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# Ground deformation at Nisyros volcano (Greece) detected by ERS-2 SAR differential interferometry

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**Abstract.** Nisyros is a volcanic island in the south-east of the Aegean volcanic arc. Over the period 1995–1998, the volcano exhibited intense seismic activity without eruption. Production and analysis of satellite radar interferograms, spanning period 1995–2000, showed continuous inflation from 1995 until May 1998 and deflation from mid-1998 to 2000, with the same deformation centre situated at the north-west part of the volcano. Assuming the crust to be an elastic homogenous medium, point source modelling of the deformation field indicates the source of deformation to be located at five kilometres depth beneath the north-west edge of the island. Recorded seismicity trend patterns suggest magma intrusion at depth as the source of the inflation sequence. The recorded migration of hypocentres indicates a probable fluid transport affecting the shallow aquifers resulting in the volcano's deflation.

## 1. Introduction

Nisyros is a Quaternary active volcanic island in the south-east of the Aegean volcanic arc. The most recent long-lasting episode of seismic unrest without eruption started in 1995, peaked in August 1997 and gradually declined to regular background levels by the end of 1998.

In September 1997, December 1997 and May 1998 the Geology Department of the University of Athens conducted a series of Global Positioning System (GPS) measurements. For the period September 1997 to May 1998, the GPS data showed a vertical uplift and horizontal extension of the island reaching 45 ± (5–10) mm at some stations (Lagios 2000). Although these observations referred to a few specific points

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on the island, they provided the general movement trend and deformation pattern for the period around the main seismic activity (1997). However, due to the lack of surface deformation data for the periods before June 1997 and after May 1998, radar interferometry was applied as a complement to the existing *in situ* observations.

## 2. InSAR data analysis and results

Differential radar interferometry has proven to be extremely useful for mapping active ground deformations (Massonnet *et al.* 1995, Massonnet and Feigl 1998, Amelung *et al.* 2000).

In the present study, nine ERS-2 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 to September 2000. The data were processed with the DIAPASON (CNES) software using as input 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 ($h_a$), which is the change in elevation resulting in the production of one topographic fringe (28 mm). To avoid noise due to topographic artefacts, topographic fringe elimination and isolation of deformation fringes 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 and Feigl (1995).

The quality of the DEM and the precise orbital data limited the possibility of deriving interferograms affected by orbital and topographic fringes.

The validity of the observed fringes was also based on systematic checks of the number and shape of the fringes between independent ascending or descending interferometric image pairs (figure 1).

The interferograms exhibited a number of fringes indicating the existence of a clear deformation signal dominated by a concentric pattern, centred at the north-west and covering the whole Nisyros island. Moreover, in all interferograms the fringes extend offshore to the north-west.

During the June 1995 to May 1996 period (figure 2(*a*)), a ground uplift of 84 mm in the slant range direction is observed (three fringes) and from May 1996 to June 1997, a further uplift movement of 56 mm (figure 2(*b*)). As expected, the interferogram spanning the entire period June 1995 to June 1997 (figure 2(*c*)) exhibits five fringes, that is an uplift of 140 mm. However, for the period June 1995 to June 1999, the observed smaller surface uplift of 98 mm (3.5 fringes) indicates a deflation movement that started after June 1997 and was confirmed by examining the independent interferogram June 1997 to June 1999. The latter shows 42 mm of surface movement in the opposite direction (about 1.5 negative fringes).

The independent interferogram May 1998 to September 2000 (figure 2(*e*)) also shows 2.5 negative fringes (70 mm), and confirms the strong tendency to deflation during that period. However, it was not possible to have a direct indication of the size of the deformation for the period June 1997 to May 1998 due to inadequate, in terms of altitude of ambiguity, interferometric pairs.

Descending pass interferograms, although less coherent, show a similar concentric pattern to the ascending ones and are compatible in amplitude and direction of surface deformation (figure 1).

