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Title: Triggering mechanisms of static stress on Mount Etna volcano. An application of the boundary element method.

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Keywords: Numerical modeling, Coulomb stress changes, volcano dynamics, Mount Etna volcano, magmatic activity.

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**Abstract:** In the last thirty years, numerous eruptions and associated deformation episodes have occurred at Mt. Etna volcano. Datasets recorded by continuous monitoring of these episodes provide a unique opportunity to study the relationships between volcanism, flank instability and faulting activity. We have investigated the stress triggering mechanism between magmatic reservoir inflation, intrusive episodes and flank dynamics. Using three-dimensional numerical Boundary Elements Models we simulated volcano-tectonic events and calculated Coulomb stress changes. Using this modeling approach, we analyzed four realistic scenarios that are representative of recent kinematics occurring at Mt. Etna. The main results obtained highlight how (1) the inflation of a deep spherical magma source transfers elastic stress to a sliding plane and faults (2) the opening of the NE Rift and S Rift (to a less efficient extent) favor movements of the instable sector and may encourage seismicity on the eastern flank faults, and (3) flank instability may trigger the uprising of magma. Defining the effects of the elastic stress transfer and relationships among the main forces acting on volcano, may help to forecast possible eruption scenarios during future episodes of unrest at Mount Etna and provide an important tool for decision makers during volcanic emergencies involving the highly populated areas of the volcano.



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29 Mt. Etna volcano. Datasets recorded by continuous monitoring of these episodes provide a unique  
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47 magmatic activity.

48

## 49 **1. Introduction**

50

51 Active volcanoes in densely populated areas represent a primary hazard that requires a operative  
52 and well-timed interaction between research institutions and civil defence authorities during unrest  
53 episodes. Consequently, involved researcher are encouraged to tune up affordable methods that can  
54 provide realistic scenarios of the eruptive evolution in near real-time.

55 Mount Etna dynamics is the result of a complex interplay between magma ascent in the plumbing  
56 system, dike emplacement, tectonic uplift, faulting and flank instability. Many studies have  
57 highlighted that at Mount Etna increases in static stress induced by dike intrusions bring faults  
58 closer to failure (Gresta et al., 2005). More recently, the pressurization of a magmatic reservoir was  
59 considered to trigger 1997-1998 Mount Etna seismic swarms as a consequence of stress  
60 redistribution (Bonanno et al, 2011).

61 The increase in collected seismic and deformation measurements and the rapid growth of  
62 computational power have enabled improving investigations into the relationship between faulting,  
63 flank dynamics and magmatic activity using numerical modeling. Walter et al. (2005) modeled the  
64 2002-2003 Mt. Etna eruption by means of Boundary Element Method, evaluating the influence of  
65 four different sources on the kinematics of the volcano's eastern flank. They found a feedback  
66 relationship between flank movements and intrusive processes The numerical models suggest that  
67 magmatic activity (inflation of a reservoir and emplacement of dikes) encourages motion of the  
68 eastern flank, which, in turn, promotes magma to rise up to shallower levels within the volcano.  
69 Currenti et al. (2008) performed a Finite Element Modeling approach to evaluate ground  
70 deformation and the resulting stress redistributions in response to magmatic processes occurring  
71 during the 2002–2003 Etna eruption. They found that the changes in the state of stress generated by  
72 the southern dike produce an extensional stress field that favors magma propagation along the  
73 north-east Rift. The static stress changes computed onto the Timpe Fault System and the Pernicana  
74 Fault indicate that the magma intrusions on the southern and northeastern flanks prompted these

75 seismogenic structures to slip. In this paper, we will use numerical simulations to hypothesize four  
76 realistic scenarios at Mt Etna in which one source at a time is active. Coulomb stress changes will  
77 be computed on three dimensional fault surfaces in order to investigate the interaction between  
78 intrusion/eruptive episodes, tectonic activity and flank instability. The method used requires a  
79 processing time of some tens of minutes and is thus suitable for a near real-time application in order  
80 to forecast the evolution of future unrest episodes.

81

82

## 83 **2. Etna volcano setting**

84

85 Mount Etna is a Quaternary basaltic stratovolcano located on the east coast of Sicily. It stands  
86 between two first-order tectonic elements: the Apenninic-Maghrebian Chain and the Hyblean  
87 Foreland (inset of Figure 1). The northern and western sectors of the volcano lie over metamorphic  
88 and sedimentary rocks belonging to the frontal nappes system of the Apenninic-Maghrebian Chain,  
89 whereas the southern and eastern sectors overlie marine clays of Quaternary age, deposited on the  
90 flexured margin of the northward-dipping downgoing Hyblean Foreland (Lentini, 1982) (inset of  
91 Figure 1).

92

### 93 *Volcanic Activity*

94 Recent volcanic activity of Mount Etna is characterized by eruptions at the four summit craters, and  
95 by fissure eruptions and dike intrusions at the rift zones oriented NE, south and west. During the  
96 last 400 years, about half of the eruptions occurred along the rift zones through fissures opened on  
97 the volcano flanks (Behncke and Neri, 2003). These fissures are usually related to the lateral  
98 intrusion of dikes radiating from a shallow magma conduit system.

99 Important results obtained during recent decades, mainly due to the rapid improvement in the  
100 seismic and deformation monitoring networks, have identified the main tectonic structures and the

101 paths along which the magma rises beneath Mount Etna. Seismic tomographic images define the  
102 basement of Mount Etna as characterized by a main upper and middle crustal intrusion complex,  
103 with high  $V_p$  values (High Velocity Body; HVB), whose top is located at about 4 km below sea  
104 level (b.s.l), beneath the southeastern flank of Mount Etna (e.g., Aloisi et al., 2002; Chiarabba et al.,  
105 2004; Patanè et al., 2006). In recent years, magma intrusions have ascended along the western  
106 boundary of the HVB, as documented by ground deformation and seismic studies (e.g., Bonforte et  
107 al., 2008; Puglisi et al., 2008 and references therein). It is noteworthy that the lack of evidence for  
108 large magmatic storage volumes strongly supports the idea that, during its ascent along the western  
109 boundary of the HVB, the magma is stored as a plexus of dikes or sills, as suggested by Armienti et  
110 al. (1989) to justify the typical polybaric evolution of the magmas within the plumbing system of  
111 Mount Etna (Corsaro and Pompilio, 2004).

112

### 113 *Structural framework*

114 The shallow geodynamic behavior of Mount Etna seems to be controlled by the flank instability  
115 processes causing the seaward sliding of the volcano eastern side as a result of a complex  
116 interaction between regional tectonic stresses, gravity forces acting on the volcanic edifice and the  
117 dike-induced rifting (Neri et al., 1991; Borgia et al., 1992; Lo Giudice and Rasà, 1992;  
118 McGuire, 1996; Rasà et al., 1996). Although the published models propose different explanations of  
119 the origin and depth of the flank movement, they all agree in identifying the Pernicana Fault system,  
120 PF (Figure 1) as the northern boundary of the unstable sector. This is a transtensive fault with left  
121 lateral movement. It is characterized by a high slip rate from 10 to 28 mm/year with shallow (<3.5  
122 km) and moderate seismic activity ( $2 < M < 4.5$ ) (Azzaro, 1997; Azzaro et al., 2001). The PF activity  
123 is kinematically connected to the episodic opening and eruptions of the nearby NE Rift (Figure 1)  
124 (Neri et al., 1991; Gardunõ et al., 1997; Tibaldi and Groppelli, 2002; Acocella and Neri, 2003;  
125 Acocella et al., 2003). The southern part of the western boundary of the unstable sector is  
126 represented by the South Rift (Rasà et al., 1996) joining, southeastward, with the Tremestieri-

127 Trecastagni fault system TTF (Figure 1). This fault system is made up of a number of NNW-SSE  
128 striking faults showing evident right-lateral displacement and is also characterized by very shallow  
129 seismicity, with typical focal depths of 1–2 km. Other tectonic lineaments dissect the southern and  
130 south-eastern sectors of the volcano, such as the Timpe Fault system (STF1 and STF2), San  
131 Leonardello Fault (SLF), Moscarello Fault (MF) and Santa Venerina Fault (SVF) (Figure 1).  
132 Most of these faults have high slip rates from 1.0 to 2.7 mm/year (Azzaro, 2004; Puglisi et al.,  
133 2008), partly due to shallow seismicity (Lo Giudice and Rasa, 1992; Montalto et al., 1996).  
134 Instrumental data, according to historical and macroseismic information (Azzaro, 1999), indicate  
135 that more than 80% of earthquakes are shallower than 5 km (Gresta et al., 1990), which, despite  
136 their moderate magnitude, have often produced coseismic surface faulting. Fault plane solutions of  
137 these events frequently indicate a right lateral strike, combined with a significant normal  
138 component. More recent proposals emphasize the complexity of the unstable sector, showing how  
139 these faults represent the main structures that separate portions with slightly different velocities of  
140 downslope movement (Bonforte et al., 2011).

141

142

### 143 **3. CFS Modeling**

144 In this paper, we investigate the relationships between volcanism, flank instability and faulting in  
145 terms of elastic stress change. We investigate possible triggering conditions in which only one  
146 deformation source at a time is active. Our modeling approach examines how (1) the inflation of a  
147 spherical deep source interacts with the sliding plane and faults, (2) the opening of an eruptive  
148 fissure (at North-East or South Rift zone) affects the sliding movement of eastern sector or seismic  
149 activity on fault planes, (3) the flank instability governs the kinematics of faults and triggers (or  
150 inhibits) the ascent of magma (Figure 3).

151

#### 152 *3.1. Modeling Method*

153 Taking into account the topographic effects, we compute boundary element solutions of  
154 deformation sources embedded in an elastic half-space, using the program Poly3D 2.1.8 (Thomas,  
155 1993; Maerten et al., 2005). Based upon the boundary element method (Crouch and Starfield,  
156 1983), Poly3D includes the fundamental solution to an angular dislocation in a homogeneous, linear  
157 elastic half-space (Comninou and Dundurs, 1975). A number of angular dislocations are juxtaposed  
158 to create polygonal boundary elements that collectively define discretized objects of arbitrary shape  
159 in three dimensions. Boundary conditions in Poly3D can be applied remotely (as constant stresses  
160 or strains), at the centers of each element of the discretized fault surface (as tractions or  
161 displacement), or as combinations. The program solves a series of linear algebraic equations that  
162 describe the influence of each element on every other element under a prescribed set of boundary  
163 conditions. Once the displacement distribution along a fault is determined, the static stress, strain  
164 and displacement fields around the fault are calculated using influence coefficient equations that  
165 relate the displacements at the fault to the resultant elastic field at any point in the surrounding  
166 linear elastic medium. This solution is superimposed upon the remote stress field boundary  
167 condition to produce the total elastic field. Note that in our modeling processes we do not take into  
168 account the regional stress field. Indeed, geological and geophysical evidences highlight the  
169 heterogeneity of the Mount Etna stress field in time and space (e.g., Barberi et al., 2000 and  
170 reference therein). According to Gresta et al. (2005), from a kinematic point of view, the  
171 coexistence of structural elements such as PF and TFS are incompatible with a homogeneous stress  
172 field. Consequently, in this paper we use only “Specified fault calculation” for  $\Delta$ CFS computation  
173 and we relinquish the evaluation of “optimally oriented faults” (strongly influenced by the regional  
174 stress field) as suggested by several authors in such cases (e.g., Gresta et al. 2005, Bonanno et al.,  
175 2011 and references therein)

176 In Poly3D we build polygonal elements for modeling complex surfaces with curving boundaries.  
177 Surface fault changes in strike are meshed without gaps. The spherical void is built by assembling  
178 triangular, hexagonal or pentagonal elements in the same manner as a football.



179 The Boundary Element Method was chosen because it is suitable for near real-time applications  
180 since it allows modifying an evolving scenario simply by adding new magmatic sources and/or  
181 receiving structures. The use of Poly3D enables avoiding meshing the medium every time a  
182 structural modification is carried out, in such a way the computational time is limited to tens of  
183 minutes.

184

### 185 *3.2. Setup of deformation source parameters*

186 Following on from recent studies (Patanè et al., 2003a; Chiarabba et al., 2004; Bonaccorso et al.,  
187 2006; Bonforte et al., 2008; Puglisi et al., 2008; ), we considered a spherical cavity constructed of  
188 815 triangular elements, simulating a 1 km in radius reservoir at 3 km depth (Figure 2). An increase  
189 in magma pressure perturbs the stress field in the surrounding crust. Using positive traction  
190 boundary conditions, normal to the element, we defined a volume increase of  $7.9 \cdot 10^6 \text{ m}^3$ , a realistic  
191 value for inflating magma bodies (Bonaccorso et al., 2006; Palano et al., 2007; Puglisi et al., 2008).  
192 The center of the MR was located beneath the Summit Craters area (for details see Table 1). In  
193 addition, in order to evaluate the influence of depth of an inflating reservoir (hereafter MR) on other  
194 considered structures and in particular on SP, we performed two further simulations moving the  
195 center of the sphere by  $\pm 2.4$  km. These steps of depth were chosen since they roughly correspond  
196 to the projections respectively of the top and the bottom of SP (see below) along the vertical line  
197 intersecting the Summit Craters.

198 Dike intrusions were modeled by rectangular planes with a curving top boundary matching the  
199 topography (Figure 2). A uniform element-normal displacement discontinuity of 2.5 m is imposed  
200 on dikes. The geometry of the North-East and South dikes used in this paper is based on values  
201 published by Puglisi et al. (2008). In any case, openings larger than 3 m do not modify the results  
202 significantly. The parameters of the modeled dikes are reported in Table 1.

203 In agreement with inversion models inferred from ground deformation measurements (Puglisi and  
204 Bonforte, 2004; Bonaccorso et al., 2006; Bonforte et al., 2008), we modeled a sub-horizontal sliding

205 plane (hereafter SP) as a rectangular surface 20 km long and 25 km wide, with a main normal (7.7  
206 cm) and minor dextral component (4.4 cm) (Figure 2). Although the slip amount depends on the  
207 period investigated, inversion models published (Puglisi and Bonforte, 2004; Palano et al, 2007)  
208 found an overall sliding in the range of 4 – 9 cm/year in the period 1993 -2000.

