Volcanic lightning: New global observations and constraints on source mechanisms

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New data on volcanic lightning from the Smithsonian Volcano Reference File are added to an existing database and greatly expand the number of cases available for study. Lightning has now been documented at 154 volcanoes in association with 394 eruptions, a significant increase from the earlier numbers of 89 volcanoes and 240 eruptions. Lightning and electrification at volcanoes are important because they represent a hazard in their own right, they are a component of the global electrical circuit, and because they contribute to ash particle aggregation and modification within ash plumes. The role of water substance (water in all forms) in particular has not been well studied. The Volcanic Explosivity Index (VEI) was determined for 177 eruptions. Eight percent of VEI=3-5 eruptions have reported lightning, and 10 percent of VEI=6, but less than 2 percent of those with VEI=1-2, suggesting consistent reporting for larger eruptions but either less lightning or under-reporting for small eruptions. Ash plume heights (142 observations) show a bimodal distribution with peaks at 7-12 km and 1-4 km. The former are similar to heights of typical thunderstorms and suggest involvement of water substance, whereas the latter suggest other factors contributing to electrical behavior near the vent. The distributions of the latitudes of volcanoes with lightning and eruptions with lightning roughly mimic the distribution of all volcanoes; flat with latitude. Meteorological lightning, on the other hand, is common in the tropics and decreases markedly with increasing latitude as the ability of the atmosphere to hold water decreases poleward. This finding supports the idea that if lightning in large eruptions depends on water substance, then the origin of the water is primarily magma and not entrainment from the surrounding atmosphere.

Volcano deformation in Kyushu (SW Japan) through InSAR data

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Kyushu Island (SW Japan) hosts several active arc volcanoes. Despite being closely monitored, our knowledge on their deformation history with regard to their activity is poor. In order to improve our understanding, we use InSAR processing of ALOS, ERS, ENVISAT and COSMO−SkyMed images. We study the surface deformation of three of the most active volcanoes in Kyushu: Aso Caldera (between 1993−2011), Aira Caldera (2006−2011), Kirishima volcano (2006−2011). The SAR images have been processed to obtain time series through the SBAS technique.

Aso caldera has several vents in its central part. Of these, Naka Dake crater is the only currently active, erupting 7 times since 1993. Between January 1996 − November 1998, after the important 1994−1995 eruption, we observed a subsidence of ∼1.5 cm/yr in the central caldera. Analytical models suggest a deflating source (with various possible shapes) at 6−7 km of depth, implying a magmatic nature for the deformation. Inversion results are consistent with available seismic and GPS data.

Aira Caldera hosts Sakurajima volcano along its southern rim, with a persistent eruptive activity since 1950s. Between May 2007−January 2009, we observe a broad uplift of ∼1.5 cm on most of Aira Caldera, with the exception of the eastern part. A preliminary analytical inversion of these data suggests a deformation source in the Caldera center, at depth of 12−15 km, implying a magmatic nature of the deformation. Inversion results are in agreement with GPS and InSAR data inversions for other periods of activity.

Kirishima is a group of volcanoes, including the most active Shinmoedake, which lately erupted in 2008 and 2011; in particular, between January−September 2011 Shinmoedake erupted several times, with a peak of activity in February. InSAR data show an uplift of 2−4 cm in the Shinmoedake area between early 2010 − April 2011, immediately predating the onset of the latest eruptive sequence, and continuing also after the onset of the sequence.

Our preliminary results suggest that the minor deformation at these three volcanoes, related to deep or relatively deep magmatic sources, may be explained by their open system.

This research has been partially performed within the frame of Italian Space Agency (ASI) and Japan Aerospace Exploration Agency (JAXA) bilateral cooperation. COSMO−SkyMed and ALOS SAR data have been provided by ASI and JAXA within the SAR4Volcanoes project (ASI agreement n. I/034/11/0). ERS and ENVISAT SAR data have been provided through the GEO Geohazards Supersite initiative and ESA Category 1 proposal 7486.

Three dimensional resistivity structure of Kirishima volcanoes inferred from magnetotelluric data

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Broad-band magnetotelluric (MT) measurements were conducted on 2010-2011 around Shinmoe-dake volcano in the Kirishima volcanic group, Japan, where sub-Plinian eruptions took place three times on 26-27 January 2011. Combining with the previous MT data, it is found that the anomalous phase in excess of 90°is commonly observed at the northern part of the Kirishima volcanic group. Because the anomalous phase is not explained by 1-D or 2-D structure with isotropic resistivity blocks, 3-D inversions were conducted. By applying the small error bars on anomalous phase, we successfully estimated a 3-D resistivity structure that explains not only the usual data but also the anomalous phase data. The final model shows a eastward inclined and clockwise twisted pillar-like conductor that connects a deep-seated conductive body (at a depth greater than 10 km) to a shallow conductive layer at the central part of Kirishima volcanoes. By using the geophysical and petrological studies of the 2011 sub-Plinian eruptions, we infer that the pillar-like conductor represent the zone of hydrothermal aqueous fluids over 400 ℃, in which a magma pathway (interconnected melt) is partly and occasionally formed before magmatic eruptions. To the north of the deep conductor, earthquake swarms occurred on 1968-69, suggesting that these earthquakes were caused by volcanic fluids.

On thermal demagnetization before the 2011 summit eruption of Mt. Shinmoe-dake, the Kirishima volcano group, in S Kyushu, SW Japan

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The Kirishima volcano group is located in the southern part of the Kyushu Island, SW Japan, and is composed of many Quaternary andesitic strato-volcanoes occupying about 600 km^2. Among more than 20 volcanoes in the Kirishima volcano group, Mt. Shinmoe-dake (SM) is one of the recently most active volcanoes and historical records tell that phreatic to magmatic eruptions with large amount of volcanic ash and pumice emission repeatedly took place at SM. Since moderate volcanic activities in 1991-1992, we have performed continuous monitoring of geomagnetic total intensities at several sites in the vicinity of the SM crater, aiming at detecting temporal variation due to thermal magnetic effect or piezo-magnetic effect before and during the main eruptions.

At the SM crater, a weak summit eruption occurred in 22th, Aug., 2008. Since then, 6 weak eruptions took place in 2010, and intense magmatic activities including generation of lava dome and explosive summit eruptions started from 26th Jan., 2011. Just before the main eruption in 2011, we measured geomagnetic total intensity at three sites (SMN, SMW and SMS) just near the SM crator. After making simple difference data by using data at Kanoya geomagnetic observatory, JMA, as a reference, we eliminated gaps and annual variations from the difference data. Then we detected 2 nT increase at SMN (north of SM), 4 nT increase at SMW (west of SM) and 0.7 nT decrease at SMS (south of SM) from Jan. 2010 to the main eruption in Jan. 2011.

Considering spatial distribution of the total force temporal variation, demagnetization source location and its size were estimated by grid search with 50 m grid spacing. Two candidate locations were derived which almost equally explain the total intensity variations. One is at the WSW flank of SM and its depth and diameter are about 300 m below sea level and about 1km, respectively. The other is just at NW rim of the SM cone and its depth and diameter are about 1100 m above sea level and about 200 m, respectively. In this estimation, magnetization is assumed as 1.5 A/m, which is estimated from unmanned helicopter survey (Ohminato et al., 2013).

In almost the same duration from Jan. 2010 to Jan. 2011, ground extension was detected by the GPS array observations (e.g. Morita et al., 2013) and its Mogi-type inflation source location and depth were determined at about 5km NW of SM and about 10km below sea level. They interpreted that the inflation was due to charging of magma and the interpretation was confirmed by sudden shrink of the source at almost the same location coincident with the main summit eruption. Thus the demagnetization must be due to fluid or gas migration from the deep and somewhat deep magma chamber to the locations near the SM summit.

Integrated processing of muon radiography and gravity anomaly data toward realizing high-resolution 3D density structural analysis of volcanoes: case study of Showa-Shinzan lava dome, Usu, Japan.

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We have developed an integrated processing of gravity anomaly and muon radiography (muography) data for determining the 3D density structures of volcanoes with high spatial resolutions (100 - 200 m). We applied the method to a dacite lava dome (Showa-Shinzan) at eastern foot of Usu volcano, Hokkaido, Japan, and we determined the shape of the lava plug and its internal density variation.

Muography is a recently developed inspection method and is based on measuring the absorption of cosmic-ray muons inside matter. From the attenuation of muon flux, one can determine the amount of matter, which is given by density-length (density times length), present along a muon trajectory. Since gravity and muography are both sensitive to density, combining the two methods is expected to give density profile with higher spatial resolutions than conventional gravity inversion alone. Moreover, it enables 3D analysis.

Forward modeling is made by supposing the region of our interest which is subdivided into several voxels with unknown density parameters. Then, both gravity anomaly and density-length data can be written as linear combinations of the unknown parameters. The observation equation is solved by using Tarantola's [1987] probabilistic approach, in which an initial guess density and a correlation length are given as a priori information. The resolution test using a checker-board density model superimposed on the shape of Showa-Shinzan ensures that the horizontal and vertical resolutions are better than 200 m and 100 m, respectively.

Showa-Shinzan, a target volcano in our case study, was formed at eastern foot of Usu volcano in the 1943-45 Usu eruption. The eruption activity is characterized by the following three stages: (1) volcanic earthquakes occurred and the ground was uplifted significantly; (2) paroxysmal explosions happened at craters on the uplifted plateau; (3) dacite magma extruded from below the plateau to form the dome.

We applied our method to the gravity data at 30 stations on/around the dome and the muography data reported by Tanaka et al. [2007]. The results show that the western part, where the dome exists, has higher density (> 2000 kg/m^3) than the eastern part of the uplifted plateau (< 2000 kg/m^3). Inside the dome, we find significant density variation, characterized by two high density anomalies. One high density anomaly (2400 - 2800 kg/m^3) is located below the dome and is considered to be the lava stuck in the conduit. We conclude from this that the diameter of the conduit is about 200 m. The other dense anomaly (2400 - 3000 kg/m^3) is near the surface and is considered to be the solidified lava which was uplifted significantly at the last stage of the eruption.

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Ionospheric disturbances recorded by DEMETER satellite over active volcanoes: August 2004 to December 2010

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Every year, Natural Hazards are the cause of millions of casualties and wounded persons. Large size economical infrastructures are devastated. Human and economical costs are so high that it may take tens of years for mitigating the effects of the catastrophes. Earthquakes and volcanic eruptions are mostly responsible of the largest disasters. Satellites appear to become unavoidable tools for monitoring the Earth at large scale, in addition to available ground based observations or when these latter are deficient. The present study analyzes electromagnetic data as well as plasma characteristics in the ionosphere recorded by DEMETER micro-satellite over erupting volcanoes during the life of the mission: August 2004 to December 2010. The database is restricted to segments of orbits located between 50S and 50N in latitude for avoiding the effects of large natural magnetic disturbances. The time window in which anomalous changes are searched brackets the onset of the eruptive activity from 60 days before to 15 days after. Along each orbit, we consider that an anomaly linked to a volcano should reasonably appear within a maximum distance of 900 km between the footprint of the satellite and the centre of the edifice; the consequence of which restricts the interesting part of a related orbit to 244 seconds duration, based on the 7.4 km/sec satellite velocity. 73 volcanoes have entered into eruption during the six years and a half of surveys. For 57 of them, 269 anomalies were found in relation with 89 eruptions. The anomalies are distributed in 5 types, similarly to the ones observed above impeding earthquakes. The two main types are electrostatic turbulences (type 1, 23.4%) and electromagnetic emissions (type 2, 69.5%). The number of anomalies is reduced at most of 27% when a daily Kp index threshold is applied and lessened from 30 to 15. Therefore, the anomalies detected in the ionosphere appear to be related to the fore coming volcanic activity. For anomalies of types 1 and 2, the maximum number of anomalies is recorded between 30 and 15 days before the surface activity, while the number drastically decreases for more remote time windows. Finally, it seems that the number of anomalies recorded for one eruption is related to the powerfulness of the eruptive activity based on the Volcanic Explosivity Index (VEI). The appearance of anomalies seems not to depend on the size of volcano or the type of activity, but rather on the likelihood to release bursts of gases during preparatory eruptive phases. In the case of the huge centenary Oct. 26, 2010 Merapi (Indonesia) eruption, 11 ionospheric type 2 anomalies appeared before the eruption. They have mainly emerged during the mechanical fatigue stage during which micro-fracturing occurred. The anomalies seem to be related with SO_2 gas discharges. Although the database is relatively small, the results show that volcanic activity may be preceded by anomalous transient ionospheric effects

A new 2012 submarine volcanic activity off the western coast of El Hierro (Canary Islands, Spain): evidences from acoustic imaging and precursory signatures

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Here we report precursory geophysical, geodetic, and geochemical signatures of a new submarine volcanic activity observed off the western coast of El Hierro, Canary Islands, which has been detected through acoustic imaging of submarine plumes on June 28, 2012, by the Spanish research vessel Hesperides. Five distinct acoustic submarine plumes have been recognized in this area at water depths between 64 and 88 m along a submarine platform located in front of the Lomo Negro volcanic cone, west of El Hierro. Submarine plumes are characterized by vertical columns of high-amplitude values rising from seafloor. These acoustic imaging data clearly support a new submarine volcanic activity in 2012 associated to the recent magmatic reactivation of El Hierro volcanic system. This new submarine volcanic activity was preceded by several precursory signatures: (i) a sharp increase of the seismic energy release and the number of daily earthquakes of magnitude higher than 2.5 on June 25, 2012, (ii) significant vertical and horizontal displacements observed at the Canary Islands GPS permanent network Nagoya University-ITER-GRAFCAN at El Hierro with uplifts up to 3 cm from June 25 to 26, 2012, (iii) an anomalous increase of the soil gas radon activity at HIE02, a geochemical station located in the northwestern of El Hierro, from the end of April until the beginning of June reaching peak values of 2.7 kBqm3 on June 3, 2012, and (iv) the highest observed corrected value of 3He4He ratio in ground waters (8,5 Ra) from San Simon well at the northwestern of El Hierro on June 16, 2012. These precursory signals have revealed important to improve and optimize the detection of early warning signals of volcanic unrest episodes at El Hierro.

