Comment on “Multidisciplinary investigation on a lava fountain preceding a flank eruption: The 10 May 2008 Etna case” by A. Bonaccorso et al.

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1. Introduction

The paper “*Multidisciplinary investigation on a lava fountain preceding a flank eruption: The 10 May 2008 Etna case*”, by Bonaccorso et al. (2011), presents a multi-parameter dataset encompassing the eruptive episode featured in the title. Through the dataset at their disposal, the authors tried to set constraints on the coupled phenomena which governed the paroxysmal event and subsequent flank eruption. Even though the joint analysis of different data offers considerable potential to extract additional information on the dynamics behind the observed phenomena, the most obvious implication is the risk of not treating all the available information with due care, which may lead to misinterpretation of the data.

In the following, we discuss issues concerning the analysis and interpretation of gravity and tilt data in Bonaccorso et al. (2011) and show why, in our opinion, the conclusion that “*all the data concur in indicating that the 10 May lava fountain was generated by the fragmentation of a foam layer trapped at the top of a shallow reservoir*” is not soundly based.

2. Gravity changes

The dataset used by Bonaccorso et al. (2011) includes gravity time series (section 6 in their paper). The authors considered data from two continuously running spring gravimeters, installed at Serra La Nave (SLN; 1740 m a.s.l.) and Belvedere (BVD; 2920 m a.s.l.). BVD and SLN are located at about 1200 and 6400 m, respectively, away from the axis of the Southeast Crater (SEC; Fig. 1), rather than about 300 and 5000 m, as reported by Bonaccorso et al. (2011).

Bonaccorso et al. (2011) observed a temporary gravity increase in the signal from SLN during the development of the lava fountaining episode. The authors reported an amplitude of 15 μGal for this anomaly, although in Figure 11d in their paper it instead appears to have an average amplitude of 25-30 μGal.

A sharp decrease of about 250 μGal was observed in the signal from BVD when the explosive phase started. This change was compensated by a marked increase of comparable amplitude, at the end of the paroxysmal activity (Fig. 11b in Bonaccorso et al., 2011).

To explain the gravity changes observed at the two sites, Bonaccorso et al. (2011) considered a composite source-model (Fig. 2), including: (i) a cylindrical-shaped body, which represents the conduit of the Southeast Crater (SEC; Fig. 1), whose top and bottom are at elevations of 2900 and 1700 m a.s.l., respectively, and (ii) a foam layer at the base of the conduit "*that increases its volume* by about 30×10^6 m^3". On considering Fig. 12 in Bonaccorso et al. (2011), one may deduce that in the calculation the foam layer is assumed to be spherical shaped. Bonaccorso et al. (2011) proposed that the observed gravity changes are generated by (i) the fast ascent of a low-density gas/magma mixture along the SEC conduit and (ii) the expansion of a foam layer at the base of the conduit. Accordingly, both parts of the composite source were assumed to undergo a density decrease (exsolved gas substituting for magma), of 2.2 and 2.0 g/cm^3 for the conduit and underlying foam, respectively. In the framework of an overall density decrease, the positive change observed at SLN station must be due to a mass change within a volume whose centroid is above the horizon of the observation point. Hence, given the elevation of SLN (1740 m a.s.l.), the authors proposed that the positive anomaly observed at that station is due to the mass change within the SEC conduit.

Bonaccorso et al. (2011) assumed a base radius of 10 m and a height of 1200 m for the conduit. Since the base radius is much smaller than the body's height and than the distance between source and observation points, the gravity effect of the conduit (Δg_z) can be safely approximated through the gravity anomaly produced by a thin vertical rod of finite height (Telford et al., 1990):

$$\Delta g_z = G * \Delta\rho * \Delta A * \left(\frac{1}{\left(x^2 + y^2 + z_1{}^2\right)^{1/2}} - \frac{1}{\left(x^2 + y^2 + z_2{}^2\right)^{1/2}} \right) \tag{1}$$

