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Integrated Mapping of Active Faults and Seismic Hazard Evaluation for the example of Haiti

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Abstract
This study presents a comprehensive mapping and analysis of active onshore and offshore faults in the North-West and South peninsula of Haiti, with implications for seismic hazard assessment. Field investigations (2017-2019), high-resolution satellite imagery, morphotectonic analysis, and structural data were integrated to identify and characterize major and secondary active faults. Kinematic analyses of onshore active faults indicate a dominant NNE–SSW compressional regime with oblique deformation. This pattern aligns with the regional stress field imposed by the relative motion of the Caribbean and North American plates. Despite limited historical seismicity, geomorphic and structural evidence demonstrates the recent and ongoing activity on the identified onshore faults. Deterministic seismic hazard assessment, incorporating fault geometry, segmentation, and kinematics, was conducted to estimate physically plausible maximum magnitudes (Mmax) and peak ground accelerations using multiple ground-motion prediction equations. Results indicate the highest onshore PGA values (up to ≥0.42 g) are associated with the Enriquillo–Plantain Garden Fault Zone, while secondary faults also contribute significantly to local ground motions. These highlight the critical role of both major and secondary active faults in controlling regional seismic hazard and underscore the importance of integrating detailed fault mapping into hazard models, particularly in regions with limited historical seismic records.

Keywords: Haiti, active fault mapping, geological hazard, PGA calculation

1. Introduction

Haiti's physiography is dominated by a rugged and highly varied terrain that shapes both its environmental dynamics and land-use patterns. Approximately three-quarters of the country consist of mountainous formations, with half of these highlands characterized by slopes exceeding 40%. Complementing these rugged highlands, several low-lying plains covering roughly 7,000 km² or about one-quarter of the national surface provide important geographic and economic spaces. Haiti's 1,500-km-long coastline further contributes to the country's complex physiographic mosaic. This diverse

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topographic framework plays a central role in shaping environmental processes, resource distribution, and human activities across the country, making it a critical factor to consider in any geographical or environmental analysis.

Geology

The study area is situated on the island of Hispaniola, part of the Antillean arc, a geologically complex chain characterized by a crystalline basement overlain since the Mesozoic by 2,000-6,000 m of sedimentary formations and coral structures (Carte géologique, 1982-1988). This tectonic framework produces a series of NW–SE oriented folds that create alternating anticlinal hills and synclinal valleys arranged in an arcuate pattern and frequently bounded by active faults (Escuder Viruete et al., 2006).

Hispaniola's mountainous core consists primarily of schists, conglomerates, and limestones (Carte géologique, 1982-1988), cut in places by syenitic intrusions. To both the north and south of this central nucleus, extensive Tertiary deposits are flanked by more recent limestones and gravels. The central and northern mountain chains include diverse lithologies: metamorphic units, sandstones, conglomerates, limestones, clays, and in several central and western sectors, these formations are disrupted by dykes and quartz veins, some of which are gold-bearing. Approximately half of the island's surface is covered by Neogene-Quaternary alluvial deposits derived from erosion of the surrounding mountain slopes.

Coastal dynamics also contribute significantly to the island's geomorphic evolution. Coral growth and sediment input from rivers and torrents continually extend the coastline, resulting in widespread low-lying marshlands. The regional tectonic pattern is further shaped by a well-developed fault system, dominated in Haiti by major left-lateral strike-slip faults (Butterlin, 1954).

Current Geodynamic Setting

Haiti is located on the Caribbean Plate, within one of the most geodynamically active regions of the Americas. This zone marks the complex boundary between several interacting tectonic plates, most notably the Caribbean, North American, and South American plates (Fig. 1).

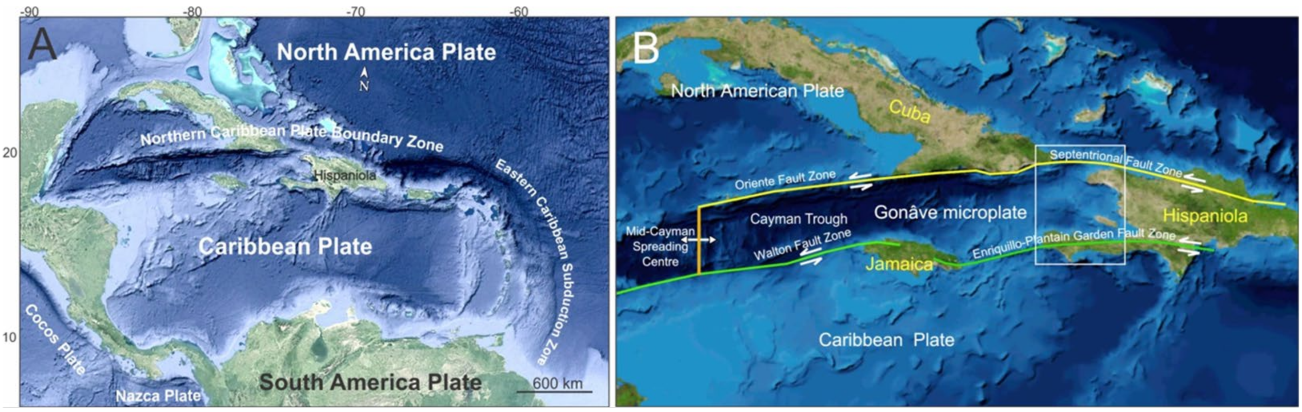

Figure 1. A-Tectonic setting of the Caribbean area on the Google satellite image. B-NASA World Wind Graphic (Public Domain) of faults around Haiti. The white rectangle indicates the study area.

The Caribbean Plate is being extruded eastward as a consequence of this confinement. Its movement is facilitated by the Eastern Caribbean Subduction Zone, which acts as a free boundary and accommodates ENE–WSW convergence with the Atlantic oceanic crust at a rate of approximately 2 cm/yr (DeMets et al., 2000).

