Crustal deformation associated with the 1995-1998 unrest of Nisyros volcano (Greece), as observed by radar SAR interferometry

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ABSTRACT

Nisyros is a Quaternary volcanic centre located southeast of the Aegean volcanic arc. The volcano is characterized by periods of intense seismic activity and paucity in eruptive episodes, sometimes accompanied by hydrothermal explosions, the last one being in 1887. After a quiet period since 1888, the volcano passed to a long lasting unrest episode from 1995 to 1998, presenting an intense seismic activity but no eruptive event. In order to be able to study the evolution of the deformation for a longer period (1995 to 2000), SAR differential interferometry techniques were applied. The produced interferograms showed that during 1995 to 1997 a continuous uplift occurred reaching a maximum of 140mm. From mid 1998 to 2000 a change in the movement trend seems to have taken place turning into a slower surface deflation. The study also showed that the maximum crust deformation occurred at the northwest part of the island, where the majority of the earthquake epicentres was located. Assuming the crust to be an elastic homogenous medium, a point source and a rectangular dislocation source model were both applied. The corresponding modeled horizontal deformation vectors are presented and compared between each other. These observations allow to further comment the current elements controlling the behavior of the Nisyros volcanic system.

1. INTRODUCTION

Nisyros is a poorly known active Quaternary volcanic island in the southeast of the Aegean Volcanic arc (Figure 1). It is situated between 36°33′ and 36°35′ latitude and 27°7′ and 27°13′ longitude. It makes part of the more complex area of the Kos-Nisyros volcanic caldera (Sachpazi *et al.*, 2002).

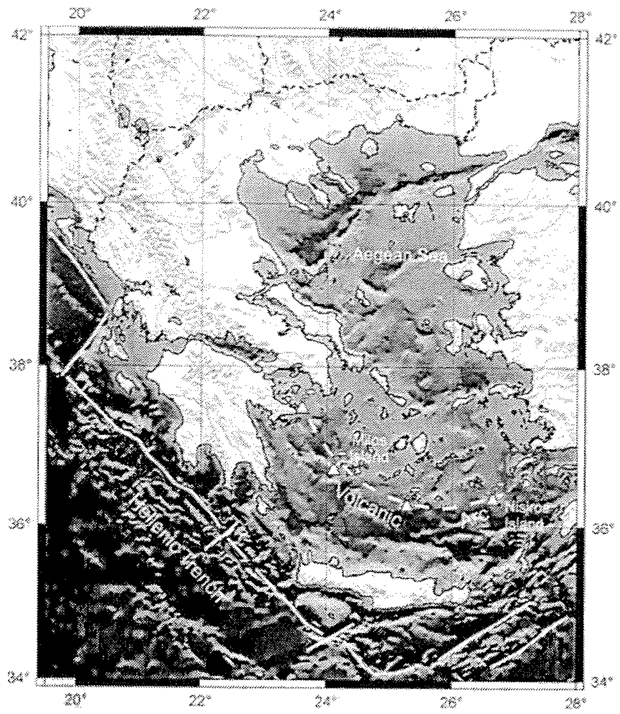

Figure 1: Location of Nisyros in the Hellenic Arc (from Sachpazi *et al.,* 2002).

The volcano is characterized by periods of intense seismic activity and paucity in eruptive episodes, sometimes accompanied by hydrothermal explosions, the last one being in 1887. After a quiet period of 107 years, the volcano passed to a long lasting unrest episode from 1995 to 1998, accompanied by an intense seismic activity but no eruptive events. There was a culmination of seismic events in August 1997 with two major earthquakes (Ms=5.3 and 5.2), located approximately 5-8 km northwest offshore of Nisyros island (Sachpazi *et al.,* 2002). The volcano gradually declined to regular background levels by the end of 1998.

Seismicity recorded by the permanent regional array of the Institute for Geodynamics of the National Observatory of Athens (GEIN/NOA) during the period 1980-2002 showed that the earthquake depths in the area were shallow and the magnitudes were varying between 4-5R (Sachpazi *et al.,* 2002). Earthquake activity becomes important in the region from mid 1996 till mid 1998 as shown in the diagram of cumulative events in time (figure 2). The curve is non-continuous with 3 breaks observed in june 1996, july 1997 and july 1999 inducing different curve slopes with different rates of seismic activity.

