Modeling of Topographic Effects of Seismic Wave Propagation Around Sakurajima Volcano, Japan

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Seismic wave propagation is strongly affected by not only subsurface structure but also topography of land and seafloor. In order to investigate seismic structure of a volcanic area and source processes of earthquakes occurring in the area, appropriate modeling of effects of the topography on seismic wave propagation is essential. In this study we model the topographic effects of Sakurajima volcano area. Sakurajima volcano is one of the most active volcanoes in Japan, which is located in a part of Kagoshima Bay, i.e. Aira caldera, in the south of the island of Kyushu, Japan.. It has elevation of 1117 m and three main peaks; Kita-dake (1117 m), Naka-dake (1060 meters) and Minami-dake (1040 m). Sakurajima is connected to the Osumi Peninsula in the east. Our model area is 20 km x 20 km wide, which includes Sakurajima volcano around the center. For the surface model construction we use the 50m-mesh DEM provided by the Geographical Survey Institute of Japan for land surface, and nearly-250m-mesh topographic data of Kishimoto (1999) for seafloor, while for the subsurface structure model construction we exploit the Japan Integrated Velocity Structure Model provided by the Headquarters for Earthquake Research Promotion. For numerical simulation we use a time-domain staggered-grid finite-difference method (FDTD), which is often employed for strong-motion simulation. To incorporate the topography of land and seafloor into the FDTD model, a simple and accurate fluid-solid boundary condition is implemented. In the presentation we illustrate the topographic effects through some numerical simulation results.

Source amplitudes of volcano-seismic signals determined by the amplitude source location method as a quantitative measure of event size

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The amplitude source location (ASL) method, which uses high-frequency amplitudes under the assumption of isotropic S-wave radiation, has been shown to be useful for locating the sources of various types of volcano-seismic signals. We tested the ASL method by using synthetic seismograms and examined the source amplitudes determined by this method for various types of volcano-seismic signals observed at different volcanoes. Our synthetic tests indicated that, although ASL results are not strongly influenced by velocity structure and noise, they do depend on site amplification factors at individual stations. We first applied the ASL method to volcano-tectonic (VT) earthquakes at Taal volcano, Philippines, where the seismic network consists of eight seismometers (five broadband and three short-period seismometers). Our ASL results for the largest VT earthquake showed that a frequency range of 7-12 Hz and a Q value of 50 were appropriate for the source location determination. We proposed a two-step approach to minimize site effects on the source amplitude estimation as follows: The source location is first determined by using a frequency band of 7-12 Hz and Q = 50 with site amplification corrections, and then the source amplitude is estimated by using waveform data at broadband seismic stations only without site amplification corrections and a reference frequency band of 5-10 Hz and Q = 50. Using this two-step approach, we systematically applied the ASL method to VT earthquakes at Taal, and estimated their source locations and amplitudes as well as seismic magnitudes. We similarly analyzed LP events at Cotopaxi and explosion events at Tungurahua. At all three volcanoes, we found a proportional relation between the magnitude and the logarithm of the source amplitude without any strong dependence on event type. At these three volcanoes, all of broadband seismometers had been installed in a similar way, which may have minimized site effects. The ASL method can be used to determine source locations of small events for which onset measurements are difficult, and thus can estimate the sizes of events over a wider range of sizes compared with conventional hypocenter determination approaches. Previously, there has been no parameter widely used to quantify the sources of volcano-seismic signals. This study showed that the source amplitude determined by the ASL method may be such a useful quantitative measure of volcano-seismic event size.

Observation of Seismicity and Eruptive Activity at Semeru Volcano, East Java, Indonesia

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Semeru volcano (3676 m above sea level) is andesitic stratovolcano located in East Java, Indonesia. Summit explosions have occurred continuously since 1967. During this period, Strombolian and Vulcanian type explosions have occurred, producing explosion plumes rising 400-1000 m above the summit. Since April 2009, the eruptive activity of Semeru volcano was slightly changed from the previous. In order to monitor the volcano, Center of Volcanology and Geological Hazard Mitigation have installed four permanent seismic stations i.e. Kepolo (KEP), Leker (LEK), Tretes (TRS) and Besuk Bang (BES). In this study, we observed some of volcano earthquakes recorded at Semeru volcano in 2009 and 2010. We analyzed the deep volcano earthquakes known as VA and also investigated the explosion earthquakes in relation with the kinds of their visual appearances. The sources distribution of VA showed that the epicenter was dominant in the northwest direction, relative to the central volcano, with a depth between 1-13 km. The hypocenter distribution, supported by past research as well as geological information around, gave initial estimates that there was a column of magma flow that leads from the northwest to the center of the crater. VA study of earthquake focal mechanism illustrate that the dominant type of normal fault occurs at the peak of eruption, and would change to reverse fault after the activity dropped to normal. From the research, VA earthquake in Semeru volcano could be classified into two types: deep VA (VAD) with a depth range of more than 6 km and the shallow VA (VAS), with a depth of 1-6 km. The frequency of eruption earthquakes ranged from 0,78 to 4,09 Hz. Correlation between visual appearances and frequency are as follow; the eruption earthquakes that is manifested by visual grayish white eruption in January-February has 0,87 to 3,8 Hz; the eruption earthquakes that is manifested by the eruption of white visual show ,87-2,64 Hz. Whereas lava dome growth at the end of 2009, the eruption of earthquake frequency content of 1.06 to 2.73 Hz. Eruption earthquake hypocenters located at a depth of less than 1km below the crater.

Tectonics or magma intrusion? – New results from the analyses of seismic swarms at Gede Volcano and Salak Volcano, West Java, Indonesia

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Gede and Salak Volcanoes are representative of plugged arc volcanoes. Gede exhibits a seismic swarm every few years, but only minor visible degassing. Salak exhibits minor degassing from its crater. The latest eruptions at Gede and Salak were in 1957 and 1930, respectively. Due to large populations nearby, the Center for Volcanology and Geological Hazard Mitigation (CVGHM) has monitored these volcanoes since 1985. In collaboration between the Earth Observatory of Singapore and CVGHM, we are upgrading geophysical, geochemical and hydrological monitoring on both volcanoes. Recent swarms occurred beneath both volcanoes and, in each case, we asked if the swarm was of magmatic or tectonic origin. If there was magma intrusion, will it lead to any eruption?

A relatively short swarm occurred at Gede in late February through early March 2012. The preliminary hypocenter determination reveals locations <1 km NE of the active crater with depths concentrated at 1-4 km. In comparison, hypocenters prior to that most recent swarm lie along a diffuse NE-SW trending line that passes between Gede and Pangrango volcanoes. Tilt data at Gede suggest that deformation was controlled by local tectonics until early Nov 2011. Then, a change in tilt vector suggested inflation due to magma intrusion, followed by swarm of earthquakes at the end of Feb 2012. Several months later tilt returned to a NE, tectonic direction. CO_2 flux measurements around Gede are high and also consistent with recent magma intrusion.

Following a M=4.8 tectonic earthquake just west of Salak on 9/9/2012, small earthquakes occurred in the nearby Awibengkok geothermal field. Further analysis of the selected earthquake mechanisms and b-values may further differentiate the origin of that swarm. Tentatively, we conclude that this seismicity was induced by the tectonic quake. We have just started deformation monitoring at Salak and, as at Gede, this will be an important constraint for interpretation of future swarms.

Repetitive hybrid earthquakes at regular intervals as a precursor of the 6 August 2012 eruption of Tongariro volcano, New Zealand.

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New Zealand's Tongariro volcano had been dormant for over a century in July 2012, when there were three episodes of seismic activity beneath its northern slopes. Small tectonic earthquakes are not uncommon in this area. However, most of the small ($ML<2.5$) events in July 2012 were hybrids and had very similar waveforms, indicating they probably had the same source mechanism and location. There were also monochromatic tornillo earthquakes,some in the coda of hybrid events and others occurring separately.

GNS Science responded to this unusual seismicity by raising the alert level for Tongariro, and increasing its seismic, deformation and chemical monitoring. Less than a month after the first events, there was a small ash and steam eruption from the upper Te Maari crater on the northern slopes of Tongariro. The eruption was phreato-magmatic, with any magmatic component being very small.

Further analysis of the pre-eruption seismicity found that it was dominated by events of similar size at regular intervals; 80% of the events had local magnitudes 1.8 ± 0.3, and the inter-event intervals in the first swarm were all between 63 and 79 minutes. The similar waveforms of these events displayed a pulsatory beating pattern. Such repetitive hybrid earthquakes, but closer-spaced and in much larger numbers, have been seen during dome-building at Soufrière Hills, Montserrat, and interpreted as being the result of repeated magmatic injections into a dome.

The repeating waveforms, consistent beating pattern and clockwork nature points to a stationary and mostly non-evolving source geometry located about 2 km beneath the 6 August eruption vent. The source of events of this type might be due to a near constant flux process through a constricted pressurised cavity. If we had recognised these features of the seismicity closer to real-time we would have been more confident of its unusual nature, and perhaps had sufficient confidence to make an eruption forecast. This activity reinforces the value of looking at all the characteristics of seismic activity on a volcano when considering whether it might be an eruption precursor.

Automatic classification of seismo-volcanic signals as a tool to improve eruption forecasting

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Seismic activity is one of the main precursors of volcanic eruptions as it usually increases before crises. The material Failure Forecast Method (FFM) is the most common approach used for eruption prediction. It is based on empirical power laws applied to observables such as the rate or energy of the seismic activity. In most seismic studies, the observable mixes together numerous types of events that are associated to different physical mechanisms at the source : brittle rupture, resonance of fluid-filled cavities, degassing, collapse, regional earthquake, or noise. Brittle rupture is associated with volcano-tectonic (VT) events. In the framework of the FFM, the acceleration of this type of seismic activity is interpreted as resulting from damaging processes preceding ruptures and eruptions. Long-period (LP) events can be generated by different physical phenomena at the source. The acceleration of LP rate observed before some eruptions is probably associated with other processes than damaging. It is thus important to understand better this accelerated behaviour of LP seismicity in order to verify if it can be used as a reliable precursor.

In order to improve eruption forecasting, it appears necessary to process separately the different types of seismicity and to identify the most pertinent ones for this task. For this purpose, we use an automatic classification tool adapted from a voice recognition system based on continuous Hidden Markov Models (HMM). Various behaviour laws (among them power laws) are then applied on the classified seismic activity and their ability to give robust predictions is tested with a hindsight approach.

We calculate the seismic energy release and the seismicity rate for each type of events and we fit behaviour laws to these observables. Then we compare the time of divergence of the theoretical curves with the time of eruption. We pay special attention to the choice of the fitting window and we analyze the evolution of the estimated parameters (exponent of the power law, time of eruption) as a function of the starting and ending times of the window in order to test the robustness of the predictions.

We present applications of this procedure to the seismic activity associated to several eruptive crises of Volcan de Colima, Mexico. The results obtained with classified seismicity and with the complete raw signals are quantified and compared. They show that the precursory patterns for LP and VT events differ from an eruptive period to an other. This observation provides insight on the precursory eruption processes. Moreover, more consistent and more robust estimations of the eruption time are obtained when separating the different types of volcano-seismic events. Finally, the approach developed in this work has been conceived for real-time applications through automatic signal recognition and automatic fitting of behaviour laws. It is thus aimed at being integrated in monitoring systems.

Listening to Ambrym volcano (Vanuatu), by a triangular acoustic network: a precursor to a Strombolian episode

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Acoustic triangular network, installed between august and december 2008, on Ambrym volcano (Vanuatu) has proven to be suitable to monitor the volcanic activity of both Benbow and Marum, the two main active craters of Ambrym volcano with open vent system. Their volcanic activity vary between exhibiting weak to strong strombolian explosions. Both craters may also produce, although rarely, eruptive columns reaching a few kilometers in the atmosphere. Since all eruptive activity is driven by gas, we use continous acoustic measurements to estimate remotely the temporal evolution of gas volume and pressure at the vent.

