Large dyke intrusion and small eruption: The December 24, 2018 Mt. Etna eruption imaged by Sentinel-1 data

Alessandro Bonforte | Francesco Guglielmino | Giuseppe Puglisi

Abstract
On December 24th, Mt. Etna volcano underwent a seismic crisis beneath the summit and upper southern flank of the volcano, accompanied by significant ash emission. Eruptive fissures opened at the base of summit craters, propagating SE-wards. This lateral eruption lasted until December 27th. Despite the small eruption, seismic swarm and ground deformation were very strong. Sentinel-1 interferograms show a wide and intense ground deformation with some additional features related to volcano-tectonic structures. We inverted DInSAR data to characterise the magma intrusion. The resulting model indicates that a large dyke intruded but aborted its upraise at about the sea level; however, this big intrusion stretched the edifice, promoting the opening of the eruptive fissures fed by a shallower small dyke, and activating also several faults. This model highlights that a big intrusion beneath a structurally complex volcano represents a main issue even if the eruption is aborted.

1 | INTRODUCTION

Mt. Etna is a composite stratovolcano rising >3,300 m above eastern Sicily. It is located in a complex geodynamic framework characterised by the overall convergence between Nubia and Eurasian plates. Continental collision dynamics is locally perturbed by lithospheric structures, dissecting the tectonic plates and allowing magma to upraise from the mantle (Angelica, Bonforte, Distefano, Serpelloni, & Gresta, 2013; Doglioni, Innocenti, & Mariotti, 2001). After the last lateral eruption in 2008–2009, mainly summit eruptive activity occurred (Acocella et al., 2016).

In the morning of December 24th, after some weeks of mild strombolian activity at summit craters, Mt. Etna showed sudden signals of unrest. First evidences were an increasing relevant ash emission from summit craters, accompanied by an important seismic swarm with thousands of events mainly localised under the summit area and the upper SE flank. Seismicity also affected the SW and NE sectors of the volcano, with significantly energetic events along the Pernicana Fault System (PFS) (Barreca, Bonforte, & Neri, 2013). Before noon, strombolian activity and fire fountains started from the NSEC (New South–East Crater, Acocella et al., 2016) along an eruptive fissure that propagated towards SE along the fracture formed during the 1989 eruption (SFS7 in Barreca et al., 2013), forming vents that fed a lava flow flowing in the Valle del Bove (VdB, Figure 1). After this initial explosive phase, the eruption rapidly evolved to an effusive phase feeding the flows that formed a small lava field on the western part of the VdB. Lava emission ended on December 27th. Despite the small eruption, both in terms of duration and extension of lava field, the seismic swarm accompanying the eruptive phase was very strong, in terms of number of events and their energy, with dozen of events with M > 3. The peculiarity of this seismic swarm was that many volcano-tectonic structures on the flanks of the volcano were active. Most of the earthquakes occurred below the upper SE flank, beneath the 1989 fracture on an area that already showed seismic and ground deformation activity during recent eruptions (Bonforte, Gambino, & Neri, 2009 and Bonforte, Guglielmino, & Puglisi, 2013). Furthermore, also the PFS - at NE - and Ragalna Fault System (RFS) (Neri, Guglielmino, & Rust, 2007) - at SW - were activated. Beside from the seismic swarm localised beneath the...
upper part of the volcano, a Mw = 4.9 earthquake struck the lower SE flank of Mt Etna on December 26th at 02:19 GMT. Seismic swarm lasted for many days, with a continuously decreasing energy, in terms of daily events and their magnitude. The observed seismic and volcanic phenomena suggest that the main evidence is that the magma intrusion occurred on December 24th produced a
too small eruption compared with the relevant seismic release of the whole volcano edifice. In this paper, we will analyse the ground deformation generated by this complex sequence of phenomena, as imaged by Sentinel-1 SAR satellite constellation, in order to detect, characterise and constrain the magma intrusion that triggered the eruption and seismic crisis.

2 | GROUND DEFORMATION

The Sentinel-1A and 1B C-band SAR (Synthetic Aperture Radar) data were exploited to image the ground deformation accompanying the eruptive and seismic sequence occurring on Etna, as soon as they were available. The new Sentinel-1A/B (S1A/B) constellation, with a temporal gap of only 6 days, allows the rapid generation of interferograms; we used the 22–28 December pair acquired in TopSAR (Terrain Observation with Progressive Scans SAR) Interferometric Wide mode on both ascending and descending orbit. The 6-day interferograms (Figure 2) were produced by applying a two-pass DInSAR (Differential Interferometry SAR) processing, using the GAMMA software and applying a multilook 5 × 1 (range and azimuth) in order to maintain the full ground resolution (11 × 13 m). For the topographic phase removal, a Shuttle Radar Topography Mission (SRTM) Version 4 digital elevation model generated by SRTM with 3 arc-sec resolution was used (Jarvis, Reuter, Nelson, & Guevara, 2008).

