

4 **Ground deformation modeling of flank dynamics prior**
5 **to the 2002 eruption of Mt. Etna**6 **Alessandro Bonforte · Salvatore Gambino ·**
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13 **Abstract** On 22 September 2002, 1 month before the
14 beginning of the flank eruption on the NE Rift, an M-3.7
15 earthquake struck the northeastern part of Mt. Etna, on the
16 westernmost part of the Pernicana fault. In order to
17 investigate the ground deformation pattern associated with
18 this event, a multi-disciplinary approach is presented here.
19 Just after the earthquake, specific GPS surveys were carried
20 out on two small sub-networks, aimed at monitoring the
21 eastern part of the Pernicana fault, and some baselines
22 belonging to the northeastern EDM monitoring network of
23 Mt. Etna were measured. The leveling route on the
24 northeastern flank of the volcano was also surveyed.
25 Furthermore, an investigation using SAR interferometry
26 was performed and also the continuous tilt data recorded at
27 a high precision sensor close to the epicenter were analyzed
28 to constrain the coseismic deformation. The results of the
29 geodetic surveys show a ground deformation pattern that
30 affects the entire northeastern flank of the volcano, clearly
31 shaped by the Pernicana fault, but too strong and wide to be
32 related only to an M-3.7 earthquake. Leveling and InSAR
33 data highlight a local strong subsidence, up to 7 cm, close
34 to the Pernicana fault. Significant displacements, up to
35 2 cm, were also detected on the upper part of the NE Rift
36 and in the summit craters area, while the displacements

decrease at lower altitude, suggesting that the dislocation 37
did not continue further eastward. Three-dimensional GPS 38
data inversions have been attempted in order to model the 39
ground deformation source and its relationship with the 40
volcano plumbing system. The model has also been 41
constrained by vertical displacements measured by the 42
leveling survey and by the deformation map obtained by 43
SAR interferometry. 44

Keywords Ground deformation · Modeling · 45
Flank dynamics · Volcano-tectonics · Pernicana fault · 46
Mt. Etna volcano 47

Introduction 48

The Pernicana fault system is very well known in recent 49
literature on Mt. Etna (Borgia et al. 1992; Lo Giudice and 50
Rasà 1992; Azzaro 1997; Azzaro et al. 2001; Obrizzo et al. 51
2001). It is described as one of the most active structures in 52
the geodynamic framework of the volcano, and models 53
proposing flank collapse (Borgia et al. 1992; Lo Giudice 54
and Rasà 1992) agree in identifying it as the northern 55
margin of the volcano's sliding flank. 56

Morphological evidence of the fault can be followed for 57
about 11 km, with an approximate E–W strike (Fig. 1). 58
From west to east, it intersects the NE Rift (1,900 m asl), 59
crossing the Piano Provenzana and Piano Pernicana areas, 60
and reaches the Rocca Campana area (900 m asl), where the 61
fault branches out southeastwards into a splay fault. 62

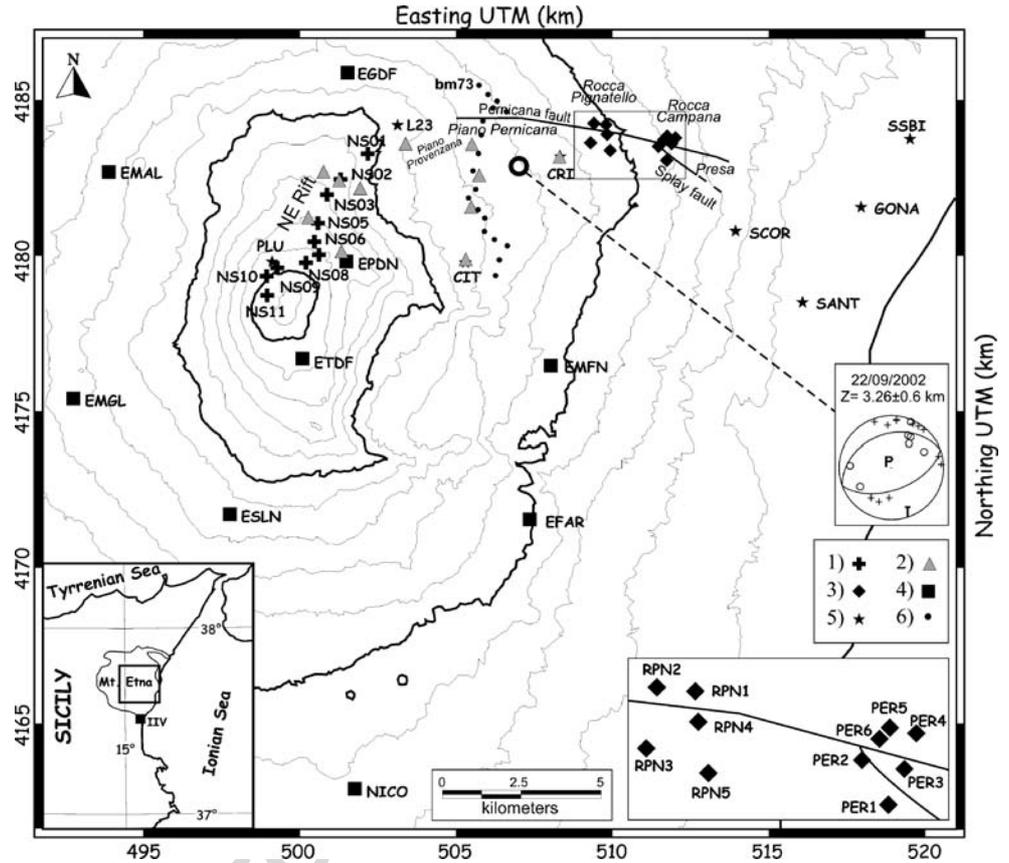
The observed direction of displacement varies along the 63
fault trace. At its upslope western end, it is almost pure 64
southward downthrown dip-slip, producing a prominent 65
south-facing scarp up to 80 m high; in the middle part, the 66
slip is left-oblique producing a south-facing scarp about 67

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Fig. 1 Mount Etna geodetic networks and main geological features of the northeastern flank of the volcano. Coordinates are in UTM projection, zone 33N. (1) GPS stations belonging to the NS kinematic profile, (2) EDM stations, (3) GPS stations belonging to the Rocca Campana and Rocca Pignatello networks (enlarged in the box in lower right corner), (4) GPS permanent stations, (5) GPS stations belonging to the Mt. Etna network periodically surveyed, (6) leveling benchmarks. Location of IIV GPS reference station is also shown. The open circle shows the location of the magnitude 3.7 earthquake of 22 September 2002



68 40 m high; at the east end, up to the village of Presa (see
 69 Fig. 1), the displacement is almost pure left-lateral strike-
 70 slip, the morphological evidence disappears, and the fault
 71 can be detected only by creep-induced damage to man-
 72 made features along the dislocation lines.

73 The western and central segments are seismogenic, with
 74 frequent shallow earthquakes, which can reach magnitudes
 75 up to 4.2, and cause surface faulting and severe damage to
 76 man-made features. The eastern segment of the fault is
 77 characterized by aseismic fault movements with evidence
 78 of activity revealed by continuous left-lateral displacements
 79 having a creep-rate of about 2 cm/year based on historic
 80 and geodetic estimations (Azzaro et al. 1998, 2001).