An overall representation of the deformation rates was intended by calculating the deformation trend in the eight time spans between the nine radar images. A least squares solution was obtained for a system using the eight deformation rates as unknowns and

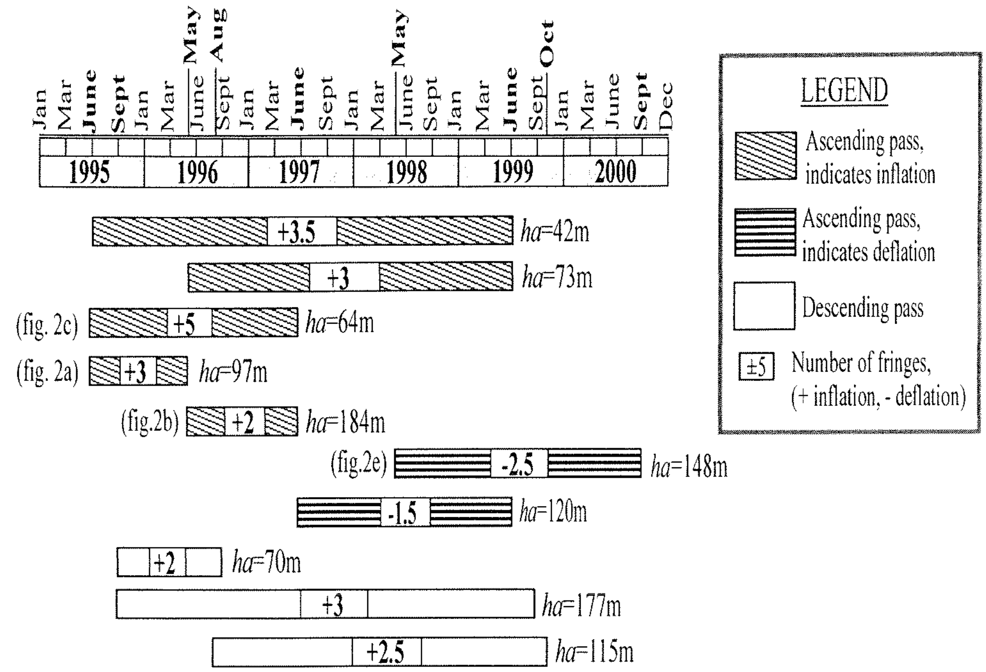

Figure 1. ERS-2 image combinations used for interferometric calculations. The month in which the data were acquired is shown in bold. The number of fringes observed indicates the movement in the slant range direction (+/− signs indicate inflation and deflation respectively) where one fringe corresponds to 28 mm of ground deformation.

the ten interferometric observations as known parameters. 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. A continuous inflation is evident between 1995 and early 1998 while a deflation movement seems to occur from May 1998 up to September 2000.

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

## 3. Modelling

A first approximation in the interpretation of the observed deformation field was proposed by using a simple model of point source inflation/deflation in an elastic medium. This model was first introduced in volcanology by Mogi (1958) and does not take into account the possible complexity of the volcano's structure, in particular shallow discontinuities, faults and variable ground geology. However, it provides, in general, a useful first quantification of the phenomena responsible for the deformation, 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 the period 1995–2000. Taking this into consideration, the clearest interferogram (June 1995 to June 1997) was used as input to solve for the four model

