5.0 DAMAGE PATTERNS

5.1 Introduction

Earthquake-induced damage in Port-au-Prince was devastating and widespread. Yet, there were clearly areas of the city where little to no damage occurred, and areas of the city where an overwhelming majority of the buildings were severely damaged or destroyed. These types of damage patterns are common in earthquakes, and a wide number of factors need to be considered in order to conclusively piece together the causes. For a given earthquake, these factors include, but are not limited to: (1) Relative distance from the fault rupture plane, (2) Construction type and quality, (3) Local soil conditions (i.e. strength/stiffness of the foundation soil, depth to bedrock, impedance contrasts, age/geology), (4) Topography (topographic and basin effects), and (5) Near fault effects (rupture directivity, fling step, hanging wall effects, polarity effects, etc.). Often several of these factors work together and it can be difficult to identify the primary cause of damage.

This section primarily attempts to identify damage patterns in Port-au-Prince relative to local soil conditions/geology, topography, and construction type. However, it must be understood that the discussion of construction type is very broad and is based on limited field observations by geotechnical engineers coupled with properties that can be identified from satellite imagery (i.e. density and size of buildings, type of roof, etc.). A detailed ground-based survey by structural engineers in some of these areas would be very valuable in piecing together damage patterns. Additionally, no discussion regarding distance from the fault rupture plane and near fault effects is provided below. Most of the locations in Port-au-Prince are at a relatively similar distance away from the fault (20 – 25 km, Figure 5.1), and due to this distance and the direction of rupture propagation (i.e. away from Port-au-Prince to the west) near fault effects are not expected to have played a role in the damage patterns. However, near fault effects (particularly forward directivity) may have played a strong role in the severe damage observed by the GEER team in Leogane (approximately 30 km due west of Port-au-Prince along the coast, Figure 5.1). Leogane also sits on top of young/soft Quaternary soil deposits, which may have also amplified shaking in this area (see Section 2.0 Regional Geology). Other than these brief observations, Leogane has not been considered in depth in this damage patterns section.

This section investigates, on a limited scale, some of the damage patterns around Port-au-Prince relative to the above mentioned factors. It is based on “boots on the ground” observations made by the GEER team members, as well as a comprehensive building damage assessment performed using satellite and aerial imagery by UNOSAT (United Nations Operational Satellite Applications Programme; http://unosat.web.cern.ch/unosat/). The basis of the investigation is heavily weighted toward general categories of structural damage, as this is the most visible manifestation of strong ground shaking in a densely populated area, and was the primary focus of the UNOSAT survey. Other types of damage were observed by the GEER team in and around Port-au-Prince, such as landslides in the foothills heading up to Petion-Ville and foundation, transportation, and lifeline failures due to soil liquefaction in coastal areas. In general, foundation and liquefaction failures seemed to be confined primarily to a limited area of man-made fills and Quaternary alluvial deposits right along Port-au-Prince Bay. Therefore, it appears that these issues did not play a large role in the widespread damage around Port-au-Prince.

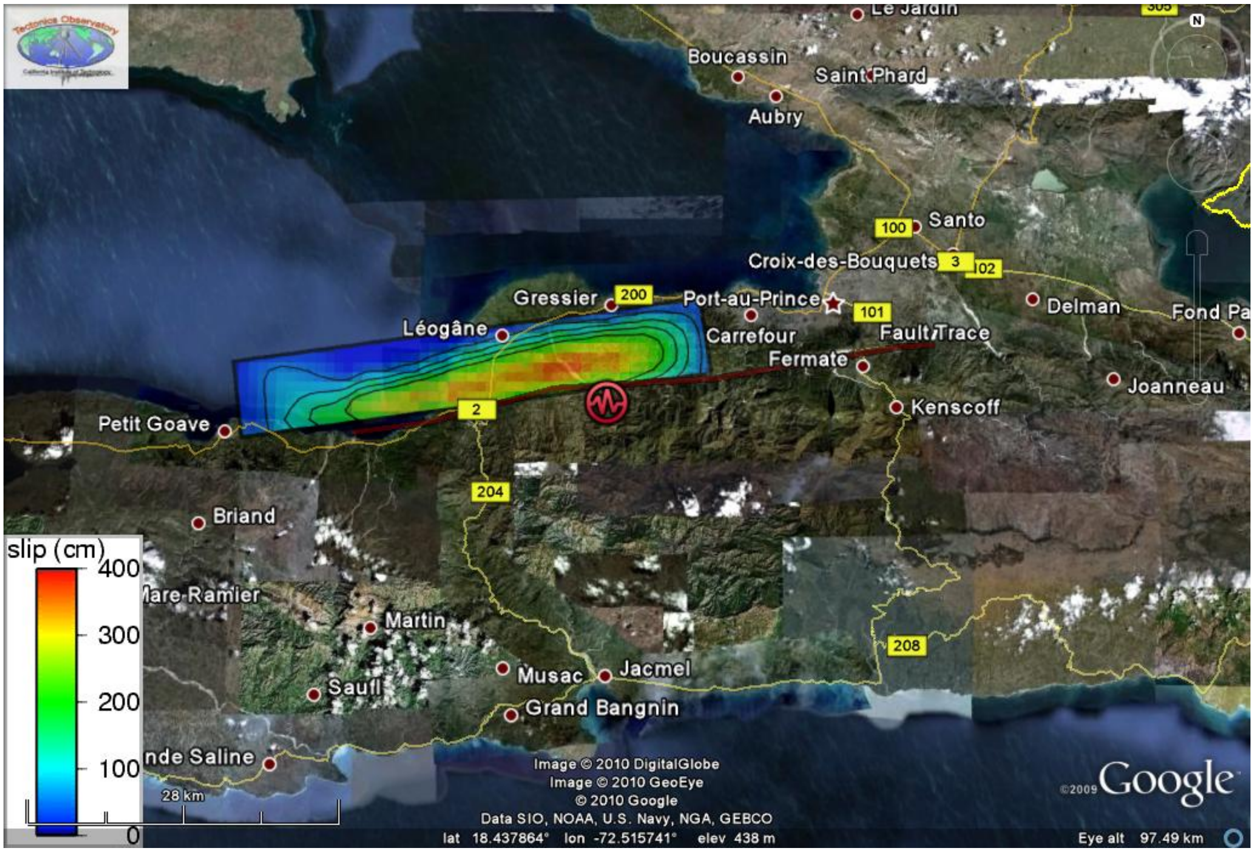

Figure 5.1 Estimated fault rupture distribution for the 2010 Haiti earthquake (http://tectonics.caltech.edu/slip_history/2010_haiti/) and location of major city centers.

