Systematic mining and reanalysis of volcano seismo-acoustic waveform datasets

Robin S. Matoza
Department of Earth Science; University of California, Santa Barbara

Image: Tyson Fisher
Large volcano-seismic waveform datasets

- Seismicity plays a central role in understanding how volcanoes work
- Growing seismic data volumes: develop techniques for systematic analyses
- Event detection and cataloging, high-precision earthquake relocation, acoustic localization, waveform and spectral event classification, and source mechanism inversions
Volcano seismology and acoustics

Acoustic
- Atmospheric acoustics (infrasound): ~0.01-20 Hz
- Variety of shallow and subaerial sources
- Explosive volcanism: powerful signals

Seismic
- Migration of fluid from mantle depths to surface
- Faulting & fluid transport in the solid earth
- Limited propagation < few hundred km
Phreatic eruption, Mount St. Helens, 8 March 2005

Seismic

Acoustic

Matoza et al. [2007]
Two broad classes of volcano-seismic signals worldwide

1) **Volcano-tectonic (VT)**

2) **Long-period (LP)** [0.5-5 Hz]

*Chouet [1996]*
Two broad classes of volcano-seismic signals worldwide

1) **Volcano-tectonic (VT)**
   - Shear/tensile failure in brittle solid
   - e.g., intrusions, loading and deformation

2) **Long-period (LP)** [0.5-5 Hz]
   - Actively involve a fluid

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Two broad classes of volcano-seismic signals worldwide

1) Volcano-tectonic (VT)
   • Shear/tensile failure in brittle solid
   • e.g., intrusions, loading and deformation

2) Long-period (LP) [0.5-5 Hz]
   • Actively involve a fluid
   • Includes LP events and tremor

Chouet [1996]
Mount St. Helens 2004–2008 eruption

Spine extrusion and long-period (LP, 0.5–5 Hz) seismicity: some “drumbeats”

USGS fact sheet 2005-3036

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48-hr seismogram ~2 km from summit, November 2004

Deformed glacier
Whaleback
Rockfall scar
Initial spine

1980-86 lava dome

Moran et al. [2008]
Mount St. Helens 2004–2008 eruption

Solid extrusion, plug stick-slip

Iverson et al. [2006]

Cyclic recharge-collapse of a hydrothermal crack

Schematic of Kusatsu-Shirane, Japan
Nakano et al. [2003]

E.g., Iverson et al. [2006]; Harrington and Brodsky [2007]; Iverson [2008]; Kendrick et al. [2014]

E.g., Waite et al. [2008]; Matoza et al. [2009]; Matoza and Chouet [2010]
LP “subevents” or small LPs

Matoza and Chouet [2010]
LP “subevents” or small LPs

Matoza and Chouet [2010]
Single-station cross-correlation to separate event types

Station BLIS 4–16 November 2004

Matoza and Chouet [2010]
Single-station cross-correlation to separate event types

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Matoza and Chouet [2010]
Network-based detection and stacking

- Employ network-based template matching and stacking to boost SNR for waveform inversion
  - e.g., Gibbons and Ringal [2006], Shelly et al. [2007], Shelly and Hill [2011]

Broadband Array at Mount St. Helens [Waite et al., 2008]

[Graphs and data plots showing velocity and correlation coefficients over time and space, indicating analysis of seismic data.]
Network-based detection and stacking

- Slide initial “seed” event through 10-hr waveform; all stations and components
- Compute network-mean correlation coefficient
- Form master event; repeat using 8-days of data 29 June to 7 July 2005
Network-based detection and stacking

- 29 June to 7 July 2005
- 8 days: 892 network triggers
- Stack 359 high-quality triggers
- Linear (mean) stack in 2-hr periods
- Phase-weight stack the 2-hr stacks
  \[\text{Schimmel et al., 2011; Thurber et al., 2014}\]
- tf-PWS: Coherence of instantaneous phase
- Repeat for all stations and components

Example at station S04

Matoza et al. [2015]
• Full seismic waveform inversion for a point-source moment-tensor and single force vector representation of the source [e.g., Ohminato et al. 1998; Chouet et al. 2003; Dawson et al. 2011; Matoza et al., 2015]
• A free inversion without constraining the source geometry.

