M. Sc.
Dissertation

Study on the eruption process in Arenal Volcano,
Costa Rica based on the ground deformation in1982-1998.

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ABSTRACT

Arenal volcano is located in the northwest-trending Costa Rican volcanic arc and it has been active in the last 42 years. Eight ground-tilt stations were established around the perimeter of the volcano as a project of Observatory Volcanology and Seismology from Costa Rica, Universidad Nacional (OVSICORI-UNA) since 1982. We employed single setup leveling (SSL), EDM (five lines) and two continuous GPS sites for measuring ground deformation on Arenal.

Large tilt vectors such as 62.2 μradian/year were observed in the west flank of the summit. We assumed a spherical pressure source by Mogi solution to explain the observed crustal deformation in 1982-1998; we divide the 16-year into three periods of 1982-1992, 1993 (August 28, 1993 pyroclastic flows), and 1994-1998. Four source parameters were estimated using a grid-search scheme.

According to our results, a spherical source is located 1km west of the summit with a depth of 1.2km, and the deflated volume change rates of $-0.57 \times 10^6 m^3$/year for the first period, $-1.00 \times 10^6 m^3$/year for the second period, and $-0.55 \times 10^6 m^3$/year for the last period. Since 1982, the SSL data has been revealing a continued deflation in the pressure source for 16 years beneath the summit. Detected by EDM and GPS, line lengths are consistent with our model.

In the previous studies, spherical pressure sources were proposed based on geodetic data they suggested shallow magma source between 2.1km to 1.8km beneath the summit and deflation volume change between $-5.6 \times 10^6 m^3$/year (June to December 1996) to $-0.2 \times 10^6 m^3$/year (1995-2000). Comparing with previous studies, we have some conclusions on the eruption process in Arenal volcano; the volcano continues the laver and pyroclastic flows for the last 42 years. However, deflation is going at the shallow pressure source since 1976. The deflation volumes are estimated between $-0.2 \times 10^6 m^3$/year and $-1.0 \times 10^6 m^3$/year, except the short period observation of only six months. There is a possibility that another pressure source exists in the depth, because of SSL accuracy is ±5μradians, we cannot detect tilt made by a source deeper than 3.5km.

INTRODUCTION

Arenal Volcano

Tectonic and volcanological setting in Arenal Volcano

Arenal is small strato volcano, with a volume of only 15 km^3 and it is located in Costa Rica along the Central American volcanic arc. The activity started around 7000 year ago and is still in the process of building its 1,670m cone by alternating periods of major explosive eruptions with lava flows that stabilize the loose material on its cone.

Arenal began the longest current ongoing eruption of any volcano worldwide in 1968 with a violent Plinian blast and resultant eruptions columns, followed by small pyroclastic flows and rapid effusion of lavas (Reagan et al., 1987). "Cerro" Arenal as local residents called it began explosive activity that literally blew the west side off the volcano. Two villages at the foot of the volcano-- Pueblo Nuevo and Tabacón were completely destroyed and 78 people were killed. Between July 29-31, 1968, three new craters were formed on the western flank of the volcano and a fifteen-square kilometer area was devastated.

Arenal lies in 30km NW of the Quesada Sharp Contortion which is a tear fault in sub ducting Cocos Plate that separates steep slab dips of 60° to ~100km beneath the volcanoes in Guanacaste from shallower dips angle of 40°, 80km beneath the volcanoes in the central Valley (Guendel and Protti, 1998) (Figure 1).

Arenal volcano is a part of the Arenal-Chato volcanic system, which lies between the Cordillera de Guanacaste to the northwest and the Cordillera Central to the southeast. The volcanic system is on a north-east-trending system of normal faults that form a boundary between the Arenal Graben and the Cordillera de Tilaran, a Tertiary volcanic range (Borgia et al., 1988). The oldest rocks exposed are Miocene continental shelf deposits of the Venado Formation overlain by Miocene-Pliocene rocks of the Aguacate Volcanic Group (Borgia et al., 1988) (Figure 2). Deposited on top of the Aguacate Volcanic Group are Quaternary volcano-sedimentary deposits and local Holocene alluvium. The Holocene volcanic system includes the Arenal volcanic edifice to the northwest and the Chato volcanic edifice to the southeast (Borgia et al., 1988). The volcanic activity within the system has migrated to the northwest from Cerro Chato, which last erupted about 3550 BP to Arenal, which began erupting about 2900 BP (Borgia et al., 1988). The stratigraphic record suggests two dominant types of volcanic activity: Plinian-Sub-Plinian eruptions and Peléan eruptions followed by extensive lava effusion (Borgia et al., 1988).

The area around Arenal Volcano is a high-risk zone--this volcano has been active for the past 40 years with regular eruptions providing tourists excellent displays of nature's awesome power. The volcano has become an important tourist attraction for Costa Rica. Several hotels, restaurants and other tourist-oriented ventures have sprung up very close to Arenal in recent years.

Previous Studies of Arenal’s Ground Deformation

In previous studies, several different models were applied to discuss pressure source under Arenal Volcano. Wadge (1983) analyzed data from four SSL stations located in the western flank of the volcano for two years from 1976 to 1978. All four stations showed downward tilting towards the summit of the volcano, with the magnitude of tilt increasing with proximity to the summit (Wadge, 1983). Using a finite element model to infer the depth of Arenal’s magma source, He obtained a shallow magma source of less than 2km below the summit; the volume of extruded material, however, did not match up the modeled magma chamber size. Finally, he proposed that the loading caused by the extruded lava depressed the west flank of the volcano causing the observed tilting (Wadge, 1983).

Since 1995, University of California at Santa Cruz (UCSC) and OVSICORI-UNA established a network consisting with four tiltmeters and two continuous GPS stations on the north and south flanks of the Arenal Volcano (Figure 3). Under the same experiment, Hagerty et al., (1997) analyzed seismic, acoustic, and GPS data on Arenal volcano from 1995 to 1997. He suggests that the data shows shortening across a north-south baseline consistent with deflation of a shallow, non-replenishing magma chamber. They did a preliminary analysis of the seismic and acoustic data, which suggested that the source of tremor and eruptions might be magmatic degassing with bubbles periodically coalescing into large gas slugs that rise and explode beneath the summit.

Schapiro (2000) inverted for the best fitting source model from the tilt and GPS data in the period of June-December 1996 using a Monte Carlo optimization technique. He concluded that a dike and a spherical source model best fits his observed tilt and GPS data with a Mogi source depth of 2.01km and a decrease in volume of $-5.6 \times 10^6 m^3$/year, and a vertical stock with 2.18km long, 2.51km wide, 1.72km depth and with an opening rate of 2.1m/year.

Baugh (2007) analyzed tilt and GPS data collected on Arenal from 1995 to 2000. She shows results with a magma chamber located northwest of the summit at a depth of 1.8km with a volume change of $-0.2 \times 10^6 m^3$/year.

She concluded that tilt data have a varied through time with radial tilt toward the volcano (deflation) at all the sites observed between 1995-1999 changing to a circular pattern of inflation, with a radius of approximately 2500m from the summit, surrounded by deflation elsewhere.

Arenal Single Setup leveling network description

Eight ground-tilt stations were established on the flanks of the Arenal Volcano in 1982 as a project of the OVSICORI-UNA (Figure 3).

We employed the "dry tilt" technique for measuring ground deformation on Arenal. This technique, developed at the Hawaii Volcano Observatory in the late 1960s, utilizes precise leveling methods to determinate changes in elevation of benchmarks affixed firmly in the ground (Yamashita, 1981). It is also called "single setup leveling" (SSL) because it is a special type of tilt leveling in which relative displacements within a small array of marks are measured from a single instrument setup to determinate local ground tilt. In our network, a dry tilt station consists of three benchmarks arranged in a roughly equilateral triangle with sides of about 40m.

The level is set up in the centre with the distance of 23.1m from each vertex and the staff placed on each of the three benchmarks in turn, and their relative altitudes are measured with a high precision. Next time the station is measured, any tilt of the ground in the intervening period will show up as a slight difference in relative altitudes of the three benchmarks. A complete description of the original spirit-level tilt technique can be found in Kinoshita and others (1974), or Yamashita (1981) also presented a detailed description.

The ground-tilt stations established by OVSICORI-UNA in the area between 350m and 750m of altitude with a maximum radio around 5km from the summit of Arenal are described on the Table 1. In our case, the numbers of stations were determined by practical considerations such as accessibility and the time required surveying the network relative to the desired survey frequency. Another important goal was long-term stability, which required an installation that was relatively free from near-surface environmental effects caused by case soil creep, and tropical conditions were a common problem as well as from disturbance or burial by hotel constructions. The geometry of this network was based more on the peculiar morphological situation than on a priori optimization decisions. It was not possible, indeed, to cover properly the southeastern area of the volcano because during the construction of the stations, the access for the mentioned area was difficult. Such dry tilt measurements are not as sensitive as tiltmeters, but dry tilt stations have a broader base than most tiltmeter designs and therefore show more stability, particularly in the long term.

GPS and EDM network

The most common types of geodetic types of surveys made at volcanoes are leveling, EDM and GPS. OVSICORI-UNA established a network of EDM (1992) and two permanent GPS stations (1995) on the north and south flanks of the Arenal Volcano (Figure 3). This EDM network is localized around the active crater C and consists of 3 stations with a geometry allowing measurement of 5 slope distances.

Total stations were used to measure horizontal and vertical angles, combined with slope-distance, repeated measurements permitted determination of displacements; taken every two weeks measurements we were able to document Arenal surface deformation, distances involved, about 2-3 km (slope distances) the uncertainties in the angle measurements, +/-5 s of arc, are about an order of magnitude greater.

The first measurement of the network was carried out in June 1992. Some were only in part complete since some points were lost and later substituted.

The network shows K-W (Park-Warn) line in the northwest of the Arenal summit with slope distance ~ 1732.4m, P-Q (Poste-Quemado) line in the southwest of the active crater C with slope distance ~ 2769.8m, M-Q (Macadamia-Quemado) line in the east south flank of the Volcano with slope distance ~ 1885.9m and M-1 (Macadamia-Numero1) line almost in the south flank with slope distance ~ 1664.1m,P-R (Poste-Koh) line with slope distance ~ 2751.7m.

Since 1995 UCSC and OVSICORI-UNA have been collecting geodetic data at two permanent GPS stations: AROL-LOLA (base line), where the first site is located in the south 3.2 km from the Arenal summit, and the second site is located in the north flank of the volcano 2.9km from the active crater C.

RESULT OF TILT MEASUREMENTS

The Mogi model

With a Mogi model, we can make a simplified representation of a natural volcano system. The reliability of model predictions depends on how well the model represents the natural system (Wang and Anderson, 1982). We applied the Mogi model (Mogi, 1958) into the deformation data to calculate the ground deformation around Arenal Volcano. The solution is:

$$U_z = \frac{3a^3 \Delta P d}{4G(r^2 + d^2)^{3/2}} \qquad (1.1)$$

For vertical displacement, U_z, source depth, d, incremental pressure change (overpressure), ΔP, source radius, a, surface radial distance from the azimuth of the source to the monitoring location, r, and shear modulus, G, where the solution has utilized Lame's constant equal to 0.25 (thus issuing a poisson ratio of 0.25). The shear modulus, may be expressed in familiar from for Young's modulus, E, and poisson ratio, ν, as G=E/2(1+ ν). Source behavior may be further constrained by measurements of surface radial tilt, Φ expressed as the derivative of displacement:

$$\Phi = \frac{9a^3 \Delta P}{4G(r^2 + d^2)^{5/2}} \frac{rd}{} \qquad (1.2)$$

Single setup leveling precision

In the field, we used a Wild Na2 universal automatic level equipped with a GP3 parallel plate micrometer and rigid tripods. The precision obtained by such a level 0.1mm as direct reading and a 0.01mm as estimation. The distance between the instrument and the vertex of the triangle is 23.1m (0.0001m/23.1m = $4.3 \times 10^{-6} \sim 5\,\mu\text{rad}$), so our accuracy is less than $5\,\mu\text{rad}$.

About closer errors for each station according with our data, all the stations show average close error of 0.6 mm (Figure 4a, 4b and 4c). The accuracy of the SSL surveys is determined by the combination of equipment, field procedures and the types of corrections applied to the field observations.

Single Mogi Source Model

For modeling each period, all the data comes from August 1982 to September 1997. We have north-south tilt and east-west tilt components for eight stations FE, BO, CO, DO, CD, PN, TJ, and PP; the observed tilt rates for each period were calculated by linear regression. Tilt rates are summarized in the figures 5a, 5b, 5c, and 5d.

We first attempted to model the observed ground deformation at Arenal using a single Mogi point source using the grid method. Best fitting models were chosen based on the closeness of fitting with the observed data, which was calculated by summing the squares of the difference between the observed and calculated data. We will refer to this as the residual value. In advance, for all the periods we decided to fix the location and depth of the pressure source with the values obtained in the first period (Figure 6a). The main notes about each period are summarized as follows:

The first period: 1982-1992 (before 1993 pyroclastic flows)

According to our survey field notes, this period has started on August 18, 1982 and finished on December 1992. For convenience, we decide to call the periods in years, therefore, 1982 to 1992 in this case. The largest tilt-rate observed during this period was tilting of 62.2 μrad/year at BO and CO also showed significant tilting of 21.9 μrad/year. Stations DO, FE, PP, PN, and TJ showed tilt rate values between 4-6 μrad/year and they were not close enough to our accuracy (± 5 μrad). Finally CD showed 7.6 μrad/year with almost 254 degrees of azimuth, therefore, we suggest that this station showed local noise (not related to our model).

For this period our best residual value was 375.90, this best-fitting model had a Mogi source at 1.2km depth, located 1km west of the summit, and the decrease in volume of this source was $-0.57\times10^{6}\text{m}^{3}$/year (Figure 6a).

The second period: 1993 (during the 1993 pyroclastic events)

This period stared on March 20, 1993 and finished on December 12, 1993. In this period we lost the BO station, the largest tilt-rate observed during this period was 31.0 μrad/year at TJ. Station DO, CD showed around 17 μrad/year while PP, PN, and CO showed values around 6-3 μrad/year, small values under accuracy.

For this period, our best residual value was 5104.09. This best-fitting model had a Mogi source at 1.2km depth, located in the same position as the first period with the decrease in volume of this source at $-1.00\times10^{6}\text{m}^{3}$/year (Figure 6b).

The third period: 1994-1998 (after 1993 pyroclastic flow)

This period stared on September 17, 1993 and finished on September 17, 1997 and we lost three stations; BO (losted in 1988-first period), CO (they are important according with the location of the estimated source), and PP. The largest tilt-rates observed during this period were tilting of 11.7μrad/yr and 6.9μrad/yr at PN and DO-TJ, respectively. Stations FE and CD showed tilt rates with small values under or close to our accuracy.

For the last period our best residual value was 321.18 and this best-fitting model had a Mogi source at 1.2km depth, located 1km west of the summit and the decrease in volume of this source was $-0.55\times10^{6}\text{m}^{3}$/year (Figure 6c).

