

Preliminary analysis of volcanoseismic signals recorded at the Tatun Volcano Group, northern Taiwan

C. H. Lin,¹ K. I. Konstantinou,¹ W. T. Liang,¹ H. C. Pu,² Y. M. Lin,³ S. H. You,³ and Y. P. Huang³

Received 28 February 2005; revised 21 April 2005; accepted 28 April 2005; published 27 May 2005.

[1] The Tatun Volcano Group lies at the northern tip of Taiwan only 15 km north of the capital Taipei. A seismic array consisting of 5 stations equipped with both broadband and short-period sensors was installed in 2003 in order to monitor the seismic activity of the area. It recorded a variety of events including common volcano-tectonic earthquakes and volcanoseismic signals like tornillos, short duration monochromatic events (10–15 s) and long duration spasmodic bursts (~15 min). An analysis of the complex frequencies of the tornillo/monochromatic signals shows that Q-values are of the order of several hundreds. Based on the model of a fluid-filled crack, such Q-values can result from the oscillations of a crack containing a misty or dusty gas. These observations put into doubt the long-standing suggestion that the Tatun volcanoes are extinct and prompt for a thorough assessment of the volcanic hazard for this area. **Citation:** Lin, C. H., K. I. Konstantinou, W. T. Liang, H. C. Pu, Y. M. Lin, S. H. You, and Y. P. Huang (2005), Preliminary analysis of volcanoseismic signals recorded at the Tatun Volcano Group, northern Taiwan, *Geophys. Res. Lett.*, *32*, L10313, doi:10.1029/2005GL022861.

1. Introduction

[2] The Tatun volcano group (hereafter called TVG) includes more than 20 volcanoes [Wang and Chen, 1990] and is located at the northern tip of Taiwan (Figure 1). TVG is about 15 km north of Taipei, the capital of Taiwan that has more than seven million inhabitants. Besides that two nuclear power plants that were built 30 years ago along the northern coast of Taiwan, are located only a few kilometers northeast of the TVG. Thus, the assessment for any potential volcanic activity in the Tatun area is not only a scientifically interesting topic, but will also have a great impact on the safety of the whole of the northern Taiwan area.

[3] Based on the K-Ar dating [Juang and Chen, 1989; Tsao, 1994] and fission track analysis [Wang and Chen, 1990], the eruption history of TVG can be divided into two major periods: the first eruptive period occurred around 2.5–2.8 Ma, while the second one started 1.5 Ma and continued until around 0.1–0.2 Ma [Song *et al.*, 2000a]. Although the Tatun volcanoes are considered to be extinct because of no previous historical eruptions, some recent

studies suggest that the possibility of future volcanic activity may not be completely excluded [Song *et al.*, 2000b]. In particular, geochemical analysis from fumarole gas shows that the Helium isotope ratios are very high and strongly indicate that some magma chambers might still exist beneath the TVG area [Yang, 2000]. Thus, it becomes a topic of great importance to assess the volcanic hazard posed by the TVG volcanoes.

[4] The installation of local seismic networks is the commonest way to monitor activity in a volcanic area, since any episode of unrest is usually accompanied by increased levels of seismicity. Typically, seismic activity in an active volcano often includes temporal and spatial variations of earthquakes and unusual seismic signals such as various kinds of low-frequency events and volcanic tremor. Although some previously seismic observations such as Yeh *et al.* [1998] were reported in the Tatun volcanic area, they were only focusing on the location of the earthquake activity and not on the analysis of the characteristics of the recorded events. As a result, typical volcanoseismic signals have not been reported in the TVG area yet.

[5] To improve the understanding of potential volcanic activities in the TVG area, in this study we have continuously monitored the seismic activity by using a small-aperture array in the Chishinshan area from May to October 2003. In addition to clusters of common volcano-tectonic earthquakes, we have detected and located some volcanoseismic events such as tornillos, monochromatic signals and spasmodic bursts in and around the Chihshingshan area. The Q-value for a fluid filled resonator has been also estimated from the tornillos and monochromatic events by using the Sompi method [Kumazawa *et al.*, 1990].

2. Data Collection

[6] A small-aperture seismic array consisting of five seismic stations has been installed in the TVG area since May 2003 (Figure 1a). The seismic array was designed to monitor a small area around the Chishinshan volcano where the earthquakes were found to be clustered during a previous seismic experiment [Yeh *et al.*, 1998]. Each seismic station was installed with both a short-period sensor (Lennartz LE3D, with a natural frequency of 1 Hz) and a broadband one (Guralp 30T, with a period up to 30 s).

