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2.4.6 PROBABLE MAXIMUM TSUNAMI HAZARDS

PTN COL 2.4-2 This subsection examines the tsunamigenic sources and identifies the probable maximum tsunami (PMT) that could affect the safety-related facilities of Units 6 & 7. It evaluates potential tsunamigenic source mechanisms, source parameters and tsunami propagation from published studies, and provides information on tsunami water levels expected at the site. Historical tsunami events recorded along the Florida coast are reviewed to support the PMT assessment. The approach taken is aligned with the PMT evaluation methodology proposed in NUREG/CR-6966 (Reference 201).

Units 6 & 7 are adjacent to the Biscayne Bay shore approximately 8 miles west of Elliott Key Barrier Island on the coast of the Atlantic Ocean, as shown on Figure 2.4.1-201. The grade elevations at the Units 6 & 7 plant area vary from approximately 19.0 feet to 25.5 feet NAVD 88. The entrance floor elevation of all safety-related structures (also referred to as the design plant grade elevation in the AP1000 DCD, which is 100 feet, or 30.48 meters, in the DCD reference datum) is at elevation 26 feet NAVD 88. The plant area is protected by a retaining wall structure with top elevation of 20.0 feet to 21.5 feet NAVD 88. As the grade is relatively high, tsunami events are not expected to pose any hazard to safety-related structures, systems, and components (SSCs) of Units 6 & 7, as described in the subsections below.

2.4.6.1 Probable Maximum Tsunami

The Atlantic and Gulf of Mexico Tsunami Hazards Assessment Group (AGMTHAG) evaluated potential tsunamigenic source mechanisms that may generate destructive tsunamis and affect the U.S. Atlantic and Gulf of Mexico coasts (Reference 202). The major tsunamigenic sources that may affect the southeastern U.S. coasts can be summarized as follows: submarine landslides along the U.S. Atlantic margin, submarine landslides in the Gulf of Mexico, far-field submarine landslide sources, earthquakes in the Azores-Gibraltar plate boundary, and earthquakes in the north Caribbean subduction zones (referred to as the Caribbean-North American plate boundary in Subsection 2.5.1.1.4).

Based on the below descriptions of the different source mechanisms, transoceanic tsunamis as a result of earthquakes in the Azores-Gibraltar (east Atlantic) plate boundary and tsunamis generated in the northeastern Caribbean region are identified as the primary candidates of the PMT generation that could affect Units 6 & 7.

2.4.6.1.1 Submarine Landslides along the U.S. Atlantic Margin

Submarine landslide zones along the U.S. Atlantic margin are concentrated along the New England and Long Island, New York sections of the margin, outward of major ancient rivers in the mid-Atlantic region, and in the salt dome province offshore of North Carolina, as shown in Figure 2.4.6-201 (Reference 202). Although submarine landslides along the U.S. Atlantic margin, from Georges Bank offshore of the New England coast to Blake Spur south of the Carolina Trough, have the potential to cause devastating tsunamis locally, the presence of a wide continental shelf is expected to reduce their impact at the shoreline (Reference 202).

AGMTHAG mapped a total of 48 landslide affected areas based on data compiled from bathymetry, GLORIA (Geological Long-Range Inclined Asdic) sidescan sonar imagery, seismic reflection profiles, and sediment core data (Reference 202). The general characteristics of the mapped landslides are summarized in Table 2.4.6-201. The distribution of landslide locations identified along the U.S. Atlantic margin from the Georges Bank to the Carolina Trough is shown in Figure 2.4.6-202. The largest submarine landslide area near Units 6 & 7 is identified in an area south of Cape Hatteras, off the Carolina Trough. The largest landslide in this area exceeds 15,241 square kilometers (5885 square miles) with a volume in excess of 150 cubic kilometers (36 cubic miles). Tectonic activities of the salt domes have been suggested as the triggering mechanism for the landslides in this area along with suggestions that decomposition of gas hydrates due to sea level change and small shallow earthquakes may also have contributed to the formation of these landslides (Reference 202).

Units 6 & 7 are located approximately 400 miles (640 kilometers) southwest of Blake Spur with a wide and shallow continental shelf in between (Figure 2.4.6-201). Additionally, the landslide zones are oriented in a manner that Units 6 & 7 would be away from the main axis of submarine landslide-generated tsunamis. Consequently, the impact of any submarine landslide-generated tsunami in the continental shelf north of Blake Spur would be considerably reduced before reaching Units 6 & 7.

Twichell et al. studied submarine erosion and characterized morphologic provinces for the Blake Escarpment (Figure 2.4.6-203) northeast of Units 6 & 7 (Reference 203). The Blake Escarpment, extending approximately 450 kilometers

(280 miles) to the south from Blake Spur, is one of the largest cliffs in the ocean with a relief of about 4000 meters (13,120 feet) (Reference 203). Near the southern edge of the escarpment, it crosses with the Jacksonville fracture zone, which underlies the Blake plateau at the location of Abaco Canyon. The escarpment was isolated from the continent-derived sediments since late Cretaceous, first by the currents in the Suwannee Straits and later by the Gulf Stream, and erosion of the escarpment is evident over the period (Reference 203).

Twichell et al. identified three morphologic provinces along the Blake Escarpment with varying erosional behavior (Reference 203). These are (1) valleys with tributary gullies, (2) box canyons, and (3) strait terraces. Valleys with tributary gullies are in the northern part of the escarpment near Blake Spur that have undergone no or very little erosion over time. Box canyons are formed by the differential settlement of base rock probably over a long period and are identified south of the Jacksonville fracture zone. The overlying carbonate strata in box canyons are fragmented with continued erosion. The middle reach of the escarpment has straight terraces formed by differential erosion of lithologic differences in the strata exposed along the cliff faces and has lower erosion potential than box canyons (Reference 203). The study by Twichell et al. identified evidence of debris accumulation at the base of the escarpment; however, it did not characterize any tsunamigenic source in the escarpment (Reference 203). Units 6 & 7 are sheltered by the islands of the Bahamas from tsunamis, if any, generated in the region, thus protecting Units 6 & 7 from being affected by large tsunamis.

Units 6 & 7, therefore, would not be impacted by significant submarine landslide-generated tsunamis from the U.S. Atlantic margin.

2.4.6.1.2 Submarine Landslides in the Gulf of Mexico

Within the Gulf of Mexico, evidences of submarine landslides are recorded in all three geological provinces (Carbonate, Salt, and Canyon/Fan) (Reference 202). The geological provinces within the Gulf of Mexico are shown in Figure 2.4.6-204. The largest submarine failures are found in the Canyon/Fan Province within the Mississippi Fan that was probably active 7500 years ago. The largest failure in the Salt Province is identified offshore of the Rio Grande River. Landslide evidences in the Carbonate Province are identified in the West Florida and Campeche Escarpments along the eastern and southern Gulf of Mexico, respectively (Reference 202).

Significant landslides on the West Florida Slope above the Florida Escarpment (Figure 2.4.6-205) are sourced in Tertiary and Quaternary carbonate deposit. This landslide zone, which is located approximately 300 miles (480 kilometers) west of Units 6 & 7, is hypothesized to be a composite of at least three generations of failures (Reference 202).

Based on the mapping of landslide zones in the Gulf of Mexico, AGMTHAG identified four likely landslide zones and characterized tsunamigenic source parameters that could be used to calculate corresponding tsunami amplitudes (Reference 202). However, because Units 6 & 7 are located on the eastern side of the Florida peninsula opposite of the Gulf of Mexico shoreline and a very wide continental shelf exists along the Gulf Coast of Florida, tsunamis generated within the Gulf of Mexico would likely be dissipated before reaching Units 6 & 7. Therefore, it was concluded that landslide-generated tsunamis from the Gulf of Mexico sources would not affect the safety-related facilities of Units 6 & 7 that have a design plant grade elevation of 26 feet NAVD 88.

2.4.6.1.3 Far-Field Submarine Landslide Sources

Ward and Day (Reference 204) postulated a mega-tsunami scenario as a result of a possible catastrophic flank failure of the Cumbre Vieja volcano at La Palma of Canary Islands. They estimated that a future volcanic eruption of Cumbre Vieja could slide up to 500 cubic kilometers (120 cubic miles) of rock volume into the ocean running westward 60 kilometers (37.3 miles) offshore at a speed of 100 meters per second (328 feet per second) resulting in a tsunami amplitude of 20–25 meters (66-82 feet) at the Florida Atlantic coast. However, Mader pointed out that the assumption of linear propagation of shallow water wave, as used in Ward and Day’s analysis, only described geometrical spreading of waves and ignored the effects of short period wave dispersion (Reference 205). Such an assumption would overpredict the tsunami amplitude. Using the SWAN computer code, Mader computed a maximum tsunami amplitude less than 3.0 meters (10.0 feet) along the U.S. Atlantic coast and less than 1.0 meter (3.3 feet) near Miami, Florida (Reference 205). Mader adopted the initial tsunami amplitude as obtained from the physical model study of the Cumbre Vieja volcano flank failure performed at the Swiss Federal Institute of Technology (Reference 205). The Swiss Federal Institute of Technology experiment considered the failure as a single monolithic block (Reference 205). Pararas-Carayannis also disputed the claim by Ward and Day that a collapse of the Cumbre Vieja volcano is imminent (Reference 206).

