Magma transfer processes at persistently active volcanoes: insights from gravity observations

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Abstract

Magma transfer processes at persistently active volcanoes are distinguished by the large magma flux required to sustain the prodigious quantities of heat and gas emitted at the surface. Although the resulting degassed magma has been conjectured to accumulate either deep within the volcanic edifice or in the upper levels of the sub-edifice system, no direct evidence for such active accumulation has been reported. Temporal gravity data are unique in being able to quantify mass changes and have been successfully used to model shallow magma movements on different temporal scales, but have not generally been applied to the investigation of postulated long-term accumulation of magma at greater spatial scales within volcanic systems. Here, we model the critical data acquisition parameters required to detect mass flux at volcanoes, we review existing data from a number of volcanoes that exemplify the measurement of shallow mass changes and present new data from Poas and Telica volcanoes. We show that if a substantial proportion of degassed magma lodges within the sub-edifice region, it would result in measurable annual to decadal gravity increases occurring over spatial scales of 10's of kilometers and propose that existing microgravity data from Sakurajima, and possibly Etna, volcanoes could be interpreted in these terms. Furthermore, such repeat microgravity data could be used to determine whether the accumulation rate is in equilibrium with the rate of production of degassed magma as calculated from the surface gas flux and hence identify the build up of gas-rich magma at depth that may be significant in terms of eruption potential. We also argue that large magma bodies, both molten and frozen, modelled beneath volcanoes from seismic and gravity data, could represent endogenous or cryptic intrusions of degassed magma based on order of magnitude calculations using present-day emission rates and typical volcano lifetimes.

Keywords: Persistently active volcanoes; gravity change; magma movement; magma accumulation

1. Introduction

Persistent activity at a volcano connotes the continuous release of significant amounts of volatiles and heat energy over a long period of time i.e. hundreds or even thousands of years. This activity may manifest in a number of different ways, for example: persistent passive degassing (e.g. at Etna; Allard, 1997), hot acidic crater lakes (at Poas; Rymer et al., 2000), lava lakes (e.g. at Erebus, Erta `Ale, Nyiragonga; Harris et al., 1999) or high-temperature fumarole fields (e.g. at Momotombo; Menyailov et al., 1986). The nature of activity at persistently active volcanoes is such that although large amounts of energy are fluxed at the surface through the emission of gas and heat, there is relatively little associated mass loss. For example, during its most vigorous phase in 20 years of observations, Etna fluxed only 5.5 x 10^3 tonnes/day of SO_2 (Allard, 1997). The essential characteristic of persistently active volcanoes (irrespective of how that activity manifests) is that significant surface activity is maintained at low mass-flux levels for long periods of time.

The occurrence of such activity at volcanoes raises a number of questions: firstly, regarding the mechanism by which the transport of large quantities of energy (in the form of gas or heat) to the surface is maintained and secondly, regarding the fate of the magma that must be degassing to provide the prodigious quantities of gas emitted. Several models have been developed from thermodynamical calculations and laboratory experiments (Stevenson and Blake, 1998; Jaupart and Vergniolle, 1988) to explain the mechanisms by which energy and gas can be transported to the summit of a volcano for extended periods of time, without the system stagnating. Models invoke a process of convective overturn where relatively gas-rich magma rises up buoyantly through a conduit system, degassing as it rises, the gas escaping either into the atmosphere directly or into an overlying hydrothermal system. This degassed magma then becomes denser due the loss of volatiles and decrease in temperature and descends (Stevenson and Blake, 1998). It has been shown to be theoretically possible to maintain a thin pathway of magma open for extended periods of time in such a conduit (e.g. Stevenson & Blake, 1998; Kazahaya et al., 1994; Jaupart & Vergniolle, 1988).

Typical magma residence times of 10-100s years deduced for several basaltic volcanoes (e.g. Gauthier et al., 2000, Pietruszka and Garcia, 1999) suggest that for surface activity at these volcanoes to be maintained over periods of 100-1000 years, a continuous input of new magma is required (Francis et al., 1993). This is endorsed by radionuclide data from the plume from Mt Etna from 1983-1995 that indicate a continuous supply of undegassed magma must have been available (Le Cloarec and Pennisi, 2001). Measurements of the amount of gas lost from such a volcano can be used to estimate the volume of parental magma that must have been degassed; for example, SO_2 plume emissions from Mt Etna from 1975-1995 indicate that 3.5-5.9 km^3 of basalt were degassed for sulfur, only 10-20% of which was erupted (Allard, 1997). It has been proposed that the unerupted degassed magma forms sub- and/or intra-volcanic intrusive complexes (Andres et al., 1991; Francis et al., 1993; Allard et al., 1994; Harris and Stevenson, 1997; Allard, 1997; Oppenheimer and Francis, 1998), accommodated by deformation (Francis et al., 1993).

Thus, the processes at persistently active volcanoes may include convective overturn within a conduit system and final accumulation of degassed magma at depth. These processes can occur over a range of time scales. Magma levels in a volcanic conduit will typically respond over days or months to magma influx or withdrawal (Rymer and Brown, 1987), or in the case of strombolian activity may reflect variations in magma level over even shorter periods. In contrast, the accumulation of degassed magma at depth will occur over years or decades. All these processes involve subsurface mass changes and hence might be investigated using gravity techniques. For example, short time-scale (seconds to years) magma movements within shallow conduit systems have been detected directly using geophysical methods (Rymer et al., 2000; Jousset et al., 2000a). Direct detection of the accumulation of degassed magma at depth has never been reported, but this approach has been advocated (Francis et al., 1993; Harris et al., 1999). However frozen magma bodies (possibly resulting from such accumulation) have been modelled within or below the edifices of a number of stratovolcanoes (Locke and Cassidy, 1997; Rymer and Brown, 1987; Williams and Finn, 1986).

