Volcanic Hybrid Earthquakes that are Brittle-Failure Events

Rebecca M. Harrington¹ and Emily E. Brodsky²

¹ Department of Earth and Space Sciences, University of California, Los Angeles, 595 Charles Young Drive East, 3806 Geology Building, Los Angeles, CA 90095-1567, Ph: (310) 825-3212, Fax: (310) 825-2779

² Dept. of Earth and Planetary Sciences, UC Santa Cruz, 1156 High St., Santa Cruz, CA 95060, Ph: (831) 459-1854, FAX: (831) 459-3074
Volcanoes commonly generate a variety of low-frequency seismic signals prior to eruption. Hybrid earthquakes comprise a class of these signals having high-frequency onsets followed by low-frequency ringing. They are used empirically to predict eruptions, but their ambiguous physical origin limits their diagnostic use. Here we use seismic source spectra to show that the hybrid earthquakes of the 2004-2006 Mount St. Helens eruption have a corner frequency-seismic moment relationship that scales consistently with brittle-failure. The scaling is inconsistent with conventional hybrid source models involving a resonating fluid cavity, and therefore hybrids should not be used as direct indicators of subsurface magmatic fluids. The unusually low frequency of these earthquakes can result from low rupture velocities combined with strong path effects due to their shallow sources. This new application of near-field instrumentation provides the first seismological evidence for brittle-failure as a major process in dome building.

Volcanic earthquakes are commonly categorized by their frequency content in order to distinguish their possible physical sources [Lahr et al., 1994; Chouet, 1996; Neuberg, 2000; McNutt, 2005]. Much work focuses on low-frequency earthquakes, as they are arguably the most poorly understood and most distinctive of volcanic systems. Prolonged ringing of ground motions at frequencies ~1 Hz distinguishes them from typical high-frequency volcano tectonic earthquakes, and is often thought to result from either moving fluids or a resonating, fluid-filled conduit [Julian, 1994; Lahr, 1994; Chouet, 1996; Neuberg, 2000]. Hybrids are a subset of low-frequency earthquakes, characterized by high-frequency onsets. Some studies suggest that the onsets represent a
separate trigger that initiates conduit resonance [Neuberg, 2006]. At some sites, hybrids
form a continuum with pure low-frequency events and therefore may be due to the same
mechanism [Neuberg et al., 2000].

Either fluids or path effects account for the low-frequency portion of hybrid
waveforms. Extreme propagation effects are particularly problematic in volcanic areas
and can cause recordings of normal, brittle failure events to appear otherwise low-
frequency [McNutt, 2005]. The protracted source durations inferred from low-frequency
ringing might be explained by trapped waves in the soft, loosely consolidated upper
layers of the volcanic edifice rather than a resonating fluid [Kedar et al., 1996]. Our goal
is to resolve the ambiguity between path and source, and by extension, the origin of
unusual seismic signals of volcanic hybrids. To do this, we first examine a raw record
section to investigate the scaling of duration with distance. We then adopt the Empirical
Green’s Function approach to separate the path effects from the source time function in
the seismic records at Mount St. Helens [Hough et al., 1991; Nakanishi, 1991]. We will
find that the source duration scales with moment in a way that is typical for brittle failure
events. We complete our study by discussing the physical mechanisms that account for
the unusual character of the seismograms.

The current eruption at Mount St. Helens commenced in late September 2004
with a series of steam and ash explosions, followed by extrusion of multiple brittle rock
spines with visible gouge that now form a new dome inside the crater [Pallister et al.,
2006]. Abraded gouge at the base of the spines suggests that the seismicity associated
with the spine extrusions may result from brittle failure between the spine and the
surrounding rock [Pallister et al., 2006]. Periodic earthquakes characterize the
seismicity, commencing with high frequency onsets and transitioning to codas with
spectral peaks at 1-2 Hz and durations longer than is typical for earthquakes of the same magnitude in a standard tectonic setting. There is a lack of purely high-frequency volcano tectonic events, and the hybrid codas do not show the monochromatic peaked spectra found for some occurrences of volcanic tremor. The high-frequency onsets, and long-period, long-duration codas are features shared by hybrid earthquakes seen at other volcanoes such as Montserrat, Redoubt, and Deception Island [Lahr et al., 1994; Miller et al., 1998; Neuberg et al., 2000; Ibanez et al., 2003] (Figure 1). The data for volcanoes other than Mount St. Helens is limited, but the waveform similarity indicates that hybrid events are similar.

