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An Enigmatic Little Earthquake Swarm near Searsport, Maine

by John E. Ebel

ABSTRACT

A swarm of 21 small earthquakes, with the largest being M_{Lg} 1.7, was recorded by regional seismic network monitoring from near Searsport, Maine, in April and May 2011. An additional five events were detected by two portable seismic instruments that were installed in the Searsport area for the later part of the swarm. Relative locations of the larger events of the swarm, computed in relation to a selected master event, showed that the swarm events extended for a distance of about 2.5 km and migrated from northeast to southwest. The events also became shallower toward the southwest. If the area of the swarm had ruptured in a single earthquake, the magnitude of the event would have been about **M** 5.1–5.5. The *S-P* time of only about 0.34 s at one of the portable seismic stations for the detected events from the swarm indicates that the station was located about 2.7 km from the hypocenters, thus constraining the location of the southwest end of the swarm. The events took place within the Devonian Mount Waldo pluton, a granitic body that locally cuts northeast–couthwest-oriented thrust faults that parallel the Norumbega fault zone. The trend of the swarm events is parallel to and on-strike with the trend of a thrust fault mapped to the southwest of the Mount Waldo pluton. The seismic data suggest that the fault might be seismically active, although the modern seismotectonic relationship of the fault and the pluton is far from clear.

INTRODUCTION

One of the very important goals of regional seismic network monitoring is to use the accumulation of earthquake hypocenters over time to delineate the seismically active geologic structures in the region of the seismic network. Large-magnitude earthquakes provide the most direct information about the seismically active structures in a region. However, large earthquakes are relatively rare, especially in areas of moderate or low strain rates. Fortunately, smaller earthquake activity often also helps indicate which geologic structures might be seismically active. In seismically active parts of the world, earthquake hypocenters align along many of the active faults, illuminating the locations and spatial configurations of those active structures. For less-active geologic structures, it might take many years of regional seismic network monitoring before a sufficient number and spatial alignment of earthquakes are detected to reveal an active fault. However, not all earthquakes detected by regional seismic networks can be attributed to active faults or other active geologic structures. Many small earthquakes within monitored regions simply appear to be rather randomly located background seismicity with no known relationship to the local geology. Perhaps with a sufficiently long record of regional seismic network hypocenters, the geologic structures associated with many, or at least some, of these background events will be revealed, although it is also possible that some small regional earthquakes are simply random rock fracturing that is not associated with an active fault of any tectonic or seismic-hazard significance. It is also possible that some active faults have little or no seismicity prior to the occurrence of large earthquakes on those faults.

For northeastern North America, there has been a relatively small number of strong earthquakes since instrumental seismic monitoring began at the end of the nineteenth century, and there have been fewer than a handful **M** ≥ 5 earthquakes since the mid-1970s, when modern regional seismic network monitoring began in the region. Even for most of the **M** ≥ 5 events since 1975, the relationship between the earthquakes and local geologic structures is not clear-cut (e.g., the 1982 **M** 5.8 Miramichi, New Brunswick, earthquakes and the 2002 **M** 5.0 Au Sable Forks, New York, earthquake). Thus, one is forced to use the more frequent, small earthquake activity in this region to look for possible seismically active structures. Because of the lack of identified seismically active structures, the seismic hazard maps for the northeastern United States are based almost exclusively on the past seismic history of the region (Petersen *et al.*, 2014).

This study reports on the occurrence of a swarm of very small earthquakes that took place near Searsport, Maine, in

