The 2006-2007 Earthquake Sequence at Bar Harbor, Maine

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Abstract

During the fall and early winter of 2006 and into the springtime of 2007, a sequence of earthquakes took place near the town of Bar Harbor on Mount Desert Island along the coast of Maine. The largest earthquake in the sequence was Lg-magnitude MLg 4.2 that caused several rock falls in Acadia National Park and the water level in a well that was being monitored by the U.S. Geological Survey to drop about 2 m immediately following this event. Double-difference relative earthquake locations were computed for 14 events of this sequence using cross-correlations of the P and S waveforms from seismic stations within about 350 km of Bar Harbor epicenters. The absolute locations of the events studied in the relative location analysis were constrained using the absolute location of one of the aftershocks that had been located using data from several portable seismograms that had been operated in the epicentral area. The earthquakes locate around Bar Harbor, with the epicenters aligning from NNW to SSE. The hypocenters indicate the fault dips to the west at about 45°. These orientations are consistent with the focal mechanism found for the MLg 4.2 event from regional waveform inversions. The projected surface expression of this fault occurs in Frenchman Bay east of the town of Bar Harbor. The earthquake sequence started on a small fault patch (about 400 m on a side) on September 22, and spread to the north and south as well as updip and downdip during the following few months. The spatial extent of the 2006 sequence suggests than an earthquake as large as MLg 5.4 might be possible in the Bar Harbor area.

Introduction

One purpose of monitoring the earthquake activity in northeastern North America is to learn which geologic structures are seismically active in this region. If seismically active structures can be found, they can be studied to decipher their past seismic history and their potential for future strong earthquakes. Unfortunately, no seismically active geologic structures have yet to be confirmed in the northeastern U.S. (Ebel and Kafka, 1991). The only earthquake with observed surface faulting in northeastern North America took place in the Angava Peninsula of northern Quebec in 1989 (Adams et al., 1990). Other than some minor offsets of glacial striations (Oliver et al., 1970), no evidence of Holocene surface faulting in the northeastern U.S. from geologic investigations has been reported in the literature. Furthermore, the seismicity that is known historically or has been detected by modern regional seismic networks in the northeastern U.S. has failed to align convincingly along known or suspected geologic structures. Nevertheless, the persistence of small earthquake activity over time and the historic occurrences of past strong earthquakes (e.g., Ebel, 1996; Ebel, 2000; Ebel et al., 2000; Ebel, 2006) indicate that there must be some seismically active structures in the region that are capable of hosting earthquakes above magnitude 6.0. Since such earthquakes are capable of causing significant damage, there is great incentive to learn which structures are seismically active in this heavily populated region of the country.

During the fall and early winter of 2006 and into the springtime of 2007, a sequence of earthquakes took place near the town of Bar Harbor on Mount Desert Island on the coast of Maine (Figure 1). The largest earthquake in the sequence was Lg-magnitude MLg 4.2. It caused several rock falls in Acadia National Park near Bar Harbor, forcing the closure of several hiking trails and one road (Figures 2 and 3). A water well that was being monitored by the U.S. Geological Survey showed an unusual drop in water level of about 2 m immediately following this event. The MLg 4.2 earthquake was felt over the southern two-thirds of Maine, with a few felt reports from New Hampshire, and was the largest event centered in Maine since 1988. A total of 38 earthquakes were detected by regional seismic stations from the Bar Harbor area from the start of the sequence on September 22 until the end of 2006. Two more events were detected in the spring of 2007. The purpose of this paper is to report on an analysis of the relative locations of the Bar Harbor earthquakes detected by the regional seismic network and to use the results of that analysis to assess what geologic structure might have been seismically active in this earthquake sequence.

The 2006-2007 Earthquake Sequence

The 2006-2007 Bar Harbor earthquake sequence took place in an area that previously had not been associated with local earthquakes. Prior to 2006, only one instrumental epicenter was known within 20 km of Bar Harbor since the establishment of the New England Seismic Network (NESN) in 1975. That event, which was located about 12 km east of Bar Harbor, took place on November 12, 1995 and had coda magnitude Mc 3.0. No historic earthquakes with known or suspected epicenters at Bar Harbor are contained in the Weston Observatory earthquake catalog for Maine.

The sequence that is the subject of this study began on September 22, 2006 with several small earthquakes that preceded an MLg 3.4 event (Figures 4 and 5). The MLg 3.4 earthquake caused no damage but was felt as far as 50 km from the epicenter. Several aftershocks were detected by the regional seismic network during the next three hours. During the 8 days following September 22, several more aftershocks were detected from the Bar Harbor area by the regional network. The largest earthquake of the 2006 sequence, which had MLg 4.2, took place on October 3. In stark contrast to the MLg 3.4 event on September 22, the October 3 event was not preceded by any earthquakes during the 48 hours prior to the event, and the first aftershock following this mainshock detected by the regional seismic network took place a week after the event. Several aftershocks were detected by the regional seismic network later in October and early November. Following a hiatus of more than a month, two aftershocks took place at Bar Harbor in December, including the third largest event of the sequence (MLg 3.1) on December 29. Since the beginning of 2007, only two events have been detected in the Bar Harbor area to date by the regional seismic network: an MLg 1.4 event on April 29 and an MLg 1.6 event on June 9. In total, 40 earthquakes from the Bar Harbor have been identified to date by the regional seismic network since the sequence began (Table 1). From reports received at Weston

Observatory, events down to at least MLg 1.4 were reported felt by residents in the Bar Harbor area.

One important observation that is seen in all of the earthquake waveforms at the closest stations is the presence of strong Rg waves with periods of about 1 sec to .25 sec (Figure 6). Rg waves are indicative of a shallow depth of focus for the seismic source. According to Kafka (1990), the observation of strong Rg waves means that the focal depths of the earthquakes are no deeper than about 4 km and likely are much shallower. Rg waves have been observed for many New England earthquakes, and most earthquakes in New England probably have a focal depth between the surface and about 10 km depth (Ebel and Kafka, 1991). A very shallow depth of focus is probably the reason why some of the very small events at Bar Harbor were felt or heard by the local residents. In fact, it is possible some smaller events that were not detected by the regional seismic network stations took place at Bar Harbor during this earthquake sequence. Some local residents have reported hearing what they thought were seismic events at times when no earthquakes were detected by the regional seismic network stations. During some earthquake swarms at Moodus, CT in the 1980s, earthquakes as small as M 1.0 were reported felt and as small as M 0.0 were reported heard (Ebel, 1982, 1989). The Moodus earthquakes had focal depths of about .5 km to 1 km. If the Bar Harbor earthquakes were within 1 km of the Earth's surface, then it is possible that events smaller than MLg 1.4 were felt or heard by members of the local population.

Relative Earthquake Location Analysis

The relatively large number of the Bar Harbor earthquakes that were recorded by stations of the regional seismic network enables the application of the double-difference earthquake location scheme of Waldhauser and Ellsworth (2000) in order to compute high quality relative locations of the individual events of this earthquake sequence. Because these earthquakes were recorded on a common set of regional seismic network stations, cross-correlations of the waveforms of different Bar Harbor earthquakes at a common seismic station can yield a highly precise measurement of the relative arrival time difference of the two seismic events at the station. In this study, time windows around the arrival times of the P waves and of the S waves, at stations within about 350 km of Bar Harbor and where the waveforms appear well-recorded, were selected for use in the cross-correlation analysis (Figure 7). The arrival-time differences between two earthquakes computed using the cross-correlation analysis at all seismic stations that yielded reliable crosscorrelations were then input into a double-difference location program to determine the relative locations of the two hypocenters.