81 The most recent earthquakes producing large surface
 82 fractures were recorded on 25 December 1985 and 29
 83 October 1986, respectively with M 4.0 and M 4.1. Until
 84 today, although no further large earthquakes have occurred,
 85 a widespread seismicity has characterized the central and
 86 western segments of the fault, confirming that the structure
 87 is highly active.

88 On 22 September 2002, an M-3.7 earthquake, whose
 89 instrumental epicenter was located a few km south of the
 90 westernmost part of the Pernicana fault, struck the
 91 northeastern part of the volcano (Fig. 1). This event
 92 produced coseismic surface fractures and damage to man-
 93 made features in the Piano Pernicana area. In order to

measure the ground deformations associated with this 94
 event, existing GPS and EDM networks were re-occupied 95
 on the northeastern part of the volcano, and the leveling 96
 route on the northeastern flank of the volcano was 97
 surveyed. 98

Data 99

EDM network and surveys 100

An electronic distance measurements (EDM) network, 101
 situated on the northeastern flank of Mt. Etna (Fig. 1), is 102
 one of the first geodetic networks installed on the volcano 103
 for ground deformation studies at the end of the 1970s. It 104
 consists of 15 benchmarks, extending from the summit area 105
 down to an altitude of about 1,000 m and is surveyed at 106
 least yearly in summer time (Falzone et al. 1988; Nunnari 107
 and Puglisi 1997). The distances between the benchmarks 108
 of the network range from 1–5 km; the measurements are 109
 carried out using a geodimeter AGA 6000 giving a 110
 measurement accuracy of 5 mm+1 ppm. Horizontal and 111
 vertical angles are also periodically measured by using a 112
 Wild DKM3 theodolite. 113

After the 22 September 2002 earthquake, in the first 114
 days of October, several baselines of this network were 115

116 measured. The selected baselines cross the westernmost end
117 of the Pernicana fault, where this structure joints the rift
118 zone. A few baselines crossing the fault could not be
119 surveyed for meteorological and logistic reasons.

120 Leveling route and surveys

121 The leveling route on Mt Etna was installed in September
122 1980 to monitor the volcano's flanks where eruptive
123 fractures have a high probability of opening. The route is
124 150 km long, distributed along the mountain roads on the
125 southern, western, and northeastern flanks of the volcano
126 and consists of 200 benchmarks. The benchmarks are
127 generally consolidated either directly into solid lava out-
128 crops or into concrete foundations. The measurements were
129 performed with Wild NA2 levels equipped with optical
130 micrometers and invar rods. We utilized the double-run
131 precise leveling method and the mean error was less than
132 1.0 mm/km.

133 Part of the leveling route crosses the Pernicana fault
134 perpendicularly at an altitude of about 1,400 m asl. This
135 segment of the network is 11 km long and consists of 18
136 benchmarks (Fig. 1). The reference benchmark used to
137 calculate the height variations is the bm73 (see Fig. 1),
138 which lies on the northern side of the fault at a distance of
139 about 1 km from it. The first measurements on this network
140 were carried out in September 1980, and 34 surveys were
141 made up to October 2002. The analysis performed on the
142 height variations resulting by comparing the two surveys
143 encompassing the earthquake (from September 2001 to
144 October 2002) indicates a strong subsidence of the southern
145 part of the fault (foot-wall) with respect to the northern one
146 (Obrizzo et al. 2001, 2004).

147 GPS networks and surveys

148 Two geodetic networks based on global positioning
149 system (GPS) techniques, lie across the eastern segment
150 of the Pernicana fault (Fig. 1). The first one, located in the
151 "Rocca Campana" area, was installed in April 1997 and
152 consists of six self-centering benchmarks. More than 20
153 surveys were made up to September 2002, every 3–
154 4 months, giving considerable detail of the motion of the
155 fault over time. The second one, located a few kilometers
156 westward, in the "Rocca Pignatello" area, was measured for
157 the first time in July 2002; it consists of five self-centering
158 benchmarks that upgrade a pre-existing EDM network
159 (Azzaro et al. 2001). The two networks are relatively small,
160 each one covering an area of about 1 km². The aim of these
161 networks is to quantify the structural framework and
162 displacements along the aseismic-creep sector of the
163 Pernicana fault to better constrain its dynamic behavior
164 (Azzaro et al. 2001).

After the 22 September 2002 earthquake, a 4-day-long
GPS survey was carried out on the northeastern part of the
volcano. The measurements were carried out on both
networks (Rocca Campana and Rocca Pignatello), together
with some benchmarks belonging to the northeastern part of
the inner GPS network of Mt. Etna (Puglisi et al. 1998;
Bonforte and Puglisi 2003), the northernmost stations of the
"Ionica" network and the northern half of the N–S
kinematic profile (Table 1). Instruments used were Trimble
receivers (models 4000 SSI, 4000 SSE, and 4700) and
Trimble antennas (Choke Ring and Compact with ground
plane models).

GPS data collected during the surveys were processed
together with those coming from the Mt. Etna permanent
GPS network (Fig. 1). Trimble Geomatics Office package v.
1.5, manufactured by Trimble, was adopted to process the
data, using precise ephemerides computed by the National
Geodetic Survey of the National Oceanic and Atmospheric
Administration (NOAA's NGS) and distributed through
Navigation Information Service (NIS) as usually adopted
for GPS surveys on Mt. Etna (Puglisi et al. 1998; Bonforte
and Puglisi 2003). The GPS data processing was performed
by computing each baseline independently.

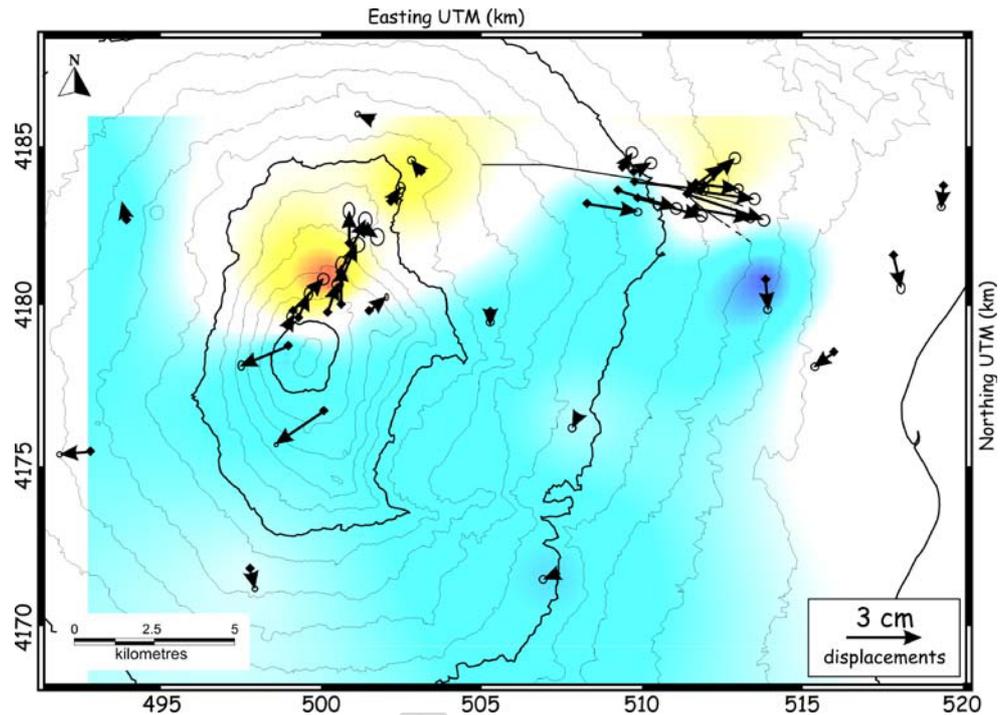
The baseline solutions were then adjusted to obtain
station coordinates with their associated errors. The
adjustment was performed using all baseline solutions,
treating the IIV station (belonging to the GPS reference
network of Mt. Etna) as fixed, to detect displacements
affecting the measured stations relative to a stable reference
(Puglisi et al. 2004).

