Prospects for Volcano Monitoring by Ambient Body-Wave Correlation Using Planar Arrays of Geophones

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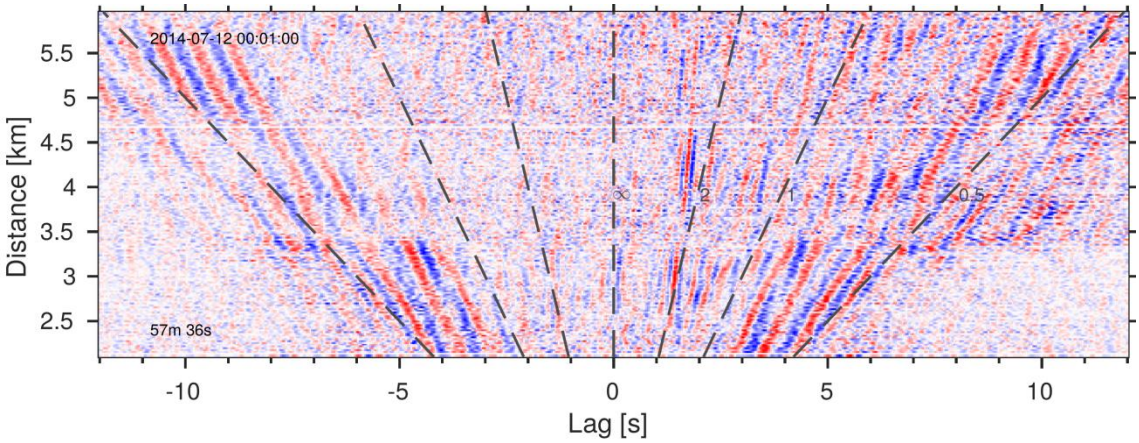
Keywords: *volcano monitoring, ambient noise correlation, frequency-wavenumber spectra.*

Large deployments of low-cost sensors are becoming more common in scientific seismology after decades of use in the oil industry. One such experiment was the VolcArray deployment in 2014 of three sub-arrays each comprising 49 geophones on the Piton de la Fournaise volcano in Réunion and lasting one month. We present an initial assessment of the dataset in terms of usability for volcano monitoring, and in particular using array processing techniques to enhance body waves in ambient noise correlations.

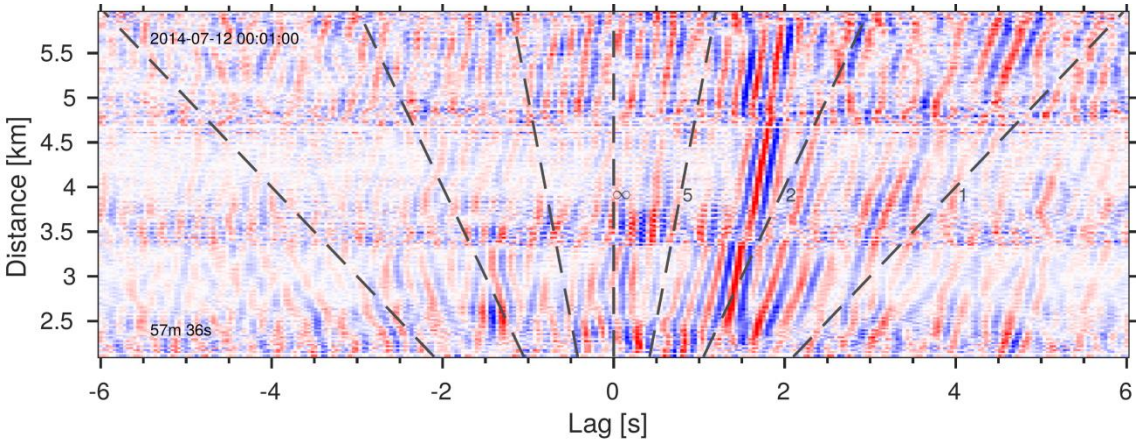
Cross-correlation of ambient seismic noise has been used to reconstruct Green's functions from teleseismic scale down to the local scale. These techniques have been used for tomography and monitoring of volcanoes, but since the seismic record is dominated by surface waves, it is mainly surface wave travel times which have been observed up until now.

Anisotropy of the wavefield causes the observed correlation to deviate from the inter-station Green's function. It has been demonstrated that low levels of anisotropy do not affect the observed travel-time stability so much as to prevent their use in monitoring, however extreme anisotropy can cause the correlogram to be dominated by source coherence rather than inter-station travel times. A wavevector whitening technique – only possible with dense arrays - was developed and shown to slightly reduce the effect of anisotropy on synthetic correlograms. This technique was then applied to the VolcArray dataset, and the observed slant-stacked body-wave correlations appear to be stable over a 24-day non-eruptive period, suggesting that these techniques could be useful for prediction of future eruptions. Future work could include evaluating the travel-time stability with more precision and determining whether wavevector whitening improves it or not.

Two correlograms are shown in Figures 1 and 2 below. Figure 1 is dominated by surface waves; Figure 2 has additionally been processed to select wavespeeds greater than 1500 m/s and is dominated by body-wave arrivals in certain directions. The physical interpretation of Figure 2 is that we are monitoring in near real-time the travel time of reflections from the main magma chamber feeding the Piton de la Fournaise. Monitoring of changes on the order of 0.1% of these travel times could allow us to accurately predict eruptions.



a) Frequency-wavenumber whitened before correlation in the band 1-6 Hz



b) Frequency-wavenumber whitened and Filtered before correlation in the band 1-6 Hz and > 1500 m/s

Figure 1: Binned correlograms computed from 25 sps VolcArray data for Julian day 193 (2014-07-12), stacked over 48 windows of 1h duration tapered with a Hann window and overlapped by 50%. Distance bins are 20 m wide and overlap where inter-array distances overlap.

The Phlegrean Fields beneath the sea: seismo-stratigraphic and marine magnetic evidence on the Gulf of Pozzuoli (Naples)

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Keywords: Phlegrean Fields, volcanology, Gulf of Pozzuoli.

A grid of Sparker Multitip seismic profiles recorded in the Gulf of Pozzuoli in the frame of research projects of submarine geologic cartography has been interpreted to give new insights on the seismic stratigraphy of the Gulf of Pozzuoli, i.e. the submarine elongation of the Phlegrean Fields volcanic complex. One aim of this paper is to provide a new seismo-stratigraphic framework for the Gulf of Pozzuoli based on geological interpretation of recently acquired data in order to delineate an improved geological setting through seismo-stratigraphic concepts. New stratigraphic and volcanological studies, mainly onshore, dealing with the definition of volcanological units during the field survey and specific volcanological features, petrographic, geochemical and petrological studies, coupled with geophysical models have been recently presented. These studies have allowed us to delineate the problems related to stratigraphy and volcanology of active volcanic districts of southern Italy, referring in particular to the Naples Bay.

