Magma plumbing processes for persistent activity at Poás Volcano, Costa Rica

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Abstract

New microgravity data from the active crater of Poás volcano, Costa Rica, collected in 2002-2004 extends the existing dataset to provide a unique 20-year time series. These data show that gravity has decreased monotonically in the north and east of the crater over the last 5 years, whilst it has increased to the west and remained approximately constant in the south. These changes are interpreted in terms of convective recharge within dendritic intrusions beneath the crater, with overall down-welling in the north and up-welling in the west. The data reveal a 5-10 year periodicity in sub-crater mass movement, but overall, the upper part of the conduit system appears to have maintained a state of mass equilibrium.

Keywords: microgravity, mass movement, Poás volcano, persistent activity

Introduction

Poás Volcano is a persistently active basaltic-andesite stratovolcano which forms part of the Cordillera Central in Costa Rica. Historical activity at Poás has been mostly phreatic and is reported in detail by *Krushensky and Escalante* [1967], *Raccichini and Bennett* [1977], *Vargas* [1979] and *Boza and Mendoza* [1981]. A small pyroclastic cone and a pit crater were formed in 1953-4, and the focus of activity in recent years has oscillated between the cone and crater lake. The pit crater hosts a hot acidic lake and intermittent, weak fumaroles occur within the main crater walls. The lake level has varied since 1965 with both volcanic activity and rainfall; geysering activity in the 1970s implies that the lake's depth must have been at least 70 m [*Dowden et al.,* 1991]. Since 1980, the lake has changed from being a greenish lake, to a rapidly convecting and geysering pond, then to a sulphur-rich boiling mud pool and finally back to a blue-green deep and tranquil lagoon, with temperatures still well above ambient levels (ca. 40^0C).

The most recent sequence of activity began in 1981 with a shallow intrusion of magma beneath the dome, which caused the fumaroles to glow red. Evidence for an intrusion of magma came from A-type seimicity and the demagnetization of the dome [*Casertano et al.,* 1987] and a depth to magma of <100 m was deduced from gas flux and temperature data [*Stevenson,* 1993]. By 1986 gravity increases on the dome and south crater floor heralded a fresh intrusion [*Rymer and Brown,* 1989], which culminated in the complete disappearance of the lake in 1989 and vigorous degassing and ejection of molten and globular sulphur through the dried lake bottom. By 1995 the lake had re-established and was as deep as it had been before the crisis. The lake level since then has remained high, slightly deeper than at any time since the late 1970s. *Rymer et al.,* [2000] suggested that the lake acts as both a moderator and an index of volcanic processes at Poás. The gas output remains stable at approx. 40 tonnes per day according to our latest (unpublished) COSPEC measurements in 2002.

Micro-gravity measurements have been made on a regular basis at Poás since 1985 using methods that have become standard for this type of monitoring work [*Rymer,* 1989]. A series of stations are reoccupied annually and any changes in gravity expressed relative to a reference station 7 km from the active region of the crater. Also, over the period 1982-2004 there are no significant gravity changes (to within 0.04%) between this reference station and a further reference station 20 km distant (in Alajuela Park). Thus gravity changes observed in the crater relative to the local reference station must be associated with local mass changes at the volcano.

The intrusion episodes in 1953-4 and the 1980's at Poás have resulted in considerable local environmental destruction and hazard to the population. Here we present data which suggest that a further intrusive episode may be occurring in the west of the lake whilst magma withdrawal is ongoing to the northeast.

Microgravity data

A time series of microgravity observations in and around the active crater of Poás volcano from 1985 to 2001 reported by *Rymer et al.,* [2000] and *Locke et al.,* [2003] are extended here with further data from 2002 to 2004.

