

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28

**Modeling ground deformation associated with the destructive earthquakes
occurring on Mt. Etna's southeastern flank in 1984**

Flavio Cannavò¹, Salvatore Gambino¹, Biagio Puglisi², Rosanna Velardita²

¹*Istituto Nazionale di Geofisica e Vulcanologia, - Osservatorio Etneo, Piazza Roma 2, Catania, Italy*

²*Istituto Nazionale di Geofisica e Vulcanologia, - Osservatorio Etneo, Via Monti Rossi, 95123 Nicolosi (CT), Italy*

Submitted to Natural Hazards and Earth System Sciences

Correspondence to:

Dr. Salvatore Gambino
Istituto Nazionale di Geofisica e Vulcanologia
Sezione di Catania Osservatorio Etneo
P.zza Roma 2, 95123 Catania, Italy
tel. number 39-95-7165877
fax number: 39-957165826
e-mail: Salvatore.gambino@ingv.it

29 **Abstract**

30 The Timpe Fault System is the source of very shallow but destructive earthquakes that affect
31 several towns and villages on the eastern flank of Mt. Etna (Italy). In 1984, several seismic events,
32 and specifically on October 25, caused one fatality, 12 injuries and produced serious damage in the
33 Zafferana and Acireale territories. This seismicity was mainly related to the activity of the Fiandaca
34 Fault, one of the structures belonging to the Timpe Fault System.

35 We inverted ground deformation data collected by a geodimeter trilateration network set up in 1977
36 at a low altitude along the eastern side of the volcano in order to define the Timpe Fault System
37 faulting mechanisms linked to the seismicity in 1984.

38 We found that in the May 1980-October 1984 period, the Fiandaca Fault was affected by a strike
39 slip and normal dip slip of about 27 and 23cm. This result is ~~in fairly good accord~~ with field
40 observations of the co-seismic ground ruptures along the fault but it's notably large compared to
41 displacements estimated by seismicity, then suggesting that most of the slip over the fault plane was
42 aseismic.

43 The results once again confirm how seismicity and in particular ground ruptures represent a very
44 high hazard to the several towns and villages situated along the Fiandaca Fault.

45 **Keywords:** *Geodetic observations, flank dynamics, fault displacements, shallow earthquakes*

46

47 **1.0 Introduction**

48 The determination of finite fault geometry and slip for severe earthquakes is important for the
49 mitigation of seismic hazard and in particular for very shallow earthquakes that entail surface
50 fracturing.

51 On the eastern flank of Etna volcano, movements along very shallow normal faults generate
52 recurrent seismicity sometimes leading to destructive events, since densely urbanized areas are

53 located on these structures (e.g. [Azzaro et al., 2012](#); [Barreca et al., 2013c](#)). The Timpe Fault System
54 (TFS) is the main source generating the strongest earthquakes known over the last 200 years
55 ([Azzaro et al., 2012](#)).

56 The TFS dissects the southern-eastern flank of Mt. Etna (Fig. 1) and is formed by several fault
57 segments that include the Fiandaca (FF), S. Tecla (STF), S. Venerina (SVF), Moscarello (MF) and
58 San Leonardello (SLF) faults (fig. 2B), generally characterized by normal and right-lateral
59 dynamics ([Azzaro, 1999](#); [Azzaro et al., 2000](#)).

60 The TFS shows right-lateral and normal dip-slip kinematics and each fault segment is characterized
61 by earthquake related displacements of tens of centimeters and aseismic sliding behavior with slip
62 rates of few mm/year ([Bonforte et al., 2011](#); [Azzaro, 2004](#)).

63 Shallow seismicity (< 3 km), associated with these faults, includes the occurrence of several
64 earthquakes with magnitude up to 4.5 ([Azzaro et al., 2000](#)) with epicenter in the fault areas. Despite
65 their low-energy release, these events produced destructive effects, with fatalities and injuries, in a
66 very narrow area where they can reach epicentral macroseismic intensity I_0 up to VIII/IX EMS
67 (European Macroseismic Scale, [Grünthal, 1998](#)), often accompanied by coseismic surface
68 fracturing (e.g. [Azzaro, 1999](#); [2004](#)) with a mean recurrence time of about 20 years ([Azzaro et al.,](#)
69 [2013c](#)). The last destructive episodes with $I_0=VIII$ were recorded on 25 October 1984 and 29
70 October 2002. The first is the subject of this work while the second, linked to the SVF dynamics,
71 caused damage at Santa Venerina village ([Azzaro et al., 2006](#); [La Delfa et al., 2007](#)).

72 During the second half of October 1984, an anomalous large number of seismic events,
73 concentrated mostly on the eastern side of the volcano, were recorded on Mt. Etna ([Gresta et al.,](#)
74 [1987](#)). The main events occurred in particular on 19 and on 25 October 1984, respectively at 17.43
75 and 01:11, with epicentral macroseismic intensity I_0 VII (19.10) and VIII (25.10) EMS, which
76 struck the territory of Zafferana and in particular the villages of Fleri and Pisano.

77 The 25 October earthquake was linked to the activity of the Fiandaca Fault (FF) ([Azzaro, 1999](#)),
78 while that on 19 October was located in proximity of the Santa Tecla fault (STF). In this paper, we

79 examine the slope distance measurements collected between 1977 and 1985 by a geodimeter
80 trilateration network (Ionica Network, Fig. 2A) set up in 1977 along the eastern edge of the volcano
81 at low altitude (0-700 m b.s.l.) and measured until 1985, to shed new light on the kinematic aspects
82 of this sequence of earthquakes. Indeed, the previously unpublished data, except for an internal
83 report (AA.VV., 1985 in Italian), have been reviewed in the wake of new knowledge acquired in the
84 last two decades, enabling insights into Etna's eastern flank dynamics that were not possible at the
85 acquisition time.