5.2 Local Geology and Topography

A 1:250,000 scale geologic map of the region around Port-au-Prince is shown in Figure 5.2. As discussed in Section 2.0 Regional Geology and shown in Figure 5.2, the city of Port-au-Prince is founded on three broad geologic units from youngest to oldest: (1) Quaternary period deposits (not differentiated into Holocene or Pleistocene epoch), (2) Pliocene epoch deposits, and (3) Miocene epoch deposits. Generally, it is expected that the older deposits consist of stiffer, stronger soils/rock. Figure 5.3 is a shaded relief map for a portion of Port-au-Prince derived from a 1-m LIDAR DEM collected by RIT for the Worldbank (http://ipler.cis.rit.edu/projects/haiti). Also shown in this figure are the geologic boundaries from a geo-referenced version of the geologic map shown in Figure 5.2. Interestingly, the geologic map indicates that the Pliocene deposits extend almost to the coastline within the central part of the city, yet the topographic data indicate that the flat plain (which presumably corresponds to the Quaternary deposits) extends a significant distance inland. It is more likely that the contact between the Quaternary and Pliocene deposits occurs at the break in slope where the topography steepens, which would indicate that most of the blue areas in Figure 5.3 represent Quaternary sediments. However, this interpretation cannot be verified without further field work.

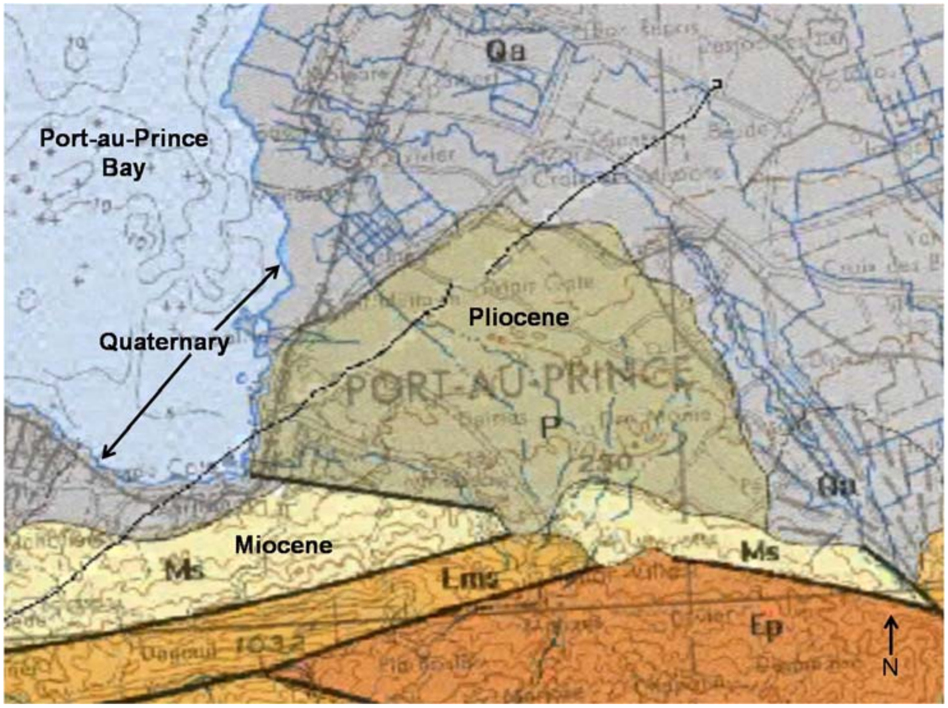

Figure 5.2 Geology of Port-au-Prince area.
(C.E.R.C.G. IMAGEO Lambert, Gaudin, and Cohen, 1987)

