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MICROGRAVITY MONITORING AT POAS VOLCANO; 1983-1986, COSTA RICA

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ABSTRACT

The discovery during a two month observation period at Poas volcano in 1983 of cyclic changes in microgravity associated with vesiculation cycles deep in the magma column led to a more detailed investigation in 1985. Statistical analysis has revealed that superimposed on the deep cycles there is a second effect. This is derived from the largest and best constrained gravity variations which occur locally at stations in the north of the active crater. Concurrent microelevation observations have revealed that there are no significant relative elevation changes in the summit area of Poas, and therefore the gravity changes must be caused by sub-surface density variations. This and the tight spatial distribution of the largest microgravity changes limits the causative sub-surface density changes to a shallow depth. It is deduced that the vertical migration of the water/steam interface, about 30 m below the crater lake is the principal cause of the largest gravity changes in the active crater. These variations, which occur in the 200-300 m wide permeable, most recently-reactivated cylindrical feeder pipe beneath the crater lake, are superimposed on the broader vesiculation-induced density changes, occurring below 500 m in the 1 km wide partially-molten magma column (inferred from the 1983 data set). These results clearly show that important information on the behaviour of active but apparently stable volcanoes may be derived by microgravity monitoring.

RESUMEN

El descubrimiento de un cambio cíclico en microgravedad, asociado con ciclos de vesiculación profunda en la columna de magma, en el volcán Poás, durante dos meses de observación en 1983, condujo a estudios más detallados en 1985. El análisis estadístico ha revelado que, sobreimpuesto en el ciclo profundo hay un segundo efecto. Esto se deriva de las mayores y mejores restricciones en las variaciones de la gravedad, las cuales ocurren localmente en las estaciones del lado norte del cráter activo. Las observaciones concurrentes de microelevación han revelado que no hay cambios significativos en la elevación relativa en el área de la cima del Poás y por eso, los cambios de gravedad deben ser causados por variaciones superficiales de la densidad. Esto, y la estrecha distribución espacial de los mayores cambios de microgravedad, limitan las causas en las variaciones de densidad superficial, a una baja profundidad.

Se deduce que la migración vertical de la interfase agua-vapor, que está aproximadamente a 30 m bajo la laguna del cráter, es la causa principal de los mayores cambios de gravedad en el cráter activo.

Estas variaciones que ocurren en una anchura permeable de 200 a 300 m, en el recientemente reactivado conducto cilíndrico, bajo la laguna del cráter, están sobreimpuestas a los más amplios cambios de densidad inducidos por vesiculación, que ocurren por debajo de los 500 m de profundidad, en una columna de magma parcialmente fundida, de 1 km de anchura (inferido del conjunto de datos del año 1983). Estos resultados muestran claramente que información importante sobre el comportamiento de volcanes activos, pero aparentemente estables, puede derivarse de estudios de registro de microgravedad.

INTRODUCTION: THE 1983-84 MONITORING PROGRAMME

Over a 43 day period in 1983, microgravity measurements were carried out on the summit areas of Poas, on its southern flank and locations remote from the volcano (Rymer & Brown 1984). In all, ten sets of measurements were made during this time and the procedure adopted was as follows. A base station reading in San Jose Central Park was taken in the morning (BM 314) then measurements were taken (always in the same order) at 3 crater rim stations, 4 flank stations, and 4 remote stations, on the San Pedro-Alajuela road. Finally a base station reading in San Jose would be made in the evening to close the loop. Gravity differences relative to the average base station reading (after correction for the effects of the Earth tides using a computer program described by Brouke et al. 1982) were then calculated. The variation of these difference through time was monitored during the 43 day period. It was found that the data had a cyclic tendency, with a large amplitude for the crater rim stations, smaller amplitude for the flank stations and a smaller still variation was observed at the remote stations (Figure 1). Best fit sine waves of period 30 days were fitted to the data,

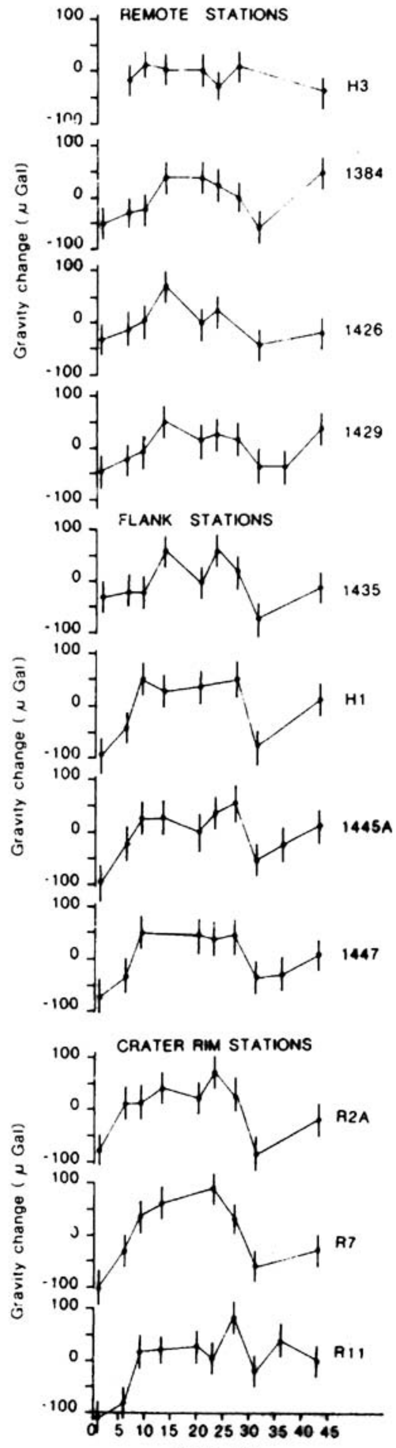

FIGURE 1

Gravity changes (u Gal) observed at the crater rim, flank and remote stations over a 43 day period in 1983.

which displayed peakes and troughs in phase with the appearance of the full and new moon respectively (Figure 2). A more limited data set collected in 1984 fits the same trend.

Analysis of the errors involved in making these measurements is complicated by a number of factors which are difficult to quantify. For example, the effects of hysteresis in the gravimeter spring, of moving the instrument between stations, of reader error and an incorrect prediction of the effect of Earth tides will all be to increase the error on each reading. A series of experiments including making half hourly measurements in one place to check the tidal prediction programme, and making several repeat measurements at different locations to check for other effects (Rymer, 1985) revealed that the error on a single reading in 16 u Gal and on a gravity difference measurement is at most 30 u Gal. Since for crater rim and flank stations successive measurements lie beyond the 30 u Gal error bars (see Figure 1) and therefore beyond one standard deviation, the gravity variations are significant at least at the 68% confidence level. Although there are uncertainties in the precision of these data, it is clear that relative to the base station in San Jose, there are cyclic changes of gravity of the order 100-150 u Gal at crater rim stations and 60-100 u Gal at flank stations. Given a standard error about the mean of 30 u Gal, variations at remote stations are insignificant. Variations at crater rim stations, however, are significantly different from variations at remote stations at the 95% confidence level and variations at flank station are likewise significant at the 87% confidence level.

The location of these significant dynamic gravity changes coincides with a static gravity anomaly. The time averaged (ie. static) gravity field (Figure 3a) reveals an extensive negative anomaly centred on Laguna del Botos and thought to outline an ancient caldera structure (Brown, Rymer, Thorpe, 1987), now eroded and largely filled with poorly-consolidate pyroclastic materials.