209

### 210 *3.3. Setup of topography and fault parameters*

211 We used the Global Digital Elevation Model (INGV-G-DEM) that merges inland DEM (Tarquini et  
212 al., 2007; Neri et al., 2008) and bathymetric data sets available for the Mount Etna area (Bosman et  
213 al., 2007; Cavallaro et al., 2008). The original data were integrated and interpolated, becoming  
214 homogenous with a final resolution of 10 m pixel size. Using INGV-G-DEM resampled with a  
215 resolution of 100 m, we built a rectangular surface of 3500 km<sup>2</sup> (extending for about 70 kilometers  
216 in longitude and 50 km in latitude) and discretized with 3184 triangular meshes (Figure 2). Volcano  
217 topography is assumed as a traction-free surface in order to study the influence on displacements  
218 and stress numerical calculations. According to geological and structural studies integrated with  
219 seismic data, we modeled the main tectonic lineaments of the eastern sector of the volcano. We  
220 built the faulting planes as rectangular surfaces with a curving top boundary matching the  
221 topography, with each plane discretized by triangular meshes with a mean areal dimension of about  
222 0.027 km<sup>2</sup>. In particular, Provenzana Fault (PR) shows a change of strike from N35°E to N55°E,  
223 thus a curving top boundary is modeled. The Pernicana Fault (PF) is made up of four segments  
224 (PF1, PF2, PF3 and PF4) striking N88°E, N102°E, N114°E, N120°E, respectively (Figure 2a). The  
225 southern border of the unstable sector is represented by the Tremestieri-Trecastagni Fault system  
226 (TTF) modeled with a sub-vertical plane with a sharp change in direction (from N103°E to  
227 N150°E). The Timpe Fault System is made up of two segments, STF1 and STF2, with strike  
228 direction N165°E and N3°W, respectively. These latter fault systems, together with SLF, MF, SVF,  
229 all striking from N173°E to N140°E, reach the depth of the sliding plane (see Figure 2b). The sub-  
230 vertical fault planes above the sliding plane (SP) have a width ranging from 1950 to 2800 m (for

231 details see Table 2). In our models, we assume that receiver faults are discontinuities embedded in  
232 an elastic half-space in which they are free to move in any direction.

233

### 234 3.4 Coulomb Stress Changes

235 We calculated Coulomb stress changes caused by volcanic sources on modeled fault planes, while  
236 computing changes in volumetric or normal stress near the magma chamber or eruptive dikes  
237 caused by flank movements or earthquakes (e.g. Savage and Clark 1982; Nostro *et al.* 1998; Toda *et*  
238 *al.* 2002). It is widely accepted that static stress changes ( $\geq 0.1$  bars) induced by a magmatic source  
239 may trigger seismicity within a rock volume close to the critical state of failure (e.g., Reasenber  
240 and Simpson, 1992; Stein, 1999). Spatial and temporal relationships between stress changes and  
241 earthquakes are explained through the Coulomb failure stress change, defined as:

$$242 \quad \Delta CFS = \Delta\tau + \mu(\Delta\sigma_n + \Delta P) \quad (1)$$

243 where  $\Delta\tau$  is the shear stress change computed in the direction of slip on the fault,  $\Delta\sigma_n$  is the normal  
244 stress change (positive for extension),  $\mu$  is the coefficient of friction and  $\Delta P$  is the pore pressure  
245 change (e.g., King *et al.*, 1994; Harris, 1998; King and Cocco, 2000). For simplicity, we considered  
246 here a constant effective friction model (Beeler *et al.*, 2000; Cocco and Rice 2002) that assumes  $\Delta P$   
247 is proportional to the normal stress changes ( $\Delta P = -B\Delta\sigma_n$ , where  $B$  is the Skempton parameter):

$$248 \quad \Delta CFS = \Delta\tau + \mu' \Delta\sigma_n \quad (2)$$

249 where  $\mu'$  is the effective friction ( $\mu' = \mu[1 - B]$ ). The fault is brought closer to failure when  $\Delta CFS$   
250 is positive. In order to verify if dike intrusions or magmatic reservoir inflations are encouraged, we  
251 evaluate the change of the volumetric strain ( $\Delta\varepsilon = \varepsilon_1 + \varepsilon_2 + \varepsilon_3$ ) on the magmatic reservoir and  
252 horizontal normal stress changes ( $\sigma_m = (\Delta\sigma_{xx} + \Delta\sigma_{yy}) / 2$ ) on the rift zone dikes. Indeed, the  
253 unclamping of a rift zone ( $\sigma_m > 0$ ) induced by fault dislocations may facilitate the ascent of new  
254 magma and dike injection. In the same way, the unclamping may favor the decompression of the  
255 magma reservoir, leading to the formation and ascent of bubbles and then increasing the magma

256 overpressure. We performed all calculations in a homogeneous Poissonian elastic half-space using a  
257 Poisson ration of  $\nu = 0.25$  and a Young modulus of  $E = 75$  GPa, and a  $\mu' = 0.4$ .

258

### 259 *3.5 Assumptions of numerical modeling*

260 Coulomb stress changes are evaluated in a homogenous elastic half-space. Thus mechanical  
261 heterogeneities, for instance due to thermal structure, a hydrothermal altered volcanic core or a  
262 mechanically rigid basement, are not taken into account by our models. As stated before, the  
263 regional stress field is not taken into account given its heterogeneity in space and time. The surface  
264 traces of the faults are visible, well-mapped and constrained, but we simplified the characteristics of  
265 the sliding plane by imposing a uniform slip on the whole rectangular surface. We did not take into  
266 account visco-elastic or elasto-plastic behaviors or any differential flank movement inferred by a  
267 number of authors recently (Palano et al., 2009; Currenti et. al, 2010; Bonforte et al., 2011).

268

269

## 270 **4. Modeling**

271 For each model,  $\Delta$ CFS values are computed on faulting planes and on the sliding surface (Figure 2).  
272 The normal stress  $\sigma_m$  is evaluated on dike fractures and volumetric strain  $\Delta\varepsilon$  on the spherical surface  
273 of magmatic reservoir. The parameters of sources and receiver structures are described in Table 1  
274 and 2, respectively. Four deformation models were tested: M1, inflating of a spherical magmatic  
275 source (Figure 3, M1); M2, opening of eruptive fissures (Figure 3, M2), divided into two models A)  
276 for South dike and B) North East dike; and M3, sliding of planar surface (Figure 3, M3). Our  
277 numerical results of  $\Delta$ CFS on each receiver structures are reported in Tables 3-6.

278

### 279 *4.1. Model 1 - Mogi Source*

#### 280 *a) Stress calculations*

281 We first considered stress changes associated with a reservoir inflation (depth = 3.0 km, roughly  
282 coincident with the center of the SP). M1 shows a decrease of CFS along the PR and PF2 segments  
283 and an increase along the PF1 segment, with the latter showing a maximum value of 1.4 bars along  
284 the western edge (see M1 in Figure 4 and Table 3 for maximum and minimum  $\Delta$ CFS values). A  
285 decrease and an increase close to zero were computed on PF3 and PF4 planes, respectively (Table  
286 3). M1 induces a stress increment on STF1 and SVF closer portions (0.3 and 0.2 bars). The MF,  
287 SLF and TTF planes are subjected to a slight positive increment on the top edge (in a range between  
288 0.1 and 0.2 bars) (Figure 4, M1). Moreover, the movement of STF2 is inhibited by the inflation of  
289 MR. Finally, the inflation of spherical chamber favors the closure of the NE and South dikes  
290 significantly. On the sliding plane, we observed a decrease of  $\Delta$ CFS in the northwestern part of the  
291 plane (minimum value about -2 bars) and a very slight positive variation (0.2 bars) along the  
292 remaining part of the surface.

293 The simulations performed moving the depth of MR do not change the scenario described before  
294 drastically and significant variations only affect a few structures. A shallow MR (depth = 0.6 km;  
295 roughly coincident with the top boundary of the SP) does not change the pattern of the static stress  
296 on all the faults considered, and the intensity is only slightly affected. Also the NE dike shows  
297 almost unaltered features and only a very small part of the dike (near MR) underwent an  
298 unclamping effect. The most important variation is observed on the SP, which experienced a  
299 positive CFS variation of 2 bars. The S dike also showed a different pattern in  $\Delta$ CFS distribution;  
300 indeed, the closure of the S dike is strongly encouraged only in the portion near MR, while the  
301 remaining part underwent an unclamping effect. The inflation of a deeper MR (depth = 5.4 km;  
302 roughly coincident with bottom boundary of the SP) does not change the static stress pattern on the  
303 SP and the S and NE dikes. A slight change in the intensity affected both dikes, enhancing the  
304 closure trend observed with a 3 km depth MR. Also the majority of the faults considered show  
305 unchanged features and only MF experienced a positive CFS variation until 1.4 bars.

306 In summary, the depth of an inflating shallow crustal reservoir may change the scenario evaluated  
307 slightly and only the flank movement seems significantly affected by the depth of MR; indeed, very  
308 shallow MR may promote flank movements, while deeper MR inhibits them. In general, a shallow  
309 MR discourages dike intrusion into the Mount Etna rift zones and promotes the stress triggering on  
310 the westernmost portion of PF.

311

#### 312 *b) Displacement calculations*

313 The expansion of MR at 3 km depth induced the uplift of the nearby structures, such as PR, PF1 and  
314 PF2 (see Figure 5 and Table 3 for maximum and minimum displacement values). The inverse  
315 component is replaced by left-lateral movement on PF3 and PF4 components. The displacement  
316 values are progressively reduced from the western to eastern part. SLF, STF2, TTF and MF shows a  
317 right-lateral movement. On STF1, SVF and SP planes an uplift is favored. In particular, on the SP a  
318 maximum value of 2.4 centimeters of thrust movement is computed. This result changes drastically  
319 if we consider a very shallow crustal reservoir, which inverts the observed trend, promoting  
320 seaward movements of the eastern flank. It is clear that for this aspect of the problem the boundary  
321 condition set in the model (source depth) plays a basic role and highlights just how crucial the depth  
322 constraint is in ground deformation inversion analyses.

323

#### 324 *4.2. Model 2A – South Dike*

##### 325 *a) Stress calculations*

326 Intrusion along the S dike favors the closure of NE dike with a negative unclamping effect ( $\sigma_m$   
327 maximum value is about of -32 bars). In the M2a we observe a decrease of  $\Delta CFS$  on the PR  
328 segment (max value -4.5 bars). On the PF system  $\Delta CFS$  values are negative except on PF1 with a  
329 positive stress variation reaching a maximum value of 1.4 bar on the upper part of plane (Table 4).  
330 PF2, PF3, PF4 and SLF segments show a slight increase but in general all planes show a reduction

331 of  $\Delta CFS$ . STF1, STF2, SVF and TTF similarly underwent a reduction of  $\Delta CFS$  (see M2A in Figure  
332 4 and Table 4 for maximum and minimum  $\Delta CFS$  values). On SP a maximum positive stress change  
333 is computed for the part of the plane closest to the magmatic feeding system. Finally, the S-dike  
334 intrusion induces a compression ( $\epsilon > 0$ ) on the MR located beneath the summit craters (see Figure 4,  
335 M2A).

336

#### 337 *b) Displacement calculations*

338 The opening of SD encourages a normal movement of SP. The direction of displacement vectors on  
339 SVF, SLF, STF1, STF2 and MF shows a right-lateral movement associated with the dip-normal  
340 component. PR and TTF segments show the reverse movement. All PF segments move with a pure  
341 left-lateral strike slip (see Figure 5 and Table 4 for maximum and minimum displacement values).  
342 In summary, magmatic activity in the South Rift closes the North East Rift and mobilizes the East  
343 and North East region of the unstable block.

344

### 345 *4.3. Model 2B – North East Dike*

#### 346 *a) Stress change calculations*

347 In M2B we find that intrusion along the NE dike into the rift zones causes significant increase of  
348  $\Delta CFS$  on PR and PF1, with maximum values of about 320 bars and 100 bars, respectively. On the  
349 upper part of PF2 elastic stress changes increase to 3.4 bars. PF3, STF1, SVF, STF2 and TTF show  
350 a decrease of static stress variations (Table 5). SLF and MF are brought close to failure on the  
351 shallower portions of fault planes with higher values of 2.3 and 5.3 bars, respectively (see M2B in  
352 Figure 4 and Table 5 for maximum and minimum  $\Delta CFS$  values). A significant negative unclamping  
353 effect on the walls of the S dike is found (max  $\sigma_m$  value about of -26 bars). The opening of the NE  
354 dike favors the decompression of MR with  $\epsilon_{max}$  about of  $-4.8e-5$  m<sup>3</sup> ( $\epsilon < 0$  volumetric strain is  
355 negative for decompression). Finally, we observe that because of its dimension and geometry, the

356 NE dike is more efficient in transferring stress on the sliding plane with respect to the S dike. On  
357 the shallower portion of SP the maximum value of  $\Delta CFS$  reaches 2.6 bars (Table 5).

358

359 *b) Displacement calculations*

360 The most important results regarding displacement calculations show that the opening of the NE  
361 dike favors the sliding of flank with a transtensive component (see Figure 5 and Table 5 for  
362 maximum and minimum displacement values). All modeled faults, such as TTF, SVF, STF1, STF2,  
363 MF and STF are kinematically compatible with a right-lateral movement associated with a normal  
364 dip component. On PR, PF1 and PF2 planes a transpressive left-lateral movement is favored.  
365 Towards the east we found only left transcurrent component on PF3 and PF4 structures.