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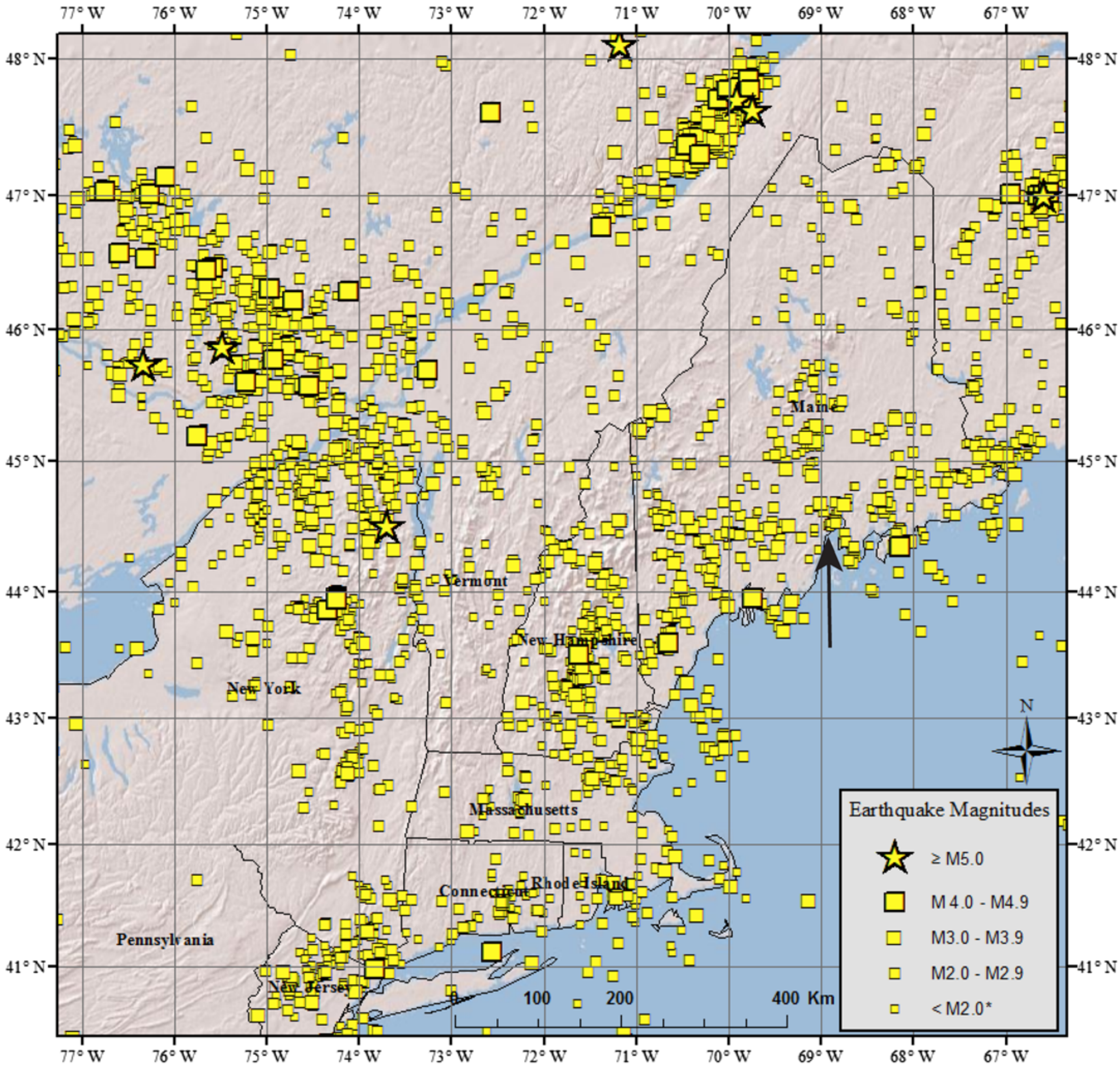


▲ **Figure 1.** Seismicity of the northeastern United States and nearby areas from 1975 to 2014 (prepared with data from http://www.bc.edu/research/westonobservatory/northeast/eqcatalogs.html, last accessed July 2015). The arrow indicates the area where the 2011 Searsport swarm took place. The color version of this figure is available only in the electronic edition.

April and May 2011 (Fig. 1; Table 1). Although the largest earthquake of the swarm was only M_{Lg} 1.7, 21 events were detected by the regional seismic network stations. Furthermore, an additional five events that were too small to be seen by the regional network were confirmed from the operation of two portable seismic instruments that were installed in the Searsport area for the later part of the swarm. Some of these microearthquakes were heard by local residents, who described the earthquake sounds as similar to "gunshots," "shotgun blasts," and "explosions." In this study, the relative and absolute locations of the events in the swarm are analyzed, and the relationship of the locations of the swarm events to the local geological structures is discussed.

