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Potential volcanological applications of the DORIS system. A geodetic study of the Socorro Island (Mexico) coordinate time-series

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SUMMARY

We analysed DORIS data from Socorro Island (Mexico), providing weekly coordinates in ITRF2000 from 1900 to 2006. Careful analysis of this time-series shows horizontal and vertical movements related to recent activity of the Mt. Evermannn volcano. A deflation of the volcano between 1993 and 1996 (–94 mm yr^{-1} in the N23°W direction, directly pointing in the direction of the crater summit) is observed. We identify also a clear horizontal discontinuity of 81 mm and a significant change in velocity on 2002 October 3. We use a Mogi formalism to provide constraints from our geodetic results on the successive locations and size of the depletion and inflation sources. Our model is consistent with a deflation source for the period 1993–1996 located beneath Mt. Evermannn at a depth of about 6.2 km below sea level. However, our data constrain only the azimuth and dip angles of the source, which could be located elsewhere along the azimuth of the summit, depth and volume varying linearly with the distance.

Key words: Time series analysis; Satellite geodesy; Reference systems; Transient deformation; Volcano monitoring.

1 INTRODUCTION

Socorro, the SE-most of the Revillagigedo Islands, Mexico (Fig. 1), is a basaltic shield volcano located on the northern Mathematician ridge, a mid-ocean ridge spreading centre that was abandoned ∼3.5 Ma, when the spreading shifted eastwards to the East Pacific Rise (Bohrson *et al.* 1996). The history of the volcanism of this island is documented for the last 0.5 Myr (Bohrson *et al.* 1996). The historical activity of the volcano is characterized by activity at the Cerro Evermannn crater, located inside a caldera formed around 0.4 Ma, as well as lateral eruptions like the most recent one in 1993, documented by Siebe *et al.* (1995), producing cones and flows around the volcano and offshore. A submarine eruption occurred between 1993 and 1995 from a vent 3 km west of the island, during which large scoriaceous blocks up to 5 m in size floated to the surface, without associated explosive activity (Siebe *et al.* 1995). The presence of a relatively shallow magma chamber, located in the upper oceanic crust of the edifice is proposed in both papers mentioned above.

The origin of the Socorro active volcanic behaviour has been discussed by several authors in the past. As the volcano lies on an abandoned mid-oceanic ridge, the Mathematician ridge, it could be a remnant volcanism related to this plate boundary volcanism. However, the time (∼3.5 Myr) of abandoned activity of the Mathematician ridge seems too long to explain a remnant activity at Socorro. Moreover, the distance between the Socorro volcano and the active East Pacific Ridge (EPR) plate boundary, about 500 km, is also too large for a possible link between the present ridge axis volcanism and the volcanism (off ridge distance of a volcanic activity to a ridge axis does not exceed 100 km).

The present Socorro volcanic activity is most probably caused by the presence of a hotspot beneath the Revillagidedo archipelago, with a morphological expression influenced by the crustal discontinuities and weakness inherited from the presence of the 3.5 Myr old Mathematician ridge. Several arguments strengthen this modern view of Socorro volcanism; two are particularly strong: the eruption rate of Socorro (subaerial) exceeds those of non-hotspot ridge volcanoes (Bohrson *et al.* 1996); and according to Taran *et al.* (2002), the lower than MORB values of ^{3}He/^{4}He in the fumarolic gas most probably characterizes the present-day magmatic system of the volcano and is typical for intraplate hotspot oceanic islands.

2 DORIS BACKGROUND

A DORIS beacon is a Doppler ground transmitter. Opposite to GPS, its signal is analysed by a dedicated receiver on-board low Earth orbiting satellites (Tavernier *et al.* 2006; Willis *et al.* 2006). This space geodetic system, initially developed as an automated tracking system for precise orbit determination of satellites, recently showed some geodetic capability for geodetic and geophysical monitoring (Willis *et al.* 2007). A 10 mm precision can be achieved using a week

*Prof. Jacques Dubois passed away on 2007 November 20.