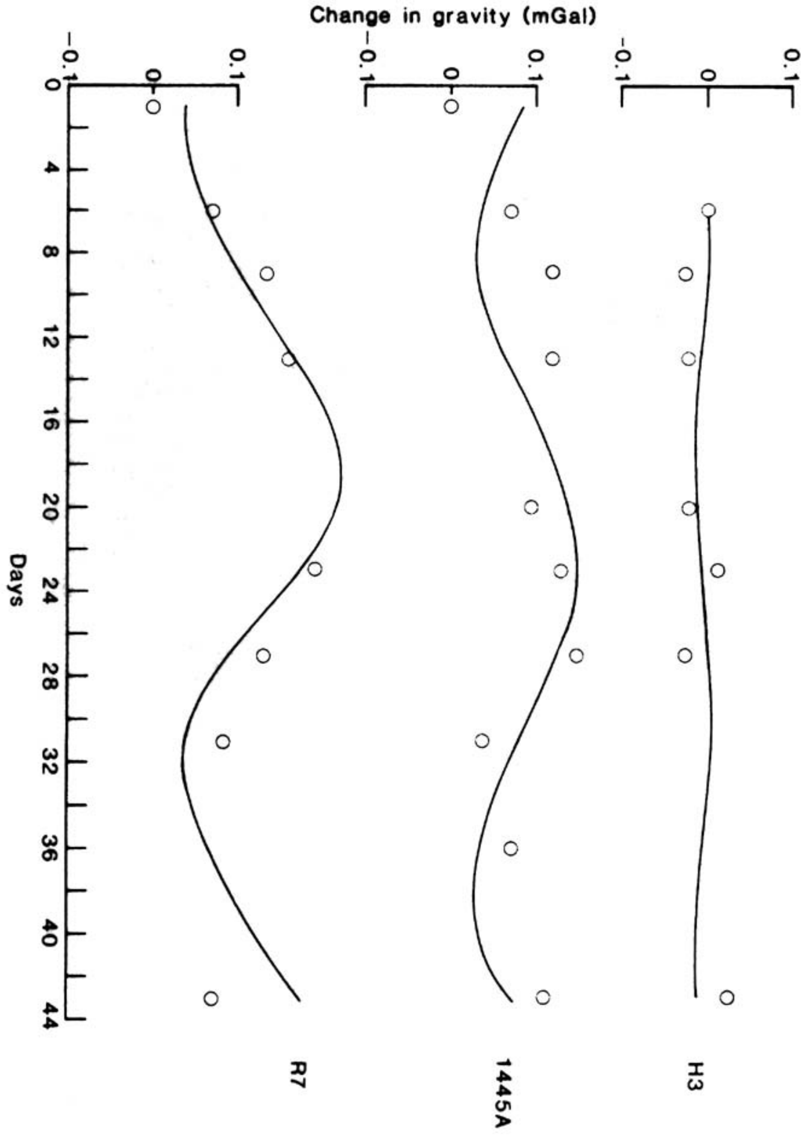

FIGURE 2

1983 Gravity variations at (R7) a crater rim station, (1445A) a flank station on Poas volcano and (H3) a remote station in Alajuela. Open circles represent the observed data points and the curves represented the calculated best fit sine wave of 30 day period through the data. The peak and troughs of the curves coincide within 4 days of the appearance of the full and new moon respectively.

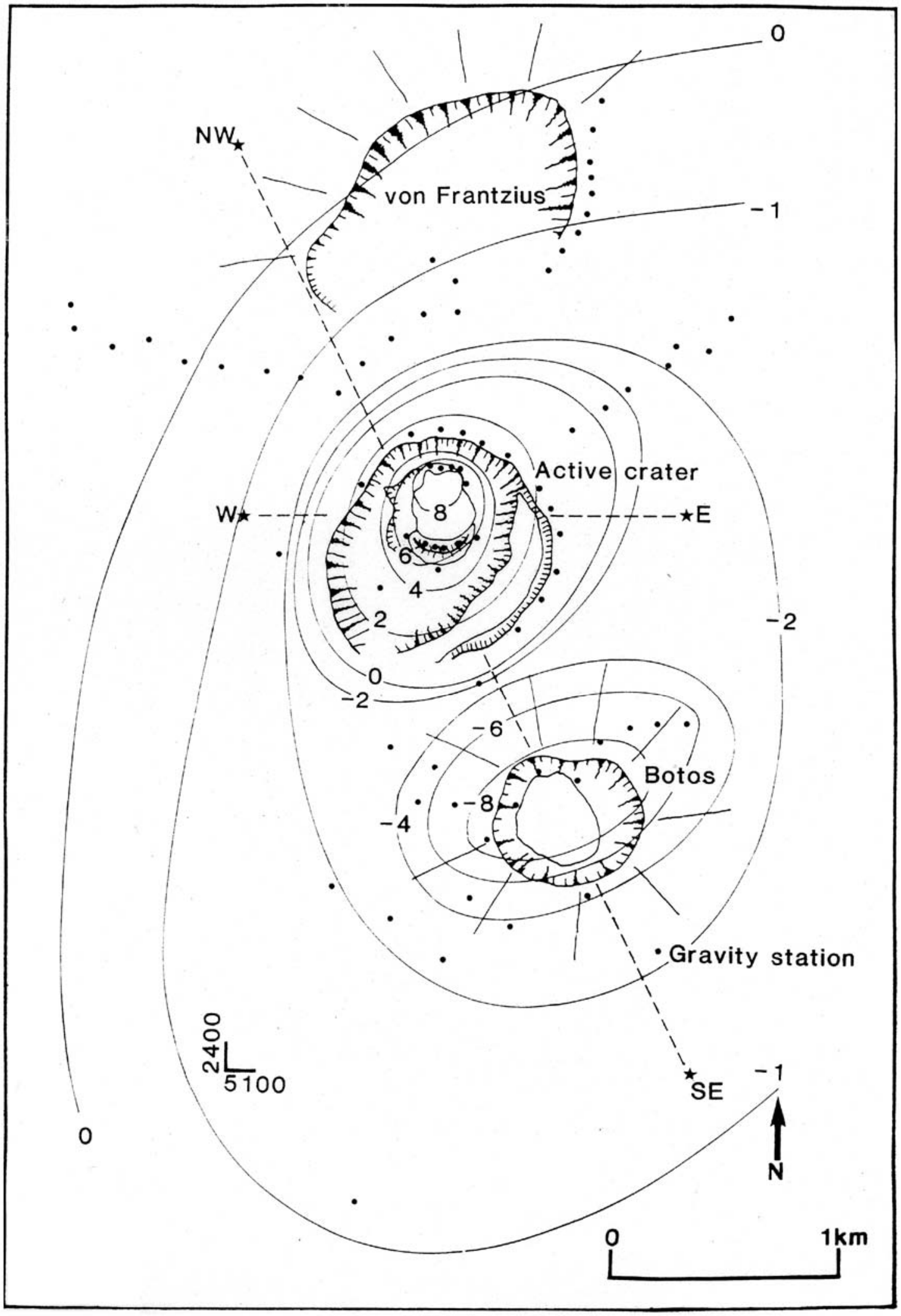

FIGURE 3 a

Static (or time averaged) gravity anomaly in the summit region of Poas volcano. Contours in mGal.