Haiti lies within the Northern Caribbean Plate Boundary Zone (NCPBZ) (A, Fig. 1), a 250-km-wide deformation belt where the Caribbean Plate moves eastward relative to the North American Plate at roughly 20 mm/year (Calais, 1990). The oblique nature of this convergence generates a transpressional regime, producing both strike-slip motion and crustal shortening across Hispaniola (Mann et al., 2002).

Shortening is also significant, with GPS-derived rates of 5.2 ± 2 mm/year (Calais, 2002). It is expressed through folding and thrusting, including numerous structures identified during this study. The island is currently undergoing overall uplift, most pronounced in the northwest, where it has produced extensive sequences of Quaternary marine terraces (Carte géologique, 1982-1988) and alluvial fans. This uplift is accompanied by tectonically controlled fissural volcanism and by frequent deformation placed in Pliocene–Quaternary strata.

Seismicity reflects this active tectonic setting. Hispaniola's historical record shows at least one major earthquake per century: destructive events in 1751, 1771, 1842, 1887, 1904, 1946, and more recently the devastating 12 January 2010 earthquake.

The study area (white rectangle, B, Fig. 1) includes the most part of the Northern and Southern Peninsulas.

2. Methodology

Seismic hazard is particularly critical, motivating the development of a hazard analysis and the transfer of methodological expertise to national professionals.

Seismic-hazard assessment focuses on identifying seismic sources, estimating ground shaking, which can induce other phenomena as landslides, liquefactions, tsunamis etc. This requires an interdisciplinary framework combining structural geology, Quaternary geology, geomorphology, seismology, geophysics, and historical records extending the temporal window beyond the historical catalogue. The data are available from various sources, including archives, technical reports, previous studies and maps, satellite imagery, aerial photographs, field surveys, digital and non-digital databases, and local knowledge.

Existing information concerning abovementioned domains compiled, including historical and instrumental seismicity, geological and tectonic studies, maps, satellite and aerial imagery, and local knowledge obtained through a participatory approach.

Preliminary hazard evaluation realized throw active faults both onshore and offshore identification and characterization using document review, remote sensing, and field observations. Hazard scenarios is developed based on fault activity and potential magnitude. Distant sources capable of affecting the study area will also be considered.

Field investigations and GIS-based analysis refined the mapping and characterization of active faults, including those not historically documented. Methods include stratigraphic and structural analysis, morphotectonic mapping, surface geophysics.

Maximum magnitudes estimated using historical and empirical data (Coppersmith, 1991; Wells and Coppersmith, 1994). Ground-motion maps generated by modeling earthquake scenarios within each seismotectonic zone and applying appropriate attenuation relationships (Earthquake Spectra, 2008).

The following datasets were compiled for seismic hazard mapping and active fault analysis:

Seismicity Catalogs

- Historical and instrumental seismicity (USGS Open-File Report 2011–1133)
- Haiti seismicity catalog since 1973 (USGS)
- Instrumental seismicity, 2015-2018 (MBU)

Geological and Topographic Data

- Geological Map of the Republic of Haiti, 1:250,000 (Carte géologique, 1982-1988)

- Topographic maps at 1:50,000 scale
- Digital elevation models with 20 m contour intervals in GIS format (Centre Nationale De l'Information Géospatiale, CNIGS)
- Topographic map at 250 m resolution (CNIGS)

Remote Sensing and Imagery

- Aerial photographs
- LIDAR images at 0.5-1 m resolution (CNIGS)
- Google satellite imagery, 200 m resolution
- ESRI satellite imagery, 100 m resolution
- Aerial ortho-photographs, 1 m resolution (CNIGS)
- Satellite ortho-images at 15 m resolution (visible to thermal infrared), freely available from www.orthocoverage.com

Geophysical Data

- Marine geophysical survey images (Campagne océanographique HAITI-SIS N/O L'Atalante, Saint Domingue - Port au Prince Fort de France, 2012, Momplaisir, 1986; Leroy et al., 2015).

3. Tectonic Context

Thirtyfive GPS benchmarks were installed and repeatedly surveyed in Haiti, complemented by a network of 40 sites in the Dominican Republic, some of which record continuous displacement since 1994. These long-term geodetic observations provide quantification of elastic strain accumulation on major active faults (Manaker et al., 2008). Prior to 2010, these results already indicated that the Enriquillo–Plantain Garden Fault Zone (EPGFZ) in Haiti had accumulated sufficient strain to generate an earthquake of approximately Mw 7.2 (Manaker et al., 2008). The North American plate descends beneath the Caribbean—and dominantly strike-slip deformation along the Cayman Trough (B, Fig. 1) (Mann et al., 1984; Calais et al., 1992; Dolan et al., 1998). GPS measurements indicate that the Caribbean plate interior moves toward the ENE at 18-20 mm/year relative to the North American plate (Dixon et al., 1998; DeMets et al., 2000). This motion results in oblique convergence of Hispaniola and Puerto Rico with the oceanic lithosphere of North America (Mann et al., 2002).

In Hispaniola, this oblique convergence is partitioned between strike-slip motion along the Septentrional Fault Zone in the north and the EPGFZ in the south, and compressional deformation along the North Hispaniola thrust system (Dolan et al., 1998; Calais et al., 2002). The Mw 7.0 earthquake that devastated Port-au-Prince on 12 January 2010 (which resulted in more than 200,000 fatalities) and the Mw 7.2 earthquake on 14 August 2021 (with 2248 fatalities) occurred on one of the principal plate-boundary structures of the northern Caribbean: the EPGFZ (B, Fig. 1). Historical records suggest that the southern Haiti segment of the EPGFZ last ruptured during major earthquakes in 1751 and 1770, both likely near magnitude 7.5 (Ali et al., 2008). No comparable events have been reported since, although several moderate earthquakes (e.g., 1701, 1784, 1860, 1864, 1953) have affected the region. Thus, both the long-term kinematics of the plate boundary and the historical earthquake record consistently point to the EPGFZ as a major seismic source in Haiti, capable of generating damaging earthquakes at recurrence intervals on the order of centuries.