More recent modeling efforts by Gisler et al. of the Cumbre Vieja volcano flank failure also showed significant wave dispersion (Reference 207). From the model simulation results, Gisler et al. demonstrated that the tsunami amplitude decay is proportional to $r^{-1.85}$ and $r^{-1.0}$, where r is the distance from tsunami source, for the two- and three-dimensional models, respectively. The simulated tsunami amplitude varied between 1 and 77 centimeters (0.4 and 30 inches) along the Florida Coast (Reference 207). Gisler et al. used smaller slide volume but much higher slide speed compared to those used in Ward and Day (Reference 202). The amplitude in Ward and Day model scales proportionally with rock volume times slide speed. Hence, the much smaller predicted amplitude of Gisler et al. for the Florida coast cannot be attributed to the smaller slide volume (Reference 202). AGMTHAG concluded that a tsunami from this source is not expected to cause a devastating tsunami along the east coast of the United States (Reference 202).

The other notable far-field submarine landslide tsunami sources are located along the glaciated margins of northern Europe and Canada (Reference 202). The Storegga landslide in northern European margin is identified as a composite of seven slides over the past one-half million years with the largest and most recent landslide dated at 8150 years before present. The resulting tsunamis affected the coasts of Norway, Faeroes islands, Shetland islands, Scotland and northern England. The impacted areas were all within 600 kilometers (375 miles) of the slide (Reference 202).

The Grand Banks landslide in the Scotian margin near Newfoundland, Canada generated a devastating tsunami locally in 1929 (References 202 and 208). AGMTHAG indicated that increased deposition and slope failure on the Scotian margin was due to glacial advance that reached close to the shelf edge about one-half million years before present. However, deposition rate decreased significantly about 8000 years ago as deglaciation ended (Reference 202). The 1929 Grand Banks landslide is one of the only two landslide occurrences in the Scotian margin postdated to the Holocene. Units 6 & 7 would not be affected by teletsunamis from these landslide sources because the tsunamis would be dissipated before reaching them.

2.4.6.1.4 Earthquakes in the Azores-Gibraltar Plate Boundary

Tsunamigenic earthquake sources that may affect the Florida Atlantic Coast are located west of Gibraltar in the Azores-Gibraltar plate boundary near Portugal in the East Atlantic Ocean (at the Africa-Eurasia plate boundary) and in the northeastern Caribbean Basin (Caribbean-North American plate boundary). The

Azores-Gibraltar plate boundary separates the African and Eurasian plates, as shown in Figure 2.4.6-206, and has been identified as the source of the largest earthquakes and tsunamis in the north Atlantic basin (Reference 202). AGMTHAG summarized six large tsunamigenic earthquakes that had occurred in this region over the past 300 years—in 1722, 1755, 1761, 1941, 1969 and 1975 (Reference 202). The 1755 Great Lisbon Earthquake, which was estimated in earthquake moment magnitude (M_w) to be 8.5–9.0, had the largest documented felt area of any shallow water earthquake in Europe, and was the largest natural disaster to have affected Europe in the past 500 years (Reference 202). The earthquake motion and ensuing submarine landslide contributed to tsunami waves of 5 to 15 meters (16.4 to 49.2 feet) that devastated the coasts of southwest Iberia and northwest Morocco and were reported as far north as Cornwall, England (Reference 202). Figure 2.4.6-206 shows the general tectonic setting and bathymetry of the eastern segment of the Azores-Gibraltar plate boundary.

The large tsunami waves also travelled across the Atlantic reaching as far north as Newfoundland, Canada and as far south as Brazil, and caused widespread damage in the eastern Lesser Antilles (Reference 202). However, there is no record of tsunami run-up on the U.S. east coast from this event, although several populated cities existed along the U.S. Atlantic coast in 1755 (Reference 202). Computer simulations by Mader (Reference 209) indicated that the maximum tsunami amplitude including run-up in the U.S. east coast was approximately 3.0 meters (10.0 feet). AGMTHAG simulated the 1755 earthquake tsunami with the source location varying within the Azores-Gibraltar region. The maximum tsunami amplitude in the deep water along the U.S. Atlantic margin was obtained as approximately 0.6 meter (2.0 feet) for a tsunami source location east of the Madeira Tore Rise (Figure 5-8, Reference 202). Further discussion of the 1755 earthquake-generated tsunami is provided in Subsections 2.4.6.2 and 2.4.6.3.

2.4.6.1.5 Earthquakes in the North Caribbean Subduction Zones

The Caribbean region is characterized by high seismic activities and is associated with a large number of past tsunamis (References 210 and 211). Tsunami sources in the northeastern Caribbean Basin that may affect the Florida Atlantic coast include the Puerto Rico and Hispaniola trenches, as shown in Figure 2.4.6-207. AGMTHAG simulated the distribution of peak offshore tsunami amplitude along the Gulf of Mexico and Atlantic Coasts from a postulated earthquake in the Puerto Rico trench. The simulation, which used a linear long-wave model for the deepwater regions and did not include frictional effects, predicted the maximum tsunami amplitude to be no more than 0.1 meter (0.3 foot) at a water depth of

250 meters (820 feet) near the longitude of approximately 80.2° W (longitude position estimated from Figure 8-2c of Reference 202). This longitude position represents generally the location within the Straits of Florida, which is south-southwest of Units 6 & 7. The maximum deepwater tsunami amplitudes along the U.S. Atlantic coast, however, were much higher, close to 5 meters (16.4 feet) near latitude 40° N (latitude position represents generally a location offshore of the New York/New Jersey coast) and approximately 3 meters (10 feet) near latitude 33.2° N (offshore of the South Carolina coast). The model simulated a maximum deepwater tsunami amplitude of about 3.5 meters (11.5 feet) near 28° N (offshore of Palm Bay, Florida) (Figure 8-3c of Reference 202). The relatively small tsunami amplitude near Units 6 & 7 is primarily a result of the presence of the Bahamas platform to the east, as shown in Figure 2.4.6-208. AGMTHAG did not model the propagation of tsunami waves across the continental shelf (water depth less than 250 meters or 820 feet) and run-up (Reference 202).

A similar tsunami model study was also performed by the West Coast and Alaska Tsunami Warning Center using a two-dimensional hydrodynamic model developed at the University of Alaska, Fairbanks (Reference 211). Four hypothetical worst-case scenarios with tsunami sources located in the Gulf of Mexico and the Caribbean regions were simulated using the West Coast and Alaska Tsunami Warning Center model. The simulations predicted the peak tsunami amplitude near Virginia Key, Florida, to be approximately 15 centimeters (0.5 foot) for an earthquake magnitude M_w of 9.0 in the Puerto Rico Trench. The simulated earthquake is larger in magnitude than any recorded earthquake in this region. The maximum recorded earthquake magnitude in this region is 8.3 (unknown earthquake scale) that struck the Guadeloupe Island in Lesser Antilles, as obtained from the National Geophysical Data Center (NGDC) earthquake database (Reference 212). Also tabulated in the NGDC earthquake database are two events with earthquake surface wave magnitude (M_s) of 8.1 that occurred near Haiti in 1842 and the Dominican Republic in 1946.

2.4.6.1.6 Other Sources

An extensive literature search did not return any information of seismically induced seiche in Biscayne Bay. In addition, because of low and flat topography near Units 6 & 7, the possibility of any subaerial slope failure that would generate tsunamis affecting Units 6 & 7 is precluded.

Earthquakes within the Gulf of Mexico are also recorded with epicenters located within the North American plate boundaries. Such “midplate” earthquakes are less common than earthquakes occurring on faults near plate boundaries and are unlikely to produce any destructive tsunami (Reference 213).

2.4.6.1.7 Summary of Potential Sources for PMT at Units 6 & 7

Units 6 & 7 are not located in the immediate vicinity of any tsunamigenic source. The landslide zone nearest to Units 6 & 7 is located on the west Florida slopes within the Gulf of Mexico, separated by a very wide and shallow continental shelf and the entire width of the Florida peninsula. There is no historical evidence of any tsunami from landslides in the Gulf of Mexico. Landslides in the U.S. Atlantic margin may potentially generate local destructive tsunamis. However, because Units 6 & 7 are located far away from any such sources, is mostly sheltered by the Bahamas platform, and is protected by a retaining wall structure with top elevation of 20.0 feet to 21.5 feet NAVD 88, such tsunamis are not expected to cause any flooding concern to the safety-related facilities of Units 6 & 7. The orientation of the Puerto Rico trench and the presence of the Bahamas platform prevents any destructive tsunami to impact Units 6 & 7 from this source. Therefore, it is concluded that the PMT would likely be caused by earthquake-generated transoceanic tsunamis from the Azores-Gibraltar plate boundary. Characteristics of tsunami source generators for both Azores-Gibraltar plate boundary and Caribbean region are presented in Subsection 2.4.6.3.

2.4.6.2 Historical Tsunami Record

Records of historical tsunami run-up events along the U.S. Atlantic coast near Units 6 & 7 are obtained from the NGDC tsunami database (Reference 214). The NGDC database contains information on source events and run-up elevations for tsunamis worldwide from approximately 2000 B.C. to the present time (Reference 214). A search of the NGDC tsunami database returned 11 historical tsunamis that have affected the U.S. and Canada east coast, as indicated in Table 2.4.6-202.

Three events in the record are the result of a combination of earthquakes and submarine landslides in the Nova Scotia margin off the coast of Newfoundland, Canada, and in the Labrador Sea off Newfoundland, Canada. The most recent and most severe tsunami from this area was that from the M_w = 7.2 earthquake and associated submarine landslide in the Nova Scotia margin in 1929. The ensuing tsunami, with a maximum run-up of approximately 7 meters (23 feet) at Taylor’s Bay, Newfoundland, Canada, was recorded as far south as Charleston, South Carolina (12 centimeters or 4.7 inches).

