Geochemistry Geophysics Geosystems G3

Published by AGU and the Geochemical Society

Reply
Volume 13, Number 1
16 November 2012
Q11009, doi:10.1029/2012GC004239
ISSN: 1525-2027

Reply to comment by D. Carbone and D. Patanè on "Multidisciplinary investigation on a lava fountain preceding a flank eruption: The 10 May 2008 Etna case"

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Components: 3300 words, 4 figures.

Keywords: Etna volcano; explosion mechanism; lava fountain; volcano multidisciplinary monitoring.

Index Terms: 8414 Volcanology: Eruption mechanisms and flow emplacement; 8419 Volcanology: Volcano monitoring (4302, 7280); 8434 Volcanology: Magma migration and fragmentation.

Received 15 May 2012; **Revised** 28 September 2012; **Accepted** 14 October 2012; **Published** 16 November 2012.

Bonaccorso, A., A. Cannata, R. A. Corsaro, G. Di Grazia, S. Gambino, F. Greco, L. Miraglia, and A. Pistorio (2012), Reply to comment by D. Carbone and D. Patanè on "Multidisciplinary investigation on a lava fountain preceding a flank eruption: The 10 May 2008 Etna case", *Geochem. Geophys. Geosyst.*, *13*, Q11009, doi:10.1029/2012GC004239.

1. Introduction

[1] *Bonaccorso et al.* [2011a] investigated the source and magma dynamics of the 10 May 2008 lava fountain at the South-East Crater (SEC) of Mount Etna through a multidisciplinary approach that integrated a wide data set ranging from bulk rock compositions of the erupted products to seismic tremor and long-period events, tilt and gravity signals. Using a large data set, the study provided a robust framework in which the mechanism of the 10 May 2008 lava fountain is explained as a violent release of bubble-rich magma layer previously trapped at the top of a shallow reservoir located between −0.5 and 1.5 km above sea level (asl). This result is in agreement with recent relevant literature [*Allard et al.*, 2005; *Vergniolle and Ripepe*, 2008; *Aiuppa et al.*, 2010; *Andronico and Corsaro*, 2011; *Bonaccorso et al.*, 2011b; *Calvari et al.*, 2011; *Vergniolle and Gaudemer*, 2012].

[2] In the introduction of their comment, *Carbone and Patanè* [2012] affirm that in their opinion the interpretation that [*Bonaccorso et al.*, 2011a, Abstract] "…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. This comment's conclusion is puzzling because one of the comment's authors (D. Patanè) is also a co-author on the paper by *Aiuppa et al.* [2010] where the same conclusion, now criticized, was well supported (see Figure 5 and conclusions of *Aiuppa et al.* [2010]). In particular, in the conclusions *Aiuppa et al.* [2010, paragraph 26] reported "That paroxysmal SEC episodes mark the violent release of a bubble-rich magma layer, with bubbles having … relatively shallow reservoir …," that is, the same conclusion now criticized in the comment. After this, the

comment raises issues concerning the analysis and interpretation of gravity and tilt data in the multidisciplinary approach presented by *Bonaccorso et al.* [2011a]. The comment by *Carbone and Patanè* [2012] is divided into 4 paragraphs, labeled "1. Introduction," "2. Gravity Changes," "3. Tilt Changes" and "4. Concluding Remarks" with only paragraphs 2 and 3 containing specific comments. In this reply, we address these two paragraphs, and we shall show how the assumptions underlying the comment are merely speculative and why the results presented by *Bonaccorso et al.* [2011a] remain valid.

2. Reply to Comment in Section 2 (Gravity Changes)

[3] The comment by *Carbone and Patanè* [2012] criticizes section 6 (Gravity) in *Bonaccorso et al.* [2011a], arguing three points: (1) the gravity data would not support the movement of the dispersed flow through the SEC conduit, since the mass decrease would produce a negligible gravity effect at the SLN station that is the most distant from the SEC; (2) the incorrect distance assumed by *Bonaccorso et al.* [2011a] from the gravity station BVD to the SEC, that would result in evaluation of a mass change three times smaller than needed to induce the observed gravity changes; and (3) the positive/negative gravity changes observed at BVD and SLN stations would not be explainable by mass redistributions occurring only below the summit craters.