366

367 *4.4. Model 3 – Sliding Plane*

368 *a) Stress calculations*

369 We found a positive  $\Delta CFS$  with max values of about 1.7 and 1.5 bars in the upper part of PF1 and  
370 PF2, respectively, and an increase of static stress in the lower portion of PF3 and PF4 (max about of  
371 3.5 bars). The relative position between SP and receiver faults also resulted in an increase in static  
372 stress on TTF plane. Thus, we estimated a positive  $\Delta CFS$  in the lower part of this structure with a  
373 maximum value of 3 bars (see M3 in Figure 4 and Table 6 for maximum and minimum  $\Delta CFS$   
374 values). Small increases of elastic stress are found on the MF, SLF, SVF, STF1 and SFT2 faults  
375 (Table 6). The sliding of the plane beneath the eastern flank seems to favor a compression for MR  
376 ( $\epsilon > 0$  volumetric strain is positive). The unclamping effects for two vertical eruptive fractures  
377 located on the northeast and southern flank of volcano was estimated. We observed that SP induces  
378 the closure in the upper part of tabular dikes. Instead, a small opening is favored in their deeper  
379 zones (about 0.1 bars) (Figure 4, M3). This interaction depends on the dimension of modeled  
380 eruptive fractures and the depth of SP. In brief, the unstable condition of flank sliding toward the



381 sea may affect the magmatic system. Decompression of plumbing system may lead to the ascent of  
382 new magma or modify the condition of overpressure with the formation of bubbles (Hill, 2002).

383

#### 384 *b) Displacement calculations*

385 The results of our simulations (see Figure 5 and Table 6 for maximum and minimum displacement  
386 values) show that the transtensive movement of SP encourages the dip normal displacement on PR,  
387 PF1 and PF2. By contrast, PF3 and PF4 moves according to a dip-normal associated to a left lateral  
388 movement. Coherently to observed kinematics STF1, STF2, SLF, SVF and MF are encouraged to  
389 move with a transtensive component, whereas a transpressive movement is determined for TTF.

390

391

### 392 **5. Discussion and conclusions**

393 During these last decades Mount Etna volcano has undergone several eruptions that have  
394 highlighted intriguing trigger mechanisms and have featured dike intrusions, activation of  
395 seismogenic faults and aseismic ground deformations.

396 Geophysical studies suggest that complex dynamics, involving more than one source (seismogenic  
397 sources and dikes), is a relatively common characteristic of eruptive episodes on Mount Etna.  
398 Gresta et al. (2005), for instance, highlighted that earthquakes along the PF and STF were induced  
399 by the static stress variations associated with the emplacement of eruptive dikes during the 1981  
400 and 2001 eruptions, respectively. More recently, the pressure increase due to magma ascent  
401 episodes occurring in 1997-1998 at Mount Etna has been demonstrated to be responsible for the  
402 reactivation of seismogenic structures on the western side of the volcano (Bonanno et al., 2011). In  
403 Bonanno et al. (2011), the intrusive process was modelled as an inflating Mogi source located at 5.5  
404 km depth, but in the present work, we emphasize the crucial role of the boundary condition set in  
405 the model (source depth) and show the possible scenarios with a shallower MR depth (Model M1).

406 The July-August 2001 eruption was characterized by a very complex field of flank eruptive  
407 fractures located largely on the upper southern slope of the volcano (Monaco et al., 2005). The  
408 eruption onset was preceded and accompanied by significant earthquakes (Patanè et al., 2003b) and  
409 marked ground deformations (Bonaccorso et al., 2002). The main source of deformations was  
410 modelled by a tensile dislocation located on the South Rift zone (Puglisi et al. 2008) as also  
411 confirmed by the Seismic Moment Tensor inversions of the best constrained earthquakes that  
412 heralded the opening of the eruptive fractures (Saraò et al., 2010). Our present model M2A takes  
413 account of the main behaviour of the magmatic source for this eruption well.

414 The October 2002 - January 2003 eruption occurred on two sides of the volcano, along the upper  
415 north-eastern (NE Rift zone) and southern (South Rift Zone) flanks. Once again, earthquakes and  
416 ground deformations preceded and accompanied the opening of the eruptive fractures (Barberi et  
417 al., 2004 and reference there in). The two intrusive dikes have been satisfactorily modelled by two  
418 separate tensile dislocations (Aloisi et al., 2003). During the first stage of the eruption, several  
419 seismogenic structures on the eastern flank became successively active. This was explained as due  
420 to the transfer of elastic stress from the magmatic source to faults (PR and PF) and afterwards from  
421 faults to faults (Barberi et al., 2004). Our present model M2B is schematically representative of the  
422 first stage of the above cited domino effect phenomena.

423 Finally, the 2004–2005 eruption emitted a highly degassed magma from a sub-terminal fracture.  
424 During the first weeks of activity, the erupted magma was already residing inside the volcano,  
425 probably since the 2002-2003 eruption, while later it mixed with new magma ascending through the  
426 central conduit system (Corsaro et al., 2009). Magma intruded passively due to the exceptional  
427 extension on the summit area caused by the large sliding of the eastern flank of the volcano (almost  
428 9 cm of slip; Bonaccorso et al., 2006). The east flank sliding toward the sea induces a  
429 decompression on the shallow magma plumbing system as foreseen by our model M3 that simulates  
430 the unstable condition of this sector.

431 In this work we have investigated, by using the Boundary Element Method, how (i) the inflating of  
432 a deep spherical source interacts with a sliding plane and with faults and rift elements; (ii) the  
433 opening of eruptive fissures affects the sliding movement of the eastern sector of Mount Etna,  
434 encouraging earthquakes on fault planes; and (iii) the instability of the eastern flank governs the  
435 kinematics of faults and/or triggers the ascent of magma. The results presented here are strongly  
436 dependent on all the assumptions made. In particular, the lack of seismological constraints  
437 (hypocenter patterns and compatible fault plane solutions) for the sliding plane induced us to  
438 simplify the geometry of a detachment volume that remains/lies at the base of the instable sector.  
439 Nevertheless, our numerical results show good agreement with deformation measurements that  
440 well-describe the eastern flank dynamics of Etna volcano (e.g., Bonforte et al., 2008; Puglisi et al.,  
441 2008).

442 The main results obtained are the following:

- 443 1. The inflation of a magma reservoir encourages the slip on the westernmost segment of the  
444 Pernicana fault (PF).
- 445 2. The depth of MR is crucial, very shallow depth MR promote seaward movement of the  
446 eastern flank, while deeper MR (3.0 - 5.5 km) inhibit the movement.
- 447 3. Dikes intruding either on the NE or/and South Rift Zones favor the sliding of the planar  
448 source in its upper part and along the westernmost of PF.
- 449 4. The intrusion (opening) of a South dike favors the closure of a NE dike, while at the same  
450 time the opening of NE tensile fracture inhibits the ascent of magma along the South zone.
- 451 5. The intrusion of a NE dike (for dimension and kinematics) favors the Eastern flank sliding,  
452 more than the opening of an S dike.
- 453 6. The opening of a NE dike encourages the decompression of the magma plumbing system  
454 (depth = 3.0 km), evaluated by a high negative value of volumetric strain.
- 455 7. The passive sliding of SP promotes an increase of CFS on the westernmost and the central  
456 segments of PF. Its easternmost segments are brought close to failure at their bases.

- 457 8. The unstable condition of flank sliding toward the sea may affect the magmatic system and  
458 decompression of plumbing system may lead to a new magma ascent.
- 459 9. The western part of Pernicana fault (PF1) experienced a positive CFS for all the scenarios  
460 hypothesized. The other segments underwent a positive stress variation only in M2B and M3.  
461 In particular, Model M2B highlights the governing role of the intrusion in the NE Rift on the  
462 dynamics of this structure and on the dynamics of the Provenzana fault too.
- 463 10. Other faults considered seem to be less sensitive to the stress variation induced by sources  
464 considered, with the exception of three structures. SLF and MF underwent a significant  
465 positive CFS variation in model M2B, and TTF experienced an increase in static stress in  
466 model M3.

467

468 These results schematically represent possible scenarios of the evolution of the kinematic “activity”  
469 of Mount Etna volcano. The three basic elements (magma dynamics, earthquake occurrence and  
470 flank instability) interact with each other, alternating their active or passive role in a broader  
471 combination of domino effects. Our results are in general agreement with the findings of Walter et  
472 al. (2005), despite the significant differences in the structural setup and in the definition of  
473 geometrical characteristics of the single geological objects. The main difference regards the effect  
474 of interaction between magma reservoir and sliding plane; the latter was defined by Walter et al.  
475 (2005) with geometrical characteristics that are entirely different from those hypothesized in this  
476 paper. Currenti et al. (2008) use a very simplified structural setup taking into account only the two  
477 rift zones and the main fault systems in eastern flank. Regardless of differences, the result obtained  
478 are similar with the exception of the NE dike response to an intrusion in the South rift. Currenti et  
479 al. (2008) have also demonstrated that the introduction of an heterogeneous medium induces  
480 variation in the intensity of  $\Delta\text{CFS}$  (as a function of modelled elastic parameters), but does not  
481 distort the geometrical pattern. The authors also show how the stress shape is affected by Mt. Etna

482 topography. The main discrepancies are largely restricted to the volcano summit area because of the  
483 accentuated topography.

484 We note that the strength of our approach lies in the fact that we evaluate the distribution of the  
485 CFS pattern while taking into account the relevant effects of topography. In addition, we use a  
486 method that requires a processing time of some tens of minutes. It allows modifying an evolving  
487 erupting scenario simply by adding or altering magmatic sources and/or receiving structures  
488 without needing any further computational time that other numerical methods require (e.g., re-mesh  
489 of medium in Finite Element Method). The real-time seismic and geodetic networks currently  
490 operating on Mount Etna are able to provide good enough data (both in number and quality) to  
491 satisfactorily (and rapidly) constrain the source(s) responsible for volcanic unrest. The application  
492 of the Boundary Element Method during volcanic unrest appears a promising tool to provide some  
493 possible scenarios of evolving volcanic activity in near real-time in terms of flank sliding and/or  
494 activation of either (both) seismogenic faults and/or magma bodies.

495

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505

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730

731 **Figure captions**

732

733

734 **Figure 1.** Structural sketch map of Mount Etna: Provenzana Fault (PR); Pernicana fault (PF); Santa  
735 Venerina fault (SVF); Timpe fault system STF; Moscarello fault (MF); Tremestieri–Trecastagni  
736 fault (TTF); San Leonardello Fault (SLF); Central Craters (CC); South Rift and North - East Rift  
737 are also indicated. In the upper inset, the location of Mount Etna in the central Mediterranean area  
738 and a simplified geological map of eastern Sicily are also reported. The INGV-G-DEM is in the  
739 WGS84 reference system and the projection is UTM33.

740

741 **Figure 2.** a) Top view and b) prospective view of the boundary Element model built in Poly3D  
742 environment show spatial relationships between topography, faults, magmatic reservoir, eruptive  
743 fractures, sliding plane and faults. For structure legend see tables 1 and 2.

744

745 **Figure 3.** Sketch of four models proposed showing: M1) Inflation of Magmatic Reservoir (MR);  
746 M2A) Opening of South Dike (SD); M2B) Opening of North-East Dike (NED); M3) Transtensive  
747 movement of Sliding Plane (SP); the acting sources (red) and the receiver structures (black) are  
748 drawn. For faults legend see table 2.

749

750 **Figure 4.** Three dimensional view showing the pattern of  $\Delta$ CFS produced by inflation of MR (M1)  
751 along modeled fault planes; Opening of SD (M2A); Opening of NED (M2B) and Transtensive  
752 movement of SP (M3). The color bar specifies the maximum and minimum  $\Delta$ CFS values that are  
753 reported for each single structure in Tables 3-6.

754

755 **Figure 5.** Three dimensional view showing the pattern of the displacement produced by inflation of  
756 MR (M1) along modeled fault planes; Opening of SD (M2A); Opening of NED (M2B) and

757 Transverse movement of SP (M3). The color bar specifies the maximum and minimum  
758 displacement values that are reported for each single structure in Tables 3-6.

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762 **Table titles**

763

764

765 **Table 1.** Description of deformation source inputs used in the numerical modeling.  $X_c$ ,  $Y_c$  and  $Z_c$   
766 represent the location of the center, while  $L$  and  $W$  correspond to length and width for each source.

767

768 **Table 2.** Position and geometrical parameters of receiver fault planes modeled in Poly3D program  
769 (for symbols explanation see table 1).

770

771 **Table 3.** Coulomb stress changes and displacements ( $U$ ) induced on considered structures (see table  
772 1 and 2 for structure names) by the inflation of MR (model M1).

773

774 **Table 4.** Coulomb stress changes and displacements ( $U$ ) induced on considered structures (see table  
775 1 and 2 for structure names) by the opening of SD (model M2A).

776

777 **Table 5.** Coulomb stress changes and displacements ( $U$ ) induced on considered structures (see table  
778 1 and 2 for structure names) by the opening of NED (model M2B).

779

780 **Table 6.** Coulomb stress changes and displacements ( $U$ ) induced on considered structures (see table  
781 1 and 2 for structure names) by the transtensive movement of SP (model M3).

782

1 | **Triggering mechanisms of static stress on ~~Mount~~ Etna volcano. An**  
2 | **application of the boundary element method.**

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4 |  
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16 | Running Title: Coulomb stress changes at ~~Mt.~~[Mount](#) Etna

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29

30 **Abstract**

31 In the last thirty years, numerous eruptions and associated deformation episodes have occurred at  
32 Mt. Etna volcano. ~~Datasets recorded by continuous~~ ~~Continuous and intense dynamics~~ monitoring of  
33 ~~these episodes magmatic processes~~ provide a unique ~~opportunity possibility~~ to study the  
34 relationships between volcanism, flank instability and faulting activity. We have investigated the  
35 stress triggering mechanism between magmatic reservoir inflation, intrusive episodes and flank  
36 dynamics. Using three-dimensional numerical Boundary Elements Models we simulated volcano-  
37 tectonic events and calculated Coulomb stress changes. ~~Using this Our~~ modeling approach, ~~we~~  
38 analyzed four realistic scenarios that ~~are representative of represent~~ recent kinematics ~~episodes~~  
39 occurring at Mt. Etna ~~well~~. The main results obtained highlight how (1) the ~~inflating-inflation~~ of a  
40 deep spherical magma source transfers elastic stress to a sliding plane and faults (2) the opening of  
41 the NE Rift and S Rift (to a less efficient extent) favor movements of the instable sector and may  
42 encourage seismicity on the eastern flank faults, and (3) ~~the~~ flank instability may trigger the  
43 uprising of magma.

