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# Low-frequency submarine volcanic swarms at the southwestern end of the Okinawa Trough

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[1] A low-frequency (LF) submarine volcanic swarm has been first observed at the southwestern end of the Okinawa Trough where some submarine volcanoes have recently been identified. A swarm of more than 24 earthquakes was recorded at land seismic stations in Taiwan between September 1st and September 4th, 2006. These earthquakes without clear S-arrivals were substantially different from other abundant tectonic earthquakes in the area. The dominant frequency of around 1 or 2 Hz recorded at all stations shows that the LF seismograms were generated by neither path nor site effects, but directly from the source. These LF earthquakes can be characterized as B-type volcanic earthquakes, which have been observed in some active volcanoes before significant eruptions. The observations of these LF volcanic earthquakes beneath submarine volcanic cones and seamounts are strong indicator that some submarine volcanoes are still active at the southwestern end of the Okinawa Trough. **Citation:** Lin, C. H., L. W. Hsu, M. Y. Ho, T. C. Shin, K. J. Chen, and Y. H. Yeh (2007), Low-frequency submarine volcanic swarms at the southwestern end of the Okinawa Trough, *Geophys. Res. Lett.*, *34*, L06310, doi:10.1029/2006GL029207.

## 1. Introduction

[2] The Okinawa Trough (OT) is a typical back-arc basin resulting from the subduction of the Philippine Sea Plate (PSP) beneath the Eurasian Plate (EUP) along the Ryukyu Trench between Taiwan and Japan (Figure 1). The back-arc opening process at the southwestern end of the OT is responsible for both abundant earthquakes [*Fournier et al.*, 2001] and submarine volcanism [*Huang et al.*, 1992; *Sibuet et al.*, 1998; *Hsu et al.*, 2001]. Seismicity at the southwestern end of the OT, in the vicinity of Taiwan where strong plate convergence has taken place, is stronger than that in the rest of the OT [*Fournier et al.*, 2001]. The opening processes at the southwestern end of the OT resemble a tensile fracture accommodating N–S displacement in accordance with the abundant focal mechanisms. In addition to earthquakes, the back-arc opening at the southwestern end of the OT is accompanied by some submarine volcanisms that have been observed in a variety of observations such as submarine morphology, volcanic outcrops, seismic profiles, magnetic anomalies and seismic tomography. Numerous volcanic cones and seamounts have been directly observed on the bathymetrical map in the southwestern end of the OT [*Hsu et al.*, 2001]. The shallow structures of the volcanic outcrops and intrusion have been obtained from seismic profiles as well as geomagnetic anomalies [*Huang et al.*, 1992; *Sibuet et al.*, 1998; *Hsu et al.*, 2001]. A melting feature of a low Vs but high Vp/Vs sausage-like body has been put forth based on the seismic tomography beneath the southwestern end of the OT [*Lin et al.*, 2004]. Furthermore, the western extension of the OT opening might well be associated with volcanism in the northern tip of Taiwan, where some recent seismic observations suggest the Tatun volcanoes might not be extinct [*Lin et al.*, 2005a, 2005b; *Konstantinos et al.*, 2006].

[3] All of the observations mentioned above suggest that potential volcanic activity could very well occur at the southwestern end of the OT, but the understanding of submarine volcanoes is still very limited. Without the appropriate instruments or monitoring systems, submarine eruptions often go unnoticed until their vents or products reach the ocean surface. To detect submarine volcanisms, seismic observation is one of the most efficient methods. Since submarine volcanoes are often at a distance from land seismic stations, hydrophone arrays are the most widely-used instruments to monitor submarine volcano activity through observations of T-waves propagating within the SOFAR (Sound Fixing and Ranging) channel in the deep ocean [*Lin*, 2001; *Tu et al.*, 2006]. Unfortunately, as of yet, no hydrophone array has been set up near the island of Taiwan for monitoring submarine volcanic activity at the southwestern end of the OT.

