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Toward continuous 4D microgravity monitoring of volcanoes

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ABSTRACT

Four-dimensional or time-lapse microgravity monitoring has been used effectively on volcanoes for decades to characterize the changes in subsurface volcanic systems. With measurements typically lasting from a few days to weeks and then repeated a year later, the spatial resolution of theses studies is often at the expense of temporal resolution and vice versa. Continuous gravity studies with one to two instruments operating for a short period of time (weeks to months) have shown enticing evidence of very rapid changes in the volcanic plumbing system (minutes to hours) and in one case precursory signals leading to eruptive activity were detected. The need for true multi-instrument networks is clear if we are to have both the temporal and spatial resolution needed for effective volcano monitoring. However, the high cost of these instruments is currently limiting the implementation of continuous microgravity networks. An interim approach to consider is the development of a collaborative network of researchers able to bring multiple instruments together at key volcanoes to investigate multitemporal physical changes in a few type volcanoes. However, to truly move forward, it is imperative that new low-cost instruments are developed to increase the number of instruments available at a single site. Only in this way can both the temporal and spatial integrity of monitoring be maintained. Integration of these instruments into a multiparameter network of continuously recording sensors is essential for effective volcano monitoring and hazard mitigation.

INTRODUCTION

Since AD 1, at least 270,000 people have been killed by volcanic eruptions, with 25% of these fatalities caused by starvation, disease, and economic hardship resulting from these eruptions (Simkin et al., 2001; Witham, 2005). Of the 600 or so active volcanoes on Earth, approximately 60 erupt subaerially each year (Simkin and Siebert, 1994; 2002); however, only a small fraction of these are monitored in any significant way.

Prior to any volcanic eruption, magma and gases accumulate deep within the volcano and begin to migrate upward. This movement will lead to pressurization and fracturing within the volcanic plumbing system, generating characteristic seismic signals (e.g., Chouet, 1996; McNutt, 2000; Neuberg et al., 2000). The intrusion of magma and vesiculation of the gas within the magma can also lead to volumetric changes of the volcanic edifice as it inflates to accommodate the new magma (e.g., Mogi, 1958; Okubo and Watanabe, 1989; Okada, 1992). Thus, of those few volcanoes that are routinely studied, seismic and deformation (tiltmeters, EDM, GPS) networks have been the principal monitoring techniques. In a few of the more accessible volcanoes (e.g., Kilauea, Hawaii; Etna, Italy), routine volcanic gas monitoring is also carried out (e.g., Caltabiano et al., 1994; Elias and Sutton, 2002). Furthermore, advances in satellite remote-sensing systems are now enabling thermal and ultraviolet monitoring of volcanoes on a global scale (e.g., Oppenheimer, 1998; Wright et al., 2004; Yang et al., 2007).

Although routine measurements of seismicity, deformation, gas flux, and heat loss from active volcanoes have provided insights into the processes of eruptions, the transfer processes of heat and mass are still poorly understood and many questions remain unanswered, such as what happens to degassed magma that is not erupted and how gas-rich magma is stored until the mixture is erupted (e.g., La Delfa

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et al., 2001; Locke et al., 2003; Stix, 2007). The large density contrast among magma, gas, and the surrounding country rock makes it possible to calculate the amount and rate of magma and gas movement. This is possible through the integration of 4D (three dimensions of space and one of time) temporal microgravity and precise deformation techniques such as precise GPS and synthetic aperture radar interferometry (InSAR). Integrated gravity and geodetic studies are able to quantify mass and/or density changes and have been successfully used to model shallow magma movements on temporal (e.g., months to years) and spatial (tens of kilometers) scales within volcanic systems (Locke et al., 2003).

DISCRETE 4D MICROGRAVITY ON VOLCANOES

Since the 1950s, microgravity surveys have proven invaluable for measuring the subsurface mass and/or density changes that take place on various temporal scales preceding volcanic eruptions (e.g., Yokoyama and Tajima, 1957). As with most 4D microgravity surveys, a single instrument can be used to cover the area of interest by making a series of measurements at several places and comparing the value of gravity with the value at a reference point. The whole survey is then repeated some time later and any changes in gravity difference between the reference point and the places of interest are noted. The effects of solid earth and ocean-loading tides, instrumental drift and calibration, and atmospheric and elevation changes (uplift/subsidence of the ground) are removed and then the residual-gravity changes can be interpreted in terms of subsurface mass and/or density changes (e.g., Rymer, 1989; Carbone and Rymer, 1999; Battaglia et al., 2008).

It is important to note that in most volcano studies, a standard grid or profile survey is impossible because of terrain restrictions and/or safety concerns, e.g., significant topography, active craters, lava flows, etc. Furthermore, given that many of the volcanoes of interest are in states of unrest, significant seismic noise can be present leading to potentially important uncertainties. Nevertheless, repeated gravity and geodetic surveys, such as at Pacaya (Guatemala), Kīlauea (Hawaii), Poás (Costa Rica), Krafla (Iceland), Usu (Japan), and Etna (Italy) have shown the power of microgravity monitoring to detect and interpret subsurface mass changes associated with volcanic activity (e.g., Eggers, 1987; Johnson, 1987; Rymer and Brown, 1989; Rymer et al., 1998a; Carbone et al., 2003a; Jousset et al. 2003; Kauahikaua and Miklius, 2003; Rymer et al., 2005).

Discrete microgravity surveys have also been fundamental in advancing our understanding of calderas in a state of unrest. These systems are characterized by repeated periods of inflation and deflation often accompanied by seismic swarms and significant thermal anomalies with low-level activity lasting many decades to centuries (Newhall and Dzurisin, 1988). There has been considerable debate regarding the source of the observed gravity and geodetic changes at some of these long-lived systems. Numerous studies have concluded magma intrusion is dominant (e.g., Dzurisin, 2003; Wicks et al., 2006), whereas many others have supported changes in the hydrothermal system as the primary mechanisms (e.g., Bonafede and Mazzanti, 1998; Battaglia et al., 2003; Gottsmann et al., 2007). There are also a growing number of studies in which a combination of these sources is thought to be responsible for the observed deformation and gravity variations (e.g., Jousset et al., 2003; Gottsmann et al., 2006).

When these time-lapse studies are integrated with other techniques such as seismicity or remotely sensed volcanic gas fluxes, significant insight can be obtained regarding the processes responsible for these gravity and geodetic changes.

Mount Etna, Italy

The largest active volcano in Europe (3326 m above sea level [a.s.l.]), Mount Etna has been active for at least 500,000 years and has been the center of numerous basaltic effusive and explosive eruptions. Mount Etna poses a significant hazard to the surrounding population (~900,000 people; Andronico and Lodato, 2005) and has thus been the focus of significant geophysical study including routine gravity monitoring since 1986 (e.g., Budetta et al., 1989; Budetta and Carbone, 1998; Budetta et al., 1999; Carbone et al., 2003a). An excellent example of the power of integrated 4D microgravity and precise levelling surveys is that of the 1991 to 1993 major lava eruption at Mount Etna. From 1990 to 1991, microgravity and deformation measurements recorded the intrusion of magma into the summit feeder system and flank fractures (Rymer et al., 1995), which were the source of the 1991–1993 dike eruption. Withdrawal of magma from the summit conduit (1992–1993) and subsequent replenishment (1993–1994) was clearly evidenced by a 170 μGal decrease and 20–70 μGal increase, respectively (Figure 1). In contrast, the lack of any change in gravity in the fracture zone supports the hypothesis that at least 10^7 m^3 of magma cooled and solidified in the fracture system, effectively sealing it so that the 1993–1994 magma replenishment remained within the conduit system (Rymer et al., 1995).