Kinematic block-model indicates slip rates of 9 ± 2 mm/year on the Septentrional Fault Zone and 7 ± 2 mm/year on the EPGFZ (Manaker et al., 2008). This left-lateral strike-slip system accommodates a significant portion of the relative motion between the Caribbean and North American plates (Mann et al., 1995; Dixon et al., 1998). Recent GPS measurements and high-resolution offshore seismic data within the transform Caribbean–North American plate boundary in southern Haiti, Greater Antilles, show 6-7 mm/year of plate boundary-normal shortening within a crustal sliver bounded to the south by the EPGFZ left-lateral strike-slip fault and to the north by a south-dipping reverse fault system offshore the northern coast of the Southern Peninsula of Haiti (Calais et al., 2023).

4. Active Fault Mapping

4.1. Regional-Scale Offshore Active Faults

Field investigations were conducted between 2017 and 2019 on the North and South Peninsulas of Haiti, within the Nord-Ouest, Grande-Anse, Nippes, and Sud departments (A, Fig. 2). The datasets used in this study are described in the Methodology section.

The contribution of offshore active structures to seismic hazard cannot be neglected, given their significance and high seismic potential (Fig. 1). Mercier et al. (2011) demonstrated the recent reactivation of one of these offshore faults located at the eastern extremity of the Southern Peninsula.

The investigation and mapping of offshore active faults were carried out through the analysis of bathymetric and marine geophysical data (e.g., Momplaisir, 1986; Leroy et al., 2015) (D, Fig. 2). A detailed morphotectonic analysis of these datasets allowed the clear identification of a set of submarine active faults framing both the North and South Peninsulas (B, C, Fig. 2).

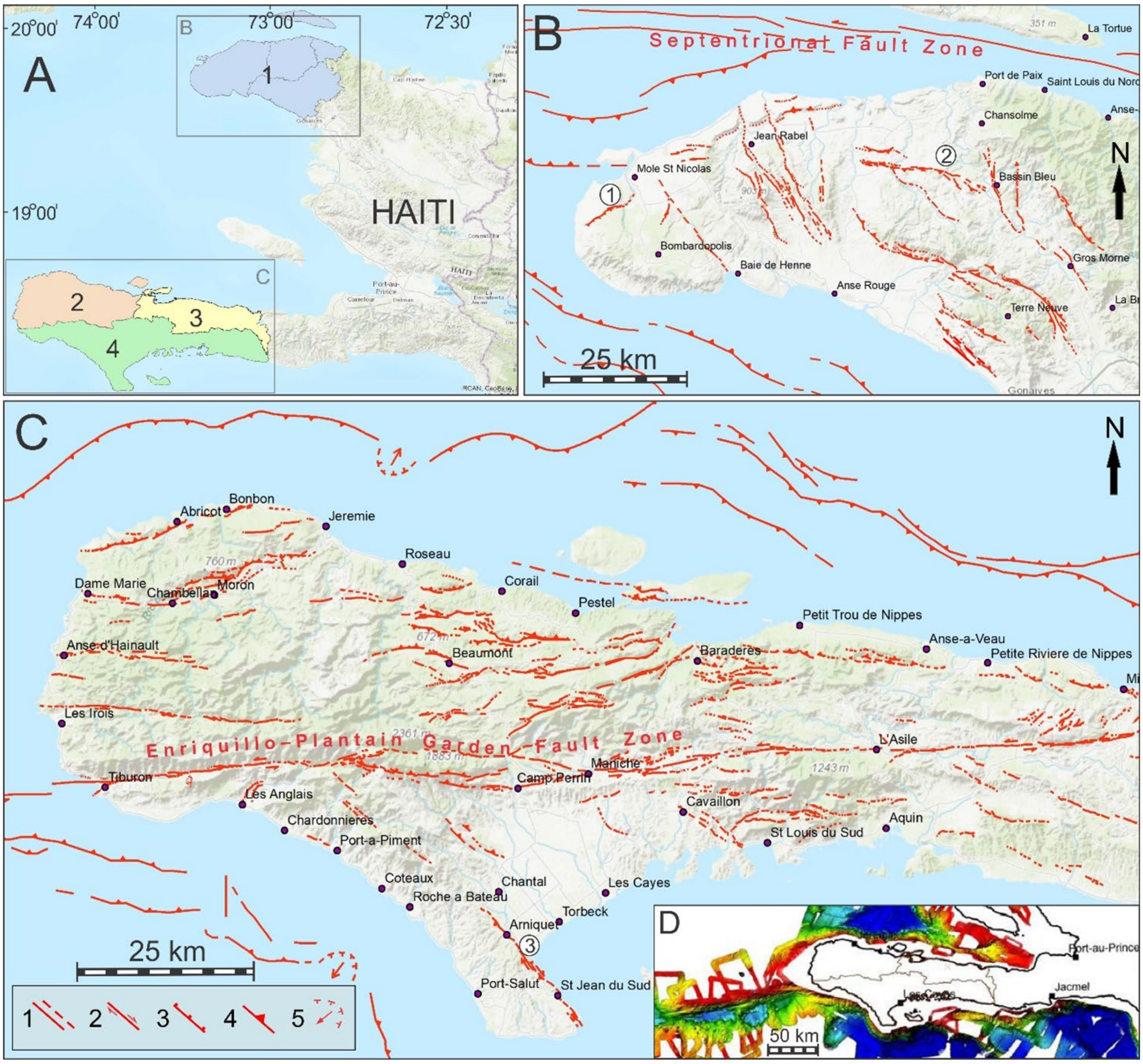

Figure 2. A-Departments of Haiti where the study was conducted: (1) Nord-Ouest, (2) Grande-Anse, (3) Nippes, (4) Sud. B, C-Synthesis maps of local- and regional-scale active onshore and offshore faults affecting the North-Western and Southern Peninsulas. (1) Active fault; (2) Active strike-slip fault; (3) Active normal fault; (4) Active reverse/thrust fault; (5) Landslide. D-3D bathymetric reconstruction of the coastal area of the Southern Peninsula (after the HAITI-SIS oceanographic campaign, R/V L'Atalante, Santo Domingo–Port-au-Prince–Fort-de-France, 2012; Momplaisir, 1986; Leroy et al., 2015).