The extraordinary period: August 1991-May 1992 (Before 1993 pyroclastic flows)

According to report field notes, the volcano activity increased during the period of August 1991 to May1992, which is almost one year before to the 1993 pyroclastic flows. The largest tilt observed during this period was tilting of 71.7 μrad at CO; TJ and FE also showed significant tilting around 20 μrad and the azimuths for these results are according with the observations. Stations DO, PP and PN showed tilt rate values between 6μrad to 9 μrad and CD showed 4.2 μrad this value under or close to our accuracy For this period our best residual value was 375.90 and this best-fitting model had a Mogi source at 1km depth, located 1km west of the summit, and the decrease in volume of this source was $-1.0 \times 10^{6} m^{3}$ (Figure 7).

EDM- GPS Results

Based on the first period (1982-1992) estimated by the Mogi model source with the parameters: y= 0, x = -1 (model coordinates) 1km west of the Arenal summit, depth 1.2km, and volume change rate at $-0.57 \times 10^{6} m^{3}$/year, by comparing with the observed data of EDM and GPS; all the lines shown shortening length rates (negative value). The observation values are denoted with (Ob) and the calculated by our model with (Ca).

The final result for each line is summarized as follow: P-Q line: -7.3cm/year (Ob) and -5.6cm/year (Ca); M-Q line: -10.9cm/year (Ob) and -10.4cm/year (Ca); M-1 line: -1.1cm/year (Ob) and -5.0cm/year (Ca); K-W line: -0.2cm/year (Ob) and -10.7cm/year (Ca); P-R line: -9.8cm/year (Ob) and -9.9cm/year (Ca); AROL-LOLA GPS line showed a north south baseline shortening of -0.8cm/year since their inception, and calculated by our model: -1.0cm/year. For more details, see table 2.

The GPS base line according with the calculation showed just -0.2cm difference while P-R line shown almost the same value between the model and the observations.

The lines P-Q and M-Q had less than -2.0cm difference between the estimated model and the observations, these lines were surveyed between 1992 and 1998 period of the SSL data, during this period 1993 pyroclastic flows occurred.

This calculation illustrated that the model could explain part of the deformation occurred in four of the six lines (EDM and including the GPS line). In the case of the EDM and GPS lines, the analyses performed on these data indicate a deflated deformation around the whole volcanic edifice. In fact these studies indicate subsidence in order of centimeters close to the summit.

DISCUSSION

Ground deformation and pressure source before-during and after the 1993 pyroclastic flow

Before the 1993 events, which OVSICORI-UNA reported increase of the level activity in Arenal, about 40 pyroclastic eruptions/day were recorded in August 1991 to May 1992 and their acoustic and seismic signals recorded; strombolian activity, lava effusion, and seismicity all increased in July-August 1991. The daily number of volcanic earthquakes rose to 59 on 11 July 1992. Seismometers recorded intermittent, vigorous tremor episodes, several hours long .The lava flow activity in September-November on the SW flank was different from other recent flows, being long, voluminous, and having well-defined levees (E. Fernandez, field notes1991). During 12-22 April 1992, 539 seismic events were recorded by fieldworks of OVSICORI and volunteers. Continuous tremor of low, medium, and high frequency, associated with lava extrusion, was recorded almost 24 hours/day during this period.

Explosive activity increased in number and magnitude from preceding months, especially since 26 May. Produced ash columns were higher than 1 km and bombs fell to 1km elevation.

During the collapse of the crater wall of the cone (28 August 1993), 3 km-long pyroclastic flow with $2.2 \pm 0.8 \times 10^6 m^3$; after March 1993 lava emission was decreased to at least half of that observed during 1992, resulting in shorter and slower lava flows (Alvarado & Soto, 2001).

After the moderately explosive behavior seen on 28 August, the intensity of explosive activity was decreased in September reported by OVSICORI-UNA. Hundreds to thousands of "seismic events" occur each month. In November 1993, the OVSICORI seismometer registered 203 seismic events, the lowest total for any month thus far in 1993. For comparison, earlier in 1993 the same seismometer registered 2-7 times more events. It is suggested that the Arenal activity before 1993 was more vigorous, changes were recorded by some of the SSL stations, it’s consistent with our models before, during, after, as well as the extraordinary period already analyzed (May 1991- August 1992).

Shallow deflated pressure source:

In the previous studies by Wadge (1983), he suggested shallow magma source less than 2 km beneath the summit in 1976 to 1980. Hagerty et al. (1997) studied seismic, acoustic and GPS data in 1995-1997, and they suggested shortening line lengths at north-southward baselines as a deflation of a shallow, non-replenishing magma chamber. They also suggested the hypo centers of the tremor are located beneath the summit. Shapiro (2000) analyzed tilt and GPS data since June to December 1996,and he concluded a pressure source depth at 2.01 km with deflation of -5.6x$10^6$$m^3$/year. Baugh (2007) analyzed tilt and GPS data in 1995-2000, and she concluded that a deflation source was located at the northwest of the summit with a depth of 1.8 km and a volume change of -0.2 x$10^6$$m^3$/year.

In the previous studies and our results, a shallow deflation source is estimated through the period since 1976. The deflation is going with rest of –(0.2-1.0) x106m3/year volumes. The deflation is going at the shallow pressure source since 1976.

Model hypothesis:

Alvarado & Soto (2001) calculated the volume of material involved on the August 28, 1993 pyroclastic flow, they used two different methods: (1) comparing previous aerial photographs, maps, and ground-based photos with post-event photos and observations, and (2) calculation of the area and thickness of pyroclastics flow deposit based on field measurements, they obtained the average volume rate of $2.2 \pm 0.8 \times 10^6 \mathrm{m}^3$.

Generally deep pressure source are estimated under the volcanoes with lava dome such as Unzen volcano (Kohono et.al., 2008), however we didn't discussed a deep pressure source in Arenal volcano; because of the measurement accuracy of SSL, it is impossible to detect tilt changes less than 5μradius. As a result, we do not detect the ground deformation caused by a deep pressure source at 3.5km with volume change of $-1.0 \times 10^6 \mathrm{m}^3$.

We estimated deflation source of $-1.3 \times 10^6 \mathrm{m}^3$ in 1.0km depth and it's good consistence with the erupted volume of $2.2 \pm 0.8 \times 10^6 \mathrm{m}^3$ (Alvarado & Soto, 2001) (Figure 8b).

CONCLUSIONS

Eight ground-tilt stations were established on the flanks of the Arenal in 1982, we studied 16 years data in 3 different periods, 1982 to 1992, 1993 and 1994 to 1998; collectively, results from these stations indicate that the volcano shows general trends tilting towards to the summit.

The maximum rates of tilt were 62.2μrad/year and 21.9μrad/year surveyed in BO and CO, respectively. Thus, it appears that BO and CO has been more affected by changes in eruptive activity than the rest of the sites.

We used modeling to explain every period. In the first period these models appear to indicate that Arenal has a Mogi source located 1km west of the summit at 1.2km depth with the volume change rate of $-0.57\times10^{6}\mathrm{m}^{3}/\mathrm{year}$. The next two periods have the same location and depth as the previous one. In the second period (when 1993 event occurred) the deflated volume change rate was $-1.0\times10^{6}\mathrm{m}^{3}/\mathrm{year}$ and finally for the last period the deflated volume change rate was $-0.55\times10^{6}\mathrm{m}^{3}/\mathrm{year}$. The EDM and GPS data lines shown shortening lengths in all the lines and this pattern is consistent with our model. In previous studies Wadge (1983), Hagerty et al. (1997), Shapiro (2000) and Baugh (2007) based on geodetic data they proposed a shallow magma source ~2km beneath the summit and deflation volume change between $-5.6\times10^{6}\mathrm{m}^{3}/\mathrm{year}$ (June to December 1996) to $-0.2\times10^{6}\mathrm{m}^{3}$ (1995-2000). Comparing with previous studies, we have some conclusions on the eruption process in Arenal volcano; the volcano continues the laver and pyroclastic flows for the last 42 years. However, deflation is going at the shallow pressure source since 1976. The deflation volumes are estimated between $-0.2\times10^{6}\mathrm{m}^{3}$ to $-1.0\times10^{6}\mathrm{m}^{3}/\mathrm{year}$, except the short period observation of only six months. There is a possibility that another pressure source exists in the depth. However we didn't discuss a deep pressure source in Arenal volcano; because of the measurement accuracy of SSL, it is impossible to detect tilt changes less than 5μradius. The Arenal-monitoring network for the future needs leveling networks, EDM lines and electronic tilt-meters supported by GPS.

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FIGURE CAPTIONS

Figure 1. Local tectonics map of Costa Rica, Arenal's Volcano is denoted by red triangle and geometry of the Wadati-Benioff zone (from Protti et al., 1995b). Isodepth contours to the top of the seismic slab are at 20km intervals, starting at 40km. Closed triangles represent active volcanoes and closed circles, the location of large (Mw ≥ 7.0) earthquakes in the twentieth century. QSC marks the projection of the Quesada Sharp Contortion.

Figure 2. Geologic map of Arenal-Chato volcano system. UPPv, undevided Pliocene-Pleistocene volcanics; LC, lower Chato; CH, Chatito (and La Espina to the northeast); mC, middle Chato lava field; uC, upper Chato; LA, lower Arenal; A4, A4 lava field; A3, A3 lavafield; A2l, A2 low lava field; A2h, A2 high lava field; A1l, A1 low lava field; A1h, A1 high lava field; utAC, undivided tephra of Arenal and Chato; utAC1235, Quebrada Guillermina pyroclastic flow; utAC1968, 1968 pyroclastic flow; utAC1975, 1975 pyroclastic flow; sd, sedimentary deposits; sda, alluvium; sdm, mudflow deposits; sdt, talus slope deposits. By Borgia et al., 1988.

Figure 3. Topographic map of Arenal Volcano, showing a location of the single setup leveling (blue triangles) established by OVSICOR-UNA in 1982. Red triangle denoted the summit location of Arenal volcano and black triangle shown the location of Chato Volcano. Black circles shown two permanent GPS sites, gray triangles shown five tiltmeter, OVSICORI-UCSC network since 1995. VACR OVSICORI-UNA seismic station denoted by gray square and Arenal location in Costa Rica is shown by the square in the inset map.

Figure 4. SSL row data at CO station and configuration of triangle benchmarks, survey for each side of the original field-triangle. The square inset map shown the survey side of the triangle **(a)** side XY (~ 40m), **(b)** side XZ (~ 40m) and **(c)** side YZ (~ 40m). The data corresponds to 1982 to 1998, high is in centimeters and the error bars show by red lines, average error is 0.6 mm.

Figure 5. Single setup leveling time series of tilting, east-west and north-south components; tilt data showed in microradians in 1982 to1998 at **(a)** and **(c)** PP, TJ, PN, CD, DO, FE stations, **(b)** and **(d)** at BO and CO stations. Red lines show linear regression lines yield tilt rates for each period.

Figure 6. Observed tilts of single setup leveling results in the three periods from 1982 to 1991 and calculated tilts by estimated Mogi model. Red arrows show the observed tilt and the black arrows show the calculated tilt. Estimated source denoted by the blue star. **(a)** period from 1982 to 1992, **(b)** period from 1993, and **(c)** period from 1994 to 1998.

Figure 7. Observed tilts of single setup leveling results from May 1991 to August 1992 and calculated tilts by estimated Mogi model. Red arrows show the observed tilt and the black arrows show the calculated tilt. Estimated source denoted by the blue star.

Figure 8. (a) Schematic diagram showing the pressure sources estimated by Mogi model based on SSL data in 1982 to 1998, and **(b)** schematic diagram hypothesis, based on August 1991- May 1992 results; showing the magma supplying system beneath Arenal Volcano. The orange circles represent a Mogi source at 1.0km (shallow) and more than ~3.5km (deep).

Table 1. Locations for all the SSL, EDM and GPS sites in Lat-Lon, and coordinates our model space.

Station	Lat (°N)	Lon (°N)	Dist. From summit (km)	East (km)	North (km)	Height (m)
Summit	10.463	-84.703	0	0	0	1660
BO	10.460	-84.720	1.87	-1.847	-0.293	753
DO	10.457	-84.737	3.56	-3.533	-0.434	584
CO	10.458	-84.726	2.52	-2.498	-0.329	645
FE	10.438	-84.718	3.01	-1.617	-2.539	622
PP	10.466	-84.687	2.74	2.736	-0.143	458
PN	10.496	-84.707	4.06	-0.705	3.998	468
CD	10.492	-84.731	4.52	-2.328	3.874	467
TJ	10.487	-84.685	3.91	1.931	3.400	343
PK	10.460	-84.736	3.68	-3.663	-0.308	591
W	10.462	-84.721	1.97	-1.960	-0.111	780
AR	10.438	-84.707	2.70	0.042	-2.695	755
Q	10.453	-84.714	1.11	-0.599	-0.933	800
PO	10.449	-84.736	3.57	-3.302	-1.360	573
R	10.450	-84.701	1.44	-1.329	0.556	760
1	10.452	-84.705	1.05	-0.094	-1.050	915
LOLA	10.490	-84.714	3.22	-1.202	2.984	576
AROL	10.437	84.709	2.95	-0.656	-2.873	746

Table 2. EDM and GPS lines, the corresponding rates, and the specific periods data last column shows the shortening calculated by a Mogi estimated source with parameters: y= 0, x = -1 (model coordinates) 1km west of the Arenal summit, depth 1.2km, and volume change rate at $-0.57\times10^{6}\,\mathrm{m}^{3}/\mathrm{year}$.