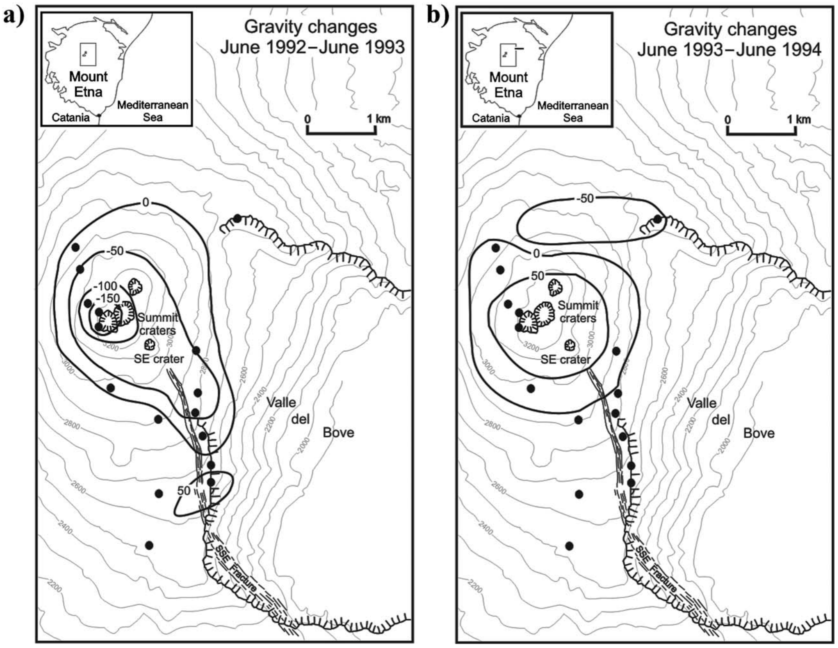

Figure 1. Gravity changes (μGal) at Mount Etna observed between (a) June 1992–June 1993 and (b) June 1993–June 1994. Modified after Rymer et al. (1995).

Another example of the potential of microgravity studies at Etna is seen in the period leading up to the 2001 eruption (Carbone et al., 2003a). Monthly campaigns of discrete gravity measurements detected a mass decrease of 2.5×10^{11} kg occurring during the five months prior to the start of the July 2001 flank eruption within a volume around 2.5 km below sea level. This decrease was followed by a sudden increase, soon after the start of the eruption that, in two weeks, partially compensated for the previous variation. Numerous tensional earthquakes took place during the first half of 2001 within the same source volume, leading Carbone et al. (2003a) to conclude the gravity decrease observed before the eruption reflected medium rarefaction by tectonic tensile stresses along a pre-existing rift zone. Magma was emplaced along the newly formed path from a deep storage zone to higher levels of Etna's plumbing system, setting off the eruption and causing the gravity increase observed soon after its start.

Masaya volcano, Nicaragua

The integration of remotely sensed geochemical data with 4D microgravity and deformation data has also proven powerful in investigating shallow processes at persistently active volcanoes. Masaya (635 m a.s.l.) is a persistently active basaltic shield volcano and caldera complex (~10 × 6 km in diameter) that is believed to have formed between 6500 and 2250 years BP by a series of large basaltic ignimbrites (Williams, 1983; Girard and van Wyk de Vries, 2005). Recent activity at Masaya is characterized by persistent degassing from a pit crater within the basaltic cone, Nindiri. Since 1993, microgravity and SO_2 gas flux measurements have been made annually and show an inverse relationship with significant gravity decreases (up to 70 μGal/yr) coinciding with periods of increased degassing and vice versa (Figure 2). These repeated changes in microgravity and SO_2 gas flux are likely caused by the formation and oscillation of a gas-rich vesiculated zone immediately beneath the summit craters leading to a significant density contrast detected as gravity change at the surface (Rymer et al., 1998b; Williams-Jones et al., 2003). The cyclic nature of these variations and lack of any significant broad gravity increase or deformation discount intrusion of new magma into the shallow plumbing system. Rather, this supports either blockage and accumulation of gas resulting from restrictions in the volcano substructure or the convective overturn of shallow degassed and denser magma that is replaced periodically by lower density, gas-rich magma from depth (Williams-Jones et al., 2003).

Krafla and Askja volcanoes, Iceland

Insight into the deeper processes controlling volcanic activity can be attained from integrated 4D microgravity and geodetic (precise levelling, GPS, and InSAR) studies, such as at the Krafla volcano, Iceland (Rymer et al., 1998a; de Zeeuw-van Dalfsen et al., 2006). The Krafla volcanic complex consists of a low basaltic shield volcano (20 km in diameter) and summit caldera (8 × 10 km) transected by a 10 × 100 km fissure swarm. Askja is a large central volcano comprising several nested calderas, the most recent one (1875) being 5 km across. Askja lies within a 10–15 km-wide fissure zone, to the southeast of Krafla. Results from microgravity and deformation studies at Askja show that deflation in the period of 1988–2003 reached a maximum of 0.46 m in the center of the caldera relative to a station outside the caldera. The source of deformation is inferred to be at ~3-km depth and a recent study infers a second deeper source at ~16-km depth. The deflation is consistent with a subsurface volume change of $0.018\ \mathrm{km}^3$. The observed microgravity decrease across the caldera corresponds to a subsurface mass decrease of 1.6×10^{11} kg between 1988 and 2003. The data were interpreted in terms of a combination of magma drainage and the cooling and contraction of the shallow magma reservoir at 3 km with extensional tectonic forces generating space in the ductile part of the crust to accommodate ongoing magma drainage from the shallow magma chamber (Rymer and Tryggvason, 1993; de Zeeuw-Van Dalfsen et al., 2005).

Similar data at Krafla revealed significant mass decreases (2×10^{10} kg/yr) beneath the center of the caldera reflecting drainage rates of $0.2 \pm 0.04\ \mathrm{m}^3/\mathrm{s}$. The similarity of this drainage rate to that of nearby Askja volcano ($0.13 \pm 0.03\ \mathrm{m}^3/\mathrm{s}$) and evidence for a second deeper stacked magma reservoir led the authors to suggest the possibility of lower crust pressure-links between the two volcanic systems (Rymer et al., 1998a; de Zeeuw-van Dalfsen et al., 2006).

Central Volcanic Complex, Tenerife, Spain

The recent reawakening of the Central Volcanic Complex (CVC), Tenerife, Spain, in 2004 after an almost century-long period of quiescence demonstrates that time-lapse microgravity monitoring of active volcanoes can provide vital and unique insights into their subsurface dynamics. This is particularly important when structural complexities and heterogeneous mechanical properties of the subsurface do not obey a simple linearly elastic relationship of stress generation and resultant ground deformation. A 14-month survey at the complex resolved significant mass migration at depth that was not accompanied by significant ground deformation (Gottsmann et al., 2006). By combining GPS, gravimetric, and seismic data, the cause of unrest was attributed to the release and upward migration of hot fluids resulting from a possible deep disturbance of the magmatic system. Such a phenomenon can be a common trigger of reactivation after long repose periods and can be quantifiable by perturbations in the gravity field but cannot induce widespread ground deformation.

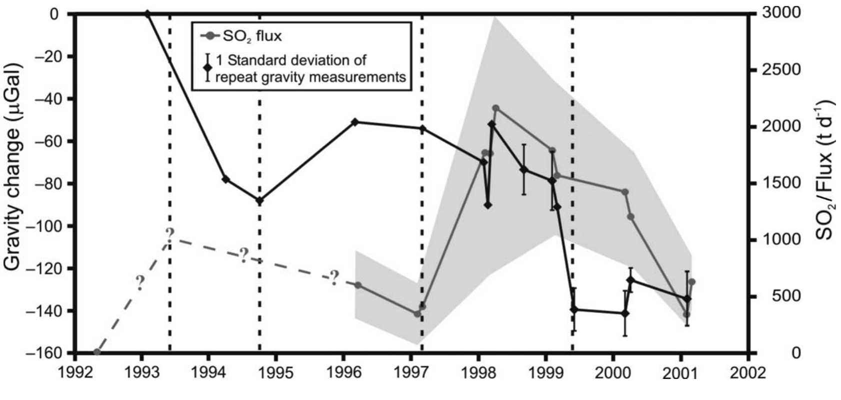

Figure 2. Average monthly gravity change (black diamonds) at a representative crater rim station compared with average monthly SO_2 flux (gray circles) at Masaya. Gray-shaded region represents one standard deviation of SO_2 flux values (~30%). Dashed lines denote five possible stages of activity between 1992 and 2001. Modified after Williams-Jones et al. (2003).