Locating changes associated to volcanic eruptions at Piton de la Fournaise using ambient seismic noise cross-correlations

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Piton de La Fournaise (PdF) on La Reunion Island, is currently one of the most active volcanoes with two eruptions per year on average. Since the nineties ambient seismic noise is constantly monitored at PdF by a varying number of stations. Brenguier et al. (2008a) have shown that after the reconstruction of the Green's functions from seismic noise cross-correlations between the different stations at PdF, the apparent relative velocity changes can be used as precursors of volcanic eruptions.

In our study, we analyze continuous ambient seismic noise records from the active volcano Piton de la Fournaise on la Reunion Island from June to December 2010. During this time two volcanic eruptions occurred. We calculate the cross-correlation functions between 19 broadband stations. We then study the coda variations of the Green's functions and distinguish two types of measurements associated to two types of changes. On the one hand, we assume that a small local velocity change (weak impedance contrast) will induce a time lapse in the coda waveforms. On the other hand, we assume that a local structural change in the medium (strong impedance contrast) will induce a distortion or decorrelation of the coda waveforms (Larose et al. 2010, Rossetto et al. 2011, Planes 2013). We observe that the temporal variations of both parameters are precursors of volcanic eruptions at Piton de la Fournaise. The strength of the coda variation depends on the position of the station pair relative to the change and the strength of the change itself.

In order to locate these changes in space, we compute sensitivity kernels between the stations using a radiative transfer approach for the intensity propagation. Then we use a linear least-square inversion to locate the changes associated to the eruptions (small velocity changes and structural changes): prior, during and after the eruption.

Numerical modeling and inversion of multidisciplinary dataset at Mt Etna: from geophysical observations toward volcano hazard assessment

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Etna volcano has become a natural laboratory for a multidisciplinary research programme that operates in a feedback mode between advancement of new numerical modeling concepts and their validation by geophysical datasets. The multidisciplinary dataset gathered from ground-based monitoring networks at Etna during the last decades constitutes a unique opportunity to investigate the behavior of the volcano in a period in which it exhibited different styles of activity characterized by inflation, flank eruptions and fountaining episodes. The long-term data allow to investigate the response of the volcano to different processes in an iterative chain with initial models being developed to explain the available data sets. As new higher resolution data from satellites techniques have become accessible, the derived numerical models have then been tested and refined.

Integrated analysis and 3D numerical modeling of gravity, magnetic and deformation data have been performed to improve the reliability of model-based assessment of geophysical observations. We will present numerical solutions based on Finite Element Method (FEM), which have been implemented and applied to jointly interpret geophysical changes recorded during the recent Etna volcanic eruptions. Despite the capability to solve complex models, the use of FEM in geophysical inverse problem has been found to be computationally expensive since the mesh is geometry-dependent and, as the geometry interface changes, the entire domain need to be re-meshed at every inverse iteration step. Therefore, traditional FEM on unstructured mesh become impractical, because most of the time would be spent to construct a new mesh that adapts to the new geometry. A fast and efficient cutting-edge numerical method would be desired, which preserves the advantage of modelling complex structures and overcomes the drawback of meshing procedures.

To afford this issue, we propose a novel strategy based on a second order Finite Difference ghost-cell method for solving the governing equations in an arbitrary domain described by a level-set function. By allowing for the domain geometry to be modeled independently of the computational grid, we improve the computational efficiency with respect to FEM and provide an efficient method to include complex geometry and medium heterogeneity avoiding time-consuming meshing procedure. The proposed methodology has been firstly validated versus exact and analytical equations, and FEM solutions. We will present preliminary results from numerical computations of rock deformation caused by pressure and dislocation sources within the physical domain of Etna volcano. This innovative approach opens up new perspectives in geophysical inverse modeling and poses the basis for future development in a volcano hazard assessment based on a critical combination of geophysical observations and numerical modeling.

Magnetic source inversion for a triaxial ellipsoid using the genetic algorithm

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A triaxial ellipsoid is an effective and versatile model as a source for the volcano- magnetic effect caused by the thermal magnetic effect. The genetic algorithm (GA) was initially introduced for the magnetic source inversion in the tectonomagnetic studies by Currenti et al. (2008). A mathematical formula to give the magnetic field produced by a uniformly magnetized triaxial ellipsoid was originally presented by Clark et al. (1987), which was applied to find volcanomagnetic sources in Taal volcano, the Philippines (Zlotnicki et al., 2008). Model parameters to be determined are the magnetization of the elliptic body (moment, declination, inclination), the coordinates of the center of the ellipsoid (xe, ye, ze), lengths of three axes (a, b, c; a > b > c), attitude angles of the ellipsoid (α, δ, γ), which are twelve in total. In the case of thermal demagnetization, first three are known. We conducted the sensitivity tests for the remaining 9 parameters. The attitude parameters (α, δ, γ) behave non-linearly, while the other parameters change linearly, when only each one of them varies for a certain parameter space while the remainders are fixed. We adopted the grid search method, in which the ellipsoid center is fixed and the shape parameters (axis length and attitude) are subject to GA inversion process. Simple but effective FORTRAN subroutines are published by Ishida et al. (1997), which are utilized in the present study.

Each parameter space for 6 unknown variables is subdivided into 256 pieces, which is regarded as a gene. A combination of arbitrary choice of 6 genes makes a chromosome and a certain number of chromosomes are generated for each generation. Genetic algorithm is applied to a set of chromosomes for each generation to search for the best-fit model which gives the minimum squared sum of the differences between observed and computed values. The genetic algorithm consists of the processes called as selection, crossover and mutation, respectively. The number of populations or chromosomes NP for each generation, which is specified in advance, is crucial to attain the final goal effectively. We examined the cases for NP = 100, 500, 1000 and 3000. For larger NP, the GA process sometimes breaks. It turned out the roulette rule, i.e. the standard technique for the selection process, does not work well for larger NP. We specified NP = 100 for the roulette selection, which enabled us to attain rapid convergence to find the minimum squared sum of (O - C)'s. A case study was done (Sasai, 2013) for the large geomagnetic dip changes observed during the 1950 eruption of Izu-Oshima volcano by Rikitake (1951).

Continuous heat accumulation beneath Tokachi-dake volcano, northern Japan, as inferred from magnetic total field changes

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Tokachi-dake is an active volcano in the central Hokkaido, northern Japan. In historic age, it experienced phreatomagmatic to magmatic eruptions in 1926, 1962, and 1988-89. Recent major geothermal anomalies and fumaroles have been concentrated on Taisho and 62-II craters. Geodetic monitoring based on GPS has revealed continuous inflation localized at 62-II crater since 2007 (Japan Meteorological Agency, 2012). In contrast, seismicity and fumarolic activity at 62-II crater were considerably low in this period. Most recently, after 2010, micro-seismicity beneath the crater area has gradually revived and thermal activity at Taisho crater has measurably elevated. We have performed magnetic repeated surveys since 2008 aiming for better understanding of ongoing subsurface processes beneath the craters.

Numerous studies have reported magnetic changes associated with volcanic activity. In many cases, such changes are attributed to the thermo-magnetic effect in which heating/cooling causes decrease/increase in magnetization of volcanic rocks. If the localized ground inflation at Tokachi-dake accompanies thermal processes beneath the crater, it should be detected as magnetic field changes.

In each survey, we recorded the magnetic total field at about 30 sites for 2 minutes on each with every 5 seconds around the craters. Repeatability of the sensor position was typically several cm in a typical field gradient of 10 nT/m (but occasionally 100 nT/m). During the survey, another magnetometer was operated at a temporary reference station that was located approximately 8 km north from the target area. Simple difference reduction was applied between each site and the reference in order to remove the variations of extra-terrestrial origins.

The first and second campaigns revealed a distinct dipolar pattern in magnetic changes, indicating magnetization loss at a depth of roughly 200 m beneath the 62-II crater. Subsequent repeat surveys suggested the continuous demagnetization at almost the same position with an approximately constant rate. The maximal cumulative change exceeded 150 nT for the four years by 2012. The equivalent change in the magnetic moment amounted to 1.3×10^{6} Am^2/yr. The most likely explanation of this demagnetization is the thermo-magnetic effect due to heating beneath the crater. This result implies that heat supply from depth is larger than discharge from the vent. Through several approximations and assumptions, we obtain an equivalent thermal accumulation as an order of $10^{14\text{-}15}$ J/yr; corresponding to several tens of MW. This thermal demagnetization accompanying the ground inflation may be a part of the preparation process to forthcoming surface manifestation, although the estimated thermal energy may also be accounted for the fluctuation of heat discharge from the vent. Further accurate measurements of surface heat loss may be a key to a better evaluation of the supply from depth.

Recent activity of Taal volcano (Philippines) inferred by electromagnetic and other geophysical monitoring networks: 2009-2012

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Taal volcano in the Philippines is a particularly hazardous volcano in a very populated region near the capital, Manila. Repeated pyroclastic flows, base surges and violent phreatic explosions, such as experienced during the previous 33 historical eruptions, threaten the region. Since the last long eruptive episode in 1965-1977, Taal volcano has exhibited sporadic and intense seismic activity, ground deformation, and surface activity. The monitoring of the volcano is one of highest priorities of the Philippines Institute of Volcanology and Seismology (PHIVOLCS, http://www.phivolcs.dost.gov.ph/). Since 2004, the Inter-Association Working Group on 'Electromagnetic Studies of Earthquakes and Volcanoes' (EMSEV, http://www.emsev-iugg.org/emsev/) and PHIVOLCS have developed a joint research program for (1) understanding the interactions between the magma feeding system, the huge hydrothermal system located beneath the volcanic Island, and ground water recharge by seasonal rainfall in the inner Main Crater Lake and the external Taal Lake and (2) building up real-time monitoring networks based on electromagnetic and other geophysical methods.

We will focus this presentation on methods we use for monitoring the volcano and results we have obtained during the recent activity of Taal. In late April 2010, after a few years of relative quiet, the volcano experienced accelerated deformation and dramatically increasing microseosmicity. This caused PHIVOLCS to temporarily raise the volcano alert level to two on a five level scale. Four periods of high seismicity were recorded from April to July 2011. The 2010 seismic crisis was accompanied by ground deformation, and re-opening of active East-West fissures located on the northern flank of the volcano. Electric, magnetic and temperatures changes were associated with the 2010 seismo-volcanic crisis.

One hypothesis is that this crisis started as a result of magma intrusion at about 5-km depth under the north side of the Main Crater Lake. Injection of volcanic fluids into the hydrothermal reservoir could have caused the inflation and seismicity observed from April to June, 2010. As activity receded in the following months, some shrinkage of the reservoir could have occurred. No noticeable surface or deep activity was subsequently observed in 2011 but, after one year of low activity, the seismicity has been again increasing since October 2012.

Since 2011, EMSEV has focused on increasing the monitoring capability on the volcano. Continuous Self-potential, magnetic, tilt, ground temperatures, resistivity measurements are made every two seconds at four stations on the volcano and data are radio-transmitted in real-time to the local Buco observatory.

Implications to the volcanic activity of a large hydrothermal reservoir beneath Taal Volcano (Philippines) as revealed by magnetotelluric observations

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Located in the island of Luzon and 60 km south of the capital city of Manila, Taal Volcano is one of the most active volcanoes in the Philippines. The first recorded eruption was in 1573 and since then it has erupted a total of 33 times, with the last eruption in 1977. These eruptions resulted in thousands of casualties and extensive damage to property. In 1995 it was declared one of the "1990s decade volcano" by IAVCEI. While the volcano remained fairly quiescent after the 1977 eruption, at the beginning of the 1990s it began to exhibit several phases of abnormal activities, such as episodes of seismic swarms, ground deformation and fissuring, and hydrothermal activities, all of which continues to the present. Careful examination of past eruptions of Taal Volcano however shows that these eruptions can be divided into 2 distinct cycles, depending on the location of the eruption: eruptions centered at the Main Crater in 1572-1645 and 1749-1911 and eruptions occurring at the flanks in 1707-1731 and 1965-1977.

