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## Post-eruptive deformation associated with the 1986-87 and 1989 lava flows of Etna detected by radar interferometry

P. Briole,<sup>1,2</sup> D. Massonnet<sup>3</sup> and C. Delacourt<sup>1</sup>

**Abstract.** We analysed 92 interferograms produced using ERS1 SAR images taken on Etna between May 1992 and October 1993. Nineteen show a local subsidence in the eastern flank of the volcano, correlated with the location of the 30 October 1986 - 1 March 1987 and 27 September - 9 October 1989 lava flows. Using fringe unwrapping and data gridding techniques, and assuming that over the sampled time-window, deformation was a linear function of time, we derive a map of along range rate of motion. The correlation between the deformation field and the area covered by recent lavas suggests that compaction of the lava flows continues several years after the eruptions. The area of maximum subsidence (47 mm/yr.) is localised at the narrowing of the 1989 flow, between 1500 and 1700 m a.s.l.. We observe that subsidence extends outside the lava flows, accounting for at least 12 mm/yr. Assuming a relaxation process of the substrate in response to loading produced by recent lavas, a simple 1D Maxwell visco-elastic model predicts a maximum subsidence rate of 25 mm/yr and a relaxation time of about 3.5 years. The relaxation time agrees with those derived from post-eruptive displacements observed by levelling on Etna and Piton de la Fournaise after several eruptions. We conclude that at the time of our measurements, 25 to 50% of the deformation was related to relaxation of the substrate and the other part due to compaction of the lava flows.

### Introduction

Post-eruptive deformations correlated with the location of lava fields have already been observed from levelling data on volcanoes, for example after the 1981 and 1983 eruptions of Etna [Murray, 1988] after the 1961, 1976, 1977, 1986 eruptions of Piton de la Fournaise [Delorme, 1994]. On Piton de la Fournaise, the data corresponding to the 1976 and 1986 eruptions showed that the deformation took place over several years (20 mm

subsidence between 1980 and 1986, then 5 mm between 1986 and 1989 for the 1976 eruption; 10 mm subsidence in the first days after the 1986 eruption, then 100 mm between 1986 and 1989). On Etna, Murray [1988] proposed that most of the observed deformation was due to compaction of the recently deposited lava, with relaxation times ranging between a few years and 15 years. As the deformation observed on Piton de la Fournaise was located outside the lava flow itself, Delorme [1994] proposed a process of relaxation of the substrate in response to the loading of the lava. Measurement and interpretation of deformations related to deposited lava is fundamental on volcanoes because it gives access to quantitative information on the sub-surface rheology that is necessary for developing realistic models of deformations associated with eruption, dike emplacements or flank instabilities. Thanks to the new capability of mapping deformations offered by radar interferometry, we analyse in this paper a deformation located in a remote area of Etna (Figure 1) where no classical geodetic data are available. In a previous paper [Massonnet *et al.*, 1995], we used radar interferometry data to assess the location (16 km depth) of a volcano-wide deflating zone associated with the 1991-93 eruption. Here, we use the same data and focus on a local anomaly (Figure 2) that is spatially well correlated with the 27 September - 9 October 1989 lava field and partly with that of 30 October 1986 - 1 March 1987 (Figure 3a, 3b). The 1989 eruption occurred inside the Valle del Bove, between 2550 m and 1100 m a.s.l., with the following characteristics [Bertagnini *et al.*, 1990]: area = 3.3 km<sup>2</sup>, volume = 26 x 10<sup>6</sup> m<sup>3</sup>, maximum thickness = 10 m. The 1986-87 eruption took place in the same area, between 2900 m and 1300 m a.s.l., with area = 6.5 km<sup>2</sup> and volume = 60 x 10<sup>6</sup> m<sup>3</sup> [Azzaro and Neri, 1992]. The coincidence between the location of the lava fields and the deforming area is clear (Figure 3a, 3b). To explain our data, in the following, we investigate the two physical processes mentioned above: compaction of the recent lava flows and relaxation of the substrate.