[4] First of all, it is fundamental to underline that *Bonaccorso et al.* [2011a] did not use the gravity data to constrain the shallow foam-source, but they tested whether the source mechanism inferred by other data (e.g., LP events and volcanic tremor) could somehow also justify the observed gravity changes.

[5] With regard to the first point, the proposed model matches quite well the gravity change at SLN [*Bonaccorso et al.*, 2011a, Figure 12b]. As stated in the text, although the change of few μGal, due to the density variation of magma flowing within the conduit, is smaller than the measured one ($\sim$15 μGal), we stress the positive sign of the gravity anomaly. In fact, the sign is compatible with a low density gas-magma flow ascending through the upper conduit located at an elevation higher than the station. The shallow foam-source, inferred by seismic data, causes negligible gravity effect at SLN since it is at the same altitude as the station.

[6] Moreover, besides the argument on the sign of the anomaly at SLN, for the interpretation of gravity data acquired at SLN and BVD, we jointly inverted data from both stations and we gave greater importance to the best fit at BVD station, mainly for two reasons: (1) the gravity variation ($\sim$250 μGal) at BVD station is greater than at least an order of magnitude than that observed at SLN ($\sim$15 μGal); (2) the BVD station is much closer to the eruptive vents and therefore may provide more robust information of the phenomena.

[7] *Carbone and Patanè* [2012] argue that to induce the measured gravity variations at SLN, a larger mass change must be assumed to take place below the SEC and above the horizon of the station. Although this aspect is theoretically correct, the ambiguity is that this argument is based on separate solutions at the two stations without considering a single overall framework that emerges from other geophysical results and volcanological observations.

[8] With regard to the second point raised by the comment of *Carbone and Patanè* [2012], it is important to highlight that the 10 May 2008 lava fountain was not sourced at the summit crater of the SEC but from a depression (pit crater) opened in 2007 on its southeastern flank. This aspect has not been explicitly defined in *Bonaccorso et al.* [2011a] but emerges by looking at Figure 3 of that work. A more detailed map is added to make clear this point (Figure 1). The model proposed in *Bonaccorso et al.* [2011a] shows that at BVD the main contribution to gravity change is given by the foam-source located at about 1.5–1.7 km asl, i.e., the top of the magmatic source revealed by the seismic tremor. Since the source of the tremor during the lava fountain migrates toward southeast [*Bonaccorso et al.*, 2011a, Figure 8], to calculate the gravity effects of the shallow foam-source at BVD station, we referred to the pit crater, the distance of which from the station is shorter than the distance of the SEC summit crater.

[9] In any case, the issue on the distance is a weak point since the proposed model is slightly affected by this parameter. If *Bonaccorso et al.* [2011a] underestimated the distance between the BVD station and the pit crater axis (the correct distance is no more than 900 m), we stress that even if we vary the horizontal distance of the station to the vertical axis of the foam-source between 300 and 1000 m, the gravity change is still explicable with a foam-source positioned at the depth of 1.7 km asl. This conclusion is illustrated in Figure 2, where we show the different foam-source radius as a function of the

