resistance of the buoyant Bahama Bank to subduction and therefore tighter seismic coupling. LaForge and McCann (Reference 577) use 80 percent coupling in the western part and 20 percent in the eastern part. Manaker et al. (Reference 643) also find low coupling, less than 50 percent, for the plate interface in this region, based on an integrated GPS strain model for the northeast Caribbean. Grindlay et al. (Reference 679) attribute this low coupling to the old age of the subducting crust and to the collapse of the northern island platform due to passage of the Bahama Bank from east to west with accompanying tectonic erosion of the upper plate.

Between the Puerto Rico Trench and the north coast of the island, the general pattern of seismicity with depth less than 30 kilometers (19 miles) (thus likely to be associated with the plate interface) shows the heaviest activity near the Main Ridge, moderate activity west of the island, and sparsest activity north of the island (Reference 588). McCann (Reference 588) proposes that this feature is a non-buoyant structure on the downgoing North America Plate, which would function as a barrier to rupture propagation along the plate interface from the west (assuming the Bahama Bank intersection with the Puerto Rico Trench is the western barrier), thus limiting the size of maximum earthquakes affecting northern Puerto Rico to M_w 8 to 8.4.

Doser et al. (Reference 681) present focal mechanisms for the larger historical events in this region (Figure 2.5.1-249). Figure 2.5.1-249 shows focal mechanisms for the region northwest and northeast of the island. With few exceptions these show the expected pattern of west southwest-directed thrust faulting, consistent with the relative plate motion. Slip vectors in Figure 2.5.1-249 show consistency with this pattern, with some apparent partitioning between more northerly and more easterly vectors in the upper left of the figure. The lack of moderate-sized earthquakes directly north of the central and eastern shore of the island is illustrated in Figure 2.5.1-249.

Seismicity of $M_w < 7$ is abundant in the PRSZ, but only two events have exceeded M_w 7 in the 500 year historical record. McCann (Reference 600) suggests that a M_w 8 to 8.25 {(Phase 2 earthquake catalog M_w 8.03)} interface event occurred on this segment in 1787, rupturing from roughly Mona Canyon on the west to the Main Ridge on the east. This event caused widespread damage on the island. In 1943, a magnitude 7.8 earthquake {(Phase 2 earthquake catalog M_w 7.60)} ruptured an approximately 80-kilometer (50-mile) wide section of the subduction zone across Mona Canyon. On the basis of its focal mechanism, it is judged to have occurred on the shallow interface (Reference 591). SOF 2.5.1-2 SOF 2.5.1-2

2.5.1.1.2.3.5 Other Tectonic Elements

Other tectonic elements in northern North America-Caribbean Plate boundary region that are associated with seismicity and/or Cenozoic tectonics include: (a) the Nicaraguan Rise and Hess Escarpment, (b) the Beata Ridge, (c) the northern boundary of the Cayman Trough west of the mid-Cayman spreading center, and (d) the Yucatan Basin and the ancestral plate boundary zone/escarpment separating the Yucatan Basin from the Maya block/Yucatan Peninsula. All these features are probably capable of earthquakes of M_w approximately 7, similar to the April 1941 M_w 7 earthquake {(Phase 2 earthquake catalog M_w 7.03)} on the SOF 2.5.1-2

Nicaraguan Rise southwest of Jamaica (References 641 and 640). However, all these features are distant from southern Florida (all greater than 200 miles or 320 kilometers), some greater than 400 miles (640 kilometers), all have low strain rates compared to the plate boundary faults (e.g., Reference 502), and all have comparable or lesser magnitude potential than plate boundary faults or source areas (i.e., Cuba) that are closer to Units 6 & 7 site.

2.5.1.1.3 Geologic Evolution of the Site Region and Beyond

The Units 6 & 7 site is located on the North America Plate, approximately 400 miles (640 kilometers) north of the Caribbean Plate boundary. This subsection provides an overview of the major tectonic and geologic events that occurred in the site region and beyond during the past few hundred million years, with an emphasis on those events that currently are expressed in the tectonic features and geology of the site region. Figure 2.5.1-329 presents a summary of these tectonic and geologic events in the evolution of the North America/Caribbean Plate boundary. Aside from buried Paleozoic and older basement rocks, the geology of the site region primarily comprises Mesozoic and younger transitional crust and overlying strata.