The DInSAR interferograms show a complex and wide ground deformation pattern affecting the volcano from December 22nd to 28th. Almost the whole volcano edifice deformed, from the summit down to almost 500 m a.s.l. Furthermore, the deformation pattern shows some additional features related to volcano-tectonic structures. The first-order deformation feature is clearly related to the magma intrusion beneath the central part of the volcano; the main dislocation produced a wide deformation imaged by the two lobes of fringes (Figure 2) on the western and eastern flanks of the volcano. The western flank is approaching to the sensor, while the eastern one is moving away, on ascending view; opposite motion is detected by the descending view, revealing a main horizontal displacement, splitting the edifice. At least eight fringes can be counted from the middle to the upper part of the edifice, on both views, that means a LOS (Line Of Sight) displacement of about 23 cm on the summit; the gradient of the deformation, represented by the density of the interferometric fringes, increases with the altitude and becomes very strong on the summit, where the very dense fringes prevents them to be counted. Overall, the features related to the magma upwelling clearly depict a dyke-shaped intrusion, with the prevailing E-W tensile component.

Another very evident deformation feature is on the lower SE flank of the volcano, related to the Mw = 4.9 earthquake. The pattern depicts the ground displacement related to the slip of a complex fault system, known as Fiandaca-Pennisi Faults (FPF) (TFS15 and 18 in Barreca et al., 2013), running on the middle-lower flank of the volcano with an azimuth ranging from NW–SE, on its upper part, to N–S on its lower segment. The displacement produced by the slip of this fault and imaged by DInSAR is quite strong (Figure 2), consistent with the dislocation and observed fracture field (Figure 1).

Other minor features are visible in the interferograms, such as the interruption of the fringes along the PFS on the NE side of the volcano. This feature confirms the activity of the PFS
accompanied also by significant seismicity) and its role in shaping the deformation and decoupling the mobile flank of the volcano from the more stable part of the edifice (Alparone, Bonaccorso, Bonforte, & Currenti, 2013; Neri, Acocella, & Behncke, 2003). Perturbations on the fringe pattern are also visible along the RFS on the SW flank, where many earthquakes of the seismic swarm were located. The interferograms also show the effect of the 1989 fracture, shaping the deformation produced by the dyke intrusion, likewise observed during the 2008–2009 eruption (Bonforte et al., 2013).

3 | MODELLING

In order to define the volcanic source of the observed deformation, we simultaneously inverted the ascending and descending interferograms under the assumption of a homogeneous, isotropic, and elastic half-space by using 3 Okada’s (1985) model plus a Yang, Davis, and Dieterich (1988) depressurizing source. In order to reduce the computational effort, we considered a subset of the whole interferograms relevant to the portion of the volcano with the largest deformation (Figure 3).

The composite deformation pattern suggested a complex set of sources. In particular, we chose to search for: (a) a shallow and small dyke (Okada-source)—below the eruptive vents—able to produce the much denser fringes observed on the summit area (Figure S1); (b) a wider and deeper dyke (Okada-source) able to produce the wide deformation field affecting the whole volcanic edifice (Figure S2); (c) a third dislocation (Okada-source) on the lower SE flank reproducing the deformation observed across the FPF, in order to improve the general fit, minimizing the strong residuals over that area (Figure S3); (d) a deflating source (Yang-source) able to modulate the wide fringe pattern to fit the observed one on the ascending and descending views (Figure S4); this kind of source was often needed in studying ground deformation of past events on Mt. Etna (Bonaccorso, 1996; Bonforte et al., 2013; Puglisi et al., 2008).

Even if the main aim of this modelling is to obtain the parameters of the volcanic sources (pressure and dykes), it was necessary to add a dislocation corresponding to the Fiandaca fault—fixed from field data—in order to facilitate the minimization process of the inversion algorithm. Thus, the sources of the minor features described in the previous section were excluded because not related to volcanic sources and the weak effect on the deformation pattern.

To search the minimum of the residuals, we used an optimization routine based on the Genetic Algorithms (GA) approach, as modified by Nunnari, Puglisi, and Guglielmino (2005). The cost function assumed is the Index of Agreement, and is defined according to Guglielmino et al. (2011).

The search grid parameters, and results of the GA search are shown in Table 1. The solution converged to a final fitness value of 97% with an average misfit of 1.3 cm both for ascending and descending interferograms.