Moment-tensor

$$M = \begin{bmatrix}
M_{xx} & M_{xy} & M_{xz} \\
M_{yx} & M_{yy} & M_{yz} \\
M_{zx} & M_{zy} & M_{zz}
\end{bmatrix}$$

$$F = \begin{bmatrix}
F_x \\
F_y \\
F_z
\end{bmatrix}$$

Full waveform inversion: fit the whole waveform

Observed
Synthetic

Matoza et al. [2015]
Full-waveform inversion

- Green’s functions estimated using 3D finite-differences [Ohminato et al., 1998] with 20-m discretized topography
- 3D velocity model of Waite and Moran [2009]

\[ u_n(x, t) = M_{pq}(t) \ast G_{np,q}(x, t) + F_p(t) \ast G_{np}(x, t), \]

- \( u_n(x, t) \) ground displacement
- \( M_{pq}(t) \) moment-tensor
- \( G_{np,q}(x, t) \) Green’s fn., spatial deriv.
- \( F_p(t) \) Force vector
- \( G_{np}(x, t) \) Green’s fn.

Compute using 3D finite differences [Ohminato and Chouet,1997]

Matoza et al. [2015]
• Perform a grid search over trial source nodes with increasing spatial density
• Define solution with the minimum $E_1$ residual error and a metric for waveform stability

\[
E_1 = \frac{\sum_{n=1}^{N_T} \sum_{p=1}^{N_s} (u_n^o(p\Delta t) - u_n^s(p\Delta t))^2}{\sum_{n=1}^{N_T} \sum_{p=1}^{N_s} (u_n^o(p\Delta t))^2}
\]

\[
\gamma = \left[ \sigma^2\left(3\frac{\alpha_1}{\alpha_3}\right) + \sigma^2\left(3\frac{\alpha_2}{\alpha_3}\right) \right]^{\frac{1}{2}}
\]

Standard deviation of the moment-tensor eigenvalues

Matoza et al. [2015]
Full-waveform inversion of a single subevent multiplet

- Volumetric $\sim 10$ m$^3$ source mechanism consistent with subhorizontal crack (assume Poisson solid, $\mu = 12$ GPa)
- Shallow depth $\sim 30$ m in southern part of crater

Moment tensor eigenvectors, scaled by eigenvalues

Horizontal crack moment-tensor:

$$
\mathbf{M} = \Delta V \begin{pmatrix}
\lambda & 0 & 0 \\
0 & \lambda & 0 \\
0 & 0 & \lambda + 2\mu
\end{pmatrix}
$$

volume change

Poisson solid ($\lambda = \mu$):

$$
\mathbf{M}(t) = 2\mu LWu(t) \begin{pmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 3
\end{pmatrix}
$$

e.g., rectangular crack $L \times W$

Matoza et al. [2015]
• Interaction point between shallow hydrothermal system and cool meteoric water in outer flank, e.g., snow melt
• Sudden condensation of metastable steam [Thiéry and Mercury, 2009]
• Horizontal structure feasible
• ~500 m depth below pre-1980 summit in old volcanic center

Figure 205.—Cross section A-A’ showing August 1979 and May 18 preeruption profiles, and May 18 posteruption profile. Geology of cone from C. A. Hopson, based on unpublished pre-May 18 mapping and inspection of amphitheater. Slide boundaries I (red), II (blue), and III (black) are approximately located, but precise configuration at depth is uncertain. Dacite intrusion of March–May 1980 indicated by light-red pattern.

Voight et al. [1981]
Velocity structure

- Waite and Moran [2008]: simple structure in shallow subsurface with spatial heterogeneities on the order of \(~1\) km.
- Waveform inversions limited to \(<2\) Hz [Waite et al., 2008; Matoza et al. 2015].
- Source depth below crater floor: LP events \(~200\) m; subevents \(~30\) m [Waite et al., 2008; Matoza et al. 2015].

