The 2006-2007 earthquake sequence at Bar Harbor, Maine

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The 2006–2007 Earthquake Sequence at Bar Harbor, Maine

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ABSTRACT

One purpose of monitoring earthquake activity in northeastern North America is to discover which geologic structures are seismically active in this region. If seismically active structures can be found, they can be studied to decipher their seismic history and their potential for strong earthquakes. No seismically active geologic structures have yet been confirmed in the northeastern United States (Ebel and Kafka 1991). The only earthquake with observed surface faulting in northeastern North America took place in the Ungava Peninsula of northern Quebec in 1989 (Adams *et al.* 1991). Other than some minor offsets of glacial striations (Oliver *et al.* 1970), no geologic evidence of Holocene surface faulting in the northeastern United States has been reported in the literature. Furthermore, the seismicity that has been detected by modern regional seismic networks in the northeastern United States does not align convincingly along known or suspected geologic structures. Nevertheless, the persistence of small-earthquake activity over time and the historic occurrences of past damaging 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. Because such earthquakes are capable of causing significant damage, there is great incentive to learn which structures are seismically active in this heavily populated region.

Between fall 2006 and spring 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; http://www.nps.gov/acad/photosmultimedia/earthquakephotos.htm). Acadia National Park has many steep (almost vertical) rock faces of jointed granite, and some rockslides occur annually due to weathering effects. In this earthquake sequence, only the largest of the events generated sufficiently strong ground motions to generate rock falls of the unstable slopes. A water well at McFarland Hill near Bar Harbor 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 water level data can be accessed through the Web site http://waterdata.usgs.gov/nwis/gw). The MLg 4.2 earthquake was felt over the southern two-thirds of Maine with a few felt reports from New Hampshire (see the community Internet intensity map at http://pasadena.wr.usgs.gov/shake/ne/STORE/Xtib1_06/ciim_display.html) and was the largest event centered in Maine since 1988. A total of 38 earthquakes were detected by seismic stations at regional distances from the Bar Harbor area from the start of the sequence on 22 September 2006 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 no known local earthquakes. Before 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 took place on 12 November 1995 and had coda magnitude (Mc) 3.0, was located about 12 km east of Bar Harbor. From 1975 to 1992 earthquakes from the Bar Harbor area as small as Mc 2.0 could have been detected and located. Since that time the routine detection and location threshold has been about Mc 3.0. No historic earthquakes with known or suspected epicenters near Bar Harbor are contained in the Weston Observatory earthquake catalog for Maine (http://www.bc.edu/research/westonobservatory/northeast/eqcatalogs.html).

The sequence that is the subject of this study began on 22 September 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 (http://pasadena.wr.usgs.gov/shake/ne/STORE/Xsyav_06/ciim_display.html). Several aftershocks were detected by the regional seismic network during the next three hours. During the eight days following 22 September, several more aftershocks were detected from the Bar Harbor area by the regional network.

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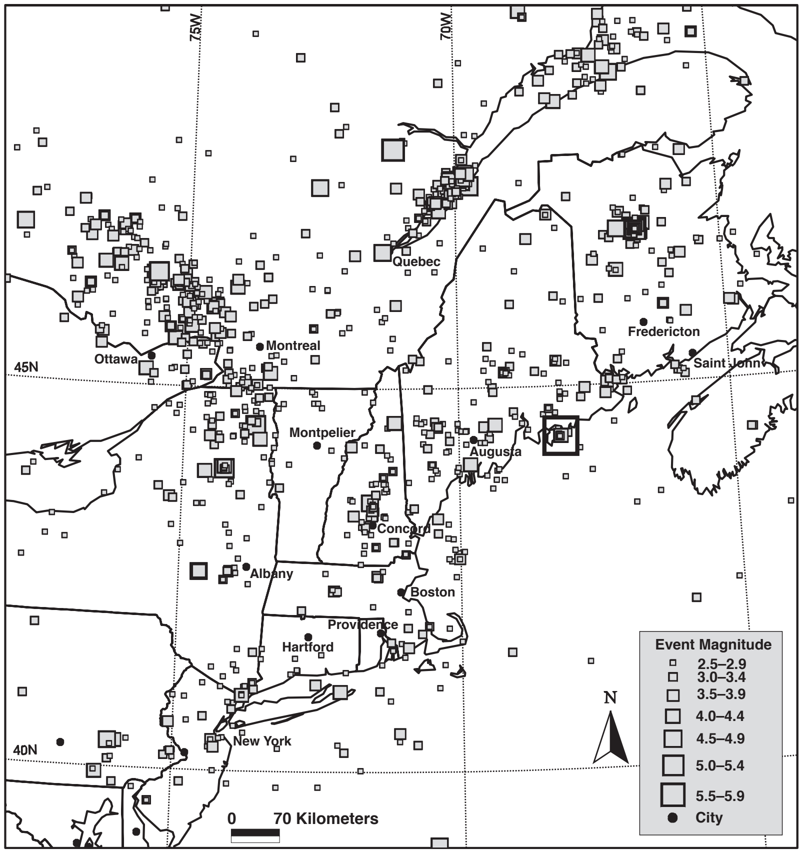
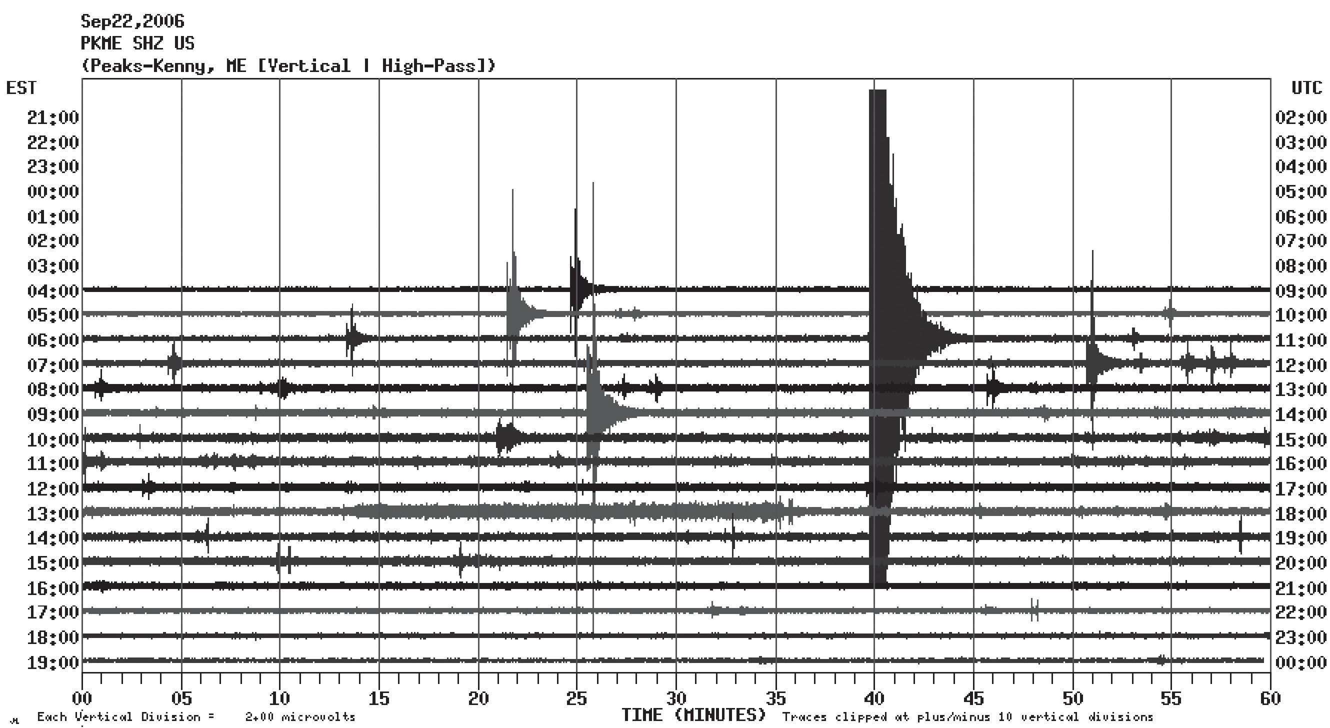


