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Broadband recording of Strombolian explosions and associated very-long-period seismic signals on Mount Erebus volcano, Ross Island, Antarctica

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Abstract. In December 1996 and January 1997, broadband seismometers were deployed on the summit plateau of Mount Erebus at radial distances of 0.7, 1.4 and 1.9 km from the central crater and lava lake. Strombolian explosions at Erebus previously have been observed to produce seismic and acoustic energy between 1 and 6 Hz. New observations document significant energy with spectral peaks as grave as 20 s. Nearly identical very-long-period (VLP) signals begin ~1.5 s prior to explosions, have dilatational onsets and persist for up to 150 s. Similar VLP waveforms were recorded at all three stations, indicating that the seismograms are essentially source-dominated. Particle motions suggest an initial depth for the VLP source of up to several hundred meters, migrating deeper in the course of ~15 s. Such explosion-associated VLP signals may indicate a nondestructive lossy resonance or nonlinear fluid-flow excitation within the shallow magmatic system.

Introduction

Mount Erebus (Figure 1) has been in essentially continuous, low-level eruption since first observations in 1841 (Kyle *et al.*, 1982). Short-period (SP) seismic monitoring since the 1970's (*e.g.*, Giggenbach *et al.*, 1973) has shown that Erebus seismicity is persistent and is dominated by Strombolian explosions originating within the summit lava lake.

In December 1996 and January 1997, IRIS/PASSCAL instruments were installed to augment the permanent, ten-station, short-period Mount Erebus Volcano Observatory (MEVO) network (Figure 1)(Rowe *et al.*, 1997). The deployment included three-component Guralp CMG-3ESP sensors, which have a low-frequency response corner at 30 seconds. These were installed as stations NKB, LVA and HUT, (Figure 1b) on the summit plateau at elevations of 3561, 3360 and 3348 m, respectively, in an approximately radial line at distances of 0.7, 1.4 and 1.9 kilometers from the crater and lava lake (elevation 3570 m). The stations were operational from December 4, 1996 through January 8, 1997.

Observations

Lava lake explosions at Erebus typically occur several times per day, with occasional swarm activity (Knight *et al.*, 1996). SP explosion seismograms exhibit similar waveforms to frequencies of several Hz, suggesting consistent source mechanism, location, and ray path parameters (Dibble *et al.* 1994). Figure 2a shows a typical explosion detected by the SP network on December 15, 1996. Explosions onsets on SP records are invariably emergent, and usually show low frequency (approximately 1 Hz) precursory signals a second or two before the first strong arrival (Dibble *et al.*, 1994). The addition of infrasonic sensor E1LI in 1996 (Figure 2a) facilitates discrimination of explosion events from other seismicity. Because of the limited dynamic range of the SP network, larger explosion signals are clipped; however, spectral analysis of smaller events shows that energy is largely confined between frequencies of 1 and 6 Hz (Knight *et al.*, 1996).

Thirteen Strombolian explosions recorded by the broadband instruments reveal significant new source features. Eight of the events occurred when negligible oceanic microseismic noise was present. Unfortunately, only one large explosion occurred while all three broadband stations were operational; however, it occurred on a very quiet day and provides excellent data (from a highly repeatable process) for this analysis. Figure 2b shows three-component velocity and displacement seismograms for this event for stations NKB, LVA and HUT (which is also shown in the SP seismograms and infrasonogram of Figure 2a). Significant long-period energy visible in the broadband traces is outside of the passband of the SP seismometers and therefore invisible to them