We conducted, as part of the PHIVOLCS-JICA-SATREPS Project, magnetotelluric and audio-magnetotelluric surveys on Volcano Island, in March 2011 and March 2012. The objective of this survey was to create a resistivity model of the hydrothermal system beneath the volcano. Initial 2-D inversion modeling revealed a prominent and large zone of relatively high resistivity between 1 to 4 kilometers beneath the volcano and located almost directly beneath the Main Crater and surrounded by zones of relatively low resistivity. The anomalous zone of high resistivity is hypothesized to be a large hydrothermal reservoir filled with volcanic fluids in a gaseous phase. Three-dimensional forward modeling reveals the size of the reservoir to be as large as 3 km in diameter and its location to be between 1 km to 4 km in depth. This reservoir appears to be overlain by an impermeable cap exhibiting a lower resistivity signature compared to the hydrothermal reservoir. The presence of such a large hydrothermal reservoir could be related to the past activities of Taal Volcano, which are characterized by repeated changes in eruption sites, i.e. alternating between the Main Crater and the flanks and separated by long repose times. During the cycle of Main Crater eruptions, this hydrothermal reservoir is depleted, while during a cycle of flank eruptions this reservoir is replenished with hydrothermal fluids. In particular, the 1911 January 30 eruption showed an anomalous feature similar to a gas explosion, which can be attributed to the large hydrothermal reservoir collapsing catastrophically.

3D imaging clay-cap and underlying gas reservoir by magnetotelluric modeling and micro-earthquake monitoring at Kusatsu-Shirane volcano, Japan

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Kusatsu-Shirane volcano, Japan, is historically known for active phreactic eruptions. The geothermal system underneath the volcano has been investigated by geochemistry and qualitative models have been proposed (ohba, 1994). During the active period in 1990s, the peculiar volcanic tremors (tornillo) were observed, which were explained by vapor-fluid resonance in a horizontal crack system under the crater lakes (Nakano et al., 2003). During the same period, temporal magnetic field showed the patter of demagnetization implying the increased temperature beneath the peak (Yamazaki et al., 1992). However, the underlying structure of the volcano remained unknown.

We have done magnetotelluric measurements at 85 sites covering the whole summit area (2kmx2km) of Kusatsu-Shirane volcano, with average site spacing of 200m. We used full impedance tensor in the frequency ranges between 100Hz to 1Hz for three-dimensional inversion (Siripunvaraorn and Egbert, 2009). We found a bell-shaped conductive layer at the peak area, which are interpreted as a layer containing clay by referencing to the borehole core samples. The top of the clay cap thins corresponding to the recent (2006-present) new active geothermal manifestations at the Yugama-Mizugama cater pits.

The bottom of the clay cap has a southward gentle slope and it coincides with upper bound of the micro-earthquake distribution. This coincidence confirms that the clay cap and gas supply from the south are causing increased pore pressure leading to active microseismic activity with magnitude between -1 to 1.

On the other hand, the bottom of the clay cap has a northward vertical slope and the northern rim has a shape of a thick vertical wall. Correspondingly, this wall shuts the seismicity completely.

The most active fumaroles distribute in the northern slope of the volcano, which is further north beyond the clay cap. This means that the most active fumaroles are located at the rim of the clay cap. The gas passage seems to be completely open as there is almost no microseismic activity under the fumaroles.

Clay cap distribution is also supported by the CO2 discharge mapping (Saito et al., 2004). The seismic resonator and source of the demagnetization during the 1990s activity are located beneath the clay cap at the peak. Thus the magnetotelluric 3d imaging of clay cap and underlying microearthquakes give important information on the phreatic eruption environment.

The oscillation theory generated by hydrothermal dynamics beneath Aso Volcano, southwest Japan: A new understanding using repeated absolute and relative gravity measurement

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At the end of 2010, the water level in the Naka dake crater reduced and then was followed by a small eruption in May 2011. After the eruption and heavy rain, the water level in the crater is recovered. To clarify this crater lake phenomenon in relation to hydrothermal dynamics in the subsurface, we were subjected to repeated gravity measurements. Relative gravity measurements were performed with Scintrex CG-5 (549) and LaCoste Romberg type G-1016 gravimeter at 28 benchmarks in April, August and November 2011, April, August and December 2012. It covered the area more than 60 km2 in the west side of Aso caldera. In another measurement, we installed a new microgravity network on May 2010 at seven benchmarks using A10-017 Absolute gravimeter, which we re-occupied in October 2010, and June 2011.

As a result, we able to detect gravity changes that seem as hydrothermal flow that has a correlation to water level fluctuation in the crater. Large residual gravity changes between the surveys are found at benchmarks around Nakadake crater. The 3D inversion models of 4-D gravity data deduce density contrast distribution beneath Aso volcano. The inversion models have good validation from Nakadake dynamic crater during these periods. The oscillation theory generated by hydrothermal dynamics in subsurface reservoirs is indicated by these inversion models. If we able to measure quantitatively this amount, it will contribute to understanding the process of eruption.

Measuring vertical gravity gradients in volcanic areas using an interferometric gravity gradiometer

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Gravity measurements, using mechanical and absolute gravimeters, have been carried out in various volcanic areas to infer the subsurface density variations caused by volcanic activities. Measured values of gravity are not only influenced by the density variations due to volcanic activities, but also by movements of groundwater and diastrophism. These non-volcanic effects have to be modelled and removed from the gravity values. However, large uncertainties in the modelling tend to hinder accurate identification of the volcanic effects. In order to improve the accuracy of identifying the volcanic effects, we propose simultaneous measurements of gravity and vertical gravity gradients. The vertical gravity gradients are obtained by taking the differences of two gravity values (g_A and g_B), simultaneously measured at different heights (A and B). By taking the difference of g_A and g_B, the common effects to the both values are cancelled out. Such common effects are originated from, for example, seismic vibrations and diastrophism at the observation point; the values of vertical gravity gradients are not severely affected by height changes of the observation point. Also, unlike gravity, which is proportional to the square of the distance from the source of gravity, gravity gradients are proportional to the cube of the distance. This indicates that the measurements of gravity gradients are likely to be more sensitive to the movement of nearby groundwater than those of gravity. Because of these intrinsic differences, the simultaneous measurements could be useful for more accurate identification of the sources of density variations.

A new type of gravity gradiometer, employing technologies for the fifth-force search, had been developed at the Institute for Cosmic Ray Research (ICRR) of the Tokyo University from 2009 to 2012. In this gravity gradiometer, a pair of test masses, set at different heights, is thrown up at the same time in vacuum and their differential acceleration is measured by interferometer. Laboratory tests at the ICRR showed that this type of gravity gradiometer was capable of measuring vertical gravity gradients to a level of a few μGal ($=10^{-8}$ m/s^2) per meter. This resolution is comparable to that of commercial absolute gravimeters, widely used in the field of geodesy. We intend to use the gravity gradiometer for the simultaneous measurements. We have moved a prototype of the gravity gradiometer to the Aso Volcanological Laboratory of Kyoto University (AVL) and carried out further improvements and trail measurements. We report the current status of the development and future prospects of the gravity-gradients measurements in volcanic areas.

Shallow structures of the rift zone in northern Iceland

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Eruptive activity in Iceland's Northern Rift Zone is not confined to central volcanoes but can act along their accompanying fissure swarms which extend outward along the rift axis. Some of the volcanic systems may operate at two central volcanoes, one of which is dominant, with subsurface connections joining them. Work by Gudmundsson and Högnadóttir (2007) in central eastern Iceland describes gravity highs between such paired volcanoes, thought to be caused by an increased density of intrusive features.

This project is centred around the production of a Bouguer gravity map of the more active, northern part of the Icelandic rift zone, from the Vatnajökull ice cap in the south, across Askja and Upptyppingar, and north to Krafla, because of the recently identified magma movements there and the implications for future eruptive activity.

Askja has a history of both effusive and explosive behaviour. Currently in a state of deflation, recent gravity measurements at Askja have shown a mass increase, thought to result from a fresh supply of magma to the upper magma chamber (Rymer et al., 2010). Meanwhile, increased seismicity extending from Askja has been explained as magma draining from the lower reservoir, northwards along the rift (Soosalu et al., 2010), while at nearby Upptyppingar, seismic activity suggests a dyke intrusion (Jakobsdóttir et al., 2008).

It is hoped that analysis of the anomalies contained in the new gravity map can shed light on this subsurface activity, both around Askja and across the region, and that the hypothesised linkages between volcanoes can be distinguished. Results of recent Bouguer gravity work and crustal modelling will be presented here.

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3D thermal structure of the Hengill volcanic complex (Iceland) revealed from electromagnetic sounding data and temperature well logs

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The indirect electromagnetic geothermometer based on using of magnetotelluric and transient electromagnetic data and calibrated by the available temperature logs is applied to determine three dimensional temperature model of the Hengill volcanic complex up to 20 km depth. The analysis of the temperature model shows that the background temperature consists of two layers. The upper layer extending from the surface to 5 km has lower temperature (below 200 degrees (C)) while the deeper one, which spans in depth to at least 20 km, is characterized by temperature ranging from 200 to 400 degrees (C).

The two-layered background temperature distribution is overlapped by a circulation system of high temperature low resistive channels, which braid through the studied area and root to a depth deeper than 20 km. Accordingly, the probable heat sources feeding the geothermal system are supposed to be the intrusions of the hot partially molten magma upwelling from the mantle through the faults and fractures.

Application of the new approach enabled us to build a new self-consistent conceptual model of the Icelandic crust in the Hengill geothermal area. It agrees with the most of previous geophysical results and provides an explanation for the facts the previous models failed to explain. In particular, joint analysis of the temperature and resistivity models indicates that highly conductive layers recognized by MT sounding at shallow and large depths are most probably the parts of the hot melted magma network overlapping generally cold Icelandic crust supposedly composed from the silica rich gabbro. This could explain why has the drilling in the Krafla geothermal field penetrated rhyolitic magmas with a temperature of 1100 degrees (C) at a shallow depth.

Joint analysis of the temperature and resistivity models together with the gravity data enabled to reveal the heat sources and discriminate the locations of relict and active parts of the volcanic geothermal complex. This, in turn, explains the observed seismicity pattern by different geothermal regimes in four adjacent parts of the area.

Structural imaging in Papandayan Volcano, Indonesia using Magnetotelluric and other geophysical methods

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Papandayan volcano is an active volcano situated in Garut, West Java, Indonesia. In 2002 eruption, it released pyroclastic volcanic material to the surface covering the 4 km2 area on the summit to the north part of the volcano and formed new craters on the southern part of the summit. We have undertaken several geophysical measurements in period of 2008 2011 such as magnetotelluric, gravity, magnetic and DC resistivity in order to delineate subsurface structure of the volcano. Magnetotelluric measurements were designed using both a grid system with the 25 sites with interval station of approximately 250m covering the summit area and long profile crossing the summit area to image regional structure of the volcano. Frequency range from 320 Hz to 0.1 Hz were obtained by recording five components of electric and magnetic fields using phoenix MTU-5 system. Magnetic and gravity data were acquired in the summit area overlapping with the MT sites to determine basement structure of the volcano. The shallow resistivity structure was constrained by four lines DC resistivity surveys that were carried out in the center of the summit to confirm the thickness of pyroclastic distribution released from 2002 eruption. The MT results derived from 2D and 3D inversion show that the resistive zone of deep structure with the circle-like shape exists in the middle of the model in coincidence with the location of new craters. A comparison of low total magnetic field appear to be consistent with the circle-like shaped resistive zone presumably related to high temperature distributed in center of the region. From gravity data, we have found the basement of the pyroclastic structure.

Density muon tomography of La Soufrière of Guadeloupe lava dome

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We present density radiographies of La Soufrière of Guadeloupe lava dome acquired from three locations around the volcano. The radiographies show that the lava dome has a very heterogeneous structure with large volumes of low-density materials, some of them corresponding to recognized hydrothermally altered areas. The main structures observed in the density radiographies are compared with those obtained from electrical resistivity measurements. Information provided by muon tomography is discussed with respect to the structure and the functioning of the hydrothermal system of the lava dome.

The MU-RAY project: volcano radiography with cosmic ray muons.

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Cosmic ray muon radiography is a technique for imaging the variation of density within the top few hundred meters of a volcanic cone. It is based on the high penetration capability of the high energy muon component of cosmic radiation. The measurement of the flux variation of the incoming muons as they pass through the volcanic cone, allows the evaluation of the average density along the observation line with a precision of a few percent and with a spatial resolution which can be of the order of ten meters once optimal detection conditions are reached. Muon radiography can provide images of the top region of a volcano edifice with a resolution that is considerably better than that typically achieved with conventional methods. Such precise measurements are expected to provide us with information on anomalies in the rock density distribution, like those expected from dense lava conduits, low density magma supply paths or the compression with depth of the overlying soil.