In the double-difference location analysis in this study, the MLg 3.4 event on 9/22/06 was used as the master event relative to which the locations of all of the other events were determined. For each station where the relative P and S arrival times were calculated, a few seconds around the arrival time (as picked by a seismic analyst) of the P wave and of the S wave were windowed out of the seismogram of the 9/22/06 event and of the event for which the relative location was being computed. The data window stretched from 1 sec before the P or S wave arrival time to 2 sec after the P or S arrival time. The windowed P waveforms from the two events were then crosscorrelated to determine the relative arrival time differences of those P phases. The same process was applied to the S waveforms. The full set of arrival time differences between the two events was then input into a double-difference event location code to calculate the relative hypocenters and origin time of the second event relative to the MLg 3.4 event. In general, only those arrival-time differences from normalized crosscorrelations with crosscorrelation coefficients above .5 proved useful in the double-difference location analysis. Figure 8 shows some examples of waveforms that were crosscorrelated along with plots of the coefficients from the normalized crosscorrelation computation.

Because of the sparseness of the regional seismic network (Figure 7), the level of background noise on some days, and the small sizes of many of the events that were detected, only14 events yielded relative locations that are considered reliable (Table 2). In most cases in Table 2, the root-mean-square (RMS) error between the predicted and computed relative arrival times is less than the sampling period of the data (.025 sec), meaning that further resolution of the relative locations is not possible. The digital sampling period of the data means that the location uncertainty cannot be reduced below about 150 m based on a P-wave velocity of 6.0 km/sec. Some of the events in Table 2 have RMS errors greater than 1 sampling period, and so they have correspondingly larger uncertainties in their hypocentral locations. Most notably, the RMS error of the MLg 3.1 event on 12/29/06 is the largest RMS value in Table 2. For this event, the largest normalized crosscorrelation coefficient is only .74, whereas most of the other events had many normalized crosscorrelation coefficients that exceeded .80 and some that exceeded .90. The crosscorrelation analysis suggests that the waveforms for the MLg3.1 event are less similar to the MLg 3.4 waveforms than are the waveforms of any of other event that was analyzed. This lower similarity of the MLg 3.1 event could be due to its location (it located much shallower and much further to the east than any of the other events) or perhaps it indicates some other difference, such as a change in the focal mechanism of the MLg 3.1 event compared to that of the other events in the sequence.

Map views and cross-sectional views of the relative event locations listed in Table 2 are shown in Figure 9. In map view, the events align approximately from NNW to SSE, with most of the events clustering in the central part of the trend. The west-east depth cross section in Figure 9 shows that the events follow a trend that is west dipping. Most of the seismicity at the beginning of the sequence on 9/22/06 is very tightly clustered around the hypocenter of the MLg 3.4 master event on the plots in Figure 9. Figure 10 zooms in on the 9/22/06 events. With one exception, an MLg 1.9 event that took place about 2 hours before the MLg 3.4 event, the seismicity on 9/22/06 was very tightly clustered spatially, extending only about 400 m in the north-south direction (Figure 10). The depth cross section in Figure 10 also indicates that a trend in the hypocenters that dips downward from east to west. Thus, with the exception of one event, it appears that the rupture on 9/22/06 was confined to a fault plane that had dimensions of about 400 m x 400 m, dimensions that are quite consistent with those predicted by Wells and Coppersmith (1994) for an **M** 3.4 earthquake. The next significant earthquake in the sequence was an MLg 2.5 event that took place on 9/28/06. This event was located about 2.5 km to the northwest of the MLg 3.4 epicenter, and it was slightly deeper than the MLg 3.4 event. On the other hand, the largest event, MLg 4.2 on 10/3/06, was located just less than 1 km to the south of and less than 1 km deeper than the MLg 3.4 master event. The MLg 4.2 mainshock was followed by an MLg 2.3 event on 10/22/06. This MLg 2.3 event was located about 2 km south of the MLg 4.2 epicenter and about 3 km south of the MLg 3.4 epicenter. The 9/28/06 and

10/22/06 epicenters suggest that the initial rupture from 9/22/06 was spreading in both the NNW and SSE directions. Curiously, the deepest event determined in the relative location analysis took place on 12/18/06 (MLg 2.3), and the shallowest event that was found by the relative location analysis took place on 12/29/06 (MLg 3.1). The locations and depths of these events suggest that in December the rupture spread both updip and downdip away from the localized focus of the seismicity at its initiation on 9/22/06. In total, the relative locations of the events span an extent that is about 5 km from NNW to SSE and about 2.5 km from the shallowest to deepest event. The Wells and Coppersmith (1994) relations predict a subsurface fault length for an **M** 4.2 earthquake of about 1 km, and so much of the seismicity detected in the three months following the MLg 4.2 mainshock appears to show that the rupture that started on 9/22/06 continued to expand in all directions and to trigger small earthquakes for at least a few months after its initiation.

While the double-difference method is able to compute highly accurate relative locations, it cannot be used to constrain the absolute location of the events. Rather, the absolute location of at least one of the events listed in Table 1 and shown in Figure 9 must be determined from *a priori* information. Fortunately, following the occurrence of the 10/3/06 event, seismologists from Lamont-Doherty Earth Observatory (LDEO) installed several portable seismographs in the Bar Harbor area. Using event arrival times from this local network, they were able to compute an absolute location of the hypocenter of the MLg 2.3 event on 10/22/06, which was well recorded by the regional network. Table 2 lists the hypocentral location for this 10/22/06 event computed using the portable seismic network stations (M. Gold, personal communication, 2007). Using the absolute location for this one event and the relative location pattern for all of the events in Table 1, the absolute locations of the events in Table 1 were determined, as shown in Figure 11. Figure 11 also shows the bedrock geology of the epicentral area from Osberg et al. (1985).

Earthquake Focal Mechanisms and Focal Depth from Regional Waveform Inversions

Because of the sparse station spacing in Maine and the sizes of the events, it is possible constrain the focal mechanism only of the largest event of the 2006 earthquake sequence at Bar Harbor. Following the occurrence of the MLg 4.2 event, R. Herrmann posted on the web (www.eas.slu.edu/Earthquake_Center/MECH.NA/20061003000737/index.html) an analysis of the focal mechanism of this event using inversions of the full waveforms and of the surface waveforms from broadband stations at regional distances. W.-Y. Kim also posted on the web (www.ldeo.columbia.edu/LCSN/Eq/20060922_Maine/mt-20061003-000737) a focal mechanism solution for this event from a regional full waveform inversion. Their focal mechanism solutions are plotted in Figure 12 along with the first-motion readings that were made in this study from the regional seismic network stations. Both the Herrmann focal mechanism solution and the Kim focal mechanism indicate that the MLg 4.2 event was a thrust event with fault planes that strike between N-S and NNW-SSE. Because of the thrust mechanism for this earthquake and the fact that most of the regional seismic network stations were at Pn distance for the first arrivals, the P-wave first motions are generally near the nodal planes and in many cases are difficult to determine unambiguously in many cases. Nevertheless, from Figure 12 it appears that the surface wave focal mechanism found by R. Herrmann is most consistent with the first-motion data from the regional network. Figure 12 also shows the first-motion readings for the MLg 3.4 event on 9/22/06 along with the focal mechanisms determined for the MLg 4.2 event. Once again, these first motions appear to be most consistent with the Herrmann surface-wave focal mechanism of the MLg 4.2 event. This focal mechanism has strike 159°, dip 45° and rake 70°. The focal mechanism for this earthquake is very similar to that for other earthquakes in the New England region (Ebel and Kafka, 1991).

The waveform inversion analyses of both Herrmann and Kim also solved for the focal depth and seismic moment of the MLg 4.2 event. Kim reported a focal depth of 2 km and a seismic moment of 1.0×10^{22} dyne-cm, which give Mw 3.95. Herrmann's regional waveform inversion also found a focal depth of 2 km but with a seismic moment of 7.2×10^{21} dyne-cm, which gives Mw 3.87. The surface wave analysis favored a depth of 1 km and a moment magnitude of Mw 3.79. The small focal depths found in these regional analyses confirm the inference of a shallow focal depth for these events based on the observation of strong Rg waves for all of the events of the sequence. They are also verified by the small focal depth found for the two aftershocks recorded by the portable seismic network that was installed following the MLg 4.2 event (Table 3).

