

The influence of the Presumpscot Formation on seismic hazard in southern coastal Maine

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ABSTRACT: As ice retreated from southern coastal Maine from 15,000 to 13,000 years ago, the ocean inundated coastal areas where the earth's crust had been temporarily depressed by the weight of glacial ice. A thick veneer of glacial-marine clay and silt – the Presumpscot Formation – was deposited in coastal Maine lowlands. Due to its fine-grained character, shear waves from seismic events travel slowly through the Presumpscot Formation in comparison to other surficial sedimentary units. Low shear-wave velocities result in amplification of seismic waves, potentially increasing local seismic hazard. Prior study demonstrated that careful assignment of National Earthquake Hazards Reduction Program (NEHRP) site classifications to surficial geologic units based on shear velocities, can greatly improve earthquake loss estimations using programs like HAZUS-MH, particularly when compared with estimates using default and proxy values.

The October 16, 2012 magnitude 4.0 earthquake in Hollis, Maine, provided another opportunity to assess the influence of the Presumpscot Formation on seismic hazard. Occurring in early evening, this strongest Maine earthquake in nearly 40 years was widely felt across the region. The Hollis area is near the transition between the western mountains which are mostly underlain by till, and the lowlands, mostly underlain by marine sand and mud. Using the USGS database of more than 2,000 “Did you feel it?” geolocated responses in southern Maine, we tested whether respondents experienced different intensities of ground shaking depending on substrate. When normalized by population density within each surficial unit, we found no statistical difference in respondents' experiences. However, when normalized for areal extent of each unit, we found that more people responded in areas underlain by NEHRP class ‘E’ materials (including the Presumpscot Formation) than for other classes. Our results suggest potentially greater intensity of ground shaking and seismic hazard in areas underlain with sediment of the Presumpscot Formation.

1 INTRODUCTION

Minor earthquakes occur in Maine on a regular basis. In a typical year, several earthquakes of magnitude 2 and one earthquake of magnitude 3 may occur in Maine – rates that are typical of much of the Appalachian region of northeastern North America. However, larger damaging earthquakes with longer recurrence intervals have occurred in the past, such as the Cape Ann earthquake of 1755, estimated at M 5.9 (Ebel, 2006). The Mineral, Virginia, earthquake of 2011 registered 5.8, caused widespread damage throughout northern Virginia and the Washington D.C. area (USGS, 2011), and serves as a reminder that northeastern North America is not immune from damaging events. Felt across a broad region of the eastern United States, this event further demonstrated that seismic waves travel greater distances with less attenuation in

the East due to cold, dense crust (Frankel, 1994), leading to the potential for broader geographic distribution of effects in northeastern U.S. if a damaging event does occur.

In general, in the eastern United States, individual mapped faults are unreliable guides to identifying seismic hazard (USGS, 2003). Recorded earthquake locations and detailed seismic motion studies do not show any clear correlation with either local or regional geologic features (Ebel, 1989). No significant amount of motion has been shown for any fault since the last Ice Age, about 20,000 years ago, and geologic evidence demonstrates that many faults have been inactive since the formation of the Appalachians, over 300 million years ago.

One explanation for seismicity in the east is that preexisting faults and/or other geological features that formed during ancient geological episodes persist in the intraplate crust, and, by

way of analogy with plate boundary seismicity, earthquakes occur when the present-day stress is released along these zones of weakness (Kafka, 2008). Some modern activity in northeastern North America may also be related to glacial rebound (Stein et al., 1979).

Our study area in southern coastal Maine is underlain with bedrock of mostly Ordovician through Devonian age consisting of variably metamorphosed stratigraphic units and igneous intrusions. This bedrock foundation is overlain with a veneer of glacial materials deposited during the waning stage of Wisconsinan glaciation. As ice retreated from this region from 15,000 to 13,000 years ago, the ocean inundated coastal areas where the earth's crust had been temporarily depressed by the weight of glacial ice and was slow to rebound. A thick veneer of

glacial-marine clay and silt – the Presumpscot Formation – was deposited in coastal Maine lowlands (Figure 1).

Due to its fine-grained character, shear waves from seismic events travel slowly through the Presumpscot Formation in comparison to other surficial sedimentary units. Low shear-wave velocities result in amplification of seismic waves, potentially increasing local seismic hazard. Prior study (Becker and others, 2012) demonstrated that careful assignment of National Earthquake Hazards Reduction Program (NEHRP) site classifications based on shear velocities to surficial geologic units, can greatly improve earthquake loss estimations using programs like HAZUS-MH, particularly when compared with estimates using default and proxy values.