In this paper we seek to exemplify the applicability of microgravity data at different temporal and spacial scales in investigating the processes of magma transport at persistently active volcanoes. We show that the process of accumulation of degassed magma at depths of a few kilometres should be resolvable using such techniques and re-interpret the significance of both some existing time series data and results from static gravity modelling.

2. Gravity effects of mass-flux processes at persistently active volcanoes

2.1. Processes in upper conduit systems

Magma levels in volcanic conduits typically vary over periods of days or months according to the magma pressure in the feeder system though at volcanoes exhibiting strombolian activity, magma levels could be expected to vary more rapidly (minutes or hours) as a result of rapid bubble growth, accumulation and collapse. The effectiveness of microgravity measurements in detecting mass changes depends in principle on the depth at which these mass changes occur and their magnitude but also in practice on having an appropriate sampling rate. Sampling strategies can be optimised by utilising theoretical modelling of gravity changes that would result from changes in the level of the magma/air or magma/foam interface within a conduit. In Figure 1, the magnitude and wavelength of such gravity effects have been calculated for a series of models based on Etna Volcano, Italy (Rymer et al., 1995). At the topographic surface, gravity effects of up to several hundred μGal occur close to vent for typical vertical magma movements as reported by Rymer et al. (1995), but decrease rapidly with horizontal distance from the conduit (Fig. 1).

Given that the microgravity technique can typically resolve changes down to about ± 20 μGal (Rymer, 1989), the maximum radius of detection is about 500m from the centre of the active crater. This limited spatial extent of detectable anomalies and the very high horizontal gravity gradients (up to 3 μGal/m) are important considerations that must be taken into account in planning microgravity campaigns.

As a comparison, Figure 2 shows the gravity effects likely to result from mass changes as might be expected at a smaller volcano such as Stromboli (based on models from Harris et al., 1996). The magnitudes of these gravity effects are similar near the active crater but diminish more rapidly with distance, mainly as a consequence of the geometry of the smaller cone. Arguably the modelled mass changes are conservative, but even these result in gravity effects that are measurable within about 200m of the active crater using standard microgravity techniques (Rymer, 1989).

A further consideration is the time period over which mass changes may occur. Case studies (discussed later) exemplify gravity changes that occur over periods of months or years. However in the case of strombolian activity, it has been postulated that mass changes can occur over much shorter periods; for example at Stromboli, activity has been modelled in terms of the bursting of large gas pockets (Blackburn et al., 1976, Vegniolle and Brandeis, 1996) that would cause the magma level in the conduit (and associated mass changes) to oscillate relatively rapidly. Such a mechanism is consistent with the seismic and infrasonic data (Vergniolle and Brandeis, 1996; Ripepe, 1996; Vergniolle et al., 1996; Ripepe and Gordeev, 1999). Ripepe and Braun (1994) suggest that these oscillations may occur over periods of only 10's – 100's of minutes and hence gravity observations would need to be made at intervals of a few minutes i.e effectively continuously. Continuous gravity recording has the advantage that it can usually resolve variations to considerably better than 20 μGal (Jousset et al., 2000a) and hence would be a more effective technique of observing magma movements at volcanoes such as Stromboli. However the calculations here show that any recording station would need to be established within a few hundred metres of the active crater, which may not be feasible logistically.

2.2 Deeper processes within or below the volcanic edifice

Substantial magma influx at greater depth below persistently active volcanoes is predicted on the basis that a continuous supply of new magma is necessary to sustain active degassing (Francis et al., 1993). The rate of production of degassed magma provides of course, a minimum estimate of the magma supply rate since magma may be intruded without being degassed. This magma (both gas-rich and degassed) could accumulate either within or below the edifice. Whether there are observable gravity changes due to this magma influx will depend primarily on whether a resultant mass change occurs, but also on the depth and degree of localisation of the intrusion.

Table 1 presents the maximum gravity effects at several persistently active volcanoes for the minimum influx of magma, based on the observed rate of production of degassed magma. Maximum gravity values are calculated (on-axis) assuming a point mass and that the entire mass influx contributes to the measured gravity anomaly i.e. the intrusion is entirely accommodated by the filling of fractures/voids, compression of host rocks or deformation. The width of detectable anomalies will depend on both the total mass and the lateral mass distribution, but assuming the most compact mass distribution (ie a small spherical body), the widths of the detectable anomalies would range from 2-30 km for depths to the source of 2-10 km.

3. Examples of observed gravity effects of mass flux processes at persistently active volcanoes – new and existing data

Repeat microgravity observations have been made over about two decades at a number of persistently active volcanoes. Existing data from Etna, Sakurajima, Komagatake, Izu-Oshima, Masaya and Poas are reviewed here and new data are presented for Poas and Telica volcanoes. In all cases, changes in the elevations of the gravity stations are negligible (generally <10 cm i.e. comparable to the error in the gravity measurements) and have been accounted for in the analysis of the gravity data. The techniques used in data collection are described in Rymer (1989).