The MU-RAY project has developed a muon telescope prototype for muon radiography. The telescope must be capable of working in a harsh environment with low power consumption, have a good angular and time resolution, with a modular design so that a relatively large active area can be transported and installed at the point of interest. The protype telescope consists of three X-Y planes of one square meter area made from plastic scintillator bars of triangular cross section. Light output from each bar is collected by a fast Wave Length Shifter fibre coupled to a silicon photomultiplier. The readout electronics is based on the SPIROC/EASIROC ASIC. The prototype is under test and will be soon installed at the Mt Vesuvio in Naples.
An overview of the muon radiography technique will be given followed by a description of the MU-RAY prototype with first results from the Vesuvio observations.

Muon radiography of the Puy de Dôme by the TOMUVOL collaboration: status and prospects.

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Muons are elementary particles analoguous to the electron but 200 times heavier. They are produced in the interaction of cosmic rays with the earth's atmosphere. High energy (above a few hundred GeV) atmospheric muons can travel through kilometres of rock. Therefore, they are a natural probe for scanning density distributions within large structures, like mountains or volcanoes.

TOMUVOL (TOmographie MUonique des VOLcans) is a French interdisciplinary collaboration of particle physicists and volcanologists. It aims to develop instruments and methods for a complete 3D muon tomography of volcanoes with high resolution (down to 10 mrad) and large scale tracking detectors. The ultimate goal is the construction and validation of an autonomous and portable radiographic device for volcano tomography, which can be used for studying their internal structure and monitoring active volcanoes. For these purposes, the project benefits from a reference site used as testbed: the Puy de Dôme (alt. 1464 m a.s.l.), an extinct 11000 years old volcanic dome in the Massif Central, south-central France. It has a remarkable composite structure with two domes originating from two subsequent eruptions, which occurred within a short time interval. Hence it is expected to exhibit an interesting and contrasted density structure.

We report on past and forecoming campaigns of radiographic measurements at the flank of the Puy de Dôme using prototypes detectors made of Glass Resistive Plate Chambers (GRPCs). First, the detectors used as well as the ongoing technical upgrades will be detailed. Secondly, we'll discuss the analysis and simulation tools developed for the radiographic reconstruction of the integrated density profiles. The first radiographic images of the volcano inner structure obtained through muon tomography are in agreement with standard geophysical measurements and show the outstanding potential of this novel imaging technique.

Inner structure of a lava dome: comparison of geophysical models

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As part of the TOMUVOL (muon tomography) project, we started geophysical measurements on a 11,000 years old trachytic lava dome, the Puy de Dome, located in the Chaine des Puys volcanic field (Massif-Central, France), in order to compare muon imaging results with those obtained through conventional geology and geophysics. Ultimately, we expect that a joint interpretation of muon imaging and conventional geophysical data will lead to more accurate models and help to define a robust methodology to study the static and dynamic structures of active volcanoes.

Here we present the first results from the geophysical study of the Puy de Dome. As most large volcanic domes, it appears to be a composite construction. A surface morphology analysis indicates two distinct constructional units. The western half is characterized by an uneven morphology corresponding mostly to massive rocks. The eastern part seems to be emplaced in a scar belonging to the first unit and it is made of thin lava lobes associated with pyroclastic and talus deposits. Recent field observations show evidence of extensive hydrothermal alteration in the upper part of the volcano.

We performed various geophysical investigations between 2011 and 2012: electrical resistivity tomography, gravity measurements and muon imaging. Resistivity surveys were performed using multi-electrode arrays with both long (35 m) and shorter (5 m) electrode spacing. The arrays with the larger electrode spacing allow to image the resistivity structure of the dome down to its base whereas the arrays with the shorter electrode spacing have been used to refine the shallow structure of the summit area. The gravity data have been acquired with a high spatial resolution. The computed residual Bouguer anomaly provides 2D and 3D models of the density distribution within the dome that can be directly compared to the muon imaging results.

New detailed ERT and gravity measurements will be performed to refine the models of the structure of the dome and of its surroundings. A complementary high resolution magnetic survey will also be carried out at the same scale and its results will be discussed at the meeting. In addition, in situ and laboratory measurements of the physical properties of the dome-rocks will allow us to constrain the models.

The preliminary results show a good correlation between the gravity and the muon models. The resistivity models provide complementary information of the geological structures. Our goal being to promote the Puy de Dome volcano as a reference experimental site for structure imaging methods, we will refine in the near future each imaging technique and will try to combine their results in order to build a robust model of its structure.

Development of multilayer muography for imaging a middle-scale volcano

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In order to perform cosmic-ray muon radiography to image a volcano with a thickness of more than 1 km, a detector with a large active area is necessary to collect the sufficient number of muon events since the penetration flux of cosmic-ray muons is reduced steeply as a function of the thickness of the target of which the muon traverses. However, the size of the active area is not a unique factor to improve the measurement. The signal-to-noise (S/N) ratio also decreases seriously as the size of the target becomes larger, and thus the density distribution cannot be accurately measured. The background (BG) noise that reduces the S/N ratio mainly consists of the fake tracks that are generated by the accidental coincidence of the vertical electromagnetic (EM) shower particles. In order to solve this problem, we developed a novel muon detection system that consists of many layers of position sensitive detectors (PSDs) in conjunction with a new analysis method to effectively reduce the BG noise. In this method, the EM shower-originated fake tracks are rejected by requesting a linear trajectory for a muon event (linear cut method) since vertical EM showers randomly hit each PSD layer and make a non-linear trajectory in the detection system. The developed detection system was tested by imaging the internal density structure (the spatial distribution of the density) of Usu volcano, Hokkaido, Japan. In this measurement, we used a muon detection system that consists of 7 layers of PSDs. One PSD layer consists of *x*- and *y*- arrays of scintillator strips to make an active area of 1.21 m^2 with a segmented area of 10x10 cm^2. The angular resolution is +/- 3°. The measurement duration was 1977 hours (82 days and 9 hours). This measurement yielded the following results: (A) by analyzing the region that has a thickness of more than 1000 m, we confirmed that our detection system is sensitive to a density variation of 10

Imaging the internal density structure of the lava dome in Unzen, Japan

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The latest lava dome in Mt. Unzen was formed in the eruption from January 1991 to early 1995 and the eruption activity was calmed down in 1995. The researchers kept to observe the eruption in this period precisely. Some of them proposed the growth model, another person proposed different model from their data(Nakada et al.,1995 and Ohta, 1996). It is significant for the growth model and the landslide prediction to investigate the density structure in the lava dome.

Cosmic-ray muon radiography is a new method that can be used to study the internal density structure of volcanoes. The original idea is very old. Many researchers tried to find something hidden in various structures. Unfortunately they couldn't find anything new at that time. Meanwhile the muon detection technology has been highly developed till today. The first successful work was done by Tanaka et al succeeded to observe the conduit in an active volcano, Mt. Asama(2007). They also succeeded to observe the root structure in lava dome in Showa-shinzan(2007). The second impressive work was the observation of the degassing magma in the conduit in Mt. Satsuma-Iwojima(2008). Mt. Satsuma-Iwojima is an active volcano and always emitting the volcanic gas. The result is compatible to the magma convection model by H. Shinohara.

The observation of the Unzen lava dome density 2D map was performed by using cosmic-ray muon and muon detector in Unzen. The muon detector, nuclear emulsion films which has high angular resolution(5mrad) and 1.0m2 effective areas, was installed in a natural cave from early December 2010 to the end of March. The developed nuclear emulsion films have been scanned by automated muon readout system. The systematic analysis to detect the number of the penetrating muons and their direction were done by taking a pattern match and making a connection of muon tracks between several films. The systematic error of the muon detection efficiency and random noise ratio were estimated carefully. After removing unwanted low energy electron tracks, the density map of Unzen lava dome appeared. The performance of the detector and the result of radiography will be shown in this topic.

Muon radiography of Stromboli volcano with nuclear emulsions

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Stromboli is one of the most known and studied active volcanoes in the world. Nevertheless the details of its internal structure are not well defined yet. The resolution of traditional geophysical survey methods (as seismic, etc) of the order of 0.1-1 km does not allow the detection of the possible gas and lava channels under Sciara di Fuoco, the most interesting part of the dome. We applied the muon radiography method for that. The spatial resolution of this method applied to volcanoes is less than 100 m and could reach 10 m in favorable exposure conditions. A nuclear emulsion detector of 0.96 m^2 was installed on the volcano slope in October 2011 and it was kept there for 5 months of exposure, integrating cosmic rays. Emulsions were extracted in March 2012, developed and sent to the scanning laboratories for their analysis. The details of the exposure and the preliminary results of data analysis will be reported here. This work was performed by Italian emulsion groups in collaboration with INGV Napoli section and with Tokyo University muon radiography lab.

Muon radiography by nuclear emulsions: data acquisition and processing

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Nuclear emulsions used as tracking devices as have unique features that make them suitable for muon radiography of volcanic edifices. They are cheap and have excellent spatial and angular resolution, respectively about 0.3 micrometers and 1 mrad. They have no dead time, but on the other hand they have no time resolution. Such specific behaviours demand the use of specific techniques.

Once a nuclear emulsion-based detector is removed from its exposure site and the films are developed, data readout can start. Modern automatic microscopes acquire images stored in the emulsion thickness and convert them to sets of tracks of charged particles. Even very thin layers, of the order of 50 micron, can provide 3D information about the local flux of muons and/or other particles present in the showers initiated by primary cosmic rays. In the case of exposures that take several months and detector surfaces of the order of a few m2, data readout time is only a fraction of the data collection time.

The performances of the data readout system play a prominent role. Fast emulsion scanning speed means ability to acquire data on large areas; high statistics implies low statistical fluctuations of data, and hence good sensitivity to the variations of the integrated flux density. Track recognition efficiency is also crucial: since emulsion films are exposed in stacks to reduce the amount of fake tracks due to ambient radioactivity and not related to cosmic rays, the ability to reconstruct penetrating tracks depends on a power of the tracking efficiency. The basic architecture and working principle of the European Scanning System (ESS) are described. Such system is currently used by muon radiography research groups in Europe and Japan. The evolution of the system to scale up its speed and data quality are also presented.

The size of data sets from a typical exposure can be 10^{10} singlet tracks. Detectors for muon radiography are built of several small stacks of emulsion films (doublets, triplets, quadruplets or multiplets with or without absorbers to stop soft components). Single layer tracks are normally correlated in the films of the same stack to reconstruct penetrating tracks. This operation dramatically increases the signal-to-noise ratio to values that range from 100:1 to 10000:1. The resulting data sets of penetrating tracks provide detailed angular spectra of integrated rock thickness. Given the amount of data, specific algorithms have been developed and optimized.

Such processed data even allow a posteriori fine-tuning of the position, direction and inclination of the individual sub-stacks that build the detector, with a precision of a few degrees. Finally, selection of the quality of tracks allows filtering different components of the flux of charged particles that cross the detector, from electromagnetic showers to muons. The method is shown with examples from data analysis activities on exposures to Unzen and Stromboli.

Upwelling Fluids interpreted by 3D Electrical Resistivity Structure beneath island-arc volcanoes in Kyushu, southern Japan

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An electrical resistivity structure beneath the entire Kyushu island is determined by three-dimensional (3D) inversion using the Network-Magnetotelluric (Network-MT) data to interpret the generation of upwelling fluids (aqueous fluids and partial melting of the mantle). Kyushu lies in a subduction zone, where the Philippine Sea plate (PSP) descends beneath the Eurasian Plate. The PSP slab around Kyushu is classified into three segments: a young segment [15-27 Ma; Okino et al., 1999], an old segment [45-55 Ma; Hilde and Lee, 1984], and the Kyushu-Palau Ridge. In the Kyushu island, there are many Quaternary active volcanoes distributing along a volcanic front (VF). The volcanoes exist at the northern and southern parts of Kyushu, whereas no volcano exists at the central part (a non-volcanic region). Additionally, it is suggested that the Kyushu-Palau Ridge subducts beneath the non-volcanic region [e.g., Saiga et al., 2010]. The discontinuous volcanic chain along the VF is considered to originate from arc magmatism including partial melting of the mantle. The partial melting is triggered by aqueous fluids released from downgoing hydrous slabs as a consequence of metamorphic reactions [e.g., Tatsumi, 1989]. The depth of metamorphic reactions (dehydration) on slabs depends on the thermal structure of the slabs, which significantly relate to the age of slabs [e.g., Iwamori, 2007]. Since electrical resistivity is highly sensitive to the temperature of rocks as well as to the presence of fluids, we have employed electrical resistivity imaging to elucidate the generation of fluids beneath Kyushu. Two-dimensional (2D) electrical resistivity models across four volcanoes revealed conductive blocks under the volcanoes extending from deep depths (>100 km) of the backarc side [Hata et al., 2012]. However, a horizontal connection among the conductive blocks has yet unknown from the 2D models. To reveal the connection among the volcanoes, we determine the 3D electrical resistivity model beneath the entire Kyushu island in large scale. The 3D model newly shows that the center of high conductive blocks beneath the volcanoes converges one by one in the northern and southern parts of Kyushu. Moreover, a relatively conductive block beneath the non-volcanic region is significantly different configuration from the high conductive blocks beneath the volcanoes. The block in the non-volcanic region extends to shallower depths towards the forearc side along the surface of the subducting PSP. Those two conductive blocks are interpreted as follows. First, the conductive blocks beneath the volcanoes show the upwelling magma sources, which include aqueous fluids and partial melting. Second, the relatively conductive block beneath the non-volcanic region shows pathways of aqueous fluids released from the slab, which indicates that the slab in the region can release almost all aqueous fluids at shallower depths than in the volcanic regions.