Campi Flegrei, Italy

One of the caldera systems that is most notable for persistent noneruptive unrest is the Campi Flegrei caldera (8–12 km in diameter), which formed during two major explosive collapse events at 37 and 12 ka, along with numerous smaller eruptions in the last 10,000 years (Rosi et al., 1983). Most notable is its continuous ground subsidence for the last 2000 years marked by periods of rapid inflation at up to 1 m/yr (Dvorak and Berrino, 1991; Dvorak and Gasparini, 1991). Many of the numerous bradyseismic events (slow long-lived vertical deformation with alternating uplift and subsidence; Casertano et al., 1976) that occur at Campi Flegrei are thought to be influenced by magmatic degassing (Chiodini et al., 2003), which, along with gravity modeling, supported magma intrusion as a likely mechanism for this unrest (Berrino et al., 1984; Dvorak and Berrino, 1991). However, the gravity and deformation data can also be explained by changes within the hydrothermal system (Bonafede and Mazzanti, 1998; Battaglia et al., 2006). More detailed 3D modeling of this data also suggests mass and pressure changes within a magma body (~5 km deep) and shallower hydrothermal system (~2 km deep) can equally explain the changes during inflation and rapid deflation between 1982 and 1984, whereas slow deflation from 1985 to 2001 is entirely hydrothermal in origin (Gottsmann et al., 2006). This inference is supported also by a numerical study taking into account structural discontinuities (boundary faults) at the caldera during geodetic data modeling (Folch and Gottsmann, 2006). However, the 1982-1984 Campi Flegrei case history is a classic example of the bias of data interpretation on employed data modeling. The limited geodetic data collected during this period are insufficient to provide wider insights into the dynamics of the caldera (Gottsmann et al., 2003; 2006).

CONTINUOUS MICROGRAVITY

An inevitable drawback of the discrete 4D approach is the fact that information on the rates of subsurface processes are restricted by the frequency of repeat surveys that can be made (rarely more than once per day and often only once per year). As mentioned above, magmatic and other subvolcanic processes occur over multiple timescales, with long-lived volcanic systems showing various types of activity on decadal to annual to monthly timescales. At persistently active volcanoes such as Masaya or Stromboli (Italy), rapid, short-term changes will be “missed” between annual surveys. Recent high temporal multiparameter monitoring campaigns at volcanoes have shown significant variations on the daily and hourly scales, which is particularly important for eruption forecasting (Branca et al., 2003; Gottsmann et al., 2007; Johnson et al., 2007). Any inference about continuous processes occurring over shorter intervals is constrained by the Nyquist limit, i.e., only the frequencies in the waveform below half the sampling frequency will be recorded (see Battaglia et al., 2008, for further discussion). To investigate these changes over a range of timescales, it is therefore necessary to monitor the systems continuously and at a high temporal resolution for extended periods of time.

In contrast to the discrete 4D spatial microgravity survey, continuous gravity measurements are made at a single location for an extended period of time. This has been done routinely for many years in tidal and geothermal gravity studies using superconducting instruments (e.g., Goodkind, 1986; Hunt et al., 2002). Absolute and superconducting gravity meters can be integrated with discrete 4D monitoring to improve the accuracy of the 4D surveying at the microgal to submicrogal levels (e.g., Yamamoto et al., 2001; Imanishi et al., 2004), which has obvious applications to volcanic activity. Although the temporal resolution of these continuous studies is excellent, the spatial resolution is currently limited because of installation and instrumentation costs such that, in the case of volcano monitoring, typically measurements are made at only one or two locations on a given volcano. Furthermore, although it can often be somewhat problematic to conduct a discrete 4D microgravity survey on an active volcano (e.g., Vigouroux et al., 2008), it becomes especially difficult to maintain these continuously recording instruments in such harsh conditions for extended periods of time.

Nevertheless, lower-cost spring-based gravity meters equipped for digital capacitive measurements (e.g., LaCoste and Romberg, Scintrex, EDCON, and ZLS; Harrison and Sato, 1984; Bonvalot et al., 1998; Pálinkás, 2007) with microgal resolution are now being used in continuous mode to investigate changes at a few active volcanoes. Preliminary results using only one or two continuously recording instruments, sometimes in concert with a traditional microgravity survey, illustrates the wealth of information on the rates and timing of subsurface mass movements that can be gleaned from even a crude attempt at continuous gravity data analysis (e.g., Jousset et al., 2000; Branca et al., 2003; Carbone et al., 2003b).

Mount Etna, Italy

Four-dimensional microgravity surveys have been made at the Mt. Etna volcano since 1986 and have led to the detection of numerous gravity variations linked to a variety of types of volcanic eruptions (Rymer et al., 1995; Budetta et al., 1999; Carbone et al., 2003a). Since 1998, three spring gravimeters (LaCoste and Romberg) have been installed on the flanks of the volcano so that Mt. Etna is now one of only a few volcanoes in the world with a network consisting of more than one permanently installed continuous gravity meter (Branca et al., 2003; Carbone et al., 2003b; 2006; 2007).

Of particular interest was the detection of precursory gravity changes leading up to the 2002-2003 eruption of Mt. Etna. Because of the logistical difficulties of maintaining a continuous network, only one station (PDN, 1 km from eruptive fractures) was operating at the time. Nevertheless, a 2.5-month-long continuous gravity time series, bracketing the starting period of the eruption, was acquired (Carbone et al., 2007). The start of the eruption on the northeastern flank was marked by a rapid gravity decrease of 400 μGal in less than one hour, followed immediately by a gravity increase at a rate of ~100 μGal/hr to near-background levels (Figure 3; Branca et al., 2003). This anomaly was interpreted as being a result of the tectonic opening of a fracture system along the northeastern rift and subsequent magma intrusion from the central conduit toward the lower-elevation eruptive vents. Following the start of activity, three smaller-amplitude anomalies (10–30 μGal decrease) were observed to occur simultaneously with increases in the amplitude of volcanic tremor detected by the seismic network. Detailed analysis of this data showed a clear inverse correlation between gravity decrease and tremor increase, suggesting a joint source. The fact that these smaller anomalies coincide with transitional periods from intense lava fountaining to mild Strombolian activity suggests they can be caused by accumulation of a low-density gas cloud within the shallow volcanic plumbing system (Carbone et al., 2006).

Masaya volcano, Nicaragua

The persistent volcanic activity at Masaya is characterized by changes in the rates of degassing and variations in the level of magma within the shallow plumbing system. Evidence of this can be seen from the various lava lakes and pit craters that make up the presently active basaltic cones (Williams-Jones et al., 2003). As mentioned above, discrete 4D gravity measurements at Masaya have shown a link between volcanic degassing and mass and/or density variations on timescales of months to years (Rymer et al., 1998; Williams-Jones et al., 2003). Although a plausible mechanism invokes convective overturn of cooler, denser, degassed magma with renewal by hot, buoyant, gas-rich magma, questions arose concerning the possibility of shorter-term variations not detected in the annual 4D survey (Bonvalot et al., 1998).

The logistical difficulties of a permanent network on an active volcanic system are exemplified by the case of the Masaya volcano. Since Masaya is a national park, access to the summit craters is very easy via a paved road. However, the extremely corrosive environment caused by persistent acid degassing limits the ability to continuously measure deformation, although annual campaign GPS surveys show no significant changes. Furthermore, it is difficult to fully secure the instrument in a structure that is sufficiently resistant to the acid gases while also remaining sensitive to the concerns of the park officials (e.g., visibility of structures within the crater, possible unwanted access by tourists, etc.)

Notwithstanding these issues, short (2–3 week) continuous experiments have been made at Masaya since 2006 with the aim of investigating very short-term variations (hours to days) within the shallow substructure (Mauri et al., 2007). Two preliminary data sets (corrected for Earth tide, ocean loading, instrument drift, atmospheric pressure, and temperature variations) collected in 2006 and 2007 showed periodic changes on the order of 60–90 μGal over approximately 26 hours. This raises the possibility that discrete 4D gravity surveys can be significantly affected by the time at which a given measurement is made because these short-term changes are of the same magnitude as those observed in our annual surveys (Williams-Jones et al., 2003; Gottsmann et al., 2005). However, the lack of a secondary meter to constrain nonvolcanic signals currently limits unambiguous interpretations. This can be rectified in future campaigns with the temporary installation of a second continuously recording meter outside the area of gravity change (observed by annual 4D surveys). Nevertheless, assuming the observed changes are volcanic in origin, Masaya's characteristic activity suggests that the likely hypotheses to investigate for these short-term variations are rapid oscillation of the level of magma (Shimozuru, 1987) and rapid changes in gas vesiculation within the magma (Connor et al., 1988) resulting from tidal forcing.