The seismograms in Fig. 1 depict hybrids recorded at distances ≥ 1 km from their hypocenters; however, increased instrumentation at Mount St. Helens in early 2005 provides records as close as ~100 meters from the active spine. The particularly hindering path effects in a volcano make close stations crucial to analyzing earthquake source processes. For example, a record section of a $M_L$ 1.1 event on February 26th, 2005 depicts an increased recorded event duration with increasing station distance, demonstrating the extreme scattering effects along the path (Figures 2-3). The shaking duration of 3 seconds at the closest station, MIDE, provides an upper bound on source duration. Although substantially less than the 20-second duration seen at distant sites, it is still two orders of magnitude longer than typical source durations for ordinary earthquakes of this magnitude. To determine whether or not this duration is due to source or path we isolate source spectra using the Empirical Green’s Function approach, and investigate their scaling.

Because the Mount St. Helens hybrids have extremely similar waveforms and are likely located in nearly the same place along the extruding spine, they are well suited for
using an Empirical Green’s Function. We deconvolve the smallest observable event with
spectral amplitude visible above noise on station MIDE with the larger events on that
station to obtain the source time functions of the larger events (Figure 4). We use the
entire length of the larger event for the deconvolution in order to ascertain that the
source-time function has effectively zero amplitude in the coda. Stations MIDE and
NED in the Cascades Chain network are closest to the extruding spine, and therefore
record the widest dynamic range of events. Using both the high- and low-gain channels
also increases the dynamic range of events used. Using the source-time functions
obtained by the Empirical Green’s Function deconvolution, we fit the seismic moment
and corner frequency of the source-time spectra using a least-squares curve fit to a $f^2$
spectrum [Boatwright, 1978; Abercrombie, 1995; Ide et al., 2003],

\[
\Omega(f) = \frac{\Omega_0}{\left[1 + (f / f_c)^4\right]^{1/2}}
\] (1)

where $f_c$ is corner frequency, and $\Omega_0$ is long period amplitude (Figure 5). We did not use
any attenuation coefficients in the fit because we make the common assumption that the
distortion due to propagation and the attenuation through the heterogeneous medium is
linear over the magnitude range considered, and that the Empirical Green’s Function
deconvolution removes these effects [Hough, 1991].

Another logical approach to constraining the source of these events would be moment
tensor inversion. Previous research on low-frequency earthquakes suggested a source
model involving fluid motion and therefore including some volumetric component
[Julian, 1994; Chouet, 1996; Neuberg, 2000]. A non-double couple source could in
principle be identified through a full waveform inversion [Chouet et al., 2003].

However, given the site’s limited near-field station coverage, unconstrained velocity
structure, and significant scattering (Fig. 2), an alternate approach is preferable

[Hardebeck and Shearer, 2002].

Earthquakes generated by a shear dislocation on a 2-D surface are mathematically equivalent to a distribution of double-couples with total moment proportional to the average slip multiplied by the fault area [Burridge and Knopoff, 1964]. The seismic moment for a planar fault is proportional to the product of the stress drop $\Delta \sigma$ and the rupture length cubed. For a circular fault

$$M_0 = \frac{16}{7} a^3 \Delta \sigma$$  \hspace{1cm} (2)

where $a$ is the radius of the rupture. The source radius can be measured from seismograms using the corner frequency $f_c$ and the relationship

$$a = 0.315 \beta / f_c$$  \hspace{1cm} (3)

which relates corner frequency to fault geometry, where $\beta$ is the shear velocity [Madariaga, 1976]. Combining eq. 1 and 2, implies that

$$M_0 \propto f_c^{-3}$$  \hspace{1cm} (4)

if stress drop is size-independent. Although the constants in eqs. (2) and (3) are model-dependent, eq. (4) is a robust relationship for double-couple events and is commonly observed for tectonic earthquakes [Kanamori and Anderson, 1975; Abercrombie, 1995].

Figure 6 shows that the correlation between the $M_0$ and $f_c$ of the Mount St. Helens hybrids is consistent with the model of a standard 2-D fault. The corner frequency, $f_c$, is proportional to $M_0$ on a logarithmic plot with a slope of -3.3 $\pm$ 0.3 (errors are 1 standard deviation of 10,000 bootstrap trials). Examples of the spectra on which the $M_0$, and $f_c$, values of Figure 6 are based are shown in Figure 5. Therefore, a source model of shear
failure on a crack with constant stress drop is consistent with the data.

Many models for hybrids focus on a resonating fluid-filled conduit as the source of the prolonged low-frequency waves. In the simplest model of a linear organ pipe, the frequency content of the signal is determined entirely by geometry and there is no reason that the amplitude (or moment) should scale with frequency in any particular relationship.