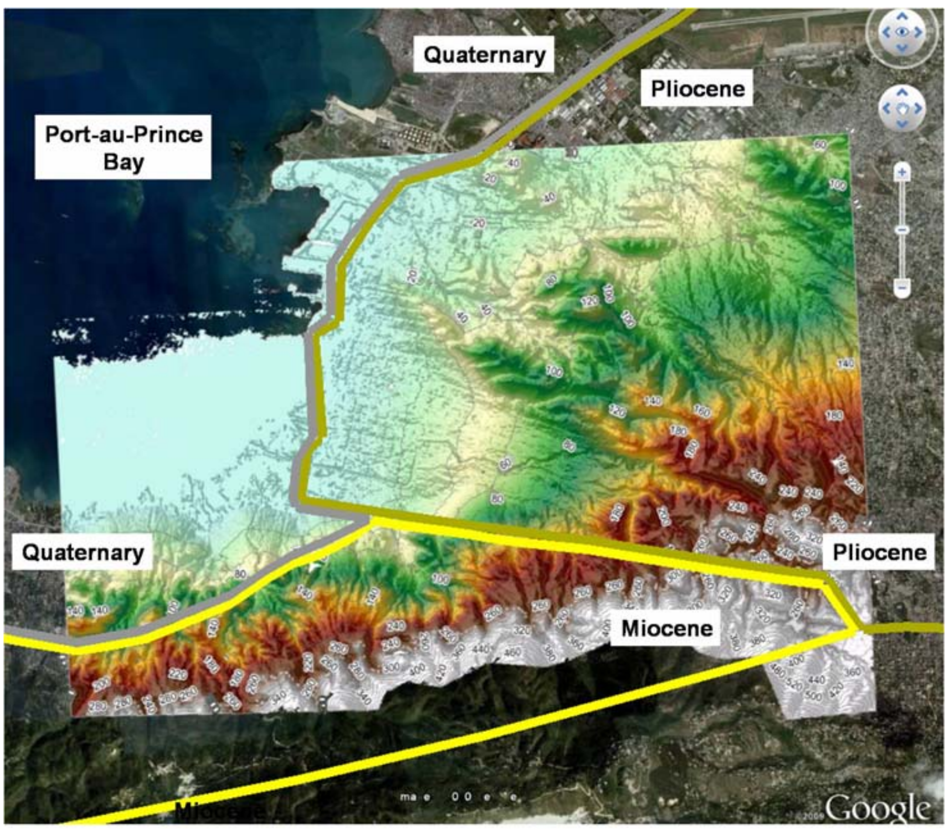

Figure 5.3 Shaded topographic relief map of the Port-au-Prince area with geologic boundaries from the geologic map shown in Figure 5.2.

5.3 UNOSAT Damage Assessment

The UNOSAT damage assessment in Port-au-Prince was a mammoth effort whereby over 90,000 buildings were visually surveyed via post-earthquake satellite and aerial imagery in order to group each structure into one of four categories: (1) Destroyed, (2) Severe Damage, (3) Moderate Damage, and (4) No Visible Damage. The survey also attempted to organize the damage according to classes such as high density built-up zone, low density built-up zone, shanty zone, industrial zone, etc. An example of one of these UNOSAT damage assessment maps is presented in Figure 5.4. The most recent versions of these maps may be found at http://unosat.web.cern.ch/unosat/asp/prod_free.asp?id=52.

The UNOSAT survey basically found that on average 9 – 12% of the 90,000 surveyed buildings were destroyed, 7 – 11% of the buildings were severely damaged, and 5 – 8% of the buildings were moderately damaged. Interestingly, on average, the overall percentage of damaged buildings in shanty zones (~ 28%) was approximately the same as the overall percentage of damaged buildings in high density (~ 30%) and moderate density (~ 27%) built-up zones. This type of work is invaluable to both the humanitarian and scientific communities and will be the basis for many future studies. However, it must also be accepted with some limitations as these types of surveys do not always capture the magnitude of destruction on the ground. As an isolated example, consider the two steel frame warehouses discussed in Section 6.0 Port Facilities and Coastal Infrastructure of this report. Both of these buildings were heavily damaged and will need to be torn down, yet they were classified as No Visible Damage by the UNOSAT survey. This is not meant to criticize the survey, it is only meant to confirm the well understood pattern that damage observed on the ground will typically be greater than the damaged observed from imagery. Therefore, as a lower-bound estimate, one might assume that on average a minimum of 30% of the buildings in Port-au-Prince sustained damage severe enough to be visible from the air. However, certain areas of the city sustained higher percentages of destroyed or severely damaged buildings, while other areas of the city sustained much lower percentages.

A Google Earth (GE) .kmz file was created from the ESRI database compiled by UNOSAT (www.unosat.org/shared/Haiti-HQ-2010/Data/UNDP_UNOSAT_v2.zip) in order to superimpose GEER team observation and measurement locations, geologic data, and topographic data onto the structural damage observations. The ability to spatially link all of this information is a critical step to understanding damage patterns. The .kmz damage assessment file from the UNOSAT database was created by personnel from CAST (Center for Advanced Spatial Technologies; http://www.cast.uark.edu/) after the GEER reconnaissance, and unfortunately was not available to the team in the field. The approximate extents of the UNOSAT survey are superimposed in red on GE imagery in Figure 5.5. Some key landmarks such as the port and airport are also included for reference. Additionally, the GPS track logs for the GEER team (shown in purple) and flag markers identifying areas where Spectral Analysis of Surface Waves (SASW) tests were conducted are also shown. SASW tests were conducted to obtain quantitative evidence of the near surface soil stiffness (i.e. shear wave velocity profiles) in various areas affected by the earthquake. Many SASW surveys were conducted at the port and along the coast west of Port-au-Prince to help assess soil liquefaction damage. However, only a limited number of profiles (three) were conducted in the city due to time constraints and the difficult nature of getting around a heavily damaged city.

