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Pit crater structure and processes governing persistent activity at Masaya Volcano, Nicaragua

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Abstract Persistent activity at Masaya Volcano, Nicaragua, is characterised by cycles of intense degassing, lava lake development and pit crater formation. It provides a useful site to study the processes which govern such activity, because of its easy accessibility and relatively short cycles (years to decades). An understanding of the present activity is important because Masaya is visited by large numbers of tourists, is located close to major cities and has produced voluminous lavas, plinian eruptions and ignimbrites in the recent past. We provide structural and geophysical data that characterise the "normal" present state of activity. These indicate that the ongoing degassing phase (1993 to present) was not caused by fresh magma intrusion. It was associated with shallow density changes within the active Santiago pit crater. The activity appears to be associated predominantly with shallow changes in the pit crater structure. More hazardous activity will occur only if there are significant departures from the present gravity, deformation and seismic signatures.

Key words Masaya · Santiago · Pit · Structure · Microgravity · Magma · Gas

Introduction

Masaya Volcano is persistently active, with a vigorously degassing lava lake periodically visible. Geological evidence shows several cycles of pyroclastic cone-building eruptions, lava flows and pit crater formation. In historic times lava lakes have been common, and two lava flows have been erupted (1670 and 1772). In the past 150 years the volcano has formed only two pit craters, with episodic lava lake development and feeble strombolian eruptions, but it has maintained a dynamic magmatic system manifested by voluminous gas emission. Five locally catastrophic degassing crises since 1852 have degassed approximately 10 km^3 of basaltic magma (Stoiber et al. 1986), contributing significantly to global SO_2 and CO_2 output. At least four large (1–10 km^3) caldera-forming eruptions have also taken place between 2700 and 30000 BP (Williams 1983; van Wyk de Vries 1991).

As with other active volcanoes in populated areas, Masaya is a major tourist attraction. As such, even small increases in activity pose a serious risk and are potentially damaging to the local economy. For this reason it is desirable to understand the processes that control variations in activity, with an aim to predicting changes in activity, including any return to the more destructive phenomena. On a broader scale, it is necessary to understand the mechanisms of long-term persistent activity in order to develop models for the rates of magmatic processes at these sites.

We present structural and geophysical (gravity, ground deformation and SO_2 flux) data from the most recent degassing crisis at Masaya (1993 to present). The aim is to constrain the shallow structure of the magma plumbing system, determine the geophysical signatures of the present activity and predict future changes. An initial gravity decrease between February 1993 and April 1994 of up to 90 μGal close to Santiago pit crater indicates that a shallow density reduction occurred just below the crater bottom. This gravity decrease correlates with increasing gas flux, indicating a change in the shallow plumbing system. A subsequent gradual increase in gravity between April 1994 and March 1997 of up to 56 μGal has occurred at the same time as minor pit crater collapse and a decline of degassing. The gravity and deformation data indicate that changes oc-

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curred at shallow depths, and that the crisis was not accompanied by major intrusion.

General geology

Masaya Volcano is a large basaltic shield volcano, located 20 km south of Managua, Nicaragua (Fig. 1a). It is composed of a nested set of calderas and craters, the largest of which is Las Sierras shield and caldera (van Wyk de Vries 1993). Within this caldera lies Masaya Volcano sensu stricto, a shallow shield composed of basaltic lavas and tephras (Fig. 1b). This hosts Masaya caldera, formed 2.5 ka ago by an 8-km^3 basaltic ignimbrite eruption (Williams 1983). Inside this caldera a new basaltic complex has grown from eruptions mainly on a semi-circular set of vents that include the Masaya and Nindiri cones. The latter host the pit craters of Masaya, Santiago, Nindiri and San Pedro. Observations in the walls of the pit craters indicate that there have been several episodes of cone and pit crater formation (Fig. 2).

The floor of Masaya caldera is covered by poorly vegetated lavas, indicating resurfacing within the past 1000 or so years, but only two lava flows have erupted since the sixteenth century. The first, in 1670, was an overflow from the Nindiri pit, which at that time hosted a 1-km-wide lava lake. The other, in 1772, issued from a fissure on the flank of the Masaya cone. Since 1772 lava has appeared at the surface only in the Santiago pit crater (presently active) and possibly within Nindiri crater in 1852.

Cone construction

Historic activity has been confined to the Masaya and Nindiri cones. They are steep sided on their western and southern sides, where exposures in the pit craters indicate a predominance of pyroclastic material, either coarse scoria and spatter layers, or fine, laminated ash beds. The northern and eastern sides are less steep and surfaced mostly by lavas. Exposures in the pit craters record a higher proportion of lava flows on these sides. This asymmetrical construction is due to the prevailing easterly wind. The deposits are consistent with the cones being built by lava fountain and strombolian activity accompanied by lava flows.

Pit Crater structure and history

Masaya pit crater

Masaya pit crater, located centrally within the Masaya cone, is now vegetated but probably formed after the late sixteenth century, as it was not described in its present state by Oviedo (1855) writing in 1525. It has nearly vertical upper walls of scoria and lava above