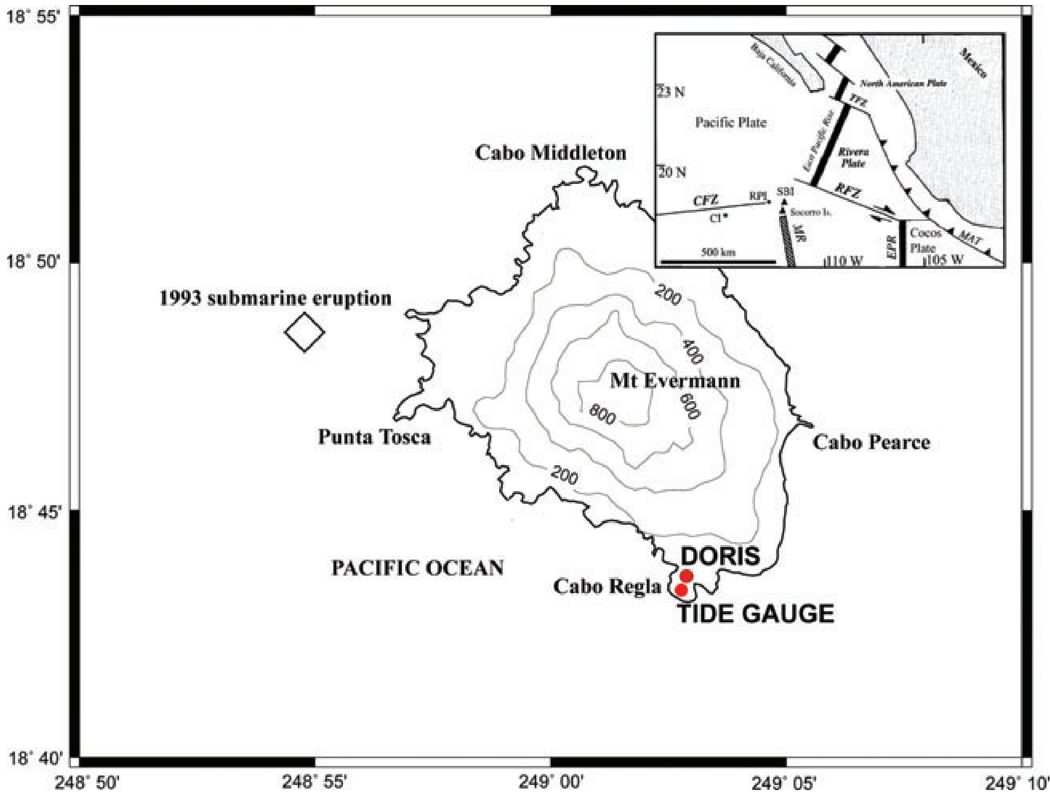

Figure 1. Sketch map of Socorro Island with the topographic contours and the location of the 1993 eruption (modified from Siebe *et al.* 1995). MR, Mathematicians ridge (inactive); RPI, Roca Partida Island; CI, Clarion Island; RFZ, Rivera Fracture Zone; EPR, East Pacific Rise; SBI, San Benedicto Island; CFZ, Clarion Fracture Zone. Altitudes were derived using SRTM data (Rabus *et al.* 2003).

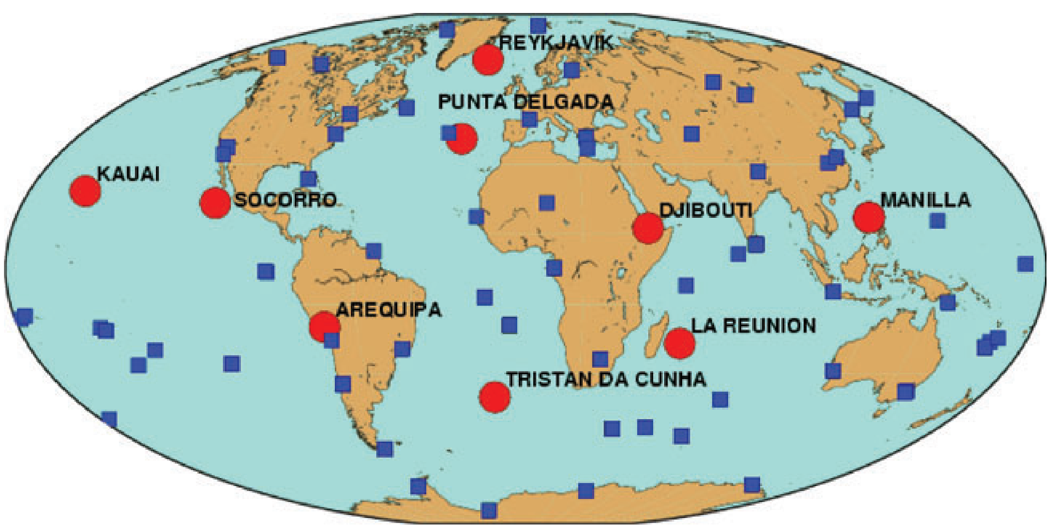

Figure 2. DORIS permanent tracking network. Circles indicate DORIS stations close to active volcanoes (status as of 2007 June).

of data both in horizontal and in vertical (Willis *et al.* 2005a,b). Unlike GPS, DORIS results have almost the same geodetic precision for horizontal and for vertical. For GPS, vertical results are somehow degraded due to the high correlation between tropospheric zenith delay and station height (Rothacher 2002). However, in case of DORIS, using low Earth orbiting satellite with rapid change in satellite–ground station geometry, such degradation between the horizontal, and the vertical results is not visible (Snajdrova *et al.* 2006). Recently, key improvements were made by several groups around the world to improve the DORIS data processing for geodetic applications (Willis *et al.* 2007). Taking into account the current geodetic accuracy of this satellite geodesy system (typically 10 mm in 3-D for position and 2 mm yr^{-1} 3-D for velocities), several geophysical applications were already investigated—global plate tectonic (Soudarin & Crétaux 2006) or regional geodynamics in Africa (Nocquet *et al.* 2006; Stamps *et al.* 2008) or in the Himalaya (Bettinelli *et al.* 2006; Poretti *et al.* 2007)—using DORIS and GPS results. Most of these scientific investigations are based on dual-use of GPS and DORIS geodetic results. Fig. 2 shows the geographic distribution of the current DORIS tracking network.