A sketch geomorphological map of the Pozzuoli area has been constructed to improve the geological knowledge of the onshore area. Main morphological lineaments are represented by lava domes, crater rims, collapse rims, Late Holocene sea cliff, faults older than the marine ingression, faults affecting La Starza terrace, rims of subaerial terraces and local elevation of terraces. Holocene marine terrace of La Starza is bounded by an abandoned sea cliff. The succession exposed in this cliff overlies a volcanic substratum of yellow tuffs, including fossiliferous littoral deposits alternating with subaerial pyroclastic deposits and paleosols. The lowest marine interval exposed in the cliff has been radiometrically dated to 10.5 ky B.P,; an overlying paleosol gave an age of about 8 ky B.P. and the uppermost beach deposits an age of 4.6 ky B.P. The continental intervals of the succession were deposited during periods of uplift having rates greater than sea-level rise. The final uplift of the terrace (about 30 m in a few centuries) was probably related to the caldera resurgence, accompanying the onset of a new period of strong volcanic activity of the Phlegrean Fields.

The Gulf of Pozzuoli represents the submerged border of the Phlegrean caldera, resulting from the volcano-tectonic collapse induced from the pyroclastic flow deposits of the Campanian Ignimbrite (35 ky B.P.). Main submerged physiographic units include the inner continental shelf, the central basin, the submerged volcanic banks and the outer continental shelf. The stratigraphic relationships between the Quaternary volcanic units related to offshore caldera border and the overlying deposits of the Late Quaternary depositional sequence in the Gulf of Pozzuoli are shown. 14 seismic units, both volcanic and sedimentary in nature appear to be tectonically-controlled by coeval folding and normal faulting. Magma uprising in correspondence to extensional structures is evidenced by volcanic dykes. A large field of tuff cones next the Nisida inlet is related to the emplacement of the Neapolitan Yellow Tuff deposits. A thick volcanic unit crops out at the sea bottom off the Capo Miseno volcanic edifice and is genetically related with the Bacoli-Isola Pennata-Capo Miseno yellow tuffs, occurring in the Northern Phlegrean district.

The Torre del Greco seismic and magnetic volcanic structure: a hypothesis for a submarine prolongation of the Somma-Vesuvius volcanic complex (Naples Bay)

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Keywords: seismic structure, magnetic structure, volcanology.

The Torre del Greco seismic and magnetic volcanic structure has been investigated in detail through seismic and magnetic data. A hypothesis that it represents a submarine prolongation of the Somma-Vesuvius volcanic complex is here presented. An integrated interpretation of densely-spaced seismic and magnetic profiles recorded by the CNR-IAMC Institute of Naples onboard of the R/V Urania (CNR) has been carried out in order to reconstruct the physiography of a large volcanic structure located offshore the Torre del Greco town (Naples). This structure is framed in the regional geological setting of the Gulf of Naples, owing its complexity to the interaction between volcanic and sedimentary processes during the Late Quaternary. Acoustically-transparent seismic units occurring in the subsurface of the gulf are here interpreted as volcanic deposits erupted during poliphasic activity of Somma-Vesuvius and Phlegrean volcanic districts. Offshore the volcano the magnetic properties have allowed to discriminate the volcanic nature of geological units identified through reflection seismics. A semi-quantitative integrated interpretation of bathymetric and seismic data has been carried out, resulting in a topographic and seismic reconstruction of the Torre del Greco volcanic structure.

Significant results have been obtained on the shallow structure of the Somma-Vesuvius volcano and the relationships among seismic velocities and rock lithologies through tomographic techniques. Onshore seismic reflection data on the volcano have indicated a lateral collapse towards SW occurred between 35 and 11 ky ago. Buried adventive craters, dykes and pyroclastic deposits have been found on the eastern side of the volcano. The warping of lowstand marine deposits by subsurface cryptodomes located about 10 km from the top of the volcano coupled with the occurrence of normal faults has indicated a seaward collapse of the volcanic edifice.

The integrated interpretation of magnetic, bathymetric and seismic data suggests a close correlation between positive magnetic anomalies offshore the volcano and three main elevated peaks of the volcanic structure located offshore the Torre del Greco town, NNW-SSE trending and located at water depths ranging between 80 and 110 m.

Seismo-stratigraphic evidence is provided by acoustically-transparent seismic facies, high contrasts of acoustic impedance with respect to the overlying marine and coastal sediments, mounded-shaped external geometry and average dimensions measured in terms of kilometers. The base of the volcanic body is not acoustically evident since it overlies the seismic unit correlated with the Campanian Ignimbrite pyroclastic flow deposits. The top of the structure is deeply eroded and shows three main culminations. The thickness of the overlying Holocene sediments is significantly reduced, otherwise the quoted sediments are lacking and the structure directly crops out at the sea bottom.

Some circular positive magnetic anomalies NNW-SSE trending are located in the Torre del Greco marine coastal belt, while other small and localized anomalies, weaker than the previous ones are located in the Torre Annunziata offshore. The Torre del Greco volcanic structure is located in a complex magnetic anomaly area, made up of several anomalies reaching a maximum intensity of 400 nT. Main trending of magnetic and seismic structure suggests the occurrence of NNW-SSE normal faulting. .

Morpho-depositional units of the southern Ischia canyon system and their influence on the erosional processes in southern Ischia (Naples Bay)

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Keywords: submarine canyon, erosion, Ischia.

Morpho-depositional units of the southern Ischia canyon system, engraving the continental slope offshore southern Ischia island and their influence on the erosional processes active in the coastal systems of Ischia are here discussed. The southern Ischia canyon system, investigated through bathymetric and seismic data, is incised on a narrow continental shelf ranging from Punta Imperatore to Punta S. Pancrazio (S Ischia). The canyon system is made of 22 drainage axes having variable extension and planimetric trending, reconstructed through the geological interpretation of Multibeam bathymetry. The margins of the canyon system appear to be controlled by different geological processes. The eastern boundary of the canyon system is tectonically-controlled, being located in correspondence to a NE-SW (counter-Apenninic) normal fault. On the contrary, its western margin is related to volcanism, being limited by Ischia monogenetic submarine volcano, whose age dating is relatively unknown.