Evidence for the activity of these faults is documented both directly—through their morphological expression on the seafloor based on bathymetric analysis and geophysical profiles—and indirectly, through morphostructural and geodynamic analyses of the coastlines of the North and South Peninsulas. Indeed, satellite image analysis and field observations reveal a series of uplifted marine terraces along the northern coastlines of both peninsulas. An example from the northwestern tip of the North Peninsula is shown in Figure 3. Seismogravitational fractures (indicated by white arrows) affect Quaternary reefal marine terraces.

These Quaternary (Carte géologique, 1982-1988) reefal limestone terraces testify to recent coastal uplift of approximately 0.19 mm/year, consistent with the kinematics of the offshore reverse faults identified in Figures 2B and 2C. The geometry and kinematics of these structures imply uplift of the southern block relative to the northern block, explaining the presence of raised terraces that record recurrent Quaternary activity. Very recent submarine landslides were also identified along these structures, likely associated with their recent reactivation (B, C, Fig. 2).

4.2. Identification of the Main Onshore Active Faults

The identification of active faults is generally based on instrumental and historical seismicity, morphostructural interpretation of satellite images, aerial photographs, and digital elevation models (DEMs). This approach allows the selection of major tectonic structures most likely to rupture in the future and, where possible, the characterization of their extent, segmentation, geometry, and kinematics.

The study area is characterized by numerous seismogravitational structures (normal faults, tilted terraces, etc.) (A, Fig. 3). Structures of purely tectonic origin (active faults) were distinguished from those of gravitational origin.

Numerous geological faults have been identified and mapped in the study area (Fig. 2), some of which were previously inferred to be active (Goreau, 1983; Momplaisir, 1986; Amilcar, 1997). In the present study, active fault identification and mapping were conducted at a scale of 1:50,000, locally refined to 1:10,000 and, in some cases, to outcrop scale (Figs. 4, 5, 6).

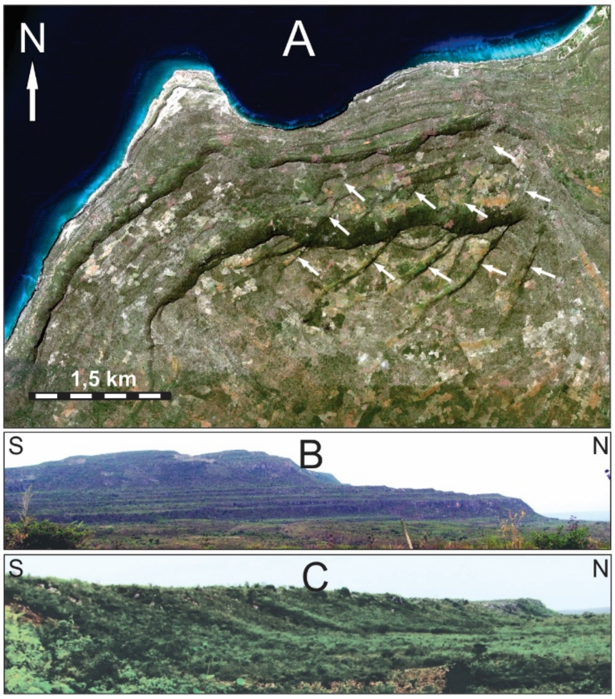

Figure 3. A-Seismogravitational fractures (white arrows) affecting Quaternary reef marine terraces along the northern margin of the North Peninsula, west of the town of Môle-Saint-Nicolas (B, Fig. 1), shown on a Google Earth image. B-Panoramic view of marine terraces from Môle-Saint-Nicolas. C-Detail of a marine terrace scarp.

One example is the Morne Basse active fault system (1 in B, Fig. 2), located in the northwestern part of the North-Western Peninsula, southwest of the town of Môle-Saint-Nicolas (Fig. 4). This normal fault strikes NE–SW (N61°) and extends for approximately 9.8 km. The western segment is particularly well expressed morphologically in aerial imagery, DEMs, and field observations (Fig. 4). The southeastern block is downthrown. Morphological analysis of LiDAR data indicates a cumulative vertical offset of ≤65 ± 2 m. The recent activity of this fault is demonstrated by stratigraphic, morphotectonic, and structural evidence, as it cuts Quaternary marine terraces after their uplift and deformation.

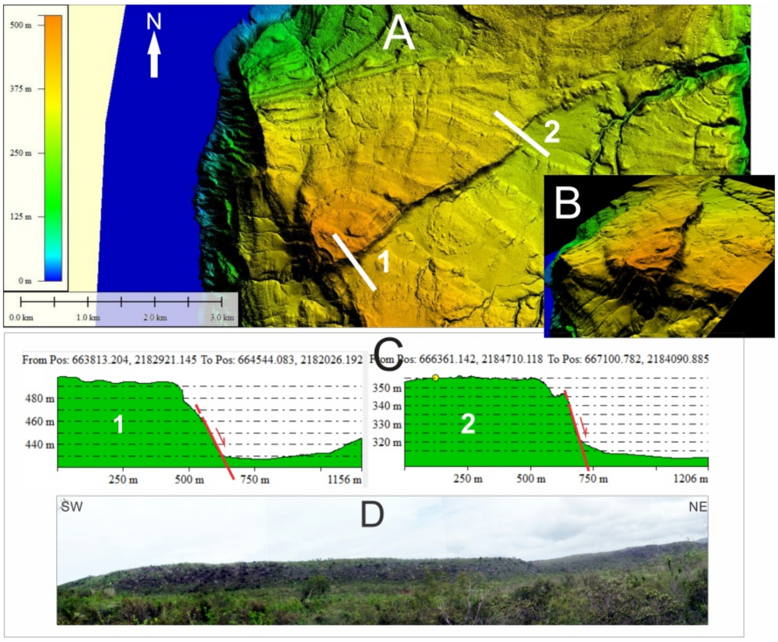

Figure 4. Morphological expression of the Morne Basse Fault system (location is indicated by circle 1 in B, Fig. 2) revealed by high-resolution DEMs (1 m) in 3D views (A, B) and topographic profiles (C: 1, 2). D-Field photograph of the fault scarp.