[4] To detect possible submarine volcanisms in the southwestern end of the OT, in this study we carefully examine available seismic data recorded at the land seismic stations of the Central Weather Bureau Seismic Network (CWBSN) in Taiwan. A seismic swarm composed of 24 volcanic earthquakes was identified in the early September, 2006. Based on seismic characteristics including low frequency contents, the absence of the S-waves and long durations, those volcanic earthquakes can clearly be distinguished from abundant tectonic earthquakes at the southwestern end of the OT. These volcanic earthquakes are further characterized as B-type volcanic earthquakes, which were in fact observed before the eruptions of the 1991 Pinatubo, Philippines [*Ramos et al.*, 1992] and the 1989 submarine Teishi Knoll, Japan [*Yamasato et al.*, 1991]. In light of the above, potential tsunami hazards might be very well be of serious concern in and around the Taiwan area if submarine volcanoes erupt at the southwestern end of the OT.

## 2. Anomalous Seismic Swarms

[5] A careful examination of the earthquake data recorded at the land seismic stations of the CWBSN in

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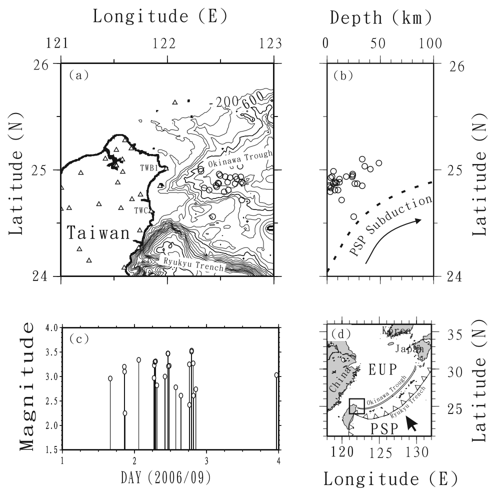


**Figure 1.** (a) Locations of seismic swarms (circles) and stations (triangles) in the northern Taiwan area. (b) Depth projection of the seismic swarms on a N-S profile. (c) Temporary variations in the seismic swarms on Sept. 1–4, 2006. (d) the study area (a box). Okinawa Trough (double-lines) and the subduction of the Philippine Sea Plate (PSP) beneath the Eurasian Plate (EUP) along the Ryukyu trench (line with triangles) are shown in the simplified tectonic map in and around the Taiwan area.

Taiwan definitively reveals that an anomalous seismic swarm took place at the southwestern end of the OT in early September, 2006 (Figure 1a). The preliminary locations through routine processes based on a 1-D model [*Chen and Shin*, 1998] show that most earthquakes were shallow (between 0 and 30 km) and that only a few of them were located below the crust (Figure 1b). Errors in depth estimates, however, are large (from 0.6 km to 2.0 km) because of the absence of S-wave arrivals. The seismic swarm composed of at least 24 earthquakes with local magnitudes ($M_L$) ranging from 2.0 to 3.5 took place within two days without any clear sign of a mainshock (Figure 1c). The local magnitudes are calibrated by the simulated Wood-Anderson seismograms for the short-period seismograms in the Taiwan area [*Shin*, 1993]. After a careful review of the seismograms recorded at all the land seismic stations, it is particularly interesting to note that the earthquakes in this seismic swarm were very unusual, when compared to other abundant tectonic earthquakes located in and around the same area.

[6] With regard to the first difference, most of the anomalous earthquakes recorded at all stations had emergent P-arrivals but lacked of clear S-arrivals (Figure 2). In fact, there is not too much difference among the seismograms shown at three component seismograms. They are very similar to seismograms that were generated by strong scattering processes [*Lin et al.*, 2003], and thus significantly different from abundant tectonic earthquakes with impulse P- and S-arrivals at the southwestern end of the OT. A vertical seismogram recorded at the same station (TWC1) and generated by an anomalous earthquake stands in sharp contrast to one generated by a tectonic earthquake (Figures 3a and 3b, respectively. Although the locations of these two different earthquakes with similar magnitudes were quite close to each other, their seismograms are considerably different. Highly scattering energy without S-wave arrivals are shown in Figure 3a, but P- and S-wave arrivals are clearly recognized in Figure 3b.