86

87 **2.0 Mt. Etna and its structural framework**

88 Mount Etna (Fig. 1) is a large basaltic volcano built up in a geodynamic setting generated during the
89 Neogene convergence between the African and European plates (e.g. Allard et al., 2006; Branca et
90 al., 2011). It is situated on the eastern coast of Sicily and is one of the most active volcanoes in the
91 world. Mount Etna's activity may be grouped into two types: persistent activity comprising
92 degassing phases alternating with strombolian activity, which may evolve into lava fountains and
93 effusive events, and lateral flank eruptions occurring along fracture systems that are generally
94 preceded by an intrusive process (e.g. Aloisi et al., 2006). The volcano is located at the intersection
95 of two main regional fault systems, having NNW–SSE and NE–SW trends ~~respectively~~ (Fig. 1).
96 The NNW–SSE structural system represents the Sicilian onshore continuation of the Malta
97 Escarpment (ME), the major crustal-scale fault separating the continental African platform from the
98 oceanic Ionian Basin. Ripe Della Naca in Fig. 1 represents surface evidence related to NE-SW
99 Messina-Fiumefreddo (MF) ~~ME~~, while the faults of the “Timpe” system are the major tectonic
100 surface manifestations of the ME. The interaction between regional stress, dike-induced rifting and
101 gravity force is the cause of a fairly continuous and roughly eastward and downward motion of its
102 eastern flank (e.g. Puglisi and Bonforte, 2003; Solaro et al., 2010). This sliding area (Fig. 1) is
103 delimited to the north by the Pernicana–Provenzana Fault System (PFS) (e.g. Obrizzo, 2001;

104 [Alparone et al., 2013a](#)), a transtensive E–W trending complex active tectonic structure, while the
105 Trecastagni ~~and~~ Tremestieri faults (e.g. [Bonforte et al., 2013](#)) represent the main southern
106 boundaries. The Mt. Etna GPS network has enabled us to determine how the entire eastern flank is
107 affected by an ESE-ward motion, at a mean rate of about 1-3 cm/year (e.g. [Bonforte et al., 2011](#);
108 [Gambino et al., 2011](#)). Moreover, starting from 1980, the sliding area underwent two marked
109 acceleration phases in October 1984–1986 and in October 2002–2005, as described in [Alparone et](#)
110 [al. \(2013c\)](#). The authors also highlight a significant temporal correlation between periods of flank
111 acceleration and intensified seismic activity. The TFS is very active from the seismic point of view,
112 both for the number of events and for maximum intensity reached at the epicentre ([Azzaro et al.,](#)
113 [2013a](#)). TFS is characterized by surface faults of considerable length (up to 8–10 km) and scarps
114 ([Azzaro, 1999](#); [Lanzafame et al., 1994](#)). It includes (Fig. 2B) N140°E striking faults (FF, STF and
115 SVF), which define normal right-lateral structures extending from the town of Acireale to Zafferana
116 Etna and the MF and SLF faults with N160°E structural trend that dissect the base of the volcano's
117 flank by prevailing vertical movements ([Azzaro et al., 2013a](#)).

118 The TFS plays a key role in the local tectonics accommodating the ESE motion; this fault system
119 divides the sliding sector into several blocks ([Solaro et al., 2010](#); [Bonforte et al., 2011](#))
120 characterized by homogeneous kinematics with relative motion measured by Permanent Scatterers
121 (PS) along the faults of about 3-5 mm/years in a “quiet” period such as 1995-2000 ([Bonforte et al.,](#)
122 [2011](#)).

123

124 **3.0 Mt. Etna seismicity during 1984**

125 In October 1984, an intense seismic sequence was recorded on Mt. Etna area that marked an
126 unusual behavior of the volcano. This swarm comprised more than 1000 earthquakes with $M > 2.0$
127 over two weeks (16-30 October) and that involved the summit area and almost the entire eastern
128 flank ([Gresta et al., 1987](#); [Gresta and Musumeci, 1997](#)).

129 In particular, thousands of events, largely concentrated on the eastern side of the volcano, occurred
130 from October 19 to October 31 (Gresta et al., 1987). The main events (Fig. 2B) were on 19th (at
131 17:43) and 25th October 1984 (at 01:12), and struck the town of Zafferana and the Fleri and Pisano
132 villages (Fig. 3).

133 The earthquakes caused one fatality in Zafferana and injured twelve people in Fleri. In Fleri, the
134 number of injuries would have been much higher, had most of the inhabitants, in great anxiety after
135 an initial shock at around 22.00 the day before, not spent the night outdoors. Serious damage was
136 caused to buildings in Zafferana but particularly in Fleri, which was almost entirely destroyed.
137 About 70% of the buildings of the entire municipality (including all public buildings) were declared
138 unfit for use (Fig. 3).

139 Figure 2 reports the location and epicentral macroseismic intensity (I_0) as reported in the
140 Macroseismic Catalogue of Mt. Etna (CMTE Working Group, 2008). An I_0 of VII EMS (European
141 Macroseismic Scale, Grünthal, 1998) is reported for the October 19th event and of VIII EMS for the
142 October 25th event.

143 In October 1984 more than 1.5 km long NW-SE trending cracks extended from the village of Fleri
144 with dip-slip displacements of about 20 cm. It is worth noting that a similar ground rupture affected
145 the southeastern part of FF on occasion of the VIII EMS event of June 19 1984 (Azzaro, 1999).

146 The volcanic district of Mt. Etna, and in particular its eastern flank, is affected by earthquakes
147 characterized by a strong attenuation of seismic energy in an orthogonal direction to the fault plane.
148 This produces damage extending along narrow zones (1-5 km long, up to 1 km wide) around the
149 seismogenic source (Azzaro et al., 2006) and coseismic surface faulting effects, reported in detail in
150 historical accounts, for the major seismic events. Regarding FF, earthquakes occurring in 1875,
151 1894, 1907, 1914 and 1931 (Azzaro, 2004) caused NNW-SSE trending fractures that opened for
152 several kilometers with prevailing extensional movement and right-lateral displacements of several
153 centimeters.

154 Figure 2B reports macroseismic and instrumental locations of the main seismic events between May
155 1980 and October 1984 in the TFS area. Given that the macroseismic epicentre is calculated as the
156 barycentre of the data points with intensity $I = I_0, I_0-1$, the macroseismic location and the
157 instrumental location may be rather different, (Azzaro et al., 2000). Indeed Gresta et al. (1987),
158 using a seismic network of just a few active stations in 1984, estimated a duration magnitude of 4.2
159 and 3.9 for the Zafferana and Fleri earthquakes respectively with different epicentres (Fig. 2B).

160

161 **4.0 The “Ionica” EDM network**

162 Between 1977 and 2002, the monitoring of the horizontal component of ground deformation at Mt.
163 Etna was carried out by trilateration geodetic techniques using EDM (electro-optical distance
164 measurements). Three separate networks were installed on the northeastern, western, and southern
165 flanks (Fig. 1).

166 A fourth EDM network (Ionica Network), was installed and measured for the first time in October
167 1977 (Fig. 1), with the aim of verifying the possible relationships between the regional tectonic
168 activity, highly evident in this area with the presence of numerous structures, and the volcanic
169 activity (Fig. 2B).