[7] To protect instruments from possible damage due to the high acidity of sulfides in the volcanic area, seismic stations were put on a concrete-platform and covered by FRP. The seismic instruments were supplied by stable AC power for continuous recording, while a battery was connected for stabilizing power and as an emergency power source. To improve the signal-to-noise ratio, the concrete-

¹Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan.

²Institute of Geophysics, National Central University, Chungli, Taiwan.

³Department of Earth Sciences, National Taiwan Normal University, Taipei, Taiwan.

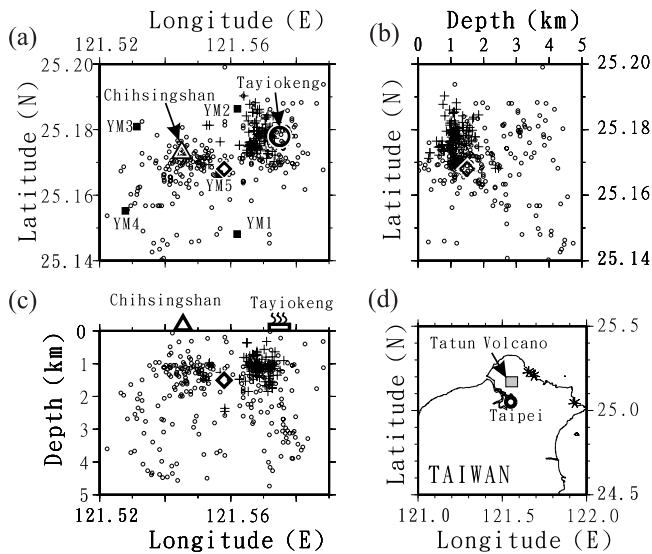


Figure 1. (a) Locations of volcano-tectonic earthquakes (small circles), burst events (pluses), a tornillo (diamond) and seismic stations (squares) in the Tatun volcanic area, northern Taiwan. The triangle and large circle respectively signify the peak of the Chihingshan volcanic cone and actively geothermal area (Tayiokeng). (b) and (c) Projections of focal depth distribution at the W-E and N-S cross-sections, respectively. (d) The locations of Tatun volcano (a box), power plants (stars) and Taipei city in northern Taiwan.

platform was constructed with a number of steel-piers plugged into the ground down to at least 50 cm.

[8] In each station, seismic data recorded by the two sensors were stored into recorders at six channels. All seismograms were continuously sampled at a rate of 100 samples per second. The timing system in each station has been automatically synchronized by the GPS satellite signals. The seismic data were usually retrieved once per month during the regular network maintenance.

3. Seismic Signals Recorded at TVG

[9] The first processing step for the TVG dataset was to create daily drum-plots of the vertical component for all the stations of the network and identify events with good signal-to-noise ratio for further analysis. We used a simple classification scheme based on waveform appearance and frequency content for events recorded at different stations, to group them into two main categories: namely volcano-tectonic earthquakes resulting from brittle failure of rock and signals related to fluid-rock interaction like low-frequency harmonic signals and spasmodic bursts. A description of the characteristics of these two groups is given below.

3.1. Volcano-Tectonic Events

[10] This type of earthquakes exhibited impulsive first P-wave arrivals, clear S-wave phases and substantial energy at higher frequencies (Figure 2a). These phases were picked and the arrival times were inverted using HYPO71 to obtain their absolute locations. The velocity model used for the location purposes is an average 1D model based on the

results of a previous experiment [Yeh *et al.*, 1998]. Formal locations errors for events inside the network did not exceed 0.2 km horizontally and 0.6 km vertically (typical values of ERH and ERZ respectively). Most events with local magnitudes smaller than 1 were located in the uppermost crust at depths less than 5 km. One group of shallow earthquakes was primarily clustered just beneath the Chihingshan volcano, which is the highest peak (1,120 meters) in the TVG area and its topographic relief has a typical volcanic-cone shape. East to this group, some other earthquakes with depths of 2–4 km were roughly scattered around Tayiokeng, where most of the superficial fumaroles showing high Helium isotope ratios are observed.

3.2. Harmonic Signals and Spasmodic Bursts

[11] In addition to volcano-tectonic earthquakes, some signals of purely volcanic origin have also been recorded by our network. During the period covered by our observations three different kinds of volcanoseismic signals were also observed: (a) multichromatic, low-frequency events known also as “tornillos” (Spanish word for screw) because of the appearance of their waveform (Figure 2b), (b) short-duration monochromatic, low-frequency events (Figure 2c), (c) long-duration, high-frequency spasmodic bursts (Figure 3).