MICROGRAVITY-POAS VOLCANO

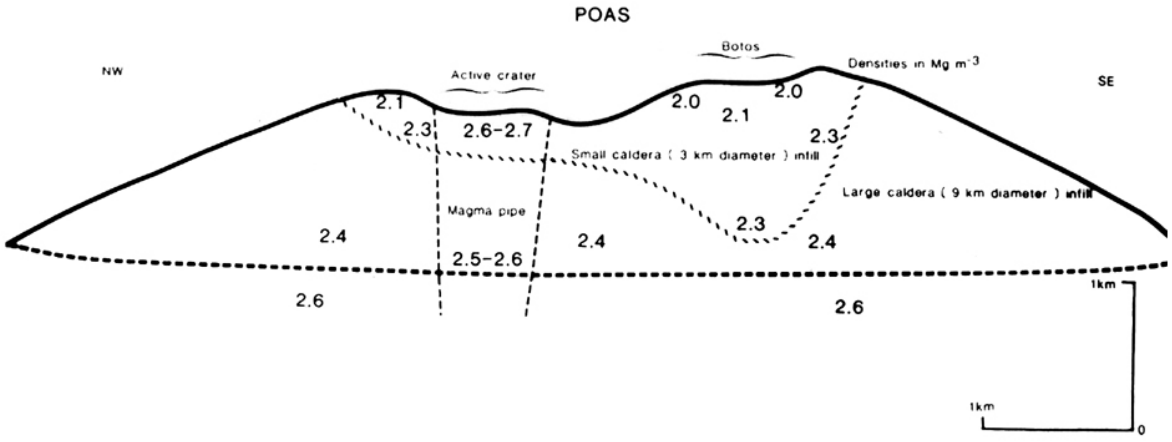

FIGURE 3b

Cartoon representing a NW-SE cross section through the summit of Poas, deduced from the gravity data summarised in (a).

Within this broad negative fields is a closed 1 km diameter circular positive anomaly representing a sub-surface density contrast between the surrounding lighter caldera infill and the more dense partly-solidified basaltic-andesite material beneath the active crater. Figure 3b shows, in summary form (details in Rymer, 1985), the magma pipe beneath the active crater and two stages of caldera infill deposits. The 1983/4 dynamic data have been considered and analysed against the background of this model (Rymer and Brown, 1987).

The various possible causes of these cyclic gravity changes have been considered as shown in Figure 4. The surface gravitational effect of variations in the radius and depth to the top of the magma pipe were calculated and compared with the observations. Similarly the effect of sub-surface water table movements were calculated. In each case, movements could be envisaged that would result in the observed surface gravity change at crater rim stations but not at flank stations (the calculated effect for magma pipe dimension changes being too small and for water table movements too large). The best fitting model was found to be for density changes within the magma pipe. In order that the range of predicted surface gravitational effects is the same as those observed, these density changes are likely to occur within an 'infinite' magma cylinder with its upper boundary ca. 500 m beneath the surface. The necessary density changes are surprisingly small, only $\pm$ 0.015 Mg m^{-3} on average throughout the magma pipe and are thought (Rymer & Brown, 1987) to represent thermally-induced changes in the degree of vesiculation within the partially molten magma. Only this type of model fitted the observation that cyclic changes of gravity up to 150 u Gal magnitude occurred at the crater rim, and up to 100 u Gal on the upper flank (Figure 4). In order to investigate these gravity changes further and to refine the model for their cause, more detailed and intensive microgravity monitoring was begun at Poas in 1985.

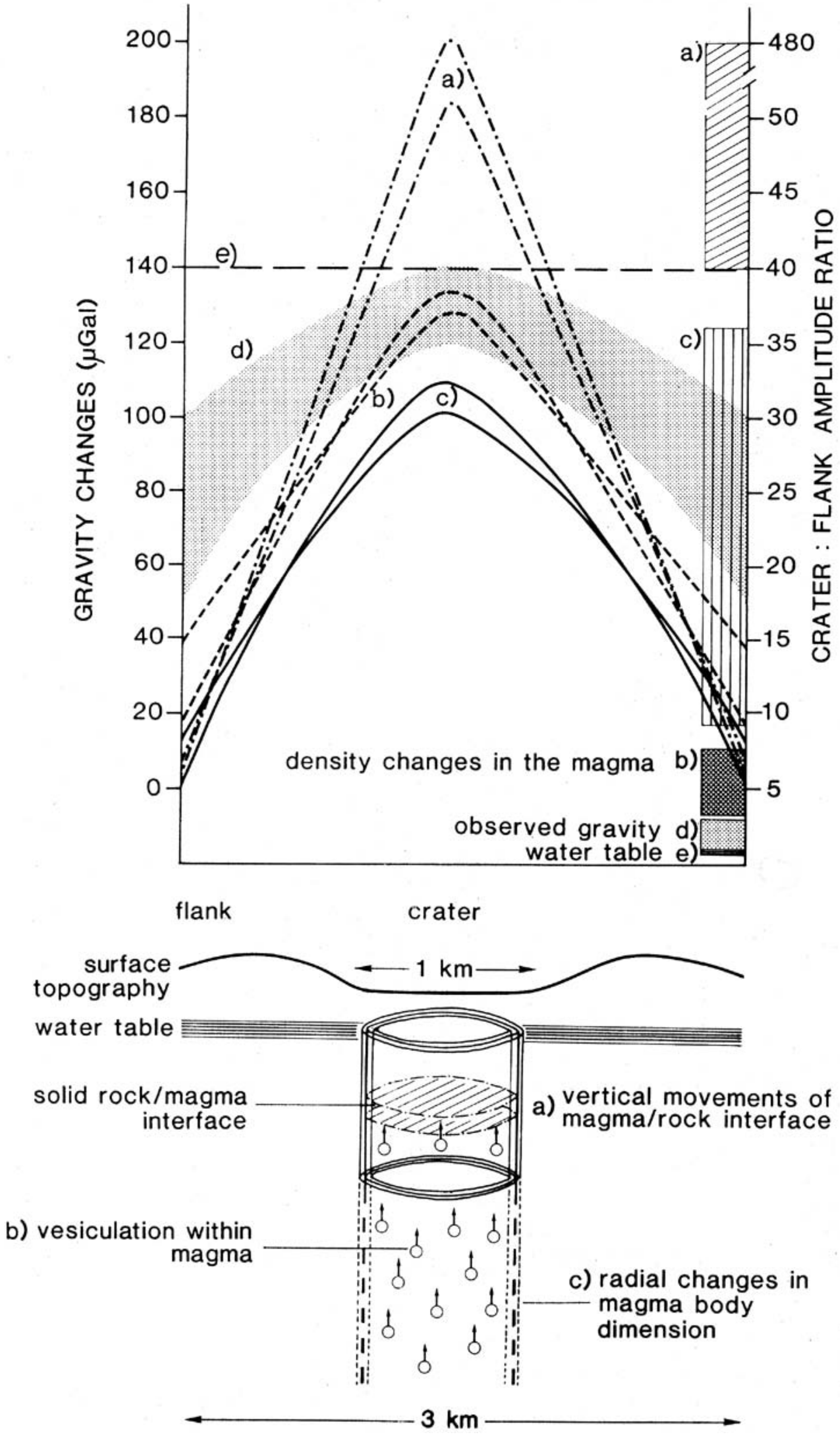

FIGURE 4: Schematic illustration of the gravity effect (top) produced at the volcano flank and summit (crater), and the ratio of the two (top right) by (a) vertical movements of the magma/rock interface, (b) vesiculation cycles within the magma column, (c) radial changes in magma body dimensions and (e) variations in water table level. The range of observed flank and crater gravity changes is shaded and labelled (d).

