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MONITORING VOLCANOES — A REVIEW

Minimising risk in volcanic regions involves a number of inter-related studies. The collection of historical data on previous eruptions is the first step, followed by detailed mapping around the volcano. The resulting volcanic hazard map can be used during volcanic crises to minimise casualties. The range of tools currently deployed on volcanoes includes seismometers, a range of gas monitoring equipment, ground deformation equipment including differential GPS, borehole strainmeters, thermal imaging cameras, micro-gravimeters, magnetometers, laser scanners, radar scanners and magneto-telluric equipment to create sub-volcanic images based on electrical conductivity. Satellites are also becoming more important, and new techniques involving solid state sensors may have a significant role to play in the future. Case studies confirm the usefulness of each of these techniques, though, even in well-monitored volcanoes, some eruptions take place without detectable precursors. To minimise the possibility of unexpected eruptions in the future will require both increased instrumentation and the application of methodologies such as advanced neural networks and expert solicitation.

INTRODUCTION

During the past 300 years, over a quarter of a million people have been killed by volcanic eruptions (Mcguire *et al.* 1995). These include 2000 deaths around El Chicon volcano in Mexico, a volcano that was considered to be inactive and was consequently not monitored, and 25,000 fatalities during the eruption of Nevados del Ruiz, Columbia in 1985 because, although the risks were identified, the town of Armero was not evacuated. On the other hand, there have been a number of instances where successful forecasting and evacuation have significantly reduced the number of casualties, for example during the 1991 eruption of Pinatubo in the Philippines when 200,000 people were move out of the danger zone.

One of the major challenges facing volcanologists is to identify which volcanoes are a potential threat and to provide warning of eruptions and their potential effects. It is important to recognise that the most potentially dangerous volcanoes are those that erupt least often and consequently those that are least likely to be extensively monitored.

In this article, the methods currently used to identify and monitor potentially hazardous volcanoes both before and during eruptions will be reviewed.

THE PROBLEM

In view of the large number of people living on and around volcanoes [10% of the world's population in 1986 according to PETERSON (1986)], there is an urgent need to identify those that are likely to cause problems in the future. Excellent catalogues of active volcanoes have been produced during the last few decades including the recent update by SIEBERT *et al.* (2011) who list over 1500 subaerial volcanoes that have erupted in the last 10,000 years. Unfortunately, most of them are currently not monitored, others are monitored using relatively unsophisticated techniques (LOCKWOOD and HAZLETT 2010) and many have not been mapped in sufficient detail to allow the full range of potential volcanic hazards to be identified. When these volcanoes show signs of increased activity, extensive monitoring networks are sometimes provided, but the lack of baseline data makes it difficult to detect when there are significant changes from normal behaviour. In addition to recording volcanic activity, SIEBERT *et al.* (2011) include population densities adjacent to listed active volcanoes. This information, in combination with the description of the eruptive history and areas affected by previous eruptions, can be used to identify those volcanoes in need of close investigation and monitoring.

One of the most effective methods of reducing risk on an active volcano is to map the volcano and the region that has been affected by previous eruptions. Resulting hazard maps include areas that have been inundated by lava flows, pyroclastic density currents, ash fall, debris from flank collapse and tsunami deposits from sector collapse of large island volcanoes. Key samples collected during this mapping should be dated and analysed chemically to determine whether the range of eruptive styles is linked to changes in chemistry.

Given the time taken for such detailed studies and the need to minimise the possibility that a major eruption may take place unexpectedly in a region thought to be inactive, it is critical that this method is augmented by additional data from satellites. It is, of course, possible that some volcanoes in remote areas are still not included (e.g. detailed analysis of SPOT satellite images of the Central Andes increased the number of potentially active volcanoes in that region from 10 to 60 (DE SILVA and FRANCIS 1991).

The next stage in the process of assessing risk on volcanoes and minimising casualties is to ensure that at least the potentially most destructive volcanoes are well monitored. At the present time, most countries containing active volcanoes operate volcano observatories, though the majority of the 71 listed on the *World Organization of Volcano Observatories (*WOVO) website have funding levels well below those in the USA (United States Geological Survey), Japan (the Geological Survey of Japan) and Italy (Istituto Nazionale di Geofisica e Vulcanologia). Other countries provide funding for the development of equipment used for volcano monitoring through their research councils and other government establishments. For example, following the eruptions of Eyjafjallajökull in 2010 and Grímsvötn in 2011, the Icelandic government approved a proposal to undertake a general risk assessment of Iceland's volcanoes. Based on previous eruption data, they anticipate that future eruptions of Grímsvötn may be expected every 2–7 years, and that both Hekla and Katla will erupt in the near future (http://en.vedur.is/about-imo/news/2011/nr/2280).

The statistical methods used to determine the probability of eruptions in Iceland can also be applied to other volcanoes (NEWHALL and HOBLITT 2002, MARZOCCHI and WOO 2009; MARZOCCHI *et al.* 2010). Unfortunately, comprehensive historical records of eruption duration, type of activity and areas affected are available for only a small proportion of the 1500 volcanoes identified by SIEBERT *et al.* (2011). However, for volcanoes which have a major body of historical data, for example, Mount Etna, rigorous statistical analyses can be undertaken (SMETHURST *et al.* 2009).