Another example studied at outcrop scale is the Morne Fouco–Morne Rampas Fault system (2 in B, Fig. 2; Fig. 5). This fault system extends for approximately 22 km, with an overall E–W orientation. It is segmented and exhibits reverse kinematics with a left-lateral strike-slip component. The fault juxtaposes Lower Cretaceous limestones against Upper Miocene marls. Morphologically, it is marked by a sharp and continuous topographic break, clearly visible in both satellite imagery and the field (Fig. 5).

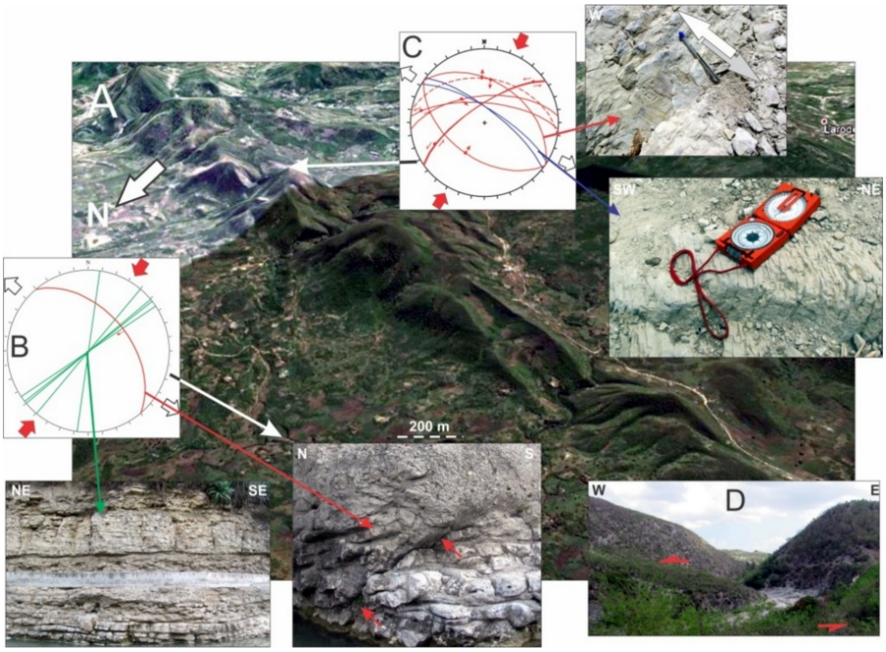

Figure 5. Central part of the Morne Fouco–Morne Rampas Fault segment (location is indicated by circle 2 in B, Fig. 2). This segment is expressed morphologically in satellite imagery (A-Google Earth view). Microtectonic analysis (on the lower hemisphere) of stations (B) and (C), located along the axis of this fault segment, indicates NNE-oriented compression and NW-oriented extension, based on both fracture analysis (green) and fault-slip data (red). D-Morphological expression of the eastern part of the Morne Rampas fault segment in the field, and left-lateral deflection of the Moustique River at the fault crossing.

Microtectonic analysis at two stations (B, C, Fig. 5) indicates NNE-directed compression and NW-directed extension, based on both fracture (green) and fault-slip (red) analyses. This implies oblique motion on the Morne Fouco–Morne Rampas Fault system, corresponding to reverse faulting with a left-lateral strike-slip component. This kinematics is further supported by the left-lateral offset of the Moustique River at the fault crossing (D, Fig. 5).

Despite the absence of known historical or instrumental earthquakes associated with this fault, its recent activity is unequivocal.

A third example is the Belsue–Saint-Jean-du-Sud Fault (3 in C, Fig. 2), approximately 50 km long and trending NNW–SSE. In its southern part, Mann et al. (1995) reported the presence of a fault segment, while Amilcar (1997) suggested a potential fault. Structural analysis conducted in this study confirms the presence of an active reverse fault with a right-lateral strike-slip component, consistent with the current regional stress field.

Towards the eastern basin filled with Quaternary sediments, the dip of limestones progressively increases from 35°E to 60°NE, eventually becoming near vertical. These limestones define a north-verging fold structure consistent with reverse fault kinematics. Approximately 2 km northwest of Saint-Jean-du-Sud (C, Fig. 2), a reverse fault striking N121° and dipping 21°SW was identified (B, C, D, Fig. 6). Secondary N017° strike-slip faults were also observed (E, Fig. 6).