where G is the gravitational constant (6.67 x 10^{-11} N m^2 kg^{-2}); ΔA is the base cross section; x, y indicate horizontal distance from the observation point to the source; z_1 and z_2 are depths of body top and bottom, respectively. Using this approximation and the model parameters reported in Bonaccorso et al. (2011), we calculate that a gravity effect of about 0.01 μGal is induced at SLN (Fig. 2 top). Gravity changes greater than 15 μGal are only produced at distances shorter than about 300 m (Fig. 2 top). Hence, the 15 μGal positive change observed by Bonaccorso et al. (2011) at SLN cannot be explained through the source model they proposed. In the middle panel of Figure 2, we report the gravity effect induced by the composite source at different distances and at the elevations of SLN (right of the vertical dashed line) and BVD (left of the vertical dashed line). The expansion of the foam layer at the base of the conduit also produces a negligible effect at SLN (~ -0.03 μGal), where the overall effect of the composite source is below the resolution threshold of the recording spring gravimeter. At the elevation of BVD (2920 m a.s.l.), the composite source produces an overall effect of about 250 μGal 300 m away from the SEC axis, while, at the real BVD-SEC distance of about 1200 m (Fig. 1), the gravity effect is equal to about -90 μGal. We calculate that a mass change about 3 times larger than assumed by Bonaccorso et al. (2001) is needed to induce a -250 mGal change at BVD.

To induce the observed gravity variations at SLN, a larger mass change must be assumed to take place below the SEC area and above the horizon of the station. To investigate this hypothesis, we ran several tests with differently-shaped source-bodies of diverse size, set in different positions below the summit craters area, and always obtained the same result: the mass change needed to induce a positive change at SLN in the order of 15 μGal, produces a gravity decrease at BVD with an amplitude much higher than observed. For example, a rectangular prism-shaped source with square base, centred on the axis of the SEC, whose top and bottom depths are 1.7 and 2.0 km a.s.l., respectively, and undergoing a density change of -2.2 g/cm^3, should have a horizontal size of about 600 m (mass change in the order of 10^{12} kg) to produce a gravity effect of 15 μGal at SLN. Besides being unrealistic from the volcanological point of view, this source would induce a gravity decrease at BVD about 6 times larger than observed.

The above observations can be summarized as follows:

1) In evaluating the gravity effect produced at SLN by the source-model they propose, Bonaccorso et al. (2011) made a serious error. Indeed, the mass decrease proposed as a well-fitting source actually produces a negligible gravity effect at SLN (~0.01 μGal), rather than the observed 15 μGal change.
2) Bonaccorso et al. (2011) considered a SEC-BVD distance that is ~ 4 times smaller than it actually is. This inaccuracy leads to a calculated mass change 3 times smaller than needed to induce the observed effect at the observation point in its real position.
3) Even considering sources other than the one put forward by Bonaccorso et al. (2011), the pattern of positive/negative changes observed at the two stations is clearly not explainable by mass redistributions occurring only below the summit craters area.

The last point has two alternative implications: (a) if they reflect actual perturbations of the gravity field, the changes observed by Bonaccorso et al. (2011) must have been induced by mass redistributions occurring (at least in part) outside the volume below the summit craters area; (b) alternatively, the observed gravity variations are affected by instrumental artifacts. As for (a), relying on the available volcanological and geophysical information, it is unlikely that the processes which drove the May 10 2008 lava fountain occurred away from the areas of magma storage and transport beneath Etna's summit craters. In any case, it is possible that the mass redistributions that induced the observed gravity changes occurred, in part, as a secondary, rather than direct, effect of the mechanism behind the paroxysm. Previous studies have shown that, at some volcanoes, the magmatic system may interact dynamically with the tectonic (e.g. Carbone et al., 2009; Hautmann et al., 2010) and/or the hydrological (e.g. Gottsmann et al., 2011) systems, leading to measurable gravity changes as a second-order effect. Using continuous gravity data from Soufrière Hills Volcano (Montserrat), spanning a Vulcanian explosion, Gottsmann et al. (2011) reported the occurrence of measurable gravity changes 7 km away from the active vent, possibly induced by the dynamic response of a local aquifer to the eruption. If the gravity changes observed by Bonaccorso et al. (2011) at SLN station were induced by a similar mechanism, a transient local water level change of up to about 6 m should have occurred, assuming the Bouguer slab approximation and a mean effective aquifer porosity of about 10% (Aureli, 1973). Compared to the results of other studies where water level changes induced by volcanic events are taken into account (Hurwitz and Johnston, 2003; Gottsmann et al., 2011), this change is unreasonably large.

The other possibility to solve the paradox posed by the increase/decrease pattern of changes at the two observation points consists in assuming instrumental artifacts on the signal from one or both recording gravimeters. The coincidence in time between the gravity anomalies observed at the two sites and the paroxysmal event implies that possible instrumental artifacts must be related to the lava fountain episode. One possibility is that mechanical instrumental effects, driven by the strong seismic perturbation during the paroxysmal event, influenced the observations.

More data (longer gravity sequences from both stations, seismic data from the Etna network, information on local water level changes) should be cross-analyzed in order to fully address the above issues.

