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Monitoring rapid temporal change in a volcano with Coda Wave Interferometry

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ABSTRACT

Multiply scattered waves dominate the late part of the seismic coda. Small changes in a medium, which would have no detectable influence on the first arrivals, are amplified by the multiple scattering and may be seen readily in the coda. We exploit this idea using *Coda Wave Interferometry* to monitor temporal changes in the subsurface of the Mt. Erebus Volcano, Antarctica. Mt. Erebus is one of the few volcanoes known to have a convecting lava lake. The convection provides a repeating seismic source producing seismic energy that propagates through the strongly scattering geology in the volcano. Over a time period of two month, the first arrivals of the seismic waves are highly reproducible. Up to one month this is also the case for the coda. After that however, the seismic coda decorrelates rapidly. This indicates a rapid change in the subsurface of the volcano, a change that could not be detected by means of single scattered seismic waves.

Key words: velocity estimation, coda wave, multiple scattering, time-lapse, volcano monitoring

Introduction

The coda of a waveform consists of that part of the signal after the directly arriving phases (Aki, 1969; Aki & Chouet, 1975). At late times the coda is dominated by multiply scattered waves. Geophysical applications based on coda waves include earthquake prediction (Aki, 1985; Sato, 1986), earthquake-magnitude estimation (Lee *et al.*, 1972), volcano monitoring (Aki & Ferrazzini, 2000; Fehler *et al.*, 1998) and monitoring of temporal changes in the subsurface (Robinson, 1987; Chouet, 1979; Revenaugh, 1995; Poupinet *et al.*, 1984). Laboratory applications include Diffusive Wave Spectroscopy (Cowan *et al.*, 2002), reversed time imaging (Fink, 1997), and medical imaging (Li *et al.*, 1997).

Small changes in a medium, which would have no detectable influence on the first arrivals, are amplified by the multiple scattering and may be seen readily in the coda. We have previously exploited ultrasonic coda waves to study non-linear temperature dependence of velocity in granite (Snieder *et al.*, 2002). This nonlinearity is related to acoustic emissions during thermal cracking (Fredrich & Wong, 1986). In contrast to other methods which use multiply scattered energy, the phase information of the coda is a central part of our analysis. There are many other possible applications of this *Coda Wave Interferometry* in geophysics, including dam monitoring, time-lapse reservoir characterization, and rock physics.

The subsurface in the regions of volcanoes is highly inhomogeneous. Such highly scattering media are attractive for the study of multiply scattering of seismic waves (Wegler & Luehr, 2001). In this paper we show the application of Coda Wave Interferometry for monitoring changes in the subsurface of Mt. Erebus, Antarctica.

Mount Erebus, it's Eruptions and the Seismic Network

Mt. Erebus, Ross Island, Antarctica, is currently the most active volcano in Antarctica. The summit of Mt. Erebus contains a persistent convecting lava lake

Figure 1. Mt. Erebus, Ross Island, Antarctica, is currently the most active volcano in Antarctica. The summit of Mt. Erebus contains a persistent convecting lava lake which undergoes several strombolian style eruptions daily. Within the past year, small ash eruptions and a small lava flow have also been observed coming from vents near the lava lake. Aerial view of the summit plateau and volcanic plume of Mt. Erebus.

that undergoes several strombolian style eruptions daily (Rowe *et al.*, 1998). Within the past year, small ash eruptions and even a small lava flow have been observed coming from vents near the lava lake (See Figure 1 for a photo).

The mountain is currently instrumented with a permanent network of nine, single-component short-period (1-Hz) seismometers and one three-component, 1-Hz station, as well as an infrasonic microphone co-located with the summit seismic station (See Figure 2). In 1999, a permanent broadband seismometer was installed along with a tiltmeter and wind speed and direction instrumentation at station E1S. Stations are powered by gel-cell batteries recharged by solar panels; many short-period stations now operate throughout the Austral winter, thanks to sufficient battery capacity combined with their low power consumption (approximately one Watt) (See (Aster *et al.*, 2003) for a more detailed description of the instrumentation at Mt. Erebus).