Between 1985 and 1989 gravity increases were observed at all stations south of the crater lake (D1, E1, E5, E6, G1, E3/125c, Figure 1). Following the 1989 eruption, gravity decreased immediately at E3/125c and later (1995) at the other stations except G1 to reach 1985 values by 1998 (1992 for E3). Data at stations along the northern shore of the lake (D2, D2a, 25c and D3) showed consistent gravity decreases between 1985 and 1991 that were interpreted as resulting from decreasing water table levels [*Rymer et al.,* 2000]. *Fournier et al.* [2004] have since shown that the evaporation of the lake and consequent lowering of the water table may be expected to have a greater negative gravity effect at these stations than that observed and they suggest that the observed gravity is the combined effect of magma intrusion and water loss. The lake re-established between 1995 and 1997 and this is reflected in gravity increases at these stations over this time [*Locke et al.,* 2003]. As the lake has remained at about the same level since 1997, recent gravity data have not been significantly affected by water table changes.

Gravity increases in the crater in the late 1980's have been interpreted in terms of a rise in magma level in the upper part of the conduit system south of the crater lake; this magma drained by 1991 from peripheral conduits in the west (E3) and later (1998) from the east [*Rymer et al.,* 2000; *Locke et al.,* 2003]. Continuing gravity decreases after 1998 at G1 and D1 were interpreted in terms of continued withdrawal from the area peripheral to the pyroclastic cone but magma levels immediately below the cone were interpreted as being stable between 1997 and 2001 [*Locke et al.,* 2003].

Gravity at stations on the dome (E6 and G1) in the period 1998 – 2004 has in fact oscillated at about 50 μGal below 1987 levels. In contrast gravity increases have been recorded at stations south and west of the dome (E1, E3/125c), a 150 μGal increase was recorded at E1 between 2000 and 2001 and since 2001 gravity has continued to increase slightly. Between 2001 and 2003 a 140 μGal increase was recorded at 125c and this elevated gravity value was maintained in 2004.

There was a clear anti-correlation between the gravity data at D1 and D2/D3/25c between 1985 and 1997, however this pattern ceased in 1997 and since then gravity changes at D1, D3 and 25c have been concordant. Between 2000 and 2004 gravity at D3 has decreased by 35 μGal/year. Station D2 was covered by the rising lake and so another station 25c was established nearby in 2000; gravity at this station has decreased consistently since 2000 at a rate of about 100 μGal/year whilst the lake level has remained high. D1 has also recorded remarkably consistent decreases between 1999 and 2004 of 50 μGal/year.

Interpretation of recent gravity changes

The new gravity change data suggest that magma levels below stations E6 and G1 on the pyroclastic cone have remained stable between 1998 and 2004. However significant gravity and hence mass increases have occurred to the west and south of the cone (E1 and 125c) and higher magnitude gravity decreases have occurred to the east (D1, D3 and 25c). The maximum gravity decreases occur at D1 and 25c, so the causative mass decrease must be located proximal to these stations and, given the recent history of activity, is likely to be under the eastern part of the lake. Thus these gravity decreases may result from ongoing drainage of a dendritic intrusion under the eastern part of the lake. The difference in the magnitude of the gravity decreases between D1, D3 and 25c which are within a horizontal distance of 300 m clearly shows that the source of the gravity change must be at shallow levels and of very limited areal extent [*Locke et al.,* 2003].

The occurrence of fumaroles in the eastern wall of the crater shows that the hydrothermal system may be more active in this area now and associated clay alteration of the rocks may therefore also be a contributor to the mass loss. However the widespread distribution and ephemeral nature of the fumaroles would suggest that clay alteration is unlikely to be sufficiently focussed that it could be a major contributor to the spatially limited gravity decreases observed.

Previous gravity increases were interpreted in terms of magma rising in dendritic intrusions and it seems likely that the recent increases observed at E1 and 125c have a similar source. Maintaining the lake at a temperature in excess of 30^{o}C requires an input of 600-700 MW which *Brown et al.* [1989] suggested came from intrusion below the lake. The facts that the lake remains well above ambient temperatures and degassing levels remain high imply that the gravity increases observed at E1 and 125c are a consequence of an intrusion below the west of the lake.