3.1 Etna Volcano

Mount Etna, Sicily, is a large basaltic stratovolcano which has exhibited ongoing summit and flank eruptions for several centuries (Chester et al., 1985). It is one of the world's most actively degassing volcanoes where degassing has occurred both during and between eruptions (Allard et al., 1991). Since the major eruption between 1991-93 which generated about 250 x10^6 m^3 of new lava flows (Stevens et al., 1997), activity has ranged from vigorous degassing to strombolian activity and the eruption of further lava flows.

Microgravity observations in the summit area of Etna Volcano (Rymer et al., 1993; Rymer et al., 1995) recorded gravity increases (up to 400 μGal) within 500m of the active crater prior to the 1991 eruption which were interpreted as magma levels rising in the shallow conduit to within 200 m of the surface. Gravity values in this area then decreased (up to 200 μGal) between 1991-3 and increased again (up to 70 μGal) between 1993-4; these changes were similarly interpreted as the magma level falling by 500 m at the end of the 1991-3 eruption and then rising 400 m again prior to recommencement of eruptive activity in 1994. All these gravity changes were focussed within 500m of the active crater emphasising the point that to observe shallow mass re-distributions, measurements must be made close to the active crater (cf Fig. 1). Data extending 2 km southeast from the crater showed increases of up to 150 μGal, interpreted as magma filling the 1989 fissure prior to the 1991 eruption (Rymer et al., 1995). At the end of the eruption these gravity values remained constant indicating that the magma had solidified within the fissure.

In contrast, broader (> 30 km wide) repeat microgravity surveys of Etna (Budetta et al., 1999) show mass changes within the edifice at about 1000 m asl. A gravity increase of 40 μGal, modelled as a mass increase of 2 x 10^{10} kg, occurred between September 1994 and October 1995, however between October 1995 and July 1996 the anomaly appeared to shift to the SSE (Budetta et al., 1999). These data were interpreted as mass either having migrated SSE or being withdrawn to a depth beyond the resolution of the data and further magma intruded. These 1994-1996 changes occurred at a time of increased strombolian activity at the volcano (Armienti et al., 1996). Also between October 1995 and November 1996, a broad (10 km wide) gravity increase of 80 μGal was identified (Budetta et al., 1999) in the southeast quadrant of the volcano. This was interpreted as a deeper mass increase of 1.5 x 10^{11} kg at 2-3 km depth below sea level. However, further observations from 1997 to 1999 (Carbone et al., 2003) show a comparable gravity decrease indicating that the plumbing dynamics are complex.

Gravity data on Etna are notable therefore in showing mass flux variations on many different spatial and temporal scales. Best resolved are those associated with fluctuating magma level changes in shallow conduits, observed generally within a limited spatial extent of the central vents and strongly correlated with eruptive activity. However, broader scale changes in gravity indicating deeper magma movements have been defined also.

3.2 Sakurajima Volcano

Sakurajima Volcano, southern Kyushu, is a large andesite stratocone which has been nearly constantly active (mostly with Strombolian eruptions) since AD 708, (Simkin and Seibert, 1994). The volcano has been vigorously active since 1955 ejecting ash and gas. Microgravity changes between 1975 and 1982 show an increase over the entire island (to a maximum of 80 μGal) and are interpreted in terms of a mass increase of 3×10^{11} kg at a depth of 3 km (Yokoyama, 1989).

3.3 Komogatake Volcano

Activity at Komogatake Volcano, Hokkaido, an andesite stratovolcano, has been characterised by phreatic and plinian eruptions (Jousset et al., 2000b). The most recent eruptions in 1996 and 1998 were very short in duration (less than 2 min). Microgravity observations between May 1997 and November 1997 showed a localised (within c.1km of the summit crater) gravity increase (15-20 μGal ± 10 μGal) which correlated with an increased heat flux. Between November 1997 and May 1998 the temperature anomaly peaked at 30 ^{o}C and an edifice-wide increase of up to 15 μGal occurred together with a crater-wide decrease of the same order (Jousset et al., 2000b). These data were interpreted in terms of a mass intrusion of about 10^{11} kg at 4-5 km depth, with this new hot magma heating the overlying hydrothermal system causing phreatic eruptions and a mass loss through evaporation.

3.4 Izu - Oshima Volcano

Repeat microgravity measurements after the 1986 fissure eruption of Izu-Oshima Volcano, a basaltic stratovolcano, show significant variations (>100 μGal) at the summit station, 550m from the centre of the crater (Watanabe et al., 1998). These variations have been modelled (Watanabe et al., 1998) in terms of variations in the magma level in the central conduit; for example, gravity decreases (70 μGal) between November 1986 and August 1987 are interpreted as magma draining back below a perched lava lake. Gravity increased between August and October 1987 (by 30 μGal) indicating that the magma level rose, which is corroborated by the simultaneous increase in activity at the surface. The subsequent collapse and drainage of the lava lake was accompanied initially by little gravity change indicating that the magma remained at high levels in the conduit. A later gravity decrease of ~45 μGal is interpreted as a lowering of the magma level in the conduit.

3.5 Masaya Volcano

Masaya Volcano, Nicaragua is a large basaltic shield volcano which has exhibited several cycles of pyroclastic cone building eruptions, lava flows and pit crater formation (Rymer et al., 1998). In historical times, lava lakes have been common and two lava flows have been erupted (1670 and 1772). A number of vents have been active during this time with vigorous degassing and episodic fire fountaining and lava lake formation.

