Revision of the geological context of the Port-au-Prince, Haiti, metropolitan area: Implications for seismic microzonation

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Abstract

After the earthquake of 12 January of Port-au-Prince, for taking more fully into account the seismic risk in the urbanization and planning of the capital of Haiti, it has been decided to make a seismic microzonation. Corresponding to the first step of the microzonation, a geological study has been conducted. It reveals the deposit of Miocene and Pliocene formations in a marine environment and the impact of the Enriquillo-Plantain Garden N80°E fault system and of N110°E faults on these deposits. The tectonic observations and the morphological analysis indicate the quaternary activity of several faults mapped in the area of Port-au-Prince. These faults are a N110° trend and show a reverse – sinistral strike-slip motion. Moreover, on the basis of these geological results and of new topographical data, a hazard assessment of ground movements has been realized. As the map of active faults, the hazard map of ground movements represents an integral component of seismic microzonation. The location and the characterization of lithological or topographical site effects are the next phase of the seismic microzoning of Port-au-Prince.

Keywords. Geology, fault, ground movement, seismic microzonation, Port-au-Prince, Haiti

1 Context

On January 12th, 2010, Haiti was struck by one of the most violent earthquakes to have affected it during the last two centuries. In its wake, the earthquake left 230,000 dead, 300,000 injured, and over a million homeless. Port-au-Prince, capital city of Haiti, and its metropolitan area suffered very massive losses. The study of the historical archives (Bakun and *al.* (2012) shows that the island of Hispaniola has been hit by several major earthquakes over the past centuries. These earthquakes are concentrated to the North or to the South of the island. In addition to the 2010 earthquake, Port-au-Prince has already been destroyed by the earthquakes of 1751 and 1770.

To better integrate seismic risk into the reconstruction and development planning of the capital, a seismic microzonation study devoted to Port-au-Prince has been undertaken, involving the PNUD, the Haitian government (LNBTP and BME) and BRGM. The selected zoning scale is 1:25,000 over the metropolitan area as a whole and 1:10,000 for sectors of particular interest. The zonation takes into account the seismic ground motion in the bedrock (regional hazard) and modifications produced by this motion due to local topographic and sedimentary conditions (location and characterization of site effects and induced effects). The techniques implemented for this mapping initiative rely on available knowledge, enriched by on-site investigations (geological, geophysical and geotechnical) and/or modeling. Intended for decision-makers, development planners, structural engineers and architects, but also for the public at large, this seismic microzonation is usefull both in rebuilding those zones of the Haitian territory that were devastated and, preventively, in the framework of a development planning policy for the territory that will take natural risks into proper account.

2 The geodynamic background

The island of Hispaniola consists of Haiti to the west and the Dominican Republic to the east. With the islands of Jamaica and Porto-Rico it goes to make of the archipelago of the Greater Antilles. These mark the boundary between the North-American and Caribbean Plates. The main motion between the two plates amounts to a relative mean rate of 2 cm/yr., with a converging direction of these two plates of N70°E that is oblique with respect to the E-W plate margins (Mann and *al.*, 2002). At Hispaniola, two great fault systems form the boundary between the two plates: the Septentrional-Oriente fault zone (SOFZ), running along the north of Hispaniola, and the Enriquillo-Plantain Garden fault zone (EPGFZ), to the south (see Fig. 1).

The SOFZ cuts across the north of the Dominican Republic and pursues its course westward beyond southern Cuba. The mean slip measured on it is 12 mm/yr. (Calais and *al.*, 2010; website http://web.ics.purdue.edu). The strongest known earthquake associated with this fault system, having a magnitude estimated at 8, is that of May 7, 1842. This event caused the death of half of the population and considerable damage in several towns in northern Haiti.

The EPGFZ runs obliquely along Haiti's entire Southern Peninsula. To the west, this fault system reaches the island of Jamaica (the Plantain Garden plain). To the East of the Haiti and Dominican Republic border, the EPGFZ ends against the Muertos fault system, which corresponds to the subduction of the Caribbean plate beneath the Greater Antilles. The mean slip measured on the EPGFZ is 7(±2) mm/yr. (Calais and *al.*, 2010; website http://web.ics.purdue.edu). In addition to the January 12, 2010 event, other major historical earthquakes in recent centuries (1701, 1751, 1770, and 1860) are ascribed to this structure. According to Bakun and *al.* (2012), the 1751 event had a magnitude of at least 7.4, and for the one in 1770, the magnitude is estimated at 7.5.

In the center of the island of Hispaniola, a number of large active thrust faults trending NW-SE are visible in the present-day morphology (Calais and *al.*, 1992; Pubellier and *al.*, 2000). These faults structure the Transhaitian Belt. To the north, they connect into the SOFZ and, to the south, into the Muertos fault system. The thrust of the Matheux range corresponds to the northern boundary of the Cul-de-Sac Plain (see Fig. 1). This is the main structure of the Transhaitian Belt. According to GPS data, the mean measured slip on this thrust is approximately 1 mm/yr. (Calais and *al.*, 2010; website http://web.ics.purdue.edu). Seismic profiles implemented in the Gulf of Gonâve (Mann and *al.*, 1995) reveal the presence of folds and reverse faults dating in age from the Miocene to the Quaternary, which signal the active frontal edge of the Transhaitian Belt. The reverse motion of the Transhaitian fault system partially compensates the oblique component of the convergence of the North-American and Caribbean Plates with respect to their edges.

The January 12, 2010 earthquake had a magnitude Mw of 7.1; its focal depth was 13 km. The epicenter was located between Gonâve Island and the eastern end of Haiti's Southern Peninsula (see Fig. 1). The focal mechanisms computed for the main shock and its aftershocks, the radar interferometry measurements, and those from GPS indicate motion along a fault striking ENE-WSW (N71°E), that is north-dipping with a reverse left-lateral component (Calais and *al.*, 2010). Thus, this fault is slightly oblique with respect to the trend of the EPGFZ (N80°E) and lies to the north of this zone. Designated the “Léogâne fault” (Calais and *al.*, 2010), it is interpreted as being a blind thrust. According to the analysis of aftershocks of the January 12, 2010 event, the main rupture on the Léogâne fault appears to have triggered a reverse movement on a N120°E fault (the Trois-Baies Fault), interpreted as a secondary fault of the EPGFZ (Mercier de Lépinay and *al.*, 2011), and the reactivation at depth in a left-lateral strike of the main fault plane of the EPGFZ (Hayes and *al.*, 2011; Douilly and *al.*, 2012).