Three earthquakes in the Caribbean region generated tsunamis that were recorded in the U.S. east coast. The strongest earthquake was the M_s = 8.1 earthquake of August 4, 1946, with an epicenter northeast of the Dominican Republic, which was followed by the August 8, 1946 aftershock (magnitude 7.9 of unknown scale). The maximum tsunami run-ups from the two events were 5.0 meters (16.4 feet) and 0.6 meter (2.0 feet) at the coasts of Dominican Republic and Puerto Rico, respectively, for the August 4 and August 8 events. No run-up data is available from these events on the Florida Atlantic coast. The other tsunami event was caused by the earthquake of 1918 (M_w = 7.3) in Mona passage, located northwest of Puerto Rico, resulting from the displacement of four segments of a normal fault (Reference 214). A recent study hypothesized a combined earthquake- and landslide-generated tsunami for this event (Reference 215). The NGDC database indicates a tsunami amplitude of 6 centimeters (2.4 inches) near Atlantic City, New Jersey. However, no run-up was reported on the Florida Atlantic coast from this event. The maximum tsunami amplitude from this event reported along the western and northern Puerto Rico was 6.1 meters (20.0 feet).

The NGDC database also includes three tsunami events generated in the U.S. Atlantic margin with the Charleston, South Carolina, earthquake-generated (M_w = 7.7) tsunami of 1886 being the only confirmed tsunami. An earthquake event was also reported at Jacksonville, Florida, on the same day approximately an hour before the Charleston, South Carolina, earthquake. It has not been established if the two events were related (Reference 214). The resulting tsunami waves were reported in Jacksonville and Mayport, Florida, although no run-up information is available. The two other tsunami events are reported as probable in the NGDC database. The first tsunami event was the result of an earthquake in High Bridge, New Jersey (magnitude computed from the felt area, Mfa = 4.4) that produced a tsunami-like wave in Long Island, New York, in 1895. The second event was a possible landslide- or explosion-generated tsunami near Long Island, New York, that produced a maximum tsunami amplitude of 0.28 meter (0.9 foot) at Plum Island, New York, in 1964. No tsunami wave from the two events was reported in the Florida Atlantic coast.

The remaining two records in the NGDC database are transoceanic tsunami events: the Great Lisbon Earthquake tsunami of 1755 off the Portugal coast and the Boxing Day tsunami of 2004 off the west Sumatra coast, Indonesia. The earthquake west of Sumatra (M_w = 9.0) generated a tsunami that was recorded nearly worldwide and killed more people than any other tsunami in recorded history (Reference 214). A tsunami amplitude of 0.17 meter (0.6 foot) was recorded at Trident Pier on the Florida Atlantic coast. The Great Lisbon Earthquake that destroyed the city of Lisbon stuck at approximately 9:40 a.m. on November 1, 1755. Mader reported an estimated magnitude (M_w) of approximately 8.75–9.0 for the earthquake that was felt over an area of a million square miles (Reference 209). The earthquake generated a tsunami, which arrived at Lisbon between 40 minutes and 1 hour after the earthquake as a withdrawing wave, that emptied the Lisbon Oeiras Bay (Reference 209). The following tsunami wave arrived with an amplitude of approximately 20 meters (65.6 feet) followed by two more waves approximately an hour apart (Reference 209). The tsunami wave had amplitudes of 4 meters (13.1 feet) along the English coast, and 7 meters (23 feet) at Saba, Netherland Antilles, in the Caribbean after approximately 7 hours of travel (Reference 209). Lockridge et al. also reported tsunami arrival in the harbor at Cape Bonavista, Newfoundland, Canada, with a retreating wave and a subsequent returning wave approximately 10 minutes later (Reference 208). Model simulation by Mader showed that the tsunami wave arrived at the Florida Atlantic coast approximately 8 hours after the earthquake (Reference 209). The deepwater tsunami amplitude off the coast of Miami, Florida, was simulated to be approximately 2 meters (6.6 feet) with a period between 1.25 and 1.5 hours. Mader suggested a maximum tsunami amplitude of approximately 3.0 meters (10 feet) including wave run-up along the U.S. east coast (Reference 209).

Lockridge et al. reported tsunamis and tsunami-like events in the U.S. east coast in addition to the events reported in the NGDC database (Reference 208). Most of these additional events originated along the New York, New Jersey, and Delaware coasts, and the Florida Atlantic coast remained unaffected. An extensive literature search did not reveal any evidence of seismic paleotsunami deposit in the region.

2.4.6.3 Source Generator Characteristics

There is no tsunamigenic source present in the immediate vicinity of Units 6 & 7. The submarine landslide zones in the U.S. Atlantic margin and along the Gulf of Mexico coast are located far away from Units 6 & 7 and are separated by a wide and shallow continental shelf, which would reduce the impact of any landslide-generated tsunamis at Units 6 & 7. The north Caribbean subduction zone and Azores-Gibraltar plate boundary are identified as the primary tsunamigenic earthquake sources that could affect the site. Model simulation results indicate that the shallow Bahamas platform shields Units 6 & 7 from tsunamis generated in the northern Caribbean region (Reference 211). Therefore, the PMT for Units 6 & 7 would likely be transoceanic tsunamis from the Azores-Gibraltar region. The most recent major earthquake in the region occurred in 1969 (M_w = 7.8) and generated a small tsunami amplitude locally (Reference 202).

2.4.6.3.1 Azores-Gibraltar Plate Boundary

The Azores-Gibraltar plate boundary separates the African and Eurasian plates and extends from Azores in the west at the junction of North American, African, and Eurasian plates to east of Gibraltar strait, the area southwest of the Iberian Peninsula (see Figure 2.4.6-206). Based on literature on plate kinematic models and focal mechanisms, AGMTHAG indicated that the motion between the two plates is slow, changing along the boundary from divergent extension in the Azores to compression towards the east end that includes the Gorringe Bank and the Gibraltar Arc (Figure 2.4.6-206). The location of plate boundary in the east near Iberia is uncertain where a diffuse compression zone exists over a 200–330 kilometers (124–205 miles) width. The dominant active structures in the region are the Gorringe Bank Fault (GBF), the Marqués de Pombal Fault (MPF), the St. Vincente Fault (SVF), and the Horseshoe Fault (HSF) (Figure 2.4.6-206) (Reference 202).

The source location of the 1755 earthquake is still the subject of research in the scientific community. AGMTHAG summarizes the three major views on fault solution for the 1755 earthquake (Reference 202). First, in 1996, Johnson (also in 2007, Grandin et al.) suggested a northeast-southwest trending thrust fault, possibly outcropping at the base of the northwest flank of the Gorringe Bank (GBF). Second, Zitellini et al. in 2001 (also Grácia et al. in 2003) suggested active thrusting along the MPF as the source located approximately 80 kilometers (50 miles) west of Cape Sao Vincente. Third, Gutscher et al. in 2002 and 2006 (also Thiebot and Gutscher in 2006) proposed a fault plane in the western Gulf of Cádiz (Gulf of Cádiz Fault, GCF), possibly as part of an African plate subduction beneath Gibraltar (Reference 202).

AGMTHAG used the same set of fault parameters as proposed by Johnson to investigate constraints on the 1755 Lisbon earthquake epicenter, and potential tsunami hazard to the U.S. East Coast from possible future earthquake sources located in the east Atlantic region (Reference 202). The parameters are (Reference 202):

Source depth at the top of the fault plane = 5 kilometers (3.1 miles)
Length = 200 kilometers (124 miles)
Width = 80 kilometers (50 miles)
Dip = 40 degrees

Strike = 60 degrees
Average slip = 13.1 meters (43 feet)

The strike orientation as proposed for MPF and GCF sources differs considerably from the description for the GBF source proposed by Johnston. AGMTHAG investigated the effects of the variation in the location of earthquake epicenter and strike orientation on near-field and far-field tsunami amplitudes. Based on a comparison of model simulation results with reported tsunami amplitudes, AGMTHAG concluded that the 1755 earthquake was likely generated by a northwest-southeast trending fault located in the center of the Horseshoe plain south of Gorringe Bank (Reference 202).

2.4.6.3.2 Hispaniola-Puerto Rico-Lesser Antilles Subduction Zone

The Hispaniola-Puerto Rico-Lesser Antilles subduction zone was formed as the North American plate was subducting southwesterly beneath the Caribbean plate (Figure 2.4.6-207) (Reference 202). Relative plate movement changed to a more easterly direction resulting in a more oblique subduction beginning at 49 million years ago, which remained fairly stable afterwards as evidenced by the opening of the Cayman Trough between Cuba and Honduras (Reference 202). AGMTHAG describes the present subduction at the Puerto Rico trench as an old oceanic crust of 90–110 million years in age, subducting under Puerto Rico and Virgin Islands and at the Hispaniola trench as a thick crust of an unknown origin, which underlies the Bahamas platform (Reference 202).

Although there are geometric similarities between the Puerto Rico trench and Sumatra-Andaman trench where the devastating 2004 Indian Ocean tsunami originated, AGMTHAG pointed out that the slip during the earthquake in the Puerto Rico trench is highly oblique and nearly parallel to the convergence direction unlike the Sumatra-Andaman trench (Reference 202). This difference in the slip angles indicates the potential for only small deformations of the overlying Caribbean plate.

In contrast to the Puerto Rico trench, slip on the Hispaniola trench is sub-perpendicular to the trench. Therefore, a large vertical motion is expected for a given magnitude of slip. Unlike the Puerto Rico trench, where a normal thickness oceanic crust is subducting, the crust entering the Hispaniola trench is very thick and would likely allow more stress to accumulate resulting in large earthquakes to occur (Reference 202).