3. Tilt changes

Section 5 (Deformation: Tilt Changes) of Bonaccorso et al. (2011) also contains ambiguities concerning both data presentation and analysis. The radial (i.e. directed towards the summit craters) components of most tilt signals (panel *a* of Figure 9 in Bonaccorso et al. (2011)) show strong diurnal changes, likely driven by meteorological parameters, that are superimposed on the changes due to the lava fountain. Consequently, in most cases, it seems that it is very difficult to estimate the amplitude of the “useful” signal. Nevertheless, nothing is reported in Bonaccorso et al. (2011) about how the data are corrected for instrumental effects, and they do not provide error bars on the observed changes (Figure 10 in their paper). The only signals which clearly show the anomaly due to the lava fountain are those from MDZ and CBD stations. Even though the radial component of the tilt signal from CBD appears to follow the general trend of deflation (panel a of Figure 9 in Bonaccorso et al. (2011)), the tilt vector at the same station (panel b) indicates inflation. Ferro et al. (2011) also presented the tilt signal recorded at CBD during the 1-13 May 2008 period (Figure 7 in their paper) and reported an increase of the radial component (inflation) during the 10 May lava fountain.

Even if the ambiguities on the amplitude and sign of the changes at the tilt stations are disregarded, the pattern of observed change does not allow defining the depth of the deformation source univocally. Indeed, in the horizontal-distance-from-the-source versus tilt plot (Figure 10 in Bonaccorso et al. (2011)) the recorded tilt at 7 stations out of 9 falls in the region where the predicted tilt curves for sources at 1.5, 2.5, and 3.5 km bsl overlap, while the remnant 2 values fall on the 2.5 (but not far away from the 1.5; MSC), and above the 3.5 (PDN) km bsl curves, respectively. It is worth noting that (i) in Figure 10 of Bonaccorso et al. (2011) the differences in the orientation of observed and calculated tilt vectors (up to about 180° at CBD station) are disregarded; (ii) the authors explain the low tilt value observed at PDN as a topographic effect, even if they state that data were corrected for this effect using the method of Williams and Wadge (2000).

4. Concluding remarks

As shown above (section 2), the treatment of the gravity data in Bonaccorso et al. (2011) contains serious errors that invalidate the inferences derived by the authors from this technique. In particular, the gravity data do not support the inferred movement of the dispersed flow through the SEC conduit. Furthermore, the incorrect crater-station distances assumed by Bonaccorso et al. (2011) result in large errors in the evaluation of the mass changes needed to induce the observed gravity changes. The involvement in the dynamics of the May 10, 2008 paroxysm of a deeper magma reservoir than that evidenced by tremor source locations, whose results were already pubblished in Di Grazia et al. (2009), is not unambiguously supported by the tilt data presented by Bonaccorso et al. (2011). Indeed, due to inherent limitations, these data do not seem to have enough resolving power to unequivocally indicate the position of the deformation source.

Finally, there is also inconsistency in the conclusions reached by Bonaccorso et al. (2011) about the mechanism behind the10 May lava fountain. Indeed, while from seismic data the authors concluded that the10 May lava fountain was triggered by "*the uprising of a deeper, more primitive and gas-rich magma*" (section 7), from petrological data they suggest that "*the 10 May lava fountain was not triggered by syneruptive degassing of an ascending new, more primitive and volatile-rich magma*" (section 3).