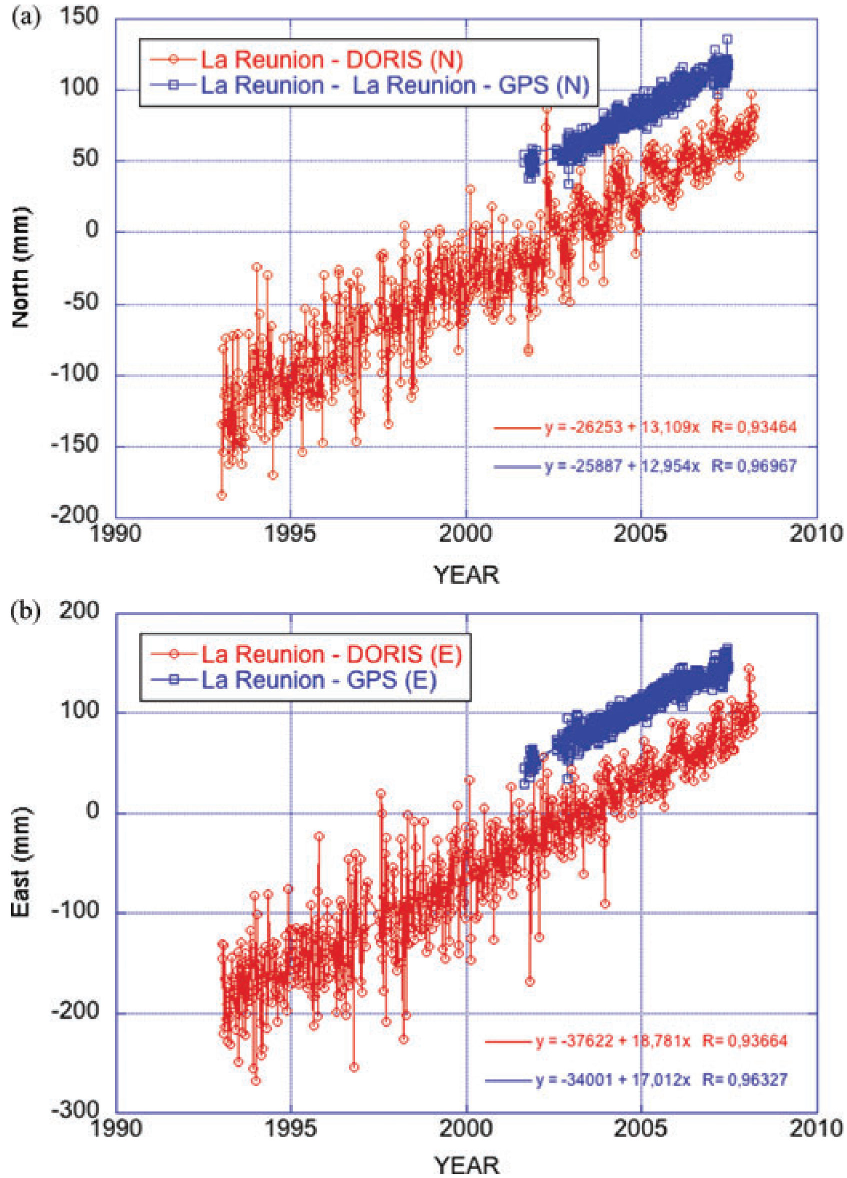

Figure 3. (a) Northward velocity of La Reunion DORIS (red) and GPS (blue) stations. Both are located at a few metres distance at the Piton de la Fournaise volcano observatory. (b) Eastward velocity of La Reunion DORIS (red) and GPS (blue) stations.

Nine stations are located relatively close to an active volcano. The Socorro station (Fagard 2006) is one of them. La Reunion island station, installed at the Piton de la Fournaise volcano observatory, is another. The data from this later DORIS station will be useful for our study as the DORIS station of La Reunion is collocated with a GPS station installed just a few metres apart. This specific site can then provide valuable information to perform an external check of the precision of the DORIS geodetic results.

Figs 3(a) and (b) present the time-series of horizontal coordinates of the two instruments in La Reunion. The observed velocities are totally compatible as derived from these two independent satellite geodesy systems collocated at Piton de la Fournaise: 13.1 ± 1.0 mm yr^{-1} toward north for DORIS and 13.0 ± 0.6 mm yr^{-1} for GPS; 18.8 ± 1.5 mm yr^{-1} toward east for DORIS and 17.0 ± 0.6 mm yr^{-1} for GPS. Whereas DORIS data were processed using the GIPSY/OASIS software package, estimating satellite orbits, GPS data were processed using the GAMIT software using precise orbits from the International GPS Service (IGS, Dow *et al.* 2005). Another independent processing of the GPS data was made by Vigny *et al.* (2006), also with the GAMIT software but with a shorter time-series of GPS data, and the solution was 10.6 ± 1.1 mm yr^{-1} toward east and 17.6 ± 1.3 mm yr^{-1} toward north. Both GPS and DORIS estimated velocities fit well, at the mm yr^{-1} level, with predictions from plate tectonic models and with the velocities of the other permanent geodetic stations located on the same plate (Vigny *et al.* 2006). This similarity between the observed velocity and the predicted one at this volcano indicates that the ground deformation frequently occurring around the summit of the active volcano does not affect the observatory located 15km WSW apart from the summit. A well described example of the typical ground deformation pattern during a recent Piton de la Fournaise eruption is shown by Longpre *et al.* (2007). The absence of an anomaly of the DORIS and GPS data at the observatory is crucial for the study of ground deformation at La Reunion, as it gives an absolute reference (with respect to the underlying oceanic plate) for all ground deformations measured on the volcano.

In the case of Socorro Island, we will show below that unlike the case of La Reunion, the predicted plate tectonic velocity (from various models) and the observed velocity significantly differ (Fig. 4). The goal of our paper is to study these differences, to explain them using volcanological considerations and to see if the observations from a unique DORIS station can provide any valuable information relative to the volcano.

3 SOCORRO DORIS DATA PROCESSING

The DORIS beacon in Socorro was among the very first installed in 1989, even before the launch of the first DORIS-capable satellite, SPOT-2. Its remote location is of great importance in this region for precise orbit determination. Without it, the DORIS permanent tracking network would show a large gap in this region, potentially creating some orbit degradation due to the lack of tracking data. Table 1 summarizes the successive installations of the DORIS beacons in this site, following the consecutive improvement in the beacon technology (Fagard 2006).

At the Institut Géographique National, France Jet Propulsion Laboratory, USA (IGN/JPL) Analysis Center, DORIS data are processed routinely on a weekly basis and results are freely available on internet for the scientific community (Willis *et al.* 2005b). However, for some stations, such as Socorro Island, some DORIS data are rejected prior to the processing, either because a malfunction of the ground antenna was detected (extremely rare case) or because of an unexplained geophysical signal. A list of periods for which DORIS should not be used is available in Willis and Ries (2005) and was specifically prepared prior to the realization of the ITRF2005 (Altamimi *et al.* 2005). For this reason, no DORIS Socorro results appear in the standard IGN/JPL results before 1996 January.

For this specific study, we entirely reprocessed the missing periods (everything before 1996 January, even using the early SPOT2-only data in 1990 in a single-satellite mode). We included DORIS Socorro data as well as DORIS data from other permanent tracking stations in a combined orbit adjustment, by simultaneously estimating orbit parameters and stations positions. Free-network solutions were computed from 1990.1 to 2005.6, projected and then transformed (Willis *et al.* 2005b) into ITRF2000 (Altamimi *et al.* 2002), after removing the Socorro station from the original ITRF2000 frame. This procedure allows derivation of precise coordinates in ITRF2000 for the Socorro station, without assuming any linear model for the station coordinates or any hypothesis from ITRF2000 computation. This is an important point, as this station does not have a constant velocity over time, as we show below. The transformation into ITRF2000 is then based on all DORIS stations but Socorro.