The comparison between the results of the GPS survey
carried out in September 2002 and those of July 2002
shows a ground deformation pattern that affects the whole
northeastern flank of the volcano (Fig. 2). The pattern is
clearly shaped by the Pernicana fault; displacements of
about 2–3 cm affect all stations lying on the southern side
of the fault at the Rocca Pignatello and Rocca Campana
networks. Furthermore, the different magnitude of bench-

Table 1 Stations surveyed during the GPS survey carried out after the earthquake

Date	Stations				
25 September 2002	SCOR	GONA	SSBI	SANT	t1.3
	L23	CRI	RPN1	RPN2	t1.4
	RPN3	RPN4	RPN5		t1.5
26 September 2002	L23	CRI	RPN1	RPN2	t1.6
	RPN3	RPN4	RPN5		t1.7
27 September 2002	CRI	RPN1	RPN2	RPN4	t1.8
30 September 2002	NS01	NS02	NS03	NS05	t1.9
	NS06	NS07	NS08	NS09	t1.10
	NS10	NS11	L23	PLU	t1.11

Fig. 2 Displacements at the GPS station between 1 July and 25 September 2002



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203 mark PER3 (Rocca Campana network, see inset in Fig. 1)
 204 with respect to those of benchmarks PER1 and PER2,
 205 indicates the partition effect induced by the splay fault,
 206 which accommodates the displacement of the Pernicana
 207 fault. Unexpected significant displacements, up to 2 cm,
 208 were also detected in the upper part of the NE Rift and the
 209 summit area.

210 DInSAR data

211 The DInSAR data processing was performed using the
 212 image processing tools developed by Atlantis (EarthView
 213 InSar v. 2.0). We used SAR data from European Space
 214 Agency's (ESA) ERS2 satellite, equipped with a C band
 215 SAR with a wavelength of 5.6 cm. The procedure used for
 216 the generation of interferometric products relevant to the
 217 selected image pairs is called "two pass interferometry"
 218 (Massonet and Feigl 1998). With this method, two SAR
 219 scenes are used to generate a real-phase interferogram that
 220 is correlated with topography and changes in topography.
 221 To analyze the topographic changes, the topography-
 222 dependant part of the phase needs to be eliminated; this
 223 requires the use of a DEM. The elevation values provided
 224 by the DEM need to be converted into synthetic phase-
 225 values. In the next step, the phase-values of the real and
 226 synthetic interferograms have to be subtracted from each
 227 other. In this way, residual phase-values are obtained,
 228 resulting in a differential interferogram, which is correlated
 229 to the changes in topography (i.e., deformation) and
 230 possibly tropospheric noise.

The advantage of this approach is that it removes many
 unwanted fringes, leaving only those related to the signal of
 interest and/or errors in the DEM. The photogrammetric
 DEM used as a source for the topographic information has
 a measured accuracy of the order of 10 m. To co-register
 the two images and calculate the interferometric geometry,
 we used the precise orbits of the ERS2 satellite, produced at
 the Delft Institute for Earth Oriented Space Research
 (DEOSR). The interferogram is projected into an ortho-
 gonal geographic coordinate system, so that users need not
 work with distorted radar geometry.

The two ascending ERS2 passes (31 July 2002 and 9
 October 2002) used to generate the interferogram have a
 perpendicular baseline (i.e., the distance between the orbits)
 of only 2 m. This produces a "height ambiguity" of
 4,400 m; this means that the interferogram is sensitive to
 topographic errors equal to or larger than 4.4 km! With a
 10-m DEM error, the phase error is less than 0.1 mm, so the
 actual interferogram is insensitive to topographic errors.
 Finally, the short temporal (3 months) and spatial baselines
 produced good coherence even on vegetated areas such as
 the northeastern flank of the volcano. The tropospheric
 noise could not be removed but the resulting effect does not
 exceed half a fringe; furthermore, DInSAR data are here
 compared with GPS and leveling data, helping us to
 distinguish between atmospheric artifacts and ground
 motion.

The differential interferogram is shown in Fig. 3a. In this
 case, each fringe corresponds to a displacement of 2.8 cm
 of the ground surface along the line of sight (LOS) of the

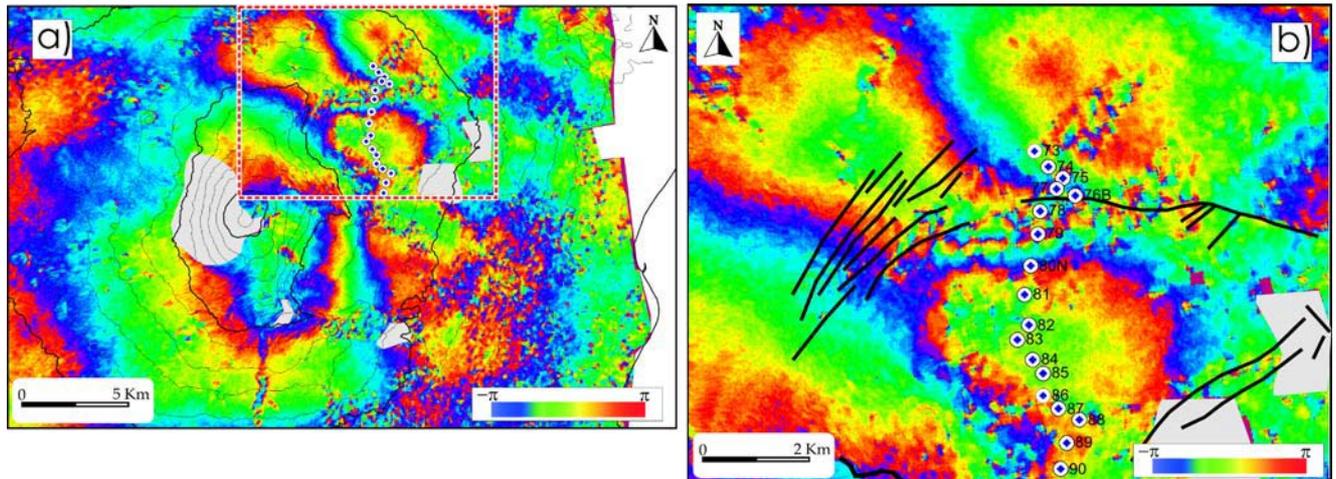


Fig. 3 Differential interferogram for ascending scene pair 31 July 2002 to 09 October 2002: **a** phase interferogram; **b** enlargement of the Pernicana area, circles indicate the leveling stations. The scale

indicates the phase variation along the LOS (negative values correspond to the approaching of the surface to the sensor)

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261 radar sensor; this means that on the interferogram we can
 262 read how the Earth surface moves away or approaches the
 263 sensor. Since the radar view angle is 23° off nadir, SAR
 264 interferometry is more sensitive to vertical movements.