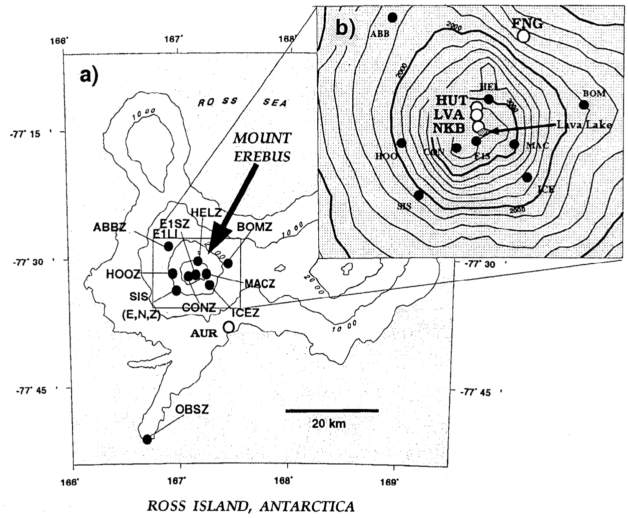

Figure 1. Map of Ross Island, Antarctica, showing stations in the permanent MEVO short-period seismic network (black circles) and IRIS/PASSCAL stations (larger, white circles). Broadband stations NKB, LVA and HUT (center inset) were deployed in a near-radial line extending N from the lava lake.

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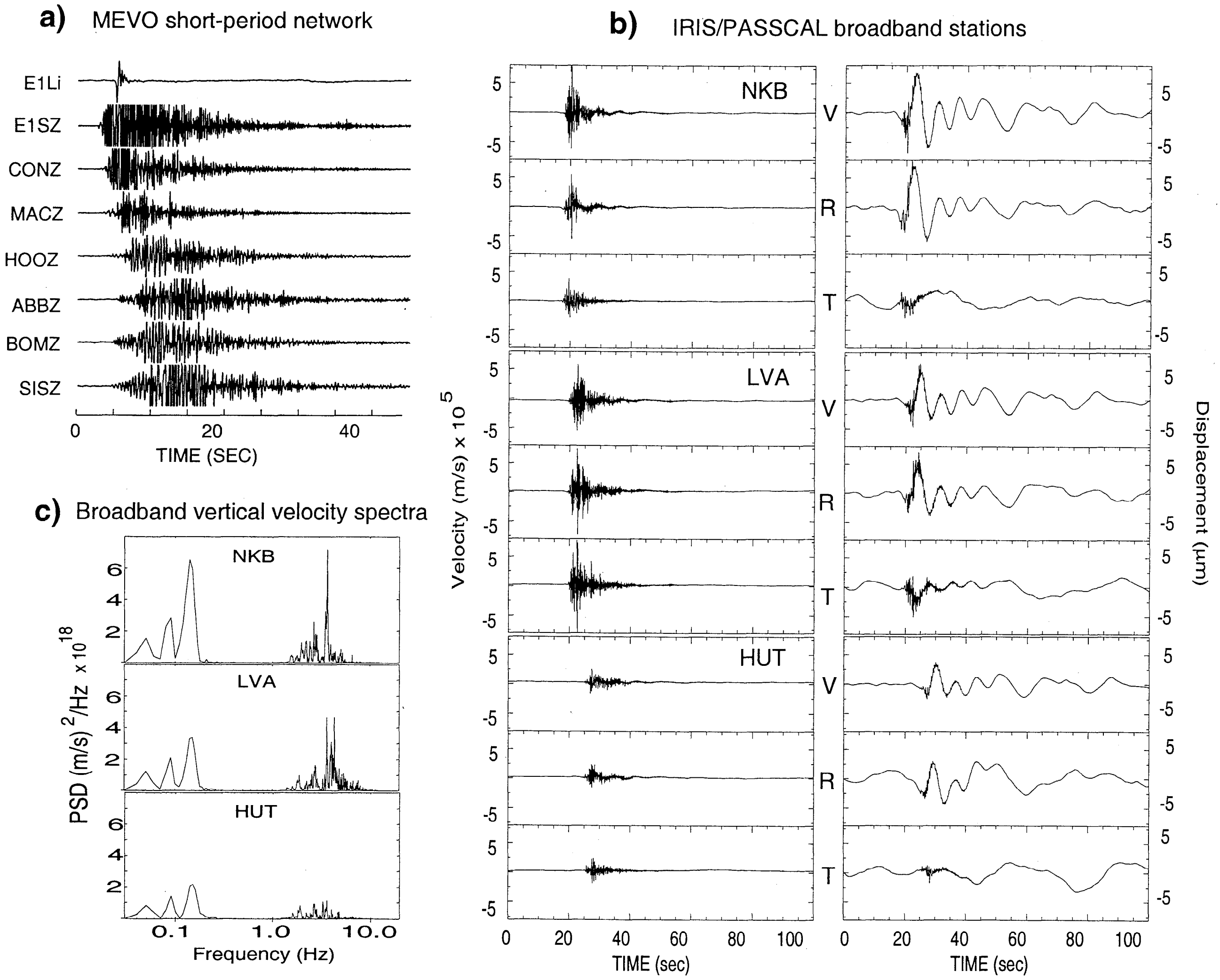