MONITORING BY SATELLITE

VISIBLE AND INFRARED

Automated monitoring of volcanoes using satellites is now routine. The NOAA GOES 9, 10 and 12 weather satellites are in geostationary orbit and update images of specific regions once every 15 minutes (see http://www.goes.noaa.gov/). These can be accessed 10–30 minutes after they were acquired at http://goes.higp.hawaii.edu/. This site is hosted by the Hawai'i Institute of Geophysics and Planetology, at the University of Hawai'i. GOES images are mostly low resolution (pixels size ~1 km across in the visible part of the spectrum and ~4 km for other images) and cover Eastern Asia and the Western Pacific, the Central and Eastern Pacific, and North, Central and South America. Image data are collected in the visible portion of the spectrum, the mid-infrared and the thermal-infrared portion of the spectrum. The Hawai'i Institute of Geophysics and Planetology also hosts an automated hot-spot detection system that identified hot spots world-wide. It uses data from MODIS, one of four sensors on NASA's EOS satellites Terra and Aqua. They have developed a MODVOLC algorithm which identified hot spots on each 1 km grid of the Earth's surface. Every 48 hours, one scan is acquired during the day and one at night. The location and intensity of each hot-spot is recorded on global maps which display the locations of all hot-spots detected in the previous 24 hour period. These images can be accessed through http://modis.higp.hawaii.edu/. Advanced Very High Resolution Radiometer (AVHRR) images from the polar orbiting NOAA satellite series allow multispectral data to be acquired for all parts of the globe every 6 hours (http://www.nationalatlas.gov/articles/mapping/a_avhrr.html). AVHRR data are used to detect and quantify thermal radiance from hot spots, and this has been used to study lava lakes and lava flows (MOUGINIS-MARK *et al.* 2000). AVHRR and Landsat Thematic Mapper™ data are also used to estimate the effusion rates from effusive volcanoes (HARRIS *et al.* 1998, WRIGHT *et al.* 2001, HARRIS and BALOGA 2009).

INTERFEROMETRIC SYNTHETIC APERTURE RADAR

Interferometric synthetic aperture radar (InSAR) can be used to map inflation and deflation of volcanoes at centimetre scale accuracy using radar images from Earth-orbiting satellites, principally ENVISAT (European Space Agency), ALOS (Japanese Space Agency), RADARSAT-1 (Canadian Space Agency) satellites and the German Space Agency's TerraSAR-X satellite. TerraSAR-X data have excellent spatial resolution (~3 m), and the satellite repeats its orbit every 11 days. The quality of the data can be improved if combined with ground truth data using GPS (DZURISIN *et al.* 2009).

Recently data from the German Space Agency's TerraSAR-X satellite were used to create a Differential SAR Interferogram of Kilauea in Hawaii. In February 2011, scientists at the Hawaiian Volcano Observatory (HVO) used these SAR data, in combination with other data, to forecast an eruption. The eruption began on March 5th, 2011. The interferogram, which can be accessed at http://www.infoterra.de/gallery/3/kilauea_volcano has a spatial resolution of 5 m. Each fringe represents an elevation change of ~15 mm, and the data show that there was ~500 mm deflation above the magma chamber accompanied by inflation of the East Rift Zone caused by dyke emplacement. This method has significant potential in other volcanic regions.

GAS AND VOLCANIC CLOUD DETECTION AND TRACKING

During the past 3 decades, over 80 jet aircraft have encountered volcanic clouds, 7 of which resulted in loss of engine power (http://volcanoes.usgs.gov/hazards/tephra/ashandaircraft.php). During the past 2 years, eruptions in Iceland have resulted in significant disruption to air traffic in Europe. There is clearly a need to locate and follow eruption clouds using satellite-based techniques. One method involves the Total Ozone Mapping Spectrometer, which can be used to detect sulphur dioxide, a ubiquitous constituent of eruption clouds. Nine Volcanic Ash Advisory Centres around the world provide advice to the international aviation industry on the location and movement of volcanic ash plumes (see http://www.ssd.noaa.gov/VAAC/vaac.html). For example, the Darwin Volcanic Ash Advisory Centre provides coverage of Indonesia, Papua New Guinea and part of the Philippines (see http://www.bom.gov.au/info/vaac/). Satellite data are used in combination with meteorological data to predict the probable movement of ash clouds (see, for example http://puff.images.alaska.edu/index.shtml). There is also a need to monitor ash at higher resolution using ground-based instruments. For example, during the 2010 Eyjafjallajökull eruption in Iceland, a mobile X-band weather radar was installed near the town of Kirkjubæjarklaustur, 80 km from the eruption site in Grímsvötn to monitor the ash clouds (http://en.vedur.is/about-imo/news/2011/nr/2183) (2011)

FISSURE DETECTION BASED ON VEGETATION CHANGES

HOULIÉ *et al.* (2006) used high-resolution multispectral (MS) satellite data on Mount Etna from the ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) instrument on the Terra satellite to demonstrate that fissures can be detected up to two years before an eruption takes place. This was achieved through a normalized difference vegetation index algorithm. The reasons for the detected changes are unclear, but may be related to a combination of increased temperature, higher groundwater levels or increased carbon dioxide levels in the soil beneath the vegetation. Similar results were obtained for Mt. Nyiragongo in 2001 (HOULIÉ *et al.* 2006).