3 The geological study of the Port-au-Prince metropolitan area

The geological facies of the Port-au-Prince Metropolitan area constitute the essential input data controlling both the soil responses to seismic vibrations and the susceptibility to ground movements. The geological information available for the Port-au-Prince region was relatively succinct, mainly consisting in the geological map of Haiti at 1:250,000 scale by Momplaisir and Boisson (1987) and the recent geomorphological sketch by Bachhuber and *al.* (2010), at a 1/50 000 scale.

For achieving the seismic microzonation, it was necessary to improve the knowledge of geological context. The geological study consisted in observing several dozen outcrops, supplemented by the analysis of geotechnical boreholes drilled earlier, of aerial photographs from 2002, of the digital terrain model with pixels 2 m to a side calculated from 2012 Pléiades satellite images (KalHaiti, SERTIT/CNES), SPOT 2010 ortho-images, and 3D-view satellite images of various dates under Google Earth.

3.1 Mapping lithological facies

The Port-au-Prince metropolitan area lies in the Cul-de-Sac alluvial plain (see Fig. 2). Eastwards, the urban area ends near the Rivière Grise, while to the west, the city is limited by the sea. In a southerly direction, the city abuts on the mornes (mounts) of Saint-Laurent and Hôpital in the La Selle range. These mornes are bounded to the south by the Rivière Froide, of which the course is, in turn, determined by the EPGFZ.

The various facies encountered have been classified into ten geological types or units ranging from the oldest to the most recent: F1 (Upper Eocene) through F10 (Plio-Quaternary to

Present) (Fig. 3). The estimated ages of these units are derived from the work of Butterlin (1960). The rocky substratum consists of limestones, silts, marls or conglomerates (or breccia). Sandy facies are rarely encountered. The marls are frequently associated with limestones to form “marly-limestone” alternations more or less rich in marine fossils according to the place. The present-day topography is largely the result of the Pliocene orogeny and of the activation of the faults that delimit the blocks, atop which Quaternary and recent erosion has occurred.

At the Saint-Laurent and Hôpital mornes, Eocene to Oligocene limestones outcrop to the south and Miocene conglomerates to the north. The main orographic axis is N80°E, parallel to the EPGFZ. Between the Cul-de-Sac alluvial plain to the north and the northern slope of Morne Hôpital, small secondary ranges trending globally N110°E mark the topography. The marly limestones and Mio-Pliocene marls or silts form the foundation of these small mounts. Here, the stratigraphic surfaces of these formations trend WNW-ESE and dip steeply (angle greater than 45°) towards the north or south (see Fig. 2). These reliefs are bounded, to the east and north, by the alluvial formations of the Grise River, and to the west by marine alluvia. To the south, colluvial deposits or dejection cones cover these mornes in spots. The colluvia in place are mostly fairly shallow, with thicknesses generally ranging between 0.1 and 0.5 m on more rugged relief and from 0.5 to 1 m on average in less hilly areas. These remobilized superficial deposits may attain thicknesses of several meters in narrow valley bottoms.

On Figure 3, the analysis of Miocene to Pliocene terrains in the Cul-de-Sac Plain shows: 1) deepwater to sublittoral marine deposits (marly limestones, mudstones, fine-grained sandstones and silts) characteristic of low-energy environments; 2) sharp intercalation of detritic formations related to sequences of sandy and gravelly to silty turbidities (conglomerates). These formations correspond to marine deposits with a proportionally variable limestone component, overlain by flysch sequences that become increasingly regular and frequent at the end of the Miocene and beginning of the Pliocene. These sharp detritic intercalations, considered to be tectonic in origin, are ascribed to the continual activation during the Mio-Pliocene of the faults bounding the Port-au-Prince plain to the south.

These Miocene and Pliocene formations are several hundreds of meters thick, possible exceeding a thousand meters, on the strength of the marine seismic profiles in the Gulf of Gonâve (Mann and *al.,* 1995) as well as the borehole drilled in the Cul-du-Sac Plain by ATLANTIC REFINING in 1947 (Momplaisir, 1987).

3.2 Fault mapping

As to fault mapping, this was performed by observing outcropping fault planes (Fig. 2), supplemented by an interpretation of morphological data. A majority of the fault planes measured trend E-W to NW-SE. Most present reverse left-lateral activation (Fig. 4). In several locations, the contact via the fault between quaternary alluvia and Miocene to Plioene formations is visible (Fig. 5).

In the center of the metropolitan area, a conglomerate formation composed of uncemented, graded, polymetric limestone elements embedded in a marly sandy matrix overlies the Mio-Pliocene marly limestone and silt formations. This formation corresponds to a piedmont alluvial cone probably deposited between the end of the Pliocene and the early Quaternary. The hydrographic system responsible for this deposit is to be sought in the limestone relief to the south, quite probably in the upstream portion of the Bristout River catchment area (Fig. 6). The debris cone is characterized by three distinct assemblages, interpreted as successive deposits from the drainage basin. The oldest lies furthest north, and the most recent, southernmost one is still fed by the present-day Bristout ravine. Based on the central axis of the north and center portions of the cone, the hypothesis of a 1000-meter offset cannot be excluded (Fig. 6). This would indicate a horizontal displacement rate of 0.6 (±0,2) mm/yr. for the WNW-ESE fault systems mapped at this location. This estimate is compatible with the values from GPS measurements on the compressive deformations of the Transhaitian Belt (Fig.1).

Furthermore, between the Musseau and Chavannes quarters, the hydrographic network presents a number of inflections in hydrographic drains following a WNW-ESE trend. These inflections may locally have sizes up to 300 m. This mean value is coherent with the hypothesized horizontal displacement rate indicated above, bearing in mind, in this instance, that these are markers of more recent date (Middle to Upper Quaternary).

4 Hazard assessment of ground movements

4.1 Method

Ground movements may be triggered by seismic vibrations. This is why these must be analyzed in the seismic microzonation process, as potential site effects. In addition to local topographic conditions, the lithologic nature of the terrains constitutes one of the main environmental factors governing ground stability.