Discussion

The results from the double-difference relative location analysis, from the portable station aftershock monitoring, and from the waveform inversions for the focal mechanism, depth and seismic moment of the largest event tell a very consistent story about the location of the fault upon which the 2006 Bar Harbor earthquake sequence occurred. The earthquake sequence apparently took place on a fault surface that is about 2 km below the town of Bar Harbor, Maine. The fault strikes NNW-SSE and dips toward the west at about 45°. Based on this geometry, the fault intersects the surface in Frenchman's Bay just east of Bar Harbor (Figure 11). The rupture initiated on a small fault patch about 400 m on a side on 9/22/06 in a series of small earthquakes with the largest being MLg 3.4. The crack extended to the south on 10/3/06 in the largest event (MLg 4.2, Mw 3.87 ±.13), and extended to the north later in October 2006. In December 2006 the crack showed further updip and downdip propagation with the occurrence additional aftershocks.

The surface geology (Figure 11) shows no onshore faults in the part of Mount Desert Island where these earthquakes took place. There are a number of surficial lineaments that are obvious from a visual inspection of the topography of the Island (and can be seen on Figure 11), and these lineaments generally strike NNW-SSE, similar in orientation to the inferred fault strike for the 2006 earthquake sequence. Perhaps these lineaments reflect basement faults that are not expressed in the surface geology, and the 2006 earthquake sequence took place on one of these basement features.

There are some important implications for seismic hazard in the New England region that arise from the analysis of this earthquake sequence. First, the Bar Harbor earthquakes occurred at a locality where no previous seismicity, either instrumental or historic, had been recorded. This suggests that all of the possible source zones for potentially significant earthquakes may not yet be known. Second, the apparent expansion of the rupture zone from September to December 2006 seems to show that the total extent of the rupture surface extends about 5 km along strike and about 2.5 km along dip. The Wells and Coppersmith (1994) scaling relations predict that a reverse faulting earthquake that is 5 km in fault length would have a moment magnitude of 5.4. Thus, the spatial extent of the seismicity in this sequence implies that a larger earthquake might be possible at this site. Third, the shallow focal depth of this earthquake sequence is similar to that found for many other earthquakes in New England. Earthquakes with shallow focal depths can generate stronger ground shaking than deeper earthquakes of the same magnitude, and so the shallow focal depths in the 2006 sequence help enhance the local seismic hazard at Bar Harbor.

Conclusions

The 2006 earthquake sequence at Bar Harbor, ME took place on a thrust fault with a NNW-SSE strike and a dip of about 45° to the west. The projected surface expression of this fault occurs in Frenchman Bay east of the town of Bar Harbor. The events of the earthquake sequence took place about 2 km below the town of Bar Harbor, which explains the large number of events that were felt or hear by local residents of the town. There is no mapped fault in the Bar Harbor area that is consistent with the fault orientation inferred from the 2006 earthquake sequence. Furthermore, no previous seismicity is known from the Bar Harbor area. This spatial extent of the 2006 sequence suggests than an earthquake as large as MLg 5.4 might be possible in the Bar Harbor area. It also indicates that all of the potentially active earthquake source locations in New England have not yet been delineated from the seismic monitoring that has been carried out to date.

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Table 1. Bar Harbor, ME foreshocks, the primary earthquake, and aftershocks

Date (UTC)	Time (UTC)	Lat	Long	Magnitude (MLg)	Felt Report
9/22/06	00:04:24.24	44.43	-68.17	1.2	
9/22/06	08:24:18	44.44	-68.17	1.9	
9/22/06	09:21:05	44.44	-68.17	1.8	
9/22/06	09:21:14	44.41	-68.20	1.4	
9/22/06	10:12:57	44.39	-68.15	1.2	
9/22/06	10:39:21	44.35	-69.19	3.4	felt
9/22/06	10:39:49	44.35	-68.19	2.6	felt
9/22/06	11:03:59	44.49	-68.15	1.0	
9/22/06	11:50:19	44.38	-68.16	1.7	
9/22/06	11:52:47	44.50	-68.16	0.8	
9/22/06	11:55:09	44.46	-68.16	1.0	
9/22/06	11:56:24	44.43	-68.18	1.0	
9/22/06	11:57:19	44.35	-68.18	0.9	
9/22/06	12:00:20	44.47	-68.18	0.8	
9/22/06	12:28:20	44.43	-68.15	1.0	
9/22/06	12:45:20	44.44	-68.13	1.3	
9/22/06	13:25:09	44.40	-68.19	2.4	
9/23/06	01:21:23	44.41	-68.16	1.5	
9/23/06	01:33:07	44.35	-68.17	1.2	
9/26/06	02:48:16	44.38	-68.18	1.6	
9/26/06	04:46:47	44.57	-68.23	1.6*	
9/28/06	13:52:47	44.45	-68.19	2.5	felt
9/28/06	13:58:59	44.44	-68.19	1.8	felt
9/30/06	08:10:39	44.34	-68.18	2.1*	
10/03/06	00:07:38	44.34	-68.14	4.2	felt
10/10/06	13:05:47	#	#	1.5	
10/15/06	04:25:38	44.35	-68.16	0.7	
10/17/06	05:39:03	44.39	-68.19	1.1	
10/22/06	18:34:31	44.40	-68.17	1.5	felt
10/22/06	19:00:52	44.39	-68.18	0.9	
10/22/06	21:36:25	44.38	-68.17	2.3	felt
10/22/06	22:49:40	44.40	-68.18	1.0	

11/03/06	01:10:34	44.33	-68.15	1.0	
11/03/06	01:34:36	44.48	-68.13	0.9	
11/04/06	04:22:42	44.44	-68.13	1.3	
11/04/06	04:50:04	44.43	-68.15	1.2	
12/18/06	19:53:23	44.37	-68.16	2.3	felt
12/29/06	21:21:10	44.35	-68.17	3.1	felt
04/29/07	14:23:25	44.37	-68.18	1.4	felt
06/09/07	11:10:10	44.35	-68.17	1.6	

* indicates a magnitude calculated by the Earthquakes Canada seismologists

# indicates a value that could not be reliably calculated with available data

Table 2
Event Locations Relative to the M3.4 Event

Date	Orig. Time	Mag.	Lat (km)	Lon (km)	Depth (km)	RMS (sec)
9/22/06	0:04:23	1.2	0.0741	-0.0611	0.0855	0.0012
9/22/06	8:24:18	1.9	-1.0775	0.4972	-0.6391	0.0563
9/22/06	9:21:06	1.8	-0.0267	-0.0571	0.1127	0.002
9/22/06	9:21:14	1.4	0.1156	-0.0718	0.353	0.0076
9/22/06	10:12:58	1.2	-0.1931	0.1028	-0.1821	0.0027
9/22/06	10:39:21	3.4	0	0	0	
9/22/06	11:50:19	1.7	-0.0886	-0.1887	0.0513	0.0028
9/22/06	13:25:09	2.4	0.1576	-0.1285	0.1538	0.0033
9/28/06	13:52:47	2.5	1.6671	-1.5319	0.7651	0.0461
9/28/06	13:58:59	1.8	-0.631	-0.0098	0.0569	0.0039
10/3/06	0:07:38	4.2	-0.7337	-0.0574	0.5363	0.016
10/22/06	21:36:25	2.3	-3.0298	0.2106	1.3771	0.0922
12/18/06	19:53:23	2.3	-1.2415	-1.0452	1.447	0.0568
12/29/06	21:21:10	3.1	-2.2084	0.6871	-1.6583	0.1039