More than hundred thousand acoustic events have been recorded within a 4 months period, indicating continuous magmatic events on Ambrym. Both Benbow and Marum have demonstrated the possibility to host strong magmatic activities with huge amount of gas released. The gas volume expelled by each crater is deduced from estimating the acoustic power in 4 frequency bands. It is also estimated on some specific signals by a series of 2 successive integrations of acoustic pressure and by waveform inversions whenever possible. The first period with strong explosions at Marum is preceded by an increase in number and amplitude of acoustic events in both craters. Several days before that Strombolian phase, the gas volume corresponding to the two lowest frequency bands, <0.8 Hz, of Benbow increase smoothly by more than a factor 2. After the Strombolian phase of october 2008, the degassing, which restarts immediately at Benbow but only after 12 days of quiescence at Marum, is characterised by a close series of small impulsive acoustic signals around 1 Hz, each corresponding to a bubble with a diameter of 7 m. The temporal evolution of the degassing (frequency, amplitude, number of events, ...) at Marum and Benbow suggests that these two active cones are connected to a unique magmatic reservoir with a sloping roof towards Marum. This subsurface configuration is responsible for the successive Strombolian phases that occurred only on Marum. This new approach in volcanic studies and monitoring appears to be a promising tool for volcanic monitoring as our acoustic network detects precursory events several days prior to major explosions.

Shallow and deep triggering of Plinian-type eruptions inferred from acoustic and seismic eruption tremors

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Plinian-type eruptions are characterized by sustained emission of large amounts of magma fragments with gas, and may cause strong impacts, both regionally and globally. Fluid dynamics models for such eruptions assume the control of parameters within the flow (pressure or magma input below the conduit, magma properties, and multi-phase flow dynamics), while shock-tube models used in the laboratory and calculations assume rapid decompression of magma from the top. Direct triggering for Plinian-type eruptions has been identified in relatively few cases.

Monitoring seismic and acoustic eruption tremor is useful for evaluating volcanic activity. Recent advances in remote sensing and image transmission techniques have provided observations that directly compare temporal changes in eruption behaviors and seismic and acoustic wave fields, thereby confirming the importance of interpreting information included in eruption tremor. Here we analyze seismic and acoustic eruption tremor during three sub-Plinian eruptions of Shinmoe-dake, a volcano in Kyushu, Japan.

Ground shaking caused by infrasound is sometimes significant, especially during relatively weak sustained eruptions. To eliminate this effect from the seismic data, the local response function of the ground to infrasound must be determined. Observations at Shinmoe-dake are unique in that a good infrasound source is available to evaluate the response function: Sakurajima, about 42 km away, frequently transmits explosion infrasound. However, because of the distance, the associated seismic waves do not reach the stations at Shinmoe-dake, or if they do, they are well separated from the infrasound signals. The spectral relation between the vertical velocity and infrasound from Sakurajima was used to empirically obtain the local response function at stations.

Comparing the amplitudes of seismic and acoustic tremor with other observations, we distinguish the shallow and deep triggering for each of the three sub-Plinian events. The first and the third events are preceded by rapid decompression near the surface and can be viewed as a delayed fragmentation observed in laboratory experiments (Kameda et al., 2008). In contrast, the second event grew without qualitative change in deformation or oscillation of the volcano. It is thus suggested that the triggering of the second event, if any, was deep and probably with in the magma itself. Petrological studies of eruption products are expected to provide further evidence for the deep triggering of spontaneous-onset eruptions.

Calibrating volcanoes: Advances through a combination of scaled experiments and monitoring tools

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Volcanic eruptions, eruptive style and the related risks are difficult to be precisely forecast. Magmatic processes defy direct observation and impede their mechanistic and quantitative understanding. During explosive volcanic eruptions, pyroclasts of any size are generated and ejected from the crater(s) over variable time spans and at variable intensity. This ejection is a direct consequence of depth and efficiency of magma fragmentation and conduit geometry.

In an attempt to decipher more info from the observable features of explosive eruptions, we used a multi-disciplinary approach and combined experimental volcanology and volcano monitoring devices. During three campaigns, we performed over 50 field-based fragmentation experiments using natural volcanic clasts and cylindrical samples, drilled from natural volcanic rock samples. Decompression and particle ejection were monitored with (1) one Doppler Radar, (2) three high-speed and high-definition cameras, (3) one high-speed thermal camera, (4) acoustic and infrasound sensors and (5) pressure transducers along with (6) dynamic piezo-film transducers to record micro-seismic signals. The experiments were performed at controlled sample porosity (25 to 75 vol. %) and size (60 mm height and 25 mm and 60 mm diameter, respectively), confinement geometry, applied gas pressure (4 to 18 MPa) and temperature (25 and 850 ℃).

Our experiments allow for narrowing down the parameter range at which volcanic eruptions take place. We constrained ejection velocities through different approaches (high-speed videography and Doppler-spectrum analysis) and showed the effect of experimental conditions and sample characteristics. We show that both approaches successfully measured the pyroclast ejection, yielding consistent results of up to 130 m/s. Acoustic signals showed different features in dependence on the used set-ups, likely reflecting the variable length of the autoclaves (between 16 and 37 cm). The high-speed thermal videos of the 850 ℃ experiments showed plume temperatures of up to 400 ℃. We measured the fragmentation and removal speed of the pyroclasts using the pressure transducers. Together with known values of sample porosity and overpressure resistivity, we are able to constrain the conditions at the onset of fragmentation (eruption trigger). Close and high-resolution volcano monitoring, spiced with results from our experiments, will allow us to understand the language of volcanoes. Such an enhanced understanding of the pre-eruption state of a volcano is an essential factor in eruption energy estimation (probability of pyroclastic density currents, range of ballistics) and will contribute to adequate risk mitigation.

Model space exploration for determining landslide source history from long period seismic data

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The seismic signals generated by high magnitude landslide events can be recorded at remote stations, which provides access to the landslide process. During the "Boxing Day" eruption at Montserrat in 1997, the long period seismic signals generated by the debris avalanche are recorded by two stations at distances of 450km and 1261km. We investigate the landslide process considering that the landslide source can be described by single forces. The period band 25-50 sec is selected for which the landslide signal is clearly visible at the two stations.

We first use the transverse component of the closest station to determine the horizontal forces. We model the seismogram by normal mode summation and investigate the model space. Two horizontal forces are found that best fit the data. These two horizontal forces have similar amplitude, but opposite direction and they are separated in time by 70 sec. The radiation pattern of the transverse component does not enable to determine the exact azimuth of these forces.

We then model the vertical component of the seismograms which enable to retrieve both the vertical and horizontal forces. Using the parameter previously determined (amplitude ratio and time shift of the 2 horizontal forces), we further investigate the model space and show that a single vertical force together with the 2 horizontal forces enable to fit the data. The complete source time function can be described as follows: a horizontal force toward the opposite direction of the landslide flow is followed 40 sec later by a vertical downward force and 30 more seconds later by a horizontal force toward the direction of the flow. Inverting directly the seismograms in the period band 25-50sec enable to retrieve a source time function that is consistent with the 3 forces determined previously. The source time function in this narrow period band alone does not enable easily to recover the corresponding single forces.

This method can be used to determine the source parameters using only 2 distant stations. It is successfully tested also on Mount St. Helens (1980) event which are recorded by more broadband stations.

Seismic records of rockfalls associated with volcanic activity (Soufrière Hills volcano, Montserrat)

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It is now widely acknowledged that seismic signals associated with rockfalls can provide important information on the characteristics of the source (volume, duration, location). Recent studies using data from the Piton de la Fournaise volcano evidenced a scaling law between seismic energy and signal duration for granular flows *(Hilbert et al., 2011, doi:10.1029/2011JF002038)*. Complementary analytical analysis and numerical simulations allowed to find a similar scaling law between the difference of potential energy of an event and the duration of its propagation phase. This link between the energy dissipated as seismic waves and the loss of potential energy for a given granular flow was used to estimate the volumes of granular flows using seismic records.

Our work used seismic data from the Soufrière Hills Volcano at Montserrat in order to test the developed signal processing for the Piton de la Fournaise seismic records. The outputs were used to investigate whether similar scaling laws can be observed for granular flows at Monserrat. Despite differences of settings when considering the topographical context or the properties of constituting rocks (the Piton de la Fournaise is a shield volcano,whereas the Soufrière is an andesitic volcano), a similar scaling law between seismic energy and potential energy was found for granular flows. This late result suggests that such studies could be relevant at a more general level. Similar approaches could be used to constitute databases of rockfall characteristics (volume, location, occurrence time) in order to study the relationship between rockfall activity and processes related to volcanic activity. In particular, data were used to study if the monitoring of rockfall activity could be used as a precursor to volcanic eruption, or as precursor to larger destabilization of the volcano flanks.

On the use of seismic broadband sensors in volcanic settings

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Good broadband seismometers are capable to record seismic transients with dominant wavelengths of several tens or even hundreds of seconds. This allows us to generate a multi-component record of seismic volcanic events that are located in between the conventional high to low-frequency seismic spectrum and deformation signals. With a much higher temporal resolution and accuracy than e.g. GPS records, these signals fill the gap between seismicity and deformation studies. Furthermore, a broadband seismometer can also be used as a tilt-meter and due to the fact that the vertical component is less susceptible to tilting than the horizontal components, true horizontal displacements can be separated from tilt effects.

In this contribution we will review the non-trivial processing steps necessary to retrieve ground deformation and tilt from the original velocity seismogram and explore which role the resulting displacement signals have in the analysis of volcanic events. We use examples from Stromboli volcano, Italy, and Soufriere Hills volcano in Montserrat, West Indies, to emphasise the benefits of using broadband seismometers to their full capacity to gain new insights into volcanic processes.

Joint inversion of ULP tilt and VLP displacement from small explosions at Fuego volcano

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Very-long-period events accompany explosive eruptions at many volcanoes and have been used to investigate conduit geometries and explosion source processes. At some volcanoes, a measurable tilt signal accompanies the VLP and can be recorded with seismometers. The horizontal components of broadband sensors are particularly sensitive to tilt, which may dominate the record at periods below the low corner of the sensor. Since tilt is typically much lower frequency than the displacement signal, it can be filtered out prior to inversion; yet the tilt data can provide additional constraint on the source process and could be a valuable addition to the inversion.

At Fuego volcano in Guatemala, we recorded dozens of small-scale explosions in 2009 and 2012 using temporary arrays of seismometers and complementary instruments. These events are frequently preceded by 5 to 20 minutes of tilt that suggest pressurization of the upper conduit. The onset of explosive eruptions, which last from many tens of seconds to more than two minutes, include VLPs with peak periods from less than 30 to nearly 50 seconds. The events are dominated by ash emission that suggests a vulcanian-style downward migration of the magma fragmentation front.

Our arrays were designed for explosion source inversion and we have derived a source model from 2009 data for periods between 10 and 30 seconds. This band was chosen to limit the affect of low-frequency tilt, especially on sensors with a 30 second corner that made up the majority of the network. On the other hand, removing the low-frequency signal means ignoring a significant portion of the signal. We are now conducting joint inversions of the seismic and tilt signals, as recorded by seismometers, using separately-derived synthetic tilt and displacement Green functions. This work should provide a more complete view of the eruption process at Fuego. Importantly, it will provide better constraint on the pre-eruption process which may lead to more accurate eruption forecasting.