2.5.1.1.3.1 Paleozoic Tectonic History

Because the site region (portions of the Florida Platform, Bahama Platform, and Cuba) was not a part of North America until the Permian Period, it has a different tectonic history. For completeness, the subsequent text includes a review of the tectonic history of southeastern North America, namely the events of the Appalachian orogenies, followed by a discussion of the evidence that exists for the tectonic history of the pre-Mesozoic basement of the site region.

Southeastern North America

Three primary mountain-building events affected the rocks of southeastern North America. The Taconic orogeny occurred in the Middle to Late Ordovician approximately 480 to 435 Ma as one or more terranes, perhaps microcontinents, and/or volcanic island arcs collided with the eastern margin of Laurentia via subduction on an east-dipping subduction zone. The onset of the Taconian event is marked regionally throughout much of the Appalachian belt by an unconformity in the passive-margin sequence and deposition of clastic sediments derived from an uplifted source area or areas to the east (References 682 and 683). The Neoacadian, or the younger portion of the Acadian orogeny exhibited in the southern Appalachians, included unconformities in foreland strata, plutonism,

limited migmatization, and some faulting (References 683 and 795). The final and most significant tectonic event of the southern Appalachians was the Alleghany orogeny, during which Gondwana (Africa, Florida Platform basement, and South America) collided with Laurentia, and the intervening Rheic Ocean was consumed in the Permian. This significantly shortened the previously-accreted terranes and translated them westward across the eastern margin of North America (Reference 683). Metamorphism, plutonism, and faulting in the Piedmont of the Carolinas and Georgia accompanied the uplift of the mountain range from New England to Alabama (Reference 683).

The Florida Platform

The collision of Africa with North America during the late Paleozoic occurred along a buried Alleghanian suture known as the Suwannee suture, the Suwannee-Wiggins suture, or the South Georgia suture (Reference 342). This suture represents the boundary between the crust of Laurentia to the north and the crust of Africa or Gondwana to the south (Reference 684). Multiple versions of this roughly east-west striking structure have been hypothesized, all of which occur generally buried beneath the coastal plain of southern Alabama and Georgia subparallel to the Brunswick magnetic anomaly and just north of the elongate Triassic South Georgia Rift system (References 342, 344, and 685) (Figure 2.5.1-229).

Limited information is available regarding the Precambrian to Paleozoic evolution of the site region, located south of the Suwannee suture. The sources of this information are: (a) borings from the Suwannee terrane in central and northern Florida, 100 miles (160 kilometers) north of the site; (b) the allochthonous Socorro complex on northern Cuba, 200 miles (320 kilometers) south of the site; and (c) borings from transitional crust of the southeastern Gulf of Mexico, 250 miles (400 kilometers) southwest of the site. No Precambrian or Paleozoic components have been encountered in the few borings on the Bahama Platform.

Rocks drilled in the Suwannee terrane in central Florida include low-grade, felsic metavolcanics of the Osceola volcanic complex; the undeformed Osceola Granite; a suite of high-grade metamorphic rocks, such as gneiss and amphibolite, belonging to the St. Lucie complex; and a succession of generally undeformed Paleozoic sedimentary rocks. These units, described in detail in Subsection 2.5.1.1.1.2.1.1, indicate that the Suwannee terrane experienced Late Proterozoic to Early Carboniferous plutonism, volcanism, and high-grade metamorphism, followed by tectonic quiescence during the lower Ordovician through Devonian.

Using correlations with rocks in West Africa, it appears that the Gondwana-derived Florida Platform basement (the Suwannee terrane) experienced tectonism from 650 to 500 Ma, a quiescent Paleozoic, and only localized thrusting or metamorphism during the Late Paleozoic amalgamation of Pangea (References 686 and 337), in contrast to the significant Paleozoic deformation of multiple orogenies experienced in Laurentia (North American craton).