Morpho-depositional systems of the Tyrrhenian sea have been studied in detail through the recognition and mapping of submarine morphological lineaments in continental slope and bathyal plain environments. The Multibeam geological interpretation has represented a useful tool to provide a detailed interpretation of morphological and sedimentary features, being extensively used in geological studies on deep sea depositional systems. A full integration in the determination of the geologic characteristics of deep sea depositional systems was permitted by the application of the techniques of seismic stratigraphy and volcanic geomorphology. The meaning of volcanic geomorphology has been improved through the introduction of quantitative classifications of volcanic landforms, based on morphometry and studies based on ground observations, remote sensing data and laboratory experiments. These classifications have been combined with the data derived from Digital Elevation Models in order to carry out the morphological analysis of volcanoes. Detailed geomorphological maps of volcanoes can be produced, expanding the use of accurate chronological framework and compositional data through eruptive sequences. The expansion of capability of geomorphology in landscape history reconstruction has contributed to the understanding of processes of building and destruction of volcanic edifices and to the analysis of structural factors contributing to the catastrophic collapses of volcanoes. This technique has allowed to identify the sedimentary facies associations and facies models for volcano-sedimentary systems and to establish criteria for the recognition of volcanic deposits in old volcanic successions, inferring the role of climatic and tectonic effects on transport and deposition.

The offshore surrounding Punta Imperatore-Capo Negro is characterized by three main submarine canyons, NE-SW trending, whose emplacement has been probably controlled by counter-Apenninic normal faults. This evidence well fits with previous structural studies, suggesting the occurrence of NE-SW extensional faults in the Ischia island. The Maronti canyons exhibit a N-S trending and begin in correspondence to some embayments of the retreated and eroded shelf break. A long canyon has been identified in correspondence to the Punta San Pancrazio promontory. Another main canyon is located in correspondence to the Ischia bank volcanic edifice. The canyon systems strongly controlled the erosional processes active in the coastal area through continuous sediment transport from shelf to basin.

The MONICA Project: Novel Monitoring of coast and sea enviroment

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Keywords: environmental monitoring, fiber Bragg grating.

The MONICA project aims to give a major contribution to prevention and management of sea and coastal environmental emergencies. In particular, the main goal of the project is to realize a monitoring network based on fiber optic communication which will connect traditional and innovative sensors. The project is conceived for monitoring emerged and submerged areas in Pozzuoli Gulf, in order to realize an early warning system and manage hydrogeological and volcanic hazard.
We are developing innovative sensors which can be easily connected in complex structures for geophysical and geochemical parameters monitoring, in particular:
- fiber Bragg grating-based sensors for mechanical strain and acceleration measurements;
- evanescent wave-based sensors for chemical analysis of liquid samples;
- 3D digital holographic systems for non-intrusive imaging of aquatic microorganisms.
The main experimental results attained during the project are presented.

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Advances on the role of Earth degassing in controlling atmospheric mercury budget

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Keywords: global pollutant; Earth degassing; volcanic; mercury.

In the last decades, the environmental hazards of mercury (Hg) have been widely publicized, and particular emphasis has been addressed to the study of Hg from Earth degassing, in light of its high toxicity, long-range atmospheric transport and its tendency to bio-accumulate in aquatic ecosystems through methylation processes. In the specific, knowledge of the contribution of volcanic degassing systems and geothermal fields to the global budgets of Hg in the Earth's atmosphere is essential to evaluate the role that the volcanoes play on the reservoir cycling of this element and the potential fates it could represent once it reaches the ecosystems. All of these features have motivated intensive research on volcanogenic Hg within the framework of a pollutant of global concern. As a result, continued field research has performed in geothermal and volcanic areas, by evaluating the Hg/SO_2 and Hg/CO_2 ratios in the emitted gases needed in estimating Hg fluxes in the atmosphere, and concentrations of gaseous Hg elevated above background levels were observed on most occasions. Based on our dataset, we propose that an average Hg/SO_2 plume mass ratio of about 7.8×10^{-6} ($\pm1.5\times10^{-6}$; $n_{volcanoes}$= 13) is best representative of open-conduit quiescent degassing. Taking into account the uncertainty in global SO_2 emissions, we infer a global volcanic Hg flux from persistent degassing of about 76±30 t yr^{-1}. These data suggest that open-conduit volcanoes in a state of passive degassing represent an important contribution to the global volcanic Hg emissions into the atmosphere. It is therefore likely that volcanic contributions to the global atmospheric Hg budget will be even more important during large eruptive events. With these new measurements, we shall critically revisit the status of the global volcanic Hg emissions budget, and its uncertainties. On the other hand, based on our dataset and previous works, we propose that an average GEM/CO_2 molar ratio of $\sim2\times10^{-8}$ is best representative of hydrothermal degassing. Taking into account the uncertainty in global hydrothermal CO_2 emissions from sub-aerial environments ($\sim10^{12}$ Mol yr^{-1}; Seward & Kerrick, 1996), we infer a global volcanic Hg flux from hydrothermal environments of ~ about 8.5 t yr^{-1}, resulting less important if compared to persistently degassing open-vent volcanoes, which dominate the global volcanic Hg budget. Finally, recent evidences have indicated the influence of submarine geothermal activity in controlling the dispersion of Hg as well. While Hg contribution from sub-aerial volcanism is now more or less constrained, the research on submarine hydrothermal activity could represent the most challenging and significant scientific advances of the 21th century in terms of Hg research as a global pollutant.

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Toward Absolute Gravity Networks to Monitor the Neapolitan Volcanoes

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Keywords: Gravity, Volcanoes, Monitoring.

As well known, measurements of the time-space changes of the gravity field are a powerful approach to detect the masses change/redistribution in the underground, such as those at volcanoes.

The most common approach to detect gravity precursory signals is the use of repeated relative measurements at benchmarks on networks. This is very good, but has some and significant limits: 1) the networks must be linked to a reference station stable over long time and if possible external to the active area. This is quite simply for land volcanoes, but is generally difficult for volcanoes on islands, particularly when far from the terra firma; 2) to reach high precision, measurements require special operative procedure implying long time surveys; 3) relative gravity changes can be affected over the long-time by changes of instrumental sensitivity and loss of vacuum in the air-tight sealing system, therefore the instruments must be subject to continuous check.

Measurements on network have the advantage to permit to define the position and the geometry of the masses change/redistribution, even if they suffer from the lack of information about the rate and/or quick changes, since variations are assumed linearly changing over the time between two consecutive surveys, usually spaced out some months or years. This is a fundamental information in the prediction of the volcanic activity changes and/or of volcanic eruptions and leads to conclude that measurements on networks cannot be excluded from a monitoring program, but moving toward absolute methodologies is advisable.

