Encyclopedia of Earthquake Engineering
DOI 10.1007/978-3-642-36197-5_41-1

Seismic Monitoring of Volcanoes

Glenn Thompson*
School of Geosciences, University of South Florida, Tampa, FL, USA

Synonyms

Volcano-seismic monitoring

Introduction

Seismicity beneath a volcano usually increases before an eruption because magma and volcanic gas must first force their way up through fractures and passageways. When magma and volcanic gases or fluids move, they will either cause rocks to break or cracks to vibrate. When rocks break, high-frequency earthquakes are triggered. When cracks vibrate, either low-frequency earthquakes or a continuous shaking called volcanic tremor, which can last from minutes to days, occurs.

Volcanic earthquakes often occur in swarms, which are clusters in time and space of similar earthquakes without an obvious mainshock. Volcano seismologists look for changes in the rate, size, and location of earthquakes and for the occurrence of swarms and tremor to forecast eruptions and to evaluate whether a volcanic eruption is intensifying or ending. Volcanic hazards including explosive eruptions, rockfall, pyroclastic flows, and lahars also cause ground vibrations and can be identified by their seismic signatures. This makes it possible, in principle, to detect them as they happen and issue warnings.

This entry discusses volcano-seismic monitoring from the viewpoint of a scientist leading a seismic monitoring program at a volcano observatory. Seismic monitoring records continuous, high-sample-rate data on the internal state of the volcano. Other monitoring techniques require manual labor to collect or process data, rely on daylight and good weather conditions, only detect volcanic activity once it has reached the surface, or have a low sample rate. For these reasons, seismic monitoring is the backbone of most volcano observatories. A volcano-seismic monitoring program comprises of a seismic network, a telemetry system, data acquisition, and alarm, analysis, and archival systems. At large observatories, personnel may include electronics engineers, volcano seismologists, seismic analysts, software developers, and network administrators. At small observatories, one person may cover most or all of these roles.

A volcano observatory has to be able to process large quantities of streaming data, detect changes in the volcanic system immediately, and respond without having to do a lot of manual analysis. This requires high levels of automation and systems engineering. While top priority is interpreting real-time data using established knowledge from the scientific field of volcano seismology, other important roles are troubleshooting data problems and conducting (or promoting) research that may lead to a better understanding of the volcano or lead to improved monitoring tools.

Much of the equipment and software used for volcano-seismic monitoring were originally developed for regional earthquake monitoring. The main difference is that the software needs to be augmented because of the diverse range of seismic signals recorded at volcanoes, many of which elude standard earthquake detection and location techniques. These signals, and the framework in which they are commonly interpreted, are discussed in the next section. The sections that follow describe volcano

*Email: thompsong@usf.edu

DOI 10.1007/978-3-642-36197-5_41-1

observatories including the operations room which is the command center during a crisis, the design of volcano-seismic networks, the real-time seismic monitoring and data analysis tools found in most observatories, and the challenges of maintaining this infrastructure and managing data effectively. In the final section, other monitoring techniques employed at observatories are briefly discussed.

Volcano-Seismic Signals

Volcano seismologists are most interested in signals which are anomalous, because they have high amplitudes, characteristic waveforms, or unusual frequency behavior. Given the variety of volcanoes around the world, with staggeringly different eruptive styles, magma compositions, and viscosities, it is perhaps remarkable that some common types of seismic signals are observed. These signals can be broken down into three broad categories: volcanic earthquakes ("events"), continuous signals, and surface signals. Each of these is discussed below. Any volcano may exhibit some or all of these at some time and perhaps may also exhibit exotic signals unique to that volcano. Classification is important because each type of signal may represent a different physical mechanism. However, classification is problematic.

By analyzing the spatial and temporal patterns between different signal types and volcanic activity, a greater understanding of a particular volcano may be revealed. There are common patterns of behavior, gleaned from analyzing the seismic data from many volcanic eruptions. These are encapsulated in the Generic Volcanic Earthquake Swarm Model (McNutt 1996), a sequence observed at many volcanoes, the main features of which are volcano-tectonic earthquake swarms, followed by low-frequency earthquake swarms, tremor, and eruption.

For a more detailed discussion of volcano-seismic signals and many other topics mentioned in this chapter, Wasserman (2012) is highly recommended.

Volcanic Earthquakes

Volcano-Tectonic Earthquakes

Volcano-tectonic (VT) earthquakes are tectonic earthquakes that occur near active volcanoes. The physical mechanism is shear failure and slip on a fault plane triggered by magma ascent or the relaxation that occurs after magma is erupted. VT earthquakes have clear P- and S-waves (if recorded with a good signal-to-noise ratio) and high-frequency content (>5 Hz). VT earthquakes can be located in the same way as other tectonic earthquakes, i.e., by using the differential travel times between the P and S phases across a seismic network. However, most VT earthquakes are small ($M_L = -0.5$–1.5), and poor signal-to-noise ratio often prevents identification of phases, so in practice many (perhaps most) VT earthquakes cannot be located. Velocity models for volcanoes are often poorly determined, making absolute depths unreliable. Trends in relative depths are a useful diagnostic tool, however, and may indicate the rise of magma toward the surface. VT earthquakes frequently occur in swarms that consist of many similar-sized events and do not occur in mainshock-aftershock sequences where one single event dominates.

Long-Period Earthquakes

Long-period (LP) earthquakes are unique to volcanic regions. They have emergent onsets and a narrow frequency range with a peak frequency typically from 1 to 4 Hz. Tornillos are LP earthquake events with a particularly monotonic appearance and an exponentially decaying tail. LP earthquakes lack discernable P or S phases; consequently, most are not located. Evidence from Soufrière Hills Volcano (Montserrat) that they are often associated with venting from the surface of the dome and often trigger rockfall suggests they may originate at depths of less than 1 km. LP earthquake focal mechanisms reveal a volumetric

DOI 10.1007/978-3-642-36197-5_41-1

component which is evidence of a fluid phase. LP earthquake swarms in volcanic systems are often associated with eruptions or intrusions and are believed to be due to processes such as pressure-induced oscillations of fluid-filled cracks in magmatic and hydrothermal systems.

Hybrid Earthquakes

Hybrid earthquakes have a high-frequency P-wave onset, typical of a VT earthquake, followed by a long-period tail. They may represent triggering of an LP earthquake by a VT earthquake. They typically occur in swarms and may be indicative of magma intrusion or extrusion.

Low-Frequency Earthquakes

Collectively, long-period and hybrid earthquakes are referred to as low-frequency earthquakes. There may be a continuum between long-period and hybrid earthquakes.

Deep Long-Period Earthquakes

Some volcanoes produce low-frequency earthquakes (e.g., 20–40 km depth), particularly in the early stages of unrest. These have been called deep long-period (DLP) earthquakes. These have emergent P and S phases, are rich in frequencies below 5 Hz, and are inferred to represent movement of deep-seated magma and associated fluids in the mid-to-lower crust. They look like VT earthquakes with the high frequencies filtered out, perhaps because they occur in a highly attenuating region.

Explosion Quakes and Very-Long-Period Signals

Explosion quakes are signals that accompany Strombolian or other (larger) explosive eruptions. These signals are identified by the occurrence of an airwave which is caused by expanding gas accelerated at the vent exit. This wave mainly travels through the air with the typical speed of sound (330 m/s at 20 °C).

With the advent of broadband volcanic seismology, very-long-period (VLP) signals have been observed in seismograms from some volcanoes. Many of these are broadband versions of explosion quakes. VLP signals may be produced by the rapid expansion of a large gas volume at shallow depth within the conduit. The gas expansion might result from shallow gas coalescence and expansion or from expansion of a gas slug formed at greater depth.

Continuous Signals

Swarms

Earthquake swarms are sequences of earthquakes closely clustered in space and time without a single mainshock. Volcanic earthquakes often occur in swarms, whereas nonvolcanic earthquakes usually follow a mainshock-aftershock sequence. The Gutenberg-Richter law describes the relative frequency of occurrence of earthquakes of different magnitudes, and this is encapsulated in a parameter called the b-value (see Sanchez et al., "► Frequency-Magnitude Distribution of Seismicity in Volcanic Regions," this volume). Volcanic earthquake swarms typically have b-values higher than one (most of the energy is in small earthquakes), whereas mainshock-aftershock sequences typically have $b \leq 1$ (most of the energy is in a single mainshock). Volcanic earthquakes occur in hot, highly heterogeneous material containing many small faults. Nonvolcanic earthquakes tend to occur in more homogeneous material with failure on a single larger fault, which then loads adjacent faults, causing many of them to fail producing aftershocks. Low-frequency earthquake swarms often contain one or more families of repeating earthquakes. Each family is identified by a unique waveform and is the result of the same nondestructive source process being activated repeatedly in the same location.

DOI 10.1007/978-3-642-36197-5_41-1

Benoit and McNutt (1996) examined the reports of over 600 swarms to compile the Global Volcanic Earthquake Swarm Database. They identify three main types of volcanic earthquake swarm. Type 1 swarms begin before an eruption and have a mean (and mode) duration of 8 days. Type 2 swarms begin coincident with, or during, an eruption. Type 3 swarms (39 % of records) were not associated with eruptions and have a mean duration of 3.5 days and a mode of 1.5 days. The most common depth for swarms is 2–3 km. Their study does not distinguish between different types of volcanic earthquakes. They suggest it may also be biased by the underreporting of swarms not associated with eruptions.

Tremor

Volcanic tremor is a narrowband (usually 1–4 Hz), continuous vibration thought to be due to sustained subsurface movement of magma or volatiles and is often observed before explosive eruptions. It may last from a few minutes to months in duration. Tremor has similar spectral characteristics as low-frequency earthquakes. Harmonic tremor shows one or many regularly spaced overtones in addition to a fundamental frequency. Sometimes spectral peaks in harmonic tremor glide upward (or downward) in frequency over as little as a few minutes. Eruption tremor, a continuous vibration coincident with explosive eruptions, has a wider frequency range (0.5–10 Hz). Dome collapses, lahars, weather storms, and telemetry problems can all produce signals that could be confused with tremor.

Tremor may be the result of continuous excitation of the source that produces low-frequency earthquakes. The resonance of a fluid-filled conduit is one model for the origin of tremor, as it is for low-frequency earthquakes. Interface waves traveling along the crack or conduit wall can produce overtones, like an organ pipe. Gliding lines could be caused by a change in the sound speed of the fluid (e.g., due to a change in bubble density) or a change in a length of the section of conduit that is resonating (e.g., a change in nucleation depth).

Tremor may also be a superposition of low-frequency earthquakes. There are many observations of low-frequency earthquake swarms merging into volcanic tremor. Modeling has shown that harmonic tremor could appear when overlapping earthquake signals occur at regular time intervals that differ by less than 2 % (Powell and Neuberg 2003). As this regular rate of earthquakes gradually increases (or decreases), gliding spectral lines are produced. In this model, tremor is a low-frequency earthquake swarm.