Discussion

The observed magma intrusion and withdrawal episodes defined by the geophysical data are interpreted in terms of convective recharge within dendritic intrusions beneath the crater. Some of these dendrites contain upwelling magma whilst in others, magma is withdrawing (Figure 2). Overall, the amount of mass rising appears to be similar to that falling, but over short periods of time (a few years) some imbalance is measurable. Thus, the system could be considered to be an assembly of self-contained convection cells which collectively allow transport of the heat and mass required to maintain persistent activity. As the focus of activity moves, the nature of the contribution of individual active cells varies.

Considering all the data over this time period, it would seem that convection cells in the form of dendritic intrusions take up to 5 years to 'charge' and 7-10 years to 'drain'. The diameter of the dendrites must be no more than about 50 m in order for the gravity effects to be so localised [as shown by *Locke et al.,* 2003]. Similarly, the depth to the top of the cells is unlikely to be more than 50 m because of the short wavelength of the gravity signature [*Locke et al.,* 2003]. These cells could be interpreted in terms of the gas driven intrusion of mud to shallower levels within the hydrothermal system or magma intrusion or a mixture of both. The magnitude of the observed mass changes and the persistent activity of Poás suggest that magma movement is the main component in these cells.

Given the observed magnitude and areal extent of the present gravity changes, the causative mass changes from 1998-2004 are estimated, by integrating the gravity effects over the area, to be of the order of 10^8 kg which is similar to mass changes estimated in previous episodes. For example, the mass increases observed in the period 1985-1989, estimated by *Rymer et al.* [2000] to be of the order of 10^8 - 10^9 kg, are similar to the approximately $5x10^8$ kg decrease now estimated in the eastern part of the crater bottom and the $1x10^8$ kg increase beneath the western portion of the dome and / or lake over the period 1998-2004. Thus it would seem that overall the mass in the upper part of the conduit system remains approximately stable although localised redistributions are constantly occurring.

In the light of the recent observation of large gravity decreases in the north of the crater bottom being clearly associated with no lake level changes, it is appropriate to revisit the earlier interpretation for this region of the crater. The decreases observed in the north of the crater bottom were previously thought to reflect the falling water table level [*Rymer et al.,* 2000; *Locke, et al.,* 2003]. While it has been difficult to quantify this effect, it has been estimated that up to 100% of the decreases are due to water table movements [*Fournier et al.,* 2004]. The longer-term decreases now evident must reflect downwelling magma in convective cells; superimposed upon this long-term signal in the mid 1980s was a shorter-term effect associated with the evaporation and re-establishment of the lake. This could only happen if there had been upwelling of magma beneath this region at an earlier time. Analysis of the historic records at Poás shows that activity was focussed under the lake in the mid 1970s as there was persistent geysering and an eruption of sulphur encrusted blocks in 1978 [*Francis et al.,* 1980]. Although there is no geophysical record of the intrusive event that preceded this activity, it may be that the long-term gravity decreases seen in the north relate to the drainage of cooling degassed magma after the event.

These geophysical data provide a unique, 20-year record of synergistic mass increases and decreases at shallow depths below the summit crater at Poás. A cyclicity is apparent in the data with a period of around 5-10 years. The source of these mass changes has migrated with time which illustrates the highly localised nature of dendritic intrusions and their associated convective processes. Hence, whilst the focus of activity has shifted over time, overall the volcano is approximately in a state of mass equilibrium.