Reproducible Seismic Events at Mount Erebus

Figure 3 shows five different events recorded at the broadband seismometer station E1S. Event one occurred on Dec. 12, event two on Dec. 13, event three on Dec. 14 and events four and five on Dec. 15, 1999. It's important to note the reproducibility of the waveforms over a time frame of several days. Even when looking at short time windows of the seismic data, the events are virtually identical (Figure 4). Not only are the first arrivals reproducible, the seismic codas of the two events overlap equally well. This means that during the period when those earthquakes were recorded, the source, receiver, and subsurface remained invariant. If either of the three had changed, the seismic waveforms would most probably have changed too.

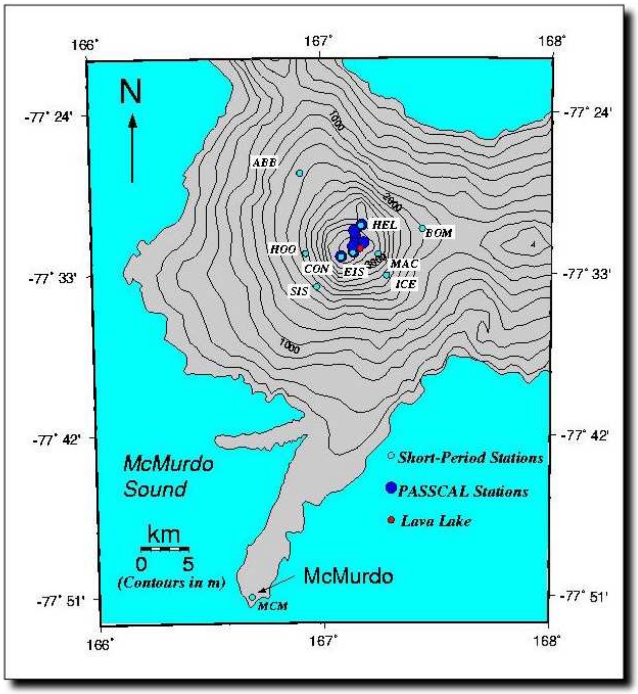

Figure 2. The mountain is currently instrumented with a permanent network of nine, single-component short-period (1-Hz) seismometers and one three-component, 1-Hz station, as well as an infrasonic microphone co-located with the summit seismic station. In 1999, a permanent broadband seismometer was installed along with a tiltmeter and wind speed and direction instrumentation at station E1S. Stations are powered by gel-cell batteries recharged by solar panels; many short-period stations now operate throughout the Austral winter, thanks to sufficient battery capacity combined with their low power consumption (approximately one Watt).

Decorrelation of Coda Waves

Figure 5 shows the same comparison of two seismic events, except that the events occurred on two days that are two weeks apart. The early parts still correlate extremely well but there is a larger difference in the late parts of the waveforms. Since the source signature (early window) is reproducible, we assume that the seismic source (strombolian eruption) for the two events and the receiver (seismometer) remained invariant. Since the codas for the two events are different, however, the medium where the waves have traveled through must have altered. We use this difference to monitor a change in the volcano. That change is too

