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Peer Review File

Magma budget, plutonic growth and lateral spreading at Mt. Etna

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9th Oct 23

Dear Dr Palano,

Please allow us to apologise for the delay in sending a decision on your manuscript titled "Magma budget, plutonic growth and lateral spreading at Mt. Etna". It has now been seen by 2 reviewers, and we include their comments at the end of this message. They find your work of interest, but some important points are raised. We are interested in the possibility of publishing your study in Communications Earth & Environment, but would like to consider your responses to these concerns and assess a revised manuscript before we make a final decision on publication.

We therefore invite you to revise and resubmit your manuscript, along with a point-by-point response that takes into account the points raised. Please highlight all changes in the manuscript text file.

We are committed to providing a fair and constructive peer-review process. Please don't hesitate to contact us if you wish to discuss the revision in more detail.

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We hope to receive your revised paper within six weeks; please let us know if you aren't able to submit it within this time so that we can discuss how best to proceed. If we don't hear from you, and the revision process takes significantly longer, we may close your file. In this event, we will still be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

Please do not hesitate to contact us if you have any questions or would like to discuss these revisions further. We look forward to seeing the revised manuscript and thank you for the opportunity to review your work.

Best regards,

Teng Wang, PhD
Editorial Board Member
Communications Earth & Environment
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Joe Aslin
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REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

This manuscript is a very comprehensive analysis of all deformations occurred at Mt. Etna in the last 20 years. It is not common to see so long time series of deformation and the associated modelling results in one paper and I appreciated the fact that the Authors not only show their modelling results, but they also tried to discuss the geological implications of their results. I think that this paper is appropriate for Communications Earth & Environment, since I see a potential high impact of their results, and I support its publication. However, before that manuscript can be accepted, I think that some moderate changes have to be made, since I think that the Authors could valorise their results better, expanding their discussion. In addition, there are some points that seem incorrect in the way they are written and that therefore have to be corrected (but the Authors can easily make these changes). Below I report my detailed reviews. I also attached an annotated version of the manuscript with further changes and comments.

Main points:
In the abstract and in the discussion section you wrote that “About 28.5% of this magma contributed to the effusive activity, the remaining 71.5% fed the endogenous volumetric growth of the plutonic crystallized mush and promoted the lateral spreading of Mt. Etna.” This sentence, written in this way, seems not correct since the ΔVi you estimated (10.7 x 10^6 m^3/yr) are lower than the eruptive rates at Etna (~25x10^6 m^3/year; Bonaccorso and Calvari, 2013). This result is consistent with what has been observed in many other volcanoes of the World, where similar differences between the pre-eruptive new volume of magma accumulated in the reservoir, estimated from the inversion of deformation with elastic models, and the erupted volume have been observed. These differences can be ascribed by many complications that usually are not considered in the modelling (e.g. compressibility). The 28.5% represents the difference between the ΔVi and the ΔVo you estimated with elastic models and not the difference between the ΔVi and the erupted volume (if you wrote “about 28.5% of this magma contributed to the effusive activity” it seems that only the 28.5% of ΔVi has been erupted, but the true erupted volume is about the double that your ΔVi). You should change this sentence in the abstract, as well as similar sentences in the discussion, to better explain what you have done and what the data from your analysis means.

Volume estimation and magma compressibility: This section represents the most important part of your manuscript. I think it should be expanded and rewrote to address the following points:
1) I think would be important to add and/or expand the discussion about the comparison between your results (ΔVi and ΔVo) and the erupted volumes. Mt. Etna is known to be usually characterized

by regular eruptive rates (~25x10^6 m3/year; Bonaccorso and Calvari, 2013; Calvari et al., 2020). Every time that Etna erupts less magma than that expected from its average eruptive rates, it is supposed that the volcano is accumulating magma (Bonaccorso and Calvari, 2013; Calvari et al., 2020) and your results agree well with this. For example, from 2016 to 2020 Etna erupted much less magma than that expected (Calvari et al., 2020) and you found and important increase in the modelled ΔVi, providing a proof that effectively the volcano was in a phase of strong accumulation of magma. You should better highlight this in your discussion, as well as you should expand this discussion also at the other periods you analysed (e.g. lines 161-164, where the "quasi-cyclic recharge" is supported also by the regular eruptive rates occurred in that time span).
2) You are using elastic models and therefore ΔVi and ΔVo are minimum estimations (would be equal to the true ΔVi and ΔVo only if the system is incompressible). For example, the difference between the ΔVo (3.3 ± 0.3 x 10^6 m3/yr) with the eruptive rates (~25x10^6 m3/year; Calvari et al., 2020) can be explained by the compressibility of the reservoir. Since the compressibility of the system is unknown and can change over the time (especially during an eruption), the comparison of the ΔVi with the ΔVo might be not necessarily correct (not sure that the sentence at line 176 is correct).
I think you should better explain somewhere how your modelling results (ΔVi and ΔVo) could be affected by the compressibility (and other parameters).

Bonaccorso, A., & Calvari, S. (2013). Major effusive eruptions and recent lava fountains: Balance between expected and erupted magma volumes at Etna volcano. Geophysical Research Letters, 40(23), 6069–6073. https://doi.org/10.1002/2013GL058291

Calvari, S., Bilotta, G., Bonaccorso, A., Caltabiano, T., Cappello, A., Corradino, C., et al. (2020). The VEI 2 Christmas 2018 Etna eruption: A small but intense eruptive event or the starting phase of a larger one? Remote Sensing, 12(6), 905. https://doi.org/10.3390/rs12060905

In the abstract you wrote that there are "two partially overlapping reservoirs located beneath the summit area in the 4-9 km (inflation sources) and in the 3-6 km (deflating sources) depth ranges". I think you arrive to this conclusion because the inflating and the deflating sources are located in different places. However, the discussion section lacks a discussion about it. I think this is one of your main results, since it is surprisingly that all inflation sources are placed NW with respect to all deflating sources, and this should be properly shown and discussed both in the result section (you do not mention this result in the result section) and in the discussion section. Here you should try to explain why you get this result and how you interpret it (e.g. by writing something like: the different location of the inflating and deflating sources might suggest the existence of two different reservoirs …). Instead of limiting to speak about two magma reservoirs, I think it is better to talk about the existence of a complex magmatic system that can have multiple reservoirs (e.g., Sparks et al., 2019; Edmonds et al., 2019), which can respond in different ways during the different inflation/deflation events. You can also try to check if there might be a geological explanation of why your deflating sources are placed SE respect to the inflating sources (e.g., any evidence that it is easier to drain magma from that part? Is this area further from the eruptive vents and therefore the subsidence in that area is not masked by the deformation of the propagating dikes?)