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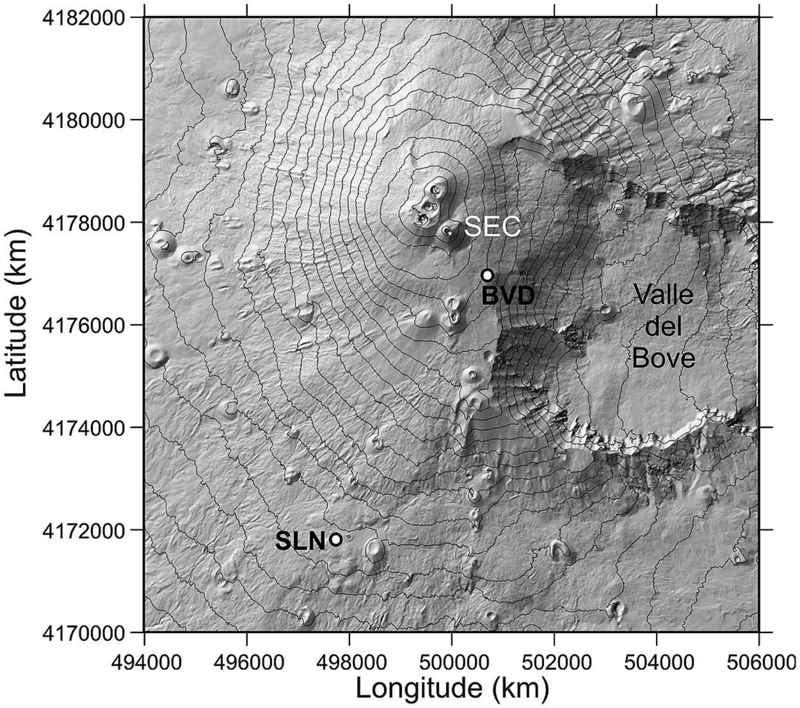
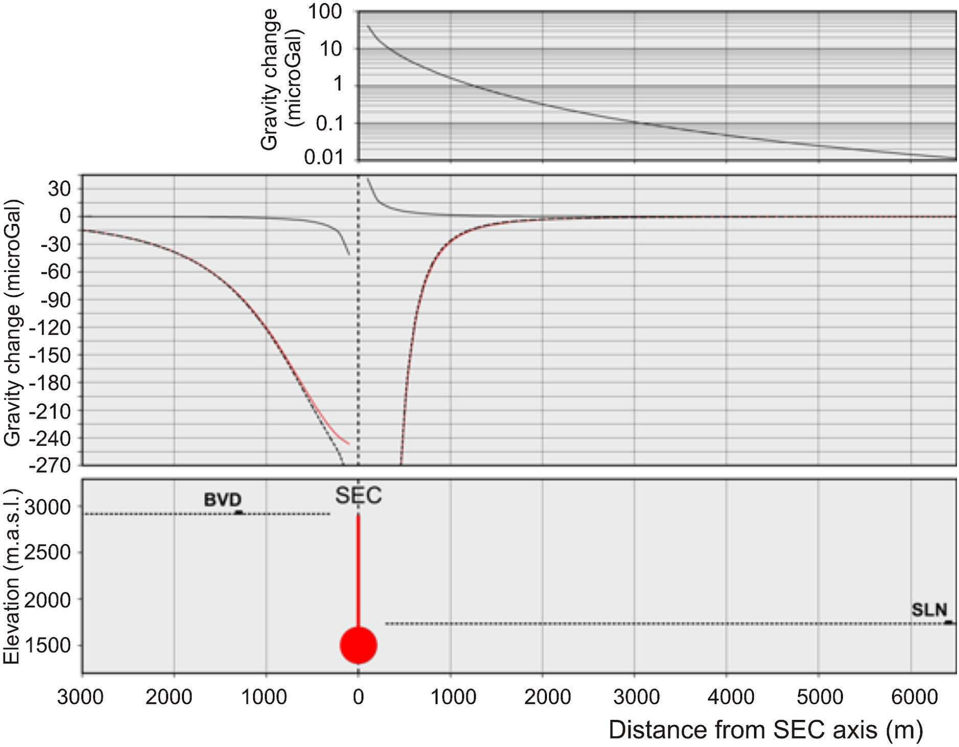
Figure captions

Figure 1 – Sketch map of Etna Volcano showing the location of SLN and BVD gravity stations and the position of the Southeast Crater (SEC).

Figure 2 – Top: Gravity effect (log scale) induced by the cylinder-shaped body (SEC conduit) proposed by Bonaccorso et al (2011), at different distances from the cylinder axis and at the elevation of SLN station (1740 m a.s.l.). Middle: Gravity changes produced by the composite source of Bonaccorso et al. (2011) at different distances from the body axis and at the elevations of SLN (right of the vertical dashed line) and BVD (left of the vertical dashed line) stations (1740 and 2920 m a.s.l., respectively). Solid black lines: effect of the cylinder (SEC conduit); solid red lines: effect of the sphere (foam); dashed lines: cumulative effect. Bottom: Schematic cross-section showing the geometrical relationship between observation points and source model.



4182000
4180000
4178000
4176000
4174000
4172000
4170000
Latitude (km)
SEC
BVD
Valle del Bove
SLN
494000
496000
498000
500000
502000
504000
506000
Longitude (km)



Gravity change (microGal)
100
10
1
0.1
0.01
30
0
-30
-60
-90
-120
-150
-180
-210
-240
-270
BVD
SEC
SLN
Elevation (m.a.s.l.)
3000
2500
2000
1500
3000
2000
1000
0
1000
2000
3000
4000
5000
6000
Distance from SEC axis (m)