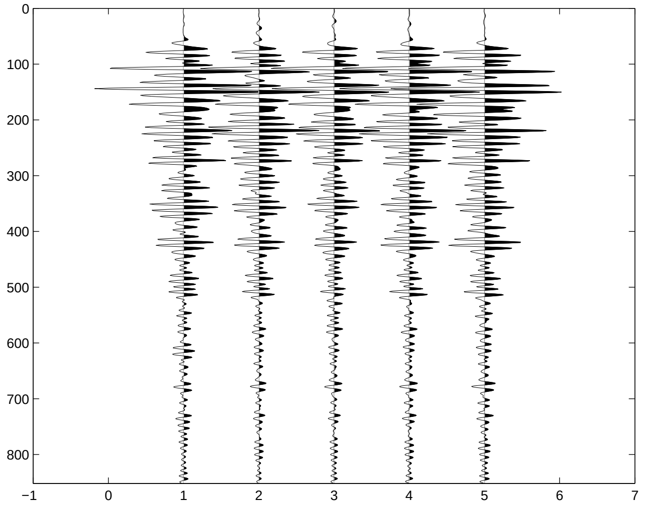

Figure 3. Five different events recorded at the broadband seismometer station E1S. Event one occurred on Dec. 12th, event two on Dec. 13th, event three on Dec. 14th and events four and five on Dec. 15th. Note how well the waveforms are reproducible over a time frame of days.

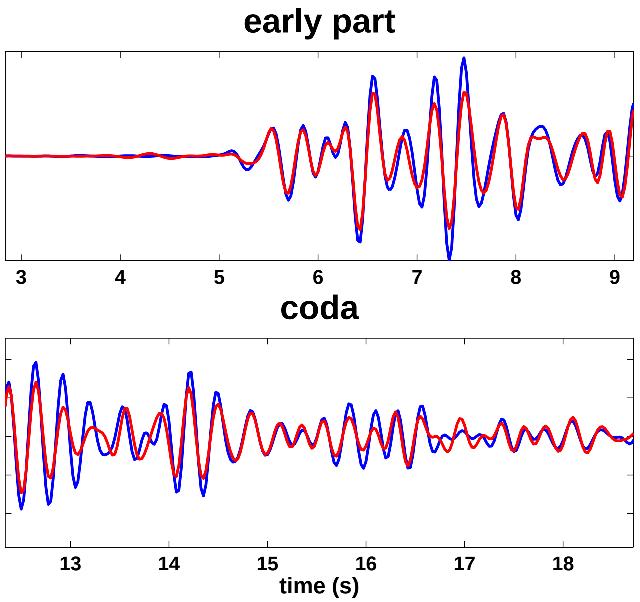

Figure 4. The top of the figure shows the early part of event one (red line) and event two (blue line), plotted on top of each other. The bottom of the figure shows the later part of the same events.

small to have an effect on the early part of the waveforms. In order to quantify the difference in waveforms, we compute maximum of the cross-correlation function for the early parts and the late parts respectively (Figure 6). In the top part of figure 6, the correlations for the early parts (source signature) stay high (around 0.9) over the whole two month period. For the later part of

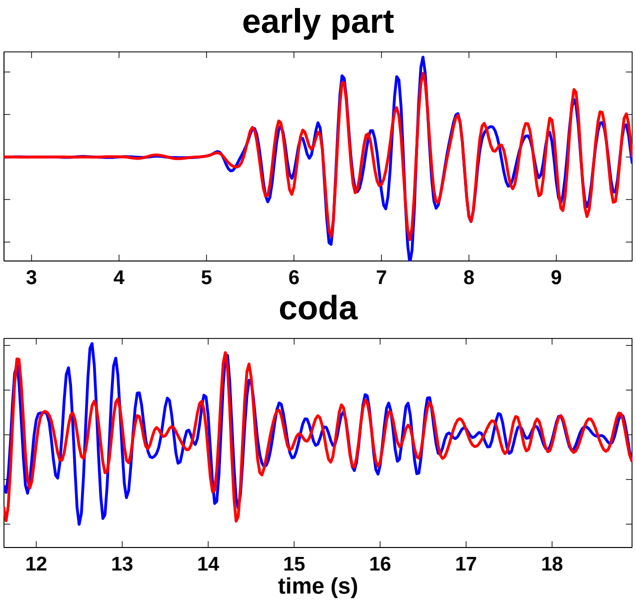

Figure 5. A plot similar to the previous one but the two events here occurred two weeks apart. The early parts still correlate extremely well but there is a larger difference in the late parts of the waveforms. We use this difference to monitor a change in the volcano. That change is too small to have an effect on the early part of the waveforms. In order to quantify the difference in waveforms, we compute the correlation coefficients for the early parts and the late parts respectively.