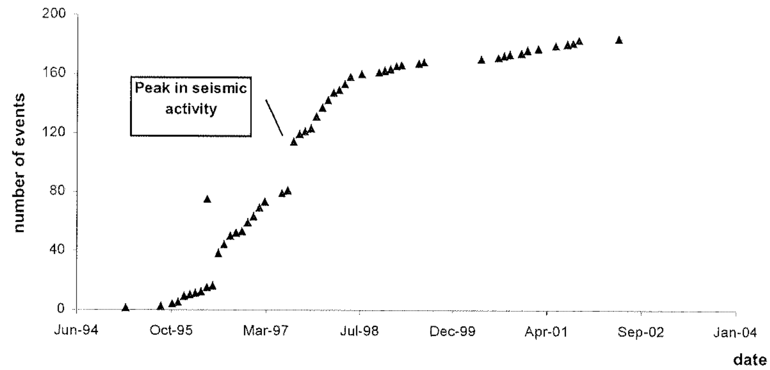

Figure 2. Cumulative number of seismic events from 1995 to 2002 recorded from the permanent regional array.

Moreover, GEIN/NOA conducted two seismic experiments in March and July 1997 with a local deployed seismographic network (Sachpazi *et al.*, 2002). The recorded seismicity patterns of the two seismic experiments vary both temporally and spatially. The first campaign demonstrates an intense seismic activity located in a rather restricted zone northwest of Nisyros. During the second experiment, the epicentres were more spread out towards the central and southern part of the island (Sachpazi *et al.*, 2002) (figure 3).

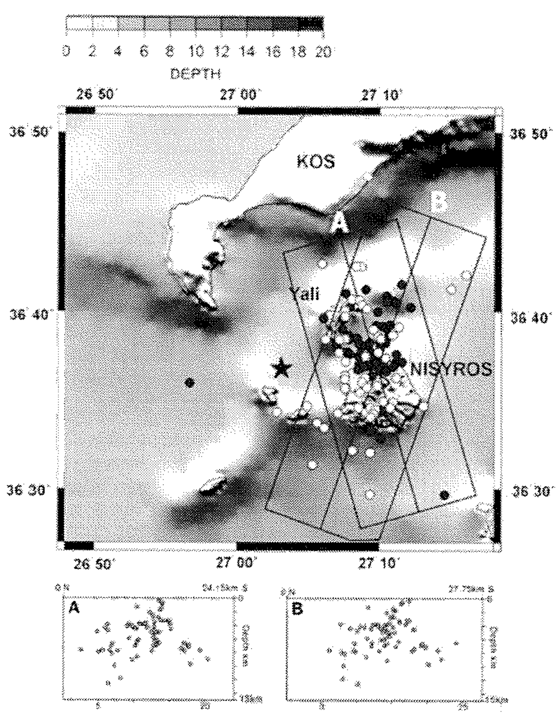

Figure 3: Map of the best-located earthquakes during the two experiments: black dots correspond to March 1997 and white dots to July 1997 respectively. The black star indicates the location of the Ml=5.3 earthquake issued from the regional network occurred in 28 August 1997. Below are given the projections at depth of the best-located events for both periods (Sachpazi *et al.*, 2002).

In September 1997, December 1997 and May 1998 the Geology Department of the University of Athens conducted a series of GPS measurements. Data showed a vertical uplift and a horizontal extension of the island reaching the 45 ±(5-10) mm at some stations (Lagios, 2000). These observations refer to few specific points on the island. However, they have provided the general surface movement trend and deformation pattern characterising this period (1997).

In the case of Nisyros, SAR interferometry was applied as a complement to afore mentioned in-situ observations.