SEISMOLOGICAL DATA FOR THE 2011 SEARSPORT SWARM

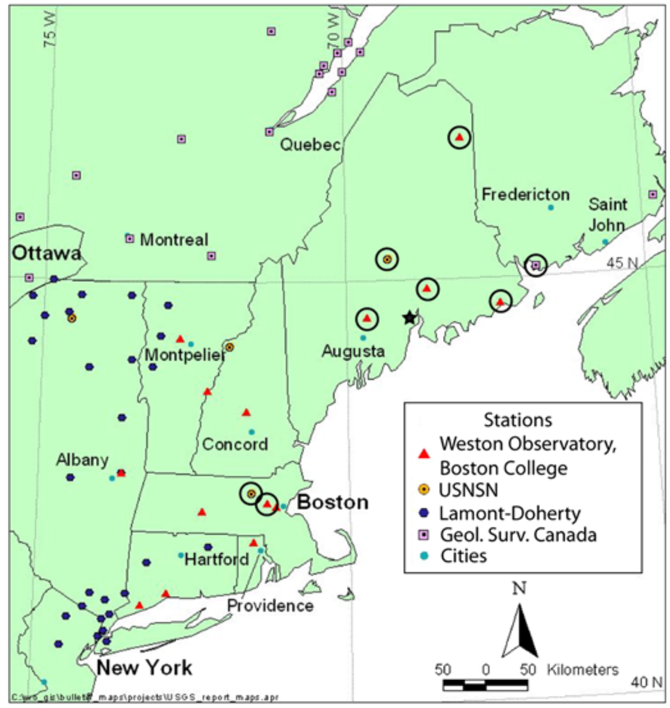
The 2011 Searsport swarm started with an earthquake of M_{Lg} 1.4 on 29 April 2011 that was detected by Weston Observatory as part of its routine regional seismic network

Table 1
Searsport, Maine, Swarm Events

Date (yyyy/mm/dd)	Origin Time (UTC, hh:mm:ss)	M_{Lg}	M_c	Regional (R) or Portable (P) Detection
2011/04/29	17:08:58	1.4	2.4	R
2011/04/30	22:34:01	1.3	2.2	R
2011/04/30	22:52:38	1.7	2.4	R
2011/04/30	23:23:08	1.6	2.3	R
2011/04/30	23:25:44	0.9	1.4	R
2011/04/30	23:26:31	1.3	2.1	R
2011/04/30	23:56:12	1.3	1.8	R
2011/05/01	5:59:51	1.7	2.4	R
2011/05/01	16:19:19	1.4	2.0	R
2011/05/02	22:24:32	1.5	2.1	R
2011/05/02	22:26:55	1.5	1.8	R
2011/05/02	23:01:36	1.7	2.3	R
2011/05/03	0:24:46	1.5	2.1	R
2011/05/03	1:04:39	1.0	1.6	R
2011/05/03	2:03:47	1.6		R
2011/05/03	2:04:23	1.3		R
2011/05/04	4:17:54	1.3	1.9	R
2011/05/04	4:24:05	0.9	2.1	R
2011/05/04	7:24:46	1.2	1.7	R
2011/05/04	8:00:09	1.3	1.7	R
2011/05/08	6:37:43	−0.6		P
2011/05/08	14:45:17	−1.0		P
2011/05/10	10:20:38	−0.6		P
2011/05/10	17:51:34		0.5	R,P
2011/05/10	23:17:12	−2.3		P
2011/05/10	23:58:58	−1.7		P

monitoring (Table 1; see Data and Resources). Just over 29 hours later, a second event with M_{Lg} 1.3 from the same general location was detected, and this small earthquake was immediately followed by several other small events. The swarm continued during the next several days. There was no single largest event; rather, there were eight events with M_{Lg} between 1.7 and 1.5 that were detected during the course of the swarm (Table 1). Another 10 events had M_{Lg} between 1.4 and 1.0.

Because of the persistence of the earthquake activity, Weston Observatory decided to install some portable seismographs in the epicentral area to better constrain the epicenters and depths of the swarm events, as well as to document the rate of microearthquakes at magnitudes below those that could be detected by the regional seismic network. Two portable instruments were installed near Searsport on 8 May and were operated until 15 May. As luck would have it, the portable instruments detected the tail end of the swarm. Six microearthquakes were found in the data recorded by the two portable instruments, one of which was also seen at the closest of the regional seismic network stations (Table 1; see Data and Resources). No events were detected from the Searsport area after 11 May by either the regional network stations or the portable instrumentation.

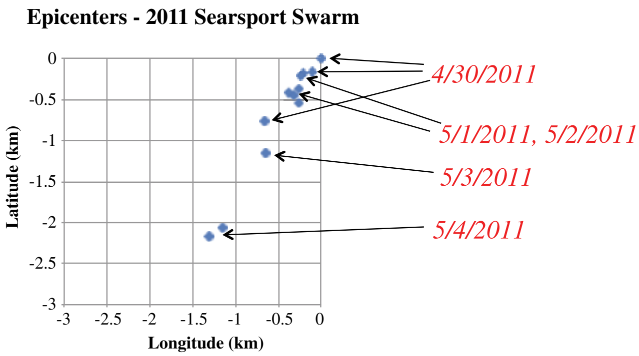


▲ **Figure 2.** Locations of the seismic stations in the northeastern United States and southeastern Canada in 2011. The star indicates the location of the Searsport earthquake swarm, and the circled seismic stations show the locations of the seismic stations that were used in the relative location analysis. USNSN, U.S. National Seismic Network. The color version of this figure is available only in the electronic edition.