The Gulf of Mexico and Northern Cuba

Two borings for the DSDP in the southeastern Gulf of Mexico encountered basement rock (Reference 687). The samples are located approximately 250 miles (400 kilometers) southwest of the Units 6 & 7 site. Sixty-six feet (thirty meters) of phyllite were found at the bottom of one boring, samples from which yielded whole rock $^{40}Ar/^{39}Ar$ ages of approximately 450 to 500 Ma. Samples from the other boring indicate that mylonitic gneiss and amphibolite were intruded by several generations of diabase dikes. Hornblende from the amphibolites yielded $^{40}Ar/^{39}Ar$ ages of approximately 500 Ma, while biotite from a gneiss yielded a 350 Ma age. The dikes have whole-rock ages that range from 190 Ma to 163 Ma (Reference 793). These results confirm that the transitional crust sampled in the basement of the southeastern Gulf of Mexico (and probably the southern Florida Platform and western Bahamas) consists of pan-African crust intruded by Jurassic diabase (Reference 410).

In northeastern Cuba, the Socorro complex consists of a metasedimentary unit of marble, quartzite, and mylonitized granite. The entire complex occupies a very small area, and structural interpretations indicate that it was thrust northward along with the surrounding Cretaceous arc rocks. Biotite separated from the marbles yield an $^{40}Ar/^{39}Ar$ age of approximately 900 Ma with the plateau indicating a reheating event at 60 Ma. Two discordant conventional U-Pb zircon fractions from the granite yield a Jurassic lower intercept age and a 900 Ma upper intercept age. These data were interpreted to reflect a 900 Ma (possibly Grenville) metamorphic event and a Paleogene heating event that probably reflects the emplacement of the Greater Antilles volcanic arc. The 900 Ma age may indicate that the Socorro complex originated from the Yucatan, Chortis, or other Central American block (References 689 and 442) (Figure 2.5.1-206).

2.5.1.1.3.2 Mesozoic Tectonic History

During the Mesozoic, major tectonic events occurred in the site region and beyond, including the opening of the Gulf of Mexico, the development of the

Caribbean Plate, and the opening of the Atlantic Ocean. This subsection presents a generalized tectonic history of the site region and beyond, with emphasis on the Gulf of Mexico and north-central Caribbean region. In summary, the super-continent Pangea began to rift apart in the Late Triassic-Early Jurassic Periods, moving North America away from conjoined South America and Africa. This led to the widespread development of a series of Triassic-Jurassic rift basins along the eastern margin of Laurentia, from New England to southern Georgia (e.g., Reference 471). Both the Atlantic Ocean Basin and the Gulf of Mexico opened, and the continental crustal extension during this time is reflected in a few buried early Mesozoic normal faults within the site region.

It should be noted that details of the interpretation may vary from author to author, but this summary represents current general ideas. Iturralde-Vinent and Lidiak (Reference 690) and Giunta et al. (Reference 691) discuss current research directions for future clarification of Caribbean Plate tectonic history. For example, details of magmatic, metamorphic, and stratigraphic events suggest that the Great Antilles Arc may have comprised more than one arc.

The discussion presented here favors the "Pacific origin" reconstruction of Caribbean Plate tectonic history, which assumes that the plate originated in the present-day Pacific Ocean to the southwest of Central America, and migrated eastward to fill the gap between the diverging North and South America plates. An opposing "in situ" reconstruction has been presented (e.g., Reference 608), which postulates that the present Caribbean is the result of simple northwest-southeast extension between the North and South America plates. The "Pacific origin" reconstruction appears to be favored by most researchers at present, and thus is presented here.

Formation of the Gulf of Mexico

Figure 2.5.1-206, modified from Pindell and Kenan (Reference 696), shows proposed relations between North America, South America, and Africa in the early Jurassic. The Suwannee suture marks the closing of the proto-Atlantic ocean and collision of combined Africa and South America (Figures 2.5.1-205 and 2.5.1-204). To the north this suture is paralleled by the Alleghanian deformation front, which occurred from middle Carboniferous (Late Mississippian) through early Permian time (Figure 2.5.1-204). The Yucatan block lay in what is now the Gulf of Mexico, and the Chortis block is seen at the southern tip of what is now North America. Note that some reconstructions interpret a portion of southern Florida originated to the west, in what is now the eastern Gulf of Mexico, moving to its current position via a hypothetical Jurassic transform (such as the Bahamas

Fracture Zone) (References 460 and 212). However, more recent reconstructions of western Pangea indicate a continuous rift system connecting the Atlantic and Gulf of Mexico, but located south of the southern margin of the Florida and Bahama Platforms (Reference 692).

