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Long-term fluctuations in volcanic activity: implications for future environmental impact

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ABSTRACT

Acidic crater lakes at persistently active volcanoes act as both an index and a moderator of volcanic processes. A catastrophic drop in lake level can therefore lead to serious local environmental damage. In the early 1990s, the crater lake at Poás volcano, Costa Rica diminished, and acid aerosols erupted with devastating consequences for local health, environment and economy. The first indications of this event can be retrospectively identified to have started from 1985, on the basis of our unique 20-year data time series, which provides evidence for the shallow intrusion of magma. New data presented in this article show similar trends and we conclude that Poás has now entered another active period with renewed intrusion. Severe environmental damage in this region is expected within the next few years if the current trend continues.

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Introduction

Eruption forecasting over relatively short periods has been demonstrated to be possible (Voight and Cornelius, 1991; Barclay *et al*., 2006; Fujinawa *et al*., 2006), and long-term predictions can be made with quantified uncertainties (Coles and Sparks, 2006; Connor *et al*., 2006). Such forecasting is essential for adopting effective preventative measures to reduce impacts on communities and economies. Although phreatic eruptions through acidic crater lakes typically present a limited hazard, activity associated with a catastrophic drop in lake level and consequent degassing directly to the atmosphere, poses a serious local environmental threat (Pasternack and Varekamp, 1997; Delmelle *et al*., 2003). Early warning of such events is, therefore crucial to mitigating the risks associated with such events. Years before symptoms of enhanced activity manifest at the surface, mass changes at the depth of the crater lake may occur, so detection of these could give vital early warning. A case in point is Poás, a persistently active volcano (Fig. 1a,b) characterised by an acid crater lake; this lake and its hydrothermal eruptions attract many tourists. Historical activity at Poás has been mostly phreatic and is well documented (Krushensky and Escalante, 1967; Raccichini and Bennett, 1978; Vargas, 1979; Boza and Mendoza, 1981; Casertano *et al*., 1983; Martinez *et al*., 2000). An active hydrothermal system has been present in the summit area throughout historical times (Rowe *et al*., 1995). Since the formation of a small composite pyroclastic cone (CPC), lava flow and pit crater in 1953–1954, the focus of gas emission activity has switched regularly between the CPC and the hot, acidic lake (pH ranging from <0 to 1.8) in the adjacent pit crater (Fig. 1c). During the period between 1988 and 1990, a change in activity caused a dramatic drop in lake level resulting in direct venting of volcanic gases to the atmosphere and severe environmental impact. The Poás National Park was closed for prolonged periods as a result of drastic acidification of the environment; local agriculture, especially coffee, annual crops, pastures and exotic tree plantations were devastated. Health problems increased in local communities (eye, skin and throat irritation, nausea and vomiting) (Nicholson *et al*., 1996) and in dairy cattle (ranging from a decrease in milk production to increased mortality including spontaneous abortions) (Erik Fernandez, personal communication, 2009). Reduced volcanic activity during the subsequent years allowed agricultural and tourism activities to renew.

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Recent activity at Poas volcano

The shallow sub-surface structure of Poás has been described previously (Fournier *et al*., 2004; Rymer *et al*., 2005) as comprising a complex zone beneath the present crater that gives way at depths of some 500 m to a region of volatile rich magma. The top of this magmatic region is thought to be capped by a fractured carapace (Rowe *et al*., 1992). Large amounts of magma need to degas in order to provide the observed volatile release at persistently active volcanoes and this is generally thought to indicate the existence of an active convective system within a magmatic conduit (Kazahara *et al*., 1994; Stephenson and Blake, 1998). A hydrothermal system may also contribute by advecting to the surface very large quantities of fluids and heat from above the magma carapace.