265 Tilt data

266 The Mt. Etna permanent tilt network (Fig. 4a) comprises
 267 nine bi-axial instruments installed in shallow boreholes at
 268 about 3 m depth, and one long baseline instrument
 269 (Bonaccorso et al. 2004). The borehole instruments use a
 270 high precision electrolytic bubble sensor to measure the
 271 angular movement and are equipped with AGI model 510
 272 tiltmeters with a precision of 0.01 μrad, or model 722, with
 273 a precision of 0.1 μrad. The long-base tilt instrument is
 274 composed of a mercury filled tube, positioned inside two
 275 80-m-long artificial underground orthogonal tunnels at the
 276 Volcanological Observatory of Pizzi Deneri, located
 277 2,850 m asl on the northeastern flank of Mount Etna
 278 volcano (3340 m asl), 2 km away from the summit craters.

279 The fluid-filled tube is connected to three beakers at the
 280 two extremities and in the central part of the tunnels; optical
 281 laser sensors, fixed at the top of each beaker, are used to
 282 measure mercury level changes. Resolution of the instru-
 283 ment is about 0.01–0.05 μrad and data sampling is 144
 284 data/day (48 data/day for bore-hole stations).

285 Shallow borehole tiltmeters are affected by noise related
 286 to local instabilities or daily and seasonal temperature
 287 changes that may mask small changes or slow deformation
 288 with a short to medium period (from weeks to months)
 289 linked to geophysical processes. Otherwise, long-base
 290 devices can record very stable high-precision signals
 291 characterized by very low noise. The Mt. Etna long
 292 baseline instrument has been able, in recent years, to also

293 detect small variations related to seismic, eruptive, and
 294 explosive events (Bonaccorso et al. 2004).

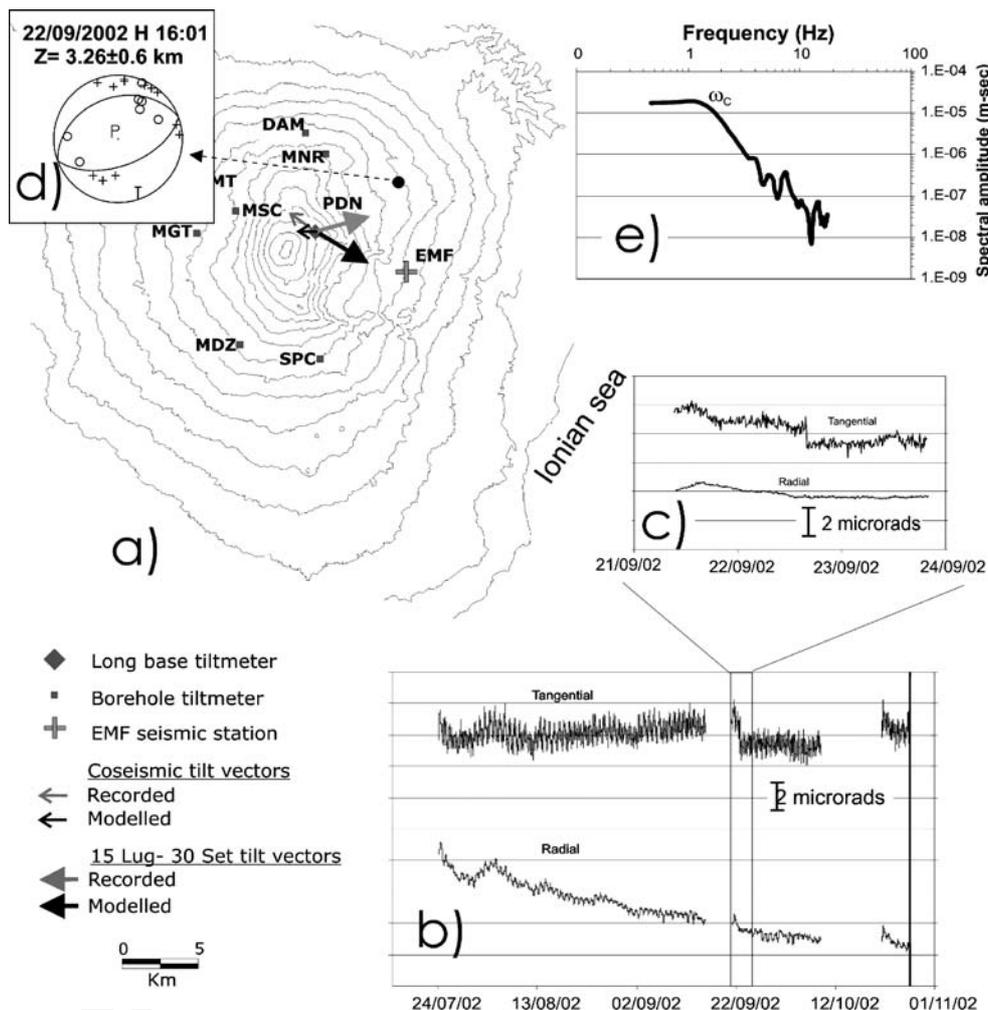
295 For the period analyzed here from July to September
 296 2002, we considered only signals recorded at the PDN long
 297 base tiltmeter (Fig. 4) that showed a clear continuous drop
 298 in the radial component (Fig. 4b). In the signals recorded at
 299 the other tilt stations, due also to the higher noise level, no
 300 significant variation is visible.

Data analysis and inversions of ground deformation data

303 The only significant data relevant to the earthquake itself is
 304 the tilt at PDN station (Fig. 4a, b). Although only one
 305 datum is not sufficient to deduce any source parameter, the
 306 PDN signal shows an evident coseismic variation that can
 307 be usefully exploited to check the agreement with the
 308 source suggested by seismic data. The PDN tilt station
 309 showed a coseismic tilt of about 1 μrad (Fig. 4c)
 310 concomitant to the strong local earthquakes (MI=3.7)
 311 recorded on 22 September at 16:01 local time by the INGV
 312 local permanent seismic network (Gambino et al. 2004).
 313 The focal solution obtained using the FPFIT algorithm
 314 (Reasenber and Oppenheimer 1985) shows a normal
 315 mechanism along a N70°E plane with a SSE 55° dip
 316 (Fig. 4d).