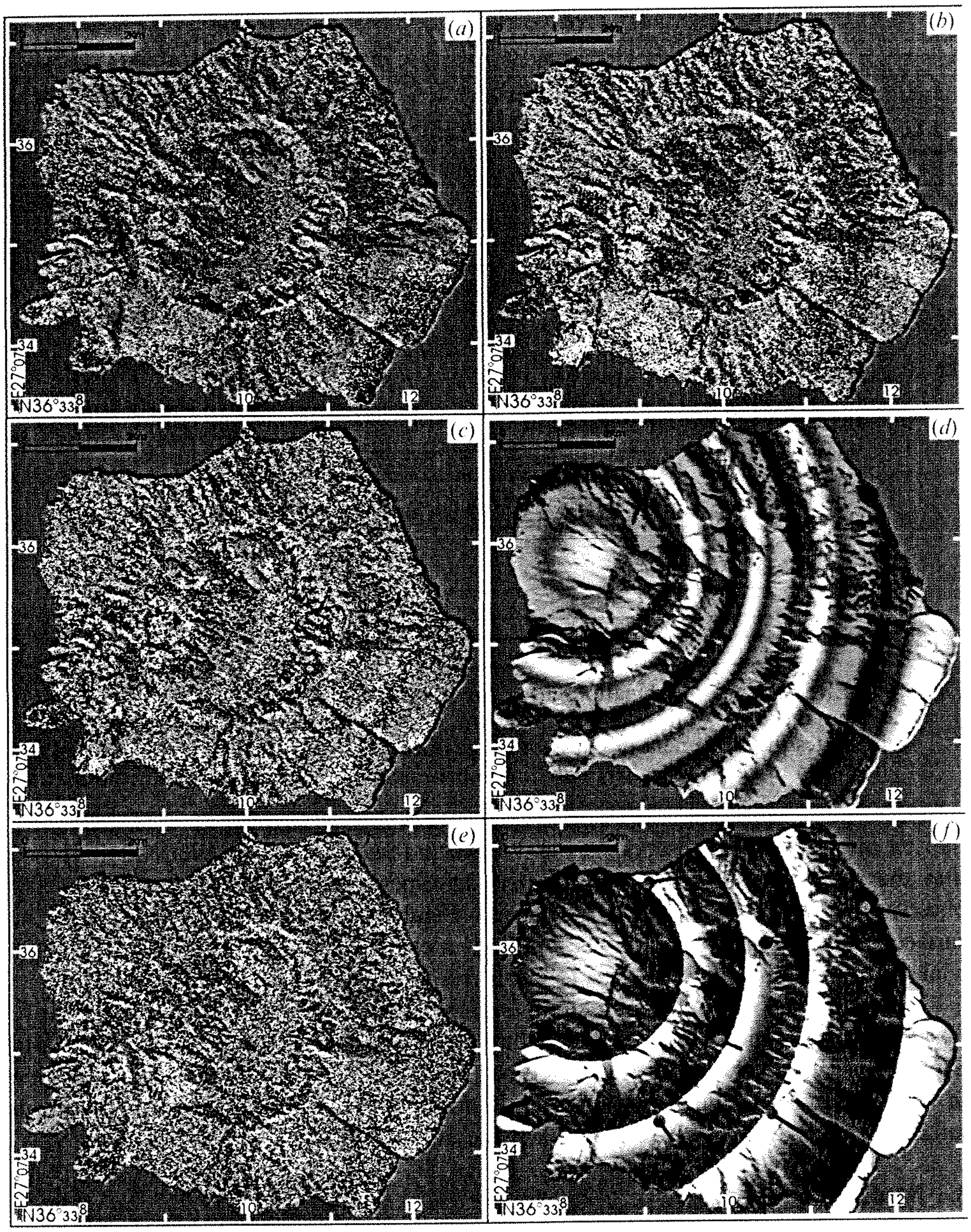

Figure 2. ERS2 SAR differential interferograms from images acquired in the ascending pass of the satellite sensor spanning: (*a*) (June 1995 to May 1996); (*b*) (May 1996 to June 1997); (*c*) (June 1995 to June 1997); (*e*) (May 1998 to September 2000). (*d*) Mogi point source model solved for the period June 1995 to June 1997. (*f*) Horizontal deformation displacements of the GPS stations for the period June 1997 to May 1998 (Lagios 2000) superposed on the solved source model. The location of the centre of the deformation source is consistent between both observations.

parameters: horizontal coordinates, depth of inflating centre and maximum amplitude of deformation at the surface. The best-fit solution was found for a point source with the characteristics presented in table 1.