At about 165 Ma, North America began to separate from (the combined) South America and Africa. Spreading ridges and new oceanic crust began to form between the eastern U.S. seaboard and western Africa, and between the Gulf Coast and Mexico and northwestern South America.

Throughout the late Jurassic and early Cretaceous, the Yucatan block became detached from North and South America, isolated by a seaway to the southwest, the Proto-Caribbean Seaway to the southeast, and the Gulf of Mexico to the north (Figure 2.5.1-206). The latter is the only one of these in existence today. Also at this time, the Bahama Platform, a region of thicker-than-oceanic crust upon which an up to 10-kilometer (6.2-mile) thick limestone (carbonate) platform developed. This feature has behaved in a continental-like manner in term of its resistance to subduction. The opening of the Gulf of Mexico and counterclockwise rotation of the Yucatan block occurred, about a pole of rotation near south Florida (Figure 2.5.1-206).

A detailed chronology of the opening of the Gulf of Mexico is presented by Bird et al. (Reference 511). The majority of the development of the Gulf of Mexico rifting began at 160 Ma. Bird et al. (Reference 511) estimate 42° of counterclockwise rotation, over a period of 20 m.y., consistent with estimates from other workers, and a completion of the formation of the Gulf of Mexico by 140 Ma (lower early Cretaceous). This includes the following major events:

1. Development of a terrestrial rift valley between the Yucatan block and the present Gulf Coast.

2. Periodic flooding of seawater from adjacent seaways, leaving behind massive salt deposits. This occurred before the oceanic spreading center developed.

3. Initiation of ocean-floor spreading. Development of a plume near the center of the rift zone left behind high-density rocks on either side of the spreading ridge. These features are not visible on the ocean floor, but are readily seen on gravity anomaly maps. The salt deposits were separated by the spreading ridge, into the Sigsbee salt to the north, and the

Campeche salt to the south. Both deposits have since flowed toward the center of the Gulf of Mexico.

4. Contemporaneous with event 3, the East Mexican transform fault developed along the coast of Mexico to accommodate the asymmetric opening of the Gulf of Mexico.

The Atlantic Ocean Basin begun to open at an earlier date, moving Africa (Gondwana) away from Laurentia via the same rift system that continued into the Gulf of Mexico. Following widespread continental rifting, seafloor spreading began in the Atlantic Ocean at ~185 Ma (Reference 421). The most detailed mapping of the seafloor indicates that oceanic crust is located northeast of the Bahama Platform and east of the Blake Spur magnetic anomaly, though its been speculated that oceanic crust may exist as far west as the East Coast magnetic anomaly north of latitude approximately 29° N (Reference 466). Spreading centers may have led to the development of the East Coast magnetic anomaly and the Blake Spur magnetic anomaly (e.g., Reference 409).

The majority of the above outlined tectonic events occurred well outside the site region during the Triassic and Jurassic. However, evidence of the regional tectonic history is seen in the two primary phenomena on the Florida and Bahama Platforms: (a) the intrusion of late Triassic and early Jurassic rift-related magmatic products, such as basalts and rhyolites (e.g., Reference 463), and (b) the existence of normal faults buried by Cretaceous and younger strata (e.g., Reference 307). Volcanics sampled in subsurface southern Florida indicate a mantle-derived source (Reference 694), and those in central and northern Florida share characteristics with rocks in the Gondwana-derived Carolina terrane (Reference 695). The compaction and differential subsidence of the sedimentary section deposited over a faulted basement topography led to the development of arches and lows on the Florida Platform, such as the Peninsular Arch and the Sarasota Arch (Reference 413, see Subsection 2.5.1.1.1.3.2.1). Extensional thinning of the basement and intrusion of rift-related magma led to the 'transitional' nature of the crust beneath the Florida and Bahama Platforms. The deposition of thick Cretaceous carbonates on the Florida and Bahama Platforms and in parts of Cuba indicate that the site region was a slowly subsiding shallow carbonate platform by that time, and that these rift-related tectonic events had ceased (References 441 and 413).

The Cretaceous Greater Antilles Arc

During the Late Cretaceous, the approach of the Greater Antilles Arc collided with the Florida and Bahama Platforms. This process eventually led to the transfer of material now found on Cuba from the Caribbean to the North America Plate.

