GEOPHYSICAL RESEARCH LETTERS, VOL. 32, L06304, doi:10.1029/2004GL021143, 2005

Monitoring rapid temporal change in a volcano with coda wave interferometry

Alexander Grêt and Roel Snieder

Center for Wave Phenomena and Department of Geophysics, Colorado School of Mines, Golden, Colorado, USA

Richard C. Aster and Philip R. Kyle

Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, New Mexico, USA

Received 29 July 2004; revised 5 November 2004; accepted 7 February 2005; published 18 March 2005.

[1] Multiply–scattered waves typically dominate the late part of the seismic coda in local earthquake seismograms. Small medium changes that have no detectable influence on the first arrivals are amplified by multiple scattering and may thus be readily observed in the coda. We exploit this idea using Coda Wave Interferometry to monitor temporal changes at Mount Erebus Volcano, Antarctica. Erebus is one of the few volcanoes on Earth with a long–lived convecting lava lake. Large exsolved gas bubbles generate impulsive Strombolian explosions that provide a repeating seismic source of seismic energy propagating through the strongly scattering geology of the volcano. We examined these signals during a particularly active eruptive two–month period between December, 1999 and February, 2000. Early seismograms are highly reproducible throughout this period. During the first month this is also the case for the coda. Approximately midway through this period, however, the seismic coda decorrelates rapidly over a period of several days. This indicates a rapid change in the scattering properties of the volcano, likely reflecting subtle changes in the near–summit magma/conduit system that would not be discernible using direct– or single–scattered seismic wave methods. **Citation:** Grêt, A., R. Snieder, R. C. Aster, and P. R. Kyle (2005), Monitoring rapid temporal change in a volcano with coda wave interferometry, *Geophys. Res. Lett.*, *32*, L06304, doi:10.1029/2004GL021143.

1. Introduction

[2] The seismic waveform coda consists of extended signal following the directly arriving phases [*Aki*, 1969; *Aki and Chouet*, 1975]. At later times the coda is dominated by multiply–scattered waves. Geophysical applications of coda analysis include attempts at earthquake prediction [*Aki*, 1985; *Sato*, 1986], earthquake magnitude estimation [*Lee et al.*, 1972], volcano monitoring [*Aki and Ferrazzini*, 2000; *Fehler et al.*, 1998], separation of intrinsic attenuation and scattering attenuation [*van Wijk et al.*, 2004; *Pride et al.*, 2003] and monitoring of temporal changes [*Chouet*, 1979; *Poupinet et al.*, 1984; *Robinson*, 1987; *Revenaugh*, 1995; *Aster et al.*, 1996; *Antolik et al.*, 1996]. Laboratory applications include Diffusive Wave Spectroscopy [*Cowan et al.*, 2002], reversed time imaging [*Fink*, 1997], and medical imaging [*Li et al.*, 1997].

[3] Small medium changes that would have no detectable influence on the first arrivals are amplified by multiple scattering so that they may be readily observable in the coda. For example, we have previously exploited ultrasonic coda waves to study nonlinear temperature dependence of velocity in granite [*Snieder et al.*, 2002], where the nonlinearity is related to acoustic emissions during thermal cracking [*Fredrich and Wong*, 1986]. Other generally intriguing applications of Coda Wave Interferometry include dam monitoring, time–lapse reservoir characterization, and rock physics.

[4] The subsurface in volcanic regions is typically highly inhomogeneous. Such highly scattering media are thus attractive for applications exploiting multiply–scattering seismic waves [*Wegler and Luhr*, 2001]. In this paper we show the application of Coda Wave Interferometry for monitoring changes at Mount Erebus, Antarctica.

2. Mount Erebus Activity and Instrumentation

[5] Mount Erebus forms the summit of Ross Island, Antarctica, the site of major bases for the U.S. and New Zealand Antarctic Program. The volcano is historically the most active on the continent. The summit conduit system terminates in several vents that host diverse eruptive activity. The most active vent is manifested as a persistent convecting phonolitic lava lake that typically produced several Strombolian eruptions daily from the mid–1990's through December, 2002 [*Rowe et al.*, 1998; *Aster et al.*, 2003]. The volcano is currently instrumented with a five–station interdisciplinary network of stations incorporating GPS, infrasound, broadband seismometers, tiltmeters, infrared, video, and environmental sensors, augmented by a long–standing network of single–component short–period (1–Hz) seismometers (Figure 1).