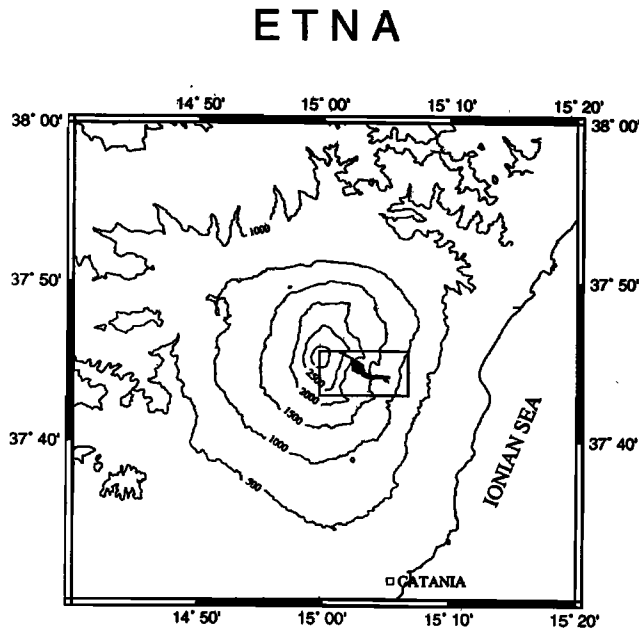
### Data analysis

We analysed 92 interferograms created with ERS1 SAR images acquired on Etna between May 1992 and October 1993. Nineteen have coherent phase returns and interference fringes that show clearly an anomalous subsidence in the eastern part of the volcano. The ten

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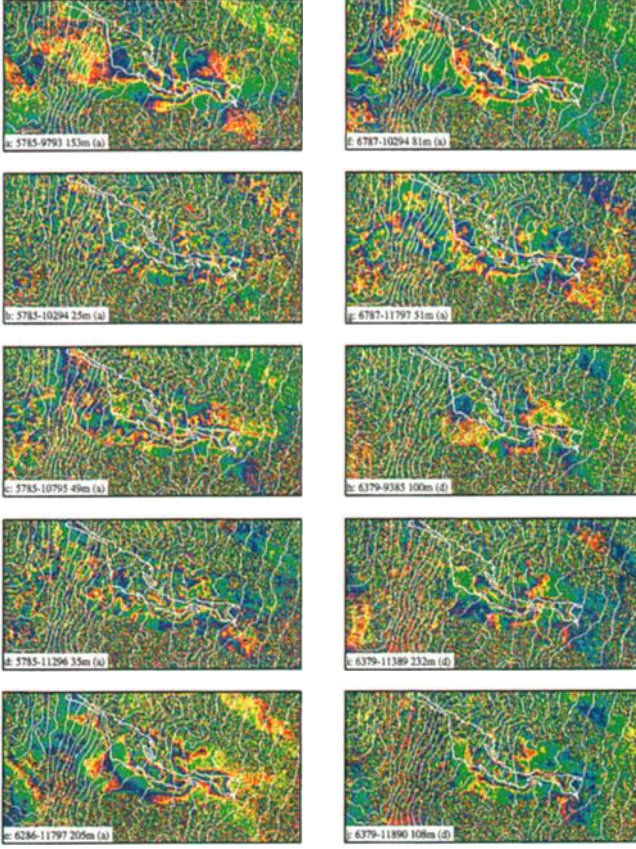
**Figure 1.** Map of Mount Etna. The box shows the location of the interferograms. The UTM33 coordinates of the NW corner of the box are:  $x = 499.560$ ,  $y = 4179.320$ . The 27 September - 9 October 1989 lava flow is reported in black.