170 The Ionica Network was set up along the eastern edge of the volcano, along a line from Catania to
171 Taormina, at low altitude (between 700 and sea level); it consisted of 19 benchmarks and 43 lines,
172 which were measured yearly from 1977 to May 1980.

173 The slope distances were recorded by using an AGA 6BL Laser Geodimeter (Fig. 1), and were
174 corrected for atmospheric conditions considering temperature and atmospheric pressure values
175 acquired at the measurement points. The instrumental error of such measurements is 5 mm plus 1
176 ppm of the surveyed distance.

177 After the Zafferana and Fleri 1984 earthquakes, four measurement surveys were performed in the
178 period October 1984 - March 1985 in the portion of the network (Fig. 2B) covering the area
179 affected by the events. The first survey was made between 26 and 31 October. These measurements

180 involved only the southern part of the network, consisting of 9 benchmarks and 19 lines (Fig. 2B)
181 whose mean length is 4.7 km.

182

183 **4.1 EDM Data**

184 The results obtained from data collected from 1977 until 1985, indicate that the variations of
185 distance with values greater than instrumental error occurred mainly in the period May 1980-
186 October 1984, while distance variations obtained from the comparison with the other surveys are
187 mainly within the error. In particular, changes are up to 108 mm and ten measurements showed
188 variations over 50 mm (Fig. 4). In the previous period (1977-1980), the changes observed are
189 generally within the instrumental error though a trend is detectable for several lines.

190 Ground deformation strain field is given by the uniform strain tensor components ϵ_{ij} which can be
191 calculated by using variations of slope distances (Jaeger, 1969):

192
$$\Delta L_{MN}/L_{MN} = \epsilon_{11} \cos^2 \delta_{MN} + \epsilon_{22} \sin^2 \delta_{MN} + \epsilon_{12} \sin 2\delta_{MN}$$

193 where ΔL_{MN} is the change in length of the line MN (with length L_{MN}) between two points M and N
194 and δ_{MN} is the angle between MN direction and x-axis.

195 This tensor indicates the average deformation occurring between two different surveys in the area
196 covered by the network and provides useful information on the ground deformation regime of the
197 area (e.g. Bonaccorso, 2002). We calculated the principal strain axes (Fig. 2C) drawn from the
198 comparison of the overall measurement interval 1980-October 1984. We obtained a positive
199 extension ($\epsilon_1 = 17 \pm 4.4 \mu\text{strain}$) oriented approximately orthogonal to and a contraction ($\epsilon_2 = -12.2$
200 $\pm 4.4 \mu\text{strain}$) parallel to the FF and STF fault systems (Fig. 2).

201

202 **5.0 Geodetic Data Modelling**

203 The surface ground deformation field for the 1980-1984 interval was used as input to
204 constrain isotropic half-space elastic inversion models using [Okada's \(1992\)](#) model. The aim of this
205 inversion is to characterize the FF and STF dynamics during this particular period. Unlike in 1985,
206 several of the geometric parameters of the two considered faults are known today ([Azzaro et al.,](#)
207 [2013](#)). Hence, reducing the unknowns, enables one to make an inversion of the limited EDM
208 dataset.

209 We fixed the more reliable parameters (Tab. 1), while for the more dubious ones (less
210 precise), we chose to leave them to be free (in a range) during the inversion together with the
211 kinematic parameters.

212 To model the displacements due to each single fault, we adopted the analytical model
213 described in [Okada \(1992\)](#), and to take the simultaneously effects of two (or more) faults into
214 account we used the superposition principle. The Okada equations give the 3D displacement (δ_p) at
215 a point P due to the fault geometry and its kinematic. For a baseline between the points P_i and P_j ,
216 we modelled the EDM distance variation as:

217

$$218 \Delta_{ij} = \left\| (P_i + \delta_{P_i}) - (P_j + \delta_{P_j}) \right\| - \|P_i - P_j\|,$$

219 where $\|\cdot\|$ is the 3-dimensional Euclidean norm operator.

220

221 In particular, we inverted for the parameters reported in gray in Table 1, where the
222 associated ranges are also shown. These values are estimations, calculated from geophysical,
223 geological and historical data; however, not all parameters are available. We excluded all the lines
224 crossing the MF. Thus we had a total of 10 free parameters and 13 EDM measurements. It is worth
225 noting in Table 1 that 5 free parameters reach an extreme in their feasible ranges. Hence, they could
226 be treated as fixed parameters and set to their maximum/minimum possible values. We considered a
227 shear modulus of 10 GPa and a Poisson's ratio of 0.25 (e.g. [Bozzano et al., 2013](#)).

228 In order to estimate simultaneously the free geometric parameters and kinematics of both the
229 considered faults, we inverted the EDM data by minimizing the weighted misfit between the
230 measured and calculated distances. Because of the free geometric parameters, the mathematical
231 problem is nonlinear and the adopted minimization algorithm was a hybrid approach of genetic
232 algorithm and pattern search (Audet & Dennis, 2002). The measurements were weighted with their
233 associated instrumental errors expressed in meters by the formula:

$$234 \quad \sigma_{\Delta_{ij}} = \sqrt{2}(0.005 + 10^{-6}\|P_i - P_j\|).$$

235 The square root of 2 is due to the error propagation in calculating the distance variation Δ_{ij}
236 neglecting the displacement.

237 The found model fits the EDM data with a WRMS of 0.98.

238 A Jackknife re-sampling method (Efron, 1982) was used to estimate the error of model
239 parameters. The technique requires several optimization executions, each one deprived of just one
240 measurement in input. The errors at 99% are estimated as 3-times the standard deviation in the set
241 of the found solutions.

242 The final results (Tab. 1 and Fig. 5) are in agreement with the dominant faulting style
243 producing a normal strike-slip movement with 27.6 cm of dextral strike movement and 22.7 cm of
244 normal dip on FF, while we obtained only 6.0 cm of dextral strike slip on STF. A comparison
245 between observed and modeled slope distance is reported in Fig. 6.