Surface Signals

Surface signals are those generated by hazardous surface processes such as rockfall, pyroclastic flows, and lahars. Since these processes occur at the surface, they mainly generate surface waves.

Rockfall and Pyroclastic Flow Signals

Actively growing lava domes are highly unstable, and blocks can be observed falling almost continuously, disintegrating into smaller blocks and plumes of hot ash. Most of these rockfalls are small, but many generate detectable seismic signals. If larger parts of the dome collapse, or if there is an explosive component destabilizing the blocks, a pyroclastic flow may be generated. Pyroclastic flows are more energetic, produce vigorously convecting ash clouds, behave more like a fluid (less friction), and are therefore able to travel farther and at higher speeds. There is a continuum from the smallest rockfalls to the largest pyroclastic flows, and they mostly are spawned from the part of the dome that is actively growing. Pyroclastic flows can also be generated by the collapse of an eruption column.

Rockfall signals are emergent, contain a wide range of frequencies (1–10 Hz, peaking 3–4 Hz), and are dominated by surface waves. They have been located by exploiting the amplitude distribution of rockfalls signals across the seismic network. On Soufrière Hills Volcano (Montserrat), some rockfall and many

DOI 10.1007/978-3-642-36197-5_41-1

pyroclastic flows have a long-period precursor, and it is possible that this is an explosive degassing signal. At Unzen Volcano (Japan), pyroclastic flow signals are found to comprise three parts. First, a dome collapse is observed simultaneously with a small LP signal. Second, free-falling blocks impact the slope below (and fragment) simultaneous with a 0.5 Hz signal. Third, the fragmented material generates a rockfall signal.

Dome collapse signals are the superposition of many rockfall events, which may be occurring simultaneously on different flanks of the volcano. Dome collapses may last minutes to hours. From studying dome collapse signals, it is possible to tell how long dome collapses lasted and which phases of the collapse were most energetic. Several major dome collapses at Soufrière Hills Volcano (Montserrat) and Merapi Volcano (Indonesia) have been triggered by intense rainfall.

Lahar Signals

The composition of lahars varies from muddy water to highly erosive, dense mixtures of wet ash, rocks, and boulders that set like concrete. Lahars usually occur during or immediately after heavy rainfall. Barclay et al. (2006) found that about 2 cm per hour of rain falling on unconsolidated materials was sufficient to trigger lahars on Soufrière Hills Volcano (Montserrat). However, hot volcanic material can generate lahars by mixing with crater lakes or with snow and ice on glaciated volcanoes. Volcanic activity may also melt the base of a glacier and cause an outbreak flood that briefly rivals the force of a major river. These are particularly common in Iceland and are known in Icelandic as *jökulhlaups*.

Lahar signals are tremor-like signals that can be distinguished from pyroclastic flow signals by their duration (tens of minutes to hours), higher-frequency content (6–10 Hz, up to 100 Hz in some cases), and slower speeds; they show amplitude peaks on different stations perhaps minutes apart as they travel down valley. To improve the detection of lahar signals, seismic stations, video cameras, and tripwires can be added at various positions adjacent to (or within) the valley.

Difficulties of Event Classification

Classification of volcano-seismic signals is difficult. The signal recorded is a convolution of the source signature, propagation and site effects, and the instrument response, superimposed on noise which varies spatially and temporally. The source signature may be the result of complex interactions between a multiphase fluid and an unknown geometry of dikes and conduits. Further from the source, the signal-to-noise ratio decreases, and increased scattering and separation between P, S, and surface waves lengthen the signal, making it less clear. Inelastic attenuation may be greatest at shallow depths where poorly consolidated, highly fractured material results in higher frequencies being filtered out. Attenuation may also be significant at depths of 20 km or more, because of high heat flow and partial melt. Similar-looking signals at two different volcanoes, or even at the same volcano, might be caused by different physical mechanisms.

Classification is also subjective. Different seismic analysts may disagree on the classification of a particular event. Discrepancies in classification also appear in published literature: an LP in Lahr et al. (1994) looks similar to a hybrid in Luckett et al. (2007). Classification might artificially separate signals that lie along a continuum. The classification scheme may also evolve during volcanic unrest as a wider variety of signals are recorded. For these reasons it is helpful to reassess the event classes used before interpreting trends in their rates of occurrence or locations.

Terminology also differs. Some of the terms describe the frequency content of the signal and others imply a physical mechanism. VT earthquakes are also called high-frequency events and A-type events. LP earthquakes are also called B-type events. Collectively, long-period and hybrid events are called low-frequency (LF) events, because they are both dominated by low-frequency coda. Low-frequency seismicity includes low-frequency events and volcanic tremor.

DOI 10.1007/978-3-642-36197-5_41-1

Interpreting Volcanic Seismicity

A common pattern of volcanic seismicity is described by the Generic Volcanic Earthquake Swarm Model (McNutt 1996). Background seismicity varies from volcano to volcano and can only be established for a particular volcano through a long-established seismic monitoring record. The first sign of unrest is often an increase in the rate of *VT earthquakes*, indicating rock fracture due to changes in stresses caused by rising magma. In some cases it may be the occurrence of *DLP earthquakes*.

When magma reaches shallower depths, volatiles exsolve, and *LP earthquakes* are recorded. Volatiles cause a reduction in the acoustic velocity and an increase in the impedance contrast of magma cavities, trapping energy and leading to longer, lower frequency signals. As the volatile content increases, more energy is trapped, and this may lead to LP earthquake events called *tornillos*. Narrowband *tremor* may be generated by continuous vesiculation as magma rises further or by the boiling of groundwater. If groundwater is heated rapidly, a phreatic explosion may result.

At any time in the sequence, magma rise may stall. This may be the end of the unrest, or it may recommence as more magma is injected at depth adding more heat and volatiles to the system. *Tremor* due to groundwater boiling may subside as the system dries out, leading to a period of relative quiescence. For basaltic systems, an eruption may then occur without further warning.

For andesitic to rhyolitic systems, *hybrid earthquake swarms* often occur due to repeated shear failure of viscous magma as it gets close to the surface. *Hybrid earthquake swarms* are frequently associated with growth of a lava dome. If the events merge into a continuous tremor, *harmonic tremor* and *gliding spectral lines* might be observed and are the strongest signs that an explosive eruption may be about to occur. During an explosive eruption, violent ground shaking typically manifests as a broadband tremor signal. *Explosion earthquakes* may be recorded, identifiable by the shockwave that travels through the air and is coupled back into the ground.

Explosive eruptions are short-lived, and hopefully before they occur, any vulnerable populations will have been evacuated. But extrusive eruptions may last for years or decades, with varying levels of activity, spawning rockfall, pyroclastic flows, and lahars. Monitoring these long-lived eruptions presents challenges of its own, since communities are often in close proximity. Escalations in activity are often preceded by short sequences of VT earthquakes, low-frequency earthquakes, and tremor, perhaps suggesting a batch of new magma rising toward the surface. However, volcano-seismic data have also been used to track the rate, energy, and location of debris flows and estimate extrusion rates.

An important question to answer once an eruption is underway is when will it stop. The first sign may be the cessation of low-frequency seismicity, indicating that volatiles are no longer present in the system, which may be confirmed with gas flux measurements. More significant may be the occurrence of VT earthquakes at depth with fault-plane solutions consistent with magma withdrawal (Roman et al. 2006). Geodetic data may also indicate deflation of the volcanic edifice.

A more detailed discussion of the interpretation of volcano-seismic data is beyond the scope of this entry. There are several excellent summaries of our evolving understanding of volcano-seismology including Chouet and Matoza (2013), Chouet (2003), and McNutt (2000, 2002, 2005).

Observatories

Volcano observatories vary greatly in their level of sophistication. The simplest observatory may be a hut on the flank of a volcano, with a single seismograph recording on paper on a revolving drum. A modern observatory, however, will have a network of seismic stations with data telemetered to the observatory using a variety of communication systems such as FM radio, satellite, and cellular networks. The observatory may be on the flanks of the volcano, within a few miles of the active vent. Or it may

DOI 10.1007/978-3-642-36197-5_41-1

be tens or hundreds of miles away, colocated with a university or a government agency. Many observatories monitor a single volcano, but some monitor several. The Alaska Volcano Observatory has operated seismic networks on as many as 32 volcanoes. The Japan Meterological Agency monitors 47 volcanoes with real-time seismic data. This poses unique challenges: how to monitor so many volcanoes in parallel, how to interpret the data without being able to see the volcanoes, how to maintain so many networks, and how to manage all the data.

Participation in a volcanic crisis, is an opportunity to help society and also witness some of nature's most spectacular phenomena. Having the right team is crucial. The leader of a volcano observatory must be experienced in volcano monitoring and be committed to the job. The work can be stressful, the hours long, and hard decisions have to be made in the heat of the moment, e.g., regarding evacuations. Weekly meetings play a vital role at many observatories by pulling the team together, integrating data from many monitoring techniques, identifying technical problems, and prioritizing work. All observatory staff must conduct themselves professionally and have the authority to perform the roles assigned to them. Fostering good communications within the observatory and with the authorities and the public builds trust and enhances public safety.

The backbone of a volcano observatory is the seismic monitoring program, and the heart of the observatory is the operations room. It is from there that seismologists track live data streams, coordinate field teams and warn them of hazardous activity, and alert the authorities (and the public) to escalations in activity. When volcanoes are at background level, the operations room may be unoccupied. Periodic data checks, perhaps coupled with automatic alarm systems, may be enough to keep seismologists abreast of significant changes in seismicity. When unrest begins, periodic checks may become more frequent. At some point the operations room is activated and manned 24 h a day.

These different stages of volcanic activity, from background to unrest to impending eruption, greatly impact the level of seismic monitoring that can be done. At background level, seismologists may be able to conduct research. When a crisis is underway, it will be difficult to do anything more than interpret available real-time data using operational tools that are in place. Part of the job of an observatory seismologist is to engineer the infrastructure of the seismic monitoring program and operations room to be able to respond effectively during a crisis. This infrastructure includes seismic networks and software systems used to monitor volcanic seismicity. These are the subjects of the next two sections.

Volcano-Seismic Networks

Around 550 volcanoes have erupted in historical times, and about 200 of these are seismically monitored. The best networks tend to be around volcanoes that pose a particularly high threat to large population centers, e.g., Etna and Vesuvius (Italy), Rainier and St. Helens (continental USA), and Kīlauea (Hawaii). Many volcanoes are monitored only by a single station, often as part of a regional network. Nevertheless, by tracking the number and cumulative energy of different types of seismic signals recorded each day on a single station, a volcanic eruption can be anticipated. It may then be possible to rapidly deploy sufficient additional stations to locate earthquakes and forecast where and when an eruption may take place.