4 DORIS RESULTS

Figs 4(a)–(c) show the DORIS-derived ITRF2000 station coordinates and formal errors (in north, east and vertical) for the three consecutive observation periods at Socorro Island (DORIS beacons SOCA, SODA and SODB). Early results show larger formal errors, as they are derived with only one satellite in 1990 (SPOT2), two satellites after 1993 but then up to five satellites after spring 2002, providing more data and more accurate results. This improvement in formal error is also visible in the results, as a smaller dispersion can be observed for the most recent years due to the increase in DORIS data availability. Station coordinates are all referred to a conventional constant value. However, reference values for the three DORIS beacons are compatible with the geodetic local ties provided by IGN (Fagard 2006). In principle, using this 'connection-technique', if the geodetic local tie vectors are perfect, no jump is to be expected in the concatenated coordinate time-series, even after successive changes in DORIS equipment (see Table 1).

On average, the north and east components are close to the expected plate motion model values. However, earlier results show significant discrepancies that we will later try to model and explain. The vertical component is affected by a large negative slope between 1992 and 1996, corresponding to almost 8 cm yr^{-1}. This large subsidence is real and was previously presented and explained by Cazenave *et al.* (1999), who only analysed the vertical motion of this DORIS station. In particular, they were able to validate this large vertical velocity with external data based on a nearby tide gauge (Fig. 1) and altimetric data. The east component shows a clear discontinuity in 2003, barely detectable in the north component and not visible at all in the vertical component.

5 REMOVING GLOBAL PLATE MOTION

The Revillagigedo archipelago is located on the Pacific plate. In the following, we assume that the long-term velocity of the Socorro Island is the plate velocity and that the residuals are due to the volcanic activity. Three recent papers (Altamimi *et al.* 2002; Kreemer *et al.* 2003; Prawirodirdjo & Bock 2004) give almost identical values, within 1–2 mm yr^{-1}, of the Pacific plate velocity at Socorro, with eastward and northward velocities of 54.6 and 20.5 mm yr^{-1}. Figs 5(a)–(c) show the residual velocities after removing the plate motion.

We propose here to divide the horizontal motion of the DORIS station into five consecutive episodes, corresponding to different periods with constant velocity. As displayed in Table 2, the exact transition epochs between these five episodes can only be approximately determined using the DORIS data, looking for possible discontinuities in the coordinate time-series and assessing their statistical significance (comparing the estimated value with their corresponding formal error).

In Table 2, the dates provided correspond to the day of mid-week, as we do not have a better time resolution for this specific study, except for Epoch C for which we did a specific study using daily results. Whereas epoch C can be very well constrained from these data, epochs A and B can only be determined within a month or two.

The first episode corresponds to the period starting with the first DORIS data in 1990 February until early 1993, when a sudden change occurs. The coordinate time-series allow locating this change between 1992 early October and 1993 late February (Table 2). This correlates well with the onset of the 1993 eruption inferred from seismicity around 1993 mid-January and first observed in the field on 1993 January 29 (Siebe *et al.* 1995). In the following, we adopted for the first discontinuity Epoch A = 01-JAN-1993. During the first period, from 1990 February to Epoch A, no significant vertical and no horizontal motion of the station can be observed with respect to the plate motion. This suggests that the magma released during the 1993 eruption was already emplaced in the volcano, and therefore that no fast reservoir filling occurred immediately before the eruption.

The second episode starts at Epoch A and lasts 3 yr until an estimated Epoch B = 01-JAN-1996 (Table 2). This period is characterized by a fast and almost linear horizontal and vertical motion of the DORIS stations, of –94 ± 3 mm yr^{-1} in the vertical