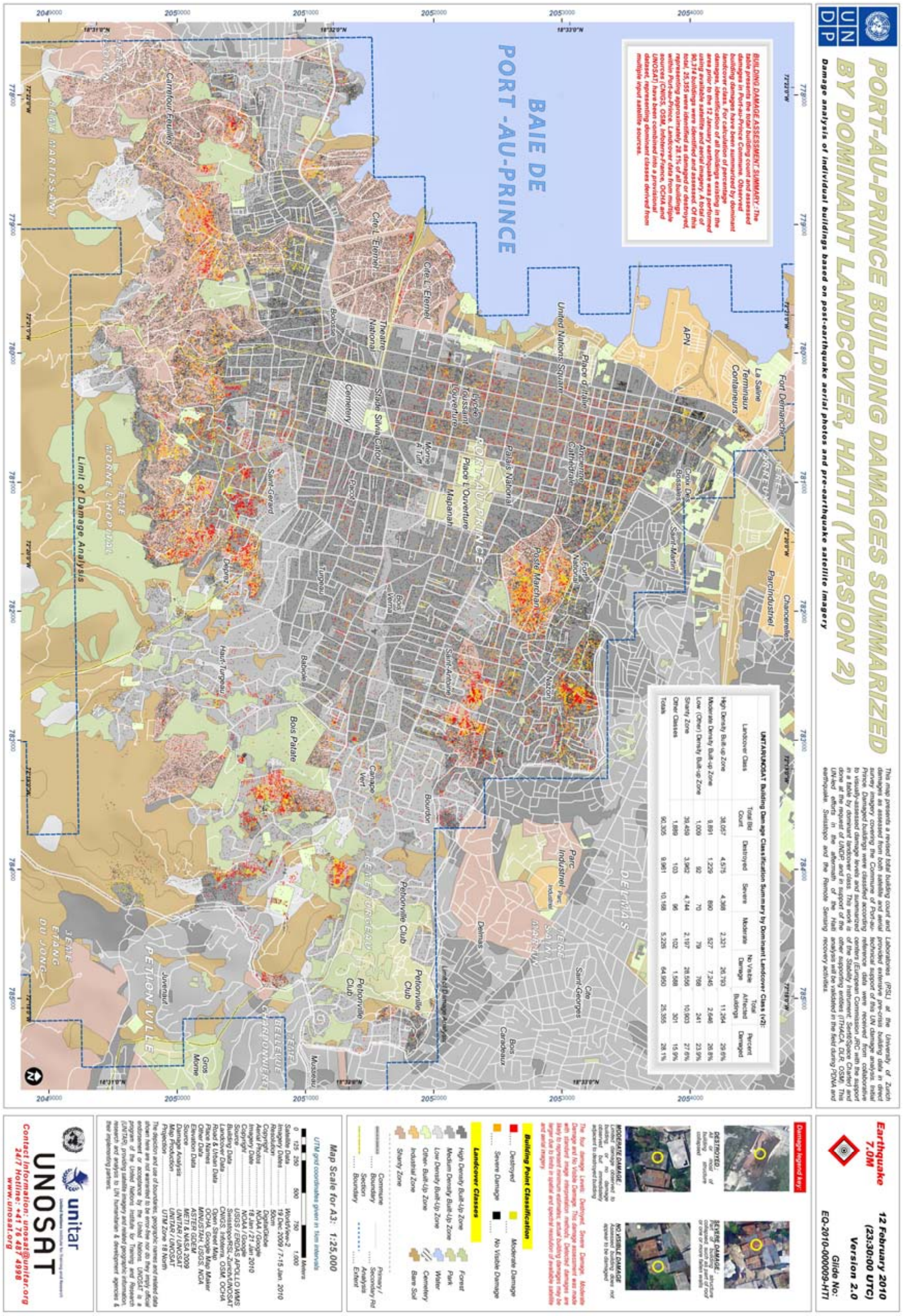

Figure 5.4 UNOSAT building damage assessment map for Port-au-Prince categorized by dominant landcover (http://unosat.web.cern.ch/unosat/asp/prod_free.asp?id=52).