The most commonly used seismometers for volcano monitoring are short-period sensors. These have a corner frequency of 0.5–2 Hz and come in single (vertical) and three component varieties. Short-period seismometers are usually deployed with analog telemetry. Both have a dynamic range (the ratio between the largest and smallest amplitudes that can be represented) of only a few thousand. This results in signal amplitudes often being "clipped," which greatly diminishes the monitoring and research value of the data. Three-component portable broadband seismometers, available since the late 1980s, use a force-feedback circuit and typically have a corner frequency of 30–120 s and a dynamic range of several million, allowing

DOI 10.1007/978-3-642-36197-5_41-1

them to record signals on-scale even right up on the volcano summit. They have to be coupled with 24-bit digital telemetry systems, which have a similar dynamic range.

Analog-telemetered data are time stamped at the observatory by a time signal from a GPS clock, but modern field digitizers have an input for a GPS clock and can time stamp data on site (which is more accurate). On-site data recording enables data to be retrieved or retransmitted later if there is a communication outage. Two-way telemetry allows data packets to be resent automatically if they are not received intact and allows troubleshooting and reconfiguring of stations from the observatory without the expense and delay of a site visit.

While a digital broadband network offers many advantages over an analog short-period network, the equipment is more expensive and power requirements are 2–3 times higher, meaning that additional solar panels and batteries are needed. Broadband sensors also require precise leveling. Many analog networks have been upgraded to digital telemetry to improve dynamic range, and most new networks use digital telemetry, but it is still common to find analog telemetry at volcano observatories.

Designing a volcano-seismic monitoring network is complicated and involves multiple trade-offs. For the same budget a volcano observatory may be able to install a few digitally telemetred broadband stations or many more analog-telemetered short-period stations. The best choice depends on the goal.

For a volcano that is far removed from population centers, the goal might be to detect eruptions so that aviation authorities can be warned of hazardous ash clouds, requiring a minimal level of monitoring. For a densely populated region around a frequently active volcano, or one capable of devastating eruptions, higher quality monitoring is needed to provide as much lead time as possible. The magnitude detection threshold may vary from 2 for a regional network to below 0 for a dense volcano-seismic network. Moran et al. (2008) identified four levels of volcano-seismic monitoring and the number of short-period, broadband, strong motion, and infrasound sensors needed within different radii to make those levels of monitoring achievable. Their findings are summarized in Table 1.

A key consideration for locating earthquakes accurately is to minimize the azimuthal gap. A ring of stations, which encloses most of the volcanic-earthquake epicenters, is ideal with a few stations closer to the volcanic center where they can help detect smaller seismic signals and be used to locate summit events with greater precision and improve depth resolution. For stratovolcanoes, all the earthquakes may be within 1–2 km of the volcanic center, whereas for calderas the seismicity might be diffused over an area 15–20 km in radius. It is useful also to have real-time data from at least one more distant station (which may be part of a regional network) to help constrain the depths of deeper events, and to discriminate more effectively between regional and local volcanic earthquakes. These steps make it possible to locate earthquake reasonably well relative to each other, but how well they match the true locations of the earthquake will depend on the velocity model and to a lesser degree, on the algorithm used to locate the events. The sophistication of the velocity model may vary from a simple one-dimensional regional model with constant velocity layers to 3-D models determined from seismic tomography.

Site selection depends on the geology, topography, accessibility, and noise. It is preferable to install seismometers in solid bedrock, but volcanoes are typically comprised of layers of ash, flow deposits, and boulders. Repeaters may be required on ridges to rebroadcast signals or boost them if transmitting over tens of kilometers, but represent additional expense and potential points of failure. Sites that require helicopter access will be expensive to maintain, so often it is better to find sites that can be easily reached with four-wheel-drive vehicles or on foot. Sites should be far from traffic and other human noise and also away from any tall obstacles that may be vibrated by the wind, such as trees, cliffs, and radio towers. Burying sensors a few feet below the surface helps suppress high-frequency wind noise and low-frequency noise due to temperature and pressure variations.

Among the best volcano-seismic networks are those used to monitor Piton de la Fournaise (Reunion), Halemaumau (Hawaii), St. Helens (USA), and Soufrière Hills (Montserrat) volcanoes (Table 2).

DOI 10.1007/978-3-642-36197-5_41-1

Table 1 Recommended instrumentation to achieve different levels of volcano-seismic monitoring from Moran et al. (2008)

Level	Goal	Recommendation
1	**Minimal monitoring/eruption detection** Detect $M > 1.5$ earthquakes; crudely locate $M > 3$ earthquakes	Site a total of five seismic stations within 200 km, including two within 50 km of the volcanic center
2	**Limited monitoring/unrest detection** Detect $M > 1$ earthquakes; crudely locate $M > 2$ earthquakes; determine event type; detect energetic seismic tremor	Site a total of five seismic stations within 50 km, including two within 10 km of the volcanic center
3	**Basic real-time monitoring** Detect $M > 0.5$ earthquakes; accurately locate $M > 1$ earthquakes; determine event type; detect seismic tremor; on-scale recording of energetic seismicity on at least one station; detect very-long-period events Detect changes in travel time; detect broad-scale changes in seismic velocity Use fault-plane solutions and b-values to determine generalized stress fields near the volcanic center	Site six to eight seismic stations within 20 km of the volcanic center, including two or three stations with at least one three-component sensor and at least one broadband station, within 5 km
4	**Advanced real-time monitoring** Detect and accurately locate $M > 0$ earthquakes; determine event type; detect and crudely locate seismic tremor; on-scale recordings of energetic seismicity on multiple stations; detect and crudely locate very-long-period events and other very-low-frequency seismicity Determine detailed source properties of tornillos; construct 3-D velocity models (provided local seismicity is sufficient) Detect explosions and possible infrasonic precursors to explosions at restless and (or) frequently active volcanoes Detect detailed stress-field changes by calculating well-constrained fault-plane solutions and (or) moment tensors, mapping b-values at high spatial resolution, and detecting changes in S-wave-splitting directions over time	Site 12 to 20 seismic stations within 20 km of the volcanic center, including at least six broadband stations, as many as possible within 5 km; at least one strong-motion station; and at least two infrasonic stations (with at least two infrasonic sensors per station) at erupting, restless, and (or) frequently active remote volcanic centers

Table 2 Some of the best volcano-seismic monitoring networks. The numbers in parentheses indicate number of borehole instruments. All of these networks surpass level 4 as defined in Table 1 of Moran et al. (2008)

	Stations within 5 km			Stations within 20 km		
Volcano	Broadband	Short period	Total	Broadband	Short period	Total
St. Helens (USA)	2	7	9	2	16 (4)	18 (4)
Soufrière Hills (Montserrat)	7 (1)	0	7 (1)	9 (1)	6 (4)	15 (5)
Piton de la Fournaise (Reunion)	14	6	20	16	17	33
Halemaumau, (Hawaii)	12	5	17	19	14	33
Stromboli (Italy)	18	0	18	18	0	18
Etna (Italy)	?	?	13	?	?	34
Vesuvius (Italy)	?	?	17	?	?	21
Erebus (Antartica)	6	6	12	6	6	12

According to the criteria in Table 1, these are all level four networks. A map of the digital seismic network that has been operational in Montserrat since 2006 is shown in Fig. 1. This utilizes a mixture of Guralp

DOI 10.1007/978-3-642-36197-5_41-1

CMG-40T broadband and Mark L4-C short-period seismometers, coupled with Guralp DM24 digitizers and FreeWave Spread Spectrum serial port radios. One of the broadband stations has a CMG-3 T seismometer in a 30-m borehole and less than 4-km from the dome. Four more sites feature a dilatometer and 2-Hz seismometer in 200-m boreholes, coupled with surface GPS. The Piton de la Fournaise network also uses CMG-40T and L4-C seismometers, coupled with Kinemetrics Q330 digitizers and a combination of wireless internet and FM radio telemetry.

Real-Time Monitoring

Volcanic activity may escalate suddenly, and the ability to rapidly identify anomalous volcano seismicity is critical. Real-time data visualization systems allow scientists to rapidly assess multiple parameters derived from seismic data such as hypocenters, magnitudes, event rates, spectral variations in tremor, etc. Alarm systems alert scientists to large events and the occurrence of high amplitude tremor and volcanic earthquake swarms. Data-rich websites and remote desktop connections allow scientists to respond rapidly to alarm: This is convenient and enhances safety. The US Geological Survey, through its Earthquake and Volcano Hazards Programs, has played a pivotal role in disseminating free, open-source software to aid in volcano-seismic monitoring. This section describes common techniques and software used to examine continuous seismic data and events in more detail.

Continuous Data

Digital Helicorder Plots

The most basic form of real-time data display is the helical drum recorder (often called "helicorders" or "drums"). A pen etches a trace on a smoked sheet (or draws an ink trace on a blank sheet) of paper wrapped around a cylindrical drum. Helical drum recorders have played a vital role in volcano-seismic monitoring, allowing rapid visualization of seismic amplitudes and event identification of signal types.

Helicorders were ubiquitous until the 1990s and are still used at many observatories today, but they have numerous drawbacks. They require considerable maintenance and provide limited dynamic range. Adjacent traces often overlap, making them hard to read. The data are not amenable to other forms of analysis, and the sheets require storage space. So there has long been a desire to replace helicorders with a software equivalent. Seismic Waveform Analysis and Real-time Monitor (SWARM) (http://volcanoes.usgs.gov/software/swarm/index.php) is an excellent solution that allows data to be plotted dynamically: The user can select the time range and the scale; the data can be filtered, and short segments of data can be highlighted and replotted as spectra or spectrograms. Many observatories have now replaced large collections of helicorders with multiple screens showing SWARM displays from different seismic channels. Figure 2 shows 48 h of seismicity at the Soufrière Hills Volcano in June 1997.

RSAM Plots

Continuous data are often downsampled to one sample per minute, which makes it easier to identify long-term trends in continuous seismic amplitude. The Real-time Seismic Amplitude Measurement system (Endo and Murray 1991) took the average amplitude of the seismic signal in each 1-min time window, and recorded these data into a file. RSAM data do not discriminate between different types of seismicity.