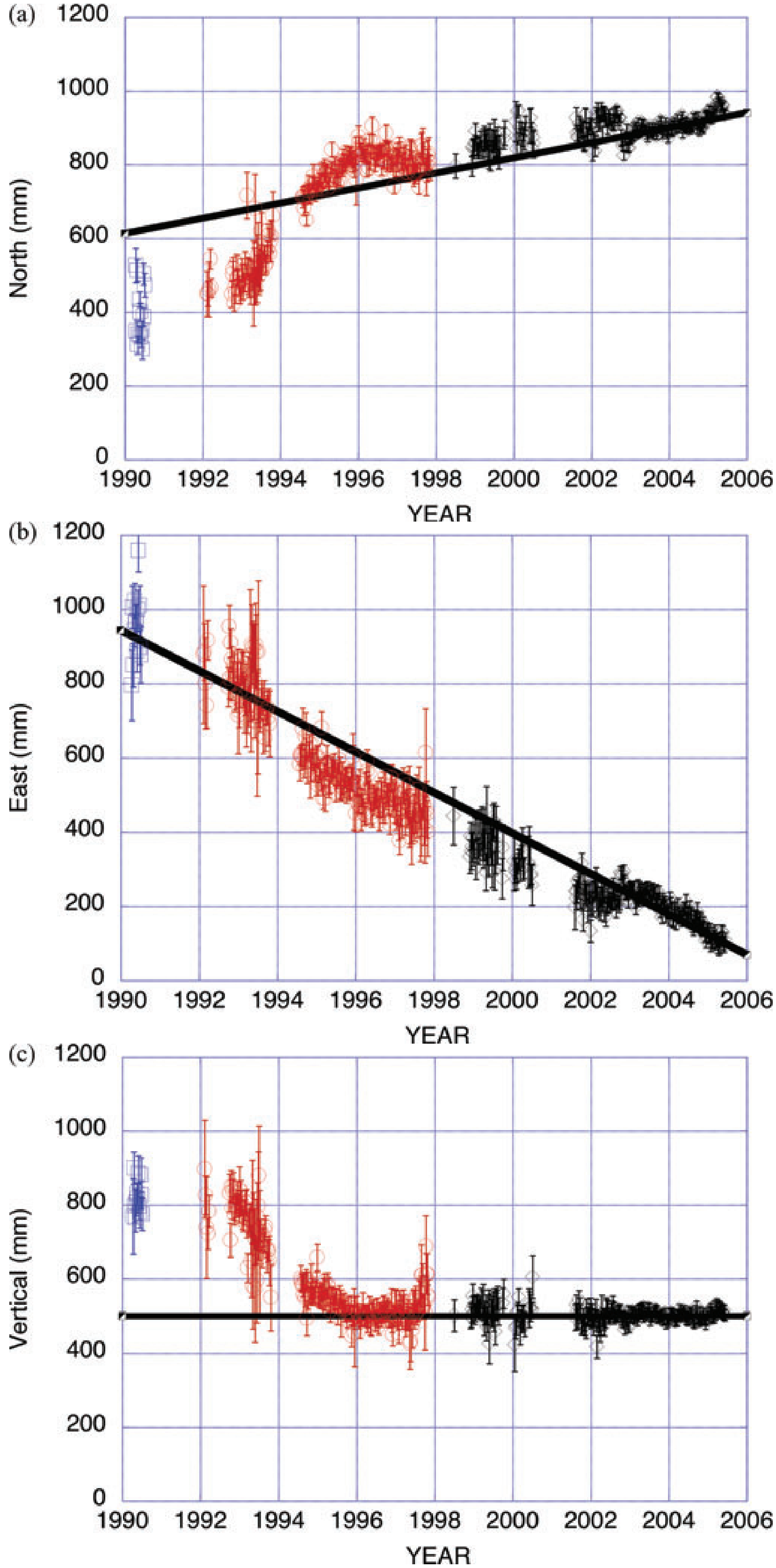

Figure 4. (a) North component (mm) of the DORIS station coordinate and formal errors for consecutive occupations of Socorro island: SOCA (blue squares); SODA (red circles) and SODB (black diamonds). Straight line corresponds to plate motion model. (b) East component (mm) of the DORIS station coordinate and formal errors for consecutive occupations of Socorro island: SOCA (blue squares); SODA (red circles) and SODB (black diamonds). Straight line corresponds to plate motion model. (c) Vertical component (mm) of the DORIS station coordinate and formal errors for consecutive occupations of Socorro island: SOCA (blue squares); SODA (red circles) and SODB (black diamonds). Straight line corresponds to zero vertical motion.

Table 1. DORIS beacons successively installed at Socorro Island.

Acronym	Antenna	DOMES	Installed	Removed
SOCA	Alcatel	40503S002	09-JUN-1989	15-SEP-1990
SODA	Alcatel	40503S003	08-FEB-1991	20-DEC-1997
SODB	Starec	40503S004	20-MAY-1998	still active

component and 106 ± 4 mm yr^{-1} toward N23°W (Table 3 and Fig. 6). We can see from Fig. 6 that the displacement estimated from the DORIS data for the 1993.0–1996.0 period is pointing towards the exact direction of the volcano submit, although no information on the volcano location was used to process the DORIS data. Additionally, the displacement observed during the 1996.0–2002.75 period or the displacement observed after the 2002 October 3 episode are pointing in opposite direction and slightly west of the volcano for reasons that will be addressed later on.

For the 1993.0–1996.0 period, the azimuth of the horizontal motion measured by the DORIS station points exactly in the direction of the summit crater. As we could not find in literature a clear assessment of the date of eruption end and according to our results, we propose that this second episode of 3 yr corresponds to the period of eruptive activity and magma release at the offshore vent. This was already proposed by Cazenave *et al.* (1999) and Willis and Ries (2005). The DORIS data shows that the motion has been almost linear during this 3 yr period. The vertical (subsidence) and the horizontal motion toward the volcano centre indicate a steady deflation of the volcano during the eruption. This vertical motion was also detected and confirmed using results from a close-by tide gauge (GLOSS number 162, 370 m away from the DORIS beacon) as well as altimeter results from TOPEX/POSEIDON (Cazenave *et al.* 1999), but no investigation, to our knowledge, was done concerning the horizontal displacement. After discussing the two other episodes, we model this subsidence using a simple elastic model.

The third episode starts in early 1996 (Epoch B) and ends in 2002 early October (Epoch C). In this period, no vertical displacement is observed, although the horizontal motion has abruptly changed to a SE motion. This reversal suggests a new inflation episode of the volcano but with different characteristics compared with the previous deflation. In particular, the absence of vertical motion implies that the deforming source is much shallower than the deflating one. Also, the azimuth of the inflation is different from that of the earlier deflation, oriented more to the west, more or less in the area where the feeding dyke of the 1993 eruption was inferred by Siebe *et al.* (1995).

The estimated discontinuity is very small (around 10 mm) and, in our opinion, not significant looking at the estimated DORIS precision. In the rest of this document, we will then ignore such a possible discontinuity and trust the quality of the geodetic local tie performed by IGN/SIMB.

As the epoch of change of velocity cannot be exactly determined (see Table 3), we also tried to estimate the impact of this choice on the derived geodetic velocities, by slightly changing the considered time period (but still within the estimated epochs derived from Table 2). Table 4 displays the results of this additional test.

From the comparison of Tables 3 and 4 (using slightly different periods to estimate the velocity), we can see that the estimated velocity remains almost the same, within the estimated precision. The slight improvement in precision was expected due to the increase in the number of observations (data periods are longer in Table 4; see also Willis *et al.* 2006). We can conclude that even if Epoch A and Epoch B can only be determined within a 1–2 month precision, this choice does not affect the estimated geodetic velocities. The formal errors (given after chi-square re-weighting) also seem to be reasonable in Tables 3 and 4, even if they may look rather small at first sight.

The fourth episode is a sudden offset in the horizontal coordinates observed in 2002 October, not associated with any change in the vertical component. This sudden event could be associated with a shallow tectonic event on the volcano but was erroneously attributed to an earthquake postseismic displacement by Willis and Ries (2005). The exact date of 03-OCT-2002 was not derived from the previously discussed weekly solutions but from our original DORIS daily solutions, providing exactly the same answer but within a 1-d confidence interval. The estimated amplitude corresponds to 81 mm in the 41°SE direction (Table 5).