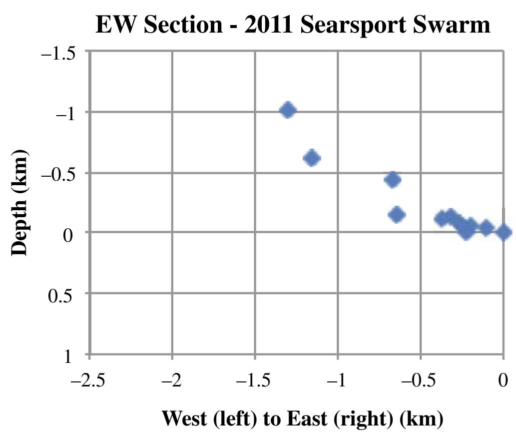
RELATIVE LOCATION ANALYSIS

The occurrence of a number of earthquakes in the Searsport area that were recorded by several of the nearby regional seismic network stations afforded an opportunity to study the spatial extent and development of the 2011 earthquake swarm. This was done using the method of Ebel *et al.* (2008), in which a master event is chosen and other events are located relative to the position of the master event. In order to compute the location of each second event relative to that of the master event, the relative arrival-time differences between the *P* waves or the *S* waves of the two events at a common station are determined by cross correlating the *P* or *S* waveforms of the master event and the second event. These arrival-time differences for a number of seismic stations surrounding the epicenter are inverted for the relative hypocenter and origin-time differences between the two events. For the Weston Observatory data used in this study, the relative arrival-time differences found in the cross-correlation analysis are accurate to about 0.025 s (one digitizing sample).

For this study, the larger earthquakes were well enough recorded by regional seismic network stations within about



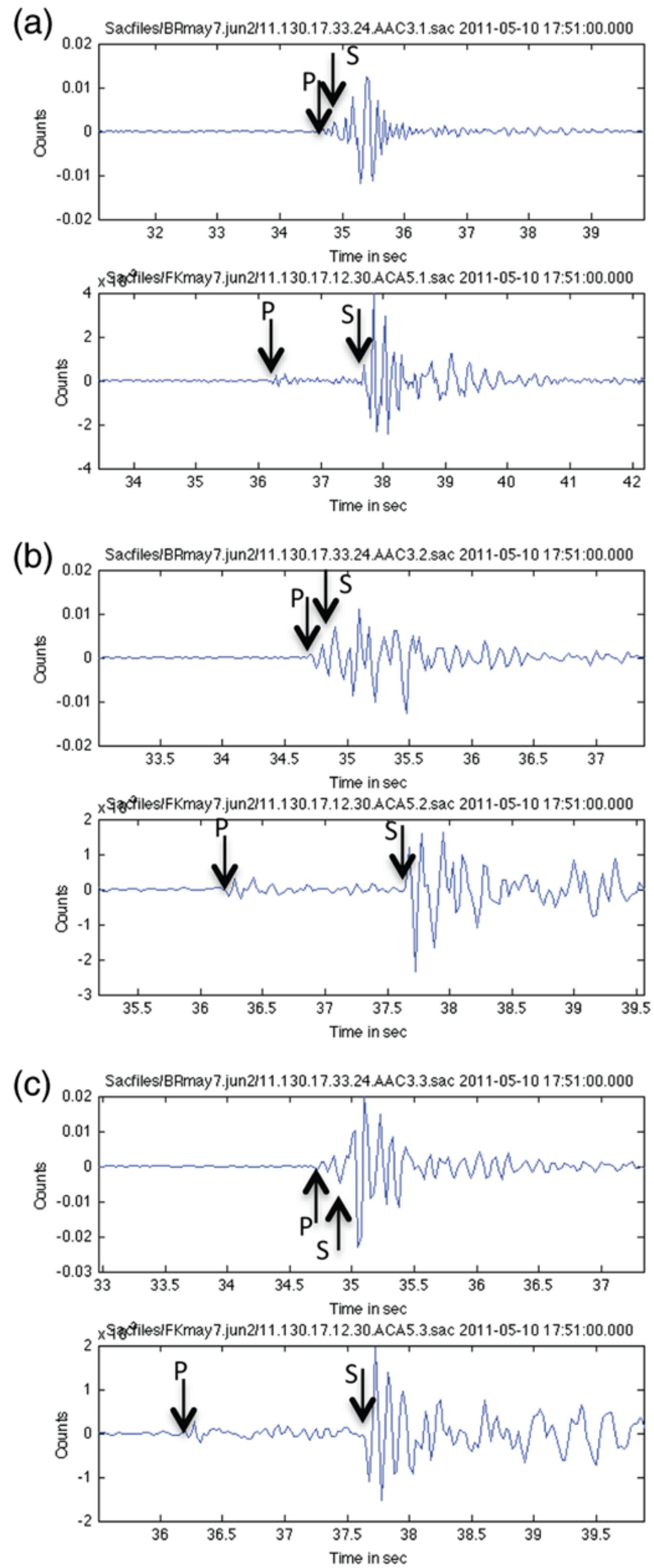
▲ **Figure 3.** Results of the relative location analysis of the 2011 Searsport swarm. The dates indicate the days on which the earthquakes took place. A migration of the swarm events from northeast to southwest is seen during the course of the swarm. The color version of this figure is available only in the electronic edition.



