Short–term eruption forecasting with BET_EF: applications and results

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Bayesian Event Tree for Eruption Forecasting (BET_EF) code was proposed several years ago as a tool to quantify probabilities, and associated uncertainty, of the most relevant outcomes of volcanic unrest, such as the detection of the state of unrest, and the probability of (i) magma actively causing unrest, (ii) eruption, (iii) vent position and(iv) eruptive type or size or class. The proposed code computes the probabilities based on heterogeneous sources of information, such as volcanological conceptual models, observed frequencies, monitoring data and expert opinion. The importance of the different pieces of information depends on the time scale of the expected changes in the volcano state, that is, ultimately, on the time term of the forecast: the most relevant evidence is respectively represented by volcanological models and observed past frequency for a long–term forecast, and monitoring information and expert opinion in the short-term.

Here, we summarize the results obtained and the lessons learned by applying the code in simulation exercises (MESIMEX in 2006 at Vesuvius, Italy; RUAUMOKO in 2008 at the Auckland Volcanic Field, New Zealand; COLIMA in 2012 at Colima, Mexico) and in an ongoing, several years long, application at Campi Flegrei, Italy, heavily based on real monitoring data and sessions of expert elicitation.

Although it is still an ongoing evaluation, one of the most important lessons learned from the application of BET_EF is that its output probabilities have so far reproduced the opinion of a pool of experts. In this view, such probabilities are a clear example of "subjective" probability, representing a "degree of belief" on the likelihood of the occurence of an uncertain–outcome event, rather than the "expected frequency" of occurrence of a generic type of events. This is enforced also by the widespread belief, within the volcanological community, that every volcano (if not every eruption) has some peculiarities, and so a "unique" model for the forecast of eruptions, based on catalogs from many volcanoes and valid for all of them, is not possible. This approach has similarities with the one taken by many hazard assessment made by the seismological communities (Marzocchi and Zechar, 2011); a recent example is Uniform California Earthquake Rupture Forecast that aims at providing, by means of expert opinion, a comprehensive framework for computing a rupture forecast for California. The testability of the "degree of belief" is still a subject of discussion, and it is not yet available a self–consistent probabilistic framework to test such a kind of probabilistic approach. In this presentation we summarize why a subjective probability is fundamental for taking decisions in managing volcanic unrest and the current initiatives that aim at evaluating scientifically such a kind of forecasts.

Testing the efficacy of volcano alert levels

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Volcano observatories and governments use volcanic alert levels to characterize escalating volcanic unrest and activity. A proper adjustment of the level of unrest at a volcano provides crucial information to local populations and civil defense authorities on the expected activity at a volcano in the immediate future, with the express purpose of keeping populations out of harms' way. Given the importance of alert levels in the anticipation of eruptions we have analyzed the 'success' rate of alert levels on a global scale. We consider a successful alert to be one that was raised step-wise until the initiation of the eruption. A 'missed' alert is one that was not changed until after the eruption began. Our study includes over 50 volcanoes and over 60 eruptions, a large range of eruption sizes and volcano types (e.g, open and plugged vents) from a wide selection of countries. To include different countries we standardized the different schemes of alert levels. Preliminary analysis of data shows that in many cases the alert status of a volcano does not change until after the eruption has begun, and the success rate for different volcanoes varies between very low to up to 50 %. Overall, about 75% of the eruptions were not preceded by stepwise increase in alert level, and about 25% of the alerts were 'successful'. The percentages of success vary depending on the type of volcano and eruption size. At open-vent volcanoes, the success is only about 20%, but increases to about 30% at plugged volcanoes. We are now analyzing the results also in terms of level of instrumentation at each volcano and population at risk. A higher societal tolerance for false alarms would probably improve the early issuance of alerts, and hence raise the 20-30% success rate in the case of eruptions, but it might also increase the number of false alarms. We hope that the identification of the main factors (e.g. structural, decision making process or others) that control the success rate will allow the design of programs to improve those factors, and thus lead to more efficient use of alert levels for mitigation of the impact from volcano hazards.