DISCUSSION OF THE 1985 DATA SET

A series of 18 sets of measurements was made during March-May 1985 at locations shown in Figure 5. To improve the precision of the results, 2 base stations (Group 1; stations H3 and F1 in Figure 5 insert) were used together with 3 lower flank stations (Group 2), 4 upper flank (Group 3), 3 east crater rim stations (Group 4), 3 west crater rim stations (Group 5), 3 southern crater floor stations (Group 6), 3 'dome' stations (Group 7) and 3 northern crater floor stations (Group 8). The stations in groups 2-8 are indentified in Table 1 and their positions are marked on Figure 5. Again, measurements were always made in the same order, but initial gravity values were now expressed relative to the average (calculated from 4 measurements) base station reading for the day. Gravity differences between the observations at each of the 22 stations and the base average were then calculated for each of the 18 days on which measurements were taken, and an average difference for each station so deduced. Deviations from this average difference for each day were recorded as gravity changes and values for stations in each group on each day were then averaged to produce a single representative figure for deviation (gravity change) from the average gravity difference for that group as compared with the base. Finally, for each station group a value for the standard error about the mean was calculated.

The change in gravity difference between the base station group and the other groups for each day of measurement is given relative to the average difference for each group, in Table 1 (first set of figures). Clearly, any errors due to hysteresis in the gravimeter spring, taking the base station readings, or in undetected tares are still present in the data and must be removed as effectively as possible. Therefore a second stage of normalisation was introduced as follows. On the assumption that relative gravity on different days for group 2 stations (lower flank: Figure 5) is a regional effect unrelated to the summit magma chamber, the final values in

Table 1

Gravity changes (μGal) for groups of stations at Poas volcano first corrected only to the base stations (first number in each set) and then (second number) normalised to the values seen at remote stations on the lower flanky. (Group 2). Details of calculation method are described in the text.

Date	7.3.85	9.3.85	10.3.85	12.3.85	16.3.85	20.3.85	24.3.85	31.3.85	2.4.85	2.5.85	4.5.85	7.6.85	10.6.85	12.6.85	14.6.85	16.6.85	19.6.85	21.6.85	Standard error about the mean
Group & Stations																			
Lower Flank																			
2	-33	-	46	-14	-21	-37	-6	-85	5	18	62	15	-114	-14	28	-24	13	23	44
F2,H2,H1	0	-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Upper Flank																			
3	44	-147	75	82	39	-67	23	-20	-4	18	71	69	-144	22	55	26	-16	14	67
1445A;1447	77	-	29	96	60	-30	29	65	-9	0	9	54	-30	36	27	50	-29	-9	39
A1, B1																			
East Rim																			
4	3	97	-30	58	12	-33	72	-100	4	30	135	99	-119	-29	70	6	-8	30	68
R2A, R7,R11	36	-	-76	72	33	4	78	-15	-1	12	73	84	-5	-15	42	30	-21	7	42
West Rim																			
5	-	-88	18	-	66	-75	88	-85	6	43	88	89	-102	10	79	34	-6	69	68
Z1A,Z2A,Z3A	-	-	-28	-	87	-38	94	0	1	25	26	74	12	24	51	58	-19	46	41
South Crater																			
6	-	-	145	-	19	-35	18	1	-34	27	-25	71	-140	-17	80	19	-41	68	66
E1,D1,E3	-	-	99	-	40	2	24	86	-39	9	-87	56	-26	-3	52	43	-54	45	52
Dome																			
7	-	-	-	-	-	-25	-49	69	-83	32	-104	110	-168	-125	82	-2	-60	-27	84
E5,E6,G1	-	-	-	-	-	12	-43	154	-88	14	-166	95	-54	-111	54	22	-73	-50	88
North Crater																			
8	-	-	182	-	49	21	56	-117	-66	76	-13	62	-106	-25	98	-9	-35	76	81
D2,D3,E7	-	-	136	-	70	58	62	-32	-71	58	-75	47	8	-11	70	15	-48	53	60

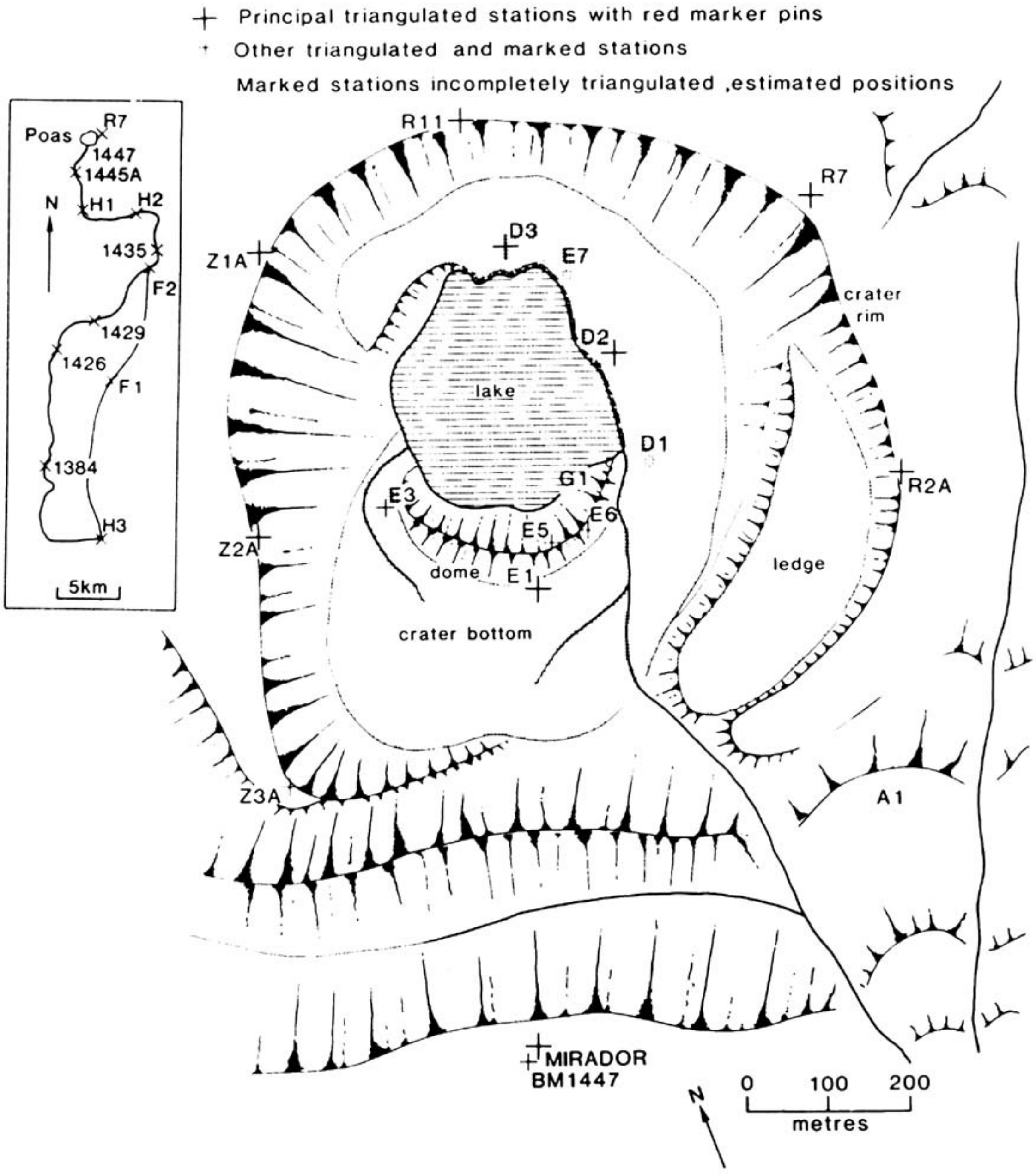

FIGURE 5

Map showing the locations of microgravity stations used during the 1985 survey.