The synthetic interferograms calculated from this set of sources, show interferometric fringes in good agreement with that observed (Figure 3) and produce residuals within ± 1 interferometric fringe on almost all the volcano. Only in the near field of eruptive fissures and along the Pernicana, Ragalna and Fiandaca Faults, some residuals are present, as expected.

The results of the inversion define (Figure 4):

1. a shallow small dyke extending from the summit area SE-ward for about 2.5 km. It shows a normal rake (~88°), a slip and an opening of almost 1 m, it is westward dipping (61°), extending...
toward the 1989 fracture. The volume of this dyke is $2.9 \times 10^6$ mc.
2. a deeper and big vertical dyke, N-S oriented, about 6.3 km long and 3.8 km wide, with depth of its top at 2.5 km, an opening of 1.3 m and a transtensive left-lateral slip of 0.3 m. The volume of this dyke is $31 \times 10^6$ mc.
3. a dislocation source shaping the Fiandaca fault, N300E trending, dipping of 68°NE, with 72 cm left-lateral normal slip.

**Table 1** Parameters of the deformation sources resulting from the modelling and search ranges used for their discovery in the inversion process

| Source Type | Parameter | Min | Max |
|-------------|-----------|-----|-----|
| Okada–Shallow dyke | Dip (°) | 61 | 89 |
| | Azimuth (°) | 135 | 360 |
| | Length (m) | 2,267 | 4,000 |
| | Width (m) | 1,406 | 2,000 |
| | Rake (°) | -88 | 180 |
| | Slip (m) | 0.977 | 5 |
| | Opening (m) | 0.922 | 5 |
| | Depth (m) | 662 | 1,500 |
| | Longitude (m) | 500,913 | 502,000 |
| | Latitude (m) | 4,176,713 | 4,180,000 |
| Okada–Deeper dyke | Dip (°) | 88 | 89 |
| | Azimuth (°) | 183 | 360 |
| | Length (m) | 6,294 | 10,000 |
| | Width (m) | 3,791 | 8,000 |
| | Rake (°) | -47 | 180 |
| | Slip (m) | 0.363 | 5 |
| | Opening (m) | 1.300 | 5 |
| | Depth (m) | 2,521 | 6,000 |
| | Longitude (m) | 500,576 | 511,000 |
| | Latitude (m) | 4,175,961 | 4,185,000 |
| Okada–Fiandaca fault | Dip (°) | 68 | 89 |
| | Azimuth (°) | 300 | 360 |
| | Length (m) | 3,868 | 6,000 |
| | Width (m) | 1,447 | 4,000 |
| | Rake (°) | -166 | 180 |
| | Slip (m) | 0.717 | 5 |
| | Opening (m) | -0.078 | 1 |
| | Depth (m) | 740 | 1,500 |
| | Longitude (m) | 510,318 | 515,000 |
| | Latitude (m) | 4,167,438 | 4,170,000 |
| Yang pressure source | Longitude (m) | 500,884 | 505,000 |
| | Latitude (m) | 4,177,612 | 4,180,000 |
| | Depth (m) | 5,696 | 8,500 |
| | Semi-major axis (m) | 150 | Fixed |
| | Aspect ratio | 0.751 | 0.9 |
| | Excess pressure ($\Delta p/\mu$) | -3.666 | 10 |
| | Dip (°) | 90.000 | Fixed |
| | Strike (°) | 0.000 | Fixed |
4. A 6 km deep depressurizing source located beneath the centroid of the deeper dike. According to Amoruso and Crescentini (2009), we estimate a volume change in $-29.5 \times 10^6$ mc.

4 | DISCUSSION AND CONCLUSION

From December 22nd to 28th, the ground deformation, imaged by Sentinel-1 interferograms, depicts a wide displacement at Mt. Etna produced by an intrusion of a wide and deep dyke, splitting the entire volcano edifice. Furthermore, a smaller and shallower dike intruded below the summit area. The deformation pattern due to the volcanic intrusion is perturbed by local displacements due to the activation of the features drawn in Bonforte, Guglielmino, Coltelli, Ferretti, and Puglisi (2011), namely the PFS on the NE, the RFS on the SW and the 1989 fracture on the SE flanks. The most significant local deformation is on the low SE flank, due to a Mw = 4.9 earthquake along the FPF.