An assessment of volcanic unrest in the 21st century: pre-eruptive processes and timescales of reactivation

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One of the most pertinent issues in volcanic risk management is the question whether volcanic unrest will culminate in an eruption in the short-term or not. This question is particularily difficult to answer at volcanoes where unrest is preceded by lengthy periods of quiescence and where hard data on pre-eruptive processes before previous eruptions is absent. Here, we review and evaluate global unrest reports between January 2000 and June 2011, which draw largely from information presented by the Global Volcanism Program but also from the scientific literature. We aim to evaluate the nature and length of unrest activity in a view to help better assess future unrest episodes. The available information on 229 volcanoes is categorised into eruptive and non-eruptive unrest to evaluate the temporal distribution of unrest activity and to test the significance of observed unrest patterns at different volcano types. Timelines for different volcanoes were created to demonstrate how unrest develops over time and to highlight different modes of unrest including reawakening, pulsatory, prolonged, and sporadic unrest. Through combination of time series and statistical analyses we find that 2 out of 3 volcanoes with reported unrest erupt in the short-term. Although this ratio varies when considering different volcano types, the median average unrest duration is about one month before eruption, regardless of the length of the inter-eruptive period. Assuming that the investigation period is representative for any given observation period then there is an almost 50% chance of an eruption within about 20 days of the beginning of unrest. By contrast, if unrest outlasts a period of about 11 weeks, the chance of an immediate eruption decreases significantly to about one in five. We find that there are very poor correlations between the length of the inter-eruptive periods and unrest durations across all investigated volcano types. This suggests that the hypothesis that volcanoes with long periods of quiescence between eruptions will undergo prolonged periods of unrest before eruption is not supported by our analysis. Our findings may have implications for hazard assessment, risk mitigation and scenario planning during future unrest crises.

Assessing probabilistic forecasts of volcanic eruption onsets

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A method for assessing prospectively the quality of a suite of eruption forecasts is proposed. Any forecast of the likely timing of the next eruption onset from a polygenetic volcano can be converted into a probability distribution $F(t)=\mathrm{Prob}(T \leq t)$, where T is the time of the onset, and $s < t < \infty$, for some time s at which the forecast is made. Since $0 \leq F(t) \leq 1$, if this *conditional repose distribution* is accurate, a series of realizations, which may be on the same or different volcanoes, should produce an IID sample $F_1 = F(T_1)$, F_2,... which has a uniform (0,1) distribution. Hence, given sufficient trials, we can use standard statistical tests, such as the Kolmogorov-Smirnov test, to determine if the forecasts are consistent with the model(s). The use of the Kolmogorov-Smirnov test enables currently open forecasts to be included via the Kaplan-Meier product limit estimator. While consistent (under-) over-estimates of the repose length will result in a median (greater) less than 0.5, the method also assesses whether the method assigns the correct degree of aleatory variability to the forecast. Note that it is possible for the forecasts to be more accurate than claimed. This would be indicated by the median of the sample being around 0.5, but the quartiles being within the (0.25,0.75) interval, for example. The method is illustrated on the author´s library of forecasts dating back 18 years, including renewal models and other point processes, on a gallery of approximately 20 volcanoes including Etna, Aso and Ruapehu.

0P1_4E-O5 Room A3 Date/Time: July 20 15:30-15:45

RETROACTIVE APPLICATION OF FORECAST FAILURE METHOD FOR PREDICTING MERAPI ERUPTION 2010 USING DEFORMATION AND SEISMIC DATA

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It has been applied Forecast Failure Method (FFM) in retroactive to estimate time of failure of the 2010 Merapi eruption. In this case, we used the slope of distance data measured by EDM and the seismic cumulative energy data before Merapi eruption. EDM measurement carried out daily while weather condition visible to see the reflectors as a target. It has been installed 12 reflectors facing radially to the South (Kaliurang), South East (Deles), West (Babadan) and North (Jrakah and Selo) where some benchmark built as fixed point in the observatories..

EDM data has showed significant shortening distance since early September from all direction, but difference in rate of distance changes. The strongest slope distance changes occurred in the South sector which has been accelerated from some millimeter/day to more than 50 cm/day for two months. FFM have been done by two-point analysis technique to increase correction factor due to variations of the data. FFM could be sensitive if the relationship between the physical parameters and time is about 2 or more. The rate of slope distance change a week before eruption have a linearity about 4. As comparation of the result, FFM methods has been applied to the cumulative seismic energy parameter (sum of energy of Volcano Tectonic, Multiphase (MP) and Low Frequency (LF) events). The result showed the prediction of eruption occurred on Julian day 297 300, it is consistent with the first eruption that occurred on October 26, 2010 or Julian Day 299.