2. InSAR DATA ANALYSIS

SAR interferometry techniques (InSAR) have the potential to measure, monitor and map active grounds deformations issued from geophysical phenomena such as active tectonic or volcanic activity (Amelung *et al.*, 2000; Massonnet *et alt.*, 1998; Massonnet *et al.*, 1995; Peltzer *et alt.*, 1995). This is possible even within geographically restricted areas where inadequate or incomplete ground monitoring data sets cannot provide enough evidence of the occurring geophysical phenomena, such as in the case of Nisyros.

In the present study, nine ERS2 SAR images in raw format were used, six in the ascending and three in the descending pass of the satellite sensor spanning the period June 1995 - September 2000. The data were processed with the DIAPASON (CNES) software using precise orbit data provided by the Delft Institute (NL).

The selection of interferometric pairs was based on their sensitivity to the topography expressed by the altitude of ambiguity (*ha*), which is the change in elevation resulting in the production of one topographic fringe (28mm). To avoid topographic effects, topographic fringe elimination was achieved by subtracting from the interferograms a synthetic fringe pattern produced by the DEM by employing the DEM-elimination (DEME) method introduced by Massonnet *et alt.* (1995). The DEM was produced by digitisation of 1/5000-scale topographic maps and spot height data achieving thus a mean height accuracy of ±10m. Accuracy was additionally tested by using a set of independent control points of known elevation.

The high DEM quality and precise orbital data limited the possibility of deriving interferograms affected by orbital and topographic fringes. However, the validity of the observed fringes was based on systematic checks of the number and shape of the fringes between independent, ascending and/or descending, interferometric image pairs (Table 1).

Date Image 1	Date Image 2	*ha* (m)	Pass	Number of fringes	Deformation in slant range (mm)
June 1995	May 1996	97	A	+3	+84
May 1996	June 1997	184	A	+2	+56
June 1995	June 1997	64	A	+5	+140
June 1995	June 1999	42	A	+3.5	+98
Sept. 1995	Oct. 1999	177	D	+3	+84
May 1996	June 1999	73	A	+3	+84
Aug. 1996	Oct. 1999	115	D	+2.5	+70
June 1997	June 1999	120	A	-1.5	-42
May 1998	Sept. 2000	148	A	-2.5	-70
Sept. 1995	Aug. 1996	70	D	+2	+56

Table 1: ERS2 image combinations used for interferometric processing. Altitudes of ambiguity are expressed in absolute values. Passes correspond to A=ascending pass / D=descending pass of the seatellite sensor. One fringe corresponds to 28mm of ground deformation in slant range direction. + / - indicate inflation / deflation respectively.

InSAR showed the existence of a clear deformation signal during the whole period with a concentric pattern, centred at the northwest and covering the whole Nisyros island, though extending offshore to the northwest.