Nowadays, and since some years, this is possible due to the commercially availability of a portable field absolute gravimeter (Micro-g_LaCoste A10), which we acquired at the end of 2014.

The main advantages of the absolute measurements on networks are: i) they are independent from any reference and the field operation are faster and easier, permitting much frequent measurements and reducing the lack of information between two consecutive surveys; ii) they are directly linked to standards of time and length therefore fairly independent from instrumental references and drift, avoiding loss of long-term information; iii) the measured value can be used without loop reductions, post processing and benchmark links. This can be translated into large advantages, such as saving of human resources, survey's time and costs.

Before to start field surveys, we carried out several measurements to test the performances of the instrument and mainly to verify the repeatability of the measured value. The test was performed at the Old Building of the Osservatorio Vesuviano, on Mount Vesuvio, that is a very low noised and good logistic site; it is one of the absolute stations installed in 80's in the Neapolitan area which value has been measured several time till 2010.

In June 2015, starting from Campi Flegrei, we set the first absolute gravity networks on the Neapolitan volcanoes, formed by stations coinciding or close to the benchmarks of the already existing relative networks.

Here we present and discuss the data collected during the test and the field surveys; we also will describe the new absolute networks.

Eruptive activity and source mechanisms inferred through the new borehole dilatometers network installed at Etna volcano

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Keywords : borehole dilatometers, lava fountains, Etna volcano

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In November 2011, the first two borehole strainmeters, dilatometers type (nominal precision ~ 10^{-10} – 10^{-11}), were installed at Etna at ~180 m depth below the ground surface with distances from the summit craters of 6 km (DEGI) and 10 km (DRUV), respectively. Since January 2011, the eruptive activity resumed at Etna producing a sequence of 44 lava fountain episodes through December 2013. Almost all the lava fountains had similar characteristics, lasting a few hours and feeding a lava flow that expands in the Valle del Bove depression with maximum lengths of 4–6 km. Significant variations in the strain signals have been detected in temporal correspondence with the volcano activity. During the lava fountain events the high precision dilatometers detected negative strain changes with amplitudes of ~0.2 and ~1 μstrain at DRUV and DEGI, respectively, indicating medium expansion. Taking into account the volcano topography and the medium heterogeneity, a Finite Element Model was set up to accurately infer the source feeding the lava fountains from tilt and volumetric strain signals. The numerical computations indicated a depressurizing source located at 0 km b.s.l., which underwent a volume change of ~2 × 10^6 m^3 accompanied by a compression of ~0.5 × 10^6 m^3 of the resident magma. This allowed to estimate an average erupted volume of ~2.5 × 10^6 m^3 for each event, which is in agreement with the mean total emitted volume calculated from field measurements and satellite data. The occurrence rate of the episodes and the fairly constant erupted volumes suggest that this shallow magma storage cannot accumulate large magma volumes and favors frequent short-term periodic eruptive events ensuing a balance between the refilling and the erupted magma.
During 2014 the network was upgraded with other two installations installed in October – November 2014 at ~120 m depth below the ground surface with distances from the summit craters of 4.8 km (DMSC) and 2.4 km (DPDN), respectively.

Perspectives for real-time monitoring of stress changes in volcanoes through the inversion of focal mechanisms.

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Stress inversion procedures can be applied both to fault kinematics and/or focal mechanisms, allowing the reconstruction of the reduced stress field tensor that carries information about the stress orientation and the corresponding ratios between principal stresses.
Hence volcano-tectonic earthquakes potentially bring valuable information about spatial and temporal patterns in the pre-, syn- and inter-eruptive stress fields. Since the dynamics of magma chambers and of hydrothermal systems are casually linked to these earthquakes, retrieving the stress field pattern in volcanoes has important implications in studying their dynamics.
Following these approaches, we have determined the spatial and temporal variations of the stress field at Mt. Vesuvius and at Campi Flegrei caldera.
At Mt. Vesuvius we evidenced a strongly depth-dependent field which allows identifying two different seismogenic volumes: a shallow one (above the sea level) in which the stress field is related to gravitative spreading processes and a deeper one (1-5 km) in which the stress field orientation is coherent with the regional stress field.
At Campi Flegrei, during the 1982-1985 interval we determined spatial and temporal variations in the stress field, from a joint inversion of ground deformation and focal mechanisms. Results show the presence of a weak NNE-SSW extensional background regional field that is progressively overcome by a local volcanic field during the unrest episode.
Our approach could be applied to any volcanic contexts and can be used as a real-time monitoring tool as well. An adequate understanding of the relationship between active stress fields and volcano dynamics is important not only from a scientific point of view, but also to support decision makers during the management of volcanic emergencies.

CHARACTERIZATION OF A SEISMO-VOLCANIC AREA USING RADIOMETRIC TECHNIQUES. FIRST RESULTS

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Keywords: radon in soill monitoring, geoindicators, soil radioactivity

Both endogenous gas release and ground deformations, have their origin in the stress field applied along faults generating tectonic or volcano-tectonic activity . It is quite natural to consider that observations about endogenous gaseous emissions have the potential to bring information useful to tracking the evolution toward conditions of volcanic unrest. Among the observed gaseous species, radon has raised interest because of its radioactivity, which makes its quantification relatively easy to obtain.

However the lack of any systematics in the identification of a causal relationship between observed seismic and volcanic phenomena and Rn anomalies, has carried in time to the disposal of Rn as a suitable geoindicator for volcanic and seismic activity.

Among limits about interpretation of Rn anomalies there are: low Rn sampling frequencies, low sampling areal density, insufficient parameterization of the role played by environmental parameters, difficulty in distinguish changes due to local effects from remote ones.

With the aim to overcome these limits started a project that sees the sharing of sections of Naples INFN and OV-INGV interesting a seismo-volcanic area: the caldera of Phlegrean Fields that falls within the municipalities of Naples and Pozzuoli (Campania, Italy).

The general plan provides for the continuous measurement of radon gas activity concentration by alpha particle spectrometry, as well of the climatic parameters with the RaMonA system in conjunction with other geochemical and geophysical parameters at multiple sites.

RaMonA allows to measure both radon and thoron concentrations, using the short living isotope, surely of local origin, for separate, in the measured radon specific activity, that one remotely originated, surely connected to remote source. Up to now, just two stations have been upgraded: MSA and OLB.

The MSA site, can be considered a test site, since it is in the area where is the Radioactivity Laboratory of the University of Naples "Federico II", where most of work was carried out.