AERIAL SURVEYS

Digital elevation models are traditionally created using data collected during aircraft overflights (e.g. FORNACIAI *et al.* 2010). However, these need to be commissioned and they are generally expensive. Recently, 2 m resolution digital elevation maps of Merapi (see http://www.infoterra.de/gallery/3/tandem-x_merapi) and Mount Etna (see http://www.infoterra.de/gallery/3/first_bi-static_dem) were created by the Tandem-X Mission partners German Aerospace Centre (DLR) and Infoterra. This was possible because satellites TerraSAR-X and TanDEM-X were only 350 m apart. Similar images have been produced following the eruption of Eyjafjallajökull Volcano, Iceland (see http://www.infoterra.de/gallery/3/eyjafjallajoekull_volcano) (Astrium Geo-Information Services 2010)). This recent methodology represents a significant advance and should allow simulations of lava flows, pyroclastic flows and lahars to be run on updated digital terrain models with a greater degree of precision than is possible at present without the expense of commissioning aircraft overflights.

MEASUREMENTS BEFORE ERUPTIONS BEGIN

SEISMIC

Before a volcano erupts, magma either migrates through existing fractures or it creates new pathways, and this generally results in levels of earthquake activity above normal background levels (SPARKS 2003; MCNUTT, 2000, 2005). This may be the first warning signs of an impending eruption, so it is not surprising that seismicity is the most widely used tool in observatories. In addition to recording seismicity caused by magmatic or volcanic activity, however, they also record earthquakes and nuclear explosions world-wide, and they can record rockfalls, avalanches, pyroclastic flows, mudflows and other events that take place above ground. Distinguishing between these different events is one of the first steps in the interpretation of seismic data. Earthquakes recorded by seismometers in volcanic regions are normally caused either by tectonic activity, volcanic activity or a combination of the two. In general, tectonic (or short-period) earthquakes occur in zones separated from the principal areas of magma movement. Volcano-tectonic earthquakes are generated by rocks responding to stress during magma movement whereas long period (or volcanic) earthquakes are caused by pressure changes during the unsteady transport of pressurised fluid. The spectrum of volcanic earthquakes is sharp and is considered to be formed by pressure induced resonance of fluids and/or gas in a fissure or conduit. Sustained injection of magma resulting in continuous earthquakes is generally known as volcanic (or harmonic) tremor and this is commonly observed before an eruption (CHOUET 1988, 1996; CHOUET *et al.* 1994).

Increased seismicity, particularly of long period events and harmonic tremor, is commonly observed before an eruption (e.g. prior to the eruption of Kilauea in 1983, Mount Redoubt, Alaska (1989–1990), Pinatubo in 1991, and Pavlof in 1996 (MCNUTT 2000)). Distinguishing between these highly significant types of seismicity was made possible thanks to the development and deployment of three component and broadband seismometers which operate over the range ~0.001–~20 Hz. Analysis of VT seismograms allows the source depth to be calculated, and, for well-monitored volcanoes, this can be used to estimate the time of a new eruption (PATANE and GIAMPICCOLO 2004).

While it is important to have a good time-series of seismic data for several years for any volcano before a crisis develops, MCNUTT (2000) states that less than half of the world's historically active volcanoes are monitored seismically (which equates to ~10% of those volcanoes that have erupted in the last 10,000 years). Given the high levels of seismicity at most active volcanoes, it is difficult to use seismic data from a recently installed seismometer without background seismic data. In view of the complexity of seismic data from volcanoes, MCNUTT (2000) stresses the need for seismic data on all volcanoes, but particularly those with little previous seismic data, to be interpreted in combination with data from the other methods discussed in this article.

GROUND DEFORMATION

During the past few decades, measurements made using traditional surveying methods have revealed that many volcanoes deform in response to magma movement before, during and after eruptions (MURRAY *et al.* 2000). However, precise levelling is labour-intensive and time-consuming, especially on large volcanoes and where a stable benchmark is some distance from the volcano. This has a significant influence on the frequency of measurements. These problems can be overcome using Differential GPS. One method involves collecting the position each time a station is visited; another involves continuous recording of GPS data. Both methods are in current use. The first method allows measurements to be made in a larger number of areas than those relying on permanently installed GPS stations (PUGLISI *et al.* 2004). This is a major advantage if such measurements are made prior to and during a volcanic crisis (though safety considerations can limit the locations of areas that can be safely occupied). However, it still suffers from data loss during periods when stations are unoccupied. Continuous recording systems clearly have many advantages over spot measurements, especially if the equipment is deployed in regions that have the potential to record inflation and deflation arising from magma injection or dyke movement (BONACCORSO *et al.* 2006, ALOISI *et al.* 2009). Continuous recording borehole tiltmeters are also being used successfully on many volcanoes (e.g. BONACCORSO *et al.* 2004).

In addition to using measurements of surface deformation as an indirect method of detecting increases in stress in volcanic systems, direct measurements can be made using strainmeters in boreholes. These can provide evidence of increased stress in a volcanic system several kilometres from the volcano, and they have proved to be one of the key methods of providing warning of impending eruptions on Hekla in 1991 (LINDE *et al.* 1993) and again in 2000 (AGUTSSON *et al.* 2000).