Sparks, R. S. J., Annen, C., Blundy, J. D., Cashman, K. V., Rust, A. C., & Jackson, M. D. (2019). Formation and dynamics of magma reservoirs. Philosophical Transactions of the Royal Society A, 377. https://doi.org/10.1098/rsta.2018.0019

Edmonds, M., Cashman, K. V., Holness, M., & Jackson, M. (2019). Architecture and dynamics of magma reservoirs. https://doi.org/10.1098/rsta.2018.0298

Minor reviews:

Abstract: I do not think that the estimation of the “location and quantitative estimation of the eruptible magma” is the most effective way to assess volcanic hazard. I think it is better to rewrite the first sentence (something like: “The location and the quantitative estimation of the eruptible magma provide an important tool to assess the volcanic hazard”).

Line 60-61: I think that other valuable examples of cycles of inflation-eruption-deflation, whose deformation has been measured and modelled, are: Krafla (e.g. Ewart et al., 1991); Axial Seamounts (Nooner and Chadwick, 2016); Sierra Negra and Fernandina (Gregg et al., 2018, 2022; Bagnardi and Amelung, 2012; Galetto et al., 2023); Piton de la Fournaise (Peltier et al., 2008). All these volcanoes are basaltic (like Etna) and their volcanic activity is similar to that of Etna, so I think it would be a good idea to quote at least some of them.

Ewart, J. A., Voight, B., & Björnsson, A. (1991). Elastic deformation models of Krafla Volcano, Iceland, for the decade 1975 through 1985. Bulletin of Volcanology, 53, 436-459.

Nooner, S. L., & Chadwick Jr, W. W. (2016). Inflation-predictable behavior and co-eruption deformation at Axial Seamount. Science, 354(6318), 1399-1403.

Gregg, P. M., Le Mével, H., Zhan, Y., Dufek, J., Geist, D., & Chadwick Jr, W. W. (2018). Stress triggering of the 2005 eruption of Sierra Negra Volcano, Galápagos. Geophysical Research Letters, 45(24), 13-288.

Gregg, P. M., Zhan, Y., Amelung, F., Geist, D., Mothes, P., Koric, S., & Yunjun, Z. (2022). Forecasting mechanical failure and the 26 June 2018 eruption of Sierra Negra volcano, Galápagos, Ecuador. Science advances, 8(22), eabm4261.

Bagnardi, M., & Amelung, F. (2012). Space-geodetic evidence for multiple magma reservoirs and subvolcanic lateral intrusions at Fernandina Volcano, Galápagos Islands. Journal of Geophysical Research: Solid Earth, 117(B10).

Galetto, F., Reale, D., Sansosti, E., & Acocella, V. (2023). Implications for shallow magma transfer during the 2017 and 2018 eruptions at Fernandina (Galápagos) inferred from InSAR data. Journal of Geophysical Research: Solid Earth, 128, e2022JB026174.

Peltier, A., Famin, V., Bachèlery, P., Cayol, V., Fukushima, Y., & Staudacher, T. (2008). Cyclic magma storages and transfers at Piton de La Fournaise volcano (La Réunion hotspot) inferred from deformation and geochemical data. Earth and Planetary Science Letters, 270(3-4), 180-188.

Lines 78-79: If you have space, here you might specify the geodynamic setting better, since it is the reason of why Mt. Etna is one of the most active volcanoes of the world. You could quickly mention that it is placed nearby the Malta escarpment, which is a fault system separating the thinner Ionian oceanic lithosphere to the thicker continental crust of the African foreland, and that this fault system creates an asthenospheric window promoting a mantle upwelling below Etna (Gvirtzman and Nur, 1999).

Lines 89-90: You have to explain what it is the EDAM-ESLN baseline. You should not assume that all the reader are familiar with the Etna ground monitoring system. It would be a good idea to show the EDAM-ESLN baseline on Figure 1.

Line 91: "throughout the investigated time interval". Before this sentence, you have never defined what time interval you investigated. Please specify.

Lines 94-95: "By dividing the time-series into piecewise linear segments with no uniform duration". You have to specify how you divided the segments (I guess every time that the deformation changed from uplift to subsidence). This is poorly defined also in the Method section. So, you should better define how you divided the time-series in at least one of the two sections. If you specify it in the methods, remember to recall the method section at the end of the sentence reported at lines 94-95, by writing "…By dividing the time-series into piecewise linear segments with no uniform duration (see Methods)".

Lines 95: here you wrote you "detected a total of 58 different ground deformation phases consisting in 28 inflation phases, 21 deflation phases, 5 magmatic intrusions and 4 periods with no significant deformation", while in the Methods you report "59 different ground deformation phases consisting in 29 inflation phases, 21 deflation phases, 5 magmatic intrusions and 4 periods with no significant deformation". Please be consistent. One of them is reported erroneously.

Results section: At the end of the Results section, you quote the figures where you show your results, but you do not describe any of your results. Even though the Figures are very good, you should dedicate few lines to describe what your figures show. For example, you can briefly summarize your results about the depth of your sources and their location (the fact that the subsidence sources seem shifted with respect to the inflating sources).

Discussion: Is there an explanation of why all your inflating sources are plated at NW and all your deflating sources are placed at SE respect to the crater? I am not wonder by the fact that the modelled sources are placed in slightly different locations, since it is normal that when you run the inversion, solutions converge for slightly different locations. For example, in Galápagos volcanoes every time that you model the deformation due to the inflation/deflation of the reservoir, the location (lon-lat) and the geometry of the sources representing the reservoir are always slightly different each other (especially at Fernandina). However, here at Etna your modelling results show that the sources are not randomly oriented as in Galápagos, but you have a trend (all the inflating sources on one side and all the deflating sources on the other side), which should be explained/motivated, since it is a very interesting result.

Lines 144-145: if you used elastic models, the estimated volume is a minimum estimation since you consider an incompressible material (for both the host rock and the magma in the reservoir). For the same reason, the volume lost by the deflating sources is a minimum estimation, since you are considering an incompressible medium (host rock and magma in the reservoir). I think it would be better to specify that these estimations are minimum estimates. This is important for the sentence you wrote at lines 147-149.