The rupture parameters for the Puerto Rico and Hispaniola trenches, as proposed by AGMTHAG, are listed below (Reference 202):

Puerto Rico Trench (single rupture)

Length = 675 kilometers along the trench between 68° W and 62° W
Depth = 5 to 40 kilometers (3.1 to 25 miles)
Dip = 20 degrees
Strike = 70 degrees
Slip = 10 meters (32.8 feet)
Slip direction = 60 degrees
Shear modulus = 3 x 10^{10} Pa (6.3 x 10^{8} pounds/square feet)
Earthquake magnitude, Mw = 8.85

Hispaniola Trench

Length = 525 kilometers (326 miles) along the trench between 73° W and 68° W
Depth = 0 to 40 kilometers (0 to 25 miles)
Dip = approximately 20 degrees
Strike = 95–102 degrees
Slip = 10 meters (32.8 feet) assuming complete rupture of the Hispaniola trench
Slip direction = 23 degrees
Earthquake magnitude, Mw = 8.81

2.4.6.4 Tsunami Analysis

The maximum tsunami water level at the Florida Atlantic coast, based on the results of published tsunami studies, is summarized in the following subsections. Detailed water level records near Units 6 & 7 are not available for tsunamis generated by past earthquakes in the Azores-Gibraltar fracture zone or in the Caribbean subduction zone for the listed earthquake magnitudes. However, tsunami water levels at Units 6 & 7 are evaluated based on the results of computer simulations from the two sources (Atlantic and Caribbean regions) with larger earthquake magnitudes compared to those described in Subsection 2.4.6.3. Thus, detailed modeling analysis of tsunami amplitude and its propagation is not performed. This qualitative approach is considered adequate in assessing the PMT hazards at Units 6 & 7 because the tsunamigenic earthquake magnitudes adopted in the reference studies are more severe than any recorded earthquake in the two source regions.

2.4.6.5 Tsunami Water Levels

Tsunami water level on the Atlantic coast near Miami, Florida, is obtained from the model simulation results performed by Mader for the 1755 Lisbon Earthquake tsunami (Reference 209). Because the source location and characteristics for the 1755 Lisbon Earthquake are not precisely known, Mader developed tsunami source parameters in such a way that the model reproduces tsunami amplitude and arrival time within reasonable accuracy at near- and far-field locations where these are known. Mader assumed the source location to be close to Gorringe Bank in the Azores-Gibraltar region, near the source location of the 1969 earthquake (1969 earthquake location is shown on Figure 2.4.6-206). To produce a tsunami amplitude of 20 meters (65.6 feet) with a 1-hour wave period that arrives at Lisbon, Portugal, 40 minutes after the earthquake, Mader considered fracture in a 300 kilometers (186.4 miles) arc-fault with a slip of 30 meters (98.4 feet). Although Mader did not provide information on the strike angle or location, the curved fault structure resembles closely to the composite fault zone assumed by Gutscher et al. in 2002, 2006 and discussed in AGMTHAG (Reference 202). In addition, the slip magnitude assumed by Mader is higher than that listed in Subsection 2.4.6.3.

AGMTHAG also performed numerical model simulations of the 1755 Lisbon Earthquake tsunami to evaluate the potential tsunami impact on the U.S. east coast. AGMTHAG first investigated the constraints on the earthquake epicenter from far field simulations. Tsunami hazards to the U.S. east coast and the Caribbean were then assessed from possible future earthquake sources located in the east Atlantic region. AGMTHAG simulated tsunami propagation for 16 such potential source locations as shown in Figure 2.4.6-209. Based on model simulation results, AGMTHAG concluded that the variation in local seafloor bathymetry significantly controls tsunami propagation across the Atlantic Ocean. The Gorringe Bank and the Madeira Tore Rise (see Figure 2.4.6-206 for locations) act as near source barriers protecting most of the U.S. east coast. For sources located east of Madeira Tore Rise and south of Gorringe Bank, Florida might be at risk if sufficient wave energy passes through the Bahamas (Reference 202). AGMTHAG did not simulate tsunami wave run-up in the near shore region and considered relative amplitude evaluation only (Reference 202). Because the simulated deepwater tsunami amplitude in the southeastern U.S. coast from AGMTHAG is smaller than the tsunami amplitude reported in Mader (References 202 and 209), the present analysis adopted tsunami amplitude from Mader as the amplitude for the PMT.

Mader performed numerical modeling of the tsunami wave using the SWAN nonlinear shallow water wave code including the coriolis and friction effects. The model domain extended from 20° N to 65° N and 100° W to 0° W with a 10-minute grid resolution. Model bathymetry information was generated from the 2-minute Mercator Global Marine Gravity topography of Sandwell and Smith of the Scripps Institute of Oceanography (Reference 209). A model time step of 10 seconds was used for the simulation. Mader obtained tsunami amplitude of 20 meters (65.6 feet) at 953 meters (3127 feet) water depth off Lisbon, Portugal, and 5 meters (16.4 feet) at 825 meters (2707 feet) water depth east of Saba, Netherlands Antilles in the Caribbean. Mader argued that with a run-up amplification of the wave, the maximum near-shore wave amplitude would be two to three times the deepwater tsunami amplitude. However, he also pointed out that some of the run-up effects were probably included in the simulation for water depths less than 1000 meters (3281 feet). This assumption would provide a maximum tsunami water level above 20 meters (65.6 feet) at Lisbon and above 7 meters (23 feet) at Saba, higher than the tsunami amplitudes reported by Lockridge et al. (Reference 208). Consequently, simulated water levels obtained by Mader along the U.S. east coast would likely be conservative. Mader obtained tsunami amplitude of 2 meters (6.6 feet) at 783 meters (2569 feet) water depth east of Miami, Florida, and suggested a maximum tsunami wave amplitude, including run-up, of approximately 10 feet (3 meters) along the U.S. east coast.

Several tsunami simulations are reported for the earthquakes in the northern Caribbean region, as presented in Subsection 2.4.6.1.2 (References 202 and 211). The maximum tsunami amplitude near the southern Florida Atlantic coast (near Virginia Key) from these studies is approximately 0.15 meter (0.5 foot), as obtained by Knight (Reference 211). AGMTHAG used a linear shallow water model for the simulation with source parameters slightly different from those listed in Subsection 2.4.6.3.2. Knight assumed an earthquake magnitude of M_w = 9.0 in the Puerto Rico trench (Reference 211), higher than the earthquake magnitude presented in Subsection 2.4.6.3.2. These simulations show higher tsunami amplitude along the U.S. Mid-Atlantic region, as described in Subsections 2.4.6.1 and 2.4.6.2. However, simulated tsunami amplitude along the U.S. southeast coast as a result of the earthquake in the Azores-Gibraltar fracture zone (by Mader) is higher than the tsunami amplitude from the Caribbean sources (by Knight).

As suggested by Mader, the maximum deepwater tsunami amplitude near Miami, Florida, would be approximately 2 meters (6.6 feet) with a period of approximately 1.5 hours (Reference 209). Assuming that the onshore maximum tsunami amplitude including run-up would be approximately twice the deepwater value, a maximum tsunami amplitude of 4 meters (13.1 feet) can be obtained corresponding to the PMT. This value is a conservative estimate because the presence of the Bahamas platform is expected to considerably reduce the tsunami amplitude before reaching Units 6 & 7. In addition, Mader suggested that the maximum tsunami amplitude along the U.S. east coast to be approximately 3 meters (10 feet) (Reference 209).

Consistent with RG 1.59, a 10 percent exceedance high spring tide and sea level anomaly (initial rise) is used as the antecedent water level for the storm surge during a probable maximum hurricane event. The same antecedent water level condition is also used to obtain the PMT maximum water level. As described in Subsection 2.4.5, the combined 10-percent exceedance high spring tide and initial rise as given in RG 1.59 for the Miami Harbor Entrance is higher than the maximum historical tidal levels recorded at the National Oceanic and Atmospheric Administration tide gages near Units 6 & 7. Therefore, the combined 10-percent exceedance high spring tide and initial rise of approximately 2.6 feet NAVD 88, which is equivalent to 4.5 feet above mean low water as given in RG 1.59 and Subsection 2.4.5, is conservatively assumed for Units 6 & 7. Additionally, the probable maximum hurricane event considers a nominal long-term sea level rise of 1.0 foot for the next 100 years, as described in Subsection 2.4.5. Combining the 10-percent exceedance high tide and initial rise (2.6 feet NAVD 88) and the long-term sea level rise (1.0 foot) with the postulated conservative PMT amplitude near Units 6 & 7 (13.1 feet or 4 meters), the PMT maximum water level at Units 6 & 7 is 16.7 feet NAVD 88. The maximum water level estimated at Units 6 & 7 as a result of the PMT is below the maximum storm surge level, as presented in Subsection 2.4.5.

The PMT event could also induce a water surface drawdown at the Florida Atlantic coast shoreline. Off the coast of Miami, Florida, a minimum tsunami drawdown (trough) of approximately 3.5 meters (11.5 feet) at a water depth of 783 meters (2569 feet) is reported from the model simulation of Mader with a period of approximately 1.5 hours (Reference 209). A similar low water level may be considered for the Atlantic coast near Units 6 & 7. Because of the presence of the chain of barrier islands offshore of Biscayne Bay including Elliott Key, the drawdown water level at the shoreline would have a reduced effect on the low water level within the Biscayne Bay. Furthermore, because the Units 6 & 7 do not rely on Biscayne Bay for plant safety-related water supply, low water levels in the bay as a result of tsunami drawdown would not affect the functions of the safety-related SSCs at Units 6 & 7.