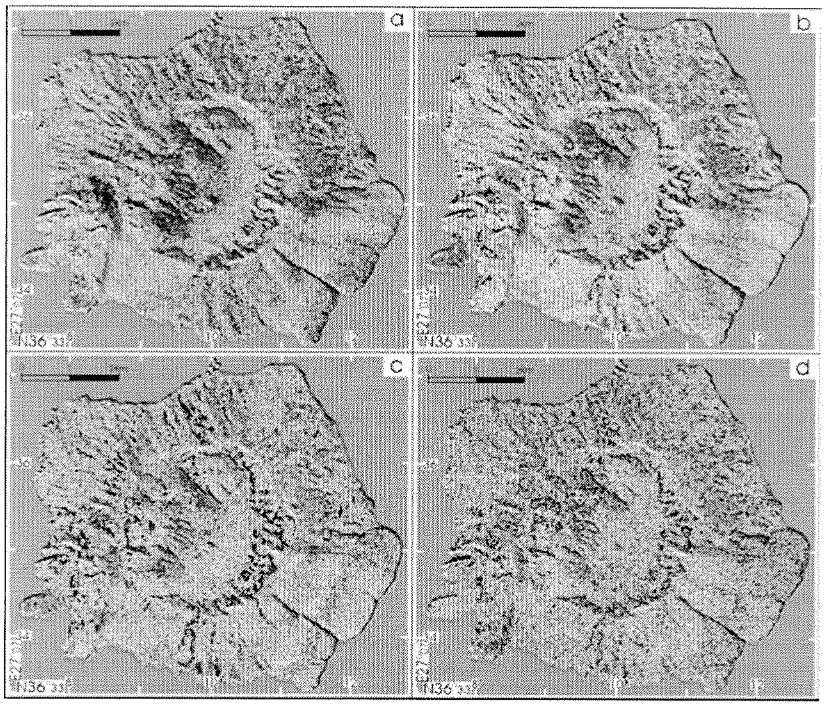

Figure 4: Differential interferograms of Nisyros volcano spanning (a) June 1995-May 1996, (b) May 1996 – June 1997; (c) June 1995-June1997; (d) June 1997 – June 1999.

During June 1995 – May 1996 (figure 4a), a ground uplift of 84mm in the slant range direction is observed (3 fringes) and from May 1996 to June 1997 (figure 4b), a further uplift movement of 56mm. As expected, the June 1995-June 1997 interferogram reveals five fringes that is an uplift of 140mm (figure 4c). However, for the period June 1995–June 1999, the observed smaller surface uplift of 98mm (3.5 fringes) indicates a deflation movement that started after June 1997. This was confirmed by the about 1.5 negative fringes, indicating a surface movement in the opposite direction (42mm), observed in the independent interferogram of June 1997 - June 1999 (figure 4d). Moreover, the independent interferogram May 1998 - September 2000 shows 2.5 negative fringes (70mm), and confirms the deflation during that period.
Deformation during June 1997 – May 1998 was impossible to calculate directly due to inadequate, in terms of altitude of ambiguity, interferometric pairs.

The descending pass interferograms are less coherent, however they show a similar concentric pattern to the ascending ones. They are also compatible to the ascending interferograms concerning the direction of the surface deformation.

The deformation trend for Nisyros during 1995-2000 was calculated in the eight time spans between the nine radar images. A least square solution was obtained for a system using the eight deformation rates as unknowns and the ten interferometric observations as known ones. A constraint was imposed that the difference between the estimated deformation rates and the interferometric observations should not exceed one fringe. Figure 3 illustrates the evolution of the surface deformation. Between 1995 and early 1998, a continuous inflation is evident. From May 1998 up to September 2000 a deflation seems to have taken place.

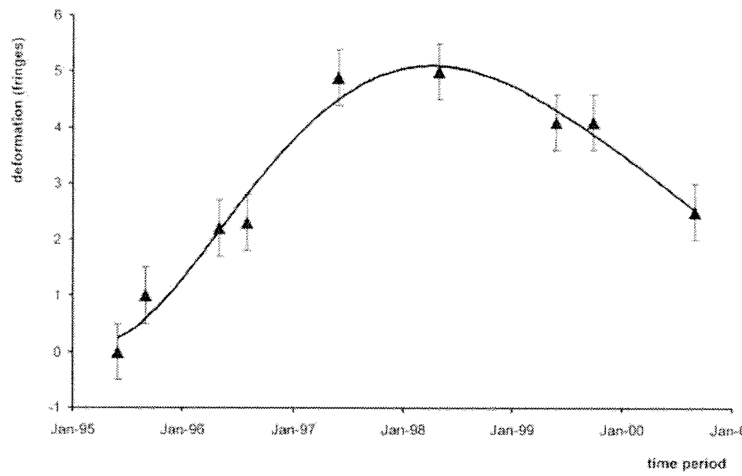

Figure 5. Deformation at Nisyros volcano from 1995 to 2000, inferred from InSAR analysis. Each fringe corresponds to 28mm of deformation in slant range direction.

The existing GPS measurements (Lagios, 2000) are consistent to the above observations. Lagios (2000) infers that uplift occurred from June 1997 till September 1997 though from September 1997 till May 1998 there was a decline in the deformation rate. Consequently, the change from inflation to deflation most likely took place at mid 1998.

3. MODELING

An approximate interpretation of the deformation field observed by InSAR was intended by applying two different models corresponding to different possible mechanisms: a point-source deformation (Mogi model) and a rectangular dislocation in a half-space elastic medium (Okada model).