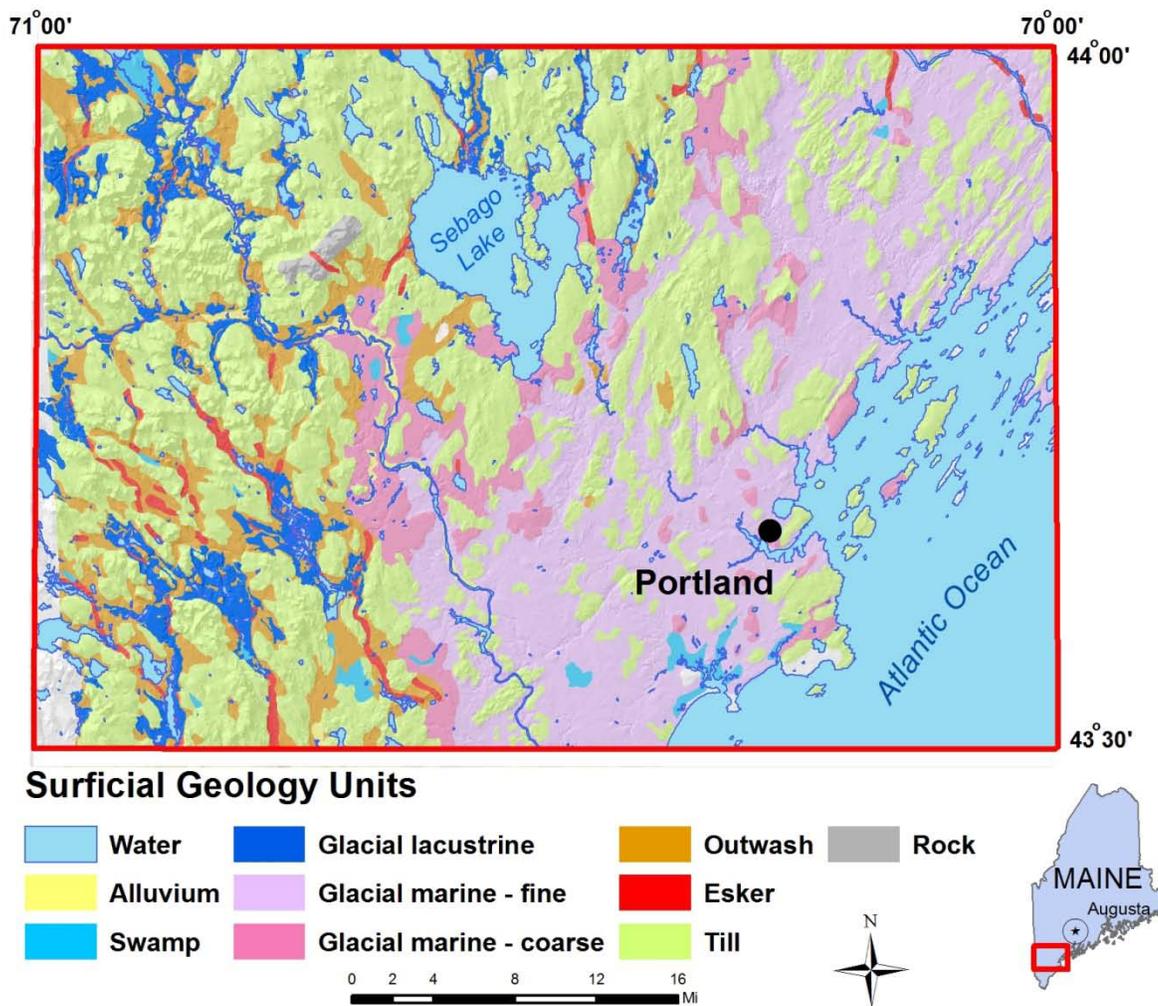


Figure 1. Generalized surficial geology of the Portland 1:100,000-scale quadrangle, modified from Thompson and Borns (1985). Study area of Becker et al. (2012).

2 PRESUMPCOT FORMATION

Much of the following description is paraphrased from Thompson (2015). The Presumpscot Formation is broadly distributed throughout southern coastal Maine, in areas below the marine limit, and extends well up the Kennebec and Penobscot valleys to Bingham and Medway, respectively. The regional elevation of the surface of the formation ranges from about 20-40 ft along parts of the coastline to over 200 ft farther inland. The thickness of the formation can be quite variable even over short distances. Where the formation filled valleys developed before the marine incursion, the thickness of the silt and clay may exceed 100 ft. Elsewhere, the formation is a thinner blanket deposit that has subdued – but not totally concealed – the preexisting topography. Most of the Presumpscot Formation overlies till or glacial sand and gravel deposits.

The formation consists of silt, clay, and fine sand that was carried by glacial meltwater and accumulated on the ocean floor. Although often termed "clay," silt-size particles are more abundant than clay at many localities (Caldwell, 1959). Many sections are massive but others are thinly stratified, and thin layers of fine sand are commonly interbedded with the silt and clay. In some areas of southern Maine, the upper part of the Presumpscot Formation consists entirely of fine to pebbly sand and minor gravel deposited during the regressive phase of marine submergence.

Often referred to as "blue clay," the color of the Presumpscot Formation is quite variable. Fresh material is usually dark bluish gray, but with increased weathering and oxidation of iron-bearing minerals, the sediment becomes gray to brownish gray Caldwell (1959).

