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Ground deformation at Colima Volcano, Mexico, 1982 to 1991

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RESUMEN

Una red de deformación, actualmente una linea de nivelación de 10 km y 6 estaciones de inclinometría seca, se ha medido 4 veces desde su instalación en el Volcán de Colima por el autor en 1982. Los resultados muestran una subsidencia contínua centrada a grandes rasgos alrededor de la cima junto con una inclinación progresiva hacia el sur o suroeste. El promedio de la tasa de subsidencia es alrededor de 0.4 cm/km por año, aunque tasas mayores (aproximadamente 1 cm/km por año) fueron medidas entre 1982-86, y nuevamente en 1990-91 que culminaron en la actividad de 1991.

La aplicación de modelos elásticos simples a los datos de nivelación es consistente con la deflación de una fuente sepultada a 2-4 km de profundidad, posiblemente una cámara drenada o la parte superior de una columna magmática. La inclinometría seca confirma la subsidencia y tasa variable, aunque inclinaciones paralelas ocurren frecuentemente en la dirección de la pendiente, sugiriendo un deslizamiento gravitacional o resbalamiento del Volcán en dirección de la pendiente.

PALABRAS CLAVE: Deformación, inclinometría seca, subsidencia.

ABSTRACT

A ground deformation network, now comprising 10 Km of levelling traverse and six dry tilt stations, has been measured four times since it was first set up at Colima Volcano by the author in 1982. The results show continuous subsidence roughly centred around the summit area, together with a progressive tilt towards the south or southwest. The rate of subsidence averages about 0.4 cm per km each year, though higher rates (around 1 cm per km per year) were measured between 1982-86, and again in 1990-91, in the build up to the 1991 increase in activity.

Simple elastic models fitted to the levelling data are consistent with the deflation of a buried source at 2 to 4 km depth, perhaps a draining magma chamber or the top of a magmatic column. The dry tilt results confirm the subsidence and its variable rate, although parallel tilts often occur in the overall downslope direction, suggesting gravitational creep or sliding of the volcano downslope.

KEY WORDS: Ground deformation, levelling, dry tilt, subsidence.

INTRODUCTION

The author originally established and measured an 8.2 km precise levelling traverse around Colima volcano in November 1982, with a view to observing the long term vertical ground deformation at this andesitic volcano which has been in continuous, slow dome-building activity since 1957 (Luhr and Carmichael 1980). This series of 47 stations was situated mainly in the Playon, at the northern foot of the summit cone, though both extremities of the traverse extended outside the limits of the pronounced caldera wall that borders the cone at its northern limit, though the stations at the western end have now been lost. At the same time, six dry tilt stations were set up at distances of from less than 1 km to 6 km from the summit (Figure 1), to look for any deformation due to deeper sources. The term "dry tilt" is used here in preference to "telescopic spirit-levelling", "tilt levelling", "single set-up levelling", "optical levelling tilt" etc., because the term is short, most widely understood, and has been adopted in other languages.

In February 1986, this network was reoccupied following the large Mexican earthquake of November 1985, and the reported increase in activity at Colima (Connor *et al.* 1985, Robin and Murray 1986). It was also extended, one dry tilt station being added 9 km to the south, and two new branches to the levelling traverse, one northwards towards the caldera wall, the other south towards the summit. The presently existing network (Figure 1), consists of 6 dry tilt stations (one of the original stations on Nevado de Colima having been destroyed during improvements to the TV station) and 10 km of levelling lines, comprising 56 stations situated from just over 1 km to nearly 3 km from the summit, at altitudes between 2750 and 3244 metres. Over the years, 26 stations have been destroyed by bulldozing or vandalization, out of a total of 82 installed. This network has since been occupied in March 1990 and March 1991.

All levelling was carried out with a Zeiss Ni2 self-levelling precision level, micrometer and invar staff. Arithmetic checks were made in the field at each instrument position, and all results reduced before leaving Me-