For this part of the study, the main steps were: (1) establishment of an inventory of the ground movements of the region of Port-au-Prince (location, type of instability, geological and morphological context); (2) depending on the type of ground movements and based on past events, analysis of predisposing factors (involved lithology, slopes value); (3) preliminary mapping of the susceptibility of the land for instability; (4) study on the field and analysis of aerial photographs in 3D vision (definition of the different levels of hazard, and mapping of the boundaries of the hazard zones); (5) restitution under GIS of the hazard map.

The geological map made in the framework of the microzonation, the digital terrain model calculated using Pléiades (KalHaiti, SERTIT/CNES) images, and the inventory of ground movements constitute the cartographic reference data for the hazard assessment of ground movements. As attested by the past ground movements, listed on Table 1, Port-au-Prince is often concerned by slope instabilities. The inventory of ground movements is resulting from field observations, interpretation of aerial photographs (especially for the instability triggered by the earthquake of 2010) or local testimonies. Among the forty or so events recorded for Port-au-Prince, 19 dispose of precise data, as the location, the geological facies involved and the instability's geometry. For the remainder, they are generally eyewitness accounts indicating some events triggered by the 2010 earthquake. These events fall into two main categories: landslides and rockfall (Table 1). The extent of the phenomena is estimated with the observations on the field and/or by means of the aerial photos. On the study area, identified landslides can reach large to very large extension (hundreds of thousands of m^3 to more than a million m^3), while the size of the rockfall is more limited. Rockfall up to 10 000 m^3 are more scarce.

Landslides generally involve marly limestone formations (F4, F5 and F6, cf. Fig. 3), which may be overlain by more recent layers (F7 and F8), while rockfall events concern mainly consolidated rocky layers (such as F3 and F2). In a few instances, calcretizations may be at issue (these may be up to 1 m thick) observed at the roof of the Morne Delmas formation (F6 to F8) or the shelly limestone banks (F6) in the marly limestone alternations.

While the lithological nature largely conditions the type and the exent of the potential ground movement, the hill slope takes also a significant part in the ground instability assessment.

Other factors influence the susceptibility of hillsides instabilities, but these are often difficult to integrate at this study scale, among them, for example, the structural data (as dip of stratigraphic or fracture planes), lithological variations within geological formations, or hydrogeological circulations.

For each geological formation, slope thresholds have been defined, mostly calibrated by means of the feedback given by the inventory (Table 1). Thus, a preliminary map was produced thanks to a data digital cross-comparison, with a 5m-resolution. At each spot, a value is assigned according to the geological nature and the value of the slope. This digital processing yields a preliminary assessment of the landslide or rockfall susceptibilities at each point of the study area.

This preliminary map is a precious document to direct the field work and the demarcation of the various zones of hazard.

4.2 The ground movement hazard map

The finalized hazard map for ground movements is at 1:10,000 scale. It preserves the distinction between the two types of ground movements, i.e. landslide and rockfall (Fig. 7). Virtually half of the studied territory is concerned by landslide. The rockfall phenomenon, involving less than 10% of the studied area, is concentrated along the southern boundary of the studied zone as well as on the foothills of the La Selle mountain chain. Landslides remain by far the most frequent and most damaging phenomenon.

Four levels of susceptibility of increasing severity are defined:

1) Zones assigned a hazard that is weak or non-existent, applying to areas that are flat or gently sloping (< 5°). These zones are generally not or little affected by landslide or rockfall. The few events that may occur are minor.

2) Zones assigned a moderate hazard may be subject to landslides of limited (a few hundred m³) or moderate scale (a few thousand m³). The areas concerned present gentle slopes (between 5 and 10° on average), composed of Miocene formations consisting of marl, marly limestone or silt (Formations F4 to F8).

3) Zones assigned an intermediate hazard may be regularly affected by landslides of intermediate intensity (several thousand m³) and, exceptionally, by larger-scale phenomena (several hundred thousand m³), as the Delmas 32 famous event that

destroyed 200 houses in 1989. Concerned are areas that feature either slopes ranging between 10 and 20°, composed of marl, marly limestone, silt or alluvia, or zones subject to the propagation of landslides initiated on steeper inclines upslope. Zones with intermediate hazard may also be at risk for rockfall; in this case, the terrains involved are rocky, with slopes exceeding 10°, or zones liable to the propagation of rockfall from above.

4) Zones assigned a high level of hazard are proned either to frequent superficial landslides or to large-scale events (active or potential). These are characterized by intermediate to steep slopes with unfavorable geology or land-use factors (typical configurations of the historical well-known landslides like Vivy Mitchell 1 and 2, Musseau), or they are subject to massive landslide propagation from higher altitude. Thus, included under this category, we find ravines and foot slopes, receptacles for materials that have slipped off slopes and may be remobilized in the ravines as mudflows.

5 Implications for preventive seismic recommandations

In the framework of the seismic microzonation, the next step is to complete these geological data with geotechnical and geophysical investigations, and then to map the terrain responses to the seismic tremors. Moreover this next step should have to take into account the topographical conditions of Port-au-Prince. A first comparison between the distribution of damage due to the earthquake of 2010 (UNOSAT, 2010) and the lithological and topographic data shows a concentration of damage at right of topographical buttes on the one hand, and on the edge of the coastline above the alluvial marine deposits (Fig. 2, see F10-ma), on the other hand.

But already, the map of the active faults and the hazard map of the ground movements which constitute two full components of the seismic microzoning were integrated into this one.

The geological study of Port-au-Prince reveals that the capital is located near or directly over two active fault systems (Fig. 2), which have been taken into account in the seismic risk assessments: 1) the EPGFZ, which bounds the southern limit of the Port-au-Prince urban area, and 2) the N110°E faults, very probably corresponding to the south-easterly extension of the reverse faults located in the Gulf of Gonâve and which connect into the EPGFZ to the east. The system of N110°E faults mapped on land has a maximum length of 15 km but, as indicated by offshore geophysical data, this system almost certainly extends WNW into the Gulf of Léogâne. Tectonic deformations in terrains dated presumably to the middle or recent Quaternary is observed at several locations along these faults. Taken in conjunction with the morphostructural data, these indicate a reverse left-lateral displacement, associated with a mean horizontal slip on the order of 0.6 (±0,2) mm/yr.