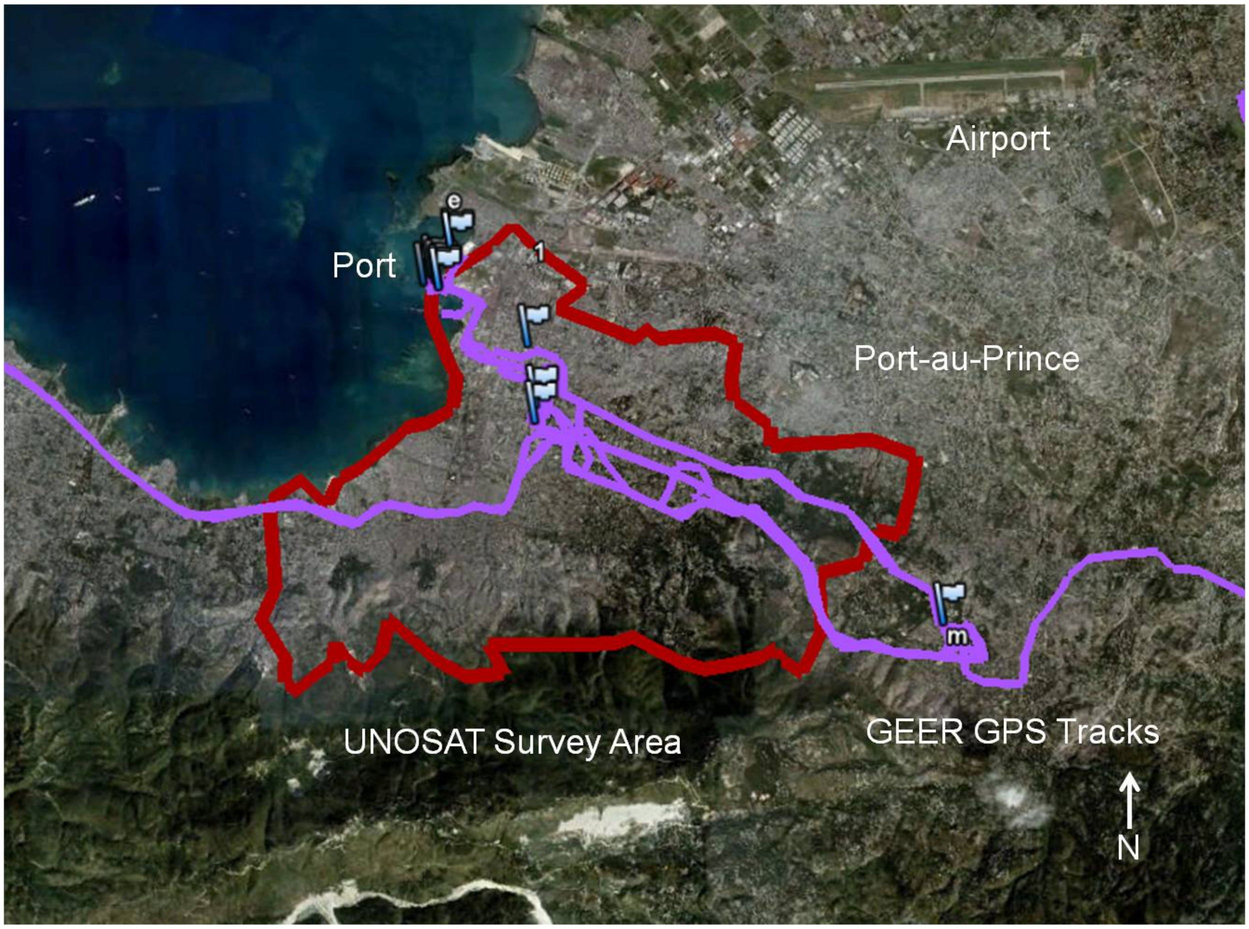

Figure 5.5 Approximate area of the UNOSAT damage survey in Port-au-Prince. Also shown are the GEER team GPS track logs and markers identifying locations where SASW testing was conducted.

5.4 Relationship between Damage Patterns and Geology

Figure 5.6 shows the buildings categorized as Destroyed in the UNOSAT survey relative to the Quaternary (Qa), Pliocene (P) and Miocene (Ms) deposits discussed in Section 5.2. It is evident from this broad view that many buildings were destroyed in each of these three deposits (however, recall that the geologic boundaries are somewhat uncertain). However, the picture is skewed somewhat because only the Destroyed buildings are shown (approximately 10,000 points). When one zooms in on the damage, certain patterns begin to emerge. The following discussion will focus on the area boxed in pink in Figure 5.6.

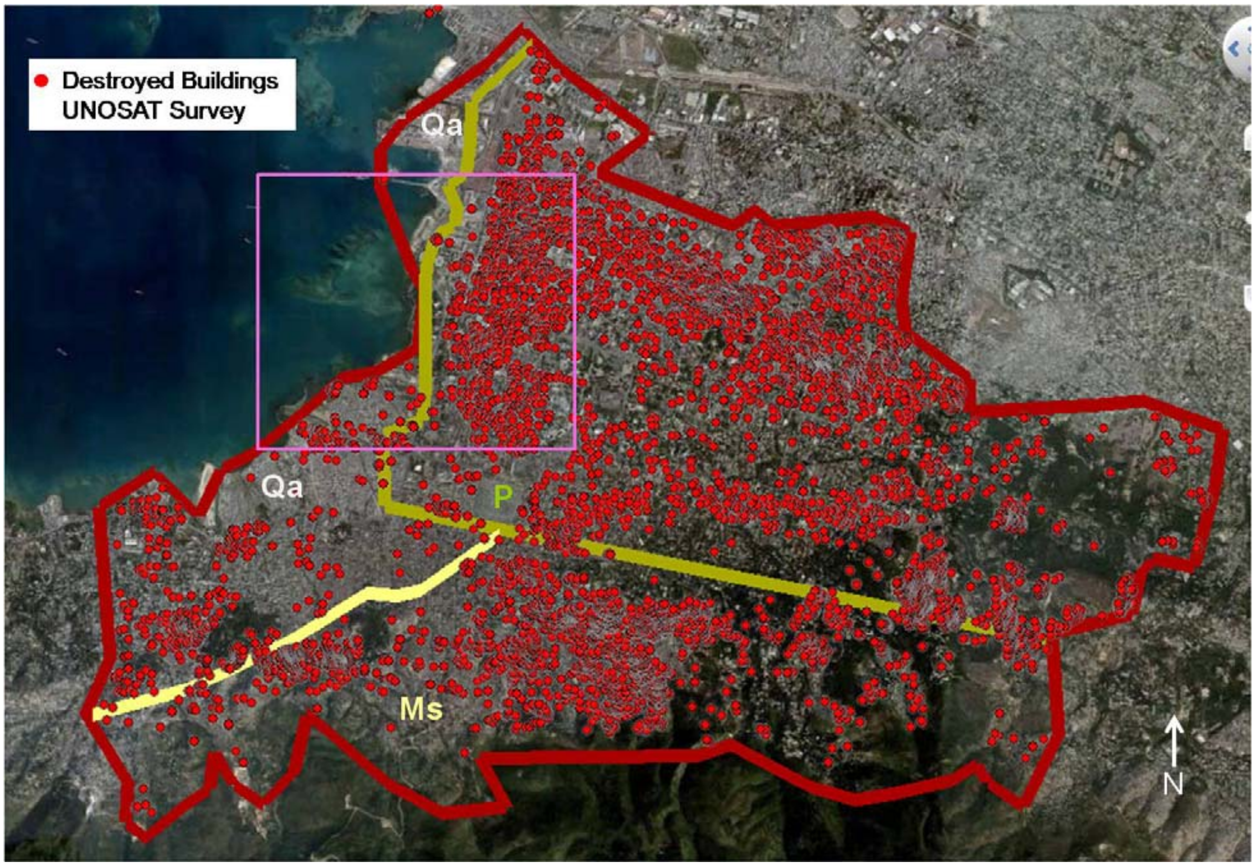

Figure 5.6 Buildings classified as Destroyed in the UNOSAT survey relative to the three geologic units (Quaternary = Qa, Pliocene = P and Miocene = Ms) underlying the survey area. Note that the destroyed buildings shown in this figure only represent about 10% of the more than 90,000 total buildings categorized in the UNOSAT survey (refer to the text for more detail).