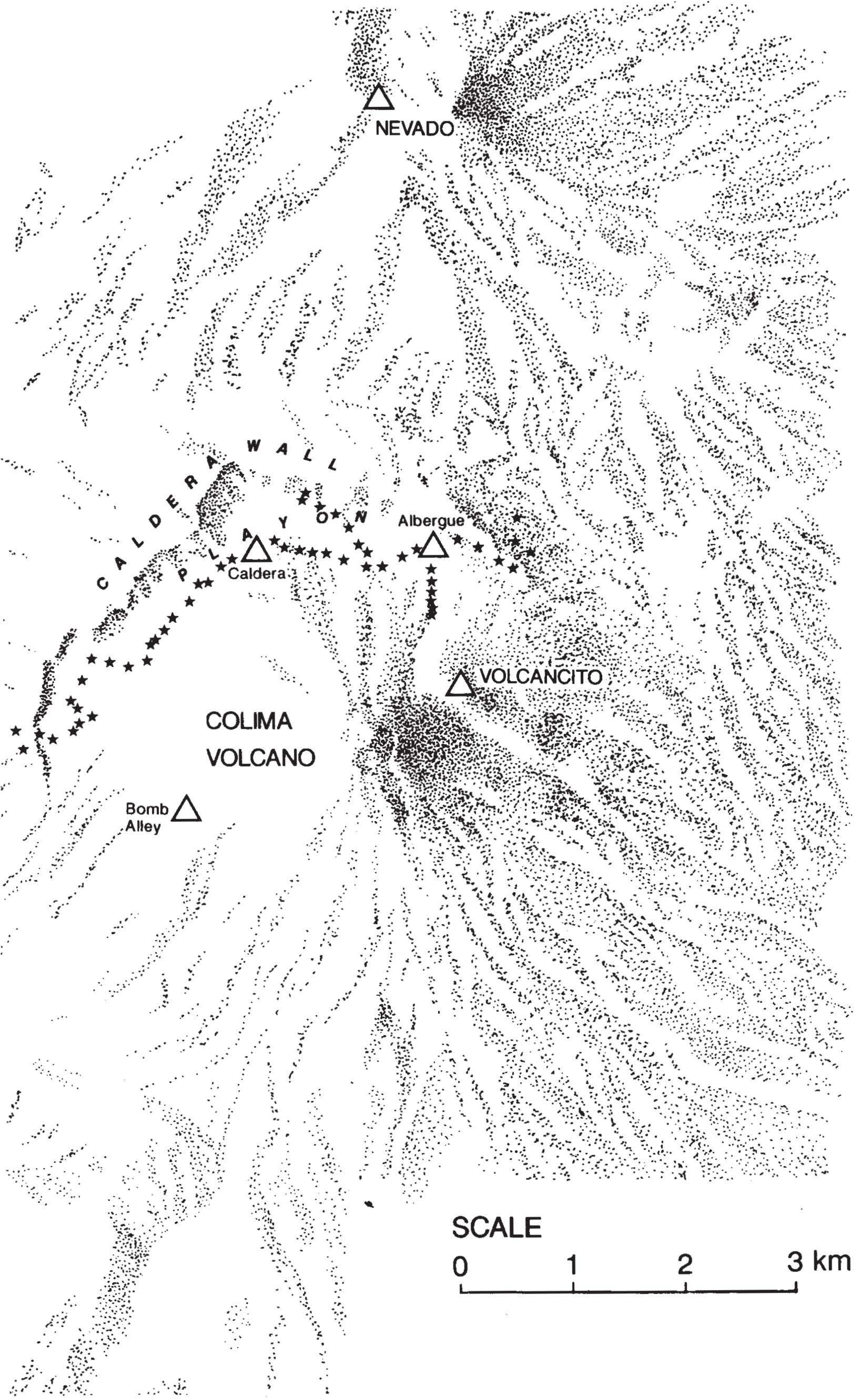

Fig. 1. Relief sketch of Colima Volcano, Mexico, with lighting from the left. Black stars show positions of principal benchmarks of the levelling traverse, and open triangles mark the sites of dry tilt stations, with names alongside. A second dry tilt station on Nevado de Colima, destroyed by public works, is not shown, nor is a station at Barranca La Arena, 9 km south of Colima summit.

xico so that any errors could be detected and dubious parts of the traverse relevelled. In view of the time and personnel available, and the problems of deformation occurring during the measuring period, the traverse was not double run, but in every other way, precise levelling techniques were used. Similar methods used on other volcanoes (Murray 1990) have given closing errors of around 1 cm over 12 km.

RESULTS

The results of the levelling are summarised in Figures 2 and 3, which show maps of the vertical movements measured between 1982 and 1991. To make presentation clearer, contours connecting points with equal amounts of vertical movement have been drawn, but the small fraction of the volcano covered by the network results in some subjectivity in the interpretations made, and demonstrate the need to extend the data base. These maps necessarily show relative movement, and it is likely that the base station chosen as a reference also shows movement relative to stations off the volcano. The reference station used in each case was the furthest point northeast of the summit, which lies outside the caldera wall.

All the maps, with the possible exception of Figure 2b (movement 1986-1990) show a general subsidence (deflation is perhaps too subjective a word) roughly centred on the volcano summit; even Figure 3 can be interpreted as subsidence, though the position of the centre of subsidence seems to be further from the summit. In view of the surprising nature of these results discussed later, it should be emphasized that the bulk of the levelling traverse illustrated in Figure 1 is broadly concentric to the volcano, and the radial branches relatively short, so that movement here is not necessarily representative of the rest of the edifice. Nevertheless, the data that we have, particularly that from the sector north to northeast of the summit which includes the two radial branches, cannot be represented by anything other than downward movement towards the summit, and this is generally confirmed by the dry tilt results described below.