The last episode starts immediately after this event and lasts until our most recent data and indicates that the volcano is not deforming since early 2003. More recent results are obtained every week and are available at the following URL: http://ids.cls.fr/

6 1993–1996 VOLCANO DEFLATION

To model the 1993–1996 deflation, we used a simple model of deflation of a spherical source buried in an elastic half-space (Mogi 1958). In the Mogi formalism, the depth of the deflating source is simply given by

$$U = H \times (\delta U/\delta H), \tag{1}$$

where, H is the horizontal distance between the station and the deflation centre, δH the horizontal displacement at the station and δU the vertical one. Having only one data point, we can constrain the azimuth of the source (pointing exactly in the direction of the summit, as seen from the station as shown in Fig. 6) and the dip angle under which the source is seen from the station (given by the ratio $\delta U/\delta H$) but not the distance between the station and the source. With a second DORIS point or with an additional source of information on this displacement, we would be able to exactly provide the depth and location of the source, using a simple intersection technique. In all discussion below, we will use the value $H = 7.5$ km, which means that we make the assumption that the deflating source is located beneath the top of the volcano. Increasing (or decreasing) this value would lead to a proportional increasing (or decreasing) of the volumes and depths deduced from the model. For instance, a source located at only 6km from the station (this means 1.5 km SSE of the top) would be 20 percent shallower and 20 percent smaller in size. Assuming $H = 7.5$ km and from the DORIS data $\delta H = 106$ mm yr^{-1} and $\delta U = -94$ mm yr^{-1}, eq. (1) leads to a value of $U = 6.7$ km (below the average surface) for the source. As the average surface is around 0.5 km (the DORIS station is near the sea and the top of the volcano is near 1000 m elevation), the inferred source depth is 6.2 km below sea level.

In the Mogi formalism, the vertical displacement is given by the following equation:

$$\delta U = \delta U_{\max} \times \cos^3 \theta, \tag{2}$$

where $\delta U_{\max}$ is the vertical motion at the vertical of the spherical source and θ the elevation angle under which the observation point is seen from the spherical source. Here, we have $\tan\theta = H/U = 1.12$ and therefore $\theta = 48°$ and $\cos\theta = 0.67$. This means that $\delta U_{\max} = 3.38 \times \delta \mathrm{U} = 318$ mm yr^{-1}, and thus the vertical subsidence of the summit of the volcano should have

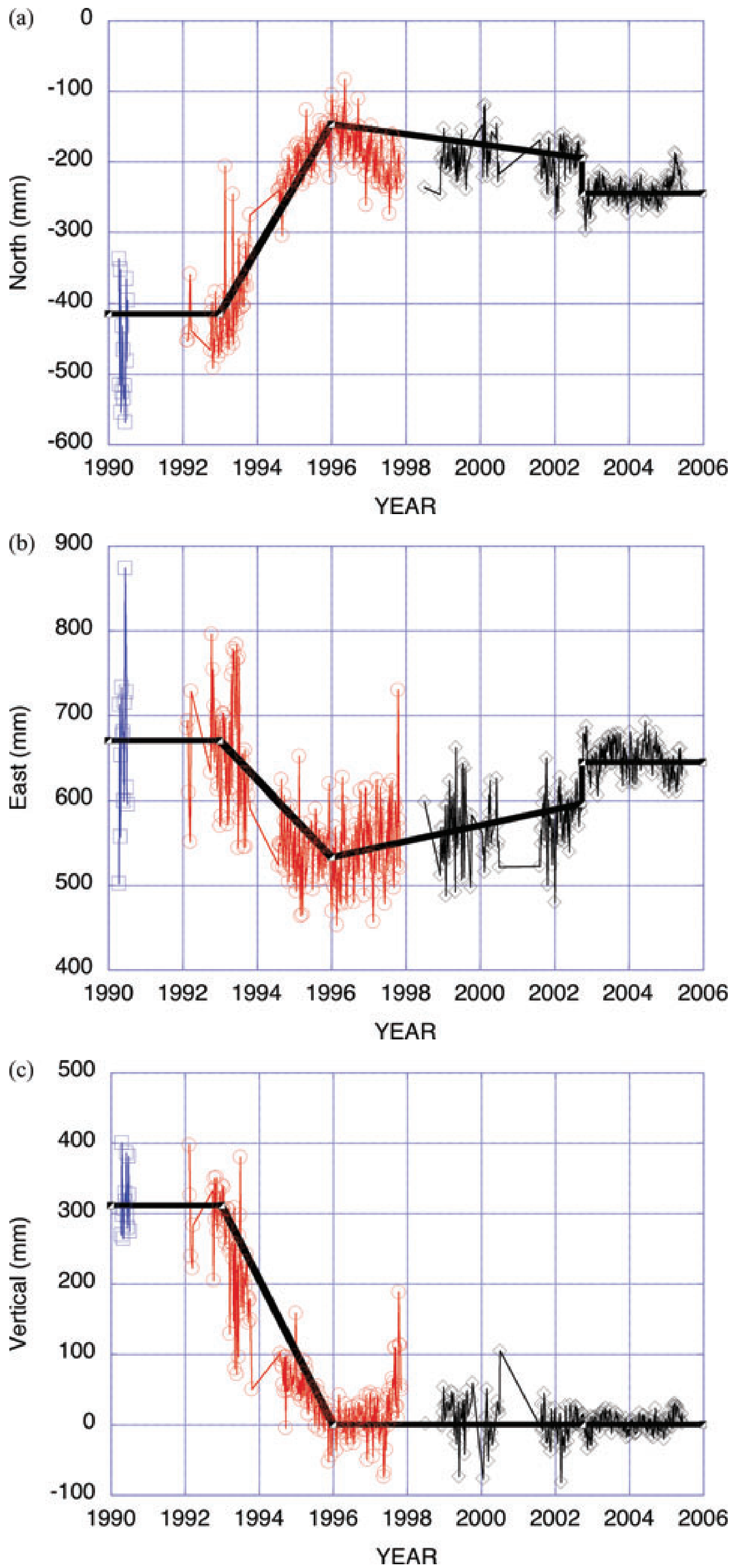

Figure 5. (a) DORIS north residuals (mm) toward plate motion model (+20.5 mm yr^{-1}). Lines correspond to our derived model (this study). SOCA (squares), SODA (circles) and SODB (diamonds). (b) DORIS east residuals (mm) toward plate motion model (−54.6 mm yr^{-1}). Lines correspond to our derived model (this study). SOCA (squares), SODA (circles) and SODB (diamonds). (c) DORIS Vertical residuals (mm). Lines correspond to our derived model (this study). SOCA (squares), SODA (circles) and SODB (diamonds).