THERMAL MONITORING

Hand-held thermal imaging cameras have been used to monitor activity on active volcanoes for over 10 years (Fig. 1). Significant technological advances in instrument design have reduced battery power, improved resolution, reduced cost and increased the number of images that can be collected. In

Fig. 1. Thermal imaging camera being used to determine cooling rate of a small lava flow on Etna in July 2004.

addition to their use during eruptions (BALL *et al.* 2008), thermal imaging cameras also have potential applications for routine monitoring of active volcanoes. In view of the relatively rapid rates of ascent of magma compared with conductive heat transfer, it is unrealistic to expect to be able to monitor magma ascent or dyke propagation directly through changes in temperature of rocks in volcanic regions. However, changes in surface temperature of hydrothermal regions can be caused by rapid convective movement in hydrothermal systems beneath active volcanic areas. Either remote or direct (using thermocouples) measurements of the temperatures of hot springs, fumaroles or water in wells can provide an early warning of sub-surface movement of magma or gas loss related to its emplacement. This approach is limited to those volcanoes with a high level plumbing system and to rocks with high permeability and active hydrothermal regions.

GAS MEASUREMENTS

As magma rises, the resulting decrease in pressure allows volcanic gas to come out of solution and escape through fractures in the overlying rocks and possibly through the active craters on some volcanoes. Different gases exsolve at different pressures. For example, on Etna, CO_2 is released at depths of ~20 km, followed by SO_2 at depths of ~3 km, while HF and HCl remain in solution until magma is ~1.5 km below the surface. Sulphur dioxide is the gas most commonly measured, and for many years one of the mainstays of volcano observatories has been a correlation spectrometer or COSPEC. These measure the amount of SO_2 in the volcanic plume, and changes in gas concentration can be used as an indication of either magma ascent or blockage of the vent. For example, on Pinatubo in the Philippines in May 1991, SO_2 emissions increased by an order of magnitude over a two week period. This was followed by a marked reduction in SO_2 levels which was interpreted as a blockage of the gas pathways by magma allowing pressure to increase in the high level magma system. A large eruption took place two weeks later. The interpretation of such changes is non-trivial (CALTABIANO *et al.* 2004) and volcano-specific, so it is important to establish a base-line set of data before a volcanic crisis develops. An alternative technique for measuring SO_2 flux involves the use of miniature ultraviolet (UV) spectrometers (DOAS) Unlike COSPEC, these instruments can be deployed in permanent locations and the data can be telemetred back to a base station or to the nearest observatory.

Another instrument which is deployed on some volcanoes is an open path Fourier Transform Infrared (FTIR) spectrometer. Unlike COSPEC, FTIR is unable to measure flux directly. Instead, it measures concentrations of SO_2, HCl and HF. From this, molar ratios are calculated for SO_2 /HCl and SO_2 /HF. Increases in these ratios are recorded before the onset of many eruptions on Etna (CALTABIANO *et al.* 2004). Using SO_2 flux from DOAS, the flux of HCl and HF is readily determined.

Prior to some eruptions on Etna, CO_2 concentrations increase in regions inferred to lie along the line of deep fracture systems. This is commonly followed by a decrease in SO_2 in the summit area (BRUNO *et al.* 2001).

CHANGES IN GRAVITATIONAL ACCELERATION

Microgravity measurements on volcanoes have recorded changes attributed to magma movement before eruptions, and they are being used on selected volcanoes as an additional monitoring technique (RYMER *et al.* 1995, MURRAY *et al.* 2000, RYMER and WILLIAMS-JONES 2000). The technique relies on the effect of changes in density of underlying rocks during periods of magma movement or vesiculation on gravitational acceleration. However, in order to quantify magmatic-induced changes, gravitational changes caused by other processes need to be taken into account. These include crustal deformation caused by earth tides; fluctuations in the level of the water table; and elevation changes resulting from magma movement. Other causes of apparent changes are instrumental drift; seismic tremor; and changes in ambient temperature, pressure and humidity (RYMER and WILLIAMS-JONES 2000, BUDETTA *et al.* 2004). While discrete measurements, repeated over periods of months to years, have provided useful information on magma movement, continuous recording provides more reliable and volcanologically useful information.

CHANGES IN MAGNETISM

During some eruptions on Etna, changes in magnetism have been detected up to 4 days before an eruption begins (DEL NEGRO and NAPOLI 2004). The reasons for changes in magnetic field measurements on active volcanoes are complex. They are also difficult to measure given other changes that take place independently of internal volcanic processes such as magnetic storms and secular variations in the Earth's core. Removing these effects is the first step in looking for volcanically-induced changes and requires synchronised measurements from remote magnetometers outside the area likely to be influenced by magma movement. Once these are removed, data from those magnetometers on the volcano can be used to determine the reasons for change and their significance.

When heated above the Curie temperature, rocks containing magnetic minerals (e.g. magnetite) are no longer magnetic. Consequently, if measurements are made of the magnetic field in volcanic areas, changes may be expected during the injection of hot magma. Detailed analysis of data from Etna confirms that some of the measured changes during some eruptions are caused by this process. Other mechanisms include piezometric effects (stress-induced magnetism) caused by faulting or pressure changes and electrokinetic effects due to the build up of electric currents in the presence of a double layer, thought to be caused by changes in groundwater flow (LANZA and MELONI 2006). Used in combination with other instruments, carefully installed magnetometers clearly have a role to play in monitoring volcanic activity.