44 Defining the effects of the elastic stress transfer and relationships among the main forces acting on  
45 volcano, may help to forecast ~~the possible~~ eruption scenarios during future ~~eruptive~~ episodes of  
46 unrest at Mount Etna, ~~and provide an important tool for decision makers during volcanic~~  
47 emergencies involving the highly populated areas ~~which is important to reduce volcanic and seismic~~  
48 hazards on the highly populated eastern sector of the volcano.

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52 **Keywords:** Numerical modeling, Coulomb stress changes, ~~flank instability,~~ volcano dynamics,  
53 ~~Mt.~~ Mount Etna volcano, magmatic activity.

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## 1. Introduction

Active volcanoes in densely populated areas represent a primary hazard that requires a operative and well-timed interaction between research institutions and civil defence authorities during unrest episodes. Consequently, involved researcher are encouraged to tune up affordable methods that can provide realistic scenarios of the eruptive evolution in near real-time.

Mount Etna dynamics is the result of a complex interplay between magma ascent in the plumbing system, dike emplacement, tectonic uplift, faulting and flank instability. At Mount Etna, many studies have evidenced highlighted that at Mount Etna increases in static stress induced by dike intrusions bring faults closer to failure (Gresta et al., 2005). More recently, the pressurization of a magmatic reservoir was considered to trigger 1997-1998 Mount Etna seismic swarms as effects a consequence of stress redistribution (Bonanno et al, 2011).

The increase in collected seismic and deformation measurements and the rapid growth of computational power have enabled improving investigations into the relationship between faulting, flank dynamics and magmatic activity using numerical modeling. Walter et al. (2005) modeled the 2002-2003 Mt. Etna eruption by means of Boundary Element Method, evaluating the influence of four different sources on the kinematics of the volcano's eastern flank. They found a feedback relationship between flank movements and intrusive processes The numerical models suggest that magmatic activity (inflation of a reservoir and emplacement of dikes) encourages motion of the eastern flank, which, in turn, promotes magma to rise up to shallower levels within the volcano. Currenti et al. (2008) performed a Finite Element Modeling approach to evaluate ground deformation and the resulting stress redistributions in response to magmatic processes occurring during the 2002–2003 Etna eruption. They found that the changes in the state of stress generated by the southern dike produce an extensional stress field that favors magma propagation along the north-east Rift. The static stress changes computed onto the Timpe Fault System and the Pernicana

81 ~~Fault indicate that the magma intrusions on the southern and northeastern flanks prompted these~~  
82 ~~seismogenic structures to slip. Volcano flank instability has been recognized at many volcanoes~~  
83 ~~around the globe. Dynamics of a flank is driven by combinations of gravity, magma pressure, lack~~  
84 ~~of buttressing support, presence of an underlying weak substrate to the edifice, increasing pore~~  
85 ~~pressure associated with volcanism, dyke emplacement, tectonic uplift and faulting (e.g. Siebert,~~  
86 ~~1984; McGuire, 1996; Merle and Borgia, 1996; Voight and Elsworth, 1997; Tibaldi, 2001; Aeocella~~  
87 ~~et al., 2006). In some cases, the interaction of several factors may make defining the main triggering~~  
88 ~~cause of the instability difficult (Voight and Elsworth, 1992).~~

89 ~~The increase in collected deformation measurements and the fast growth of computational power~~  
90 ~~have permitted better investigating the relationship between flank dynamics and magmatic activity~~  
91 ~~using numerical modeling. In this last decade, a significant proliferation of numerical modeling~~  
92 ~~studies have highlighted that eruptions, flank instability and faulting episodes are related. Through~~  
93 ~~limit equilibrium methods (LEM) and finite difference modeling (FEM), a 2D stability analysis of~~  
94 ~~the NW flank of the Stromboli edifice was performed by Apuani and Corazzato (2009). The authors~~  
95 ~~show that the tectonic seismicity of the area alone does not destabilize the studied slope. On the~~  
96 ~~contrary, magma pressure in dykes can represent a destabilizing factor. Walter et al. (2005)~~  
97 ~~modeled the 2002-2003 Mt. Etna eruption by means of Boundary Element Method, evaluating the~~  
98 ~~influence of four different sources on the kinematics of the volcano's eastern flank. They found a~~  
99 ~~feedback relationship between flank movements and intrusive processes. The numerical models~~  
100 ~~suggest that magmatic activity (inflation of a reservoir and emplacement of dykes) encourages~~  
101 ~~motion of the eastern flank, which, in turn, encourages the rise of magma to shallower levels within~~  
102 ~~the volcano. Using Coulomb stress simulations, Segall et al., (2006) have demonstrated that a recent~~  
103 ~~dike intrusion probably triggered a slow fault slip event on Kilauea volcano's mobile south flank.~~

104 ~~At Mount Etna, many studies have evidenced that increases in static stress induced by dike~~  
105 ~~intrusions bring faults closer to failure (Gresta et al., 2005). More recently, the pressurization of a~~

~~magma reservoir was considered to trigger seismic swarms as effects of stress redistribution (Bonanno et al., 2011).~~

In this paper, we will use numerical simulations to hypothesize four realistic scenarios at Mt Etna in which one source at a time is active. Coulomb stress changes will be computed on three dimensional fault surfaces in order to investigate the interaction between intrusion/eruptive episodes, tectonic activity and flank instability. ~~Understanding which factor influences the instability of the Mt. Etna volcanic edifice is therefore crucial for hazard assessment and mitigation. The method used requires a processing time of some tens of minutes and is thus suitable for a near real-time application in order to forecast the evolution of future unrest episodes.~~

## 2. Etna volcano setting

~~Mount~~ Etna is a Quaternary basaltic stratovolcano located on the east coast of Sicily. It stands between two first-order tectonic elements: the Apenninic-Maghrebian Chain and the Hyblean Foreland (inset of Figure 1). The northern and western sectors of the volcano lie over metamorphic and sedimentary rocks belonging to the frontal nappes system of the Apenninic-Maghrebian Chain, whereas the southern and eastern sectors overlie marine clays of Quaternary age, deposited on the flexured margin of the northward-dipping downgoing Hyblean Foreland (Lentini, 1982) (inset of Figure 1).

### *Volcanic Activity*

Recent volcanic activity of Mount Etna is characterized by eruptions at the four summit craters, and by fissure eruptions and dike intrusions at the rift zones oriented NE, south and west. During the last 400 years, about half of the eruptions occurred along the rift zones through fissures opened on

131 the volcano flanks (Behncke and Neri, 2003). These fissures are usually related to the lateral  
132 intrusion of dikes radiating from a shallow magma conduit system.

133 Important results obtained during recent decades, mainly due to the rapid improvement in the  
134 seismic and deformation monitoring networks, have identified the main tectonic structures and the  
135 paths along which the magma rises beneath Mount Etna. Seismic tomographic images define the  
136 basement of Mount Etna as characterized by a main upper and middle crustal intrusion complex,  
137 with high  $V_p$  values (High Velocity Body; HVB), whose top is located at about 4 km below sea  
138 level (b.s.l), beneath the southeastern flank of Mount Etna (~~e.g., i.e.~~ Aloisi et al., 2002; Chiarabba et  
139 al., 2004; Patanè et al., 2006). In recent years, magma intrusions have ascended along the western  
140 boundary of the HVB, as documented by ground deformation and seismic studies (e.g., Bonforte et  
141 al., 2008; Puglisi et al., 2008 and references therein). It is noteworthy that the lack of evidence for  
142 large magmatic storage volumes strongly supports the idea that, during its ascent along the western  
143 boundary of the HVB, the magma is stored as a plexus of dikes or sills, as suggested by Armienti et  
144 al. (1989) to justify the typical polybaric evolution of the magmas within the plumbing system of  
145 Mount Etna (Corsaro and Pompilio, 2004).

146

#### 147 *Structural framework*

148 The shallow geodynamic behavior of Mount Etna seems to be controlled by the flank instability  
149 processes ~~implying causing~~ the seaward sliding of the volcano eastern side as a result of a complex  
150 interaction between regional tectonic stresses, gravity forces acting on the volcanic edifice and the  
151 ~~dykedike~~-induced rifting (Neri et al., 1991; Borgia et al., 1992; Lo Giudice and Rasà, 1992;  
152 McGuire, 1996; Rasà et al., 1996).

153 Although the published models propose different explanations of the origin and depth of the flank  
154 movement, they all agree in identifying the Pernicana Fault system, PF (Figure 1) as the northern  
155 boundary of the unstable sector. This is a transtensive fault with left lateral movement. It is  
156 characterized by a high slip rate from 10 to 28 mm/year with shallow (<3.5 km) and moderate



157 seismic activity ( $2 < M < 4.5$ ) (Azzaro, ~~et al.~~, 1997; [Azzaro et al., 2001](#)). The PF activity is  
158 kinematically connected to the episodic opening and eruptions of the nearby NE Rift (Figure 1)  
159 (Neri et al., 1991; Gardunō et al., 1997; Tibaldi and Groppelli, 2002; Acocella and Neri, 2003;  
160 Acocella et al., 2003). The southern part of the western boundary of the unstable sector is  
161 represented by the South Rift (Rasà et al., 1996) joining, southeastward, with the Tremestieri-  
162 Trecastagni fault system TTF (Figure 1). This fault system is made up of a number of NNW-SSE  
163 striking faults showing evident right-lateral displacement and is also characterized by very shallow  
164 seismicity, with typical focal depths of 1–2 km. Other tectonic lineaments dissect the southern and  
165 south-eastern sectors of the volcano, such as the Timpe Fault system (STF1 and STF2), San  
166 Leonardello Fault (SLF), Moscarello Fault (MF) and Santa Venerina Fault (SVF) (Figure 1).

167 Most of these faults have high slip-rates from 1.0 to 2.7 mm/year (Azzaro, 2004; Puglisi et al.,  
168 2008), partly due to shallow seismicity (Lo Giudice and Rasa, 1992; Montalto et al., 1996).

169 Instrumental data, according to historical and macroseismic information (Azzaro ~~et al.~~, 1999),  
170 indicate that more than 80% of earthquakes are shallower than 5 km (Gresta et al., 1990),  
171 ~~which where~~, despite their moderate magnitude, have often produced coseismic surface faulting.  
172 Fault plane solutions of these events frequently indicate a right lateral strike, combined with ~~an~~  
173 ~~importanta significant~~ normal component.

174 More recent proposals emphasize the complexity of the unstable sector, showing how these faults  
175 represent the main structures that separate portions with slightly different velocities of downslope  
176 movement ~~of this sector of the volcano~~ (Bonforte et al., 2011).

177

178

### 179 3. CFS Modeling

180 In this paper, we investigate the relationships between volcanism, flank instability and ~~the~~ faulting  
181 ~~activity~~ in terms of elastic stress change. We ~~investigate hypothesize the~~ possible triggering  
182 conditions in which only one deformation source at a time is active. Our modeling approach

183 | ~~investigates-examines~~ how (1) the inflation of a spherical deep source interacts with the sliding  
184 | plane and faults, (2) the opening of an eruptive fissure (at North-East or South Rift zone) affects the  
185 | sliding movement of eastern sector or seismic activity on fault planes, (3) the flank instability  
186 | governs the kinematics of faults and triggers (or inhibits) the ascent of magma (Figure 3).

187

### 188 | *3.1. Modeling Method*

189 | Taking into account the topographic effects, we compute boundary element solutions of  
190 | deformation sources ~~e~~imbedded in an elastic half-space, using the program Poly3D 2.1.8 (Thomas,  
191 | 1993; Maerten et al., 2005). Based upon the boundary element method, ~~BEM~~ (Crouch and Starfield,  
192 | 1983), Poly3D includes the fundamental solution to an angular dislocation in a homogeneous, linear  
193 | elastic half-space (Comninou and Dundurs, 1975). A number of angular dislocations are juxtaposed  
194 | to create polygonal boundary elements that collectively define discretized objects of arbitrary shape  
195 | in three dimensions. Boundary conditions in Poly3D can be applied remotely (as constant stresses  
196 | or strains), at the centers of each element of the discretized fault surface (as tractions or  
197 | displacement), or as combinations. The program solves a series of linear algebraic equations that  
198 | describe the influence ~~of on~~ each element ~~of on~~ every other element under a prescribed set of  
199 | boundary conditions. Once the displacement distribution along a fault is determined, the static  
200 | stress, strain and displacement fields around the fault are calculated using influence coefficient  
201 | equations that relate the displacements at the fault to the resultant elastic field at any point in the  
202 | surrounding linear elastic medium. This solution is superimposed upon the remote stress field  
203 | boundary condition to produce the total elastic field. Note that in our modeling processes we do not  
204 | take into account the regional stress field. Indeed, geological and geophysical evidences highlight  
205 | the heterogeneity of the Mount Etna stress field in time and space (e.g., Barberi et al., 2000 and  
206 | reference therein). According to Gresta et al. (2005), from a kinematic point of view, the  
207 | coexistence of structural elements such as PF and TFS are incompatible with a homogeneous stress  
208 | field. Consequently, in this paper we use only “Specified fault calculation” for  $\Delta$ CFS computation

209 and we relinquish the evaluation of “optimally oriented faults” (strongly influenced by the regional  
210 stress field) as suggested by several authors in such cases (e.g., Gresta et al. 2005, Bonanno et al.,  
211 2011 and references therein)

212 In Poly3D we build polygonal elements for modeling complex surfaces with curving boundaries.  
213 Surface fault changes in strike are meshed without gaps. The spherical void is built by assembling  
214 triangular, hexagonal or pentagonal elements in the same manner as a football.

215 The Boundary Element Method was chosen because it is suitable for near real-time applications  
216 since it allows modifying an evolving scenario simply by adding new magmatic sources and/or  
217 receiving structures. The use of Poly3D enables avoiding meshing the medium every time a  
218 structural modification is carried out, in such a way the computational time is limited to tens of  
219 minutes.

220

### 221 *3.2. Setup of deformation source parameters*

222 Following on from ~~In agreement with~~ recent ~~geophysical evidences~~ studies (Patanè et al., 2003a;  
223 Chiarabba et al., 2004; Bonaccorso et al., 2006; Bonforte et al., 2008; Puglisi et al., 2008; Chiarabba  
224 et al., 2004; Patanè et al., 2003b), we considered a spherical cavity constructed ~~by of~~ 815 triangular  
225 elements, simulating a 1 km in radius reservoir ~~1 km in radius~~ at 3 km depth (Figure 2). An increase  
226 in ~~the~~ magma pressure perturbs the stress field in the surrounding crust. Using positive traction  
227 boundary conditions, normal to the element, we defined a volume increase of  $7.9 \cdot 10^6 \text{ m}^3$ , a realistic  
228 value for inflating magma bodies (Bonaccorso et al., 2006; Palano et al., 2007; Puglisi et al., 2008).