One intensely damaged zone noticed on the GEER reconnaissance was an area located due west and north of the Presidential Palace. This area is boxed in pink in Figure 5.6 and shown in Figure 5.7 along with the buildings that were categorized as either Destroyed (red dots) or No Visible Damage (black dots) in the UNOSAT survey. Also shown are three flag markers where Spectral Analysis of Surface Waves (SASW) testing was performed to investigate the near-surface soil layering and stiffness in the area. It is clear that nearly every building on some of these blocks was completely destroyed (particularly just west and south of SASW 8). However, it is also clear that other areas nearby (e.g. the extreme left-hand bottom corner of Figure 5.7) had very few destroyed buildings. Interestingly, according to the published geologic map, the heavily damaged area lies on Pliocene deposits, while the lightly damaged area lies on younger (presumably softer) Quaternary deposits. However, the revised interpretation of the Quaternary/Pliocene contact (see Section 5.2) would place both of these areas within Quaternary alluvium. One reason for these differences in damage may be building type. Most of the buildings in the heavily damaged zone were larger, multi-story, reinforced concrete structures, while most of the buildings in the lightly damaged area were smaller, densely packed Shanty's with tin roofs (note the difference in density of black dots in the two areas). Several pictures of the type of structures and damage encountered in the heavily damaged zone near SASW 8 are shown in Figure 5.8.

The Presidential Palace also lies on the eastern edge of this heavily damaged zone. The damage to the Presidential Palace (Figure 5.9) was documented by many news crews covering the aftermath of the earthquake due to its symbolism for the widespread, devastating destruction throughout the city. The GEER team conducted two SASW tests (SASW 6 and SASW 7) and one H/V Spectral Ratio test on the grounds of the Presidential Palace. These results have not been fully processed yet, but will be made available as soon as they are complete.

Figure 5.7 Buildings classified as No Visible Damage and Destroyed in the UNOSAT survey for the boxed area specified in Figure 5.6. Notice the heavily damaged zone lying on P deposits to the north and west of the Presidential Palace and the lightly damaged zone lying on Qa deposits in the lower left-hand corner. Most of the buildings in the heavily damaged zone were larger, multi-story, reinforced concrete structures, while most of the buildings in the lightly damaged area were smaller, densely spaced Shanty’s with tin roofs (refer to the text for more detail).

Figure 5.8 Typical types of structures and damage found within the heavily damaged zone near SASW 8 (N18.550210°, W -72.339638°).

Figure 5.9 The Presidential Palace lies within the heavily damaged zone noted above. Two SASW tests and one H/V Spectral Ratio test were conducted here (N 18.543633°, W -72.338905°).

5.5 Relationship between Damage Patterns and Topography

Figure 5.10 shows the buildings categorized as Destroyed in the UNOSAT survey relative to a color-shaded topographic map of the Port-au-Prince area. These 20-m, color-shaded contours were generated by personnel from CAST using LiDAR data processed by Chris Crosby at OpenTopography (http://opentopo.sdsc.edu/files/Haiti/WorldBank_Haiti_lidar_hs_v1.kmz). As was the case with the varied geologic deposits shown in Figure 5.6, it is evident that many buildings were destroyed in all types of topography. However, when one zooms in on the damage, certain patterns begin to emerge. The following discussion will focus on the two areas labeled in Figure 5.10.

One interesting area lying on steep topography is shown in Figure 5.11 along with the buildings that were categorized as either Destroyed (red dots) or No Visible Damage (black dots) in the UNOSAT survey. This zone is labeled as Area 1 in Figure 5.10. There is almost a distinct line that could be drawn from east-to-west that separates heavy damage to the south from almost no visible damage to the north. When one zooms in on this area there appears to be no significant difference in the type of structures. All of them appear to be densely packed Shanty-type buildings. It is possible that the steepness of the slope affected this pattern, but no conclusive evidence is known at this time.

Another interesting area lying on a transition from moderate to steep topography is shown in Figure 5.12. This zone is labeled as Area 2 in Figure 5.10. Once again, there is almost a distinct line that can be drawn from east-to-west that separates heavy damage to the south from no visible damage to the north. However, in this case there is both a distinct difference in the type of structure (and likely quality of construction) and type of topography. The structures to the north are larger buildings that appear to be nice homes (some with swimming pools). They are also constructed on more gradual topography. Very few of these homes were damaged. The structures to the south are Shanty-type structures, and the ones that are damaged most severely are located near the top of the hillsides/ridges. This could be evidence of ridge-top focusing of seismic energy. Conversely, the line of Shanty's where no visible damage is noted (bottom center of Figure 5.12) are constructed in a valley.

5.6 Conclusions

The observations of damage patterns noted above are just that: isolated observations made from a combination of field information and aerial imagery without rigorous analysis. As discussed at the beginning of this section, there are a wide range of factors that affect damage patterns during earthquakes and many times multiple factors combine to create a complicated mosaic of destruction. However, there is important information to be gained from these damage patterns and there is a wealth of information available for examination from the Haiti earthquake. This pool of information will only continue to grow as more research teams are deployed to the area.

Further investigations regarding damage patterns around Port-au-Prince would benefit greatly from better geologic mapping, local measurements of shear wave velocity profiles throughout the city, structural damage assessments in areas where abrupt changes in the level of destruction were noted, and further investigations of topography such as the direction and angle of slope. The GEER team will continue to conduct more detailed analyses related to this topic.