2.4.6.6 Hydrography and Harbor or Breakwater Influences on Tsunami

Units 6 & 7 are located adjacent to Biscayne Bay approximately 8 miles west of the Elliott Key barrier island. The PMT water level near Units 6 & 7 is analyzed based on published numerical simulation results and includes a conservatively assumed tsunami run-up. Therefore, the effect of hydrography of the area has been considered in the estimation of the PMT water level. There are no breakwaters located near the Units 6 & 7 that may affect the PMT water level.

2.4.6.7 Effects on Safety-Related Facilities

A conservative estimate of the PMT still water level near Units 6 & 7 is approximately 16.7 feet NAVD 88. This PMT water level along with coincidental wind-wave run-up, as presented in Subsection 2.4.5, would be lower than the design plant grade elevation of 26 feet NAVD 88 for the safety-related facilities. Therefore, the postulated PMT event does not affect the safety functions of Units 6 & 7. Because the PMT water level is lower than the design plant grade, debris, waterborne projectiles, sediment erosion, and deposits are not a concern to the functioning of the safety-related SSCs of Units 6 & 7.

2.4.6.8 References

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Table 2.4.6-201
Characteristics of Landslides on the U.S. Atlantic Margin

Dimension	Minimum	Maximum	Mean	Median
Area (square kilometer)	9	15,241	1,880	424
Length (kilometer)	2.7	>291	85	51
Width (kilometer)	2.1	151	21	12
Source Depth (meter)	92	3,263	1,630	1,785
Toe Depth (meter)	2,126	4,735	3,101	2,991
Scarp Height (meter)	3	410	90	63

Source: Reference 202

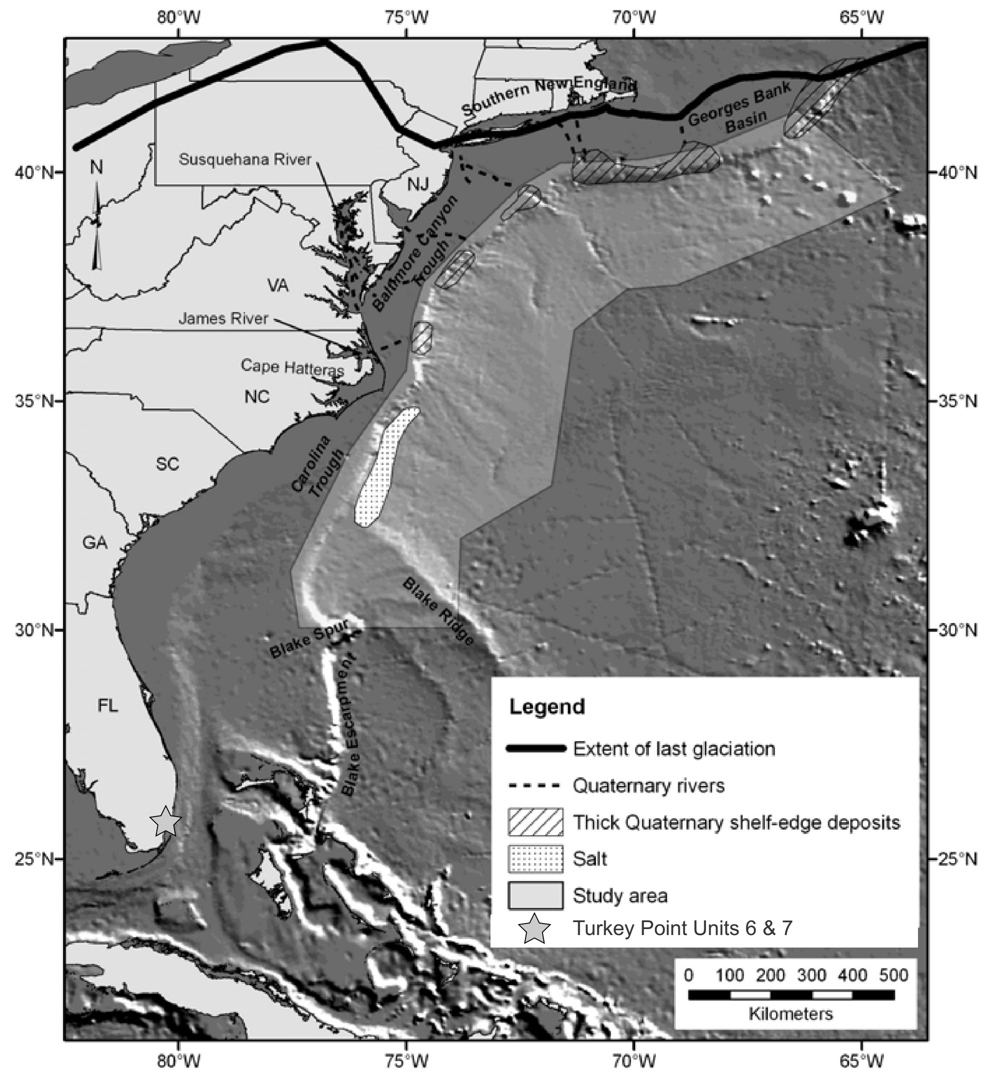
Table 2.4.6-202 (Sheet 1 of 2)
Summary of Historical Tsunami Run-Up Events in the East Coast of U.S.

Date[(a)]	Time (Hours)	Validity Code[(b)]	Cause Code[(c)]	Source Location (latitude, longitude)	Run-Up Location Along U.S. East Coast (lat, long)	Run-Up Type[(d)]	Run-Up Height (meters)
11/01/1755	08:50	4	1	Lisbon, Portugal (36.0°N 11.0°W)	—[(e)]	—	—
09/24/1848		3	8	Fishing Ships Harbor, Newfoundland, Canada (52.616°N 55.766°W)	—	—	—
06/27/1864	22:30	3	1	SW Avalon Peninsula, Newfoundland, Canada (46.5°N 53.7°W)	—	—	—
09/01/1886	02:51	4	1	Charleston, SC (32.9°N 80.0°W)	Jacksonville, FL (30.317°N 81.65°W) Mayport, FL (30.39°N 81.43°W) Copper River, SC (32.87°N 79.93°W)	1 1 1	—
09/01/1895	11:09	3	1	High Bridge, NJ (40.667°N 74.883°W)	Long Island, NY (40.591°N 73.796°W)	1	—
10/11/1918	14:14	4	1	Puerto Rico, Mona Passage (18.5°N 67.5°W)	Atlantic City, NJ (39.364°N 74.423°W)	2	0.06
11/18/1929	20:32	4	3	Grand Banks[(f)], Newfoundland, Canada (44.69°N 56.0°W)	Ocean City, MD (38.333°N 75.083°W) Atlantic City, NJ (39.35°N 74.417°W) Charleston, SC (32.75°N 79.916°W)	2 2 2	0.30 0.68 0.12
08/04/1946	17:51	4	1	Northeastern Cost, Dominican Republic (19.3°N 68.9°W)	Daytona Beach, FL (29.20°N 81.017°W) Atlantic City, NJ (39.364°N 74.423°W)	2 2	—
08/08/1946	13:28	4	1	Northeastern Cost, Dominican Republic (19.71°N 69.51°W)	Daytona Beach, FL (29.21°N 81.02°W) Atlantic City, NJ (39.364°N 74.423°W)	2 2	—
05/19/1964	00:00	3	8	Long Island, NY[(f)] (40.8°N 73.10°W)	Montauk, NY (41.033°N 71.950°W) Plum Island, NY (41.181°N 72.194°W) Willetts Point, NY (40.683°N 73.283°W) Newport, RI (41.493°N 71.327°W)	2 2 2 2	0.10 0.28 0.10 0.10
12/26/2004	00:58	4	1	Off Sumatra, Indonesia (3.295°N 95.982°E)	Trident Pier, FL (28.415°N 80.593°W) Atlantic City, NJ (39.35°N 74.417°W) Cape May, NJ (38.97°N 74.96°W)	2 2 2	0.17 0.11 0.06

Table 2.4.6-202 (Sheet 2 of 2)
Summary of Historical Tsunami Run-Up Events in the East Coast of U.S.