[7] As for the second difference, a detailed examination of the swarm frequency content from seismograms recorded at all stations shows the seismic energy was largely dominated by low-frequencies only, which is largely different

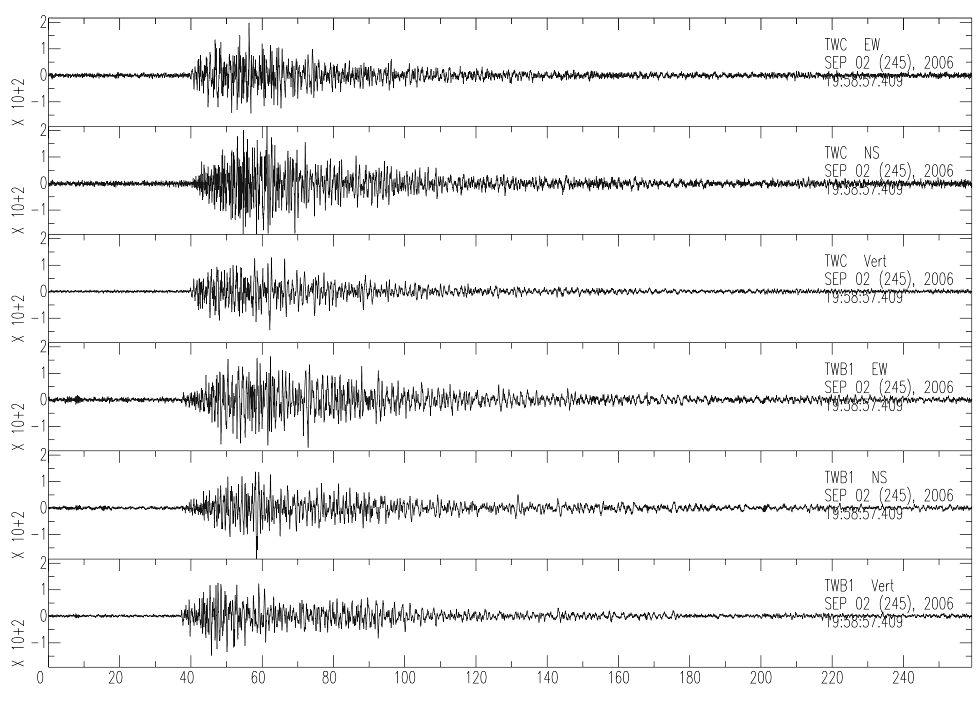


**Figure 2.** Three-component seismograms of a B-type volcanic event recorded at stations TWC and TWB1.

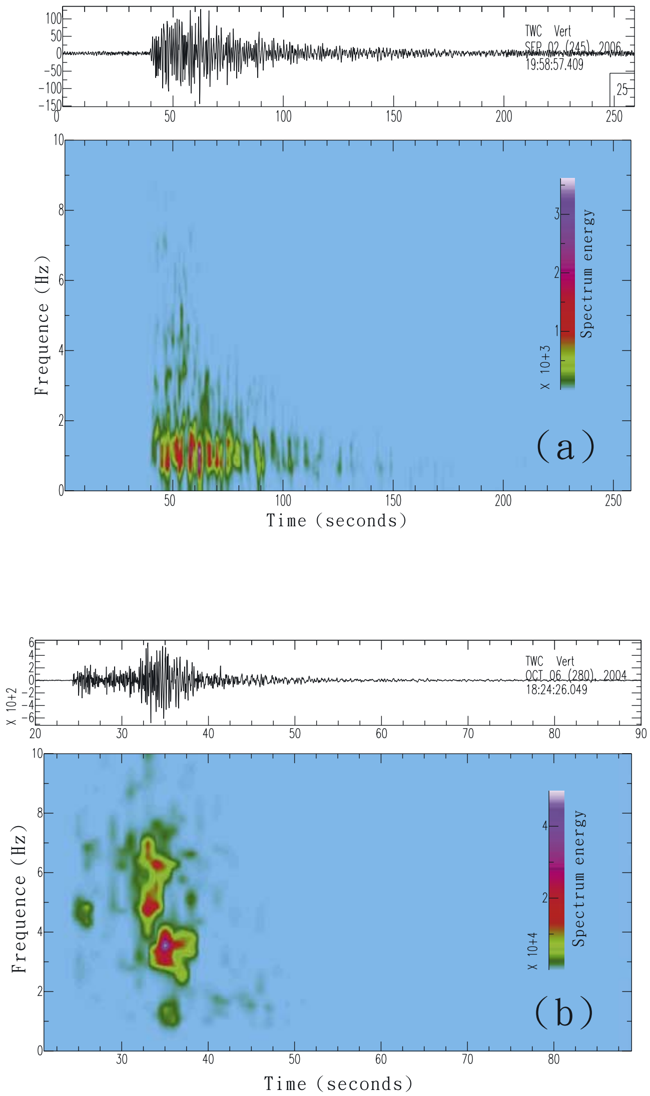


**Figure 3.** (a) Example of (top) a long-period seismogram and (bottom) its spectrogram generated by an earthquake (122.65°E, 24.91°N, 11.6 km, $M_L$ = 3.5) and recorded at station TWC. (b) Example of a high-frequency seismogram with impulse P- and S-arrivals generated by a tectonic earthquake located at (122.345°E, 24.919°N, 2.1 km, $M_L$ = 3.6) and recorded at station TWC.

other tectonic earthquakes with higher frequencies. On the one hand, for example, the earthquake recorded at Station TWC1 (Figure 3a) clearly shows the dominant frequency is 1 Hz with only a very small portion of the seismic energy reaching up 4 Hz. On the other hand, the frequency band of the other tectonic earthquake (Figure 3b) is dominated by 4 ∼ 5 Hz for the P-waves and 2 ∼ 7 Hz for the S-waves.

[8] Finally, the duration of the seismograms of each anomalous earthquake is significantly longer than that of the tectonic earthquakes. For example, the duration of the seismic swarm shown at Figure 3a is more than 100 seconds; against this, that of the tectonic earthquake shown in Figure 3b is only about 30 ∼ 40 seconds (Figure 3b). In other words, the duration of the seismic swarm is at least three times longer than that of the other earthquakes with significantly lower amplitude.

## 3. Discussion

[9] Based on the seismic characteristics mentioned above, the anomalous seismic swarms with low-frequency contents that occurred at the southwestern end of the OT are considered as B-type volcanic earthquakes, which were first characterized by *Minakami* [1960]. *McNutt* [2000] further defines that B-type or LF volcanic earthquakes as consisting of either enriched low frequencies or deficient high frequencies. For example, the dominant frequency of the LF volcanic earthquakes in some active volcanoes is commonly reported to be around 1 or 2 Hz, whereas that of A-type high-frequency earthquake is reportedly 5 to 10 Hz. In this study, the dominant frequency of around 1 or 2 Hz recorded at the CWBSN stations (Figure 3a) shows that the LF seismograms were caused by neither path nor site effects, but directly from the source. Not only that the consistent features of the emergent onset of P-wave arrivals but the absence of the S-wave arrivals further suggest earthquake sources did not belong to the shear-faulting in the brittle crust, but were probably caused by the magmatic activity in the volcanic or geothermal areas, which is typical of B-type volcanic earthquakes. Extremely long duration recorded at all stations also confirm that the LF seismograms were primarily generated by the volcanic earthquakes.