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Figures and Captions

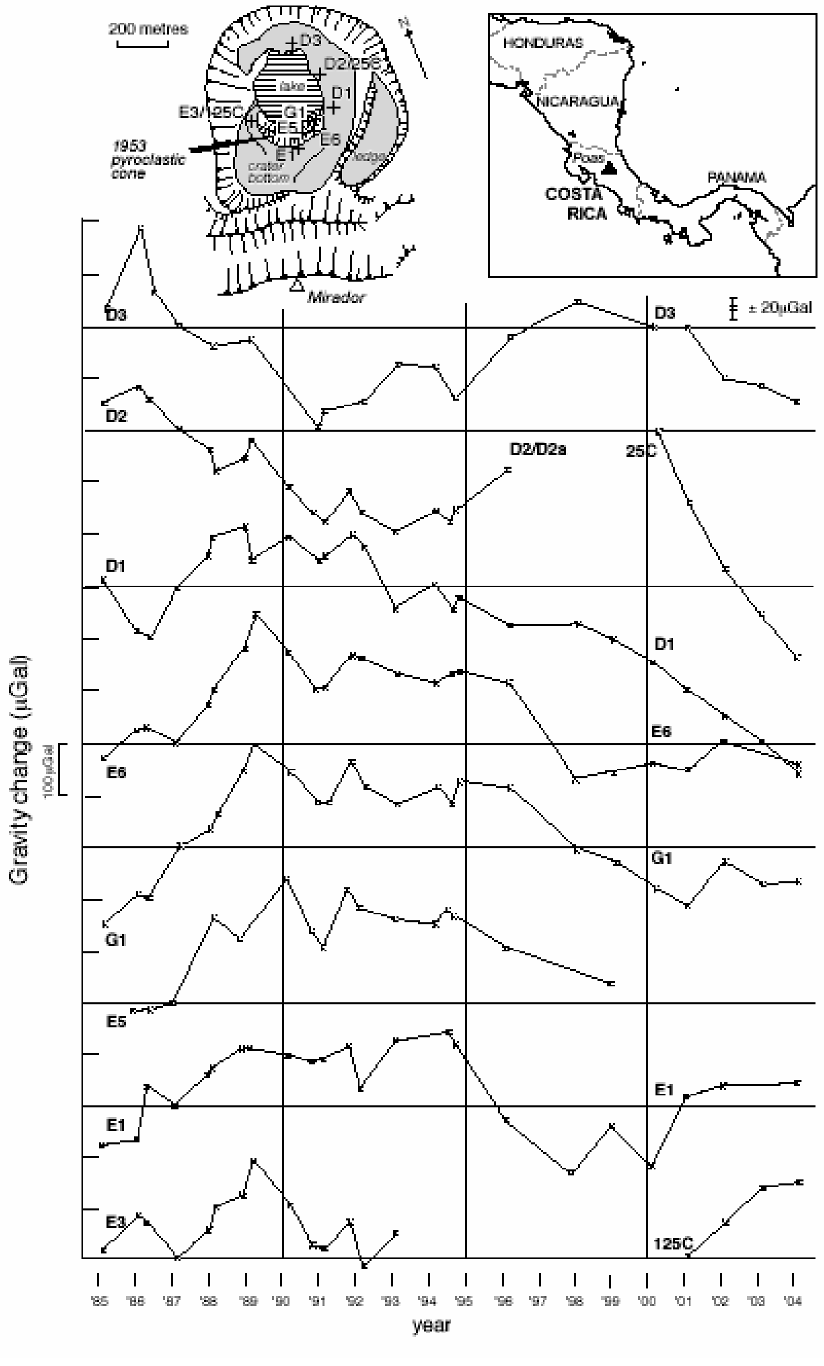

Figure 1. Gravity changes relative to a base station 7 km from the crater are normalised to the difference observed in 1987. Stations in very close proximity (E3 & 125C and D2,

D2A & 25C) are not distinguished in the figure. Inset 1: Station location map within the active crater area of Poás volcano. Inset 2: Map showing location of Poás Volcano.