COMBINED SEISMIC, MAGNETO-TELLURIC AND GRAVITY TOMOGRAPHY

In addition to using seismic data to determine the processes taking place during the injection of magma, seismic signals can be used to provide information on the location and shape of magma chambers. The method relies on the well-known inability of shear waves to propagate through hot magma. An additional method, which is currently being used on selected volcanoes, uses magnetotelluric measurements (MAURIELLO *et al.* 2004). This relies on the principle that the resistivity of rocks varies significantly depending on its composition and temperature. Measurements of resistivity therefore have significant potential to determine the location of regions in the Earth's crust that have elevated temperatures. Recent measurements in Yellowstone using MT have revealed that the magma chamber is significantly larger than was inferred from seismic tomography (ZHDANOV *et al.* 2011). More reliable models of the sub-surface can be created if the seismic data are combined with gravity and magneto-telluric data. These data can either be inverted separately (MAURIELLO *et al.*, 2004) or more robust models can be created if a joint inversion of seismic and MT data is undertaken (GALLARDO and MEJU 2007).

LASER RANGING

There are many volcanoes where it is unsafe or inappropriate to use GPS to monitor important topographic changes. Some of these volcanoes require close and regular monitoring to reduce the possibility of unexpected activity. Of particular concern are those volcanoes that contain growing domes; unexpected collapse of domes is a major cause of loss of life on many volcanoes. While it may be possible to survey some of these using satellite-based interferometry, lack of coherence is a major problem on, for example, Soufrière Hills Volcano on Montserrat. Alternative methods therefore need to be employed. One method is regular ground-based photogrammetry (see later). An alternative method involves regular scanning using a long-range laser ranging system. These have improved significantly since they were first used on active volcanoes by HUNTER *et al.* (2003). The latest instrument has a claimed viewing distance of 6 km (Fig. 2), though this is reduced in volcanic terrain to a maximum of 3.5 km (JAMES *et al.* 2009). While this method is useful to monitor either small changes over a long time-period or rapid changes over a period of hours to days, field deployment on many volcanoes is labour intensive and there is, as

Fig. 2. Laser Scanner being deployed on Etna, June 2008.

yet, no semi-autonomous version of this type of instrument. While they undoubtedly have a significant role to play in volcanological monitoring, they are currently expensive and hence unlikely to be used routinely in the foreseeable future. There is, however, another major problem with the use of laser scanner in many volcanoes. They rely on clear atmospheric conditions. Mist, volcanic gas or ash between the instrument and the volcano result in significant backscatter and absorbtion, preventing the collection of meaningful data.

RADAR

To address the problem of collecting topographic data on volcanoes where continuous coverage by mist is a problem (e.g. on Soufrière Hills volcano, Montserrat), a new series of radar instruments have been developed. They are devised to scan the scene of interest in a similar way to conventional laser scanners (WADGE *et al.* 2008). Two versions of this instrument have been developed. One is, like a conventional laser scanner, designed to be portable and operated by a 2-man team. The other, which is semi-autonomous, sends data back on a regular basis to the Montserrat Volcano Observatory (http://www.mvo.ms/en/home-page-content/slideshow-home-page/new-radar-monitoring-tool-at-mvo). This instrument will assist staff at MVO to monitor dome growth during the prolonged periods when visible observations and measurements are not possible. This is an essential requirement during periods of dome growth which commonly culminates in major dome collapse and the formation of pyroclastic flows.

SPECIALIST EQUIPMENT REQUIRED ON VOLCANOES WITH CRATER LAKES

Ruapehu in New Zealand has had a permanent crater lake since records began. When the lake level rises close to the lowest point on the crater rim, the water can break out of the crater and erode a large channel in the ash. The resulting rapidly increasing discharge rates can flow down the flanks of the volcano, causing extensive erosion. The resulting dense assemblage of ash and water forms a rapidly moving, highly erosive lahar with the power to destroy roads, bridges and other structures in its path. Detecting when such lahars will form is one of the tasks facing volcanologists in many parts of the world. Continuous video recording of the breach mechanism can provide invaluable information on the breakthough mechanism, and geophones and trip wires in the predicted path of the lahar can give advance warning of a potentially damaging event (CARRIVICK *et al.* 2009). Similar mechanisms can be used to detect increases in discharge from subglacial volcanoes which may be the first indication of a subglacial eruption.

DEVELOPMENT OF NEW SENSORS

Many of the above methods are now in common use on some volcanoes, and a significant proportion of instruments send data back to the local observatory in real-time. While it would be desirable to install all of this equipment in all volcanoes which have recorded eruptions during the past 10,000 years, this is unrealistic at present, given the installation and maintenance costs. In the longer term, major advances in solid state technology may help to provide limited monitoring capability on many volcanoes that are currently not monitored, and they may usefully augment data from other volcanoes that lack comprehensive monitoring equipment.

Compact, low cost silicon carbide solid state sensors are currently being developed and they have the potential to detect and measure emissions of volcanic gas under extreme environmental conditions. These can operate at temperatures up to 900°C and the data can be telemetred in real time from these sensors (WENG *et al.* 2008, WRIGHT and HORSFALL 2007). These devices are also capable of measuring and transmitting temperature and position. These and other sensors, such as seismic sensors, can be deployed on volcanoes as part of a wireless sensor network (WERNER-ALLEN *et al.* 2006). There are significant problems to be overcome before they can rival conventional geophysical equipment. However they are lighter, significantly less expensive, disposable and easier to deploy, and they require considerably less power. They therefore have significant potential in volcanoes that are currently not monitored and as an inexpensive way of increasing coverage of volcanoes with limited monitoring.

