Bayesian source inference of the 1993–1997 deformation at Mount Etna (Italy) by numerical solutions

E. Trasatti,1 S. Cianetti,1 C. Giunchi,1 M. Bonafede,2 N. Piana Agostinetti,1 F. Casu3 and M. Manzo3

1Istituto Nazionale di Geofisica e Vulcanologia, 00143 Roma, Italy. E-mail: elisa.trasatti@ingv.it
2Università degli Studi di Bologna, 40127 Bologna, Italy
3Istituto per il Rilevamento Elettromagnetico dell’Ambiente, 80124 Napoli, Italy

SUMMARY
Deformation data collected at Mount Etna from 1993 to 1997 show that the inflation of the volcano edifice is accompanied by instability of the eastern flank. We propose a 3-D finite element model including topography and lateral variations of elastic constants. Source parameters of the inflating source are constrained by a direct search followed by an appraisal stage of the sampled solutions. The instability of the eastern flank is addressed using a kinematic approach, consisting of a rigid-body translation over a prescribed area. The aim is to evaluate how source parameters are affected by sliding of the eastern flank. When sliding is accounted for, the inferred source location shifts ~1 km SE and its strength decreases by ~20 per cent.

Key words: Numerical solutions; Inverse theory; Radar interferometry; Crustal structure; Volcano monitoring.

1 INTRODUCTION
The structure of Mt Etna, NE Sicily (Italy), is characterized by complex fault systems extending from the summit craters (NE Rift and S Rift) to its flanks (a simplified map is shown in Fig. 1a). Several studies show evidence of instability in the SE flank, consisting of a southeastward sliding movement. The sliding is commonly ascribed to gravitational instability and/or magma intrusion (e.g. Lo Giudice & Rasà 1992; Borgia et al. 1992; Rust & Neri 1996; Bonforte & Puglisi 2003; Neri et al. 2004; Walter et al. 2005). However, the relationship between these processes is poorly understood and still the subject of debate. The surface structures delimiting the SE flank are the left-lateral Pernicana Fault System (PFS), which borders the N margin, and the Ragalna Fault (RF) and the S Rift at the SW margin. Two sliding blocks, separated by NW-SE trending faults (Santa Venerina, SV, and Timpe Fault System, TFS, Fig. 1a) can be recognized within the unstable sector (Neri et al. 2004). The slip recorded on the PFS is related not only to the sliding of the SE flank but also to the summit activity (Puglisi & Bonforte 2004). The sliding movement shows a southward progression from the PFS, reaching the TFS and the Trecastagni Fault, TF (Neri et al. 2004). The estimated slip rates on the PFS range from 0.8 ± 0.2 cm yr⁻¹ to 2.2 ± 0.4 cm yr⁻¹, even though large and long-lasting creep episodes occurred in 2002–2003 with a maximum displacement of 1.25 m in its western segment, in connection with the opening of eruptive fractures along the NE Rift (Neri et al. 2004). Slip rates on PFS can be considered as lower bounds during quiescent or recharge phases, such as 1993–1997, because the sliding movement can also be accommodated by different strike-slip faults mapped in the SE sector (e.g. Neri et al. 2004; Monaco et al. 2005; Rust et al. 2005). Even during the deflation in 2004–2005, a continuous and independent eastward movement of the eastern sector was observed, whereas geodetic data on the summit of Mt Etna showed general contraction (Bonforte et al. 2008). All these studies show evidence of the complex temporal and spatial evolution of the sliding mechanism.

Volcanic inflation is commonly described in terms of a pressurized cavity embedded in a homogeneous half-space such as the isotropic Mogi model (Mogi 1958) or the triaxial ellipsoid model (Davis 1986). However, the retrieved source parameters are strongly biased if the finite dimension of the source, the topography of the edifice and the rigidity heterogeneities are ignored (e.g. Mc Tigue 1987; Yang et al. 1988; Cayol & Cornet 1998; Trasatti et al. 2005; Manconi et al. 2007). The inflation observed at Mt Etna during 1993–1997 has been studied by deformation models of expanding sources (Lanari et al. 1998; Bonaccorso et al. 2005; Trasatti et al. 2008) whereas flank instability was addressed using sub-horizontal dip-slip faults based on the elastic dislocation theory (Lundgren et al. 2003; Puglisi & Bonforte 2004; Palano et al. 2008). Moreover, Walter et al. (2005) investigated the interaction between magma emplacement and eruptions at Mt Etna, testing the consistency between the temporal evolution of flank instability and static stress field changes. However, assumptions, such as a homogeneous elastic medium or an a priori assigned source shape, and the large
Bayesian source inference at Mt Etna