Line	Start/Date	End/Date	Rate (cm)/yr	Cal.by Mogi (cm)
P-Q	Apr-92	Jan-98	-7.3	-5.6
M-1	Jan-97	Apr-01	-1.1	-5.0
K-W	Nov-97	Jun-03	-0.2	-10.7
M-Q	Apr-92	Dec-96	-10.9	-10.4
P-R	Jan-97	Jun-03	-9.8	-9.9
LOLA-AROL	Oct-95	Oct-01	-0.8	-1.0

Figure 1

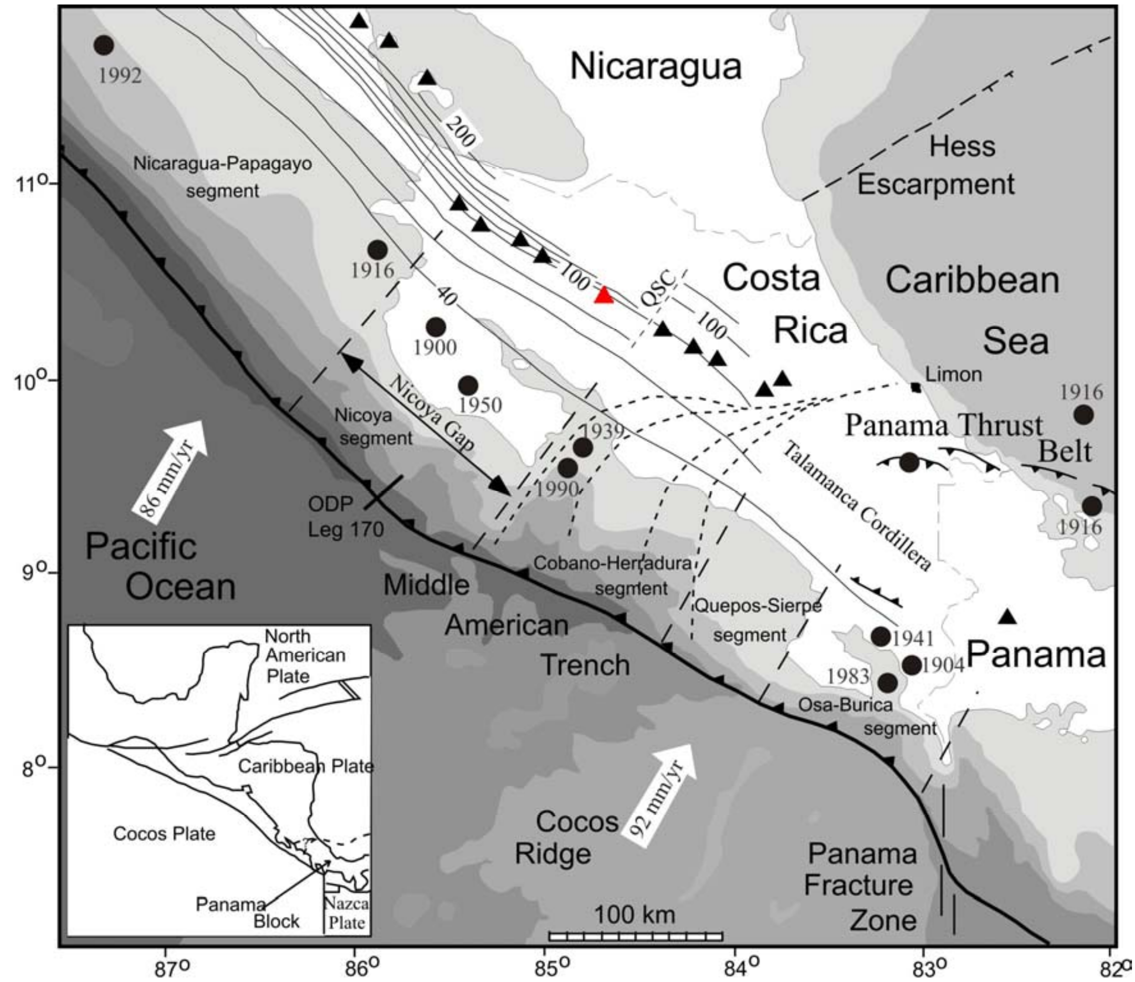

Nicaragua
Hess
Escarpment
Costa
Rica
Caribbean
Sea
Nicaragua-Papagayo
segment
Nicoya
segment
Nicoya Gap
ODP
Leg 170
Pacific
Ocean
86 mm/yr
Middle
American
Trench
Cobano-Herradura
segment
Quepos-Sierpe
segment
Osa-Burica
segment
Talamanca Cordillera
Panama Thrust
Belt
Limon
Panama
QSC
200
100
100
40
1992
1916
1900
1950
1939
1990
1916
1916
1941
1904
1983
Cocos
Ridge
92 mm/yr
Panama
Fracture
Zone
100 km
North
American
Plate
Caribbean Plate
Cocos Plate
Panama
Block
Nazca
Plate
11°
10°
9°
8°
87°
86°
85°
84°
83°
82°

Figure 2

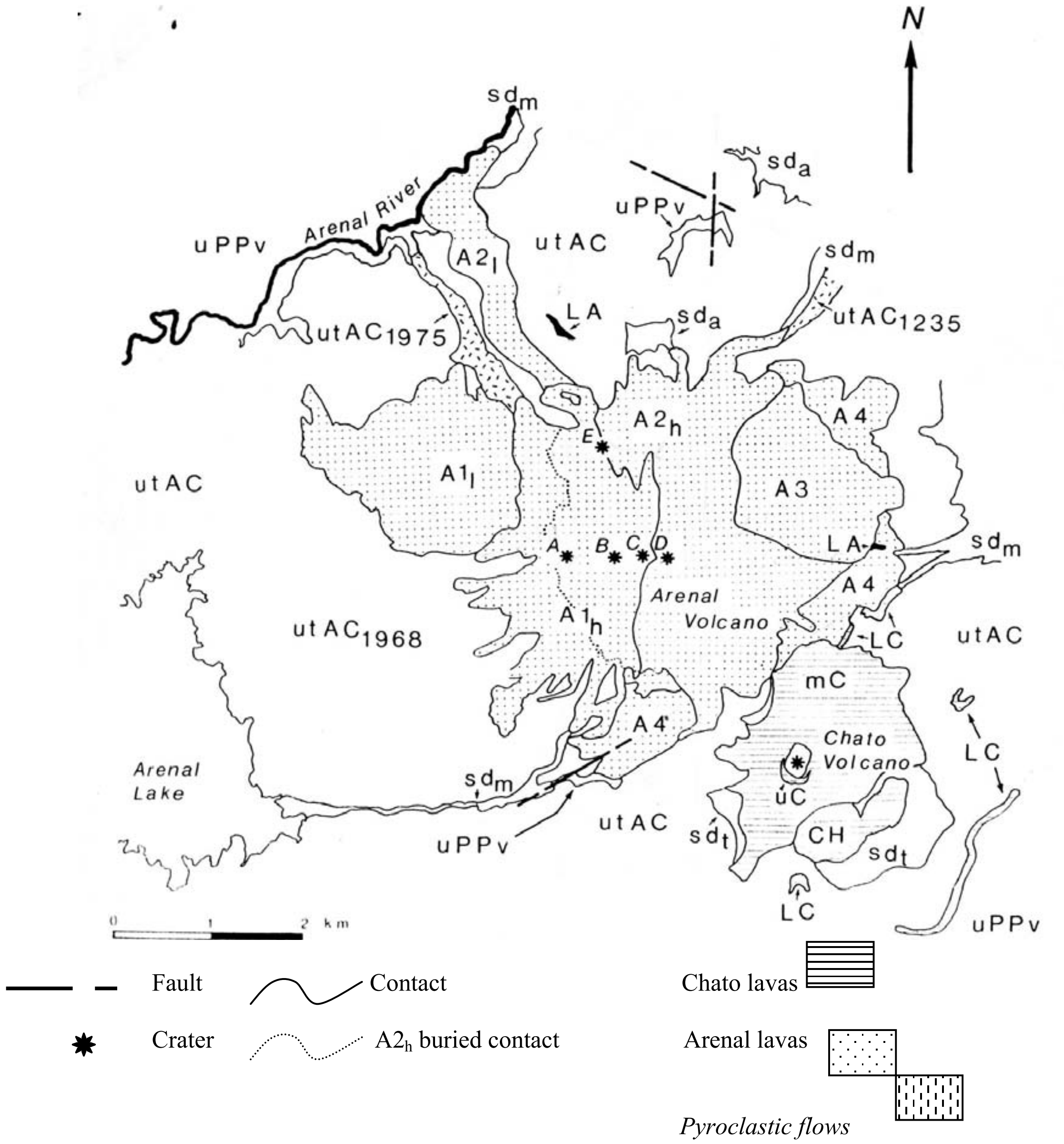

N
sdm
Arenal River
uPPv
utAC
A2l
sda
uPPv
sdm
LA
sda
utAC1975
utAC1235
A2h
A4
E
A1l
utAC
A3
A B C D
LA
sdm
A4
Arenal
Volcano
A1h
utAC1968
LC
utAC
mC
A4'
Chato
Volcano
LC
Arenal
Lake
sdm
uC
uPPv
utAC
sdt
CH
sdt
LC
uPPv
0 1 2 km
Fault
Contact
Chato lavas
Crater
A2h buried contact
Arenal lavas
Pyroclastic flows

Figure 3

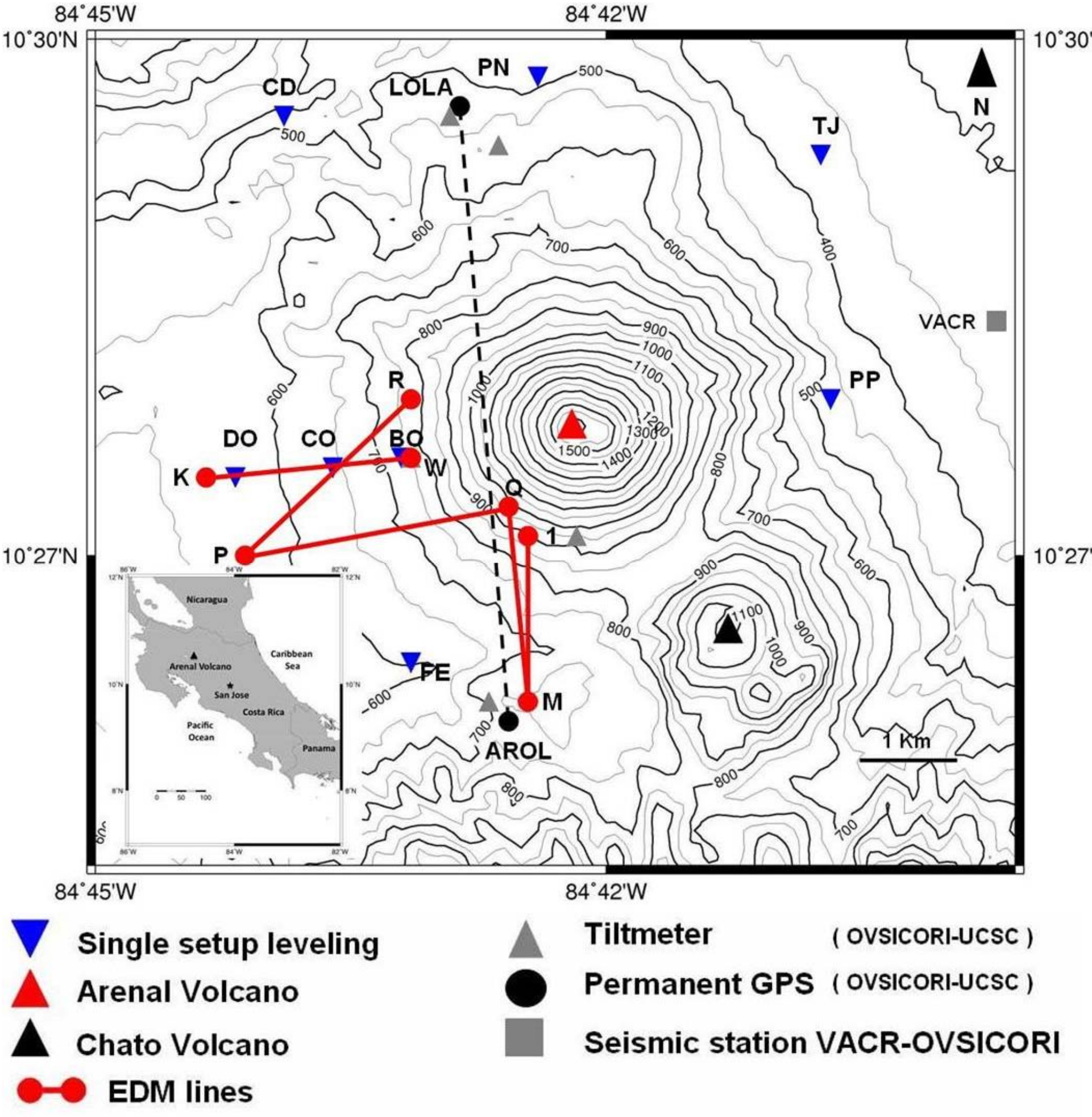

84°45'W
84°42'W
10°30'N
10°27'N
N
CD
PN
LOLA
TJ
VACR
PP
R
DO
CO
BO
W
K
Q
1
P
FE
M
AROL
1 Km
Nicaragua
Arenal Volcano
Caribbean Sea
San Jose
Costa Rica
Pacific Ocean
Panama
Single setup leveling
Arenal Volcano
Chato Volcano
EDM lines
Tiltmeter (OVSICORI-UCSC)
Permanent GPS (OVSICORI-UCSC)
Seismic station VACR-OVSICORI

Figure 4a

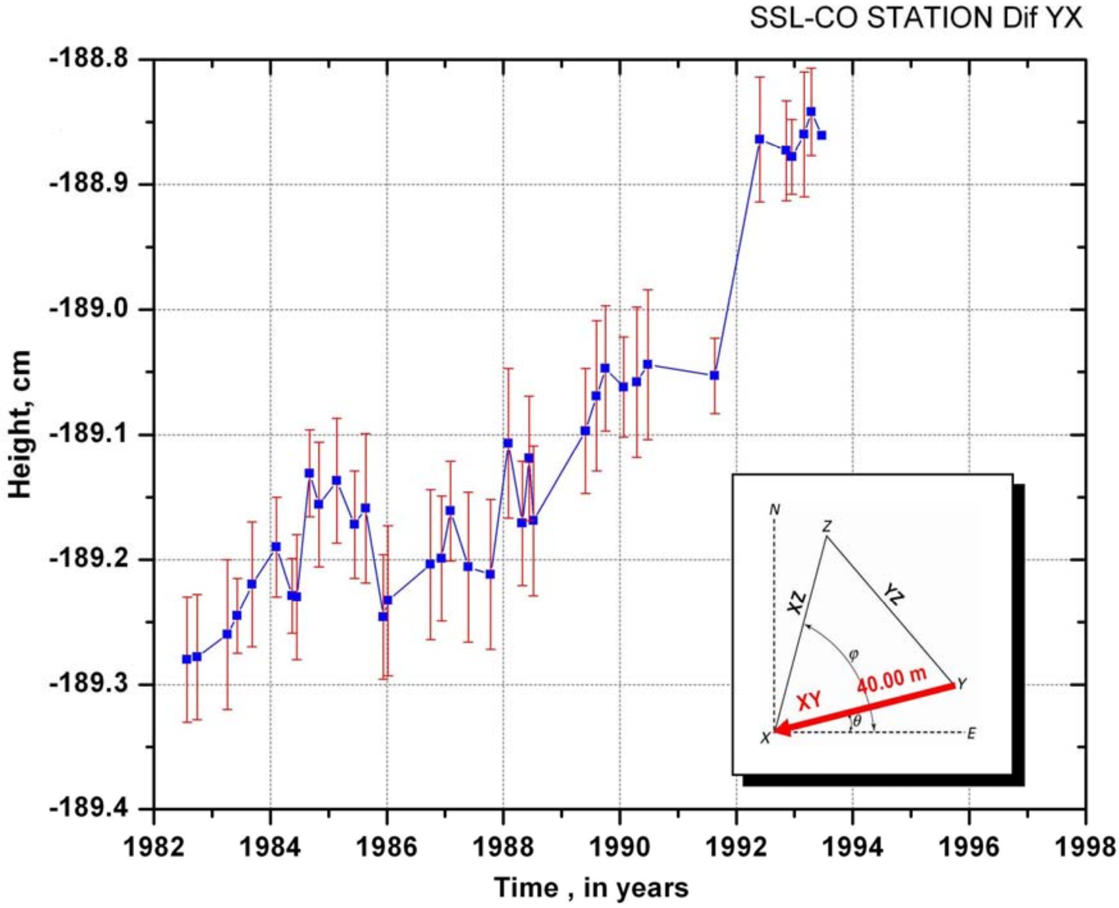

SSL-CO STATION Dif YX
-188.8
-188.9
-189.0
-189.1
-189.2
-189.3
-189.4
Height, cm
1982
1984
1986
1988
1990
1992
1994
1996
1998
Time , in years
N
Z
XZ
YZ
φ
40.00 m
XY
θ
X
Y
E