4D COLLABORATIVE GRAVITY NETWORK

The difficulty for one researcher or institution to have multiple instruments can be overcome through the formation of a network of researchers able to pool instruments with the goal of a multi-instrument and multitemporal study of active volcanoes or calderas in a state of unrest. By establishing an international network, more instruments will be available for each campaign than any single institution can obtain on its own. Following comparison of the gravity meters on a gravity-calibration line (e.g., Becker et al., 1995), the instruments would be deployed together as an integrated monitoring system, providing broad spatial coverage and recording data at intervals of between one minute and one hour (depending on volcanic activity) for periods of a few weeks (initially). The establishment of such a network would thus provide measurements with a good temporal and spatial resolution, because several instruments will be making measurements simultaneously. Although collaborative networks of like-minded scientists have the potential to facilitate campaign-style continuous gravity studies, it is clear that permanent installations are required to effectively monitor persistently active hazardous volcanoes.

TOWARD A TRUE 4D VOLCANO NETWORK

Volcanologists are acutely aware of the need for high-resolution temporal and spatial data to understand the mechanisms controlling magma emplacement and pressurization of the volcanic system prior to an eruption. In conjunction with this, there is also the need for longer time-series data and near-real-time analysis to investigate long-lived systems in a state of unrest. Although it is impossible to prevent a volcanic eruption, precursory changes within the system can allow for eruption forecasting and risk mitigation.

Nisyros, Greece

The benefits of an integrated, multiparameter approach are exemplified in the recent investigations of Nisyros caldera, Greece. The Nisyros caldera, which formed during a large eruption approximately 25 ka BP, is characterized by widespread hydrothermal activity (fumaroles, hot springs, mudpools) and numerous phreatic explosion craters. During the execution of discrete 4D gravity surveys in 2003 and 2004, rapid residual-gravity changes (tens of minutes) were detected within the shallow hydrothermal system (Gottsmann et al., 2005). To further investigate these variations, simultaneous geodetic, seismic, electromagnetic, and gravimetric data were col-

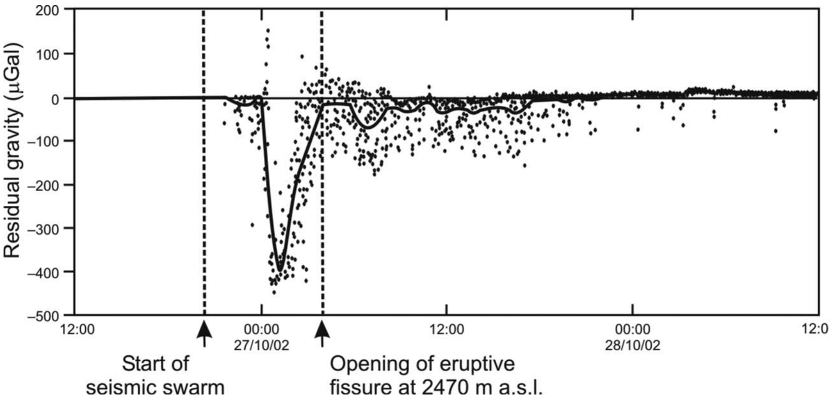

Figure 3. Residual-gravity sequence acquired at station PDN, Mount Etna, Italy, from October 27–28, 2002 encompassing the start of the 2002-2003 eruption. A best linear fit and theoretical Earth tide have been removed. Solid curve represents a low-pass filter applied to the signal to enhance the main gravity change with respect to the strong background noise. Dashed lines mark the start of the seismic swarm before the eruption and the opening of the eruptive fissures at 2470 m a.s.l. Modified after Branca et al. (2003).

lected during a ten-day campaign (Gottsmann et al., 2007). Rapid short-term changes in gravity, on the order of 40–60 minutes, had amplitudes of 20–30 μGal and were seen in conjunction with seismic bursts and rapid ground deformation (Figure 4). This suggests that quantifiable subsurface processes dominate this caldera during background behavior. The importance of this study lies in the fact that if such background dynamics are not quantified, deviations are very difficult to assess and any information on causes of the deviation remains ambiguous. As a consequence, recorded geodetic or other geophysical signals during unrest might not be able to identify the causative source of unrest, i.e., changes in the shallow hydrothermal system or deeper-seated magmatic processes such as replenishment. At Nisyros, the data indicate the system is governed by shallow aqueous fluid movement within the hydrothermal system. Specifically, the data can be best explained by thermohydromechanical changes caused by the release and upward migration of hydrothermal fluids during anomalous degassing of a deeper magmatic reservoir (Gottsmann et al., 2007). It is important to note that signals from magmatic processes need to exceed the background signals to be detected. To achieve this, it is important to simultaneously perform discrete 4D microgravimetry over a larger area to capture deeper-seated magmatic processes. Failure to discriminate between shallow hydrothermal and deep magmatic contribution to volcanic unrest can lead to unrealistic inferences as to the causative source if deep magmatic processes are exclusively regarded as causes of unrest.

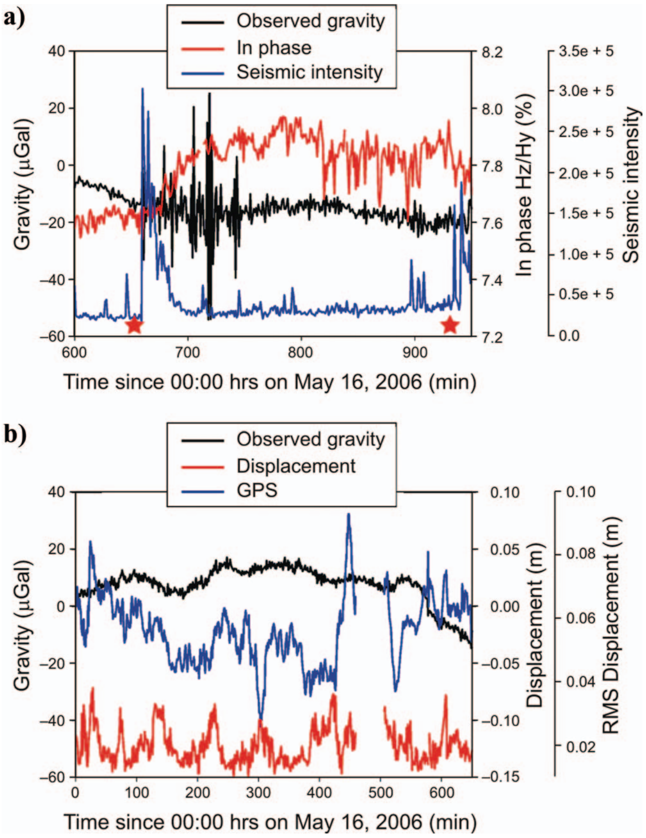

Figure 4. Continuous gravity, GPS, VLF, and seismicity from the Nisyros caldera, Greece, on May 16, 2006. (a) Includes signals caused by the arrival of surface waves at min 659 from a Mw = 7.4 seismic event (10:39 UTC) at the Kermadec Islands and a Mw = 6.8 earthquake in the Nias region of Indonesia approximately five hours later marked by red stars. The VLF in-phase (20.8 kHz) record displays a break in slope about 15–20 minutes later indicating a change in the electrical properties of the subsurface. (b) Shows periodic oscillations in observed gravity and GPS data over approximately 10 hours including several spikes and troughs in the GPS record, which cannot be explained by artifacts or poor satellite coverage. GPS data are reported relative to a reference located outside the caldera. The GPS root-mean-square (rms) error is below 0.03 m for these events. During the observation period, the weather was sunny and dry. Air pressure and temperature were recorded for tropospheric corrections. Modified after Gottsmann et al. (2005).