The amount of absolute subsidence is difficult to pin down, as the zone of maximum subsidence changes position, and has always been outside the area of the traverse. To try and give some idea of relative amounts of subsidence therefore, the amount of subsidence per kilometre has been measured normal to the contours of deformation shown in Figures 2 and 3. The results are shown in Table 1. The discrepancy between the subsidence measured between consecutive occupations and the accumulated amounts between 1982 and 1991 is due to the fact that the centre of subsidence changed position, and also that the radial branches of the traverse, established in 1986, could not be used in the 1982-1991 values.

Table 1 shows that rates of subsidence were higher between 1982 and 1986, and from 1990 to 1991. The first period of high subsidence encompasses the Mexican earthquake of September 1985, which may have caused the whole volcano to settle. This earthquake probably opened new fractures and accentuated previous ones as seen in November 1985 (Connor *et al* 1985). This cracking appears to have provoked some depressurization of the near-surface magma, causing fumarole temperatures to rise, and also giving rise to some small ash eruptions in January (Robin and Murray 1986).

The second period of high subsidence rate occurred prior to the increased activity of early 1991, which culminated in the lava flow and major avalanche of 16th April (Bulletin of the Global Volcanism Network, March 1991).

Table 1

Rates of subsidence measured from vertical ground deformation data illustrated in Figures 2 and 3.

Time interval	Total subsidence	Subsidence per km per year
1982-1986	2.8 cm per km	0.9 cm per year
1986-1990	1.9 cm per km	0.5 cm per year
1990-1991	1.1 cm per km	1.0 cm per year
1982-1991	3.2 cm per km	0.4 cm per year

DRY TILT

The results of the dry tilt measurements are shown in Figure 4. These maps have arrows to indicate the direction of downward tilt in the time interval indicated; the length of arrow is proportional to the amount of tilt. The two stations in the Playon ("Albergue" and "Caldera") broadly follow the movement recorded in the levelling traverse, in that the tilt is generally towards the summit, at least to a first approximation, suggesting continuing subsidence. The rates of downward tilt are summarised in Table 2. These rates vary in a similar way to the subsidence recorded in the levelling traverse, the rates 1982-1986 and 1990-1991 being about twice the rate recorded between 1986 and 1990.

The other two stations close to the summit, "Volcancito" to the northeast and "Bomb Alley" to the southwest, also usually show tilts towards the summit for the periods when they have been measured. Unfortunately, the Volcancito station was vandalised between 1982 and 1986, as was the Nevado station between 1986 and 1991, and Bomb Alley station has not been visited recently due to the danger of avalanches down the western side. Of the other three dry tilt stations established, one of the two stations at Nevado de Colima was abandoned after building work at the T.V. station there destroyed the site. The other showed a tilt towards the summit of Nevado between 1982 and 1986, apparently unrelated to events at the presently active volcano. The station established in