Thus, in the context of Port-au-Prince metropolitan area, it is recommended to prohibit the construction of high-stake buildings as schools, hospitals, disaster relief centers or structures of strategic importance in the vicinity of active faults.

Concerning the ground movement hazard, each specific zone identified on the hazard map (Fig. 7) is subject to specific recommendations (measures) designed to take the ground movement risk into account in existing or future urban land-use development. No recommendation is made for zone of low hazard, only to plan and to build according to the proper rules. The zones associated with a moderate, intermediate or high hazard categories are governed by specific recommendations which depend of the hazard level.

6 Conclusion

The geological study performed in the framework of the seismic microzonation of Port-au-Prince has enabled the environmental context of the deposit of the Miocene and Pliocene formations to be established. These are marine deposits, either deep or sublittoral, which are characteristic of low-energy environments and showing occasionnaly sudden inputs of detrital materials. These inputs are turbidites and are related to the continual activation of the southern boundary faults of the Port-au-Prince Plain during the Miocene and Pliocene. Moreover, the study confirms the presence of several active faults which are not only the EPGFZ bounding the Port-au-Prince metropolitan area to the south, but also faults trending N110°E that are directly visible within it.

Concerning the main uncertainties, the age of the lithological units should be confirmed by chronostratigraphic dating. Moreover, it would be necessary to determine the relationships and contours for units F6 through F8, which are characterized by specific environments of deposition. Furthermore, the deposit of F9 needs to be determined with greater precision, notably its relationship with the upstream portion of the catchment area. Recommandations are made for taking into account the risk of surface rupture along active fault, but it would be preferable to reduce uncertainties on the fault traces and to better understand the seismogenic potential of these structures. To this end, the analysis could be pursued by studies local geophysics and paleoseismic trench investigations.

The hazard map of ground movements at scale 1:10,000 is realized mainly on the basis of geological map and inventory of past events. It takes into account both the initial predisposition and the propagation of instabilities, while also distinguishing between landslide and rockfall phenomena. The results will be directly integrated into the seismic microzonation of Port-au-Prince.

The location and characterization of lithological or topographical site effects is the aim of the next phase of the seismic microzoning of Port-au-Prince. To this end, the realized lithological map will be an essential basic data.

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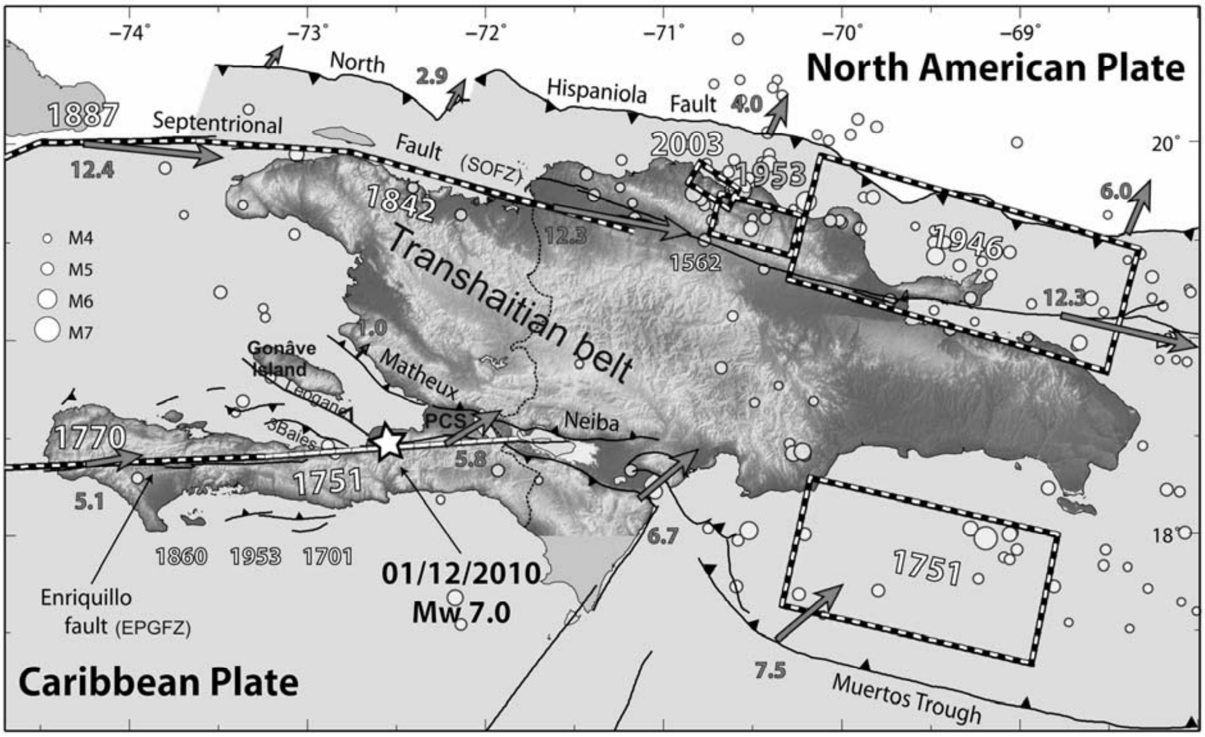

Figure 1 – Locations of historical rupture zones and indications (red arrows) of the active slip rates derived from geodetic measurements (modified from Calais and *al.*, 2010, http://web.ics.purdue.edu/~ecalais/haiti/context/).