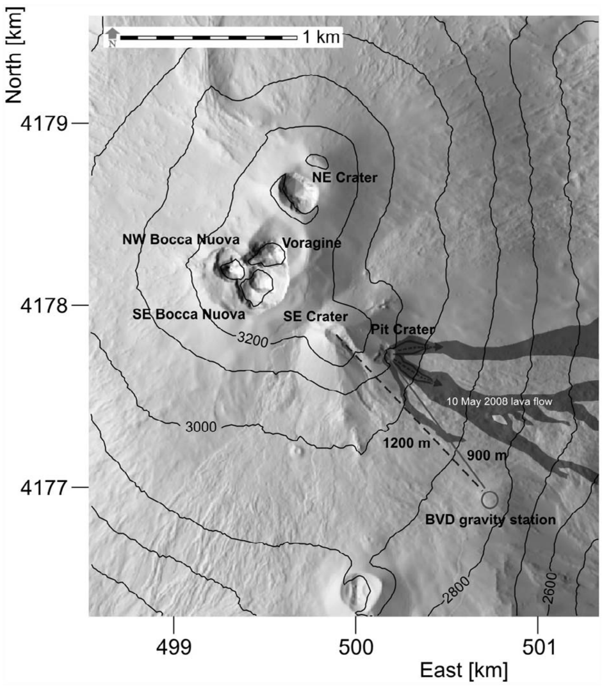

Figure 1. Sketch map based on 10-m resolution DEM [*Neri et al.*, 2008] showing the positions of the BVD gravity station, SEC and the pit crater where 10 May lava fountaining took place. The eruptive fissures propagated from the pit crater and the lava flows outpoured during the paroxysm are also mapped (black area; M. Neri, personal communication). The distances between BVD gravity station with the SEC and the pit crater are also reported. Geographical coordinates are expressed in UTM projection, zone 33N.

horizontal distance of the station to produce a 250 μGal gravity change. From the graph it is clear that a source positioned at 1.7 km asl can cause a 250 μGal gravity change at a station horizontally distant from 300 to 1000 m just by varying its radius from about 200 to about 250 m, respectively.

[10] Finally, to explain the pattern of positive/negative changes observed at the two gravity stations, the third point made by *Carbone and Patanè* [2012] gives two alternative solutions: (1) mass redistribution phenomena occurring (at least in part) outside the volume below the summit craters area and (2) instrumental artifacts. For the solution (1) they proposed the interaction between the magmatic system and the tectonic and/or the hydrological systems, as possible causes of second-order effects on gravity changes. Regarding the hydrological effect, *Carbone and Patanè* [2012] only raise generic comments which are not supported by precise calculations. It is, however, really difficult to make quantitative estimations since at SLN station the volcanic permeable pile is about 700–800 m thick [*Ferrara and Pappalardo*, 2008] and the water table should be located at the bottom of this pile. Wells are not present for measuring variations of the water table level. In any case, the changes in the water table level needed to justify the variation recorded at SLN seem unrealistic, as the authors of the comment themselves conclude. For solution (2), Carbone and Patanè cite possible causes as well as instrumental artifacts, to explain the gravity pattern without furnishing any estimate of the effects. To date, several studies have been carried out taking into account gravity changes observed during paroxysmal events [e.g., *Bonaccorso et al.*, 2011b; *Carbone et al.*, 2006, 2008]. For example, the cross analyses of the gravity sequences with simultaneous seismic data allowed interpreting the observed gravity changes as due to local mass redistributions triggered by the magma/gas dynamics in the shallow portion of the plumbing system. However, although instrumental effects could occur during the development of volcanic processes, their quantification has never been made. In conclusion, the comment

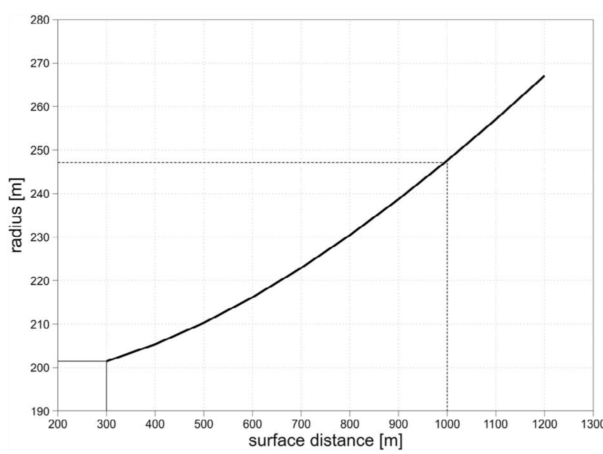

Figure 2. Variation of the foam-source radius (assumed to be spherical shaped) as a function of the horizontal distance from the surface source projection to induce a gravity effect of 250 μGal. Using the parameters of the foam-source reported in *Bonaccorso et al.* [2011a], we calculate the radius r of a Mogi-type magma reservoir from the following equation: $r = [(3 \cdot \Delta M_m) \cdot (4 \cdot \pi \cdot \rho)^{-1}]^{1/3}$. The term ρ is the assumed density contrast between the resident magma and the gas-magma foam and ΔM_m (total mass change) is obtained by the following relationship: $\Delta M_m = \Delta g \cdot (x^2 + z^2)^{3/2} \cdot (G \cdot z \cdot 10^8)^{-1}$, where Δg is the observed gravity change, G is the universal gravitational constant, x is the surface distance (m) from the center of the Mogi source, and z is the depth (m) to the Mogi point source [*Dzurisin et al.*, 1980; *Johnson*, 1987; *Eggers*, 1987; *Williams-Jones and Rymer*, 2002].