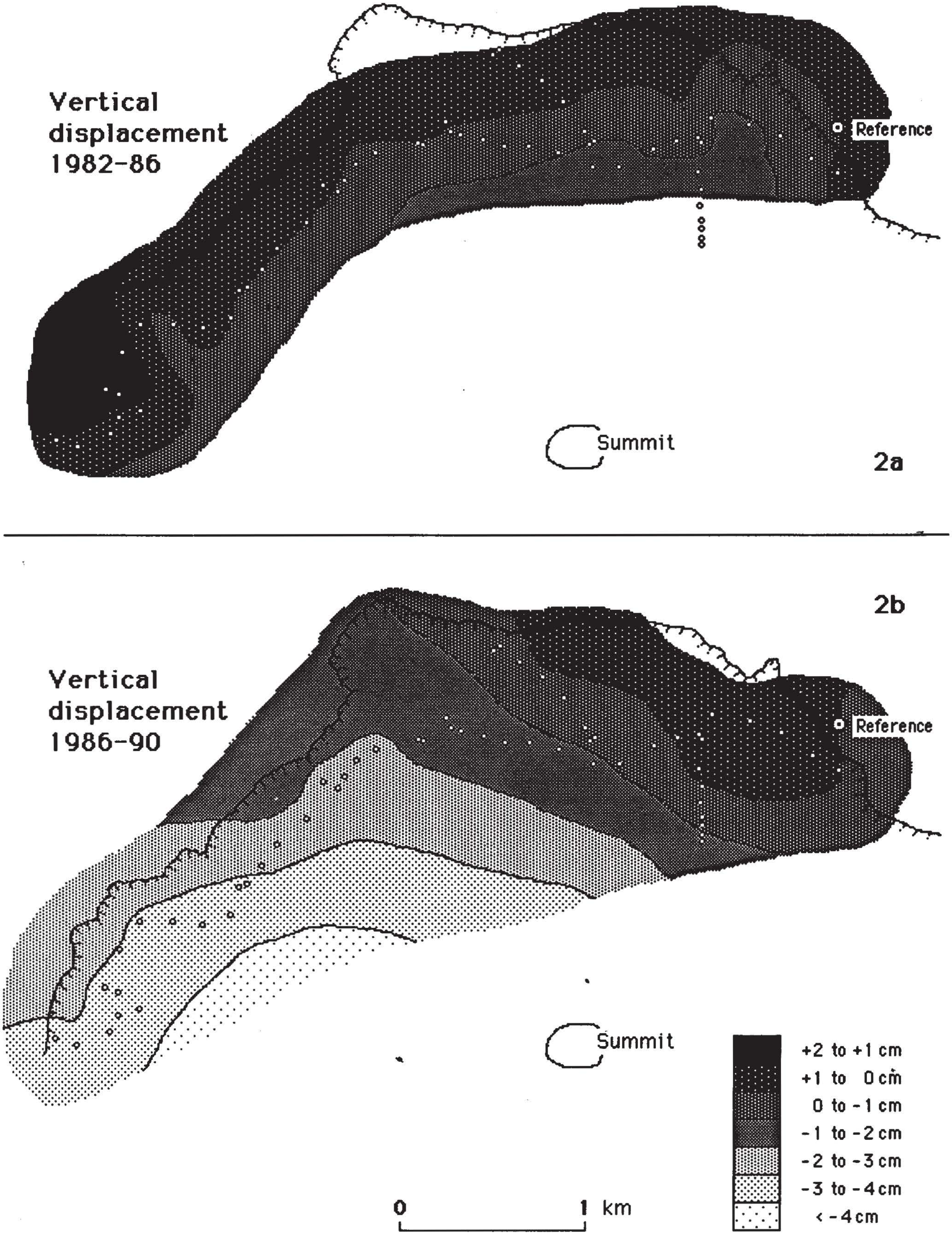

Fig. 2. Maps of vertical ground deformation at Colima Volcano measured: (a) between December 1982 and February 1986, and (b) between February 1986 and March 1990. Contours of deformation (1 cm interval) have been interpolated between values of height change at the benchmarks (black dots). All height changes are referred to the reference station outside the caldera to the northeast.