[10] Like the difficulty in locating volcanic earthquakes or tremors in other areas, the location accuracy of the LF earthquakes at the southwestern end of the OT has some uncertainty not least because of poor station coverage and the absence of S-wave arrivals. First of all, the accuracy of the earthquake locations might be contested because they are located outside the seismic network. But the plot of the seismograms with epicentral distances shows the P-wave arrivals were consistently aligned along a constant of apparent velocity (Figure 4). The implication being that the epicenter located by the land seismic stations might be acceptable. Meanwhile, the shallow depths of most of the LF earthquakes without clear S-wave arrivals might be confirmed by apparent velocities estimated from the P-wave arrivals. For most of the shallow earthquakes, the apparent velocities rang from 5.8 to 6.7 km/sec indicate that the earthquakes were probably located in the shallow crust and that the first P-wave arrivals were refracted from some major discontinuities in the upper or mid crust.

[11] A detailed examination of the LF earthquakes on the bathymetrical map and the geomagnetic anomalies shows that the LF earthquakes were clustered in the southwestern end of the OT where numerous volcanic cones and seamounts have previously been observed (Figure 5a). Based on the bathymetric map [*Sibuet et al.*, 1998] and the geomagnetic anomalies [*Hsu et al.*, 2001], some typical volcanic cones and seamounts have been clearly found as shown in Figure 5b. In particular, two typical volcanic cones have been identified at Sites A (122.54°E, 24.90°N) and B (122.65°E, 24.91°N) within the deepest back-arc basin. Another two groups of seamounts are also identified at Sites C (122.70°E, 24.86°N) and D (122.75°E, 24.91°N). In general, the epicenters of the LF earthquakes were clustered around the volcanic cones and seamounts at the

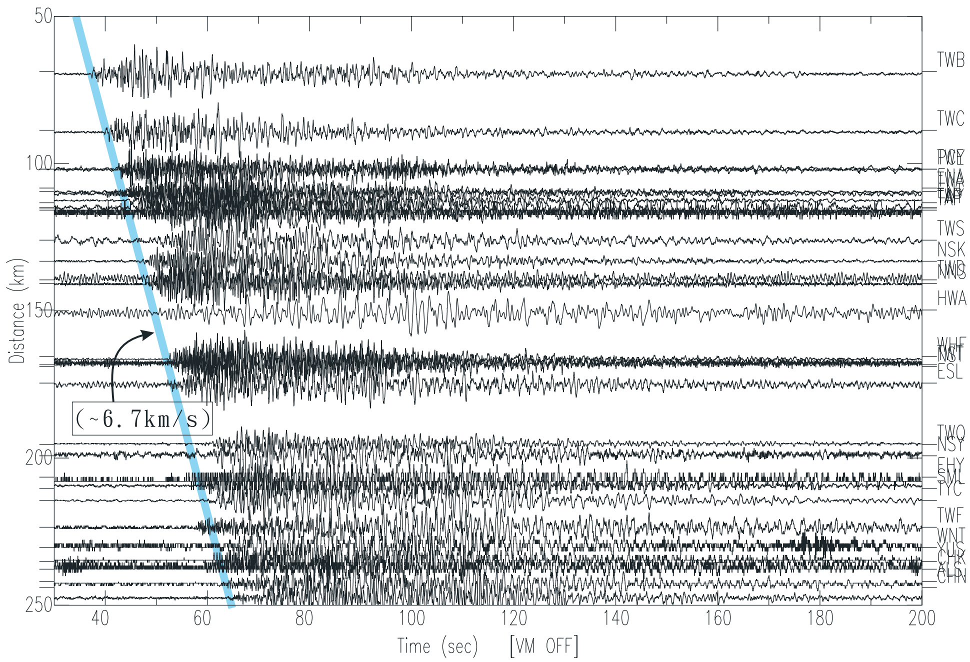


**Figure 4.** Vertical seismograms of a long-period event recorded at all stations.

southwestern end of the OT back-arc basin. As a result, it seems quite probable that the LF earthquakes were associated with those volcanic cones or seamounts, strongly indicative of some recent volcanic activity.