MEASUREMENTS DURING ERUPTIONS

Each of the above sets of measurements will continue to be useful during eruptions. However, it may be appropriate during eruptions to re-focus some of the equipment to address issues related to hazard mitigation.

Fig. 3. View of active lava flow during daily helicopter flight by INGV staff over Etna, July 2001.

For example, thermal imaging equipment could be used to monitor activity either at the vent or on the flanks (Fig. 3), for example where large lava flows are formed. Some of the complex processes involved in the emplacement of lava flows (e.g. fluctuations in flux, the formation of accidental breaches, lava tube formation, etc.) are significantly easier to detect during the day using thermal imaging cameras than using conventional cameras. Laser ranging instruments and radar also have significant roles to play during eruptions.

Additional resources may be deployed during some eruptions. For example, if a lava flow is threatening communities downflow, helicopters can be used to map the advancing flows on a regular basis to minimise the risk of unexpected inundation of key structures. Volcanologists can update maps manually while on board; they can take multiple images during the flight; and they may also use hand-held thermal imaging cameras to determine the most active parts of the flow field.

Another tool is the use of ground-based photogrammetry. This has been used to determine dome growth rates on Mount St Helens (MAJOR *et al.* 2009) as well as key parameters required during the eruption of lava flows on Etna, including flux rates of flow fronts, velocities and thicknesses of lava in channels (allowing the rheological properties of the lava to be determined), etc. (JAMES *et al.* 2007, 2011). Two cameras are mounted on stable tripods at an appropriate distance, depending on the area to be imaged, and they take simultaneous images at a time-scale which is sufficient to measure topographic changes.

CASE STUDY BASED ON RECENT ERUPTIONS OF MT ETNA

Mount Etna has hundreds of permanent stations, including seismic, GPS, tilt, video and thermal cameras, gravity, magnetic and a comprehensive gas monitoring network (BONACCORSO *et al.* 2011). As the best monitored volcano in the world at the present time, it is appropriate to review how successful they have been at forecasting volcanic eruptions during the past decade.

One of the most destructive eruptions during this period took place in July 2001. During the twelve months leading up to the 2001 eruptions, microgravimeters revealed an increase of up to 80 mGal at some of the summit stations compatible with the intrusion of new magma (CALVARI *et al.* 2001). Six months before the eruption, there was a slow increase of the total geomagnetic field of up to 2–3 nT on the northern flank of the volcano, considered to result from demagnetization caused by rising magma. Over 2 months before the eruption, SO_2 flux from the summit craters increased, suggesting the ascent of new magma in that region. The formation of a graben, four days before the eruption began, was accompanied by a seismic swarm of 800 earthquakes, and by significant tilt variations close to the fracture field which led to the conclusion that an intrusion was being emplaced along a ca. N-S direction. During the same period, FTIR measurements revealed a sudden increase in SO_2/HCl in the plume from the summit craters, also suggesting the ascent of new magma in that region. On the 17th July, the eruption began and lava flows were erupted from a large number of vents along a 7 km long field of N-S fractures that intersected the summit of the volcano. Gas geochemistry and petrology revealed the presence of two different magmas, one from a new feeder dyke, the other from the summit feeding system (CALVARI *et al.* 2001).

Seismic and other precursors were also detected before the eruption of Etna in May 2008 (BONACCORSO *et al.* 2011). For

12 months prior to the eruption, inflation, recorded using continuous GPS measurements, was accompanied by significantly higher than normal seismicity. This period of unrest was interpreted to result from upward migration of magma. Three days before the eruption, a new vent opened at the base of the South East Crater, followed by very intensive fire fountaining. Three hours before the main eruption began, there were marked increases in tremor, and the source locations rose higher in the edifice. In this case, there were no significant changes in magnetism until 30 minutes before the main eruption (NAPOLI *et al.* 2008), and tilt changes were noted in the summit area only 40 minutes before the main eruption. Accompanying GPS measurements revealed radial outward movement up to a few tens of centimetres in the summit area (ALOISI *et al.* 2009).

INGV runs an ash surveillance programme (SCOLLO *et al.* 2009) and four air dispersal and fallout models: HAZMAP (MACEDONIO *et al.* 2005), TEPHRA (BONADONNA *et al.* 2005), FALL3D (COSTA *et al.* 2006) and PUFF (SEARCY *et al.* 1998). Each model is run continuously, and the simulations are sent via Internet to the Civil Protection Department which is responsible for hazard bulletins issued to airports. Thanks to the reliability of modelling data, the airport remained open throughout the eruption. In addition, daily updates to the MAGFLOW lava flow simulation model (VICARI *et al.* 2007, 2009; DEL NEGRO *et al.* 2008) were communicated to the Civil Protection Department. The simulated scenario was broadly similar to the final lava flow field.