Lines 158-160: To be considered as “re-equilibrium episodes” the volume of new magma added by these two periods of inflation should be similar (or lower) to the volume lost by the two eruptions. You should check if it is true. Otherwise, if the volume added during the inflation is higher than the volume lost by the previous eruption, it means that a certain point the “re-equilibrium phase” ended.

Lines 212-214: Where EINT and EMEG are placed? On figure 1b, you show only EPLU. Please add the location of EINT and EMEG on Figure 1b or Figure 1c.

Figure 2. Panel b: on the y axis please do not write 106 m3, but 10^6 m^3. Panel c: in the grey box you have to specify the size (you simply write 30, but I think they are 30x10^6 m^3).
I hope these reviews can help you.

I hope that the reviews can help you.
Federico Galetto

Reviewer #2 (Remarks to the Author):

With the accumulation of decades-long geodetic data, it has become possible to investigate the long-term evolutionary behavior of volcanoes. This paper analyzed and inverted 20 years of GPS observations of the Etna volcano. The authors found 59 different deformation phases of the Etna volcano and inverted those with significant ground deformation. The inversion results show differences in the location of inflation and deflation sources. The interesting results of two partially overlapping magmatic reservoirs and the continuous magma supply are found. These results help answer the magma budget and plutonic growth of Mt. Etna.
The authors discussed key magma parameters such as magma chamber volume change and magma compressibility, as well as the contribution of magma accumulation to flank growth through time-series variations in the location of the source. This paper provides an excellent view of the effects of continued magma replenishment and eruption on volcanic growth. However, many issues in this paper must be corrected to make it easier for the reader to understand the authors' contributions.
My main concern is the separation of the deformation time interval. How do you “divide the time-series into piecewise linear segments with no uniform duration”, most of them seems to be 6 month or 8 months, and others are short. Please write the principle of time interval separation, and make a visible figure to show the time Interval. Moreover, the eruptions were also unclear, what is 2002-2003 eruption and what is 2004-2005 eruption? My suggestion is to make a table to show these eruptions.
Comments for figures and table:
Figure 1:
Please add the full descriptions of AMC and ME in Fig.1a, as well as the faults in Fig.1c;
The captions of Fig.1 b and c do not correspond to the figures;
Key GPS stations cited in Fig.2 (e.g., EDAM, ESLN, etc.) are not found in Fig.1, and I suggest that the authors add a list of GPS stations or label important GPS stations;
Please draw the range of Fig.1b in Fig.1c;

The captures of the elements in Fig.1c don't match the actual figure, the city area is only black (no yellow-to-black gradient), and the white diamonds seem to be GPS?
What's the red dot?
Figure 2:
I suggest the authors directly label the meaning of the three lines, Δvi, Δvo, and Δvb, in Fig.2b.
In Fig.2d, label the names of the GPS stations, and label these stations in Fig.1;
What is the meaning of the yellow line in Fig.2b?
Figure 3:
The circles in Fig.3 a and b represent earthquakes, and should be labeled with the magnitude size corresponding to the circle size. If necessary, it should be focused on highlighting earthquakes with larger magnitude.
Add the description of Fig.3c and d. What is the meaning of the purple line?
Table1:
The authors claim to have detected 59 different phases of deformation, so why are only 58 shown in the Table 1;
The authors inverted some of the weak inflation and weak deflation phases in addition to the 26 inflation and 14 deflation phases, and Δv of these 'weak' events was even larger. Please explain in detail the specifics and logic of the processing of GPS data;
Add a column to show the duration of each phase, which could be in days.
There are many hidden results remains to describe. For instance, why the higher ratio (Aspect ratio>0.5) often associated with deflation. Moreover, I suggest the magma ratio (Volume/year) added behind the delta V.
Comments for the paper:
Line 42, 27 instead of 26?
Line 65: The authors emphasized the eruptive cycle paradigm of volcanoes several times in the paper and found that the Etna volcano has a replenishment phase that precedes all eruptions. The authors should have presented this cycle better, e.g., by dividing all the deformation phases into different cycles in Fig.2c.
In addition, whether there is consistency between replenishment and eruption in different cycles is a question worth exploring, and the present results tell us that magma accumulation is close to linear on longer time scales, but the consistency between different cycles seems ambiguous.
Line 80, Please draw the third rift zone.
Line 90, is it Fig. 2b?
Result: It would have made the results more convincing if the authors could have shown all the observations, the inverted model values, and the residuals in an appendix.
Line 127-129: From Fig. 2c, it seems the deflating source is always shallower than the inflating source. Please explain the difference in location between the inflating and deflating sources.
Line 150-158: There seems to be a T55.5 between T55 and T56 (24.12.2018 - 02.02.2019) and seems like an Inflation event, why you missed it? Is the data missing or may affect the discussion?
Line 195-197: Please explain in detail the process of CO_2 exsolved in the volcano.
Line 200: What is the value of "our estimations"?
Line 208-211: According to the conclusion, the contribution of the replenishing magma to the overall vertical deformation of the volcano is limited, contributing mainly to the horizontal movement of the eastern flanks of the volcano. However, with this inference, the authors did not take into account the effect of the horizontal movement of the volcano's eastern flanks in their inversion, which would have significantly biased the estimate of the volcano's supplemental magma volume. Please explain it;
Line 212-213: "EINT" and "EMEG" are not found in Fig.1;

Line 213: What does "dowlift" mean?
Line 255-256: Highlighting these earthquakes in Fig.3 can help the reader understand the importance of the work;
Method: Since not all GPS stations are available from 2001 to 2021, the authors should give details of the availability of GPS stations and describe in detail the basis for judging the different phases. For example, which GPS stations did the authors use to determine significant changes in magma replenishment rates during continuous inflation phases?
Line 320-321: it is suggested that different symbols be used in Fig.1 to mark these unused GPS stations.

Magma budget, plutonic growth and lateral spreading at Mt. Etna

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Abstract

The most effective way to assess volcano hazard is with a robust location and quantitative estimation of the eruptible magma. When the volcanic activity is high and frequent, different episodes and cycles can be captured and used to ~~make inference on~~ magma residence and volcano dynamics. Here we show that gigantic mush of crystallized magma is the common way to grow for stratovolcanoes. Surface ground deformation for 26 inflation and 14 deflation phases at Mt. Etna depicts two partially overlapping magmatic reservoirs located beneath the summit area in the 4-9 km (inflation sources) and in the 3-6 km (deflating sources) depth ranges. In two decades, a continuous magma supply of ca. 10.7 x 10^6 m^3/yr took place. About 28.5% of this magma contributed to the effusive activity, the remaining 71.5% fed the endogenous volumetric growth of the plutonic crystallized mush and promoted the lateral spreading of Mt. Etna. The consistency of this behavior through time poses strong constraints on the eruptible quantity of magma to forecast the activity during a paroxysm.