**Fig. 7.** A west-east cross section through a single fine-grid model highlights the low velocity anomaly directly beneath the volcano. There is no vertical exaggeration.
Future Work: Better imaging of near-surface velocity structure

- Improved knowledge of shallow subsurface velocity structure at volcanoes (upper 500 m, within edifice)
- Resolve controversies about source vs. path effects
- Better constrained full-waveform inversion of smaller and higher frequency sources

Seismogram: \( w(t) = s(t) \times l(t) \times g(t) \)

Excitation/trigger

Crack/conduit resonance

Path & site effects

Homogeneous model

Near-surface layer model

Goldstein and Chouet [1994]

Bean et al. [2008]
Yasur Volcano, Vanuatu, July 2016

• Frequently active and accessible, ~300 m edifice
• “Strombolian” style activity: high-amplitude explosions every ~1–5 minutes from 2–3 main eruptive vents
• Regularly recorded at International Monitoring System infrasound station IS22, New Caledonia (400 km)
Seismo-acoustic network

YS: seismic; YI: infrasound
Contour interval: 20 m

Seismic data
- 11 broadband seismometers (Trillium Compact 120 s; Omnirecs DATA-CUBE digitizer)

Infrasound data
- 6 single infrasound sensors (Chaparral C60V)
- 7 small-aperture 3-element infrasound arrays
- 2 tethered balloon infrasound systems

Gas geochemistry data
- FTIR
- 2 scanning Flyspecs (SO₂)

Imaging data
- High-frame rate DSLR
- UAV DJI Phantom
- Go-Pro cameras
- FLIR (infrared)

Geologic samples
- Scoria and ash samples for petrologic analysis

University of California, Santa Barbara; GNS New Zealand; University of Alaska Fairbanks; University of Canterbury, New Zealand
Rapid deployment of broadband network

- Nanometrics Trillium Compact 120-s post-hole
- Omnirecs DATA-CUBE digitizer
- 8 x D-Cell battery pack per 4 days
• First order event detection with network-coincident STA/LTA automatic triggering
• 6-day dataset, >8,400 infrasound explosions, >10,400 seismic events
• ~1–2 events per minute
• First order event detection with network-coincident STA/LTA automatic triggering
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Seismo-acoustic waveforms

Infrasound

Seismic

YS: seismic; YI: infrasound
Contour interval: 20 m
Seismo-acoustic waveforms

Infrasound

- Short-duration asymmetric explosion waveforms
- Near-continuous broadband infrasonic tremor consisting of repetitive positively skewed pulses

Marchetti et al., 2013; Meier et al., 2016; Spina et al., 2016

Seismic

- Numerous repetitive long-period (LP) events
- Underlain by very-long-period (VLP) signals with periods of ~10 s

Kremers et al., 2013; Battaglia et al., 2012; 2016

LP: 0.5–5 Hz (0.2–2 s period)
VLP: 0.01–0.5 Hz (2–100 s period)
Full-waveform inversion of VLP seismic events

- Frequency of inversion: 0.002 to 2 Hz
- Perform a grid search over trial source nodes with increasing spatial density (3 stages down to 20-m spacing)
- Define solution with the minimum $E_2$ residual error

$$E_2 = \frac{1}{N_r} \sum_{n=1}^{N_r} \left[ \sum_{j=1}^{3} \sum_{p=1}^{N_s} (u_{n,j}^o(p\Delta t) - u_{n,j}^s(p\Delta t))^2 \right]$$
Network-based detection

- Individual VLP seismic events are contaminated by noise from microseisms and from the continuous VLP tremor oscillation
- Employ network-based template matching and stacking to boost the signal-to-noise ratios and isolate the transient VLP waveform signature
• Derived source location is beneath the main summit vent area at 680 m below sea level (870 m below the topography at this location)

Global minimum $E_1$ (red) and $E_2$ (blue) 31 July 2016 (circles) and 29 July 2016 (squares)

E2 error is 4.2% based on the waveform portion from 10 to 50 s; in the band 0.002 to 2 Hz

Preliminary results:
• Horizontal sill (80% of moment tensor (volume change) &
• Two sub-dominant and orthogonal vertical cracks
• Or a subdominant vertical pipe.
Hawaiian Volcano Observatory (HVO) network

- Hawaii Island: tectonic, VT, and LP earthquakes at a range of depths from mantle to surface; ~5,000-10,000 earthquakes per year
- Digital waveform data available from mid-1980s
Full-waveform inversion of VLP seismic events