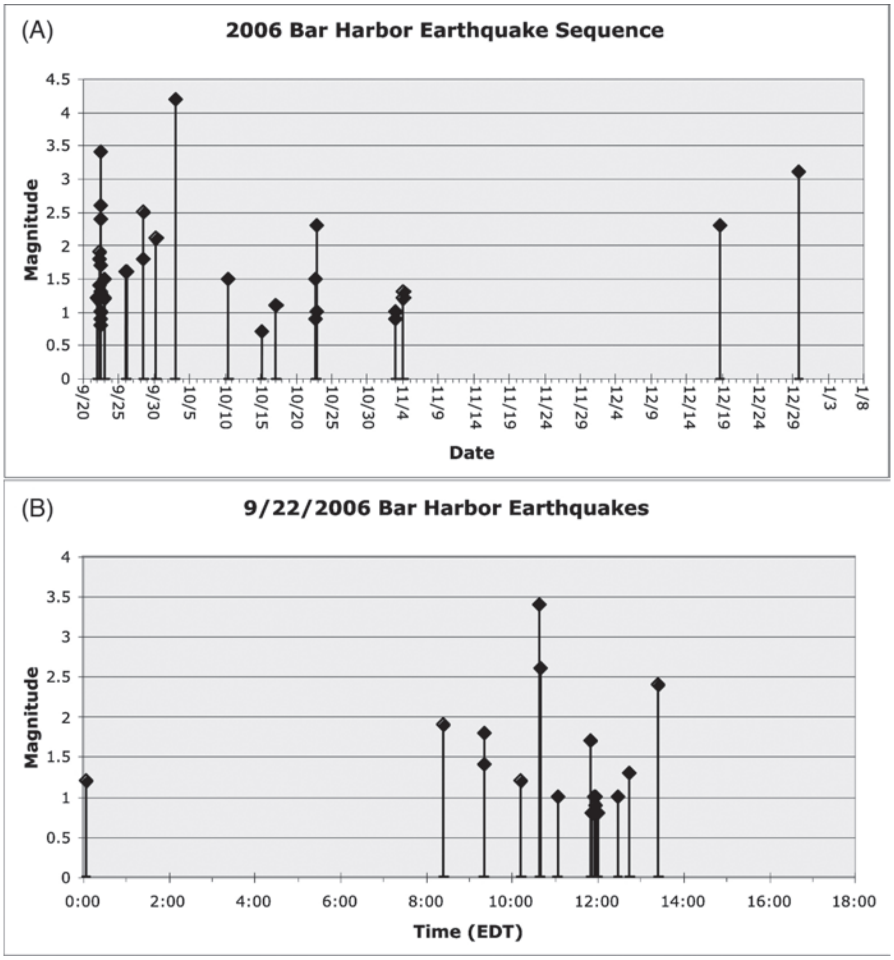
▲ **Figure 1.** Seismicity with **M** ≥ 2.5 from 1975 through 2007. The location of the Bar Harbor earthquake sequence is shown by the box along coastal Maine.

▲ **Figure 2.** Rockslide (near right side of photo) down a steep granite cliff face in Acadia National Park due to the MLg 4.2 earthquake on 3 October 2006.

▲ **Figure 3.** Rockslide onto the park loop road in Acadia National Park due to the MLg 4.2 earthquake on 3 October 2006.