Figure 2. a) December 15, 1996 explosion recorded by the short-period MEVO network (vertical velocity sensors, and infrasonic sensor E1LI. b) Same explosion recorded by broadband sensors NKB, LVA and HUT, rotated into V (vertical), R (radial) and T (tangential) components, with velocity records, *left,* and corresponding displacement records, *right.* c) Velocity power spectral density for vertical broadband components. Note prominent VLP signal peaks at 7.7, 11.4, and 20.4 s and high-frequency energy generated by the surface explosion.

(Figure 2a). Velocity power spectra (Figure 2c) show large peaks at 7-7.5, 10.5-11 and 20-21 s, which we refer to as "very long period" (VLP) signals (*e.g.*, Chouet, 1996). Spectral peak frequencies are consistent with a 20 -21 s fundamental mode and its first two overtones.

Displacement VLP records (Figure 2b) are very similar between events and among stations for 80 s. Interevent similarity (recorded at HUT) persists >150 s for the largest events, indicating a nondestructive source process (Figure 3a). Displacement records show that VLP signals are largely restricted to the vertical-radial (VR) plane (Figure 2b), precede the SP arrival by ~1.5 s, and have first motions indicating implosive initiation.

To examine particle motion in the VR plane, displacement records for the explosion shown in Figure 2 were low-pass filtered at 0.5 Hz to remove less-repeatable SP signals associated with the surface burst (Figure 3b). At all three stations, the initial 15 s of signal display a retrograde elliptical displacement particle motion with a major axis dipping inwards and downwards towards the volcano axis (Figure 3c, top). The initial dip angle ranges from 23° at NKB (0.7 km from the lava lake) to 16° at HUT (1.9 km). In the course of ~15 s, the axis steepens, and motion becomes more linear (Figure 3c, bottom) although it is more erratic at the most distant station (HUT). Later inclinations range from 58°(NKB) to 45°(HUT). Seven other high-quality explosion recordings from HUT confirm the consistency of this behavior.

Geodetic (or near-field, dynamic) displacements due to a spherical pressure source at depth in an elastic half-space (*e.g.*, Mogi, 1958) will be radial with respect to the source centroid. A back-projection of the particle-motion axis thus suggests that a Mogi source associated with the VLP onset would reside at a surprisingly deep 300 to 800 m beneath the lava lake, requiring unrealistically high velocities for mass transfer for subsequent surface explosion. Figure 3d illustrates the projections of both initial and later, linear particle motions for this explosion. Both HUT and LVA are in good agreement as to the volcano axis intercept (800 m), whereas NKB suggests a shallower depth of 300 m. Several factors may influence these estimates. Steeper topography at NKB may produce sharper topographic distortions to the signal than at HUT and LVA, although VLP wavelengths are sufficiently long (λ = 14 to 40 km) to be generally insensitive to the topography of the Erebus summit plateau (Figure 3d). Structural heterogeneity may contribute to an exaggerated apparent depth, although at these