Hawaiian Volcano Observatory (HVO) network

- ~50-station permanent HVO network; mostly short-period, vertical component only 1986–2009
- Systematic analyses (e.g., 198k events 1986-2009; 23 years of data from CUSP system; Matoza et al. [2013], Lin and Okubo [2016])
- Currently working on data post 2009 (AQMS), more broadband stations; continuous waveform data
• Considered waveforms for 198k events, 23 years
• Time-domain cross correlations computed for ~71 million event pairs, $P$- and $S$-waves, 243 million differential times
• Combined cluster analysis and relative relocation using grid-search $L_1$-norm method
• Relocated 157k (79%) event pairs
• Based on methods developed for Southern California

- Solve for relative location between nearby events
- Without solving for complex 3D velocity structure
- Waveform cross correlation dramatically reduces phase pick uncertainty
- Sharpening of earthquake clustering along faults, streaks, rift zones, rings, and magmatic features
- Generally consistent with previous relocation studies, but many more events

Matoza et al., [2013]
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- Generally consistent with previous relocation studies, but many more events
Relative event location

CUSP catalog

Matoza et al., [2013]
Relative event location

Matoza et al., [2013]
Volcano seismology and acoustics

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- Explosive volcanism: powerful signals
- Can propagate thousands of kilometers

Ray-tracing with HARPA code [Jones et al. 1986]
International Monitoring System (IMS)

- CTBTO IMS: Growing global network of infrasound arrays (50 certified, 60 planned)
- Each station is a 4–8 element infrasound array (2–3 km aperture)
- Average station spacing: ~2,000 km for complete network

Potentially active volcanoes [Siebert and Simkin, 2002-]
IMS infrasound network

Le Pichon, Matoza, et al. [2010]
• Infrasound 640-6,400 km from Sarychev Peak
• Only ground-based data (remote location, no local monitoring)
• **We can:** Detect, locate, and provide chronologies of explosive volcanism

• **Caveat:** Latency ~15 minutes per 250 km; IS44 ~35 minute latency.

June 2009 Eruption of Sarychev Peak, Kuriles
• We can: Detect, locate, and provide chronologies of explosive volcanism
- Systematic search of IMS data for eruption infrasound
- Aim: build a global quantitative acoustic catalog of explosive volcanism
1. Go backwards from infrasound data, blind search for eruption signals
2. Analyze all IMS data globally, not just individual case studies or regions
Combined association and location: brute-force, grid-search, cross-bearings approach

Planned: Public release of Fortran 90 code

- Link each station to a grid of trial source nodes based on backazimuth
- No atmospheric propagation correction

Matoza et al. [2017]
Example grid function: Sarychev Peak 2009

- Sarychev Peak, 4 stations
- 11–16 June 2009

Matoza et al. [2017]
Combined association and location: brute-force, grid-search, cross-bearings approach

Sarychev Peak 4 stations

- 5-day cumulative stack
- 11–16 June 2009

Grid value (number of pixels)

19.1 km from true

• Link each station to a grid of trial source nodes based on backazimuth
• No atmospheric propagation correction

Matoza et al. [2017]
Matoza et al. [2017]; Data from 2005–2010: IMS under construction, 2/3 complete
Results with more recent data 2005–2017, more complete network (in progress)
Results with more recent data 2005–2017, more complete network (in progress)

- 2009 Sarychev Peak
- 2011 Nabro
- 2011 Cordón-Caulle; 2015 Calbuco
- 2010 Eyjafjallajökull
- 2016 Etna
- 2011 Cordón-Caulle; 2015 Calbuco
- 2013 Sheveluch?
- Detection capability improves as IMS network nears completion
- Utility of additional infrasound stations in regions of dense volcanism [e.g., Guilbert et al., 2005; Matoza et al., 2007; Garces et al., 2008; De Angelis et al., 2012; Taisne et al., 2012; Tailpied et al., 2013]
- Add more infrasound sensors to existing regional seismic networks

Matoza et al. [2017]
• VEI 4 explosive volcanic eruption in Chile
• 22–23 April 2015; plume heights > 23 km a.s.l.
• Recorded on 5 stations of the IMS network: 1,525 to 5,122 km ranges
• Recorded by local monitoring stations and seismo-acoustic stations across Chile
April 2015 eruption of Calbuco

No ray tracing (522 km from true)

3D ray-tracing + ECMWF (172 km from true)

IMS infrasound array
Calbuco
Source location

Matoza et al. [2018]
Regional seismo-acoustic observations

- Chilean National Seismic Network: 10 seismo-acoustic stations
- Infrasound recorded well on 4 stations out to 1,540 km
- Only 1 station (GO07, 216 km) recorded both infrasound and seismic from Calbuco
Regional seismo-acoustic observations