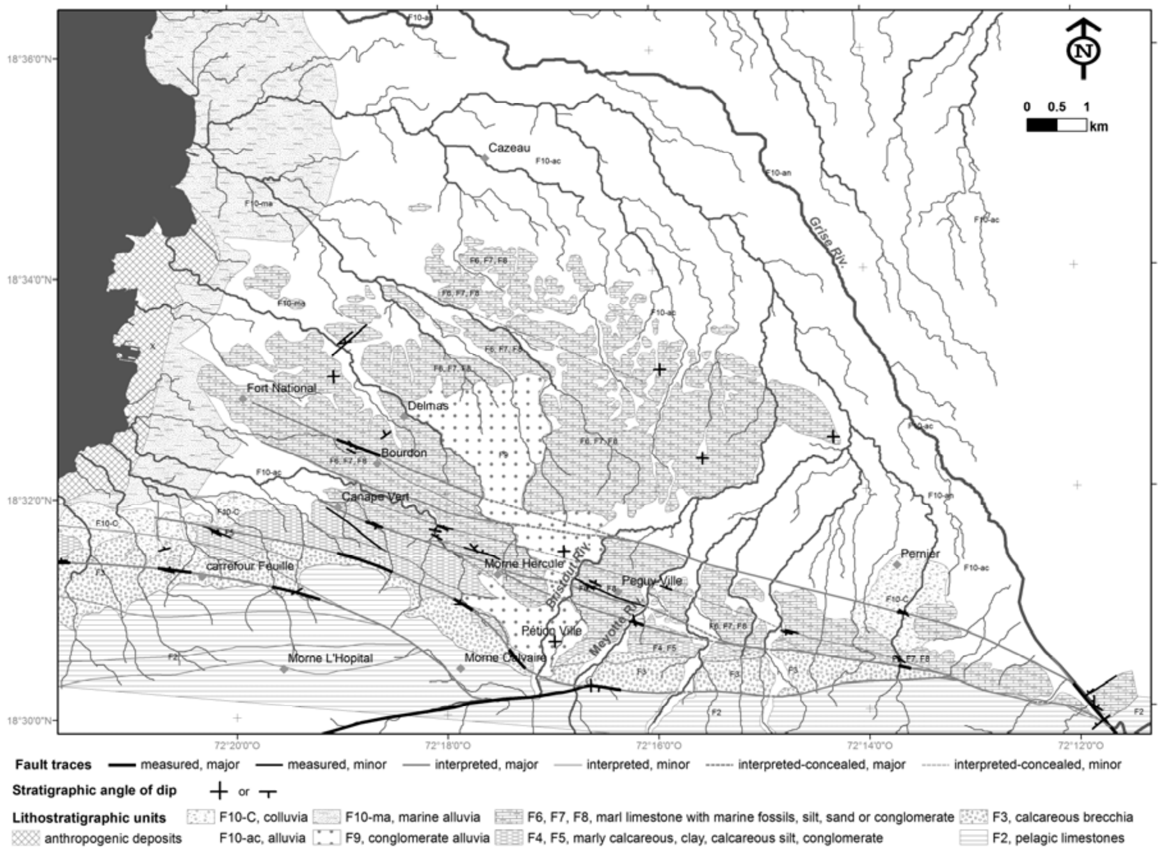

Figure 2 – Geological map of the Port-au-Prince metropolitan area.

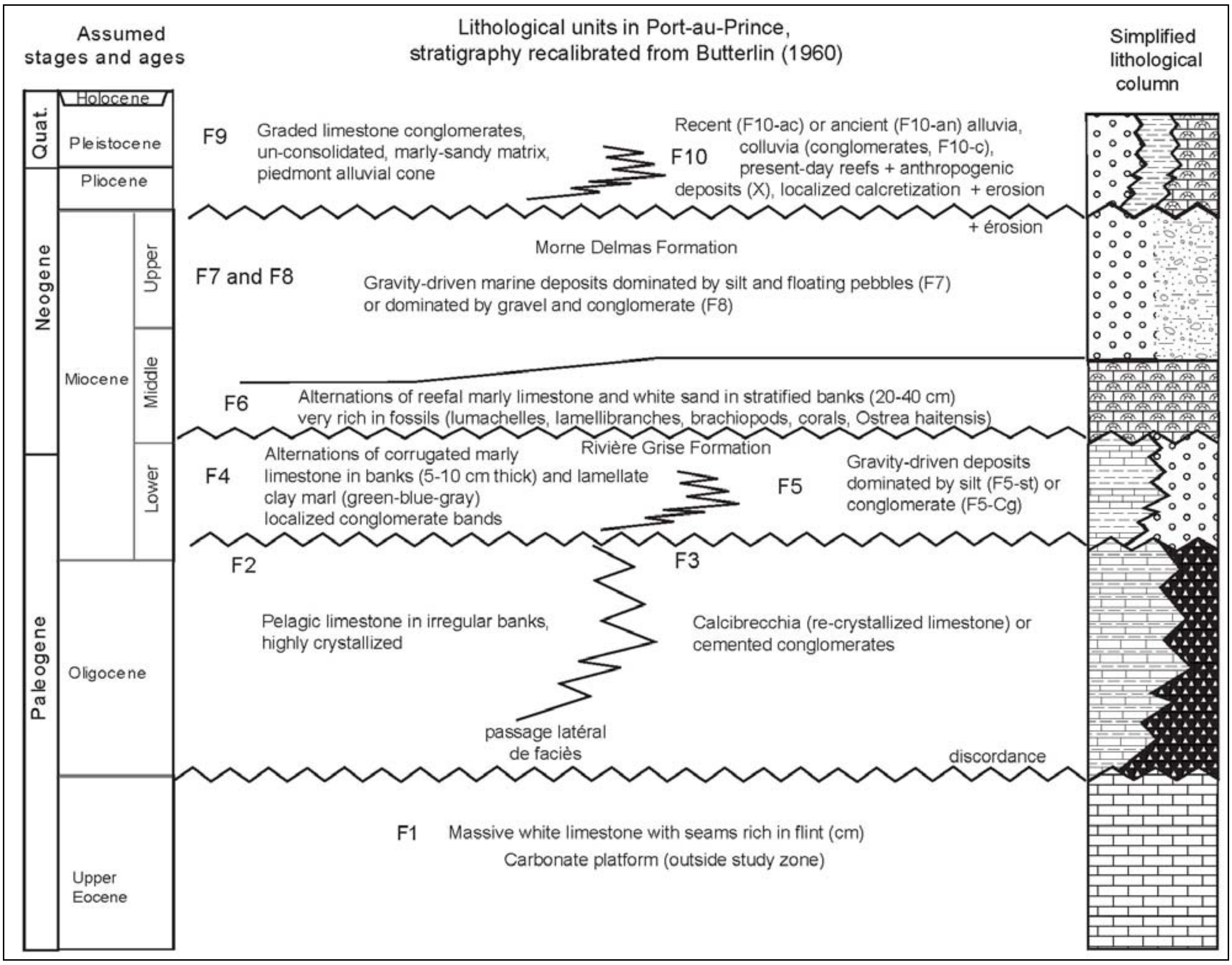

Figure 3 – Litho-stratigraphic synthesis for the Port-au-Prince study sector (stratigraphic séquence based on the work by Butterlin (1960).