Study of magma accumulation and supply processes at Sakurajima volcano from 1998 to 2005

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Sakurajima is an active volcano located at the southern edge of Aira caldera. Vertical ground deformation of Sakurajima and Aira caldera during summit eruption activity from 1955 has been mainly detected by precise leveling. The vertical ground deformation has been related to the eruptive activity. The ground has been uplifting since 1946. The uplifting of ground stopped and had showed subsidence since 1974 when number of volcanic eruption began to increase. The subsidence pattern has been modeled with the 2 spherical pressure sources at the center of the Aira caldera (about 10km depth) and at beneath the summit crater (about 5km depth) (e.g. Eto and Nakamura, 1986; Eto, 1989). In contrast, the ground around the Aira caldera turned to uplift since 1993 and eruptive activity decreased except temporal increase in eruptions in 1999. Eruptive activity was shifted to Showa crater in June 2006. In this study, we analyzed GPS data to make clear process of magma accumulation and movement prior to eruptive activity at the summit crater in December 1999 and eruptive activity at Showa crater in June 2006. GPS data observed by SVO (Sakurajima Volcano Observatory) and GEONET data during 1998-2005 were analyzed. The stations are distributed within about 30 km from Sakurajima. Variable deformation rates are found by the continuous GPS observation. In the periods of small deformation rate from January to December 1998 (phase A) and from September 1999 to November 2004 (phase C), we obtained pressure source at depths 9.6-9.7 km near the center of Aira caldera by assuming a spherical source. By contrast, in the periods of large deformation rate from December 1998 to September 1999 (phase B) and from November 2004 to March 2005 (phase D), we obtained the depths of pressure sources at depths 6-7 km, which were shallower than sources in the periods of small deformation rate. In the periods of small deformation rate (phases A and C), magma was thought to be accumulated to the magma reservoir at the center of Aira caldera. On the other hand, the periods of large deformation rate (phases B and D), pressure source migrated to shallower place. Those periods preceded the eruptive activities at the summit crater in 1999 and beginning of the eruption of the Showa crater from 2006. It is suggested that magma moved to relatively shallow place in those periods. Volume change rates of the sources in phases A, B, and D were estimated to be 0.95×10^7 m^3/year, which was close to average magma supply rate at Sakurajima (1×10^7 m^3/year). On the other hand, in phase C when the eruptive activity declined after eruptive activity in 1999, volume change rates of the source was estimated to be 0.5×10^7 m^3/year which was about half of other phases. Increase in eruptive activity may be related to accumulate rate of magma.

A novel hydrological observation using cosmic ray air showers : A measurement of underground water stream on Sakurajima volcano

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We have established a novel method to measure the underground water stream using cosmic ray air showers. An air shower generated by high energy cosmic ray consists of electro-magnetic (EM) component and muon component. Muons can penetrate very thick object (> 1km), so radiography using muon has been performed for volcanoes and seismic faults. But because of its strong penetration power, radiography using muon for thin structure (< 20m) is not possible. The penetration power of electro-magnetic component is much weaker than muons. Thus, EM component is suitable for thin structure, like buildings or small hills.

EM component is good for thin structure, but it requires particle identification (PID). We developed a new method to distinguish EM component and muons statistically, and this method is much cheaper and easier to handle than common PID methods.

We also applied this method to measure the underground water stream. Measuring the underground water stream is important to compensate the absolute gravity measurement or diastrophic measurements because they are easy to receive turbulence by precipitation.

We report this novel radiographic method and the result of underground water stream measurement.

Magnetotelluric monitoring at Sakurajima volcano, Japan

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In order to detect the temporal change of the resistivity structure, broad-band magnetotelluric (MT) measurements were conducted from February to July, 2010 at Sakurajima volcano. Six observation sites were established at locations approximately 2-3 km away from the summit crater. By using a Metronix ADU07 system, electric and geomagnetic data were recorded everyday at a sampling frequency of 32Hz (15:00-20:00 UT), 1024Hz (17:00-18:00UT), and 32768Hz (23:10-23:11 UT). By applying the comb filter to reduce the 60 Hz noise and its overtones, we obtained the monthly MT response functions in the frequency range of 10,000-0.001 Hz. Temporal change of MT response function was observed at frequencies higher than 1 Hz. This result is consistent with the previous observations at Sakurajima volcano by using Phoenix MTU5 systems (Aizawa et al., 2011, JVGR). Temporal change was found on not only on the impedance but also on the geomagnetic transfer function. On the other hand, no significant change beyond error bars was observed at lower frequencies. To explain the temporal change of the MT response functions, we performed 3D inversion by using the code WSINV3DMT (Siripunvaraporn and Egbert, 2009). First, we obtained the high-quality MT response functions by stacking all MT data. Then, reference 3-D resistivity structure was estimated by a 3-D inversion. Second, inversions for the temporal change were performed by setting the reference model as an initial model of each inversion. In this presentation, we will show the 3D resistivity structure of Sakurajima volcano, and its temporal change.

Temporal geomagnetic field changes on Sakurajima volcano, Kyushu Japan, obtained by repeated aeromagnetic survey.

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Sakurajima volcano in southern Kyushu, Japan, is one of the most active volcanoes in the world. The volcano is located in the Aira Caldera which formed as a result of a massive eruption approximately 22,000 years ago.

On June 7, 2006, a small eruption was occurred in the vicinity of the Showa crater, and later, the number of explosions began to increase again centered on the Showa crater. The total number of explosive eruptions reaches 548 times in 2009, 896 times in 2010, 996 times in 2011 and 885 times in 2012. In now, due to these recent intense activities, the size of Showa crater grew about 2.5 times than that on Nov. 2006.

It is expected that the geomagnetic field is changed around Sakurajima volcano due to this subsurface temperature change associated with these recent activities on Showa crater. To detect the temporal change of the geomagnetic field associated with these recent volcanic activities on Sakurajima volcano, we conducted helicopter-borne aeromagnetic survey around Sakurajima volcano on Oct. 24 to 26, 2011. The survey was conducted on 22 N-E (2-8km) and 15 E-W (5-12km) lines inside the Sakurajima Island. The spacing of each survey line is about 500 m, the altitude of flight was about 150-200 m from the ground. The total flight time was about 6 hours. On this volcano, dense aeromagnetic survey was made on Nov. 2007. Using this data as a reference field, we tried to detect the temporal geomagnetic field changes during 2007 to 2011 periods. On this analysis, we applied the equivalent anomaly method to calculate the upward continuation of the observed geomagnetic field (Nakatsuka and Okuma, 2002). As the result, a remarkable dipoler temporal change was detected around the eastern part of Sakurajima volcano. On this area, active volcanic eruptions occurred in a new crater, Showa-crater, repeatedly. It is possible that the temporal geomagnetic field change detected in this area is related with the activities of the Showa crater. In our presentation, we will show the detail of the result of our data analysis and its interpretation.

Continuous GPS measurement in Kuchinoerabujima volcano, Kyushu, Japan

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Kuchinoerabujima is a volcanic island, which is located about 80 km south of Kyushu, Japan. In recorded history, phreatic or phreatomagmatic explosions occurred repeatedly with dormant periods of about 30 years. Almost of the recent eruptions occurred at the summit area of Shindake, which is the youngest cone of Kuchinoerabujima. The latest eruption occurred in 1980 at a fissure located in the eastern side of the summit crater. Various phenomena, such as the increases of volcanic earthquake, crustal deformation, geomagnetic anomaly and discharge rate of volcanic gas have been observed from 1999, which indicate the change of underground condition for the next eruption.

In order to detect signals due to changes of volcanic activities, we have conducted continuous GPS observation since 2004 at five stations in the volcano. Two of them are located at 250m northwest (SDW) and 600m south (FDK) of Shindake. The data are sampled every 30 seconds and are sent by mobile phones. Referring a station located at 3 km NW of Shinadake, SDW and FDK show a trend of westward movement at the rate about 0.4 cm/year. Intermittent events overlapped the trend 4 times. They started in June 2005, September 2006, September 2008 and October 2010 lasting for more than a few months, and deformation caused by these events attained 2-4 cm in total. They are characterized by a cumulative northwestward and upward movement of SDW, and a slight southward movement of FDK. Such a deformation was only detected near the crater, and stations at foots of the volcano did not show significant movements. This crustal deformation indicates the inflation of a shallow source just under the summit crater of Shindake. Seismicity of volcanic earthquakes increased, and total intensities of geomagnetic field changed at the same time, showing increase in temperature beneath the crater (Iguchi, 2007; Kanda et al., 2010). Some of these events were also accompanied with the temporal increase of the discharge rate of volcanic gas. It is inferred that the intermittent deformations induced by an upward movement of volcanic fluid due to increase of a deep magmatic activity.

The temporal changes of the shallower resistivity structure associated with the eruption on 2011 at Aso volcano, Japan.

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On Aso volcano, central Kyushu, Japan, a small eruption was occurred on May 2011. Before and after this eruption, we carried out the electromagnetic survey around Nakadake crater of Aso volcano. From these observations, we obtained the data which suggest a decrease of the subsurface resistivity in the deeper part beneath Nakadake crater just after the eruption. In our presentation, we will show the observation data and the resistivity structure obtained by the 1-D analysis of our data.

On Aso volcano, many observations and researches have been made to detect the subsurface structure and detailed information about the distribution of the subsurface hydrothermal system have been obtained from previous studies. From the high-density AMT survey, Kanda et al. (2008) found a low resistivity area is localized just beneath the Nakadake first crater. This area is considered as a chamber of the hydrothermal fluid which is formed by a part of the hydrothermal fluid which is supplied from the deeper magma. In recently, the activities of the Nakadake crater were often temporarily increased. Associated with these activities, it is expected that the distribution of the subsurface hydrothermal fluid is changed and subsurface resistivity structure is temporally changed. In order to detect such a temporal change of shallow resistivity structure according to these activities, we carried out the repeated control sourced electromagnetic survey around the Nakadake crater using ACTIVE observation system (Utada et al., 2007). In these observations, we installed electric current transmitter on 1 km NNE from the crater, and magnetic receiver was also installed on the 4 points around crater. We have performed a totally five repeated electromagnetic observation from April 2011 to April 2012 across the small eruption of May 2011.

From these observations, we obtained the data which suggest a temporal change of the subsurface resistivity structure. The result of the 1-D analysis of the resistivity structure shows that, the resistivity was changed beneath the crater During the period of May to July including the eruption. This resistivity change was occurred on 200 to 300 m depth and this is corresponding to the depth of the upper end of the localized low resistivity area beneath the crater which was found by Kanda et al. (2008). In our presentation, we will show the observation data and the detail of the resistivity structure obtained by the 1-D analysis of our data.

Resistivity structure around the Aira caldera, SW Japan, inferred from the magnetotelluric measurements

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The Aira caldera is located in southern Kyushu, the southwestern part of Japan, and was formed by the catastrophic eruptions (VEI=7) of the Aira volcano approximately 29,000 years ago. Total volume of the magma erupted was estimated to be about 400 km^3(Aramaki, 1984). There are two active volcanoes in the caldera: Sakurajima and Wakamiko. Sakurajima is a post-caldera volcano and started to grow in the southwestern part of the caldera after 3,000 years of the Aira eruptions. It repeats explosive eruptions more than eight hundred times per year in recent three years. Wakamiko is a submarine volcano occupying the northeastern part of the caldera. Although there is no clear evidence showing the fact of an eruption, hydrothermal fluids exceeding 200 degrees centigrade are extensively discharged from several fumaroles located at the sea bottom.

Since co-eruptive depression of the ground around the Kagoshima Bay was observed before and after the 1914 eruption of Sakurajima volcano (Omori, 1916), a magma reservoir of Sakurajima volcano is presumed to be located at a depth of 10 km beneath the Aira caldera (Mogi, 1958). Accumulation of the magma to the reservoir is still lasting because an upheaval of the ground around the Sakurajima has been observed since the first half of the 1990's. The objective of this study is to clarify the corresponding electrical resistivity structure to the assumed magma reservoir and to the supply paths to Sakurajima volcano and to the submarine volcano.

We have conducted the magnetotelluric (MT) measurement mainly along two traverse lines in the direction of WNW-ESE crossing the Aira caldera since 2009. The MT data at 39 sites in total, including 16 seafloor sites, were obtained for the last four years. For the seafloor observation, the electromagnetic field was recorded for about two to three weeks with a sampling interval of 8 Hz using several OBEMs (Ocean Bottom Electro-Magnetometers). For the land observation, the MTU-5 systems of Phoenix Geophysics Ltd. were used to measure the EM field with the frequency range of 0.001-320 Hz. We performed a 2-D analysis along two lines across the Aira caldera. The strike direction for 2-D analysis was estimated from the individual impedance data obtained on land by using a decomposition technique (Groom and Bailey, 1989). Then, a 2-D inversion (Ogawa and Uchida, 1996) was applied to the TM-mode data set.