Ground Deformation Cycles in a Magma-effusive Stage, Sub-Plinian and Vulcanian Eruptions at Kirishima Volcanoes, Japan

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Volcanoes display several kinds of explosive eruptions, such as Plinian, sub-Plinian, Vulcanian, and Strombolian. The dynamics of explosive eruptions is one of most fascinating subjects in volcano physics. The Kirishima volcanoes lie at the southern rim of the Kakuto caldera in the southern part of the Kyushu Island and consist of twenty small andesitic stratovolcanoes and pyroclastic cones. The Shinmoe-dake volcano, one of pyroclastic cones, started a magmatic eruption at 15:29 (JST) on 26 January 2011. During the early period of volcanic activity at the Shinmoe-dake volcano in 2011, sub-Plinian eruptions, a magma effusion, and Vulcanian eruptions, occurred sequentially. The initial period from 26 January to 10 February could be divided into three stages: a sub-Plinian stage (26-27 January), a magma-effusive stage (28-31 January), and a Vulcanian stage (1-10 February). A different kind of tilt motion accompanied each stage. Here, we clarify the characteristics of the tilt motions and of their time sequences, presenting a new image of triggering process of Vulcanian eruptions. The sub-Plinian and the Vulcanian eruptions at the Shinmoe-dake volcano were preceded by inflations at shallow depths near the summit. The inflation-deflation cycles were also recorded during the magma-effusive stage with a typical period of one hour, synchronized with volcanic tremors or long-period events. Almost all Vulcanian eruptions were preceded by trapezoidal inflations, whose durations systematically lengthened as time progressed, and were followed by various time sequences of tilt motions, which became progressively more complicated throughout the frequent Vulcanian eruptions. In spite of the complicated time sequences of the preceding inflations, we have revealed the clear linearity with a constant gradient of 0.45 between the logarithm of the preceding durations versus elapsed time for each sub-stage. These observations can be consistently explained based on the assumption that a Vulcanian eruption is induced by a catastrophic rupture of the closed magma frame due to overpressure caused by magma degassing, and the degassing from magma declines exponentially with time.

Sources of long-period swarms and very-long-period signals during the explosive and dome-building phases of the 2009 eruption of Redoubt Volcano

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The 2009 eruption of Redoubt Volcano, Alaska, produced as many as 4 lava domes and over 19 explosions between March 23 and April 4. Following the explosive phase, the volcano began a dome-building phase that continued until mid-summer. We present the analysis of swarms of small, repetitive, long-period (LP, 0.5-2 s period) events that occurred during both the explosive and dome-building phases of the eruption. The results complement previous research conducted on the source of very-long-period (VLP, 2-30 s period) signals observed to accompany several of the explosions. We also observe ultra-long-period (ULP, >100 s period) signals following the onset of certain explosions in the local seismic and infrasound that vary from 120 s to more than 400 s, which may indicate ultra-long-period oscillations of both the explosion ash plumes and the surrounding atmosphere, the latter producing acoustic-gravity waves.

We apply waveform inversion to locate the LPs and find their source mechanism. We focus on two prolific LP swarms from the eruption: a swarm of 5500+ similar events that occurred from April 2-4 (the April swarm) and a swarm of 30,000+ similar events that took place in early May (the May swarm). The April swarm ended with the final explosion of the eruption, a dome-collapse on April 4. The May swarm, in contrast, was not associated with an explosion, although a small dome-failure and steam and ash emission occurred approximately midway through the swarm.

A challenge in the analysis of the swarms is that the individual LPs are relatively small in amplitude. We exploit the similarity in waveforms among the individual LPs and improve the signal-to-noise ratio substantially by stacking over all events on each station. An additional challenge is that the LPs, being higher in frequency than the VLPs, suffer more from path effects. This limits the maximum range for stations to be included in the inversion. From waveform inversion using the 5 broadband seismometers on the Redoubt edifice within 4.5 km of the summit crater, we find a source depth of 1.5 km ASL, slightly shallower than obtained from a standard earthquake location. This places the LPs between the VLP source at Redoubt (0.8 km ASL) and the summit crater (2.3 km ASL). Based on our previous study of VLPs at Redoubt, we consider a moment-only inversion since the local network is not dense enough to uniquely resolve both moments and forces. The obtained moment tensor indicates the LPs are dominantly volumetric with consistently shaped source-time functions. Typical moments are on the order of 10^{10} Nm. We plan to further refine the LP source model by conducting reconstructions of the moment tensor with combinations of cracks and pipes. In addition, waveform inversion of the May swarm should provide clues to the variation in the dynamics of LP generation during different phases of the eruption.

New insights into the source mechanism of long period seismic events recorded at Turrialba volcano, Costa Rica

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Long period (LP) seismic events occur at volcanoes across the world, but the source processes generating these events are still relatively poorly understood. LPs often occur in increasing numbers before volcanic eruptions, so a better understanding of the source is a major aim of volcano seismology. Full-waveform moment tensor inversion has been carried out at many volcanoes in order to attempt to constrain the mechanism of LPs. An experiment was carried out in 2011 at Turrialba volcano in Costa Rica, where 25 temporary seismic stations were deployed in addition to the three permanent stations. The aim of this experiment was to perform 3D full-waveform moment tensor inversion as accurately as possible, by using a dense seismic network with stations especially concentrated across the summit of the volcano, which has been shown by previous studies to reduce path effects and therefore improve the solution. Source locations are obtained by implementing a grid search while carrying out the moment tensor inversion. Analysis demonstrates that the LPs are located at shallow depths below the active Southwest and Central Craters and, as in the majority of studies investigating LP source mechanism, a crack mechanism is obtained from the moment tensor inversion. However, this result does not resolve the processes causing the events. Many studies have argued that the events are caused by the resonance of fluid-filled cavities within the volcano. The crack mechanism supports this hypothesis, suggesting that a fluid-filled crack is the resonator. However a crack mechanism could also be generated by the opening or closing of a tensile crack. In order to better constrain the most likely mechanism at Turrialba volcano, we undertake source corner frequency analysis. The results of this analysis suggest that typical earthquake relationships hold for LP events, contrary to what one might expect from a crack resonance model. Detailed results and possible interpretations will be presented.

Moment-tensor solutions for Long-Period (LP) volcanic sources: do they validate existing LP source models?

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Long period (LP) events on volcanoes are thought to be related to the fluid pressure fluctuations in cracks and conduits beneath volcanoes. Sudden pressure fluctuations give rise to the generation of slow/crack waves propagating along the fluid-solid boundaries between the source region and surrounding medium, and in turn sustain the resonance of the source. There are several variations of this model proposed in the literature, but all of them include the source resonance sustained by crack waves.

The difficulty in definite validation (or rejection) of this model stems from the facts that (i) physical properties of the source region (bulk modulus of the fluid, rigidity of the solid, geometry of the source and intrinsic attenuation of the medium) are poorly known, so their favourable (but not necessarily real) combination allows for the reconstruction of almost any type of the oscillating signature, (ii) moment-tensor (MT) inversions of LP signals are extremely sensitive to (usually poorly known) shallow volcano structure, and (iii) due to the very noisy volcanic environments and small-amplitude LP signals, it is generally not possible to obtain an acceptable MT solution unless the observed seismograms are filtered within their most energetic frequency range. An unfortunate consequence of the last two points is that the true source-time history is exceedingly difficult to recover and consequently we are left with a band-limited view of the source. Hence we ask the question: If we band limit alternative models for LP generation, are they consistent with observed data?

Therefore in this study we investigate how the signals generated by alternative possible sources map into MT solutions. Specifically, we use full waveform numerical modelling and analytical solutions for the wave propagation in an unbounded homogeneous medium to simulate signals generated by kinematic extended tensile crack sources. We then invert these signals for source mechanisms, using the standard assumption about the point-source moment tensor. We highlight the differences in the MT solution produced by the standard crack resonance model and this new model and demonstrate that it is equally consistent with field data. The aim of this exercise is to improve our understanding of MT solutions obtained for real data and to help either further validate or falsify existing LP source models.

Signs of magma ascent in LP and VLP seismic events and link to degassing: an example from the 2010 explosive eruption at Merapi volcano, Indonesia

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The link between seismicity and degassing is investigated during the VEI 4 eruptions of Merapi volcano (Indonesia) in October and early November 2010. Seismicity comprised a large number and variety of earthquakes including Volcano-Tectonic events, a sustained Long Period Seismicity (LPS), i.e., Long-Period events (LP), Very Long Period events (VLP) and tremor. LP seismicity is ascribed to the excitation of fluid-filled cavity resonance and inertial displacement of fluids and magma. During the eruption, Merapi released more than 0.4 Tg of SO2. We investigate here LPS that occurred between 17 October and 4 November 2010 to get insights into the volcano eruption processes which preceded the paroxysmal phase of the eruption on 4-5 November. We proceed to the moment tensor inversion of a well recorded large VLP event during the intrusion phase on 17 October 2010, i.e., before the first explosion on 26 October. By using two simplified models (crack and pipe), we find a shallow source for this VLP event at about 1 km to the South of the summit and less than 1 km below the surface. We also analyse more than 100 LP events that occurred during the multi-phase eruption (29 October - 4 November). We show that most of them have a dominant frequency in the range 0.2-4 Hz. Within the 31 clearest LP events, at least 3 clusters occurred successivefully. We interpret them as generated by different fluid-containers in the summit area, possibly excited by the magma rise. We observe significant variations of the complex frequency during the course of the eruption. We discuss these changes in terms of a variable ratio of fluid to solid densities and/or by possible conduit geometry change and/or permeability of the conduit or the edifice, in relation with the release of magma/gas during main eruptive phases. Finally, we also discuss how the major explosions of the eruption were potentially triggered by passing waves, resulting from regional tectonic earthquakes on 3 and 4 November.

Dynamics of Hydrothermal Activities Implied from the Complex Frequencies of Long-Period Events at Papandayan Volcano, Indonesia

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A passive seismic monitoring study initiated in December 2009 with the deployment of one permanent broadband seismic station and 8 temporal short period seismic stations around the Papandayan Volcano. Papandayan is a composite andesitic volcano with numerous of solfataras emitting hot fumes and small vents within four large overlapping craters (Kawah Mas, Kawah Nangklak, Kawah Manuk, and Kawah Baru) located in approximately 20 km southwest of the nearest district Garut. Papandayan volcano produced a catastrophic debris avalanche during a violent eruption in 1772, there after several phreatic eruptions registered in 1923, 1924, 1925, 1926, 1927, 1942, 1993, and the most recent one in November 2002.

In order to improve the understanding of the state of fluids and physical processes beneath the volcano, we assess the dynamics of hydrothermal activities through the complex frequencies of long-period (LP) events. The observed complex frequencies of LP events can provide important information about the compositions of fluids beneath volcanoes (Kumagai et. al., 2002). We have analyzed long-period events at Papandayan volcano within the periods of 2010-2011 by using the Sompi method (Kumazawa et al., 1990; Hori et al., 1989). In the beginning of August 2011, seismic activities at Papandayan volcano were increased. Numerous of volcanic earthquakes were recorded and long-period events were also appeared. The alert level of the volcano was raised, despite no eruption occurred in the end. We found temporal variations of the complex frequencies (f and Q factors) of long period events suggesting the response of hydrothermal system to changes of heat pulse transferred by the flux of volcanic gases from the magma beneath the volcano.

When magma breaks - the source mechanisms of low frequency events at volcanoes

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Low frequency (LF) events have been observed in many volcanic settings worldwide. In a number of cases, this type of seismic signal has been successfully used to forecast volcanic eruptions. LF seismicity in volcanoes is associated with a stable, non-destructive and repeatable process such as fluid movement in, or resonance of a fluid-filled conduit. Both magmatic and hydrothermal origins of the fluid have been proposed. In-depth investigation of the trigger of LF events, as well as their spatial and temporal extent, is crucial to gain a better understanding of the sub-surface dynamics leading to, or preventing, volcanic eruptions. Neuberg et al. (2006) proposed a conceptual model for the trigger of LF events at Montserrat involving the brittle failure of magma in the glass transition in response to high shear stresses during the upwards movement of magma in the volcanic edifice.

For this study, synthetic seismograms were generated following the proposed concept of Neuberg et al. (2006) by using an extended source modelled as an octagonal arrangement of double couple sources approximating a ring fault. The model adopts the seismic station distribution and velocity structure as encountered on Soufrière Hills Volcano, Montserrat.

