Hundred-year advances in volcano seismology and acoustics

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• Well-established that volcanic eruptions are preceded by earthquakes (e.g., Scrope [1825])

• Some recognition of different ‘classes’ of volcano-seismic events (e.g., Omori [1912], Jaggar [1920])

• Recognition of need to record volcano-seismic events on multiple instruments (e.g., Cross [1920])
Kilauea 1912-
Pelee 1903-
Vesuvius 1856-1906(?) 1913-
Usu 1910
Asama 1912-14
Sakurajima 1914

Permanent Station
Temporary Station

Volcano Seismology in 1919
Mechanism of volcanic earthquakes:
“...a seismic disturbance...due to the direct action of the volcanic force, or one whose origin lies under, or in the immediate vicinity of a volcano, whether active, dormant, or extinct.”

Omori [1912]
Mechanism of volcanic earthquakes:

“Local earthquakes and tremors may be caused variously, but the centers are more or less fixed rift surfaces at points of maximum friction…. Where so-called tectonic control ends and magmatic thrust begins, are matters as yet rather of philosophy than of measurement.”

Jaggar [1920]
Expansion of Permanent Seismic Networks

- Pelee
- Kilauea
- Vesuvius
36 years earlier...

- 1883 August 27 VEI 6 eruption of Krakatoa a major focus of scientific investigation (Royal Society collection); e.g., earliest work in volcano acoustics
- Audible “canon-like” sounds documented by eyewitnesses at ~5,000 km
36 years earlier...

- Weather barographs (measuring atmospheric pressure) around the world record the blast wave from Krakatoa
- Pressure waves observed globally on >50 weather barometers; low-frequency acoustic wave periods 100–200 min; 7 laps of the globe
36 years earlier...

- Weather barographs (measuring atmospheric pressure) around the world record the blast wave from Krakatoa
- Pressure waves observed globally on >50 weather barometers; low-frequency acoustic wave periods 100–200 min; 7 laps of the globe

- Development of theory to explain these acoustic-gravity waves (e.g., LeConte 1884; Lamb 1911; Taylor 1929, 1936; Pekeris 1939; Pierce 1963; Press and Harkrider 1962, 1966; Harkrider 1964; Harkrider and Press 1967)

Scott [1883]
Early work in volcano seismology

- e.g., Luigi Palmieri 1856 “continuous tremor” at Vesuvius
- Omori [1912]: “The eruptions and earthquakes of the Asama-Yama”
- Omori’s two-component horizontal pendulum seismograph “tromometer” was the basis of the Bosch-Omori seismograph, later deployed worldwide

Mount Asama, 10:26 AM 23 December 1911

Omori [1912]
Early work in volcano acoustics

- Omori [1912] used seismometers and barometers to discriminate seismic signals from airborne explosions ("detonations") and non-explosion earthquakes at Mount Asama, Japan.
Early work in volcano acoustics

- **1906–1943**
  - Pioneering seismic and acoustic work by Frank Perret at Vesuvius, Etna, Stromboli, Kilauea, Sakurajima, Pelee, Montserrat using moving-coil microphones (audible acoustic signals)

- **1912**
  - Omori [1912] used seismometers and barometers to discriminate seismic signals from airborne explosions (“detonations”) and non-explosion earthquakes at Mount Asama, Japan

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Barogram at the Meteorological Observatory of Yokosuka
• Volcano seismology and acoustics are highly observational fields
• What you see depends on instrumentation

1919–2019 major advances in:

• Bandwidth (frequency range) of signals captured
• Portability and ruggedness of instrumentation, telemetry
• Computer revolution: Efficiency with which data can be processed and stored

Ackerley [2015]
https://doi.org/10.1007/978-3-642-35344-4_172
e.g., Kilauea Iki, 1976

- **1970s:** limited portability
  - Installing and maintaining seismic equipment highly laborious
  - e.g., 4 miles of military grade Spiral-4 cable. Spiral-4 came in spools weighing 100 pounds each; 40 were used.
  - Data stored on paper, digitized by hand to punch cards