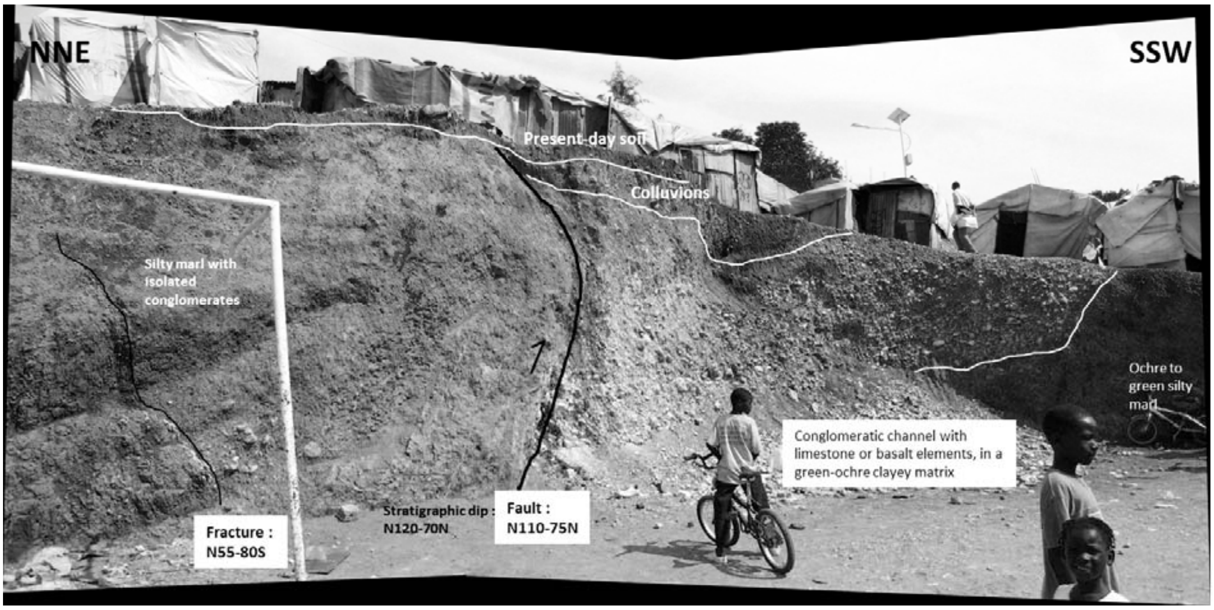

Figure 4 – Fault contact in Mio-Pliocene terrains between the deposits of sandy, ochre-colored silts and conglomerates (observations situated between the quarter of Morne Hercule and Péguy-Ville, cf. Figure 2).

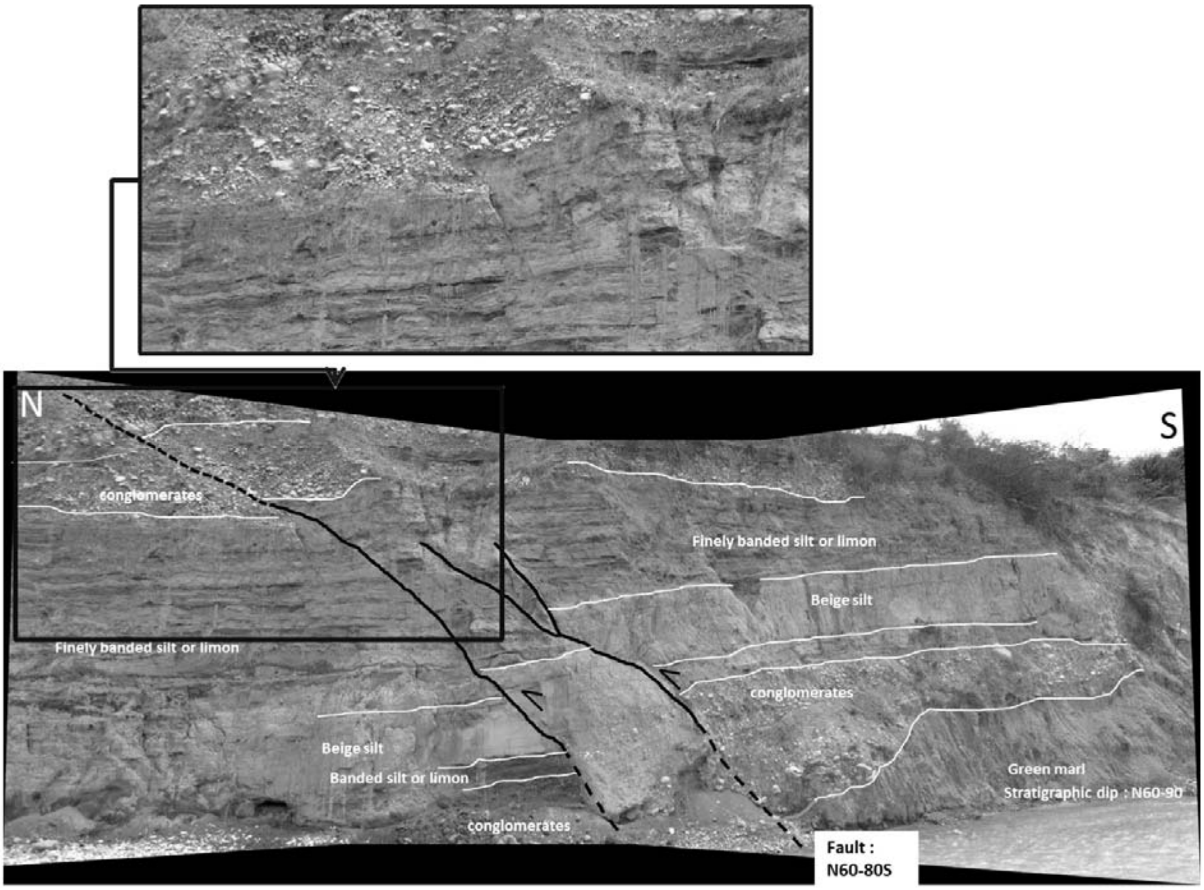

Figure 5 - Reverse faults trending NE-SW, visible along Rivière Grise in the Quaternary conglomerates and silt deposits.