In an attempt to gain a better quantitative understanding of the driving forces of LFs, inversions for the physical source mechanisms have become increasingly common. Therefore, we performed moment tensor inversions using the synthetic data as well as a chosen set of seismograms recorded on Soufrière Hills Volcano. The inversions were carried out under the common (but wrong) assumption of a point source rather than an extended source triggering the low frequency seismic events. For comparison we interpreted the same data in terms of a ring fault structure.

We discuss these inversion results and differences between the synthetic and real data, and how to interpret the moment tensor components (double couple, isotropic, or CLVD), which were based on a point source in comparison to an extended source. Due to interference, the amplitude of the seismic signals of a ring fault is greatly reduced when compared to a single double couple source. Furthermore, best (but misleading) inversion results yield a solution comprised of positive isotropic and compensated linear vector dipole components. Thus, the physical source mechanisms of volcano seismic signals may be misinterpreted as opening shear or tensile cracks when wrongly assuming a point source. If interpreted as magma movement the reduced amplitudes will lead to an underestimation of magma ascent rate by an order of magnitude, and finally the time history of the magma motion will be distorted as well.

References:

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What causes shallow short-duration low-frequency seismic events on volcanoes?

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Low frequency (or Long Period) seismic events are commonly observed at active volcanoes. They are usually thought to be of long duration and to be related to the presence of magma or gas in sub-surface conduits. Over the past number of years we have installed very high density seismic networks close to the summits on several volcanoes worldwide. We make a new observation, the existence of swarms of very near-summit low-frequency events which are of very short duration (pulses), whenever we have placed seismometers in the summit area. In the absence of extreme damping these events cannot be readily explained by the resonating conduit model. Moment tensor inversion demonstrates that they are likely generated by tensile cracking. Rupture dynamic simulations, damage mechanics modelling and source scaling analysis show that they are consistent with a brittle failure mechanism and do not require the presence of fluids in the source process. We conclude that they may play an important role in bridging our understanding of the relationship between shallow seismicity and deformation. They may also help in the determination of the rheological properties of the uppermost edifice.

Time-dependent volcanic tremor during the 2011 Kamoamoa eruption, Kilauea, Hawai'i

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Volcanic tremor is a ubiquitous feature of active volcanism. However, the use of volcanic tremor as an accurate forecasting tool is still not possible because the underlying physical processes and their variation from one volcanic setting to the next remain opaque.

In order to identify key dynamics of tremor and their relationship to magmatic and tectonic processes, we investigate links between the temporal evolution of tremor properties (e.g. frequency) and other indicators of volcanic unrest (e.g. changes in lava lake height, tilt). A practical hurdle is that appropriately correlated geophysical time series must be available.

We examine seismic data from 8 stations during the 2011 Kamoamoa eruption (05-10 March), Kilauea, Hawai'i. Volcanic tremor persists throughout the eruptive episode with varying amplitudes. The spectra show a broadband signal without clear harmonics. Most of its energy is concentrated below 15 Hz, with a peak between 1 and 2 Hz. For the first time on Kilauea, we detect a systematic temporal variation in the frequency of a spectral peak (frequency gliding). During the gliding episodes, the broadband signal is overprinted by energy linearly shifting up and down between 0.5-5.5 Hz over several hours. These energy shifts roughly coincide with increasing and decreasing tremor intensity. Whereas volcanic activity is high around the time of the first gliding episode, the second energy shift happens during a more quiescent time.

We present a methodology for identifying temporal and spatial correlations of time-dependent tremor properties with other geophysical and geological observables. We also search for gliding during previous episodes of activity at Kilauea in 2007-2008. Our approach can provide critical clues for the tremor source mechanism at Kilauea. Furthermore, we will investigate how the characteristics of tremor at Kilauea compare to other ocean island settings and continental and oceanic arc volcanoes.

Meditation on the basis for volcanic tremor

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Volcanic tremor is a unique interesting subject not only as a scientific research target but also in science application fields such as hazard reduction program. At first it is widely accepted as a precursory symptom of volcanic eruption in practical usages and believed to provide real-time information of on-going eruption process although its physical mechanism is still quite unclear. From a standpoint of scientific rationalism this seems strange while close relationship to eruptions has been established empirically. The second point to mention is that volcanic tremors are observed in wide range of volcanoes and volcanic eruptions. This indicates not only a single mechanism should be relevant to the generation of apparently similar-looking phenomena. This is the point to charm and excite scientists. In this presentation at first we briefly summarize current new aspects in observational evidences and modeling and argue future prospects to combine them.

Among recent progresses of observational evidences correlation between the termor and volumetric strain changes and discharge flux should put an important constraint on the generation mechanism(for example, Cannata et al 2008 at Etna,Lyons et al 2010 at Fuego). Particularly Kamata et al (2013 in this meeting) clarify clear correlation between the emergence of tremor and compression/decompression stages of the edifice deduced by tilt data at Shinmoedake Eruption of 2011. Associated with this they find change of the spectrum of tremor. These features strongly remind us of similarity in the situations between the volcanic tremor and self-excited oscillation through a collapsible tube(Betran and Tscherry 2006), which was first proposed for modeling blood flow dynamics through an artery.

There have been proposed variety of models to explain the generation of volcanic tremor(recent review can be found in Jellinek et al 2011). They are roughly grouped into two categories, resonance of some parts in magma system and flow-induced vibrations. The resonance model requires an additional mechanism to continuously excite the resonant oscillation. The flow-induced vibrations include variety of significantly different physics from stick-slip frictional sliding to boiling-induced density waves. But comment to all phenomena is an existence of negative relationship between the driving force and the induced flux. Because of this sustained oscillations become possible. Recently Kurokawa et al (2013 in this meeting) demonstrate suspensions in general could have this relationship as an intrinsic nature of rheology. Magmatic suspension could have this negative relationship, which satisfies the necessary condition for generation of self-excited oscillation.

Combined these two recent insights we would like to propose a working model of volcanic tremor,which can be tested in further field observations.

Nonlinear characteristic of magma rheology: implications for self-induced oscillation

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Volcanic tremor has been recognized as a useful precursory phenomenon of volcanic eruption and hence has been studied extensively. Although a wide variety of models have been proposed, most models can be applied in quite limited conditions and physical mechanism for volcanic tremor is not clarified yet. Here, we propose a mechanism of the self-induced oscillation caused by a nonlinear property of magma rheology, which is the multiplicity in the relation between driving pressure and flow rate. This property possesses a potential for applying volcanoes over a wide range since it is generated by changes of flow field called as wall slip or shear banding, which are probable situations in crystal-bearing magma system. In fact, this property is utilized to explain lava dome collapses and volcanic earthquakes [*A. Costa et al., 2012; A. J. Hale and H.B. Muhlhaus, 2007*]. However there is little evidence for its existence in magma and the mechanism is not revealed. To explore the possibility that magma has the multiplicity, we conducted laboratory experiments by using *p*-NIPAM aqueous suspension as an analogue of magma to see characteristics caused by the deformability of solid-phase networks, which is related to the multiplicity.

In this presentation, we focus on rheological and flow characteristics caused by aging effect, which are related to the multiplicity. In respect to rheology, firstly it is revealed that *p*-NIPAM aqueous suspension has the critical volume fraction for the emergence of yield strength, which is almost equivalent to that of magma. This result indicates *p*-NIPAM aqueous suspension can be an analogue of magma. At the same time we found this suspension has a multiplicity relationship between shear stress and shear rate that is linked to the yield stress inextricably via aging effect; the multiplicity appears only after long rest time while the yield stress exists just after the pre-shear. This should be a universal characteristic for two-phase mixture system, which can be applied to the magma system.

By flow experiments, it is revealed that pressure perturbations generated under careful treatment of aging effect, which suggest the induced pressure perturbations should be driven by non-linear rheological property; the multiplicity in the relation between the shear stress and the shear rate. By results from experiments under various flow conditions, changing the concentration, the volume of chamber and so on, we can conclude that the pressure perturbation is caused by the formation / destruction of networked structure of solid phase. Although the aging effect and resultant multiplicity are not yet confirmed for the magmatic suspension, this nonlinear characteristics should be responsible for generation of self-induced oscillations in volcanoes since it is universal to the suspension.

Tilt motion and volcanic tremor during lava-effusive stage in the 2011 Shinome-dake eruption

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Introduction

Observations such as tilt motions and tremors are important in considering magma behavior. Tilt motions observed near a crater may represent pressure change in conduit and tremors observed near a crater may be generated by volcanic fluid in conduit. In this research, we focused on tilt motions and tremors during lava-effusive stage in the 2011 Sinmoe-dake eruptions and revealed the character of them.

A series of eruptions at Shinmoe – dake

The Shinmoe-dake volcano started a magmatic eruption at 15:29 (JST) on 26 January 2011. Three sub-Plinian eruptions occurred between 26 and 27 January 2011. Midmorning on 28 January 2011, a small magma dome emerged from the center of the summit crater, progressively increasing in volume. After 1 February 2011, Vulcanian eruptions occurred frequently. In this research, we focused on a lava-effusive stage (28-31 January). In this stage, deflation-inflation cycles of tilt motions with a typical period of one hour were observed at stations near by the summit of Shinmoe-dake (Maehara 2012). We also observed volcanic tremors synchronized with tilt motions. Only when the tilt motions were lower than the threshold, tremors occurred.

The frequency structure of tremors

The frequency structure of tremors differed in deflation stage from in inflation stage. In frequency domain under 2Hz, tremors are dominated by two frequencies (about 1Hz and about 1.5Hz) during deflation stage, but are dominated by a frequency (about 1.2Hz) during inflation stage. In frequency domain over 2Hz, the intensity of frequency structure in inflation stage is much smaller than in deflation stage only on 31 January.

Pressure source exciting tilt motions

We estimated the depth of pressure source exciting tilt motions by using the ratio of tilt amplitude recorded at two stations, under the assumption that pressure source was located under the center of crater and cylindrical pressure source. When the centroidal depth of pressure source was located at 600m above sea-level, the point sources extending 250m from 475m to 725m above sea-level could explain the observed ratio. In this case, at most a few MPa pressure change could generate tilt motions comparable to observation.

Evolution of seismic reflectors beneath Sakurajima Volcano after 2008, revealed through the rounds of controlled source seismic experiments

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Evolution of seismic reflectors beneath Sakurajima Volcano is presented, which is revealed with rounds of seismic experiments after 2008. Sakurajima Volcano is one of the most active volcanoes in Japan. The rounds of seismic experiments have been carried out while the activity on the 1946's crater in the eastern frank rose up after its revival on 2006, after the pilot survey in 2008. A round of seismic experiments includes 14 shot points with charges and 252 temporary stations with a vertical seismometer for seismic reflection survey. The temporary stations were deployed along two lines in the east foot and in the northern frank of the volcano. The evolutions of seismic response are detected in seismic records corresponding to the ray paths passing through the northern to north eastern part of Sakurajima. The migrated sections from the differential seismograms show detailed evolution in the seismic reflector distribution beneath the depth of 4km which can represent magma intrusion. A seismic reflector with negative polarity rose up to the depth of 4km in the north-eastern portion of Sakurajima Volcano where a chimney like structure locates, during 2008 to 2009 while constant inflation of the volcano. Other negative reflectors enhanced and decayed in the deeper part. These movement of seismic reflectors is consistent with geodetic evidence of the magma movement in the period. Therefore such evolution of seismic reflectors can represent intrusion of magma towards the craters. On the other hand, sporadic reflectors with positive polarity appear around the depth of 2km in two sections on the 2009's and the 2011's round which obtained while frequent explosions at the 1946's crater. The depth of the sporadic reflectors are coincident with the bottom depth of the effective part in the explosion models which have been presented by Iguchi(1994) and Tameguri(2004). Therefore the sporadic reflectors in the shallow part can represent a sort of mass deficiency raised by the explosions. We found controlled source seismic monitoring of volcano is feasible. The controlled source seismic monitoring will provide certain advantages in understanding scale and in evaluation of its potential risk in the next phase of current activity. Detail of our method will be presented.