Table 3

Absolute Locations From Portable Seismograph Data
(From Lamont-Doherty Earth Observatory)

Date	Orig. Time	Lat (deg.)	Lon (deg.)	Depth (km)	Mag.
10/22/06	18:34:31	44.3423	-68.1888	1.86	2.16
10/22/06	21:36:25	44.3552	-68.1877	1.94	2.56

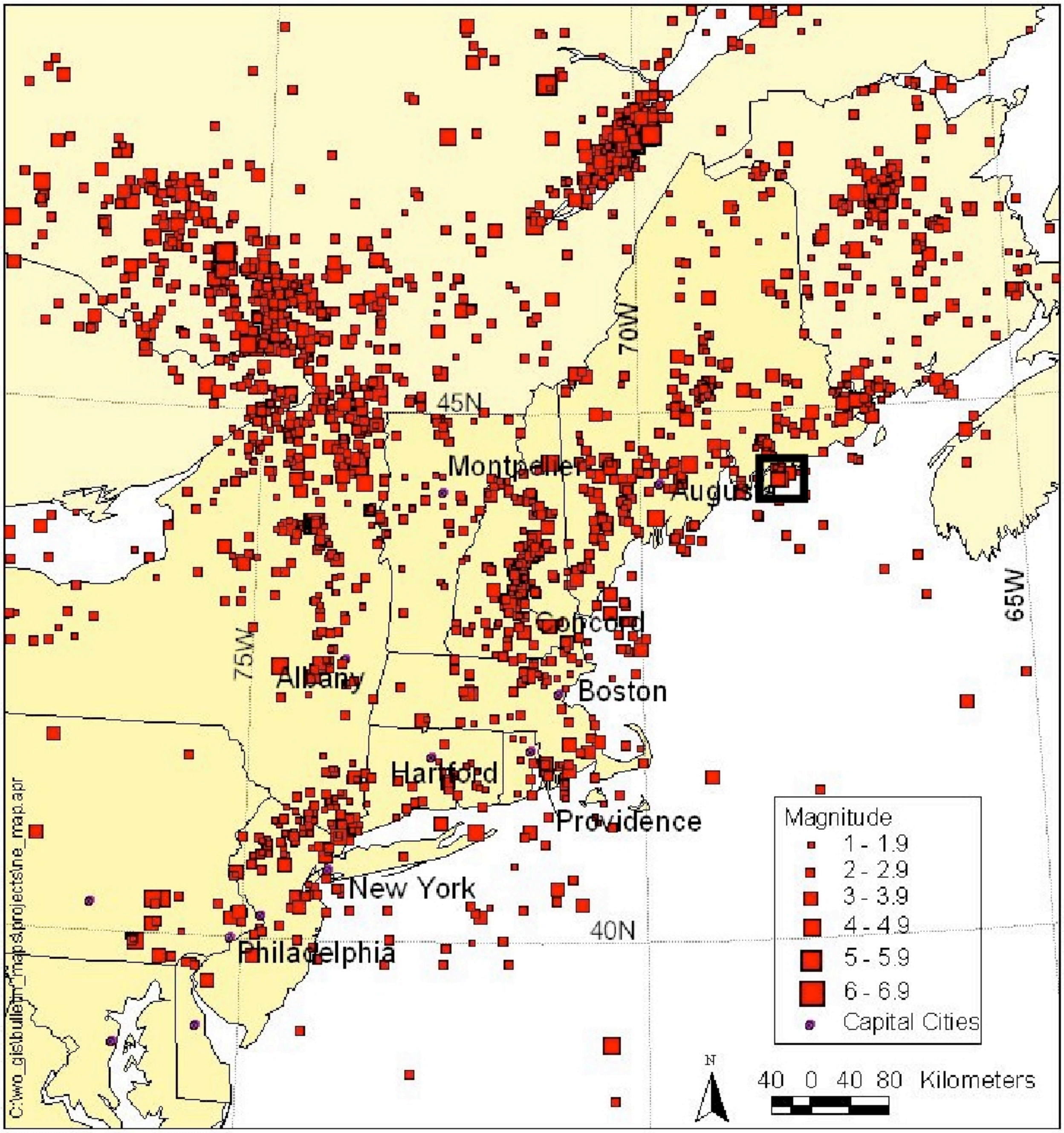


Figure 1. Seismicity from 1972-2007. The location of the Bar Harbor earthquake sequence is shown by the box along coastal Maine.

Figure 2. Rockslide down a steep granite cliff face in Acadia National Park due to the MLg 4.2 earthquake on 10/3/06.

Figure 3. Rockslide onto the Park Loop Road in Acadia National Park due to the MLg 4.2 earthquake on 10/3/06.

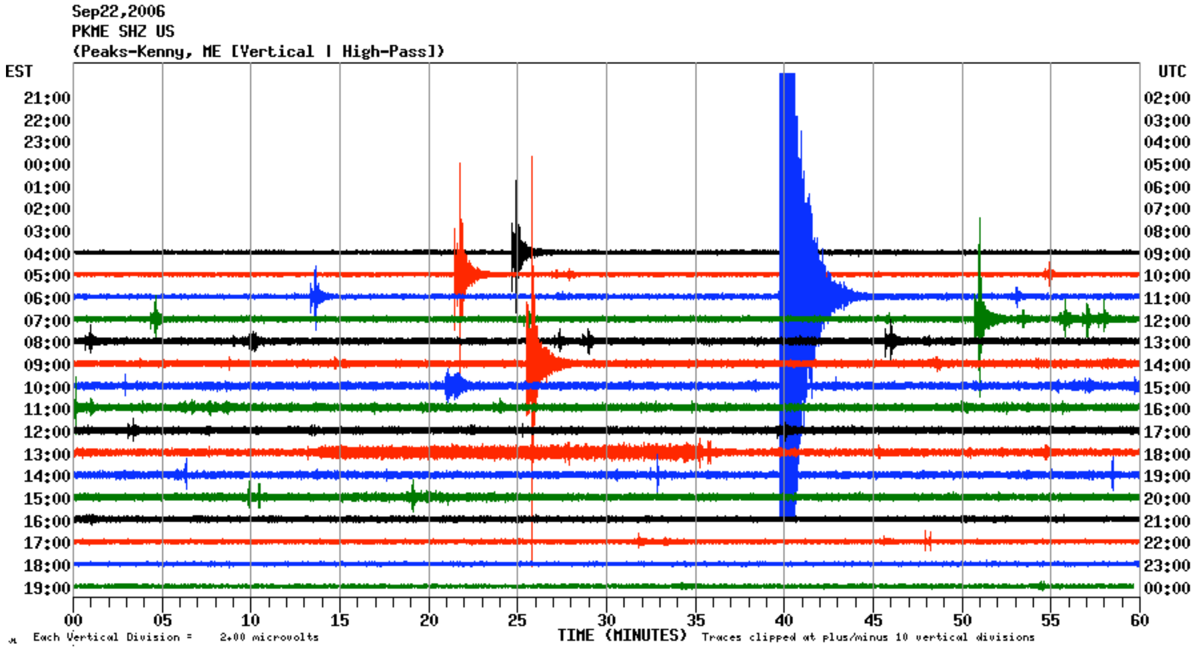


Figure 4. Screen shot of the Weston Observatory web page showing the helicorder view of the vertical component seismic data from station PKME for 9/22/2006. The large event is the MLg 3.4 event from Bar Harbor (epicentral distance about 127 km), and it is preceded and followed by a number of smaller earthquakes. No data were received from PKME for the first 8 hours of the day.