A high conductive region of less than 10 Ωm (C1) was found in the southern profile beneath eastern Aira caldera at depths greater than 7-8 km. This conductor appears to extend upward, but it is not clear because of shortage of the higher frequency data obtained by OBEMs. Location of the conductor C1 seen in the resistivity model is roughly in agreement with the location of depression source inferred from the geodetic data (Eto and Nakamura, 1986). This indicates that C1 is possibly the structure relevant to the magma reservoir.

Resistivity structure in southern part of Zao volcano, Japan

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In the tectonic zone, dehydrated fluid from a subducted oceanic plate is estimated to be localized in the crust and the upper mantle. It is considered that identifying the localized fluid is the critical key to clarify the mechanism of tectonic zone. Therefore, measuring of electrical resistivity structure which is highly sensitive to fluid, is thought to be contributing to clarify the mechanism of the tectonic zone. We started wideband magnetotelluric (MT) surveys in the northeastern margin of Japan sea tectonic zone since 2008. In 2010, we performed 27 MT surveys on YNZ line (Murakami, Niigata <-> Soma, Fukushima) from east to west in the southern part of Tohoku region.The surveys have been continued about 20 days at each site by using 12 measurement devices(11 of ADU07[Metronix Geophysics] and a MTU[Phoenix Geophysics]). We obtained impedance responses by using the robust code of BIRRP (Chave and Thomson, 2004), and estimated 2D resistivity structure by using a 2D inversion code (Ogawa and Uchida, 1996). 2D models from a TM mode show a conductive part between two resistive parts in the middle of the survey line. The conductive part is located at the volcanic front, beneath Mt. Zao which can be imaged that the conductive part is volcanic fluid such as partial melts or hydrothermal zone.

La Soufrière de Guadeloupe volcano large-scale electrical resistivity 3D imaging

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A three dimensional image of the electrical resistivity was constructed from data sets acquired across La Soufrière de Guadeloupe volcano. In a previous study, a 1D reconstruction was performed showing the large range of resistivity variations across the edifice highlighting its important heterogeneity. La Soufrière de Guadeloupe lava dome is indeed crossed by major radial fractures separating relatively unaltered massive andesite blocks. Some regions are also covered by ashes emitted during the last eruptions. Moreover, the dome is crossed by a hydrothermal system of acid fluids supplied by tropical rains. The hydrothermal field is revealed by fumaroles and hot springs present on and around the dome and an acid lake is boiling inside a deep pit at the summit. It is therefore highly pertinent to image the internal structures of the volcano, as this could provide information for models estimating the potential hazards in case of a future eruption.

As is often the case on volcanoes, the complex topography and lush vegetation of La Soufrière dome render some regions of the volcano inaccessible so the deployment of regular electrodes profiles is impossible. This lack of information causes classical methods of 3D electrical resistivity imaging to fail in the reconstruction process. Recently developed methods based on adaptive wavelet parameterization are also unfeasible due to the complexity of the topography.

We therefore developed an original parameterization of the volcano electrical resistivity with the objective to reconstruct the global structure of the edifice. A 3D finite element model is constructed to represent the volcano and simulate the measurements of a reduced data set. The selected data correspond to the more distant electrodes as they are more sensitive to the deeper part of the volcano. The image reconstruction is performed using the EIDORS suite allowing the development of specific parameterizations. The method used here is inspired from the pilot points method developed for hydrogeological purposes. The approach consists in determining the location of a reduced number of points highly sensitive to resistivity variations and limit the inversion at the selected pilot points. The inversion is repeated several times, increasing the number of pilot points and allowing for their movement.

The reconstructed 3D image reveals the main paths of fluids and allows to distinguish unaltered materials from highly altered rocks saturated by fluids. The resulting image is compared with density images obtained from gravity measurements and muon flux detection. Despite their sensitivity to a different physical parameter, the images show similar structures inside the volcano. Some conductive regions correspond well to less dense structures as showed by muon flux measurements, and so probably represent water-saturated altered rock, while some more resistive regions coincide with denser rock and could represent massive andesite.

Temporal variations of self-potential at summit area of Izu-Oshima volcano

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Volcanic gas is released from magma which intrudes at the shallow crust. The detection of gas flow uprising to ground surface is important to estimate the increase of volcanic activity. We focus on the Self-potential (SP) variation associated with the degassing activity to develop a new method predicting the transition of volcanic activity. In this paper, we show SP in the dormant period at Izu-Oshima volcano to understand the annual change with climatic conditions. Then, SP variation caused by the supposed degassing activity is studied using numerical simulation.

SP is measured continuously at 11 stations in the summit crater of Izu-Oshima volcano from 2006. Electrical differences between sites are recorded every one minute. Rain fall and soil water content are recorded every ten minutes at one station. SP data commonly show the annual change; the values are high in summer and low in winter. The amplitude of the annual change is observed to be 100mV in maximum. The short period variations in several days are also observed after rain fall. These variations are produced by the change of soil water content near surface. On the analogy of the short period variation, the annual variation is thought to be caused by the seasonal change of soil water content at depth. The temporary trends excluding the annual variation do not show any signals suggesting the increase of volcanic activity.

We estimate SP variations when magmatic activity has increased using the simulation code named STAR. The simulation considers mass and heat transfer of vapor and liquid fluid within porous media, and calculates the drag electrical current with fluid flow and electrical potentials induced by the drag current. For the initial condition which is satisfied with the present state of SP distribution in Izu-oshima volcano (Onizawa et al., 2009), we simulate SP variation if magma intrudes at seawater level and degassing occurs at the top of magma. The resistivity of formations is approximated with the parallel circuit of solid and pore resistivity. The pore resistivity changes remarkably with dissolved component. We assume that the acid fluid produced by the condensed volcanic gas has the resistivity similar to that of sea water (0.25 Ωm). When permeability of the degassing vent is higher than the surrounding formations with two order of magnitude, and degassing occurs at the rate of 80 kg/s which corresponds to half the maximum vapor discharge rate during 1986 eruption, the positive SP anomaly up to 100 mV appears near the summit crater at 1 year after the onset of degassing, although volcanic gas does not reach to ground surface at that time. Due to the cooling of volcanic gas, the counter flow of upward vapor and downward liquid develops around the degassing vent. The drag electric current is produced only by downward liquid flow, but low resistivity of the acid liquid causes a strong positive anomaly at ground surface.

3-D density modeling of the EGM2008 gravity field over the Mt. Paekdu volcanic area

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Here we use the satellite-derived gravity field dataset EGM2998 for 3-D crustal density modeling of the Mt. Paekdu stratovolcano and surrounding area located on the border between North Korea and China. The modeling is constrained by geological, geophysical, and potential field data analysis, and curvature analysis and Euler deconvolution are used to assist interpretation. Mt. Paekdu is characterized by low Bouguer anomaly values down to -110 X 10^{-5}m/s^2, which are caused by the combined gravity effects of a depth to Moho of about 40 Km, a low velocity zone with lower P-wave velocity and lower density than the surrounding material, volcanic rocks with a mean density of 2200 kb/m^3 on the surface, and a predicted magma chamber that has not previously been identified. The newly modeled magma chamber has a mean thickness of 5 km and density of about 2350 kg/m^3, and lies at <10 km from the surface. Magma chambers are also modeled to occupy the crust beneath Mt Wangtian and Mt. Nampotae. However, the results of the 3-D density modeling do not confirm the existance of a previously proposed mid-crustal low velocity zone in the area 70 km to the north of Mt. Paekdu

Resistivity structure around Chishinshan volcano area in Tatun Volcano Group, northern Taiwan, revealed by AMT surveys.

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The active volcanoes have the low resistivity region beneath the edifices; that is because high- salinity and temperature hydrothermal fluids dramatically decrease the resistivity of the pore water and rock matrix, when the volcanic fluids are released from magma and injected into the aquifer. The spatial extent of the low resistivity region could evaluate the eruptive potentiality of volcanoes from the viewpoint of magma degassing.

Tatun Volcano Group is composed of over twenty volcanoes, which were formed within the graben at the northern part of Taiwan. Recent geological, geochemical, and seismological studies have suggested the presence of potentially eruptive magma. Vigorous heat discharge from fumaroles and springs also suggests a large amount of the volcanic fluids released from magma beneath Chishinshan volcano. Utsugi et al. (2012) conducted AMT surveys at the volcano for a better understanding of this magma degassing, and showed the preliminary resistivity structure suggesting the low resistivity region at the depths of 1-2km.

On the basis of their work, the authors conducted further AMT surveys around Matsao hot spring and Tayukeng fumarole areas, about 2 km northeast of the volcano. First of all, the spatial extent of the rotational-invariant apparent resistivity was estimated, using the both data obtained by the authors in 2012 and Utsugi et al. (2012) in 2011. At a several thousands Hz, the low resistivity areas of 10-30 Ohm-m are found separately at Lengshueiken, Matsao, and Tayukeng. At a several tens Hz, the above three low resistivity areas are connected to each other, and the extremely low resistivity area less than 3 Ohm-m emerges near the central part of Chishinshan volcano. These features suggest the hydrothermal fluids are flowing from the central area of the volcano toward Lengshueiken, Matsao, and Tayukeng areas. In the presentation, the estimated two-dimensional resistivity structures beneath three areas will be shown.

An attempt for magnetometric detection of the hydrothermal reservoir beneath Taal Volcano (Philippines)

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MT and AMT surveys on Volcano Island of Taal revealed a large hydrothermal reservoir beneath the island (Yamaya et al., 2013). The reservoir is located at a shallow depth, of which size is about 3 km in diameter. The average magnetization of the shallower part of the volcano was estimated as 5 A/m (Harada et al., 2005). On the other hand, the temperature of volcanic fluids released from the bottom of the main crater lake is as low as 100℃ (Zlotnicki et al., 2008). The reservoir is assumed as the aggregate of tensile cracks filled with volanic fluids within host rocks, which is partially but not completely demagnetized (Alanis et al., 2013). This area could be identified as a partially demagnetized block in a strongly magnetized volcano edifice by magnetometry. The average magnetization of the block can be an important information on the temperature. The formula for the magnetic fields produced by a triaxial ellipsoid is the basis for the present study (Clark, et al., 1986). We have a number of TMF measurements, which can be used to identify it as a demagnetized body having an ellipsoidal shape. The data sources are magnetic surveys on Volcano Island of Taal volcano conducted in 2005, repeat precise measurements at 28 repeat survey points and continuous magnetometer stations and those to be newly obtained by areal surveys in March this year. First, an approximate position of the center of a spherical source (dipole approximation) and its source depth as well as the magnetic moment is sought by a standard technique of grid search. The terrain correction should be necessary, which will be done using DEM data. The best-fit model for a triaxial ellipsoid will be determined with the aid of genetic algorithm (GA), which has been applied to volcanomagnetic models (Currenti, et al., 2005; Sasai, 2013).

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Magnetic signatures of volcanic unrest: learning from long-term data at Mt Etna, Stromboli and La Fournaise volcano

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The long-term monitoring of the geomagnetic field at different volcanoes can give valuable information for improving the understanding of the volcanic structures and the dynamics of eruptions. The modifications of the magnetic properties of volcanic rocks as well as the hydrothermal activity can generate a wide variety of magnetic signals, as piezomagnetic, thermomagnetic and electrokinetic effects. In addition, the local magnetic field changes are strongly related to magma dynamics.

The characterization of these signals, which depends on the structural heterogeneity, the stress field, and the hydrothermal state of each volcanic edifice, is a key step for improving the detection of small magnetic signals and for understanding the mechanisms that produce them.

During the last decades, geomagnetic observations have been intensively carried out at different volcanoes around the world (Japan: Miyake-jima; Italy: Etna and Stromboli; France: La Fournaise Philippines: Taal), and significant correlations between volcanic activity and changes in the local magnetic field have been observed. In particular, a series of coherent observations on Etna, Stromboli and La Fournaise volcanoes have led to significant advances in the systematic study of the amplitude and the origin of measurable volcanomagnetic effects. The spatio-temporal evolution of the signals observed at Etna and Stromboli during the latest eruptions (2003, 2007, 2008 and 2011) are of piezomagnetic origin. They allowed to model the magmatic intrusions at shallow depth and the stress field progress within the volcanoes. Volcanomagnetic signals recorded at La Fournaise, between 1986 and 2004, have contributed to improve the knowledge of the eruptive behavior of this volcano. Signals up to a tens of nanoTeslas were observed in the last weeks to a few hours before effusive activity. The signals were mainly attributed to electrokinetic effect. The magnetic field observations highlight the usefulness of magnetic monitoring networks as complementary techniques to traditional permanent geophysical arrays.