Table 2. Determination of exact epochs of discontinuities or change in trend in DORIS Socorro station coordinates using different type of DORIS solutions (weekly or daily) and different time-series (north, east or vertical) and comparison with earlier determination.

	Epoch A	Epoch B	Epoch C
Using weekly north data	[30-SEP-1992, 07-APR-1993]	[25-OCT-1995, 27-MAR-1996]	[25-SEP-2002, 09-OCT-2002]
Using weekly east data	[07-OCT-1992, 03-MAR-1993]	[08-MAR-1995, 12-JUN-1996]	[02-OCT-2002, 09-OCT-2002]
Using weekly vertical data	[11-NOV-1992, 24-FEB-1993]	[08-NOV-1995, 14-FEB-1996]	Not observable
Using all DORIS data (north, east and vertical)	03-JAN-1993 ± 53 d	27-DEC-1995 ± 49 d	05-OCT-2002 ± 3 d
Using daily east data	Not done	Not done	03-OCT-2002 ± 1 d
Proposed value (this study)	03-JAN-1993	27-DEC-1995	03-OCT-2002
Earlier determination (Willis & Ries 2005)	01-JAN-1993	01-JAN-1996	03-OCT-2002

Table 3. Motion of the Socorro DORIS station with respect to the Pacific plate, assuming an absolute velocity of the plate of 54.6 mm yr^{-1} eastward and 20.5 mm yr^{-1} northward. There are two cases for the period 1996.0–2002.75, one assuming no offset in 1990.0 when the antenna was replaced (SODA to SODB), one estimating an offset (three right columns) an offset in our adjustment.

	North Vel. (mm yr^{-1})	East Vel. (mm yr^{-1})	Up Vel. (mm yr^{-1})	North Offset in 1998.0 (mm)	East Offset in 1998.0 (mm)	Up Offset in 1998.0 (mm)
1993.0–1996.0	98.3 ± 3.1	−40.8 ± 4.4	−93.9 ± 3.2	0	0	0
1996.0–2002.75	−3.9 ± 0.8	8.1 ± 0.9	−0.9 ± 0.6	0	0	0
1996.0–2002.75	−5.8 ± 1.8	10.9 ± 2.2	−1.2 ± 1.5	10.3 ± 9.2	−16.0 ± 11.4	1.7 ± 7.6

been in total 0.95 m during the 3 yr of the eruption, according to our data and model. The lack of ERS and ENVISAT data over this volcano unfortunately prevents us to control this result using SAR interferometry.

The volume change at depth can also be retrieved form the Mogi formalism with the following equation:

$$\delta V \sim 4 \times U^2 \times \delta U. \quad (3)$$

With $U = 6.7$ km and $\delta U = 0.95$ m, the estimated deflation of the magma reservoir for the whole period is 171 millions of cubic metres, which corresponds to a volume change rate of 1.8 $m^3 s^{-1}$ during the 3 yr of the eruption. Assuming that this volume change rate is equal to the effusion rate at the offshore eruption, such a value of effusion rate is normal for this type of basaltic eruption. As mentioned above, provided that we have only one data point, the accuracy of this estimated volume is rather limited. Given the fact

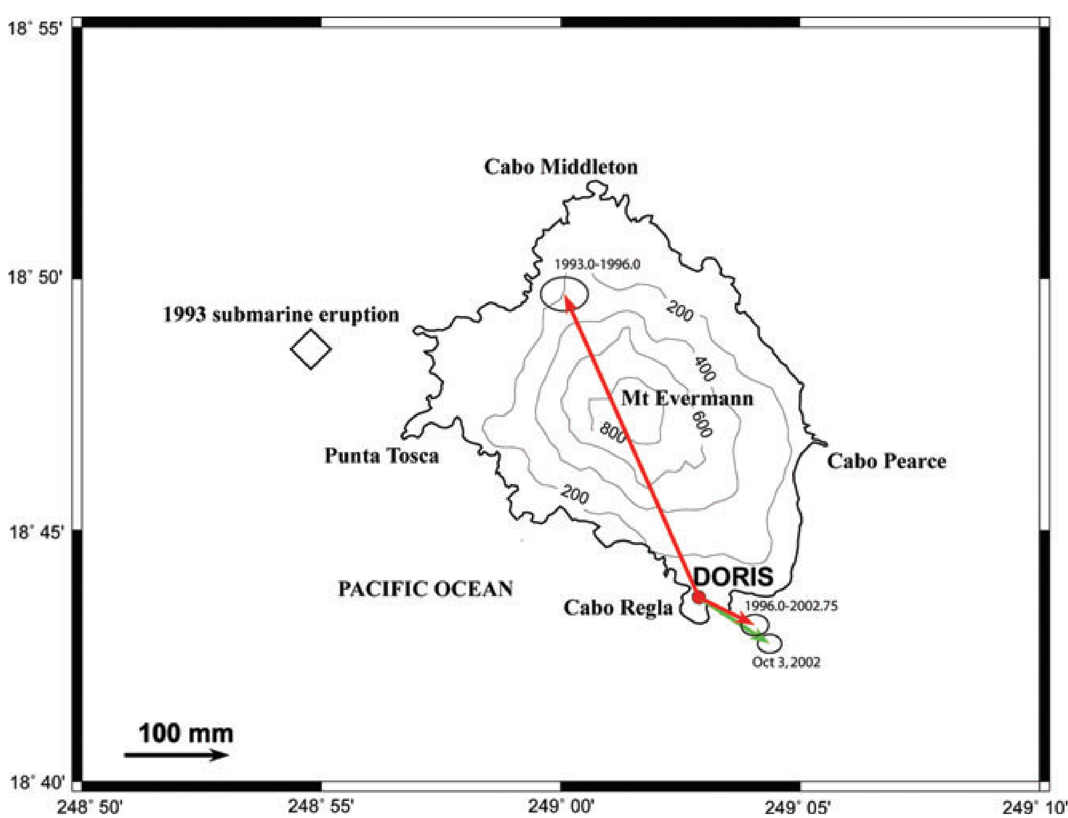

Figure 6. Cumulative displacements of the DORIS station observed between 1993.0 and 1996.0, between 1996.0 and 2002.75 and almost instantaneously on 2003 October 3.