Instrumentation changes 1919–2019

**1980s:** beginning of digital data capture and storage

- e.g., Fehler (1983) — a prototype 12-bit recorder designed and built at MIT primarily for ocean bottom deployment.
- Records long-period (LP) 0.5–5 Hz seismicity and tremor at Mount St. Helens

Mount St. Helens 1980

Mount St. Helens, May 18, 1980, Station CPW, 70 miles to the northwest

Pinatubo 1991

Pinatubo, 1991

Ramos et al. [1996]

Sabit et al. [1996]
Instrumentation changes 1919–2019

**1990s**: the advent of (portable) broadband seismometry at volcanoes

- Led to discoveries of new signals:
  - Very-Long-Period (VLP) $0.01–0.5$ Hz
  - Ultra-Long-Period (ULP) $<0.01$ Hz

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**Sakurajima**
*Kawakatsu et al. [1992]*

**Stromboli**
*Neuberg et al. [1994]*

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**Aso**
*Kaneshima et al. [1996]*
Instrumentation changes 1919–2019

**1990s:** first deployments of infrasound sensors at volcanoes

- **Arenal, Costa Rica; Garces et al. [1998]**
- **Sakurajima; Sakai et al. [1996]**

**Stromboli; Ripepe et al. [1996]**

**Stromboli; Vergniolle and Brandeis [1994]**

**Seismic**

**Acoustic**
Instrumentation changes 1919–2019

- Increasing seismic network density
- **1990s**: transition from event-triggered to continuous digital waveform data storage; analog to digital telemetry, etc.

Seismic station coverage, Island of Hawai`i 1950

Klein and Koyanagi [1980]

Figure from Matoza et al. [2019]
• The computer revolution enabled increasingly sophisticated data processing and source modeling, and facilitated the transition from event-triggered to continuous digital waveform recording by about the 1990s.

• The first deployments of broadband seismic instrumentation and infrasound sensors on volcanoes in the 1990s led to discoveries of new signals and phenomena.

Phreatic explosion, Mount St. Helens, 8 March 2005; recorded by a broadband seismometer and broadband infrasound array

Matoza et al. [2007]
Event Classification

**Four classes of volcanic earthquakes:**
(location of foci, nature of motion)

- **A-type** (from a depth of 1-10 km, sometimes 20 km)
- **B-type** (originating in swarms from a shallow depth near the crater)
- **Explosion earthquakes** accompanying (causing!) explosive eruptions of the Vulcanian type
- **Volcanic microtremors** accompanying Strombolian eruptions

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Minakami [1960]
Event Classification

Four classes of volcanic earthquakes: (location of foci, nature of motion)

- **A-type** (depths of 1-10 km, similar to shallow tectonic quakes, double-couple?)
- **B-type** (depths of < 1 km, small-magnitude, 1-5 Hz waveform, no clear S-phase, first-motion pattern unresolvable)
- **Explosion earthquakes**
- **Volcanic tremors or pulsations**

Minakami [1974]
Event Classification

Multiple classes of volcanic earthquakes:

- **Volcano-Tectonic** (VT), or high-frequency (HF) (=A-Type)
- Hybrid events
- **Long-Period** (LP), or low-frequency (LF) (=B-Type)
- Very-Long-Period (VLP)

- Explosion earthquakes
- Volcanic tremor

e.g., Lahr et al. [1994]
High-frequency (VT) earthquakes

“I think the greater number of so-called volcanic earthquakes are due to tension-cracks. The pressure caused by upwelling lava must produce cracks, which the lava fills, and which appear later as radial dykes about partially disintegrated volcanoes. The strong but very limited earthquakes that occur on Mt. Etna often follow straight lines along which lava shortly afterwards pours out.”