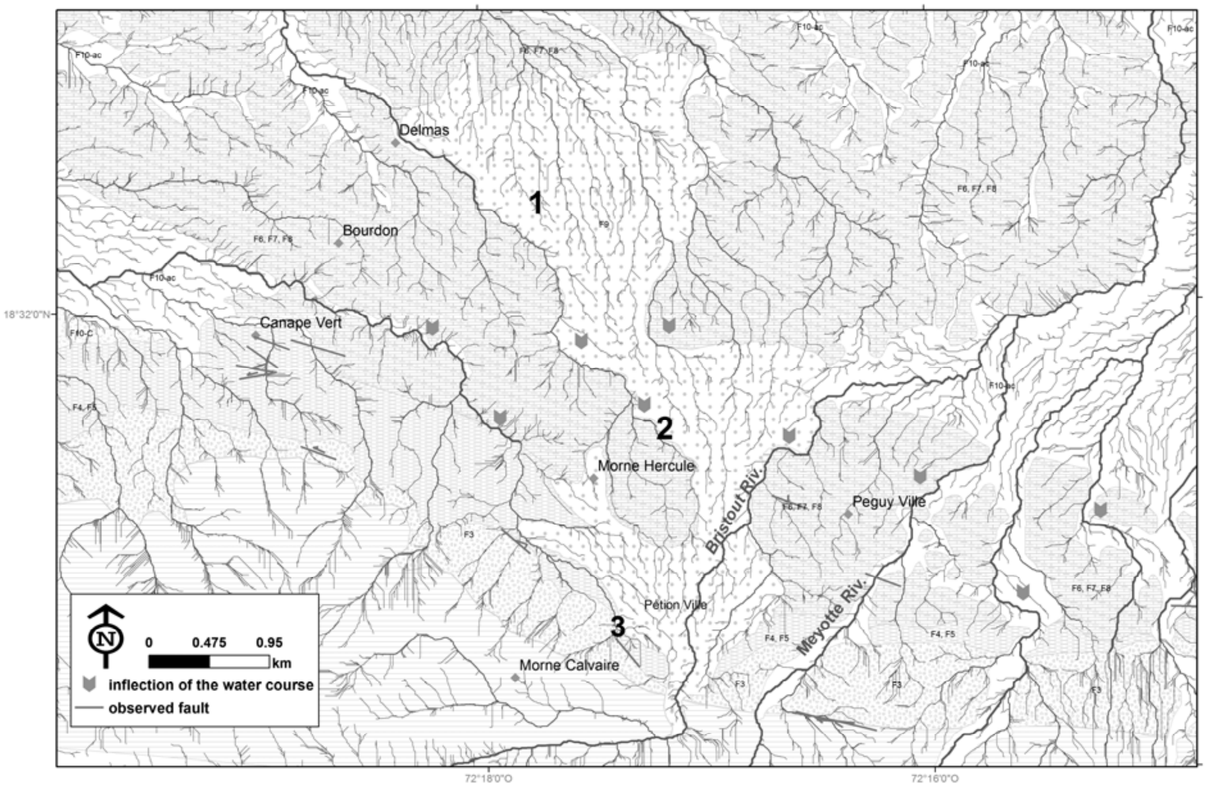

Figure 6 – Hydrographic network calculated from the Pléiades DTM: zoom on the catchment area of the Bristout and Meyotte Rivers. Numbers 1 to 3: successive segments of the alluvial cone (ranging from the oldest to the youngest; For stratigraphic units, see legend Fig.2).

Table 1 - Characteristics of the most important ground movements inventories over the Port-au-Prince metropolitan area (L : landslide ; R : Rockfall ; B : Bank Erosion)

NAME	Type of MVT	DAMAGE	DESCRIPTION	LITHOLOGY	Triggering factor	DATE	OBSERVATION	SEEN	Size
Musseau, imp Avalon	L	Several houses destroyed	30 m high by 50 m wide, initial slope > 37°. Bordered at the base by the Musseau ravine	Limey channel silt isolated from conglomerates (F7, F8). Marly layer at the base (F6?)	Heavy rains	2008	Accentuation in 2008 of an earlier landslide.	Yes	Large to very large
Djobel1	L	7 fatalities and 11 houses destroyed	Scarp 25 m high , by 50 m wide	Brown argilaceous silts with more indurated levels of very fine sand	Heavy rains	2003	Triggered in 2001.	Yes	Large to very large
Djobel3	L/R	None	Subvertical scarp. Rockslide over a width of 40 m and a height of 60 m.	Poorly consolidated conglomerate banks	Heavy rains, ravine	Après 2002	Bordered at the base by a ravine.	Yes	Large to very large
Djobel2	L/R	None	Scarp 40 m high. Rockslide over a width of 10 m.		Heavy rains		Slope of approximately 35°	Yes	Inter-mediate
Marcadieu	L	Road blocked	Rockslide over a height of 40 m and a width of 40 m	Poorly consolidated conglomerate banks	Heavy rains, ravine	1987?	Bordered at the base by the Bois de Chaine ravine.	Yes	Large
Vivy Mitchell 2	L	5 houses destroyed, some ten houses displaying cracking	125 m long by 30 m high, Over 100,000 m^3. Moderate slope (< 20°).	Marly limestone (F6?) overlain by calcretization at the summit. Same dip as the topography	Heavy rains	>2002	Triggered in 1998. Clearly visible from DTM shading	Yes	Large to very large?
Vivy Mitchell 1	L	Several houses destroyed or with cracking	Landslide scar revealed over 60 m. Moderate slope (< 20°)	Marly limestone (F6?) overlain by calcretization at the summit. Same dip as the topography	?	Post 2002	Same configuration as Vivy Mitchell 2.	Yes	Large
Boulard / Acacia	L	Cracking in some thirty houses			Micro-earthquake	2003	Information by word-of-mouth. Nothing in the field. Intensely built-up area. Gentle slope	No	Large?
Rue Rosa	R ?		150 m long by 10 m wide.	-	?	?		No	Inter-mediate
Ravine Bristout	B	Houses		Alluvia (F10)	?	?		No	Limited to inter-mediate