229 The center of the MR was located beneath the Summit Craters area (for details see Table 1). In  
230 addition, in order to evaluate the influence of ~~the~~ depth of an inflating reservoir (hereafter MR) on  
231 ~~the~~ other considered structures and in particular on SP, we performed two further simulations  
232 moving the center of the sphere by  $\pm 2.4$  km. These steps of depth were chosen since they roughly  
233 correspond to the projections respectively of the top and the bottom of SP (see below) along the  
234 vertical line intersecting the Summit Craters.

235 ~~The center of the MR was located beneath the Summit Craters (for details see Table 1).~~

236 ~~DykeDike~~ intrusions were modeled by rectangular planes with a curving top boundary matching the  
237 topography (Figure 2). A uniform element-normal displacement discontinuity of 2.5 ~~metersm~~ is  
238 imposed on ~~dykesdikes~~. The geometry of the North-East and South dikes used in this paper is based  
239 on values published by Puglisi et al. (2008). In any case, openings larger than 3 m do not modify  
240 the results significantly. The parameters of the modeled dikes are reported in Table 1.

241 In agreement ~~with te~~-inversion models inferred from ground deformation measurements (Puglisi  
242 and Bonforte, 2004; Bonaccorso et al., 2006; Bonforte et al., 2008), we modeled ~~ed~~ a sub-horizontal  
243 sliding plane (hereafter SP) as a rectangular surface ~~long-20 km long~~ and ~~wide-25 km wide~~, with a  
244 main normal (7.7 cm) and minor dextral component (4.4 cm) (Figure 2). Although the slip amount  
245 depends on the period investigated, inversion models published (Puglisi and Bonforte, 2004; Palano  
246 et al, 2007) found an overall sliding in the range of 4 – 9 cm/year in the period 1993 -2000.

247

### 248 *3.3. Setup of topography and fault parameters*

249 We used ~~ed~~ the Global Digital Elevation Model (~~hereafter the~~ INGV-G-DEM) that merges inland  
250 DEM (Tarquini et al., 2007; Neri et al., 2008) and bathymetric data sets available for the ~~Mt-Mount~~  
251 Etna area (Bosman et al., 2007; Cavallaro et al., 2008). The original data ~~are-were~~ integrated and  
252 interpolated, becoming homogenous with a final resolution of 10 m pixel size. Using INGV-G-  
253 DEM resampled with a resolution of 100 m, we built ~~ed~~ a rectangular surface of 3500 km<sup>2</sup> (extending  
254 for about 70 kilometers in longitude and 50 km in latitude) and discretized with 3184 triangular  
255 meshes (Figure 2). Volcano topography is assumed as a traction-free surface in order to study the  
256 influence on displacements and stress numerical calculations. According to geological and  
257 structural studies integrated with seismic data, we modeled ~~ed~~ the main tectonic lineaments of the  
258 eastern sector of the volcano. We built ~~ed~~ the faulting planes as rectangular surfaces with a curving  
259 top boundary matching the topography, ~~with~~ each plane ~~is~~-discretized by triangular meshes with a  
260 mean areal dimension of about 0.027 km<sup>2</sup>. In particular, Provenzana Fault (PR) shows a change of

261 strike from N35°E to N55°E, thus a curving top boundary is modeled. The Pernicana Fault (PF) is  
262 ~~composed-made up~~ of four segments, ~~defined-~~(PF1, PF2, PF3 and PF4), striking N88°E, N102°E,  
263 N114°E, N120°E, respectively (Figure 2a). The southern border of the unstable sector is  
264 represented by the Tremestieri-Trecastragni Fault system (TTF) modeled with a sub-vertical plane  
265 with a sharp change in direction (from N103°E to N150°E). The Timpe Fault System is made up ~~to~~  
266 of two segments, STF1 and STF-2, with strike direction N165°E and N3°W, respectively. These  
267 latter fault systems, together with SLF, MF, SVF, all striking from N173°E to N140°E, reached ~~ed~~  
268 depth of the sliding plane (see Figure 2b). The sub-vertical fault~~s~~ planes above the sliding plane  
269 (SP) have a width ranging from 1950 to 2800 ~~metersm~~ (for details see Table 2). In our models, we  
270 assume that receiver faults are discontinuities embedded in an elastic half-space in which they are  
271 free to move in any direction.

272

### 273 3.4 Coulomb Stress Changes

274 We calculated d Coulomb stress changes caused by volcanic sources on modeled fault planes, while  
275 computing changes in volumetric or normal stress near the magma chamber or eruptive dikes  
276 caused by flank movements or earthquakes (e.g. Savage and Clark 1982; Nostro *et al.* 1998; Toda *et*  
277 *al.* 2002).

278 It is widely accepted that static stress changes ( $\geq 0.1$  bars) induced by a magmatic source may  
279 trigger seismicity within a rock volume close to the critical state of failure (e.g., Reasenber and  
280 Simpson, 1992; Stein, 1999). Spatial and temporal relationships between stress changes and  
281 earthquakes are explained through the Coulomb failure stress change, defined as:

$$282 \quad \Delta CFS = \Delta\tau + \mu(\Delta\sigma_n + \Delta P) \quad (1)$$

283 where  $\Delta\tau$  is the shear stress change computed in the direction of slip on the fault,  $\Delta\sigma_n$  is the normal  
284 stress change (positive for extension),  $\mu$  is the coefficient of friction and  $\Delta P$  is the pore pressure  
285 change (e.g., King *et al.*, 1994; Harris, 1998; King and Cocco, 2000). For simplicity, we considered

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286 here a constant effective friction model (Beeler *et al.*, 2000; Cocco and Rice 2002) ~~that~~ ~~,-which~~  
287 assumes ~~that~~  $\Delta P$  is proportional to the normal stress changes ( $\Delta P = -B\Delta\sigma_n$ , where  $B$  is the Skempton  
288 parameter):

$$289 \quad \Delta CFS = \Delta\tau + \mu' \Delta\sigma_n \quad (2)$$

290 where  $\mu'$  is the effective friction ( $\mu' = \mu[1 - B]$ ). The fault is brought closer to failure when  $\Delta CFS$   
291 is positive. In order to verify if dike intrusions or magmatic reservoir inflations are encouraged, we  
292 evaluate the change of the volumetric strain ( $\Delta\varepsilon = \varepsilon_1 + \varepsilon_2 + \varepsilon_3$ ) on the magmatic reservoir and  
293 horizontal normal stress changes ( $\sigma_m = (\Delta\sigma_{xx} + \Delta\sigma_{yy}) / 2$ ) on the rift zone dikes. Indeed, the  
294 unclamping of a rift zone ( $\sigma_m > 0$ ) induced by fault dislocations may facilitate the ascent of new  
295 magma and dike injection. In the same way, the unclamping may favor the decompression of the  
296 magma reservoir, leading to the formation and ascent of bubbles and then increasing the magma  
297 overpressure. We performed all calculations in a homogeneous Poissonian elastic half-space using a  
298 Poisson's ratio of  $\nu = 0.25$  and a Young's modulus of  $E = 75$  GPa, and a  $\mu' = 0.4$ .

299

### 300 3.5 Assumptions of numerical modeling

301 Coulomb stress changes are evaluated in a homogenous elastic half-space. Thus mechanical  
302 heterogeneities, for instance due to thermal structure, a hydrothermal altered volcanic core or a  
303 mechanically rigid basement, are not taken into account by our models. As stated before, the  
304 regional stress field is not taken into account given its heterogeneity in space and time. The surface  
305 traces of the faults are visible, well-mapped and constrained, but we ~~simplify~~ simplified the characteristics  
306 of the sliding plane by imposing a uniform slip on the whole rectangular surface. We ~~do~~ did not  
307 take into account visco-elastic or elasto-plastic behaviors or any differential flank movement  
308 supposed-inferred by a number of authors recently (Palano *et al.*, 2009; Currenti *et al.*,  
309 2010; Bonforte *et al.*, 2011; ~~Palano *et al.*, 2009~~).

310

311

## 312 4. Modeling

313 For each model,  $\Delta\text{CFS}$  values are computed on faulting planes and on the sliding surface (Figure 2).  
314 The normal stress  $\sigma_m$  is evaluated on dike fractures and volumetric strain  $\Delta\varepsilon$  on the spherical surface  
315 of magmatic reservoir. The parameters of sources and receiver structures are described in Table 1  
316 and 2, respectively. Four deformation models ~~were tested; have been carried out:~~ M1, inflating of a  
317 spherical magmatic source (Figure 3, M1); M2, opening of eruptive fissures (Figure 3, M2), divided  
318 into two models A) for South dike and B) North East dike; and M3, sliding of planar surface (Figure  
319 3, M3). Our numerical results of  $\Delta\text{CFS}$  on each receiver structures are ~~summarized-reported in~~  
320 Tables 3-6.

321

### 322 4.1. Model 1 - Mogi Source

#### 323 a) Stress calculations

324 We first considered stress changes associated with a reservoir inflation (depth = 3.0 km, roughly  
325 coincident with the center of the SP). ~~The~~ M1 shows a decrease of CFS along the PR and PF2  
326 segments, ~~and an increase along the~~ PF1 segment, ~~has experienced positive stress~~ with the latter  
327 showing a maximum value of 1.4 bars along the western edge (see M1 in Figure 4, M1 and Table  
328 3 for maximum and minimum  $\Delta\text{CFS}$  values). A decrease and an increase close to zero ~~are were~~  
329 computed on PF3 and PF4 planes, respectively (Table 3). ~~The inflation of magmatic reservoir~~ M1  
330 induces ~~on STF1 and on SVF~~ a stress increment on STF1 and SVF on the closer portions (0.3 and  
331 0.2 bars). The MF, SLF and TTF planes are subjected to a slight positive increment on the top edge  
332 (in a range between 0.1 and 0.2 bars) (Figure 4, M1). Moreover, the movement of STF2 is inhibited  
333 by the inflation of MR. Finally, the inflation of spherical chamber favors the closure of the NE and  
334 South dikes significantly. On the sliding plane, we observed a decrease of  $\Delta\text{CFS}$  in the northwestern

335 part of the plane (minimum value about -2 bars) and a very slight positive variation (0.2 bars) along  
336 the remaining part of the surface.

337 The simulations performed moving the depth of MR do not change the scenario described before  
338 drastically and significant variations only affect a few structures. A shallow MR (depth = 0.6 km;  
339 roughly coincident with the top boundary of the SP) does not change the pattern of the static stress  
340 on all the faults considered, and the intensity is only slightly affected. Also the NE dike shows  
341 almost unaltered features and only a very small part of the dike (near MR) underwent an  
342 unclamping effect. The most important variation is observed on the SP, which experienced a  
343 positive CFS variation ~~until of~~ 2 bars. ~~Also The S dike~~ also showed a different pattern in  $\Delta$ CFS  
344 distribution; indeed, the closure of the S dike is strongly encouraged only in the portion near MR,  
345 while the remaining part underwent an unclamping effect. The inflation of a deeper MR (depth =  
346 5.4 km; roughly coincident with bottom boundary of the SP) does not change the static stress  
347 pattern on the SP and the S and NE ~~dykes~~dikes. A slight change in the intensity affected both dikes,  
348 enhancing the closure trend observed with a 3 km depth MR. Also the majority of the faults  
349 considered show unchanged features and only MF experienced a positive CFS variation until 1.4  
350 bars.

351 In summary, the depth of an inflating shallow crustal reservoir may change the scenario evaluated  
352 slightly and only the flank movement seems significantly affected by the depth of MR; indeed, very  
353 shallow MR may promote flank movements, while deeper MR inhibits them. In general, a shallow  
354 ~~erust~~-MR discourages dike intrusion into the Mount Etna rift zones and promotes the stress  
355 triggering on the westernmost portion of PF.

356

#### 357 *b) Displacement calculations*

358 The expansion of MR ~~at the magmatic reservoir~~ at 3 km depth induced the uplift of the nearby  
359 structures, such as PR, PF1 and PF2 (see Figure 5 and Table 3 for maximum and minimum  
360 displacement values). The inverse component is replaced by left-~~lateral~~ movement on PF3 and PF4



361 components. The displacement values are progressively reduced from the western to eastern part.  
362 SLF, STF2, TTF and MF shows a right-lateral movement. On STF1, SVF and SP planes an uplift is  
363 favored. In particular, on the ~~Sliding Plane (SP)~~ a maximum value of 2.4 centimeters ~~as of~~ thrust  
364 movement is computed. This result changes drastically if we consider a very shallow crustal  
365 reservoir, ~~which that~~ inverts the observed trend, promoting seaward movements of the eastern flank.  
366 It is clear that for this aspect of the problem the boundary condition set in the model (source depth)  
367 plays a basic role and highlights just how crucial the depth constraint is in ground deformation  
368 inversion analyses.

369

#### 370 4.2. Model 2A – South Dike

##### 371 a) Stress calculations

372 Intrusion ~~along the of~~ S dike favors the closure of NE dike with a negative unclamping effect ( $\sigma_m$   
373 maximum value is about of -32 bars). In the M2a we observe ~~PR segment with~~ a decrease of  $\Delta CFS$   
374 on the PR segment (max value -4.5 bars). On the PF system  $\Delta CFS$  values are negative except on  
375 PF1 with a positive stress variation reaching a maximum value of 1.4 bar on the upper part of plane  
376 (Table 4). PF2, PF3, PF4 and SLF segments show a slight increase but in general all planes show  
377 ~~are involved with~~ a reduction of ~~stress changes~~  $\Delta CFS$ . STF1, STF2, SVF and TTF similarly  
378 underwent a reduction of  ~~$\Delta CFS$  stress effect~~ (see M2A in Figure 4 and Table 4 for maximum and  
379 minimum  $\Delta CFS$  values, M2A). On SP a maximum positive stress change is computed for  
380 ~~evaluated on~~ the part of the plane ~~closer~~ closest to the magmatic feeding system. Finally, the S-dike  
381 ~~south~~ intrusion induces a compression ( $\epsilon > 0$ ) on the ~~MR magmatic reservoir~~ located beneath the  
382 summit craters (see Figure 4, M2A).