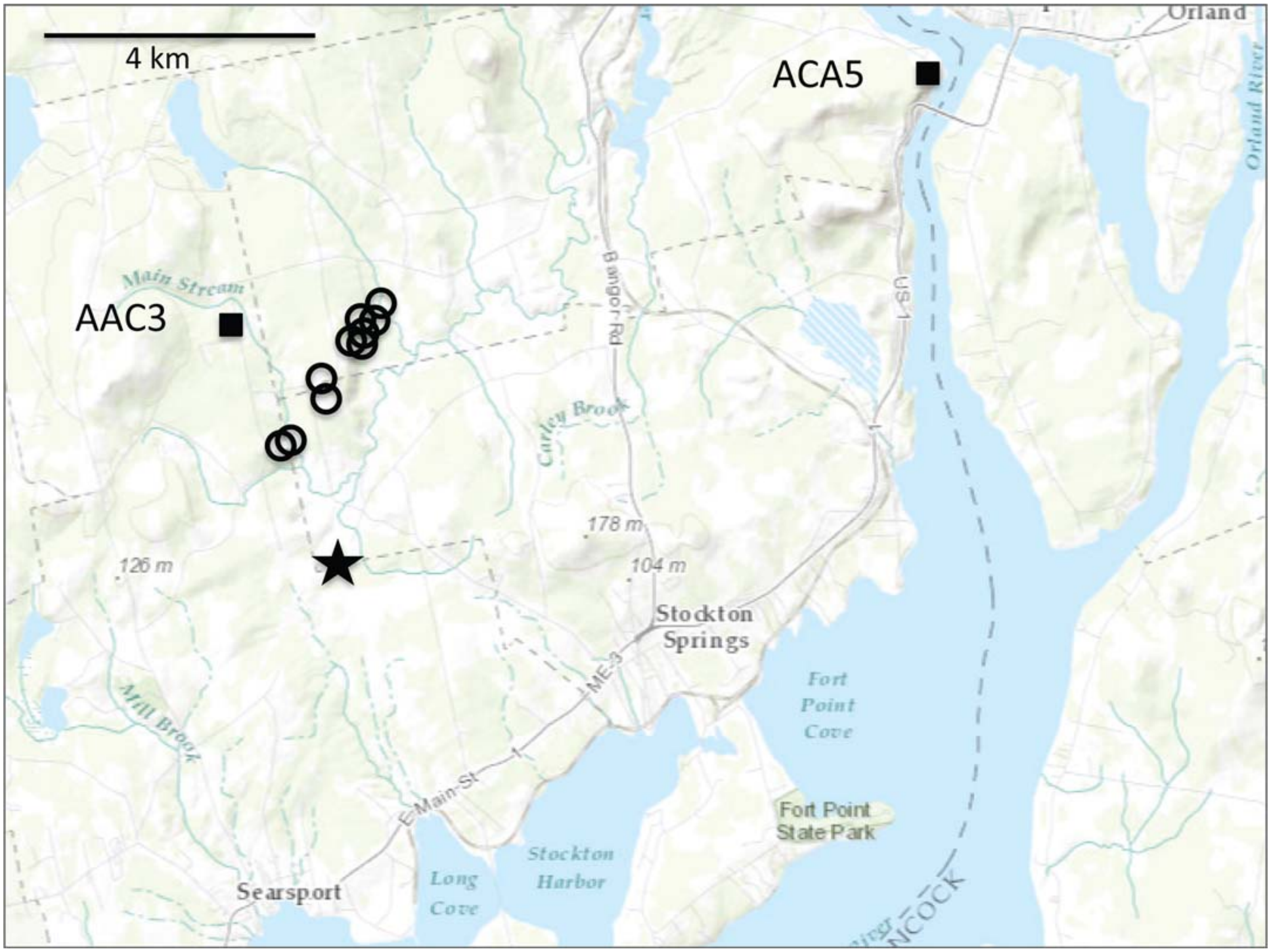
▲ **Figure 4.** West–east cross-sectional plot of the results of the relative location analysis of the 2011 Searsport swarm, showing that the event hypocenters became shallower toward the west. The color version of this figure is available only in the electronic edition.