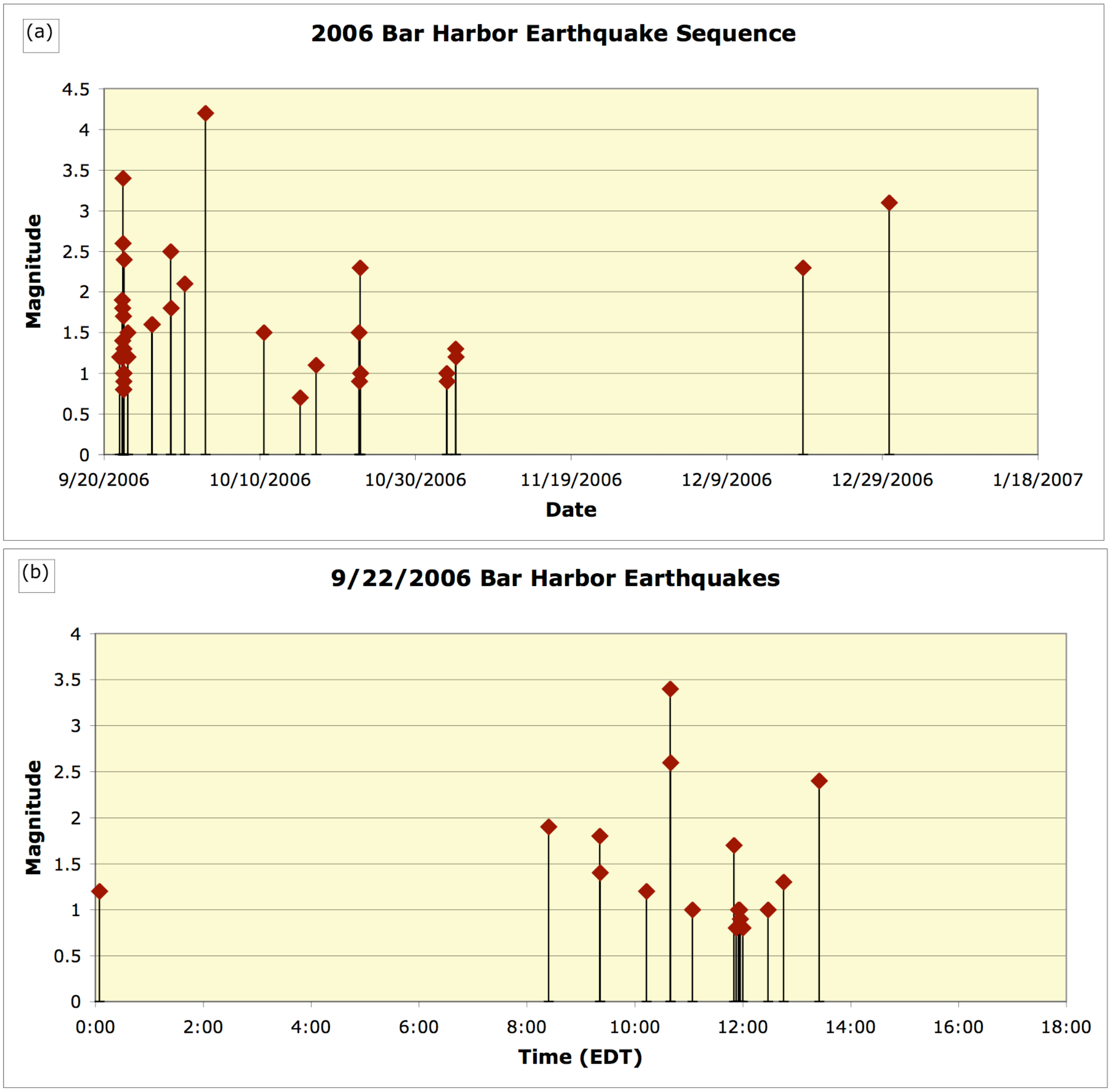


Figure 5. (a) Timeline of the Bar Harbor earthquake sequence to the end of 2006. (b) Expansion of the timeline in (a) showing the development of the Bar Harbor earthquake sequence on 9/22/06.

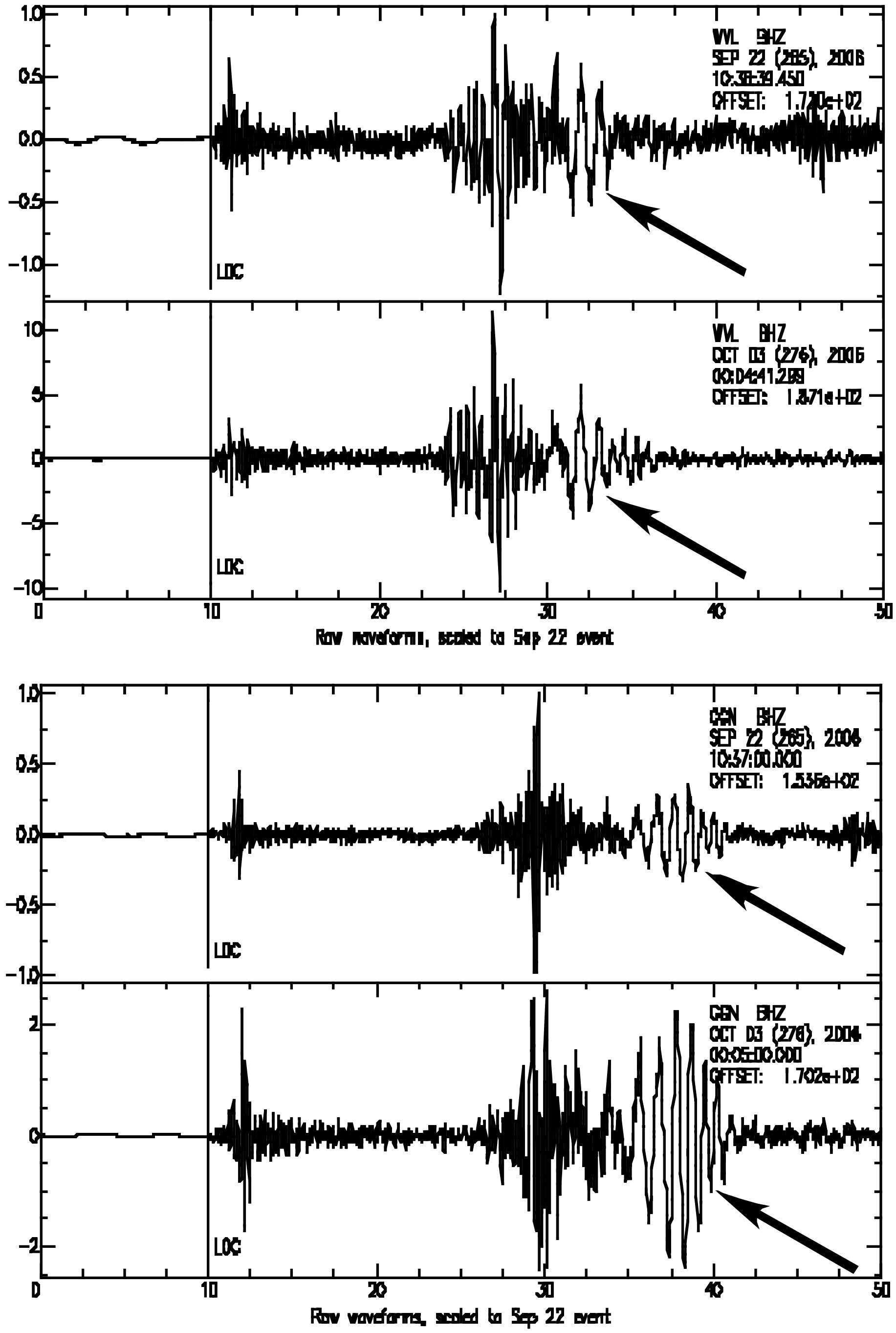


Figure 6. Waveforms of the 9/22/06 MLg 3.4 and 10/3/06 MLg 4.2 earthquakes at station WVL (epicentral distance 123 km) in Maine and station GGN (epicentral distance 135 km) in New Brunswick. The arrows point to the strong Rg waves observed for these earthquakes.