2 DATA

After the 1991–1993 strong eruptions Mt Etna experienced a progressive inflation detected by several geodetic techniques. In particular, we employ geodetic data recorded between 1993 and 1997, consisting of 20 GPS (with errors ranging between 3 mm and 17 mm) and 147 EDM measurements (with formal uncertainty of 1 cm). Deformation models of pure inflation are implemented to interpret these data, specifically analytical inversions by Bonaccorso et al. (2005) and numerical inversions by Trasatti et al. (2008). Fig. 1b shows the GPS velocities and the coverage of the EDM network (translucent yellow areas). Although the GPS sites are not uniformly distributed over the volcano, the observed deformation is characterized by a radial pattern with larger amplitude in the eastern sector compared to the western flank. Furthermore, geodetic sites located along the coast move faster than those closer to the volcano summit (e.g. Borgia et al. 1992).

This evidence is also strongly supported by independent ascending and descending DInSAR data, which was processed via the Small BAseline Subset (SBAS) algorithm (Berardino et al. 2002). This technique allows generation of mean deformation velocity...
maps and the corresponding time series in the sensor line of sight (LOS). These data, due to their large and homogeneous surface coverage in zones where GPS and EDM data are lacking, constitute a valid complement to understand the deformation mechanisms involved. The SBAS data set was processed and published by Lundgren et al. (2004). We select data from the ascending and descending mean velocity maps at the 6 863 common pixels, compute the E–W and vertical velocity components and convert into the displacement maps shown in Figs 1(c) and (d), respectively. The error associated with the SBAS-DInSAR mean velocity is ~2 mm yr\(^{-1}\), corresponding to 8 mm for the ascending, descending and vertical components of the displacement, whereas it is approximately twice for the E–W component (Casu et al. 2006). DInSAR data show eastward and downward movement of the eastern flank of the volcano.

3 MODELLING

We perform inversions of the data described in Section 2 focusing on two different models: INFLation (INFL), in which the deformation is caused by a moment tensor applied to a single element of the FE grid, and INflation and SLiding (INSL), in which an additional rigid-body translation of the eastern flank of Mt Etna is included. With respect to Trasatti et al. (2008), we have the following twofold aim: on one hand to strengthen the source inference using the additional DInSAR data set and on the other hand, to understand how the sliding process affects the inferred source parameters.

The inversion method used is the same described and tested in Trasatti et al. (2008) and is briefly outlined as follows: (i) a FE model of the medium is deployed, taking into account the topography of the volcanic edifice and the elastic heterogeneities derived from seismic tomography (Chiarabba et al. 2000). The shear modulus is assigned to each FE, as computed from the \(v_p\) value interpolated at the centroid. A reference density of 2 500 km m\(^{-3}\) and a Poisson ratio of 0.25 are assumed. The whole computational domain spans a volume of 140 \(\times\) 140 \(\times\) 60 km\(^3\), discretized into \(~150\ 000\) isoparametric 8-node brick elements; (ii) the central volume below Mt Etna is discretized into regular cubic elements of length \(l = 400\) m; a subset extending \(8 \times 8 \times 8\) km\(^3\) is assumed to include the potential sources of deformation; (iii) the ground deformation, caused by unitary perturbation of the tractions \(\sigma_{ij}\) on the opposite faces of each potential source, is computed and stored in a library. This library consists of 48 000 entries for each observation point at the surface; (iv) linear combinations of these elementary solutions are used as forward models for the Neighbourhood Algorithm (Sambridge 1999a), performing a direct search of the parameter space. The ensemble of models is then evaluated by Bayesian inference to determine the statistical distribution of the inverted parameters (Sambridge 1999b). We carefully tuned the parameters of the algorithms to avoid under/oversampling of the parameter space (see Trasatti et al. 2008). With this approach we recover the best fitting and the most statistically significant position of the source and its moment tensor \(M_j = \sigma_{ij}\). Finally, we show that the retrieved moment tensor can be approximately interpreted in terms of a pressurized ellipsoidal cavity (Davis 1986).