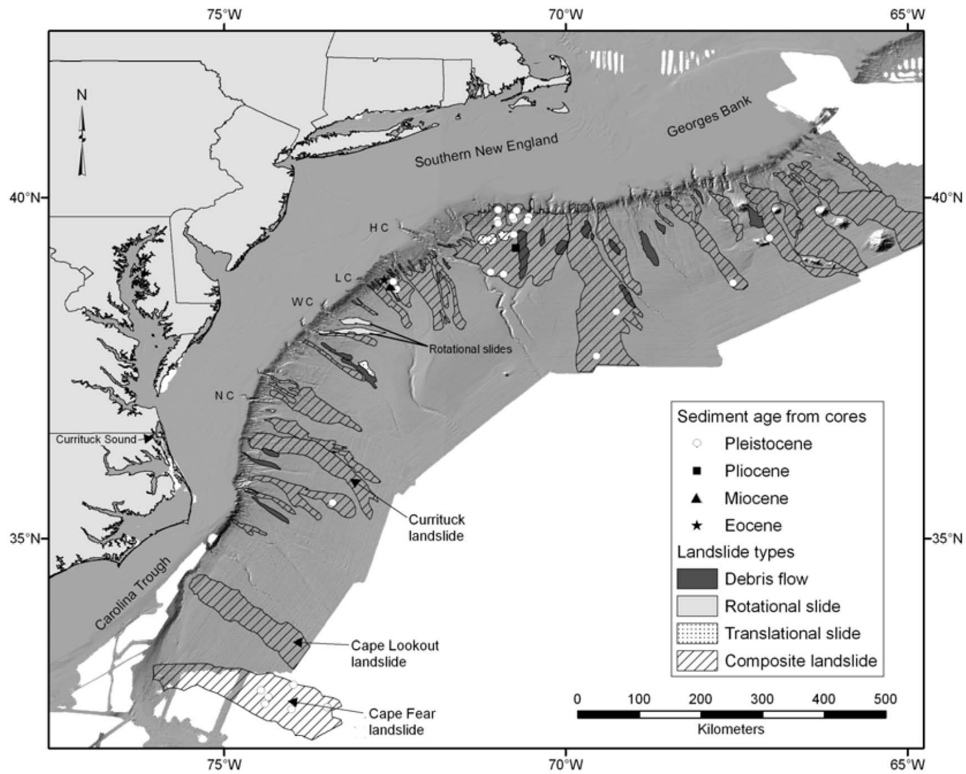
(a) Date and time given in Universal Coordinated Time (also known as Greenwich Mean Time).
(b) Tsunami event validity:
Valid values: 0 to 4
Validity of the actual tsunami occurrence is indicated by a numerical rating of the reports of that event:
0 = Erroneous entry
1 = Very doubtful tsunami
2 = Questionable tsunami
3 = Probable tsunami
4 = Definite tsunami
(c) Tsunami cause code:
Valid values: 0 to 11
The source of the tsunami:
0 = Unknown cause
1 = Earthquake
2 = Questionable earthquake
3 = Earthquake and landslide
4 = Volcano and earthquake
5 = Volcano, earthquake, and landslide
6 = Volcano
7 = Volcano and landslide
8 = Landslide
9 = Meteorological
10 = Explosion
11 = Astronomical tide
(d) Type of run-up measurement:
Valid values: 1 to 7
1 = Water height measurement
2 = Tide-gage measurement
3 = Deep ocean gage
4 = Paleodeposit
5 = Computer modeled
6 = Atmospheric pressure wave
7 = Seiche
(e) Data not available
(f) Only locations with measured run-up values are presented
Source: Reference 214

Figure 2.4.6-201 Location Map Showing the Extent of the AGMTHAG Study Area and Geologic Features That May Influence Landslide Distribution Along the U.S. Atlantic Margin



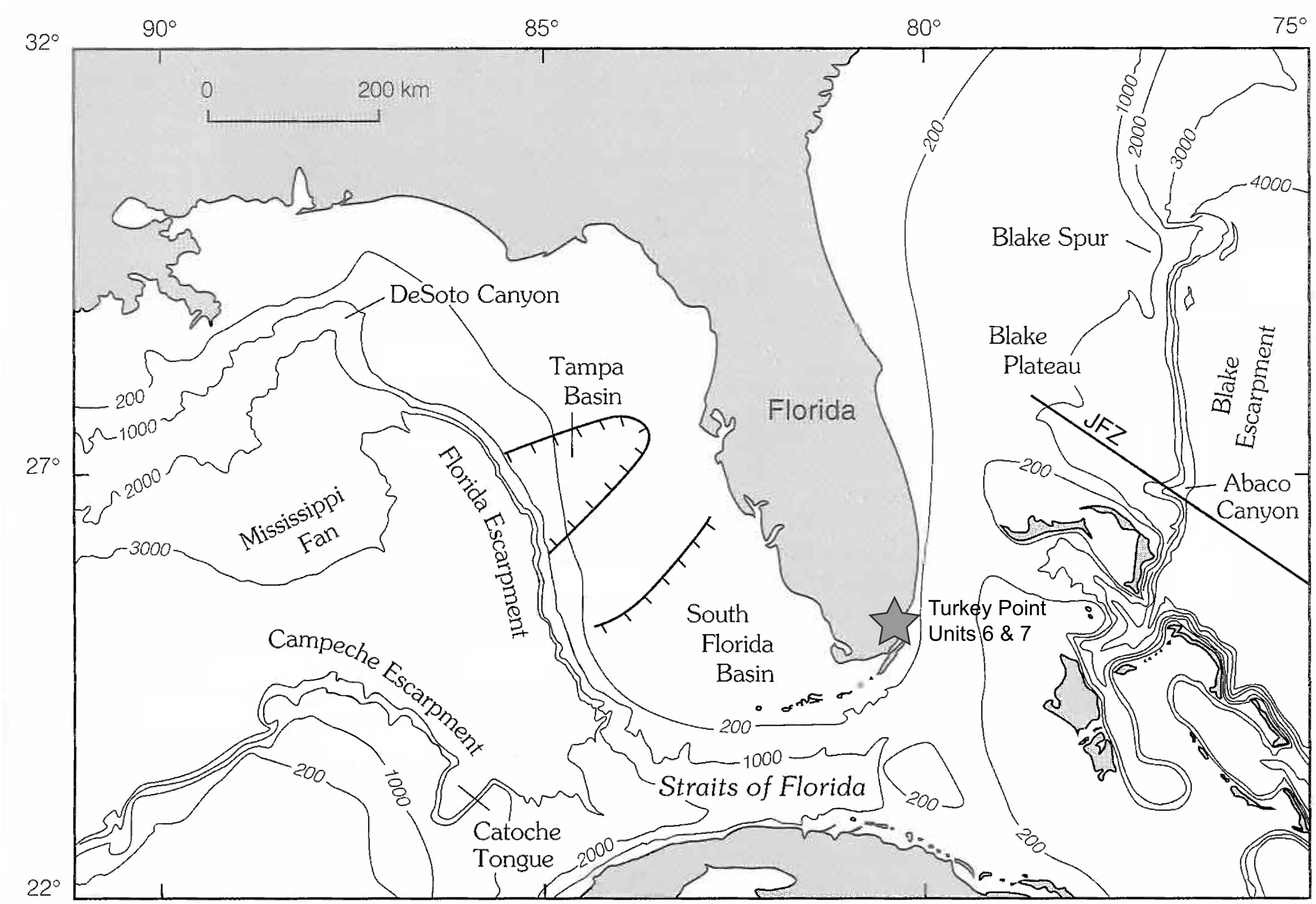
Modified from Reference 202

Figure 2.4.6-202 Distribution of Different Landslide Types Along the U.S. Atlantic Margin



Notes: HC = Hudson Canyon; LC = Lindenkohl Canyon; WC = Wilmington Canyon; NC = Norfolk Canyon
Source: Reference 202

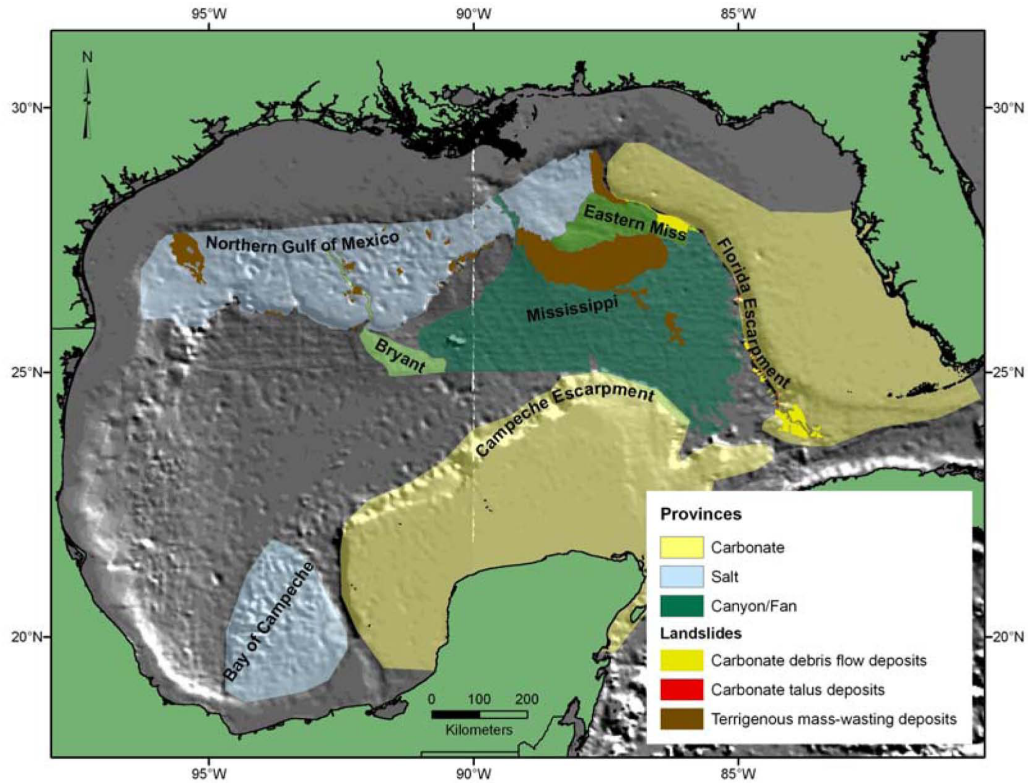
Figure 2.4.6-203 Location of Blake Escarpment Offshore of the Florida Coast



JFZ = Jacksonville fracture zone from Klitgord and Schouten (1986)