Eruption forerunners from multi-parameter monitoring and the corresponding predictability skills (Piton de la Fournaise)

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Volcanic eruptions impact on societal risk, and volcanic hazard assessment is a necessary ingredient for decision-makers. However, the prediction of volcanic eruptions remains challenging due to the complexity and the non-linearity of volcanic processes. Identified forerunners such as increasing seismicity or deformation or velocity changes within of the volcanic edifice prior to eruption are not deterministic. We analyzed the short-term (i.e. the inter-eruptive period) time series of the seismicity rate, the deformation and the seismic velocity changes (deduced from seismic noise cross-correlations) over the period 2000-2007, with two main goals. First, we characterize the average pre-eruptive time patterns before 23 eruptions using superposed epoch analysis for the three observables. Using daily rate values, we resolve (i) a velocity change within 100-50 days from the eruptions onsets, then a plateau value up to eruption onset; (ii) a power law increase in seismicity rate from noise level 15-10 days before eruption time; (iii) an increase of displacement rate on the eruption day. These results support a three steps mechanics leading to magma transfers towards the surface. Second we use pattern recognition techniques and the formalization of error diagrams to quantify the predictive power of each forerunners either as used independently or as combined to each others. We show that when seismicity rate alone performs the best in the failure to predict and alarm duration space, the combination of the displacement and seismicity data allows to reduce the false alarm rate. We further propose a tool which explores the prediction results in order to optimize prediction strategy for decision-makers, as a function of the risk value.

Real-time forecasting of catastrophic rock failure and implications for predictability of volcanic eruptions

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There are a variety of methods for forecasting the probability of a volcanic eruption in a given time period, often relying as much on expert judgement as formal analysis of geophysical, geodetic and geochemical data. Physical theories are commonly based on laboratory constitutive rules for catastrophic rock failure due to sub-critical crack growth under a constant load or loading rate. In both cases an accelerating rate of deformation or acoustic emissions is predicted with a well-defined inverse power law form that is consistent with independent laboratory observation. Similar precursors have also been seen to first order in seismicity data before volcanic eruptions in individual and stacked sequences, as well as prior to some intrusion events. To date most of these analyses are retrospective, so the failure time and outcome is already known. Success in such hind-casts is a necessary but not sufficient criterion for assessing the true forecasting power or quality in real time, and is a prime motivation for the development of the global Collaboratory for the Study of Earthquake Predictability (CSEP), where forecasts are lodged verifiably in advance. Here we assess the potential significance and utility of real-time forecasting using such constitutive rules by applying a variety of techniques. First we describe the results of Monte-Carlo simulation of realistic ideal model sequences with an appropriate degree of noise added. The best results are obtained when maximum likelihood statistical models that take appropriate account of the error structure are used. This method has yet to be commonly applied in volcanic seismology. Even so there is large uncertainty quite close to the catastrophic failure time, so reliable forecasting may not be possible even in this ideal case. Communication of this uncertainty, and deciding in advance on appropriate actions to be taken with low-probability forecasts, then become as indispensable as making the forecast itself. The next step is to quantify forecast quality in a controlled laboratory setting by modern real-time data assimilation techniques. We describe a prototype infrastructure for this exercise that streams live data from a participating laboratory via a user-friendly portal, analyses the data and makes continuously-updated forecasts in real time including uncertainty, and will present some preliminary results if available. Finally we apply the method to data from recent volcanic eruptions, analysing the results as if they had come in real time. In this case the uncertainties are not purely statistical, they are also epistemic, and continuous multiple-hypothesis testing along the CSEP model is likely to be needed in cases which do not follow the simple laboratory pattern. In this case model discrimination using standard methods such as Information Criteria or Bayes ratio may also not be possible in real time until very near the eruption.