Microgravity data at Masaya Volcano recorded between 1993-1997 (Rymer et al., 1998) show that gravity increases (up to 60 μGal) occurred at stations 700 – 5000 m from the crater from 1993-1997 with similar increases at stations closer to the crater from 1994-1997; localised gravity decreases (up to 200 μGal) having occurred at stations within 700m of the active crater between 1993 and 1994. These data suggest that mass changes may be occurring at two different depths within the volcano. A local shallow (<500m depth, Rymer et al., 1998) mass decrease must have occurred within the conduit between 1993 and 1994, and in addition a deeper mass increase may have occurred throughout the measurement period. The uniformity of the gravity increases at stations over a 5000 m extent indicates this mass increase probably occurred at depths greater than 1-2 km. If there was a long-term mass increase at depth, the gravity effects of local shallow mass changes will be underestimated. A continuation of this trend is indicated at some stations in more recent data (Williams-Jones, 2001), but these data appear to be more variable i.e. dominated by the effects of local shallow mass changes.

3.6 Poas Volcano

Poas Volcano, Costa Rica, is a large basaltic-andesite stratovolcano with a hot, acidic crater lake and shallow hydrothermal system confined within the region of the active crater. It has been persistently active throughout historical times, undergoing cycles of phreatic and phreato-magmatic activity focussed on the crater lake. The crater lake level fell between 1986 and 1989 and there was an ash eruption in 1989 from the bed of the dried crater lake (Smithsonian Institution, 1989). The lake was dry from 1989-1994 and then began to re-establish in 1994 and has continued to rise to the present day. A uniquely long time-series of microgravity observations in and around the active crater has been made; the results from 1985-1998 (Rymer et al., 2000) are extended here with further data from 1999-2001.

Between 1985 and 1989 gravity increases were observed at all stations south of the crater lake (D1, E1, E3, E5, E6, G1 Fig. 3). After the 1989 eruption, gravity increases at these stations ceased and by 1992 gravity began to decrease, reaching 1985 values at E6, E1 and D1 by 1998 and earlier at E3. The gravity increases were interpreted as reflecting a rise in magma level in the upper part of the conduit system. After the 1989 eruption the magma pressure reduced and the magma level dropped, draining completely by 1991 from peripheral conduits in the west (E3) and later (1993) from the east (D1).

The new data (Fig. 3) show gravity decreases, which started at E1 in 1994 and at D1, E6 and G1 around 1997, to continue at G1 and D1 to 2001 whereas since 1998 values at E1 and E6 have either remained constant or oscillated at about 50 μGal below 1985 levels. This suggests that magma has continued to withdraw from the area peripheral to the dome but the magma levels immediately below the dome appear to have been stable since 1997. This is evidenced also by the fact that while the crater lake has remained hot (40-50^{o}C), the dome has become fumarolically very active during the last 2 years with considerable sulphur deposition and dome collapse due to high pressure and temperature gases corroding the structure. This suggests that the magma level is still high and degassing straight through the dome and lake.

Data at stations north of the crater lake (D2, D2a and D3) showed consistent gravity decreases between 1985 and 1991 that were interpreted as due to a falling water table (Rymer et al., 2000). Increases in gravity since 1992 heralded the recovery of the hydrothermal system but pre-dated the re-establishment of the lake. The recent data show that gravity values were stable between 1998-2001 at about the 1985 level.

All these data at Poas Volcano are either on the active dome, or within 200m of it. The gravity observations show that both substantial and subtle variations occur on horizontal scales of 10s-100s m which must result from mass changes within the upper few hundred metres in the cone. Stations on the rim of the crater (500 m from the dome) show little systematic gravity variation throughout the survey period. Thus if deeper processes involving mass changes are occurring, such as the accumulation of dense degassed magma, this must be happening at depths beyond the resolution of this survey.

3.7 Telica Volcano

Telica Volcano, Nicaragua, an andesite stratovolcano, is one of Nicaragua's most active volcanoes and records of intermittent activity go back to the 16th century. Over the period 1994 – 2000 for which we have new microgravity data, Telica developed from very quiet degassing (1993) to a more active phase. Phreatic eruptions in July 1997 reached 800 m elevation and followed a seismic event in June 1997 located at a depth of 6 km below the volcano and a steady increase in seismicity (Smithsonian Institution, 1997). Further gas and ash eruptions occur periodically, usually preceded by increased levels of seismicity. In August 1999 a lava lake was observed in the crater. Degassing through jet-like fumaroles was intense and wall collapse enlarged the crater (Smithsonian Institution, 2000).

The microgravity data (Fig. 4) are referenced to a base station 800 m from the active crater in order to study the shallow processes. In contrast to the data from Poas, microgravity variations at Telica are remarkably consistent over the entire area surveyed, showing net gravity increases (up to about 100 μGal) occurred between June 1994 and March 2000. These data suggest that processes involving localised mass redistribution within a conduit immediately below the active crater are probably absent but that the overall increase in gravity at all stations relative to the base station indicates that there may have been a small mass increase over the total observation period at depths of at least several 100 m.