3. Reproducible Seismic Events at Mount Erebus

[6] *Dibble et al.* [1994] first noted the high degree of seismic waveform similarity for Strombolian eruptions of the Erebus lava lake, which are caused by large (up to 10-m diameter) exsolved bubbles that explosively decompress near its surface [*Aster et al.*, 2003]. Because the lava lake rapidly refills, this eruptive scenario is especially conducive to producing nearly identical events. Figure 2 shows five different events recorded by a broadband seismometer at station E1S. Note the reproducibility of the waveforms over a time frame of several days, with the similarity extending

0094-8276/05/2004GL021143$05.00

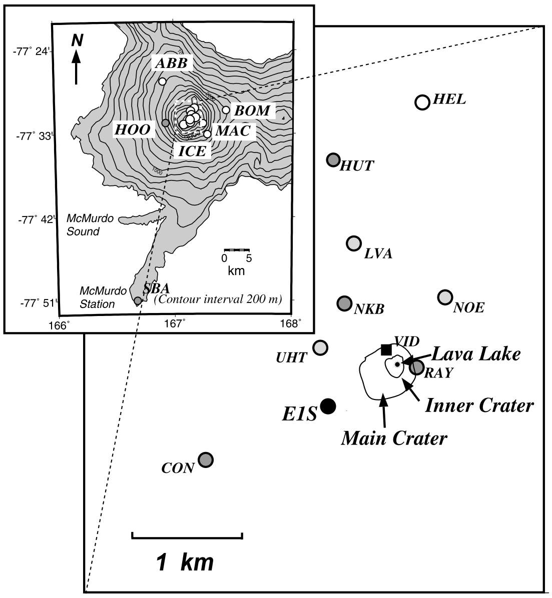

Figure 1. Map of Mount Erebus instrumentation sites (as of 2004). Interdisciplinary sites [*Aster et al.*, 2004], are shown as stars, and short–period seismic stations are shown as circles. VID is the video camera site and SBA is a Global Seismic Network station near Scott Base.

well into the coda (Figure 3). This indicates that, during the period when those earthquakes were recorded, the source, receiver, and seismic Green's function remained nearly invariant.

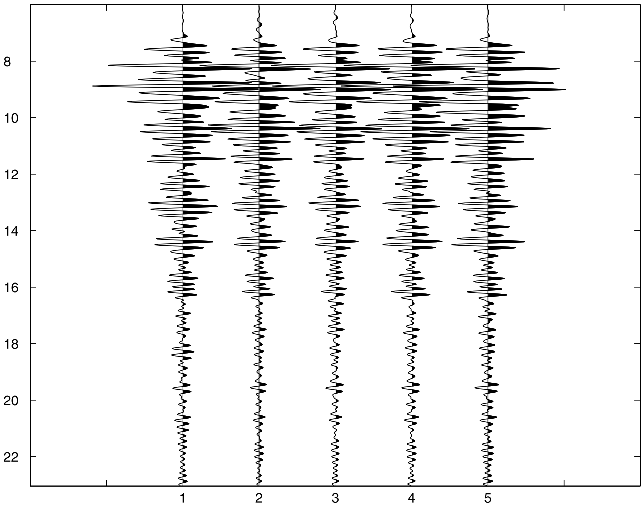

Figure 2. Example lava lake eruptions (Bandpass 0.5–20 Hz) recorded in December, 1999 by a broadband (Guralp 40–T) seismometer at station E1S (vertical component). The station is located approximately 0.7 km from the lava lake (Figure 1). Event 1 occurred on December 12, event 2 on December 13, event 3 on December 14 and events four and five on December 15.

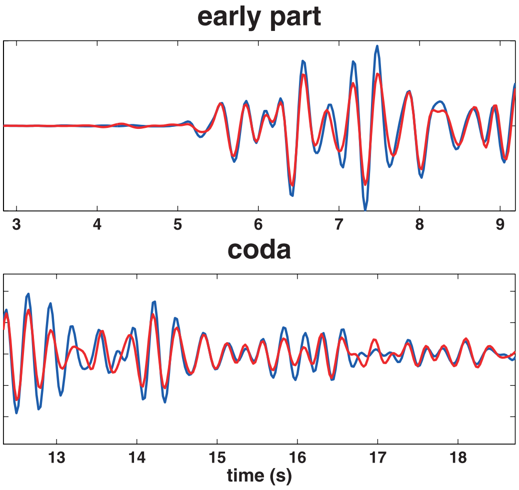

Figure 3. Superimposed early (top) and coda (bottom) seismograms for event 1 (December 12; red) and event 2 (December 13; blue) of Figure 2.