Kīlauea volcano, Hawaii

Kīlauea volcano, on the island of Hawaii, is one of the world's best-monitored volcanoes, with spatially extensive and long-lived continuous deformation and seismic networks, and frequent geologic and gas emission measurements (Heliker et al., 2003). As such, Kīlauea provides an excellent example of what can be achieved though long-duration multiparameter volcano monitoring. Included in the monitoring of Kīlauea are discrete 4D microgravity surveys dating back to 1975. Gravity measurements at Kīlauea have been collected concurrently with deformation data, allowing for the determination of mass changes at depth beneath the volcano (Dzurisin et al., 1980; Jachens and Eaton, 1980; Johnson, 1987; Johnson, 1992; Kauahikaua and Miklius, 2003).

Since 1983, Kīlauea has erupted almost continuously from the Pu‘u ‘Ō‘ō-Kupaianaha vent system on the volcano's east rift zone, about 17 km from the summit. During the eruption, gravity surveys have identified periods of magma accumulation (1983–1985 and 1991–1993), magma withdrawal (1992–2002), and no (or minor) net change in magma storage beneath the summit (1985–1991). In all time periods, however, mass changes beneath the summit are only a few percent of the total lava effusion, supporting the model that magma feeding the eruption is not supplied from the summit magma reservoir but rather travels through that reservoir from a source at greater depth (Kauahikaua and Miklius, 2003).

Kīlauea experienced a major change in eruption style in mid-2007, when a one-day outbreak of lava occurred about halfway between the summit and Pu‘u ‘Ō‘ō. Effusive activity at Pu‘u ‘Ō‘ō paused and the crater floor at Pu‘u ‘Ō‘ō collapsed as a result of the diversion of magma to the new vent. Within a few weeks, lava returned to Pu‘u ‘Ō‘ō, only to drain again upon the formation of another vent 2 km to the east. The new vent remained the eruptive center of Kīlauea as of early 2008 (Poland et al., 2008). As the focus of the eruption shifted in location during 2007, the summit of Kīlauea experienced dramatic changes in deformation style. The summit inflated between January and June (as magma accumulated beneath the summit), rapidly subsided during June 17–19 (as magma from the summit fed an intrusion and eruption uprift of Pu‘u ‘Ō‘ō), inflated during June 19–July 20 (when the eruption returned to Pu‘u ‘Ō‘ō), and deflated during July 21 through to the end of the year (when the eruption shifted downrift of Pu‘u ‘Ō‘ō; see Figure 3a in Poland et al., 2008).

Discrete gravity data are insufficient to resolve the complex history of mass changes in the summit magma reservoir in 2007 because of the relative infrequency of measurements, yet gravity data are critical to resolving the dynamics or subsurface magma transport at Kīlauea. For example, models of InSAR data, spanning the June 17–19 summit deflation, suggest a volume loss of $1–2\times10^6$ m^3. However, they also show a corresponding volume increase of 15 $\times10^6$ m^3 in the east rift zone where the new eruptive vent formed

(Poland et al., 2008). The discrepancy in volumes raises the possibility that the new eruptive vent was fed both by the summit magma reservoir and a second source. Elastic models of deformation, however, do not take magma compressibility into account, and therefore underestimate the actual amount of subsurface volume change (Johnson, 1992; Johnson et al., 2000). As a result, it is possible that more magma left the summit reservoir at Kīlauea and less magma intruded at the site of the new vent during June 17–19 than is suggested by deformation data alone, thereby reducing the discrepancy between summit volume loss and east rift volume gain.

To map such rapid changes in mass at Kīlauea, continuous gravity recordings, collocated with continuous deformation measurements (preferably by GPS), are required at multiple sites around both the summit and eruptive vent. A gravity meter was installed together with a broadband seismometer (in a vault) on the crater rim near the Hawaiian Volcano Observatory (HVO) and has been continuously recording since February 2007. During the summer of 2008, a small continuous gravity network is scheduled for deployment at Kīlauea (National Science Foundation grant to Rensselaer Polytechnic Institute, PIs: Anahita Tikku, ExxonMobil/Rensselaer Polytechnic Institute; Steve Roecker, Rensselaer Polytechnic Institute; Michael Poland, U. S. Geological Survey). Sites will be installed at the HVO, on the caldera floor above a modeled shallow (within several hundred meters of the surface) region of magma storage (Cervelli and Miklius, 2003), in the south caldera above the 2.5-km-deep long-term site of summit magma storage (Cervelli and Miklius, 2003), and at Pu'u 'Ō'ō. The network is designed to map gravity changes associated with multiple summit magma reservoirs and at the eruption site. Results from this network will be used to calculate mass changes within Kīlauea's shallow volcanic system and should capture short-term transient activity in unprecedented detail, allowing for better estimates of volumes of magma accumulation and withdrawal than are currently available from deformation data alone.

Real-time modeling

This vastly increased data quality and quantity available for modeling will lead to more robust interpretation. However, modeling at present uses at best simple 3D bodies with rather few physical parameters as variables. To achieve the resolution of gravimetric time series required to assess causative sources, factors need to be addressed: Gravimetric observations on volcanic islands suffer from absence of accurate ocean-load models to predict ocean-loading effects. Although this is not a serious concern in the Mediterranean, for example, other volcanoes under gravimetric investigation such as Merapi, Indonesia (Jousset et al., 2000; Tiede et al., 2005), Teide, Spain (Gottsmann et al., 2006), or Soufrière Hills, Montserrat (Fournier et al., 2006) require accurate reduction of gravimetric time series for the effect of ocean loading. At the CVC on Tenerife, ocean-loading effects amounting to 30 μGal were found to be negligible given the larger amplitude of gravity changes between 2004 and 2005. In contrast, a continuously recording gravimeter installed for two weeks near the Soufrière Hills volcano during a phase of dome growth stagnation in 2007 resolved residual ocean-loading effects of up to 10 μGal. With many explosive volcanoes preventing near-site installation of gravimeters (resulting in a decrease in the signal amplitude with distance), these effects require quantification to deduce the residual gravimetric signal because of changes in the magmatic plumbing system over periods matching periodicities of ocean loading (~12 hours).

Hydrologic phenomena, such as variations in the water table, contribute significantly to residual-gravity changes at volcanoes. Although dependent on medium permeability, as a rule of thumb, changing the level of a shallow water table by half a meter can result in residual changes on the order of 10 μGal (see Battaglia et al. [2008] for further discussion). At the CVC, the continuous monitoring of groundwater levels allowed a gravity decrease in the eastern part of the Las Canadas Caldera to be attributed entirely to an overall water-level decrease during the observation period (Gottsmann et al., 2006). Alternatively, geostatistical tools can be applied to deduce the effects of shallow groundwater level variations in areas lacking direct level measurements (Battaglia et al., 2003).

In addition, all model results suffer from the well-known problem of nonuniqueness (Al-Chalabi, 1971) and, combined with the almost infinite number of degrees of freedom in mathematical modeling, this eventually results in an infinite number of possible scenarios to explain the subsurface processes. The only way forward is to compare and correlate integrated geodetic time series with other geophysical or geochemical observations. This coherent assessment will enable identification of a domain of most likely scenarios on which to base inferences as to the causative processes aiding hazard assessment and risk mitigation for future activity.

Thus, a particularly challenging issue is the integration of this multiparameter and multifrequency continuous data feed and development of new modeling packages for near-real-time solutions in terms of subsurface mass movements. The modeling approach must build on recent advances (e.g., Gottsmann et al., 2006) in which dependent variables (e.g., temperature and pressure dependent rheology) and, exceptionally here, a time-dependent data array rather than single points as inputs, are integrated (Battaglia et al., 2008).

Technological advances

Multiparameter studies are fundamental to the detection and determination of the reduction of ambiguities in assessing causative sources. Continuous permanent networks are now required and recent technological advances in the development of low-cost continuous GPS sensors (e.g., Janssen et al., 2002; Chadwick et al., 2006) and seismometers (Wallenstein et al., 2003) are making deformation and seismic networks a reality. The installation of near-continuous scanning volcanic gas sensors is also becoming widespread (Edmonds et al., 2003; Horton et al., 2006; Galle et al., 2007), whereas small infrasound sensors and continuous high-resolution video are showing promise in significantly advancing our understanding of eruption dynamics (Johnson et al., 2007). The development of wireless networks greatly facilitates simultaneous time-synchronized measurements from a distributed network of sensors (Werner-Allen et al., 2005).