HF Reid [1929]

Figure from Di Franco [1928]
High-frequency (VT) earthquakes

- Early evidence of double-couple mechanism for some (all?) A-type quakes

Minakami [1974]
High-frequency (VT) earthquakes

- Earthquake swarms on mid-ocean ridges reflect the breakup and collapse of the central-rift valley floors due to a drop in pressure in the underlying magma chamber

Filson et al. [1973], Francis [1974]
• ‘Hill mesh’ hypothesis – swarms of volcanic earthquakes in transitional regions between spreading centers and transform faults occur on cracks connecting tips of en-echelon, fluid-filled fractures
Evidence from Mt. St. Helens that post-eruptive earthquakes occurred in response to stresses from relaxation of emptied conduit
High-frequency (VT) earthquakes

- VT source process/location depends on magma rheology

Roman and Cashman [2006]
High-frequency (VT) earthquakes

- Evidence for ‘distal VT’ seismicity due to stress transfer onto regional faults

Hurst et al. [2018]
High-frequency (VT) earthquakes

- Propagating VT seismicity at base of laterally-intruding dike, Holuhraun 2014
Volcano seismology: signal classification

Classification based on mechanism

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

Lahr et al. [1994]; Chouet [1996]
Classification based on mechanism

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**

*Lahr et al. [1994]; Chouet [1996]*
**Volcanic tremor** a catch-all term for *sustained* seismic and acoustic signals associated with a wide range of volcanic activity

*multifarious*: many and of various types; having or occurring in great variety

- Harmonic
- Monotonic/monochromatic
- Spasmodic
- Eruption
- Banded
- Tremor storm

etc.? ...

e.g., McNutt [1992], Konstantinou and Schlindwein [2002]
Spasmodic vs. harmonic tremor

Jaggar/Omori: early 20th Century

**Spasmodic tremor:**
irregular vibrations

**Harmonic tremor:**
more rhythmic vibrations
Spasmodic vs. harmonic tremor

Jaggar/Omori: early 20th Century

**Spasmodic tremor:**
irregular vibrations

**Harmonic tremor:**
more rhythmic vibrations

Seismograms from Galeras, Colombia, *Gil Cruz* [1999]
Volcanic tremor mechanisms

• Omer [1950] attributes tremor to a path effect: the reverberation of volcanic strata excited into motion by lava moving though feeding conduits.

**VOLCANIC TREMOR**

(Part Two: The Theory of Volcanic Tremor)

By Guy C. Omer, Jr.

ABSTRACT

It is proposed that volcanic tremor originates in the vibration of laminae which are partly freed by the differential tilting of the surface of the earth around a volcanic vent during an eruption. The topographic evidence around Kilauea caldera is examined and a probable range of the free vibrating lengths is determined. The various possible modes of vibration are considered and it is concluded that longitudinal vibration would best explain the observed seismograms.

Finch [1949]; Omer [1950]
Shima [1958] and Kubotera [1974]: peaked tremor spectrum at Aso modeled as free oscillations of a spherical magma chamber

Shimozuru [1961]: longitudinal resonance of a cylindrical magma column

However, these early models required implausibly large dimensions for the resonating cavities
e.g., Kubotera [1974] determined the source of 3.5–7 s period tremor at Mount Aso to be a resonating spherical magma chamber of 4–6 km radius.

Kubotera [1974]
“Volcanic tremors at Aso Volcano”
LPs as the impulse response of the resonant tremor system

- Individual LP events (transients) and certain types of tremor are closely linked
- LPs merge into tremor

[e.g., Latter, 1979; Fehler, 1983; Neuberg, 2011; Hotovec et al., 2012]
LP events: repetitive waveforms

- LP waveform families or multiplets

Small LP events at Mount St. Helens, 2005

Redoubt 1989

Soufrière Hills Volcano, Montserrat, 1997

Green and Neuberg [2006]

Stephens and Chouet [2001]

Matoza et al. [2015]
LPs as the impulse response of the resonant tremor system

• LPs interpreted as the impulse response of a resonant tremor-generating system

Resonance of a fluid-filled conduit

Excitation of a Buried Magmatic Pipe: A Seismic Source Model for Volcanic Tremor

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Recent observations of seismic events at various volcanoes suggest that harmonic tremor results from the sustained occurrence of so-called long-period or low-frequency events. Accordingly, we can view the long-period volcanic event as the elementary process of tremor and interpret it as the impulse response of the tremor-generating system. We present a seismic model in which the source of tremor is the acoustic resonance of a fluid-filled volcanic pipe triggered by excess gas pressure. The model consists of three elements, namely, a triggering mechanism, a resonator, and a radiator...

see also Jousset et al. [2003]; finite-difference solution of conduit resonance
Resonance of a fluid-driven crack: Radiation Properties and Implications for the Source of Long-Period Events and Harmonic Tremor