▲ **Figure 4.** Screen shot of the Weston Observatory Web page showing the helicorder view of the vertical component seismic data from station PKME at Peaks-Kenny State Park, Maine, for 22 September 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 eight 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 22 September 2006.

The largest earthquake of the 2006–2007 sequence, which registered MLg 4.2, took place on 3 October. In stark contrast to the MLg 3.4 event on 22 September, the 3 October event was not preceded by any earthquakes during the 48 hours before 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 in 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 29 December. During 2007, only three events were detected and located in the Bar Harbor area by the regional seismic network: an MLg 1.4 event on 29 April, an MLg 1.6 event on 9 June, and an Mc 1.6 event on 15 October. In total, 41 earthquakes from Bar Harbor have been detected 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 the 4,800 residents in the Bar Harbor area.

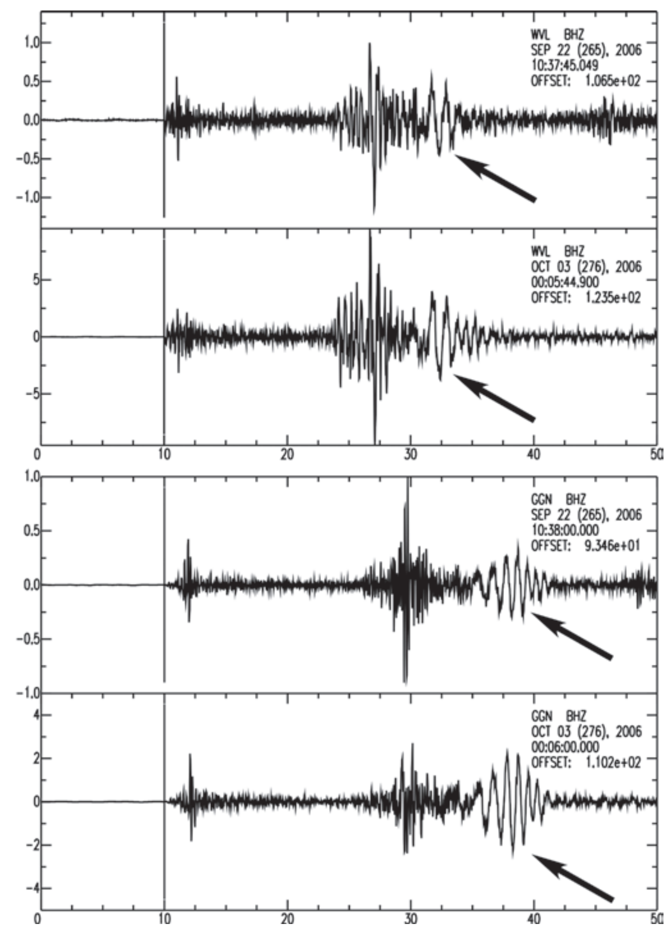
One important characteristic of the earthquake waveforms at the closest stations is the presence of strong *Rg* waves with periods of about 1.0 s to 0.25 s (figure 6). *Rg* waves are indicative of a shallow depth of focus for the seismic source. According to Kafka (1990), the observation of strong *Rg* 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 probably explains why some of the very small events at Bar Harbor were felt or heard by local residents. In fact, it is possible that some smaller events not detected by the regional seismic network stations took place at Bar Harbor during this earthquake sequence due to the epicentral distance of the closest seismic station (about 70 km). 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, Connecticut, in the 1980s, earthquakes as small as Mc 1.0 were reported felt and as small as Mc 0.0 were reported heard (Ebel 1982, 1989). The Moodus earthquakes had focal depths of about 0.5 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 because Mc and MLg are approximately equal for most earthquakes in New England.

Date (UTC)	Time (UTC)	Magnitude (MLg)	Felt Report
20060922	00:04:24.24	1.2	
20060922	08:24:18	1.9	
20060922	09:21:05	1.8	
20060922	09:21:14	1.4	
20060922	10:12:57	1.2	
20060922	10:39:21	3.4	felt
20060922	10:39:49	2.6	felt
20060922	11:03:59	1.0	
20060922	11:50:19	1.7	
20060922	11:52:47	0.8	
20060922	11:55:09	1.0	
20060922	11:56:24	1.0	
20060922	11:57:19	0.9	
20060922	12:00:20	0.8	
20060922	12:28:20	1.0	
20060922	12:45:20	1.3	
20060922	13:25:09	2.4	
20060923	01:21:23	1.5	
20060923	01:33:07	1.2	
20060926	02:48:16	1.6	
20060926	04:46:47	1.6	
20060928	13:52:47	2.5	felt
20060928	13:58:59	1.8	felt
20060930	08:10:39	2.1	
20061003	00:07:38	4.2	felt
20061010	13:05:47	1.5	
20061015	04:25:38	0.7	
20061017	05:39:03	1.1	
20061022	18:34:31	1.5	felt
20061022	19:00:52	0.9	
20061022	21:36:25	2.3	felt
20061022	22:49:40	1.0	
20061103	01:10:34	1.0	
20061103	01:34:36	0.9	
20061104	04:22:42	1.3	
20061104	04:50:04	1.2	
20061218	19:53:23	2.3	felt
20061229	21:21:10	3.1	felt
20070429	14:23:25	1.4	felt
20070609	11:10:10	1.6	
20071015	01:06:27	1.6	