The OLB site, located to 1.5 km Est of maximum uplift, under Mount Olibano. In this site are installed a Tiltmetric and a Seismic stations belonging to the monitoring networks of INGV "Osservatorio Vesuviano". The surface tiltmetric station, named OLB (equipped with an analog sensor), the seismic station COLB (digital three-component broadband).

Some analysis procedures and some preliminary observations have been carried out; in order to identify the possible meaning of observations relatively to dynamical phenomena occurring inside the earth crust. Moreover, it clear that the long term observation of radon signal in many sites of a seismic-volcanic area, could produce the characterization of each site and of the area, and also contribute to do meaning to anomalous signals.

Others three sites will be equipped with RaMonA system: the first located to 1.2 km NNE of maximum uplift, nearness the borehole tiltmeter, named ECO (equipped with a digital sensor high sensitivity) and seismic station, named CCVA (vertical array in the well that consist of 6 three components sensors broadband); the second located to 2.6 km NW of maximum uplift, nearness the borehole tiltmeter, named ARC (equipped with an analog sensor) and seismic station, named ARCO (digital station three components broadband); the third located to 1.9 km NE of the maximum uplift, nearness the borehole tiltmeter, named PSC (equipped with a analog sensor) and seismic station, named STH (analog station three components short period).

Volcano unrest at Piton de la Fournaise: the problem of linking deep and shallow parts of the plumbing system

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Keywords: volcano unrest, precursors, rift, central volcano.

Piton de la Fournaise (PdF) is one of the most active effusive basaltic volcanoes of the world with an average of one eruption/9 months since at least 100 years. In the last century, eruption duration (a few hours - 6 months) and volumes (< 1 Mm^3 - 240 Mm^3) span a relatively large range. Most important, sequences of closely spaced eruptions can end with major eruptions, caldera forming events, and be followed by long (several years) phases of quiescence. PdF experienced its largest historical eruption in April 2007 that was followed by i) a sharp decrease in erupted volume and eruption duration and ii) by a long (3.5 years between 2011 and 2014) phase of rest. Since mid-2014, the volcano seems to increase again its rate of activity with three eruptions in June 2014, February 2015 and May 2015. Since 2009, the Piton de la Fournaise Volcanological Observatory performed major investments in the modernization and extension of the geophysical and geochemical networks.

The new networks were able to identify deep (ca. 20 km bsl) eccentric activity along the NW-SE rift as possible long term (months) precursor of the volcano reactivation. For the first time since 1998, thousands of weak deep volcano-tectonic events imaged a seismic pipe extended ca. 10 km below the summit cone. Geodetic and geochemical networks detected rift dilatation and a continuous summit cone inflation since mid-2014 coupled with increase in gas soil fluxes and evolution of the composition of summit fumaroles.

This contribution discussed the evidences for a possible link between lateral rift activity and reactivation of the volcano activity based on multidisciplinary approach.

Monitoring of Volcanoes using Ambient Seismic Noise: MSNoise !

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Volcanic eruptions represent a great hazard to populations leaving nearby volcanoes. It is of primary importance to better image and monitor de structure of volcanic edifices in order to better understand volcanic activity and thus to improve eruption forecasting. In the field of ultrasonics, it has been shown that a random wave field has correlations which, on average, take the form of the Green's function of the medium. In seismology, it is now accepted that cross-correlation functions of coda waves and ambient noise converge towards the Green's function between pairs of seismographs. Moreover, more and more authors have succeeded extracting and inverting Rayleigh waves to produce high-resolution seismic images of the shallow crustal layers.

In this entry, we first present MSNoise, a python package for processing ambient seismic noise. The aim of the package are 1) to provide a robust workflow, starting from an existing archive and ending in high quality figures of the dv/v ; 2) to provide an API for interacting with the workflow and 3) to provide a rapid solution for testing/evaluating the method on any data. We will then show results of the application of MSNoise on the data from the Piton de la Fournaise volcano (La Réunion) where MSNoise successfully raised a warning flag for the June 2014 and May 2015.

Volcanos, Boreholes and 4-C Seismology in Urban Environments

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Keywords: Seismograms, Strainmeters, Volcanos.

In this presentation we describe the installation, operation, analysis, and interpretation of borehole geophysical observatories in near-city volcanic and other geological hazard settings. The emphasis is on not only dramatically increased sensitivity to small but important changes, but the sorting out of complex signals using combinations of sensors. The specific example discussed here is the use of velocity and strain sensors on Montserrat in recognizing the origin of different seismic and deformation signals.

Mexico City, Al Medina and Auckland are built near or directly on potentially active volcanic and earthquake systems. The prime modern example of what could happen to these cities is the city of Plymoth on Monsterrat. While not near any volcanoes, the city of Basel sits on the seismically active Rhine rift and the city of Istanbul faces the North Anatolian Fault, just off shore in the Marmara Sea. Basel experienced a man-made tremor resulting from an attempt to create an engineered geothermal system and Istanbul lies in 30 km seismic gap on the fault.

In all 6 cases the local environmental conditions make it difficult to monitor these potential hazards – their geography, weather, or cultural noise present major obstacles to surface recording of earthquake and rapid deformation data. Further, low levels of historical seismicity make detection and monitoring of the active hazards we know underlie, for example, Auckland, particularly challenging. In these circumstances, borehole geophysical monitoring may be the only technique available for keeping track of the small signals that might relate to any magmatic, tectonic, or man-made movements that might put these places in risk.

In the case of Montserrat, 4 boreholes were instrumented with both 3-component seismometers and volumetric strainmeters. The combined recording by these instruments have helped sort out different types of seismic and deformation signal, including the timing and size of an eruption induced tsunami. A similar 8-station system is being installed in the Istanbul-Marmara area, only in this case with 3-component strainmeters and vertical arrays of 3- and 1 component seismometers. Our presentation describes some of the results from both the former and latter installations.

Detecting small, frequent, nearly aseismic resupply (and leakage) of gas and magma from depth

Chris Newhall, for Advances in Volcano Monitoring workshop, Naples, Sept 2015

Improvements in the sensitivity and density of instruments around volcanoes often lead to discovery of new details of volcanic behaviour. As a case in point, close-in tiltmeters at Mount St. Helens led to discovery of regular but very subtle tilt cycles associated broadly but not 1:1 with tiny hybrid earthquakes and incremental ascent of a viscous plug from 2004-2008 (Anderson, Segall, et al). The tilt data combined with seismic, GPS, and a video record of steaming is leading to interesting, ongoing debates on the details of the dome extrusion process.

A densely populated caldera like Campi Flegrei benefits even more from the highest possible precision and density of instruments, the subject of this meeting. Might these new instruments be able to spot and quantify sub-caldera processes never before documented?