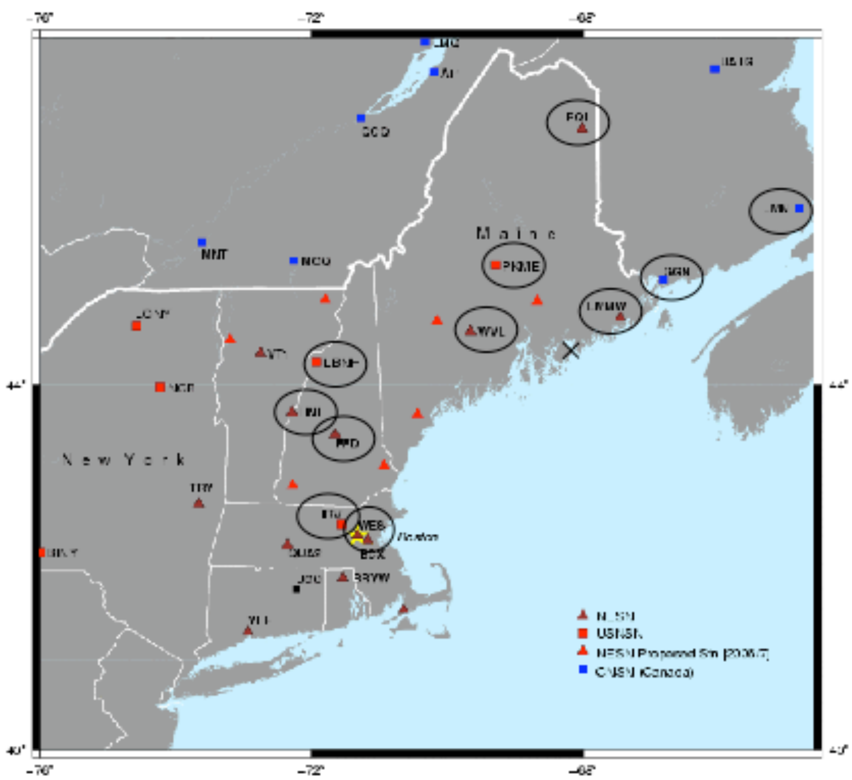


Figure 7. Map of seismic stations in the northeastern U.S. Data from those stations that are circled were used in the double-difference relative location analysis. The x shows the epicentral area of the 2006-2007 Bar Harbor earthquake sequence.

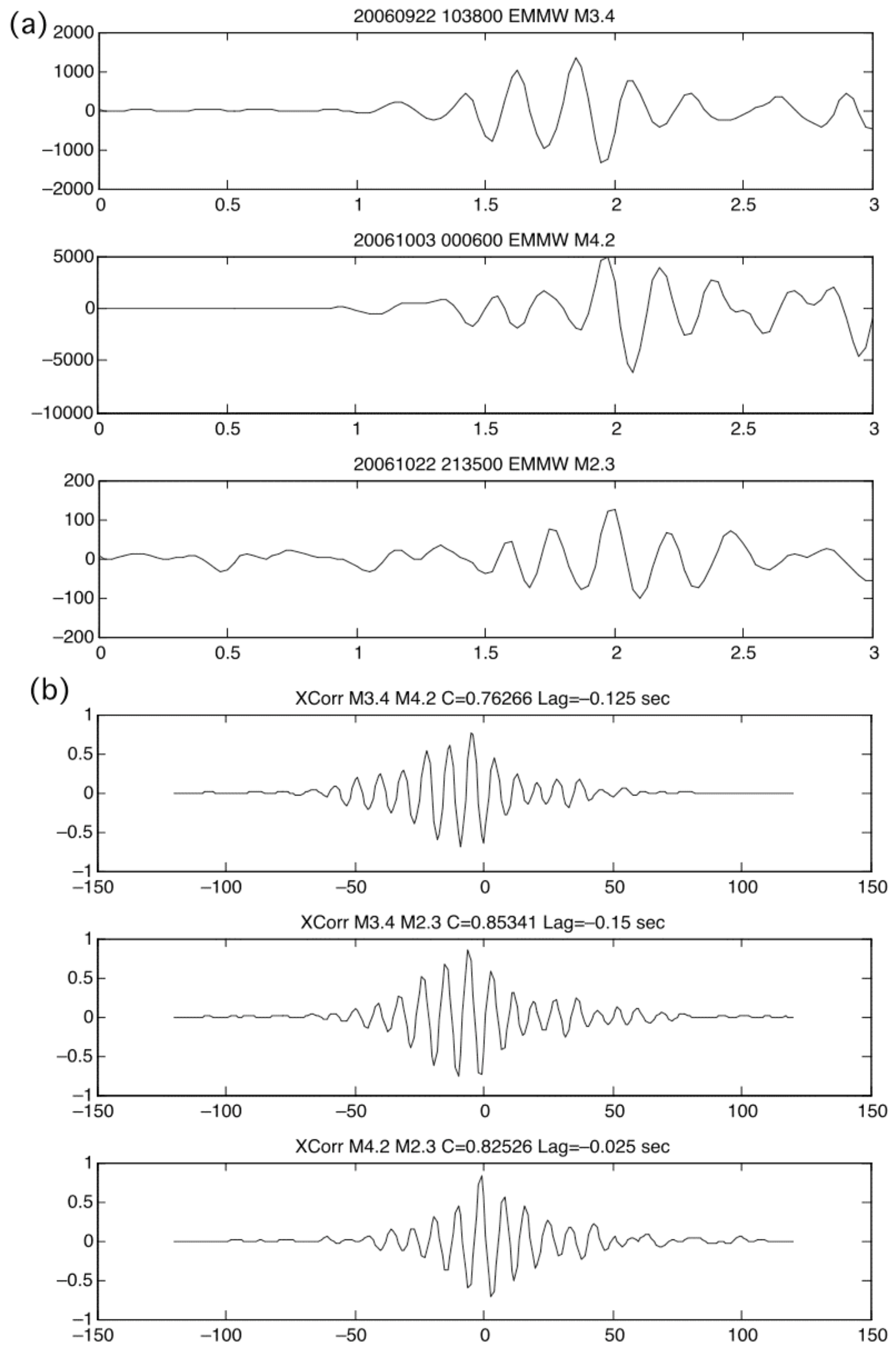
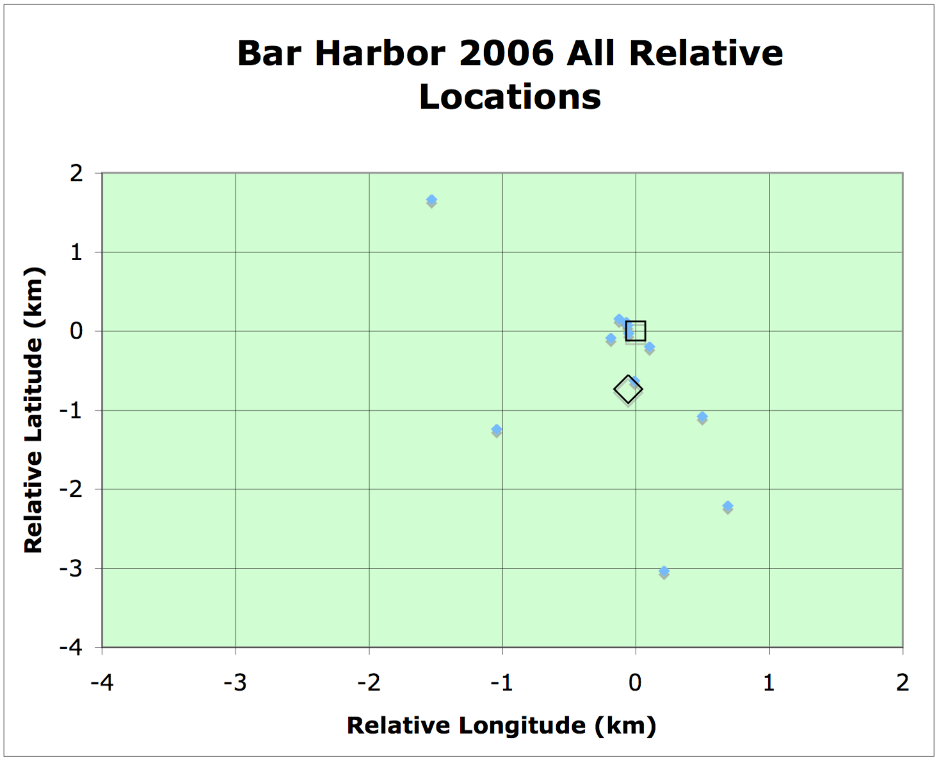