In the Early Aptian, North and South America drifted farther apart (Figure 2.5.1-206). The eastern Bahama Platform is postulated to be created by a "leaky" transform fault or "hot spot" along the proto-mid-Atlantic Ridge (Reference 696). The creation of the Gulf of Mexico and accretion of the Yucatan block to North America are complete.

During the late Cretaceous, the Greater Antilles Arc was initiated, and the Caribbean plate developed. In detail:

1. In the Aptian, a central section of subducting Farallon Plate between North and South America switched polarity (the dip of subducted oceanic crust switched to west), and started moving into the proto-Caribbean Seaway. The eastern boundary of the new Caribbean Plate was the Greater Antilles Arc (Figure 2.5.1-206).

2. Behind it, the Central American Arc was initiated, accommodating most of the Farallon-North America Plate motion. The new Caribbean Plate lay between the two arcs, as it does today (Figure 2.5.1-206).

3. Collision of the Greater Antilles Arc with southeast Yucatan accreted continental material to the western Greater Antilles Arc, indicated by detrital mica ages from western Cuba (Reference 442) (Figures 2.5.1-206 and 2.5.1-250).

After the Greater Antilles Arc collided with the Yucatan Platform, it moved northward into the proto-Caribbean seaway and approached the Bahama Platform (Figure 2.5.1-250). The southeast Yucatan margin was then a strike-slip boundary, and at the Paleocene (60 Ma), the arc collided with the Bahama Platform. The Yucatan Basin formed behind the Greater Antilles Arc, and the Chortis block (Figure 2.5.1-206) moved to the east, forming present day southern Guatemala, Honduras, and northern Nicaragua.

2.5.1.1.3.3 Tertiary Tectonic History

Paleocene - Miocene Greater Antilles Arc Collision with Bahama Platform

By early Cenozoic time, the Greater Antilles Arc had moved northwards, consuming proto-Caribbean oceanic crust along the way, far enough to make contact with the Bahama Platform, which initiated an arc-continent collision. This event led to the following effects, which gave rise to the configuration of the present-day northern Caribbean:

1. Greater Antilles Arc collided with Bahama Platform. In western Cuba, the Greater Antilles Arc reached the Bahama Platform, and because the Bahama Platform crust was buoyant, subduction ceased at the northwestern end of the arc (Reference 697). As a result, arc volcanism ceased, ophiolites and Bahama Platform carbonates were obducted and transferred northward, and the arc massif collapsed and began to erode. The collision initiated in western Cuba in late Paleocene to early Eocene time, and continued eastward (Reference 220). The Cretaceous arc and ophiolite sequence now exposed on Cuba was thrust onto Cuba and transported northward over the Bahama Platform along the Domingo thrust fault and other structures (Reference 439).

2. Rotation of Caribbean Plate movement to the east. As further northward movement of the plate was impeded, the direction of movement rotated to the east where less resistance was encountered; i.e., the North America oceanic plate to the east of the Bahama Platform. The change in plate direction resulted in the creation of a set of left-lateral strike-slip faults that progressively shifted position from northwest to southeast (References 219 and 697). These are, respectively, the Pinar, La Trocha, Camaguey, and Nipe faults (Figure 2.5.1-247). These faults represent paleo-plate boundaries as the landmass on the northwest side became attached to the North America Plate. This process occurred over a period of 40 m.y., from Late Paleocene (60 Ma) to early Miocene (20 Ma) (Figure 2.5.1-250). The last, and currently active, fault in the progression is the Oriente fault.

Within the site region, the effects of the collision of the Greater Antilles arc with the Bahama Platform led to the development of faulting in northern Cuba and in the Straits of Florida during the Eocene time. The Walkers Cay fault and Santaren anticline were also active at this time, and deformation or later reactivation may

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have occurred in the Miocene on all of these structures and may have continued into the Quaternary on the Walkers Cay, Santaren anticline, and faults in Cuba.