Most Maine landslides occur in the Presumpscot Formation. While most are minor, periodically landslides occur that damage buildings and infrastructure, such as the 1983 Gorham landslide (Novak, 1987) and the 1996 Rockland landslide (Berry et al., 1996). Such landslides have typically occurred along the coast or stream valleys where slopes are locally steep. Besides these geomorphic factors, other natural factors that contribute to landslide hazard are internal stratigraphy within the Presumpscot, in particular with regard to low-strength layers,

thickness, water saturation, and undercutting of slopes (Berry et al., 1996). Berry et al. (1996) concluded that areas at Rockland underlain with more than 25 feet (8 m) of marine clay were at higher risk for landslides than areas underlain with thinner clay sections.

3 PRESUMPCOT AND SEISMICITY

3.1 *Impact on hazard assessments*

Many studies show that decreasing mean shear-wave velocity in the near surface generally correlates with an increase in the average amplification of earthquake ground motion (e.g. Borchardt, 1970; Borchardt and Gibbs, 1976; Seed et al., 1988). Becker et al. (2012) used available information to assign shear wave velocities to surficial materials in study areas throughout New England, with the purpose of determining the impact of using this information in earthquake loss modeling. The values assigned by Becker et al. (2012) are used here. The study assessed how surficial geologic information coded to National Earthquake Hazard Reduction Program (NEHRP) site classes compared with Hazards U.S. Multi-Hazard (HAZUS-MH) earthquake loss modeling program default values and a classification based on the methodology developed by Wald and Allen (2007). NEHRP ranks soil types based on their amplification effects of bedrock seismic waves as they pass through soil, with A having the least and E having the greatest amplification effects. Wald and Allen (2007) used topographic slope as a proxy to estimate NEHRP site classifications, and derived a map of average shear wave velocity down to 30 meters below the surface from a global digital elevation database. In New England, the surficial units most susceptible to seismic amplification are glacial lake clays and the Presumpscot Formation.

The Maine portion of this study focused on the Presumpscot Formation from Portland to the border with New Hampshire, an area in which surficial materials are mapped consistently at a detailed scale. Earlier studies identified characteristics of the Presumpscot that are of interest in seismic analysis. In their study of slope stability in the Presumpscot Formation, Devin and Sandford (1990) note the particular susceptibility of the formation to landslides and

describe its sensitivity (ratio of undisturbed undrained shear strength to remolded undrained shear strength) as “slightly sensitive to medium quick” using the Rosenqvist (1953) sensitivity classification. Reynolds (1995) describes the Presumpscot as a strain-softening soil. Through investigations of the 1996 Rockland landslide, Berry et al. (1996) determined a minimum p-wave velocity in the Presumpscot of 177 m/s using a 12-channel seismic refraction system. Presumably s-wave velocities at this same location would be lower. Materials with shear wave velocities < 180 m/s are considered “soft clays,” – “E” in the NEHRP site classification. In risk assessment programs like HAZUS-MH, E soils are more susceptible to amplification of seismic waves. All other factors being equal, structures built over E soils are likely to sustain more damage than structures on lower site class soils. NEHRP site classifications are assigned based on seismic shear velocities of soils (Table 1).

Table 1. NEHRP Site Classification Categories

NEHRP Site Classification Category	Description	Average shear wave velocity to 30m
A	Hard Rock	> 1500 m/s
B	Firm to hard rock	760-1500 m/s
C	Dense soil, soft rock	360-760 m/s
D	Stiff soil	180-360 m/s
E	Soft clays	< 180 m/s

Becker et al. (2012) used measured shear wave velocities determined by Cadwell (2003) for glacial deposits in New York (Table 2) as the basis for assigning NEHRP site classifications to other study areas in New England. Based on the average shear wave ranges for NEHRP site classes (Table 1) and the shear wave velocities determined for various surficial materials (Table 2), we assigned NEHRP classes to surficial materials in the Portland area (Table 3).

The E classification of the Presumpscot Formation had a significant impact on seismic risk modeling. When no site-specific information is available, the HAZUS-MH program uses class D for all New England areas. This underestimates seismic risk throughout coastal

Maine in areas underlain with the Presumpscot. The Wald and Allen (2007) topographic slope proxy method produces results that are an improvement over the HAZUS-MH default value, but still does not adequately represent the nature of surficial materials in coastal Maine. In Figure 2, Becker et al. (2012) compare the NEHRP classes by the Wald method, and values assigned based on detailed maps of surficial materials (identified as “State Geo” in the upper right map). The blue areas on the comparison map represent places where NEHRP classes assigned by the Wald method would have lower (less conservative) amplification effects compared to areas where site classes are assigned based on surficial geology. Many of the blue areas are underlain with Presumpscot or glacial lake deposits. Areas in red on the comparison map are places where the site classes assigned by the Wald method would have greater amplification effects (more conservative) compared to areas assigned site classes based on surficial geology. HAZUS simulations using the NEHRP classes based on geology showed higher losses for modeled events compared to the Wald method. Becker et al. (2012) also concluded that the Wald method does not adequately reflect three-dimensional geology in glaciated terrains.