However, other eruptions have taken place on Etna in the last decade with little or no significant precursory activity. The eruption in 2004-2005 was fed by a dyke that was emplaced during a period of significantly increased eastward movement of the eastern flank of the volcano (BONACCORSO *et al.* 2006). Emplacement of this dyke, which passed through the central conduit of the volcano (BURTON *et al.* 2005, NERI and ACOCELLA 2006) was not accompanied by any significant geophysical precursors, changes in gas emission or increased explosive activity to warn of an impending eruption. Post-processing of the data revealed no evidence of seismic tremor, ground deformation or any of the other changes normally recorded before an eruption on Etna (BURTON *et al.* 2005, BONACCORSO *et al.* 2006). This was also true of the July 2006 eruption.

We therefore have to recognise that, for some basaltic volcanoes, especially those whose flanks are sliding, eruptions may take place with no precursory activity using the instruments we currently have available. Fortunately, eruptions without precursors are less likely to occur on andesitic, dacitic or rhyolitic volcanoes - unless there are high level intrusions in the volcanic edifice (e.g. at Mount St Helens in 1980) when flank failure can take place without warning, or during periods of active dome growth, when general warnings of collapse events may be possible, but without any specific information on when this is likely.

COMMUNICATION ISSUES

While it is clear that scientific advice has been critical in saving lives on many volcanoes (e.g. on Pinatubo in 1991), there are many other instances where advice was ignored, either for political reasons or because of complex issues including communication problems (VOIGHT 1989, 1996). There have been other unfortunate instances where advice was acted upon, but evacuation was not followed by volcanic activity. The reasons for poor advice resulting in inappropriate evacuations are complex, but are generally because of inadequate monitoring. Advice can be based on the use of only one method, and without base-line data, the data can be over- or wrongly-interpreted. The reasons why advice is not acted upon are also complex and often specific to individual populations. In some cases, scientific advice can be conflicting, especially in countries lacking any structure for co-ordinating advice from the scientific community. In the absence of readily intelligible advice from an authority that is respected, it is inevitable that less well-qualified individuals who are more highly respected (e.g. local politicians or members of the church) will be listened to more sympathetically (VOIGHT 1989).

All of the above is based on an assumption that scientists involved in a volcanic crisis agree on likely outcomes based on the data they possess. In well-monitored volcanoes with a well documented history of previous eruptions and an observatory staffed by a coherent team of scientists who have close links with the National and local Civil Defence, this is a likely outcome. However, even in this situation, there are potential problems given the range of eruptive styles and locations on many volcanoes. In some instances, the location and timing of an eruption can be forecast reasonably accurately whereas this is less easily done during other volcanic crises. A recurrent problem on many volcanoes is that there are many instances when increases in seismicity are not followed by eruptions. The problem is that most ascending magma is unable to make it to the surface (POLAND 2010). Much is injected at different levels into the subsurface parts of the volcano because of factors such as insufficient volume or driving pressure for crack propagation (TAISNE and TAIT 2009), or dike widths too narrow to overcome cooling and viscosity increases (WILSON and HEAD 1981). In cases where the potential outcome is unclear, a useful approach, which has been used successfully on Montserrat, is based on Expert Solicitation (ASPINALL 2006). Alternative approaches using advanced neural networks have significant potential to analyse multiple data sets, but these are only as good as the input data and the algorithms used to identify critical thresholds (CASTELLARO and MULARGIA 2007).

Another issue that needs to be addressed is the inability of many members of the public, or civil authorities or politicians, to recognise the issue of uncertainty associated with eruption forecasting. Everyone liable to be affected by an eruption wishes for a definitive statement on potential outcomes of increased activity on a volcano (DECKER1986). Even for the handful of well-monitored volcanoes with a long history of eruptions, there are occasions when precursory signals are detected only a few hours before an eruption begins. For those unfortunate enough to live near to less well-monitored volcanoes, there will inevitably be occasions when the evidence is difficult to interpret. Under these circumstances, false alarms will take place in the future, unless there is significant investment in equipment.

One method of alerting the public to the possible consequences of an eruption involves presenting the results of models designed to investigate the likely effect of a future eruption. This was recently undertaken (ZUCCARO *et al.* 2008) for a possible hypothetical sub-plinian eruption of Vesuvius. Deterministic modelling suggests that the number of fatalities will be around 8000. However, Vesuvius is well-monitored, with a permanent staff who have considerable expertise in the interpretation of all of the instruments deployed on the volcano. They predict that there will be sufficient warning to evacuate 98.5% of the population at risk. If a similar scenario were to be run on less well-monitored volcanoes, the predicted outcome would be less reassuring.

DISCUSSION

Volcanoes may be responsible for significantly fewer casualties than earthquakes, but, unlike earthquakes, many volcanic eruptions can be forecast — but only if they are well monitored. In addition, if there is sufficient historical data on previous eruptions and if volcanoes are adequately mapped, the range of possible outcomes can be portrayed on hazard maps which can be used during volcanic crises to minimise casualties.