BERNARD CHOUET

U.S. Geological Survey, Menlo Park, California

A dynamic source model is presented, in which a three-dimensional crack containing a viscous compressible fluid is excited into resonance by an impulsive pressure transient applied over a small area $\Delta S$ of the crack surface. The crack excitation depends critically on two dimensionless parameters called the crack stiffness, $C = (b/\mu L/d)$, and viscous damping loss, $F = (12\mu L)/(\rho_e c^3)$, where $b$ is the bulk modulus, $\eta$ is the viscosity, $\rho_f$ is the density of the fluid, $\mu$ is the rigidity, $c$ is the compressional velocity of the solid, $L$ is the crack length, and $d$ is the crack thickness.

Chouet [1988]

SOURCE MECHANISM OF VOLCANIC TREMOR: FLUID-DRIVEN CRACK MODELS AND THEIR APPLICATION TO THE 1963 KILAUEA ERUPTION

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(Received November 1, 1976; revised version accepted March 17, 1977)

Aki, Fehler, and Das [1977]
LPs: the fluid-driven crack model

Figure 17

Chouet [1996]
LPs: the fluid-driven crack model

“Crack waves” Solid-fluid interface waves; fluid-filled crack in elastic solid

Ferrazzini and Aki [1987]: analytic expressions of the crack waves, considering normal modes in a fluid layer sandwiched between two homogeneous half-spaces.

Chouet [1986, 1988, 1992]

Chouet [1996]

~100 m

Figure from Chouet and Matoza [2013]
Resonant response
- Fluid-filled crack or conduit
- Bubbly magma, water, steam, dusty gas

Data (Galeras 1993)

Synthetic

Chouet [1996]

“Crack waves” Solid-fluid interface waves; fluid-filled crack in elastic solid
Chouet [1986, 1988, 1992]

Ferrazzini and Aki [1987]: analytic expressions of the crack waves, considering normal modes in a fluid layer sandwiched between two homogeneous half-spaces.

Figure from Chouet and Matoza [2013]
LPs: the fluid-driven crack model

The trigger mechanism

- What excites the resonance?
- Impulsive trigger: discrete LP event
- Sustained trigger: tremor

Where: $s(t) * l(t)$

Chouet [1996]
LPs: trigger mechanism in magmatic-hydrothermal systems

Mount St. Helens
2152:37 UTC, 9 November 2005
S04 HHZ
distance 1.1 km

Cyclic recharge-collapse of a hydrothermal crack

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

e.g., Matoza and Chouet [2010]

Resonator: a reservoir of hydrothermal fluid

fumarole

aquifer

heat supply

magma body

e.g., Kumagai et al. [2005]; Ohminato [2006]; Waite et al. [2008]; Matoza and Chouet [2010]; Maeda et al. [2013]
Mount St. Helens 2004–2008 eruption

Solid extrusion, plug stick-slip

Cyclic recharge-collapse of a hydrothermal crack

Schematic of Kusatsu-Shirane, Japan

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

e.g., Kumagai et al. [2005]; Ohminato [2006]; Waite et al. [2008]; Matoza and Chouet [2010]; Maeda et al. [2013]
Brittle failure of melt

- Brittle failure of melt in the glass transition
- Multiplets: repeated fracture and heal or ascent through a depth-limited seismogenic window

*Tuffen et al. [2008]*

*Neuberg et al. [2006]*
Eruption cycles and forecasting

- Probability of eruptions based on the occurrence rate of B-type earthquakes (=explosion quakes)
- Increase in rate leads to increased probability of a B-type earthquake large enough to cause an explosion

Minakami [1960, 1974]

Fig. 8. The practical application of the 1960 formula to eruptions which took place in 1961, based on the daily frequency of B-type quakes. Arrows = eruptions; $P$ = probability of eruption given from the 1960 formula; $F_2$ = seismic daily frequency of B-type quakes originating in Asama.
Eruption cycles and forecasting

- Location and time of Tolbachik 1975 eruption forecast 3 days beforehand on the basis of epicenter locations
- Rapid deployment of additional seismometers for earthquake location