383

##### 384 b) Displacement calculations

385 The opening of SD encourages a normal movement of SP. The direction of displacement vectors on  
386 SVF, SLF, STF1, STF2 and MF shows a right-lateral movement associated ~~with the to-dip-normal~~  
387 component. PR and TTF segments ~~show the reverse underwent an inverse~~ movement. All PF  
388 segments move with a pure left-lateral strike slip (see Figure 5 and Table ~~4 4-for maximum and~~  
389 ~~minimum displacement valuesfor details on the amount of slip~~). In summary, magmatic activity in  
390 the South Rift closes<sup>2</sup> the North East Rift and mobilizes the East and North East region of the  
391 unstable block.

392

### 393 4.3. Model 2B – North East Dike

#### 394 a) Stress change calculations

395 In M2B we find that intrusion ~~along the of~~ NE dike into the rift zones causes significant increase of  
396  $\Delta$ CFS on PR and PF1, with maximum values of about 320 bars and 100 bars, respectively. On the  
397 upper part of PF2 ~~fault~~ elastic stress changes increase to 3.4 bars. PF3, STF1, SVF, STF2 and TTF  
398 show a decrease of static stress variations (Table 5). SLF and MF are brought close to failure on the  
399 shallower portions of fault planes with higher values of 2.3 and 5.3 bars, respectively (see ~~M2B in~~  
400 ~~Figure 4 and Table 5 for maximum and minimum  $\Delta$ CFS values, M2B~~). A significant negative  
401 unclamping effect on the walls of ~~the S~~ dike is found (max  $\sigma_m$  value about of -26 bars). The opening  
402 of ~~the~~ NE dike favors the decompression of ~~magmatic reservoir~~ MR with  $\epsilon_{max}$  about of  $-4.8e-5$   
403  $m^3$  ( $\epsilon < 0$  volumetric strain is negative for decompression). Finally, we observe that because of its  
404 dimension and geometry, the NE dike ~~is more efficient in shows stress-transferring stress~~  
405 ~~mechanism~~ on the sliding plane ~~more efficiently~~ with respect to the S dike. On the shallower  
406 portion of SP the maximum value of  $\Delta$ CFS reaches 2.6 bars (Table 5).

407

#### 408 b) Displacement calculations

409 The most important results regarding displacement calculations show that the opening of the NE  
410 dike favors the sliding of flank with a transtensive component (see Figure 5 and Table 5 for  
411 maximum and minimum displacement values). All modeled faults, such as TTF, SVF, STF1, STF2,  
412 MF and STF are kinematically compatible with a right-lateral movement associated ~~to~~-with a  
413 normal dip component. On PR, PF1 and PF2 planes a transpressive left-lateral movement is  
414 favored. Towards the eEast we found only left transcurrent component on PF3 and PF4 structures.

415

#### 416 4.4. Model 3 – Sliding Plane

##### 417 a) Stress calculations

418 We ~~find~~-found a positive  $\Delta CFS$  with max values of about 1.7 and 1.5 bars in the upper part of PF1  
419 and PF2, respectively, and. ~~On the contrary, we evaluated~~ an increase of static stress in the lower  
420 portion of PF3 and PF4 (max about of 3.5 bars). The relative position between SP and receiver  
421 faults also resulted in an increase in ~~conditioned the increasing of~~ static stress on TTF plane ~~also~~.

422 Thus, we estimated a positive  $\Delta CFS$  in the lower part of this structure with a maximum value of 3  
423 bars (see M3 Table 6 and in Figure 4 and Table 6 for maximum and minimum  $\Delta CFS$  values, ~~M3~~).

424 Small increases of elastic stress are ~~evaluated~~-found on the MF, SLF, SVF, STF1 and SFT2 faults  
425 (Table 6). The sliding of the plane beneath the eastern flank seems to favor a compression for a  
426 ~~magmatic reservoir~~-(MR) ( $\epsilon > 0$  volumetric strain is positive). The unclamping effects for two  
427 vertical eruptive fractures located on the northeast and southern flank of volcano ~~is~~-was estimated.

428 We ~~find~~-observed that SP induces the closure in the upper part of tabular dikes. Instead, a small  
429 opening is favored in their deeper zones (about 0.1 bars) (Figure 4, M3). This interaction depends  
430 on the dimension of modeled eruptive fractures and the depth of ~~sliding plane~~SP. In brief, the  
431 unstable condition of flank sliding toward the sea may affect the magmatic system. Decompression  
432 of plumbing system may lead to the ascent of new magma or modify the condition of overpressure  
433 with the formation of bubbles (Hill, 2002).

434

435 *b) Displacement calculations*

436 The results of our simulations (see Figure 5 and Table 6 ~~for maximum and minimum displacement~~  
437 ~~values~~) show that the transtensive movement of SP encourages the dip normal displacement on PR,  
438 PF1 and PF2. ~~By contrast. On contrary,~~ PF3 and PF4 moves according to a dip-normal associated  
439 to a left lateral movement. Coherently to observed kinematics STF1, STF2, SLF, SVF and MF are  
440 encouraged to move with a transtensive component, ~~whereas a~~ ~~Instead,~~ transpressive movement is  
441 ~~determined evaluated~~ for TTF.

442

443

444 **5. Discussion and conclusions**

445 During these last decades ~~Mt. Mount~~ Etna volcano has ~~experienced undergone~~ several eruptions ~~that~~  
446 ~~have highlighted of different nature highlighting~~ intriguing trigger mechanisms ~~and have featured~~  
447 ~~among~~ dike intrusions, activation of seismogenic faults and aseismic ground deformations. ~~For~~  
448 ~~instance, in 1985 and 1986 (Azzaro, 1997) the simultaneous occurrence of significant earthquakes~~  
449 ~~on Provenzana—Pernicana fault systems and the opening of the eruptive fracture some kilometers~~  
450 ~~away occurred, but the lack of good quality ground deformation data hindered the understanding of~~  
451 ~~the causal relationship.~~

452 ~~The different patterns of ground deformation observed on Mt. Etna volcano during the last decade~~  
453 ~~through GPS and InSAR data have enabled modeling the complex volcano tectonic phenomena that~~  
454 ~~have occurred. In detail, both point sources (Mogi) and planar dislocations (i.e. Bonforte et al.,~~  
455 ~~2008; 2011; Palano et al., 2008) have been widely used. Point pressure sources roughly take into~~  
456 ~~account the radial component of the deformations occurred with respect to the central plumbing~~  
457 ~~system, whereas planar sources well represent the deformation field produced by the dikes opening~~  
458 ~~(tensile sources) and by faults or the seaward sliding of the eastern sector of the volcano,~~  
459 ~~respectively (strike slip or dip slip sources).~~

460 ~~On the whole, irrespective of the numerical results (i.e. source depth and/or dimensions), point~~  
461 ~~pressure sources and planar dislocations have fully satisfied the need for modelling the different~~  
462 ~~ground deformation patterns observed during the different states of the volcano dynamics. In some~~  
463 ~~cases (i.e. Palano et al., 2008), the simultaneous effect of at least two different sources was invoked~~  
464 ~~to better fit the measured deformations.~~ Geophysical studies suggest that complex dynamics,  
465 involving more than one source (seismogenic sources and dykes/dikes), is a relatively common  
466 characteristic of eruptive episodes on Mt. Mount Etna. Gresta et al. (2005), for instance, ~~had~~  
467 highlighted that earthquakes along the PF and STF were induced by the static stress variations  
468 associated ~~to~~ with the emplacement of eruptive dikes during the 1981 and 2001 eruptions,  
469 respectively. More recently, the pressure increase due to magma ascent episodes occurring in 1997-  
470 1998 at Mt. Mount Etna has been demonstrated to be responsible for the reactivation of seismogenic  
471 structures on the western side of the volcano (Bonanno et al., 2011). In Bonanno et al. (2011), the  
472 intrusive process was modelled as an inflating Mogi source located at 5.5 km depth, but in the  
473 present work, we highlight-emphasize the crucial role of the boundary condition set in the model  
474 (source depth) and ~~we~~ show the possible scenarios with a shallower MR depth (Model M1).  
475 ~~Gresta et al. (2005) highlighted that earthquakes along PF and STF were induced by the static stress~~  
476 ~~variations associated to the emplacement of eruptive dikes during 1981 and 2001 eruptions,~~  
477 ~~respectively. In greater detail,~~ The July-August 2001 eruption was characterized by a very complex  
478 field of flank eruptive fractures located largely on the upper southern slope of the volcano (Monaco  
479 et al., 2005). The eruption onset was preceded and accompanied by significant earthquakes (Patanè  
480 et al., 2003b) and marked ground deformations (Bonaccorso et al., 2002). The main source of  
481 deformations was modelled by a tensile dislocation located on the South Rift zone (Puglisi et al.  
482 2008) as also confirmed by the Seismic Moment Tensor inversions of the best constrained  
483 earthquakes that heralded the opening of the eruptive fractures (Saraò et al., 2010). Our present  
484 model M2A takes ~~into~~ account of the main behaviour of the magmatic source for this eruption well.

485 The October 2002 - January 2003 eruption occurred on two sides of the volcano, along the upper  
486 north-eastern (NE Rift zone) and southern (South Rift Zone) flanks. Once again, earthquakes and  
487 ground deformations preceded and accompanied the opening of the eruptive fractures notably  
488 (Barberi et al., 2004 and reference there in). The two intrusive dikes have been satisfactorily  
489 modelled by two separate tensile dislocations (Aloisi et al., 2003). During the first stage of the  
490 eruption, several seismogenic structures on the eastern flank became successively active. This was  
491 explained as due to the transfer of elastic stress from the magmatic source to faults (PR and PF) and  
492 afterwards from faults to faults (Barberi et al., 2004). Our present model M2B is schematically  
493 representative of the first stage of the above cited domino effect phenomena.

494 Finally, the 2004–2005 eruption emitted a highly degassed magma from a sub-terminal fracture.  
495 During the first weeks of activity, the erupted magma was already residing inside the volcano,  
496 probably since the 2002-2003 eruption, while later it mixed with new magma ~~a new one~~ ascending  
497 through the central conduits system (Corsaro et al., 2009). Magma intruded passively due to the  
498 exceptional extension on the summit area caused by the large sliding of the eastern flank of the  
499 volcano (almost 9 cm of slip; Bonaccorso et al., 2006). The east flank sliding toward the sea ~~is able~~  
500 ~~to induce~~ a decompression on the shallow magma plumbing system as foreseen by our model M3  
501 that simulates the unstable condition of this sector.

502 In this work we have investigated, by using the Boundary Element Method, how (i) the inflating of  
503 a deep spherical source interacts with a sliding plane and with faults and rift elements; (ii) the  
504 opening of eruptive fissures affects the sliding movement of the eastern sector of Mount Etna,  
505 encouraging earthquakes ~~occurrence~~ on fault planes; and (iii) the instability of the eastern flank  
506 governs the kinematics of faults and/or triggers the ascent of magma.

507 The results presented here are strongly dependent on all the assumptions made. In particular, the  
508 lack of seismological constraints (hypocenter patterns and compatible fault plane solutions) ~~to for~~  
509 the sliding plane induced us to simplify the geometry of a detachment volume that remains/lies at  
510 the base of the instable sector. Nevertheless, our numerical results show good agreement with

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511 deformation measurements that well describe the eastern flank dynamics of Etna volcano (e.g., i.e.  
512 Bonforte et al., 2008; Puglisi et al., 2008). ~~The strength of our approach consists in evaluating the~~  
513 ~~distribution of the CFS pattern along the receiver fault planes using numerical simulations, taking~~  
514 ~~into account the effects of topography and with a processing time of about tens of minutes.~~

515 The main results obtained are the following:

- 516 1. The inflation of a magma reservoir encourages the slip on the westernmost segment of the  
517 Pernicana fault (PF).
- 518 2. The depth of MR is crucial, very shallow depth MR promote seaward movement of the  
519 eastern flank, while deeper MR (3.0 - 5.5 km) inhibit the movement.
- 520 3. Dikes intruding either on the NE or/and South Rift Zones favor the sliding of the planar  
521 source in its upper part and along the westernmost of PF.
- 522 4. The intrusion (opening) of a South dike favors the closure of a NE dike, while at the same  
523 time the opening of NE tensile fracture inhibits the ascent of magma along the South zone.
- 524 5. The intrusion of a NE dike (for dimension and kinematics) favors the Eastern flank sliding,  
525 more than the opening of an S dike.
- 526 6. The opening of a NE dike encourages the decompression of the magma plumbing system  
527 (depth = 3.0 km), evaluated by a high negative value of volumetric strain.
- 528 7. The passive sliding of SP promotes an increase of CFS on the westernmost and the central  
529 segments of PF. Its easternmost segments are brought close to failure at their bases.
- 530 8. The unstable condition of flank sliding toward the sea may affect the magmatic system and  
531 decompression of plumbing system may lead to a new magma ascent.
- 532 9. The western part of Pernicana fault (PF1) experienced a positive CFS for all the scenarios  
533 hypothesized. The other segments underwent a positive stress variation only in M2B and M3.  
534 In particular, Model M2B highlights the governing role of the intrusion in the NE Rift on the  
535 dynamics of this structure and on the dynamics of the Provenzana fault too.

536 10. Other faults considered seem to be less sensitive to the stress variation induced by sources  
537 considered, with the exception of three structures. SLF and MF underwent a significant  
538 positive CFS variation in model M2B, and TTF experienced an increase in static stress in  
539 model M3.

540

541 ~~The above listed~~ These results schematically represent possible scenarios of the evolution of the  
542 kinematic “activity” of ~~Mt. Mount~~ Etna volcano. The three basic elements: (magma dynamics,  
543 earthquake occurrence and flank instability) interact with each other, alternating their active or  
544 passive role in a broader combination of domino effects.