One conceptual model which I and colleagues are exploring now is that of many calderas receive frequent, small, almost continuous increments of magma from depth, and that some can leak incoming gas without necessarily erupting the magma it accompanied. One of the most efficient ways to leak volatiles is to have magma in conduits near the surface remain molten and convecting. At smaller, simpler stratovolcanoes, sulfur budgets suggest a spectrum of conduit plugging and conduit convection between eruptions. Similar budgets are harder to estimate for calderas, owing to their extensive hydrothermal systems.

Can new instruments detect episodic, virtually aseismic resupply of magma from depth? GPS and InSAR are a powerful combination, but are there other data (especially, from boreholes) to constrain GPS and InSAR even more? Using continuous CO_2 monitoring, will it be possible to quantify how much gas was released and correlate with deformation data to estimate the volume (and depth) of magma from which it was released? Are there subtle, very long-period seismic-deformation, gravity, gas, or other signals by which magma convection, in either a large reservoir or in smaller conduits, can be detected? Can we tell, before an eruption, whether the leakage of gas over a repose period has been more or less than the probable influx from depth, respectively decreasing or increasing explosive potential? In the case of calderas where gas leaks << gas input, can advanced instruments track changes in seismic attenuation and/or changes in response to earth tides to test for the presence of an excess bubble phase in magma at depth, a possible prerequisite for plinian eruptions?

Finally, if the effects of many small increments of magma supply can eventually bring a system to a critical, runaway state, how can we know in advance what thresholds of indicators will be the most useful for forecasting the onset and explosivity of an eruption? Here, we must take advantage of
experience at other calderas, both those which have erupted and those which have not.

A Review of the Geophysical and Geochemical Methods for Volcanic Forecasting Eruptions. A Methodology to Apply to an High Risk Volcano: The Somma-Vesuvius, Naples, Italy

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Keywords: Somma-Vesuvio, Geochemistry, Geophysics.

A major issue in the study of active volcanoes is the link between eruption history, the changes in magma compositions and volumes observed on the surface, and the nature and the time scale of magma differentiation processes underground (Hawkesworth et al. 2000, Hawkesworth et al., 2004). It is the latter which determine the timing and the style of eruptions, and which are therefore fundamental to models of how particular volcanic systems behave and evolve, and hence to determine hazard mitigation. The immediate targets are those volcanoes that are active, have a history of devastating eruptions and which are in highly populated areas. To make best use of the latest analytical technology, it is also important to work on a well studied volcano with an established stratigraphy and rocks (i.e, Somma-Vesuvius, Southern Italy). Studies of volcanic samples, experimental investigations and theoretical modelling are providing insights into the dynamics of magmatic systems and how the plumbing system evolves with time, giving a physical framework with which to interpret volcanic phenomena. All the volcanic processes evolving before and during an eruption leading to the variation of geochemical and geophysical parameters (Sparks, 2003). Hence, computational and analytical facilities, instrumentation, and collection of comprehensive observational, geophysical, geochemical, and petrological datasets associated with recent volcanic activity have enormously improved our view how volcanoes works (Cashman and Sparks, 2013). Many active volcanoes have been studied in terms of volcanic forecasting using only some of these techniques. The challenge is to try to employ a volcanological methodology where the main chemical, petrologic, physical and geophysical parameters are linked all together in order to build a framework where the history of magma ascent velocities, the time scales of magma differentiation, the past, a present situation of the magmatic conduit, present state of degassing must be considered simultaneously. Such conceptual scenario can be commensurate with monitoring quiescent volcanoes, thus forecasting volcanic eruptions.

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Fumarolic CO_2 flux variations at Campi Flegrei restless caldera: comparison between two different monitoring techniques

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Keywords: CO_2 flux, monitoring techniques, Campi Flegrei.

In the last decades, the use of near-infrared room temperature diode lasers for gas sensing has grown significantly. The use of these devices, for instance, in combination with optical fibers, is particularly convenient for volcanic monitoring applications. Here, we report on the results of the application of Infrared tunable diode laser-based measurements performed simultaneously with a portable MultiGAS (equipped with a Licor LI-840A NDIR closed-path spectrometer; 0–60,000 ppm range), during the field campaigns carried out at Campi Flegrei (Southern Italy) from October 2012 to October 2014, in the attempt to obtain novel information on the current degassing unrest of Solfatara and Pisciarelli fumarolic fields. At each site, we used an ad-hoc designed measurement geometry to scan the fumaroles' plume from different angles and distances. From post-processing of the diode laser datasets, we derived tomographic maps of CO_2 concentrations in the plume and, by integration and combination with vertical plume transport speed (by using a GoPro video camera), we inferred the CO_2 flux directly. The so calculated fluxes, the first ever obtained at Campi Flegrei, match closely the CO_2 output independently evaluated by using the portable MultiGAS.

Moreover, the total (Pisciarelli+Solfatara) fumarolic CO_2 output (~ 500 tons/day) is an additional/significant contribution to the soil CO_2 output from Campi Flegrei (~1100 tons/day, Chiodini et al. 2010; and from 1400 to 1520 during our study period). This latter has repeatedly been evaluated by soil surveys with the accumulation chamber method, which typically covered a large degassing structure around the fumarolised areas, but not the fumaroles themselves.

More recent results, obtained on 10-11 February and 23-24 October 2014, point out an important CO_2 flux variation. In detail, the CO_2 flux values decreased at both sites in February 2014, followed by a sharp increase in October 2014 (at Pisciarelli, the CO_2 fluxes peaked at ~560 t/d, above the total time-average of Campi Flegrei area). It is worth noting that this increase in degassing has occurred in concomitance with a phase of resumed ground uplift and (weak) seismicity at Campi Flegrei. Actually, most of these events concentrated in a small earthquake swarm occurred on 25 October 2014, between 19:27 and 19:32 UT (data from "Bollettino di sorveglianza settimanale" of 28-10-2014, by INGV-OV, "Osservatorio Vesuviano – sezione di Napoli").

Finally, combining Pisciarelli + Solfatara datasets (on 24 October 2014), a total fumarolic CO_2 output of ~1000 t/d (twice as much as measured before) was estimated for Campi Flegrei.This result agrees well with an independent CO_2 flux value of ~900 t/d evaluated by using the MultiGAS technique during the same campaign.

Chiodini G. *et al.* (2010) Journal of Geophysical Research,Volume 115, B03205, doi:10.1029/2008JB006258.