A cycle of activity at Poás began in 1981 when fumarole temperatures rose to 1020 °C, and a red glow appeared on the northern face of the CPC. A-type seismicity, high sulphate levels, fumarole temperatures on the CPC and

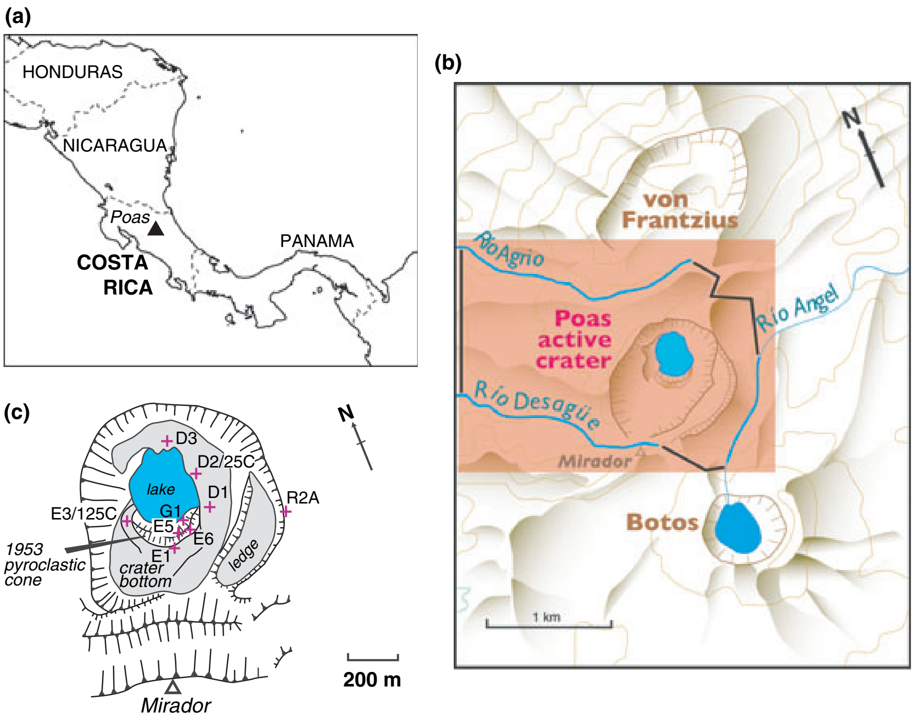


Fig. 1 Map locating Poás volcano in Costa Rica. (a) Map showing location of Poas volcano in Costa Rica. (b) Topographic map (contour interval 100 m) showing the active crater in relation to surrounding water courses and older craters. The region shown lies within the northern part of a larger summit caldera structure. The groundwater flow model extends between the rivers shown in blue; the area between the rivers at the edge of the model is assumed to be impermeable boundaries (shown in black). (c) Locations of the gravity stations and features of the crater including the pyroclastic cone erupted in 1952, referred to in this article as the CPC. Reference gravity station is located several kilometres south of the active region.

power output are consistent with an intrusion bringing gas-rich magma close to the surface beneath the CPC in late 1980/early 1981 (Casertano *et al*., 1987; Rymer *et al*., 2000). Estimates of falling power output and sulphate levels from 1983 indicate that the effects of the intrusive episode(s) were beginning to wane by this time. Lake level fell over the next few years until the lake floor was exposed in 1989. Activity in the late 1980s and early 1990s was consequently characterised by intense outgassing and sulphur eruptions (Oppenheimer and Stevenson, 1989). Acid gases and particles rained out across the southern and western regions of the volcano, impacting everyday life in nearby residential communities, agriculture and tourism.

By 1995, the lake had re-established to its pre-crisis level. The lake level then remained higher than at any time since the late 1970s until early 2005, when the level began to fall again. Fumarolic activity in the crater walls developed in the mid-late 1990s and intensified over the next 10 years. By 2006, energetic phreatic eruptions began to occur again from the deep lake, ejecting lake sediments and globular sulphur 200 m high, plastering the inner walls of the main active crater (OVSICORI, 2008). One of us (MM) observed that during a particularly intense phreatic explosion in March 2006, fumaroles on the eastern inner crater walls simultaneously emitted a distinct pulse of vapour, suggesting a direct, shallow depth coupling of the whole hydrothermal system.

Gravity time series

A time series of microgravity data collected between 1985 and 2008 (corrected for tides and deformation) shows two characteristic signatures (Fig. 2a,b). Gravity variations at stations in the south of the crater (E1, E3/125c, E5, E6 and G1; Fig. 1c) were clearly concordant (Fig. 2a) as were the variations (Fig. 2b) at the north crater stations (D2/2a/25c and D3/3a; Fig. 1c). Gravity variations at station D1 (in the east) correlated with those at the southern stations until 1994, with the northern stations from 2000 to 2004, and finally with the southern stations again until 2008. The volume, temperature, and sulphate concentration of the acid lake from 1978 to 2008 are also shown in Fig. 2e–g along with power estimates from 1978 to 1989 (Fig. 2h). Throughout this period, deformation in the summit region, measured by EDM theodolite and dual frequency GPS, was negligible (i.e. $<$ a few centimetres of deflation).