Spring-based land gravity meters have traditionally been analog, requiring manual readings with resulting precisions of tens of μGal and low observation rates (e.g., Rymer, 1989). The advent of instruments equipped with capacitive or electronic nulling systems and microgal resolution (e.g., Bonvalot et al., 1998) has substantially increased our ability to conduct high-precision discrete and continuous gravity surveys over extended periods of time. However, to make a true 4D gravity network a reality, substantial reductions in the cost, size, and energy requirements of gravity meters are necessary. Development work is currently underway to produce low-cost instruments that will be used as permanently installed arrays, continuously recording gravity (Rymer et al., 2002; Rymer and Matela, 2004). The usual constraints of temporal resolution at the expense of spatial resolution and vice versa would be overcome and streamed gravity data could then be combined with satellite- and ground-based deformation data (InSAR and GPS) remotely. A substantial advantage would be that once installed, the array would require minimal maintenance. Since cost (both of instrumentation and more importantly, man power) is the main restriction on gravity measurements, new and valuable data will be available through the expansion of real-time continuous gravity arrays. Within the next five to ten years, we anticipate these measurements to become routine at many volcano observatories.

CONCLUSIONS

An in-depth understanding of the physical processes responsible for volcanic activity can be achieved only through the integration of multitemporal geophysical and geochemical techniques. Microgravity studies have proven to be crucial in the determination of magma and/or gas migration within a magmatic system and volcanic edifice in the period leading up to an eruption. Deployment of an array of gravity instruments transmitting data in real-time with near-real-time data analysis would increase the scope for monitoring immeasurably as a principal component of a seismic, gas, video, and infrasound network. A new chapter in volcano monitoring will be opened, because continuous 4D gravity data will, for the first time, allow the rate of subsurface mass and/or density changes to be quantified in near-real-time for an unambiguous assessment of the sources of volcanic phenomena.

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REFERENCES

Al-Chalabi, M., 1971, Some studies relating to nonuniqueness in gravity and magnetic inverse problems: Geophysics, **36**, 835–855, doi: 10.1190/1.1440219.

Andronico, D., and L. Lodato, 2005, Effusive activity at Mount Etna volcano (Italy) during the 20th century: A contribution to volcanic hazard assessment: Natural Hazards, **36**, 407–443.

Battaglia, M., J. Gottsmann, D. Carbone, and J. Fernández, 2008, 4D volcano gravimetry: Geophysics, **73**, this volume.

Battaglia, M., P. Segall, and C. Roberts, 2003, The mechanics of unrest at Long Valley caldera, California: 2. Constraining the nature of the source using geodetic and micro-gravity data: Journal of Volcanology and Geothermal Research, **127**, 219–245.

Battaglia, M., C. Troise, F. Obrizzo, F. Pingue, and G. De Natale, 2006, Evidence for fluid migration as the source of deformation at Campi Flegrei caldera (Italy): Geophysical Research Letters, **33**, doi: 10.1029/2005GL024904.

Becker, M., et al., 1995, Microgravimetric measurements at the 1994 international comparison of absolute gravimeters: Metrologia, **32**, 145–152, doi: 10.1088/0026-1394/32/3/002.

Berrino, G., G. Corrado, G. Luongo, and B. Toro, 1984, Ground deformation and gravity changes accompanying the 1982 Pozzuoli uplift: Bulletin of Volcanology, **47**, 187–200.

Bonafede, M., and M. Mazzanti, 1998, Modelling gravity variations consistent with ground deformation in the Campi Flegrei caldera (Italy): Journal of Volcanology and Geothermal Research, **81**, 137–157.

Bonvalot, S., M. Diament, and G. Gabalda, 1998, Continuous gravity recording with Scintrex CG–3M meters: A promising tool for monitoring active zones: Geophysical Journal International, **135**, 470–494.

Branca, S., D. Carbone, and F. Greco, 2003, Intrusive mechanism of the 2002 NE-Rift eruption at Mt. Etna (Italy) inferred through continuous microgravity data and volcanological evidence, Geophysical Research Letters, **30**, 2077, doi: 10.1029/2003GL018250.

Budetta, G., and D. Carbone, 1998, Temporal variations in gravity at Mt. Etna (Italy) associated with the 1989 and 1991 eruptions: Bulletin of Volcanology, **59**, 311–326.

Budetta, G., D. Carbone, and F. Greco, 1999, Subsurface mass redistribution at Mount Etna (Italy) during the 1995–96 explosive activity detected by microgravity studies, Geophysical Journal International, **138**, 77–88.

Budetta, G., M. Grimaldi, and G. Luongo, 1989, Variazioni di gravita‘nell’area etnea (1986–1989): Bollettino del Gruppo Nazionale per la Vulcanologia, **5**, 137–146.

Caltabiano, T., R. Romano, and G. Budetta, 1994, SO_2 flux measurements at Mount Etna (Sicily): Journal of Geophysical Research, **99**, 12809–12819.

Carbone, D., G. Budetta, and F. Greco, 2003a, Bulk processes prior to the 2001 Mount Etna eruption, highlighted through microgravity studies: Journal of Geophysical Research, **108**, 2556, doi: 10.1029/2003JB002542.

Carbone, D., G. Budetta, F. Greco, and H. Rymer, 2003b, Combined discrete and continuous gravity observations at Mount Etna: Journal of Volcanology and Geothermal Research, **123**, 123–135.

Carbone, D., G. Budetta, F. Greco, and L. Zuccarello, 2007, A data sequence acquired at Mt. Etna during the 2002–2003 eruption highlights the potential of continuous gravity observations as a tool to monitor and study active volcanoes: Journal of Geodynamics, **43**, 320–329.

Carbone, D., and H. Rymer, 1999, Calibration shifts in a LaCoste-and-Romberg gravimeter; Comparison with a Scintrex CG-3M: Geophysical Prospecting, **47**, 73–83.

Carbone, D., L. Zuccarello, G. Saccorotti, and F. Greco, 2006, Analysis of simultaneous gravity and tremor anomalies observed during the 2002–2003 Etna eruption, Earth and Planetary Science Letters, **245**, 616–629.

Casertano, L., A. Oliveri, and M. T. Quagliarello, 1976, Hydrodynamics and geodynamics in the Phlegraean Fields area of Italy: Nature, **264**, 161–164.

Cervelli, P. F., and A. Miklius, 2003, The shallow magmatic system of Kilauea volcano: U. S. Geological Survey Professional Paper, **1676**, 149–163.

Chadwick, W. W., D. J. Geist, S. Jonsson, M. Poland, D. J. Johnson, and C. M. Meertens, 2006, A volcano bursting at the seams: Inflation, faulting, and eruption at Sierra Negra volcano, Galapagos: Geology, **34**, 1025–1028, doi: 10.1130/G22826A.1.

Chiodini, G., M. Todesco, S. Caliro, C. Del Gaudio, G. Macedonio, and M. Russo, 2003, Magma degassing as a trigger of bradyseismic events: The case of Phlegrean Fields (Italy): Geophysical Research Letters, **30**, 1434.

Chouet, B., 1996, Long-period volcano seismicity: Its source and use in eruption forecasting: Nature, **380**, 309–316.

Connor, C. B., R. E. Stoiber, and L. L. Malinconico, 1988, Variation in sulfur dioxide emissions related to Earth tides, Halemaumau crater, Kilauea volcano, Hawaii: Journal of Geophysical Research, **93**, 14867–14871.

de Zeeuw-van Dalfsen, E., H. Rymer, F. Sigmundsson, and E. Sturkell, 2005, Net gravity decrease at Askja volcano, Iceland: Constraints on processes responsible for continuous caldera deflation, 1988–2003. Journal of Volcanology and Geothermal Research, **139**, 227–239.

de Zeeuw-van Dalfsen, E., H. Rymer, G. Williams-Jones, E. Sturkell, and F. Sigmundsson, 2006, Integration of micro-gravity and geodetic data to constrain shallow system mass changes at Krafla Volcano, N. Iceland: Bulletin of Volcanology, **68**, 420–431, doi: 10.1007/s0445-005-0018-5.