RSAM data show cyclic seismicity clearly (Fig. 3a). Changes in earthquake activity associated with dome-building episodes (Fig. 3b), weather, and instrumental difficulties are recognized as distinct patterns in RSAM datasets. RSAM data for dome-building episodes gradually develop into exponential increases that terminate just before the time of magma extrusion. Volcanic earthquakes and rockfall show up as

Encyclopedia of Earthquake Engineering
DOI 10.1007/978-3-642-36197-5_41-1

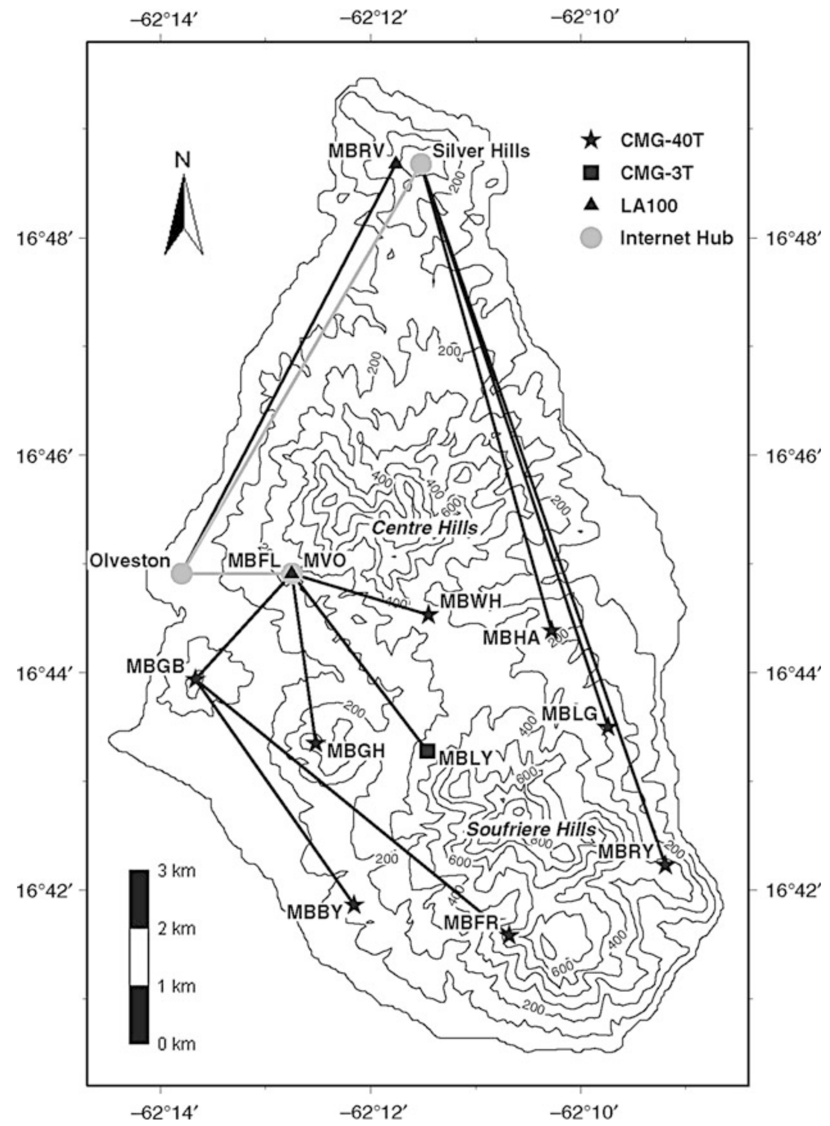

Fig. 1 The Montserrat seismic network from April 2006 (Modified after Luckett et al. (2007)). Telemetry paths are shown as *lines*. The observatory is marked with MVO. Repeater sites are marked with a *gray circle*. Short-period stations are marked with a *triangle*. Broadband stations are marked with a *star*, except for the borehole broadband, MBLY, marked with a *square*. Not shown are the four 200-m borehole short-period stations, operated by the CALIPSO consortium since 2002

isolated spikes on RSAM plots for seismic stations close to the edifice, but seldom for more distant stations. Weather-related noise shows up as low-level, long-term disturbances on all seismic stations, regardless of distance from the volcano. The RSAM system proved valuable in providing up-to-date information on seismic activity for three Mount St. Helens eruptive episodes from 1985 to 1986 and in numerous eruptions at other volcanoes since. Exponential increases in RSAM data commonly precede explosive eruptions. Inspired by RSAM, many other parameters have been computed on 1-min (or 10-min) timescale. For example, RSEM provides a relative measurement of energy on a 1-min (or 10-min) timescale. Computing the median (rather than mean) amplitude in each time window provides a measurement of tremor amplitude less biased by events or spikes in the data - but is no longer strictly ‘RSAM’ data. Corrected for the instrument response and geometrical spreading, and then integrating the data, produces reduced displacement. Since 1996 the Alaska Volcano Observatory has recorded an

Encyclopedia of Earthquake Engineering
DOI 10.1007/978-3-642-36197-5_41-1

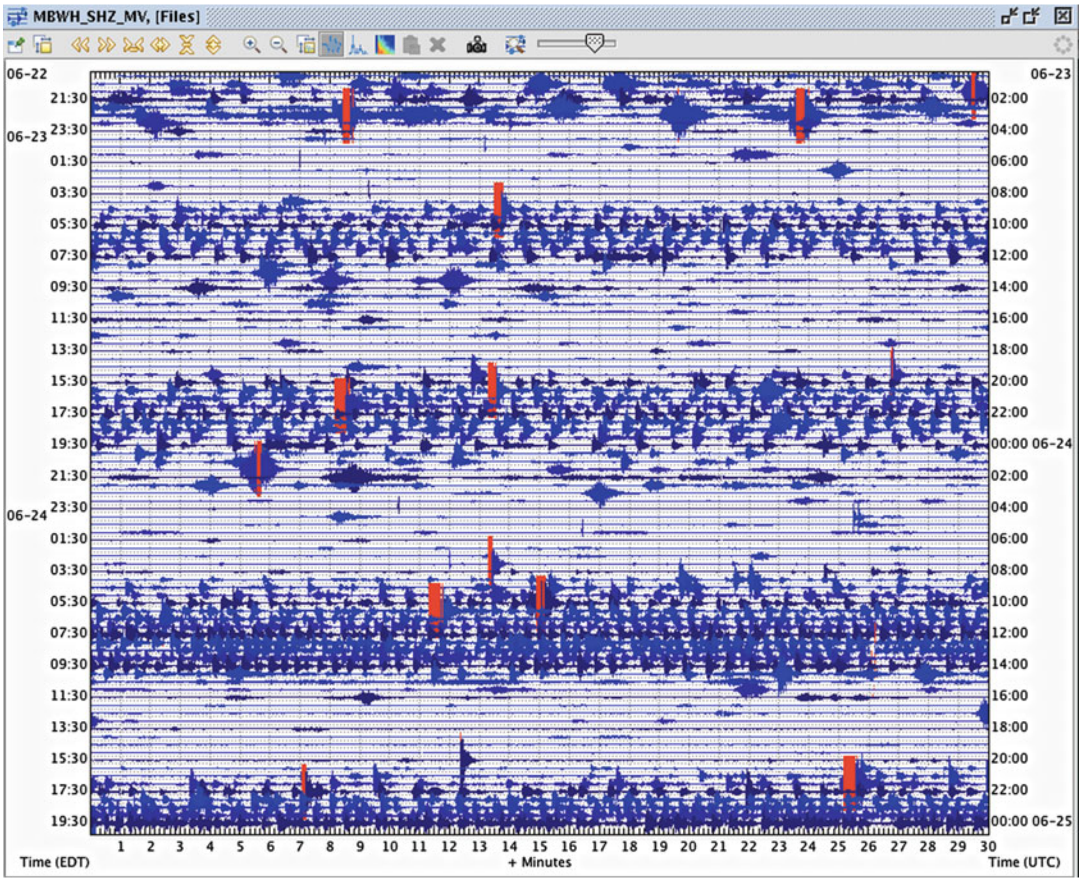

Fig. 2 Screenshot of the software Swarm, showing a digital helicorder plot from station MBWH channel SHZ for 48 h from June 23, 1997. Remarkable cyclic hybrid swarms are visible. In June 25, a moderate dome collapse sent pyroclastic flows the northern flanks of the Soufrière Hills Volcano, claiming 19 lives

instrument corrected seismic amplitude and the peak frequency for each vertical-component seismic channel, on a 10-min timescale.

Spectrograms

Changes in tremor spectra may indicate different flow regimes or changes in source parameters such as geometry, sound speed, or ascent rate (Thompson et al. 2002). Harmonic tremor and gliding spectral lines are frequently followed by eruptions. Spectral monitoring can help differentiate between VT and low-frequency earthquakes, or tremor; wind noise; and electronic noise.

The Alaska Volcano Observatory (AVO) began experimenting with high-resolution spectrograms in 1996. For up to eight stations, a spectrogram is plotted underneath a normalized seismic trace. The time resolution is about 10 s and the frequency resolution 0.1 Hz. Each image file (Fig. 4) displays a 10-min seismic trace and spectrogram for up to eight seismic-data channels. These are ordered in increasing distance from the volcano. The data are instrument corrected and color coded, so that ground motions at one station can be easily compared with those at another station, even at a different volcano.

These web-based spectrograms have been a core AVO monitoring tool since 1998, and a seismologist reviews them twice a day. A convenient web interface (http://www.aeic.alaska.edu/spectrograms/mosaicMaker.php) shows mosaics of 10-min spectrogram image files (Fig. 5) and enables 12 h of data from more than 20 volcanoes to be reviewed in just 30–45 min. Similar web-based spectrograms are used for monitoring volcanic seismicity in the Cascades and Hawaii.

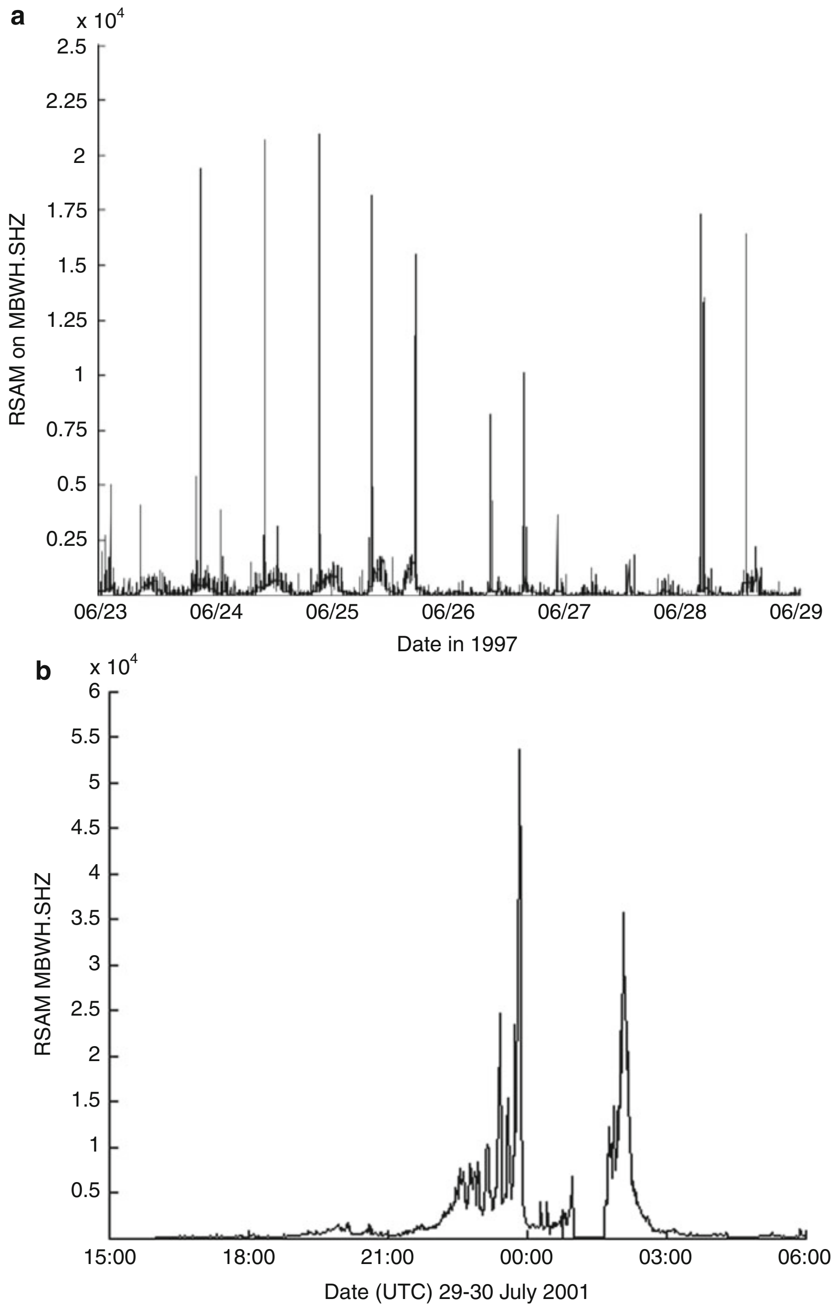

Fig. 3 (**a**) Plot of RSAM data with one sample per minute for station MBWH channel SHZ from June 22 to 29, 1997. The cyclic hybrid swarms mentioned in Fig. 2 are shown clearly. The spikes represent discrete events, e.g., pyroclastic flows. (**b**) RSAM plot showing the major dome collapse of the Soufrière Hills Volcano (Montserrat) which occurred on July 29, 2001