Julian proposes a more complex model where the frequency of oscillation is dependent on the strength of the resonating wave due to a coupling between the fluid and elastic systems [1994]. However, even in this nonlinear oscillator, there is no reason that the amplitude (and moment) should scale according to the relationship in equation (4).

Although the $M_0 - f_c$ relationship of the Mount St. Helens hybrids scales in the same way as typical earthquakes, the corner frequencies are lower than expected for a given moment. This suggests that rupture velocity, $V_R$, is low. For example, the local moment magnitudes of the earthquakes in Figure 6 range from 0.2 to 1.5 and corner frequencies range from 5 to 14 Hz, whereas corner frequencies for tectonic earthquakes in this magnitude range are more on the order of tens of Hz [Abercrombie, 1995; Ide, 2003; Venkataraman, 2006]. Earthquake locations and time-lapse photographs of concurrent motion suggest that the earthquakes occur on the rock spine in the crater [Moran et al., 2005]. This unusual situation constrains the absolute epicenter of the earthquakes and therefore measures the seismic wave velocities. Using S-P arrival time and the relation between P and S velocity in a Poisson solid, we calculate the P- and S-velocity in the path to that station. Repeating this for all of the stations within 5 km produces an average value of 700 m/s for the S-velocity, $\beta$. Rayleigh wave velocity, which has a half-space value of $0.9\beta$, generally limits rupture velocity. This estimation
implies a rupture velocity of 650 m/s or less, much lower than typical values of 2-3 km/s at ordinary tectonic sites. The low rupture velocity is the origin of the apparently low corner-frequency of the hybrids, and this combines with strong scattering in the heterogeneous volcanic crust to yield the unusual hybrid seismograms.

Our analysis clearly indicates a source with a spectral scaling consistent with brittle failure. However, it is still possible that the path from the earthquake to the receiver includes a resonating fluid-filled cavity that responds to all the hybrid events and is therefore lumped into the path term of our analysis. We evaluate this possibility using Fig. 2. The increased duration of the waveform with increased distance implies the scattering attenuation is large. In fact, an amplitude decay by a factor ~10$^3$ between stations MIDE and JUN, at distances of 0.110, and 6.2 km from the crater, implies that scattering $Q$ is approximately 10. As is common in scattering attenuation studies, we assume that the duration of the coda increases linearly with distance, and extrapolate the trend to the source duration inferred from the moment estimation of the source-time function obtained from the Empirical Green’s function deconvolution [Aki and Richards, 2002]. Using an $e^t$ decay time as a measurement of duration yields a duration of 0.9 s at a distance of 60 m. While this procedure does not determine the source duration directly, it is a tool to evaluate the extent to which path attenuation outside the conduit makes the source appear extended at the closest stations. Since a resonating conduit should extend the duration of the waveform as recorded near the source, the resonating waves can only account for at most an extension of 0.8 s in the signal. A resonating pipe is not producing the key features of this signal as observed at more typical stations distances of a few kilometers and therefore the extended durations in Fig. 2 cannot be taken as evidence of a
fluid-filled conduit.

Figure 6 implies the self-similarity of earthquakes down to $M_w 0.2$ (the smallest magnitude shown). By combining equations (2) and (3), we see that fitting a straight line to the data in Figure 6 requires that the quantity $\Delta \sigma \beta^3$ must be constant. There is no compelling reason to assume that either $\beta$ or rupture velocity varies dramatically with size, and hence no reason to assume that stress drop does either. This self-similarity for small earthquakes is consistent with results shown by Abercrombie, however we are able to extend these results down to a smaller magnitude [1995].

In summary, the Mount St. Helens earthquakes produce unusual seismograms typical of volcanic hybrids, yet our analysis shows that their $M_{/f}$ relationship is consistent with standard tectonic earthquakes and might be explained simply by brittle-failure in combination with a very complicated path and low rupture velocities. This seismic evidence for the prevalence of brittle failure events favors new eruptive models that use stick-slip failure as the primary mechanism of dome growth [Iverson, 2005]. Furthermore, the data imply that earthquakes are scale invariant down to $M_w 0.2$ with typical stress drops of ~0.5 MPa.

Hybrid earthquakes occur at many volcanoes, and are often precursors to explosive eruption. The continuum of frequency spectra between hybrids and other low-frequency events implies that all of these types of earthquakes may share the same type of mechanism [Neuberg et al., 2000]. Our study shows that in some cases hybrids are consistent with brittle failure, suggesting that fluids are no more necessary to explain the generation of these seismic waves than to explain ordinary earthquakes. Therefore, hybrid earthquakes on volcanoes do not directly and definitively indicate the movement
of a free fluid. Although copious hydrates, or earthquakes of any type, may be useful
indicators of magma pressurization on surrounding rock and hence impending eruptions,
they are unfortunately not fingerprints of magma on the move.