246

247 **5.1. Sensitivity analysis**

248 We carried out a sensitivity analysis in order to ascertain whether our data could constrain a
249 valid set of fault parameters. We adopted the Sobol' analysis (Sobol', 1990), a variance-based
250 global method to measure sensitivity across the whole input space, deal with nonlinear responses,
251 and estimate the effect of interactions in non-additive systems. The method breaks the variance of
252 the output of the model down into fractions (normalized to 1) which can be attributed (in

253 percentage) to input terms. The Sobol' first-order indices indicate the contribution of the main
254 effect of each input parameter to the output variance, therefore measuring the effect of varying the
255 input parameter alone, averaged over variations in other input parameters. We adopted the
256 algorithm in [Cannavò \(2012\)](#) to calculate the first-order Sobol' indices of all the fault parameters
257 given in our EDM data. The indices reported in Table 2 represent the fraction of variance in the data
258 that can be attributed to each fault parameter. The higher the fraction, the more constrained is the
259 parameter by the data. Results show that, among all the parameters, the data are more sensitive to
260 fault lengths and mainly to strike-slips which, in turn, can be estimated more accurately than the
261 other parameters.

262

263 **6.0 Discussion and conclusions**

264 The Timpe ~~is a normal~~ fault system dissecting the Mt. Etna's lower eastern flank. It is
265 formed of several segments (FF, STF, SVF, SLF and MF) that show right-lateral kinematics and
266 normal dip-slip with slip-rates ranging from 3.0 to 5.0 mm/y ([Bonforte et al., 2011](#)).

267 Timpe dynamics are linked to the ESE-ward motion of the eastern flank of Mt. Etna (e.g.
268 [Azzaro, 2013a](#)). Since 1980, the ESE-ward motion has shown phases of increased velocity, the first
269 being observed in the October 1984-1987 period ([Alparone et al., 2013c](#)). The TFS accommodates
270 this motion and becomes very active from the seismic point of view when acceleration phases
271 characterize the ESE-ward motion of the eastern flank.

272 These severe/destructive events, with a mean recurrence time of about 20 years for [Azzaro](#)
273 [et al. \(2013c\)](#), make the Timpe fault system extremely important in terms of seismic hazard.

274 These events are distributed on the several segments and in the last decades the destructive
275 episodes have affected FF in October 1984 and SVF in November 2002.

276 The 25th October 1984 event most likely represents the strongest event recorded on FF since
277 1875 ([Azzaro et al., 2004](#)); we tried to characterize the finite fault geometry and slip of FF by

278 ground deformation observations. We recovered and analyzed the EDM measurements of the
279 “Ionica” network crossing the TFS and measured only between 1977 and 1985. These data
280 highlight major variations between 1980 and 1984; the principal components of the strain tensor
281 obtained in this time period, show a positive extension oriented approximately orthogonal and a
282 negative extension parallel to the FF and STF fault systems and are consistent with normal right-
283 lateral dynamics of the two structures.

284 We inverted data showing that, between 1980 and November 1984, the FF (7 km length and
285 2.6 km depth) was affected by a strike slip component of 26.7 ± 1.5 cm and a normal dip slip of
286 22.7 ± 2.4 cm (overall displacement ca. 35 cm). The sensitivity analysis indicates that fault length
287 and strike-slip represent the most accurately constrained parameter obtained by data inversion.

288 In consideration of these results, and assuming a medium rigidity (μ) of a shear modulus of
289 10 GPa in the general relation (Aki, 1966):

290

291
$$M_0 = \mu * S * \bar{u}$$

292  we obtained a geodetic moment $M_G = 6.0 * 10^{23}$ dyne-cm.

293 An estimate of the seismic moment release associated with the seismic events was obtained
294 using the relation (Giampiccolo et al., 2007) for Etnean earthquakes:

295

296
$$\text{Log}(M_0) = (17.60 \pm 0.37) + (1.12 \pm 0.10) * M_L$$

297 It shows that M_0 cannot be greater than $= 1.6 * 10^{23}$ dyne-cm for the 25 October 1984
298 earthquake and $4.0 * 10^{22}$ dyne-cm for that on 19 June 1984. Therefore only a part (from 5% to a
299 maximum of 30%) of the stick-slip obtained by modeling is related to the co-seismic effects of the
300 earthquakes recorded along the FF, suggesting that most of the slip over the fault must be aseismic.
301 These results are similar to those obtained by [Obrizzo et al., \(2001\)](#) for the Pernicana Fault System,
302 on analyzing 17 years of levelling data. These authors concluded that only 30% of the total
303 deformation of Pernicana Fault System is attributable to co-seismic displacements.

304 Data inversion cover a long period (1980-84); however from May 1980 to May 1984, no events
305 with epicentral intensities $I_0 \geq VI$ EMS were recorded (Fig. 2B) along FF that probably was only
306 subjected to a few centimeters of aseismic displacement (taking in consideration the 3-5 mm/year
307 measured by PS by [Bonforte et al., \(2011\)](#). An acceleration of the FF dynamics could have occurred
308 since June 1984 when an EMS VII was recorded on southeastern part of the fault (Fig. 2B) or after
309 October, 16 when more than 1000 earthquakes with $M > 2.0$ took place on the eastern flank in two
310 weeks. Field observations certainly suggest that co-seismic ground displacements are larger than
311 what would be expected from the June 19 and October 25 earthquakes. If we exclude any coseismic
312 effect, it is difficult to determine when the dynamics of the FF underwent an acceleration in June-
313 October 1984. If this were the case, it could mean that a destructive seismic event, such as the 25
314 October 1984 one, might have been preceded by a measurable increase of the ground deformation
315 close to the fault.

316 Few variations have been detected on the Santa Tecla Fault (STF), which seems to have been little
317 affected by the October 1984 dynamics. The June 19 event does actually appear to be located at the
318 northern edge of the fault ([Gresta et al., 1987](#)). The model estimated only 6.0 (± 2.0) cm of strike
319 slip on STF. Then the October 19 event does not seem related to significant shifts of the STF.
320 Precise locations of the earthquakes ($M_{\max}=3.7$) recorded in the same area between 1995 and 2006
321 ([Alparone and Gambino, 2003](#); [Alparone et al., 2013b](#)) have shown that the seismicity in this sector
322 is generally 3-5 km b.s.l. deep and related to NE-SW oriented seismogenetic structures (MF line).
323 For all these reasons we retain that the October 19 event is not attributable to TDF dynamics.