Morne Calvaire	R	None	Blocks measuring approximately 1 m³	Calcibrecchia (F3)	Earthquake	?		No	Limited
Desermite	B	Houses	Deposit of detritic material	Calcibrecchia (F3)	?	?		No	Limited
PanAméricaine_2	L		Suspected landslide	Marly limestone (F5, F6, F7, F8)	?	?	Gabion retaining wall uphill from the highway and stabilization wall below	Yes	Intermediate?
RivBoisDe Chaine	L	-	Over some 100 m along the Bois de Chaine ravine and 20 m in height. Probably the same configuration as Marcadieu.	Recent formations overlying the Delmas formation?	Rain, ravine?	Prior to 2010	Niche of plucking visible from the rue Panaméricaine. Probably triggered by the action of the ravine.	Yes	Intermediate to large
Meyotte	L		Undulating terrain observed on the hillside	-	?	?		Yes	Intermediate?
PanAméricaine_1	R	-	Rockfall on the roadway, approximately 1 m³	Calcretization	?	?	Several blocks on the pavement along the rue Panaméricaine	Yes	Limited
Delmas32	L	200 houses destroyed, 60 reported injured	Hillside with a limited slope (< 15°), over ca. 30,000 m²		Rains / earthquake	1989	Moderately-sloping hillside (< 20°)	No	Very large
StGérard_2	B	One house	Sliding of the banks that probably carried off the house	Recent, poorly consolidated conglomerate	Ravine at the base?	2010?	Influence of the ravine at the base. No explicit outcrop of marl	Yes	Limited
StGérard_1	L	-	Landslide niches some 15 m long by 8 m high	Conglomerate overlying marly limestone	Ravine at the base?	?	Influence of the ravine at the base? Marly limestone outcropping at the base	Yes	Limited to intermediate

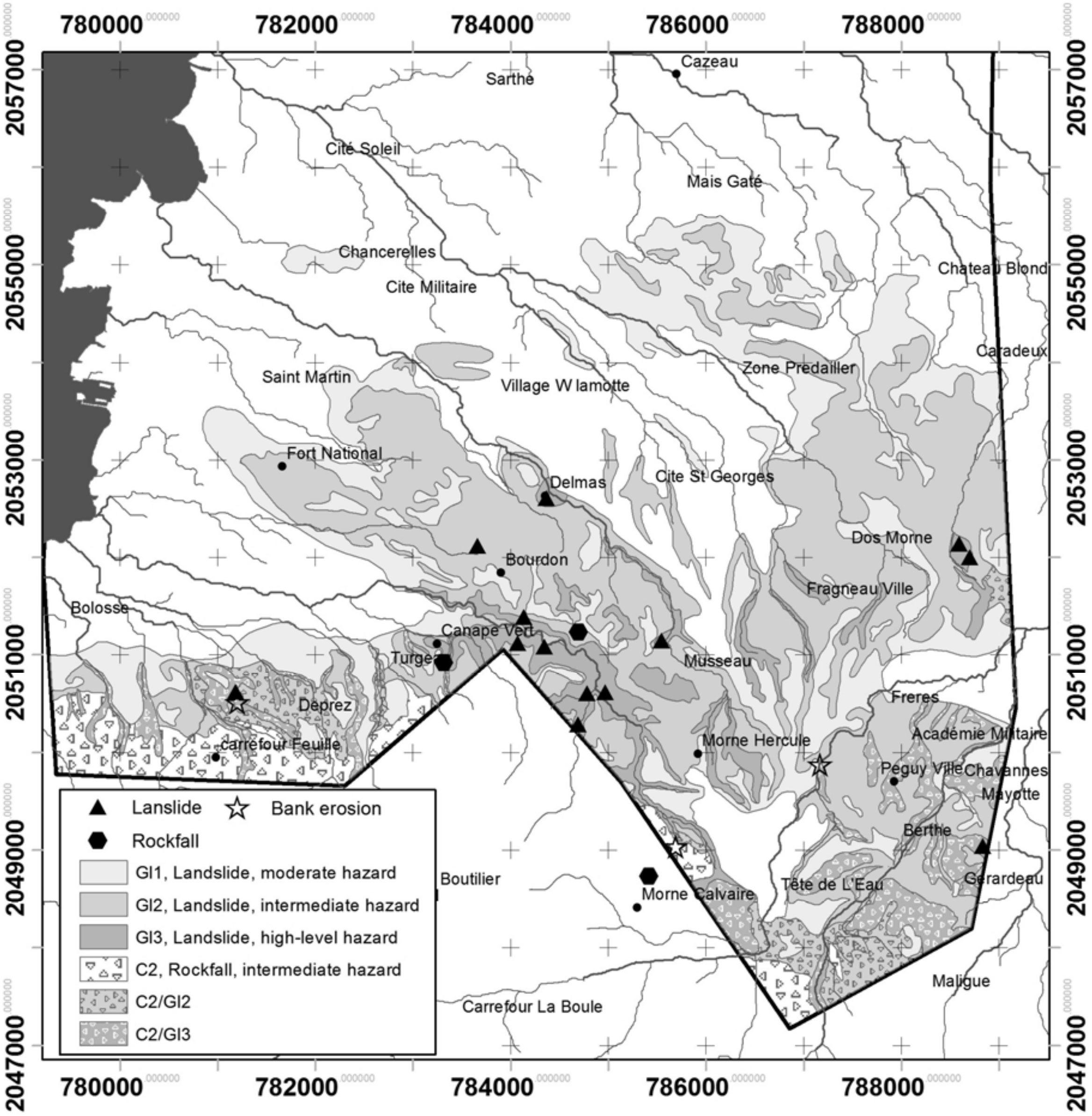

Figure 7 : Hazard map of ground movements for the Port-au-Prince metropolitan area.