Identifying the form of precursory trends before eruptions: reducing uncertainty with rock-physics experiments

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A key goal in forecasting eruptions is to quantify accelerating rates of precursory signals. Exponential and faster-than-exponential (FTE) changes with time are two common forms of acceleration identified from field data, especially for rates of volcano-tectonic (VT) events. Although both types of acceleration have been described by recent theoretical models (Refs. 1 and 2), the noise in field data can introduce ambiguities in identifying the appropriate trend (Ref. 3). The nature of the expected trends can additionally be investigated in the laboratory by deforming and breaking rock under controlled conditions. Most previous experimental studies have focussed on failure in compression. In the field, however, at least local extension must occur for a pathway to open ahead of rising magma. Here we present results on precursory rates of fracturing, using a novel experimental apparatus that recreates rock failure in extension.

To recreate field conditions, we used the fault jog method to generate extensional stress within a background compressional stress field. Two parallel slots, 2 mm wide, were cut at 30° to the vertical axis in cylindrical samples, 40 mm across and 110 mm long. The perpendicular offset between slots was held at 10 mm, but the slot overlap was varied from 0 to 10 mm. Water saturated samples were deformed under triaxial stress at a strain rate of 10^{-5} s^{-1}, 60 MPa confining pressure and 20 MPa pore fluid pressure. Using acoustic emissions (AE) as laboratory analogues of VT events, the number and energy of AE were measured, together with axial and volumetric strain, to investigate the accumulation of crack damage within each sample.

We performed the experiments on samples of alkali baslt from Mt Etna, in Sicily. Our results show that AE rates tend to increase exponentially with time until immediately before bulk failure, when the rate abruptly becomes faster than exponential. The behaviour is well-described by a new theoretical model (Ref. 2) for which the exponential trend is characterised by the energy stored in the atomic structure at absolute temperatures and confining pressures above zero. The characteristic stored energy can be calculated using rock composition, temperature and confining pressure. In our experiments, the exponential trends yield values for the characteristic stored energy of 28-36 MJ m^{-3}. These compare well with the calculated values of 32 ($\pm$ 20%) MJ m^{-3}. The good agreement suggests that VT precursors in the field are likely to evolve with time from exponential to FTE trends and that the onset of an FTE acceleration may be an essential signal to indicate that an eruption is imminent.

1. Kilburn, CRJ (2003) J Volcanol Geotherm Res, 125. 271-289.
2. Kilburn CRJ (2012) J Geophys Res, doi. 10.1029/2011JB008703.
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Long swarms and short swarms

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Many earthquake swarms at volcanoes last several months, then have a sharp uptick in rate in the hours before eruption. Examples include 2006 Augustine, 8.5 months then 10 hours; 1992 Spurr, 10 months then 4 hours; 1994 Rabaul, 1 year then 27 hours; 2008 Kasatochi, 6 weeks then 2 days; and 2011 Puyuehue Cordon Caulle, 5 weeks then 2 days. For the well studied Augustine case, broadband data showed that very long period (VLP) energy accompanied 221 of 722 located earthquakes in the 10 hours before the first explosive eruption on 11 January 2006. This was revealed by low-pass filtering and the period of the VLP signal was 50 sec. The Augustine broadband stations were campaign instruments at distances of 2-3 km from the vent. No similar VLP energy has been found in events during the 8.5 month long swarm. Okmok volcano had a short swarm only lasting 5 hours prior to its 12 July 2008 eruption. Low-pass filtering of data from broadband station OKSO, 10 km from the vent, showed that 23 of 42 located events had VLP energy with a period of 30-40 sec. Events from Kasatochi volcano were scanned on station ATKA. Here the broadband station is much farther away at 88 km but the earthquakes in the short swarm 7 August 2008 were much larger with many M>3 events. The station suffered data gaps so only a few hours of data were scanned but numerous events were observed with VLP energy starting just after the P phase. Low-pass filtering showed VLP energy with a period of 10-12 sec. No VLP energy has been found in events of the preceding 6 week long swarm. These observations at three different volcanoes suggest that the short swarms represent a different process than the long swarms. The long swarms likely reflect pressure increases in the surrounding country rock caused by increasing magma pressure. The short swarms in contrast, appear to represent discrete pulses of magma injection at shallow depths. For all three volcanoes the earthquakes looked like typical volcano-tectonic (VT) earthquakes on short-period stations. This demonstrates that broadband stations are needed at close distances to be able to make the needed observations. The short swarms are very short, a few hours to 2 days, and have important implications for hazards assessments. It is not known how commonly the long swarm-short swarm pairs occur and the false alarm rate is also not known.