4. Discussion

Magma transfer processes at persistently active volcanoes occur on a range of spatial and temporal scales (Fig. 5). Processes occurring in upper conduit systems have been successfully investigated at many volcanoes using microgravity techniques. For example, at volcanoes which de-gas but do not exhibit strombolian activity, spatially limited microgravity variations (over months – years) characteristically reflect changes in the magma level in the shallow conduit (as described earlier for Poas). At volcanoes that exhibit strombolian activity, spatially limited microgravity variations will be more complex. In these cases, very short-period gravity variations (minutes - hours) could be expected to result from mass changes associated with bubble formation and collapse, however variations in the magma level due to changes in the deeper magma flux would cause a longer term variation superimposed on the short-term changes. For a convecting system including a surface lava lake, which may be in mass balance for a considerable period of time, no microgravity variations reflecting shallow mass changes may be observed.

Because persistently active volcanoes require a continuous supply of new gas-rich magma, large volumes of degassed magma have either to be accommodated within and/or below the volcanic edifice, or to withdraw to greater depths. We have shown that if a substantial proportion of this degassed magma lodges within or just below the edifice, it would result in measureable annual to decadel gravity increases occurring over spatial scales of 10's of kilometres. Few microgravity surveys have been designed to investigate magma accumulation of this nature but the existing microgravity data from Sakurajima, and possibly Etna, described previously, could be interpreted in these terms.

Furthermore, such accumulation would result in the formation of dense, high seismic velocity bodies underlying volcanoes that have been persistently active for extended periods of time. It is interesting to note therefore that at Etna Volcano, the locus of mass increases modelled from microgravity observations (Budetta et al., 1999) coincides with the high-velocity zones located by seismic tomography at depths below sea level of 0-6 km (Hirn, et al., 1991; Hirn et al., 1997; DeLuca et al., 1997). Also, in the same location, an extensive high-density layer has been modelled from Bouguer gravity data (Loddo et al., 1989). At Izu-Oshima Volcano a high-velocity, high-density layer has been located by seismic studies (Hasegawa et al., 1987) extending down from 2 km below the volcano.

If a process of accumulation of dense degassed magma at shallow levels is common at persistently active volcanoes, the existence of extensive dense shallow intrusions below volcanoes might imply that they have exhibited persistent activity in their history. For example, stratovolcanoes in the Cascades (USA) and in Taranaki (New Zealand) have been shown by gravity studies to have such dense bodies within and below their edifices (Williams and Finn, 1986, Locke and Cassidy, 1997). The modelled masses of these intrusions range from about 1.2 x 10^{15} kg (volume about 400 km^3) in the Cascades to 6 x

10^{14} kg (volume about 200 km^3) at Egmont Volcano. The size of these intrusions is of a similar order of magnitude, for example, to the volume (140-200 km^3) of degassed magma estimated from 15000 years of persistent activity at Izu-Oshima (Kazahaya et al., 1994). Therefore, although these bodies have generally been interpreted (Williams & Finn, 1986; Locke & Cassidy, 1997) as relics of shallow (eruptable) magma storage systems, it is possible that they represent endogenous or cryptic degassed magma intrusions resulting from considerable periods of persistent activity.

That volcanic edifices grow by endogenous intrusion is well known from observations of eroded edifices (e.g. Walker and Eyre, 1995) and from geodetic and seismic monitoring (e.g. Decker 1987), however what proportion of the degassed magma generated by persistent activity might be accommodated by endogenous growth is less well known. Allard (1997) estimates that 10% of the unerupted degassed magma generated at Mt Etna between 1975-1995 could have been accommodated in the edifice. However, rheological modeling (Annen et al., 2001) indicates that intruded dykes could constitute 30% of a volcanic edifice. Given that the edifice volume of Etna Volcano is about 14×10^{11} m^3, and assuming this might comprise 30% dykes (i.e. 4.2×10^{11} m^3), this is equivalent to the unerupted degassed magma estimated to result from about 100-2000 years degassing (Table 1). Thus, the accommodation of degassed magma may contribute significantly to the endogenous growth of edifices and hence may be important in terms of edifice growth, stability and associated hazards.

If, as we suggest here, the accumulation of degassed magma within and below a volcano can be directly measured, this offers a means of monitoring the evolution of a volcanic system. The rate of accumulation of magma determined from repeat microgravity measurements could be compared with estimates of the amount of degassed magma deduced from monitoring of gas and heat output at the surface. An accumulation rate of endogenous or cryptic magma at the same or a slower rate than that estimated from gas/heat measurements would indicate that activity at the volcano is in an equilibrium or decay state, or that degassed magma has withdrawn to depths beyond the resolution of the gravity survey. However, an observed mass accumulation rate significantly greater than that estimated may indicate that gas-rich magma is accumulating at shallow depths. This would imply increased pressurisation in the volcanic conduit and hence a significant increase in the potential for explosive eruption.

Acknowledgments

We thank personnel from INETER, Nicaragua and OVSICORI, Costa Rica, especially Helman Taleno and Jorge Brenes for logistic support, Bill Whittaker for help in the field and Louise Cotterall and John Taylor for assistance with manuscript preparation. We also thank Giovanna Berrino and Gennaro Budetta for valuable comments.

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Table 1
Predicted annual gravity changes at persistently active volcanoes.