317 An estimate of the seismic moment release and source
 318 dimension associated with the event was obtained using the
 319 spectral analysis (omega-zero level and and corner frequen-
 320 cy) of the seismic signal recorded at EMF seismic station
 321 (Fig. 4a, e). Source parameters have been estimated after
 322 the application of instrumental, attenuation, and geometrical
 323 spreading corrections on P-wave displacement spectra

Fig. 4 **a** Mount Etna permanent tilt network with recorded and expected tilt vectors at PDN station. **b** Tilt signals recorded at PDN station; with tilt radial to the summit (positive means uplift anticlockwise). **c** Coseismic tilt variation at PDN station. **d** Focal solution of the 22 September 2002 earthquake. **e** P-wave displacement spectrum



324 (Fig. 4e). The seismic moment obtained by omega-zero
 325 level (Brune 1970) is 3.6×10^{21} dyne \times cm, while a fault
 326 radius of 0.8 km has been estimated using the corner
 327 frequency (Brune 1970).
 328 The average slip has been obtained by the general
 329 relation (Aki 1966):

$$M_0 = \mu * S * \bar{u}$$

330 As medium rigidity is not well known, we considered a
 331 value ranging from 10^{11} dyne/cm² (Bonaccorso and Patané
 332 2001) to 2×10^{11} dyne/cm² obtaining an average slip \bar{u} of
 333 about 1–2 cm.
 334 Taking these results (fault area and average slip) into
 335 account, we computed ca. 0.3–0.5 μ rad of expected tilt
 336 change (at PDN station) (Fig. 4a) for a tabular dislocation
 337 model (Okada 1985) striking N70°E, dip 55°, located at the
 338 earthquake hypocenter.
 339 The recorded and expected (from the model) tilt vectors
 340 are comparable in magnitude and show slightly different
 341 directions (Fig. 4a). Conversely, the slip observed along the
 342 fault (R. Pignatello and R. Campana areas) from July to
 343
 344

September is more than that expected from an M-3.7
 345 earthquake. The average slip measured by GPS measure-
 346 ments is of the order of 2–3 cm over a period of about
 347 2 months, while the surface movements that the earthquake
 348 should produce from the above model, are of the order of
 349 1 mm. The resulting measured slip rate is of the order of
 350 10 cm/year. Compared with the mean rate measured after
 351 the 2001 eruption, this value does not indicate a significant
 352 short-term acceleration. Furthermore, even in the years pre-
 353 2001, acceleration was sometimes observed, not necessarily
 354 associated to volcanic or seismic events (Azzaro et al.
 355 2001; Fig. 5).
 356

The comparison between the EDM measurements
 357 carried out in October 2002 and those carried out on the
 358 entire network in June 2002 (Fig. 6) shows significant
 359 deformation only on the lines crossing the western end of
 360 the Pernicana fault. The only variations exceeding the
 361 experimental error of 5 mm+1 ppm are extensions,
 362 measured on the slope distances connecting Mt. Nero,
 363 Bocche 1809, C. Linguaglossa and Pizzi Deneri bench-
 364 marks, on the northwestern side, with R. Puchoz, Due
 365

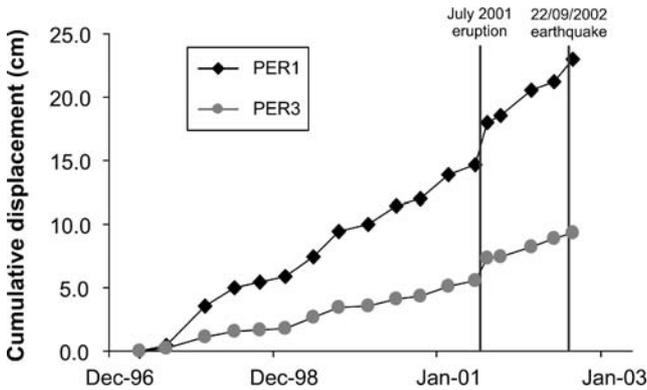


Fig. 5 Slip rate measured at “Rocca Campana” GPS network since 1997. The displacements are referred to PER5 benchmark (see Fig. 1)

366 Monti, Lave 1865, R. Citelli and M. Crisimo benchmarks,
 367 on the southeastern side of the fault. These extensions range
 368 between 1.3 and 3.1 cm.

369 The comparison of the two leveling surveys (Fig. 7)
 370 shows an abrupt vertical displacement of the southern side
 371 of the Pernicana fault, with a local maximum subsidence of
 372 -65 mm very close to the fault plane, rapidly decreasing to
 373 zero about 2 km to the south. The southernmost part of the
 374 route shows a slight uplift of less than 10 mm. As with the
 375 tilt data, the measured ground deformation seems larger
 376 than expected from the model of the M-3.7 earthquake,
 377 even if we consider that the time since the previous leveling
 378 survey is longer; from September 2001 to October 2002.

379 A preliminary analysis of the interferogram (Fig. 3)
 380 shows relative stability in the imaged area, especially taking
 381 into account the uncertainty of half a fringe due to

instrumental and atmospheric effects, apart from a SE– 382
 NW elongated area in the upper part of the Pernicana fault, 383
 between the Piano Provenzana and the Piano Pernicana 384
 areas, and shown in detail in the inset, Fig. 3b. Here, a 385
 gradient of three fringes between benchmarks 76B and 80N 386
 induces a maximum dislocation of about +8 cm along the 387
 line of sight of the SAR sensor, on the southern side of the 388
 fault. DInSAR ground deformation data at the pixels 389
 corresponding to the leveling benchmarks are compared to 390
 leveling values in Fig. 7. The measurements are in good 391
 agreement, showing relative stability of the area, apart from 392
 a very local subsidence just south of the Pernicana fault. 393
 The stronger deformation measured by DInSAR at bench- 394
 marks 78, 79 and 80N is perhaps due to the horizontal 395
 component of motion. In the eastern part of the interfero- 396
 gram, a progressive increase of the ground-satellite distance 397
 of the order of 1.5 fringes, is visible. This type of fringe 398
 pattern is known from previous ERS observations of Mt. 399
 Etna and has been interpreted as a local effect of the 400
 Pernicana fault (Lundgren et al. 2003). 401

402 All the above data depict ground movement in relatively 402
 small areas and are most probably not produced by the M- 403
 3.7 earthquake alone, because the displacement is too large. 404
 Together with the significant ground deformation measured 405
 by GPS network, this suggests that the origin of this 406
 complex ground deformation pattern measured during the 407
 months encompassing the earthquake, is not just related to 408
 the seismic event. To investigate the origin of this pattern, 409
 the GPS data shown in Fig. 2 were inverted, because they 410
 are the only data suitable for an analytic inversion of 411
 sufficient detail to deduce source locations with confidence. 412