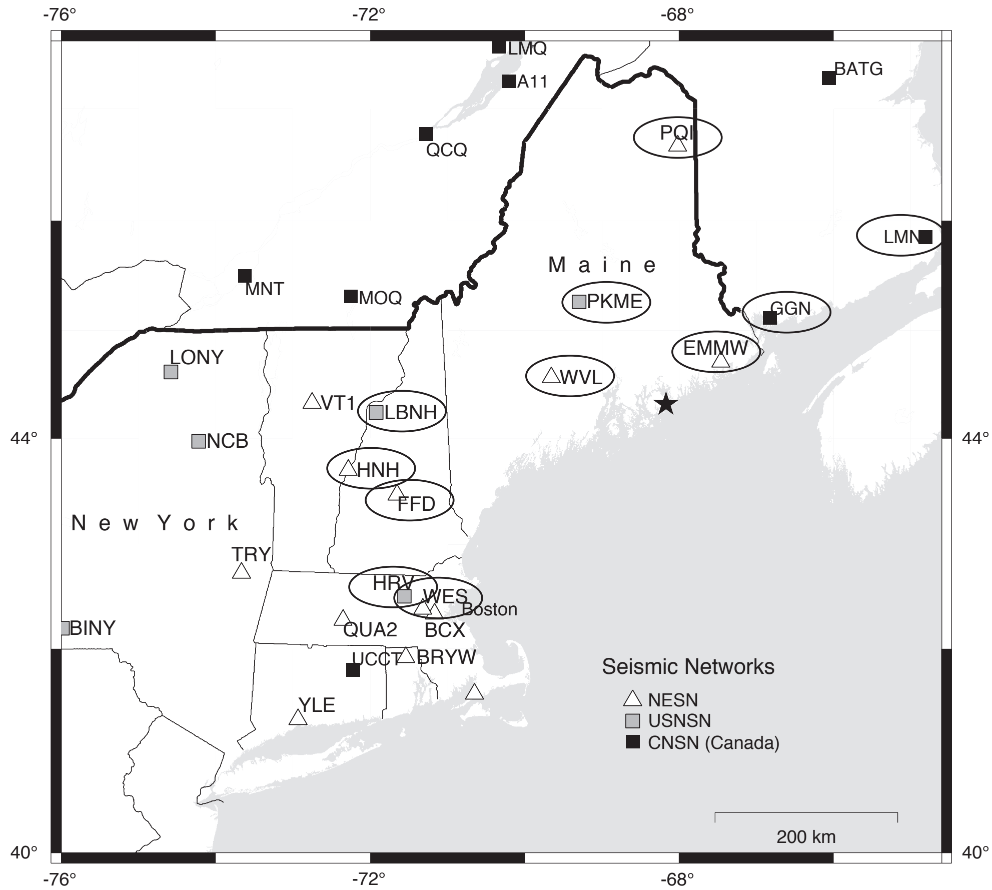
TABLE 1
Bar Harbor, Maine, Foreshocks, the Primary Earthquake, and Aftershocks

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. The double-difference relative location analysis method assumes that the earthquakes are located close enough together that seismic velocity structure in the hypocentral area is approximately uniform, and that the seismic structure along the propagation paths has the



▲ **Figure 6.** Waveforms of the 22 September 2006 MLg 3.4 and 3 October 2006 MLg 4.2 earthquakes at station WVL at Waterville, Maine (epicentral distance 123 km), and station GGN at St. George, New Brunswick (epicentral distance 135 km), aligned at the *P*-wave first-arrival times. The arrows point to the strong *Rg* waves observed for these earthquakes. The horizontal axis is time in seconds. For each station the vertical axis is in counts and is normalized to make the peak positive amplitude of the 22 September 2006 waveform equal to 1.



▲ **Figure 7.** Map of seismic stations in the northeastern U.S. The seismic networks are: NESN—New England Seismic Network; USNSN—U.S. National Seismic Network; CNSN—Canadian National Seismic Network. Data from those stations that are circled were used in the double-difference relative location analysis. The star shows the epicentral area of the 2006–2007 Bar Harbor earthquake sequence.

same effect on the waveforms of all events recorded at a common seismic station. The method also assumes that all of the events have comparable focal mechanisms.

The effectiveness of the relative location analysis using regional seismic network stations relies on the availability of relative arrival times from stations distributed around the epicentral region and at a range of epicentral distances. While there are no seismic stations in the Gulf of Maine to the east or south of the Bar Harbor area, stations to the north and west of the epicentral area are sufficient to constrain the relative epicenters of the events. Furthermore, the relative depths of the events can be constrained if station data are available at epicentral distances both less than and greater than 180 km, which is the approximate distance at which *Pn* becomes the first arrival in this region. For stations at epicentral distances of less than 180 km, a midcrustal head wave is the first body-wave arrival, and a change in focal depth of 1 km changes the arrival times of the *P* and *S* phases by 0.05 s and 0.09 s, respectively. For stations at epicentral distances of greater than 180 km, a Moho head wave is the first body-wave arrival, and a change in focal depth of 1 km changes the arrival times of the *P* and *S* phases by 0.10 s and 0.18 s, respectively. Thus, even though the closest regional seismic station was 70 km from the epicentral region, the relative location analysis can constrain relative event depths as long as some arrivals from both less than and greater than the 180-km epicentral distance are used.