324 To summarize, the destructive 25 October 1984 event is an effect of an important dynamic episode
325 that affected the FF structure time related with a flank acceleration phase ([Alparone et al., 2013c](#)).
326 EDM data inversion indicated a total stick-slip of ca. 30-35 cm between 1980 and 1984, mainly
327 between June and October 1984 along a fault length of 7 km. This result is in some ways
328 comparable with field observations that detected a co-seismic ground rupture of the northwestern

329 and southeastern sectors of the fault of up to 20 cm (Azzaro, 1999 and reference therein), while a
330 discrepancy between the seismic and geodetic moment is present. Indeed, FF shows a low seismic
331 efficiency (lower than 30%), a feature that seems common to other very shallow faults on the
332 eastern flank (e.g. the Pernicana Fault System) and that highlights that most of the energy is
333 involved in aseismic ground displacements.

334 These considerations again confirm the high level of seismic risk, in particular ground rupture
335 hazard of the Fiandaca Fault and generally of the Timpe Fault System, for the several towns and
336 villages located on these structures.

337 **Acknowledgements**




338 We are indebted to Prof. Letterio Villari who, since the 1970s, understood the importance of
339 monitoring Etna's eastern flank, and who planned and worked to set up the "Ionica" EDM network.

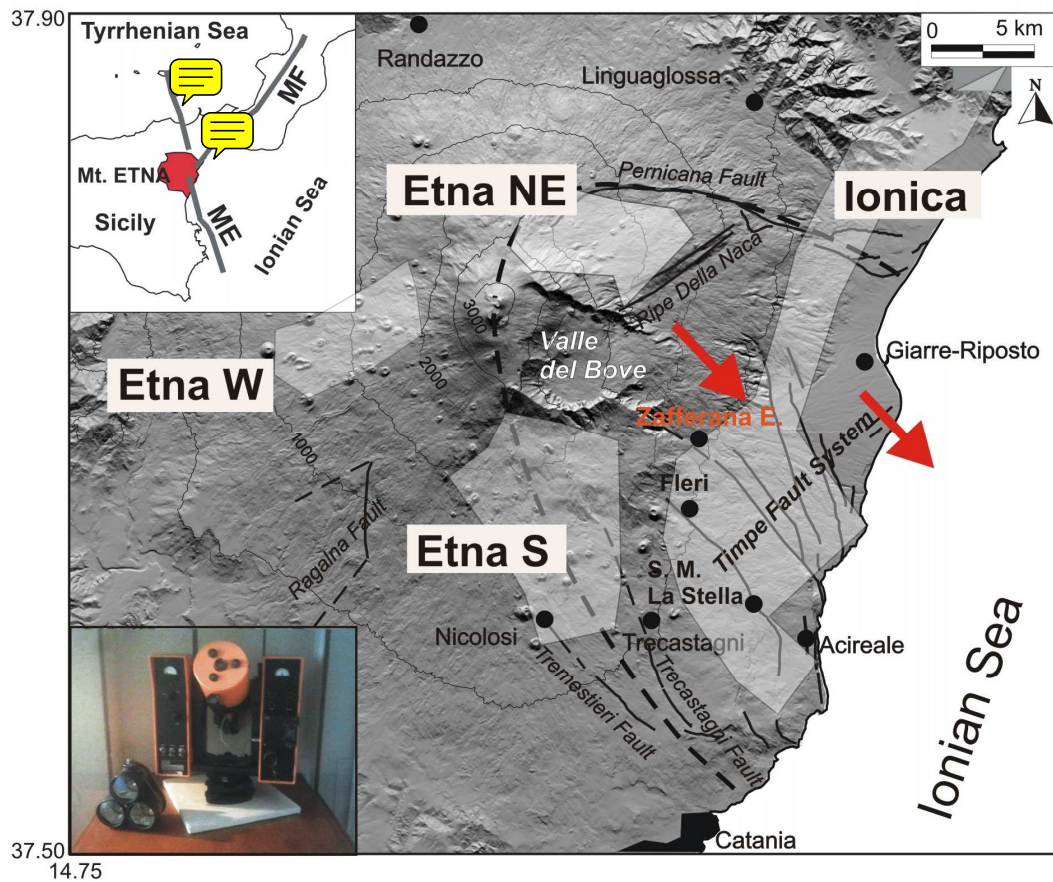
342 **References**

- 343 AA. VV. 1985. Rapporto trimestrale sullo stato dell'attività nell'area etnea. Trimestre ottobre-dicembre
344 1984. Gruppo Nazionale per la Vulcanologia: Unità di ricerca dell'Istituto Internazionale di
345 Vulcanologia, CNR e dell'Istituto di Scienze della terra, Università di Catania.
- 346 Aki, K., 1966. Generation and propagation of G waves from Niigata earthquake of June 16, 1964,
347 II, Estimation of earthquake moment, released energy, and stress-strain drop from the G wave
348 spectrum, Bull. Earthquake Res. Inst. Univ. Tokyo, 44, 73-88.
- 349 Allard, P., B. Behncke, S. D'Amico, M. Neri and S. Gambino, 2006. Mount Etna 1993-2005: anatomy of an
350 evolving eruptive cycle, Earth-Sci. Rev., 78, 85-114; doi:10.1016/j.earscirev.2006.04.002.
- 351 Aloisi, M., Bonaccorso, A., Gambino, S., 2006. Imaging compositive dike propagation (Etna, 2002 case). J.
352 Geophys. Res. 111, B06404. <http://dx.doi.org/10.1029/2005JB003908>.
- 353 Alparone, S. and S. Gambino, S., 2003. High precision locations of multiplets on south-eastern flank of Mt.
354 Etna (Italy): reconstruction of fault plan geometry, Physics Earth and Planetary Interiors, 135, 281-
355 289.
- 356 Alparone, S., O. Cocina, S. Gambino, A. Mostaccio, S. Spampinato, T. Tuvè and A. Ursino, 2013a.
357 Seismological features of the Pernicana-Provenzana fault system and implications for the dynamics of