Fig. 6 Baseline variations measured by EDM between June and October 2002

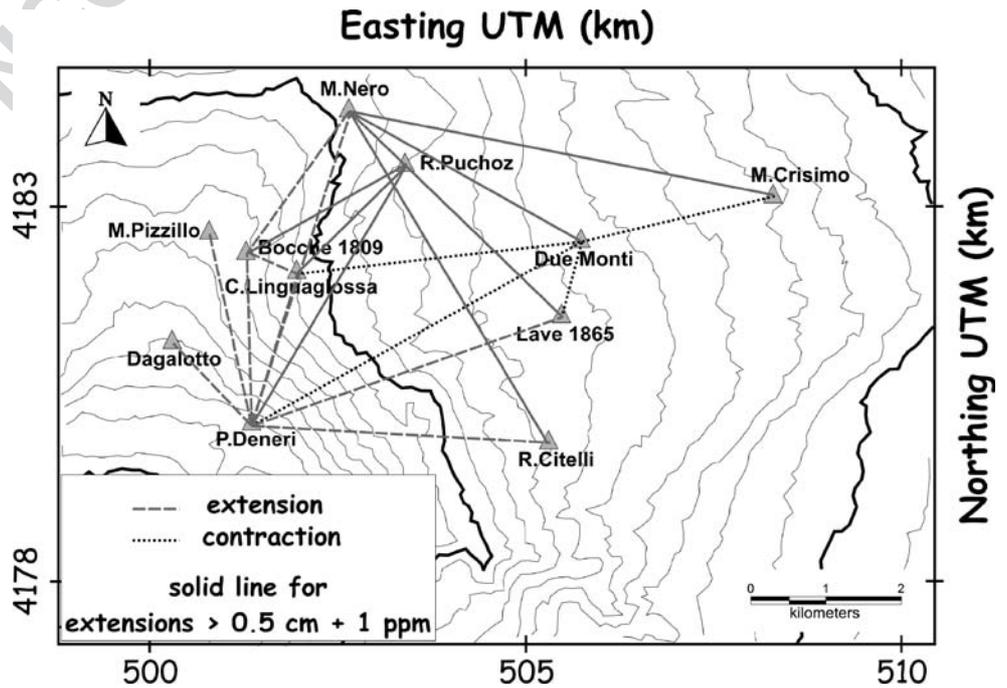
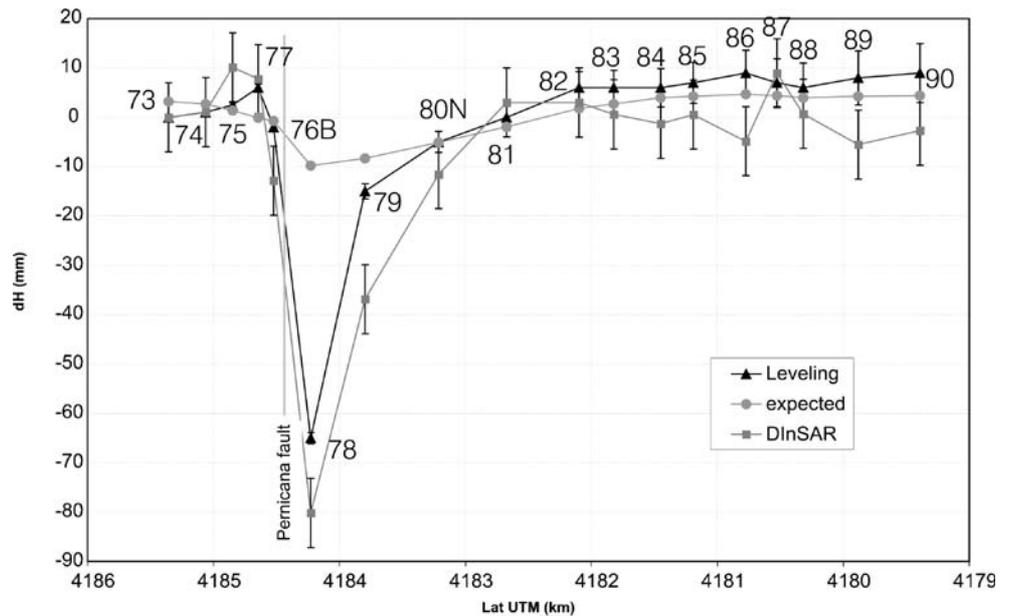


Fig. 7 Measured and expected (from the model) vertical displacements along the leveling route. The LOS displacements measured by DInSAR are also reported



413 GPS provides three-dimensional displacement measurements across the entire deformed area within a relatively short-time interval (3 months) encompassing the seismic event. The other ground deformation data (i.e., leveling, InSAR, EDM, and tilt) is useful in refining the model obtained from GPS data.

419 The Okada (1985) dislocation model and a least squares algorithm (LQA) were used to perform the data inversions, using a procedure that has been successfully applied to Mt. Etna GPS data (Puglisi et al. 2004 and references herein). The use of the Okada model requires the estimation of 10 dislocation parameters: its three-dimensional position, dimensions, orientation of both azimuth and dip, displacement of strike slip and dip slip and opening, and width. The use of LQA needs an appropriate set of starting values for each source parameter, as close as possible to the true value. To this end, available broad geological information is taken into account.

431 Visual inspection of the GPS displacement vectors (Fig. 2) suggests that besides the Pernicana and splay faults, there could be at least three other sources in the higher part of the volcano. Firstly, the NE Rift, secondly the structural link between the Pernicana and the NE Rift in the area of Piano Provenzana, and thirdly beneath the summit craters. The latter probably tensile, judging from the displacement vectors measured at the uppermost stations of the N-S kinematic profile and the TDF permanent station. The inversion was therefore performed using five dislocation sources, excluding the fault producing the earthquake, because the very small movements expected from this source are within the errors of the GPS surveys. The first two sources, in the central eastern part of the Pernicana fault, were located in position, azimuth, and length, using field evidence. The other three sources: the

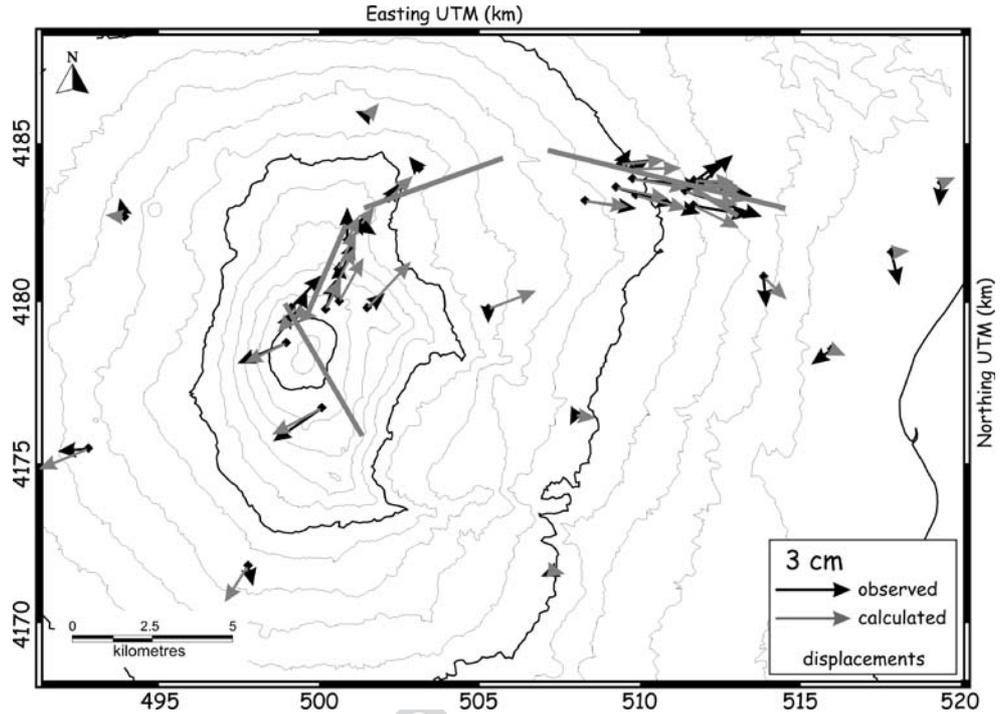
447 NE Rift, the Provenzana, and the summit craters dislocations were positioned as shallow vertical planes bordering the sliding sector of the NE Rift and beneath the summit craters. The azimuth of the summit craters dislocation was oriented approximately perpendicular to the displacement vectors, and the motion was fixed as pure tensile. The Provenzana fault trend, clearly visible in the field was then added to fit the very local deformation measured by EDM, InSAR, and leveling.