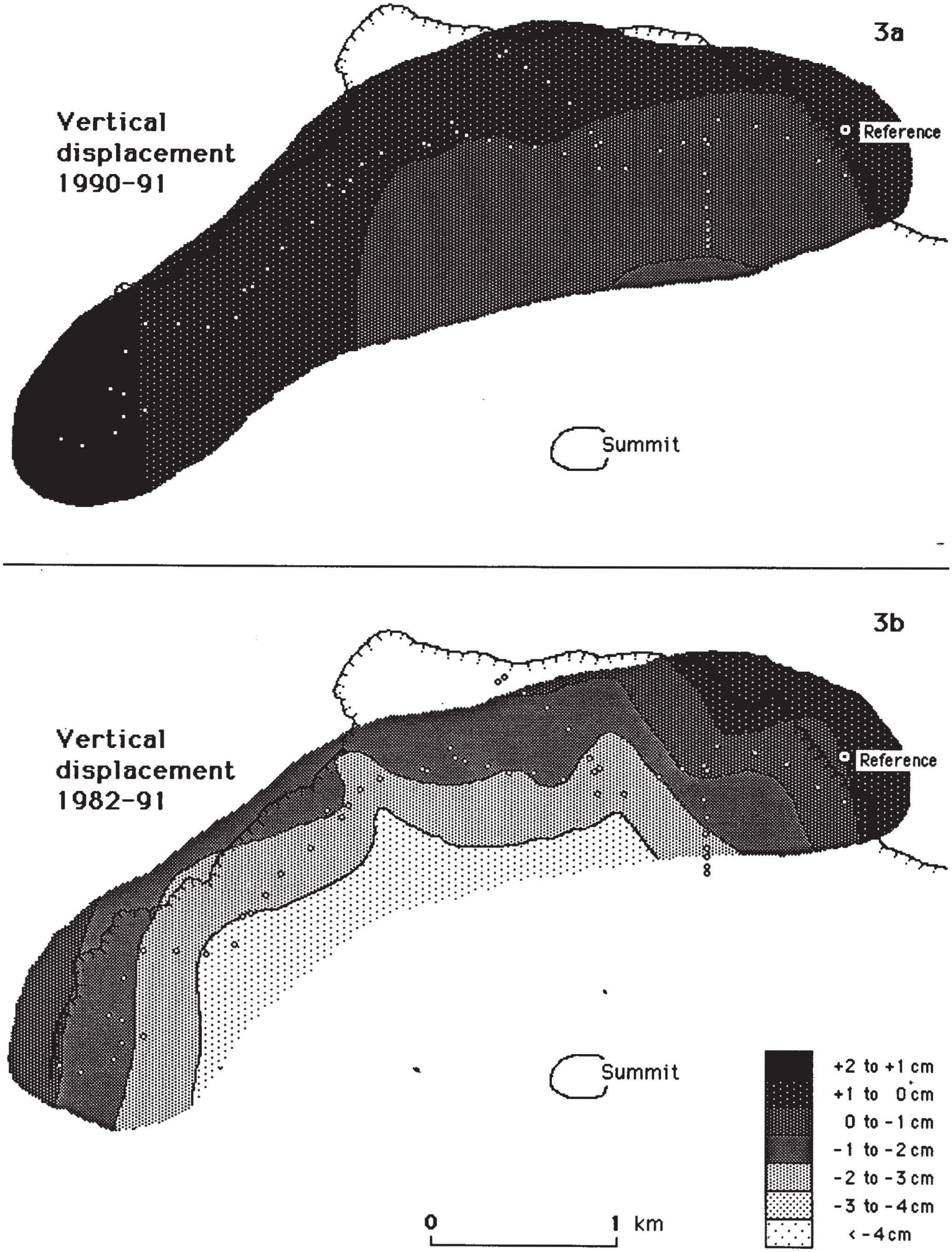

Fig. 3. As for Figure 2, but for the periods: (a) March 1990 to March 1991, and (b) December 1982 to March 1991.

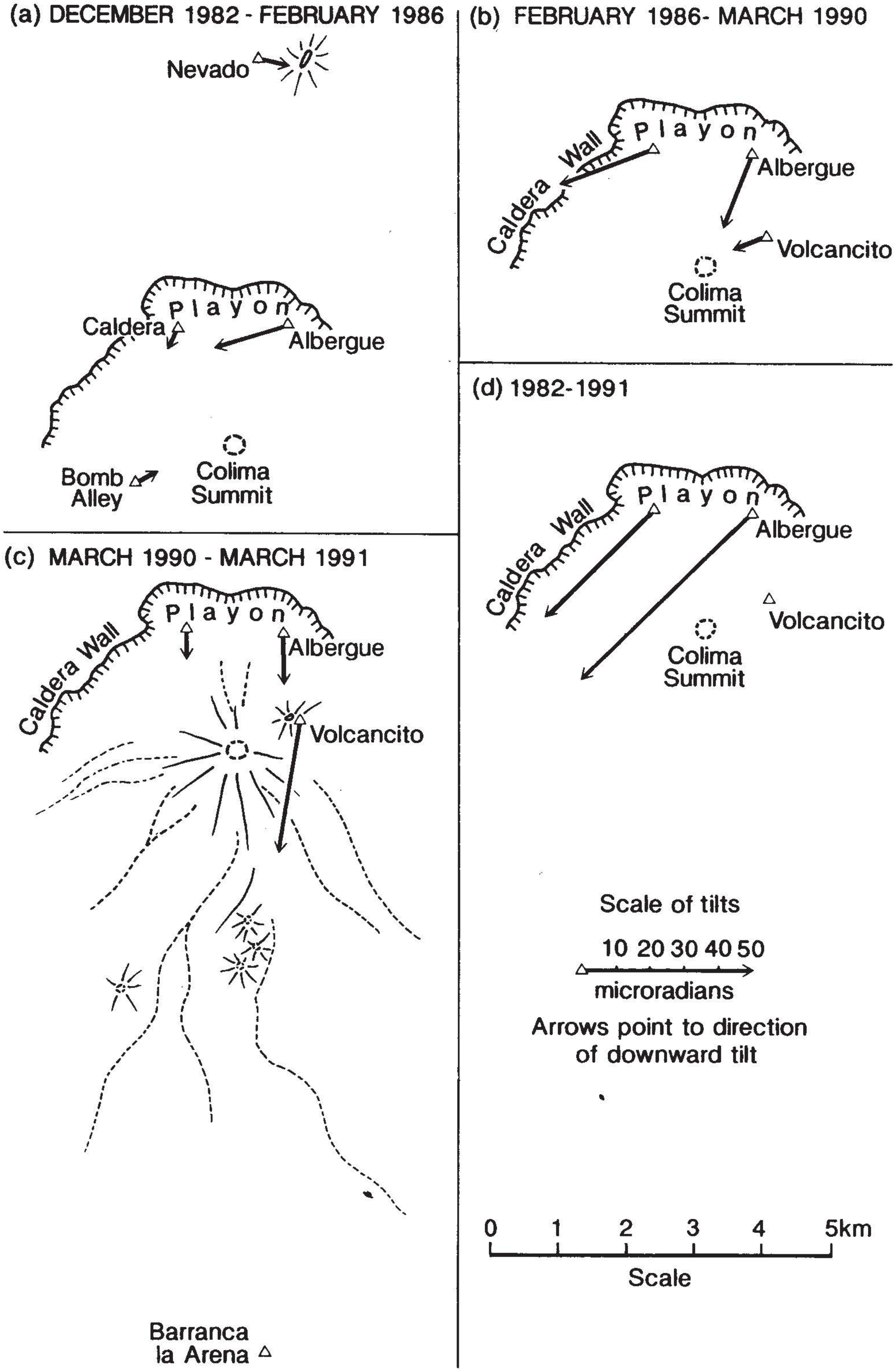

Fig. 4. Maps of direction and amount of ground tilt (in microradians) derived from dry tilt stations at Colima Volcano, for the periods: (a) December 1982 to February 1986, (b) February 1986 to March 1990, (c) March 1990 to March 1991, (d) December 1982 to March 1991. Arrows point to the direction of downward tilt.