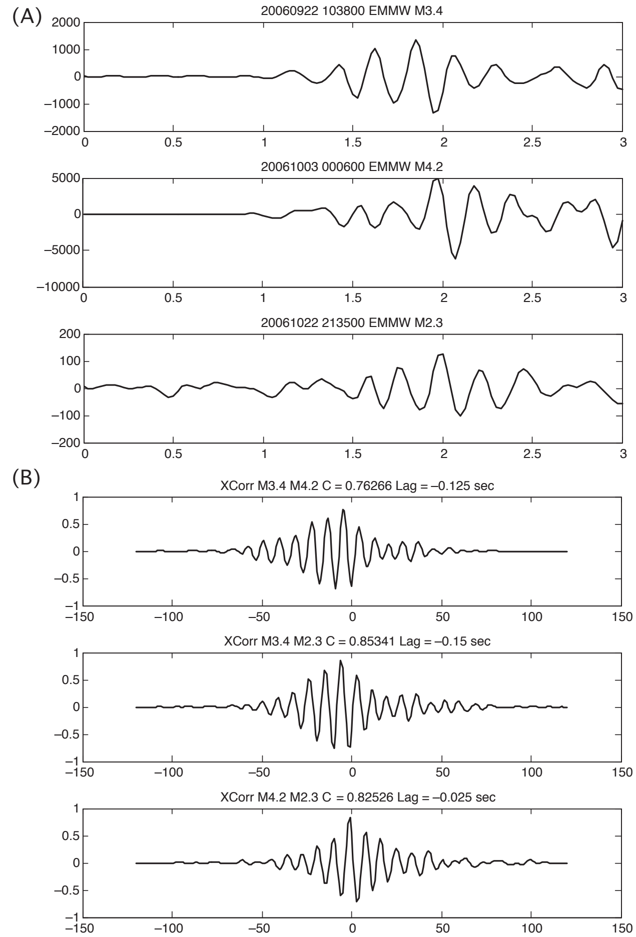
In this study, time windows around the arrival times of the *P* waves and of the *S* waves, at stations within about 350 km of Bar Harbor and where the waveforms appear well-recorded, were selected for use in the cross-correlation analysis (figure 7; table 2). The arrival-time differences between two earthquakes computed using the cross-correlation analysis at all seismic stations that yielded reliable cross correlations 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 22 September 2006 was used as the master event relative to which the locations of all 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 22 September 2006 event and of the event for which the relative location was being computed. The data window stretched from 1 s before the *P*- or *S*-wave arrival time to 2 s after the *P* or *S* arrival time. The windowed *P* waveforms from the two events were then

TABLE 2 Stations Used in the Relative Location Analysis					
Station	Lat. (deg. N)	Lon. (deg. E)	Delta (km)	Azimuth (deg.)	Sensor
EMMW	44.7105	–67.4576	71	55	CMG-40T
WVL	44.5300	–69.6666	120	280	CMG-40T
PKME	45.2644	–69.2917	134	319	STS-2
GGN	45.1170	–66.8220	138	52	CMG-3R
PQI	46.6710	–68.0168	258	3	CMG-40T
FFD	43.4701	–71.6533	295	251	CMG-40T
LBNH	44.2400	–71.9260	299	268	STS-2
WES	42.3848	–71.3218	337	230	CMG-40T
HRV	42.5063	–71.5583	344	234	STS-2
HNH	43.7053	–72.2855	340	258	CMG-40T
LMN	45.8520	–64.8060	314	58	CMG-3E

cross-correlated 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 cross correlations with cross-correlation coefficients greater than 0.5 proved useful in the double-difference location analysis. Figure 8 shows some examples of waveforms that were cross-correlated along with plots of the coefficients from the normalized cross-correlation 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, only 14 events yielded relative locations that are considered reliable (table 3). In most cases in table 3, the root-mean-square (RMS) error between the predicted and computed relative arrival times is less than the sampling period of the data (0.025 s), 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/s. Some of the events in table 3 have RMS errors greater than one 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 29 December 2006 is the largest RMS value in table 3. For this event, the largest normalized cross-correlation coefficient is only 0.74, whereas most of the other events had many normalized cross-correlation coefficients that exceeded 0.80 and some that exceeded 0.90. The cross-correlation analysis suggests that the waveforms for the MLg 3.1 event are less similar to the MLg 3.4 waveforms than are the waveforms of any other event that was analyzed. This lower similarity of the MLg 3.1 event could be due to its location (much shallower and much farther 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.



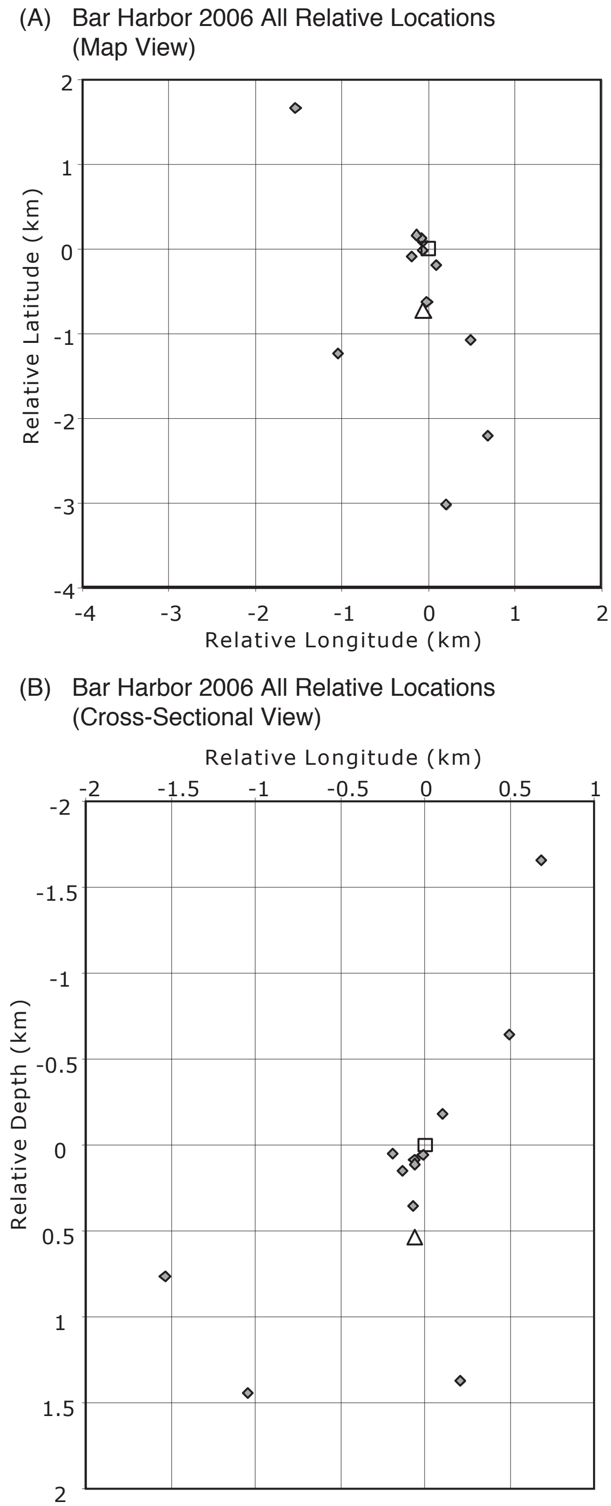
▲ **Figure 8.** (A) Initial *P* waveforms for the MLg 3.4 earthquake on 22 September 2006, the MLg 4.2 earthquake on 3 October 2006, and the MLg 2.3 earthquake at 21:35 on 22 October 2006. The horizontal axis is in seconds. Each trace is positioned such that the analyst's pick occurs exactly 1 second 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 cross-correlation coefficient and the relative time shift at the maximum correlation point.