Of the monitoring tools available to volcanologists at the present time, it is clear that seismology is the single most important. However, it is also important to recognise that decisions based on single sets of measurements may lead to inappropriate conclusions; hence the need for additional monitoring tools. Of these, it is clear that satellite-based InSAR has significant potential for detecting inflation on volcanoes that are relatively unforested, while ASTER may be useful to detect fissures in forested regions some time before an eruption. Gas monitoring technology continues to improve, and has proved to be useful during many crises. Deformation monitoring and borehole strain measurements also have a major role to play in eruption forecasting. Thermal monitoring has yet to prove itself as a forecasting tool (though it is deployed on a small number of volcanoes at present), but is useful during eruptions as a lava flow monitoring tool. Changes in gravity and magnetic field strength are linked to magma movement and will continue to be deployed on selected volcanoes. Seismic and magnetotelluric tomography are showing considerable potential. However, their role could become even more important if they can be used to model magma flow. This information is critical during the many situations (e.g. in El Hierro at the time of writing; September, 2011) where seismic activity indicates magma movement, but there is a question over whether magma is being intruded laterally or continuing to move upwards. Laser scanning and radar are key instruments for situations where dome growth and possible collapse are a problem. They are also important monitoring tools during eruptions. If solid state sensors and sensor networks continue to develop, their low cost and power requirements may allow them to be deployed widely in the future.

The Etna case study revealed the success of much of the equipment described above during some recent eruptions. However, the lack of precursory activity on other eruptions is a concern both on Etna and on other volcanoes where edifice instability may allow magma to travel rapidly to the surface.

And finally, even on volcanoes that are well monitored, there are many situations where decision-making and communication have caused problems in the past. There is clearly a need for the continued development of tools such as expert solicitation and advanced neural networks to minimise the risk of unexpected eruptions. Similarly, it is important to ensure that local populations are made aware of the possible outcomes of eruptions by, for example, showing videos of eruptions similar to those expected and by modelling possible eruption scenarios.

MONITORING VOLCANOES — A REVIEW

Summary

Minimising risk in volcanic regions involves a number of inter-related studies. First is the collection of historical data on previous eruptions, followed by detailed mapping around the volcano. The resulting volcanic hazard map can be used during volcanic crises to minimise casualties. The range of tools currently deployed on volcanoes includes seismometers, a range of gas monitoring equipment, ground deformation equipment including differential GPS, borehole strainmeters, thermal imaging cameras, micro-gravimeters, magnetometers, laser scanners, radar scanners and magnetotelluric equipment to create subvolcanic images based on electrical conductivity. Satellites are also becoming more important, and new techniques involving solid state sensors may have a significant role to play in the future. Case studies confirm the usefulness of each of these techniques, although even in well-monitored volcanoes some eruptions take place without detectable precursors. To minimise the possibility of unexpected eruptions in the future will involve both increased instrumentation and the application of methodologies such as advanced neural networks and expert solicitation.

MONITORING WULKANÓW

Streszczenie

Podczas ostatnich 300 lat ponad 250 tys. ludzi zginęło w wyniku erupcji wulkanicznych. Największe tragedie miały miejsce tam gdzie nie prowadzono monitoringu zachowania się wulkanów (El Chicon, Meksyk) lub nie przestrzegano zasad ewakuacji ludności (Nevado del Ruiz, Kolumbia). Z drugiej strony ścisłe przestrzeganie zasad i wyciąganie wniosków z danych monitoringu uratowały setki tysięcy ludzi przed zagładą w gęsto zaludnionych regionach świata (Pinatubo, Filipiny).

Ograniczenie ryzyka związanego z przebywaniem ludzi w obszarach zagrożonych bezpośrednim oddziaływaniem wulkanów wymaga wielowątkowych badań. Pierwszym krokiem jest zebranie informacji dotyczących historycznych zapisów i relacji o wcześniejszych erupcjach. Opracowana na tej podstawie mapa potencjalnych zagrożeń może być bardzo pomocą podczas kryzysowej sytuacji. Pozwala ona zorientować się w rozmiarach jak i typie erupcji jaka może mieć miejsce. Szeroki wachlarz narzędzi do monitorowania zachowania się wulkanów obejmuje: sejsmometry, urządzenia do badania gazów wulkanicznych, deformacji gruntu, w tym precyzyjne przyrządy GPS, kamery termowizyjne, mikro-grawimetry, magnetometry, skanery laserowe, urządzenia do pomiarów magneto-tellurycznych (urządzenia do tworzenia obrazów wnętrza wulkanu na podstawie badań zmian własności elektrycznych i magnetycznych skał). Ważną rolę we współczesnym monitoringu odgrywają satelity jak również zastosowanie nowoczesnych metodologii, takich jak sieci neuronowe czy burze mózgów ekspertów od monitoringu

(realizowane z użyciem najnowszych osiągnięć telekomunikacji i łączności). Jednak w praktyce najważniejsze okazuje się szybkie i precyzyjne przekazanie uzyskanych wniosków z pomiarów zagrożonym ludziom. Od szybkości i precyzji tych informacji zależą istnienia tysięcy ludzi.

Pomimo dużej nieprzewidywalności zjawisk geologicznych dzięki dokładnemu monitoringowi możliwe jest w wielu przypadkach z dużą dozą prawdopodobieństwa określenie momentu i zasięgu mających nastąpić erupcji wulkanicznych. Gromadzenie nowych danych i doświadczeń w dziedzinie monitoringu to najskuteczniejsza obrona przed nieokiełznaną naturą pozwalająca coraz precyzyjniej określać zagrożenia dla ok. 10% populacji ludności świata, tylu bowiem ludzi znajduje się w „strefie rażenia" aktywnych wulkanów.

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