Shallow crustal stress field deduced from shear wave splitting measurements in Mt. Fuji region

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The 2011 Great Tohoku Earthquake affects seismic activity in the volcanic regions of Japan islands. After 11 March 2011, an aftershock (Mw5.9) occurred in Mt. Fuji region. These two earthquakes may influence the geologic processes in the area. In addition to these recent major events, it has been more than a few hundred years since the last eruption of Mt. Fuji and a future increase of volcanic activity is expected. Consequently, quantitative approaches to understand the upper crustal structure of Mt. Fuji region are important not only for scientific purposes but also for disaster mitigations. We measure shear wave splitting in Mt. Fuji region from 2009 to 2011 to interpret the upper crustal structure and stress fields by using MFAST (Savage et al., 2010).

SWS measurement results from earthquakes with shallow depths (<20km) indicate that the trends of fast polarization direction in the shallow crust of area are N-S to NE-SW. We did not observe significant temporal change of fast polarization directions or delay times before and after 11 March 2011. Results of SWS from deep events were unstable due to noise levels and to a few number of events.

The maximum horizontal stress of the regional stress field in the area is presumed to be NW-SE from the nearby earthquake focal mechanism and the strike of dike formations.Thus, the fast polarization directions are not parallel to the regional maximum horizontal stresses, as is expected for stress-aligned microcracks. The fast polarization directions of a station close to the hypocenter of the Mw5.9 event are consistent with the strike of the fault plane of the event. These observations suggest that the area is affected by factors such as nearby structures or local stress perturbations in addition to the regional ones.

Lack of significant temporal change of fast polarization directions may indicate that the shallow stress fields of Mt Fuji area is constant before and after 11 March 2011. At least, the stress perturbations by the Great Tohoku earthquake does not significantly affect the seismic anisotropy in the shallow(<20km) crust around Mt. Fuji region at the end of 2011.

Temporal change of Vp/Vs ratios in the upper crust during eruptions of Redoubt volcano

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For mitigation of volcanic hazards, it is essential to to understand the change of medium properties before and after eruptions. The velocity ratios between P and S waves, Vp/Vs, reflect the physical and chemical properties of medium including temperature, density, and rock composition. Temporal variations of Vp/Vs ratios in volcanic regions allow us to infer the changes in medium and magma properties beneath volcanoes. Redoubt volcano is an active volcano that is located at 175 km southwest from Anchorage. The dimension of volcano is about 10 km in diameter, and its volume is around 30-35 km^2. The volcano has erupted several times since 1902, and most recently in 2009. The eruptions were generally explosive, and produced lava and pyroclastic flows. Seismic events in the volcano-tectonic (VT) seismic swarm zones of Redoubt volcano are well monitored by Alaska Volcanic Observatory (AVO). We investigate the Vp/Vs ratios in the VT seismic swarm zones from observed P and S arrival times. The hypocentral information is collected from the AVO seismic catalogue. Seismic data with high signal-to-noise ratios for earthquakes with epicentral distance less than 10 km are selected for analysis. A total of 6425 P and S travel-time pairs is collected. The Vp/Vs ratios are estimated using a modified Wadati method that is based on the S-P differential travel times versus P travel times. Tomographic Vp/Vs ratio models are calculated before and after eruptions eruption. It is observed that the Vp/Vs ratios drop significantly from 1.95 to 1.73 during eruptions, reflecting the changes in the properties of medium.

Studying low-energy seismic activity in Elbrus volcanic area using underground seismic array

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Results of experiment with underground seismic array for studying low-energy seismic activity in the Elbrus volcanic area (north Caucasus, Russia) are presented. Linear seismic array of 2.5 km aperture is created in the tunnel of Baksan neutrino observatory of INR RAS. Horizontal tunnel of 4.3 km length is located in the mount Andyrchi at a distance of 20 km from Elbrus volcano. Array includes 6 three-component seismic sensors SC-1P with 24-byte recorders "Baikal". The placement of seismic sensors in the array are uniform, sensors are mounted on a concrete base on bedrock at 500 m from each other along the tunnel. Underground seismic array is the new instrument of geophysical observatory organized for studies of geophysical processes in the Elbrus volcanic area. The observatory equipped with modern geophysical instruments including broadband tri-axial seismometers, quartz tilt-meters, magnetic variometers, geo-acoustic sensors, hi-precision distributed thermal sensors and gravimeters.

The experiment identified the main characteristics of microseismic noise in the points of seismic sensors installation, their mutual correlation, diurnal variations in the noise level, the characteristics of man-made noise, signal levels from regional and local seismic events recorded by the group. Over the experiment period dozens of local seismic events were recorded. The analysis of seismic signals recorded by seismic array allows us to detect low-energy seismic activity in the Elbrus volcanic area beginning from the distance of 3-10 km (the faults in a vicinity of mount Andyrchi) up to 15-25 km (area of Elbrus volcano). The regional micro-earthquakes with magnitude 1-2 at the distances 50-100 km was also recorded.

Underground linear seismic array with 2.5 km aperture make it possible to determine with high accuracy hypocenters of local seismic events associated with geodynamic of volcanic magmatic structures and to realize seismo-emission tomography of the active zones of Elbrus volcano. Creation the permanent working seismic group of BNO with short-period and middle-period three-component seismometers complements the network of seismic stations GS RAS in the Caucasus region new seismological system of high spatial resolution for problems of regional seismology and monitoring of microseismic activity Elbrus region to identify areas with active seismic processes related to geodynamics magma chamber of the volcano.

Volcanic activity of Mount Guntur over the 22 last year

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Mt Guntur is an active strato volcano which located in West Java Province, Indonesia (60 km to the south of Bandung). Mt Guntur with elevation about 2,249 m above sea level has several cones at summit which form one large group named Mt Guntur. Base on historical records of Mt Guntur, the first eruption was in 1690 and the last was in 1847 which produced lava flow and pyroclastic material. During such periode eruption there was at least 3 main eruption which occured with repose time between main eruption about 60 - 100 years. It has been 162 years since the last eruption of Mt Guntur, the volcanic activity data of Mt Guntur show a slow increase in seismic and deformation activity at least in the period 1990-2009. For instance, during 1990-1997 the seismic activity data showed an increase average number of daily volcanic quakes from 20 quakes/day (the maximum number was about 40) to become 40 quakes/day (the maximum number was about 60 quakes). The number of quakes again increased from the average number of 40 to become 60 (the maximum number was about 160 quakes). At the same period, especially during 1996-2000, the increase of volcanic quake activity was accompanied with 2 mm of inflation deformation (based on leveling data) and occurrences of tremor in 1997. Estimate of volume change of pressure source based on Mogi model was about 1.5 x 106 m3. In the meantime during 1997-2006, the volume change of pressure source obtained from interpretation result of episodic and continuous GPS measurements was about 2.75 x105 m3, and tremor in 2006. In the period 2010-2012 the average number of daily volcanic quakes had relatively decreased compared to the number of daily quakes in the period 1990-2009, namely, about < 20 quakes/day. Short tremor was recorded in September 2011 and followed with a slight variation of the distance (several millimeters) from January to December 2012, it is between three GPS continuous stations around the crater and a GPS base station at Mt Guntur observatory.

The Eruption of Mount Sinabung after long dormancy

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Mt Sinabung lies in the region of the North Sumatera Province, or about 80 km to the west of Medan. Mt Sinabung with a peak of 2,460 m a.s.l is one of the 127 active volcanoes in Indonesia, belonging to B-type Indonesia volcano classification. B-type volcano means that it is a volcano with an unknown history of eruption in Indonesia since 1600. Like other B-type volcanoes in Indonesia, Mt Sinabung is not equipped with monitoring equipment, because the main priority of Center for Volcanology and Geological Hazard Mitigation (CVGHM) of Indonesia is the 77 A-type active volcanoes (meaning that at least there was once one eruption after 1600). After more than 400 years of dormant volcanic activity, Mt Sinabung crater suddenly blowed water vapor and volcanic ash for the first time at 18:15 Local Time, on August 27 2010. Ash spreaded mainly to the east and west of Mt Sinabung and covered the villages of Sukanalu and Mardinding. Those villages locate at 3 km radius from Mt Sinabung crater. Once again, on August 28 the volcano erupted with a thin white plume at an elevation of 20 meters from the volcanic crater with weak-medium pressure. At 00:08 Local Time, on August 29, a thundering sound was heard from the top of the volcano reported by the CVGHM team on field. From that moment CVGHM classify Mt Sinabung into A-type volcano and its status activity was at the highest level (level 4 of four levels). Digital seismic telemetry and seismic data logger system, as well as two deformation monitoring equipment (tiltmeter and EDM) had been installed. During this period eruption the most significant seismic activty was volcanic tremor and shallow volcanic earthquakes. After coordination with the field team and local government, CVGHM decided that the people living within 6 km radius from the volcanic crater were to be evacuated. At least 25,000 residents were evacuated. Again, four minutes later after thundering sound, a thick explosion plume with an elevation of 1,500 m occured. Ash explosions continued with ash height columns varying between 1,000-2,000 meters. On September 7, 2010, the latest strongest eruption in the series of eruptions was a one-time eruption with an ash column of more than 5,000 meters. Over the last two years the volcanic activity of Mt Sinabung is dominated by shallow volcanic earthquakes and degassing of thin white vapor with height colomn elevation of several tens of meters from the volcanic crater. Since 2012, the volcanic activity monitoring system of Mt Sinabung has been equipped with 4 continuous GPS stations.

Earthquake relocations and InSAR time series analysis of the June 12th 2011 eruption of Nabro Volcano, Afar

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Nabro volcano sits on the southern part of Danakil block to the east of the Afar depression, on the Arabian plate. It is the largest volcano in the Nabro Volcanic Range (NVR) and sits in the middle of the 110 km long volcanic lineament which trends NNE-SSW, extending from the Afar depression to the Red Sea. On the 12th June 2011, Nabro volcano suddenly erupted after being inactive for 10, 000 years. We installed a network of 8 seismometers around Nabro caldera which began recording on the 31st August and tasked SAR acquisitions from TerraSAR-X and Cosmo-SkyMed satellites to monitor how the ground deformed after the eruption.

In total, 37 stripmap acquisitions from TerraSAR-X were used to create 70 image pairs which span from the 1st July 2011 to the 10th October 2012. Concurrent with the TerraSAR-X acquisitions, the Cosmo-SkyMed satellite also imaged the volcano on a descending track between 26th June 2011 and 18th July 2012 and 64 images were used to produce 171 interferograms. Each dataset were used to create mean velocity maps and a detailed time series of incremental deformation of the Nabro caldera. Velocity maps from both satellites show subsidence up to 25cm/yr centred at Nabro. The subsidence signal from the TerraSAR-X velocity map was initially modelled assuming continuous deflation of a Mogi source at 5 km depth under Nabro, buried in an elastic halfspace. The location and depth of the magmatic source was constrained from a combined interpretation of InSAR and seismic data. The observed subsidence may also be created by a viscoelastic shell surrounding a magma chamber, which has started to contract following depletion after the eruption. Other possible interpretations of the signal include degassing and cooling and contraction of the residing magma. Preliminary results from the Cosmo-SkyMed time series show a fluctuating subsidence unlike the more linear trend established by the TerraSAR-X data. This pattern may be magmatic or caused by a seasonal atmospheric disturbance, future time-series analysis of InSAR and GPS will clarify this.

We processed the seismic signals detected by the network to provide accurate earthquake locations for the period September-October, 2011. We used Hypoinverse2000 to provide preliminary locations for events, which were then relocated using HypoDD. The majority of the earthquakes are located at the active vent and within Nabro caldera, with fewer events located on the flanks. There also appears to be a smaller cluster of events to the south-west of Nabro beneath neighbouring Mallahle volcanic caldera, despite no eruption occurring here nor any post-eruptive deformation. This may imply some stress triggering mechanism or some pressure connection between the magma system of the two calderas. We also investigated temporal patterns in the seismicity, but none were apparent in the short time window processed to date. We also found the fault plane solutions in order to assess the stress regime.