545 Our results are in ~~a~~ general agreement with the findings of Walter et al. (2005), despite the  
546 significant differences in the structural setup and in the definition of geometrical characteristics of  
547 the single geological objects. The main difference regards the effect of interaction between magma  
548 reservoir and sliding plane; ~~as a matter of fact,~~ the latter was defined by Walter et al. (2005) with  
549 geometrical characteristics that are entirely different from those hypothesized in this paper. Currenti  
550 et al. (2008) use a very simplified structural setup taking into account only the two rift zones and  
551 the main fault systems in eastern flank. Regardless of differences, the result obtained are similar  
552 with the exception of the NE dike response to an intrusion in the South rift. Currenti et al. (2008)  
553 have also demonstrated that the introduction of an heterogeneous medium induces variation in the  
554 intensity of  $\Delta$ CFS (as a function of modelled elastic parameters), but does not distort the  
555 geometrical pattern. The authors also show how the stress shape is affected by Mt. Etna topography.  
556 The main discrepancies are largely restricted to the volcano summit area because of the accentuated  
557 topography.  
558 We note that the strength of our approach lies in the fact that we evaluate the distribution of the  
559 CFS pattern while taking into account the relevant effects of topography. In addition, we use a  
560 method that requires a processing time of some tens of minutes.



561 It allows modifying an evolving erupting scenario simply by adding or altering magmatic sources  
562 and/or receiving structures without needing any further computational time that other numerical  
563 methods require (e.g., re-mesh of medium in Finite Element Method). The real-time seismic and  
564 geodetic networks currently operating on ~~Mt.~~Mount Etna are able to provide good enough data  
565 (both in number and quality) to satisfactorily (and rapidly) constrain the source(s) responsible for  
566 volcanic unrest. The application of the Boundary Element Method during volcanic unrest appears ~~to~~  
567 ~~be~~ a promising tool ~~for to~~ providing in near real-time some possible scenarios of ~~the~~ evolutioning  
568 ~~of the~~ volcanic activity in near real-time in terms of ~~eastern~~ flank sliding and/or activation of either  
569 (both) seismogenic faults and/or magma bodies.

570

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837 **Figure captions**

838

839

840 **Figure 1.** Structural sketch map of ~~Mt-Mount~~ Etna: Provenzana Fault (PR); Pernicana fault (PF);  
841 Santa Venerina fault (SVF); Timpe fault system STF; Moscarello fault (MF); Tremestieri–  
842 Trecastagni fault (TTF); San Leonardello Fault (SLF); Central Craters (CC); South Rift and North -  
843 East Rift are also indicated. In the upper inset, the location of ~~Mt-Mount~~ Etna in the central  
844 Mediterranean area and a simplified geological map of eastern Sicily are also reported. The INGV-  
845 G-DEM is in the WGS84 reference system and the projection is UTM33.

846

847 **Figure 2.** a) Top view and b) prospective view of the boundary Element model built in Poly3D  
848 environment show spatial relationships between topography, faults, magmatic reservoir, eruptive  
849 fractures, sliding plane and faults. For structure legend see tables 1 and 2.

850

851 **Figure 3.** Sketch of four models proposed showing: M1) Inflation of Magmatic Reservoir (MR);  
852 M2A) Opening of South Dike (SD); M2B) Opening of North-East Dike (NED); M3) Transtensive  
853 movement of Sliding Plane (SP); the ~~acting~~ sources ~~acting~~ (red) and the receiver structures (black)  
854 are drawn. For faults legend see table 2.

855

856 **Figure 4.** Three dimensional view showing the pattern of  $\Delta$ CFS produced by inflation of MR (M1)  
857 along modeled fault planes; Opening of SD (M2A); Opening of NED (M2B) and Transtensive  
858 movement of SP (M3). The color bar specifies ~~only the relative~~ maximum and minimum  $\Delta$ CFS  
859 values- ~~that are reported for~~ ~~These values calculated for~~ each single ~~plane structure are reported in~~  
860 Tables 3-6.

861

862 **Figure 5.** Three dimensional view showing the pattern of the displacement produced by inflation of  
863 MR (M1) along modeled fault planes; Opening of SD (M2A); Opening of NED (M2B) and  
864 Transtensive movement of SP (M3). The color bar specifies the maximum and minimum  
865 displacement values that are reported for each single structure in Tables 3-6. ~~The color bar specifies~~  
866 ~~only the relative maximum and minimum displacement values. The maximum displacement values~~  
867 ~~calculated for each single plane are reported in Tables 3-6.~~

868

869

870

871 **Table titles**

872

873

874 **Table 1.** Description of deformation source inputs used in the numerical modeling.  $X_c$ ,  $Y_c$  and  $Z_c$   
875 represent the location of the center, while L and W correspond to length and width for each source.

876

877 **Table 2.** Position and geometrical parameters of receiver fault planes modeled in Poly3D program  
878 (for symbols explanation see table 1)-

879

880 **Table 3.** Coulomb stress changes and displacements (U) induced on considered structures (see table  
881 1 and 2 for structure names) by the inflation of MR (model M1).

882

883 **Table 4.** Coulomb stress changes and displacements (U) induced on considered structures (see table  
884 1 and 2 for structure names) by the opening of SD (model M2A).

885

886 **Table 5.** Coulomb stress changes and displacements (U) induced on considered structures (see table  
887 1 and 2 for structure names) by the opening of NED (model M2B).

888

889 **Table 6.** Coulomb stress changes and displacements (U) induced on considered structures (see table  
890 1 and 2 for structure names) by the transtensive movement of SP (model M3).

891

**Table 1**[Click here to download Table: Table 1.docx](#)**Table 1**

<b>Name</b>	<b>Source</b>	<b>Xc (m)</b>	<b>Yc (m)</b>	<b>Zc (m)</b>	<b>L (m)</b>	<b>W (m)</b>	<b>Dip (°)</b>	<b>Dislocation (m)</b>	<b>N° nodes</b>	<b>N° elements</b>
NED	Northeastern Dike	501518.5	4181600	960.4715	5956	3914	90	Opening 2.5	511	893
SD	Southern Dike	500053	4175720	1071.465	3132	3022	90	Opening 2.5	691	1234
SP	Sliding Plane	517526	4170940	-2997.11	20000	25000	11	Left Lateral 0.077 Normal slip 0.042	6519	12736
MR	Magmatic Reservoir	499593	4177480	-2900	R = 1000			$\Delta V$ 7.9*10e6	815	1624

**Table 2**[Click here to download Table: Table 2.docx](#)**Table 2**

<b>Name</b>	<b>Tectonic Lineament</b>	<b>Xc</b>	<b>Yc</b>	<b>Zc</b>	<b>L</b>	<b>W</b>	<b>Dip</b>	<b>N° Nodes</b>	<b>N° Elements</b>
PR	Provenzana Fault	503089	4183165	492	2326	4000	87	473	830
PF1	Pernicana Segment 1	506317	4184280	311	4972	4000	87	703	1241
PF2	Pernicana Segment 2	510575	4183870	-9	3465	4000	87	583	1049
PF3	Pernicana Segment 3	513277	4182470	-131	4582	4000	87	572	1015
PF4	Pernicana Segment 4	516913.5	4180680	-418	2962	4000	87	495	873
STF1	S. Tecla Fault 1	512725.5	4168130	-1065	7602	1948	87	353	624
STF2	S. Tecla Fault 2	515354.5	4162020	-1376	6252	2809	87	342	610
SVF	S.Venerina Fault	512891	4169375	-1013	5556	2577	87	313	536
SLF	S.Leonardello Fault	515289.5	4170575	-1302	9040	2788	87	304	513
MF	Moscarello Fault	513805	4170660	-1074	11190	2664	87	231	374
TTF	Tremestieri - Trecastagni Fault	508857.5	4159625	-1265	6377	3252	87	340	1227



**Table 3**[Click here to download Table: Table 3.docx](#)**Table 3**

	Coulomb (bars)		Stress Component (bars)		U (cm)	
	min	max	Shear	Normal	min	max
PR	-3.0	-1.0	-1.4	-0.4	1.6	3.0
PF1	0.3	1.4	0.7	0.0	0.9	2.0
PF2	-0.5	-0.2	-0.4	0.0	0.6	1.1
PF3	0.0	0.2	0.2	-0.2	0.5	0.9
PF4	-0.2	-0.1	-0.1	-0.1	0.4	0.6
STF1	0.1	0.3	0.2	0.1	0.4	0.9
STF2	-0.1	-0.1	0.0	-0.1	0.3	0.4
SVF	0.1	0.2	0.1	0.3	0.4	0.9
SLF	-0.1	0.1	-0.1	0.2	0.3	0.7
MF	0.0	0.2	0.1	0.2	0.4	0.9
TTF	0.1	0.2	0.1	0.0	0.3	0.5
SP	-1.9	0.2	0.0	-0.1	0.1	2.4
SD	-20.7	-0.2	$\Delta\sigma$ (bars)		4.7	12.7
NED	-8.3	0.4	$\Delta\sigma$ (bars)		1.9	12.7

Table 4

	Coulomb (bars)		Stress Component (bars)		U (cm)	
	min	max	Shear	Normal	min	max
<i>PR</i>	-4.5	-0.8	-3.1	-1.2	2.2	3.9
<i>PF1</i>	-0.7	1.4	1.4	2.4	2.1	3.8
<i>PF2</i>	-1.2	0.1	0.7	2.8	3.0	3.8
<i>PF3</i>	-0.7	0.4	-0.4	-0.5	2.8	3.7
<i>PF4</i>	0.3	0.7	0.4	-0.2	2.3	3.0
<i>STF1</i>	-2.2	-0.3	-1.0	0.4	0.9	3.8
<i>STF2</i>	-0.4	-0.2	-0.3	-0.1	0.4	1.2
<i>SVF</i>	-2.1	-0.5	-1.2	0.3	1.3	3.8
<i>SLF</i>	-0.3	0.7	-0.2	1.5	1.0	3.8
<i>MF</i>	0.3	1.6	0.3	1.8	0.9	4.9
<i>TTF</i>	-0.2	-0.1	-0.1	-0.1	0.4	0.7
<i>SP</i>	-8.8	2.6	-0.5	0.3	0.4	11.5
<i>MR</i>	-6.42E-05	1464.33	$\Delta\varepsilon$		6.9	33.1
<i>NED</i>	-32.4	-0.1	$\Delta\sigma$ (bars)		2.1	9.9

Table 5

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Table 5

	Coulomb (bars)		Stress Component (bars)		U (cm)	
	min	max	Shear	Normal	min	max
<i>PR</i>	-135.0	323.5	38.9	120.6	16.4	130.1
<i>PF1</i>	6.3	102.2	20.8	-13.5	5.8	19.9
<i>PF2</i>	1.9	3.4	4.4	3.9	5.1	8.0
<i>PF3</i>	-2.9	-0.7	-2.7	-1.3	5.0	7.3
<i>PF4</i>	0.0	0.7	-0.1	-1.0	4.2	5.5
<i>STF1</i>	-2.0	-0.5	-1.8	2.1	3.1	7.7
<i>STF2</i>	-0.9	-0.4	-0.7	0.1	1.9	3.5
<i>SVF</i>	-2.4	-0.7	-2.2	2.1	3.7	7.8
<i>SLF</i>	1.2	2.3	3.3	0.5	3.2	7.7
<i>MF</i>	1.3	5.3	1.8	3.3	3.1	9.8
<i>TTF</i>	-0.5	-0.2	-0.6	0.6	1.5	2.4
<i>SP</i>	-18.5	5.7	-1.2	1.7	1.3	24.8
<i>MR</i>	-4.88E-05	-1.5E-5	$\Delta\varepsilon$		8.9	15.6
<i>SD</i>	-25.9	-3.7	$\Delta\sigma$ (bars)		5.5	13.3

Table 6

	Coulomb (bars)		Stress Component (bars)		U (cm)	
	min	max	Shear	Normal	min	max
<b>PR</b>	-0.5	0.1	-0.1	0.1	0.6	9.3
<b>PF1</b>	-0.7	1.7	0.6	-0.6	0.6	9.0
<b>PF2</b>	-0.2	1.5	0.9	-0.3	1.1	2.3
<b>PF3</b>	0.3	1.0	-0.7	-2.9	1.5	3.1
<b>PF4</b>	1.3	3.5	1.2	-2.1	3.0	3.5
<b>STF1</b>	-0.2	0.2	-0.2	0.4	3.8	5.5
<b>STF2</b>	-24.9	0.0	-1.4	0.5	0.8	5.2
<b>SVF</b>	-0.2	0.2	-0.1	0.4	4.2	5.5
<b>SLF</b>	-0.1	0.6	0.0	0.5	4.0	5.4
<b>MF</b>	-0.2	0.7	0.1	0.3	3.9	5.5
<b>TTF</b>	-4.7	3.1	-0.2	0.1	0.3	8.9
<b>MR</b>	1.97E-07	6.5E-7	$\Delta\varepsilon$		0.5	0.9
<b>Sdike</b>	-0.9	0.2	$\Delta\sigma$ (bars)		0.5	1.2
<b>NEdike</b>	-0.8	0.1	$\Delta\sigma$ (bars)		0.4	8.9