1986 at Barranca La Arena, 9 km south of the summit, unfortunately shows large differential movements between the four benchmarks, perhaps as a result of tree root growth beneath them, so reliable ground tilt cannot be derived from this station. Tilt over the period 1982-1991 is therefore only available for Albergue and Caldera stations in the Playon (Figure 4d and Table 2). They both show large tilts towards the southwest (i.e. not entirely radial) of 70μrad and 44μrad respectively for the entire nine year interval.

Table 2

Mean rates of tilt at two dry tilt stations in the Playon.

Time interval	Total tilt	Tilt per year
1982-1986	29μrad	9μrad
1986-1990	26μrad	6μrad
1990-1991	12μrad	12μrad
1982-1991	57μrad	8μrad

ANALYSIS

Levelling data

The relative downward displacement of benchmarks nearer the summit revealed by the levelling data can be interpreted in terms of deflation of the edifice in response to an emptying magma reservoir. The simplest model of the surface response to inflation or deflation of a buried source is that developed by Mogi (1958). His model assumes a point or small spherical source, a flat ground surface and elastic behaviour of materials. Although none of these assumptions strictly applies to Colima volcano, work on volcanoes elsewhere (e.g. Mogi 1958, Fiske and Kinoshita 1969, Dieterich and Decker 1975, Murray and Pullen 1984) has demonstrated that the layered rock and ash of which a volcano is composed can behave approximately elastically, at least on a scale of kilometres. Also, the layout of the levelling traverse at Colima, with its necessary lack of stations near the summit of the volcano (Figure 1), means that the data available do not justify the application of recent more detailed models with more complex shapes for the buried source. Only the flat surface assumed by Mogi's model may be an important limitation as described later.

The model has been applied by plotting the amount of vertical deformation against distance from the centre of deflation, as approximately determined by inspection of Figures 2 and 3. Curves of deformation expected from the model for sources at different depths were then superimposed on these plots. Results for the two periods of high subsidence rate (1982-86 and 1990-91) are shown in Figure 5. The theoretical curves of vertical deformation expected from deflating sources at 1 km, 2 km and 4 km depth are shown in these figures, which for both periods represent the closest fits to the data. For the period 1982 to 1986, it is not possible to limit the modelled depth any further than this, but for the period 1990-91 the best fit to the data appears to be from a source between 2 km and 4 km in depth.

Dry Tilt data

Tilts measured at the dry tilt stations conform with the levelling results in a general way, and can also be invoked to support the deflation of a buried magma chamber. However, the fact that many of the tilts illustrated in Figure 4b, c and d are parallel to each other also suggests that a broader scale tilt may be in operation, though the relatively close spacing of the stations involved (all are within 3 km of each other) raises questions as to the validity of applying this to the whole volcano. If this apparent broader tilt is real, it might be controlled by the gravitational influence of the topography (i.e. the edifice deforming under its own weight). Colima volcano lies on the southern slopes of the larger extinct volcano Nevado de Colima (Figure 1), so it is possible that downslope movements are causing the whole volcano to tilt towards the south. Such a tilt would be expected to accelerate during periods of increased activity, when increased stresses and cracking within the volcano might lead to a decrease in effective tensile strength of the edifice.

The tilts measured over the whole 9 year period, however, (Figure 4d) are closely parallel and not radial to the volcano or parallel to the slope of the older volcano. They do lie normal to the subduction zone at the north-easterly margin of the Cocos plate, and parallel to its direction of motion, but it would be unrealistic to propose any secular regional tilt on the basis of only two stations. Furthermore, it is clear from Figure 3b that other parts of the volcano have not tilted in this uniform way, but that subsidence radial to the summit has taken place, and that the situation of the two dry tilt stations, which are included in the levelling traverse, is somewhat fortuitous. This instance illustrates well the problems of relying upon tilt measurements, which are necessarily spatially punctual in nature, without an accompanying levelling network, in which the actual relative height changes are measured.

DISCUSSION

The above analysis suggests that the observed deformation may be due to a combination of (a) deflation of a buried magma source and (b) downslope tilting in response to the southward sloping topography. The levelling data are consistent with the existence of a hypothetical magma chamber between 2 and 4 km beneath the surface, deflating as the magma is transported to the surface. This is similar to the depth of some earthquake swarms, reported by Nuñez-Cornu *et al.* (1991) as 1 to 3 km depth in February 1991.