Volcano	**Annual magma supply rate required by degassing (kg yr^{-1})**	**Annual gravity change (on axis) for degassed magma accumulation at depth (μGal yr^{-1})**				**Comments**
		2 km depth	**4 km depth**	**6 km depth**	**10 km depth**	
Masaya	1.9×10^{11} (a)	300	80	40	13	Annual changes measurable
Izu-Oshima	3.2×10^{12} (b)	5300	1300	600	210	Annual or monthly changes measurable.
Stromboli	$9.5 \times 10^{9} – 4.1 \times 10^{10}$ (c)	16 – 68	4 - 16	2 - 8	1 – 3	Changes measurable over 5-10 years
Vulcano	$1.3 \times 10^{9} – 1.2 \times 10^{10}$ (d)	2 – 19	1 - 6	0 - 2	0 – 2	Changes measurable over 10-20 years
Etna	$5 \times 10^{11} – 8 \times 10^{12}$ (e,f)	800 – 13000	210 - 3300	95 - 1500	30 - 530	Annual changes measurable

Annual gravity changes calculated (on-axis) from the magma mass inputs (at the given depths) required to maintain the observed rates of degassing at selected persistently active volcanoes. References: (a) Stoiber et al 1986; (b) Kazahaya et al., 1994; (c) Harris and Stevenson 1997; (d) Harris and Stevenson, 1997; (e) Allard, 1997; (f) LeCloarec and Pennisi, 2001.

Figures and captions

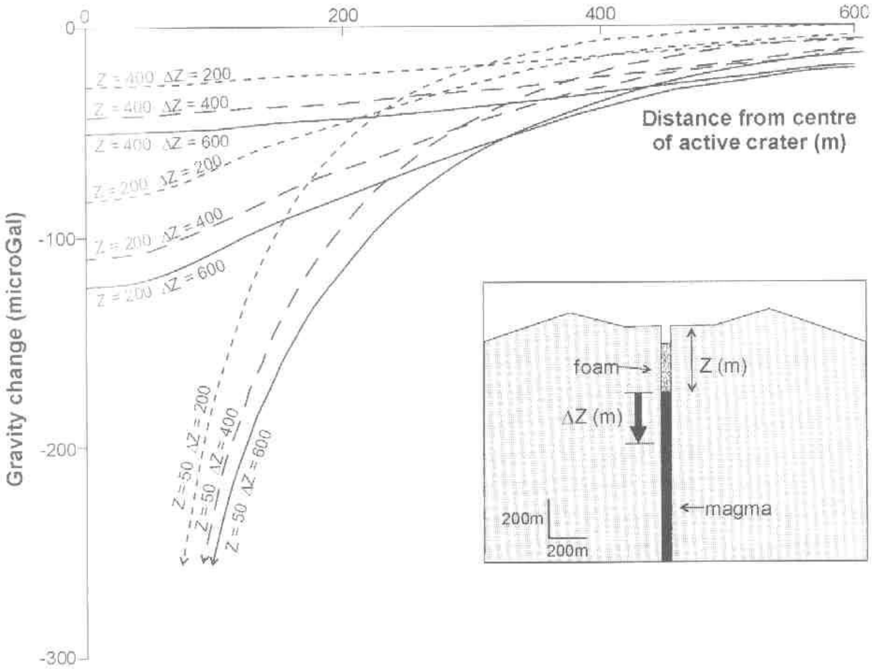

Fig. 1. Calculated gravity effects versus horizontal distance from central vent for a series of models of vertical magma movement (withdrawal) in a shallow conduit system (shown schematically in inset) based on Etna Volcano (Rymer et al., 1995). The modelled conduit diameter is 50m and the assumed density contrast between magma and foam is 2000 kg m^{-3} (note: calculations are made at the topographic surface and the level of the top surface of foam is kept constant).

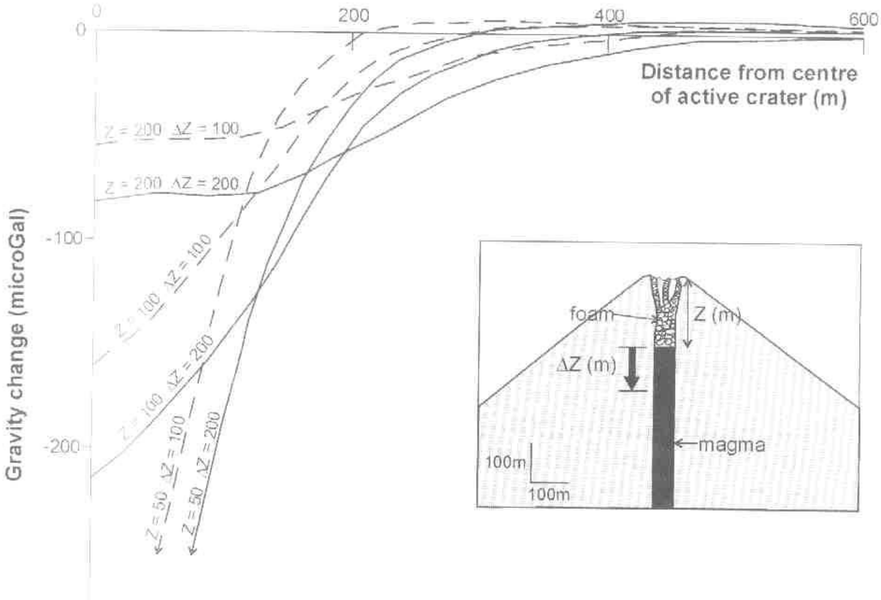

Fig. 2. Calculated gravity effects versus horizontal distance from central vent for a series of models of vertical magma movement (withdrawal) in a shallow conduit system (shown schematically in inset) based on Stromboli Volcano (Harris et al., 1996). The modelled conduit diameter is 50m and the assumed density contrast between magma and foam is 2000 kg m^{-3} (note: calculations are made at the topographic surface and the level of the top surface of foam is kept constant).