Dvorak, J. J., and G. Berrino, 1991, Recent ground movement and seismic activity in Campi Flegrei, southern Italy: Episodic growth of a resurgent dome: Journal of Geophysical Research, **96**, 2309–2323.

Dvorak, J. J., and P. Gasparini, 1991, History of earthquakes and vertical ground movement in Campi Flegrei caldera, southern Italy: Comparison of precursory events to the A. D. 1538 eruption of Monte Nuovo and of activity since 1968: Journal of Volcanology and Geothermal Research, **48**, 77–92.

Dzurisin, D., 2003, A comprehensive approach to monitoring volcano deformation as a window on the eruption cycle: Reviews of Geophysics, **41**, 1001, doi: 10.1029/2001RG000107.

Dzurisin, D., L. A. Anderson, G. P. Eaton, R. Y. Koyanagi, P. W. Lipman, J. P. Lockwood, R. T. Okamura, G. S. Puniwai, M. K. Sako, and K. M. Yamashita, 1980, Geophysical observations of Kilauea volcano, Hawaii: 2. Constraints on the magma supply during November 1975-September 1977: Journal of Volcanology and Geothermal Research, **7**, 241–269.

Edmonds, M., R. A. Herd, B. Galle, and C. Oppenheimer, 2003, Automated, high time-resolution measurements of SO_2 flux at Soufrière Hills volcano, Montserrat: Bulletin of Volcanology, **65**, 578–586.

Eggers, A. A., 1987, Residual gravity changes and eruption magnitudes:

Journal of Volcanology and Geothermal Research, **33**, 201–216.

Elias, T., and A. J. Sutton, 2002, Sulfur dioxide emission rates from Kilauea Volcano, Hawai‘i, an update: 1998–2001: U. S. Geological Survey Open-File Report, 02–460.

Folch, A., and J. Gottsmann, 2006, Faults and ground uplift at active calderas: Geological Society, London, Special Publications, **269**, 109–120, doi: 10.1144/GSL.SP.2006.269.01.07.

Fournier, N., J. Gottsmann, and R. Sparks, 2006, Mass and density changes associated with the ongoing eruption of Soufrière Hills volcano, Montserrat (W. I.) via a new joint elevation and microgravity network: Eos, Transactions, American Geophysical Union, **87**, V51A-1649.

Galle, B., U. Platt, M. Van Roozendael, C. Oppenheimer, T. Hansteen, G. Boudon, M. Burton, H. Delgado, W. Strauch, and E. Duarte, 2007, NOVAC-Network for observation of volcanic and atmospheric change, first installations and results: Eos, Transactions, American Geophysical Union, **88**, V44A-04.

Girard, G., and B. van Wyk de Vries, 2005, The Managua Graben and Las Sierras-Masaya volcanic complex (Nicaragua); pull-apart localisation by an intrusive complex: Results from analogue modelling: Journal of Volcanology and Geothermal Research, **144**, 37–57.

Goodkind, J. M., 1986, Continuous measurement of nontidal variations of gravity: Journal of Geophysical Research, **91**, 9125–9134.

Gottsmann, J., G. Berrino, H. Rymer, and G. Williams-Jones, 2003, Hazard assessment during caldera unrest at the Campi Flegrei, Italy: A contribution from gravity-height gradients: Earth and Planetary Science Letters, **211**, 295–309.

Gottsmann, J., R. Carniel, N. Coppo, L. Wooller, S. Hautmann, and H. Rymer, 2007, Oscillations in hydrothermal systems as a source of periodic unrest at caldera volcanoes: Multiparameter insights from Nisyros, Greece: Geophysical Research Letters, **34**, L07307, doi: 10.1029/2007GL029594.

Gottsmann, J., A. Folch, and H. Rymer, 2006, Unrest at Campi Flegrei: A contribution to the magmatic versus hydrothermal debate from inverse and finite element modeling: Journal of Geophysical Research, **111**, 7203, doi: 10.1029/2005JB003745.

Gottsmann, J., H. Rymer, and L. K. Wooller, 2005, On the interpretation of gravity variations in the presence of active hydrothermal systems: Insights from the Nisyros caldera, Greece: Geophysical Research Letters, **32**, L23310, doi: 10.1029/2005GL024061.

Gottsmann, J., L. K. Wooller, J. Martí, J. Fernández, A. G. Camacho, P. J. Gonzalez, A. Garcia, and H. Rymer, 2006, New evidence for the reawakening of Teide volcano: Geophysical Research Letters, **33**, L20311, doi: 10.1029/2006GL027523.

Harrison, J. C., and T. Sato, 1984, Implementation of electrostatic feedback with a LaCoste-Romberg Model G gravity meter: Journal of Geophysical Research, **89**, 7957–7961.

Heliker, C., J. Kauahikaua, D. R. Sherrod, M. Lisowski, and P. F. Cervelli, 2003, The rise and fall of Pu’u’ō’Ō cone, 1983–2002: U. S. Geological Survey Professional Paper, **1676**, 29–51.

Horton, K., G. Williams-Jones, H. Garbeil, T. Elias, A. J. Sutton, P. Mouginis-Mark, J. N. Porter, and S. Clegg, 2006, Real-time measurement of volcanic SO_2 emissions: Validation of a new UV correlation spectrometer (FLYSPEC): Bulletin of Volcanology, **68**, 323–327, doi: 10.1007/s00445-005-0014-9.

Hunt, T., M. Sugihara, T. Sato, and T. Takemura, 2002, Measurement and use of the vertical gravity gradient in correcting repeat microgravity measurements for the effects of ground subsidence in geothermal systems: Geothermics, **31**, 525–543.

Imanishi, Y., T. Sato, T. Higashi, W. Sun, and S. Okubo, 2004, A network of superconducting gravimeters detects submicrogal coseismic gravity changes: Science, **306**, 476–478, doi: 10.1126/science.1101875.

Jachens, R. C., and G. P. Eaton, 1980, Geophysical observations of Kilauea volcano, Hawaii: 1. Temporal gravity variations related to the 29 November, 1975, $M = 7.2$ earthquake and associated summit collapse: Journal of Volcanology and Geothermal Research, **7**, 225–240.

Janssen, V., C. Roberts, C. Rizos, and H. Z. Abidin, 2002, Low-cost GPS-based volcano deformation monitoring at Mt. Papandayan, Indonesia: Journal of Volcanology and Geothermal Research, **115**, 139–151, doi: 10.1016/S0377-0273(01)00312-2.

Johnson, D. J., 1987, Elastic and inelastic magma storage at Kilauea volcano: U. S. Geological Survey Professional Paper, **1350**, 1297–1306.

Johnson, D. J., 1992, Dynamics of magma storage in the summit reservoir of Kilauea volcano, Hawaii: Journal of Geophysical Research, **97**, 1807–1820.

Johnson, D. J., F. Sigmundsson, and P. T. Delaney, 2000, Comment on “Volume of magma accumulation or withdrawal estimated from surface uplift or subsidence with application to the 1960 collapse of Kilauea volcano,” P. T. Delaney and D. F. McTigue, authors: Bulletin of Volcanology, **61**, 491–493.

Johnson, J. B., N. Varley, R. Sanderson, A. Gerst, J. Lees, M. Dalton, O. Marcillo, S. Every, J. Normand, and M. Ruiz, 2007, Eruption dynamics at the active Santiaguito Dome inferred from a multidisciplinary geophysical experiment: Eos, Transactions, American Geophysical Union, **88**, V41B-07.

Jousset, P., S. Dwipa, F. Beauducel, T. Duquesnoy, and M. Diament, 2000, Temporal gravity at Merapi during the 1993–1995 crisis: An insight into the dynamical behaviour of volcanoes: Journal of Volcanology and Geothermal Research, **100**, 289–320.

Jousset, P., H. Mori, and H. Okada, 2003, Elastic models for the magma intrusion associated with the 2000 eruption of Usu volcano, Hokkaido, Japan: Journal of Volcanology and Geothermal Research, **125**, 81–106.

Kauahikaua, J., and A. Miklius, 2003, Long-term trends in microgravity at Kīlauea’s summit during the Pu’u’ō’Ō-Kũpaianaha eruption: U. S. Geological Survey Professional Paper **1676**, 165–171.