456 In Fig. 8, the location of the sources and the relevant expected horizontal displacement vectors are shown as are the comparisons with EDM data in Table 2. The final parameters of the model are given in Table 3. The expected vertical displacements fit the leveling measurements well, except for the very local deformation observed close to the Pernicana fault (Fig. 7), where the leveling line shows a greater subsidence than the model. The good agreement between leveling and InSAR confirms that an intense local deformation episode occurred close to the Pernicana fault, perturbing the ground deformation pattern expected from the theoretical model. Just 1 km south of the fault, the misfit between the expected and measured displacements is within the errors. These considerations represent a strong validation of both the model and dataset.

Discussions

472 GPS, EDM, leveling, and DInSAR data analyzed in this paper depict a very complex ground deformation pattern resulting from the intersection of several individual patterns, each one characterized by different temporal and spatial wavelength and intensity. As far as the earthquake is concerned, it produced a much weaker ground deformation

Fig. 8 Expected and measured displacements for the GPS network. The modeled structures are also shown. Coordinates are in UTM projection, zone 33N



t2.1 **Table 2** Observed and calculated length variations at EDM benchmarks

t2.2	EDM lines	Measured variations (cm)	Expected variations (cm)
t2.3	C. Linguaglossa–Due Monti	−0.2	−0.1
t2.4	P. Deneri–Due Monti	−0.2	−0.4
t2.5	P. Deneri–R. Citelli	0.7	0.5
t2.6	Lave 1865–Due Monti	−0.4	0.0
t2.7	P. Deneri–Lave 1865	0.9	−0.1
t2.8	M. Pizzillo–P. Deneri	0.3	−1.0
t2.9	Dagalotto–P. Deneri	0.2	−0.1
t2.10	P. Deneri–R. Puchoz	1.3	−0.8
t2.11	Bocche 1809–P. Deneri	0.2	−0.7
t2.12	Bocche 1809–R. Puchoz	2.8	0.0
t2.13	Due Monti–M. Crisimo	−0.9	−0.5
t2.14	C. Linguaglossa–Lave 1865	0.0	0.3
t2.15	C. Linguaglossa–R. Puchoz	2.4	−0.5
t2.16	P. Deneri–C. Linguaglossa	0.7	−0.3
t2.17	Bocche 1809–C. Linguaglossa	0.7	0.2
t2.18	M. Nero–Due Monti	2.5	1.6
t2.19	M. Nero–M. Crisimo	1.6	1.8
t2.20	M. Nero–Lave 1865	2.5	1.8
t2.21	M. Nero–R. Citelli	3.1	1.9
t2.22	Bocche 1809–M. Nero	−0.1	−0.2
t2.23	P. Deneri–M. Nero	−0.3	−0.6

field, giving rise to millimetric movements also close to the epicenter area. The only instrumental data relevant to this pattern is from the very sensitive long-base tilt station, about five km away from the epicenter, which measured a tilt of about 1 μ rad.

Conversely, very intense but local deformations were measured by the leveling and InSAR techniques close to the Pernicana fault, in the area between the Piano Pernicana and the Piano Provenzana, probably linked to instability along the fault plane triggered by the earthquake. Several conditions could favor such phenomenon: first of all, the topographic and structural conditions, and/or the properties of the outcropping rocks. This area is located near the junction between the Pernicana fault and the NE Rift zone, which is defined by several southeasterly dipping right-stepping *en échelon* extensional fractures (Tibaldi and Groppelli 2002). The fault displacements measured by Tibaldi and Groppelli (2002) here in recent decades clearly indicate an oblique movement (mainly a normal dip-slip with a significant left-lateral component) along the Pernicana fault. Certainly, these sliding movements are facilitated by the scoria outcropping in this area. The instability seems to be confirmed by the subsidence of the benchmark located just north of the fault (Fig. 7). Since this benchmark lies on the footwall of the fault, it is reasonable to relate its motion to sliding of the unstable fault scarp. Our data and the geological framework summarized above are also consistent with the very large movements observed by Acocella et al. (2003) in this area using strainmeters installed in the wall bordering the road that has clearly been affected by instability. The local uplift measured by

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t3.1 **Table 3** Parameters of the modelled sources for the eastern part of the Pernicana fault

t3.2	Tensile fault	NE Rift	Provenzana fault	Pernicana fault	Splay fault	
t3.3	Longitude (km)	500.200±0.2	499.900±0.2	503.650±0.04	510.590	512.200
t3.4	Latitude (km)	4178.100±0.3	4181.300±0.2	4183.890±0.03	4183.930	4183.400
t3.5	Azimuth	N150°E	N23°E	N70°E	N104°E	N123°E
t3.6	Depth (km asl)	0.9±0.3	1.1±0.2	1.2	0.9±0.02	0.96±0.02
t3.7	Length (km)	4.8±0.4	3.2±0.3	4.6±0.4	7.6	1.0
t3.8	Width (km)	4.7±0.3	1.6±0.2	2.6±0.1	2.3±0.1	1.6±0.1
t3.9	Dip	77°±2°	60.8°±3°	60°±2°	58°±2°	81.8°±2°
t3.10	Strike slip (>0 if left-lateral) (cm)	0	1.6±0.3	0.5±0.2	2.9±0.3	2.9±0.5
t3.11	Dip slip (>0 if normal) (cm)	0	3.4±0.4	4.0±0.5	-0.7±0.5	0.6±0.3
t3.12	Opening (cm)	17.2±2.3	-2.2±0.8	0.5±0.2	1.2±0.3	1.5±0.3

509 SAR northwest of the Provenzana area (including the NE
510 Rift; Fig. 3b) is outside the area monitored. This unfortu-
511 nately prevents any meaningful discussion on the origin of
512 this unexpected feature. A simple analytical model predicts
513 an uplift of the same magnitude as the subsidence measured
514 on the hangingwall (benchmark 78), due to the normal
515 movement of the Pernicana fault. The available data do not
516 confirm either that this interferometric feature is a tropo-
517 spheric effect or that it is produced by deformation related
518 to local dynamics of the NE Rift. It is remarkable that this
519 area corresponds to the lower part of the eruptive fissure
520 field opened 1 month later.

521 The GPS data inversion also indicates broader ground
522 deformation pattern. The movements of the five planar
523 structures produce a general eastward motion of the
524 northeastern sector of Mt. Etna. The moving sector is
525 bounded westward by the Provenzana fault–NE Rift
526 system, which behaves mainly as a normal fault, and
527 northward by the left-lateral transcurrent Pernicana fault.
528 Southwestward it is bounded by a tensile structure that
529 could indicate shallow intrusion of a dyke beneath the
530 summit craters (Fig. 8).

531 The general eastward motion is accompanied by a
532 westward tilt of the sliding block, as shown by the data
533 from the PDN tilt station (Fig. 4), and a lowering of the NE
534 Rift. The rotation of this block is also clear both by the
535 normal behavior of the Provenzana fault–NE Rift system
536 and by the left-lateral behavior of the Pernicana fault (see
537 fault parameters in Table 3). It is also confirmed by EDM
538 measurements on the upper part of this flank of the
539 volcano, which show significant extensions of the lines
540 crossing the NE Rift and the uppermost part of the
541 Pernicana fault. The EDM measurements, generally agree
542 with the GPS excluding those baselines involving the R.
543 Puchoz benchmark, which is very close to the uppermost
544 part of the Pernicana fault. This misfit is probably due to
545 the non-elastic behavior of the medium so close to the fault.