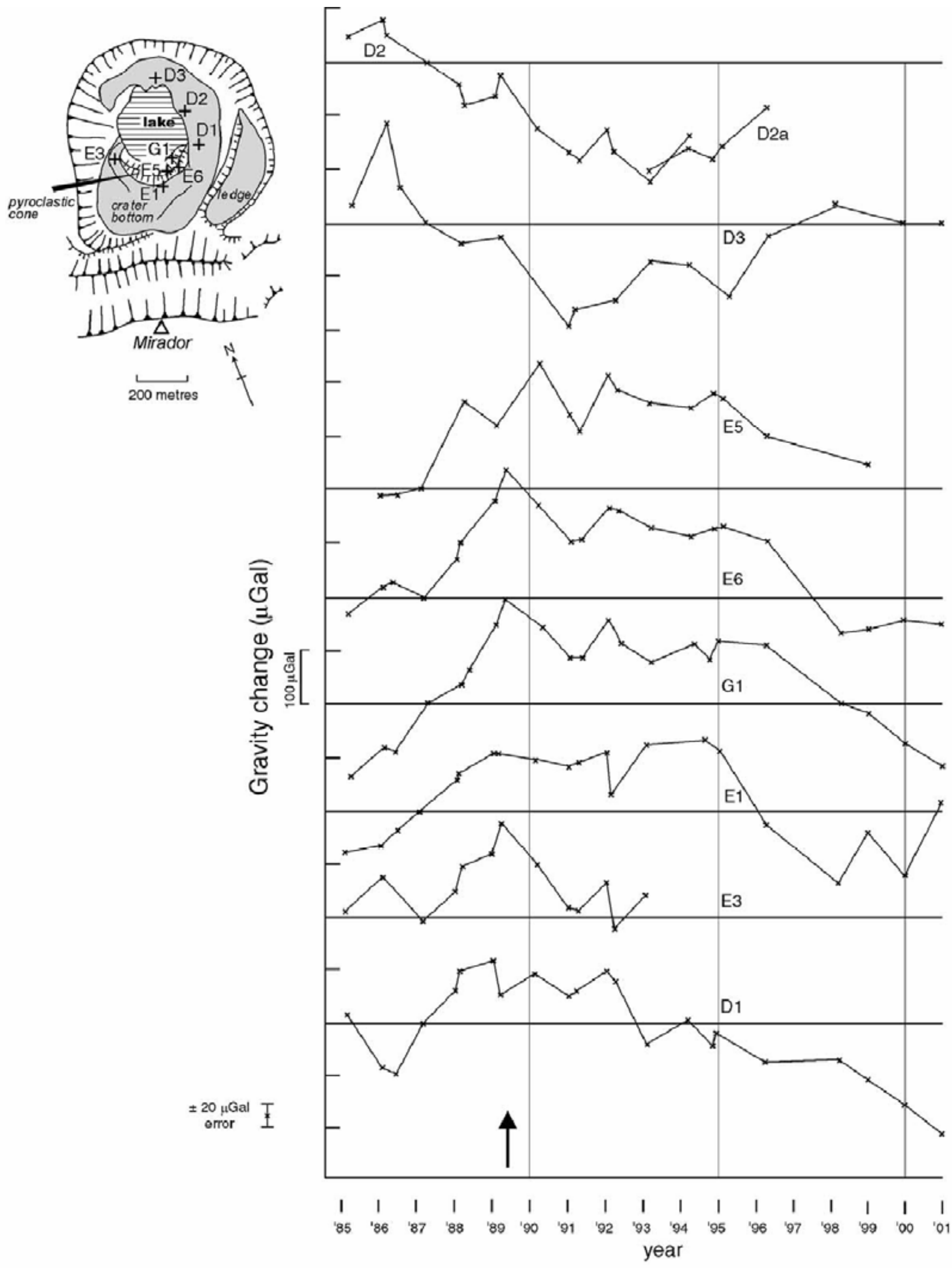

Fig. 3. Microgravity variations within the summit crater of Poas Volcano between 1985 and 2001. Locations of gravity stations are shown on inset map of the crater area (D2 was replaced by D2a in 1993).