Predicting the unpredictable: using families of low frequency seismicity to forecast volcanic unrest

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The use of volcano seismology has recently been thrust to the forefront of forecasting and managing volcanic unrest primarily because it offers near real time analysis of the activity as it unfolds. It has already been recognised that seismicity associated with volcanic eruptions can be split into a number of sub-types, and it is this that allows us to try and comprehend the processes which are occurring at depth, and therefore relate it to the surface expression of the volcano.

Analysis of swarms of low frequency seismicity prior to dome collapse at Soufriere Hills volcano, Montserrat suggest that the success of the Material Failure Law, which is increasingly applied to many volcanoes worldwide in the forecasting of collapse events, may have some dependence upon whether the entirety of observed low frequency seismicity is used in forecasting, or whether the events are further sub-categorised. It appears that the identification and use of singular low frequency seismic "families" (events which have the same waveform and are therefore considered to be from the same source) allows a more accurate forecasting of the timing of dome collapse.

A multi parameter approach to the use of the material failure law in forecasting collapse events using accelerating event rates, seismic amplitudes and energy released from events is under investigation, both in terms of using all observed low frequency seismicity, and using only one "family" of events. In particular, analysis of swarms prior to collapse events in hindsight suggests that using only a single "family" of low frequency seismicity appears to provide a more concise estimate to the timing of failure when only a few swarms are observed and those swarms are temporally far from the known timing of the dome collapse. Therfore we suggest that the use of the material failure law may need refining further in terms of pre-processing of the seismicity in order to find such "families" when used in real time forecasting scenarios, if the most accurate forecast is to be made.

On the self-similarity of rifting episodes

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The relative motion of divergent plate boundaries is accommodated by means of rifting episodes, where sequences of magma-filled dikes compensate crustal splitting with creation of volume. Rifting episodes liken main shock - aftershock sequences at convergent or transform plate boundaries in many respects, for example they start with a large intrusion and are followed by several events of smaller magnitude. There is general consensus on the idea that the frequency of earthquakes is self-similar from local to global scale. Self-similarity is generally seen as manifestation of a non-linear chaotic process in which the earth self-organizes critically. The critical state "at the edge of chaos" is mirrored in a power law behavior of several quantities such as the scalar seismic moment or the aftershock decay time. The group properties of the frequency of dike intrusions during rifting and their possible self-organization have never been investigated in detail. In analogy with earthquakes (shear cracks), we derive a basic theoretical power-law equation for the geodetic moment-frequency distribution for tensile cracks, then we investigate whether a power law distribution describes the statistics of dikes from the two rifting episodes recorded since modern monitoring techniques are available: the 1975-1984 Krafla (Iceland) and the 2005-2010, possibly still ongoing, Manda-Harraro (Ethiopia) dike sequences. We find self-similarity over the entire geodetic moment scale of 2 orders of magnitude observed in the diking: as for mainshock-aftershock sequences, a power law relationship describes well the geodetic moment - frequency distribution of the dikes. We also check the correlation between the volume intruded in a dike and the waiting time to the successive intrusion (i.e. interevent time). We find that the volumes and successive interevent times are correlated being indicative of the role played by the magma recharge rate in the occurrence of dike intrusions. At the same time, big dikes trigger successive smaller dikes as in Omori-type sequences. Overall the rifting segments and cluster of dike intrusions seem to be the manifestation of a critical system that reacts to both the tectonic load, long-term magma accumulation and dike induced-stress interaction.

Simplifying assumptions in volcano modeling: are we missing something crucial?