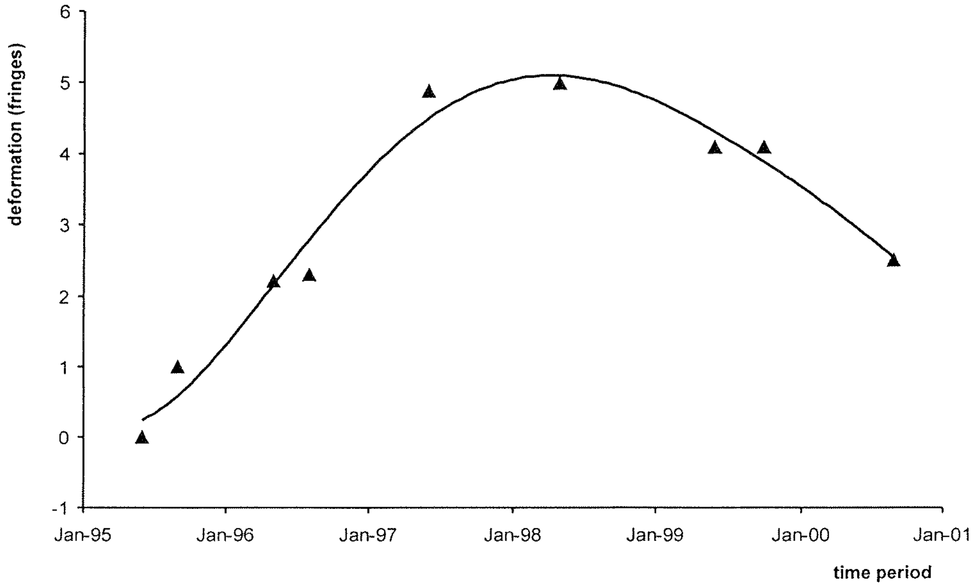

Figure 3. Deformation at Nisyros from 1995 to 2000, inferred from InSAR data analysis. Each fringe corresponds to 28 mm of deformation in the slant range direction.

Table 1. Parameters describing the point source deformation obtained by Mogi modelling solved for the period June 1995–June 1997.

| Point source deformation parameters derived by Mogi model | |
|---|---|
| E (UTM/Zone35/ED50): | (513.4 ± 0.3) km |
| N (UTM/Zone35/ED50): | (4050.6 ± 0.3) km |
| Depth: | (5 ± 0.5 km) |
| Max. amplitude of the deformation at the surface: | (0.14 ± 0.02) m |
| Volume change at depth for 1995–1997 | $(26 \pm 4) \times 10^6\,m^3$ |

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 the 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 removal of the volume previously intruded.

## 4. Seismicity

The Institute for Geodynamics of the National Observatory of Athens conducted two seismic experiments with a local seismographic network in March and July 1997 (Sachpazi *et al.* 2002).

The recorded seismicity patterns for the two seismic experiments varied both temporally and spatially. The first campaign recorded intense seismic activity in a rather restricted zone north-west of Nisyros. During the second experiment, the epicentres were spread towards the central and southern part of the island.

Sachpazi *et al.* (2002) consider this 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 hypocentres 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 fumarolic activity, peaking one day after the occurrence of the two strongest earthquakes. Moreover, the existence of an aseismic area north of Nisyros indicates a volcanic volume having being extruded from the magma chamber located 7 km south-southwest where the maximum deformation area is inferred by InSAR and GPS. 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 $\text{year}^{-1}$ took place.

## 5. Discussion

Interferometric analysis demonstrated significant ground deformations across the whole Nisyros island trending to the north-west during the period 1995–2000. Inflation lasted until mid-1998 and was then followed by a deflation up to 2000. The interferometric results from ascending and descending passes have been cross-checked against each other and compared with the existing GPS measurements (Lagios 2000). GPS measurements agree with the InSAR observations concerning the location of the deformation centre (figure 2(*f*)) and the ending of the inflation.

The features of earthquake activity in relation to the InSAR results and the characteristics of the hydrothermal field of Nisyros (Marini *et al.* 1993) favour the modelled inflation/deflation sequence. Indeed, the process could 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.

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