- 358 northeastern flank of the volcano, *Journal of Volcanology and Geothermal Research*, 251, 16-26.
359 doi:10.1016/j.jvolgeores.2012.03.010.
- 360 Alparone, S., D'Amico, S., Gambino, S., Maiolino V. 2013b. Buried active faults in the Zafferana Etnea
361 territory (south-eastern flank of Mt. Etna): geometry and kinematics by earthquake relocation and
362 focal mechanisms. *Annals of Geophysics* 56 (1), R0112.
- 363 Alparone, S., A. Bonaccorso, A. Bonforte, and G. Currenti 2013c, Long-term stress–strain analysis of
364 volcano flank instability: The eastern sector of Etna from 1980 to 2012, *J. Geophys. Res. Solid Earth*,
365 118, 5098–5108, doi:10.1002/jgrb.50364.
- 366 Audet, C., & Dennis Jr, J. E. 2002. Analysis of generalized pattern searches. *SIAM Journal on Optimization*,
367 13(3), 889-903.
- 368 Azzaro, R. 1999. Earthquake Surface Faulting At Mount Etna Volcano (Sicily) And Implications For Active
369 Tectonics, *Journal of Geodynamics*, 28 (2-3), 193-213.
- 370 Azzaro, R., M.S. Barbano, B. Antichi and R. Rigano 2000. Macroseismic catalogue of Mt. Etna earthquakes
371 from 1832 to 1998, *Acta Vulcanologica*, 12 (1-2), 3-36.
- 372 Azzaro, R. 2004. Seismicity and active tectonics in the Etna region: constraints for a seismotectonic model,
373 in Mt. Etna: volcano laboratory, Bonaccorso A., S. Calvari, M. Coltelli, C. Del Negro and S.
374 Falsaperla (Editors), American Geophysical Union, Geophysical monograph, 143, 205-220.
- 375 Azzaro, R., S. D'Amico, A. Mostaccio, L. Scarfi and Y. Tuvè 2006. Terremoti con effetti macrosismici in
376 Sicilia Orientale - Calabria Meridionale nel periodo Gennaio 2002 – Dicembre 2005, *Quaderni di*
377 *Geofisica*, 41, 1-60.
- 378 Azzaro, R., D'Amico, S., Peruzza, L., Tuvè, T., 2012. Earthquakes and faults at Mt. Etna: problems and
379 perspectives for a time-dependent probabilistic seismic hazard assessment in a volcanic region.
380 *Bollettino di Geofisica Teorica ed Applicata* (1), 75–88.
- 381 Azzaro R., A. Bonforte, S. Branca, F. Guglielmino 2013a. Geometry and kinematics of the fault systems
382 controlling the unstable flank of Etna volcano (Sicily). *J. Volc. Geotherm. Res.* 251, 5–15.
- 383 Azzaro R., S. D'Amico, R. Rotondi, T. Tuvè and G. Zonno 2013b. Forecasting seismic scenarios on Etna
384 volcano (Italy) through probabilistic intensity attenuation models: a Bayesian approach *J. Volc.*
385 *Geotherm. Res.*, 251, 149-157.
- 386 Azzaro, R., D'Amico, S., Peruzza, L., Tuvè, T., 2013c. Probabilistic seismic hazard at Mt. Etna (Italy): the
387 contribution of local fault activity in mid-term assessment. *J. Volc. Geotherm. Res.* 251, 158-169.

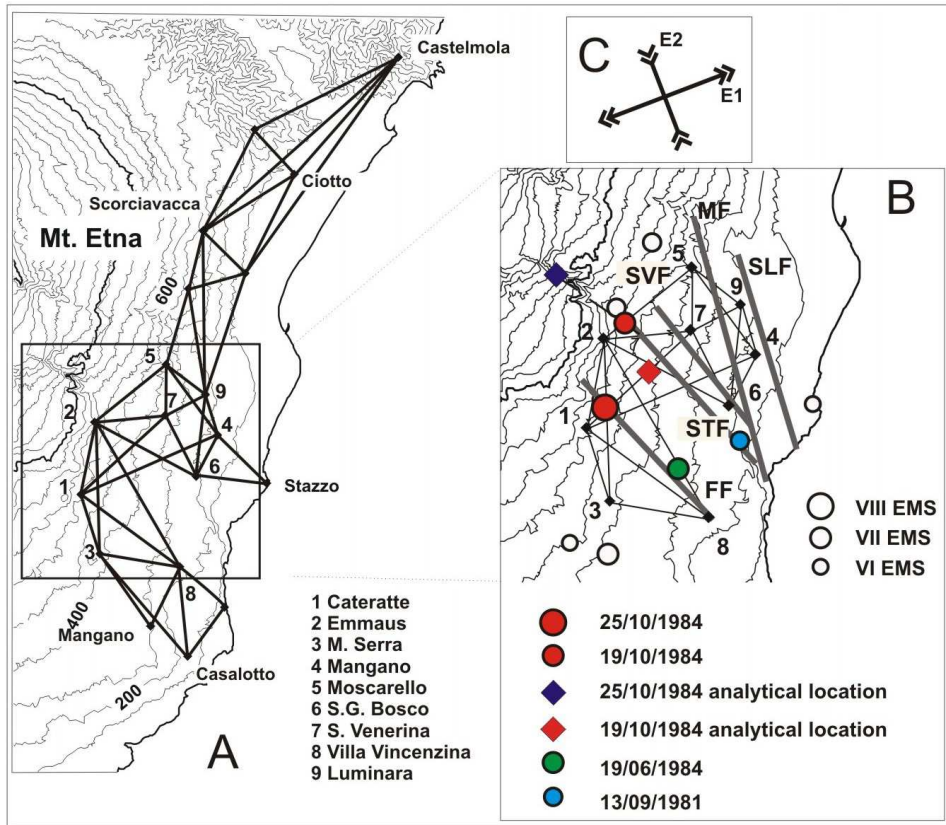
- 388 Bonaccorso, 2002. Ground deformation of the southern sector of the Aeolian islands volcanic arc from
389 geodetic data. *Tectonophysics*, 351- 3, 181-192.
- 390 Bonforte, A, Puglisi G., 2003. Magma uprising and flank dynamics on Mt. Etna volcano, studied by GPS
391 data (1994–1995). *J. Geophys. Res.* 108, 2153–2162.
- 392 Bonforte, A., Guglielmino, F., Coltelli, M., Ferretti, A., Puglisi, G., 2011. Structural assessment of Mt. Etna
393 volcano from Permanent Scatterers analysis. *Geochemistry, Geophysics, Geosystems* 12, Q02002.
394 <http://dx.doi.org/10.1029/2010GC003213>.
- 395 Bonforte, A., Carnazzo, A., Gambino, S., Guglielmino, F., Obrizzo, F., Puglisi, G., 2013. The Trecastagni
396 Fault (Mt. Etna, Italy): a multidisciplinary study by continuous, discrete and satellite ground
397 deformation measurements. *Journal of Volcanology and Geothermal Research* 251, 42–50.
- 398 Bozzano, F., Gaeta, M., Lenti, L., Martino, S., Paciello, A., Palladino, D. M., & Sottili, G. 2013. Modeling
399 the effects of eruptive and seismic activities on flank instability at Mount Etna, Italy. *Journal of*
400 *Geophysical Research: Solid Earth*, 118(10), 5252-5273.
- 401 Branca et al., Coltelli M., Groppelli G., 2011. Geological evolution of a complex basaltic stratovolcano:
402 Mount Etna, Italy. *Ital. J. Geosci.*, 130, 306-317.
- 403 Cannavó, F. 2012. Sensitivity analysis for volcanic source modeling quality assessment and model selection.
404 *Computers & Geosciences*, 44, 52-59.
- 405 CMTE Working Group, 2008. *Catalogo Macrosismico dei Terremoti Etnei, 1832-2008*, INGV, Catania,
406 <http://www.ct.ingv.it/ufs/macro/>
- 407 Efron, B., 1982. *The Jackknife, Bootstrap and Other Resampling Plans*. Philadelphia: Society for Industrial
408 and Applied Mathematics.
- 409 Gambino, S., Bonforte, A., Carnazzo, A., Falzone, G., Ferrari, F., Ferro, A., Guglielmino, F., Laudani, G.,
410 Maiolino, V., Puglisi, G., 2011. Displacement across the Trecastagni Fault (Mt. Etna) and induced
411 seismicity: the October 2009–January 2010 episode. *Ann. Geophys.*, 54, 414–423.
- 412 Giampiccolo, E., S. D'Amico, D. Patanè, and S. Gresta, 2007, Attenuation and source parameters of shallow
413 microearthquakes at Mt. Etna Volcano, Italy, *Bull. Seismol. Soc. Am.*, 97, 184–197,
414 doi:10.1785/0120050252.
- 415 Gresta, S., Glot, J.P., Patanè, G., Poupinet, G., Menza, S., 1987. The October seismic crisis at Mount Etna.
416 Part I: Space-Time evolution of events. *Ann. Geophys.* 5B (6), 671–680.
- 417 Gresta, S., Musumeci, C., 1997. Stress tensor computation from earthquake fault-plane solutions: an
418 application to seismic swarms at Mt. Etna volcano (Italy). *Annali di Geofisica*, XL, 5, 1250-1260.