The observed deformation does raise some interesting points, however. If the volcano has been in continuous dome extrusion throughout the period of measurement, why does the volcano show continuous deflation (albeit at different rates), rather than inflation? The implication is clearly that the dome is being extruded, and gas

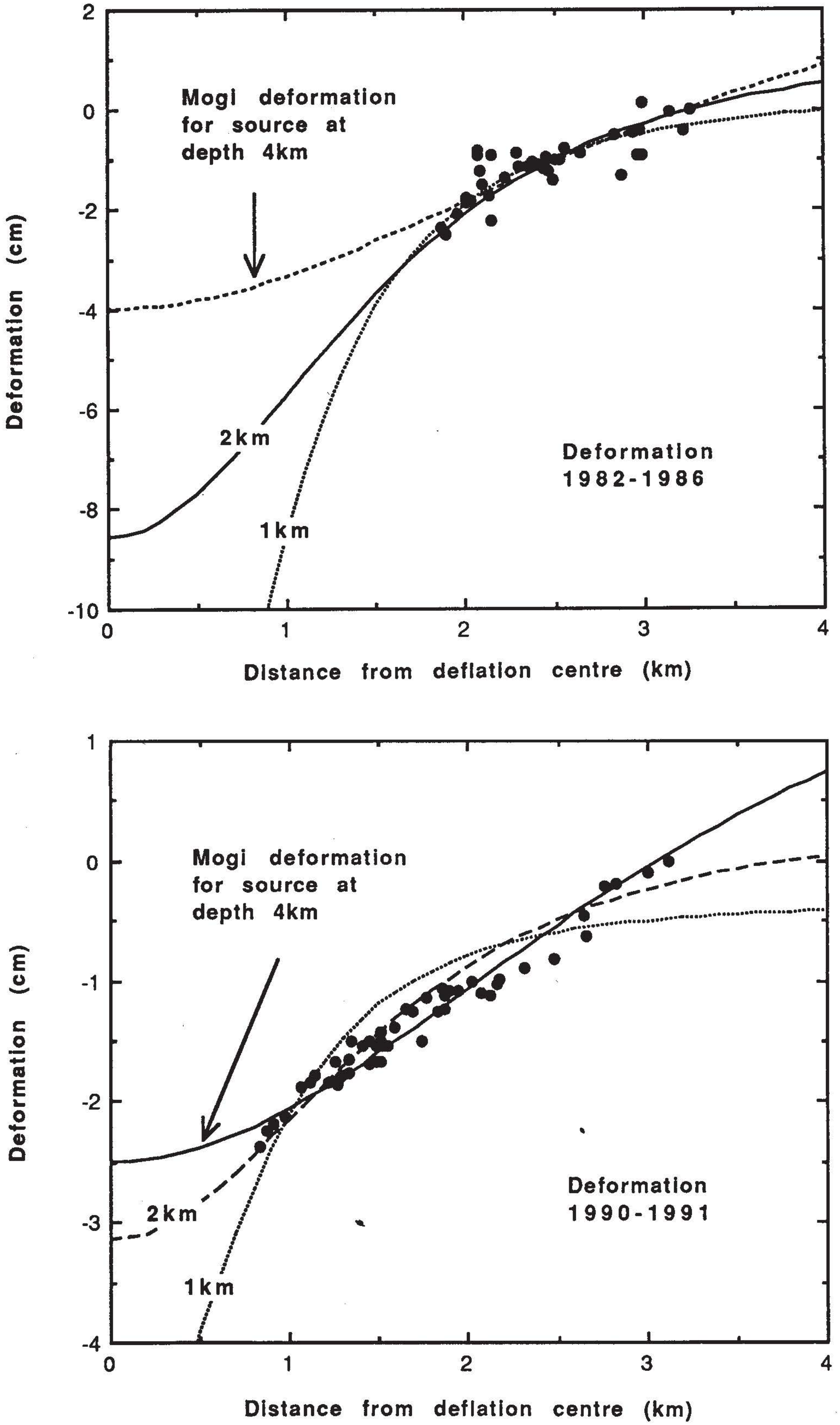

Fig. 5. Plots of vertical ground deformation (black dots) against distance from the centre of inflation for the periods: (top) December 1982 to February 1986; (bottom) March 1990 to March 1991. Also shown are theoretical curves of elastic vertical displacement of the surface of an infinite elastic half-space in response to pressure decrease of a small buried source at depths of 1, 2 and 4 km.

expelled, faster than magma is being intruded into the system at depth. But if this is the case, then a period of higher output, such as occurred in 1991, should have been preceded by a period of inflation as the magma pressure which produced the surge was building up within the edifice. This incongruity may be simply explained by the long interval between measurements. The period 1986 to 1990, for example, may well have been mainly deflationary, with a period of inflation at the end prior to the 1991 increase in activity.

Other questions surround the mechanics of what is actually going on inside the volcano. The model described above and illustrated in Figure 5 suggests a distinct magma storage space 2 to 4 km beneath the surface. Despite the agreement of this conclusion with independent methods, it must be remembered that the radial extension of benchmarks is small, and the scatter of their movements about the theoretical curve is not sufficient to define the geometry of the source area, and this must remain the subject of speculation. Although Figures 2 and 3 clearly show that subsidence has taken place approximately radial to the summit, such subsidence could equally well have accompanied the lowering of the top of a magma column from, say 2 to 4 km, or a drop in magma pressure at the top of magma column at a similar depth, but such a drop or decrease in pressure contradicts the observed continued rise in magma at the summit.