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Opening of the Cayman Spreading Center and Trough

The Cayman Trough is postulated to have initiated from a pull-apart basin at about 49 Ma, or early Eocene (Reference 499). This is the result of the left-step in the left-lateral North America-Caribbean Plate boundary (Reference 655). Magnetic stripes on the ocean floor indicate that the Cayman Trough began generating oceanic crust at approximately 44 Ma (References 460 and 222). This signified the end of significant Caribbean-North America Plate boundary motion being accommodated in northern and central Cuba. A Paleogene arc along the Cayman Ridge (a submarine ridge parallel to and north of the Cayman Trough) has been postulated by Sigurdsson et al. (Reference 299) to be the remnants of a volcanic arc that would have formed behind the Greater Antilles Arc, after its passage to the north. However, arguments against this interpretation have been presented by Leroy et al. (Reference 499).

By expansion of the Cayman Trough, development of the Oriente fault as the northern bounding transform fault, the Walton fault as the southeastern bounding fault, and the Swan Islands fault as the southwestern bounding fault occurred. According to Leroy et al. (Reference 499), Hispaniola was connected to Cuba until about early Oligocene (30 m.y.), after which motion on the Oriente fault separated the two. Detailed analysis of depth and age relations of the magnetic reversals in the Cayman Trough indicates that it was spreading at 20 to 30 millimeters/year before 26 Ma, but spreading slowed to a rate of less than 15 millimeters per year after 26 Ma (Reference 222). Sometime after the Late Miocene the Oriente fault connected with the Septentrional fault of northern Hispaniola, which developed as a result of highly oblique left-lateral North America-Caribbean Plate motion. After the Late Miocene, the Enriquillo-Plantain Garden fault extended eastward into southern Hispaniola. It now extends halfway into that island, where it terminates against the Beata Ridge and Muertos subduction zone. Sykes et al. (Reference 660) suggest that spreading rates in the Cayman Trough slowed at 2.4 Ma because the Enriquillo-Plantain Garden fault system became the new plate boundary (References 699 and 655).

Convergence between North America and South America Plates

Sometime in the mid-Tertiary (probably early Miocene, about 15 Ma [Reference 593]) minor north-south convergence between the North America and South America Plates initiated. Evidence for this includes northward migration of

the Beata Ridge and development of the Muertos subduction zone. The Beata Ridge is now "docked" onto south-central Hispaniola, and coincides with the eastern termination of the Enriquillo-Plantain Garden fault and western termination of the Muertos subduction zone.

During the Miocene, clastic sediments of the Hawthorn group were deposited over parts of the Florida Platform, while southernmost Florida and the Bahama Platform continued to be sites of carbonate deposition (References 368 and 393). The deposition of the Hawthorn clastics is important because it reflects that the channels connecting the Gulf of Mexico and Atlantic Ocean that formally prevented the progradation of Appalachian-derived clastics were finally overwhelmed by Appalachian-derived sediment (References 257, 234, 473, and 396). These channels were located in northern Florida and southern Georgia, and existed as the Suwannee Straits in the late Cretaceous to Paleocene and Gulf Trough during the Eocene to Oligocene (References 257, 234, and 473). This Miocene phenomenon, progradation of clastics across the Florida Platform after the Suwannee channel system was filled, was possibly influenced by increased clastic supply from the Appalachians and increased flow through the Straits of Florida (References 221 and 396).

2.5.1.1.3.4 Quaternary Tectonic History

Within the site region, the Quaternary Period is characterized by sedimentary deposition in both marine and terrestrial environments. On the Florida Platform, the Pleistocene Anastasia formation and the Miami Limestone were deposited. The Miami Limestone grades into the Key Largo Limestone, which is a shallow shelf-margin coral reef deposit. Within the submerged areas of the Straits of Florida and the Bahama Banks, Neogene sedimentation is dominated by basinal carbonates and slope deposits of peri-platform oozes intercalcated with turbidites and often controlled by ocean current activity and sea level changes (Reference 228).

Faults within the Straits of Florida, the Santaren anticline, the Walkers Cay fault, and faults in Cuba were all active in the Tertiary (Figure 2.5.1-229). The Santaren anticline, the Walkers Cay fault, and faults in Cuba may have experienced continued tectonic activity into the Quaternary period. PTN RAI 02.05.01-3

Present day tectonic features of the northern Caribbean region are shown in (Figure 2.5.1-202). The Nortecubana fault system, sometimes interpreted as a suture between the northwestern Caribbean Plate and the North America Plate, is more aptly described as the fold-and-thrust belt from the collision. The

collision-and-suture process proceeded from northwest to southeast, beginning at 60 Ma and ending at 40 Ma. The portions of Cuba within the site region are far (>300 kilometers) from the active plate boundary between the Caribbean and North American plates and exhibit low to moderate seismicity rates. | PTN RAI 02.05.01-3

West of 71° W, the Cayman Trough separates the current Caribbean-North America Plate boundary into two subparallel, predominantly left-lateral strike-slip features, the Oriente and Septentrional faults on the north, and the Swan Islands-Walton-Duanvale-Enriquillo-Plantain Garden fault system on the south. These accommodate a relative plate motion of about 20 millimeters/year, which appears to be about equally divided between the two features (References 358, 652, and 643).