- 419 Grünthal, G. (ed) 1998. European macroseismic scale 1998 (EMS-98). European Seismological
420 Commission, subcommission on Engineering Seismology, working Group Macroseismic Scales.
421 Conseil de l'Europe, Cahiers du Centre Européen de Géodynamique et de Séismologie, 15,
422  Luxembourg, 99 pp
- 423 Jaeger, J.C., 1969. Elasticity, Fracture and Flow. With Engineering and Geological Applications. Chapman
424 & Hall, London, 268 pp.
- 425 La Delfa S, Patanè G, Presti F, Tringali G. 2007. Changing in crust mechanical behaviour due to raising
426 magma: a fracturing model of SE flank of Mt Etna (Sicily). *Earth Planet Sci Lett* 256:493–509
- 427 Lanzafame, G., M. Neri and D. Rust, 1994. Active tectonics affecting the eastern flank of Mount Etna:
428 structural interactions at a regional and local scale, in *Etna: fifteen years on Gravestock*, P.J. and W. J.
429  Mc Guire, (Editors.), Cheltenham and Gloucester Special Publication, 25-33.
- 430 Obrizzo, F., Pingue, F., Troise, C., De Natale, G., 2001. Coseismic displacements and creeping along
431 Pernicana fault (Mt. Etna) in the last seventeen years: a detailed study of a structure on a volcano.
432 *Journal of Volcanology and Geothermal Research* 9, 109–131.
- 433 Okada, Y. 1992. Internal deformation due to shear and tensile faults in a half-space. *Bull Seism Soc Am*
434  82(2), 1018-1040.
- 435 Sobol', I. Y. M. 1990. On sensitivity estimation for nonlinear mathematical models. *Matematicheskoe*
436 *Modelirovanie*, 2(1), 112-118.
- 437 Solaro, G., V. Acocella, S. Pepe, J. Ruch, M. Neri, Sansosti E. 2010. Anatomy of an unstable volcano from
438 InSAR: Multiple processes affecting flank instability at Mt. Etna, 1994-2008, *Journal of Geophysical*
439 *Research*, 115, B10405, doi:10.1029/2009JB000820.



440

441 **Fig. 1** –Surface faults map of Mt. Etna. Top inset map shows the main regional fault
 442 systems: MF=Messina-Fiumefreddo ~~line~~, ME=Malta Escarpment.  Dashed line defines the
 443 sliding sector and red arrows indicate its movement direction. White areas are covered by EDM
 444 networks. In the bottom insert, the AGA 6BL Laser Geodimeter.



445

446

447

448

449

Fig. 2. – Ionica EDM network (a) EDM benchmarks and lines measured between 1977 and 1985 (b) Macroseismic epicentres of earthquakes with epicentral intensities $I_0 \geq VI$ EMS occurring from 1980 to October 1984 in the south-eastern flank of Mt Etna. (c) Principal strain axes obtained from the comparison of the overall measurement interval 1980-October 1984.