Introduction

The eruptive cycle paradigm (inflation-eruption-deflation[1]) assumes that the influx of new magma and/or volatile exsolution leads to the pressurization of a magmatic reservoir and the inflation of the volcanic edifice. When the internal pressure exceeds the strength of the reservoir wall, the wall breaks and magma ascends through conduits or dikes toward the surface, feeding the eruption. The subsequent drainage of magma and volatiles from the reservoir releases overpressure, causes the edifice deflation and terminates the eruption. After a repose period of weeks to years, the cycle begins anew. In such a context, long time-series of ground deformation data can capture one or more eruptive cycle, by tracking subsurface fluid (i.e., magma, volatiles, or hydrothermal ~~waters~~) movements within the crust and allowing quantitative constraints on the geometry, size, and depth range of magmatic reservoirs. Valuable examples come from Soufriere Hills[2], Aktun[3,4], Westdahl[4], Makushin[4]. These extensive datasets help also the definition of the spatial and temporal patterns of flank instability, a major hazard affecting active volcanoes as Kilauea (Hawaii, USA), Piton de la Fournaise (Reunion Island), Cumbre Vie (La Palma, Canary Islands), Mt. Etna (Italy), with the triggering of large landslides, tsunamis, and earthquakes.

A step forward is to track magma stagnation and migration during eruptive cycles coupling deformation data with tomographic images of the plumbing system. The location and estimation of stored magma volumes provide constraints on deep recharging processes and on the estimation of the magma budget entering/leaving the system. The gain of consistent budget estimates is crucial to understanding if the replenishment of fresh magma within the stagnation levels occurs continuously or with episodic batches. One of the most desirable aspects is to estimate the volume of magma residing at shallow depth that could be mobilized by episodic supplies or sharp deformation at the volcano.

The exceptionally high volcanic activity continuously monitored by GNSS observations and the detailed definition of the plumbing system by tomography promote Mt. Etna as a paradigmatic example to compute such volumetric estimates. Mt. Etna is one of the most monitored volcanoes in the world with an almost continuous eruptive activity extending from its summit craters and fairly frequent lava flow eruptions to fissures opened up on its flanks (Figure 1). The volcano built up since 500 ka[5] on the Apennine-Maghrebian accretionary wedge (Fig. 1a) at the convergent margin between the Eurasia and Africa plates[6]. Mt. Etna has a central conduit, with five summit craters located westward of the Valle del Bove depression (Fig. 1b). Three rift zones radiate from the summit following the locations and orientations of pyroclastic cones and eruptive fissures (Fig. 1c). Two of them, e.g. the North-East and the South rift zones, defining an overall NE-SE arcuate shape passing through the summit area, have guided the magmatic intrusions and the lateral eruptions in the last 20 years. This arcuate summital rift connects with faults edging a 25 km-wide horseshoe-shaped region (Fig. 1c), i.e. the unstable flank of the volcano[7]. The seaward motion of this sector of the volcano has been documented since the early 1980s[8] and is temporally modulated by vigorous volcanic activity[9].

Results

The EDAM-ESLN baseline time-series yields the detection of significant changes in the volcanic activity of Mt. Etna (Fig. 2a). EDAM and ESLN GNSS stations were quasi-continuously operating throughout the investigated time interval and their relative motion over time is sensitive to magma movement within the volcano plumbing system[10]. This baseline time-series spans the January 2001 - April 2021 time interval, and shows distinctly non-linear motion well evidencing the vivid activity of the volcano during the whole considered time interval. By dividing the time-series into piecewise linear segments with no uniform duration, we detected a total of 58 different ground deformation phases consisting in 28 inflation phases, 21 deflation phases, 5 magmatic intrusions and 4 periods with no significant deformation (Table 1).

Roughly speaking, each intrusion/eruptive phase was preceded by a recharge phase characterized by one or more inflation phases (in case of changes of the inflation rate) and then accompanied by a deflation phase during the lava discharge. Some of the inflation and deflation phases are characterized by weak signals and data fail in constraining elastic models (see Table 1). By excluding these phases as well as those characterized by magmatic intrusions (generally related to fast migration of magma toward the surface in the last 2-3 km) and/or null deformation, we computed elastic deformation models for 26 inflation and 14 deflation phases (see the Methods section). Achieved results for each modeled phase are reported in Table 1, Fig. 2 and Fig. 3.

Discussion

Plumbing system and magmatic reservoirs. In the last decades, petrological and geophysical data provide detailed images of the Mt. Etna plumbing system as a gigantic multi-level system extending down to a depth of ca. 30 km. The deeper part has been inferred through petrological data with two main magmatic environments located respectively at 19-23 km and below 25 km depth[11,12]. These two main magmatic environments coincide with a region of low P-wave velocity anomalies[13]. The shallow (0-9 km) and intermediate depth (10-19 km) portions are dominated by a ~~huge~~ plexus of P-wave high-velocity body located in the central-southern sector of the volcano and extending from 18 km depth to the surface[14-17]. In the shallower part, all geodetically-detected pressure sources are located along the western border of the high-velocity body, defining at least three different levels of magmatic stagnation and storage, at 0-2 km[18-21], 4-6 km[10,18,22-25], 7-9 km[26-28], respectively. Most of these levels well match the ~~ones~~ inferred by petrological studies[11,12,29-31]. In the intermediate part, available petrological data inferred some magmatic environments located in the 10-12 km[29,32-34] and 13-16 km depth interval[11,12,31,35,36]. This last magmatic environment roughly coincides with the magmatic sources related to the long-term uplift of the volcano edifice[37]. The magmatic reservoirs defining the shallower part of the magmatic system have been identified several times in the last 3 decades, while the ones defining the intermediate and deeper portions have been detected/inferred only occasionally.