La Delfa, S., G. Patane, R. Clocchiatti, J.-L. Joron, and J.-C. Tanguy, 2001, Activity of Mount Etna preceding the February 1999 fissure eruption: Inferred mechanism from seismological and geochemical data: Journal of Volcanology and Geothermal Research, **105**, 121–139, doi: 10.1016/S0377-0273(00)00249-3.

Locke, C. A., H. Rymer, and J. Cassidy, 2003, Magma transfer processes at persistently active volcanoes: Insights from gravity observations: Journal of Volcanology and Geothermal Research, **127**, 73–86.

Mauri, G., G. Williams-Jones, and G. Saracco, 2007, Short-term dynamic behaviour of Masaya volcano by geophysical surveys: Cordilleran Section — Geological Survey of America, 23–7.

McNutt, S., 2000, Seismic monitoring, *in* H. Sigurdsson, B. Houghton, S. McNutt, H. Rymer, and J. Stix, eds., Encyclopedia of volcanoes: Academic Press, 1095–1119.

Mogi, K., 1958, Relations between the eruptions of various volcanoes and the deformations of the ground surfaces around them: Bulletin of the Earthquake Research Institute, **36**, 99–134.

Neuberg, J., R. Luckett, B. Baptie, and K. Olsen, 2000, Models of tremor and low-frequency earthquake swarms on Montserrat: Journal of Volcanology and Geothermal Research, **101**, 83–104, doi: 10.1016/S0377-0273(00)00169-4.

Newhall, C. A., and D. Dzurisin, 1988, Historical unrest at large calderas of the world: U. S. Geological Survey Bulletin, **1855**, 1108.

Okada, Y., 1992, Internal deformation due to shear and tensile faults in a half-space: Bulletin of the Seismological Society of America, **82**, 1018–1040.

Okubo, S., and H. Watanabe, 1989, Gravity change caused by a fissure eruption: Geophysical Research Letters, **16**, 445–448.

Oppenheimer, C., 1998, Volcanological applications of meteorological satellites: International Journal of Remote Sensing, **19**, 2829–2864.

Pálinkás, V., 2007, Experiences with the ZLS Burris gravimeter: Geophysical Research Abstracts, **9**, 06897.

Poland, M., A. Miklius, T. Orr, J. Sutton, C. Thornber, and D. Wilson, 2008, New episodes of volcanism at Kilauea volcano, Hawaii: Eos, Transactions, American Geophysical Union, **89**, 37–38.

Rosi, M., A. Sbrana, and C. Principe, 1983, The Phlegraean Fields: Structural evolution, volcanic history and eruptive mechanisms: Journal of Volcanology and Geothermal Research, **17**, 273–288.

Rymer, H., 1989, A contribution to precision microgravity data analysis using LaCoste and Romberg gravity meters: Geophysical Journal, **97**, 311–322.

Rymer, H., and G. C. Brown, 1989, Gravity changes as a precursor to volcanic eruptions at Poás volcano, Costa Rica: Nature, **342**, 902–905.

Rymer, H., J. Cassidy, C. A. Locke, and J. B. Murray, 1995, Magma movements in Etna volcano associated with the major 1991–1993 lava eruption: Evidence from gravity and deformation: Bulletin of Volcanology, **57**, 451–461.

Rymer, H., J. Cassidy, C. A. Locke, and F. Sigmundsson, 1998a, Post-eruptive gravity changes from 1990 to 1996 at Krafla volcano, Iceland: Journal of Volcanology and Geothermal Research, **87**, 141–149.

Rymer, H., B. van Wyk de Vries, J. Stix, and G. Williams-Jones, 1998b, Pit crater structure and processes governing persistent activity at Masaya Volcano, Nicaragua: Bulletin of Volcanology, **59**, 345–355.

Rymer, H., C. A. Locke, J. Brenes, and G. Williams-Jones, 2005, Magma plumbing processes for persistent activity at Poás volcano, Costa Rica: Geophysical Research Letters, **32**, L08307, doi: 10.1029/2004GL022284.

Rymer, H., and R. J. Matela, 2004, Gravity meter: U.S. Patent US6 68 646.

Rymer, H., R. J. Matela, and M. A. Davies, 2002, Gravity meter: U. K. Patent GB2376751.

Rymer H., and E. Tryggvason, 1993, Gravity and elevation changes at Askja, Iceland: Bulletin of Volcanology, **55**, 362–371.

Shimozuru, D., 1987, Tidal effects on Hawaiian volcanism: U. S. Geological Survey Professional Paper, **1350**, 1337–1344.

Simkin, T., and L. Siebert, 1994, Volcanoes of the world: Geoscience Press, Inc.

Simkin, T., and L. Siebert, 2002, Volcanoes of the world: An illustrated catalog of Holocene volcanoes and their eruptions: Global volcanism program digital information series, GVP-3, Smithsonian Institution, http://www.volcano.si.edu/world/.

Simkin, T., L. Siebert, and R. Blong, 2001, Volcano fatalities — Lessons from the historical record: Science, **291**, 255.

Stix, J., 2007, Stability and instability of quiescently active volcanoes: The case of Masaya, Nicaragua: Geology, **35**, 535–538, doi: 10.1.130/G23198A.1.

Tiede, C., A. G. Camacho, C. Gerstenecker, J. Fernandez, and I. Suyanto, 2005, Modeling the density at Merapi volcano area, Indonesia, via the inverse gravimetric problem: Geochemistry Geophysics Geosystems, **6**, Q09011, doi: 10.1029/2005GC000986.

Vigouroux, N., G. Williams-Jones, W. W. Chadwick, D. J. Geist, A. Ruiz, and D. J. Johnson, 2008, Gravity changes associated with the 2005 eruption of Sierra Negra volcano, Galapagos: Geophysics, **73**, this issue.

Wallenstein, N., A. Montalvo, U. Barata, and R. Ortiz, 2003, The implementation of a volcano seismic monitoring network in Sete Cidades Volcano, São Miguel, Açores: EGS-AGU-EUG Joint Assembly.

Werner-Allen, G., J. Johnson, M. Ruiz, J. Lees, and M. Welsh, 2005, Monitoring volcanic eruptions with a wireless sensor network, presented at the Proceedings of the Second European Workshop on Wireless Sensor Networks.

Wicks, C. W., W. Thatcher, D. Dzurisin, and J. Svarc, 2006, Uplift, thermal unrest and magma intrusion at Yellowstone caldera: Nature, **440**, 72–75, doi: 10.1038/nature04507.

Williams, S. N., 1983, Plinian airfall deposits of basaltic composition: Geology, **11**, 211–214.

Williams-Jones, G., H. Rymer, and D. A. Rothery, 2003, Gravity changes and passive SO_2 degassing at the Masaya caldera complex, Nicaragua: Journal of Volcanology and Geothermal Research, **123**, 137–160.

Witham, C. S., 2005, Volcanic disasters and incidents: A new database: Journal of Volcanology and Geothermal Research, **148**, 191–233, doi: 10.1016/j.jvolgeores.2005.04.017.

Wright, R., L. P. Flynn, H. Garbeil, A. J. L. Harris, and E. Pilger, 2004, MODVOLC: Near-real-time thermal monitoring of global volcanism: Journal of Volcanology and Geothermal Research, **135**, 29–49.

Yamamoto, K., K. Ishihara, S. Okubo, and A. Araya, 2001, Accurate evaluation of ocean tide loading effects for gravity in nearshore region: the FG5 measurements at Sakurajima volcano in Kagoshima Bay, Japan: Geophysical Research Letters, **28**, 1807–1810.

Yang, K., N. A. Krotkov, A. J. Krueger, S. A. Carn, P. K. Bhartia, and P. F. Levelt, 2007, Retrieval of large volcanic SO_2 columns from the Aura ozone monitoring instrument: Comparison and limitations: Journal of Geophysical Research, **112**, D24S43, doi: 10.1029/2007JD008825.

Yokoyama, I., and H. Tajima, 1957, A gravity survey on Volcano Mihara, Ooshima Island by means of a Worden gravimeter: Bulletin of the Earthquake Research Institute, **35**, 23–33.