For EDM and GPS measurements, the FE predictions are computed at the geodetic sites, whereas the resolution of the FE grid (400 m at best, in the central area of Mt Etna) is coarser than the coverage of DInSAR pixels. The DInSAR data set is down-sampled using a bilinear interpolation to deal with only one value within each FE face at the surface. With this assumption, the DInSAR data effectively used in the inversion are reduced to 1 141 points out of the 6 863 original pixels. We performed several tests to verify that different down-sampling of the DInSAR data yielded negligible differences in the inversion results, as showed by Fukushima et al. (2005).

The second model, INSL, takes into account the sliding of the SE flank. A few models of flank sliding based on the dislocation theory were published (Lundgren et al. 2003; Puglisi & Bonforte 2004; Walter et al. 2005; Palano et al. 2008), but here we propose a simple kinematic model, consisting of a rigid translation of a specific area, shown in Figs 1(c) and (d) by the dashed line. The rigid sliding is very different from fault dislocation because it does not predict strain within the sliding domain. The deformation of this area is computed as the sum of the displacements caused by the inflation source and a uniform sliding vector whose components are three new parameters included in the inversion procedure. The rigid sliding is only a first-order approximation of the deformation occurring in this area, which may be due to several active tectonic structures accommodating the flank instability in a much more complex pattern. However, this simple assumption allows estimation of the effects of the sliding with only three additional unknowns.

A mechanically decoupling model is physically more appropriate, but it requires additional speculations about the depth, inclination and shape of the detachment surface, about the frictional properties of the contact surface and the rheology of rocks above and below this discontinuity. For example, Walter et al. (2005) accounted for a W dipping decoupling plane, whereas Puglisi & Bonforte (2004) favoured an E dipping surface. This knowledge of the internal structure below the SE flank is not sufficient to constrain any of these unknowns. In any case, such a model could not be included in the framework of our inversion scheme due to the large number of free parameters. Although we consider a simple kinematic model of flank sliding, we must still delimit the sliding sector, which is, to some extent, an arbitrary task. Our choice is based both on the geodetic data available and the distribution of mapped faults; this avoids any further assumption about decoupling structures at depth. The N border of the sliding sector corresponds to the NE Rift and to the surface trace of the PFS. In this case, the activity of these structures is corroborated by the GPS and DInSAR data (Fig. 1). The definition of the S and W borders of the sliding sector is more problematic since there is no unambiguous correlation between mapped faults and observed deformation. This mismatch is not surprising since some of these structures may not have been active during 1993–1997. Assuming that the sliding sector is bounded by known faults, the southern margin may consist of (i) S Rift and RF; (ii) S Rift and TF and (iii) SV and TFS. However, the low coherence of DInSAR data in the SW flank of Mt Etna does not allow to constrain the boundary along the RF. Furthermore, DInSAR data show consistent deformation S of SV and TFS. After a trial and error process aimed to match the active deformation evidenced by the DInSAR data, a better solution encloses the S Rift secondary structures at mid altitudes and toward the TFS at low altitudes. The chosen boundary follows the transition from westward to eastward displacements (green to yellow colour bands in Fig. 1c). We do not constrain the polygon vertices by NA inversion because of the large number of parameters required. We acknowledge that multiple sliding blocks have been proposed (separated by the SV-TFS, e.g. Neri et al. 2004; Puglisi & Bonforte 2004; Walter et al. 2005) but, again, the increasing number of parameters required to model two or more separate blocks could not be warranted given the resolving power of the data set considered.
Figure 2. PPD distributions (red line for model INFL, blue line for model INSL) of the inverted parameters: source position ($S_x$, $S_y$, $S_z$); principal stresses ($\sigma_1$, $\sigma_2$, $\sigma_3$); Euler angles (see text for details): $\delta$, dip angle of the eigenvector $\hat{v}_3$ of $\sigma_3$; $\phi$, strike angle of $\hat{v}_3$; $\theta$, self-rotation, that is rotation of $\hat{v}_1$ and $\hat{v}_2$ around $\hat{v}_3$; sliding vector ($L_x$, $L_y$, $L_z$), only for model INSL. The mean values of each distribution are indicated with the dashed vertical lines and are summarized in Table 1.