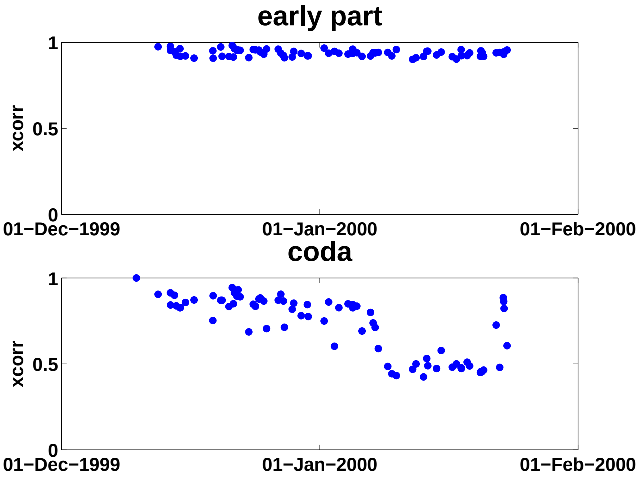

Figure 6. In the top of the figure the correlation coefficients for the early parts stay high (around 0.9) over the whole two month period. For the later part of the waveforms, however, the correlation coefficients have a sudden drop around the 8th of January 2000. This means, that around January 8 something has changed in the volcano that can't be seen in the early part of the waveforms.

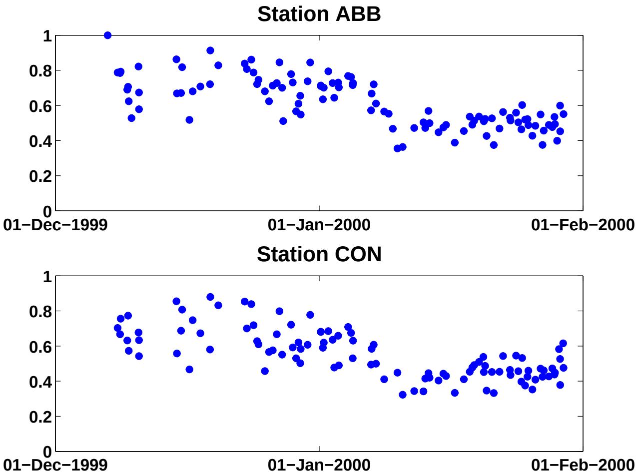

Figure 7. In order to exclude nonlinear artifacts of the instrument at station E1S, we processed four other stations in the same manner. We find a similar jump in correlation coefficients at all four stations (ABB, CON shown here). The correlation level is in general lower than at station E1S because of the higher noise level and the difference in instrument type (some measurements are clipped). Station ABB, CON, HEL and HOO are equipped with short-period (1-Hz) seismometers.

the waveforms, however, the correlations drop sharply around the 8 of January 2000. This means, that around January 8th something has changed in the volcano that can't be monitored with the early part of the waveforms only.

Measurements at different Locations

Since we have more seismic stations on Mt. Erebus we can reproduce this result, therefore excluding nonlinear artifacts of the instrument at the station E1S. We processed four more stations in the same manner as previously described. We find a similar jump in correlation coefficients at all four stations (ABB, CON, HEL and HOO)(Figure 7 and 8). The correlation-level is in general lower than at station E1S because of the higher noise level and the difference in instrument type (some measurements are clipped). Stations ABB, CON, HEL and HOO are equipped with short-period (1-Hz) seismometers with a lower dynamic range than the broadband seismometer at station E1S.

What has Changed?