Table 3. NEHRP soil class assignments for the Portland, Maine area based on shear wave velocities for similar surficial materials, as presented in Table 2.

Unit	Description	NEHRP Site Class
af	Artificial fill	E
Ha	Stream alluvium	D
Hw	Wetlands	E
Hb	Coastal beaches	D
Qst	Stream terraces	D
Pl	Glaciolacustrine deposits	E
Pmc	Marine nearshore deposits	C
Pp	Presumpscot Formation	E
Pmd	Glaciomarine deltas	C
Pg	Glacial stream deposits	C
Pem	End moraine complexes	C
Pt	Till	C

Table 2. Range of shear-wave velocities in meters per second (m/s), New York counties (from Cadwell, 2003).

Surficial material	Onondaga m/s (n)	Rensselaer m/s (n)	Dutchess m/s (n)	Columbia m/s (n)	Westchester m/s (n)	Mean m/s
Fill	76-181 (8)				150-364 (8)	175
Outwash	84-117 (4)	197-308 (3)	75-324 (5)	367-368 (2)	149-700 (10)	231
Kames	100-704 (3)	91-411 (3)	82-445 (6)	383-539 (7)	271 (1)	305
Lake sand	95-133 (4)	86-350 (6)	82-254 (6)	568-569 (2)	164 (1)	287
Lake silt & clay	157-478 (7)	70-1114 (7)	82-467 (4)	370-419 (3)	233-363 (2)	312
Alluvium	105-125 (3)	137 (1)	109-437 (3)	427-518 (2)	183 (1)	216
Till	232-1077 (11)	106-675 (4)	109-797 (8)	371-1163 (6)	194-1311 (7)	664
Swamp					152-219 (2)	186