### 4 RESULTS

Fig. 2 shows the Posterior Probability Density (PPD) functions (PPD, see Sambridge 1999b) for parameters of models INFL (red solid line) and INSL (blue solid line), respectively. The vertical dashed lines show the mean value of each probability distribution and identify the most likely parameter values, summarized in Table 1. The width of the PPD curves can be considered a measure of parameter uncertainties; source position (Figs 2a–c) is well constrained for each model. In detail, the INFL source is located $\sim$100 m NW of model INSL. A possible explanation for this difference is that model INFL tries to reproduce simultaneously the large horizontal displacement and the negative vertical displacement recorded on the eastern flank by DInSAR, by shifting the source

<table>
<thead>
<tr>
<th>Model</th>
<th>$S_x$ (km)</th>
<th>$S_y$ (km)</th>
<th>$S_z$ (km)</th>
<th>$\sigma_1$ (MPa)</th>
<th>$\sigma_2$ (MPa)</th>
<th>$\sigma_3$ (MPa)</th>
<th>$\delta$ (deg)</th>
<th>$\phi$ (deg)</th>
<th>$\theta$ (deg)</th>
<th>$L_x$ (cm)</th>
<th>$L_y$ (cm)</th>
<th>$L_z$ (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>INFL</td>
<td>496.8</td>
<td>4180.3</td>
<td>$-7.7$</td>
<td>4693</td>
<td>3053</td>
<td>2382</td>
<td>66</td>
<td>147</td>
<td>25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>INSL</td>
<td>497.5</td>
<td>4179.5</td>
<td>$-7.7$</td>
<td>3406</td>
<td>2692</td>
<td>1892</td>
<td>47</td>
<td>145</td>
<td>45</td>
<td>5.2</td>
<td>$-3.1$</td>
<td>$-1.9$</td>
</tr>
<tr>
<td>HET</td>
<td>498.5</td>
<td>4179.8</td>
<td>$-7.3$</td>
<td>5048</td>
<td>3671</td>
<td>2800</td>
<td>62</td>
<td>120</td>
<td>$-3$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: Results of model HET from Trasatti et al. (2008) are shown for comparison.
toward the NW to lower the vertical and to increase the horizontal deformation. Otherwise, model INSL reproduces the subsidence of the eastern sector with the additional negative vertical displacement provided by the sliding vector. The source depth is practically the same for both models, which means that the correction to the uplift pattern due to sliding in case of model INSL does not significantly affect this parameter.

In Figs 2(d)-(i) the moment tensor $M_{ij} = l^i \sigma_{ij}$ is analyzed in terms of principal stresses $(\sigma_1 > \sigma_2 > \sigma_3)$ and orientations of the corresponding eigenvectors $\hat{v}_1, \hat{v}_2, \hat{v}_3$, respectively. The orientation of the eigenvectors is described splitting the complete rotation of a Cartesian coordinate system into three rotations about single axes of the system (in analogy with Euler’s angles). Supposing that initially $\hat{v}_1, \hat{v}_2, \hat{v}_3$ are oriented along the $x, y, z$-axes (corresponding to $E$, $N$, up, respectively), we compute a first rotation about $z \equiv \hat{v}_3$ by an angle $\phi$ (strike angle of $\sigma_1$), then a second rotation by an angle $\delta$ about $\hat{v}_1$ (dip angle of $\sigma_3$) and finally a third rotation by an angle $\theta$ about $\hat{v}_1$ (self-rotation angle of $\sigma_3$).