Tremor Alarms

Tremor is common precursor to eruptions, and strong tremor frequently accompanies eruptions. Observatory seismologists therefore need to be aware when tremor is being recorded. The earliest widely used volcano-seismic alarm system was part of the RSAM system (Endo and Murray 1991), and this is now incorporated in Earthworm (discussed below). The seismologist can choose which stations to monitor and define an amplitude threshold and a duration for each station. Both must be exceeded to trigger a station. The seismologist also must define the number of stations that must trigger simultaneously to declare an

DOI 10.1007/978-3-642-36197-5_41-1

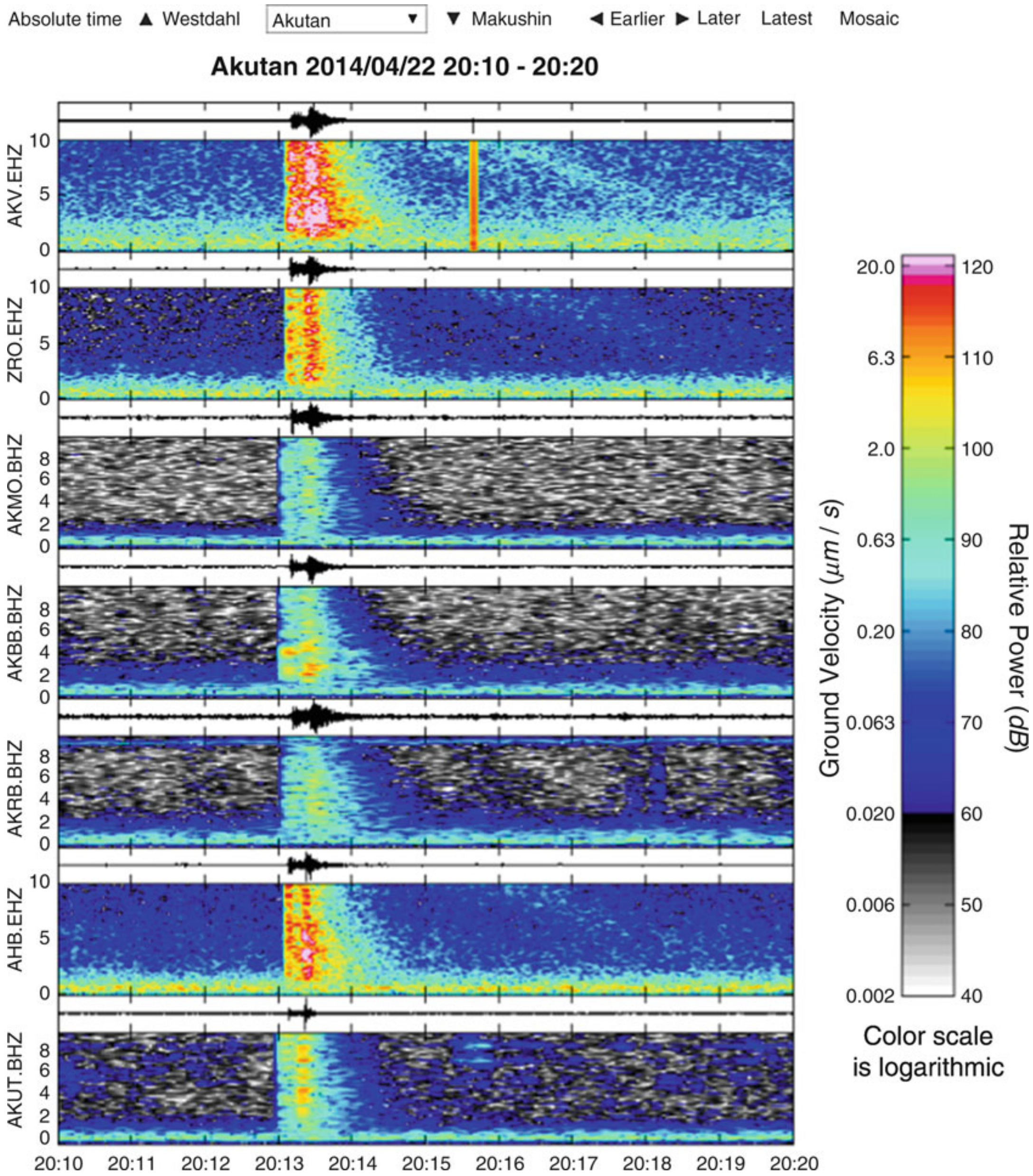

Fig. 4 Seismic traces and corresponding spectrograms for the vertical components of seven seismic stations near Akutan Volcano, corresponding to 10 min of data on April 22, 2014. A regional earthquake is visible clearly around 20:13 UTC. The hottest colors shown (*pink*) suggest an S-wave ground velocity of 0.02 mm/s. Near-real-time spectrogram plots like this have been linked to the AVO internal website since 1996. The menu at the top of the screen allows easy navigation to other volcanoes or time periods

alarm. There is also a mechanism which reduces the false alarms due to regional or teleseismic earthquakes: A far away station can be chosen which prevents an alarm being declared when it exceeds an amplitude threshold. The tremor alarm is typically configured for a moderate amplitude and a duration of several minutes (the RSAM system also included an event alarm, which would typically be configured for high amplitude and duration of a few to tens of seconds).

The RSAM tremor alarm system was used to monitor the Soufrière Hills Volcano (Montserrat) from 1999 to 2003. Figure 6 shows the number of alarms issued over this period.

DOI 10.1007/978-3-642-36197-5_41-1

Fig. 5 A spectrogram mosaic, part of the same application shown in Fig. 4. Three hours of data are shown. Regional earthquakes are visible at 20:13 (Fig. 4) and 22:15. A calibration signal occurs on the top station (AKV) at 22:03. The apparent data dropouts are due to data latency

Events

Real-Time Seismic Event Catalogs

During a volcanic crisis, it is vital to have near-real-time information about the rates, sizes, and locations of seismic events, and for this a real-time event catalog is needed. Providing there are at least four stations, event detection software automates the process of capturing anomalous signals in large volumes of continuous data. Each channel of seismic data is detrended, filtered, and rectified, and a running short-term average (typically 1 to a few seconds) and long-term average (typically a few tens of seconds) are computed. Where the STA (short-term average) to LTA (long-term average) ratio exceeds a threshold, a candidate P or S arrival is declared. Association is the process whereby candidate arrivals' "picks" are grouped together based on similar arrival times and geographic location to declare an event. Location techniques typically use a 3-D grid search to minimize the difference between measured and theoretical travel times, given a particular velocity model. For volcanic earthquakes, it is most common to compute a duration magnitude due to the prevalence of clipped signals from short-period analog telemetry. For on-scale recordings, local magnitude is often also computed. To visualize catalogs, it is helpful to view event rate and energy rate plots (Fig. 7) and hypocenter plots (Fig. 8).

There are some caveats with event catalogs. Discrete events are only one aspect of volcanic seismicity. Signals such as precursory earthquake swarms and tremor episodes, or those generated by explosive eruptions, dome collapses, pyroclastic density currents, and lahars, are of the greatest interest from a

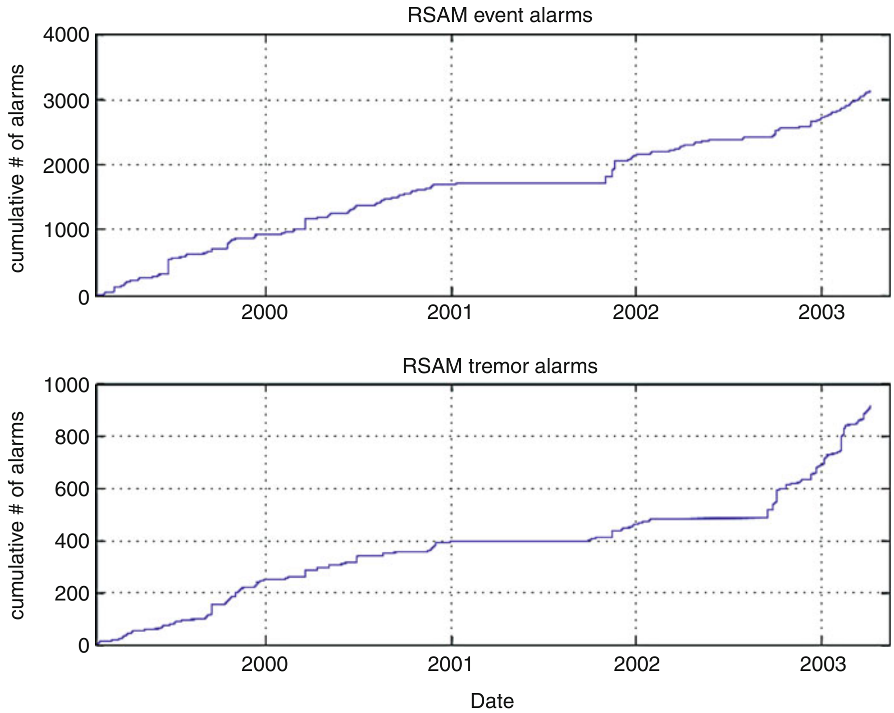

Fig. 6 RSAM event alarms (*top panel*) and tremor alarms (*bottom panel*) issued at Montserrat Volcano Observatory between February 1999 and May 2003. In total there were about 4,000 alarms, an average of almost three alarms per day. The alarm thresholds configured for each station were raised throughout 2000 and 2001 as activity increased. Event alarms typically corresponded to pyroclastic flows and regional earthquakes, and tremor alarms to dome collapses (i.e., a series of pyroclastic flows)

hazard perspective. Such signals generally evade standard earthquake-detection schemes based on comparing the short-term and long-term signal averages and are not systematically cataloged. The vast majority of volcano-seismic signals lack identifiable phases and so cannot be located with differential travel-time techniques. Earthquake catalogs therefore present only a narrow view of volcanic seismicity. Many volcano-seismic signals are emergent or long in duration, so STA/LTA detectors break down. Events may be masked by high background signals (e.g., tremor, wind, or electronic noise). Station outages also increase the magnitude at which earthquakes become detectable. Times when an event catalog suggests there is little seismicity may actually be times of high seismicity. Real-time catalogs also suffer from poorly resolved locations and magnitudes – also a review by an analyst later corrects for these.