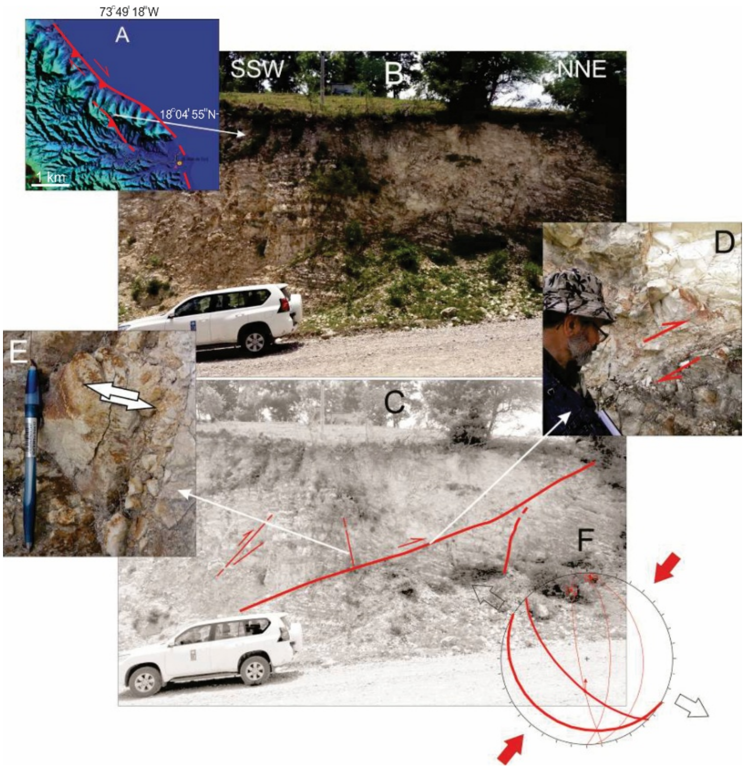

Figure 6. Reverse fault (B, C, D) striking N121° and dipping 21°SW was identified 2 km northwest of Saint-Jean-du-Sud (A) (Belsue–Saint-Jean-du-Sud Fault zone (3 in C, Fig. 2)). Location is indicated by circle 3 in C, Fig. 2. E-Secondary right-lateral strike slip fault. F- Faults representation on the lower hemisphere indicating NNE-oriented compression and NW-oriented extension.

Regarding the Haitian sector, the Enriquillo–Plantain Garden Fault Zone (EPGFZ) (C, Fig. 2) has long been recognized as a major seismic hazard. This fault system cuts across the entire Southern Peninsula of Haiti. To the east, it extends offshore toward eastern Jamaica, bounding the Gonâve microplate to the south (Fig. 1). To the west, it terminates offshore south of Hispaniola. Together with the Septentrional Fault Zone, it represents one of the two most significant fault systems in Haiti and has hosted major historical earthquakes.

These faults accommodate plate motion by accumulating elastic strain over decades to centuries before releasing it abruptly during earthquakes. Moreau de Saint-Méry (1797-1798) provided detailed accounts of the catastrophic destruction of Port-au-Prince and Léogâne during the 1751 and 1770 earthquakes. Since then, the region has repeatedly experienced seismic activity, including a major earthquake (estimated M > 7) in 1862 in the central Southern Peninsula (USGS Open-File Report 2011–1133).

In this study, particular attention was given to the EPGFZ in order to refine its seismogenic potential. Analysis of fault geometry, kinematics, and aerial photographs allowed the identification of three major segments, two of which cross the Nippes and Sud departments (Fig. 2).

5. Seismic Hazard Assessment

Seismic hazard assessment, including determination of maximum magnitude (Mmax) and peak ground acceleration (PGA), was carried out for the Nippes and Sud departments.

5.1. Evaluation of Maximum Magnitudes of Seismic Sources

Based on detailed mapping of seismic sources (active faults) in the study area, plausible rupture scenarios were defined for each structure, considering their geometry, kinematics, and segmentation (Fig. 2). Using a conservative approach and assuming the most plausible segmentations, maximum magnitudes were calculated using empirical relationships proposed by Coppersmith (1991) and Wells and Coppersmith (1994).

Twelve seismic sources were selected as having the greatest potential impact and were therefore included in the PGA calculations (Table 1; A, Fig. 7).

Table 1. Selected seismic sources (1-12, Fig. 12) and estimated Mmax values used for bedrock seismic acceleration (seismic hazard) assessment in the Sud and Nippes departments.

seismic zones	Id	Fault (length. km)	Segm.	Seg. len-gth. (km)	Kine-mat.	M max Cop. 91	Sig.	Mw max WC 94	Sig. 1	M max	Sig.
EPGFZ	1	EPGFZ, ~1000	West	102 ±8	-	7.41	0.03	7.4	0.04	7.41	0.03
	2	EPGFZ, ~1000	East	127 ±13	SS	7.52	0.05	7.52	0.04	7.52	0.05
Trois Baies	3	Trois-Baies, 107±7	-	-	R	7.43	0.03	7.47	0.03	7.47	0.03
Port salut-Tiburon	4	Port-Salut-Tiburon, 172±15	-	-	R	7.68	0.04	7.72	0.05	7.72	0,05
Ile a Vache	5	Ile a Vache, 115±15	-	-	R	7.47	0.06	7.51	0.06	7.51	0.06
Saint Louis du Sud-Bainet Nord	6	St Luis du Sud-Bainet Nord, 82±7	East - North	-	R	7.29	0.04	7.33	0.04	7.33	0.04
Bainet	7	Bainet, 122±9	-	122 ±9	SS	7.5	0.04	7.49	0.04	7.5	0.04
Baraderes	8	Baraderes, 60±10	-	-	R	7.13	0.08	7.25	0.09	7.25	0,09
Marcelline	9	Marcelline-Baraderes, 28±4	-	28± 4	-	6.73	0.07	6.75	0.07	6.75	0.07
Petite Rivière des Nippes	10	Petite Riviere de Nippes-Miragoane-GrandGoave, 55±10	-	55± 10	R	7.08	0.09	7.12	0.09	7.12	0.09
Cavaillon Nord	11	Cavaillon Nord, 43±3	-	-	R	6.96	0.03	6.99	0.03	6.99	0.03
Belsue-St Jean du Sud	12	Belsue-St Jean du Sud, 49±3	-	-	All	7.02	0.05	7.06	0.05	7.06	0.05

In practice, the maximum plausible earthquake is estimated from the largest known historical event, if it exceeds the magnitude derived from fault length. Due to the lack of well-documented historical earthquakes, magnitudes were inferred using empirical relationships linking fault geometry and kinematics (rupture length, coseismic displacement) to earthquake magnitude.

Accordingly, maximum physically plausible magnitudes were recalculated for all identified structures in the Sud and Nippes departments using the relationships of Coppersmith (1991) and Wells and Coppersmith (1994). Under a conservative assumption, fault segments 7, 8, 9, and 10 were assumed to rupture along their entire lengths. Similarly, major fault systems in the Nippes and Sud departments were divided into two principal segments, each approximately 100 km long. The resulting updated maximum plausible magnitudes were then used for PGA calculations (Table 1).