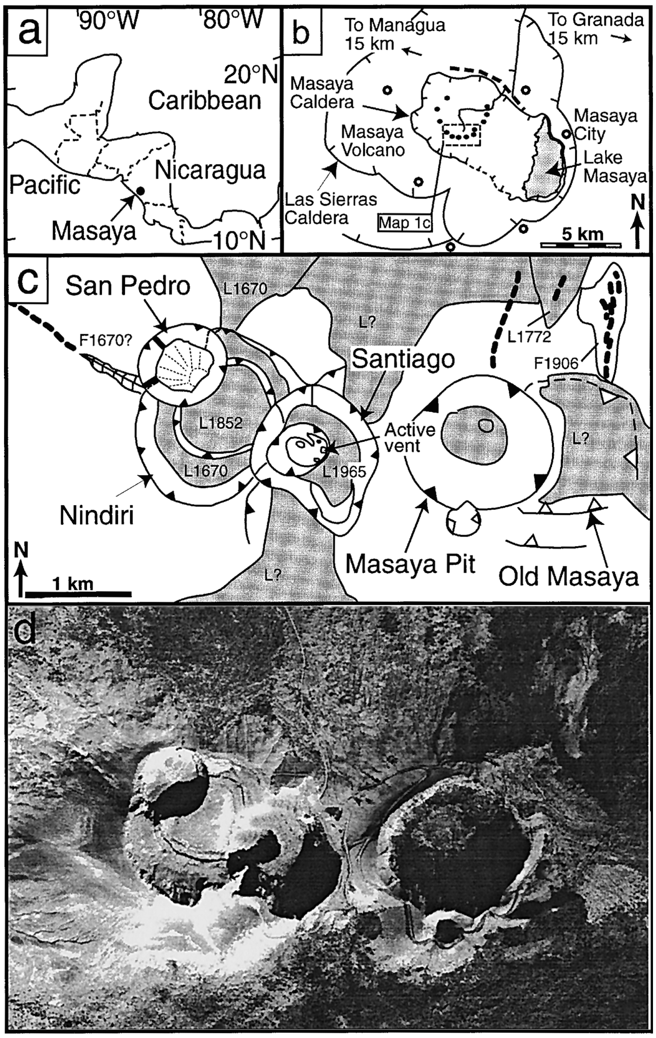

Fig. 1a–d Masaya Volcano. **a** Regional location of Masaya. **b** Map showing the Las Sierras Caldera enclosing the Masaya caldera, which in turn encloses the recent vents (*black dots*). Map shows proximity of major towns (*circles*) and cities to Masaya caldera: approximately 1.5 million people live within 25 km of the volcano. *Heavy dashed line* indicates location of COSPEC traverses. **c** Map of active crater area showing structural features, such as eruptive fissures (*dashed lines*), pit crater edges (*filled triangles*) and explosion crater edges (*open triangles*). Lava flows and lakes (*shaded*) and tephra cover (*blank*) are also shown. Lavas and fissures are given dates of eruption (e.g. L1772 is the 1772 flow and F1906 is the fissure that erupted gas in 1906). **d** Aerial photo of the same area as the map in **c**

steep scree slopes that lead to a flat base and a 10-m-high spatter cone (Fig. 1c). This cone is fresher than the rest of the crater and was probably erupted concurrently with the 1772 lava flow. East of Masaya pit crater is a lava-filled crater, which is probably the "funnel shaped" crater that Oviedo (1855) mentions, and which was probably filled sometime between 1529 and 1670 (McBirney 1956). The "funnel shaped" nature of this crater, and the local abundance of scoria, suggest that it originated from pyroclastic cone-building activity rather than pit collapse.

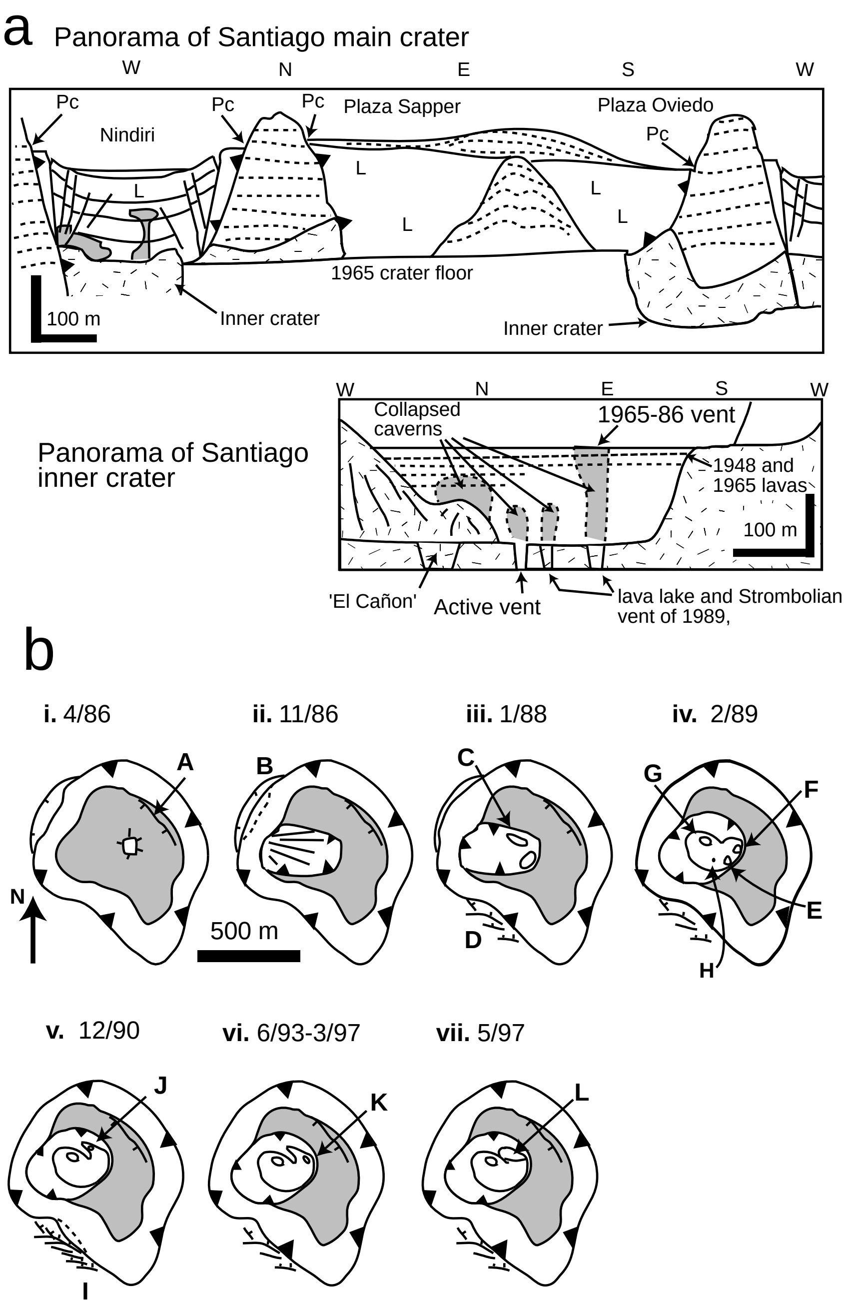

Fig. 2a, b Structure of pit craters. **a** Panoramic sketch of the walls of Santiago main and inner craters, showing crater walls and major structural features. Lava-dominated walls are indicated by *L,* tephra layers by *dotted lines,* and crater breccias by speckled pattern. Pit crater walls indicated by *Pc* and *closed triangles.* The sketch of the inner pit crater shows the location of caverns and vents seen opening up from 1986 to 1989. **b** Maps of crater evolution at Santiago from 1986 to 1997. These show locations of vents, the enlarging of the inner crater and fissures and collapses in the main crater. *A* fault in 1965 lava lake; *B* collapse fault on edge of Nindiri wall, which produced a major rockfall in November 1986; *C* two caverns open and degassing in 1987–1988; *D* faults opening at the surface from 1988 to present; *E* lava-filled vent of February 1989; *F* chamber with lava fountain within, during February 1989; *G* the "Cañon" vent, briefly a broad glowing hole in 1989, subsequently blocked, which still has fumarolic activity; *H* small strombolian vent active in February 1989; *I* collapse along faults on south side of Santiago; *J* intermittent vent from 1990 to 1993; *K* vent opened in June 1993; *L* the enlarged vent observed on 27 May 1997