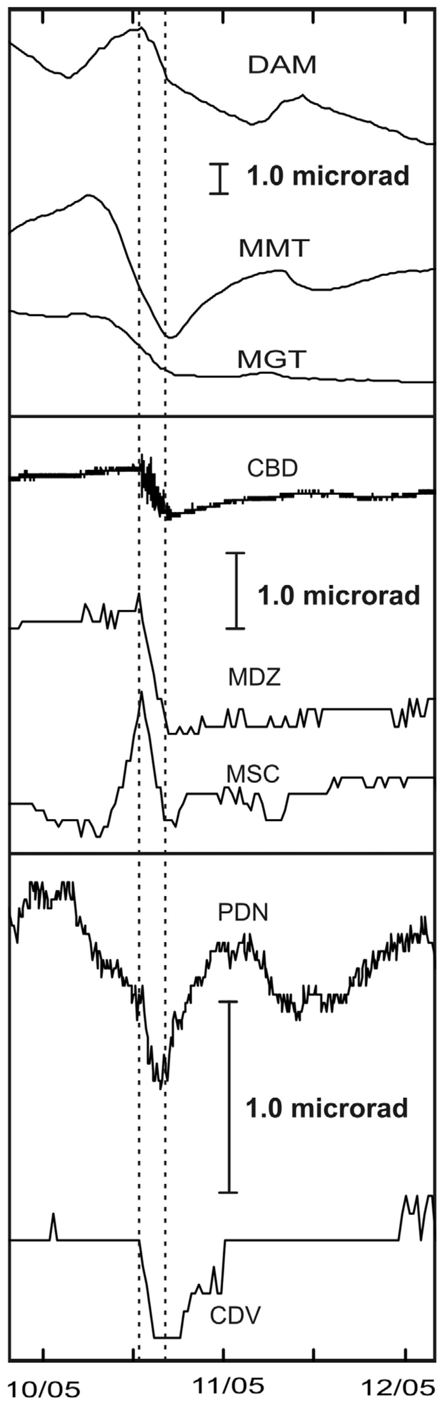

Figure 3. Stacked records of tilt signals (radial component except CBD) collected during the interval 10–12 May 2008. Changes associated with the lava fountain are clear at almost all stations of the tilt network. The dashed lines indicate the lava fountain time interval. The 1.0 microrad bars indicate the scale unit of the signals.

does not support the hypothesis of issues (1) and (2) with valid quantitative data.

3. Reply to Comment in Section 3 (Tilt Changes)

[11] *Carbone and Patanè* [2012, section 3] criticize section 5 (Deformation: Tilt Changes) of *Bonaccorso et al.* [2011a] affirming that this "contains ambiguities concerning both data presentation and analysis." Figure 9a of *Bonaccorso et al.* [2011a] shows eight tilt signals recorded during the lava fountain episode that were represented by a single unit scale. The first three (DAM, MMT and MGT) show daily oscillations that are almost absent on the other five signals (CBD, MDZ, MSC, PDN, CDV). In the caption of Figure 9 in *Bonaccorso et al.* [2011a] this aspect was already reported by writing: "signals of some stations are modulated by thermoelastic daily effects." However, to better show the tilt changes, now we report a modified version of this figure in which we have used different unit scales (Figure 3).

[12] The shallow borehole tiltmeters have resolution of the order of 0.1 μrad [*Bonaccorso et al.*, 1999] which is mainly appreciable during rapid tilt changes [*Bonaccorso and Gambino*, 1997; *Bonaccorso*, 2006]. Therefore, error on the estimation of the tilt changes during the few hours of the lava fountain is of this order of magnitude. The PDN station is a long-base fluid tiltmeter with a higher resolution of 0.01 μrad. The first three signals (DAM, MMT and MGT) could be affected by a higher error (about 0.1–0.2 μrad) due to the daily oscillation. However, all these errors are very small and were not considered in the tilt vector figure. *Bonaccorso et al.* [2011a] did not report that in their Figure 9a the CDB signal corresponds to N130.5E direction, which is closer to its tangential component. However, the correct tilt vector of CBD is shown in Figure 9b of *Bonaccorso et al.* [2011a]. Furthermore, we underline that the CBD signals show a different behavior, which may be caused by a sliding effect of the eastern flank [*Bonaccorso et al.*, 2011b].