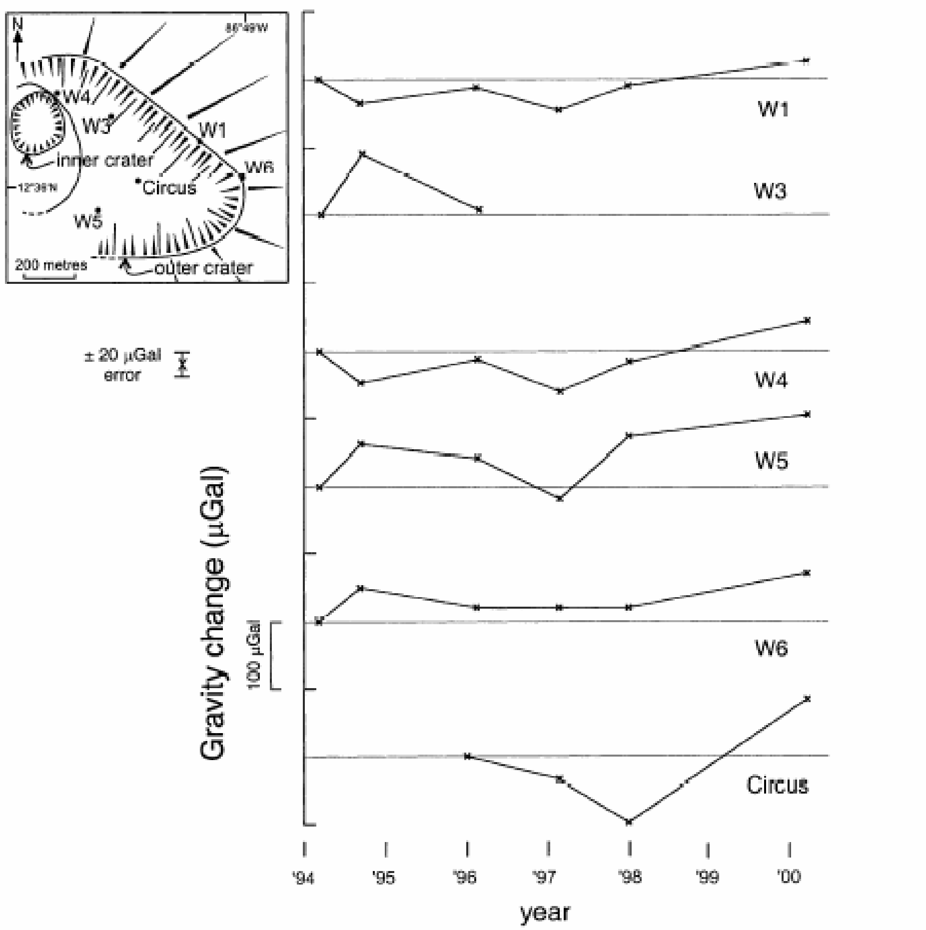

Fig. 4. Microgravity variations within the main crater of Telica Volcano between 1994 and 2000. Locations of gravity stations are shown on inset map of the summit area.

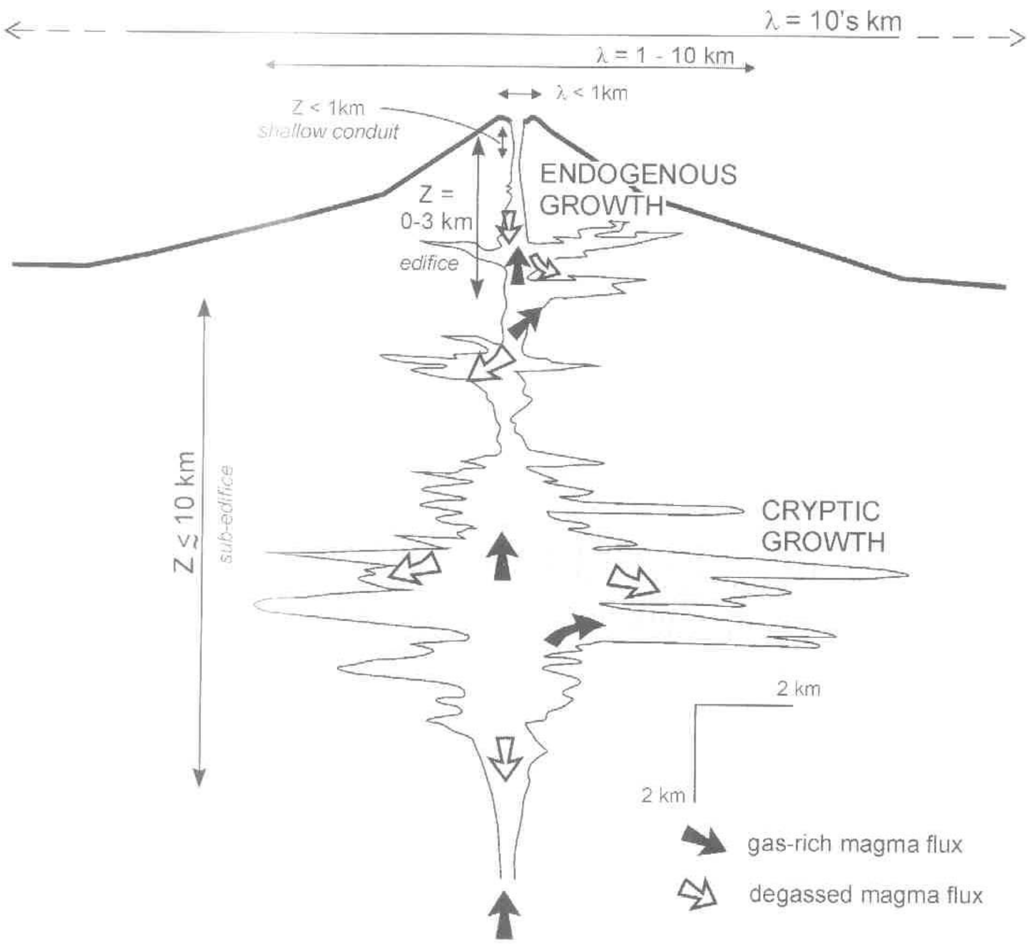

Fig. 5. Schematic diagram of magma transfer processes depicting magma movements at shallow, edifice and sub-edifice levels, with their corresponding wavelengths of measurable gravity signals. Deep cryptic magma movements are associated with timescales up to decades whilst shallow magma movements may have timescales as short as minutes.