4. Coda Wave Decorrelation

[7] Figure 4 shows a comparison between two events in the manner of Figure 3 for events occurring two weeks apart in time. The early seismogram still correlate extremely well but there is a larger difference in the late parts of the waveforms. *Snieder et al.* [2004] show that a change in source location has an effect on the seismic coda which of the same order of magnitude as the effect on the first arriving energy. Furthermore, the small extension of the lava lake (20 m) restricts the source location to that small area and since the source signature, characterized by the early seismogram, is reproducible, we conclude that the seismic source for the two events and the seismometer remained essentially unchanged. Because the two event codas differ significantly, however, we infer that the medium through which the waves have traveled changed, although the change was too small to significantly affect the early waveforms.

[8] To quantify the waveform differences, we compute the normalized cross-correlation coefficient as defined by

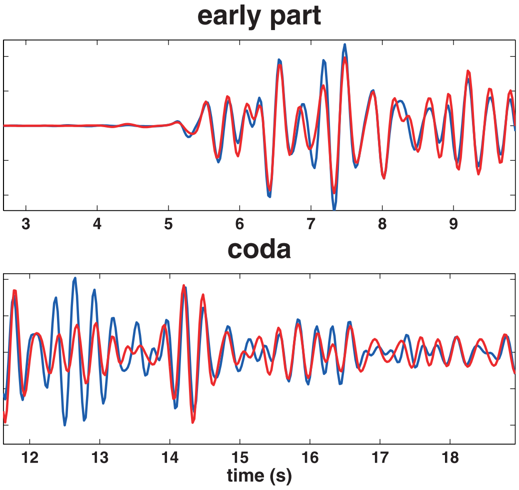

Figure 4. Two vertical–component seismograms recorded at E1S with a two–week time separation, depicted in an identical manner as Figure 3. The early seismogram still correlates very well but there is a significant correlation decrease in the later waveform.

Snieder et al. [2002] for the windows shown in Figure 3. We compute the cross–correlation function maximum for early and late seismogram segments, respectively (Figure 5), using event 1 as a reference. In the top part of Figure 5, the correlations for the early seismograms (dominated by the source signature) are high (all above approximately 0.9) throughout the entire two–month period. For the later waveforms (dominated by the scattering signature), however, correlations drop sharply around January 8, 2000, indicating an internal change at the volcano. The last few points in Figure 5 suggest that the change in the subsurface is a reversible process. The analysis of additional seismic stations (see next paragraph), however, does not support this suggestion.

5. Measurements at Different Stations

[9] To preclude the possibility that local site or instrumentation changes drove the temporal effect depicted in Figure 5, we verified that the phenomenon is also visible at other seismic stations that where operational during the studied time period. Processed four contemporaneously–operation stations (ABB, CON, HEL and HOO), we note a similar correlation coefficient variation at all sites (Figure 6). The correlation levels are generally lower for these stations than at station E1S because of the higher noise levels and the difference in instrument type.

[10] It is difficult to precisely determine the nature of the observed subsurface change because of general uncertainty in the complex paths that the multiply–scattered waves travel and the absence of obvious simultaneous geophysical or physiographic changes at the volcano during the study period. However, there are some scenarios we can clearly exclude. The decorrelation of the coda cannot be due to a widespread change in seismic velocity because that would lead to a diagnostic linear increase in phase shift with increasing travel time [*Snieder et al.*, 2002]. We can also exclude process associated with gradual temporal changes because the observed variation is clearly restricted to a period of a few days around January, 8, 2000. We suggest that geometric or thermal changes in the near–summit lava lake system, fluid migrations in the vicinity of the magmatic system, or fault creep in the upper crater system during this active eruptive period are possible candidates. *Dibble* [1994] showed that much of the coda energy in near–summit recordings from lava lake eruptions probably arises from leaky trapped modes in the low–velocity conduit system. We may thus possibly be observing subtle changes in the uppermost lava lake system and/or associated shallow magma reservoir and its surroundings.