5.2. Bedrock PGA Evaluation

To obtain results as close to reality as possible, four ground-motion attenuation models were applied (Earthquake Spectra, 2008):

- Abrahamson–Silva NGA model
- Boore–Atkinson NGA model
- Campbell–Bozorgnia NGA model
- Chiou–Youngs NGA model

The mean value of these calculations was adopted as the final PGA estimate.

Two approaches can be used to assess regional-scale seismic hazard (Philip, 2007):

Deterministic approach: This method is based on determining the maximum plausible earthquake and requires detailed knowledge of the location and characteristics of seismic sources. It does not account for earthquake recurrence frequency and may lead to over- or underestimation of hazard.

Probabilistic approach: This method estimates the probability of exceeding specific ground-motion values over a given time period (e.g., 100 or 500 years). Its main limitation is the representativeness of seismic catalogs, particularly in regions of low to moderate seismicity or regions such as Haiti, where historical data cover only approximately three centuries.

Given these limitations, the deterministic approach was adopted in this study. Dominant earthquake scenarios controlling ground acceleration in the Sud and Nippes departments were identified. Using the defined reference earthquakes and the ground-motion models described above, bedrock PGA values were calculated across the entire study area. Dominant scenarios were then identified for each location.

PGA calculations considered 12 seismic sources to evaluate the individual contribution of each fault (Fig. 7). Calculated bedrock PGA values range from approximately 0.09 g to ≥0.42 g. The highest accelerations affecting the Sud and Nippes departments are associated with segments of the EPGFZ. Faults 7, 8, 9, 10, and 12 also exert a significant local influence on PGA values.

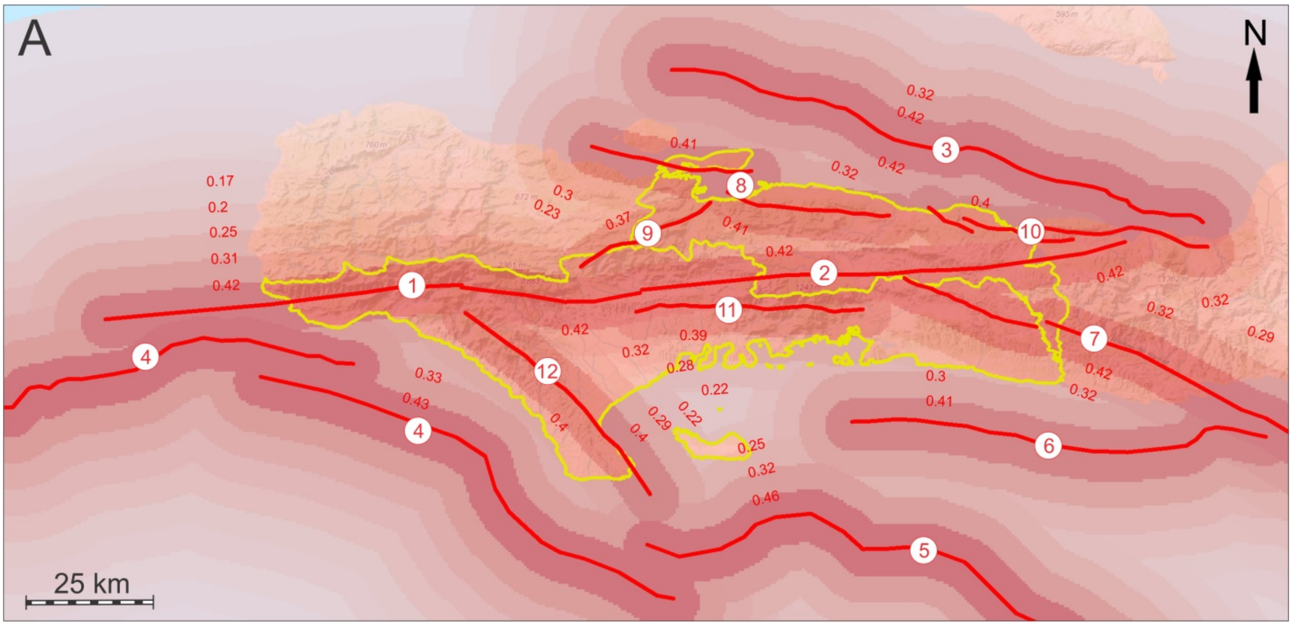

Figure 7. The 12 selected seismic sources considered in the hazard assessment and the resulting PGA calculations for the Nippes and Sud departments.

6. Discussion

The results of this study demonstrate that both offshore and onshore active faults play a critical role in controlling the seismic hazard of the North-West and South peninsulas of Haiti. Offshore structures exhibit clear morphotectonic evidence of recent activity, including fault scarps, submarine landslides, and deformation of the seafloor. These observations, combined with the uplifted Quaternary marine terraces observed along the coastlines, indicate ongoing tectonic coastal uplift of approximately 0.19 mm/year consistent with the regional stress regime.

The coherence between offshore fault kinematics and onshore deformation patterns strongly suggests mechanical coupling between these structures. The uplift of reef terraces along the northern margins of the North-West and South peninsulas is consistent with reverse faulting identified offshore, implying recurrent activity throughout the Quaternary. The presence of recent submarine landslides along these faults further supports their potential for coseismic reactivation and associated secondary hazards, such as tsunamis or coastal instability.

Onshore, the detailed mapping carried out at multiple scales (from regional to outcrop scale) allowed discrimination between purely tectonic faults and seismogravitational structures. Several fault systems previously inferred or poorly constrained were confirmed as active, with clear morphologic, stratigraphic, and structural evidence and new ones mapped. The earthquake of 24 January 2022 of magnitude 5.3 and its aftershocks of magnitude 4.1-5.1 confirmed the existence and activity of the Baraderes fault (8, Fig. 7).

The kinematic analysis of the mapped faults indicates a dominant compressional regime with oblique deformation, expressed by reverse faulting associated with strike-slip components. Microtectonic data consistently indicate NNE–SSW compression and NW–SE extension, in agreement with the regional tectonic framework imposed by the relative motion between the Caribbean and North American plates.