Swarm Alarms

Earthquake swarms, like tremor, are a common precursor to volcanic eruptions. A real-time event catalog can be used as the basis for detecting earthquake swarms.

Okmok Volcano (Alaska) erupted ash to a height of 15 km on July 12, 2008, after less than 5 hours of precursory seismicity which included an earthquake swarm. Concerned by this, the Alaska Volcano Observatory developed a swarm alarm system. The system identified the start and end of five swarms that occurred between February and April 2009, as well as significant escalations in the rate of earthquakes and energy release during those swarms (Thompson and West 2010).

Encyclopedia of Earthquake Engineering
DOI 10.1007/978-3-642-36197-5_41-1

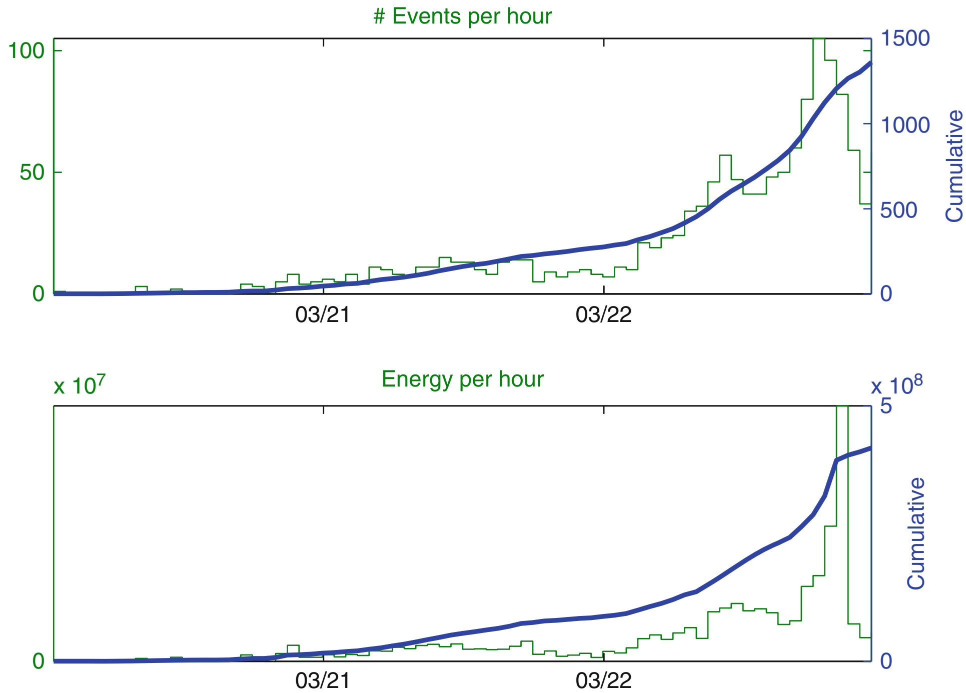

Fig. 7 Two common ways of examining trends in detected events are (upper panel) event rate (also called 'counts'- the number of detected events per unit time) plots, and (lower panel) energy release rate plots (computed from magnitude data). The data shown are from Redoubt volcano, Alaska, from 2009/03/20 to 2009/03/23 and are produced using the GISMO toolbox. Energy units are arbitrary

Software

Earthworm (http://folkworm.ceri.memphis.edu/ew-doc/), is the most widely used system for earthquake and volcano-seismic monitoring today. It is an open-source, data acquisition, and earthquake detection framework developed by the US Geological Survey. It comprises of modules that communicate via messages on shared memory rings. It is used in the National Earthquake Information Center, tsunami warning centers, and regional seismic networks. Earthworm is in widespread use at volcano observatories today, in conjunction with other tools that expand its real-time monitoring capabilities. Two reasons for this are that all US volcano observatories use them, and the USGS Volcano Disaster Assistance Program deployed them in many countries at the request of foreign governments.

Earthworm is not the only widely used seismic monitoring systems: Alternatives are SeisComP3 (https://www.seiscomp3.org/wiki/doc) and Antelope (http://www.brtt.com/software.html). Antelope is an excellent framework for developing new monitoring and research tools, but requires a commercial license except for US higher education institutions. SeisComP3 provides a rich set of graphical user interfaces for global and regional seismic monitoring and is particularly suited for tsunami early warning. However, neither currently has adaptations for volcano-seismic monitoring.

Earthworm, SeisComP3, and Antelope are capable of generating real-time earthquake catalogs within a few minutes of event occurrence, and they work well for regional earthquakes and volcano-tectonic earthquakes. However, other volcano-seismic signals lack clear P- and S-waves required to compute even an approximate location. Fortunately, Earthworm includes another mode of event detection called "subnet triggering," which determines only an approximate event time, and does not attempt to locate an event. This approach is employed by many volcano observatories. Custom code can be added to monitor these events and trigger other calculations. For example, at the Montserrat Volcano Observatory from 2000 to

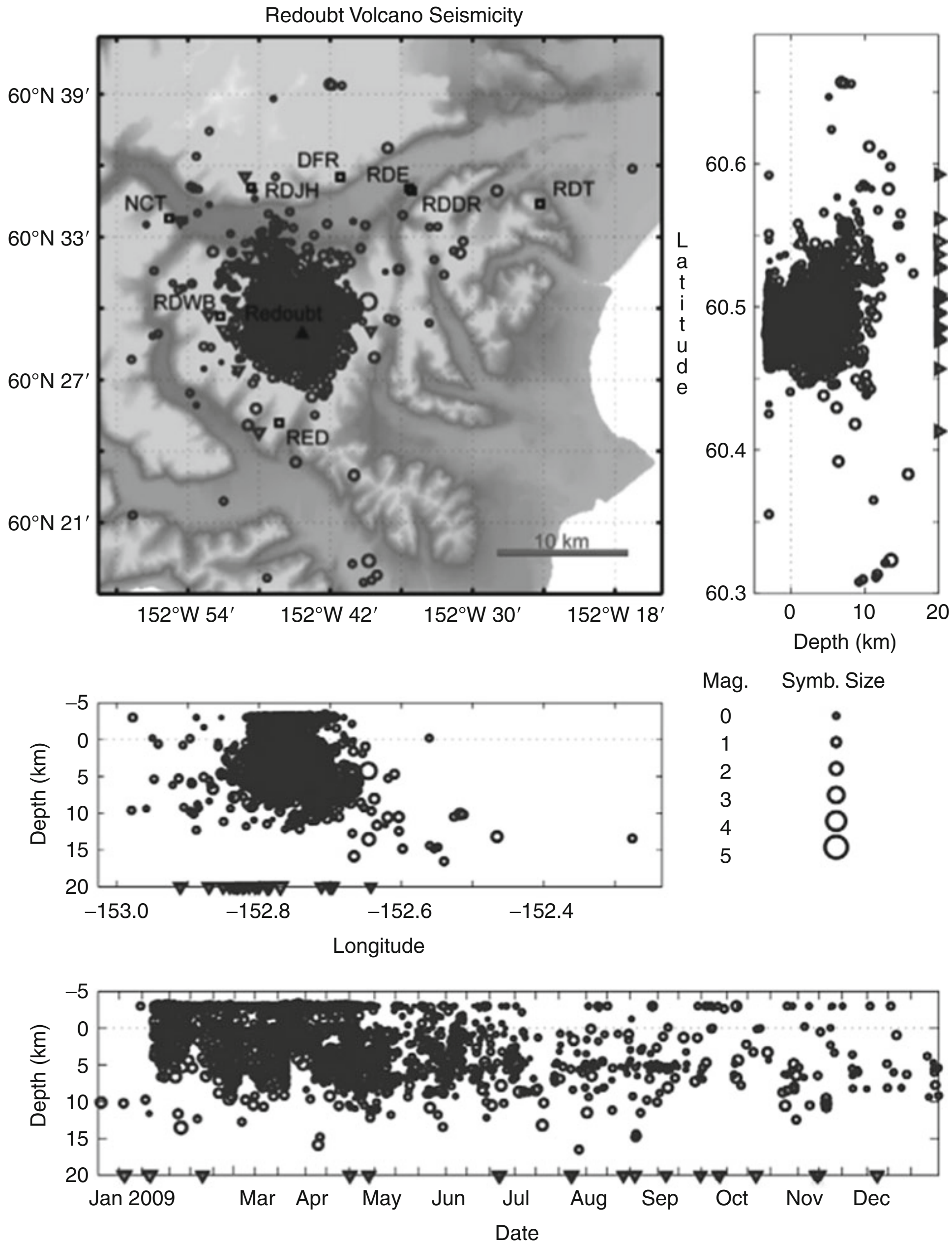

Fig. 8 A common way of presenting 3-D hypocenter data is as a set of 2-D slices through the data. In this plot, generated by VolPlot, a program used for many years at the Alaska Volcano Observatory, earthquake hypocenters from Redoubt Volcano in 2009 are shown. The main panel shows epicenters in map view, and adjacent panels show depth versus latitude and depth versus longitude. These help scientists identify spatial relationships in hypocenter data. At the bottom, depth versus time is shown, which helps scientists recognize if earthquakes are getting closer to the surface. The size of the symbols indicates magnitude

2003, real-time measurements of the amplitude, energy, and frequency content of new events were made, and used to regenerate plots on a private web site used by observatory scientists.

Earthworm has the ability to import data from a wide variety of field instrumentation and data servers and includes a variety of earthquake detection, location, and magnitude algorithms. There are modules which compute RSAM data and create daily helicorder and spectrogram plots. Tremor and swarm alarm systems are now included in Earthworm. Other modules can harvest messages about detected events,

Encyclopedia of Earthquake Engineering
DOI 10.1007/978-3-642-36197-5_41-1

arrivals, locations, and magnitudes to create a real-time event catalog, serve up plots of event rates and Google Maps of epicenters, and serve data in QuakeML format.

SWARM can either draw data from a SeedLink server, an Earthworm wave server, or an FDSN (International Federation of Digital Seismograph Networks) web service. Another option is a Winston wave server, which emulates an Earthworm wave server, but stores data in a MySQL database, providing rapid access and a deep data archive. Winston also provides a web interface that allows plotting of helicorder images and RSAM data (RSAM data are precomputed on import to Winston).