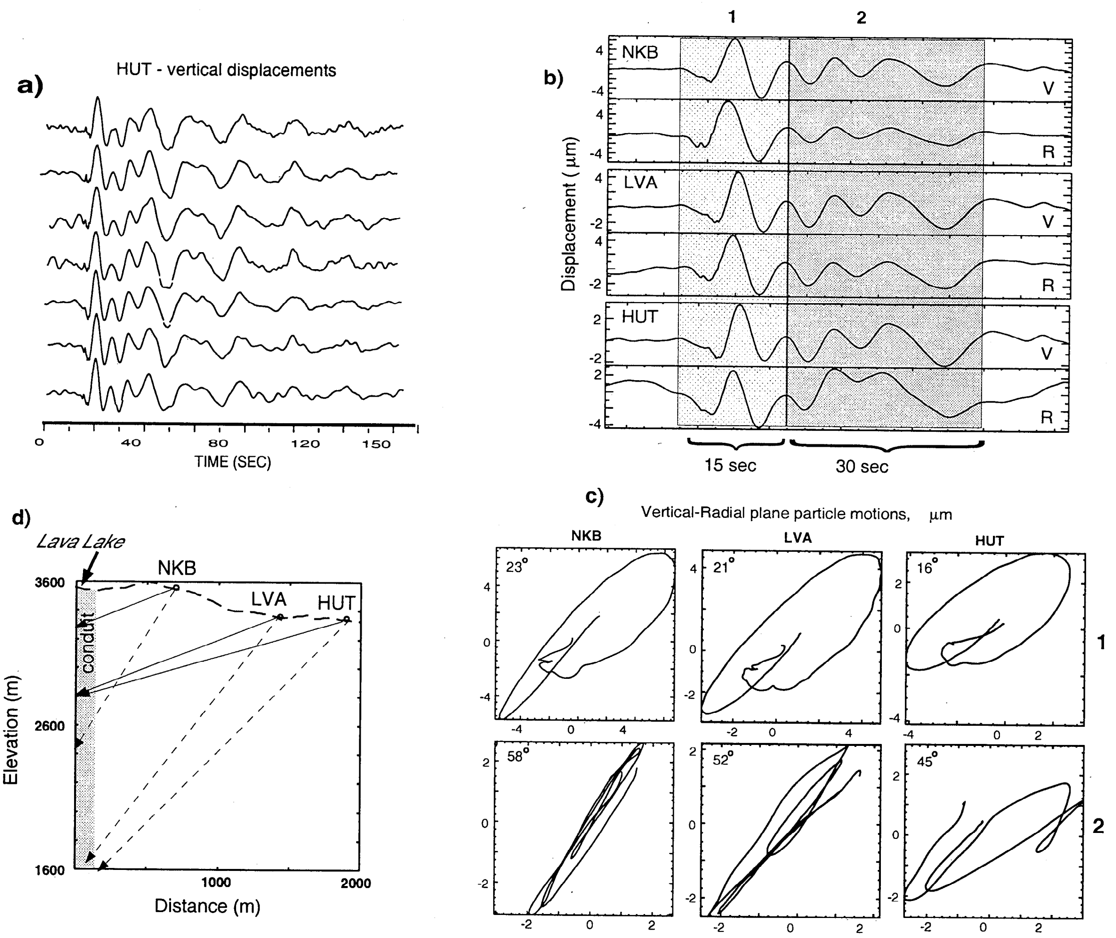

Figure 3. a) Vertical displacement records of seven explosions recorded at HUT. Records are self-scaled. b) Vertical (V) and radial (R) displacement records for the explosion in Figure 2. The 15 s time window "1" and the 30 s time window "2" correspond to the upper and lower particle motion plots, respectively, in 4c. A 0.5 Hz low-pass filter was applied. c) Particle motions in the VR plane, for the traces in 4b, time segments 1 and 2. Initial and final inclination of the elliptical major axis is indicated for each. d) Projections of initial and final particle motion directions. Solid lines correspond to initial inclinations in (1) and dotted lines indicate projections for (2).

wavelengths this should also be minimal in the near field. Strain-coupled tilt, however, may contribute significantly to an overestimation of source depth. If the initial deflation signal also produces tilting towards the volcano axis, the resulting apparent radial-outward acceleration at the sensor (*e.g.*, Aki and Richards, 1980) would be of opposite sign to the inward component of ground acceleration, increasing the apparent source depth. Finally, the Mogi model neglects the possibility that we are observing effects of a non-spherical source region.