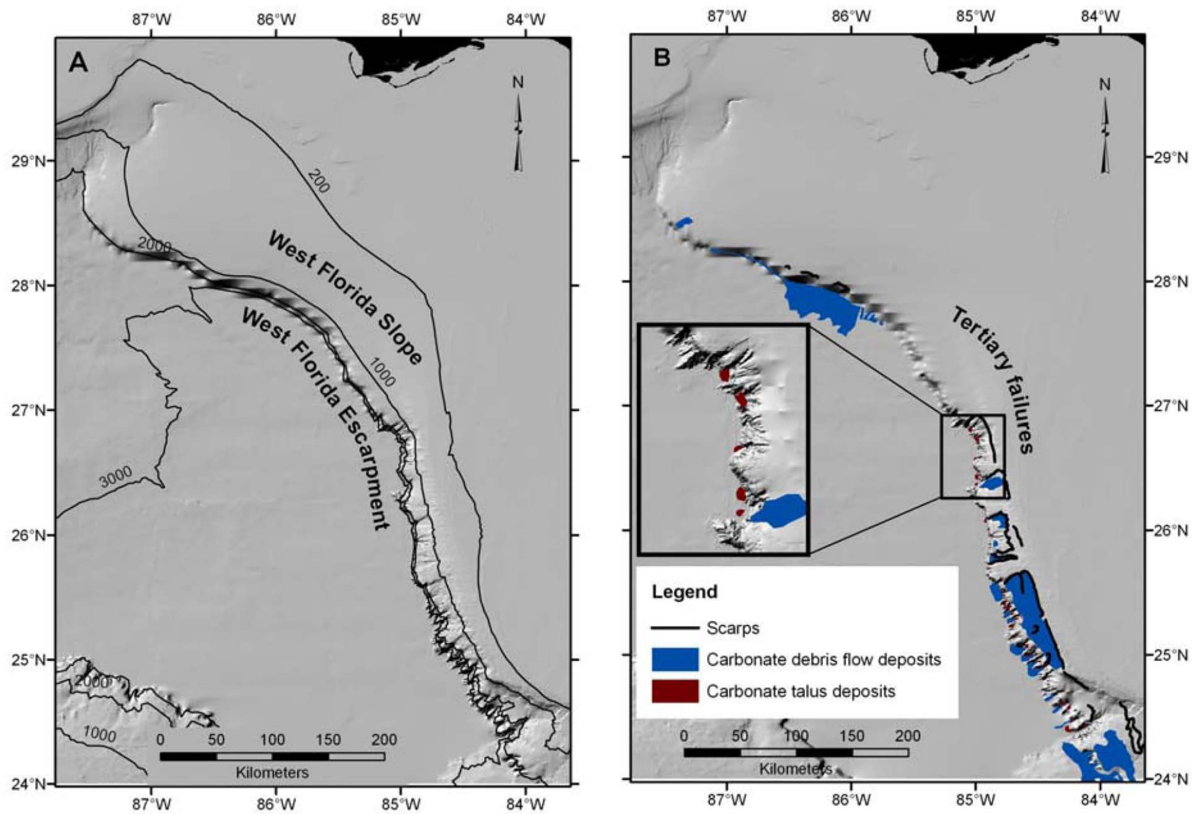
Note: Depth contours are in meters.
Modified from Reference 203

Figure 2.4.6-204 Location Map Showing the Extent of the Physiographic Features in the Gulf of Mexico Basin



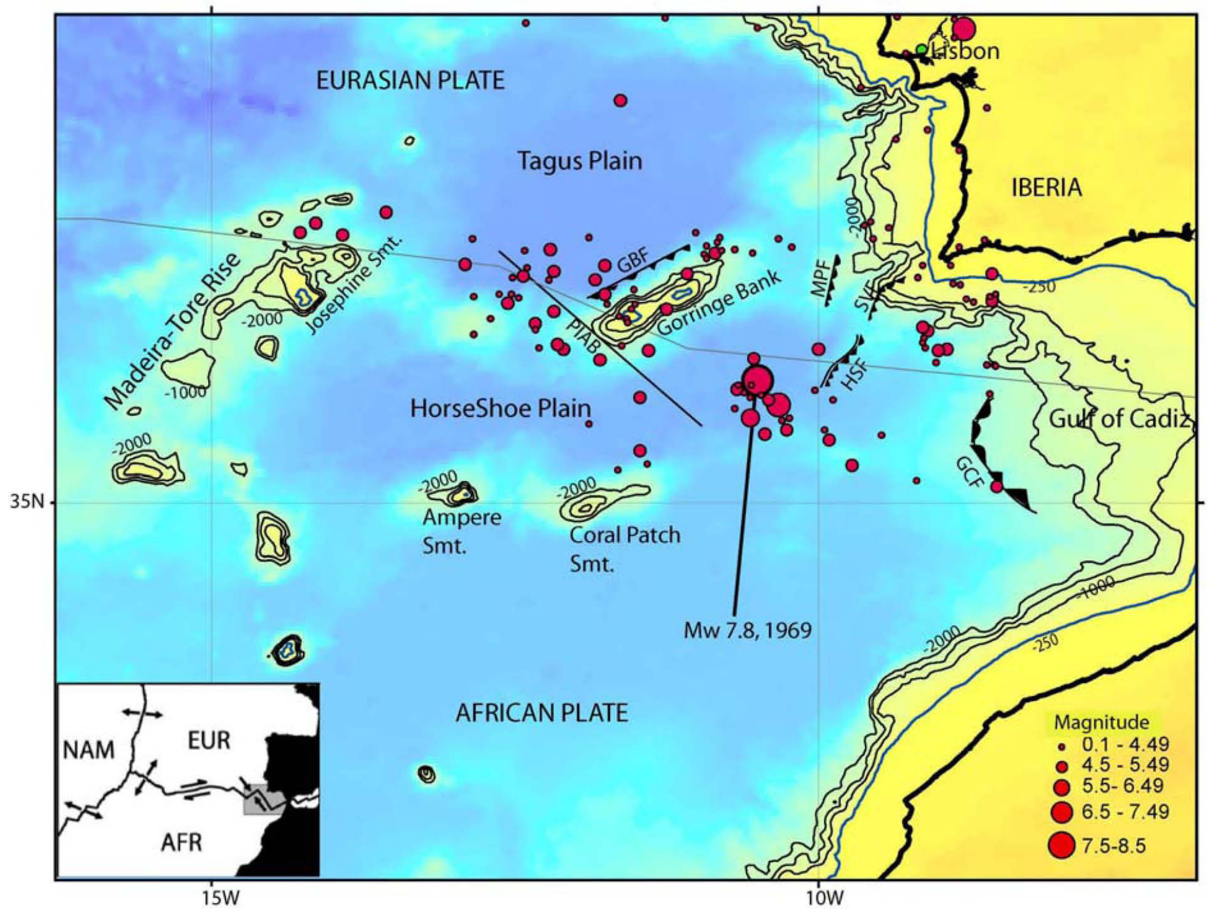
Source: Reference 202

Figure 2.4.6-205 (A) Morphology of the Florida Escarpment and the West Florida Slope, and (B) the Extent and Distribution of Carbonate Debris Flow Deposits and Talus Deposits



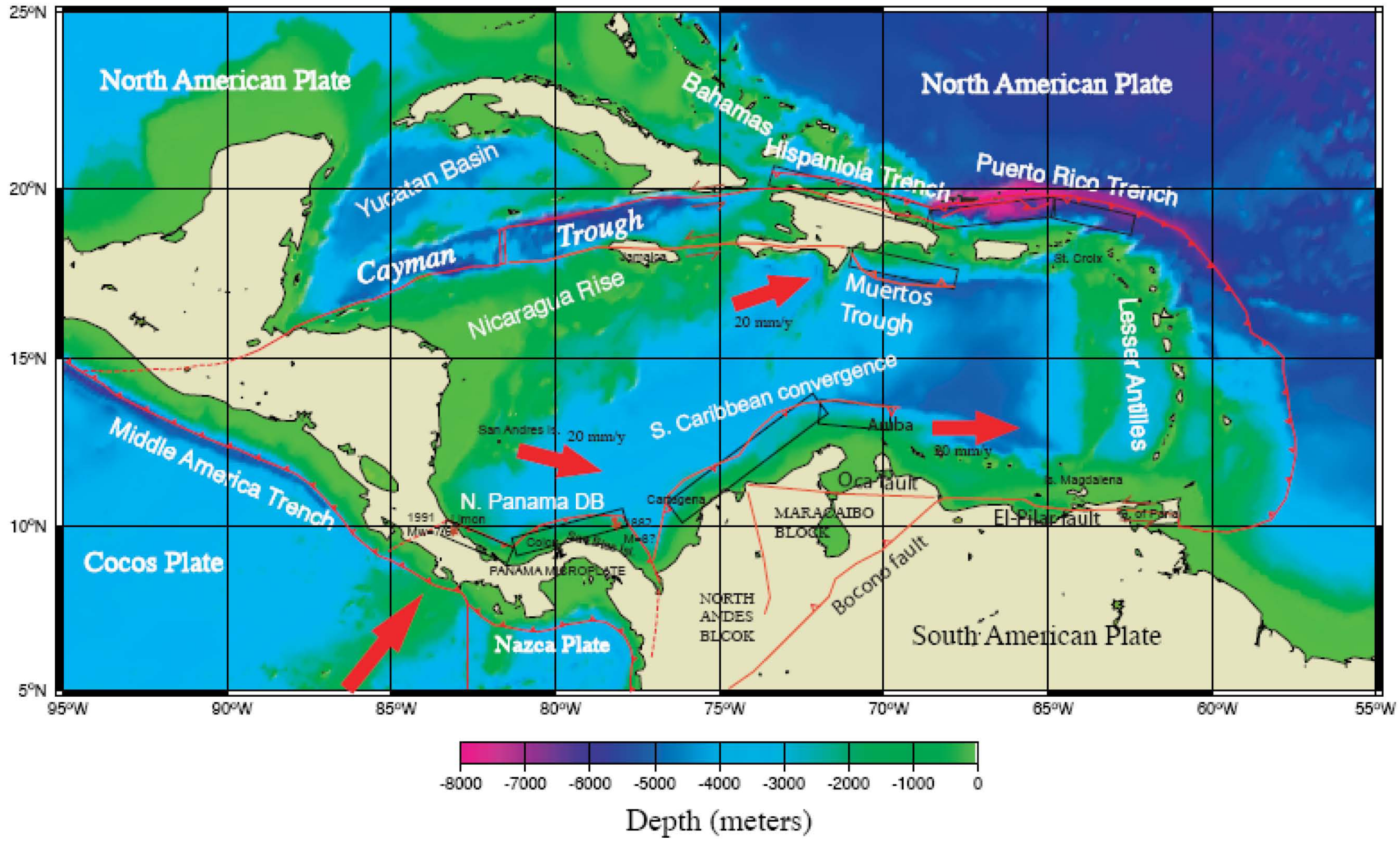
Note: Depth contours are in meters.
Modified from Reference 202