Map views and cross-sectional views of the relative event locations listed in table 3 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 22 September 2006 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 22 September 2006 events. With one exception, an MLg 1.9 event that took place about two hours before the MLg 3.4 event, the seismicity on 22 September 2006 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 a trend in the hypocenters that dips downward from east to west. Thus, with

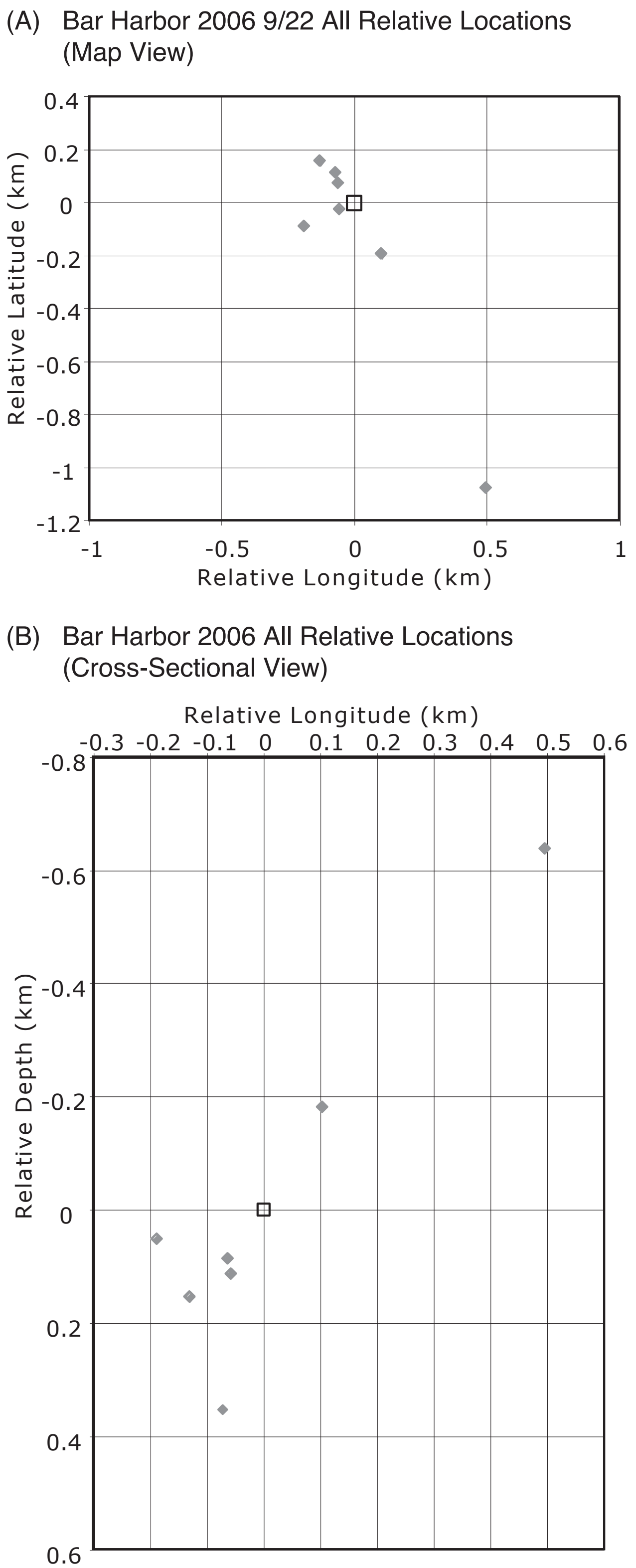
Date	Orig. Time	Mag.	Lat (km)	Lon (km)	Depth (km)	RMS (s)
20060922	00:04:23	1.2	0.07	–0.06	0.09	0.00
20060922	08:24:18	1.9	–1.08	0.50	–0.64	0.06
20060922	09:21:06	1.8	–0.03	–0.06	0.11	0.00
20060922	09:21:14	1.4	0.12	–0.07	0.35	0.01
20060922	10:12:58	1.2	–0.19	0.10	–0.18	0.00
20060922	10:39:21	3.4	0	0	0	
20060922	11:50:19	1.7	–0.09	–0.19	0.05	0.00
20060922	13:25:09	2.4	0.16	–0.13	0.15	0.00
20060928	13:52:47	2.5	1.67	–1.53	0.77	0.05
20060928	13:58:59	1.8	–0.63	–0.01	0.06	0.00
20061003	00:07:38	4.2	–0.73	–0.06	0.54	0.02
20061022	21:36:25	2.3	–3.03	0.21	1.38	0.09
20061218	19:53:23	2.3	–1.24	–1.05	1.45	0.06
20061229	21:21:10	3.1	–2.21	0.69	–1.66	0.10