Figure 1  
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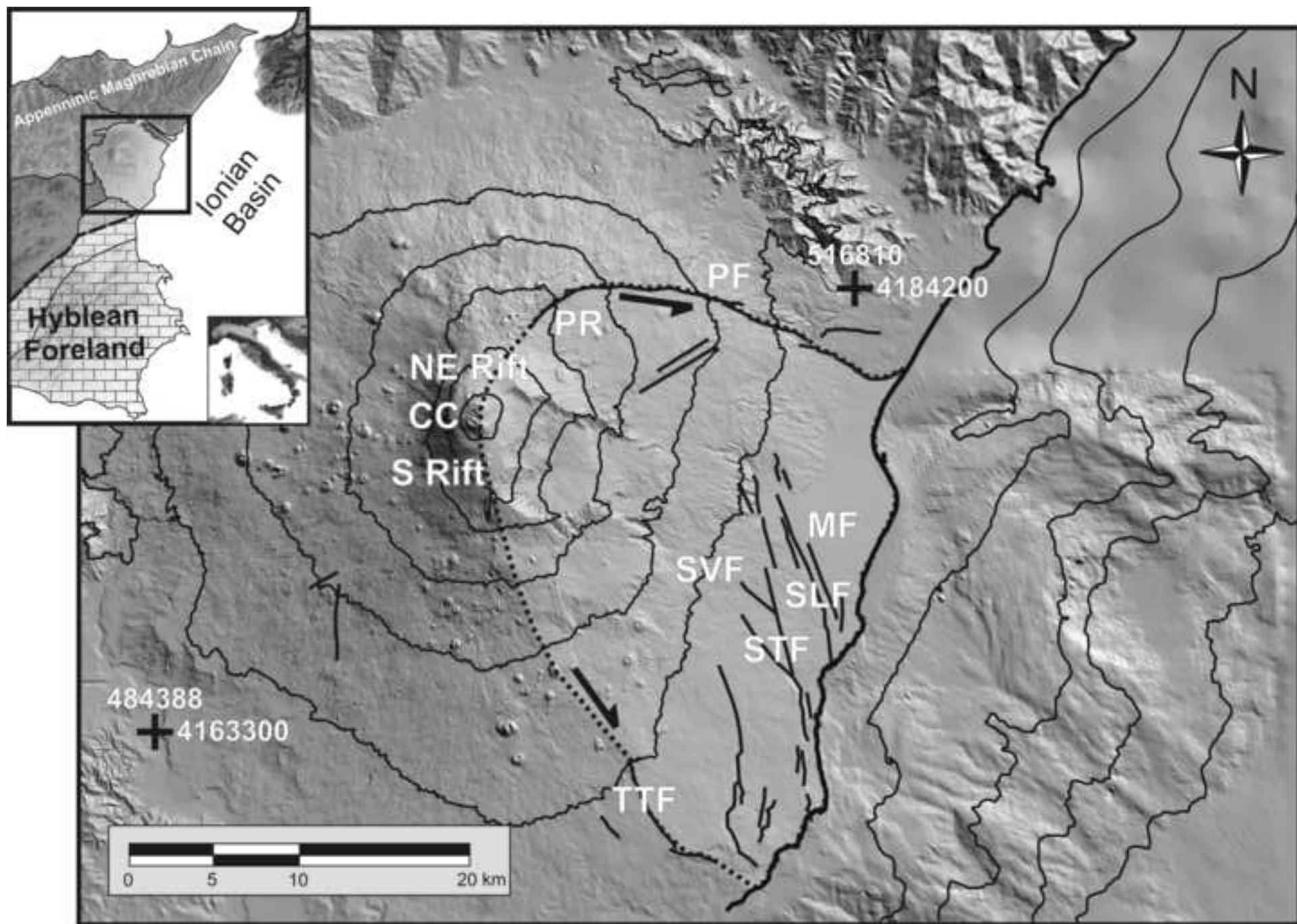


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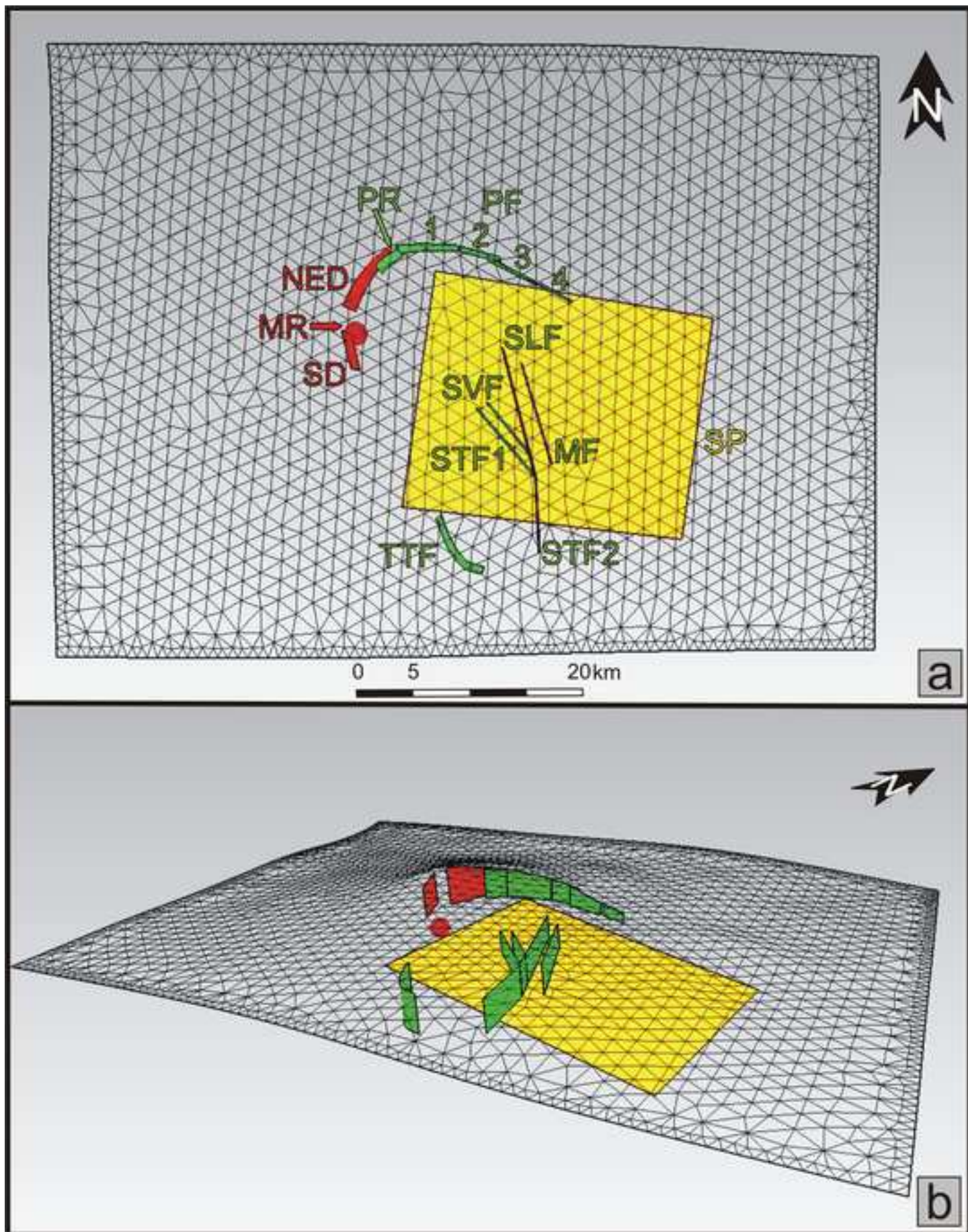


Figure 3  
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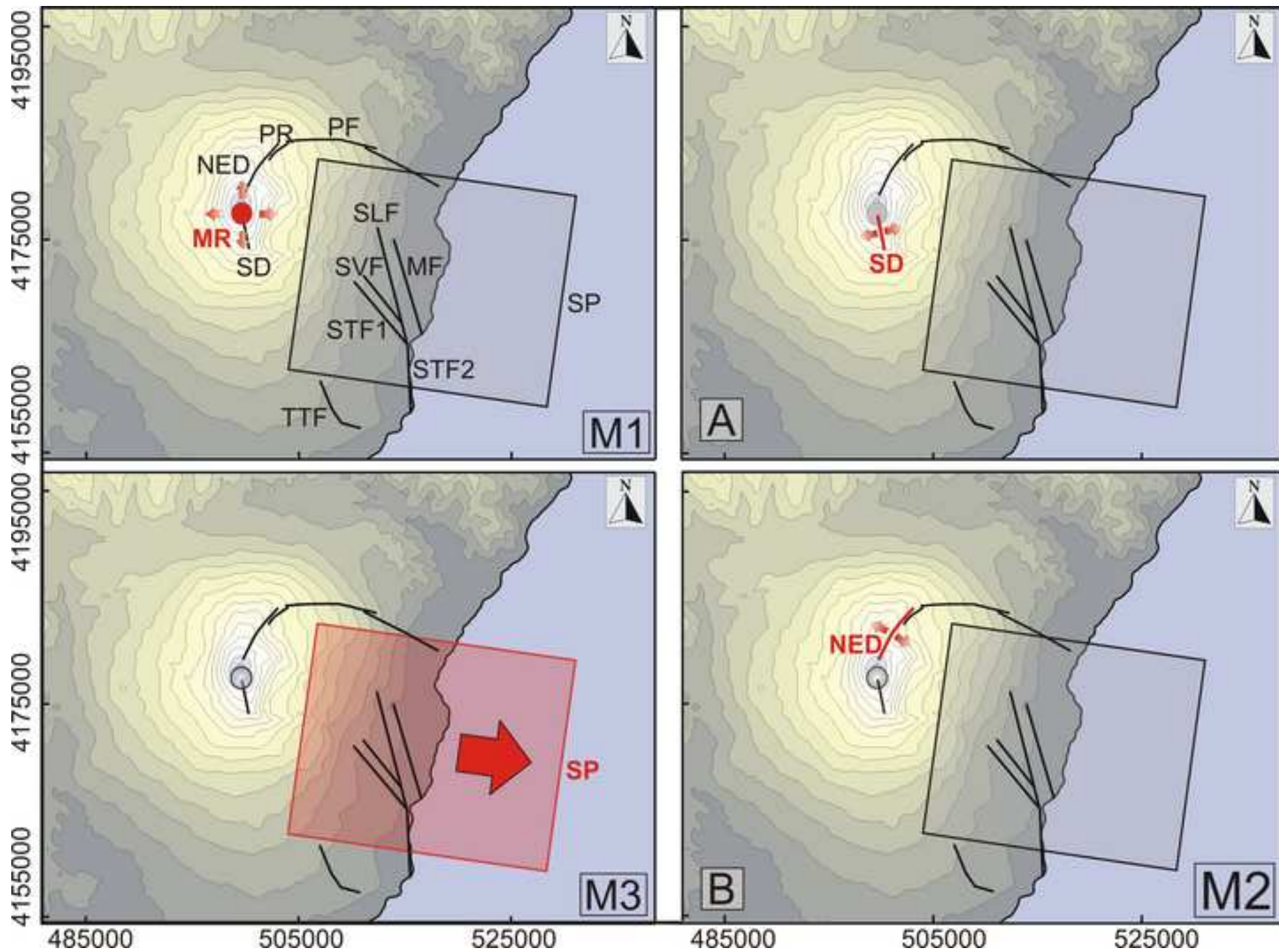


Figure 4  
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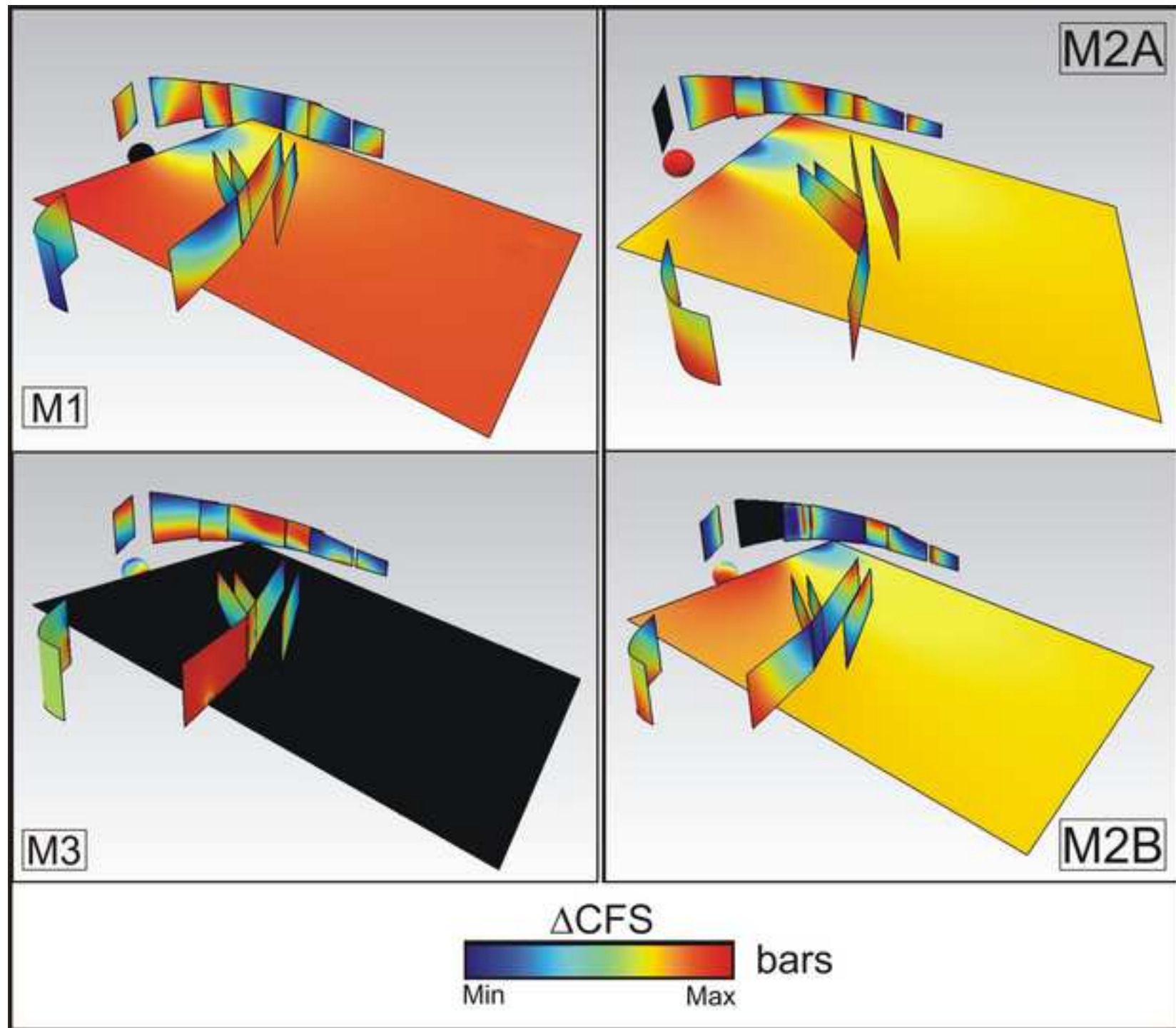




Figure 5  
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