[12] The tornillo signals are characterized by a low-frequency multichromatic waveform and slowly decaying codas that increase the duration of the signal up to 40 seconds. The first arrivals of two tornillo signals that were clear enough, were picked at five stations and their source was located (using HYPO71) between Chihingshan and Tayiokeng at a depth of 1.5 km, but with a vertical error estimate of 4 km (Figure 1). We further analyzed the tornillos waveforms by using the Sompí method [Kumazawa *et al.*, 1990] that performs a spectral analysis based on an autoregressive (AR) model and determines the complex frequencies (frequency and quality factor Q) of decaying oscillations. The results of such an analysis are described in a diagram of the frequency (f), versus the

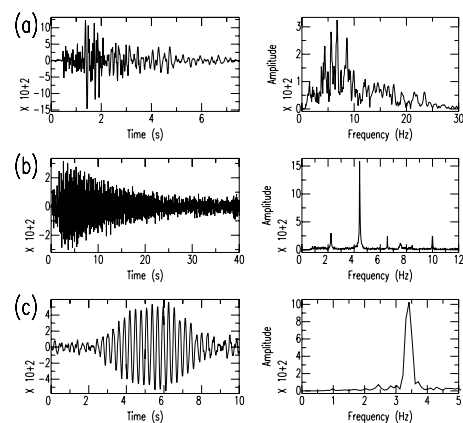


Figure 2. Vertical component velocity waveforms recorded at one seismic station and corresponding spectra of (a) a volcano-tectonic earthquake, (b) a tornillo event, and (c) a short duration monochromatic event. Waveforms have been high-pass filtered at 1 Hz so as to eliminate ocean microseismic and local noise. Note the different time scales of the recorded signals.

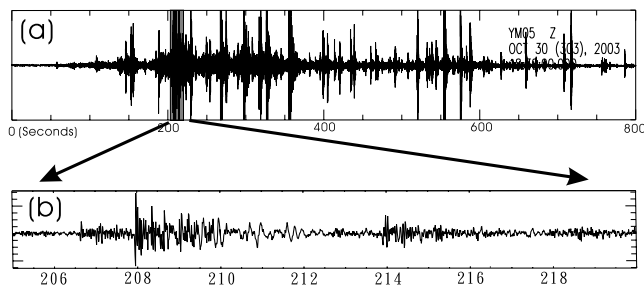


Figure 3. (a) Vertical component velocity waveforms of a high-frequency spasmodic burst recorded at one seismic station, (b) an enhanced section of the highlighted part of the waveform shown in Figure 3a.

growth rate (g), defined as $g = -2Q/f$, where the complex frequencies for different trial AR orders between 20–60 are plotted [see Kumagai and Chouet, 2000]. Areas of the diagram that are densely populated represent stably determined complex frequencies, while scattered points indicate incoherent noise. Figure 4a shows such a diagram for one of the tornillo events we analyzed indicating a Q -value ranging for different frequencies from 400 to more than 1000.

[13] Monochromatic low-frequency signals have usually only a short duration of about 10–15 s. In the frequency domain there is only one broad peak visible, ranging from 3.2 to 3.7 Hz having its largest amplitude at 3.4 Hz. These events appear to have a striking similarity with the “Gota” or drop-shape signals recorded at Galeras volcano, Colombia described by *Narváez et al.* [1997]. We also applied the Sompi method to the decaying part of the waveforms of these events and the corresponding frequency-growth diagram is shown in Figure 4b. These results indicate somewhat lower values of Q between 250–500, but still significantly higher than 100.

[14] Finally, spasmodic bursts are quite occasionally observed in the TVG area and have durations that can range from several tens of seconds to more than 15 minutes. A detailed examination of these signals showed that they are composed of tens of small earthquakes that have clear P and S phases (Figure 3b). We manually picked and located these events in the same way as the volcano-tectonic earthquakes mentioned in the previous section. In total, 119 of such events were located around the hydrothermally active area of Tayiokeng at depths that extended from 0 to 2 km (Figure 1).

4. Discussion

[15] Similar to the results from previous seismic experiments in the TVG area [Yeh *et al.*, 1998], most of the seismic activity manifests itself as clusters of common volcano-tectonic earthquakes. It is interesting to point out that the cluster of small, shallow earthquakes beneath the Chihsingshan volcanic cone is roughly located at depths between 1 and 2 km, which is about the deepest boundary between the Tertiary sedimentary and Quaternary volcanic rocks [Song *et al.*, 2000a]. We may conclude therefore that this kind of activity is the response of the brittle upper part of the crust to the combined effect of the local hydrothermal fluid pressure and the regional stress field.