Modelling of this complex ground deformation pattern has been really challenging and at least an additional source (not-volcanic), roughly corresponding to the FPF, was necessary to improve the general fitness of the model. The active magmatic system detected by data inversion depicts a complex framework (Figure 4). Magma
moved upwards depleting a deep source (at about 6 km b.s.l.) and intruding along a roughly N-S oriented dyke up to about the sea level. The volume involved in this vertical migration is ~30 × 10^6 m^3 (the relative difference between depleting source and deeper dyke volumes is negligible), which correspond to the order of magnitude of the 2001 eruption, when ~40 × 10^6 m^3 were erupted in about 3 weeks (Coltelli et al., 2007). Above this system, a smaller dyke cut the volcano edifice above the sea level, with a NW–SE orientation, involving a much smaller volume, compatible with the small eruption occurred.

In general, the interferograms and the resulting model describe the dynamics of the recent unrest of Mt. Etna. At the first order, a dyke intruded beneath the central-southern part of the volcano, splitting the edifice in two parts, similarly to what happened in 2001 (Puglisi et al., 2008). This wide and intense deformation was accommodated by the slip on some faults on the volcano’s flanks. It is noteworthy that the dynamics of the faults cutting the flanks of the volcano is often solicited by significant pressure increase in the plumbing system (Le Corvec, Walter, Ruch, Bonforte, & Puglisi, 2014; Bonforte, Bonaccorso, Guglielmino, Palano, & Puglisi, 2008). This is the case, for instance, of the SE fault activated during the 2001 (Bonforte, Guglielmino, Palano, & Puglisi, 2004; Bonforte et al., 2009) and 2008 eruptions (Bonforte et al., 2013) and of the PFS, activated in 1994 (Puglisi, Bonforte, & Maugeri, 2001; Neri et al., 2003; Bonforte, Branca, & Palano, 2007; Bonforte, Carbone, Greco, & Palano, 2007). The peculiar characteristic of the 2018 intrusion is the simultaneous activation of several faults during the same intrusive event, which was never observed since DinSAR is used on Etna.

The volume poured out during the eruption is much smaller than the volume of magma intruded in the deeper dyke. This deep intrusion stretched the upper part of the volcano, characterised by an extensional regime (Alparone, Barberi, Bonforte, Maiolino, & Ursino, 2011). Here, the general spreading of the volcano was enhanced, activating several peripheral faults and promoting the opening of the eruptive fissures that propagated radially from the summit towards SE, where data inversion located the shallower dyke. This dynamics is very similar to the opening of the Upper Vents related to the 2001 eruption (Acocella & Neri, 2003) or the NE Rift intrusion in 2002 (Alosi, Bonaccorso, Gambino, Mattia, & Puglisi, 2003; Bonforte, Carbone, Greco, & Palano, 2007).

In this way, we defined the magmatic sources triggering the succession of eruptive and seismic phenomena, resolving the discrepancy between the large ground deformation and the small eruption occurred. We can hypothesise that the erupted magma was drained from the upper plumbing system by the shallow radial dyke (likewise in 2004; Bonaccorso, Bonforte, Guglielmino, Palano, & Puglisi, 2006) and not from the deeper eccentric intrusion. Next studies on geochemical and petrologic data could confirm this hypothesis. In any case, we can surely assess that a large volume of magma (~30 × 10^6 m^3) has not been erupted and stopped beneath the volcano, running out of its energy at about the sea level. According to Bonaccorso, Aoki, and Rivalta (2017), we estimated a Total Seismic Moment Mo for the modelled deep dyke of 4 × 10^{15} Nm; next detailed studies about the overall seismicity accompanying the intrusion could investigate if the seismic crisis balanced the energy carried by the deep dyke and hence stopping it.

The 2018 December Mt. Etna eruption shows that the eccentric upraise of a large magma body carries a potential energy on structurally complex volcanoes that can be released by activating peripheral faults; this is the case, in particular, of lateral spreading volcanoes (Poland, Peltier, Bonforte, & Puglisi, 2017). The fault slip discharges the energy and may lead the intrusion to stop, eventually aborting the eruption. Furthermore, it forces to have a multi-hazard approach in the hazard assessment on complex volcanoes, even if the eruption is aborted.

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ORCID

Alessandro Bonforte https://orcid.org/0000-0003-0435-7763
Francesco Guglielmino https://orcid.org/0000-0003-3258-9975
Giuseppe Puglisi https://orcid.org/0000-0003-4503-5808

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Figure S1. The real, synthetic and residual interferograms resulting by inversion of the shallow dyke (Okada source).

Figure S2. The real, synthetic and residual interferograms resulting by inversion of the deep dyke (Okada source).

Figure S3. The real, synthetic and residual interferograms resulting by inversion of the Fiandaca-Pennisi fault system (Okada source).

Figure S4. The real, synthetic and residual interferograms resulting by inversion of the deep deflating source (Yang source).

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