3.a. Point-source deformation

A simple model of point source inflation/deflation in an elastic medium was used, which was first introduced in volcanology by Mogi (1958). It does not take into account the possible complexity of the volcano's tectonic structure, in particular shallow discontinuities, faults and variable ground geology. However, it provides a useful first quantification of the deformation mechanism, especially depth and volume change involved in the process.

The fact that all interferograms reveal a rather constant in shape and location deformation field suggests that the depth of the deformation source remained stationary during 1995-2000. For this reason, the clearest interferogram (June 1995 - June 1997) was used as input to solve for the four model parameters: the horizontal coordinates and depth of the inflating centre and the maximum amplitude of the deformation at the surface (Figure 6a). The best-fit solution was found for a point source with characteristics as presented in Table 2.

E (km) (UTM/Zone 35/ED50)	N (km) (UTM/Zone 35/ED50)	Depth (km)	Max. amplitude of deformation at surface (m)	Volume change at depth (m^3)
513.4	4050.6	5 ± 0.5	0.14 ± 0.02	$26 \pm 4 \times 10^6$

Table 2: Best-fit point source parameters.

Considering the model's characteristics and the fact that at mid 1998 inflation reversed to subsidence rather quickly, the deformation is most probably not directly linked to a usual mechanical effect of the injection of a magma body at depth. Although the injection of such a volume of new material could explain the inflation period 1995-1998, the deflation observed between 1998 and 2000 would imply the removal of the volume previously intruded.

Therefore the process could rather correspond to a thermo-mechanical effect of magma intrusion at depth. The heating/cooling mechanisms and variation of the aquifers within the volcano could be the cause of the rather quick reversible ground deformation with variable rates and magnitudes inferred by InSAR. Sachpazi *et al.* (2002) consider the less concentrated pattern of earthquake distribution as most likely suggesting the transport of magmatic fluids from the north-west coast, where the maximum ground deformation occurs, towards the central south where very shallow aquifers heated by steam are located. The magmatic fluids could form a shallow magmatic intrusion, and the seismic migration of hypocenters may indicate shallow magma transport. This activation of the hydrothermal feeding faults to the central south part of Nisyros is supported by field observations (Sachpazi *et al.*, 2002). The authors reported the ascent of steam from the very shallow aquifers and the intensification of the fumarolic activity, peaking up one day after the occurrence of the two strongest earthquakes. Sachpazi et al., 2002 assume that this intrusion may have occurred as a poro-elastic response of the chamber most probably during the period 1995-1996 when the maximum deformation of 84 mm/y took place.

3.b. Rectangular dislocation

Apart from the point source model, we have also solved for a dike intrusion using an inversion model assuming a single rectangular dislocation surface in elastic half-space (Okada, 1985). The period June 1995 - June 1997 was also used as main input. The inverse algorithm is developed by Briole *et al.* (1986) using the least squares approach proposed by Tarantola *et al.* (1982). The resulting best fit (Figure 6b) is a quasi-rectangular dike (2km long and 2.2 height) striking to the SW (Table 3) with an opening of 4m. The volume change for the period 1995-1997 is 17.6 x 106 m3. The centre of the upper edge of the dike is situated within the active caldera of the volcano.

E (km) (UTM/Zone 35/ED50)	N (km) (UTM/Zone 35/ED50)	Depth (km)	Azimuth	Dip	Length (km)	Width (km)	Opening (mm)	Volume (m^3)
514.8	4049.1	6.4	210	30°	2	2.2	4000	17.6×10^6

Table 3: Parameters calculated for the best-fit dike. E and N coordinates correspond the upper edge centre of the fault. Azimuth corresponds to strike angle considering north=0. Depth corresponds to the depth of the upper edge of the fault.