[16] In addition to the usually reported volcano-tectonic events, it is the first time in the TVG area to observe volcanoseismic signals such as multichromatic tornillos, monochromatic events and high-frequency spasmodic bursts. Tornillos and monochromatic events have long been considered to be the linear or nonlinear response of a fluid-filled cavity to fluid pressure variations, while their different frequency content probably reflects compositional differences of the fluid phase [Seidl and Hellweg, 2003]. If the harmonic signatures observed in TVG are interpreted as oscillations of a fluid-filled resonator, then ash-gas or water droplet-gas mixtures are required in order to explain their long-lasting oscillations with Q significantly larger than 100 [Kumagai and Chouet, 2000]. On the other hand, the difference in the Q values between the tornillos and the monochromatic events can be attributed to two reasons: (a) a variation of the fluid composition that is filling the crack, where the fluid with the lower gas-weight fraction causes oscillations with a higher Q as shown by Kumagai and Chouet [2000]; or (b) a different crack geometry for each kind of event, with the crack having smaller aspect ratio generating oscillations with higher Q values [Kumagai and Chouet, 2001]. The latter explanation has also the effect of increasing the frequency of the generated signal, which seems consistent with the higher dominant frequency of the tornillos (4.2 Hz) in comparison to the monochromatic events (3.4 Hz).

[17] Spasmodic bursts of the type described in this study, have also been observed at Long Valley caldera [Hill *et al.*, 1990] and White island, New Zealand [Nishi *et al.*, 1996]. Even though they seem to consist of ordinary volcano-tectonic earthquakes, the studies mentioned above suggest that they represent the response of an extended network of cracks to the pressure variations generated by fluid injected from a deeper source. Our results seem consistent with this interpretation, since most of the spasmodic bursts events are located in the area of Tayiokeng where there is an abun-

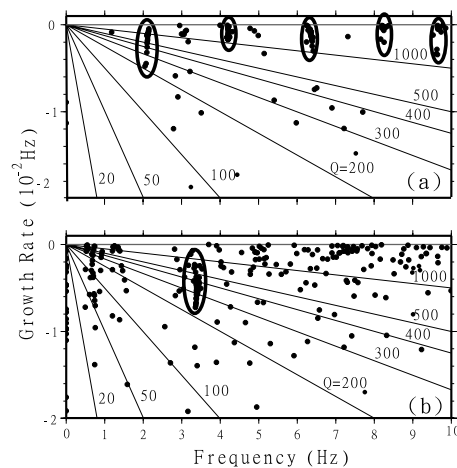


Figure 4. Plots of the complex frequencies of individual wave elements for all the trial AR orders (20–60) estimated for (a) tornillo and (b) monochromatic signals shown in Figures 2b and 2c. The clusters of points within ellipses indicate consistent signals, and the solid lines mark constant Q values.

dance of hydrothermal activity in the form of fumaroles and hot springs.

[18] The manifold seismic activity described in this study puts forward the question whether a magmatic plumbing system may still be working beneath the TVG area. This further leads to the consideration of whether such a vigorous hydrothermal activity can be sustained by a residual magma body 0.1 Ma after its last eruption without any replenishment from a deeper source, if we accept that the Tatun volcanoes are indeed extinct. The answers to these questions are of considerable importance, since according to a phenomenological definition of active volcanoes proposed by Szakacs [1994], TVG may be considered active if its magmatic plumbing system is still working.

[19] The seismic features described in this preliminary study and the geochemical analysis cited previously, suggest that further research should be done in order to be able to assess the volcanic hazard posed by TVG. As a step towards fulfilling this need, we increased the number of the temporary stations of our local network so that they can also cover the seismically active area of Tayiokeng providing additional high-quality digital data. Future work, therefore, will focus on the following aspects: (a) acquiring high precision absolute and relative locations of the best recorded events, so as to be able to accurately delineate the seismic structures inside the study area, (b) spectral analysis of the whole dataset in order to determine the existence of low-amplitude tremor or Very Long-Period (VLP) signals and provide information about the acoustic properties of magmatic/hydrothermal fluids, and (c) determination of focal mechanisms of volcano-tectonic earthquakes for the purpose of inferring faulting-type and stress distribution patterns.