We define here with unprecedented detail the spatial distribution of deformation sources for the past two decades of activity (Fig. 3a). We observe a clear spatial separation between the inflation and the deflation sources. In particular, the inflating sources are located beneath the north-western sector of the summit area in the 4-9 km depth range, while the deflating sources are located beneath the south-eastern sector of the summit area in the 3-6 km depth range (Fig. 3b). All these sources are located along the north-western edge of the crustal volume defined by the earthquake distribution at shallow depth (0-6 km) beneath the southern and eastern flanks of the volcano (Fig. 3b). Such a crustal volume mainly corresponds to the high-velocity body detected by the P-wave tomographies (Fig. 3c,d) published in the last two decades[14-17]. Therefore, our modeled sources grossly define a northwestern dipping and elongated body where fresh magma likely arises directly from the mantle and interacts with residing magma at shallow depth (Fig. 3b). The sources of deformation well match the volume at the northern edge of the high-velocity crystallized plexus where transient low-velocities indicated the residence of magma during the most recent large eruption episodes[17]. Moreover, the northwestern dipping body well resembles the active reverse structure beneath Mt. Etna[38], suggesting therefore that arising magma is controlled/channeled by inverse faults of the Apennine-Maghrebian accretionary wedge. Some studies have recently proven that magma arising toward the surface is a feasible mechanism also in coeval compressional settings[39-41]. Valuable examples come from Guagua Pichincha, Ecuador[42], Socompa, Chile[43], and Taapaca, Chile[44].

Volume estimation and magma compressibility. Geodetically estimated volumes are commonly considered as the injected volume of a magmatic fluid within the reservoir[45]. For simplicity, we refer to the positive (inflation) and negative (deflation) volume changes as magma input (ΔVi) and magma output (ΔVo), respectively. The former represents the deeply-sourced magma entering into the plumbing system of the volcano, while the latter is the magma leaving the magmatic reservoir because of eruptive onsets at the surface.

Large quantity of magma (Fig. 2b,c) entered into the system during the inflation stages preceding the 2002-2003 lateral eruption (ca. 30.8 x 10^6 m^3, T07 in Table 1) and the lava fountains occurring during the 16 February - 1 April 2021 period (ca. 27.0 x 10^6 m^3, T57 in Table 1). For these stages, the modeled sources are located in the 7-8.5 km depth range, at the bottom of the previously defined shallow part (0-9 km) of the plumbing system (Fig. 2c). Both stages follow two eruptive episodes as the July-August 2001 lateral eruption (T06 in Table 1) and the late December 2018 one (T55 in Table 1) which generated large deformations along the South rift zone and the summit area, leading also to a large scale seaward motion of the eastern flank of the volcano[10,46]. In this contest, the post-eruptive inflations (T07 and T57) can be considered as re-equilibrium episodes related to the drastic drop in pressure along the upper portion of the plumbing system which creates a pressure imbalance with the deeper portions, favoring the ascent of fresh magma from depth. The ΔVi time-series (Fig. 2b) reveals also that during the September 2004 - February 2013 period, moderate quantities of magma (ca. 13-18 x 10^6 m^3 for each inflation stage) entered in the system every 2.8 ± 0.3 years (e.g. T10, T18, T25 and T30; Table 1), suggesting a quasi-cyclic recharge of the lower portion of the shallow plumbing system. Moreover, after a period characterized by inflations with small volume variations (April 2013 - April 2015; e.g. T32, T34, T38 and T42), a magma accumulation resumed since May 2015 at increasing rates (T44, T46, T49, T51, T53, T56 and T57; Table 1) highlighting an impressive pressurization of the shallow plumbing system. Overall, the ΔVi cumulative time-series defines a near continuous magma accumulation in the feeding system at a rate of 10.7 ± 0.3 x 10^6 m^3/yr (Fig. 2b).

By considering the ΔVo time-series (Fig. 2b), the largest negative variation (ca. 15.4 x 10^6 m^3; T05 on Table 1) occurred during the July-August 2001 eruption, while moderate variations have been observed during the 2002-2003 lateral eruption (ca. 8.7 x 10^6 m^3; T09 on Table 1), the 2004-2005 eruption (ca. 8.7 x 10^6 m^3; T11 on Table 1), and during the early 2021 lava fountains sequence (ca. 11.6 x 10^6 m^3; T58 on Table 1). The other deflation phases have been characterized by negative variations generally smaller than 5.0 x 10^6 m^3 (Table 1). Overall, the ΔVo cumulative time-series defines a magma discharge occurring at a rate of 3.3 ± 0.3 x 10^6 m^3/yr (Fig. 2b), evidencing as during the investigated time interval only the 28.5% of the magma entered in the magmatic system has been drainage during the deflation phases. Therefore, this percentage could be considered as a realistic measure of the possible eruptible quantity of magma during each eruptive cycle. By combining the ΔVi and ΔVo quantities over the time, we can estimate the balance (ΔVb) between the magma entering and leaving the storage system. Such a balance is not constant over the time (Fig. 2b) but showed phases of major magma accumulation and drainage. As previously observed, the balance is positive and defines a net magma supply of 7.4 ± 0.3 x 10^6 m^3/yr (Fig. 2b) resulting in a continuous accumulation of magma along the plumbing system of the volcano, and in turn in the volumetric growth of the volcano edifice. This vigorous and continuous magma accumulation well agrees with the marked eruption frequency increase observed at least since 1975[47].

Erupted magma is one of the main volcanic outputs and its volume has been compared with the volume change measured by geodetic measurements on several active volcanoes[48-52]. Observed eruptive volumes are commonly 1-7 times larger than the geodetically modeled ones during volcanic eruptions[50-53-55]. This is also the case of Mt. Etna, where our estimated magma discharge (ca. 3.3 ± 0.3 x 10^6 m^3/yr) is lower than the one estimated by field measurements and satellite observations[56-60]. Roughly speaking, such a general discrepancy is thought to be due to the compressibility of magma, which is largely controlled by the presence of highly compressible exsolving volatile phase[61]. Due to the lack of information on the compressibility and other physical parameters (e.g. density, magma composition, volatile contents in the melt, gas volume fraction, etc.) defining the bulk magma at Mt. Etna, no well constrained relations have been yet derived. However, CO_2 is thought to become exsolved at considerable depth[62], suggesting the presence of a significant amount of volatiles in the magmatic reservoirs at Mt. Etna. Coppola et al. [63] by comparing the volume estimations derived from thermal and SO_2 flux satellite measurements with the geodetically-derived ones found an excellent correlation and inferred a gross ratio of 3.6 between the two estimates for the 2004 - 2007 period. Taking into account this value, our estimations fall within the 25.1 × 10^6 m^3/yr - 64.1 × 10^6 m^3/yr range defined for the 1975-1995[64] and for the 1993-2005[65] periods, respectively. This agreement is largely promising and suggests that more accurate estimations on magma budget can be easily achieved in future by considering long time-series of geodetic and geochemical data, along with other observables as ground SO_2 flux measurements. Rapid and accurate estimations of magma budget on active volcanoes as Mt. Etna are of large interest and impact to the territory management since they can provide useful constraints on possible eruptive events in terms of volcanic risk assessment.