The long and high-quality geomagnetic sequences recorded during the last two decades at Etna, Stromboli and La Fournaise volcanoes are an essential database for a detail comparison between these volcanoes. Their specific magnetic signatures will be highlighted in accordance to the different types of eruptive activity. The expected results should contribute to the evaluation in real time of the typology and the level of activity of the volcanoes. It could help to estimate pre-alarm/alarm thresholds relevant for civil protection decisions.

3Dmagnetic modeling of damavands magma chamber and seismic concepts

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There is little information of Damavands magma chamber in volume,spatial and its dimensions. This strato-volcano situated 60 km northeast of the Tehran, is a large Quaternary composite cone, 5670 m peak which includes trachyandesite lava and pyroclastic deposits overlying the bending location or hinge of the Central Alborz ranges.The seismotectonics of the area is influenced largely by the most prominent Mosha fault, an
active, high dip angle with length of400 km (Berberian et al, 1993), that had experienced several destructive earthquakes,(Berberian and Yeats, 2001). Seismo-volcanic interaction of seismic faults around the volcano edifice is not known.An issue that would be complex problematic if, the volcano or this part of the fault becomes activate.Most of recent micro-earthquakes have occurred in the southern flank of the Central Alborz and the south of the Damavand volcano, mainly in the approximate east-west trend part of the Mosha fault (Abbasi,et al2010).Recent studies have illustrated magnetic anomalies at3 to6 km depth levels were mainly located under the main edifice cone of the volcano (Oskooi and Omidian, 2010).Other studies have shown, the edifice is composed of two cones that the earlier located SW of the older ones. A low velocity zone at depth of 7 km beneath the volcano and relatively high velocity body in the southern side of the volcano is considered as the magma chamber and the fractured zone of the Mosha fault,respectively (Mostafanejad, et al., 2011).In this study the 3DMAG (UBC) modeling software is executed several times to recognize the susceptibility changes versus depth. The inversion program generates a three dimensional block model that shows one possible subsurface distribution of the susceptibilities that could generate the observed data. The magnetic data are interpreted in the geological structure models to detect the3D distribution of the susceptibility and to produce a more geophysical interpretable model.First the aeromagnetic data is used to model the volcano for initial view of the magma chamber relevant to the observed anomaly.Then by help of the well-located micro earthquakes in the neighboring Mosha fault zone at the south of the volcano and by the mag3D estimated model, a better perspective of the magma chamber is presented.There is no reliable micro-seismic event between the Mosha zone and at least 5 km around the cone axis in the south of the volcano at 5 to 20 km depth ranges. The results illustrate two distinct anomalies at3and8 km depth which may be relevant to the intersected twin cones that had erupted in different times. This model is in comparable with the recent studies.Our studies could lead us and authorities to make more precise decisions in future site selection of the prospect seismic and or magnetic observatories for an understanding of the next probable volcanic activities.

TILTMETER OBSERVATIONS IN KAMCHATKA REGION. KLUCHEVSKOY VOLCANO MONITORING BY TILTMETERS NETWORK. RUSSIA.

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In 2010, after the long interruption, was started the tiltmeter observations in Kamchatka region. The modern tiltmeter systems are seriously expands a spectrum of geodynamic observations. Development of the tiltmeter station network allows receiving the additional information on geodynamic processes in the region, to specify the earth surface deformations caused by seismic and volcanic activity.

The results of tiltmeter monitoring in active volcano areas are the unique data reflecting processes of preparation of eruption, eruption phase and post-eruption processes. On the data analysis is probably simulation of pressurizing sources under volcanic constructions, the searching the forecast parameters of volcanic process development and realization of the volcanic activity forecast.

For today in Kamchatka region is present the tiltmeters network of 8 stations in 2 groups. 1st group is concentrated in Petropavlovsk-Kamchatsky city area and is used for registration of deformation processes caused by seismic activity. 2nd group is concentrated in Kluchevskoy volcano area and realizes deformation monitoring volcanic activity Klyuchevskoy group of volcanoes. The tiltmeter monitoring of Kluchevskoy volcanoes group are provided in collaboration between Hokkaido University, Japan, and Institute of Volcanology and Seismology (IVS), Russia, by international project: Geological and geophysical investigation of Kluchevskoy volcano, Kamchatka.

During 3 years of continuous observations is accepted the significant archive of data reflecting regional and local deformation processes caused by seismic and volcanic activity.

2005-2010 InSAR time series at Dallol, a proto-volcanic system in North Afar (Ethiopia)

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Quaternary extension and volcanism in Afar focus along magmatic segments, among which the Erta Ale segment, which includes the Dallol hydrothermal area. Dallol lies in a depressed area ∼120 m below sea level, and consists of a ∼40 m high mound hosting an active hydrothermal field, without volcanism.

Previous results show that in October 2004 a ∼6 km long dyke intrusion occurred SE of Dallol, opening the rift axis up to 4.5 m in ∼10 days. Analytical inversion models suggest the concomitant withdrawal of a shallow (1.5–3.3 km) magma chamber that partially fed the intrusion.

Using InSAR analysis, here we study the ground deformation at Dallol after this rifting event, between 2005 and 2010.

Our ground deformation time series, obtained using the π–rate software, suggest that, between Nov. 2005 and Nov. 2007 the Dallol mound slowly uplifted (∼1cm/yr) and that between Nov. 2007 and Feb. 2010 it quickly subsided (4–6 cm/yr).

Analytical models for the subsidence period suggest a sill like deformation source at shallow depth (0.8–1.8 km), that is probably the same magmatic source that fed the dyke intrusion. Although a contribution from an hydrothermal source cannot be excluded.

Preliminary results highlight a correlation between the subsidence in Dallol and vertical movements in other volcanoes belonging to the Erta Ale segment (–2.8 cm/yr at Gada Ale, +4 cm/yr at Alu Dalafilla and +2 cm/yr at the Erta Ale caldera) suggesting a possible interaction at regional scale.

Geology of a volcanic edifice selected as a reference experimental site for structure imaging using muography and standard geophysical methods: the Puy de Dome volcano, Chaine des Puys, France

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The muon imaging technique is rapidly developing in geosciences through collaborations between particle physicists and geoscientists. The Tomuvol project contributes to this effort and has started to carry out experiences on a lava-dome (the Puy de Dome) located in a field of quaternary monogenetic volcanoes in the France mainland (Chaine des Puys). Thanks to the extensive geological, geophysical and muon imaging observations and measurements already acquired or planned for the near future, this volcano is appropriate for becoming a reference site for testing structure imaging techniques. With a height of 400 m, a base-diameter of 2 km and a simple shape, Puy de Dome volcano has also an adequate topography for being a representative enough testbed. Puy de Dome was built about 11 ka ago by accumulation of viscous trachytic lava over a vent opened between pre-existing strombolian basaltic cones. Its construction is interpreted as the one of a classic lava-dome, accompanied by weakly energetic pyroclastic flows which embedded its basis. However, as most large volcanic domes, it appears to be composite. From a morphology analysis, at least two structural units can be distinguished. The western half is characterized by an uneven surface formed by ridges and pinnacles as for bristle lava-domes. The eastern part has a more gentle surface morphology, suggesting thick pyroclastic and talus deposits at the surface. Also it seems to be emplaced in a scar formed in the initial dome after a flank collapse.

With new observations, in particular those provided by outcrops created by excavations during installation of new touristic facilities, a new high resolution Lidar survey and the preliminary geophysical results from the Tomuvol project, the geology of the dome is being significantly refined. Among the new elements to take into account are: the importance of the remains of cinder basaltic cones beneath the flanks of the Puy de Dome and the extensive hydrothermal alteration observed in the summit area. Also, the even morphology of the east and south-east parts of the volcano could be partly due to the existence of 6 - 10 m thick lava lobes or flows emitted from a summit vent.

A planned drill hole for geothermal heat pump is expected to provide soon a glimpse of the interior of the dome.

Therefore, in addition to being interesting to the general understanding of lava-domes construction, the detailed study of the geology of this volcano is important to provide strong constraints on the nature of the rocks and on the structure of the dome to help in the interpretation of muon and geophysical data. An accurate model of the dome should become available by combining data from all these methods.

Geophysical study of a volcanic edifice for comparison with muon imaging

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The muon imaging is rapidly developing in geosciences through collaborations between particle physicists and geoscientists. The Tomuvol project contributes to this effort and has started to carry out experiences on a lava dome (the Puy de Dome) located in a field of monogenic volcanoes in the France mainland (Chaine des Puys). Because muon imaging is still in a development stage, it is useful to compare its results with those obtained through conventional geology and geophysics. Moreover, it can be expected that a joint interpretation of muon imaging and conventional geophysical data will lead to more accurate models and help to define the optimal procedure to study the static and dynamic structures of active volcanoes.

Here we present the first results from the geophysical study of the dome. The other aspects (geology, muon imaging are presented in companion abstracts). The trachytic dome is less than 2km wide at its base and about 400 m high. It is about 11,000 years old. As most large volcanic domes, it appears to be a composite construction. From a surface morphology analysis, at least two constructional units can be distinguished. The western half is characterized by an uneven morphology corresponding mostly to massive rocks. The eastern part seems to be emplaced in a scar in the western part and has a more gentle surface morphology, suggesting pyroclastic and talus deposits at the surface although lava lobes less than 10 m thick are also observed.

Gravity, resistivity and magnetic investigations have been carried out on the dome and its surrounding. The gravity data have been acquired with a high spatial resolution and the residual Bouguer anomaly have been modelled in order to provide an information that can be directly compared to the muon imaging. Resistivity surveys have been performed using multi-electrode arrays with both long (35 m) and shorter (5 m) electrode spacing. The arrays with the larger electrode spacing allow to virtually image the resistivity structure of the dome down to its base whereas the arrays with the shorter electrode spacing have been used to refine the shallow structure of the summit area. The magnetic data are not available at the time of writing (Jan. 2013) but will be discussed at the meeting. In addition, the physical properties of rock samples representative of the different facies of the dome are being measured in order to constrain the models.

The initial results show a good correlation between the gravity and preliminary muon results. The resistivity parameter carries a different information and therefore the resistivity models provide a complementary image of the dome structure. Because it is also intended to promote the site as a reference experimental site for geophysical and muon methods, we aim at refining the knowledge of the structure of the dome using all geological, geophysical and muon data.

A telescope for rock mass density imaging based on muon TPC with Micromegas detector

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In the framework of the realization of field telescopes dedicated to the densitometry of geological objects, the choice of proportional detectors parallel plate type Micromegas was motivated by reasons of robustness, lightness and adaptability to various configurations of measurements. This choice was also driven for its intrinsic qualities:

- The rise and fall times of the pulse measured lower than 1 ns is sufficiently rapid to allow determining the direction (azimuths and zeniths) of muons by temporal discrimination,
- The ability to build compact detectors, dedicated to karst galleries and small section tunnels since only one detector is required to measure the direction of the muons,
- The stability of the gain, adjustable from 1 to about 100000,
- The printed circuit technique that allows facilitating future developments and applications.

We present the progress of the project T2DM2 (Temporal Tomography of Density by Muons flux Measurements) developed jointly by GEOAZUR, CPPM, CEA/IRFU and CERN/RD51 within the LSBB underground lab test site (http://www.lsbb.eu). The goal is to reach accuracy of the muon flux measurement required to characterize the temporal variations of the density associated with the water transfer accross the unsaturated zone of the main european karstic aquifer for depth ranging from 10 m to 500 m. The expected changes are greater than 3

The DIAPHANE telescopes: architecture and recent upgrades

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The DIAPHANE project is a pluri-disciplinary collaboration between particle and geo-physicists to perform the tomography of large geological structure mainly devoted to the study of active volcanoes. The detector used for this tomography, hereafter referred to as "telescope", uses a standard, robust, cost-effective and well-known technology based on solid plastic scintillator readout by photomultiplier(s). We present the global architecture of the telescopes, prefectly adapted to the volcanic harsh environment and in particular the electronics system, built on the concept of autonomous, triggerless, smart e-Sensors.
First radiographies have been performed on the Mont-Terri undergound laboratory (St-Ursanne, Switzerland) and on active volcanoes: La Soufrière of Guadeloupe in the Lesser Antilles, France and mount Etna, Italy. The first generation of those telescopes uses Hamamatsu H8804-200mod photomultipliers.
In this article we present upgrades of those telescopes, based on the use of Silicon PhotoMultipliers to increase the m.i.p. detection efficiency and of embedded sub-nanosecond resolution TDC. Those upgrades are completely compatible with the existing set of telescopes and allows to compare different detection technology in the same framework.

Density variations in La Soufrière of Guadeloupe detected with muon radiography: relation with hydrothermal activity

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A muon telescope has been installed during 18 months to perform a density monitoring of La Soufrière of Guadeloupe. The telescope was located on the Eastern side of the volcano and configured to acquire global radiographies in the North-South plane. Radio links enabled to download and process the data in near real time. The data show that density decreases occurred in the bottom part of a low-density reservoir located beneath the active vents of the lava dome. The density variations start sharply in a couple of weeks and precede the apparition of new vents at the summit of the volcano.