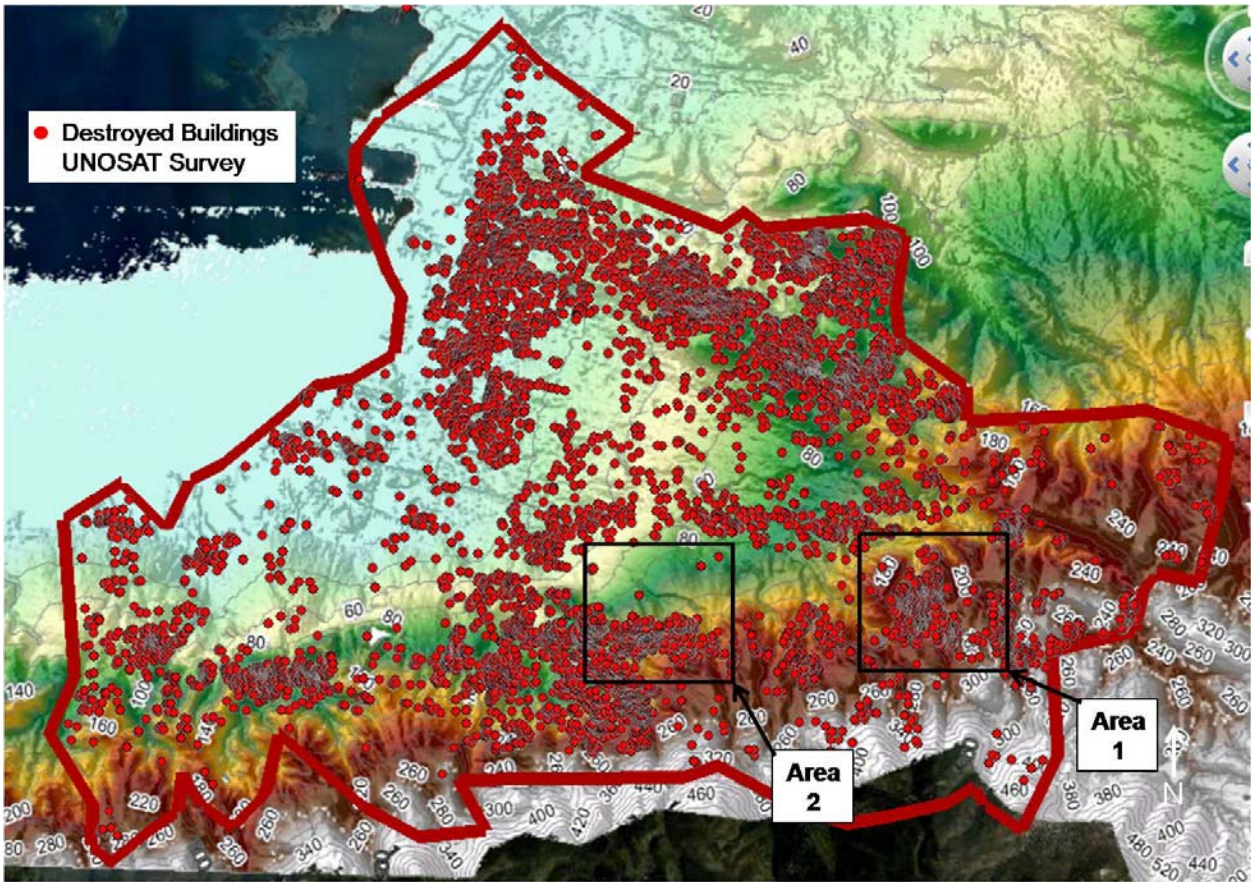

Figure 5.10 Buildings classified as Destroyed in the UNOSAT survey relative to topography in the Port-au-Prince area. Note that the destroyed buildings shown in this figure only represent about 10% of the more than 90,000 total buildings categorized in the UNOSAT survey (refer to the text for more detail).