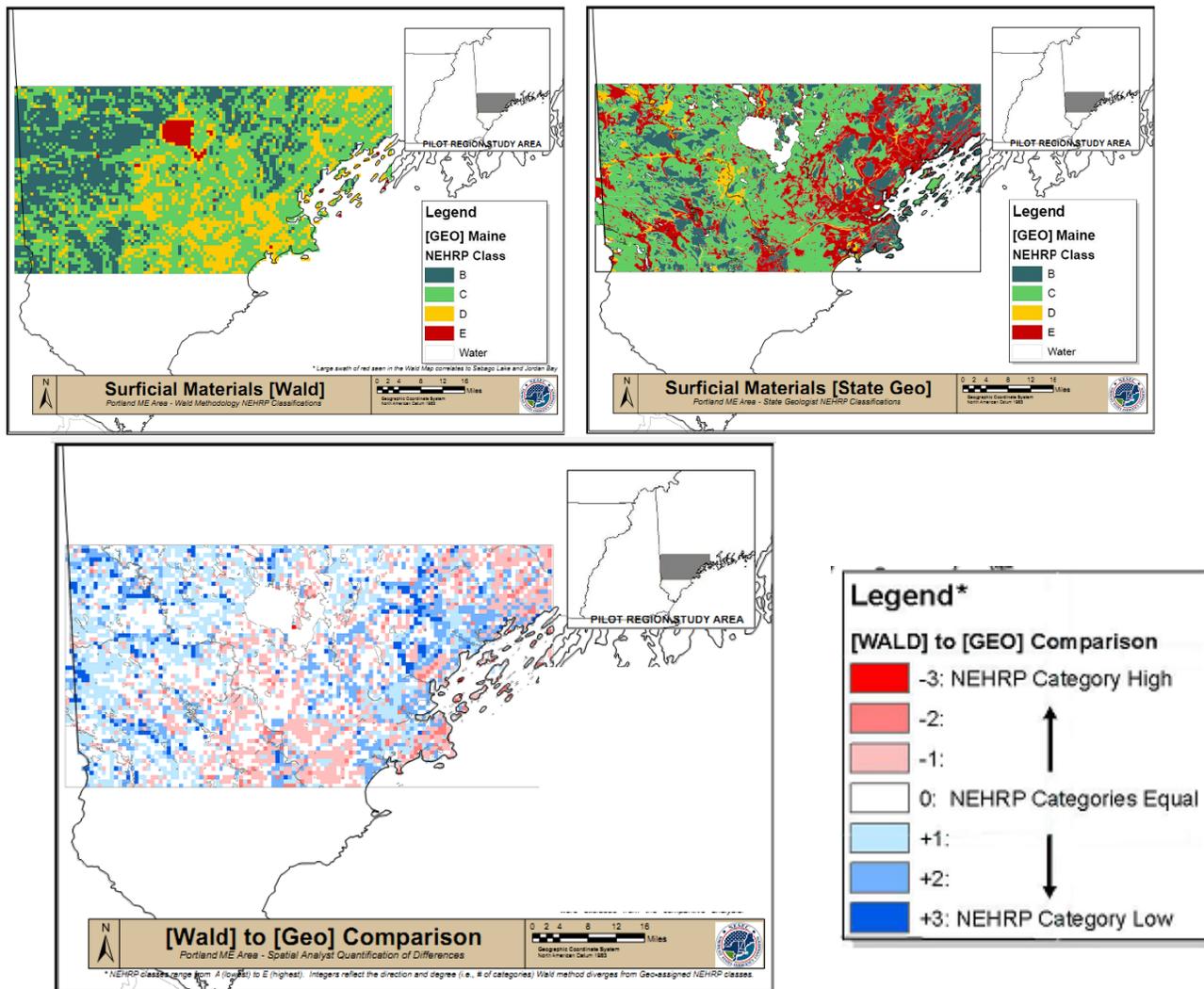


Figure 2: Comparison of Wald method of determining NEHRP site classifications and those based on surficial geological materials. Top left map illustrates NEHRP categorizations based on Wald methodology. Top right map illustrates NEHRP categorizations based on local surficial materials data. In each, areas shown in blue are underlain with materials that would have lower seismic amplification, and areas shown in red are underlain with materials that would have higher amplifications. (Note: the red area in the Wald map and the corresponding white area in the State Geo map is Sebago Lake.) The bottom map illustrates the Wald map's level of agreement with local soils data; more muted colors indicate areas of better agreement. From Becker et al. (2012).

3.2 2012 Hollis earthquake

3.2.1 The event

A 4.0 magnitude earthquake occurred at 7:12 PM (EDT) on October 16, 2012 along the border between Hollis Center and Waterboro, York County, Maine. The coordinates of the epicenter are 43.60°N, 70.65°W (calculated by [Weston Observatory](#), Boston College, Weston, MA). It was felt throughout New England and was given a maximum Modified Mercalli rating of V. This scale describes the intensity of the effects of an earthquake, with I being unnoticeable and X or greater being complete destruction. A V is strong enough to be felt by most people and cause minor damage. The October 16th earthquake was the largest event in Maine in nearly forty years and occurred within a zone of modern and historically higher activity around Casco Bay (Berry, 2006).

The USGS compiles local reports of earthquakes through their [Did You Feel It?](#) website. Users of the site provide their location and respond to questions about their experience during the earthquake. A sophisticated algorithm determines intensity for each record based on the user's responses to the questionnaire. For web mapping, this intensity is averaged for a community (in the U.S. by zip code), and the resulting Community Decimal Intensity (CDI) is displayed on the map (Figure 3). For our analysis we had access to the individual responses and their locations, and use what we term the User-Community Decimal Intensity (User CDI) in our analysis.

This earthquake occurred in a highly populated area of Maine and the large number of reports (more than 20,000 throughout the Northeast and more than 2,500 in Maine) provides an opportunity to study how surficial materials may amplify seismic waves. In our previous study (Becker et al., 2012) we assigned NEHRP site classifications to the surficial geology units found in southern Maine (Table 3). The Hollis area lies close to the border between the fine-grained glacial-marine deposits near the coast (higher NEHRP site class) and glacial till and coarse-grained deposits in the foothills (lower NEHRP site class). Based on previous research, we expect the Presumpscot Formation and artificial fill (e.g. Boatwright et al., 1992) to preferentially amplify seismic waves. All other things being equal, did people have different earthquake

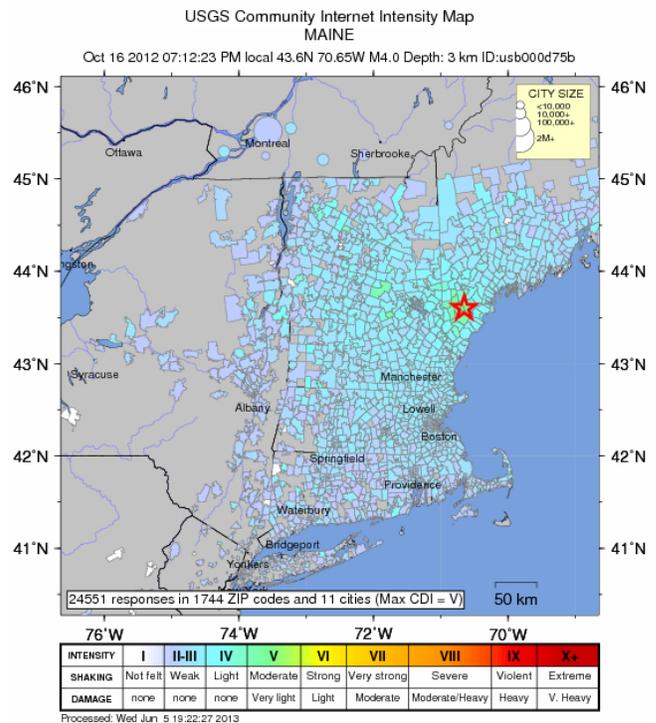


Figure 3. USGS Intensity map for the October 16th, 2012 Earthquake.

experiences in buildings on different surficial materials? Figure 4 shows the locations of individual responses plotted on a generalized map of surficial materials.