Height variations and lateral spreading. The elastic models predict a general vertical growth of the volcanic edifice, continuous during almost the entire investigated period. The vertical growth is vigorous, despite episodically being interrupted by local-to-volcano-scale subsidence related to the short-term deflation phases. However, the time-series of vertical components of stations located around the summit area (EPLU and EINT; red and blue time-series in Fig. 2d, respectively) and on the upper western flank of the volcano (EMEG; black time-series in Fig. 2d) define a long-term dowlift, despite cyclic (EPLU station) or episodic (EMEG and EINT stations) transients. EPLU and EMEG show a dowlift of ~5 mm/yr and most of the observed vertical motion occurred before the 2002-03 eruption, while EINT exhibits a near continuous dowlift of ~11 mm/yr. EPLU and EINT stations are externally located with respect to the small N-S elongated graben-like structure inferred by Murray et al.[66], therefore their behavior is not (or little) influenced by the strong subsidence measured within the graben (~4 m during the August 1975 - September 2018 period). Moreover, the overall subsiding pattern along with the near continuous magma accumulation beneath the volcano suggest that the volumetric growth of the edifice is dominantly horizontal. The long-term picture of Mt. Etna deformation shows an inhomogeneous pattern with the largest rates measured on the eastern flank of the volcano (Fig. 3a). An increase in the horizontal motion moving away from the volcano summit can be recognized, suggesting a gravitational control on the southeastward spreading of the edifice[9,46]. Such an asymmetric spreading pattern is controlled by the basement topography beneath the volcano and the SE gently dipping shallow interface between rocks and Quaternary sediments[5]. Moreover, the buttressing of the volcano by the Apennines-Maghrebian prevents the spreading toward north and west. In such a context, the steady-state seaward motion of the eastern flank induces a progressive depressurization of the crust beneath the rift areas, encouraging the deep resourcing of magma and its accumulation in the shallower part of the plumbing volcano, contributing therefore to the endogenous growth of the plutonic complex (the high P-wave velocity body) beneath Mt. Etna volcano.

Conclusions

We demonstrate here that volumetric estimates of the magma budget entering and leaving a volcanic system are now possible and give constraints to forecasting volcanic activity during sharp episodes or activity climaxes. We tracked magma movements within the Mt. Etna's plumbing system, revealing a continuous magma supply of ca. 10.7 x 10^6 m^3/yr over a period of almost two decades. The enveloped geometry of the deformation sources suggests that the final rising of magma through the crust is controlled by a NW-dipping interface that we hypothesize being a structure of the compressional belt. About 28.5% of this magma contributed to the decennial effusive activity, providing a valuable constraint on the eruptible quantity of magma during each eruptive cycle. The remaining quantity (ca. 71.5%) is stored within the plumbing system and contributes to the endogenous volumetric growth of the plutonic crystallized mush, and in turn, to the lateral spreading of Mt. Etna.

The huge amount of stocked magma beneath stratovolcanoes opens new questions whether they could be remobilized to feed eruptions by sharp deformation episodes or unrests. Increasingly tight constraints on the volume of magma will also substantially improve our understanding of the magmatic systems, revolutionizing the volcanic hazard assessment. At Mt. Etna, the huge quantity of magma would lead to a substantial increase of volcanic activity both from the summit area as well as from the flanks of the volcano. The occurrence of lateral eruptions dramatically increases the hazard, especially for the potential opening of eruptive fractures on the lower slopes of the volcano[67,68], where almost a million people live. Moreover, the continuous magma accumulation increases the probability of a seaward acceleration of the unstable flank of the volcano, and the occurrence of moderate earthquake at very shallow depth, as already observed during the 2002-03 and 2018 eruptive events[46,69]. On a kyrs time scale, the prolonged accumulation of magma in the shallow crust would potentially lead to catastrophic flank instability episodes, triggering in turn tsunamis which can hit the densely populated coasts surrounding the eastern Mediterranean Sea. A similar episode occurred in the early Holocene, probably related to the collapse of the Valle del Bove[70].

Achieved results can be easily exported and compared with the ones coming from other densely monitored volcanoes as well as used to validate/integrate the available information on most of the other worldwide active volcanoes where the monitoring system is spatially and temporally limited.

Methods

GNSS network and data processing. The setting up of a continuous GNSS network at Etna began in November 2000 reaching a configuration of 13 stations in late summer of 2001 with a daily session of ~8 hours. The network geometry was gradually upgraded over the years in order to cover all the slopes of the volcano edifice and to replace the sites destroyed by natural (lava flows) and human (vandalism) activities or affected by local instability, reaching the current configuration of 33 stations (Fig. 1). The upgrade was coupled also with a general improvement of technologies (e.g. receivers, antennas, real-time data streaming and long-term power supply - typically a combination of batteries and solar panels at remote sites), therefore allowing continuous acquisition on sessions of 24 hours, at least since early 2005. Raw GNSS observations, collected since November 2000, were processed by using the GAMIT/GLOBK software (http://geoweb.mit.edu/gg/) and by adopting the same strategy described in Palano et al.[71]. Achieved results as daily coordinates (i.e., time-series) and velocity fields have been referred to the MERF23 frame[71]. This reference frame allows i) to isolate the Mt. Etna volcanic deformation from the background tectonic pattern and ii) allow a direct combination and comparison between different deformation phases (inflation, deflation, dike intrusion) affecting the volcano edifice over the time.

GNSS time-series analyses and data modeling. As mentioned above, we detected a total of 59 different ground deformation phases consisting in 29 inflation phases, 21 deflation phases, 5 magmatic intrusions and 4 periods with no significant deformation (Table 1). For each detected phase we estimated the ground deformation field in terms of geodetic velocities by combining the daily GAMIT solutions into a consistent set of station positions and velocities, referred to MERF23[71].