best interferograms are listed in Table 1 and shown in Figure 2. The subsidence pattern is stable spatially. This can be easily checked in two places: the narrowing of the 1989 lava flow at 1600 m a.s.l. and the lower end of this lava flow at 1200 m a.s.l.. The amplitude of the movement ranges between 2 and 4 fringes (about 6 to 12 cm) depending on the interferogram. The dependence between elapsed time and amplitude cannot be assessed over a wide time frame because most of the interferograms have relatively comparable elapsed times (210 to 385 days). We further assume that the amplitude of the observed phenomenon is a linear function of time. The altitude of ambiguity [Massonnet and Rabaute, 1993] of most interferograms we use is above 50 m (Table 1). This ensures that the uncertainty due to the inaccuracy of the digital elevation model (DEM) is at most one sixth of a fringe, or about 5 mm. To quantify the observed subsidence, we unwrapped the fringes in the places where they were clearly separable. This was possible in seven of the ten interferograms shown in Figure 2 (a, c, d, e, f, g, j). Then, using a gridding algorithm (triangulation with linear interpolation), we created an image of the deformation field for each interferogram, limited to the area where effective information was obtained from the fringes. Finally, we averaged the seven images weighted by their duration, to obtain a map of along range rates of subsidence (Figure 3c). The area where a deformation is observed is 4.1 km<sup>2</sup> and the rate of volume change is  $90 \cdot 10^3$  m<sup>3</sup>/yr. The average subsidence rate is then 22 mm/yr. The maximum rate is 47 mm/yr at the narrowing of the 1989 lava flow near elevation 1600 m. Figure 4 shows the rate of range

change along a N45E section A-A' (Figure 3c) crossing the lava field near this maximum. In order to validate the quality of our interferograms, we processed the data using two codes: the code developed by CNES (the reference in this study) and the code developed at IPG on a Connection Machine (CM5-128). We also used two different digital elevation models (DEMs): CNES used a DEM obtained from a SPOT stereoscopic pair acquired in July 1991, whose vertical accuracy is 8 m (r.m.s. error) and IPG used a DEM obtained from an aero-photogrammetric survey carried out in September 1985. A comparison of the interferograms obtained using both different codes and DEMs is shown in Figure 3a and 3b for our best interferogram (interferogram (e) in Table 1). Only minor difference is visible in the western edge of the scene. The r.m.s. scatter between the two DEMs (Figure 3d) is 22 m. This ensures *a posteriori* the independence of the DEM for the generation of the interferogram. However, as one DEM is using 1985 data and the other 1991 data, their difference contains signatures of the 1986-87 and 1989 lavas at the places where their thickness exceeds 20 m. The average difference of the DEMs in the area delimited by the lava flows is 15 m, that is compatible with the average thickness deduced from the surfaces and volumes reported above. The maximum positive difference is +80 m (largest red spot in figure 3d) and is observed inside the lava flows area and could be due to a thickening of the 1986-87 lava field. The maximum negative difference (violet spot of -170 m in the southwest on figure 3d) is an artefact due to a cloud masking the terrain in one of the SPOT images.

## Discussion

Three observations of the deformation field are significant: 1. the deformation field is correlated with the area covered by lava in 1986-87 and 1989; 2. part of the deformation is located outside the lava flow itself; 3. there is a maximum of subsidence concentrated at the narrowing observable on the 1989 lava flow between 1500 and 1700 m a.s.l. We suggest that this last observation is associated with a relative thickening of the 1986-87 and/or 1989 lava flows there, that, however, could not exceed 40 m as this is constrained by the difference of the two DEMs discussed in the previous section. We propose that the observed signal corresponds to both visco-elastic relaxation of the medium in response to the loading and compaction of the recent lava flows. To quantify the relaxation, we use a simple model of Maxwell visco-elasticity strain relaxation [Turcotte and Schubert, 1982], that is compatible with the temporal and spatial scales of our problem. We assume that the deformation is mostly vertical, and neglect the contribution of the horizontal movement to the change in range. Using equation 7-243 of these authors (p. 338), with  $\nu = 0.25$ , we obtain:



**Figure 2.** The 10 interferograms used quantitatively in our study. Each image contains  $128 \times 257$  pixels of 40 m. The two orbit numbers, the ambiguity height and the characteristic ascending (a) or descending (d) are indicated. The contour lines (every 100 m) are drawn.