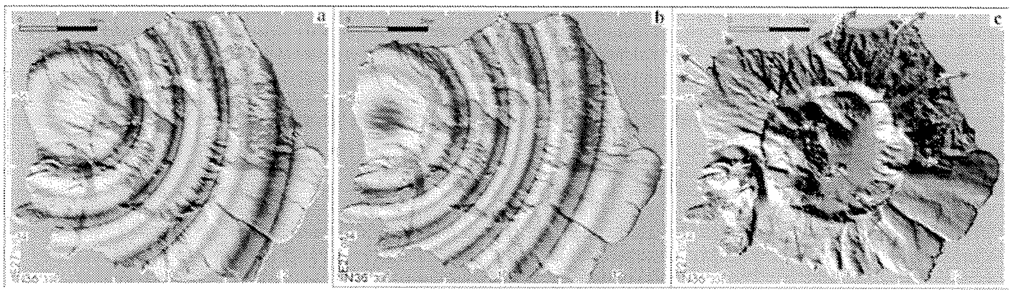

Figure 6. Modelled interferogram for the period June 1995-June 1997. (a) Simulated Mogi point-source deformation (described in table 2); (b) simulated deformation from a dike source, according to Okada model (described in table 3); (c) simulated deformation vectors resulted from modelling. Red arrows correspond to point-source deformation; yellow arrows correspond to dike deformation.

In autumn 1997, Makris and Chonia (2000) conducted a series of active and seismic studies in Nisyros and concluded that the recorded seismic activity is partly controlled by tectonic processes and partly by volcanic intrusions and hydrothermalism. A dike source could reflect such a combination of tectonic and volcanic activity. The best-fit dike is below the caldera where also Makris and Chonia (2000) propose magma intrusion at very shallow depth explaining the very high temperature of 300C observed in the aquifers at 1.5km depth.

The observed seismic events recorded from the regional array from 1995 till mid 1998 (Figure 1) could indeed reflect a magma intrusion through dike opening and filling inducing inflation of the surface as observed by InSAR. As inflation changes to deflation rather quickly at mid 1998 till 2000, this would suggest that magma cooling in the dike occurs rather quickly. The cooling mechanism could correspond to the rapid heating of very shallow aquifers expressed by steam and intense hydrothermal activity observed during field campaigns (Sachpazi *et al.*, 2002).

Moreover, the very shallow dip (30°) of the dike would imply a rotation of the local extensional axis from the horizontal as is in the case of sub-vertical dikes. Jonsson *et al.*, (1999) refer to a similar case where a small dip dike of 34° was simulated for a flunk eruption at Fernandina volcano, implying a rotation of $\sigma 3$ in the horizontal plane about the vertical axis and in the horizontal axis as well. Indeed, in the case of Nisyros, an oblique direction of the maximum compressive axis was calculated from seismic events away from the maximum deformation area by Sachpazi *et al.* (2002). Such rotation would probably suggest the existence of a more complex tectonic regime in the area as suggested by the Okada model.

Simulated surface deformation vectors for both deformation sources were calculated (Figure 6c). In all points, both models render vectors, which are similar in general. Differences are observed in the magnitude of the deformation calculated for each point. In the case of the point source a rather uniform circular surface deformation is given around the source, as expected. In the case of the dike, the induced surface deformation differs between the northwest and the southeast part of the island. It seems to be stronger at the north-northwest edge of the island than in the rest of the volcano.

4. CONCLUSION

Interferometric analysis has demonstrated significant ground deformations across the whole Nisyros island trending to the northwest during the period 1995-2000. Inflation lasted till mid 1998 and was then followed by deflation up to 2000. GPS measurements (Lagios, 2000) agree with the InSAR observations regarding the location of the deformation centre and the trend of inflation/deflation.
Modelling showed two possible best-fit deformation sources, a point source and a shallow-dipping dike. Both solutions are suitable and provide good fit to the observed surface deformation pattern centered to the northwest. Although they provide enough

indicative knowledge about the behavior controlling the volcanic activity there is still need of further investigations to determine which is the exact mechanism responsible of the inflation/deflation sequence and take the appropriate decisions on the volcanic and/or seismic hazard of the area.

In any case, the above results suggest that the present activity is restricted at the northwest part of the Nisyros island, which is a much smaller area than the large ancient volcanic caldera extending from Nisyros to the southern coast of Kos proposed by several volcanologists, (e.g. Keller *et al.*, 1990). This is the same area that Stiros (2000) describes as a tectonic block having suffered the maximum uplift in the geological history of the island.

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