Looking at the estimated surface geodetic velocities, some of the inflation and deflation phases are characterized by weak signals and perhaps poorly able to constraint elastic models (see Table 1 and Figures in the supplementary material). By excluding these phases as well as those characterized by magmatic intrusions (generally related to fast migration of magma toward the surface in the last 2-3 km) and/or null deformation, in the following we computed elastic deformation models for 26 inflation and 14 deflation phases.

The surface deformation for each of these phases was used to constrain isotropic half-space elastic inversion models by adopting a uniform approach in order to define all modeled parameters in a robust and unambiguous way over the studied period and to allow a direct comparison between the obtained results. To this aim, the inversions were performed by adopting the following uniform approach:

- to properly model the asymmetric surface ground deformation patterns, as commonly observed at Mt. Etna[10], we adopted the analytical formulation related to a spheroidal pressure source[72]. This source is determined by eight parameters: location (longitude, latitude and depth) of the center of the spheroid, strike and dip of the major semi-axis a, length of the major semi-axis *a*, ratio *b/a* between the minor and major axes, and the pressure change required to produce the observed surface deformation;

- values of 30 GPa and 0.25 were assumed for the shear modulus (μ) and Poisson's ratio in the half-space, respectively;
- since Mt. Etna volcano is characterized by significant topography, the effects of topography have been included in each computation[73];
- both horizontal and vertical GPS components were inverted by taking into account the weights proportional to the estimated geodetic velocity errors;
- to obtain realistic estimations of the pressure change parameter, we limited the ratio of the pressure change to the shear modulus within the elastic limits of the surrounding rock;
- the model parameters optimization was performed by using a genetic algorithms methodology[74], an approach which starting with an initial range of models, progressively modifies the solution by incorporating the evolutionary behavior as the biological systems. The fitness of each solution is measured by a quantitative, objective function, i.e., a measure of the discrepancy (χ^2) between the measurements and the predicted values from the model, defined as: $\chi^2 = \sum_i^N \frac{[(O_i - P_i)]^2}{e_i^2}$, where O_i is measured value, P_i is the predicted value from the model, e_i is the uncertainty associated to each measured value and i= 1, ….N, the total number of measurements;
- all sites located on the lower eastern flank of the volcano have been excluded from the inversion because of their continuous seaward motion[71].

For each modeled phase, the volume change of the ellipsoidal cavity have been estimated by adopting the following empirical formulation: $\Delta V = \frac{3V\Delta P}{4\mu}\left(\frac{A^2}{3} - cA + d\right)$ where *V* is the volume of the ellipsoidal cavity, *ΔP* is the pressure change, *A=b/a* represents the geometric aspect ratio between the semi-major axis *a* and the semi-minor axis *b* of analytical spheroidal pressure source[72]. Constants *c* and *d* have been determined by the polynomial best fit to the numerical solutions spheroidal[75] and have values of 0.7 and 1.37, respectively. The uncertainties of the best fitting parameters were estimated by adopting a Jackknife sampling method[76]. Best fitting parameters for each modeled phase, along with the estimated uncertainties, are reported in Table 1.

Figure Captions

Figure 1. a) Map of southern Italy; b) Sketch map of Mt. Etna volcano showing the GNSS network (red diamonds) and the urbanized areas defined from low (yellow) to high (black) density. c) Zoom of the summit area of Mt. Etna[77]; NEC, North-East Crater; VC, Voragine Crater; BNC, Bocca Nuova Crater; SEC, South-East Crater; NSEC, New South-East Crater.

Figure 2. Time-series of volcanic activity (on the top: eruptive periods as red boxes, inflation and deflation phases as green and black boxes, respectively; inside the panels: shallow intrusions and lava fountaining episodes as blue and gray vertical lines, respectively) and geophysical data and results. a) EDAM-ESLN baseline (see Figure 1 for stations location). b) Time-series of estimated ΔVi, ΔVo and ΔVb. Estimated average rates are also reported. c) Depth variations of the inflation (red) and deflation (blue) modeled sources. These last are sized accordingly to the estimated volume. d) height variations of EPLU (red), EINT (black) and EMEG (blue) stations.

Figure 3. a) Seismicity (M>1) occurred ~~in the~~ January 2000 - April 2021 ~~period~~; ~~the~~ modeled sources (sized according to the estimated volume and colored in red and blue for inflation and deflation phases, respectively; Table 1) are also reported. The gray arrows represent the long-term (2004.42 - 2018.95) GNSS horizontal velocity field with 95% confidence ellipses[71]. ~~b~~) vertical A-A' ~~section~~ through the DVp and DVp/Vs time-lapse model[17]. Note that the volume of transient low Vp corresponds to the deformation modeled sources defining the magma interested during inflations and deflations. The sources correspond to an area of loss of resolution of the Vp/Vs model, because S-waves are strongly attenuated during their travel within the magma filled volume.

Table 1. Parameters of modelled sources.