2.5.1.1.4 Contemporary Stress Regime

Three types of forces are generally responsible for the stress in the lithosphere:

- Gravitational body forces or buoyancy forces, such as the ridge-push force resulting from hot, positively buoyant young oceanic lithosphere near the ridge against the older, colder, less buoyant lithosphere away from the ridge (Reference 700). This force is transmitted by the elastic strength of the lithosphere into the continental interior.
- Shear and compressive stresses transmitted across plate boundaries (such as strike-slip faults or subduction zones).
- Shear tractions acting on the base of the lithosphere from relative flow of the underlying asthenospheric mantle.

Contemporary Stress Regime within the Site Region

The Earth Science Teams (ESTs) that participated in the EPRI (Reference 456) evaluation of intra-plate stress concluded that tectonic stress in the CEUS region is primarily characterized by northeast-southwest-directed horizontal compression. In general, the ESTs concluded that the most likely source of tectonic stress in the mid-continent region is ridge-push force associated with the mid-Atlantic Ridge, transmitted to the interior of the North America Plate by the elastic strength of the lithosphere. Other potential forces acting on the North America Plate were judged to be less significant in contributing to the magnitude and orientation of the maximum compressive principal stress.

In general, the ESTs focused on evaluating the state of stress in the mid-continent and Atlantic seaboard regions, for which stress indicator data were relatively abundant. Fewer stress indicator data were available for the Gulf of Mexico, Gulf Coastal Plain, and Florida Peninsula, and thus these areas received less scrutiny in the EPRI (Reference 456) studies. Since 1986, an international effort to collate and evaluate stress indicator data culminated in publication of a new *World Stress Map* (Reference 702) that has been periodically updated (Reference 703). Plate-scale trends in the orientations of principal stresses were assessed qualitatively based on analysis of high-quality data (Reference 704), and previous delineations of regional stress provinces were refined (Reference 705). Statistical analyses of stress indicators confirmed that the trajectory of the maximum principal compressive stress is uniform across broad continental regions at a high level of confidence (Reference 706). In particular, the northeast-southwest orientation of principal stress in the CEUS inferred by the EPRI ESTs is statistically robust and is consistent with the theoretical orientation of compressive forces acting on the North America Plate from the mid-Atlantic Ridge (Reference 704).

According to the continental United States stress map of Zoback and Zoback (Reference 707), most of the CEUS is in the mid-plate stress province, which displays a consistent northeast-southwest maximum compressive stress orientation. However, coastal regions of Texas, Louisiana, Mississippi, Alabama, and northwestern Florida can exhibit down-to-the-gulf growth faulting. Hence, this area has been designated as the Gulf Coast stress province, characterized by northeast-southwest to north-northeast to south-southwest horizontal tension (Reference 702). The boundary between the mid-plate and Gulf Coast stress provinces terminates in the northern Florida Peninsula, but there is a lack of stress data from areas near the Florida Peninsula and most of Cuba. Because the southern Florida Peninsula doesn't exhibit the geologic features (such as salt-rooted normal faults) associated with the Gulf Coast stress province, the site region is generally interpreted to be part of the mid-plate stress province (Reference 705) (Figure 2.5.1-330).

The mid-plate stress province may exhibit reverse or strike-slip faulting under east-northeast- to west-southwest- to northwest-southeast-oriented compressive stress. This region extends from an approximately north-south-oriented line through Texas, Colorado, Wyoming, and Montana to the Atlantic margin and potentially into the Atlantic Ocean Basin. Within this province, the orientation of maximum compressive stress is generally parallel to plate velocity direction (Reference 702). Richardson and Reding (Reference 646) conclude that the