Figure 4b

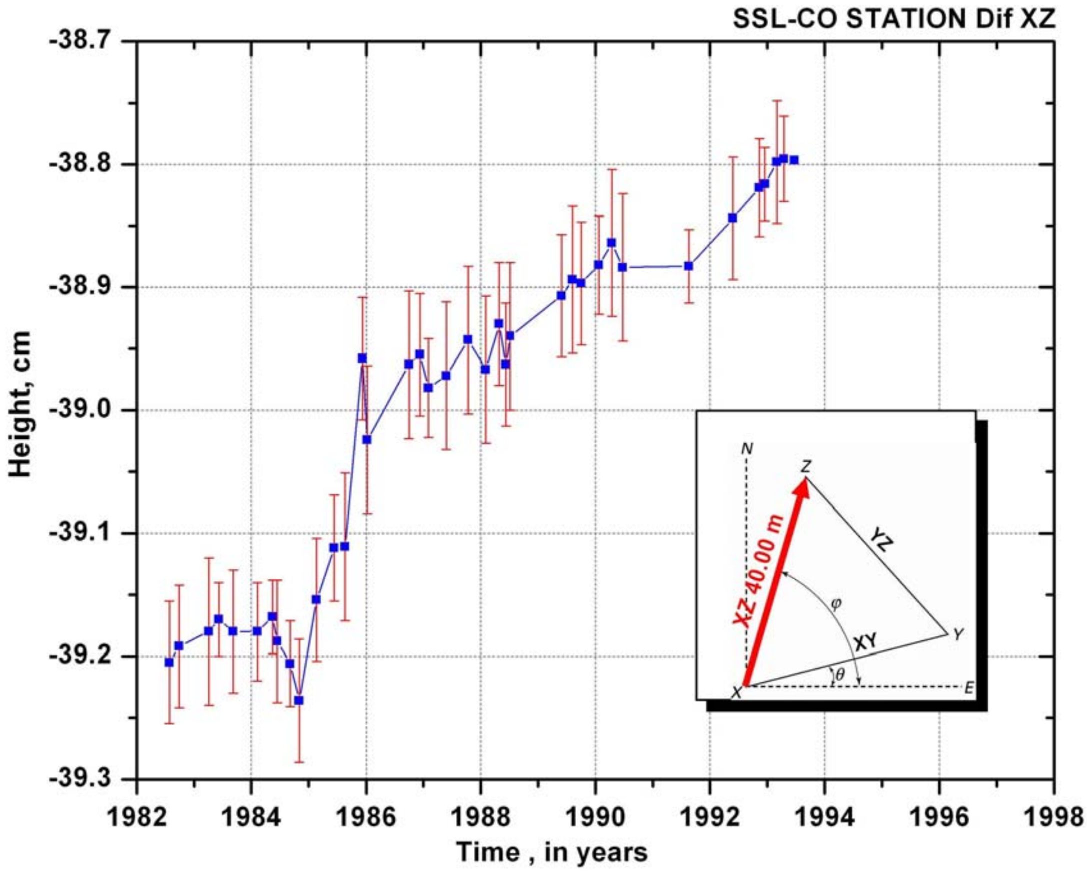

SSL-CO STATION Dif XZ
Height, cm
Time , in years
-38.7
-38.8
-38.9
-39.0
-39.1
-39.2
-39.3
1982
1984
1986
1988
1990
1992
1994
1996
1998
N
Z
YZ
XZ 40.00 m
φ
XY
Y
θ
X
E

Figure 4c

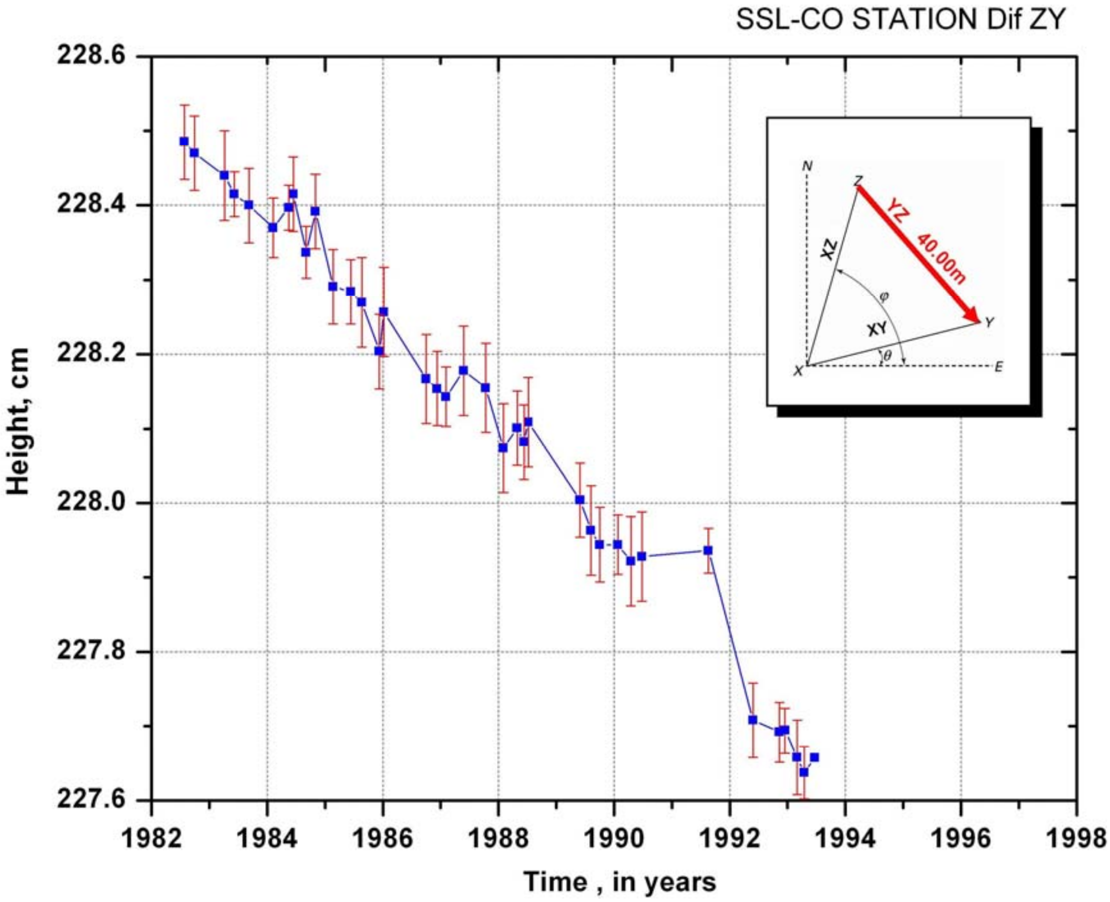

SSL-CO STATION Dif ZY
228.6
228.4
228.2
228.0
227.8
227.6
Height, cm
1982
1984
1986
1988
1990
1992
1994
1996
1998
Time , in years
N
Z
YZ 40.00m
XZ
φ
XY
θ
X
Y
E

Figure 5a

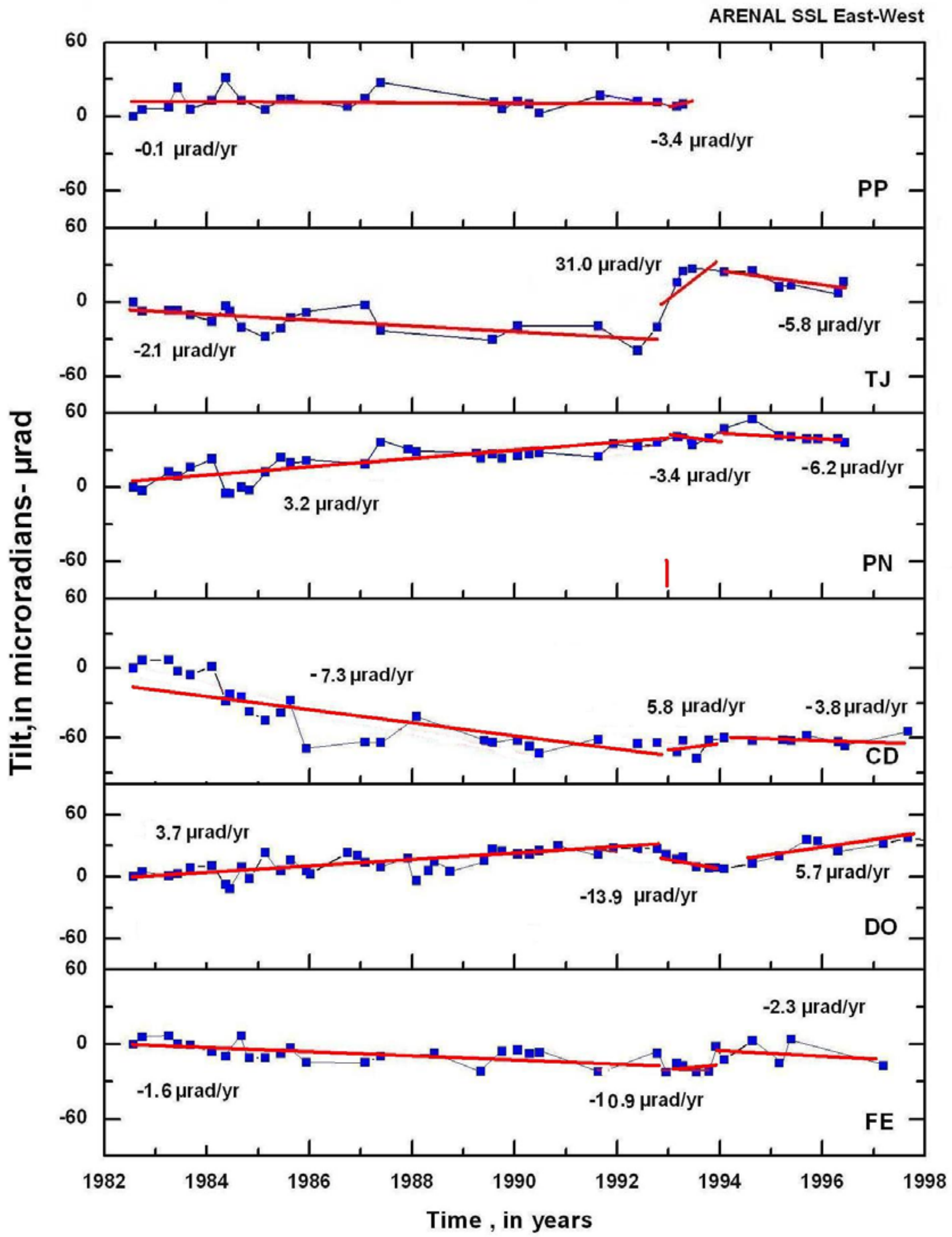
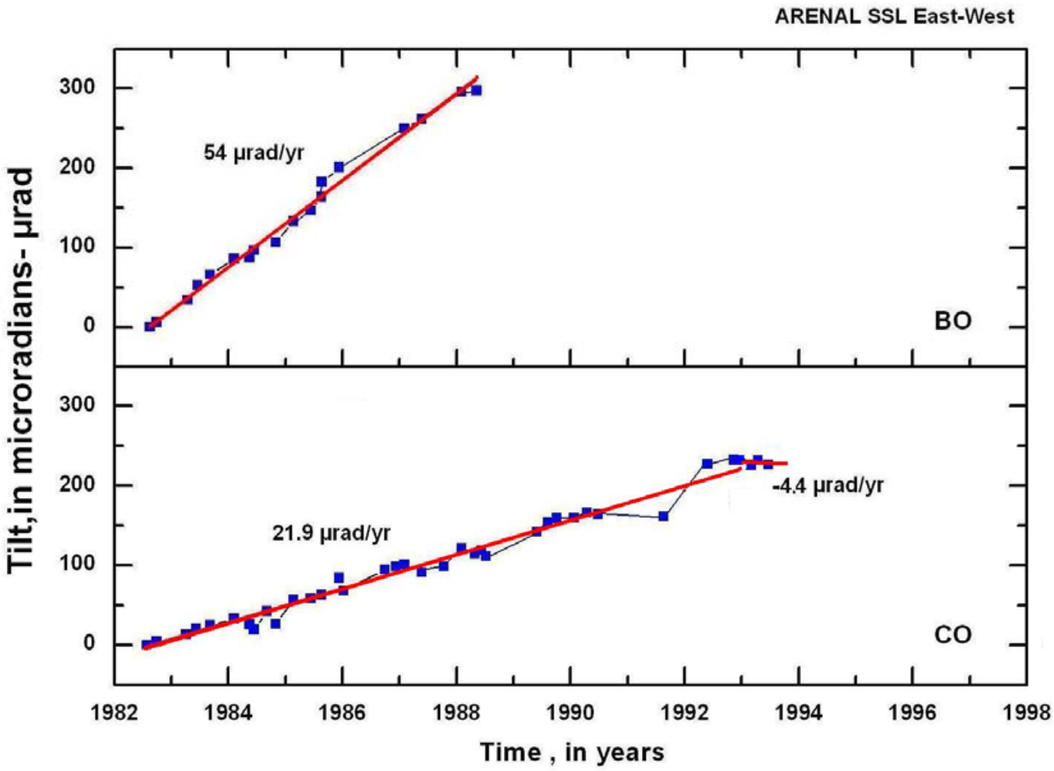
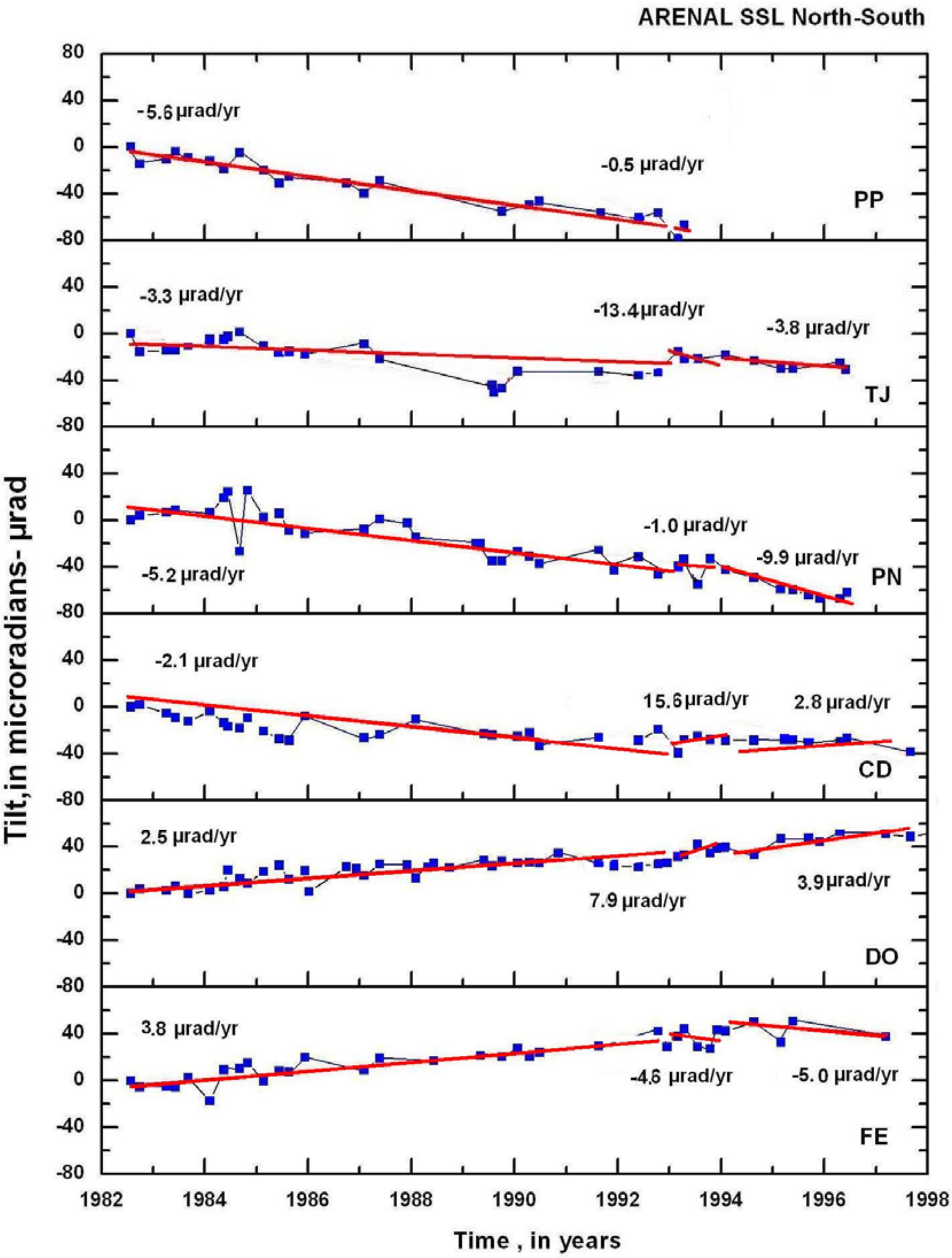