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Volcanoes are extremely complex natural systems, in which the interplay of different forces and physical processes determines a variety of behaviors that can be hard to interpret. The deep magmatic systems cannot be directly observed, and we must rely on indirect information. The latter typically consists of data from a variety of monitoring techniques, be it geochemical, geohpysical or petrological. Even though technology is making gorgeous improvements in terms of resolution and quality of collected data, it is still not obvious and univocally determined how to interpret them in terms of deep processes. Physical models of volcanic systems try to capture the essence of these processes, even though they are limited by the intrinsic uncertainty of initial and boundary conditions, as well as by the necessary simplifying assumptions that need to be made in order to make the system mathematically manageable. We try to assess the importance of some of the most commonly employed assumptions, and show that results are very sensitive to the choices made.

Results from forward modeling of magmatic processes, such as the arrival of magma from depth into an established, shallower reservoir, show that the patterns of pressure and density variations are complex both in space and time (Longo et al., 2012). Even within a relatively small magma chamber, there are regions undergoing pressurization and others being depressurized, evolving with time. Conversely, the most common models for the inversion of deformation data assume that the source is uniformly pressurized (e.g., Mogi, 1958). Therefore, inversion of synthetic data obtained from forward modeling does not reproduce the actual synthetic sources of deformation: preliminary results show that magma recharge into an already established reservoir does not have any signature in the deformation signal. On the other hand, inversion of gravity anomaly data is able to identify more precisely processes that involve complex space-time variations of density, including replenishment of emplaced reservoirs. It is thus evident how our assumptions can bias the understanding of complex volcanic processes. On the other hand, it is obviously impossible to describe such systems in complete detail: when should we stop approximating? Defining the processes that determine the first-order behavior of a volcanic system is a much needed but extremely hard goal to achieve.

On the unrest and eruptive behaviour of large calderas, with examples from Campi Flegrei

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Large calderas are the site of the most devastating eruptions occurred on Earth; they often display substantial unrest dynamics that puzzle volcanologists, and in some cases like the Campi Flegrei case, trouble them as well as the society for the enormous risks associated to their eruptions. Calderas display sequences of signals that would almost certainly prelude to an eruption if observed at central volcanoes; nonetheless, volcanic eruptions may not follow, while they may happen with definitely much weaker signals preceding them, as for the Rabaul eruption in 1994. Although largely debated, the origin of this controversial behaviour is still unclear. The caldera structure favours the development of large geothermal circulation, that is often invoked as an important controlling factor for the observed geophysical and geochemical changes. At least at Campi Flegrei, the structural setting of the caldera appears to have repeatedly favoured emplacement of small magma bodies at shallow (< 4 km) depth, creating a network of interconnected reservoirs capable to exchange mass and heat. The different efficiency of interconnections likely controlled the scale of the eruptions, resulting therefore in limited role of the most shallow batch on the eruption impact, and complicating the forecasts. Essentially, although our knowledge of caldera systems has evolved substantially, our understanding is still limited, contributing to increase their associated risk.

0P2_4E-O14 Room A3 Date/Time: July 20 18:00-18:15

Rumbles and mumbles: what we know we know - and don't know - about recent volcanic activity in New Zealand

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Volcanic activity in New Zealand was particularly elevated in 2012 and 2013, with two volcanoes erupting and another showing signs of increased unrest. A few years before, Lake Taupo caldera also showed signs of unrest. Here we present a summary of recent activity at various volcanoes such as White Island, Tongariro and Lake Taupo volcanoes and how multiscale and multidisciplinary approaches allowed us to either untangle the various processes driving unrest, or gain insights into the details of an eruptive sequence. These approaches include geodesy, seismology, geochemistry and results from numerical modelling. We also present some open and yet unanswered questions about the recent activity.

Tornillos modeled as self-oscillations of fluid filling a cavity: implications for the 1992-1993 activity at Galeras volcano, Colombia