Seismic swarm activity in Maruyama volcano, Hokkaido, Japan

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Maruyama volcanic field is post-caldera volcanism in central Hokkaido, southwestern Kuril subduction zone. Only one small phreatic eruption had been recorded at a century before in historical time. Maruyama cone, only less than 500m height from basement, was constructed by lower magma effusion rate during 0.1Ma. Several quaternary volcanisms and geothermal activity are recognized in surrounding area. A cluster of these magmatisms is recognized as resurgent activity of Tokachi-Mitsumata caldera.

Regional seismic monitoring had been in operation, but no clear seismicity was recognized before 1988. New seismic stage started in 1989 and has still continued. This abrupt break coincided with magmatic eruption activity of neighboring Tokachi-dake volcano of about 30km west of Maruyama. Earthquake catalogues has indicated very high micro-seismic activity in and surrounding area. Hypocenter distribution indicated discrete clustering, and intermittently time series sequence has been observed. Spatiotemporal hypocenter distribution indicated complex patterns, e.g. diffusive migration, abrupt jump of activity location to another cluster. Strike-slip and normal faulting has been suggested from focal mechanisms. Regional strain from geodetic data indicated compressional stress field. This discrepancy was possibly due to excess pore pressure. Triggered seismic activity associated with the 2011 Tohoku earthquake (Mw9.0) (epicentral distance was 600km) and the 2003 Tokachi-oki earthquake (epicentral distance was 180km) were additional information for supporting excess pore pressure hypothesis. Remarkable high activity of deep, low-frequency earthquakes around Moho has been observed beneath this volcano. High shallow seismic and geothermal activity might reflect magmatic fluid supply from upper mantle. Isotope analysis of noble gas from hot springs is required.

Seismic events accompanying the effusive-explosive eruption of Kizimen volcano (Kamchatka) in December 2009 - January 2013.

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In December 2010 began explosive–effusive eruption of andesitic Kizimen volcano after 91 years of silence. It was preceded by sluggish seismic preparation for more than two years. Volcanic eruption from December 2010 to January 2013 can be divided into several stages based on remote sensing observations, particularly seismic and visual data.

1) The first stage (December 9, 2010 – May 11, 2011) was associated with destruction of top part of approach channel and formation of apical extrusion. The last was accompanied by strong explosions and eruption of pyroclastic flows. During this period explosive earthquakes and micro earthquakes regime drumbeats was recorded by the closest telemetry station (RTSS) KZV (R = 2.6 km) to the volcano. This regime is characterized by the appearance of quasi periodic micro earthquakes with a quasi– amplitudes ($K<5$, where $K = \lg E$, J) for the long–time plots. The first phase is characterized by the appearance of a short-term regime drumbeats.

2) The second stage (May – October 2011) was associated with squeezing of the lava flow coming down to the base of the volcano on its east side. The squeezing was accompanied by micro earthquakes regime drumbeats with long periods to several days. The maximum intensity of this regime was in June–September 2011.

3) The third stage (October 2011 – June 2012) was associated with formation and movement of a new tongue of the lava flow, detached from the eastern tongue in height 1300 meters above sea level. The movement of lava tongue was accompanied by micro earthquakes of regime drumbeats II significantly lower intensity than drumbeats I. At this stage it should be noted another period, November 25, 2011 – January 12, 2012, when there were no micro earthquakes and were eruption of pyroclastic flows frequently.

4) From June 2012 to January 2013 was recorded slow squeezing extrusive dome visually, accompanied by a weak explosive activity and the absence of regime drumbeats. Micro earthquakes were appeared in January again. This indicated a change in speed of squeezing viscous andesitic lava.

Relation between tilt oscillation and seismicity during the 1991-1995 dome eruption at Unzen Volcano, Japan

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Unzen Volcano in SW Japan began to erupt on November 17, 1990, and growth of an associated dacite lava dome occurred from May 20, 1991 to early February 1995. In this study, the relationship between tilt oscillation and temporal changes of seismicity level during the dome growth was investigated. Just before the dome emergence and during the dome growth, cyclic tilt oscillation within a period of 1 to 3 h was observed in the EW component at the FG1 station located about 680m west from the crater. Yamashina et al. (1994) assumed that the oscillation presented the repetition of inflation and deflation at the uppermost part of the active vent, suggesting a cyclic upward flow of lava with high viscosity. They made a formula to successfully estimate the daily supply rate of lava using the magnitude of tilt oscillation. Umakoshi et al. (2011) revealed that the HF seismicity in the crater area around the dome emergence of May 20, 1991, increased and decreased repeatedly within a period of 1 to 2 h, which correlated with tilt cycles in such a way that the seismicity increased during uplifting on the craterward side. In contrast, when the craterward ground was subsiding, the seismicity rate was much lower. They concluded that the cyclic tilt is caused by repeated inflation and deflation of the conduit and the HF earthquakes represent brittle failure of the stiff rock near the conduit. Although high seismicity in the crater area continued through the entire period of dome growth, it has yet to be investigated whether such synchronization emerged in other periods of dome growth or not. Comparing tilt data with earthquake counts in 10-min intervals, it was found in a few cases that the temporal changes of the seismicity level correlated with the tilt oscillation. These were in November- December in 1993, February-March in 1994, and April-May in 1994, when the HF seismicity level was high. However, the manner of synchronization was different from that found in May 1991, that is, seismicity rate increased gradually during uplifting on the craterward side, and then decreased gradually during subsidence on the craterward side. The period was generally 2-4 h, which was longer than the period in May 1991. This suggests that the source process of HF earthquakes is different between the cases in May 1991 and those after November 1993. No clear correlation with tilt oscillation was found in the period from June 1991 to October 1993, when the LF seismicity level was high. Also, there are some cases in which the temporal changes of HF seismicity did not correlate with the tilt oscillation. These indicate that the synchronization between tilt oscillation and seismicity level emerged only in parts of the periods when the HF seismicity level was high.

Source dynamics of vulcanian explosions analysed with a high-resolution multicomponent seismic arrays technique

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A series of sixteen vulcanian explosions occurred at Ubinas volcano, between May 24 and June 14, 2009. The explosions occurred at intervals of 2.1 hours to 6 days 8.6 hours, with a mean value is 33 hours. Considering only the first 9 explosions, between May 24 and 27, the average time interval is 7.8 hours. Most of the explosions occurring after a short time interval (<8h) have low energy, suggesting that the refilling time is not sufficient for a large accumulation of gas. All the explosions, except 4 are followed by a tremor episode coinciding with pulses of ash emission. The duration of tremor following explosion is longer for the two highest energy explosions. To better understand the physical processes associated with these eruptive events, we localized the sources of explosions using 2 seismic antennas composed respectively of 10 and 12 sensors 3 components. We used the High resolution MUSIC-3C algorithm to estimate the slowness vector for the first waves composing the explosion signals recorded by the two antennas. The initial part of the explosion is dominated by two frequencies at 1.1 Hz and 1.5 Hz for which we identified two separated sources located respectively at 4810 m and 3890 m + / - 390 m altitude. The position of these two sources is the same for the 16 explosions. This implies the reproduction of similar mechanisms in the conduit. Based on the eruptive mechanisms proposed for other volcanoes of the same type, we interpret the position of these two sources as the limits of the conduit portion involved in the fragmentation process. Seismic data and ground deformations recorded simultaneously less than 2 km from the crater show a decompression movement 2 sec prior to the explosion. This movement can be interpreted by gas leakage at the level of the cap before its destruction. The pressure drop generated in the conduit could be the cause of the fragmentation process that propagates deeper. Based on this observation, we interpret the position of the highest source as the part of the conduit under the cap and the deeper source as the limit of the fragmentation zone.

Explosive activity at Santiaguito Dome (Guatemala): insights from Fast MoUltiparametric Setup

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Santiaguito volcano (Guatemala) is an active dome complex volcano characterized by persistent degassing to mild Vulcanian explosive activity, well known to generate a broad variety of pressure waves. Between 4^{th} and 8^{th} January 2012, we recorded discrete explosive events at Caliente dome by means of a multiparametric station, comprising thermal and visual high–speed cameras and two ECM microphones recording both infrasonic and sonic signals at 10 kHz sampling frequency. These impulsive events, occurring at intervals ranging from 20 to 100 minutes, vary from bursts producing 1-3 km high, white, buoyant clouds to ash-rich emissions. These gas-jetting eruptions occur at two geometrically-distinct systems of fractures: one controlled by the flow field at the upheaved lava tumuli at the summit (S1), and a second marking the rim between the issuing lavas and the confining wall rocks (S2). Each event is accompanied by tilt inflation/deflation cycles, and by seismic and acoustic signals exhibiting a broad waveform variability. Rapid vertical inflation of the dome surface can occur at the onset of explosive events. The deformation is generally confined at a prism delimited by two intersecting fractures. High speed video-sequences capturing the last 2-5 seconds prior an explosive event (500 fps, 1280x1024 pixel resolution), with horizontal field of view of 160 m (ca. 0.13 m/pixel), were extracted to quantify dome uplift by performing a particle image velocimetry (PIV) analysis, obtaining vertical velocity components of up to 0.87 m/s. Thermal video-sequences, spanning the 10-15 minutes of the degassing activity preceding a main explosive event and the explosion itself, were used to analyse the spatial-temporal evolution of thermal fluxes along S1 and S2 type fractures. For each video, the apparent maximum (T_{max}) and cumulative (T_{cum}) temperatures were measured for each opening fissure. The following observations arise: 1) T_{max} from S2 always exceeds T_{max} from S1; 2) S1 is activated before S2, although different portions of eruptive fissures can be involved in each system; 3) after S1 is activated, S2 reaches T_{max} with some delay; 4) a marked decrease in the apparent temperature is always observed immediately prior the triggering of an explosion. Our multi-parametric observations reveal a general, direct correlation between dome surface temperature, erupted ash flux volume, rate of ground uplift, and amplitude of seismo-acoustic signals. More specifically, ash-rich explosions occur at higher thermal fluxes. During such explosions dome uplifts more rapidly and, presumably as a consequence, produce higher-amplitude seismic and acoustic emissions.

Volcano tectonic earthquakes related with the large scale uplift of Iwojima Volcano, Japan

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Increase of volcanic earthquakes and crustal deformation are usually observed before a volcanic eruption. Just before the small submarine eruption near Iwojima Volcano, Japan, in April 2012, we observed precursory volcanic earthquakes and rapid crustal deformation. However Iwojima regularly very active without eruptions except for small phreatic explosions; more than 20000 earthquakes and an uplift of about 3m were observed during 2006-2012. For eruption predictions at very active volcanoes, we have to distinguish a volcanic activity leading to an eruption from a normal activity. We examine a possibility of eruption prediction on the basis of a relationship between earthquakes and crustal deformation observed in Iwojima.

Iwojima Island, located about 1250 km to the south of Tokyo, Japan, is a volcanic island where a seismic activity and crustal deformation are very active. The island, measuring 8km in length and 4 km across, has a dome-like mountain Motoyama (a post caldera dome) at the earthen part of the island and a volcanic cone Suribachi at the southwestern edge of the island. According to a long period geodetic observation by Ukawa et al. (2006), the crustal deformation can be classify into 2 phases. The first is an island wide large uplift centering on Motoyama, and the second is contraction and subsidence at local area centering on Motoyama and uplift around that area. They are interpreted by superposition of crustal deformations by a shallow contraction source and a deep seated inflation source beneath Motoyama.