ARENAL SSL East-West
Tilt,in microradians- µrad
60
0
-60
-0.1 µrad/yr
-3.4 µrad/yr
PP
31.0 µrad/yr
-2.1 µrad/yr
-5.8 µrad/yr
TJ
-3.4 µrad/yr
-6.2 µrad/yr
3.2 µrad/yr
PN
-7.3 µrad/yr
5.8 µrad/yr
-3.8 µrad/yr
CD
3.7 µrad/yr
-13.9 µrad/yr
5.7 µrad/yr
DO
-2.3 µrad/yr
-1.6 µrad/yr
-10.9 µrad/yr
FE
1982
1984
1986
1988
1990
1992
1994
1996
1998
Time , in years

Figure 5b



ARENAL SSL East-West
54 µrad/yr
BO
21.9 µrad/yr
-4.4 µrad/yr
CO
Tilt,in microradians- µrad
Time , in years
300
200
100
0
1982
1984
1986
1988
1990
1992
1994
1996
1998

Figure 5c



ARENAL SSL North-South
-5.6 µrad/yr
-0.5 µrad/yr
PP
-3.3 µrad/yr
-13.4µrad/yr
-3.8 µrad/yr
TJ
-1.0 µrad/yr
-9.9 µrad/yr
-5.2 µrad/yr
PN
-2.1 µrad/yr
15.6µrad/yr
2.8 µrad/yr
CD
2.5 µrad/yr
7.9 µrad/yr
3.9µrad/yr
DO
3.8 µrad/yr
-4.6 µrad/yr
-5.0 µrad/yr
FE
Tilt,in microradians- µrad
Time , in years
80
40
0
-40
-80
1982
1984
1986
1988
1990
1992
1994
1996
1998

Figure 5d

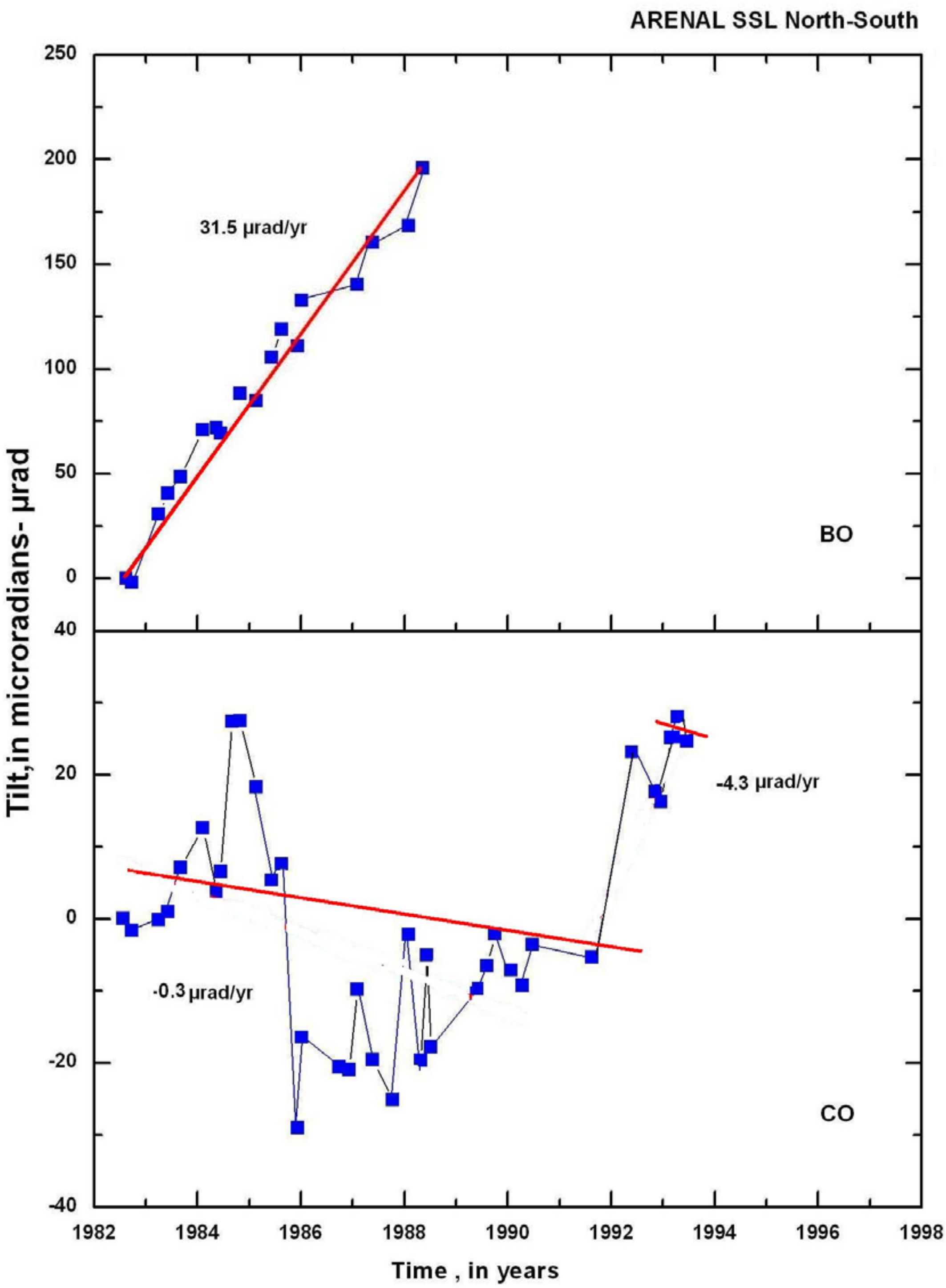

ARENAL SSL North-South
31.5 µrad/yr
BO
-4.3 µrad/yr
-0.3 µrad/yr
CO
Tilt,in microradians- µrad
Time , in years
250
200
150
100
50
0
40
20
0
-20
-40
1982
1984
1986
1988
1990
1992
1994
1996
1998

Figure 6a

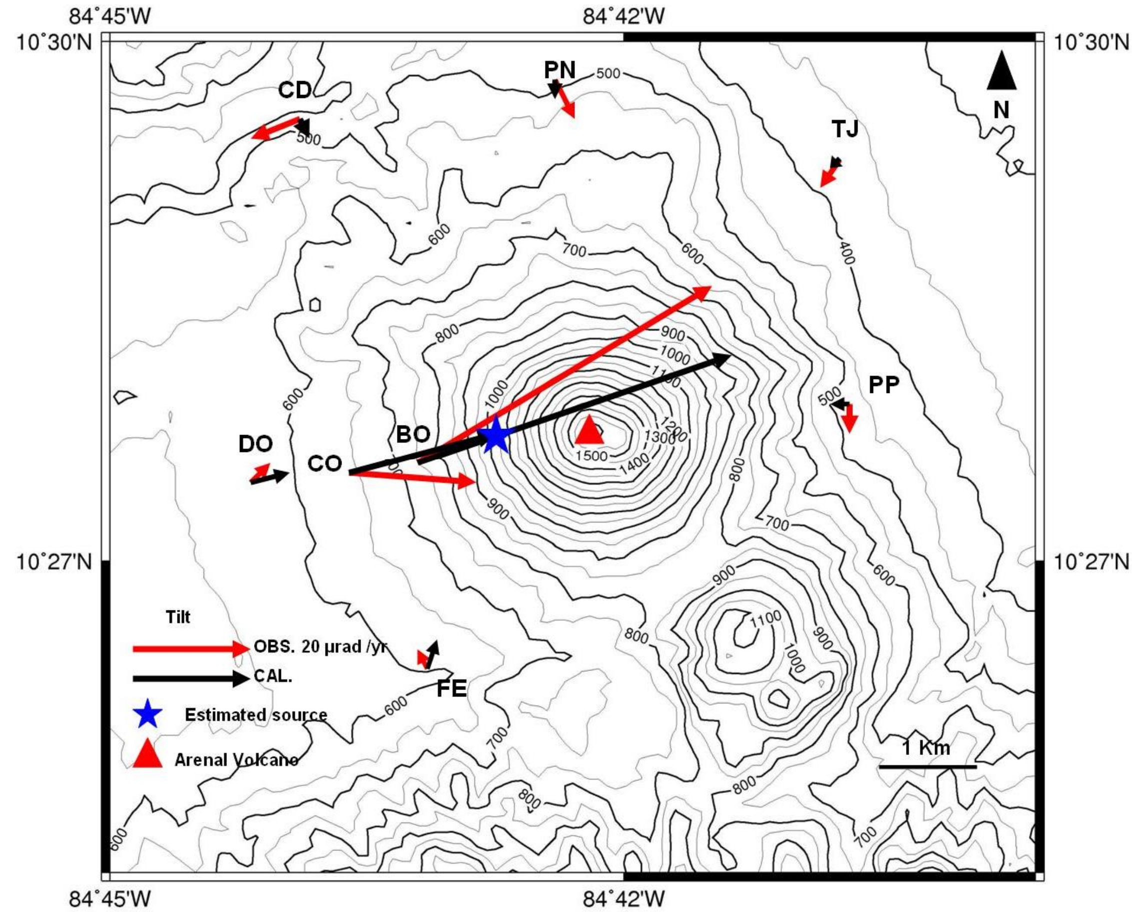

84°45'W
84°42'W
10°30'N
10°27'N
N
CD
PN
TJ
PP
DO
CO
BO
FE
Tilt
OBS. 20 μrad /yr
CAL.
Estimated source
Arenal Volcano
1 Km

Figure 6b

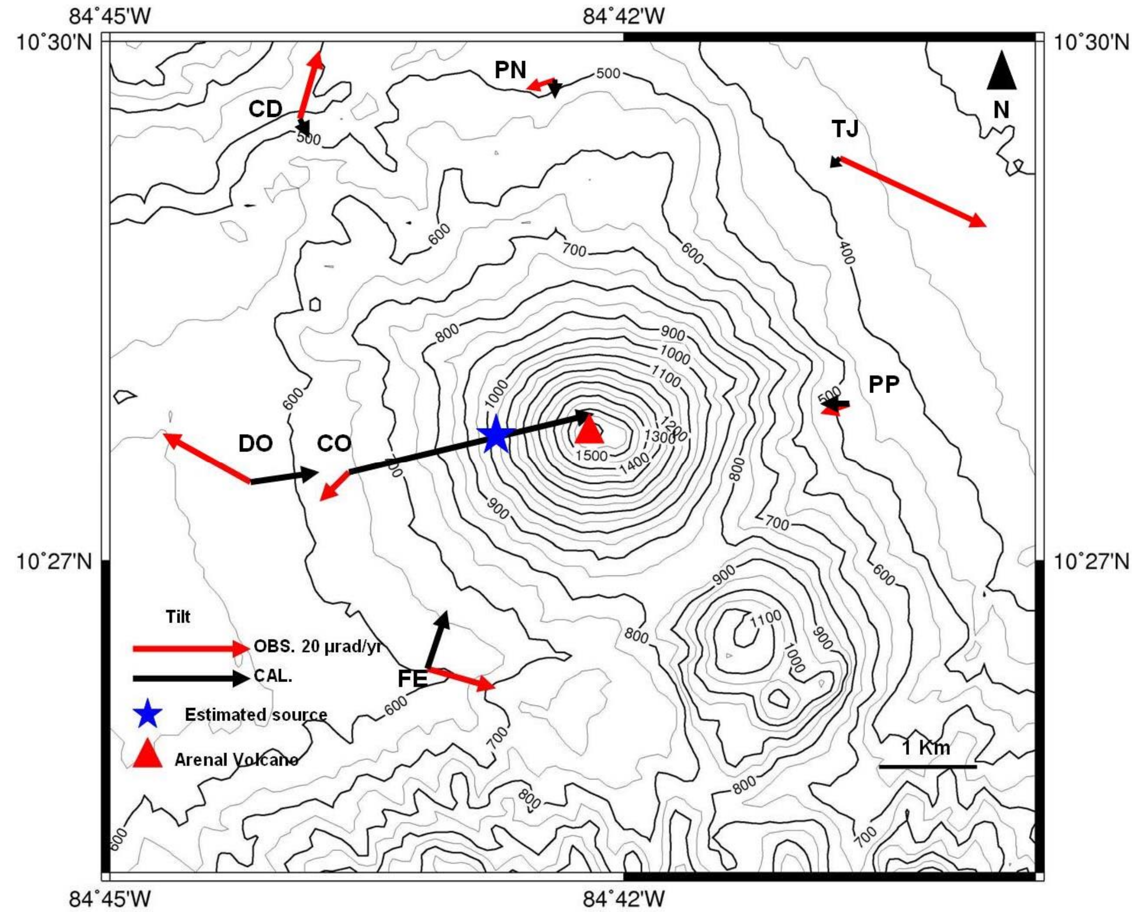
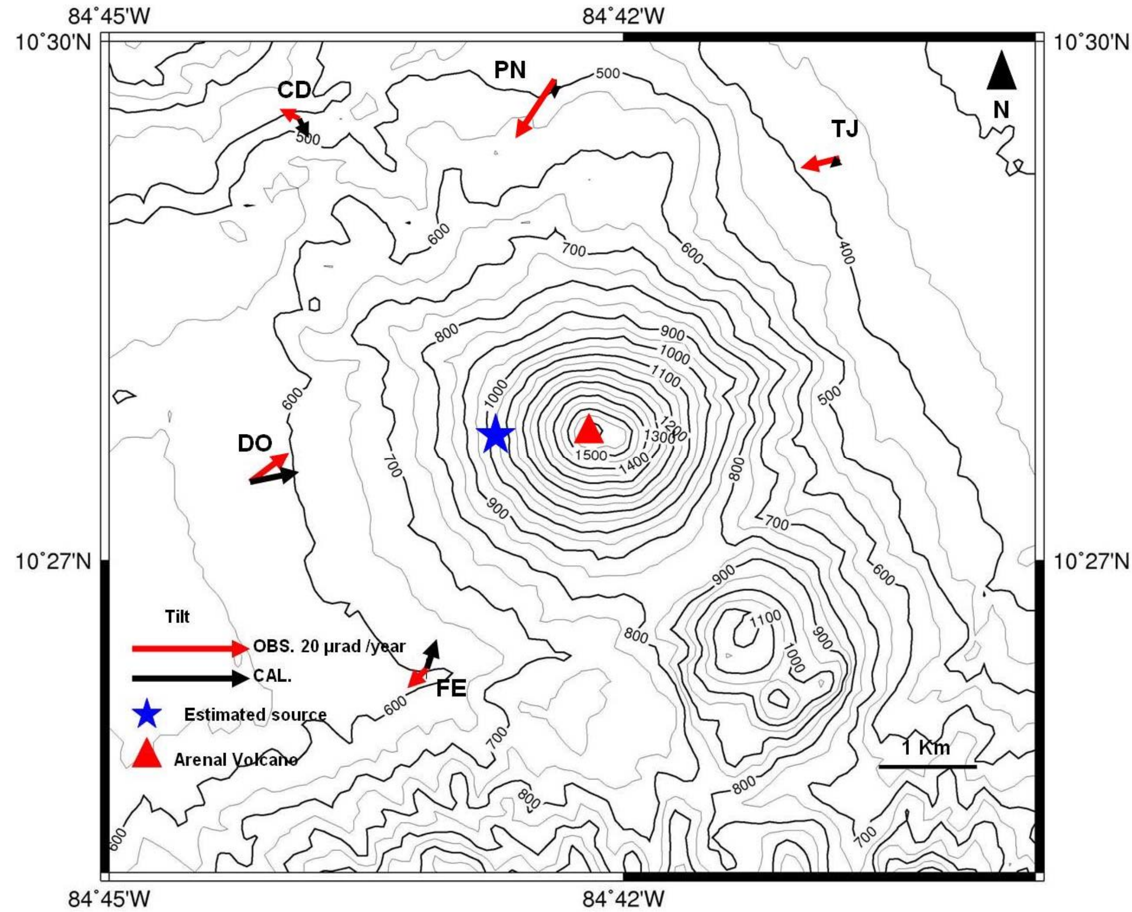