Nindiri pit crater

At the time of Oviedo's observations (1525), Nindiri crater was approximately 210 m deep, with a vent at the bottom hosting a lava lake (McBirney 1956). Nindiri is now filled by frozen lava lakes erupted between 1570 and 1670 (Fig. 1c). A lava lake overflowed Nindiri to the north in 1670, forming a thick 3-km-long aa flow (Fig. 1c). The lava surface in the crater subsequently sagged downward on circular faults. These faults, now cut by the San Pedro and Santiago crater walls, dip outward at approximately 80°, and the lava flows are tilted inward. The faults extend down to the former crater floor of Nindiri, where they widen into broad fracture zones on the north side and join with a few main faults on the south side (Fig. 3).

A final lava lake was erupted onto the sagged crater floor (Fig. 3). Spatter on the edge of San Pedro and within Nindiri indicates that this may be the lava flow described by Montesssus de Ballore (McBirney 1956). He reported that the flow was extruded in July 1852, a few years before the formation of Santiago and San Pedro pit craters in 1858–1859 (McBirney 1956).

San Pedro pit crater

San Pedro pit crater is a vertically sided cylinder, 400 m wide and approximately 200 m deep. The base is mostly

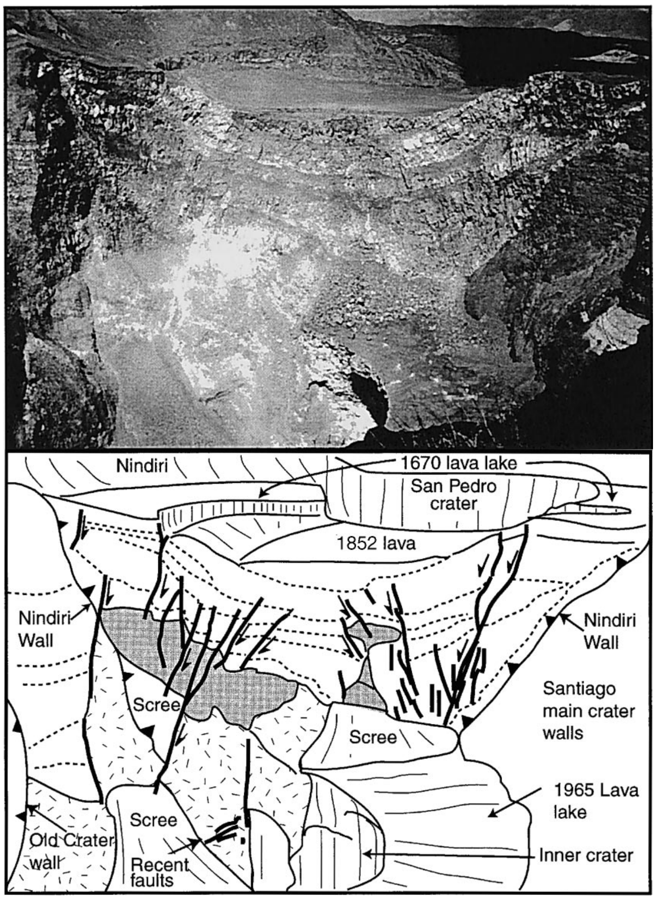

Fig. 3 Photograph and sketch of the Nindiri wall of Santiago crater, including the inner pit crater formed since 1986. The sketch shows the main concentric faults and fractures in the 1670 lava lake of Nindiri. *Shaded areas* are probably intrusions or solidified magma-filled caverns. Textured areas indicate intercrater breccias

scree, descending to a small flat area under a slight overhang directly below the eastern Nindiri side. This flat area may be the remains of a lava lake.

Santiago pit crater

Since its formation in 1858–1959, Santiago has been the main site of activity at Masaya, hosting the vent for all major degassing episodes except that of 1906 from fissures on the north flank of Masaya cone (McBirney 1956). After its initial collapse, Santiago pit crater was a vertical cylinder approximately 150 m deep and 600 m wide. The original scree-covered floor was resurfaced in 1948 and 1965 with lava lakes, which are broken by concentric faults and are similar to those seen in Nindiri (McBirney 1956). One of these faults is still visible on the north side of the crater (Fig. 2b). From 1948 until 1986 a small circular vent was the locus of activity (Fig. 2b, i). Santiago now consists of the main crater 150 m deep, and an inner crater 150 m deep, in which the active vent is located (Fig. 2b, iv).

The walls of the east and north side expose flat layers of lava, either thin lava flows or lakes (Fig. 2a). These lavas lap onto a cinder cone to the southeast and abut old pit crater walls to the southwest and northeast (Pc in Fig. 2a). These old crater walls are composed mainly of fine ash and scoria layers. The bedding becomes indistinct approximately 150 m down the southwestern side, and below this a massive breccia forms the wall of the inner crater (Fig. 2a). On the north side the layering is distinct to 30 m above the 1965 lava layer, below which there is a massive breccia.

The western side of the crater wall is composed of the lava infill of Nindiri crater (Fig. 3). The upper crater walls of Nindiri dip steeply inward, gradually becoming less steep 100–200 m down, where there are large scree fans. The base of the walls, now exposed in the inner crater, consist of a massive homogeneous breccia.

The concentric downthrown faults in Nindiri are well exposed in the walls. They dip approximately 70–80° outward and extend into highly fractured areas, where no discrete fault planes can be seen. In addition to the fractures and faults, several areas of massive rock locate solidified magma-filled cavities in the lower part of the crater, such as those described below during the formation of the inner crater of Santiago (Fig. 2a).

Santiago pit crater development 1986–1997

Progressive deepening of the Santiago crater began in November 1986 and continues through 1997. Observations in this period illustrate how pit crater formation proceeds.

In 1986 there was an 80-m-wide vent at the bottom of Santiago crater (Fig. 2b, i). In 1979–1980 magma had been occasionally visible near the surface, but in 1986 only a red glow was visible. During early to mid 1986 the vent was degassing vigorously, although less so than in the crisis of 1980–1983. By late 1986 the vent had enlarged toward the southwest, and a large portion of the southwest crater wall had collapsed (Fig. 2b, ii). The collapses blocked the vent and the degassing stopped. Two new vents had opened by 1987, and observations by van Wyk de Vries (1993) during this period indicated that the vents widened with depth. The vents slowly enlarged by the collapse of their edges, progressively exposing a large hollow area beneath the crater floor. This process is very similar to the formation of the Bocca Nuova on Etna in 1968–1969 (Murray 1977).