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Tornillos represent an enigmatic class of quasi-monochromatic seismic signals with a slowly decaying coda that are observed near active volcanoes and geothermal areas worldwide. In this work, a model describing the tornillo source process is investigated that is based on the self-oscillations of fluid filling a cavity. A nonlinear ordinary differential equation is derived that governs the behavior of the model taking into account viscous damping, nonlinear damping and the reaction force of the fluid inside the cavity. This equation is numerically integrated both for different cavity sizes and different fluids of volcanological interest, such as gas (H2O+CO2, H2O+SO2) and gas-particle mixtures (ash-SO2, water droplets-H2O). A cavity with a smaller radius compared to its vertical extent produces synthetic tornillos with broader frequency range (1-20 Hz) that may also exhibit amplitude modulation effects. On the contrary, a cavity with a radius much larger than its vertical dimension generates signals with lower frequencies (1-7 Hz). When the fluid filling the cavity is a gas-particle mixture the total duration of the synthetic signals attains values of tens of seconds and quality factors of several hundred. The tornillo activity preceding five of the six vulcanian eruptions during 1992-1993 at Galeras volcano is consistent with the self-oscillations of a mixture of ash-SO2 filling a cavity that is gradually enriched in ash particles. Additionally, the model predicts a progressive increase of the tornillo signal duration followed by a small decrease as was observed at Galeras. It can be inferred that the time dependent rheology of the andesitic dome that was emplaced earlier at Galeras may have played a very important role in the formation of these cavities and the seismic phenomena observed during each eruptive cycle.

Testing the performance limits of eruption forecasting models using synthetic precursory data

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A range of models have been proposed to explain trends in eruption precursors, such as strain and seismicity. These models potentially promise quantitative forecasts of the timing of future eruptions. However, the models, and their forecasting power, remain largely untested. Here we use simulations to quantify variability in forecast eruption times based on the inverse Omori law in the ’best-case’ scenario that uncertainty only arises from model parameter estimation from single realizations of a stochastic point process. A maximum-likelihood method yields the most reliable forecasts. For typical model parameter values, at 10 days before the eruption, 1 in 10 of the forecasts are more than 3 days early or late in the case that the power-law exponent is known a priori, and more than 5 days early or late if the power-law exponent is unknown. Much larger variability can be expected in practice. Methods to manage such uncertainties must be incorporated within hazard mitigation strategies. Our results demonstrate the large inherent uncertainty in eruption forecasts even in these ideal scenarios, and highlight the necessity for: (1) greater experimental and theoretical constraint on model parameters; and (2) the need for truly prospective testing of forecast performance.

The challenge in quantifying magma input and output to active volcanoes—an example from Kilauea

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Two of the most fundamental parameters governing volcanic activity are magma supply to and effusion from the volcanic edifice. Both are especially relevant at persistently active volcanoes, where an imbalance in the two can result in changes in eruptive activity. Kilauea Volcano, in Hawai‘i—one of the best–studied volcanoes in the world—provides an excellent example of the challenges in quantifying magma supply and effusion rates.

Magma supply to the volcano has been calculated by combining the volume of effusion with the volume of storage as determined from deformation modeling, but that approach assumes all magma storage areas are known and that models of surface deformation provide accurate volume change estimates. Simple elastic models of deformation, however, fail to account for magma compressibility, which can bias volume calculations by up to an order of magnitude. Carbon dioxide emissions provide a means of gauging changes in supply but are only useful in a relative sense because the CO_2 content of the hotspot supplied magma currently remains an estimate.

Numerous techniques have been employed to gauge lava effusion rates, including SO_2 emissions based on a known SO_2 content of the magma, lava tube cross-section and flux, topographic change due to lava emplacement, and thermal measurements. Extensive lava flow fields, however, confound efforts to image thermal and topographic change, since airborne measurements often lack sufficient areal coverage and satellite monitoring may not have adequate temporal resolution. In addition, lava that enters the ocean cannot be satisfactorily accounted for by measuring changes in subaerial topography. If no observable lava tubes are present, geophysical methods of determining flux through tubes are not possible. Finally, equating the rates of lava effusion to SO_2 emission assumes that all magma that degasses SO_2 also erupts. This assumption does not account for pre-eruptive degassing—a process that has been occurring since the start of Kilauea’s summit eruption in 2008. Moreover, some magma may degas but not erupt, instead sinking to deeper levels after it has lost its volatiles.

Improved spatial and temporal resolution of satellite measurements can address the effusion rate question. This technique is best for flows that remain on land and do not enter the ocean. We are currently testing the TanDEM-X topographic mission as a means of mapping the volume change of Kilauea’s Pu‘u ‘O‘o flow field. Absolute determinations of magma supply, however, will continue to involve numerous assumptions until better understanding of primary melt composition and magma storage are available. For now, magma supply rate measurements remain most useful in a relative sense.