It is difficult to determine what is the cause of the change in the subsurface because of the complex paths that multiply scattered waves travel. However, there are some scenarios we can clearly exclude. The decorrelation of the coda waves can't be due to a change in seismic velocity only since that would lead to a linear increase in phase-shift with increasing traveltime (Snieder *et al.*, 2002). We can also exclude all gradual changes with time since the time of change can be restricted to a few days around January, 8, 2000. This leaves sudden events such as landslides, movement of lava, or slips on a fault

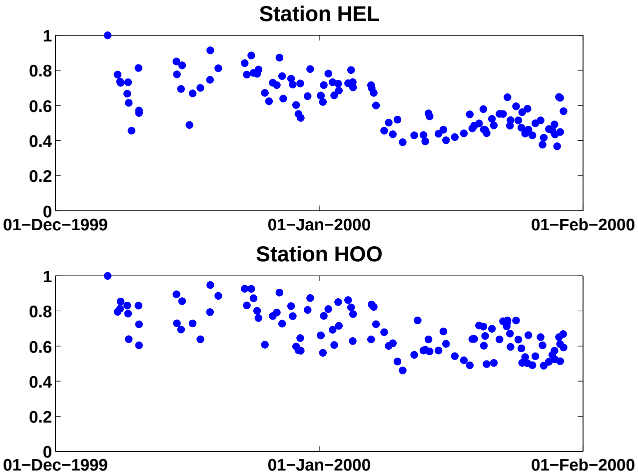

Figure 8. Correlations of first arrivals and coda waves for stations HEL and HOO

Conclusions

The strombolian style eruptions at Mt. Erebus provide a repeatable source for monitoring the volcano with seismic methods. The geology of volcanoes is known to be highly scattering, which provides a good medium for multiple scattering to occur. The seismic waveforms recorded around the volcano are highly reproducible, not only their early arriving phases but also the seismic coda. The source signature remains virtually the same over the whole two-month period. The coda, however, has a distinct drop in correlation around January 8, suggesting a change in the subsurface of the volcano. The change is not gradual but occurs within a time frame of a few days. Furthermore, while the change is so small, that it has no effect on the first arrivals, it's influence can be seen in the coda with its higher sensitivity to a change in the medium.

Acknowledgments

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REFERENCES

Aki, K. 1969. Analysis of seismic coda of local earthquakes as acattered 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., & Chouet, B. 1975. Origin of coda waves: Source, attenuation, and scattering effects. *J. Geophys. Res.*, **80**, 3322–3342.

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

Aster, R., Mah, S. Y., Kyle, P., McIntosh, W., Dunbar, N., Johnson, J., Ruiz, M., & McNamara, S. 2003. Very long period oscillations of Mount Erebus Volcano. *J. Geophys. Res.*, **108**.

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

Cowan, M. L., Jones, I. P., Page, J. H., & Weitz, D. A. 2002. Diffusing acoustic wave spectroscopy. *Physical Review E*, **65**, 066605–1–11.

Fehler, M., Roberts, P., & Fairbanks, T. 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. *Physics Today*, **20**, 34–40.

Fredrich, J.T., & Wong, T. 1986. Micromechanics of thermally induced cracking in three crustal rocks. *J. Geophys. Res.*, **91**, 12743–12764.

Lee, W. H. K., Bennett, R. E., & Meagher, K. L. 1972. A method of estimated magnitude of local earthquakes from signal duration. *U.S. Geol. Surv. Open File Report.*

Li, X., Durduran, T., Chance, B., Yodh, A.G., & Pattanayak, D. 1997. Diffraction Tomography for Biomedical Imaging with Diffuese-photon Density Waves. *Optic Letters*, **22**, 573–75.

Poupinet, G., Ellsworth, W.L., & Frechet, J. 1984. Monitoring Velocity Variations in the Crust Using Earthquake Doublets: an Application to the Calaveras Fault, California. *J. Geophys. Res.*, **89**, 5719–5731.

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**.

Rowe, C., Aster, R., Schlue, R. Kyle P., & Dibble, J. 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., Grêt, A., Douma, H., & Scales, J. 2002. Coda Wave Interferometry for Estimating Nonlinear Behavior in Seismic Velocity. *Science*, **295**, 2253–2255.

Wegler, U., & Luehr, B. 2001. Scattering behaviour at Merapi volcano (Java) revealed from an active seismic experiment. *Geophysical Journal International*, **147**, 579–592.