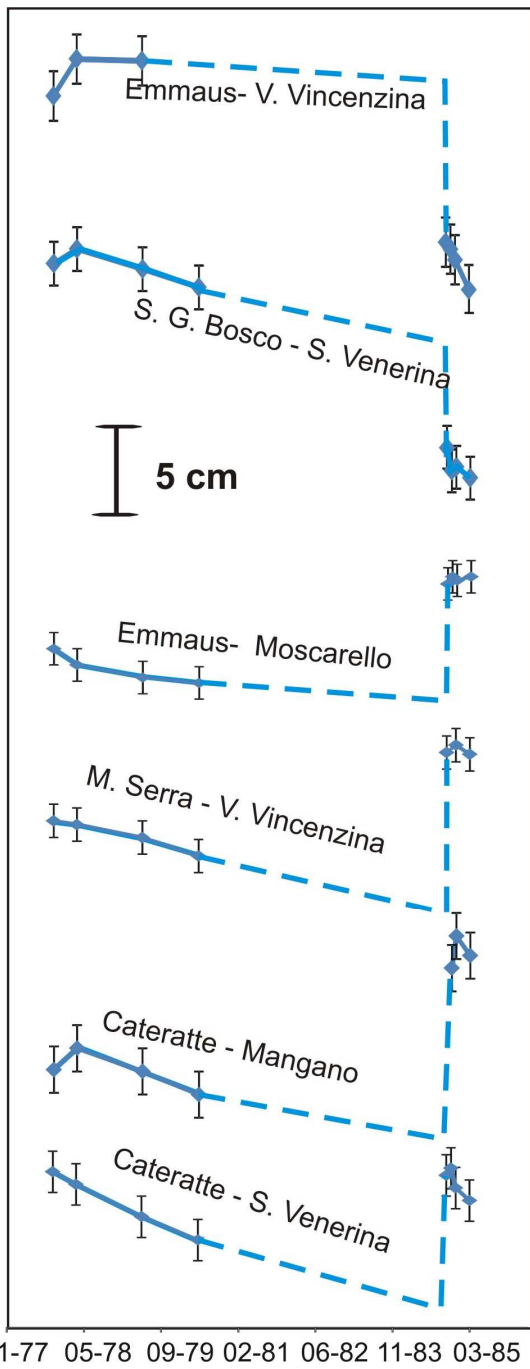


450

451

452

Fig. 3. Photos of damage caused during the 25th October earthquake at Fleri village (http://www.ct.ingv.it/macro/etna/html_index.php).



454

01-77 05-78 09-79 02-81 06-82 11-83 03-85

455

Fig. 4. Changes of measured line lengths with respect to time of surveying time (interval

456

1977– 1985) in the “Ionica” network. Note how the lines are subject to marked variations in the

457

1980-1984 period. Solid lines connect measurements and dashed lines represent the plausible trend

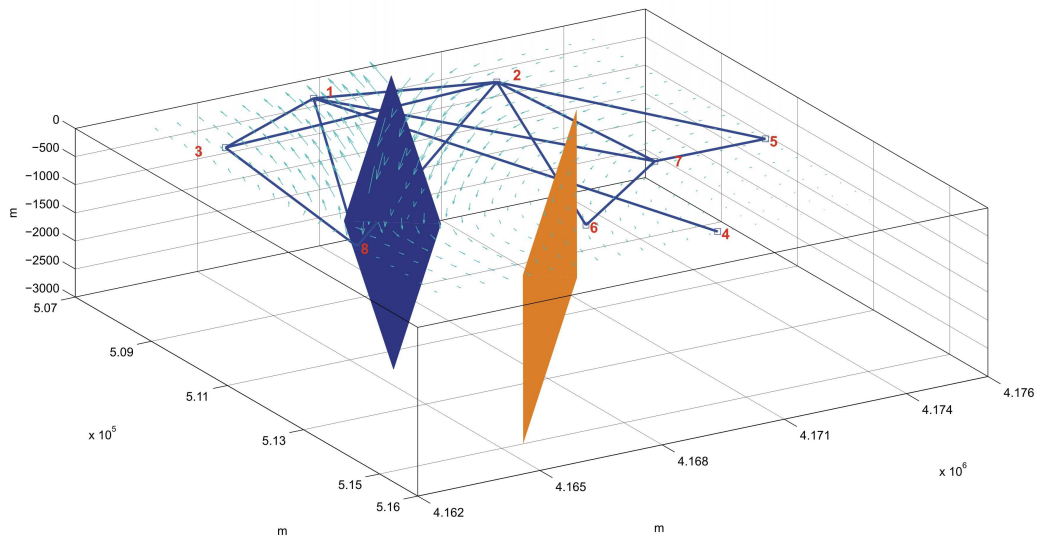
458

of the May 1980-October 1984 period.

459

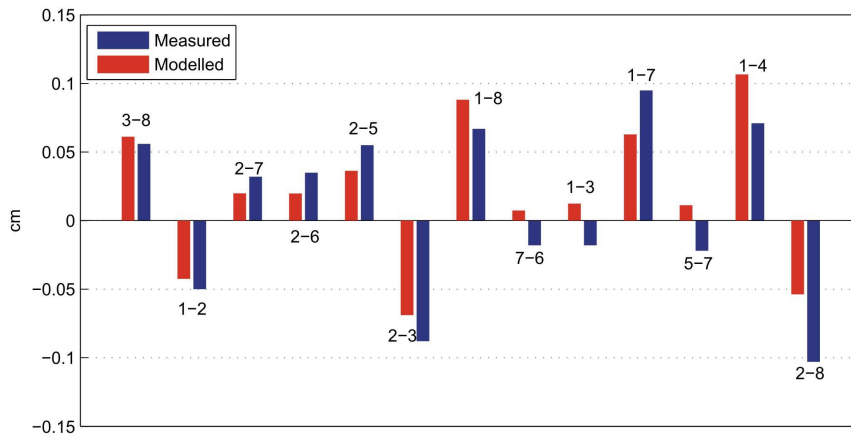
460

461



462

463 **Fig. 5.** Location and E-W cross-section of the source modelled. The arrows represent the
464 simulated deformation field due to the estimated fault kinematics. Numbers as in Fig. 2.



465

466 **Fig. 6.** Comparison between observed (blue bars) and modeled (red bars) slope distance.
467 Numbers as in figure 2.

468

469

470

471

472

473 **Table 1.** Best Fitting Range for the model.

	Fault 1 (FF)		Fault 2 (STF)	
X (m, center top)	509700	fixed	512423	fixed
Y (m, center top)	4166660	fixed	4168595	fixed
Depth (m, top)	0	fixed	0	fixed
Azimuth (°)	140	fixed	140	fixed
Dip (°)	70 ± 0.0	70 ÷ 89.9	89.9 ± 25	70 ÷ 89.9
Semi-Length (m)	3500 ± 0.0	2000 ÷ 3500	4000 ± 0.0	2000 ÷ 4000
Width (m)	2610 ± 70	1000 ÷ 3000	3000 ± 100	1000 ÷ 3000
Strike-s (cm)	26.7 ± 1.5	0 ÷ 100 (dextral)	6.0 ± 2.0	0 ÷ 100 (dextral)
Dip Slip (cm)	-22.7 ± 2.4	-100 ÷ 0 (normal)	0.0 ± 3.0	-100 ÷ 0 (normal)

474

475 **Table 2.** Global sensitivity analysis. First-order Sobol' coefficients for the fault parameters
 476 and total sums.

	Fault 1 (FF)	Fault 2 (STF)	TOTAL
Azimuth (°)	0.000	0.002	0.002
Dip (°)	0.000	0.005	0.005
Semi-Length (m)	0.119	0.126	0.245
Width (m)	0.012	0.019	0.031
Strike-s (m)	0.125	0.284	0.409
Dip Slip (m)	0.013	0.014	0.027
TOTAL	0.269	0.450	

477