84°45'W
84°42'W
10°30'N
10°27'N
N
CD
PN
TJ
PP
DO
CO
FE
Tilt
OBS. 20 μrad/yr
CAL.
Estimated source
Arenal Volcano
1 Km

Figure 6c



84°45'W
84°42'W
10°30'N
10°27'N
PN
CD
TJ
N
DO
FE
Tilt
OBS. 20 μrad /year
CAL.
Estimated source
Arenal Volcano
1 Km

Figure 7

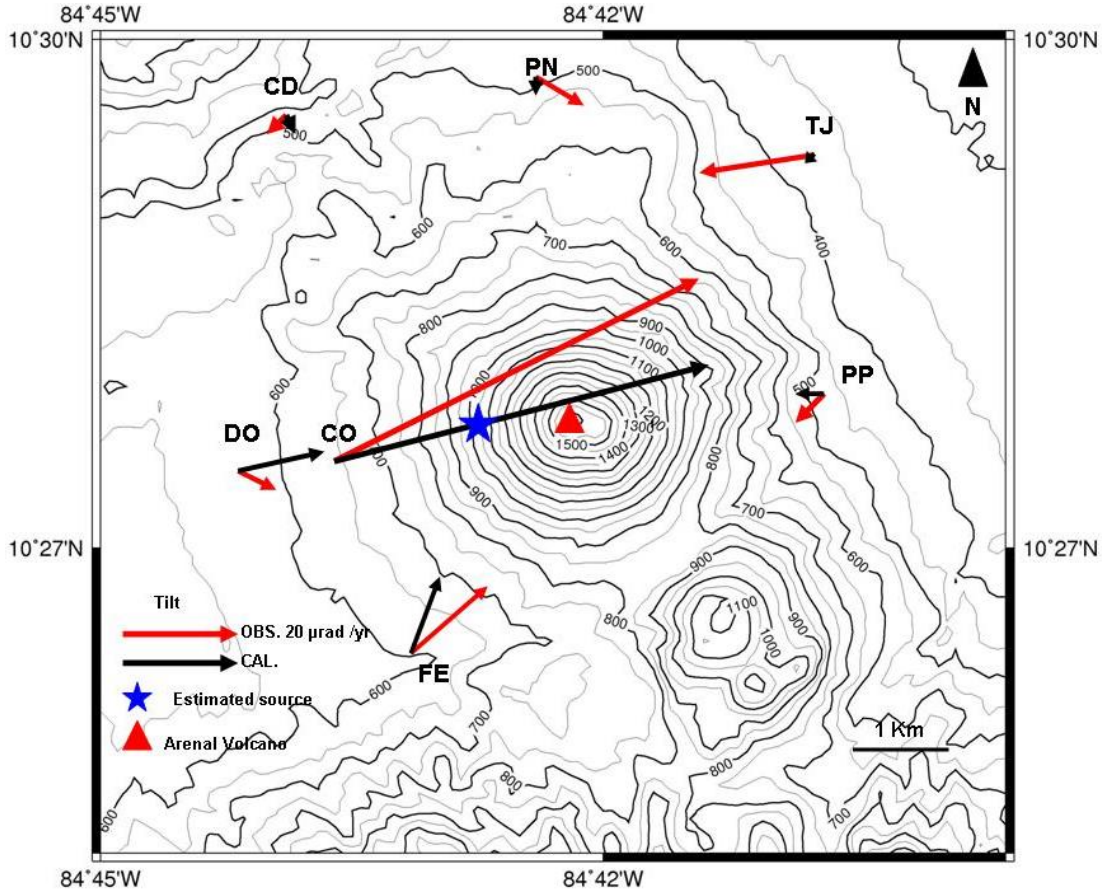

84°45'W
84°42'W
10°30'N
10°27'N
N
CD
PN
TJ
PP
DO
CO
FE
Tilt
OBS. 20 µrad /yr
CAL.
Estimated source
Arenal Volcano
1 Km

Figure 8a

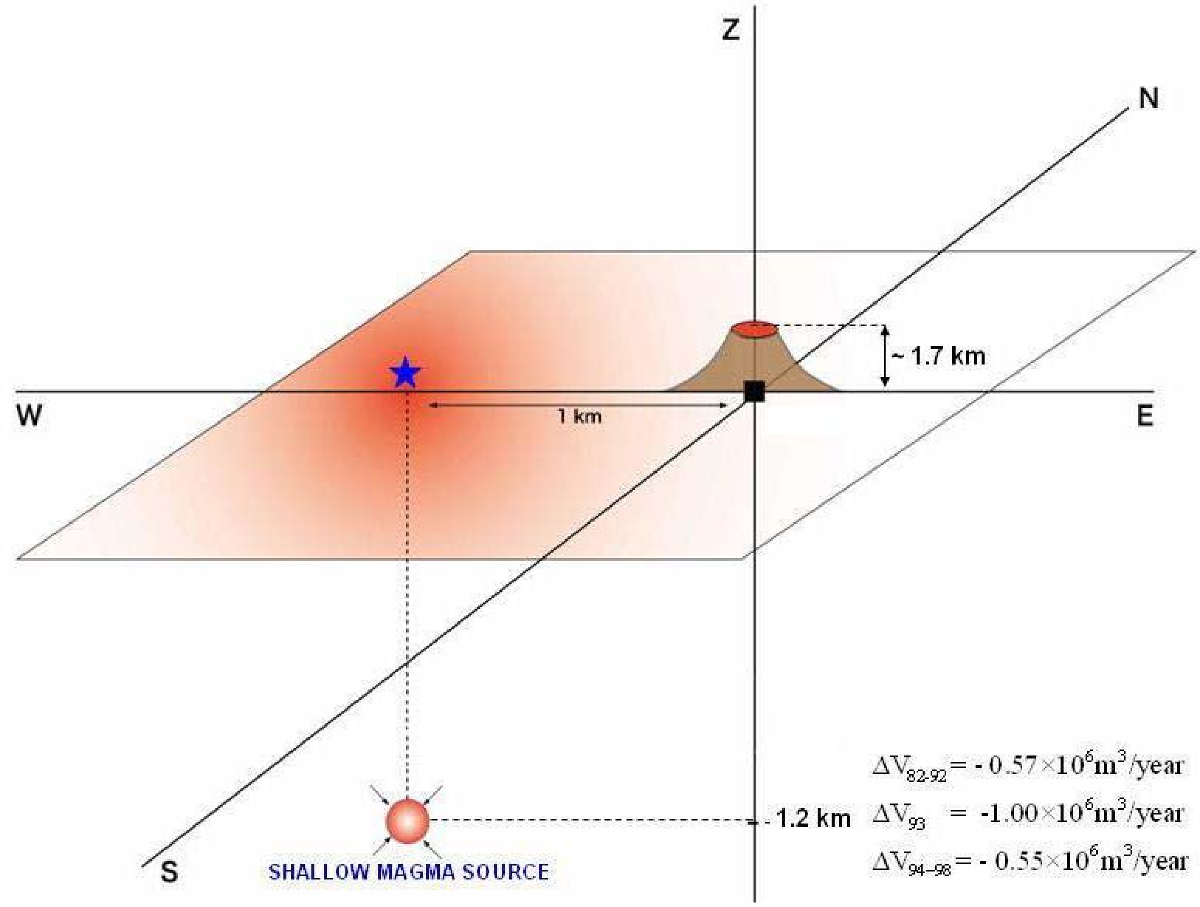
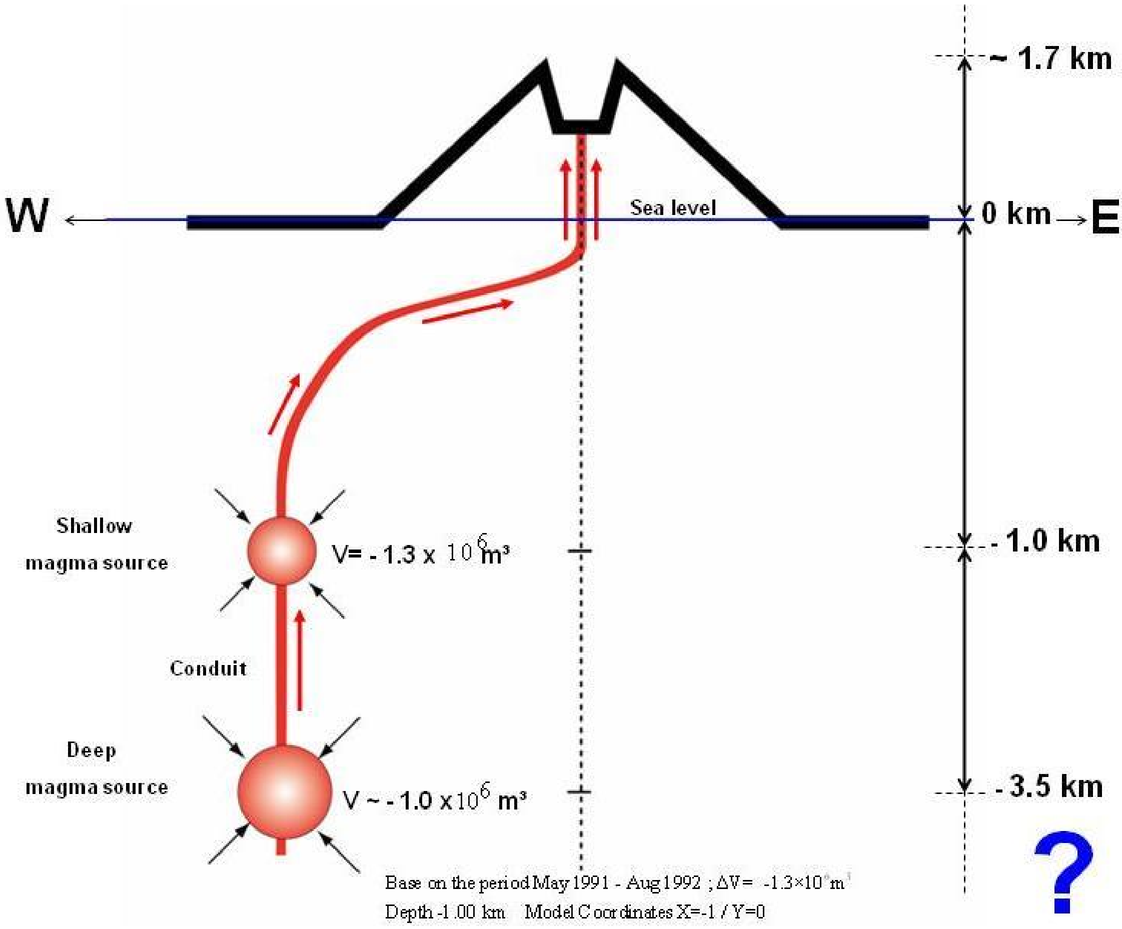

Z
N
~ 1.7 km
W
1 km
E
$\Delta V_{82\text{-}92}$ = - 0.57×10^{6}m^3/year
- 1.2 km
ΔV_{93} = -1.00×10^{6}m^3/year
S
SHALLOW MAGMA SOURCE
$\Delta V_{94\text{-}98}$ = - 0.55×10^{6}m^3/year