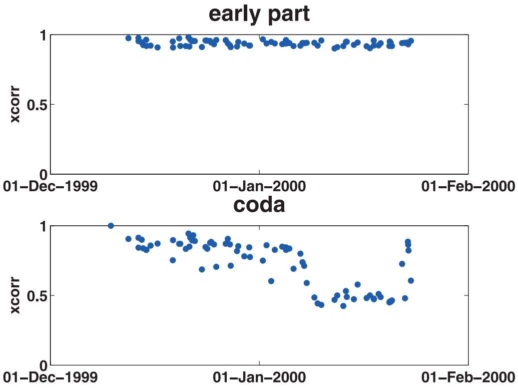

Figure 5. Correlation coefficients for vertical–component Strombolian explosion seismograms recorded at E1S for the early (top) and later (bottom) time segments. All events are correlated with event number 1.

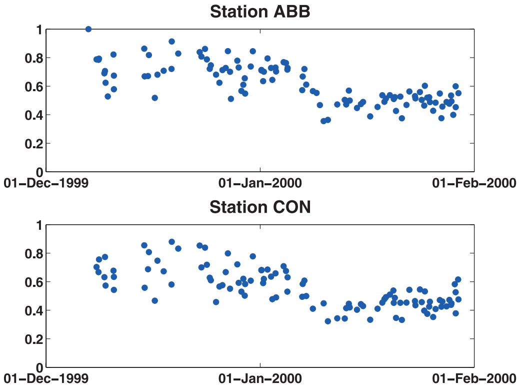

Figure 6. Coda wave interferometry results for short–period stations ABB and CON (Figure 1). The correlation level is in general lower than at station E1S because of the higher noise levels at these analog sites and because some portions of the seismogram are clipped for larger events. (Due to lack of space, results for stations HEL and HOO are not shown.)

6. Conclusions

[11] Strombolian eruptions from the self–reconstructing lava lake at Mount Erebus provide a natural repeating source for monitoring the scattering properties of the volcano with seismic methods. Seismic waveforms from these events recorded at multiple sites around the volcano are highly reproducible in both their early and late portions. During a 2–month period from December, 1999 through February, 2000, we found the source signature, characterized by the early seismogram, to remain virtually identical. The coda, however, shows a distinct drop in correlation across several days around January 8, 2000. This change reflects a subsurface evolution of the volcano that has affected its scattering properties. The change is sufficiently small that it is invisible in the early seismogram. However, the change can readily be seen in the coda because of its high sensitivity to medium changes. Previous modeling of near–summit seismograms suggests that the observed change may be due to subtle evolution of the active Strombolian near–surface conduit system.

[12] **Acknowledgments.** This work was supported by NSF grants EAR-0106668, OPP-9814291, OPP-0116577, and OPP-0229305. We also thank the members of the Center for Wave Phenomena and the Physical Acoustics Laboratory for stimulating discussions.

References

Aki, K. (1969), Analysis of seismic coda of local earthquakes as scattered waves, *J. Geophys. Res.*, *74*, 615–631.

Aki, K. (1985), Theory of earthquake prediction with special reference to monitoring of the quality factor of lithosphere by the coda method, *Earthquake Res. Bull.*, *3*, 219–230.

Aki, K., and B. Chouet (1975), Origin of coda waves: Source, attenuation, and scattering effects, *J. Geophys. Res.*, *80*, 3322–3342.

Aki, K., and V. Ferrazzini (2000), Seismic monitoring and modeling of an active volcano for prediction, *J. Geophys. Res.*, *105*, 16,617–16,640.

Antolik, M., R. Nadeau, R. Aster, and T. McEvilly (1996), Differential analysis of coda Q using similar microearthquakes in seismic gaps. part 2: Application to seismograms recorded by the Parkfield high resolution seismic network, *Bull. Seismol. Soc. Am.*, *86*, 890–910.

Aster, R., G. Slad, J. Henton, and M. Antolik (1996), Differential analysis of coda Q using similar microearthquakes in seismic gaps. part 1: Techniques and application to seismograms recorded in the anza seismic gap, southern California, *Bull. Seismol. Soc. Am.*, *86*, 868–889.

Aster, R., S. Y. Mah, P. Kyle, W. McIntosh, N. Dunbar, J. Johnson, M. Ruiz, and S. McNamara (2003), Very long period oscillations of Mount Erebus volcano, *J. Geophys. Res.*, *108*(B11), 2522, doi:10.1029/2002JB002101.