Data Analysis

Some analyses are not performed in real time, because it cannot be fully automated or just because the tools to do it well have not yet been developed; but they nevertheless provide timely information that can affect the way scientists interpret activity.

Analyst-Reviewed Event Catalogs

A real-time event catalog is valuable, but it cannot approach the quality of an analyst-reviewed catalog. A seismic analyst will periodically review the detected events, classify them, and delete false events. They might also pick P and S phases, run software to locate events, and compute magnitudes. Such a catalog is essential for research, but can be difficult to produce in a timely manner as volcanic unrest intensifies and decisions need to be made on timescales of minutes and hours, rather than days. During earthquake swarms (and major aftershock sequences), human analysts may be overwhelmed, increasing latency further just when it matters most.

While Antelope and SeisComP3 include an analyst review capability, Earthworm does not: So it is commonly paired with Seisan (http://seis.geus.net/software/seisan/seisan.pdf), which is an excellent free software package for processing and editing event catalogs. Seisan can estimate fault-plane solutions, moment tensors, and b-values too. Seisan includes some adaptations for volcano-seismic analysis: It supports event classes such as VT, LP, hybrid, and rockfall and can generate event-rate plots. Event waveforms are typically examined as spectra as well as time series. However, automated event classification is highly desirable because different real-time processing schemes could then be applied to different event classes. For example, at the Montserrat Volcano Observatory from 2000 to 2003, rockfall signals were directed into an automated rockfall location system.

Automated techniques for classifying events have been tried at some observatories, but remain rare. Many researchers have had success with frequency-based analysis, artificial neural networks, and hidden Markov chains, but typically for only certain types of events recorded at a particular volcano on a particular station. Neither Earthworm, Antelope, or SeisComP3 currently include an auto-classification module.

Swarm Analysis

While event detection software captures many (perhaps most) volcanic earthquake signals, additional events can be found by using a match filter. This technique is particularly useful for tracking repeating, low-frequency earthquakes, since the emergent onsets of this type of event make them notoriously difficult to trigger using an STA/LTA detector. A known event waveform (or part of it) is cross-correlated against continuous data to find additional events in the same “family.” Each family represents a source which is repeatedly activated in a volume that is small compared to the wavelength of the correlated signal. A number of volcanic processes are thought to be able to generate repeating earthquakes, including repeated resonances of fluid-filled cracks, a propagating crack tip that is driven by intruding magma, or even repeated shear failure within a body of magma. Additional analyses of the earthquake locations and the waveform frequency spectra are needed in order to distinguish between these various models. Double-difference relocation can be used to image the spatial evolution of the swarm more clearly.

A related technique is to cross-correlate waveforms from all events in a catalog against each other, to discover all event families. The MATLAB toolbox "GISMO" includes tools to automate this process. During unrest at Redoubt Volcano in 2009, this was used in near real time to monitor the evolution of swarms (Buurman et al. 2012) (Fig. 9).

Locating Phaseless Seismic Signals

The tremor alarm systems mentioned previously are very simple and they lack the ability to locate tremor. Some observatories have exploited seismic data to track the location of tremor and map debris-flow trajectories, which could help mitigate hazards.

Phaseless signals, once identified (via an STA/LTA algorithm or visual inspection), can be approximately located by exploiting the manner in which seismic wave amplitudes decay with increasing distance from the source, due to geometrical spreading and attenuation (Jolly et al. 2002). Alternatively, they can be located by cross-correlating data to determine travel-time differences and then using traditional differential travel-time techniques to locate the source (assuming the wave type is known). The Waveform Envelope Clustering and Correlation (WECC) system (Wech and Creager 2008) reverses this approach. It continuously locates envelopes of continuous waveform data, and if the location errors are small, it declares an event. Designed to locate the episodic tremor associated with the slow slip, it is now being applied to volcanoes.

Detecting Lahars

Lahar signals may appear as high-frequency tremor signals on a volcano-seismic network, but may be difficult to detect and locate without designing a network for lahar monitoring. High-frequency surface waves attenuate rapidly with increasing distance, so the amplitude of high-frequency signals can be indicative of how close a flow is to a seismometer. More dilute flows are also richer in higher frequencies. An existing volcano-seismic network can be adapted for lahar monitoring by adding stations close to the flow channel at various points, enabling lahar signals to be more easily resolved and crudely located using the times of the peak amplitudes on each station, and also the amplitude distribution across the seismic network. Trip wires can be positioned across the valley at different points and at different heights, and the arrival time and location are known precisely when the wire is cut. Disadvantages are that trip wires only work once and a dilute flow may leave the wire intact. Sophisticated lahar-monitoring systems have been installed at many volcanoes including Rainier, Merapi, and Nevado del Ruiz.

Imaging Spatial Changes in Volcanic Seismicity

There are many techniques for imaging magma storage regions. A volume devoid of volcano-tectonic earthquakes may indicate a large magma storage body, incapable of shear failure. Seismic tomography can reveal volumes with low P- or S-wave propagation speeds. B-value mapping (see Sanchez et al., "► Frequency-Magnitude Distribution of Seismicity in Volcanic Regions," this volume) can reveal volumes incapable of sustaining large failures, which are often inferred as being associated with magma. In the region around Uturuncu Volcano (Bolivia), the presence of a sill at around 15–20-km depth has been inferred by an S-wave shadow zone. Roman et al. (2006) found that changes in the orientation of fault-plane solutions could be used (retrospectively) to differentiate between volcano-tectonic earthquakes related to the injection of new magma and posteruptive relaxation.

Ambient noise tomography is another technique, which can be used to detect velocity changes. In active source seismology, an impulsive source is generated at one location and recorded at another. The

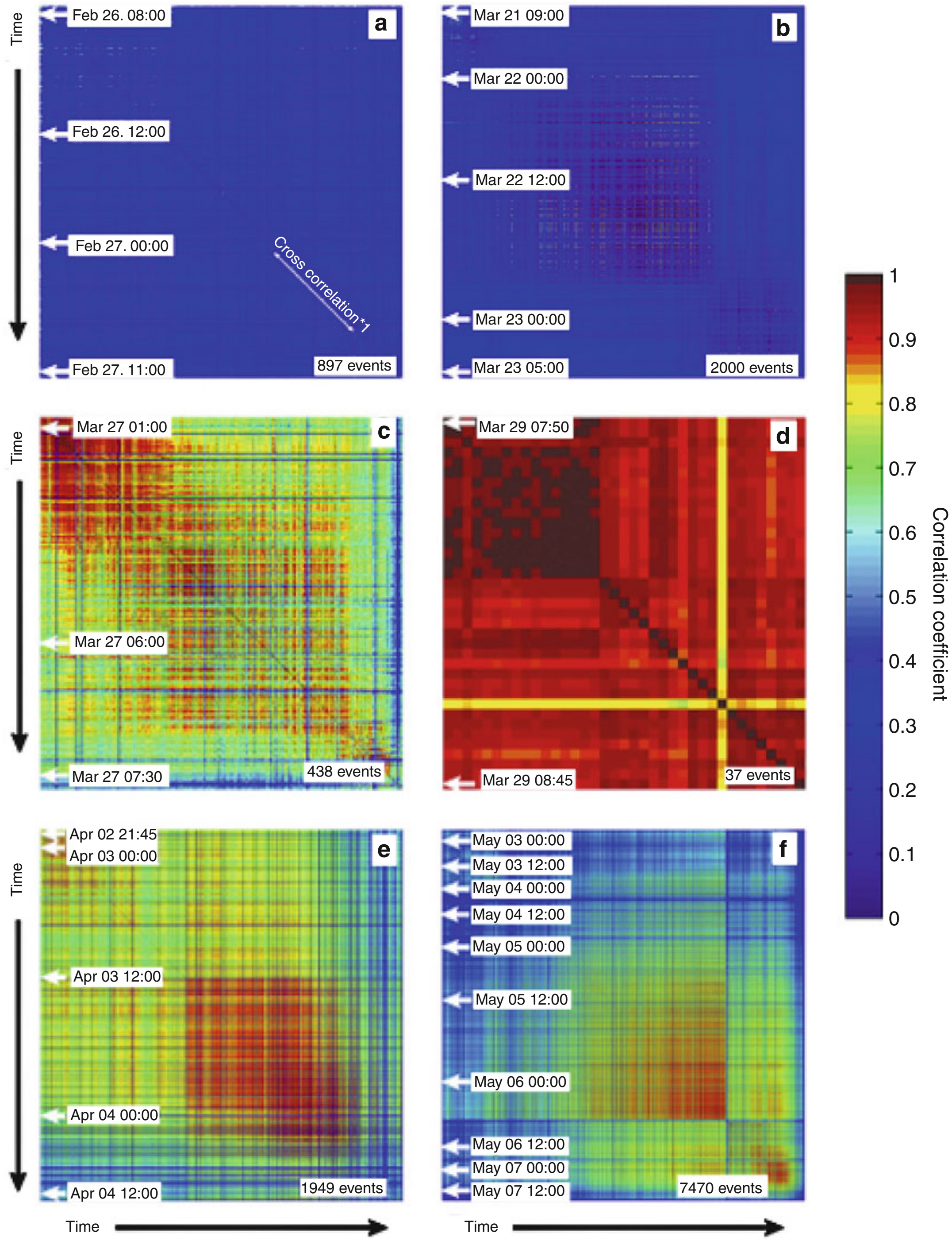

Fig. 9 Cross-correlation plots for six swarms during the crisis at Redoubt Volcano in 2009 (reproduced from Buurman et al. (2012)). Each pixel represents of pair of waveforms that have been cross-correlated. Color represents the maximum cross-correlation coefficient. Time progresses from *top to bottom* and *left to right* in each panel. The *top-left* to *lower-right* diagonal represents the autocorrelation of each waveform. The swarms began on: (**a**) February 26, (**b**) March 21, (**c**) March 27, (**d**) March 29, (**e**) April 2, and (**f**) May 2

resulting seismogram is the Green's function of the path between the sites. If this were done repeatedly, seismic velocity changes along the travel path could be detected. At a volcano, a drop in velocity could be indicative of increased heat flow, faulting, fluid injection, or expansion of the volcanic edifice. MSNoise

Encyclopedia of Earthquake Engineering
DOI 10.1007/978-3-642-36197-5_41-1

(http://www.msnoise.org/) is a package which has been developed to automate the computation of Green's functions between all station pairs on a daily basis, allowing velocity changes as small as 0.1 % to be identified. At Piton de la Fournaise Volcano, the locations of dike injections and eruptive fissures have been inferred.