TABLE 3
Event Locations Relative to the M3.4 Event

the exception of one event, it appears that the rupture on 22 September 2006 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 a moment magnitude (Mw) 3.4 earthquake. The next significant earthquake in the sequence was an MLg 2.5 event that took place on 28 September 2006. 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 3 October 2006, 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 22 October 2006. 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 28 September 2006 and 22 October 2006 epicenters suggest that the initial rupture from 22 September 2006 was spreading in both the NNW and SSE directions. Curiously, the deepest event determined in the relative location analysis took place on 18 December 2006 (MLg 2.3), and the shallowest event that was found by the relative location analysis took place on 29 December 2006 (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 22 September 2006. 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 Mw 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 22 September 2006 continued to expand in all directions and to trigger small earthquakes for at least a few months after its initiation. The interpretation described here assumes that all of the



▲ **Figure 9.** (A) Map view of the double-difference locations of 13 Bar Harbor earthquakes relative to the location of the 22 September 2006 MLg 3.4 event (open square). The location of the MLg 4.2 event is shown by the open triangle. (Bottom) Cross-sectional view of the double-difference locations of 13 Bar Harbor earthquakes relative to the location of the 22 September 2006 MLg 3.4 event (open square). The location of the MLg 4.2 event is shown by the open triangle.



▲ **Figure 10.** (A) Map view of the double-difference locations of the Bar Harbor earthquakes on 22 September 2006 relative to the location of the MLg 3.4 event (open square). (B) Cross-sectional view of the double-difference locations of the Bar Harbor earthquakes on 22 September 2006 relative to the location of the MLg 3.4 event (open square).

TABLE 4
Absolute Locations from Portable Seismograph Data (from Lamont-Doherty Earth Observatory)

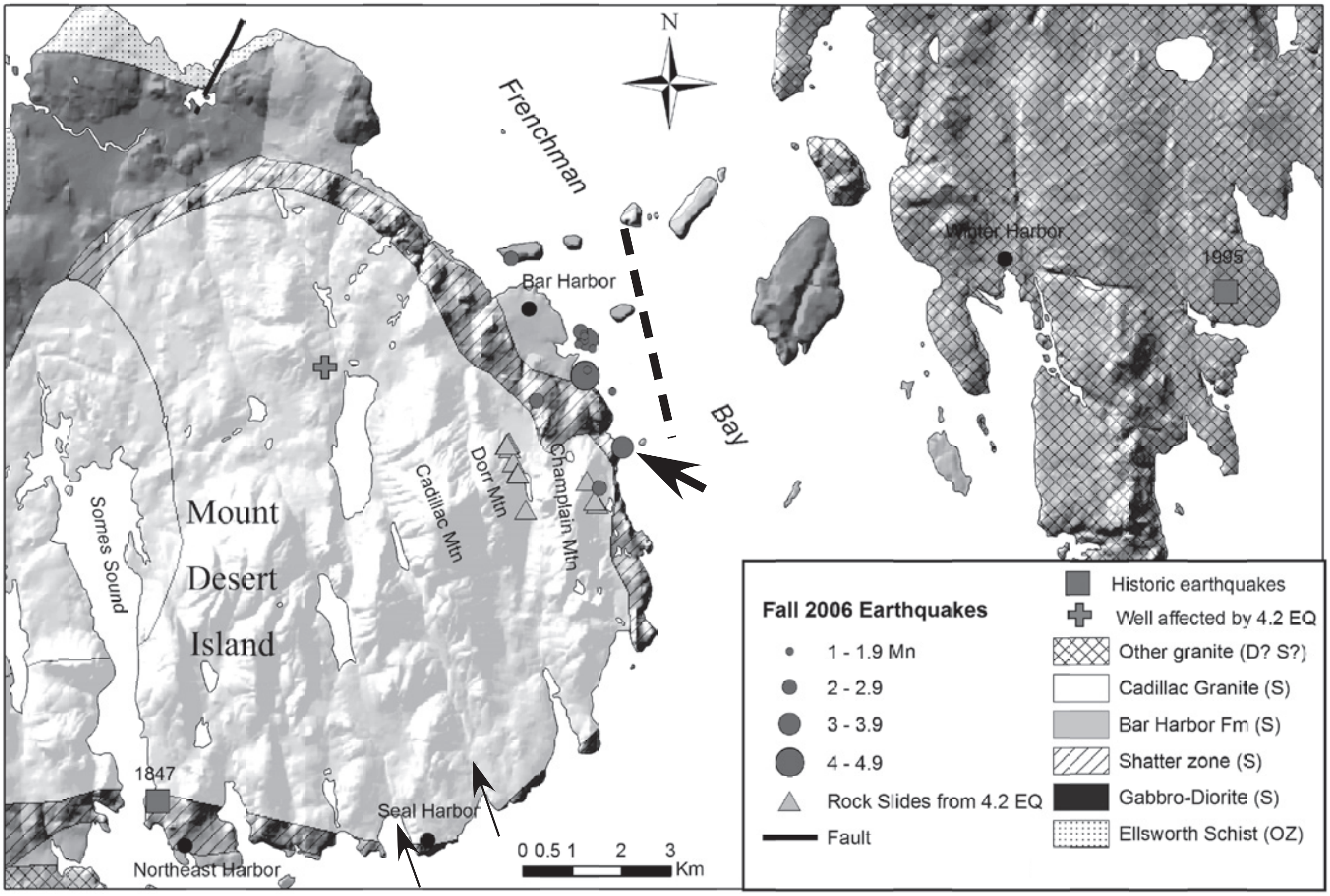
Date	Orig. Time	Lat (deg.)	Lon (deg.)	Depth (km)	Mag.
10/22/06	18:34:31	44.3423	–68.1888	1.86	2.16
10/22/06	21:36:25	44.3552	–68.1877	1.94	2.56

earthquakes located in the relative location analysis took place on a common fault surface.