Influence of a perturbing backward upward flux on the quality of muon tomography

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Density muon tomography of large volumes of rocks involves the measurement of tiny fluxes of muons that are blurred by particles coming from other directions. This is particularly the case of the huge open-sky flux that produces fortuitous events when independent particles simultaneously hit the detectors of the telescope and mimic a false track coming from the target to image. To get reliable data, this type of noise must be eliminated by using telescopes equipped with three or more detector matrices that make the probability for a false track negligible. The filtering is further improved by using clock with a 1 ns resolution as implemented in our telescopes.

Muon tomography of volcanoes constitutes a particular situation where the telescopes are installed on mountain flanks with their backward side oriented toward deep valleys. In such a case, a non negligible flux of muons coming from below the horizon may be produced by sub-horizontal atmospheric showers that continue to develop in the air volume below the horizontal plane located at the telescope altitude.

Such backward upward flux have been detected during experiments performed on La Soufrière of Guadeloupe and on Mount Etna in Sicily. We show how the high-resolution clock of our telescopes allows to determine the flight direction of the particles in order to detect an eventual upward flux and determine its intensity. We discuss the influence of such a noise on the quality of the density radiographies.

Application of emulsion imaging system for cosmic-ray muon radiography to explore the internal structure of Teide and Cumbre Vieja volcanoes in the Canary Islands, Spain

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The internal structure of volcanoes, especially in their upper part, is product of past eruptions. Therefore, the knowledge of the internal structure of a volcano is of great importance for understanding its behaviour and to forecast the nature and style of the next eruptions. For these reasons, during past years scientists have made a big effort to investigate the internal structure of the volcanoes with different geophysical techniques, including deep drilling, passive and active seismic tomography, geoelectrics and magnetotellurics and gravimetry. One of the limits of conventional geophysical methods is the spatial resolution, which typically ranges between some tens of meters up to 1 km. In this sense, the radiography of active volcanoes based on natural muons, even if limited to the external part of the volcano, represents an important tool for investigating the internal structure of a volcano at higher spatial resolution. Moreover, muon radiography is able to resolve density contrasts of the order of 1-3 per cent, significantly greater than the resolution obtained with conventional methods. As example, the experiment of muon radiography carried out at Mt. Asama volcano, allowed the reconstruction of the density map of the cone and detection of a dense region that corresponds to the position and shape of a lava deposit created during the last eruption in 2004. In the framework of a research project financed by the Canary Agency of Research, Innovation and Information Society, we will implement muon measurements at Teide volcano in Tenerife Island and Cumbre Vieja volcano in La Palma Island, Canary Islands, to radiographically image the subsurface structure of these two volcanic edifices. The data analysis will involve the study both of the shallow structure of both volcanoes and of the requirements for the implementation of the muon detectors. Both Cumbre Vieja and Teide are two active volcanoes that arouse great interest in the scientific community and society due to their volcanic features and specific hazards associated with volcanic activity.

Perspectives for the analysis of the internal structure of Colima volcano using muon radiography

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Colima volcano (Mexico) is one of the most active in the North-American continent. The geological record shows major eruptions occurring in the Holocene, including massive sector collapses. One of the largest of such events destroyed most of the ancient Colima volcano, blanketing an area over 1000 km2, and leaving a 5 km diameter semi-circular somma crater. In the center of this crater, the present Colima volcano slowly grew up in the Holocene. The actual date of this event is still controversial. Nevertheless, the present volcano was probably born as a dome of the somma crater left after the destruction of the paleovolcano. That dome grew at a remarkably constant rate, forming an almost perfect volcanic cone, currently reaching about 840 m over the floor of the somma crater floor (at nearly 3000 m asl). The historical record (last 500 year) includes at least 29 eruptions with VEI greater or equal than 2, six of them with Plinian phases (VEI=4). The Colima volcano modes of activity show that decades-lasting periods of high explosive activity, in which most of the VEI=4 eruptions occur alternate with periods with a lower rate of explosive activity, characterized by effusive dome emplacement and destruction episodes. After the last Plinian eruption in 1913, Colima volcano has remained in a predominantly effusive phase, in which different types of domes have been emplaced, from spreading, lava-flow producing domes to plug-flows and even spines. Also, in a previous episode in 1869, a dome was extruded on the NE flank of the volcano. All of this reveals a complex magma plumbing system, and very little is known about the role it plays in determining the nature of the eruptions. This emphasizes the need to study the volcano with a technique that, along with other seismic, deformation, thermal, and geochemical monitoring methods, allows a better understanding of the internal structure of the volcano. Imaging the volcano interior using muon radiography is the first-option technique, since the semi-circular somma ring surrounding the volcano may provide of several adequate sites to set a muon-radiography detector. In addition, Colima volcano summit stands at only 5.5 km of a volcanic observatory located at about the same altitude, in the neighboring Nevado de Colima volcano, an ideal location to measure the horizontal and vertical distribution of muon fluxes, and to explore possibilities to developing high-altitude techniques of volcano muon radiography.

Potential of muon tomography for identifying internal structure of the andesite volcanoes of Tongariro National Park, New Zealand

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Ngauruhoe (2287 m high) was New Zealand's most active volcano for over a century until 1975, when after a series of Vulcanian eruptions, it became quiescent. It is a steep conical volcano, which had an open vent about 200 metres deep in late 1973, which has since filled up. It is important in considering the hazard of future eruptions to know whether its former vent is blocked by solid lava or just rubble.

Tongariro (1967 m high) on the other hand, was dormant for over 100 years until a small steam and ash eruption on 6 August 2012. This opened a number of steaming vents and fissures. On 21 November 2012, a smaller eruption occurred, indicating that activity is continuing. With limits on access to the immediate area of the vents, investigations of the new vents will have to be done remotely.

Muon tomography offers a method to measure the density within the parts of a volcano that are above an observing point, and can potentially answer such questions.

For Ngauruhoe, we have calculated the effect on the muon attenuation profile of a density anomaly in the old vent region, based on measurements of the deep open vent that existed in late 1973, and using the current topography. This shows that an indication of any different density region within the upper cone can be obtained with a muon recording site on the summit of Pukekaikiore. This is an older nearby volcano, which could provide a more favourable site for a muon telescope, than the exposed slopes of Ngauruhoe.

For Tongariro, preliminary analysis suggests that we may be able to get limits on the vent diameter using a site on the northern slopes that is a safe distance below Upper Te Maari crater, where the recent activity is centred.

Possible application of stroboscopic muography to monitoring periodic eruptions

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Most of the muon radiography measurements have been applied to stationary objects, but only a few dynamic studies have so far been performed (e.g. imaging before and after the 2009 Asama eruption; Tanaka et al., 2009). One of the reasons which makes it difficult for us to perform real time or rapid time sequence radiography is the relatively low intensity of the cosmic ray muon flux that leads to long integration times to reach an adequate contrast in muon transmission images. However, such low cosmic ray muon flux can be compensated for by averaging a large number of short acquisition frames, as in the case of periodic processes. If we assume a vent, with a radius of 10 m to detect it through 400-mwe-thick rock, the horizontal penetrating muon flux will be $5x10^{-5}$ sr^{-1} $cm^{-2}s^{-1}$ and $7x10^{-5}$ sr^{-1} $cm^{-2}s^{-1}$ and the required angular resolution of 100 mrad, located at a distance of 200 m from the vent, can therefore collect 0.02 and 0.03 s^{-1} for each condition, and 2500 eruption events can distinguish these conditions at a 3 sigma confidence level. 2500 eruption events are not unrealistic if we consider that 110 eruptions were observed in Stromboli between 14 and 17 October 2007 (Goto et al., 2008). In this work, we evaluated this idea by utilizing a comprehensive model system that consists of a muon detector with an active area of 0.16 m^2 and an electric furnace with a diameter of 15 m as a periodic test target. The variations in the density contrast were clearly observed with a period of 12 hours by averaging 17 frames. The result infers a possible application of stroboscopic muography to monitoring periodic eruptions.

Operation of a muon detection system under extremely high humidity environment for monitoring underground water table

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Introduction

The technology that enables us to observe the internal structure of a volcano and the city foundation is being developed by utilizing the muon's significant penetration power. From the possibility to use this technology for monitoring underground table, we conducted a test measurement in a scupper tunnel in the base rock.

General Instruction

Our conventional muon detection system consists of plastic scintillator, photomultipliers (PMTs), and a high voltage (HV) power supply. The HV power supply and long HV cable requirement is specific to our choice of PMT (Hamamatsu R7724). Under extremely high humidity environment (constantly 100

In this work, a Cockroft-Walton (CW) high-voltage PMT socket was designed for use in a scupper tunnel where humidity is constantly 100

The test measurement was carried out from the inside of a scupper tunnel in the base rock. The equipment was installed and the measurement was started in August, 2012. During the observationperiod between August 9 and 17, the data which suggests the density change in the stratum accompanying a rise of groundwater was obtained. The result will be compared with the independent groundwater level measurement and the resistivity measurements in order to perform quantitative evaluation of muon radiography. The observation will be continued until December, 2013. We anticipate that the measurement technique to observe the density change of the rock overburden from inside of the horizontal tunnel will be useful for the future volcanological measurement.

A Study on Cosmic Ray Muon Energy Spectra for Radiography

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Cosmic ray muon radiography provides a powerful method for observing the internal structure of volcanos and large civil engineering structures, such as dams and bridges. Since this method utilizes a natural radiation source, an accurate analysis of the behavior of cosmic ray muons as a radiation source forms a significant part of this method.

It is important for us to know the energy distribution of muons that arrives at the surface of the earth in order to construct a theoretical model accurately since the measurement of the cosmic ray muon energy spectra has previously been performed only within the limited energy regions and zenith angles, and therefore, we have to estimate the behavior in the energy regions where the spectra have not measured.

A fundamental theoretical model for describing the energy spectra has been derived by Matsuo et. al. (1984), but the values of the individual parameters in the numerical formula of the model contains uncertainty intrinsicly, and no consensus exists on determining these values.

We have improved the theoretical model that is capable to estimate the cosmic ray muon flux for the energy regions where the measurement has not performed.

We will talk about the derivation process of our model and the role of the model in radiography. This study will contribute to more accurate muography of a volcano.

Interrogating the Martian Subsurface using Muon Radiography

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Muon radiography is a technique that uses naturally occurring showers of muons, generated by cosmic rays, to image the interior of geological structures in much the same way as standard X-ray radiography. Unlike gamma rays and neutrons that penetrate only a few meters of rock, muons can traverse through up to several kilometers of a geological target. Recent developments and applications of the technique to terrestrial volcanoes, caves, and mines have demonstrated that a low-power, passive muon detector can image deep into kilometer-scale geological structures and provide unprecedentedly crisp density profile images of their interior. Preliminary estimates of muon production on Mars indicate that the near-horizontal Martian muon flux, which is used for muon radiography of surface features, is close to that seen on Earth, making the technique suitable for geological exploration of Mars.
The muon telescope represents an entirely new class of instruments for planetary exploration, providing a wholly new type of measurement for delineation of potentially habitable subsurface environments through detection of caves, sub-surface ice, and water, and for the interpretation of composition and evolutionary state of the Martian surface. Muon radiography is a proven, simple, low cost, and efficient technology that could detect subsurface radiation-shielded habitable environments that would not be detectable by any other technique available today. Thanks to its low power and low data rate demands, it could be integrated as a secondary instrument on future missions with minimal impact on primary mission operations. A mission that includes a muon detector could set the stage for a future mission to directly explore subsurface habitable environments on Mars. Developing the technology now would position it favorably for a surface mission in the next decade to explore Martian regions with previously-identified potential trace gas sources, especially if they are associated with caverns, lava tubes, or hydrothermal vents.

Ground deformation associated with the eruption of Lumpur Sidoardjo mud volcano, East Java, Indonesia

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Mud volcano is a rare phenomena happen in recent human history. Lumpur Sidoardjo (LUSI) mud volcano provide a noteworthy opportunity to study its mechanism from its very beginning. Since it first eruption on May 2006, LUSI has been released more than 12 million meter cubic of mud, buried more than 640 Hectare of land, and force more than 30 thousand peoples to be relocated.

We use 93 of ALOS PALSAR images to gain temporal evolution of the ground deformation. The time-series displacement evolution were derived using Small Baseline Subset (SBAS) method from 915 interferograms by utilizing STAMPS software (Hooper, GRL, 2008).

Although the deformation adjacent to the center of activity were not able to obtain due to low coherence resulting from the mud-flow, a line-of-sight (LOS) extension were still observed along the elongated rim around 1.5-2 km from the center of activity as large as 20 cm/year. This fact inferred that the deformation is dominated by subsidence. However, a shortening of LOS which indicated an uplift, were observed, but limited only to the ascending images. We also found another elongated-shape subsidence area in the north-west side, and almost perpendicular to the main subsidence area with similar rate. However, we are considering these two deformation area are explained by different source.

Despite the decreasing rate of gas emission, our time series analysis shows that the deformation is quasi-linear during the time of the analysis. This suggests that the source of deformation has been stationary over time and and also it will a take long time for this eruption to cease.