Figure 8. (a) Initial P waveforms for the MLg 3.4 earthquake on 9/22/06, the MLg 4.2 earthquake on 10/3/06, and the MLg 2.3 earthquake at 21:35 on 10/22/06 The horizontal axis is in seconds. . Each trace is positioned such that the analyst's pick occurs exactly 1 second into the displayed trace. (b) Normalized cross correlations of the MLg 3.4 and MLg 4.2 P waves, of the MLg 3.4 and MLg 2.3 P waves, and of the MLg 4.2 and MLg 2.3 P waves. The header above each plot gives the maximum normalized crosscorrelation coefficient and the relative time shift at for the maximum correlation point.



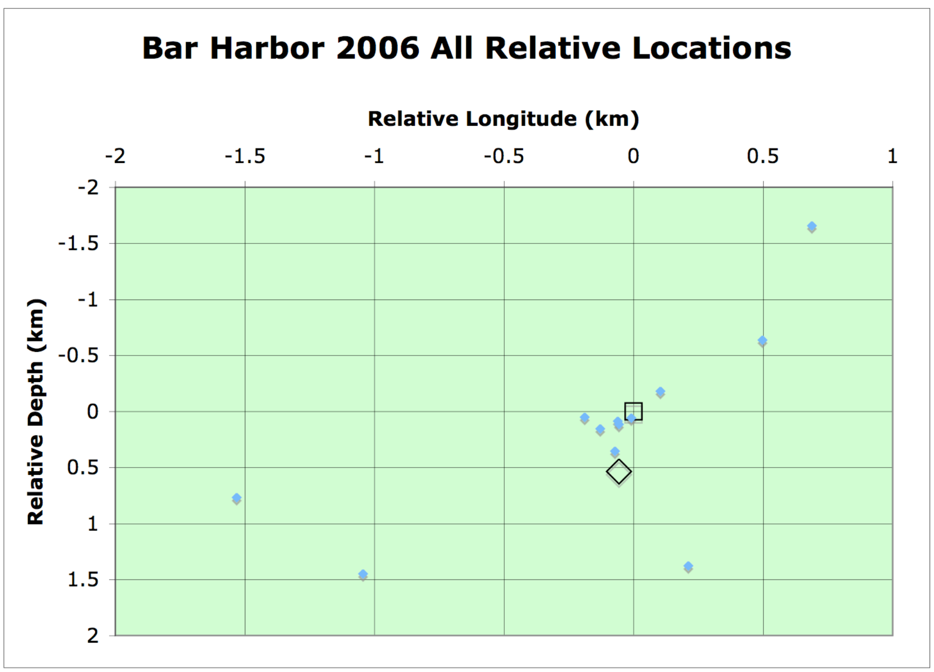
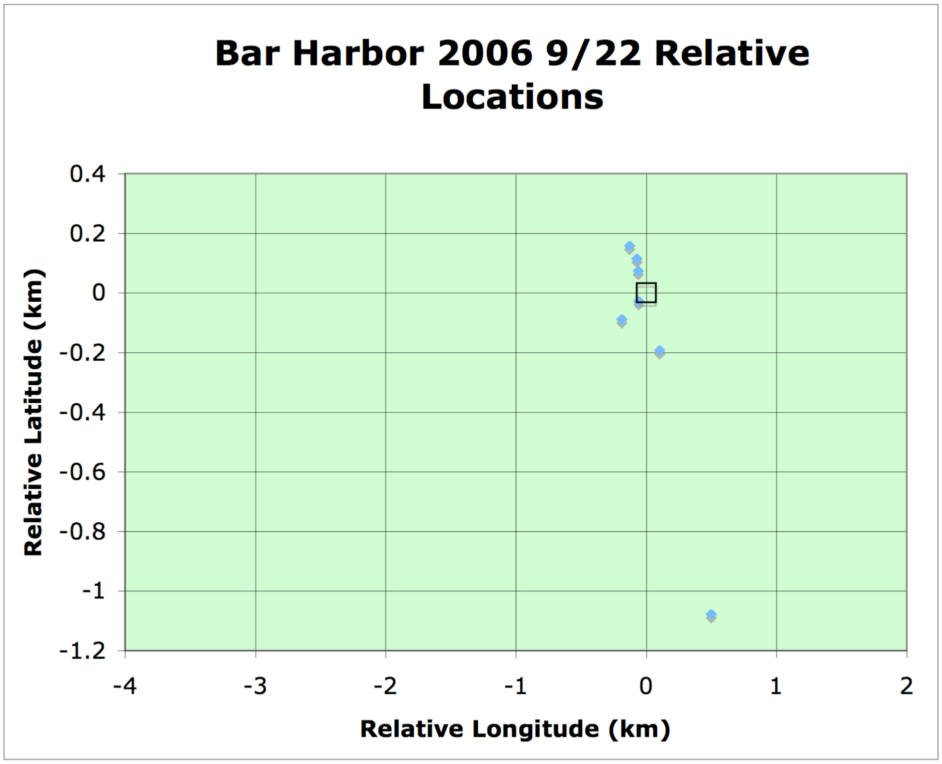


Figure 9. (Top) Map view of the double-difference locations of 13 Bar Harbor earthquakes relative to the location of the 9/22/06 MLg 3.4 event (open square). The location of the MLg 4.2 event is shown by the open diamond. (Bottom) Cross-sectional view of the double-difference locations of 13 Bar Harbor earthquakes relative to the location of the 9/22/06 MLg 3.4 event (open square). The location of the MLg 4.2 event is shown by the open diamond.