Principal stress values are well constrained in both models. For INFL, $\sigma_1$ is much larger than $\sigma_2$ and almost twice than $\sigma_3$. For INSL, instead, $\sigma_1, \sigma_2$ and $\sigma_3$ are closer to each other and $\sigma_1 - \sigma_2 \cong \sigma_2 - \sigma_3$. Stress intensities for model INSL are smaller than for INFL because the deformation is partially accommodated by the sliding, and this yields an overall reduction of the strength of inflation. For models INFL and INSL, the dip angles $\delta$ of $\sigma_3$ are 66° and 47°, respectively, whereas the orientation is NW-SE since $\phi \cong 145^\circ$ in both cases. The self-rotation angles $\theta$ exhibit two different patterns. Whereas for model INFL we find a unimodal distribution around $\theta = 24^\circ$, for model INSL we retrieve a bimodal distribution with two relative maxima around $\theta = \pm 45^\circ$. This difference is probably due to the fact that for model INSL the ratio $\sigma_1/\sigma_2$ is closer to 1 than for model INFL; this could indicate an approximate axial symmetry about $\hat{v}_1$, which cannot be resolved by the inversion. In Figs 2(j)-(l) the PPD distributions for $L_x$, $L_y$, and $L_z$ define a rigid translation vector of 6.3 cm oriented toward the SE. This displacement, averaged over the 4 yr, corresponds to a rate of 1.6 cm yr$^{-1}$, a value compatible with the slip rate on the PFS recorded during quiescent/recharge phases (Neri et al. 2004).

Our next goal is to image the inflation source responsible for the observed deformation. Following Davis (1986), we try to interpret the source moment tensor in terms of a triaxial point-like ellipsoidal cavity with volume $V$ and internal overpressure $\Delta p$. The ellipsoid can be described by an equivalent system of double forces and double couples, and its orientation is directly related to the orientation of the principal stress axes $\hat{v}_i$. Furthermore, the axes of the ellipsoid are inversely related to the principal stresses $\sigma_i$; the semi-major axis $a$ is associated with the minimum stress $\sigma_3$, and so on. Once the ellipsoid orientation is assigned, Davis’ solution describes the ellipsoidal source in terms of its strength $V \Delta p$ and the two ratios $b/a$ and $c/a$. We point out that our inversion does not prescribe any $a$ priori constraint on the principal stress ratios since only upper and lower bounds for each stress component are fixed. As a consequence, the inverted stress tensor describes a general point source but its unambiguous interpretation as a pressurized cavity is not always possible. An additional drawback is that the analytical expressions provided by Davis (1986) allow us to compute the moment eigenvalues $M_1, M_2, M_3$ knowing $a, b, c$, but contain elliptic integrals that cannot be backward substituted.

To find the best fitting source, we perform a grid-search over the semi-axes ratios $b/a$ versus $c/a$ and we compute the misfit function

$$E = \frac{1}{2} \sqrt{\left(\frac{M_1 - M'_1}{M_1^2}\right)^2 + \left(\frac{M_2 - M'_2}{M_2^2}\right)^2}$$

where $M'_i = l^i \sigma_i (i = 1, 2, 3)$, $\sigma_i$ are the mean stress values obtained from PPD functions for models INFL and INSL (Table 1) and $M_1, M_2, M_3$ are calculated for a pressurized ellipsoidal cavity from Davis (1986). If an ellipsoidal cavity exists that provides the same moment tensor inferred from the observed deformation $E$ vanishes for the appropriate values of the ratios $b/a$ and $c/a$.

Figs 3(a) and (c) shows, in a logarithmic scale, $E$ as a function of $M_2/M_1$ and $M_2/M_3$, whereas Figs 3(b) and (d) shows $E$ as a function of $b/a$ and $c/a$. Among all the possible combinations, only moment ratios enclosed within coloured areas are compatible with ellipsoidal cavities. The best fit moment ratios inferred from our inversions, depicted by crosses in Figs 3(a) and (c), are very close but they do not lie within the filled areas. For this reason, they can be considered only approximately as ellipsoidal cavities. Furthermore, the ratios $b/a$ and $c/a$ are poorly resolvable, since the low $E$ zones are elongated (Figs 3b and d). This feature suggests a linear trade-off between $b/a$ and $c/a$ that can be used to constrain only the $b/c$ ratio. For model INFL, acceptable values of $b/a$ and $c/a$ are in the ranges 0.05–0.3 and 0.05–0.15, respectively, and $b \cong 2c$. For model INSL, $b/a$ and $c/a$ are in the ranges 0.05–0.2 and 0.05–0.2, respectively, and $b \cong c$; this confirms that model INSL is characterized by a large degree of axial symmetry around the semi-major axis $a$.