Detecting Explosions

Cleveland Volcano (Alaska) has been erupting frequently in recent years, generating ash clouds that threaten aviation travelling between North America and Asia, and, without a functioning seismic station within a few tens of kilometers, many of these eruptions were previously missed or only recognized later in satellite images. De Angelis et al. (2012) describe a system which exploits data from a seismic network on Okmok Volcano, operated by the Alaska Volcano Observatory, to detect explosions at Cleveland Volcano (about 120 km away). An STA/LTA detector creates candidate arrivals. For those that fall within a 2-min sliding window, the differential travel times are computed by cross-correlating envelopes of the seismograms and then inverted for apparent slowness. If this is consistent with a sound speed of 340 +/−30 m/s in the direction of Cleveland, an alarm is sent by email. An alternative to the Cleveland explosion alarm mentioned above looks for a coherent signal across an infrasound array instead. The advantage is that infrasound sensors record explosion signals less ambiguously, and the technique could be used to detect explosions in other regions where installation of a local seismic network is unrealistic.

Technical Challenges

One of the major challenges for observatories and seismic networks is monitoring the state of health of a seismic network. There is only one chance to gather data, and in a crisis, data not collected in real-time have little value. Seismic and repeater stations need to be engineered to withstand weather variations which may include heavy rain, snow and ice accumulation, strong winds, and months of little solar energy. Spare equipment needs to be available so that stations can be fixed quickly when a seismic station component breaks. Vandalization by humans, damage by animals, and theft are other considerations. During unrest, ash build-up on solar panels can quickly cause power loss at a seismic station.

Problems will usually be apparent with tools volcano seismologists use every day. RSAM plots may reveal diurnal cycles in the data which may indicate undercharging of batteries or anthropogenic noise. Spectrograms and seismograms may show a flat signal (power loss), a one-sided signal (stuck seismometer), large offset (seismometer not level), white noise (loss of seismic signal), or spikes and dropouts (interference). These can cause havoc with automated detection and alarm systems, leading to corrupted event catalogs and false alarms, so one strategy is to identify and eliminate affected stations from automated processing schemes. SeisNetWatch (http://www.isti.com/products/seisnetwatch/) is used by many seismic network operators to monitor all ip-addressible nodes in a network, including field digitizers, to monitor data latency and other state-of-health parameters.

The volume of data flowing into an observatory can be overwhelming. A single channel of 24-bit, three-component data recorded at 100 Hz requires 620 MB of storage per day (uncompressed). Twenty channels of data, a typical amount for a small volcano observatory, are about 1.5 TB per year. Although this would fit on a single hard drive today, it is about 100 times the capacity of a hard drive available 20 years ago (the storage capacity of hard drives increases by a factor of about 10 every decade). Continuous digital volcano-seismic data before the mid 1990s are rare but, remarkably, the Pacific Northwest Seismic Network recently recovered continuous data saved to tape during the 1980 eruption of St. Helens Volcano.

To improve the reliability of data acquisition and processing systems, several measures can be taken. To protect against power failures, all mission-critical computers can be connected to uninterruptible power supplies and configured to automatically reboot and restart critical processes once power is restored. No one wants to arrive at an observatory on a Monday morning and finds that the alarm computer suffered a power outage on Friday night and has not been running since, especially if a significant event occurred. Another measure is to run all mission-critical computers in parallel, providing automatic failover or at least have pre-configured spare computers ready to plug in whenever a primary computer failed. All potential points of failure can be monitored by a diagnostic alarm system. Finally, a daily checklist helps catch any other problems. All of these measures were taken at the Montserrat Volcano Observatory in 2000, leading to an improvement in the data capture rate and public safety.

Once captured, data need to be managed effectively to preserve them for further analysis and research. Given the capacity of modern hard drives, it is now possible to keep many years of data “online.” Copying data to an off-site location is also becoming more common. Many observatories now transmit real-time data to the IRIS Data Management Center, which not only serves as a backup, but outsources the resources needed to disseminate the data more easily to the research community.

Summary

Volcano-seismologists forecast volcanic activity by analyzing the rates, energy release and spatial distribution of different types of characteristic seismic signals recorded in the vicinity of volcanoes. The most commonly identified signals are VT, LP or hybrid earthquakes. Explosive and effusive eruptions can cause rockfalls and pyroclastic flows, which also generate characteristic seismic signals. Volcanic earthquakes frequently occur in swarms. Swarms and tremor are both common precursors to escalations in volcanic activity. While there is still much that is not understood – the origin of LP earthquakes for example - no other technique provides such detailed information about the internal state of a volcano, or about debris flows as they occur, or provides such a detailed chronology of an eruption.

Volcano-seismic monitoring provides high-sample-rate data, 24 hours a day. Short-period seismometers and analog telemetry are gradually being phased out and replaced with modern broadband seismometers and field digitizers. Two-way telemetry allows observatory staff to diagnose and fix problems sometimes without an expensive field visit or lengthy data outage. Free, community supported software is available for data acquisition, event detection and location (e.g. Earthworm), real-time data visualization (e.g. SWARM), event processing and catalog production (e.g. Seisan), instead of each observatory reinventing the wheel. Archiving data - including continuous waveform data, derived data such as RSAM, event catalogs and station metadata – is a crucial task that has become much easier thanks to the expanding capacity of hard drives, faster internet, and data management centers such as the IRIS DMC.

Real-time monitoring may rely on an operations room which is manned 24 h a day. Or it may rely on automated alarm systems that alert observatory staff to escalations in seismicity (and data outages) outside of normal office hours. Research and development is often driven by the need for better real-time monitoring tools – automated classification of volcano-seismic signals, for example. Ambient noise tomography and detection of multiplets are examples of techniques that might become routine at volcano observatories as computational power continues to increase. As automated monitoring becomes increasingly sophisticated, observatory seismologists will need to spend less time on troubleshooting and development and more time analyzing and interpreting volcanic-seismicity, and collaborating on research.

Cross-References

► Broadband Seismometers
► Earthquake Location
► Earthquake Swarms
► Frequency-Magnitude Distribution of Seismicity in Volcanic regions
► Infrasound Monitoring of Active Volcanoes
► Long-Period and Very-Long-Period Seismicity on Active Volcanoes: Significance
► Rockfall Seismicity Accompanying Dome Building Eruptions
► Seismic Anisotropy in Volcanic Regions
► Seismic Event Detection
► Seismic Tomography of Volcanoes
► Very-Long-Period Seismicity at Active Volcanoes: Source Mechanisms
► Volcanic Eruptions, Real-Time Forecasting of
► Volcanic Tremor
► Volcano-Tectonic Seismicity of Soufrière Hills Volcano, Montserrat

References

Barclay J, Johnstone J, Matthews A (2006) Meteorological monitoring of an active volcano: implications for eruption prediction. J Volcanol Geotherm Res 150(4):339–358. doi:10.1016/j.jvolgeores.2005.07.020

Benoit JP, McNutt SR (1996) Global volcanic earthquake swarm database and prelimary analysis of volcanic earthquake swarm duration. Annali Di Geofisica 39(2):221–229

Buurman H, West ME, Thompson G (2012) The seismicity of the 2009 redoubt eruption. J Volcanol Geotherm Res. doi:10.1016/j.jvolgeores.2012.04.024

Chouet B (2003) Volcano seismology. Pure Appl Geophys 160(3):739–788. doi:10.1007/PL00012556

Chouet BA, Matoza RS (2013) A multi-decadal view of seismic methods for detecting precursors of magma movement and eruption. J Volcanol Geotherm Res 252:108–175. doi:10.1016/j.jvolgeores.2012.11.013

De Angelis S, Fee D, Haney MM, Schneider DJ (2012) Detecting hidden volcanic explosions from Mt. Cleveland Volcano, Alaska with infrasound and ground-coupled airwaves. Geophys Res Lett 39:1–6. doi:10.1029/2012GL053635

Endo ET, Murray TL (1991) Volcanology a volcano monitoring and prediction tool. Bull Volcanol 53:533–545

Jolly AD, Thompson G, Norton G (2002) Locating pyroclastic flows on Soufriere Hills Volcano, Montserrat, West Indies, using amplitude signals from high dynamic range instruments. J Volcanol Geotherm Res 118(3–4):299–317. doi:10.1016/S0377-0273(02)00299-8

Lahr JC, Chouet BA, Stephens CD, Power JA, Page RA (1994) Earthquake classification, location, and error analysis in a volcanic environment: implications for the magmatic system of the 1989–1990 eruptions at redoubt volcano, Alaska. J Volcanol Geotherm Res 62(1–4):137–151. doi:10.1016/0377-0273(94)90031-0

Luckett R, Baptie B, Ottemoller L, Thompson G (2007) Seismic monitoring of the Soufriere Hills Volcano, Montserrat. Seismol Res Lett 78(2):192–200. doi:10.1785/gssrl.78.2.192

McNutt SR (1996) Seismic monitoring of volcanoes: A review of the state-of-the-art and recent trends. In: Scarpa R, Tilling R (eds) Monitoring and mitigation of volcano hazards, Chapter 3, Springer-Verlag, Berlin, pp 99–146

McNutt SR (2000) Volcanic seismicity. In: Houghton HB, McNutt SR, Rymer H, Stix J (eds) Chapter 63 of encyclopedia of volcanoes. Academic Press, San Diego CA, 1015-1033

McNutt SR (2002) Volcano seismology. In: Lee WHK, Kanamori H, Jennings PC (eds), Chapter 25 of international handbook of earthquake and engineering seismology, IASPEI, Palo Alto, CA, 81A: 383–406

McNutt SR (2005) Volcanic seismology. Annu Rev Earth Planet Sci 33(1):461–491. doi:10.1146/annurev.earth.33.092203.122459

Moran SC, Freymueller JT, LaHusen RG, McGee KA, Poland MP, Power JA, White RA (2008) Instrumentation recommendations for volcano monitoring at U.S. Volcanoes under the national volcano early warning system: scientific investigations report 2008 – 5114, p 47. Retrieved from http://pubs.usgs.gov/sir/2008/5114/

Powell TW, Neuberg JW (2003) Time dependent features in tremor spectra. J Volcanol Geotherm Res 128(1–3):177–185. doi:10.1016/S0377-0273(03)00253-1

Roman DC, Neuberg J, Luckett RR (2006) Assessing the likelihood of volcanic eruption through analysis of volcanotectonic earthquake fault–plane solutions. Earth Planet Sci Lett 248(1–2):244–252. doi:10.1016/j.epsl.2006.05.029

Thompson G, West ME (2010) Real-time detection of earthquake swarms at redoubt Volcano, 2009. Seismol Res Lett 81(3):505–513. doi:10.1785/gssrl.81.3.505

Thompson G, McNutt SR, Tytgat G (2002) Three distinct regimes of volcanic tremor associated with the eruption of Shishaldin Volcano, Alaska 1999. Bull Volcanol 64(8):535–547. doi:10.1007/s00445-002-0228-z

Wassermann J (2012) Volcano seismology. In: Peter B (ed) IASPEI new manual of seismological observatory practice 2 (NMSOP-2), second. Potsdam : Deutsches GeoForschungsZentrum GFZ, Potsdam, pp 1–77. doi:10.2312/GFZ.NMSOP-2_ch13

Wech AG, Creager KC (2008) Automated detection and location of Cascadia tremor. Geophys Res Lett 35(20), L20302. doi:10.1029/2008GL035458