By January 1988 these two vents were both degassing at varying rates (Fig. 2b, iii). Gas then obscured the new inner crater until late 1988, by which time it had widened 50 m and deepened by approximately the same amount to an uneven base. In February 1989 several new vents opened in the inner crater bottom; one was lava filled, one produced small strombolian eruptions and one glowed red. A fourth vent in the northeast corner of the crater opened into a subcrater cavern. It first glowed red, but as the vent enlarged lava fountaining became visible below an overhanging wall. This lasted for approximately 1 day, after which the vent glowed red. (Fig. 2b, iv). Each of these vents formed by the opening of cracks and then the collapse of material into the vent.

Eruptive activity stopped in April 1989, and in May the roof of the fourth cavern collapsed farther to reveal a deeper vent. This became the focus of weak strombolian activity during May and June 1989 (Fig. 2b, v). Over the latter half of 1989 eruption noises could be heard, but the source was too deep within the vent to be seen. During this period rockfalls became frequent in Santiago, and fissures opened up above the southern wall. In November 1989 a large collapse occurred from this wall and filled the crater bottom. From 1990 to 1993, there was no distinct vent, and gas emission dwindled to less than 25×10^3 kg per day SO_2 (Bulletin of the Global Volcanism Network 1992).

A vent became established again in June 1993, hosting a new lava pool and building a small cone of ejecta (Fig. 2b, vi). This vent plunged approximately 80° under the northeast wall of the inner crater to approximately 40 m depth, from where it appeared to extend vertically. The vent was partially blocked by a rockfall in April 1997, but gas still escaped through the boulders. Observations on 27 May 1997 by van Wyk de Vries (1993) revealed that a 20-m-wide vent had appeared. The vent had overhanging sides and was freely ejecting gas again. Park guards reported the resumption of a red glow on 3 June 1997.

Characteristics of the pit craters at Masaya Volcano

Each of the pit craters is a nearly vertical cylinder whose walls may be slightly overhanging. They cut through all types of cone material without any apparent response to lithology. The bottoms of the craters are funnel shaped unless they have been refilled by lava lakes. Sections though Nindiri indicate that collapse occurred mainly along outward-dipping faults. Such fault scarps are also present in Santiago. Vertical faults and fractures around Santiago indicate that the steep walls of the pit craters are probably formed by collapse above the outward-dipping fault set. Debris from collapsed slices of vertical faults forms large scree fans in the craters.

Much of the collapse of the inner crater at Santiago since 1986 has occurred by a process distinct from collapse along faults: that of unroofing small chambers, as observed during the progressive collapse of Santiago inner crater between 1988 and 1991 and again during 1997. These collapses have happened episodically and rapidly; usually a small hole appears first, which then collapses to reveal a cavern. The caverns have varied in size from 5 to 30 m diameter. During the 1989 activity four cavernous vents were present. The vents themselves covered approximately 15% of the inner crater floor area. Subsequent collapse revealed the caverns below, which took up approximately 25% of the area of the inner crater, although not all of these were open at the same time.

There have been many small collapses of this type since 1986, and they have been more common in the waning period of the degassing cycle. Some of these events have exposed lava-filled vents, such as in February 1989 and May 1989 (Fig. 2b). The appearance of these lakes may be caused by the level of the crater floor reaching down to the magma level, not the usual opposite case where magma rises to the surface.

Geophysical data

In order to model the distribution and movement of gas and magma, microgravity and ground deformation measurements were made on five separate occasions between February 1993 and March 1997. Gas flux data, providing information about the amount of SO_2 degassing and by inference the total degassing budget, were obtained using a correlation spectrometer (COSPEC) in March 1996 and March 1997.

Sulphur dioxide flux

Following a degassing crisis in 1979, activity waned gradually into the late 1980s, until a weakly degassing lava lake appeared in 1989 (Bulletin of the Global Volcanism Network 1991). In April 1992 the SO_2 flux was estimated (S. N. Williams, pers. commun.) at less than 25×10^3 kg per day. In mid-1993 strombolian eruptions and a lava lake indicated reactivation, which continued with a persistent incandescent vent and gas plumes comparable to those of 1980 (Bulletin of the Global Volcanism Network 1993a, b, 1994b). Measurements of SO_2 flux were made with a COSPEC on 16 March 1996 over eight traverses under the gas column from Santiago crater (Fig. 1b). On this occasion, the column was being blown northeastward, and the errors are less than 30%. Measured SO_2 flux values ranged from a low of 2.4×10^5 kg per day to a high of 1.1×10^6 kg per day). The mean flux was $6.0\pm2.9\times10^5$ kg per day (1 sigma). Our data fall between the averages of 3.8×10^5 kg per day prior to 1979 and 1.2×10^5 kg per day during 1980 (Stoiber et al. 1986).

The continuous gas release was augmented in early October 1996 by short bursts of increased gas output accompanied by minor ash emission. Access to the Santiago crater viewing area was restricted during this period because of the obvious hazard to tourists. Rapid and short-lived changes in the amount of gas released have been notable features at Masaya and are most likely due to small alterations in the structure of the Santiago pit crater. Although we were unable to make new COSPEC measurements during this phase, seismic data are available (W. Strauch, pers. commun.). There was an increase only in shallow tremor, which is normally associated with degassing at Masaya. COSPEC measurements were again made on several occasions during January to April 1997 and a lower flux of $3.3 \pm 1.8 \times 10^5$ kg per day was observed.

Assuming an average gas flux since reactivation in 1993, then our observations of approximately 4.0×10^5 kg per day SO_2 suggest that at least 7.2×10^8 kg of sulphur have been released from 1993 through mid-1997. If magma releases ca. 240 ppm sulphur during passive degassing (Stoiber et al. 1986, Table 5), then petrological calculations (Stix and Layne 1996) suggest that 1.5×10^{12}–kg magma have been degassed since reactivation. The total amount of gas released can also be calculated using appropriate H_2O/SO_2 and CO_2/SO_2 molar ratios of 3.86 and 2.18, respectively (Williams et al. 1992; Symonds et al. 1994, Table 5). Applying these ratios to the amount of SO_2 gives 2.6×10^9 kg of gas ($H_2O + CO_2 + SO_2$) released from 1993 through mid-1997.