During the October earthquake, responders to the USGS website felt slight vibrations to rolling motions. Many respondents thought “that something had hit the house” or “that the furnace had exploded.” Many also heard a deep rumbling sound. Movement was reported to have lasted for 5-30 seconds. Reported damage was minor and included broken windows, cracked plaster, and items falling off of shelves.

3.2.2 Analytical methods

The USGS reports were imported into ArcGIS 10.1 and compared to 1:24,000 surficial geology maps for southern Maine. Population data was taken from the 2010 Census. The average User CDI and the number of reports were calculated for each formation and NEHRP site class presented in Table 3.

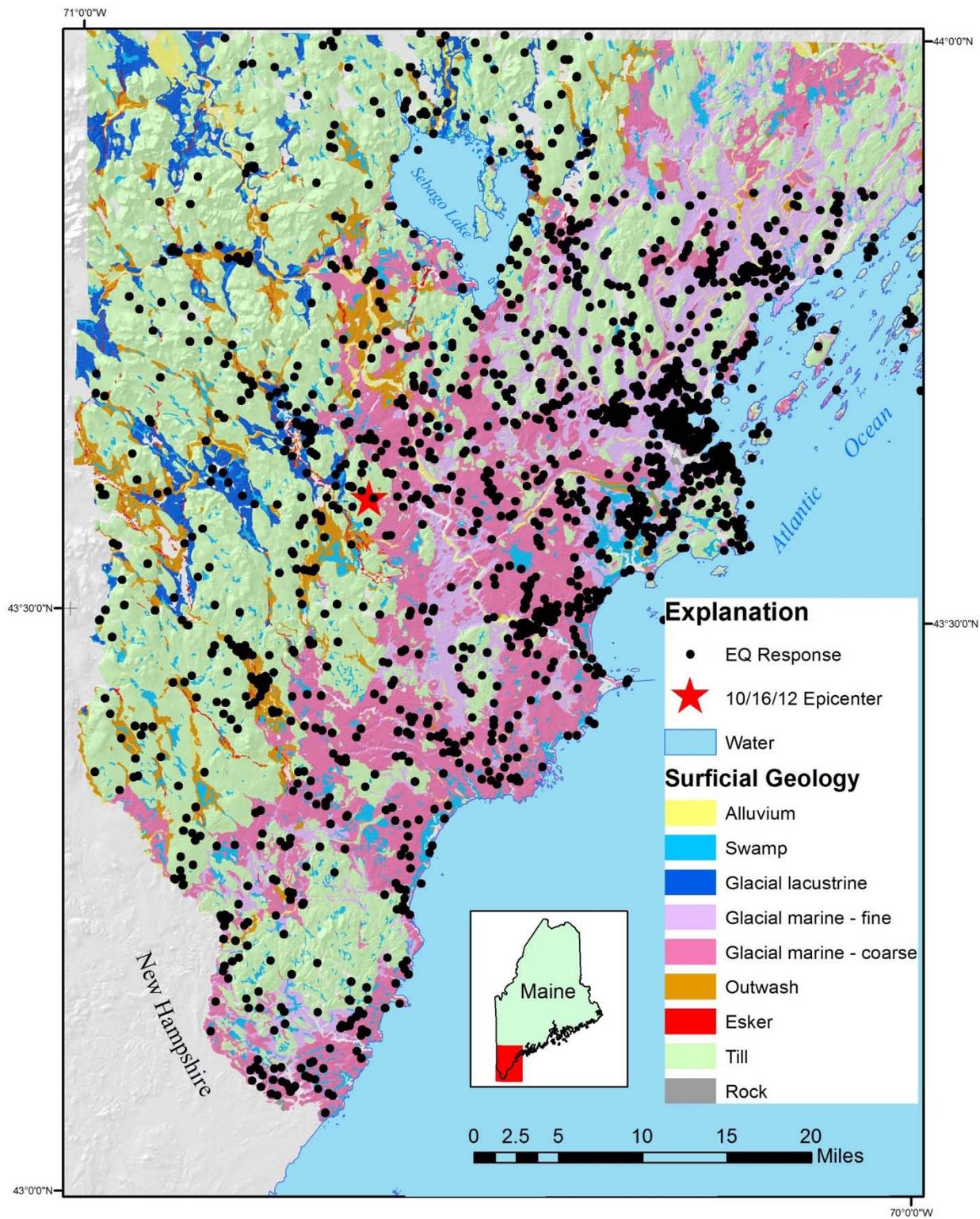


Figure 4. October 16, 2012 Hollis earthquake epicenter with individual response locations, displayed on generalized map of surficial geology for southern Maine (modified from Thompson and Borns, 1985). The fine glacial-marine unit is the Presumpscot Formation.