A more likely limitation of the proposed model may be due to the substantial topography of the Colima Volcano. The model used assumes a flat surface, whereas the summit cone of Colima rises well over 1000 m above the slopes of Nevado upon which it lies, and the cone itself has steep slopes averaging almost 20°. It may well be, therefore, that the weight of this edifice is sufficient to cause compaction, or that during inflation of a buried magma chamber, this topographic excess over the centre of the chamber causes subsidence at the summit at the same time as inflation and spreading of the flanks, as has been observed at Mt Etna (Murray 1990). Against this hypothesis, however, is the fact that the lavas (and therefore presumably the magmas) of Colima are far more viscous than those of Etna, and therefore more capable of supporting the summit cone than at Mt Etna, though this will depend mainly on the size and geometry of the magma storage space and conduit to the surface, which are unknown.

The possible broader scale downslope movement of the entire Colima edifice on the slopes of Nevado, suggested by some of the dry tilt results, raises the whole question of slope stability and possible future slope failure. A major slope failure on the south flank of Nevado, apparently removing a 10 Km^3 previous terminal cone of Colima, took place as recently as 4300 years B.P, and reached distances of 70 km, including the site of the present city of Colima (Robin *et al.* 1987, Luhr and Prestegaard 1988, Robin *et al.* 1990). At least three such events have occurred in the region during the past 20,000 years, so a similar major slope failure in the future is a serious possibility.

Such a slope failure would be expected to be preceded by slope creep. This is a phenomenon which precedes slope failures of all types. It was well observed before the slope failure of October 1963 above the Vaiont reservoir, northern Italy, which resulted in the deaths of 2000 people (Muller 1964), and also prior to the catastrophic slope failure and resulting pyroclastic eruption of 18th May 1980 at Mount St Helens Volcano, U.S.A (Voight *et al.* 1981). The latter event is the most applicable to Colima, as it occurred on a similar type of volcano, and was provoked by similar circumstances to those which might occur at Colima. In late March 1980, magma within Mount St Helens volcano began to intrude laterally northwards, rather than upwards to the summit crater. This lateral intrusion of viscous magma began pushing a segment of the northern slope of the volcano northwards at rates as high as 2.5 metres per day (Lipman *et al.*, 1981). This caused the summit to subside and the north slope to bulge. Maximum displacements totalled more than 100 metres before the slope failure occurred.

Slope creep prior to the Vaiont landslide of 1963 steadily accelerated prior to failure, and recent measurements by the author at Mt Etna show a similar acceleration in downslope creep before flank eruptions there. However, Mount St Helens downslope movements did not show any acceleration in the two months prior to the 18th May slope failure and consequent eruption, which seems to have been triggered by a magnitude 5 earthquake.

All the large measured displacements at Mount St Helens prior to the May 18th eruption occurred on the north flank of the volcano. Were this type of deformation to occur at Colima volcano, it is the south flank that would be affected, since the ground slopes in this direction overall, the north flank being buttressed by Nevado. The levelling and ground deformation networks lie mainly around the north side of Colima, however, so are not well placed for observing slope creep on the southern slopes. Little or no movement was recorded at comparable sites at Mount St Helens far from the north flank where eventual failure took place. Any major slope creep on Colima's southern flank would be detectable first at Volcancito dry tilt station, where a large increase in downslope tilt would be expected.

CONCLUSIONS

Colima volcano has shown continuous subsidence since it was first measured in 1982. The rate of subsidence has been variable, averaging 0.4 cm per kilometre per year, though rates of about 1 cm per km per year were observed between 1982 and 1986, and again in 1990-1991. Simple modelling of this subsidence suggests the presence of a magma storage space 2 to 4 km below the surface, slowly draining as magma is transported to the surface to form a gradually growing dome, or lava flows in periods of higher extrusion. It is also possible that a gradual downslope creep of the whole edifice is occurring, the weight of the volcano causing it to slowly settle under gravity down the slope of Nevado, the older and larger extinct volcano upon whose southern slopes it lies. The network configuration is such that any precursive movements to a major failure of this southern slope cannot be detected, with the possible exception of the Volcancito tilt station which might be affected by preliminary slope movement.

A major conclusion of this work is that adequate monitoring coverage, and resolution of the incongruities described above can only be achieved by expanding the deformation network to cover the summit area. The steep, loose slopes of the summit cone make levelling impracticable, and GPS has insufficient accuracy in the vertical component, but trigonometric levelling with total stations would provide sufficient height accuracy (~±1cm)) to get a good idea of how the summit and dome are behaving. Preliminary stations were installed here in March 1992.

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