In order to interpret the significance of these very large gravity changes, the effects of variations in lake level and the surrounding water table were quantified by developing a pseudo-steady-state numerical groundwater-flow model of the summit region around Poás active crater. The one-layer groundwater flow model (with $>14\,000$ cells, each of 10 m^2) extends from the constant head flow boundaries formed by Rio Angel, Rio Desague and Rio Von Frantzius to

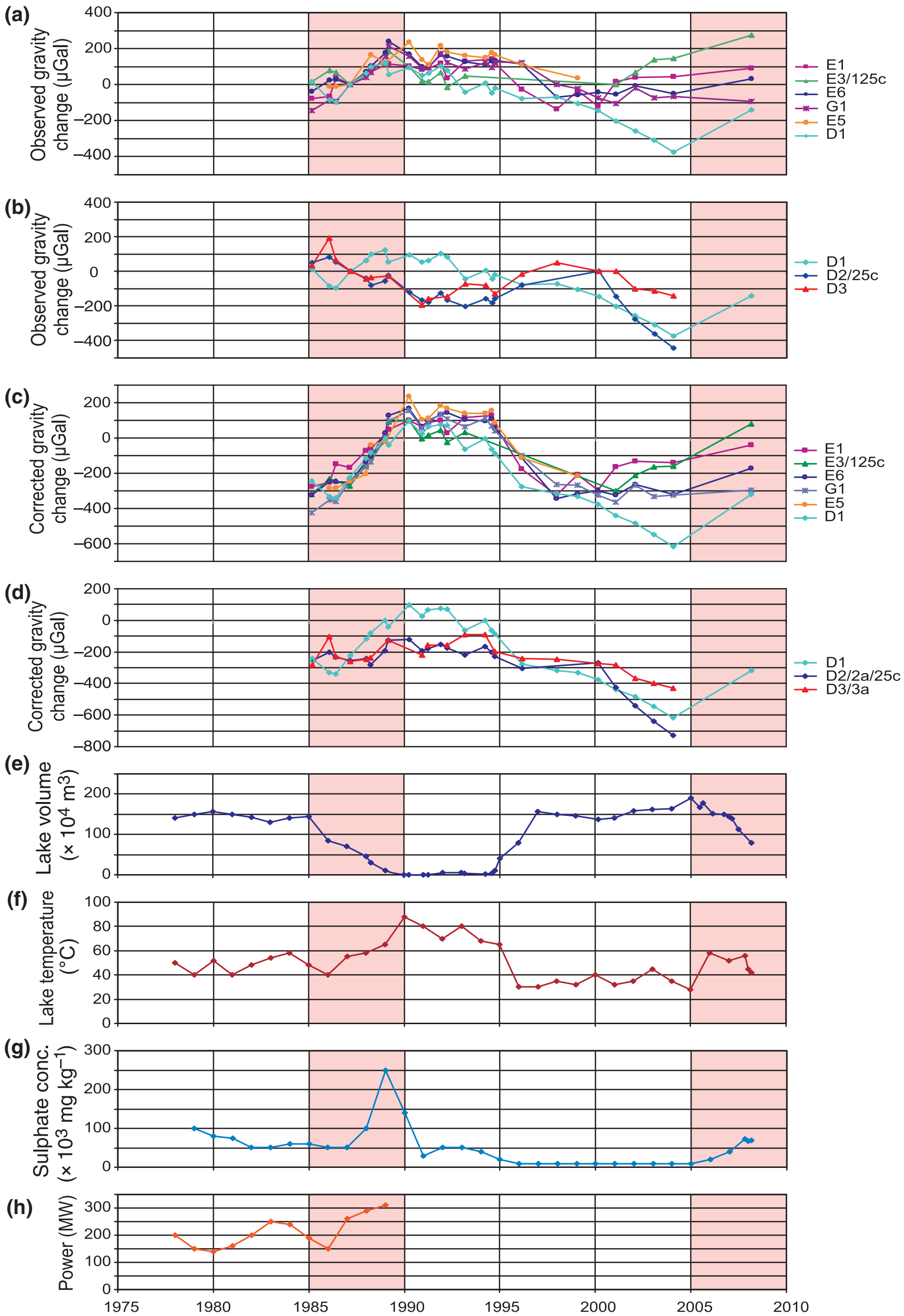


Fig. 2 Variations between 1978 and 2008 in (a) observed gravity data from stations in the southern crater corrected for earth tides and deformation; (b) observed gravity data from stations in the northern crater corrected for earth tides and deformation; (c) corrected gravity data from stations in the southern crater corrected for earth tides, deformation and variations in lake level and water table; (d) corrected gravity data from stations in the northern crater corrected for earth tides, deformation and variations in lake level and water table; (e) lake volume; (f) lake temperature; (g) sulphate concentration; and (h)power output. These graphs include new and previously published data (Casertano *et al*., 1987; Brown *et al*., 1989; Martinez *et al*., 2000; Rymer *et al*., 2005; OVSICORI, 2008). At times of low lake volume, temperatures of the vestiges of the lake are given. Power output calculations are based on using the lake as a calorimeter (Brown *et al*., 1989) and using measurements of temperature of lake and air, volume, surface area, wind speed and rainfall. Volcanic activity in 1989 resulted in the closure of the meteorological observation station on Poás and so data are not available to calculate power output since that time. The repeat gravity survey was carried out using previously published techniques (Rymer *et al*., 2000). Data are corrected for earth tide and calibration effects; the resulting uncertainty in the data presented in Fig. 2 is ~20 μGal. Lake temperature, sulphate concentrations (mostly determined by ion chromatography) and lake volume data include new and existing (Rowe *et al*., 1992; Martinez *et al*., 2000) data.

the crater lake (Fig. 1b). The areas between these rivers at the edge of the model are assumed to be impermeable boundaries. All of these boundaries are far enough from the crater area that they do not affect significantly the flow pattern and the level of the water table. The lower boundary of the model is assumed to be formed by the more-impermeable clay-altered lithologies related to the Von