$$\epsilon_2 = \sigma_0 / 2E (3 - 4/3 \exp(-t/\tau)), \quad (1)$$

where  $\epsilon_2$  is the strain,  $\tau = (9 \mu / 2 E)$  the Maxwell relaxation time and  $\mu$  the viscosity of the medium. The derivative of (1) gives the rate of along range displacement  $dR/dt$ :

$$dR/dt = (2\sigma_0 h \cos \alpha / 3E\tau) \exp(-t/\tau), \quad (2)$$

where  $\sigma_0$  is the load applied to the medium,  $E$  Young's modulus,  $\tau$  the Maxwell visco-elastic relaxation time,  $h$  the thickness of the medium and  $\cos \alpha$  the cosine director between vertical and range (0.904 for ascending orbits here). The superficial structures of Etna are characterized by low values of velocities of the seismic waves that we can convert into low values of the elastic parameters. Using typical values between 1 and 2 km/s [Hirn, personal communication] for the first kilometre, the Young's modulus ranges between 2 GPa and 10 GPa. Below, the increasing velocities imply Young's modulus increasing to about 35 GPa. Due to the fast increase of Young's modulus below 1 km, we next assume that our model consists of a 1 km thick visco-elastic body with a Young's modulus of 2.5 GPa surrounded by a perfect rigid body. The same value for the Young's modulus has been used by Cayol (1996), for the mod-

eling of deformations associated with dike intrusions at low depth on Piton de la Fournaise. The value of  $\sigma_0$  (1 MPa) is deduced from a 40 m height of lava of density  $2500 \text{ kg m}^{-3}$  at the place of maximum subsidence. Assuming that most of the observed deformation is associated with the 1989 lava flow, the function  $dR/dt(\tau)$  is maximum for  $t=\tau=3.5 \text{ yr}$ , and is equal to 25 mm/yr. On the other hand, a minimum rate of subsidence of 12 mm/yr is given by the values observed at the edges of the lava flows (close to both ends of section A-A' in Figure 4). Relaxation could, thus, account for 25 to 50 % of the subsidence, the other part (22 to 35 mm/yr) being due to compaction of the recent lava flows. Using a typical thickness of 12 m for the sum of the 1986-87 and 1989 lava flow, given the average rate of subsidence of 22 mm/yr for the whole area of the lava flows and assuming about half of the movement due to compaction, we find a strain rate of  $10^{-3} \text{ yr}^{-1}$  for the compacting volume. Taking a coefficient of dilatation of  $10^{-5}$  for the basalts, this would imply a decrease of temperature of  $120^\circ/\text{yr}$  about 4 years after the eruption. This high value implies that most of the compaction is not of thermal origin. In order to check the validity of our analytic model, especially for the amplitude of the signal and the lateral extension, we ran simulations of the same problem on two 2D finite element codes (TECTON and ADELI). Our solutions agreed with the predictions of the above model. The numerical simulations were also used to estimate the amplitude of the expected lateral bulges (less than 10-15% of the maximum subsidence and thus not detectable in our data) and the contribution of the horizontal movement to the change of range (also less than 10-15% of the maximum subsidence, thus negligible as assumed before).

## Conclusions

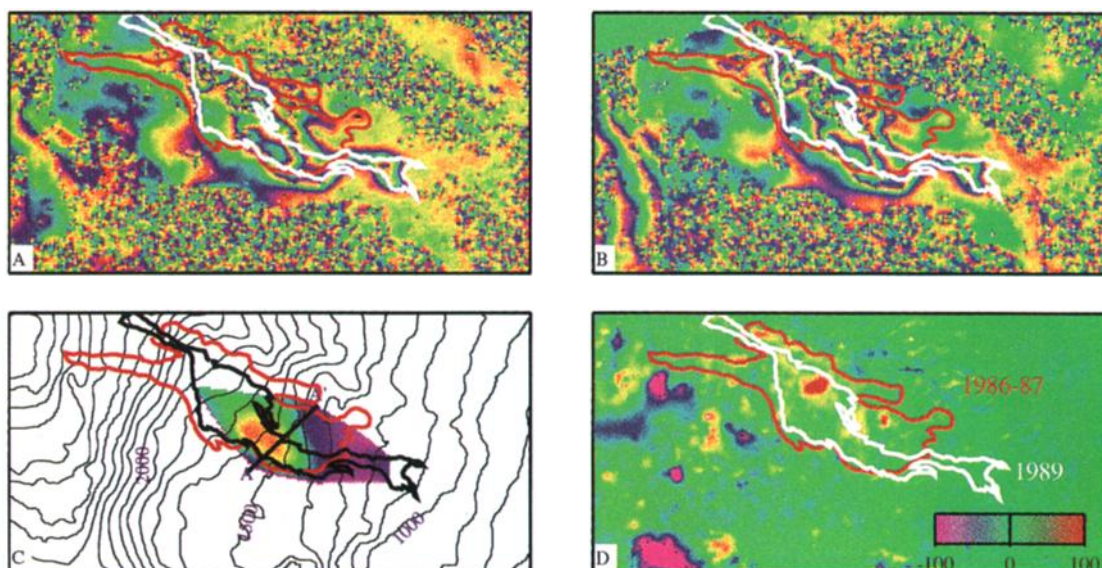
In our study, we show that, using radar interferometry, it was possible to detect a deformation moderate in size and amplitude in an almost inaccessible area of Etna. A process of relaxation of the substrate associated with the load of the 1986-87 and 1989 lava flow ex-