Volcanology of Phlegrean Fields: an Advanced Study

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Keywords: Phlegrean Fields, tiltmeters, tides, Fourier Analysis, Power Spectral Density, Gabor-Morlet wavelet, Caputo fractional derivative.

The Phlegrean Fields are an area in the west of Naples (Italy), with a huge interest in Geophysical community being a volcanic caldera among the most dangerous in the world. For monitoring, the control of ground deformations and variations in sea level have a considerable importance: the first one are used to verify the presence of possible traces related to a magma resurgence, while the second one comes in handy to check the phenomenon of the *bradyseism*, which afflicts this volcanic area.
We have found time series of ground deformation and tidal data in this area to highlight the important geophysical features and comparing these results with those obtained from similar data in other time periods. In concrete terms, we have analyzed data coming from the tiltmeter network of Phlegrean Fields monitoring and from tidal data coming from the tide gauge in Pozzuoli.
In order to realize an advance analysis of these experimental data, we have used a wavelet approach, to take advantage of its ability to examine the signals simultaneously, in both the time and frequency domain: this is impossible using the conventional Fourier Transform, because it gives us information only in frequency; furthermore, it works well only with stationary signals, showing huge problems in the non-stationary case.
The Short Transform Fourier Transform show similar problems: indeed, even if it is time-frequency localized, the introduction of the window brings with it resolution problems.
So, spectral analysis has been obtained by a wavelet approach: results are a local spectrum, for each scale in which signal has been decomposed, and a global one achieved by average on each period of local spectrum.
For each time series, we have the principal harmonic constituents: lunar semidiurnal (M2), solar semidiurnal (S2) and lunar diurnal (K1). Besides, time series show peaks for some frequencies higher than 1/hour. These peaks highlight the presence of seiches. Frequencies at which we notice these seiches are in agreement with previous studies. Wavelet local spectra highlight a variation in variance included between 8 and 16 hours for each time series. On the contrary, depending on various time series, local spectra highlight other variations in variance. These two kinds of variation underline the presence of principal harmonic constituents and of seiches, respectively. Since Wavelet analysis preserve time information about happening of these frequencies, we can obtain time periods where seiches recur in an evident way. Moreover, this analysis has located not stationary characteristics of various time series. Then, we have made use of Caputo fractional derivative to analyze data and we have made a comparison between these two approaches. Studies about occurrence of these seiches are very important in volcanic areas, because these oscillations could be link up with generation of discrete plumes of rising magma.
The Wavelet Analysis succeeds to go beyond all these difficulties: in this work we have used the Gabor-Morlet wavelet, which is a complex function modulated by a Gaussian window: this characteristic makes it extremely suitable for the Geophysical applications.

Taal volcano in The Philippines: Understanding and monitoring

presented by Jacques Zlotnicki

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Taal volcano (14°N, 21°E) 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. The most violent eruptions occurred in 1749, 1911, and 1965. 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/) 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 a *real-time* monitoring network based on electromagnetic and other geophysical methods.

Right now, EMSEV team involves researchers from France, Japan, USA, Italy, Greece, and Belgium. In addition to land observations, satellite Aster thermal imagery, Robust Satellite Techniques are now carried out.

– The first objective is performed by combining magnetic, self-potential, ground temperature and soil degassing surveys, bathymetry and bottom lake temperature mappings of the inner acidic lake, as well as electrical and magnetotelluric tomography's. Two geothermal fields are present on both sides on the northern crater rim, and are linked at depth. The area is undergoing strong thermal transfers, degassing, and mineralization. This mineralization strongly weakens the mechanical cohesion of a large volume of bedrocks outside the crater which can collapse in the crater lake.

– The second objective is based on multi-parametric monitoring stations collecting observations of EM field, thermal flux, seismicity, and ground deformation. Data are automatically transferred by radio-transmission to Taal volcano observatory located 10 km away, and then to PHIVOLCS and EMSEV servers by Internet where data can be processed with a short delay of time. In late April 2010, after a few years of relative quiet, the volcano experienced accelerated deformation and dramatically increasing seismicity. This caused PHIVOLCS to temporarily raise the volcano alert level to two on a five level scale. The crisis ended in March 2011. The 2010 seismic crisis was accompanied by re-opening of active East-West fissures located on the northern flank of the volcano. Tilt, electric, magnetic and temperatures changes were associated with the crisis and were correlated with three decreasing periods of seismic activity. The cross-correlation of data has shown that a deep inflating source took initially place to the northwest of the northern crater rim at about 5 km depth,

moved into the crater along a regional NE-SW fault, before to give rise within one day to a northward inflation, and the migration of the activity in the heart of the hydrothermal system located above at 2.5 km depth. After July 13, the depth of the deformation source receded while three decreasing phases of north-south inflating periods were caused by the enhancement of the hydrothermal activity. The rapid changes of the location of deformation sources on Taal clearly emphasizes the possibility to observe sudden and violent phreatic eruptions.

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Monitoring heat transfer modality changes in hydrothermal systems

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Keywords: thermal monitoring, heat transfer, coefficient of determination R^2.

Detecting volcanic unrest is of first importance for eruption forecasting, especially on volcanoes characterized by highly dangerous phreatic or phreatomagmatic eruptions. We present a simple and innovative analysis of shallow vertical temperature profiles up to 70 cm depth. These data were recorded at La Fossa cone of Vulcano, characterized by recurrent and peculiar changes of its hydrothermal activity. In particular we considered an episode of increased hydrothermal and seismic activities that occurred between September and December 2009. The innovative aspect of this survey involves the use of the coefficient of determination (R^2) on vertical temperature profiles in order to identify changes in conductive vs. convective heat transfer modality. The increase of convective heat transfer can be related to the disruption of the hydrothermal system due to its pressurization and/or variation of ground permeability between the hydrothermal system and the surface. While raw temperature data do not evidence any significant variation during the period investigated and the classic temperature gradient is highly influenced by seasonal variations, the fluctuation of R^2 displayed striking spikes in perfect correspondence with the seismic swarm occurring inside the volcanic edifice. Such a low cost device associated with easy, real time data processing could constitute a very promising and innovative technique to monitor hydrothermal systems, assessing the hazard posed by high energy eruptions for populations living close to active volcanoes.

Campi Flegrei, Vesuvius and Ischia island: improvement and expansion of the tiltmetric network, old and new results.

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Keywords: tilt, volcano, ground deformation.