546 All the above considerations lead us to hypothesize that
547 the earthquake resulted from the movement of the entire

northeastern flank of the volcano rather than its cause. Also
548 the tilt station did not measure any evident change in the
549 trend of motion after the earthquake, highlighting how the
550 coseismic ground deformation is much less significant than
551 that occurring before and after the earthquake, as observed
552 by GPS, EDM, leveling, and InSAR techniques. This
553 confirms the hypothesis that the earthquake was not an
554 exceptional event and did not represent a change in the
555 dynamics of the volcano.
556

557 Although this study does not deal with the origins of the
558 eastward movement of the eastern flank of Mt. Etna, it is
559 indisputable that this movement exists, as confirmed by
560 several geological and geophysical studies. This motion is
561 supposed to originate from gravity (e.g., the weight of the
562 plutonic intrusion beneath the volcano or the mass of the
563 eastern flank) and/or from the pressure induced by
564 magmatic intrusion into the volcanic edifice. GPS and
565 InSAR data have extended the knowledge of the eastward
566 sliding of the eastern flank, pointing out that it exists
567 together with the southward displacement of southern
568 flanks (Froger et al. 2001; Bonforte 2002; Bonforte and
569 Puglisi 2003; Palano 2003). These slow movements are
570 active even without any evidence of shallow intrusions, so
571 that an independent source with respect to the current
572 volcanic activity is the most probable origin in the long
573 term. Furthermore, these movements require two near-
574 horizontal detachment surfaces modeled at depths of about
575 2 and 0.5 km (Bonforte 2002; Bonforte and Puglisi 2003).
576 However, Bonforte and Puglisi (2003) didn't exclude the
577 possibility that shallow intrusions might accelerate the
578 motions, producing significant slips along fault surfaces,
579 e.g., as observed during the 2001 eruption (Bonforte et al.
580 2004) and seismic stress release along the Pernicana fault,
581 e.g., the case of the 1994 earthquake (Puglisi et al. 2001).
582 However, the data discussed here suggest that this is not the
583 case for the September earthquake, because the two local
584 networks at Pernicana do not show any significantly strong
585 acceleration. The slip rate measured for the July–September
586 period is indeed rather higher than the mean slip rate of the

587 fault, but falls within the range of variation observed since
 588 1996 (Fig. 5). Other periods characterized by higher slip
 589 rates have been detected (e.g., in 1999), accompanied by no
 590 significant seismic events; and in any case, the acceleration
 591 accompanying the 22 September 2002, earthquake was not
 592 comparable to that produced by the 2001 dyke intrusion
 593 that produced almost twice the usual slip rate, even though
 594 the eruptive fissures opened on the southern flank of the
 595 volcano far from the Pernicana area. These considerations
 596 indicate that the earthquake released the energy accumulat-
 597 ed along a particular segment of the Pernicana fault (or
 598 some other structure linked to it) by widespread and
 599 continuous eastward sliding of this flank of the volcano
 600 during the summer of 2002.

601 Regarding the summit tensile structure, it is probably an
 602 effect of the eastward and southward motion of the eastern
 603 flanks of the volcano because its trend and the tensional
 604 component are compatible with the movements of the two
 605 near-horizontal detachment surfaces modeled by Bonforte
 606 and Puglisi (2003). The movements of these two surfaces
 607 produce a depressurization in the upper part of the volcano
 608 along a NNW–SSE trend, allowing the subsequent ascent
 609 of magma towards the surface. It is noteworthy that the
 610 lateral eruption, which started about 1 month after 22
 611 September 2002, was triggered by a fast-evolving dyke
 612 located at the southern end of the intrusion modeled here,
 613 having similar depth, trend, and dip (Aloisi et al. 2003). In
 614 conclusion, we interpret this tensile structure as a dyke
 615 formed in the same area as the intrusion that led to the 2001
 616 eruption, confirming that the NNW–SSE trend in the upper
 617 southern flank of the volcano is the preferential path for
 618 shallow magmatic ascent, even for recent volcanic activity
 619 (Puglisi and Bonforte 2004).

620 Finally, earthquake and intrusion occurring on Mt. Etna
 621 in the summer of 2002 seem to originate from the eastward
 622 motion of the eastern flank. This motion, together with that
 623 of the southern flank, is nearly continuous on Mt. Etna, and
 624 GPS data do not show any significant acceleration in the
 625 summer of 2002, so that eastward sliding cannot be
 626 considered the direct cause of the eruption occurring
 627 1 month after the earthquake, as suggested, for instance,
 628 by Acocella et al. (2003). However, this motion certainly
 629 broadly facilitated the eruption onset for several reasons.
 630 First, the intrusion modeled by GPS data “prepared” the
 631 path for the uprising magma along a NNW–SSE trend, in
 632 which the dyke feeding the eruption intruded (Aloisi et al.
 633 2003). Furthermore, the extension detected on the Proven-
 634 zana fault–NE Rift system weakened this flank of the
 635 volcano, facilitating the very fast intrusion of the batch of
 636 magma coming from the summit conduit, along the NE
 637 Rift, feeding the vents of the eruption of 28 October to 3
 638 November 2002. Finally, if the earthquake released the
 639 stress accumulated along a locked segment of the Pernicana

640 fault that was resistant to sliding, it allowed the eastward
 641 motion to continue.

642 Conclusions

643 The 22 September 2002 earthquake spurred three field
 644 campaigns and five ground deformation techniques to
 645 define the strain pattern associated with this event. The
 646 results of these researches throw new light on the dynamics
 647 of Mt. Etna just before the onset of the 2002–2003
 648 eruption.

649 A first remarkable result is that the ground deformation
 650 pattern detected by integrating GPS, EDM, leveling, and
 651 DinSAR is too big (both in intensity and extension) for an
 652 M-3.7 earthquake. The coseismic tilt variation produces
 653 significant effects only at the PDN station (a high precision
 654 long-base tiltmeter). The expected ground deformation
 655 produced by the earthquake source alone, as deduced by
 656 seismic data, is too small to be measured by GPS, leveling,
 657 EDM surveys and by DInSAR measurements.

658 To investigate the true origin of this unexpected pattern,
 659 GPS displacement vectors from a 2-month period encom-
 660 passing the seismic event were inverted. The results show a
 661 transcurrent fault-system (the Pernicana), a normal fault-
 662 system (the Provenzana–Rift system) and an intrusion
 663 bounding the eastward moving northeastern sector of Mt.
 664 Etna. Whatever the origin of this eastward motion, which is
 665 nearly continuous on Mt. Etna, it did not significantly
 666 accelerate in the late summer of 2002; even if some local
 667 effects, due to the instabilities along the fault plane
 668 triggered by the earthquake, emphasizes the coseismic
 669 deformation at the surface. We may thus affirm that the
 670 earthquake was a result of the continuous motion that had
 671 accumulated stress along a locked segment of the fault,
 672 rather than the cause of the measured ground deformation
 673 pattern.

674 The complex of structure resulting from these inver-
 675 sions coincide with the principal structures that were
 676 active during the early days of the 2002–2003 eruption:
 677 the NNW–SSE trending tensile plane that apparently
 678 facilitated the injection of the dyke triggering the eruption,
 679 the Provenzana–NE Rift system that was intruded in a
 680 few hours on 28–29 October, and the Pernicana fault that
 681 moved about 0.6 m from 27–28 October. In that context,
 682 the dynamics of Mt. Etna in the summer of 2002 resulted
 683 in optimal conditions for the onset of the 2002–2003
 684 eruption.

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