310 km of the source area that several S and some P relative arrival times could be determined. The stations used in the analysis are shown in Figure 2. The earthquake that was selected as the master event was the M_{Lg} 1.7 shock on 30 April at 22:52 UTC. This event was particularly well recorded by the seismic stations across the region, with very clear P and S waveforms at many seismic stations. Seismic station data were available from stations to the east, north, west, and southwest of the mainshock, which together provided good epicentral constraints in both the north–south and east–west directions, even though there were no seismic stations in the offshore area south and southeast of the swarm.

Well-resolved locations were computed for 11 of the events relative to the location of the master event. All of the events for which well-constrained relative locations could



▲ **Figure 5.** Waveforms of 10 May 2011, 17:51 swarm event. In each pair of plots, the top waveform is from station AAC3 and the bottom waveform is from station ACA5. The plots show (a) the Z components, (b) the north–south components, and (c) the east–west components. The color version of this figure is available only in the electronic edition.

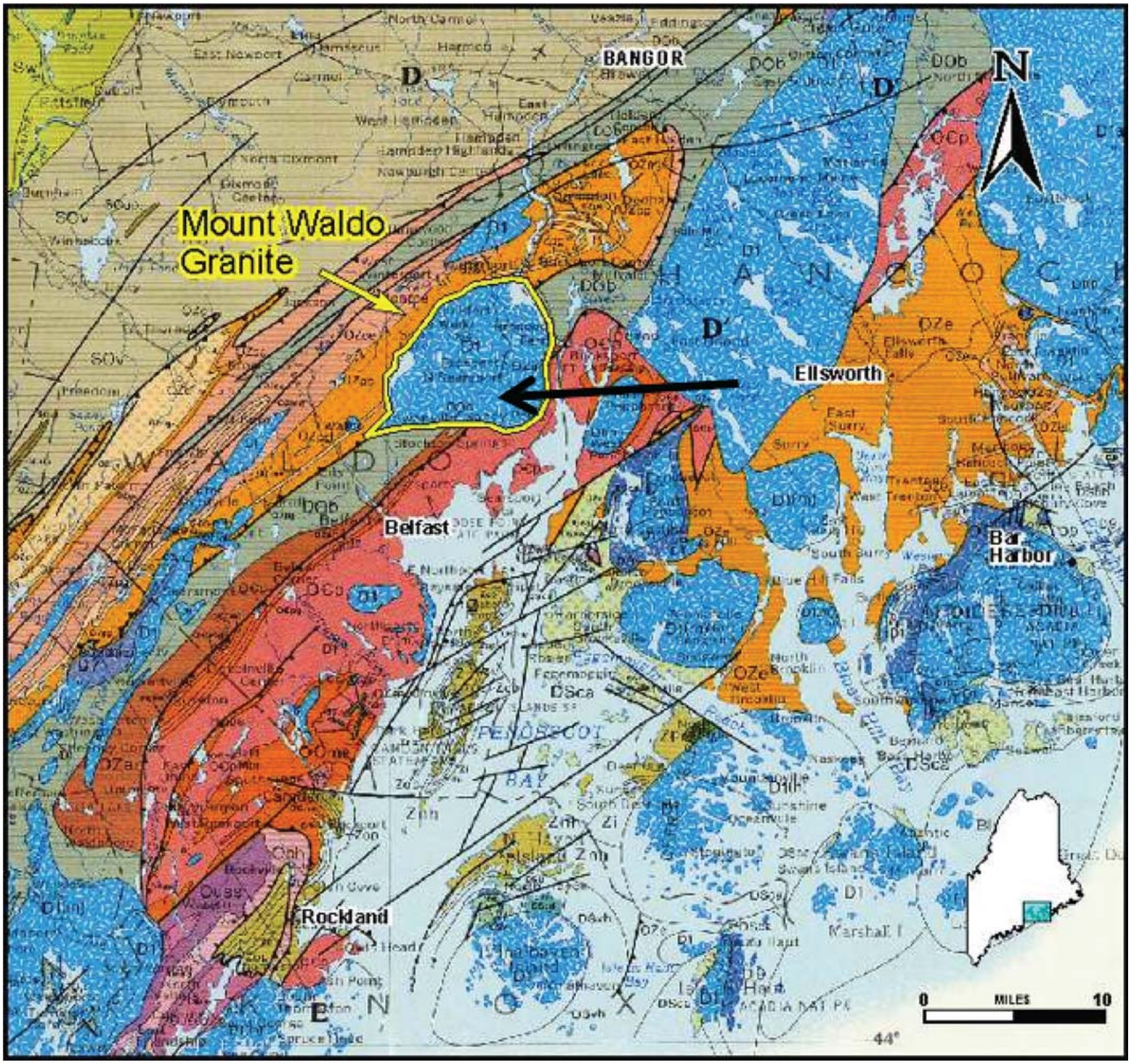


▲ **Figure 6.** Map of the Searsport, Maine, area showing the locations of the portable instruments (AAC3 and ACA5), along with the location (star) of the one aftershock (10 May 2011, 17:51) that was computed with HYPO2000 using data from both the portable instruments and regional seismic network stations. The circles show the estimated locations of the swarm events from the relative location analysis (Fig. 3), with the southernmost event positioned 2 km south-southeast of station AAC3. The color version of this figure is available only in the electronic edition.

be computed had M_{Lg} 1.3 or larger. A map of the relative locations is shown in Figure 3. Two interesting characteristics of the swarm can be seen in Figure 3. The first interesting aspect is that the epicenters of the swarm events trend from northeast to southwest and extend along a distance of about 2.5 km. This trend is resolved in the relative location analysis because the variance of the relative locations is about 100 m for the events near the master event to about 2 km for the events farthest from the master event, as determined by a jackknife analysis (Ebel *et al.*, 2008). The events also appear to trend to shallower depths toward the west (Fig. 4), suggesting that they moved toward the surface as the swarm spread toward the southwest.

The second interesting aspect of this swarm can be seen in the temporal pattern of the epicenters in Figure 3. The swarm started at the northeast end of the epicentral trend and the events migrated toward the southwest with time. On 30 April the epicenters spread over a distance of about 1 km, extending that trend to about 1.5 km on 3 May and then to about 2.5 km on 4 May. The swarm appears to have been associated with the propagation of a crack from northeast to southwest and toward the surface over the course of about—five to six days.