The goal of this work is to propose the technological development and expansion that has had, since 1986, the Osservatorio Vesuviano tiltmetric network, through the presentation of some of the most important results obtained from the analysis of the acquired signals.
Ground tilt monitoring is continuous measurement of changes in slope of the ground surface, it's able to detect the tilt variations in direction and amplitude of volcano edifice caused by magma uprising.
In the end of 1985 the first devices were installed at Campi Flegrei in collaboration with the Institut de Phisique du Globe de Paris (I.P.G.P.), which provided the instruments. Each station was equipped with two horizontal pendulums, sensitive along two orthogonal directions, made by P.A. Blum (I.P.G.P.). The first two station of this type, called DMB and BAI, were installed at the end of 1985, the first in Pozzuoli, located in a underground gallery and the second in Bacoli, inside the Castle of Baia. Later two more stations were installed (DMA and DMC) in the same gallery of DMB station.
Between 1991 and 1992, these sensors were replaced by new stations with electronic analog sensors, bi-axial, bubble-type, short baselength platform tiltmeters, more handable and easy to install (mod.702-A, Applied Geomechanics Instruments).
At Vesuvius, ground tilt monitoring started in 1993, with the installation of the first data acquisition system named OVO, in the gallery of the Osservatorio Vesuviano near historical building in Ercolano. In 1996 were installed two other stations (CMD and TRC) located at Torre del Greco and Trecase.
Because the bubble-tiltmeters are very sensitive to temperature variations, due to solar radiation, from 2002 to 2003, 2 borehole analog tiltmeters were installed in Campi Flegrei TOI and ARC respectively at 7 and 5 meters depth, where thermal oscillations are minimum.
The renovation project of the networks began in 2011with the realization of a new tiltmetric station at Vesuvius employing a Lily digital sensor (Jewell Instruments ex A.G.I.), placed 26 m deep in a drilled well, replacing the pre-existing TRC station. This tiltmeter is made with a self-levelling sensor on a range of ± 10 degrees, with a dynamic range of ± 330 μradians and a resolution less than 5 nanoradians. It has a cylindrical shape and it is of stainless steel. Inside, at the bottom, bubbles electrolyte, the temperature sensor and the magnetic are positioned.
Since 2011 till now day we have been installed another 2 Lily sensors on Vesuvius, IMB and CMG (located to Ercolano and Torre del Greco near CMD station), 3 at the Campi Flegrei, HDM, ECO and CMP (to Pozzuoli). CMP station was placed near the old DMB station because the gallery that hosted DMA, DMB and DMC was destroyed by road works. 3 other stations were installed on the Ischia island: ISC, BRN and FOR (respectively located in the town of Ischia, in Barano and Forio).
At present are working 10 analog and 9 digital stations that allow recording tilt changes in the three volcanoes areas. During the last 30 years of data acquired in the different sites, we were obtained useful results for the study of ground deformation and the assessment of the volcanic precursors for Neapolitan active volcanoes.
This data integrated with measures of vertical displacement obtained by different methodologies (Levellings Precision, SAR and GPS) are used for modeling of the deformation field.

HYPOCENTER DETERMINATIONS OF VOLCANIC EARTHQUAKES PRIOR TO THE 2006 AND 2011 ERUPTIONS AT VOLCANO NYAMULAGIRA, VIRUNGA VOLCANIC AREA

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Keywords: Hypocenter distribution; Earthquake swarms; Virunga volcanic area; RSAM

ABSTRACT:

Earthquake swarms observed before the 2006 and 2011 Nyamuragira eruptions were analysed. The activities and hypocenter distributions of these earthquake swarms were mainly examined.

The former swarm was characterised by a higher seismic activity than the later. Although the two swarms accompanied eruptions, most of the swarms observed in 2006 and 2011 were not followed by any eruptions. These swarms probably represent an intrusion of magma at a shallow depth. Hypocenters of these earthquake swarms show that most of the events are located in and around the crater of Nyamuragira summit at a shallow depth less than 5km. Some of events were located at a deep depth around 20-25km. Numerical examinations of the hypocenter determination indicate that some small errors in arrival times make the hypocenters not re-located or relocated at a depth of 0km. This suggests that to obtain more reliable hypocenter distribution, it is necessary to deploy seismic stations on and around Volcano Nyamuragira. Such a dense seismic network will enable us to discuss more in detail the swarm activity preceding eruptions and differences between the swarms preceding eruptions and those caused only by magma intrusion at a shallow depth.

The analysis of the RSAM showed that, two months before the eruption, the energy increases linearly, from 7.46 * 106 A.U to 1.8 * 107 A.U and from 1.80 x 105 to 1.76 *106 A.U respectively for the 2006 and 2011 Nyamulagira eruptions.

Ground deformation signals at Campi Flegrei from borehole dilatometers and long-baseline tiltmeter data.

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Since spring 2004 a small network of borehole Sacks-Evertson strainmeters, aimed to improve monitoring systems at the Italian volcanoes, has been installed around Campi Flegrei and Vesuvius. This small network has been implemented by two arrays of long-baseline water tube tiltmeters installed in underground tunnels since 2008.

Relevant strainmeter and tiltmeter data have been collected and analyzed at the instruments installed at Campi Flegrei during the recent unrest episodes. Renewed activity started since 2004-2005, characterized by a quite low rate of vertical vertical displacement, amounting initially to a few cm/year. A long term strain episode occurred during summer 2006, in correspondence to an increase of CO_2 emission and displacements measured also by tiltmeters and GPS transducers. This strain episode preceded the seismic activity by few months, as also observed during the 1982 most significant unrest. Other aseismic slip episodes have been recorded in October 2006, in correspondence of a seismic swarm of VT/LP events, in 2008, in correspondence of the renewal of gas emission activity at Solfatara, in 2010, one day before a seismic swarm, and in September 2012, few days before the most significant seismic swarm occurred after the 1982-1984 uplift. The time scale of these phenomena is ranging from some hours to several days, putting further constraints on the origin of ground uplifts at Campi Flegrei.

In March 2010 borehole-strainmeters and Michelson tiltmeters registered an abrupt 40 minute change in strain associated with a swarm of microseismicity on two normal faults near the instruments. Deformation models of the event show that the strain changes can be attributed to volume decreases in a previously-identified subsurface magma chamber with ellipsoidal geometry, but that the strain changes resulting from faulting were too small to be detected. The association of normal faulting with transient subsurface magma chamber deflation may account for the ubiquitous normal faulting that is recorded in the Campi Flegrei region. The inferred transient decrease in magma volume occurred at a rate that was more than two orders of magnitude slower than typical magma volume increase rates associated with inflation in the region, suggesting that microseismicity depends significantly on strain rate changes. The 20 minute delay between the onset of strain and the occurrence of microseismicity may have utility in forecasting future damaging events.