Tokarev [1978]
Eruption cycles and forecasting

- Quantitative forecasting of eruption time at Mt. St. Helens based on event rate acceleration (‘Failure Forecast Method’)

Swanson et al. [1985], Cornelius and Voight [1994]
Eruption cycles and forecasting

- Use of RSAM (Real-time Seismic Amplitude Measurement) for rapid assessment of eruption potential at Pinatubo (1991)

Harlow et al. [1996]
Eruption cycles and forecasting

- Eruption forecasting without a local seismo-acoustic network at Bogoslof (2016-17)

Wech et al. [2018]
Most volcanic earthquake swarms do not culminate in eruption.
Eruption cycles and forecasting

- Full-eruption-cycle records are key to understanding volcanic seismicity

Mt. St. Helens earthquakes 1981-2017

W. Thelen (USGS/CVO), personal comm.
• Laboratory and numerical experiments are elucidating seismo-acoustic source processes in volcanic fluid systems
• Observationally constrained by increasingly dense geophysical and multi-parametric field deployments.

Yasur, Vanuatu 2016

Jolly et al., [2017]; Matoza et al. [2018]; Iezzi et al. [in press]
• Observationally constrained by increasingly dense geophysical and multi-parametric field deployments

Yasur, Vanuatu 2016

Contours: 20 m

YS: seismic; YI: infrasound

Contour interval: 20 m

Jolly et al., [2017]; Matoza et al. [2018]; Iezzi et al. [in press]
State of the art and future trends

- Observationally constrained by increasingly dense geophysical and multi-parametric field deployments

**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 (SO\textsubscript{2})

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

**Geologic samples**
- Scoria and ash samples for petrologic analysis

Jolly et al., [2017]; Matoza et al. [2018]; Iezzi et al. [in press]
State of the art and future trends

Infrasonic jet noise from volcanic eruptions

Mount St. Helens
8 March 2005, r = 13.4 km

Tungurahua
4-15 July 2006, r = 36.9 km

Tungurahua
16-17 August 2006, r = 36.9 km

Tungurahua
6 February 2008, r = 36.9 km

Redoubt
23 March 2009, r = 547 km

Redoubt
28 March 2009, r = 547 km

Sarychev Peak
12 June 2009, r = 643 km

Sarychev Peak
14 June 2009, r = 643 km

Mount St. Helens
March 2005

Tungurahua
February 2006

Pressure [Pa]

Time [sec]

Pressure [Pa]

Time [sec]

Pressure [Pa]

Time [sec]

Mount St. Helens
March 2005

Tungurahua
February 2006

Mount St. Helens
March 2005

Tungurahua
February 2006

Sparks [1986]

Matoza et al. [2009, 2013]; Fee et al. [2013]; Taddeucci et al. [2014]; Matoza and Fee [2018]
Infrasonic jet noise from volcanic eruptions

Matoza et al. [2009, 2013]; Fee et al. [2013]; Taddeucci et al. [2014]; Matoza and Fee [2018]
State of the art and future trends

- Large $N$ and nodal deployments
- 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

$w(t) = s(t) * l(t) * g(t)$

seismogram: $w(t) = s(t) \ast l(t) \ast g(t)$

excitation/trigger

crack/conduit resonance

path & site effects

Goldstein and Chouet [1994]

iMUSH active source experiment, Mount St. Helens

Hansen et al. [2016]
State of the art and future trends

- Laboratory and numerical experiments are elucidating seismo-acoustic source processes in volcanic fluid systems
- Observationally constrained by increasingly dense geophysical and multi-parametric field deployments, which, e.g., enable full seismic and acoustic waveform inversions
- The fields of volcano geodesy, seismology, and acoustics are now merging to track processes on a continuum of spatial and temporal scales in the ground and atmosphere

- Despite vast progress over the past century, major questions remain regarding source processes, patterns of volcano-seismic unrest, internal volcanic structure, and the relationship between seismic unrest and volcanic processes
State of the art and future trends

- More seismic and acoustic sensors on more volcanoes worldwide
- Steady expansion of operational regional and global volcano-acoustic monitoring systems

Seismic stations on the Island of Hawai`i

2009–2016 (AQMS)

e.g., Thelen et al. [2014]

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

Matoza et al. [2017]