A further analysis of retrieved source properties can be carried out computing the associated volume change $\Delta V$ and overpressure $\Delta p$. The source volume change can be computed from the moment tensor as follows:

$$\Delta V = \frac{M'_1 + M'_2 + M'_3}{3(\lambda + 2\mu)}$$

where $\lambda, \mu$ are the Lamé constants. Note that this value is the actual $\Delta V$ of the element-source and it scales linearly with the initial volume $V$. The volume variation of the INSL source is reduced by 20 per cent compared to model INFL, as suggested by the 20 per cent reduction of the trace of the best fitting tensor $\sigma_{kk} = \sigma_1 + \sigma_2 + \sigma_3$ (see Table 1). As pointed out before, this is due to the sliding vector accommodating part of the deformation. The relationship between the real dimensions of the sources and the overpressure acting inside them is discussed in Trasatti et al. (2008). The ratio between the overpressure and the maximum principal stress $\Delta P/\sigma_1$ can be calculated, following Davis (1986), knowing the principal stress ratios $\sigma_3/\sigma_1$ and $\sigma_2/\sigma_1$. Assuming a source volume $V \sim 3$ km$^3$ (Bonaccorso et al. 2005), we obtain $\Delta P \sim 25$ MPa for model INFL and 20 MPa for model INSL. Note that the $\Delta P$ reduction between INFL and INSL amounts to 20 per cent, according to the lowering of $\Delta V$.

We compare model performances showing the residuals, that is theoretical minus observed displacements, in Fig. 4. GPS residuals of model INSL are, in general, lower than model INFL. This is particularly true for the vertical component (Fig. 4c), where INSL residuals are mostly very low. EDM elongations (Fig. 4b) are more difficult to evaluate since in some cases the fit improves enormously, whereas in others it worsens badly. The most relevant differences are found in the DInSAR residuals (Figs 4d and f, for model INFL and Figs 4e and g, for model INSL). The fit improves when the sliding is included, considering that the yellow pixels indicate that data and predictions are within error bars. DInSAR residuals are strongly reduced inside the sliding area and also in the western side.
Bayesian source inference at Mt Etna

Figure 3. Log10 Misfit $E$ as a function of $M_2/M_1$ versus $M_3/M_1$ and $b/a$ versus $c/a$ for models INFL (a, b) and INSL (c, d). The crosses mark the INFL and INSL principal moment ratios retrieved by the NAB inversion and shown in Table 1.

of the volcano, suggesting that, in this case, the inflation source is better constrained. Furthermore, there is no evidence of systematic unmodelled features common to all the data considered. For example, if the horizontal component of GPS in Fig. 4(a) may suggest a deficit in the retrieved inflation, the corresponding DInSAR residuals in Figs 4(f) and (g), show just the opposite.

It is reasonable asking whether the improved fit of INSL with respect to INFL is significant or is randomly related to the increased number of free parameters. We perform a formal linear regression analysis of observed versus predicted data, for both models (Fig. 5). Black lines are the best regression curves constrained to have a null intercept. The slopes of the lines approach the ideal value of 1 for both models (0.87 and 0.9 for INFL and INSL, respectively). However, model INFL shows larger scatter of data around the regression line as shown by the correlation coefficient $R^2 = 0.36$ with respect to model INSL with $R^2 = 0.75$. Furthermore, we perform the $F$-test (Fisher 1922) to check the statistical significance of the improvement of fit. We obtain $F = \chi^2_{\text{INFL}}/\chi^2_{\text{INSL}} = 1.586$; this value is larger than the critical value $F = 1.068$ (at 95 per cent confidence) corresponding to the degrees of freedom of the two models (total number of data points minus the number of unknowns). We can reasonably state that the $\chi^2$ reduction is a result of a significant difference between the models.

Finally, we can evaluate model performances by analyzing the misfit function reduction of each data set in the inversion procedure. The evaluation function is computed as a weighted average of the reduced $\chi^2$ of the three data sets (weight = 1/3), yielding 9.8 for model INFL and 6.2 for INSL. Although the null tests of single data sets emphasize the relevant role of GPS data, being 55.5 against 37.2 of EDM and 26.2 of DInSAR, the $\chi^2$ reduction attests to the importance of DInSAR data. For models INFL and INSL, respectively, the $\chi^2$ is reduced by 70 and 82 per cent for GPS, 84 and 85 per cent for EDM, 73 and 87 per cent for DInSAR, so that this data set is the best fitted among the others.