Microgravity and ground deformation

Microgravity measurements were made in February 1993, April 1994, October 1994, March 1996 and March 1997 at 17 stations within the caldera (Fig. 4) and for reference in Masaya city using LaCoste and Romberg meter G513. Leica GPS 200 dual-frequency differential receivers were used in April and October 1994, and March 1996 and 1997, to provide ground deformation data. Strict survey procedures were followed to reduce errors in the field (Rymer 1996; Murray et al. 1995). The microgravity measurements are subject to errors of much less than ± 25 μGal (twice the standard deviation) and the GPS data have errors of ± 7 cm (vertical) for April 1994, reducing to ± 2 cm for October 1994 and March 1996 and 1997. Between February 1993 and April 1994, precision levelling (± 1 cm) was carried out within the Masaya caldera, and there were no height changes anywhere in the caldera greater than 6 cm in that period (J. B. Murray, pers. commun.; Smithsonian Institution Bulletin of Global Volcanism Network 1994a).

The gravity data obtained between February 1993 and April 1994 (months 0 and 14) fall into two distinct groups (Fig. 5). More than 2 km from the crater (stations A1–A6), all data lie within 25 μGal of zero and indicate no significant gravity changes at the 95% confidence level. In contrast, there was a marked decrease in gravity at stations near the active crater area. Station E3 appears to behave anomalously between 1993 and 1994. This may be due to the dilation of fissures on the edge of the crater (H on Fig. 3b) or possibly to an unreliable initial reading in 1993, or, being the station closest to the crater, it may indicate that gravity decreases are much larger within the crater. The rate of gravity decrease between 1993 and 1994 was approximately –70 μGal/year for near-crater stations. During Februa-

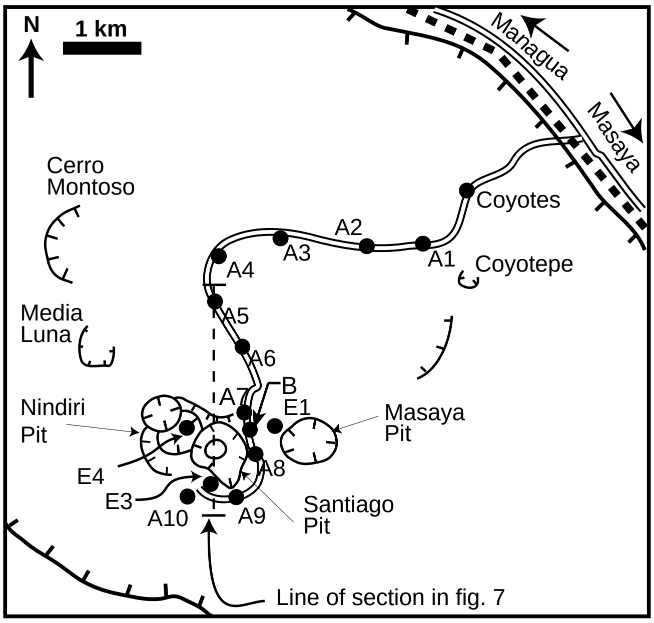

Fig. 4 Location of gravity stations in the Masaya caldera

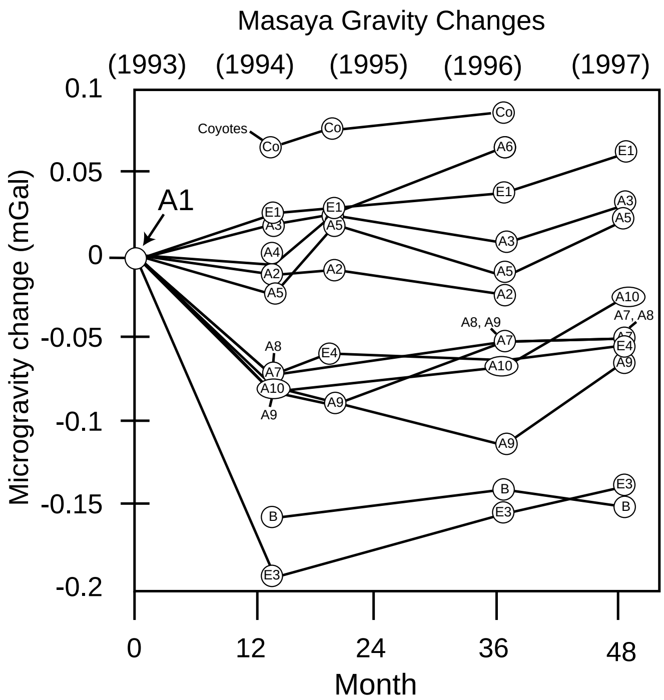

Fig. 5 Gravity changes at stations within Masaya caldera measured using Lacoste and Romberg meter G513. Station locations are shown in Fig. 4. The data clearly fall into two groups during the period 1993–1994 (months 0–14): (a) no significant change in gravity through time at stations along the road from the northern caldera margin toward the active crater up to and including station A6, and (b) significant decreases at stations in and around the active crater area. Stations Coyotes and B were not measured in February 1993, so their position on the figure is arbitrary, although the gradients are comparable to the others

ry 1993 to March 1994, precision levelling within the caldera revealed an uplift of just 2–3 cm at the summit relative to a station 5 km east (J. B. Murray, pers. commun.; Smithsonian Institution Bulletin of Global Volcanism Network 1994a). The GPS data indicate that there have been no vertical or horizontal movements in excess of 2 or 1 cm, respectively, between 1994 and 1997. The gravity data have not been height corrected, because the maximum size of the correction (ca. 9 μGal for 3 cm at –308 μGal m^{-1} assuming the free air gradient, or ca. 6 μGal assuming the Bouguer-corrected free air gradient) is insignificant compared with the observed gravity changes. Since 1994 there is some evidence for an increase in gravity in the crater area (Fig. 5), although the shape of the change is not very clear (Fig. 6). It would also appear that the values obtained at stations A6 and A9 in 1996 are inconsistent with the rest of the data; this may be due to local vegetation effects.

In summary, the gravity data indicate a crater-centred decrease in excess of 90 μGal (largest value observed is –192 μGal and maximum may be even larger within the active crater, closer to the vent) between February 1993 and April 1994, followed by a less well-defined increase over the following years until February 1997 of approximately 30 μGal in approximately the same location.