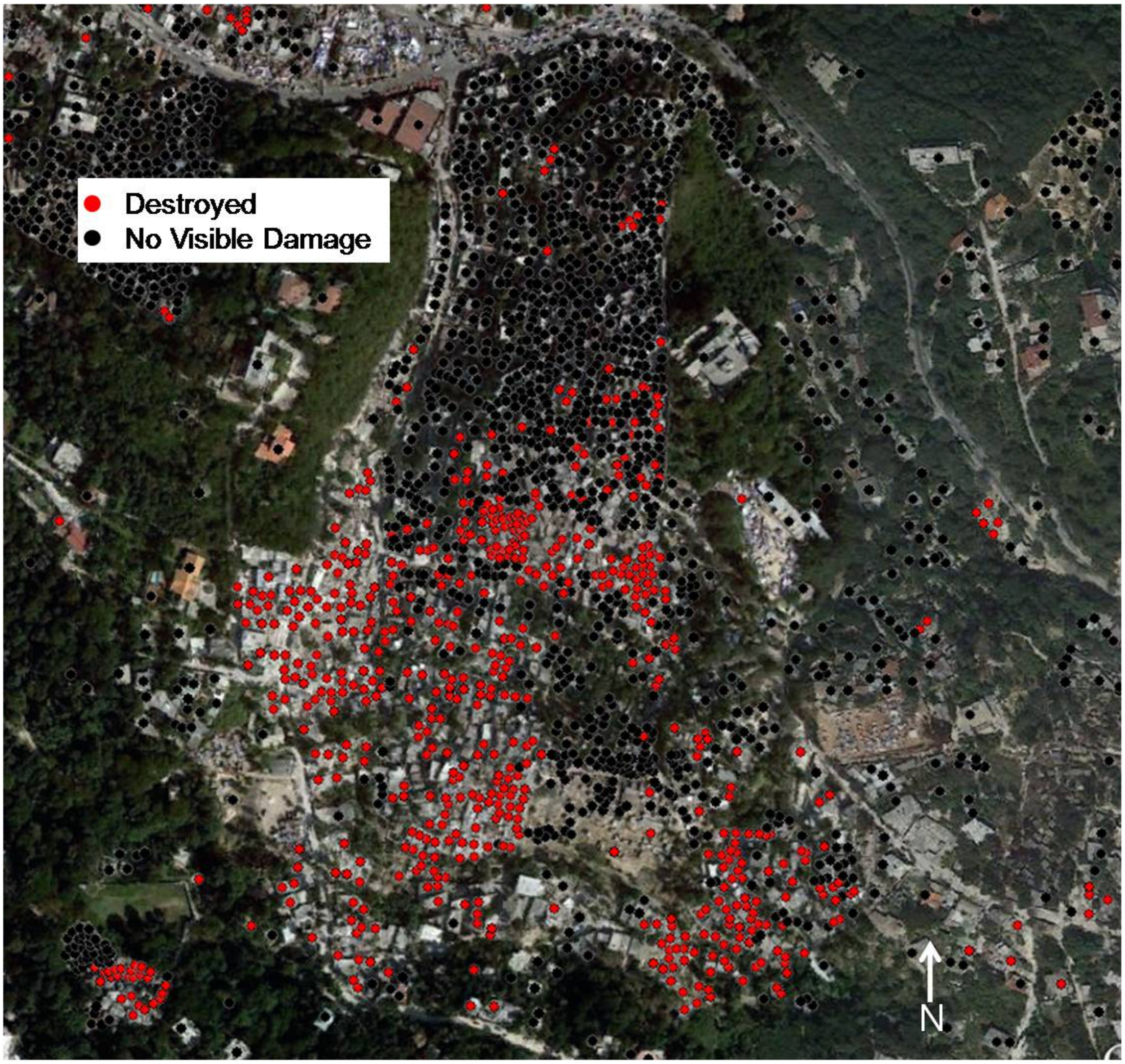

Figure 5.11 Buildings classified as No Visible Damage and Destroyed in the UNOSAT survey for the boxed area labeled as Area 1 in Figure 5.10. Notice the clear north-south separation between no visible damage and destroyed buildings that bisects the ridgeline east-to-west. All of these buildings appear to by Shanty-type structures with similar construction (refer to the text for more detail).

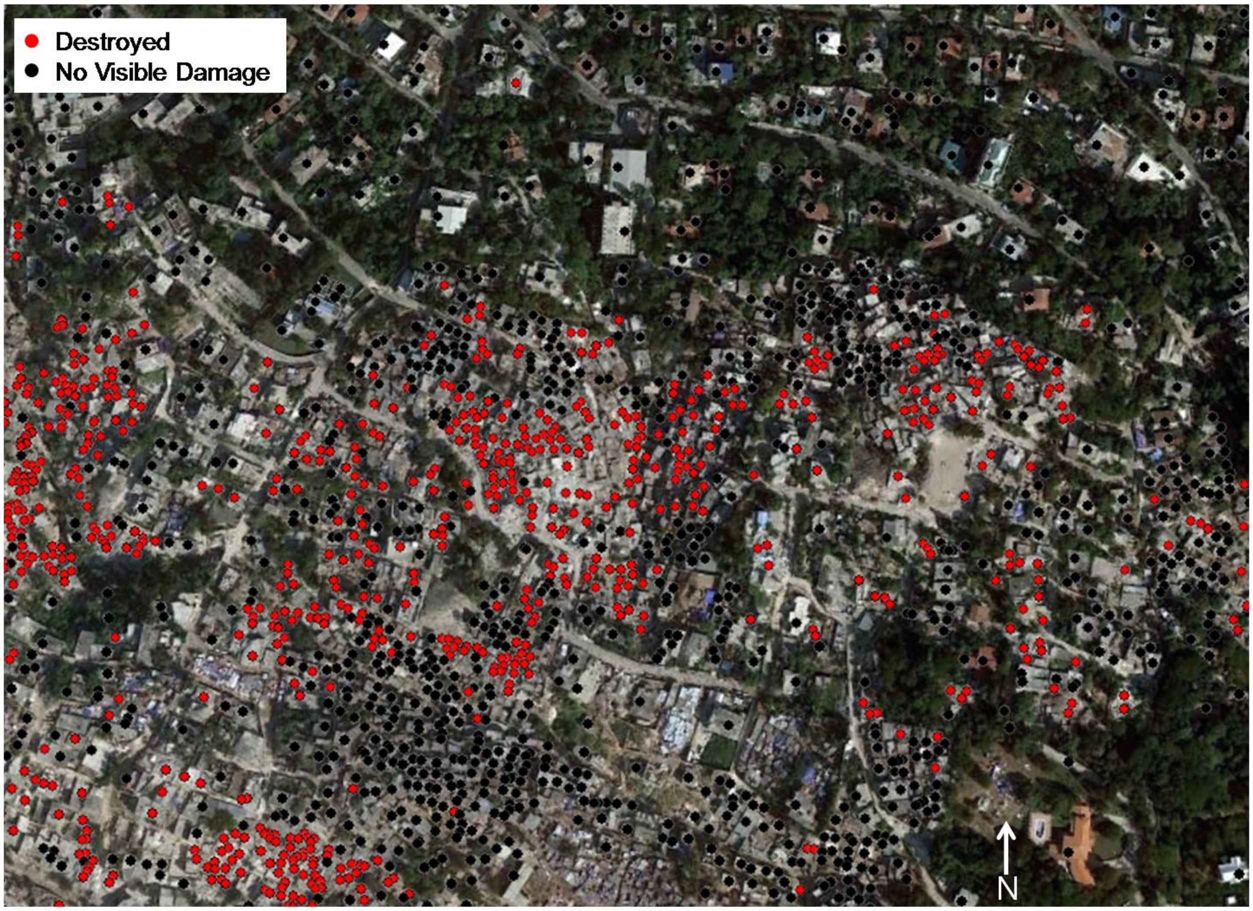

Figure 5.12: Buildings classified as No Visible Damage and Destroyed in the UNOSAT survey for the boxed area labeled as "Area for Fig. 10" in Figure 3.8. Notice the clear north-south separation between no visible damage and destroyed buildings that bisects this area from east-to-west. The undamaged buildings to the north are larger homes that appear to be well constructed. Furthermore, they also sit on more moderate topography. The destroyed buildings appear to be Shanty-type structures that sit near the top of the hillsides/ridges (refer to the text for more detail).