**Table 1.** ERS1 images used in this study

N°	Orb. 1	Date	Orb. 2	Date	$H_{amb}$	Days
a	5785	23/08/92	9793	30/05/93	153	280
b	5785	23/08/92	10294	4/07/93	25	315
c	5785	23/08/92	10795	8/08/93	49	350
d	5785	23/08/92	11296	12/09/93	35	385
e	6286	27/09/92	11797	17/10/93	205	385
f	6787	1/11/92	10294	4/07/93	81	245
g	6787	1/11/92	11797	17/10/93	51	350
h	6379	4/10/92	9385	2/05/93	100	210
i	6379	4/10/92	11389	19/09/93	232	350
j	6379	4/10/92	11890	24/10/93	108	385

Starting and ending orbit number and dates of each interferogram, altitude of ambiguity in meters ( $H_{amb}$ ) and duration in days. Letters in the first row refer to Figure 2.





**Figure 3.** 3a: Interferogram (e) produced by CNES using the SPOT DEM. The 1986-87 lava flow is reported in red and the 1989 one in white ; 3b: Same interferogram produced at IPG using the CNR DEM; 3c: Rate of along range change found by averaging the values obtained on the seven best interferograms after fringe unwrapping and data gridding. The maximum rate, in red corresponds to 47 mm/yr. Section A-A' refers to figure 4 ; 3d: difference of the two DEM, the scale in meters is given by the palette.

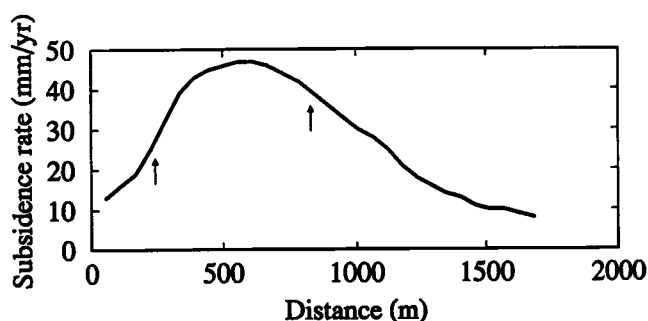
plains 25 to 50 % of the amplitude of the post-eruptive displacements observed on a one year window in 1992-93. The amplitude of deformation outside the lava flows is used to show that the relaxation time cannot be very different from the 3.5 years elapsed between the eruption and the data collection. Such a value agrees with relaxation times observed after other eruptions on Etna and Piton de la Fournaise. The compaction of the lava flow itself contributes for at least half of the total subsidence. This is consistent with Murray's [1988] observations on Etna after the 1981 eruption. The occurrence of the large 1991-93 eruption will offer in the next years the opportunity to test our model, with a volume of deposited lava ten times larger and thus with much larger deformations expected.

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**Figure 4.** Rate of range change along a section A-A' (Figure 3) crossing the lava flow in a N45E azimuth at 1600 m a.s.l. The two marks on the curve correspond to the edges of the 1989 lava field.

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