Table 1 were produced by subtracting the group 2 values, thus automatically setting all group 2 values to zero. These normalised gravity values are thought to provide a more precise reflection of the true gravity difference variations though minor tares may still exist in the data set: they are shown in Figure 6. Almost 400 gravity difference measurements are summarised in Figure 6 and from these it is obvious, as first suggested by the 1983/4 data, that there are larger gravity changes at the summit area of Poas, particularly within the crater (Groups 6-8), than on the flanks.

It is difficult to quantify any remaining errors in these values, but the standard error about the mean for each station group in Table 1 (final column) gives an indication of the spread of the data. Having normalised the data by removing the gravity variations seen at group 2 stations and thereby removing most instrumental effects, the expected standard error about the mean becomes less than 30 u Gal (see earlier). This is because reading errors become the most significant factor and, since the largest expected error on a difference reading is 2 x 16 u Gal ≈ 22 u Gal. In this case, the observed standard error about the mean for group 3 (upper flank) stations (see Table 1) is significantly greater than expected at the 97.5% confidence level using the F test. Similarly variations at group 4 and 5 stations are significant at the 99% confidence level. However, variations at group 6, 7 and 8 stations are significant at the 99.9% confidence level. This supports evidence from the 1983/4 data that significant gravity changes are observed at flank stations and that the changes become more significant towards the crater.

In order to examine the data in more detail a more stringent approach is taken in which the standard error about the mean for each of groups 3-8 is compared with that for group 2 before normalization and the F test is used to investigate whether any differences are significant. In this way instrument related effects are more certainly filtered out as the standard error about the mean for group 2 stations (44 u Gal) is quite high. It is found

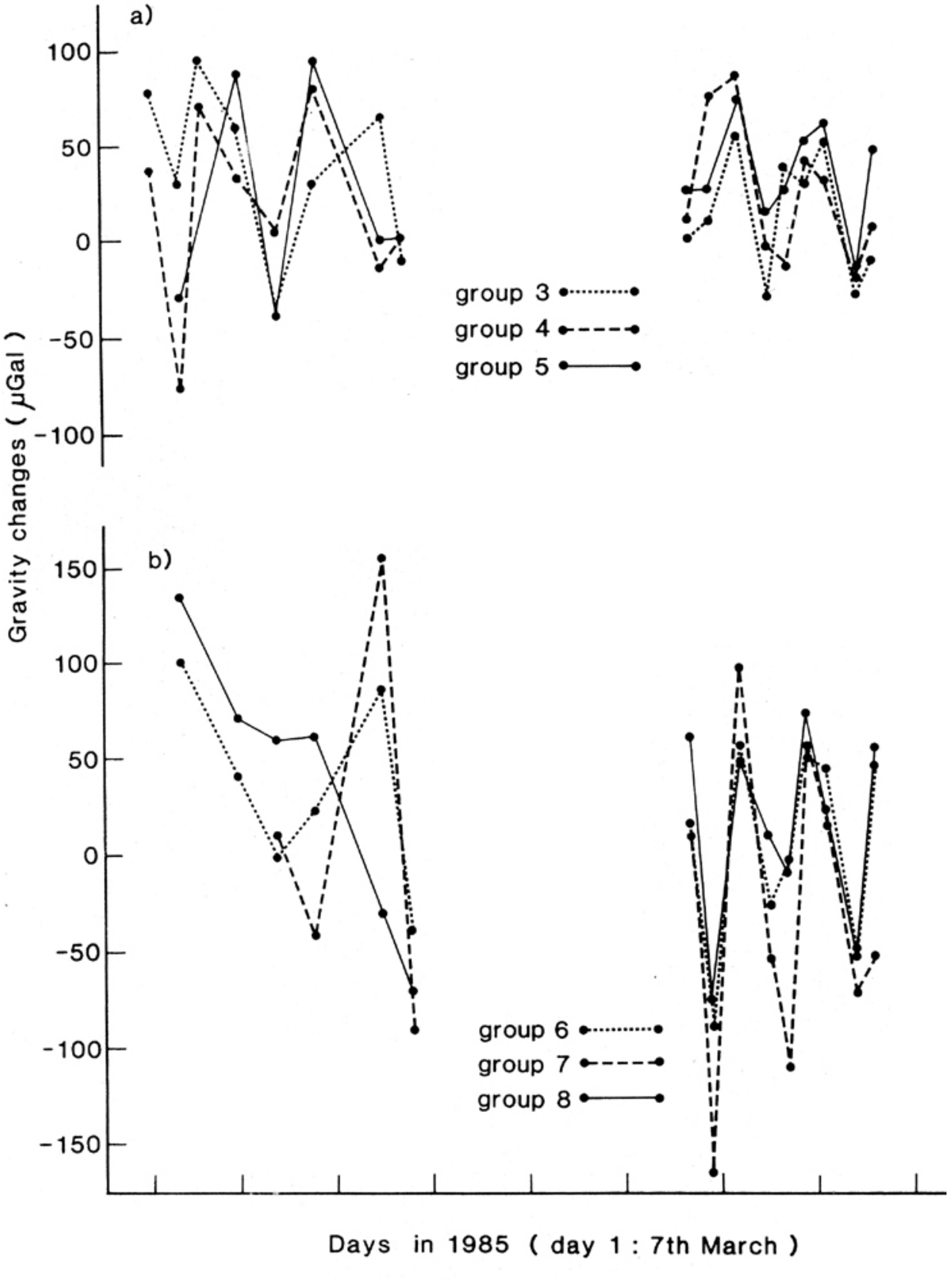

FIGURE 6

Relative gravity changes, normalised to the lower flank (Group 2) values for the 75 day period of observations in 1985: (a) upper flank and crater rim stations (b) crater bottom stations.

that groups 3-6 show variations that are not significant at the 90% confidence level. However, groups 7 & 8 (dome and north crater bottom stations) show significant variations at the 99% and 97.5% confidence levels respectively. In other words there is a more significant gravity change focused over these stations.

The analysis above indicates the complex way in which gravity changes appear to be distributed across the summit area at Poas. Towards the northern part of the crater bottom, including the pyroclastic dome stations (groups 7 & 8), significantly larger gravity changes occur, relative to the remove off-volcano stations, than for groups 4-6 on the rim and south crater bottom. Gravity changes at upper flank and southern crater bottom stations, with are smaller than those to the north, are significantly greater than would be expected from the possible errors in the data set at the 99% confidence level However, the 1985 data also substantiate the larger wavelength component of gravity change across the entire summit and upper flank regions that were previously detected and modelled (Rymer & Brown, 1987). We suggest therefore that there are both long (groups 3-8) and an additional short (groups 7-8) wavelength components of gravity change at Poas Volcano.

In summary, relative gravity changes, first recorded during 1983/4, extend beyond the region of the active crater onto the flanks. In partial contrast, the more precise and aerially extensive data from the 1985 survey reveal that <u>at least part of the effect is confined</u> to the most active northern part of the crater. Since this part of the effect is so localised, it may be due to a shallow source probably only tens of meters below the surface: its nature is considered below.

While the microgravity observations were being made in 1985, concurrent microelevation measurements were carried out. An infra-red e.d.m., theodolite and prism set was used to monitor relative elevation changes between the upper flank of Poas (the Mirador, at station 1447; see Figure 5), the northern and north western crater rim stations (groups 4 and 5) and the crater floor and dome stations (groups 6, 7 and 8). Error were large (up to ca. 10 cm) due to the effects of bad weather and the steam plume from the fumaroles. The elevation data (Table 2) are expressed as absolute heights relative to the Mirador bench mark 1447 which is assumed not to change in height (from 2573.766 m). They show no trend that correlates with the gravity data. For example on 24.3.85, the general trend of relative elevation is downwards and that of gravity is upwards whereas on 9.5.85 both elevation and gravity trend downwards. Apparent elevation changes then, are thought to represent Solely measurements errors. The approximate residual gravity change at the northern crater rim stations after variations at the flanks have been removed is about 50 u Gal. A vertical movement of 25 cm would be required by the Bouguer-corrected free air gradient (-200 u Gal m^{-1} for a density of 2.6 Mg m^{-3}) to account for gravity changes of 50 u Gal.