[12] To be sure, the potential eruption of some submarine volcanoes can not be totally eliminated due to the observation of the anomalous seismic swarms consisting of a group of LF earthquakes at the southwestern end of the OT. Low-frequency volcanic earthquakes have been observed before eruptions at some volcanoes such as the 1991 eruption of the Pinatubo volcano, Philippines [*Ramos et al.*, 1992] and the 1989 submarine Teishi Knoll eruption, Japan [*Yamasato et al.*, 1991]. The eruption of a submarine volcano might generate tsunamis [*Smith and Shepherd*, 1993, 1995], and some fatal volcanic tsunamis have been reported in many places such as in the Indonesia region [*Rynn*, 2002], the Caribbean region [*Lander et al.*, 2002] and the Mediterranean Sea (ATWS web-site, http://www.bom.gov.au/nmoc/oceanography/volcanic_tsunami.shtml). Therefore, further seismic monitoring, such as with the submarine cable-OBS, would be extremely valuable to monitor potential eruptions in submarine volcanoes in the southwestern end of the OT that might generate tsunamis and probably affect all cities near the coastline in Taiwan, Japan, China and even Korea.

## 4. Conclusions

[13] This is the first time that a group of low-frequency volcanic swarms has been identified at the southwestern end of the Okinawa Trough. The volcanic swarms were composed of at least 24 earthquakes with magnitudes ranging from 2.2 to 3.5 that all occurred within two days in early Sept. 2006. The preliminary locations of these volcanic swarms, as determined in the routine process by the Central Weather Bureau in Taipei, were clustered at some submarine volcanoes directly recognized from earlier bathymetrical maps, seismic profiles and geomagnetic observations at the southwestern end of the Okinawa Trough. Each of the volcanic earthquakes was largely dominated by the low-frequency signals (1–2 Hz) without clear S-wave arrivals recorded at most of on-land seismic stations in Taiwan. Thus, they can be classified as B-type volcanic earthquakes,

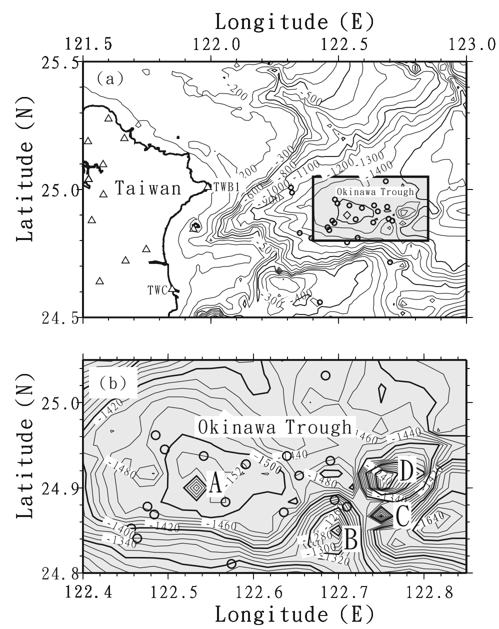


**Figure 5.** (a) Bathymetry and locations of volcanic swarms (circles) and seismic stations (triangles) in the northeastern Taiwan area. (b) Volcanic swarms (circles) and detailed bathymetry in both of grey-scale and contours at the southwestern end of the Okinawa Trough marked with a box in Figure 5a. Local bathymetrical highs are marked by A, B, C and D.

which have been reported in some active volcanoes before significant eruptions occurred. The observations of low-frequency volcanic swarms beneath the submarine volcanoes in the southeastern end of the Okinawa Trough strongly suggest that some submarine volcanoes are still active. Further, it should not be ignored that potential volcanic eruptions could very well generate tsunamis along nearby coastlines.

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