3.2.3 Results

As anticipated, distance from the epicenter was a significant factor in determining the intensities for each response (Figure 5). The large range of respondents' experiences at each distance and low correlation factor of distance and User CDI are likely due to the small magnitude of the event (M4.0) which may not have produced drastically different ground motions at these distances. Surficial materials may also have played a role in the range of experiences at each distance.

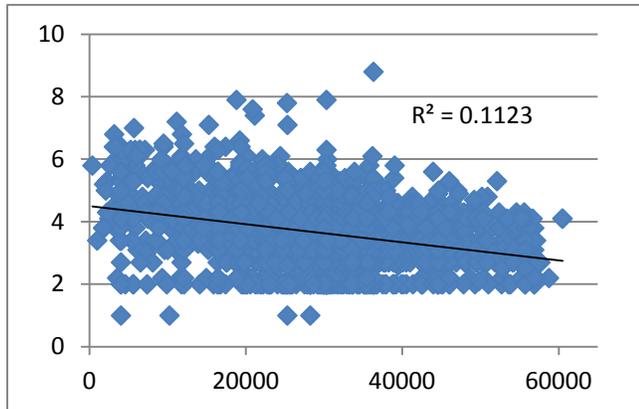


Figure 5. User CDI compared to distance from epicenter (meters). Trend line shows decreasing intensity with distance, but the correlation is low.

The average User CDI for each formation (Figure 6) and NEHRP site class (Figure 7) were calculated overall and for concentric 10 km rings around the epicenter. Neither analysis produced statistically significant results. The overall User CDIs (Figure 6A) show that there was no difference in the reported intensity of the earthquake based on the surficial material. Similarly, there is no clear distinction in User CDIs by formation in successive distances from the epicenter (Figures 6 B-D). These results probably reflect the fact that with an event of this magnitude, the primary factor in determining a respondent's experience was distance from the epicenter.

The number of reports to the USGS did change based on the surficial material. The number of reports was normalized based on the area of each formation to account for bias due to differences in formation extent. The three units with the highest number of reports are artificial fill, beaches and the Presumpscot Formation (Figure 8), probably related to their relative unconsolidated nature and higher water content compared to other surficial units. The number of reports showed a general