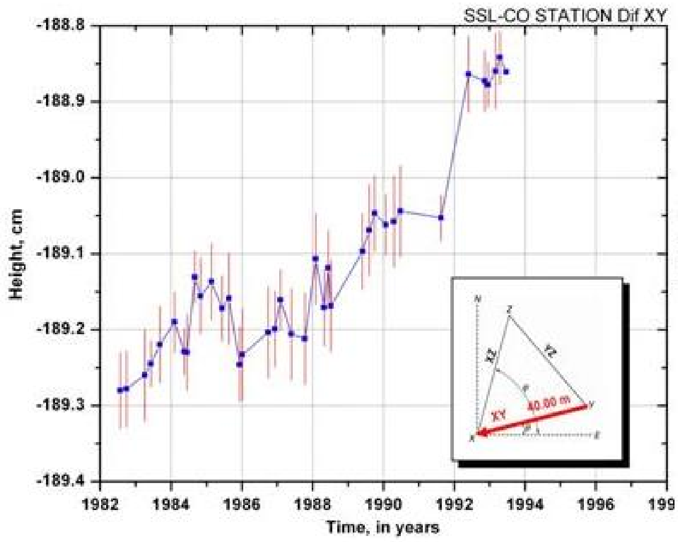
Figure 8b

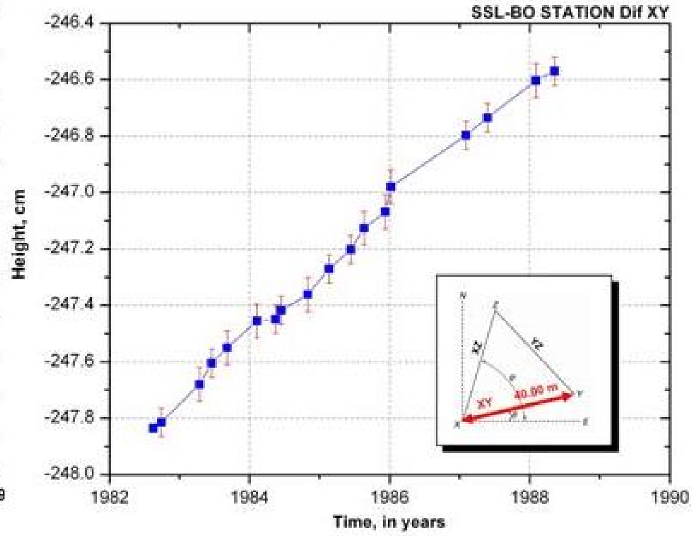


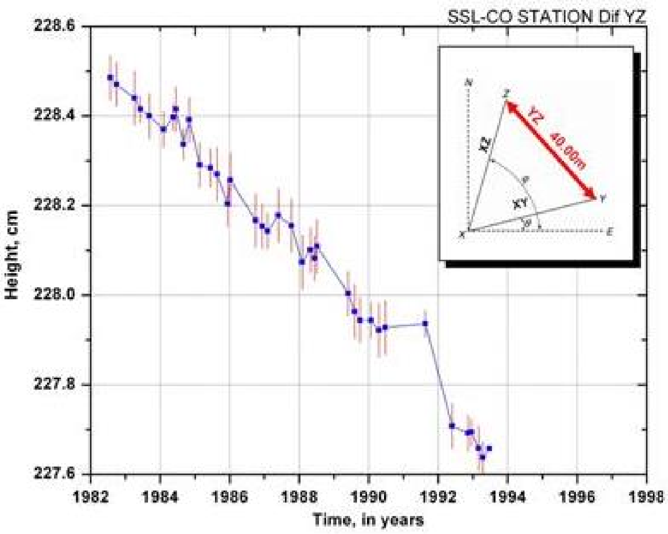
~ 1.7 km
W
Sea level
0 km
E
Shallow
magma source
V= - 1.3 x 10^6 m³
- 1.0 km
Conduit
Deep
magma source
V ~ - 1.0 x 10^6 m³
- 3.5 km
?
Base on the period May 1991 - Aug 1992 ; ΔV= -1.3×10 m
Depth -1.00 km Model Coordinates X=-1 / Y=0