We used the coordinates of the 3 GPS stations of NIED (after 2003) and 2 GPS stations of GEONET of GSI (after 1999) in Iwojima with reference to Chichijima station of GEONET (about 220km to the northwest of Iwojima), and daily numbers of earthquakes counted at seismic stations of NIED at Motoyama after 2001 and JSDF during 1999-2001.

We found that the cumulative number of earthquakes and displacements of Suribachi stations have the highest correlation coefficient of about 0.998 during 1999-2012. The cumulative number is almost proportional to the displacements with a coefficient of 156.6±0.2 events/cm. The movements of the Suribachi stations are mainly caused by the island wide large uplift originated from the deep seated inflation source. The high correlation shows the earthquakes are controlled by the uplift of Iwojima. However, the precursory activity of the eruption in 2012 is largely different from the proportional relation, suggesting that it was caused by a different source related with the eruption. The result suggests we can probably judge an abnormal activity related with a volcanic eruption when we observe an activity deviated from the proportional relation.

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Source mechanism of explosive eruptions: seismic moment tensor inversion coupled with infrasound analysis

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Using high quality data recorded on two exploding volcanoes we investigate source dynamics using seismic moment tensor inversion and infrasound observations. The use of infrasound, coupled with seismic analysis is critical for understanding volcanic processes during low level explosive activity. Seismic moment tensor inversion provides insight to physical processes of source regions deeper in the volcanic conduit, whereas infrasound signals may be used to infer onset times and physical properties of vent explosions. The two, very different volcanoes presented here are Tungurahua, Ecuador, and Karymsky of Kamchatka, Russia. Tungurahua volcano exhibited a massive swarm of volcanic explosions in May, 2010, when eruption style ranged from Strombolian to Vulcanian. The active vent radius was 100 m, exhibiting intense infrasound (> 100 Pa). Stations at Tungurahua were deployed at about 5-km distance during this eruption episode. Observed seismic signals included low frequency waves (2s - 10s) at the onset of surface explosions, and long coda of LP waves followed by tremor. Karymsky volcano, an andesitic cone with a 80-m wide vent, exhibited vigorous Strombolian activities during the observation period 1997 to 1999. Infrasound amplitudes ranged up to 10 Pa at 1-km distance from the vent, much smaller than that of Tungurahua. Karymsky seismic signals are characterized by a leading impulsive signal associated with the explosion often followed by long quasi-periodic volcanic tremor. The dominant frequency of the explosive signal was 1 Hz, higher than those recorded at Tungurahua. In this study, seismic moment tensor inversion is applied to observations from both volcanoes, and source time functions and focal mechanisms are derived. Onset times of the surface explosions were estimated by origin times of infrasound and compared with the excitation of the seismic source time functions. We present here detailed results and discuss physical mechanisms of the different styles of eruptions of these two volcanoes.

A fluctuating lava lake at Villarrica volcano, Chile, inferred from repetitive long-period seismic and infrasonic arrivals in conjunction with persistent infrasonic tremor

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Villarrica volcano, which has exhibited nearly continuous open-vent status since the last major eruption in 1985, hosts a persistent lava lake in its summit crater. Minor strombolian style eruptions produce occasional spatter from large bubble bursting events, while persistent outgassing has been shown to produce continuous shallow seismic and acoustic tremor. During three campaigns from 2010 to 2012, we deployed seismometers and infrasound microphones around Villarrica, on the flanks, and within the crater itself to further study the characteristic seismicity and link it to magmatic processes. We noticed an LP event in 2011 with our linear array configuration, and linked it to a strombolian eruption. We then identified hundreds of thousands of smaller amplitude, but nearly identical events using a time domain matched filter technique. We returned in 2012 to better instrument this event type azimuthally, and performed a full-waveform inversion to understand the source mechanism of this repetitive event. The source inversion revealed a shallow east-directed single force, approximately located near the top of the lava lake, and can be explained by restoring forces within the lava lake as a result of mass escape during outgassing. Based upon the infrasonic and seismic travel times of the station located within the crater, we concluded that the infrasonic and seismic sources were nearly collocated.

Using the repetitive LP event observed in 2011 and 2012, we applied knowledge of this event to our longest running deployment in 2010. Using a collocated infrasonic array and a long-running seismic station, we calculated the seismic-acoustic time delay, calculated event energies, calculated the volcano acoustic-seismic ratio (VASR), and analyzed the peak infrasonic tremor frequency with time. These seismic and infrasonic attributes pointed to a fluctuating lava lake level, consistent with at least two injections of juvenile volatile rich magma. We also propose a new model for the source of infrasonic tremor consistent with our observations in 2010, using the combination of the shaft and crater as a stable resonator.

Explosion quakes and Long Period events with similar waveforms at Tungurahua volcano (Ecuador)

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Tungurahua is one of the most active volcanoes in Ecuador. It is a large andesitic stratovolcano which has been erupting since 1999. Its activity during recent years is characterized by the occurrence of well-defined eruptive phases lasting from several weeks to months, separated by quiescence periods with a comparable duration range. Eruptive phases include the emission of ash and gases with periods of enhanced activity and the occurrence of Strombolian to Vulcanian explosions that can cause pyroclastic flows. The volcano is monitored by the Instituto Geofisico, whose monitoring networks include 5 broadband stations coupled with acoustic sensors. These instruments record a wide range of seismic signals generated by the volcano. During quiescence periods, mostly LP events and few volcano-tectonic events are observed. During eruptive phases, the seismicity is dominated by the occurrence of tremors, LP events and explosion quakes characterized by the presence of acoustic phases.

We examined the seismicity recorded from August 2009 to December 2010 with the aim to determine the characteristic events among the transients recorded by the seismic monitoring network. For this purpose, an LTA/STA algorithm has been applied to data from a reference station located 4.5 km from the summit in order to identify the transients. The detected signal windows have been classified using cross-correlation to identify families of events with similar waveforms. For each family, a synthetic master event has been generated by stacking the similar waveforms. To recompose precisely the temporal evolution of each family, the different stacks have been used to scan the continuous data using matched filtering.

The procedure indicates a rather reduced number of families as only 6 are identified with more than 5 events. Most of these are families of explosion quakes or LP events active during the eruptive phases which occurred during our study period. The largest include 182 explosion quakes recorded during the May 2010 eruptive phase. Most interestingly, the second largest family with 121 events is active during the entire year 2010, during eruptive phases as well as during quiescence periods. It groups explosion quakes with clear acoustic phases, occurring during enhanced periods of activity, as well as smaller events identified as LP events, occurring during repose periods associated with no surface activity. This result has two possible outcomes. (1) Some of the explosion quakes and LP events at Tungurahua may share a common location and source process such as the resonance of the same fluid column or crack but caused by diverse triggering mechanisms. (2) Alternately, our result may indicate the existence of small undetected explosions at depth during quiescence period leading to no significant surface emissions. In both cases, our result may have important implications in terms of signal interpretation and monitoring.

Source process of long-period seismic events at Taal volcano, Philippines: Vapor transportation and condensation in a shallow hydrothermal fissure

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We analyzed observations of a swarm of more than 40,000 long-period (LP) seismic events at Taal volcano, Philippines, in 2010–2011. Each event waveform has a peak frequency around 0.8 Hz and $Q = 6$. The waveforms were strongly correlated with no phase differences among events, consistent with a fixed source location and mechanism. We therefore stacked the waveforms to improve the signal-to-noise ratios in our analysis. The stacked waveform at a station on the rim of the main crater begins with a dilatational first motion. Our travel time analysis of the stacked waveforms pointed to a shallow (100–200 m) source beneath the northeastern flank of the active volcano island. A *P*-wave velocity of 2800 m s^{-1} minimized the travel time residual. Using these results, we performed waveform inversion, with and without corrections for site amplification factors, for four source geometries (vertical crack, horizontal crack, vertical pipe, and sphere). We obtained the minimum AIC value with a vertical crack and corrected waveforms. A grid search for the location, strike, and dip of a crack source using corrected waveforms yielded small residuals for cracks with dips of 30–60° near the location estimated by the travel time analysis. To explain the complex frequencies of the waveforms, we performed a simulation of the fluid-filled crack model of Chouet (1986, JGR). The observed *Q* was explained by the fundamental longitudinal mode resonance of a vapor-filled crack. Assuming that this mode represents oscillations of 0.8 Hz, the crack size was estimated to be 188 m. A satellite thermal infrared image taken during the swarm period suggested that the events were not directly linked to surface gas releases. The persistence and abundance of LP events during the swarm suggest that a considerable amount of vapor was continuously transported to the LP source. We considered a vapor transportation model in which vapor exsolved from magma and rose in a fissure connected to the LP source. This model suggested that 10^6 m^3 of magma was involved in the LP swarm and that the temperature of the vapor in the LP source crack was around 600 K, slightly higher than the boiling point of water at that depth. We modeled a triggering mechanism of the crack resonance based on sudden condensation of vapor at the tip in a cold aquifer. This model also explains the waveform and statistical characteristics of the events, including their fixed source location.

Intermittent inflations recorded by broadband seismometers prior to caldera formation at Miyake-jima volcano in 2000

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Preface: Miyake-jima island, which is about 200 km south of Tokyo, is one of the most active volcanoes in Japan. In most historical events of this volcano, basaltic magma have erupted mainly from part of the flank in a more or less constant time interval, but the 2000 eruption took place in a quite different way. One of the main phases of the 2000 activity was a formation of caldera as had happened 2500 years ago. Interesting seismic signals that have a pulse width of about 20 s on velocity seismograms, called very-long-period (VLP) seismic pulse events hereafter, are recorded by broadband seismometers deployed in the island. The VLP events were observed frequently 1-2 days prior to the first summit subsidence producing the caldera. The seismic events were hardly recognized after the subsidence began. Considering this temporal sequence in relation to the summit subsidence event, the VLP signals likely took place in the preparatory process of the caldera formation. In this presentation, we will report the analysis results for the VLP signals.

Data analysis: From the displacement records, we clearly find that the VLP signals have smoothed step-like changes. The vertical seismograms display significant uplifts for all the stations. The particle orbits of the VLP signals show that all the stations have elliptical or rectilinear particle orbits, the major axes of which point to a region at the depth of a few km beneath the south 1-2 km of the summit. Each initial motion is oriented outwardly from the region that the particle orbits point to. This evidence strongly suggests that the VLP event was excited by a volumetric expansion. The waveform inversion we conducted shows that the source time histories have step-like shapes with a rise time of 20 s. Prominent step-like increases of the diagonal components indicate a significant dilatational variation of the source. A candidate for the source mechanism is the inflation of an elliptical cylinder with axis tilted 20-30 degrees from vertical and major axis of the elliptical cross section oriented northeast-southwest.

Speculation: We may interpret that the 20 s-VLP events were produced by falling mass injection into a magma reservoir associated with the caldera formation, whose idea was proposed by Kumagai et al (2001) to explain a reproducible nature that repeated with almost same duration times synchronously with successive caldera growth. We assume here that the falling mass events already started in the period when 20 s-VLP events were recognized prior to the caldera collapse on the surface. Applying the model for the 50 s-VLP events, we estimate injection of mass having the piston length of 560 m from the duration of 20 s for the 20 s-VLP events with the other parameter values fixed. We speculate that the repeated occurrences of the rock collapses resultantly lead to the caldera formation due to the gravitational instability in the crust.

Two-decades-long broadband seismic observations at Aso volcano, Japan

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Aso volcano is one of the most active volcanoes in Japan. It has erupted in Strombolian style repeatedly, and recent activities take place at the central cone composed of seven craters aligned NW-SE direction with a length of 1 km. At Aso volcano, various kinds of volcanic signals with broad frequency contents have been observed since the pioneering work by Sassa, who installed Wiechert and Galitzin long-period seismometers in 1930s. Our observations using modern broadband seismometers have revealed the details of conduit system and physical processes generating these seismic signals. In this presentation, we review the results of our 20-year-long broadband observations at Aso volcano, and discuss future direction of our study.