Table 4. Motion of the Socorro DORIS station with respect to the Pacific plate, assuming an absolute velocity of the plate of 54.6 mm yr^{-1} eastward and 20.5 mm yr^{-1} northward. Here, we assume that there is no station coordinate discontinuity after DORIS antenna replacement (vector from SODA to SODB) for the Socorro station using DORIS data.

	North Vel. (mm yr^{-1})	East Vel. (mm yr^{-1})	Up Vel. (mm yr^{-1})
1993.0–1996.0	96.6 ± 2.5	−42.9 ± 3.5	−94.7 ± 2.6
1996.0–2002.75	−3.9 ± 0.7	7.9 ± 0.9	−0.8 ± 0.6

Table 5. Station coordinate discontinuity observed at the DORIS Socorro station (SODB) in 03-OCT-2002 derived from daily solutions (this study).

	North (mm)	East (mm)	Up (mm)
03-OCT-2002	−44.1 ± 4.1	67.4 ± 5.3	−5.9 ± 3.4

that the volume is a linear function of the source–station distance, if we make the assumption that the reservoir might be located not exactly beneath the top but up to 2 km apart, which is already quite large (Massonnet *et al.* 1995 found 1.5 km from the top for the 15 km deep deflating source of the 1991–1993 eruption), then the uncertainties on the volume (and depth) are on the order of 25 percent, which means a volume of 171 ± 45 million cubic metre and a depth of 6.7 ± 1.7 km.

7 POST-1996 MOVEMENTS

The movement observed after 1996 is in the opposite direction of that observed in the previous period; it, thus, indicates that the volcano entered in an inflating phase but with no significant vertical motion. The absence of vertical motion implies that the deforming source is much shallower than the horizontal distance between it and the DORIS antenna. The azimuth of the vector indicates that the deformation source is not in the azimuth of the main crater of Mount Evermann but in the azimuth of the offshore crater of the 1993–1995 eruption. Thus, the post-1996 deformation might be due to the arrival of new magma in a secondary reservoir located beneath the off-shore crater. However, there is no direct evidence for that. It could also correspond to the thermomechanical response of the crust around the off-shore crater, where the hydrothermal system was heated by the feeding dykes of the eruption.

In the following, we use the same Mogi approach as before to roughly estimate the volume change and depth of an equivalent inflating sphere capable to produce the observed motion. The azimuth of the source is that of the offshore crater of the 1993–1996 eruption, 18.794°N and 111.079°W. If we assume that it corresponds to the location of the 1993 crater, the corresponding distance to the DORIS station is 15.3 km. Eq. 1 and the uncertainties on the vertical determination of ground velocity (Table 3) allow us to estimate a maximum value of the source depth of ${U^2}_{\max} = H \times (\delta U_{\max}/\delta H)$.

When $H \gg U$, the volume change associated with an inflating source is approximately

$$\delta V \sim 4 \times H^2 \times \delta H. \quad (4)$$

With $\delta H = 13$ mm yr^{-1}, we find $\delta V = 77$ million cubic metres for the whole period of 6.75 yr, which corresponds to an inflation rate of 0.35 $m^3 s^{-1}$, five times smaller that the previous deflation rate.

The fast offset dated around 2002 October 3 can be quantified in the same manner (Table 5); the azimuth of the motion is almost the same as that of the inflation recorded in the previous years and the amplitude is slightly larger than that of the accumulated motion during the previous 6.75 yr. For this event, we find a volume change of 102 million cubic metre. This amount of volume change in a short period of time is rather large to correspond to a sudden dyke intrusion along the same fracture zone that feed the 1993 eruption, and additional data from seismology or other source are necessary to better characterize this event.

8 CONCLUSIONS

The ground deformation modelled in this work is based on the time-series at one station, the DORIS station located near Cabo Regla in the southeast sector of Socorro island. After correcting for the local plate motion, the local ground motion at the DORIS station was verified for its vertical component by the observation of a tide gauge. Although there is no other data to validate the horizontal motion, this motion is compatible in azimuth and amplitude with a subsidence of the entire island, associated with a deflation of a 6.7 ± 1.5 km deep magma chamber at a rate of 1.8 ± 0.5 $m^3 s^{-1}$ during the 3 yr period of the eruption between 1993 and 1995. However, our data constrains only the azimuth and dip angles of the source, which could be located elsewhere along the azimuth of the summit, depth and volume varying linearly with the distance. The post-1996 ground deformation is oriented towards the place of the 1993 off-shore eruption and indicated an uplift of the volcano in that direction, possibly due the feeding of shallow dykes.

The absence of available ERS and ENVISAT SAR data prevents us from using this information to complete, check and extend our analysis. Such data would also have been useful for proposing more sophisticated models. Here, given the limited information available, we decided to use the simplest possible modelling approach, that is, the assumption of spherical deforming zones. Although we were unable to find such data in literature, observations of sea level changes around the island between 1993 and 1995 at locations different form the tide gauge might exit and constitute very valuable information for further refined analysis. Indeed, the vertical motion at the DORIS station is 28 cm during the 3 yr period, and it should reach 54 and 44 cm along the shorelines closest to Mount Evermann to its southwest ($H = 4.5$ km) and northeast ($H = 5.5$ km), respectively. The predicted motion of half a metre could have been observable by field observations.

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