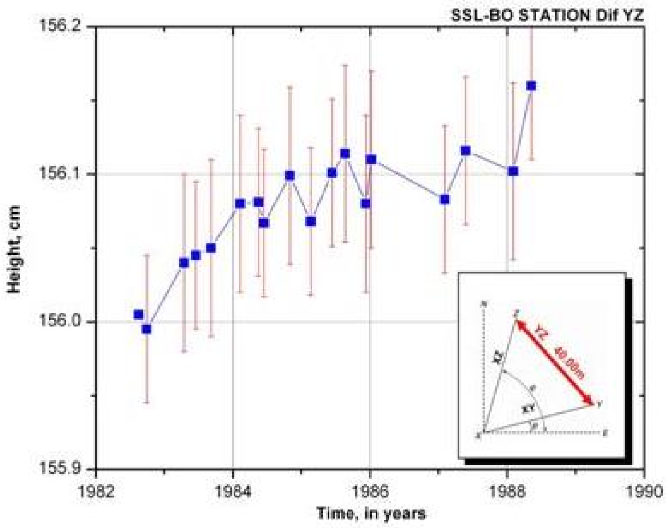
APPENDIX

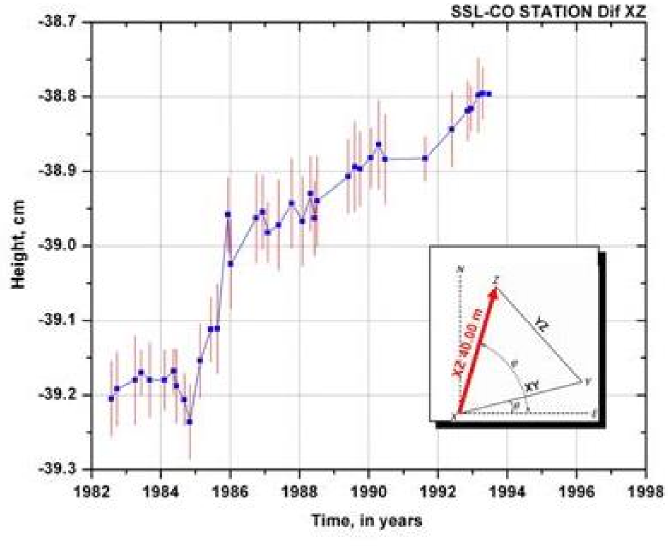
i

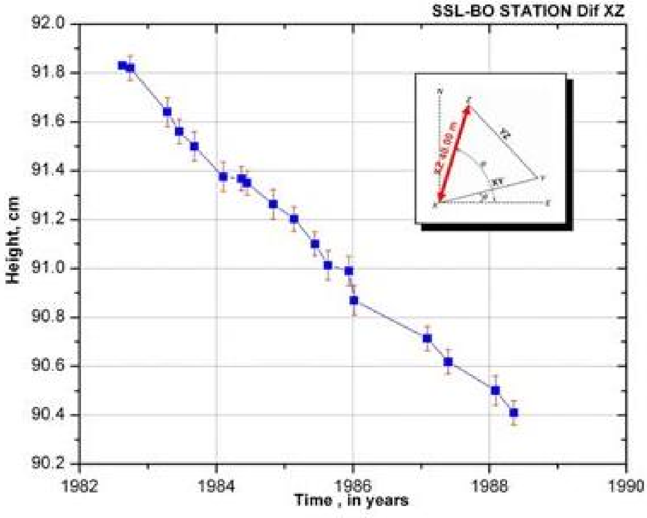

SSL-CO STATION Dif XY
Height, cm
Time, in years
XY
40.00 m
XZ
YZ

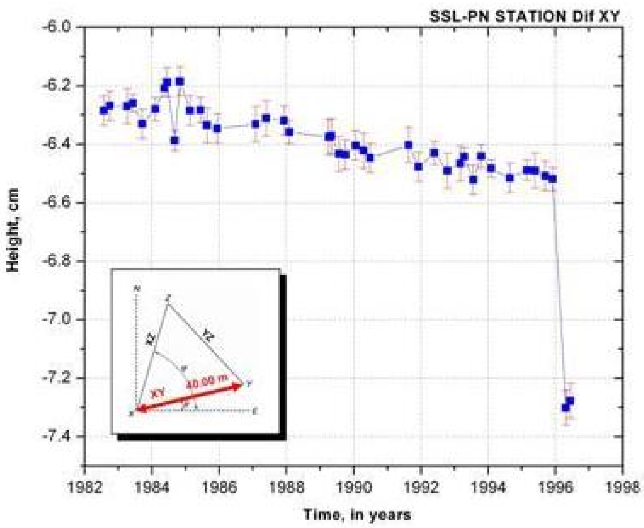

SSL-BO STATION Dif XY
Height, cm
Time, in years
XY
40.00 m
XZ
YZ

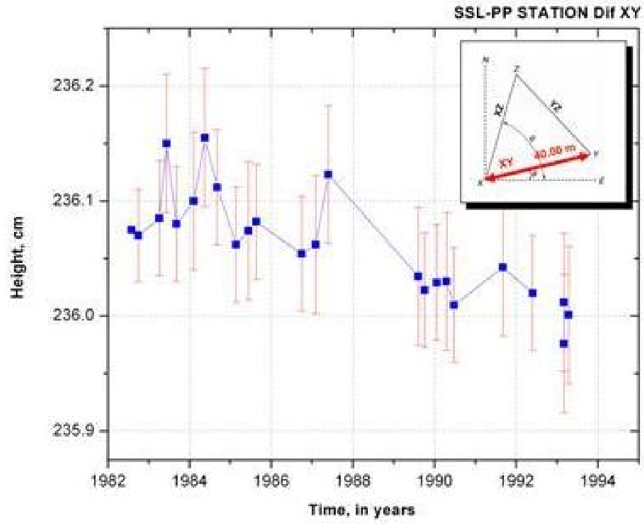

SSL-CO STATION Dif YZ
Height, cm
Time, in years
YZ
40.00m
XZ
XY

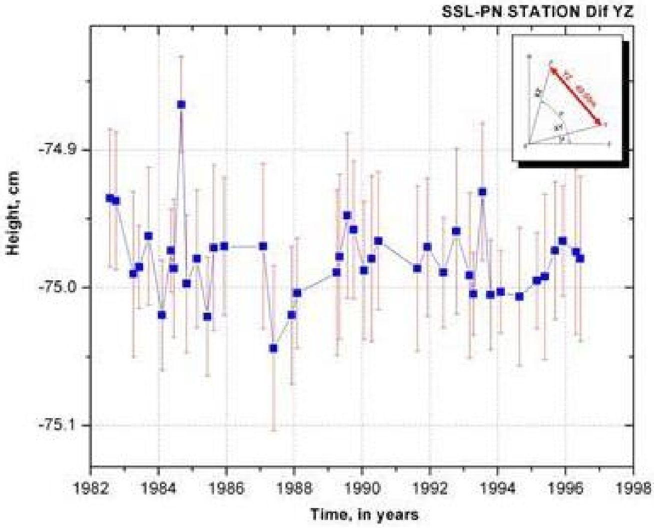

SSL-BO STATION Dif YZ
Height, cm
Time, in years
YZ
40.00m
XZ
XY

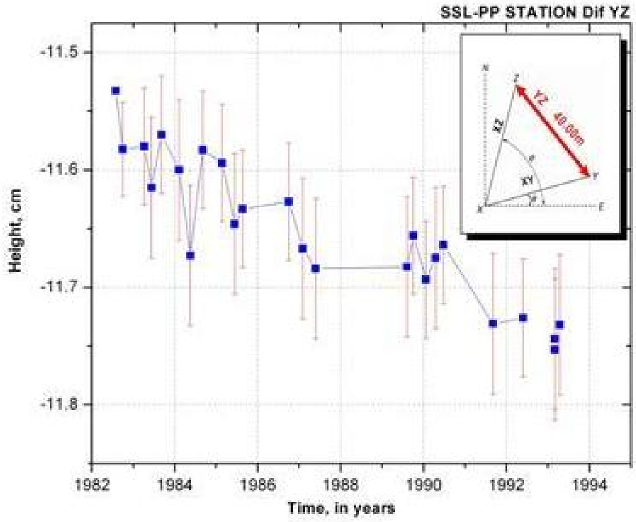

SSL-CO STATION Dif XZ
Height, cm
Time, in years
XZ 40.00 m
YZ
XY

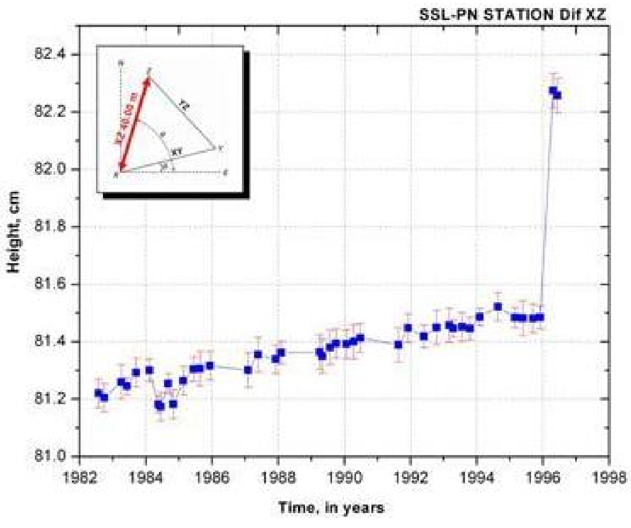

SSL-BO STATION Dif XZ
Height, cm
Time , in years
XZ 40.00 m
YZ
XY

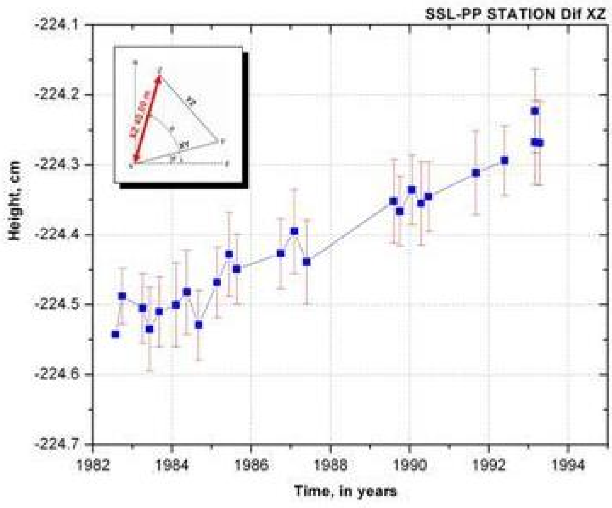

SSL-PN STATION Dif XY
Height, cm
Time, in years
XY 40.00 m
XZ
YZ

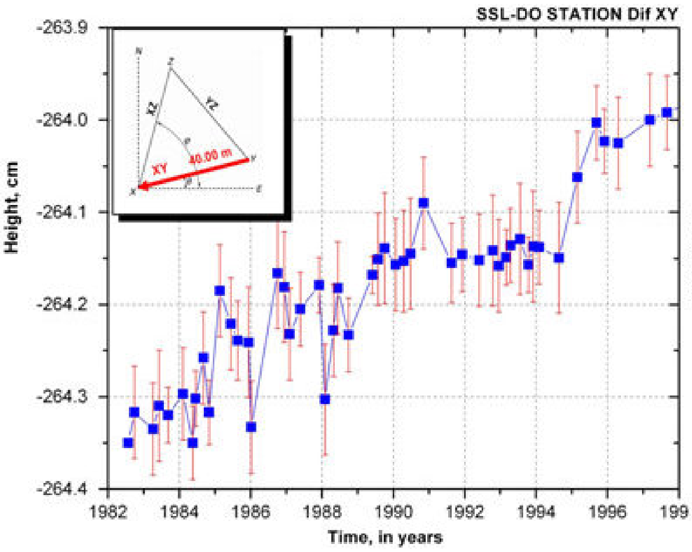

SSL-PP STATION Dif XY
Height, cm
Time, in years
XY 40.00 m
XZ
YZ

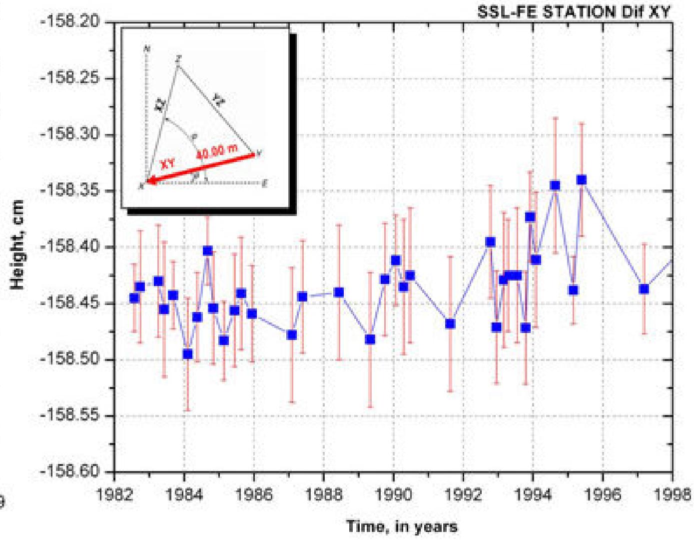

SSL-PN STATION Dif YZ
Height, cm
Time, in years
YZ 40.00m
XZ
XY

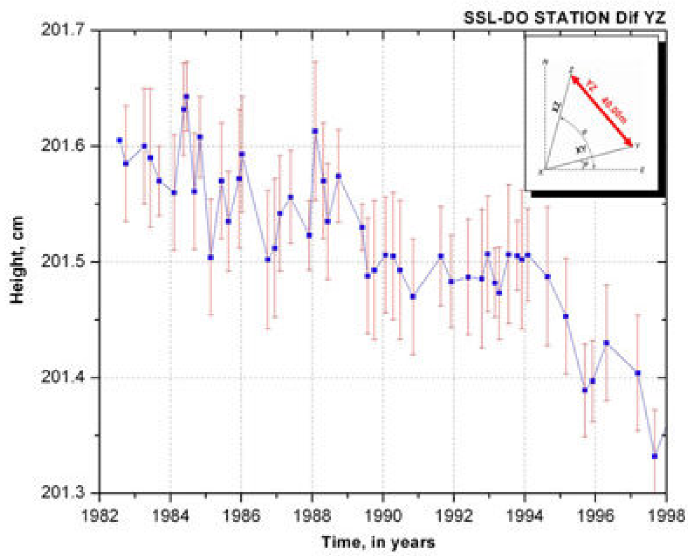

SSL-PP STATION Dif YZ
Height, cm
Time, in years
YZ 40.00m
XZ
XY

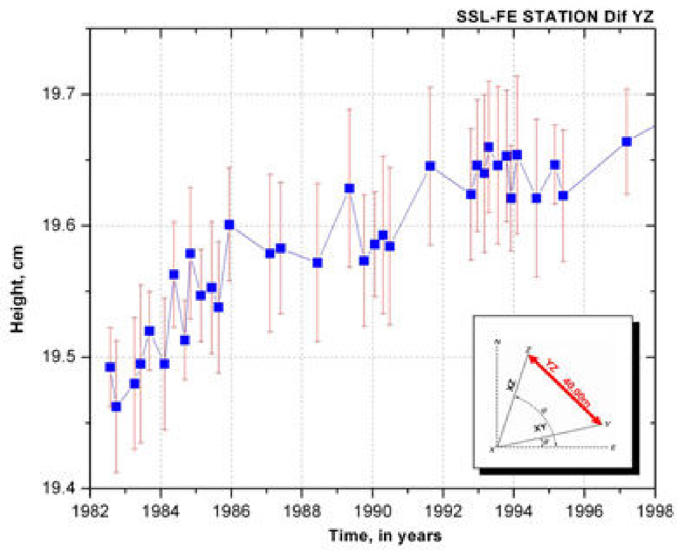

SSL-PN STATION Dif XZ
Height, cm
Time, in years
XZ 40.00 m
YZ
XY

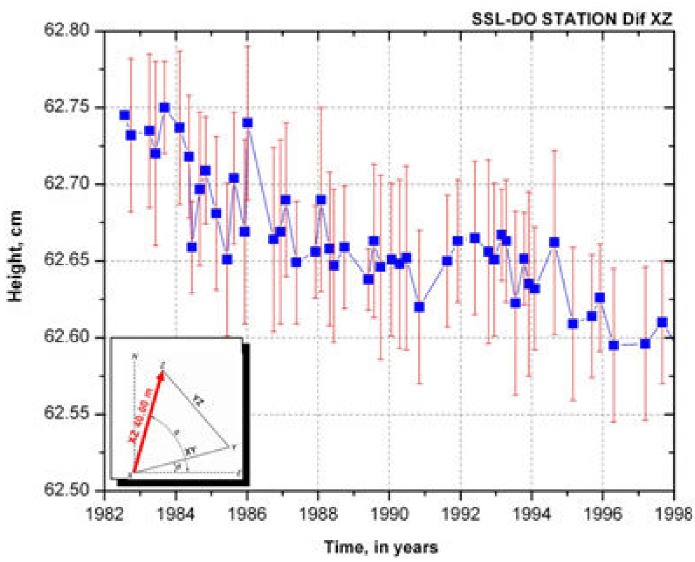

SSL-PP STATION Dif XZ
Height, cm
Time, in years
XZ 40.00 m
YZ
XY

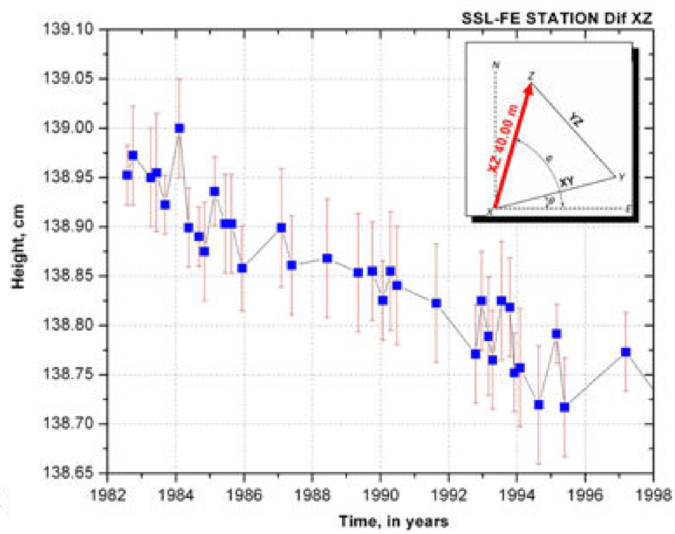

SSL-DO STATION Dif XY
Height, cm
Time, in years

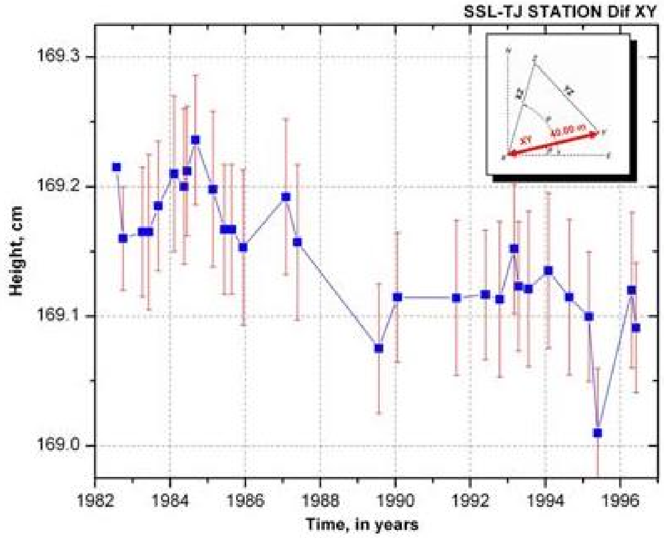

SSL-FE STATION Dif XY
Height, cm
Time, in years

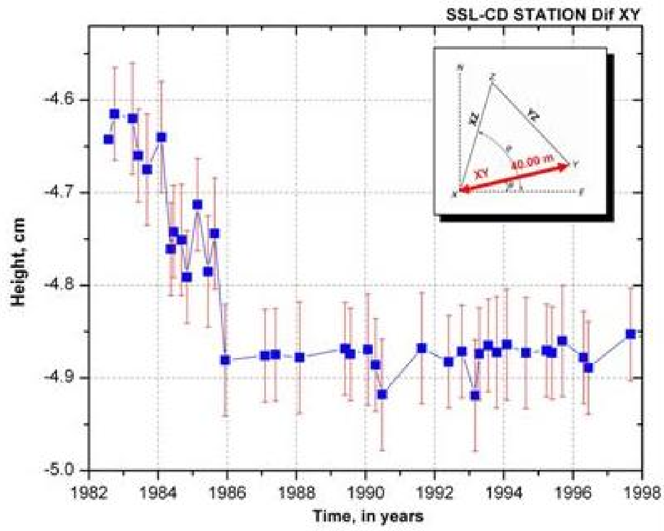

SSL-DO STATION Dif YZ
Height, cm
Time, in years

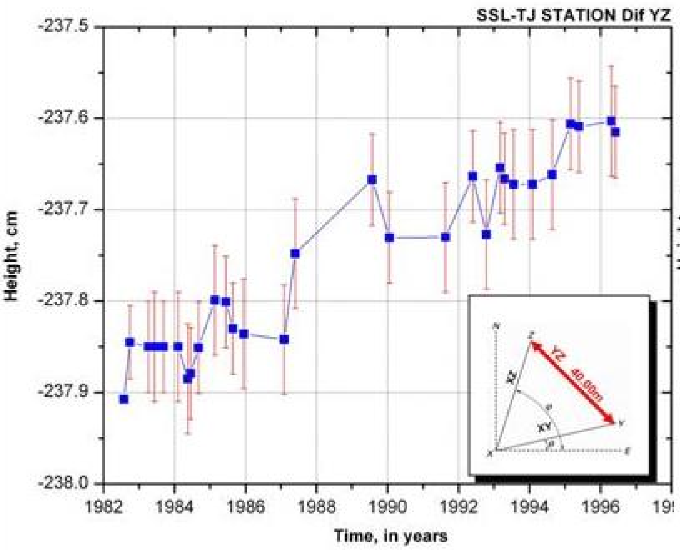

SSL-FE STATION Dif YZ
Height, cm
Time, in years

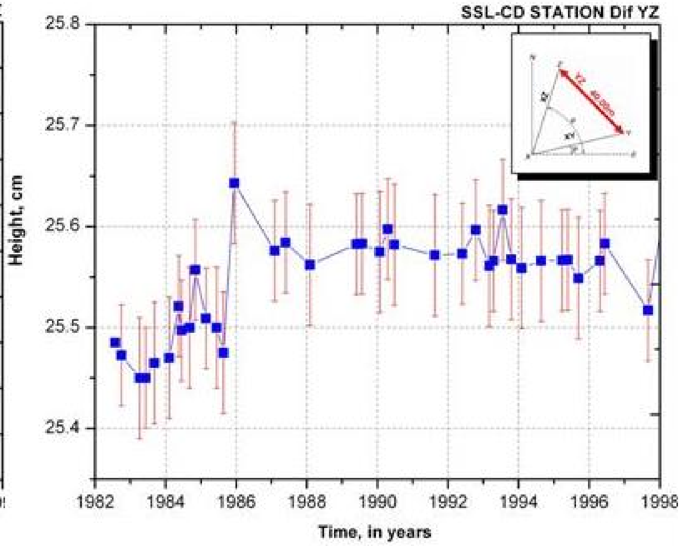

SSL-DO STATION Dif XZ
Height, cm
Time, in years

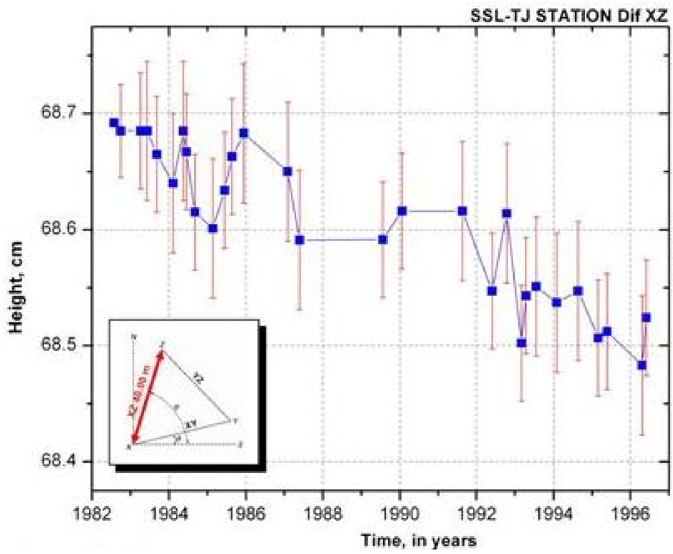

SSL-FE STATION Dif XZ
Height, cm
Time, in years

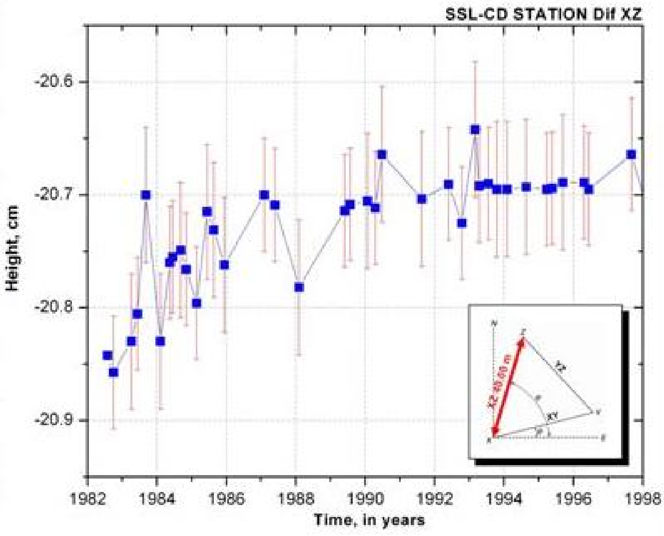

SSL-TJ STATION Dif XY
Height, cm
Time, in years
XY
40.00 m


SSL-CD STATION Dif XY
Height, cm
Time, in years
XY
40.00 m


SSL-TJ STATION Dif YZ
Height, cm
Time, in years
YZ
40.00m


SSL-CD STATION Dif YZ
Height, cm
Time, in years


SSL-TJ STATION Dif XZ
Height, cm
Time, in years
XZ 40.00 m


SSL-CD STATION Dif XZ
Height, cm
Time, in years
XZ 40.00 m

Arenal Volcano

Photo by Enrique Hernandez Rodriguez. taken from Arenal Observatory lodge, april-2007.

"Science is a sports, made by humans to enjoy the natural things"

Enrique Nagoya-Daigaku, Japan 2010.