Acknowledgements

The seismic data used here was collected by the Cascades Volcano Observatory (CVO) and the Pacific Northwest Seismograph Network (PNSN), and distributed by the Incorporated Research Institutions for Seismology (IRIS) Consortium. This work was funded in part by the National Science Foundation. We thank Thorne Lay for the use of his empirical Green’s function code. We thank Seth Moran and the staff at CVO for their extensive support during the ongoing eruption, and many valuable insights.
Figure 1. Seismograms for typical hybrid earthquakes at Mount St. Helens, Montserrat, Redoubt and Deception Island [Chouet, 1994; Miller, 1998; Ibanez, 2003; Neuberg et al., 2000]. No obvious differences are apparent between hybrid earthquakes at different volcanoes, suggesting that the physical process causing these events is similar. (All stations recordings are ≥ 1 km from the earthquakes).
Figure 2. Seismic record section plot of a $M_L$ 1.1 hybrid earthquake on February 26, 2005 in the crater at Mount St. Helens. Amplitudes have been normalized by the peak for each trace. The plot shows the duration lengthening with increasing distance from the crater. P-, S- and Rayleigh wave arrivals are annotated on the signal for STD (the only 3-component station shown), where Rayleigh waves were identified using particle motion plots with a band-pass filter of 0.5-2 Hz. The “X” at each station denotes the time duration required for the amplitude to decay to $e^{-1}$ times the value of the peak amplitude (see text). The “O” indicates the intersection of the trend with the source length as determined by the corner frequency.
Figure 3. Seismic Record section shown in Figure 2 band-passed using a 2-pass Butterworth filter from 1-2 Hz to show the peak frequency of this event. Amplitudes have been normalized by the peak of each trace to show the lengthening of duration with distance from the source. This plot shows that source duration is no more protracted above the noise at the dominant low-frequency of 1.6 Hz than the unfiltered record.
Figure 4. Source time function of the earthquake shown in Figure 2, obtained by an Empirical Green’s Function deconvolution on data from station MIDE. The amplitude is the relative amplitude to the smaller event used in the spectral division. The spectral fit yields a Moment of $5.5 \times 10^{10}$ Nm, and a corner frequency of 7 Hz.
Figure 5. (a) Example of a small event used as the denominator in spectral division (Empirical Green’s function analysis) for the February 2005 events at station MIDE. The absolute moment of this event gives the moment of each event using the relative value of \( \Omega_0 \). (b)-(f) Examples of source time function spectra; solid lines indicate data, and dashed lines indicate the fit of eqn. 3. Example (b) is the same event as shown in Figure 2. The table indicates the values obtained from the fit of eqn. (3).

<table>
<thead>
<tr>
<th>Event</th>
<th>( M_w )</th>
<th>( M_0 ) (Nm)</th>
<th>Relative ( \Omega_0 )</th>
<th>( f_c ) (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>0.07</td>
<td>1.5 ( \times ) 10^9</td>
<td>--</td>
<td>13</td>
</tr>
<tr>
<td>(b)</td>
<td>1.1</td>
<td>5.5 ( \times ) 10^{10}</td>
<td>69</td>
<td>7</td>
</tr>
<tr>
<td>(c)</td>
<td>1.0</td>
<td>3.4 ( \times ) 10^{10}</td>
<td>42</td>
<td>6</td>
</tr>
<tr>
<td>(d)</td>
<td>1.3</td>
<td>1.3 ( \times ) 10^{11}</td>
<td>156</td>
<td>6</td>
</tr>
<tr>
<td>(e)</td>
<td>0.9</td>
<td>2.8 ( \times ) 10^{10}</td>
<td>35</td>
<td>8</td>
</tr>
<tr>
<td>(f)</td>
<td>1.1</td>
<td>6.5 ( \times ) 10^{10}</td>
<td>81</td>
<td>7</td>
</tr>
</tbody>
</table>
Figure 6. Logarithmic plot of $M_0$ vs. corner frequency, $f_c$, modeled from the source time functions of the Mount St. Helens hybrids in 2005. Both high- and low-gain channels from stations MIDE and NED of the Cascades chain are used for the Empirical Green’s Function deconvolution. A least-squares fit gives a slope of $3.3 \pm 0.3$, which is consistent with the standard model of a 2-D fault. Most of the earthquakes have stress drops of about 0.5 MPa, falling well within the typical range of values for earthquakes (0.1 to 100 MPa) (14).
References