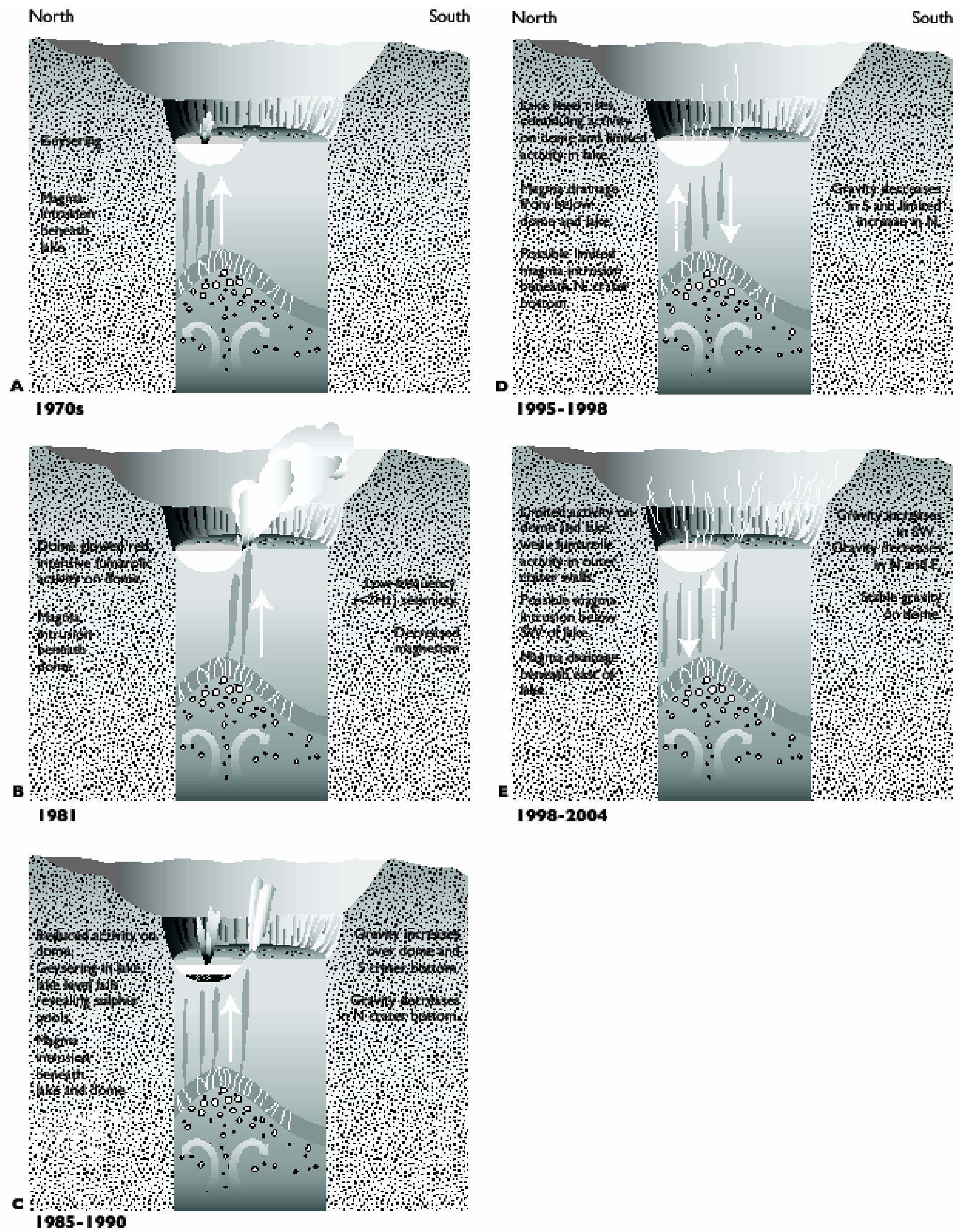

Figure 2. Cartoons depicting possible locations and direction (up or down) of flow within cells. Seismicity and magnetic information from *Rymer et al, 2000*.