In 1994, we started our broadband seismic observation close to the active crater of Aso volcano. At the first stage of our observation, we revealed that Sassa's "second kind" of tremor has an even longer period component, and those Sassa and others were observing are higher modes of the long period tremors (LPTs). The characteristics of the LPTs are summarized as follows: (1) continually emitted regardless of surface activity; (2) spectra show several common spectral peaks (15, 7.5, 5 s); (3) decay fairly fast and the duration is only a few cycles; and (4) often accompanied with short-period tremors. Analyzing the dense broadband network data, we have revealed that the kinematic source of the LPTs is an oscillation of a crack-like conduit beneath the crater. The strike and width of the crack are almost the same as those of the chain of craters, and it extends nearly vertically from a depth of 300-400m below the surface to a depth of about 2.5 km.

We also studied the physical properties of the crack-like conduit. To qualitatively interpret the nature of the LPT source, we developed an efficient method for modeling fluid-filled crack, and demonstrated that the LPTs can be modeled as an oscillation of a thin crack filled with gas-ash mixture. The existence of such crack-like conduit is also supported by other geophysical studies like seismic reflection and magnetotelluric surveys, and the crack is considered as a subsurface path connecting a postulated magma chamber at a depth of around 5 km and the surface craters.

In addition to obtaining such static image of volcanic system, our continuous broadband observation over years also enabled us to monitor the temporal changes in the system. For example, during our observation, we sometimes observed fluctuations in the dominant periods of LPTs which seem to correlate with changes in SO2 emission rate, and we could estimate the changes in thermal state of the volcanic fluid by seismological means based on our conduit model.

These results suggest the importance of continuous observation, and at the same time, imply that constructing quantitative physical model explaining multi-disciplinary observations is crucial to deepen our understanding of volcanic systems.

Spatio-temporal variations of the volcanic tremors during 2011 Kirishima eruption estimated by dense seismic array

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Shinmoedake Volcano, mount Kirishima, Japan, began a series of eruptions on January 19, 2011. We installed 25 seismometers near Shinyu springs located at about 3 km away from the crater. On the other hand 16 seismometers were installed at Hinamori-dai located at about 5 km away from the crater by Nagoya University.

Detection of spatial and temporal variations of volcanic tremors is important for understanding the mechanism of volcanic eruptions. However, short-term temporal variations within a tremor event have not been revealed. Here, we observed change in the seismic ray direction during the volcanic tremor sequence through MUSIC spectrum processing and estimated spatial distribution of the source of volcanic tremors by combination of the two dense seismic arrays. MUSIC spectrum processing was applied to seismograms of a volcanic tremor occurred on February 2, 2011, and its duration was about 40 minutes. Most part of the tremor arrived from Shinmoedake crater. However, at some parts of the tremor sequence the slowness vectors show change in the tremor's source location. One part of the tremor with large slowness and with relatively long duration was generated at a shallow region beneath the crater. Another part of the tremor with short duration was found near Ohnami pond, 3.3 km northeast of the crater. Because of using a constant velocity structure model, accuracy of locations for tremor with small slowness was not enough to discussion relationship between their and volcanic activities. We will estimate distribution of the volcanic tremor source by using more realistic velocity model, and compare other geophysical data in order to understand the eruption activity.

Detection and location of weak continuous tremor episodes using a seismic array during the 2011 Shinmoedake eruption activity of Kirishima volcano, southwest Japan

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We deployed a seismic array at a site 5 km east of Shinmoedake volcano, in the Kirishima volcanic complex of southwest Japan, five days after the sub-Plinian eruption on 26 January 2011. The 2011 eruptions began as a small phreato-magmatic eruption on 19 January that was followed by the sub-Plinian eruption, with an eruption column reaching an elevation of 2 km. Explosive eruptions started on 28 January and occurred several times during the first half of February. Explosive and non-explosive eruptions mainly occurred between early February and the middle of April, and in late June. The last eruptions occurred from late August to early September 2011. Therefore, it is important to reveal the magmatic process below the volcano for the period from the early stage of the eruptive activity to the last eruption. We report our array analysis for continuous waveform data from the period February to September 2011 to detect coherent waves from the volcano. We estimated slownesses and back azimuths of seismic waves on a sliding 1 min window for the continuous waveform data using the semblance method. We detected several episodes of weak volcanic tremor in the periods in early February, late February to early March, late June, and late August to early September. These periods correspond to explosive and non-explosive eruptions, although there were a few eruptions when no tremor was detected in middle and late March. The weak tremor of each episode continued to several days to and has small amplitude. We successfully estimated the slowness and back azimuths of body waves of nine explosion earthquakes. The P and S wave slowness of the explosion earthquakes are 0.30 and 0.40 s/km, respectively. The slownesses of the weak continuous tremor clustered within the range 0.2-0.8 s/km, consistent with a mix of body and surface waves. A probabilistic approach based on a grid search was used to estimate the source locations of the explosion earthquakes and weak continuous tremor. The sources of the explosion earthquakes were beneath the crater at depths of -0.5-1 km above sea level, while the source of the weak continuous tremor was beneath the northern part of Shinmoedake at depths between 1 km below sea level and 1 km above sea level. This latter region corresponds to a shallow low-resistivity layer, suggesting that hydrothermal processes are more plausible than magmatic processes as the generating mechanism of the weak continuous tremor. The synchronization of weak continuous tremor and eruptions suggests that hydrothermal activity is activated by magma transport during eruptions periods.

Filtering wind noise in seismic and infrasonic data by Non-negative Matrix Factorization: methodology and case studies

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Non-negative Matrix Factorization (NMF) is being applied to an increasing number of different fields, including volcanic geophysical signals. In fact, volcanic tremor and infrasonic signals recorded close to volcanoes often result from the superposition of signals with very different origin, ranging from natural to anthropogenic. In this work we propose a framework where NMF is applied to the separation of such a mixture of foreground / interesting / target "signals" from background / interference / undesired "noise". Case studies presented here focus on the problem of separating seismic and infrasonic signals of volcanic origin from wind noise when only a single station is available, a common situation especially when monitoring remote volcanoes. Examples will be shown from Villarrica volcano in Chile and Mt. Shinmoe-dake, Kirishima in Japan.

4D velocity and attenuation tomography at Etna volcano (Italy) during 1994-2008

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A total of 4,000 well constrained earthquakes (40,000 P-wave arrivals and ca. 9,000 S-wave arrivals) recorded at Etna volcano during 1994-2008 interval time, have been inverted to compute a new 3D velocity and attenuation structure. The new velocity model has been calculated by using tomoDDPS code (Zhang et al., 2009) which simultaneously determines VP, VS, VP/VS models and event locations, according to a combination of absolute and differential arrival times. This method is able to produce more accurate event locations and velocity structures near the source region than standard tomography, which only uses absolute arrival times. The new attenuation structure has been computed following the approach outlined by Rietbrock, 2001. The inversion process of attenuation tomography can be divided into two main steps: the determination of t* in the frequency domain by the inversion of the P-wave spectrum, and the spatial inversion of the whole t* data set. t* is obtained modeling the far-field displacement of velocity spectrum. The medium is parameterized with the same 3D grid of nodes and velocity values obtained from 3D velocity model. The joint analysis of velocity and attenuation models (VP, VS, VP/VS, QP and QS) allows to better constrain the physical parameters of the area, in order to identify local lateral heterogeneities and/or fluid-filled cracked volumes. In particular, the attenuation of body waves is very sensitive to the thermal state of the crustal volume through which seismic waves travel and to the saturation of rocks with fluids and partial melts (Sato and Sacks, 1990 and references therein), giving the possibility to better understand the transient variations of the physical properties underneath the volcano during magma emplacement in the shallow crust.

After calculating the new velocity and attenuation structures using the whole initial data set and, on the basis of volcanological and geophysical observations indicating some cyclic recharging and discharging phases, we divided the initial data set into 9 different epochs. Then, we applied repeated three-dimensional tomography (4D tomography) thecniques to recognize possible changes in the velocity and attenuation anomalies during the different volcanic cycles observed in the study period (1999, 2001, 2002-2003, 2004, 2006-2007, 2008-2009). The results of this study suggest that time repeated tomography could provide a basis for more efficient volcano monitoring and short and midterm eruption forecasting.

Three-Dimensional Modelling of stress-induced anisotropy with application to Mount Asama, Japan

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In order to investigate the link between observed temporal changes in anisotropy and volcanic activity in the crust, we have developed a three dimensional forward model to simulate shear wave splitting (SWS) in seismic rays. Anisotropy is expressed in shear waves when wave velocity is dependent on its polarisation, splitting the wave as one polarisation travels at a higher velocity than its orthogonal counterpart. Fast wave polarisation and delay time between fast and slow shear wave components can be measured to give an idea of the strength and orientation of anisotropy along the ray path. At volcanoes, changes in anisotropy are attributed to changing stress conditions as magma moves through the crust (e.g. Savage *et al.* "Stress magnitude and its temporal variation at Mt. Asama Volcano, Japan, from seismic anisotropy and GPS").

We have combined finite element stress modelling with the 3D analytical solution for stress induced elastic anisotropy developed by Gurevich *et al.* in order to produce synthetic SWS. This approach is based on the hypothesis that microcracks (i.e. pore scale fractures and discontinuities) oriented perpendicular to the maximum compressive stress are closed preferentially, inducing anisotropy in the rock mass. We find that stress changes produced by the dyke at Mount Asama, an andesitic volcano in central Japan, determined for an eruption in 2004 are only of significance within its immediate vicinity when regional stresses are nearly isotropic. Small differential stresses and resulting low values of anisotropy indicate that a pure dry crack closure model for changing anisotropy may be overly simplistic. Current implementations of this stress effect suggest that realistic crack compliance ratios cannot explain the large values of anisotropy measured. The following hypotheses are suggested:

1. The cracks are fluid filled and hydraulically connected.
2. New crack distributions are formed due to the stresses.
3. The cracks that do exist change the relative content of fluid versus gasses.
4. Background anisotropy due to mineral alignment or structure is overprinted by crack-induced anisotropy in such a way that small changes in the crack-induced anisotropy are amplified by the method we are using to measure anisotropy. ♠

Enhanced multi-parameter monitoring network in Taal Volcano, Philippines

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Taal is the active Philippine volcano that poses the highest volcanic threat to the country's National Capital Region. Its explosive hydrovolcanic eruptions in 1754,1911 and 1965 generated lethal base surges,volcanic tsunami and widespread fallout tephra, the occurrence of which today could cause immense social and economic losses. Taal's current repose period that began in 1977 has been punctuated from 1990 onwards by episodes of volcanic unrest characterized by seismic swarms,fissuring,ground inflation and hydrothermal activity. Through the past decade, the Philippine Institute of Volcanology and Seismology or PHIVOLCS,together with expert partners from Japanese,French,and US organizations,has developed what has become a multi-parameter monitoring network in Taal with real-time communication links to Taal Volcano Observatory (TVO)and the PHIVOLCS Main Office (MO). The current network is composed of mostly co-located deployments of five broadband and three short-period seismographs, three continuous GPS,three geomagnetic instruments,two infrasonic sensors,tiltmeters,magneto-telluric instruments and a prototype crater lake sensor. Multi-parameter data are transmitted in real-time via spread spectrum transceiver or GSM telemetry to TVO, where these are processed,archived and retransmitted to the MO in near-real-time via satellite and DSL links. Seismic,GPS and electromagnetic data are automatically processed and visualized in parallel via web portal in the MO. Broadband seismic data further augments automatic hypocentral solutions of the Philippine Seismic Network.

Enhanced monitoring of Taal in consequence has yielded new insights into the volcano's subsurface geology that could promote catostrophic eruption, its energetic geothermal system and one possible trigger for low frequency earthquakes. More importantly, the enhanced network has emplaced technology that ensures data redundancy and continuity of monitoring operations at the MO even when volcanic activity warrants decampment of TVO, ensuring the continuity of PHIVOLCS' vital eruption warning services.