Unfortunately, it is difficult to tie the relative location pattern shown in Figures 3 and 4 to absolute locations in the Earth given the data that were recorded for the swarm. Only one swarm event that was recorded by the portable seismic stations was also detected by the regional seismic network (Table 1). Using data from the two portable seismic stations and from regional seismic networks stations WVL, PKME, and EMMW, the computed origin time and absolute location for this event are 10 May 2011 17:51:34.36 UTC, latitude 42.526° N, longitude −68.930° E, and depth 1.78 km. The errors ERH and ERZ reported by the HYPO2000 computation for this event are 1.3 and 0.8 km, respectively.



▲ **Figure 7.** Bedrock geology map of central Maine (from Osberg *et al.*, 1985). The arrow indicates the epicentral location of the Searsport within the Mount Waldo granitic pluton. The Mount Waldo granitic pluton is outlined by a thick light line. This figure was provided by the State Geologist of Maine, Robert Marvinney. The color version of this figure is available only in the electronic edition.

In addition to the hypocentral calculation based on the arrival-time data, the waveforms of the event on 10 May at 17:51, reproduced in Figure 5, provide a strong constraint on the absolute location of that event. Figure 6 shows the locations of the two portable stations, AAC3 and ACA5, used in this analysis. The waveform at station AAC3 shows an *S-P* time of about 0.34 s, which corresponds to a hypocentral distance of about 2.7 km based on a local seismic *P* velocity of 5.8 km/s (Klemperer and Luetgert, 1987). The *S-P* time at station ACA5, situated 10.8 km from AAC3, is about 1.43 s in Figure 5, which corresponds to a hypocentral distance of about 11.3 km. Thus, AAC3 was effectively atop the hypocenter of this event. If the focal depth of this event is constrained to be 1.78 km from the absolute location described above, then station AAC3 had an epicentral distance of about 2.0 km. Similar *S-P* times were observed for the other swarm events that were detected by the portable seismic instruments. If it is assumed that the events detected by the portable instruments took place at the southwest end of the swarm, then the absolute locations of the events in the swarm can be estimated, as shown in Figure 6. In this scenario, the most southwestern event from Figure 3 was positioned 2 km south-southeast of station AAC3 at a depth of 1.78 km. This location is about 2 km north-northwest of the absolute location of the 10 May 17:51 event (Fig. 6), and it is somewhat outside the epicentral uncertainty computed by HYPO2000. Nevertheless, this is considered the best estimate of the location of the 10 May 17:51 event, given all of the data that are available.