Discussion

VLP signals associated with Strombolian explosions at Erebus share features with those recently reported at other volcanoes. Neuberg *et al.* (1994) recorded eruptions on Stromboli and observed associated VLP displacements which were also initiated with implosions. Beam-forming and particle motion analyses at periods longer than 10 s suggested a source 100 to 600 m below the crater. In this case, SP surface explosion signals lagged behind initial VLP contractions by up to three seconds. In a broadband experiment on Sakurajima, Tsuruga *et al.* (1997) observed a variety of polarizations associated with long-period volcanic earthquakes, which began in the VR plane and evolved into transverse motions; however, no VLP signals were reported in association with discrete events. Kaneshima *et al.* (1996) conducted a broadband study at Aso during a period of phreatic activity, and observed slow inflations lasting 50 to 150 seconds before explosive events. VLP particle motion associated with tremor was observed at periods of 15, 7.5, 5, and 3 s. As with Erebus recordings, VLP signals were restricted largely to the VR plane and particle motions suggested a source depth 1 to 1.5 km below the summit.

Chouet *et al.* (1997) investigated explosions at Stromboli with a SP seismic array. Using azimuth and slowness analyses and particle motion evaluations, they concluded that the source resided at shallow depth (<200 m), with occasional energy radiating from as deep as 2.3 km. Haggerty *et al.* (1997) reached similar conclusions from a broadband seismic experiment at Arenal volcano, Costa Rica. Their observations are in accordance with those of Chouet *et al.*, and support a model wherein steady degassing is punctuated by episodes of trapped bubble growth at the top of a magma chamber or conduit constriction, forming a foam layer which escapes as a large rising gas slug that explodes near the surface. Chouet *et al.* (1997) do not address the question of VLP signals, which clearly comprise a significant portion of the explosion signals at Erebus, nevertheless our observations of an initial implosion centered 300 to 800 m (or shallower) beneath the lava lake are consistent with their model, although the apparent increase in source depth over a period of 15 s and the source of the prolonged VLP oscillations remain unknown.

Excitation of a resonance with periods of tens of seconds in such a narrow feeder system (50 to 100 m diameter at the surface) requires very low phase velocities. We speculate that the gas evacuation source could excite longitudinal modes involving shear-coupled tube waves propagating at the conduit boundary, where partial melt would produce very low S-wave velocities. If the VLP signal is a resonance in the conduit, the low Q of the system (approximately 3) indicates a very leaky and/or attenuative resonance mechanism. An alternative possibility is that the VLP signal represents the nonlinear forced excitation of a low-rigidity constriction (e.g., Julian, 1994), generated by recharge flow preceding and following the surface explosion.

Conclusions

Strombolian explosions at Mount Erebus are associated with precursory, implosively initiated VLP signals with periods at least as grave as 20 s. Particle motions suggest an initial source region 0.3 to 0.8 km beneath the summit, although tilt effects may exaggerate this determination. VLP signals are essentially confined to the vertical/radial plane for up to 150 s and are highly similar among events. Surface explosions occur, and associated high-frequency (1-6 Hz) signals begin, ~1.5 s after the VLP onset. Our observations are consistent with a model wherein explosions initiate with the sudden evacuation of a large gas slug accumulating at some constriction at depth (perhaps following a slow inflation, outside of the instrumental passband). VLP signals at periods of 20, 10 and 7 s may be generated by the conduit system through the interaction of low-rigidity structures in association with resonance and/or nonlinear excitation during gas slug removal and recharge.

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