[13] With regard to the depth of the deformation source, inferred in a range of ~3 km below sea level (bsl) by the horizontal-distance-from-the-source versus tilt plot [*Bonaccorso et al.*, 2011a, Figure 10], it was already written by *Bonaccorso et al.* [2011a, paragraph 23] that this evaluation represents "a first-order estimation of the source depth." We calculated the predicted tilt amplitude at the surface due to a source with a removed volume of 1.5×10^6 m^3, i.e., the lava volume emitted during the lava fountain, by

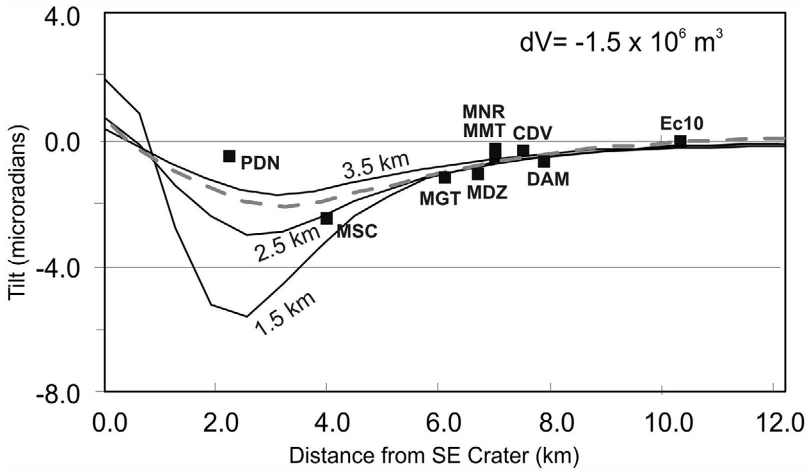

Figure 4. Predicted tilt amplitudes at the surface as a function of the horizontal distance from the Mogi source with a volume of 1.5×10^6 m^3 removed by eruption. The source is located below the summit crater area at 1.5, 2.5, and 3.5 km bsl. The predicted tilt is calculated along the east-west direction by including the volcano topography effects [*Williams and Wadge*, 2000] for an east-west profile crossing the summit crater area. The squares are the recorded tilt at the different stations plotted versus their horizontal distance from the summit crater area. The CDB positive tilt has not been reported in the graph. The dashed line represents the curve fitting our data.

varying the depth of the source. In Figure 4 we reported the same Figure 10 of *Bonaccorso et al.* [2011a] superimposing a dashed line representing the curve fitting our data. Finally, with regard to the low tilt value observed at PDN and the topographic effect, *Carbone and Patanè* [2012, section 3] incorrectly presumed that "data were corrected for this effect using the method of *Williams and Wadge* [2000]." We underline that the data shown are raw data and were not corrected by topographic methods. In *Bonaccorso et al.* [2011a] the topography effect was instead considered to calculate the predicted tilt curves in their Figure 10. This figure, slightly modified, is here shown as Figure 4.

4. Final Remarks

[14] As reported in sections 2 and 3, we highlighted that the issues raised in the comment are mainly speculative with regard to the gravity and approximate with regard to the tilt, respectively. The comment's statements do not invalidate the results achieved in *Bonaccorso et al.* [2011a] that are further supported by a multidisciplinary approach.

[15] Finally, we stress that both seismic and petrologic data concur to define the same mechanism of the 10 May lava fountain. In particular, during the ascent of a deeper, more primitive and gas rich magma occurring one week before the paroxysm, the volatiles migrated and accumulated at the top of SEC reservoir triggering the 10 May lava fountain. In this framework, the gases, decoupled from the primitive melt, played a fundamental role in driving the explosive activity, which removed the upper residing and less primitive magma.

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