Figure 2.4.6-206 Plate Tectonic Setting and Bathymetry of the Eastern Azores-Gibraltar Region



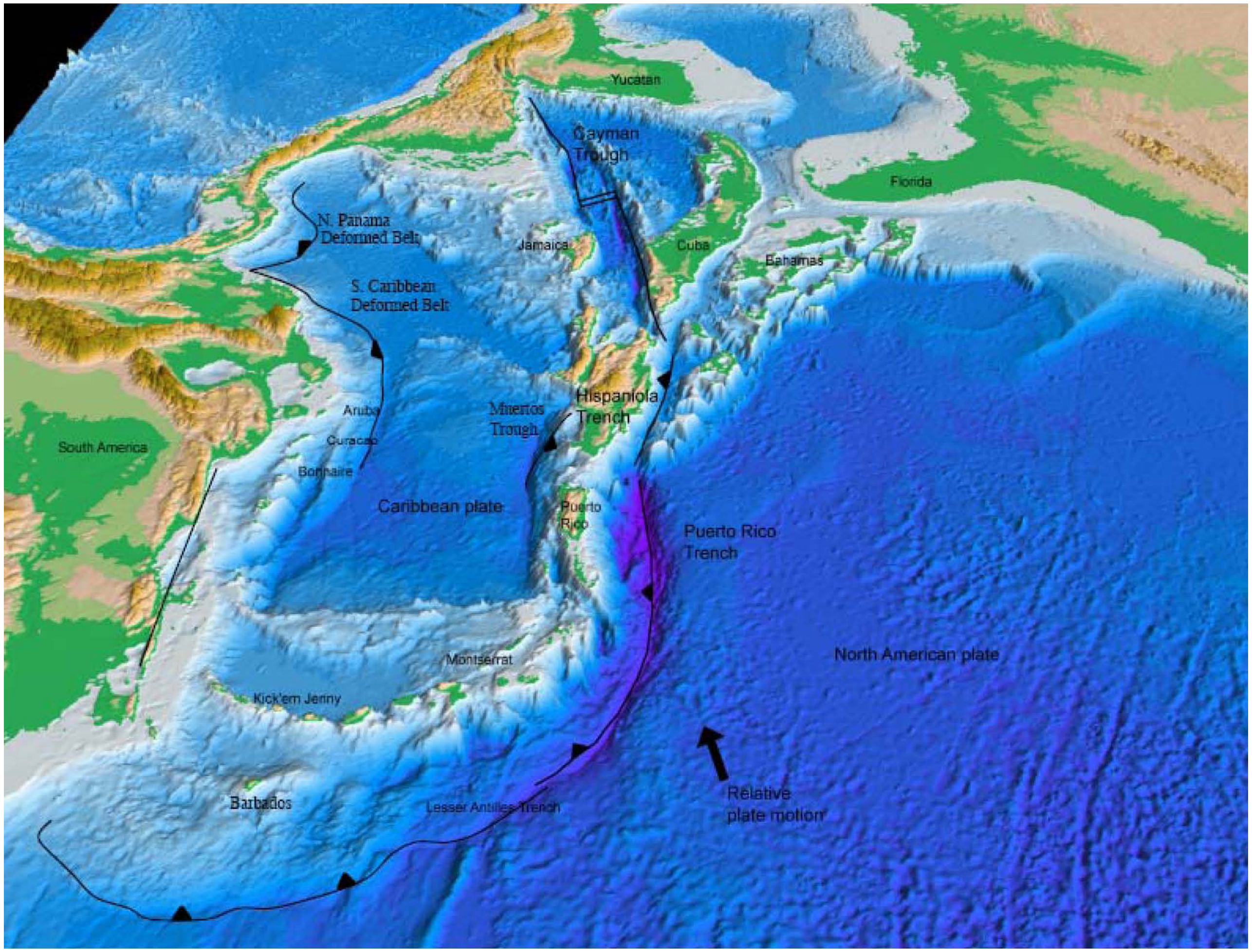
Note: Barbed lines show faults proposed in various past studies, GBF — Gorringe Bank Fault; MPF —- Marqués de Pombal Fault; SVF — St. Vicente Fault; HSF — Horseshoe Fault; GCF — Gulf of Cádiz Fault; PIAB - Paleo Iberia-Africa Plate Boundary. Inset plates: NAM - North American Plate; EUR — Eurasian Plate; AFR — African Plate. Depth contours are in meters (only contours from –250 to –2000 meters are shown).
Source: Reference 202

Figure 2.4.6-207 The Caribbean Plate Boundary and its Tectonic Elements



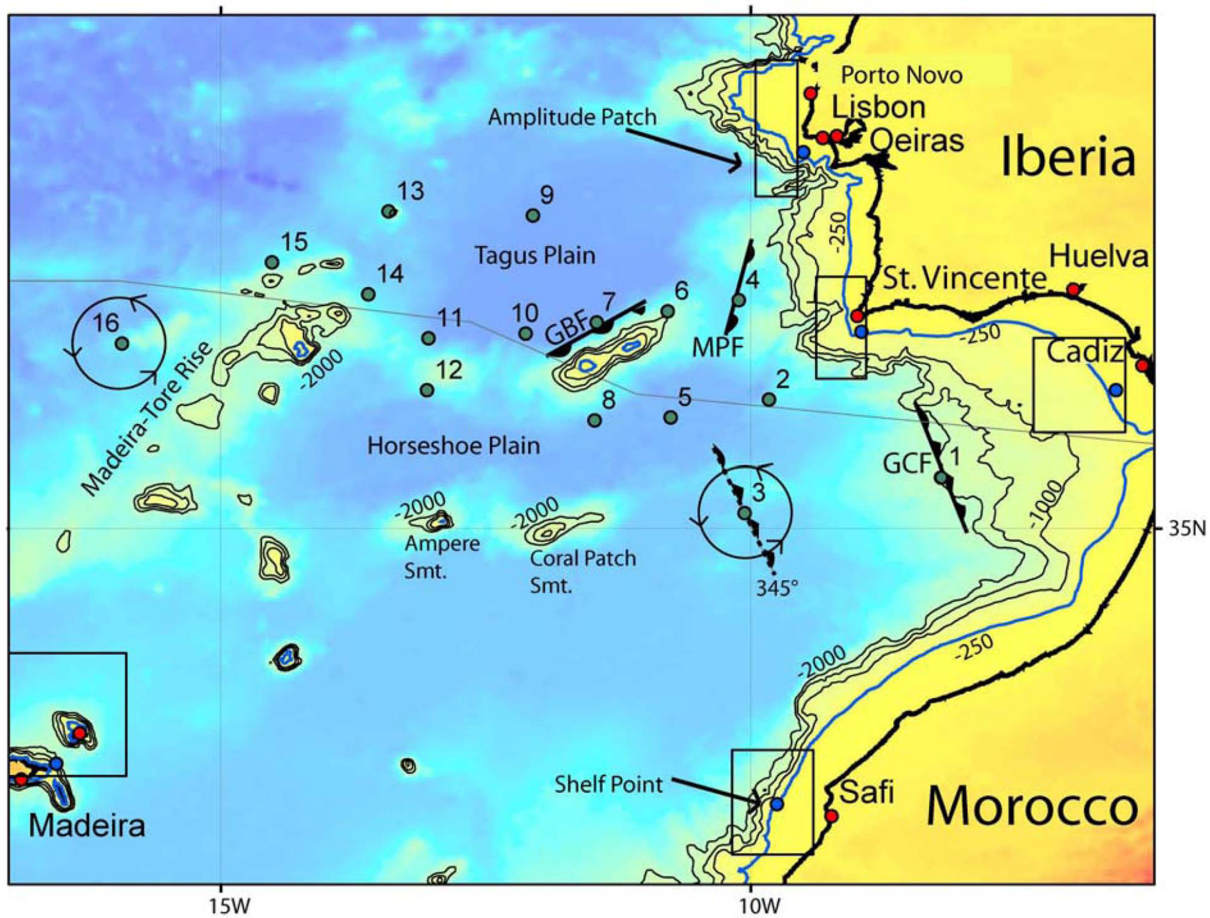
Note: Red lines are plate boundaries and red arrows indicate relative plate movement
Source: Reference 202

Figure 2.4.6-208 Perspective (Schematic) View of the Tectonic Elements in the Caribbean Plate and Seafloor Topography



Source: Reference 202

Figure 2.4.6-209 Postulated Epicenter Locations for the 1755 Lisbon Earthquake by AGMTHJAG



Note: Fault orientation for source locations 3 and 16 were rotated 360° at 15° to test the optimal strike angle generating maximum tsunami amplitude in the Caribbean. Depth contours are in meters.
Source: Reference 202