Since the gravity variations cannot be explained in terms of elevation changes, the cause must be a sub-surface change in density, this time focused beneath the most active (northern) part of the crater. This follows because the additional component of gravity change observed in 1985, superimposed on broader changes first observed in 1983, are so much more localised and concentrated within the active part of the crater. Therefore they are unlikely to be produced by the same widespread physical changes implied by the analysis in Figure 4. Water table movements and changes in the conduit size, shape or density are discounted as possible mechanisms because the gravitational effect at flank stations would be larger than observed. The sub-surface density changes are more likely to take place within a shallow ($<$ 500 m deep) portion of the conduit of limited lateral extent. In reality, this part is likely to be centred beneath the active area, and to be about 200-300 m across (the distance across which significant gravity changes area seen). An active ca. 200 m diameter cylinder within the main 1 km ring-

TABLE 2: Summary of elevation data for selected Poas gravity stations (March-May 1985)

Elevations in metres expressed relative to BM1447 = 2573.766 m above sea level.

Station	13.3.85	16.3.85	18.3.85	19.3.85	20.3.85	24.3.85	25.3.85	30.3.85	31.3.85	2.4.85	3.5.85	9.5.85	14.5.85	19.5.85	Mean of good quality readings	Standard error
R11, Group 4 Crater rim east				2440.699		2440.370	(2440.301)				2440.663	2439.347*	2440.665		2440.592	0.122
Z1a, Group 5 Crater rim west				2432.016	2432.205		(2431.442)				2431.421				2431.881	0.332
E1, Group 6 Crater floor South	233.539			2333.516	2333.548	2333.474	(2333.096)	2333.437	2333.524	2333.599	2333.688*	2333.356	2333.210*	2333.449	2333.494	0.033
D2, Group 8 Crater floor east		2321.409	2321.388*	2321.391	2321.381		(2321.350)	2321.383*			2321.310*	2320.609*	2321.353		2321.384	0.020
D3, Group 8 Crater floor east		2327.696	2327.722*	2327.687	2327.665		(2327.587)	2327.748*			2327.633*	2327.351		2327.873*	2327.600	0.132

Bracketed numbers less certain due to poor weather.

* Measurements less accurate, pin rather than target used.

fracture controlled pipe beneath the Poás crater is envisage which contains material more recently mobilised, especially during the 1953 eruption, and subsequently maintained at a higher temperature and in a more porous state than the rest of the surrounding conduit.

Because the effect is so localised the changes that produce it are likely to have a strong vertical component. Possible causes are changes in density due to migration of magma or water up and down shallow fractures, or a variable degree of vesiculation within the upper most section of the body if it were molten. For a simple model, the body is represented by a vertical right cylinder of diameter 200 m (minimum based on northern crater component of gravity change). The surface gravitational effect at a point to the axis of this cylinder (which represents the northern crater bottom and dome stations: groups 7 & 8) is calculated as the physical parameters of the cylinder are varied. Also the effects 150-200 m from the axis of the cylinder are calculated (which represent the southern crater bottom, group 6, and to a lesser extent the upper flank stations, group 3). The results are then compared with the magnitude of the observed gravity changes at these stations.

ANALYSIS OF THE 1985 DATA

The calculations summarised in Table 3 are used to model the localised, residual gravity changes at northern crater bottom and rim stations, having removed the effect seen at upper flank stations. Clearly in order to obtain gravity variations of the magnitude observed 'on axis' (ca. 50 u Gal; see Figure 6) that fall away to a very low level 'off axis' (probably 10 u Gal), only small subsurface changes at shallow levels are required. In (a) for example, density changes throughout the infinite cylinder of ± 0.015 Mg m^{-3} produce the observed gravity changes. An overall change in density by this amount in a partially-molten intrusion with average density 2.6 Mg m^{-3} could be accommodated by a 0.6% change in the degree of vesiculation within the magma. However it is unrealistic to model the body in this way for two reasons. First the approximation of an infinitely long cylinder is not appropiate, because (Figure 4) it

TABLE 3

Calculated gravitational effect at the northern and southern crater bottom stations as the average density of the supposed 200 m diameter body beneath the active crater and as the upper surface of the body and the water/steam interface migrate vertically.

a) Changes in the average density of the whole body, using the infinite cylinder approximation (radius 100 m, depth to upper surface 100 m).

Density change (Mg m^{-3})	Effect at northern crater stations (μGal)	Effect (a) 150 m and (b) 200 m, off axis, representing southern crater stations (μGal)	
		(a)	(b)
± 0.02	70	57	34
± 0.01	35	29	17

b) Changes in the average density of the whole body, using the finite cylinder approximation (radius 100 m, depth to upper surface 100 m, depth to lower surface 300 m).

Density change (Mg m^{-3})	Effect at northern crater stations (μGal)	Effect (a) 150 m and (b) 200 m off axis, representing southern crater stations (μGal)	
		(a)	(b)
±0.02	42	31	0.4
±0.01	21	15	0.2

c) Vertical movements of the upper surface of the body (assuming a density contrast between the body and the pyroclastic rubble above of 0.15 Mg m^{-3})

Depth to Interface (m)	Vertical migration (m)	Effect at northern crater stations (μGal)	Effect (a) 150 m and (b) 200 m off axis representing southern crater stations (μGal).	
			(a)	(b)
10	±3	34	0.2	0.05
50	±10	70	24	0.6

d) Vertical movements of the steam/water interface, assuming change in total density of 0.05 Mg m^{-3}.

Depth to interface (m)	Vertical migration (m)	Effect at northern crater stations (μGal)	Effect (a) 150 m and (b) 200 m off axis representing southern crater stations (μGal)	
			(a)	(b)
20	±10	34	0.5	0.4
50	±20	47	16	0.4
100	±20	25	14	0.5

can only be distinct from the main conduit to a depth of 500 m at most. A greater average density change ((b) in Table 3) is required in a finite cylinder to produce the observed gravity changes. Secondly, while variations in the degree of vesiculation of the main conduit magma may be used to explain the widespread 1983/4 gravity changes, the larger more localised component resolved by analysis of the 1985 data and constrained to a cause within a narrow cylindrical body is unlikely to be related to magma density changes. This is because this shallow body will consist of blocky solidified material rather than partially molten magma. While minor changes in the degree of vesiculation in magma below 500 m depth (see Rymer & Brown, 1987) can be envisaged without a change in surface activity, similar vesiculation within the uppermost hundred meters (required by this model to produce the observed amplitude of changes) without some sort of surface expression is highly improbable.

Two plausible options are left, the first ((c) in Table 3) is that the top surface of the body is moving vertically (up and down) with time. Although mathematically possible, this model is physically somewhat unrealistic because an osicllating shallow magma-solid rock interface is not expected within the top 100 m beneath Poas crater. However, if the depth to this surface were only 10 m, then movements of just ± 3 m would produce gravity changes both on and off axis of the magnitude observed. This assumes a density contrast between the body (density ca. 2.3-2.6 Mg m^{-3}) and the overlying lava fragments of 0.15 Mg m^{-3}. If the top surface is deeper, much larger movements are required. The periodic trend in the data (Figure 6) suggest that a cycle of these magma movements would have to occur every 10-15 days. Such extensive magma movements would inevitably cause intense microseismic activity and even surface magma eruptions, but seismic records from the permanent station at Poas are not consistent with this model and, indeed, showed an overall decline in activity during the period in question.