Aster, R., et al. (2004), Real-time data received from Mount Erebus volcano, Antarctica, *Eos Trans. AGU*, *85*(10), 97.

Chouet, B. (1979), Temporal variation in the attenuation of earthquake coda near Stone Canyon, California, *Geophys. Res. Lett.*, *6*, 143–146.

Cowan, M. L., I. P. Jones, J. H. Page, and D. A. Weitz (2002), Diffusing acoustic wave spectroscopy, *Phys. Rev. E*, *65*, 066605-1-11.

Dibble, R. (1994), Velocity modeling in the erupting magma column of Mount Erebus, Antarctica, in *Volcanological and Environmental Studies of Mount Erebus, Antarctica*, *Antarct. Res. Ser.*, vol. 66, edited by P. Kyle, pp. 17–32, AGU, Washington, D. C.

Dibble, R., B. O'Brien, and C. Rowe (1994), The velocity structure of Mount Erebus, Antarctica, and its lava lake, in *Volcanological and Environmental Studies of Mount Erebus, Antarctica*, *Antarct. Res. Ser.*, vol. 66, edited by P. Kyle, pp. 1–16, AGU, Washington, D. C.

Fehler, M., P. Roberts, and T. Fairbanks (1998), A temporal change in coda wave attenuation observed during an eruption of Mount St. Helens, *J. Geophys. Res.*, *93*, 4367–4373.

Fink, M. (1997), Time reversed acoustics, *Phys. Today*, *50*, 34–40.

Fredrich, J., and T. Wong (1986), Micromechanics of thermally induced cracking in three crustal rocks, *J. Geophys. Res.*, *91*, 2743–2764.

Lee, W. H. K., R. E. Bennett, and K. L. Meagher (1972), A method of estimated magnitude of local earthquakes from signal duration, *U.S. Geol. Surv. Open File Rep. 28*, Reston, Va.

Li, X., T. Durduran, B. Chance, A. Yodh, and D. Pattanayak (1997), Diffraction tomography for biomedical imaging with diffuse-photon density waves, *Opt. Lett.*, *22*, 573–575.

Poupinet, G., W. L. Ellsworth, and J. Frechet (1984), Monitoring velocity variations in the crust using earthquake doublets: An application to the Calaveras Fault, California, *J. Geophys. Res.*, *89*, 5719–5731.

Pride, S. R., et al. (2003), Permeability dependence of seismic amplitudes, *Leading Edge*, *22*, 518–525.

Revenaugh, J. (1995), The contribution of topographic scattering to teleseismic coda in southern California, *Geophys. Res. Lett.*, *22*, 543–546.

Robinson, R. (1987), Temporal variations in coda duration of local earthquakes in the Wellington region, New Zealand, *Pure Appl. Geophys.*, *125*, 579–596.

Rowe, C., R. Aster, R. K. P. Schlue, and J. Dibble (1998), Broadband recording of strombolian explosions and associated very-long-period seismic signals on Mount Erebus volcano, Ross Island, Antarctica, *Geophys. Res. Lett.*, *25*, 2297–2300.

Sato, H. (1986), Temporal change in attenuation intensity before and after the eastern Yamanashi earthquake of 1983 in central Japan, *J. Geophys. Res.*, *91*, 2049–2061.

Snieder, R., and M. Vrijlandt (2005), Constraining relative source locations with coda wave interferometry: Theory and application to earthquake doublets in the Hayward Fault, California, *J. Geophys. Res.*, in press, doi:10.1029/2004JB003317.

Snieder, R., A. Grêt, H. Douma, and J. Scales (2002), Coda wave interferometry for estimating nonlinear behavior in seismic velocity, *Science*, *295*, 2253–2255.

van Wijk, K., D. Komatitsch, J. Scales, and J. Tromp (2004), Analysis of strong scattering at the micro-scale, *J. Acoust. Soc. Am.*, *3*, 1006–1011.

Wegler, U., and B. Luhr (2001), Scattering behaviour at Merapi volcano (Java) revealed from an active seismic experiment, *Geophys. J. Int.*, *145*, 579–592.

R. C. Aster and P. R. Kyle, Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, NM 87801, USA.

A. Grêt and R. Snieder, Department of Geophysics and Center for Wave Phenomena, Colorado School of Mines, Golden, CO 80401-1887, USA. (rsnieder@mines.edu)