This behavior of secondary active faults reflects the complex interaction between major structures, such as the Enriquillo–Plantain Garden Fault Zone (EPGFZ), and secondary faults accommodating deformation at a more local scale.

Despite the lack of documented historical earthquakes on some of these faults, their geomorphic expression and structural relationships clearly indicate recent and potentially ongoing activity. This highlights the limitation of relying solely on historical and instrumental seismicity catalogs in regions with short observation periods, such as Haiti.

The deterministic seismic hazard assessment conducted in this study emphasizes the importance of integrating detailed fault geometry, segmentation, and kinematics into hazard models. The recalculated maximum plausible magnitudes (Mmax), derived from empirical relationships based on seismic source length, provide physically realistic upper bounds for seismic scenarios in the absence of well-constrained historical events.

The PGA results show significant spatial variability across the Sud and Nippes departments, with the highest accelerations associated with segments of the EPGFZ. However, several secondary faults (notably sources 7, 8, 9, 10, and 12) also contribute substantially to local ground-motion levels. This finding underscores that seismic hazard in the region is not controlled by a single, even secondary fault system but rather by a network of active structures.

The use of multiple ground-motion prediction equations and the adoption of their mean value reduce model-related uncertainty and provide robust PGA estimates at bedrock level. The resulting acceleration values (up to ≥ 0.42 g) indicate a high level of seismic hazard, particularly for areas located near major fault segments.

7. Conclusion

This study provides a comprehensive characterization of active onshore and offshore faults in the North-West and South peninsulas of Haiti and evaluates their implications for seismic hazard. High-resolution morphotectonic analysis, combined with field observations and structural data, allowed the identification and detailed mapping of numerous active faults, many of which were previously poorly constrained or underestimated.

The results demonstrate that offshore faults are an integral component of the regional seismotectonic system and significantly contribute to seismic hazard. The consistency between offshore deformation, coastal uplift, and onshore fault kinematics indicates long-term, recurrent activity throughout the Quaternary.

The deterministic seismic hazard assessment for the departments Nippes and Sud, based on conservative rupture scenarios and physically plausible maximum magnitudes, reveals that the highest PGA values are associated with the Enriquillo–Plantain Garden Fault Zone, while several secondary fault systems exert a strong local influence. These findings highlight the necessity of incorporating both major and secondary faults into seismic hazard models.

Overall, this work underscores the critical need for detailed active fault mapping in regions with limited historical seismic records and important instrumental devastated earthquake of 12 January 2010 (which resulted in more than 200,000 fatalities) and 14 August 2021 (with 2248 fatalities). The results provide essential constraints for seismic hazard mitigation, land-use planning, and risk reduction strategies in southern Haiti and constitute a robust framework for future probabilistic assessments and site-specific studies.

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ԱՄՓՈՓԱԳԻՐ

Ակտիվ խզվածքների ինտեգրված քարտեզագրում և սեյսմիկ վտանգի գնահատում. Հայիթիի օրինակը

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Սույն հետազոտությունը ներկայացնում է Հայիթիի հյուսիս-արևմտյան հատվածում և հարավային թերակղզում գտնվող ցամաքային և ափամերձ ծովային ակտիվ խզվածքների քարտեզագրումն ու վերլուծությունը՝ սեյսմիկ վտանգի գնահատման համատեքստում: Դաշտային հետազոտությունները (2017-2019 թթ.), բարձր լուծաչափի արբանյակային պատկերները, մորֆոտեկտոնական վերլուծությունը և կառուցվածքային տվյալները ինտեգրվել են՝ հիմնական և երկրորդային ակտիվ խզվածքները հայտնաբերելու և բնութագրելու նպատակով: Ցամաքային ակտիվ խզվածքների կինեմատիկ վերլուծությունները ցույց են տալիս գերիշխող Հյուսիս-հյուսիսարևելք–Հարավ-հարավարևմուտք ուղղված սեղմման ռեժիմ՝ թեք դեֆորմացիայով: Այս օրինաչափությունը համապատասխանում է Կարիբյան և Հյուսիսամերիկյան տեկտոնական սալերի հարաբերական շարժմամբ պայմանավորված տարածաշրջանային լարվածության դաշտին: Չնայած պատմական սեյսմիկության սահմանափակ տվյալներին, գեոմորֆոլոգիական և կառուցվածքային ապացույցները վկայում են հայտնաբերված ցամաքային խզվածքների ժամանակակից ակտիվության մասին: Կատարվել է դետերմինիստական սեյսմիկ վտանգի գնահատում, հաշվի են առնված խզվածքների երկրաչափությունը, սեգմենտավորումը և կինեմատիկան: Գնահատվել են ֆիզիկապես հնարավոր առավելագույն մագնիտուդները (Mmax) և արագացումները՝ կիրառելով գետնային շարժումների կանխատեսման մի քանի հավասարումներ: Արդյունքները ցույց են տալիս, որ ամենաբարձր ցամաքային PGA արժեքները (մինչև ≥ 0.42 g) կապված են Էնրիկիլյո–Պլանտեն Գարդեն խզվածքային գոտու հետ, մինչդեռ երկրորդային խզվածքները նույնպես էական ներդրում ունեն տեղական գետնային շարժումների մեջ: Այս արդյունքները ընդգծում են ինչպես հիմնական, այնպես էլ երկրորդային ակտիվ խզվածքների կարևոր դերը տարածաշրջանային սեյսմիկ վտանգի վերահսկման գործում և ցույց են տալիս խզվածքների մանրամասն քարտեզագրման ինտեգրման կարևորությունը վտանգի մոդելներում, հատկապես այն տարածաշրջաններում, որտեղ պատմական սեյսմիկ տվյալները սահմանափակ են:

Բանալի բառեր՝ Հայիթի, ակտիվ խզվածքների քարտեզագրում, երկրաբանական վտանգ, PGA հաշվարկ