In view of the negligible volume change of the edifice (determined from the lack of deformation), the decrease in gravity between February 1993 and April 1994 near the crater must reflect a subsurface mass and density decrease. In order to model this decrease, an interactive 2.5D forward-modelling program GRAVMAG (Pedley 1991) was employed. This program calculates the gravitational effect at the topographic surface along a profile of polygons of any size and density beneath the surface. The models are 2.5D rather than truly 3D, because each polygon must be symmetrical about the profile, although its thickness or "half strike" is user defined. Obvious causes of subsurface mass and density decreases at an active volcano are (a) water-table movement, (b) magma drainage and (c) magma vesiculation within a feeder pipe. The observed gravity changes are so localised, and the water table so deep in the area (>300 m), that (a) is not considered likely in this case. Magma drainage is also unlikely, since the period was characterised by increased degassing and some strombolian activity.

The plausible dimensions for a feeder pipe (up to several tens of metres across) are too small for the maximum possible density change (–2600 kg m^{-3}; basalt melt replaced by air) to produce the observed gravity signature. The gravity changes during this period are centred about the crater (Fig. 6a) and extend over a distance in excess of 1800 m (the wavelength of the anomaly). Density changes within the feeder pipe would produce an anomaly with a much smaller wavelength. On the other hand, density changes within a deep magma chamber (even in only the upper part)

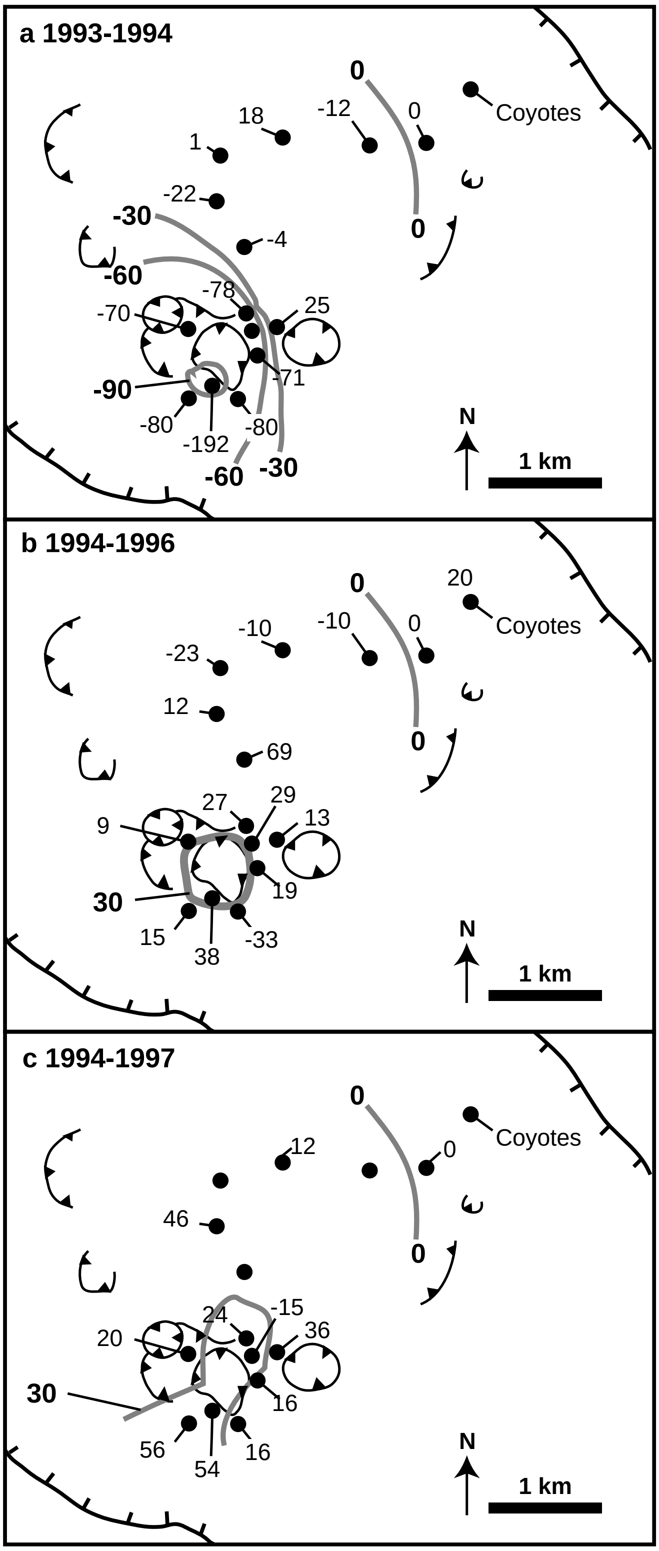

Fig. 6 Contour maps showing schematically the approximate gravity changes through time for the periods **a** 1993–1994, **b** 1994–1996 and **c** 1994–1997. Numbers at stations indicate changes in the gravity difference (μGal) between each station relative to the value at A1. Contour interval is 30 μGal

would produce an anomaly with a much larger wavelength than that observed. The wavelength of the anomaly, therefore, constrains the depth and approximate dimensions of the causative body. The magnitude of the anomaly is determined largely by the density change within the causative body, but since there are no observations inside the crater, the gravity change in this region must be inferred.

For a N–S profile crossing the active crater (Fig. 4), the model that best fits the observed anomaly suggests a region of reduced density approximately 440 m in diameter at a depth of only a few tens of metres below the active vent (Fig. 7). This diameter is similar to that of Santiago and its inferred boundary faults. The correlation with observed structure lends strong support to the model. Models consistent with the data include a body approximately 100 m thick with a density contrast of $-300\ kg\ m^{-3}$, or a stratified body approximately 200 m thick, with a thin (25 m) upper layer of high contrast (e.g. $-600\ kg\ m^{-3}$) above a smaller contrast, close to $-100\ kg\ m^{-3}$.

It is not possible to resolve the differences between these end-member models with this data set, but it is clear that a shallow body of relatively low density developed during the period of this study. These models suggest a mass decrease of approximately 3.7×10^9 kg to 4.0×10^9 kg. The low-density bodies probably represent an accumulation of highly vesiculated magma with-