- Seismic signals recorded out to ~250 km
- Combined seismic + air-ground coupled infrasound

Data from Chilean National Seismic Network, Red Sismologica Nacional, Global Telemetered Seismograph Network. Downloaded via IRIS

Matoza et al. [2018]
Regional seismo-acoustic observations

-80° to -20° latitude, 60° to 40° longitude

**IMS infrasound array:**

- Detecting seismic and infrasound waves

**Station Location:**

- Calbuco

**Seismic data:**

- P and S phases propagating with move-outs of 6.8 km/s and 3.8 km/s

**Figure Notes:**

- Map showing locations of GO04, GO07, LL01, GO08, PLCA, IS02, and IS09
- Waveforms showing seismic data for GO07, PLCA, LL01, and VER

Data from Chilean National Seismic Network, Red Sismologica Nacional, Global Telemetered Seismograph Network. Downloaded via IRIS

Matoza et al. [2018]
Regional seismo-acoustic observations

Also infrasound arrivals ~0.3 km/s move out (celerity)

Infrasound data

Seismic data

Data from Chilean National Seismic Network, Red Sismologica Nacional, Global Telemetered Seismograph Network. Downloaded via IRIS

Matoza et al. [2018]
Seismo-acoustic cross-correlation and coherence

Examine air-ground coupling using cross-correlation and coherence
Ichihara et al. [2012], Matoza and Fee. [2014]

\[ \gamma_{wp}(f) = \frac{|S_{wp}|^2}{S_{ww}S_{pp}} \]

\[ \gamma_{wp}(f) = \tan^{-1} \frac{Q_{wp}}{C_{wp}} \]

Seismo-acoustic cross-correlation and coherence

Station GO07 (216 km)
Seismo-acoustic cross-correlation and coherence

Station GO07 (216 km)

Matoza et al. [2018]
EarthScope TA Reverse-Time Migration (RTM)

- Bogoslof volcano; eruptions December 2016 to August 2017
- More than 60 eruptive events from Bogoslof provide a unique calibration dataset

**Figure:** D. Fee, UAF

210 EarthScope Transportable Array (TA) colocated seismic and infrasound stations spread across Alaska, ~85 km spacing

Sanderson et al.; Identifying and Mitigating Hazards in the 21st Century

H2. Remote explosive volcanic eruption detection, location, and characterization using the EarthScope Transportable Array in Alaska
Sanderson et al.; Identifying and Mitigating Hazards in the 21st Century

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H2. Remote explosive volcanic eruption detection, location, and characterization using the EarthScope Transportable Array in Alaska
Conclusions

- Seismology and infrasound are complementary methods for understanding and monitoring volcanoes.
- Source size varies: from tiny ~10 m³ volumetric oscillations of fluid-filled cracks, observable only within crater, to explosive eruptions detectable globally with infrasound.
- Rich multi-year seismo-acoustic datasets are becoming available from volcanoes worldwide.
- Developing computational techniques to systematically investigate datasets, compare and contrast different volcanic systems, catalog and quantify Earth’s volcanism, and test hypotheses about how volcanoes work.
Recommendations

- Automated detection and cataloging of global explosive eruptions feasible with IMS
- Augmenting seismic networks with infrasound sensors in volcanic regions will dramatically enhance volcanic signal detection, reduce latency, and improve discrimination capability
- Adding single infrasound sensors to seismic stations helps significantly (~250–500 km spacing)
- Adding small arrays (e.g., 3–4 infrasound sensors, ~100 m aperture) would help even more
Acknowledgements

Lars Ceranna
Bernard Chouet
Phillip Dawson
David Fee
Rebecca Fitzgerald
Luis Franco
Milton Garces
David Green
Matthew Haney
Michael Hedlin
Alexandra Iezzi
Richard Johnson
Arthur Jolly
Megan Kelley
Ben Kennedy

Guoqing Lin
Alexis Le Pichon
John Lyons
Kathleen McKee
Pierrick Mialle
T. Dylan Mikesell
Seth C. Moran
Paul Okubo
Richard Sanderson
Peter Shearer
O. Alberto Valderrama
Julien Vergoz
Gregory Waite
Cecily Wolfe