Secondly, the circulation of water within the blocky innermost cylinder could cause the observed gravity changes through variations in the depth of the steam-water interface. For the purposes of illustration let us assume that this blocky region has an average density of 2.47 Mg m^{-3} because it comprises solidified lava of density 2.6 Mg m^{-3} together with an average of 5% vesicles and spaces between fragments (minimum estimate based on surface sample observation). If the spaces are filled with water, then the average density of the region will be 2.52 Mg m^{-3}; if the water boils and is converted to steam the average density will fall back to 2.47 Mg m^{-3}. Calculations show ((d) Table 3), that migration of the water/steam interface in this manner over a distance of ± 10 to ± 20 m at depths between 20 and 100 m could produce the observed additional component of gravity change both at the northern crater bottom and dome stations If, as seems likely, the porosity of the column exceeds 5% then lesser vertical migrations would be required. This model is thought to be the most realistic on both geological and physical grounds. Of course, its gravitational effects are superimposed on the lesser, but significant gravity changes that occur at southern crater bottom, rim an upper flank stations and which are mainly accounted for by density variations at greater depth in the colum (Figure 4).

CONCLUDING DISCUSSION

The best fitting model for the total spectrum of gravity changes observed at Poas requires two components of subsurface density change and is summarised in Figure 7. From the static gravity data (Rymer, 1985) it is thought that a large cylindrical shaped intrusion (1 km diameter) lies under the active crater at Poas (Figure 3b). Below a depth of ca. 500 m, this body is at least partially molten, and thermally-induced vesiculation cycles either due to convection within the pipe or to variations in the cooling of its upper surface are thought to be responsible for the cyclic gravity variations visible at crater rim and flank stations. The new gravity data suggest that above a depth of ca. 500 m, a narrow (200 m minimum diameter) body

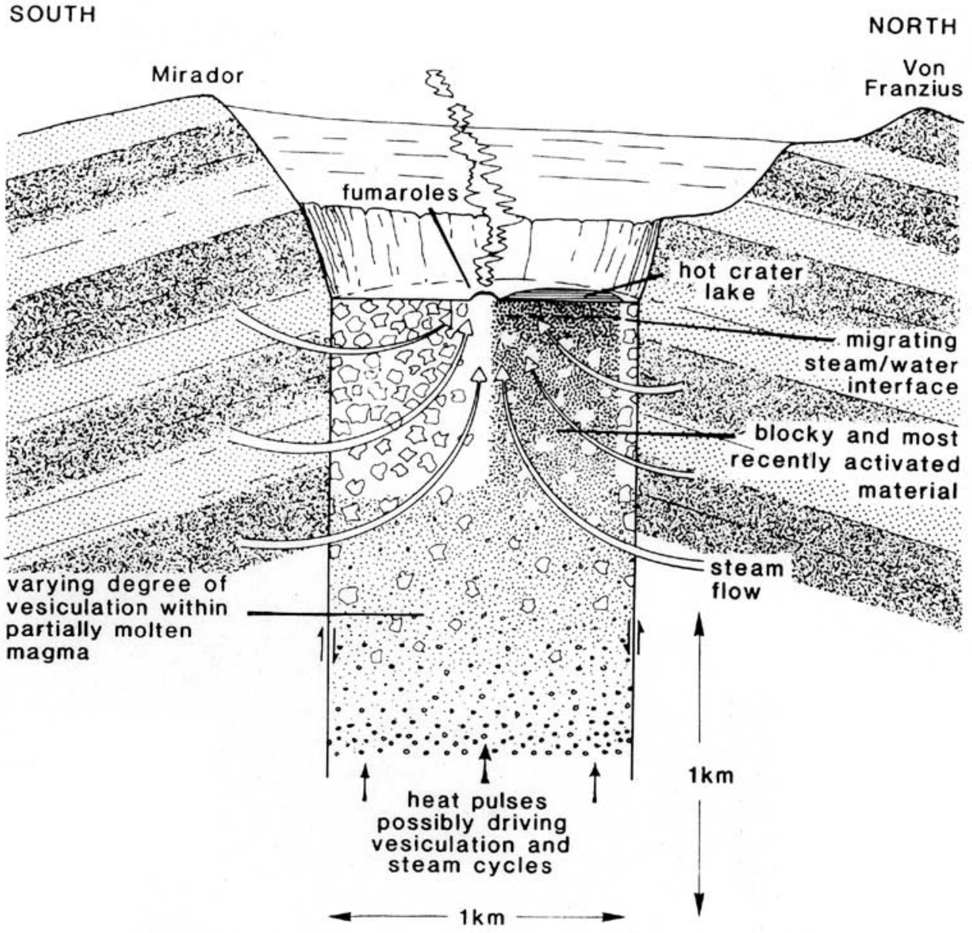

FIGURE 7

Cartoom representing a north-south cross section through the active crater at Poas showing, below 500 m depth, the partially molten magma conduit intruding pyroclastic 'caldera' infill. The upper parts of the conduit are solidified and comprise blocky andesite, generally of low permeability but intruded by a narrow cylinder of steam-satured permeable blocky lava (minimum porosity 5%). The steam-water interface is at a maximum depth of 30 m below the crater lake but reaches the surface over the fumaroles where upwelling meteoric hydrothermal convection is focused. Further discussion in text.

offset to the north acts as a focus for hydrothermal transmission within the upper part of the main magma plug. Meteoric water is thought to percolate beneath the whole of the crater area but, as shown in Figure 7, the concentration of active fumaroles and the hot crater lake towards the north suggests that convection cells are drawn towards this zone of higher heat flow, perhaps due to a strong permeability contrast between the older and newer parts of the plug. When ground water approaches the more permeable recently-reactivated pipe beneath the crater lake, it will become superheated and turn into steam. This steam is ejected vigorously at the fumaroles where hydrothermal transmission along the margins of the ca. 200 m plug is most effective. Elsewhere the steam/water interface is buried at shallow levels yet is thought to fluctuate to explain much of the gravity variation at group 7 and 8 stations. We suspect that partially molten magma exists at ca. 500 m depth (see Rymer & Brown, 1987) and envisage a 1000°C isothermal surface at this depth. The lake water temperature is 40°C so, assuming a uniform thermal gradient between the two, the maximum depth to the steam/water interface beneath the lake is ca. 30 meters. From Table 3d, and bearing in mind that porosity at this depth probably exceeds 5%, it is clear that the depth to this interface need only migrate by a few meters to explain the additional gravity changes at group 7/8 stations as compared with elsewhere. Such fluctuations could be due to temporary blockages at the furmaroles or due to heat pulses passing through the magma pipe either from the deep chamber or due to surface meteoric change.

This model of the present dynamic equilibrium observed at Poas has implications for the future monitoring and probable activity of the volcano. Clearly the steady flow of steam through the permeable cylinder overlying the deeper magma column but beneath the lake is sufficient to prevent a catastrophic build up of gas or temperature. Lower down, convection brings up volatiles from the degassing magma, probably venting together with meteoric steam and hot water through the narrow part of the plug. Regular measurement of microgravity at Poas is obviously a useful and important way of monitoring the activity of this volcano since, historically, it is throught the advanced build up of gas pressure that pyroclastic eruptions have been initiated. While the measurement of fumarole temperatures provides a reliable long-term indication of heating or cooling in the column, the addition of gravity observations allows us to estimate the depth and vigour of the active source. For example, an intrusion of juvenile material and a decrease in the volume of circulating ground water would both produce an increase in fumarole temperature, but gravity measurements could distinguish between the two, since the former would be observed at both crater flank stations, while the latter would be observed only at crater stations.