5 CONCLUSIONS

In this paper we extend the analysis of the deformation recorded at Mt Etna during the 1993–1997 inflation. In particular, this study is complementary to Trasatti et al. (2008), improving the observational constraints with the large spatial coverage SBAS-DInSAR data set. Additionally, we account for the sliding of the SE flank of Mt Etna with a simple rigid translation of a suitably defined sliding sector to estimate its influence on the retrieved source parameters.

We discuss further the role of extended high quality data, such as DInSAR, on source inference at Mt Etna by comparing with previous results from Trasatti et al. (2008). We consider model HET, whose retrieved parameters are listed in Table 1; this model is characterized by the same topography and elastic heterogeneities of model INFL. The inversion setting differs only for the data set adopted; optimization for HET is performed employing a reduced data set consisting of GPS and EDM measurements over the same time period. If we compare INFL and HET sources, we find larger differences than those emerging from models INSL and INFL.
Indeed, we observe that the source position for model HET is located \( \sim 1800 \) m SE with respect to INFL and it is slightly shallower, whereas the coordinates of the INSL source are \( \sim 1100 \) m SE of INFL at the same depth. The discrepancy between source locations is due to the deformation recorded by DInSAR data (negative vertical displacement affecting a large extent of the eastern flank of Mt Etna, as reported in Fig. 1d), a signal scarcely visible in the sparse EDM and GPS networks. Trying to match this additional information, the inversion performed with model INFL retrieves a source characterized by a high dip angle \( \delta = 66^\circ \) similar to model HET \( \delta = 62^\circ \) but located NW with respect to model HET. The shift of the source position and its more vertical dip translate into an increased...
Among all the models considered, INSL plausibly provides more accurate estimates of source parameters because it includes topography, elastic heterogeneities and the kinematic sliding of the SE sector. However, even though we show that the improvement of data fitting is statistically significant with respect to the additional complexity of INSL, the retrieved source location and geometry are still close to predictions of model INFL. We may ask whether these differences may have some relevance. It is not possible to give a general answer because this depends largely on the context. For example, the shift of 1 km (as actually found) may be slightly significant if the purpose is to determine whether the source is inside or outside the high velocity body imaged by seismic tomography (Chiarabba et al. 2004; Patanè et al. 2003). On the other hand, the same shift of 1 km may bear enormous consequences for the opening location of eruptive fractures and the path of the ensuing lava flow. This would be very important for volcanic risk mitigation and management during eruptive events. Another important issue raised in this paper concerns the interpretation of the retrieved moment tensor in terms of a small pressurized ellipsoidal cavity, following Davis (1986). We show that the implemented inversion procedure provides a generalized moment tensor that could not be univocally interpreted as an ellipsoidal cavity. Indeed, only a few combinations of principal moment tensor ratios are compatible with a pressurized ellipsoidal cavity. The moment tensors retrieved for both models INFL and INSL are very close and seismological elastic parameters, the inferred stresses (or moments) would be proportionally smaller. However, estimations of source shape and volume variation would be unchanged.

Finally, whereas Trasatti et al. (2008) focused on models characterized by realistic features such as topographic relief and crustal heterogeneities, in this work we stress the relevant role of the high quality and uniform distribution of data. Both these factors—more detailed description of the medium and wider data coverage—allow addressing with greater confidence the study of complex or multiple deformation sources. Last but not least, the small differences between the source parameters retrieved in this paper suggest that inversions should always be supported by an analysis of the statistical significance of parameter distributions.

ACKNOWLEDGMENTS

We thank A. Bonaccorso and R. Lanari for fruitful discussions. The paper benefited from constructive reviews of T. R. Walter and T. Masterlark. This research has benefited from funding provided by the Italian Presidenza del Consiglio dei Ministri—Dipartimento della Protezione Civile (DPC). Scientific papers funded by DPC do not represent its official opinion and policies.

REFERENCES


Bonforte, A., Bonaccorso, A., Guglielmino, F., Palano, M. & Puglisi, G., 2008. Feeding system and magma storage beneath Mount Etna as...