5. Conclusion

[20] A small aperture seismic array has been deployed for monitoring seismicity at the Tatun volcanic area in northern Taiwan. In addition to volcano-tectonic earthquakes, we recorded several volcanoseismic signals such as tornillos, monochromatic events and spasmodic bursts, that have often been reported in active volcanoes worldwide. Although the detailed source mechanism of these signals is still unknown, it is most probable that they are associated with the direct or indirect interaction between hydrothermal or magmatic fluids and solid rock in the upper crust. Combining the earthquake activity and the volcanic signals observed in this study along with the previous analysis of Helium isotope ratios, we suggest that it should be further investigated whether the magmatic plumbing system beneath the TVG is still working. It is thus necessary to

evaluate the volcanic hazard posed by TVG, through detailed geophysical and geochemical monitoring of this area.

[21] **Acknowledgments.** We would like to thank two anonymous reviewers for constructive comments. Gratitude is also extended to the Yangminshan National Park and the National Science Council of Taiwan for financial support through the form of research grants and fellowships.

References

- Hill, D. P., et al. (1990), The 1989 earthquake swarm beneath Mammoth mountain, California: An initial look at the 4 May through 30 September activity, *Bull. Seismol. Soc. Am.*, *80*, 325–339.
- Juang, W. S., and J. C. Chen (1989), Geochronology and geochemistry of volcanic rocks in northern Taiwan, *Bull. Geol. Surv.*, *5*, 31–66.
- Kumagai, H., and B. A. Chouet (2000), Acoustic properties of a crack containing magmatic or hydrothermal fluids, *J. Geophys. Res.*, *105*, 25,493–25,512.
- Kumagai, H., and B. A. Chouet (2001), The dependence of acoustic properties of a crack on the resonance mode and geometry, *Geophys. Res. Lett.*, *28*, 3325–3328.
- Kumazawa, M., Y. Imanishi, Y. Fukao, M. Furumoto, and A. Yamamoto (1990), A theory of spectral analysis based on the characteristic property of a linear dynamic system, *Geophys. J. Int.*, *101*, 613–630.
- Narváez, M., R. A. C. Torres, D. M. M. Gomez, G. P. J. Cortes, H. V. Cepeda, and J. Stix (1997), “Tornillo”-type seismic signals at Galeras volcano, Colombia, *J. Volcanol. Geotherm. Res.*, *77*, 159–171.
- Nishi, Y., S. Sherburn, B. J. Scott, and M. Sugihara (1996), High-frequency earthquakes at White Island volcano, New Zealand: Insights into the shallow structure of a volcano-hydrothermal system, *J. Volcanol. Geotherm. Res.*, *72*, 183–197.
- Seidl, D., and M. Hellweg (2003), Parameterization of multichromatic tornillo signals observed at Galeras Volcano (Colombia), *J. Volcanol. Geotherm. Res.*, *125*, doi:10.1016/S0377-0273(03)00095-7.
- Song, S. R., S. J. Tsao, and H. J. Lo (2000a), Characteristics of the Tatun volcanic eruptions, north Taiwan: Implications for a cauldron formation and volcanic evolution, *Proc. Geol. Soc. China*, *43*, 361–378.
- Song, S. R., T. F. Yang, Y. H. Yeh, S. J. Tsao, and H. J. Lo (2000b), The Tatun volcano group is active or extinct?, *Proc. Geol. Soc. China*, *43*, 521–534.
- Szakacs, A. (1994), Redefining active volcanoes: A discussion, *Bull. Volcanol.*, *56*, 321–325.
- Tsao, S. J. (1994), Potassium-argon age determination of volcanic rocks from the Tatun Volcano Group, *Bull. Geol. Surv.*, *9*, 137–154.
- Wang, W. H., and C. H. Chen (1990), The volcanology and fission track age dating of pyroclastic deposits in Tatun Volcano Group, *Acta Geol. Taiwan.*, *28*, 1–30.
- Yang, T. F. (2000), The helium isotopic ratios of fumaroles from Tatun Volcano Group of Yangmingshan National Park, n. Taiwan, *J. Nat. Park*, *10*, 73–94.
- Yeh, Y. H., C. C. Liu, C. H. Lin, C. C. Liu, and H. Y. Yen (1998), Geophysical monitoring of volcano activities at Mt. Tatun, *Eos Trans. AGU*, *79*(24), West. Pac. Geophys. Meet. Suppl., W124.

Y. P. Huang, Y. M. Lin, and S. H. You, Department of Earth Sciences, National Taiwan Normal University, Taipei, 106 Taiwan.

K. I. Konstantinou, W. T. Liang, and C. H. Lin, Institute of Earth Sciences, Academia Sinica, P O Box 1-55, Nankang, Taipei, 115 Taiwan. (lin@earth.sinica.edu.tw)

H. C. Pu, Institute of Geophysics, National Central University, Chungli, 320 Taiwan.