In order that comprehensive monitoring of this temporally stable but inherently active system may be continued, gravity base line values have been established. Small calibration and other spring characteristics of individual LaCoste and Romberg gravity meters mean that for microgravity measurements, comparison between instruments is unreliable. For this reason, comparison of sets of relative gravity observations should only be made using the same instrument, or instruments that have been closely compared. Table 4 gives a 'base line' series of raw and tidally corrected gravity measurements at the stations located on Figure 5 (precise locations available from the authors) for 3 LaCoste and Romberg meters. Figure 8 gives time averaged (over the period March-May 1985) distance measurements and positions for crater bottom and rim station used in the gravity survey. A programme of gravity monitoring by UK and Costa Rican scientists using these stations and the data in Table 4 for reference has now been initiated as the next stage in this programme of investigations. Significant measured departures from these 'base lines' should be considered carefully because of their implications for future volcanic activity at Poas.

TABLE 4

Example of raw and tidally corrected gravity differences for LaCoste and Romberg gravity meters used on the Poas microgravity survey on 15 February 1986. These values are given for reference and will be used to compare measurements made in the future with these instruments. Similar values for other instruments could now be established by comparison with these data but a carefully controlled set of base-line values is always needed before microgravity monitoring programmes can be pursued

Instrument	G513		G23		G772	
	(a)	(b)	(a)	(b)	(a)	(b)
Station	Reading (mGal)	Tidally corrected reading w.r.t. average bases H3 & F1 (mGal)				
H3	1520.286		1680.014		1471.240	
F1	1427.442		1587.454		1378.540	
1445A	1201.464	272.386	1361.693	272.135	1152.524	272.254
1447	1185.144	288.695	1345.381	288.440	1136.097	288.675
E1	1248.098	225.734	1408.207	225.599	1198.935	225.819
E3	1244.104	229.716	1405.991	227.809	1196.828	227.921
E5	1240.233	233.580	1400.495	233.296	1191.143	233.598
E6	1242.277	231.532	1402.393	231.396	1193.144	231.591
G1	1244.135	229.672	1404.246	229.537	1195.066	229.669
D1	1249.007	224.797	1409.047	224.731	1199.889	224.840
D2	1250.150	223.650	1410.386	223.388	1201.045	223.682
D3	1248.276	225.518	1408.312	225.456	1198.961	225.760
E7	1249.301	224.491	1409.428	224.338	1200.175	224.542
E1	1247.934	225.852	1408.097	225.664	1198.829	225.885
Z3A	1213.488	260.282	1373.657	260.092	1164.411	260.289
Z2A	1216.946	256.815	1377.170	256.570	1167.802	256.889
Z1A	1219.682	254.075	1379.904	253.833	1170.620	254.069
R11	1217.796	255.957	1378.081	255.652	1168.741	255.942
R7	1218.395	255.355	1378.691	255.038	1169.348	255.332
R2A	1215.694	258.053	1375.881	257.846	1166.641	258.036
A1	1197.020	276.723	1357.310	276.412	1147.851	276.822
B1	1178.760	294.980	1338.962	294.755	1129.523	295.146
1447	1185.111	288.628	1345.331	288.386	1135.956	288.712
1445A	1201.363	272.376	1361.596	272.121	1152.214	272.456
H1	1200.371	273.379	1360.490	273.238	1151.161	273.516
H2	1276.173	197.582	1436.323	197.410	1227.026	197.656
F2	1354.978	118.779	1515.115	118.620	1305.761	118.928
F1	1427.370		1587.512		1378.245	
H3	1520.123		1680.152		1470.916	

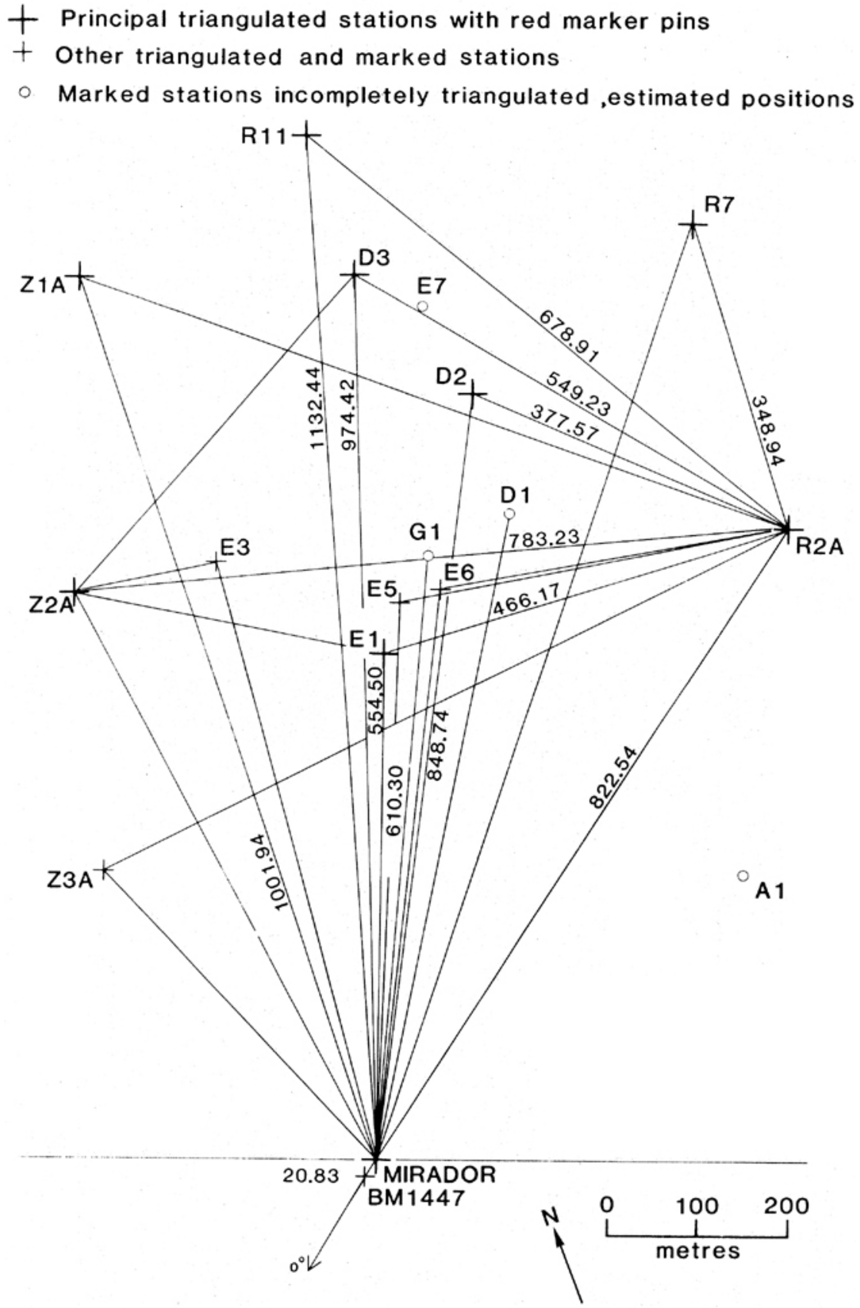

FIGURE 8

Scaled diagram showing the horizontal distances to crater station from the Mirador at Poas.

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