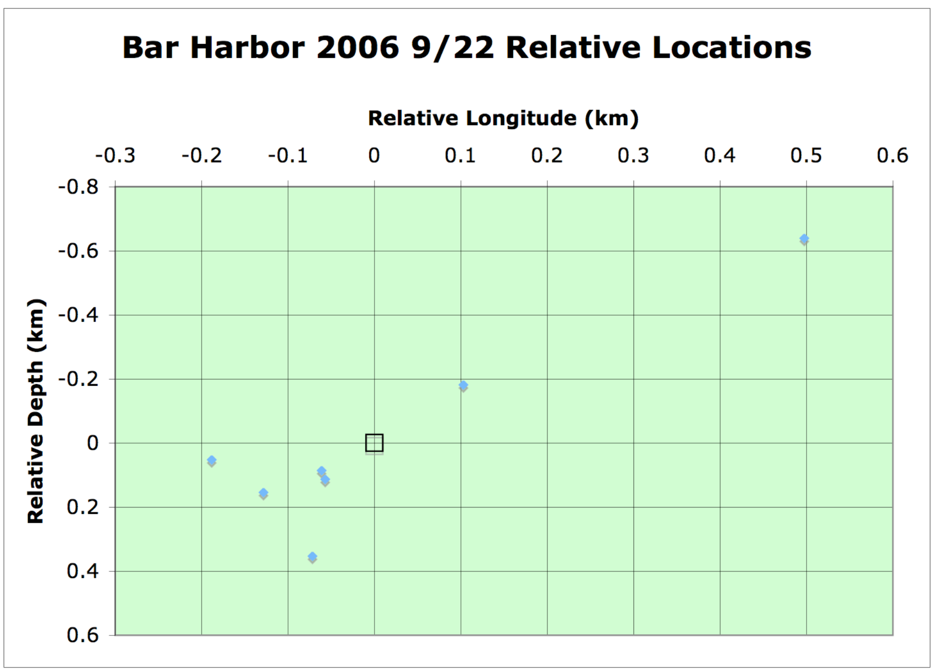


Figure 10. (Top) Map view of the double-difference locations of the Bar Harbor earthquakes on 9/22/06 relative to the location of the MLg 3.4 event (open square). The location of the MLg 4.2 event is shown by the open diamond. (Bottom) Cross-sectional view of the double-difference locations of the Bar Harbor earthquakes on 9/22/06 relative to the location of the MLg 3.4 event (open square).

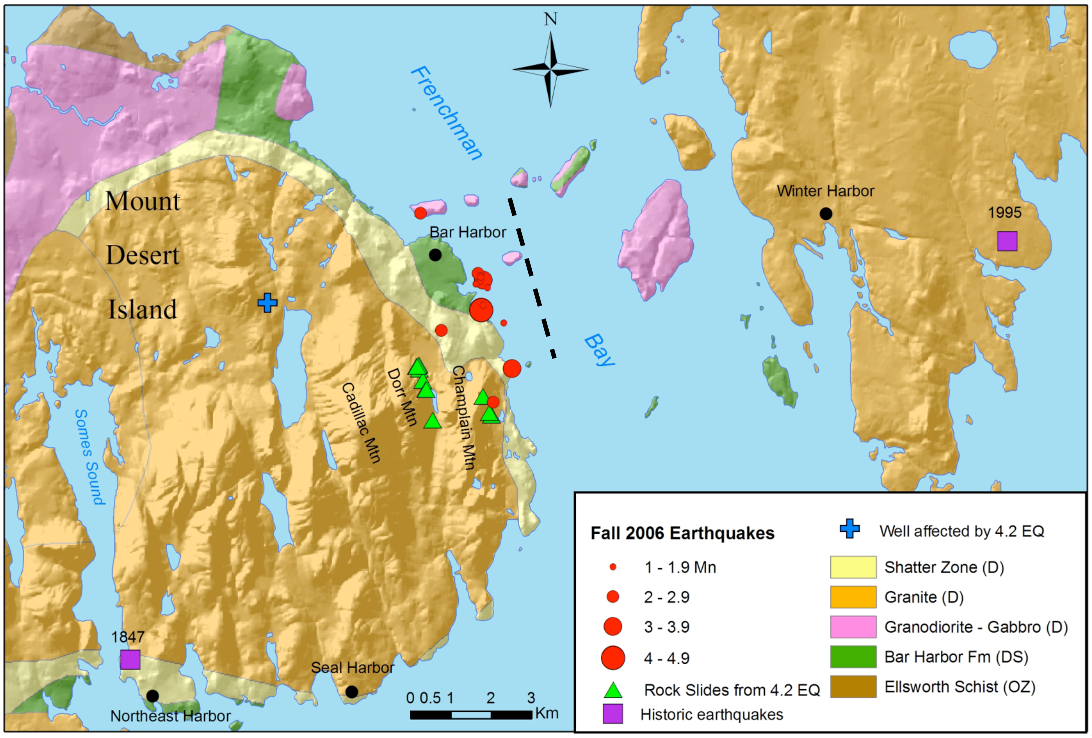


Figure 11. Generalized geology of Mount Desert Island and vicinity (modified from Osberg et al., 1985) showing the locations of 13 events of the Bar Harbor sequence as determined from the double-difference relative location analysis. The absolute locations of the events were determined using the absolute location for the 10/22/06 18:34 event found using the portable seismographic data. The locations of the rock slides generated by the MLg 4.2 event and the well that experienced a sudden 2-m drop immediately after the MLg 4.2 event are also shown. The dashed line is an extrapolation to the approximate location where the fault that was active in the 2006 Bar Harbor earthquake sequence projects to the surface (Figure from R. Marvinney, Maine State Geological Survey).

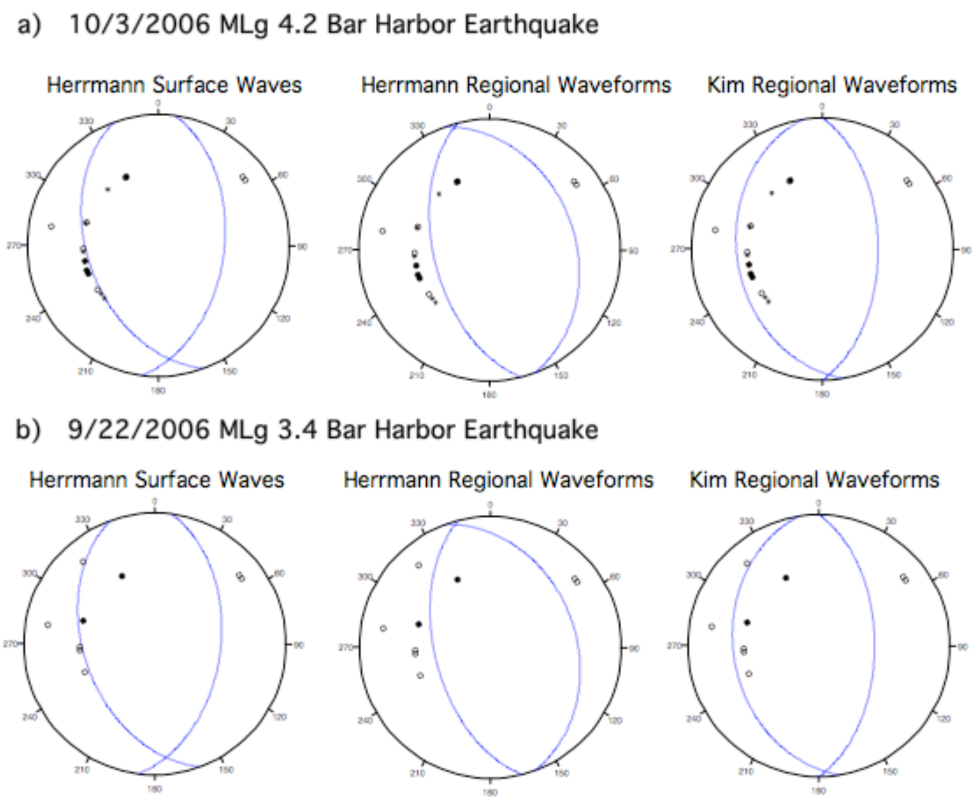


Figure 12. (a) Focal mechanisms calculated by R. Herrmann (www.eas.slu.edu/Earthquake_Center/MECH.NA/20061003000737/index.html) from regional surface waves and from regional full waveforms and by W.-Y. Kim (www.ldeo.columbia.edu/LCSN/Eq/20060922_Maine/mt-20061003-000737) from regional full waveforms for the 10/3/06 MLg 4.2 Bar Harbor earthquake. The first motions read from regional seismic network stations (close circles are compressions; open circles are dilatations; stars are nodal arrivals) are also shown. (b) The same focal mechanisms as in part (a) but here superimposed on the first motions of the MLg 3.4 Bar Harbor earthquake on 9/22/06.