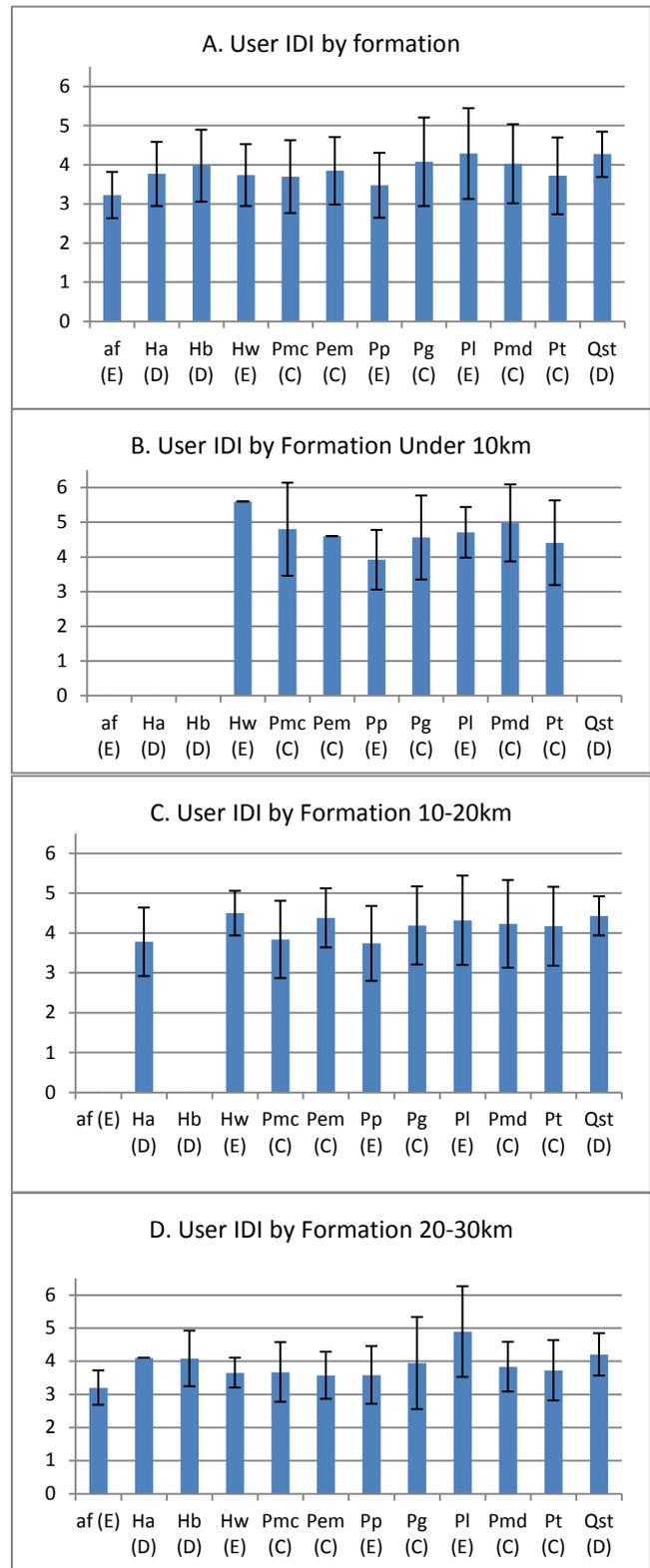


Figure 6. User CDI by formation with standard deviation error bars. A) overall average; B) average at less than 10 km from epicenter; C) by formation at 10-20 km; D) by formation at 20-30 km. NEHRP site classes shown in parentheses.

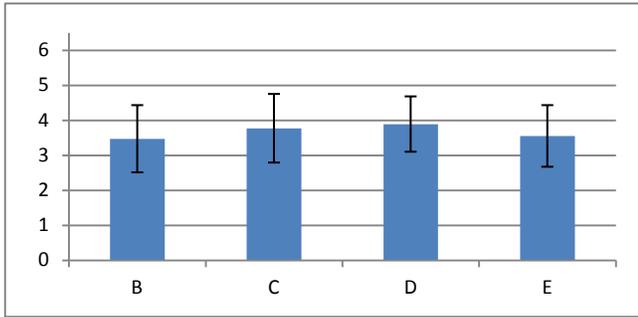


Figure 7. Average User CDI broken down by NEHRP site class with standard deviation error bars.

increase with increasing NEHRP site class (Figure 9). The number of reports did not show a trend when normalized by population in each formation.

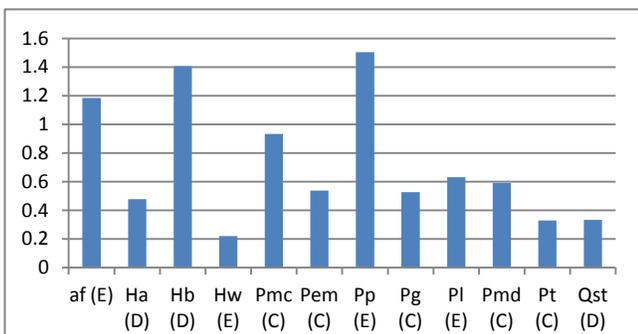


Figure 8. Number of reports by formation, normalized by formation area.

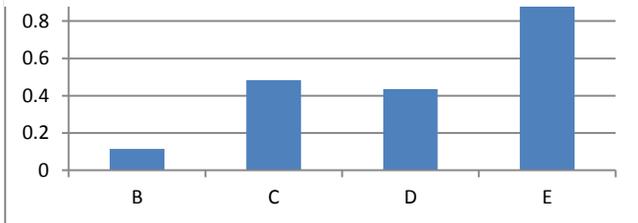


Figure 9. Number of reports by all surficial materials with the same NEHRP site class, normalized by NEHRP site class area.

4 CONCLUSIONS

The fine-grained, unconsolidated sedimentary material of the Presumpscot Formation has an impact on seismic risk assessment in Maine. Earlier work (Becker et al., 2012) detailed the impact of utilizing detailed surficial geologic maps in risk assessments such as HAZUS-MH. More realistic loss assessments result when NEHRP site classifications are assigned to surficial materials through consideration of likely shear wave velocities of those materials. This is

particularly true when compared to the HAZUS default value of ‘D’ for all of New England, which greatly overestimates risk in many areas and underestimates it in others. While an approach for assigning NEHRP site classifications based on topographic slope is an improvement over the default approach, it inadequately represents the surficial materials in glaciated terranes such as New England. A greater database of shear wave velocity measurements in Maine’s surficial materials will improve future assessments based on surficial geologic maps.

The Presumpscot Formation likely has an influence on the way people experience a seismic event in areas underlain with the formation. While we hypothesized respondents to the USGS [Did You Feel It?](#) website would report different experiences based on the surficial materials at their location, this was not the result. This is likely due to the low magnitude of the earthquake; it was not large enough for there to be a significant difference in the experience of respondents regardless of distance or substrate.

Our analysis suggests, however, that when normalized for area of each surficial material, there were more reports from people whose structures are built artificial fill, beaches and the Presumpscot Formation. Furthermore, there were more reports from soils with an E site class. The earthquake was more noticeable or alarming on the formations that were expected to amplify the effect of the earthquake. This suggests that there may be subtle differences in the intensity of the earthquake that are not reflected in the User CDI value. The population density in the Portland area, underlain in large part by the Presumpscot and artificial fill is a factor that requires further scrutiny in terms of impact on the number of people reporting their earthquake experiences. Future work on this subject in Maine will depend on the occurrence of more moderate earthquakes. An earthquake larger than M4.0 may be necessary to clearly distinguish seismic wave amplification in areas underlain by the Presumpscot Formation.

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