Frantzius and Botos tephra and lava volcanic units. The areal distribution of permeability within the model was calibrated using geology, topography (Instituto Geografico Nacional, 1967; Fournier *et al*., 2004) variable flow along drainages, estimated average yearly recharge from rainfall and recorded crater-lake water levels. The lowest lake level (no lake present), corresponding to the lowest water table, is taken as the reference level, and water table differences for the time at which each micro-gravity measurement was taken are calculated relative to this reference; the maximum lake level during the period of observation is 47 m above reference level. Gravity changes resulting from water table oscillations were calculated and subtracted from the measured gravity data to give corrected gravity changes (Fig. 2c,d). The maximum correction was 336 μGal at station E3 in March 1985, i.e. at a time when the lake level was high.

The 'water table' correction does not affect the pattern (i.e. periodicity and areal extent) of the measured gravity variations, (compare Fig. 2a with Fig. 2c and Fig. 2b with Fig. 2d) and in fact the magnitude of some of the variations is actually increased by the correction. Uncertainty in the corrections would affect the magnitude of the corrected variations to some degree but the overall pattern of changes would remain the same.

For the period 1985–1988, applying corrections to the observed gravity data for the lowering water table resulted in greater increases in the south of the crater (Fig. 2c) and small corrected gravity increases in the north (Fig. 2d). Between 1990 and 1995, the lake level was relatively stable, so the water table corrections were constant and there was no significant difference in the trends of the corrected and observed gravity data. The period 1995–2000 was characterised by a rising lake level and corrections for this rise in the water table resulted in larger gravity decreases in the south of the crater (Fig. 2c) and relatively constant corrected gravity values in the north of the crater bottom (Fig. 2d). Between 2000 and 2005, the lake level was high and stable and so the small gravity increases in the south of the crater were unchanged by the corrections. After correction, the 2008 dataset revealed gravity increases at stations in the south and the remaining northern station, even though the lake level was falling rapidly. Unfortunately, high lake levels between 2004 and 2006 prevented the taking of measurements and resulted in the destruction of two of the north crater stations.