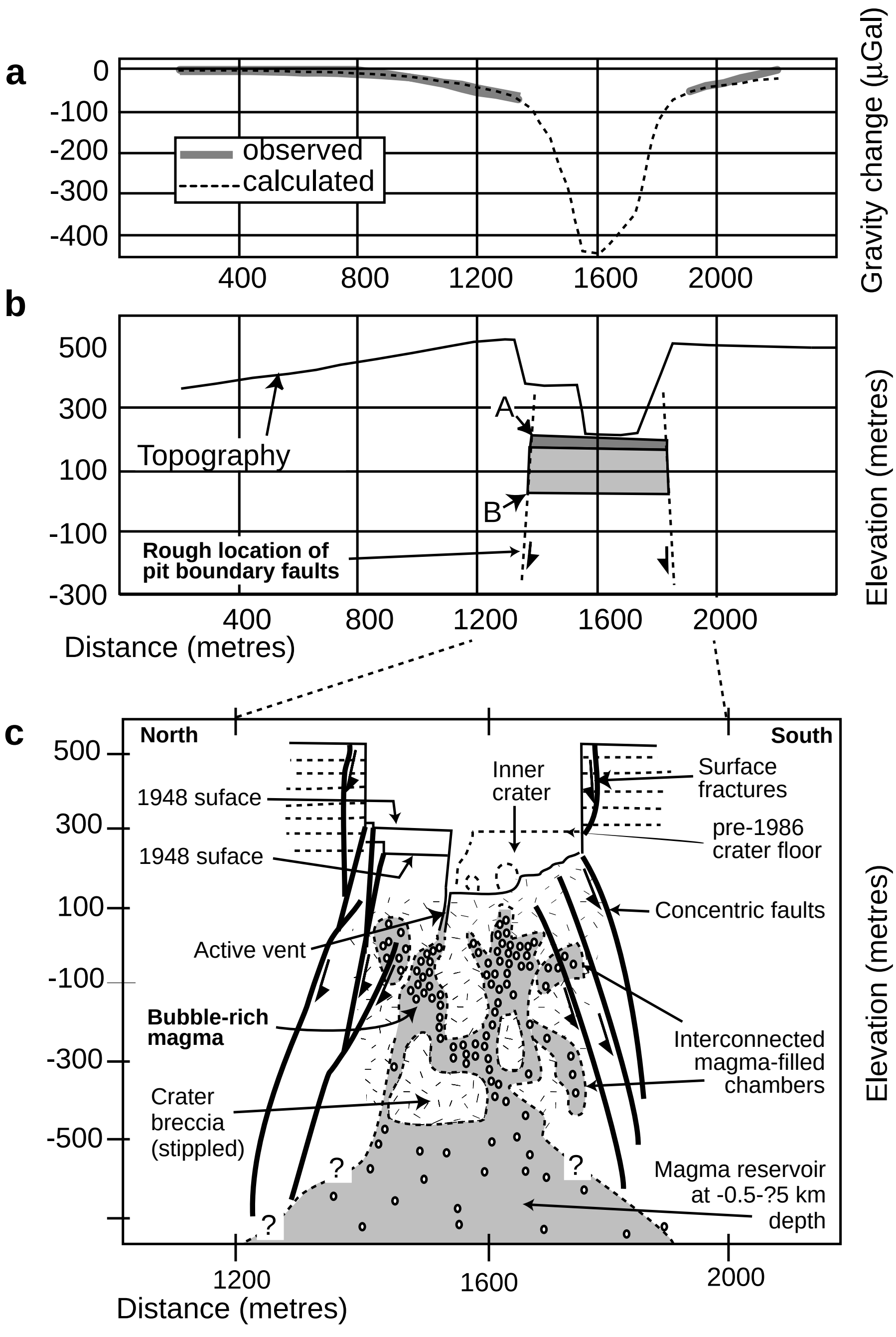

Fig. 7 **a** The observed and calculated gravity changes for the period February 1993–April 1994 along the profile shown in Figs. 4 and 5 for the model illustrated in part b. **b** Subsurface body of reduced density ($-600\ kg\ m^{-3}$ for *A* and $-100\ kg\ m^{-3}$ for *B*). The gravity effect of this body is shown in **a**. A thinner body of density change $-300\ kg\ m^{-3}$ produces a similar calculated gravity profile. **c** Interpretative cross section through Santiago, taking into account the observed structure, the observed development of the inner crater by cavern collapse and the structural features in Nindiri crater. This diagram also shows proposed area of accumulation of the gas-rich frothy magma layer beneath the Santiago pit crater (shown by white "bubbles")

in several caverns whose horizontal distribution is comparable with the diameter of Santiago crater. A 10% increase in the degree of magma vesiculation would produce the inferred density decrease. The gravity increases observed between 1994 and 1997 (Figs. 5, 6b, c) occur over the same region as the preceding decreases and probably reflect a slight decrease in thickness of the vesiculated layer.

Interpretation

Geophysical data

Integrating the microgravity, ground deformation and gas flux data, we note that between February 1993 and April 1994 there was a shallow mass decrease of approximately 4.0×10^9 kg, followed over the next 3 years by a slight mass increase, that a minimum of 2.6×10^9 kg of gas has been released between 1993 and mid-1997, and that 1.5×10^{12} kg of magma has degassed. Shallow intrusion of new magma is clearly not indicated by the microgravity data, since gravity decreased during the early period of reactivation, and the slight increase in gravity was associated with steady low-level activity. However, the replacement of relatively dense, degassed magma by gas-rich material between February 1993 and April 1994 is consistent with the data. We suggest that convection within a deep chamber caused magma overturn during early 1993 and that, as a result, gas-rich magma was transported to the top of the chamber while denser magma was displaced to a greater depth (>1 km) the magma level beneath the crater floor may also have fallen but not so deep to have precluded occasional ejecta at the surface. The gas-rich magma began to vesiculate due to decompression, and a layer of relatively vesiculated, fizzing magma formed at the top of the magma column within caverns beneath the Santiago vent, causing a shallow density reduction and a corresponding decrease in gravity (Fig. 7c). The gradual gravity increase since 1994 (Figs. 5, 6) suggests that the thickness of the vesiculated layer has reached a maximum and may be decreasing (in thickness or bubble density).