RELATIONSHIP TO THE LOCAL GEOLOGY

The event hypocenters discussed in the previous section are sufficiently precise that the relationship of these events to the local geology can be analyzed in detail. The picture that emerges from this comparison is both intriguing and enigmatic. Figure 7 shows the location of the swarm plotted on the bedrock geology of the Searsport area. The events plot within Mount Waldo pluton, a granitic body of Devonian age. The pluton is thought to be several kilometers thick in the area where the earthquake swarm took place (Sweeney, 1976), and so the events appear to have taken place within the rocks of the pluton itself. As mapped in Figure 7, the pluton cuts a northeast–southwest-trending thrust fault on its southeast side, although Sweeney (1976) notes that the Mount Waldo pluton has two separated deep roots with a shallower zone between them. The 2011 Searsport swarm events appear to have taken place in the shallower zone of the pluton between the two deep plutonic roots. Furthermore, the trend of the earthquakes is approximately parallel to the strike of the fault that is cut by the pluton, and the location of the swarm is on-strike with the projection of the fault into the pluton.

The location of the earthquakes within the granitic pluton but on-strike with a fault outside the pluton presents some challenges. Several possible explanations come to mind, although none of them is fully satisfactory. It is possible that the fault mapped outside the pluton is being reactivated aseismically in the modern stress field and that this fault reactivation is causing local deformations that extend into the pluton. A second possibility is that the thickness of the pluton has been significantly overestimated in the area of the swarm and that the earthquakes occurred on the thrust fault beneath the pluton. The shallowing of the swarm events toward the southwest may even reflect the topography of the bottom of the pluton, if the 2011 events took place along the contact between the granite and the fault beneath the granite. A third possibility is that the fault actually extends through the pluton but that the extension is not expressed (or has not been discovered) at the Earth's surface. In any case, the location and trend of the 2011 Searsport swarm provide some circumstantial evidence that a thrust fault cut by the Mount Waldo pluton might be a seismically active structure.

The 2006–2007 earthquake swarm near Bar Harbor, Maine, also was associated with a granitic pluton (Ebel *et al.*, 2008). The Bar Harbor swarm appears to have taken place on a north-northwest–southsoutheast-trending fault that dips beneath the granitic body that comprises Mount Desert Island, and it seems to have been located near or at the boundary between the granite and the basement rocks into which the pluton was intruded. In that case, the magnitudes of the earthquakes in the swarm reached M_{Lg} 4.2. The Bar Harbor swarm events spread over a distance that was roughly comparable to that at Searsport in 2011. For the Searsport swarm, if the entire earthquake trend had ruptured in a single earthquake, that earthquake would have been about **M** 5.5, based on the surface-rupture scaling relationships for reverse faults of Wells and Coppersmith (1994). For the Wells and Coppersmith (1994) subsurface rupture relationship for reverse faults, the magnitude would have been about **M** 5.1. Thus, an earthquake large enough to have caused some local damage would have taken place if this length of rock had ruptured in a single seismic event.

CONCLUSIONS

The swarm of small earthquakes at Searsport, Maine, in April and May 2011 took place at a focal depth of about 1.8 km and was located apparently within the Mount Waldo granitic pluton. The 2011 swarm epicenters trended—northeast to southwest, on-strike with and parallel to the trend of a thrust fault mapped on either side of the Mount Waldo pluton. The seismic data suggest that the fault outside the pluton might be seismically active, although the modern seismotectonic relationship of the fault and the pluton is far from clear.

DATA AND RESOURCES

The regional seismic network data used in this study can be accessed at the Incorporated Research Institutions for Seismology Data Management Center (IRIS-DMC; http://ds.iris.edu/ds/nodes/dmc/). The map of earthquake epicenters in Figure 1 is from the Weston Observatory website http://www.bc.9edu/research/westonobservatory/northeast/eqcatalogs.html (last accessed July 2015).

ACKNOWLEDGMENTS

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