Interpretation

The corrected gravity data, particularly in the southern crater, show a clear, systematic fluctuation over the 23-year observation-period. Coherent corrected gravity increases of 400–600 μGal across the southern crater between 1985 and 1990 were synchronous with a fall in lake level and related temperature increase. During the period between 1982 and 1987, sulphate concentration was approximately constant at 50×10^3 mg kg^{-1}; it rose rapidly in 1988/1989. Thus these changes preceded the rapid increase in sulphate concentration (Fig. 2g). It appears that a new cycle of activity started in 2002 with increases in gravity in the southern crater followed by changes in lake level, temperature and sulphate concentration in 2006 comparable with the changes observed during the previous cycle (highlighted in Fig. 2).

Activity at the volcano, together with physical and chemical observations are summarised in Fig. 3 along with possible interpretations. The corrected gravity changes must be caused by sub-surface mass changes of magmatic and/or hydrothermal (vapour/fluid interface) origin, as outlined in Fig. 3, though it is not possible to distinguish unambiguously the relative contributions of these processes. Gravity increases in the south of the crater bottom during the period between 1985 and 1990 have previously been interpreted in terms of an intrusive event (Rymer *et al*., 2000). These increases began at least 5 years before the onset of the period of intense outgassing and were apparently a precursor to this activity. In this article, we correlate for the first time, sulphate concentration in the lake with gravity changes over the last 20 years. During 1985–1990, sulphate concentrations were initially stable but then increased from 1987 to a maximum of 250×10^3 mg kg^{-1} in 1989. It is notable that the current cycle of gravity increases in the south starting in 2002 is once again followed (~4 years later) by an increase in sulphate levels and subsequent phreatic activity. We interpret this as indicating that a further intrusive event is occurring. It appears therefore that volatile rich magma pulses escape periodically through fractures in the magma carapace and form upwelling dendritic intrusions (finger-like injections of gas-rich magmatic fluids) reaching shallow levels immediately beneath the crater floor, where the hydrothermal system occurs.

Thermodynamic models for dykes and other small magmatic intrusions suggest that they must freeze within weeks of formation unless there is active communication with an ongoing supply of heat (Huppert and Woods, 2002). Convective recharge is the only way in which small, shallow magma dendrites can remain viable, but at any particular time, upwelling or downwelling flow may be dominant. Over the 23-year period studied, the corrected gravity data suggest that beneath the south and west part of the Poás crater, dendritic intrusions are mainly upwelling whilst beneath the north and east, they are mainly downwelling. However, the south and east intrusions do apparently show downwelling in relatively quiet periods. These dendritic intrusions are probably ephemeral. The whole upper conduit region beneath the crater bottom appears to behave as a convective zone with individual dendrites being active at different times. Variations of the size and position of the vapour zone will, of course, accompany magma movements in the dendrites (Fig. 3).

Gravity increases precede increases in sulphate concentration and temperature changes in the lake suggesting that the increased volatile and heat influx may be buffered by the hydrothermal system. In the 1985–1990