If the gas flux were reasonably constant during 1993–1997, then the mass of gas lost in 1993–1994 was approximately 7.0×10^8 kg, approximately six times less than the mass decrease according to the gravity calculations. If magma containing 2–3 wt.% dissolved water rose to replace magma with little or no water, the magma density would decrease by approximately 200 kg m^{-3} (Kazahaya et al. 1994). To satisfy the 300 kg m^{-3} decrease required by the gravity data, the further 100 kg m^{-3} reduction could be caused by a 5% increase in the degree in vesiculation. In this scenario, a combination of shallow gas-rich magma intrusion and vesiculation processes caused the decline in gravity. The second possibility, which we favour, is that the gas flux was substantially higher in 1993–1994 compared with that in 1996–1997. If this were the case, then an SO_2 flux into the vesiculated layer of approximately 2.6×10^6 kg per day would correspond to a total gas flux in this period comparable with the mass loss calculated from the gravity data (ca. 4.0×10^9 kg). In this case, an increase of approximately 10% in the degree of vesiculation occurred early and is the main cause of the gravity decrease. The COSPEC data suggest that at least 2.0×10^9 kg of gas has been erupted, corresponding to 8.85×10^{11} kg of degassed magma. The gas within the vesiculated layer accounts for a further 2×10^9 kg, which means that at least twice the calculated mass of magma has actually been degassed (e.g. 1.77×10^{12} kg). The amount of gas stored within the vesiculated layer indicates that gas release is a slow process and that the system could continue to vent gas at the same rate (approximately 3.0×10^5 kg) for 4 more years – or longer at a reduced flux, even if additional deep magma does not degas. The calculated mass of degassed magma (1.8×10^{12} kg) relates to material within a deep magma reservoir. The volume of degassed magma, assuming a density of 2700 kg m^{-3}, is 0.6 km^3, half that calculated by Stoiber et al. (1986) for the 1979-1985 episode. There is no net change in mass within the deep reservoir level and therefore no gravity change because volatile-rich material leaving the chamber is replaced by downward convection of denser degassed magma from the shallow system above. This process is similar to one proposed by Andres et al. (1991) to account for excess SO_2 observed at Lonquimay and Lascar volcanoes (Chile) using COSPEC observations and petrological calculations.

We interpret the observed increase in activity at Masaya in terms of a single convective pulse in 1993. We suggest that the cyclic degassing crises at Masaya since the mid-19th century have been caused by periodic convective overturns of magma. Convection may be initiated by intrusion of fresh material from below, but it may also be triggered by density contrasts produced either by magma crystallisation or shallow degassing (Jaupart and Vergniolle 1989; Kazahaya et al. 1994). Thus, dramatic changes in surface activity are not necessarily preceded by subsurface intrusion. This classic example of open system degassing is maintained at Masaya by the combination of a long-lived magma reservoir and an open vent.

Discussion and conclusion

We propose a structural model for the Masaya pit craters illustrated along with the gravity interpretation in Fig. 7c. This model is based on the study of pit crater walls (i.e. Fig. 2), observation of the progressive opening of the inner crater of Santiago since 1987 (Fig. 3) and the gravity data (Figs. 5, 6). Cylindrical faults, dipping slightly outward, guide collapse into a magma reservoir. The vertical sides of the craters are produced by collapse on fractures formed above the concentric faults (Fig. 7c). The inner material is broken into a coarse breccia, and continued collapse occurs either by the formation of new inner faults or by the coalescence and unroofing of caverns. These caverns may be formed by magma intrusion and withdrawal or by localised subsidence of the breccia, possibly caused by stopping of material into the magma reservoir. Whatever the mode of formation, the caverns appear to form an interconnected network through which magma and gas can reach the surface.

Changes in the pit crater structure will alter the near-surface magma plumbing system, resulting in changes in activity. Cavern collapse can expose magma, leading to mild strombolian activity and lava-filled vents; cavern blocking may cause pressure buildup and short-term explosive activity. Small-scale magma-level fluctuations may fill caverns or create more caverns by intrusion and subsequent withdrawal, leading to further collapse. Using the analogy of the activity at Nindiri crater in the seventeenth century, new magmatic input will cause lava lake formation and may slowly fill up Santiago but is unlikely to cause activity outside the pit until it overflows. This scenario is valid as long as the cavern system provides free access to the surface.

For at least the last several thousand years Masaya has built pyroclastic cones with associated lava flow fields and has formed pit craters. For the past 150 years, activity has been confined to pit crater formation accompanied by cycles of intense degassing. Evidence from the present pit craters suggests that they develop episodically and are associated with degassing activity and the presence of shallow magma in a cavernous region below the pit crater floor. Geophysical data collected during the present reactivation at Masaya suggest that no new magma has entered the upper volcanic system and that the increase in activity is probably associated with changes within the shallow pit crater structure. We suggest that the beginning of this degassing episode may have been triggered by convective overturn of magma left within the shallow plumbing system since the previous (1980s) episode. This degassed magma briefly appeared at the surface in February and May 1989 as collapse unroofed caverns in the inner pit crater. With reactivation in 1993, a vesiculated layer of magma developed immediately below the pit crater, leading to local gravity decreases. As the degassing episode waned, this layer has become thinner or less vesiculated, leading to the observed gravity increases. We suggest that, toward the end of the present cycle, there will be further collapse of the pit crater as the pressure within this layer decreases, and magma may again be uncovered. Indeed this was apparently occurring in May to June of 1997.

The best-fit model for the gravity anomaly suggests that a region approximately 200 m thick, extending to the structural margins of the pit crater, underwent a density decrease as the degassing began. This indicates that all of the pit crater substructure is involved in the magmatic system, rather than a restricted pipe (Fig 7c). Many small caverns were seen to form and collapse during the formation of the inner crater; thus, the present pit crater structure probably also contains several caverns, filled with magma or empty.

Pit crater collapse occurs by two processes. One process is the large-scale collapse of material from outwardly dipping planes (Figs. 3, 7c). This is responsible for the creation of the general structure of the pit craters and is probably related to major episodes of magma withdrawal in the main reservoir. It may tend to block vents. The other process is the incremental collapse of caverns, formed within the boundaries of the pit crater (Figs. 2, 7c). This appears to occur toward the end of a degassing phase, from either a loss of gas pressure or the gradual downward movement of breccia within the pit crater relative to magma levels. This incremental collapse tends to lower the crater floor relative to the magma level, thus exposing magma to the surface.

The onset of major explosive or effusive activity at Masaya will probably be preceded by a marked alteration in the present equilibrium state. We expect a major change in activity to be heralded by large increases in gravity over a wider area than the observed variations reported here, perhaps accompanied by edifice inflation and a change in gas flux (possibly even a decrease following vent blockage). We also expect any major change to be preceded by considerable increases in seismicity, well above the normal shallow tremor. Such activity would not be restricted to pit craters and could produce new structures.

Integrated studies, such as the preliminary microgravity, ground deformation and SO_2 flux study presented here, have a vital role to play in hazard assessment, as they provide independent data on the triggers and likely outcome of volcanic events. Our geophysical data could not be used to predict rapid minor changes in activity such as occurred in October 1996, but they do show that the magmatic system at Masaya is in a stable state. On the other hand, close observation of structural changes, such as vent blocking and cavern development, may give clues to short-term minor events. Our model for a single convective overturn in 1993 followed by steady degassing is consistent with this event being only a minor, short-lived departure from the equilibrium state related to ongoing pit crater evolution. The larger eruptions, such as plinian and ignimbrite-forming events, will probably be preceded by much larger structural changes and marked geophysical anomalies, although the sequence of events leading up to these is still unknown and is an important area of study.

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