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 3 and shown in figure 9 must be determined from *a priori* information. Fortunately, following the occurrence of the 3 October 2006 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 22 October 2006, which also was well-recorded by the regional network. Table 4 lists the absolute hypocentral location for this 22 October 2006 event computed using the data from the portable seismic network stations (M. Gold, personal communication 2007). Using the absolute location for this one event in table 4 and the relative location pattern for all of the events in table 3, the absolute locations of the events in table 3 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 to constrain the focal mechanism only of the largest event of the 2006–2007 earthquake sequence at Bar Harbor. Following the occurrence of the MLg 4.2 event, R. Herrmann posted on the Web (http://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 (http://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



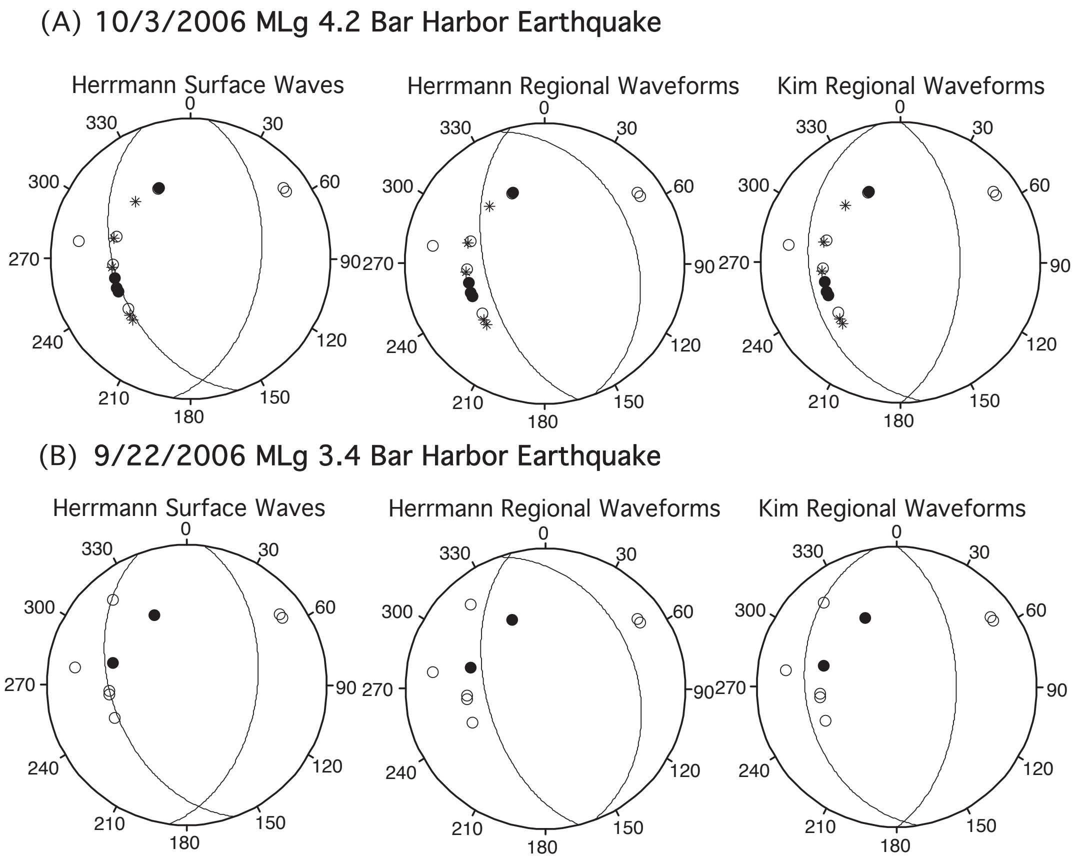
▲ **Figure 11.** Generalized geology of Mount Desert Island and vicinity (modified from Osberg *et al.* 1985) showing the locations of 13 events of the Bar Harbor sequence as determined from the double-difference relative location analysis. The absolute locations of the events were determined using the absolute location for the 22 September 2006 18:34 event (indicated by the bold arrow) found using the portable seismographic data. The locations of the rockslides 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 2006–2007 Bar Harbor earthquake sequence projects to the surface. The thin arrows indicate some of the topographic lineaments on Mount Desert Island. *Figure from R. Marvinney, Maine State Geological Survey.*

planes and in many cases are difficult to determine unambiguously. Nevertheless, from figure 12 it appears that the surface wave focal mechanism found by 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 22 September 2006 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 in fault strike and rake to those values 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 x 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 x 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 4).

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



▲ **Figure 12.** (A) Focal mechanisms calculated by R. Herrmann (http://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 (http://www.ldeo.columbia.edu/LCSN/Eq/20060922_Maine/mt-20061003-000737) from regional full waveforms for the 3 October 2006 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 (A) but here superimposed on the first motions of the MLg 3.4 Bar Harbor earthquake on 22 September 2006.

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 Bay just east of Bar Harbor (figure 11). The rupture initiated on a small fault patch about 400 m on each side in a series of small earthquakes on 22 September 2006 with the largest being MLg 3.4. The crack extended to the south on 3 October 2006 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 of additional aftershocks.

The mapped surface geology (figure 11) has no onshore faults in the part of Mount Desert Island where these earthquakes took place. A number of lineaments 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 bedrock faults that are not expressed in the surface geology, and the 2006 earthquake sequence took place on one of these bedrock features.

Some important implications for seismic hazard in the New England region arise from this 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 assuming that all of the earthquakes occurred on the same fault. 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, enhancing the local seismic hazard at Bar Harbor.

CONCLUSIONS

The 2006–2007 earthquake sequence at Bar Harbor, Maine, 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 heard by local residents of the town. No mapped fault in the Bar Harbor area is consistent with the fault orientation inferred from the 2006–2007 earthquake sequence. Furthermore, no previous seismicity is known from the Bar Harbor area. The spatial extent of the 2006–2007 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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