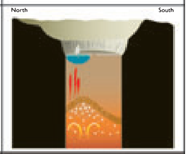
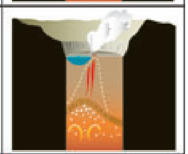
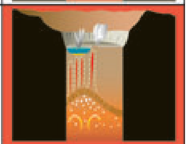
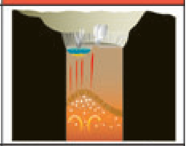
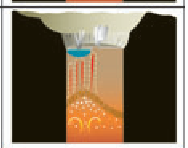
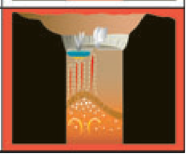
Date	Observations	Interpretations		
		Magmatic processes	Hydrothermal processes	
1948–1952	• Intermittent phreatic explosions and intense fumarolic activity			
1953–1955	• Magmatic eruption, growth of CPC	Intrusion and formation of CPC	Extensive vapour zone	
1968–1980	• Activity focussed on lake • Vigorous geysering (phreatic explosions) • Lake level high • Intense swarm of A-type earthquakes in July 1980	Intrusion cooling.	The aquifer floods the conduit. Vapour zone persists around intrusion.	
1981–1984	• Focus of activity moved to CPC • Intense fumarole activity and incandescence on CPC • Lake level remained high • No A-type earthquakes • Sharp rise in harmonic tremor and B-type earthquakes in March 1981 which declined through 1985.	***This marks the beginning of a new magmatic cycle*** Breakage of the magma carapace and intrusion beneath CPC.	Vapour zone begins to vent substantially to the atmosphere.	
1985–1990	• Focus of activity moves from CPC back to lake • Phreatic activity continued • Lake level fell revealing sulphur pools • Increasing B-type earthquakes; some A-type swarms in 1989-1991 • Deformation in crater <5 cm • Gravity increased by up to 600 µGal in south and 100 µGal in north • Sulphate concentration increased increased from 1987 to a maximum of 250 x 10^3 mg kg^{-1} and then declined • Lake temperature increased to 90 °C	Ongoing intrusion perhaps now beneath lake.	Vapour zone vents directly to the atmosphere, including through the lake bottom. Volume of vapour zone may shrink due to large loss of thermal energy.	
1990–1995	• Lake essentially dry • Intense degassing and acidification of the environment • Negligible deformation • Gravity in south decreased by ~100 µGal and then stabilised; remained stable in north and decreased by 200 µGal in east • Sulphate concentration decreased and then stabilised at 50 x 10^3 mg kg^{-1} • Lake temperature decreased; briefly falling to 26 °C in November 1995	Possible drainage of magma beneath CPC and lake.	Vapour zone continues to vent directly to the atmosphere, shrink and flood at depth	
1995–2000	• Activity confined to fumaroles in crater; new fumaroles develop on the CPC, inner crater walls and the crater floor • Lake level rose rapidly • Gravity in south decreased by ~400 µGal and then stabilised; gravity stable at 100 µGal below 1990–1995 level in north and east • Sulphate concentration low and stable at ~10 x 10^3 mg kg^{-1} • Lake temperature decreased to ~40 °C	Possible drainage of magma beneath CPC and lake.	Vapour zone reforms at depth	
2000–2005	• Fumarolic activity focussed on the innercrater walls, mainly the eastern wall and later beneath the lake • Phreatic eruptions recommenced • Lake level rose rapidly • Gravity in south decreased by ~400 µGal and then stabilised; gravity stable at 100 µGal below 1990–1995 level in north and east • Sulphate concentration low and stable at ~10 x 10^3 mg kg^{-1} • Lake temperature decreased to ~40 °C	***2nd cycle begins*** Breakage of the magma carapace and intrusion west/south of CPC.	Vapour zone grows toward the north and east, and begins to vent to the atmosphere.	
2005–2008	• Intermittent vigorous phreatic eruptions • Fumaroles in the northern and eastern side of the crater weakened after 2006 • Lake level fell rapidly • Deformation negligible - just 3 cm subsidence locally on crater floor • Gravity increased by ~250 µGal in south • Sulphate concentration increasing to 98 x 10^3 mg kg^{-1} • Lake temperature increased to ~58 °C	Ongoing intrusion west of CPC; intrusion east of CPC.	Vapour zone venting and shrinking	

Fig. 3 Summary of observations from Poás volcano from 1953 to 2008 interpreted in terms of cyclical magmatic and hydrothermal processes. Includes new and existing data (Martinez *et al*., 2000; Rymer *et al*., 2005; OVSICORI, 2008). Cartoons (some after Rymer *et al*., 2005); North–South sections through the active crater area showing the relationship between the lake and the CPC. Crater is ~1 km across and 200 m deep. Molten gas-rich magma is capped by a fractured carapace. Upwelling and downwelling magma dendrites transport heat and mass. Broken line indicates schematically the extent of the vapour zone. Variations in lake level and fumarolic activity are also shown.

episode, the sulphate increase began 2 years after the gravity increase began. In the 2002–2008 episode, the sulphate increase lagged by 4 years. In both cases, increased phreatic activity occurred within a year of the increased sulphate levels being recorded. Significantly, in both cases, clearly observable gravity changes occurred for at least 5 years prior to the commencement of increased eruptive activity.

The unique long-term dataset presented in this article demonstrates the effectiveness of gravity combined with sulphate and other parameters in identifying sub-surface processes at active volcanoes. Early recognition of these processes provides, for the first time, a new opportunity for timely hazard warning and the initiation of preventative measures. These recent measurements at Poás volcano strongly suggest that a new cycle of activity is now underway. If the cycle continues to develop as before, and the lake level continues to fall, we may expect a repeat of the environmental damage that occurred in the early 1990s within the next few years.

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