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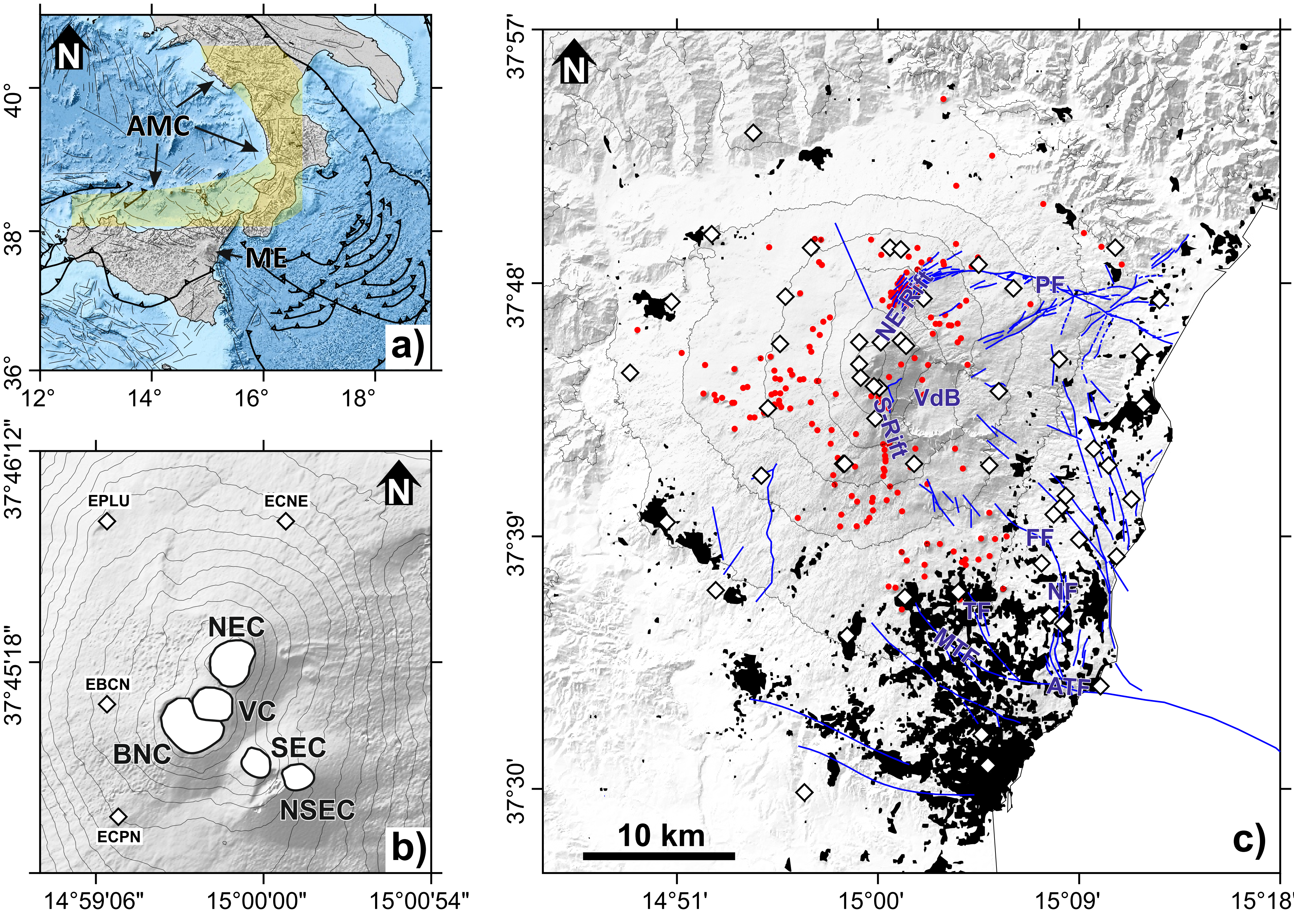
N
AMC
ME
a)
40°
38°
36°
12°
14°
16°
18°
37°46'12"
37°45'18"
EPLU
ECNE
EBCN
ECPN
NEC
VC
BNC
SEC
NSEC
b)
14°59'06"
15°00'00"
15°00'54"
37°57'
37°48'
37°39'
37°30'
NE-Rift
S-Rift
VdB
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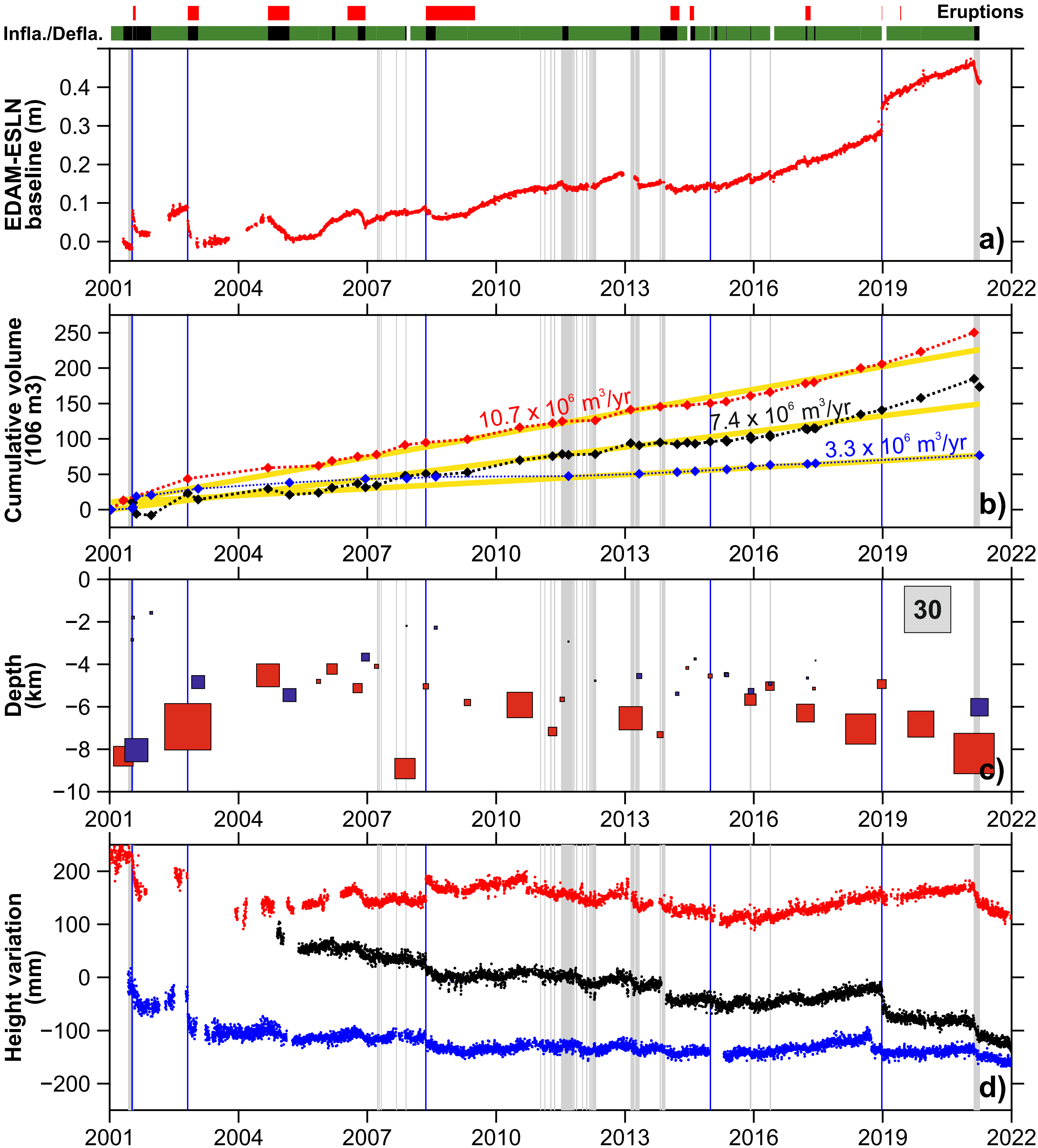
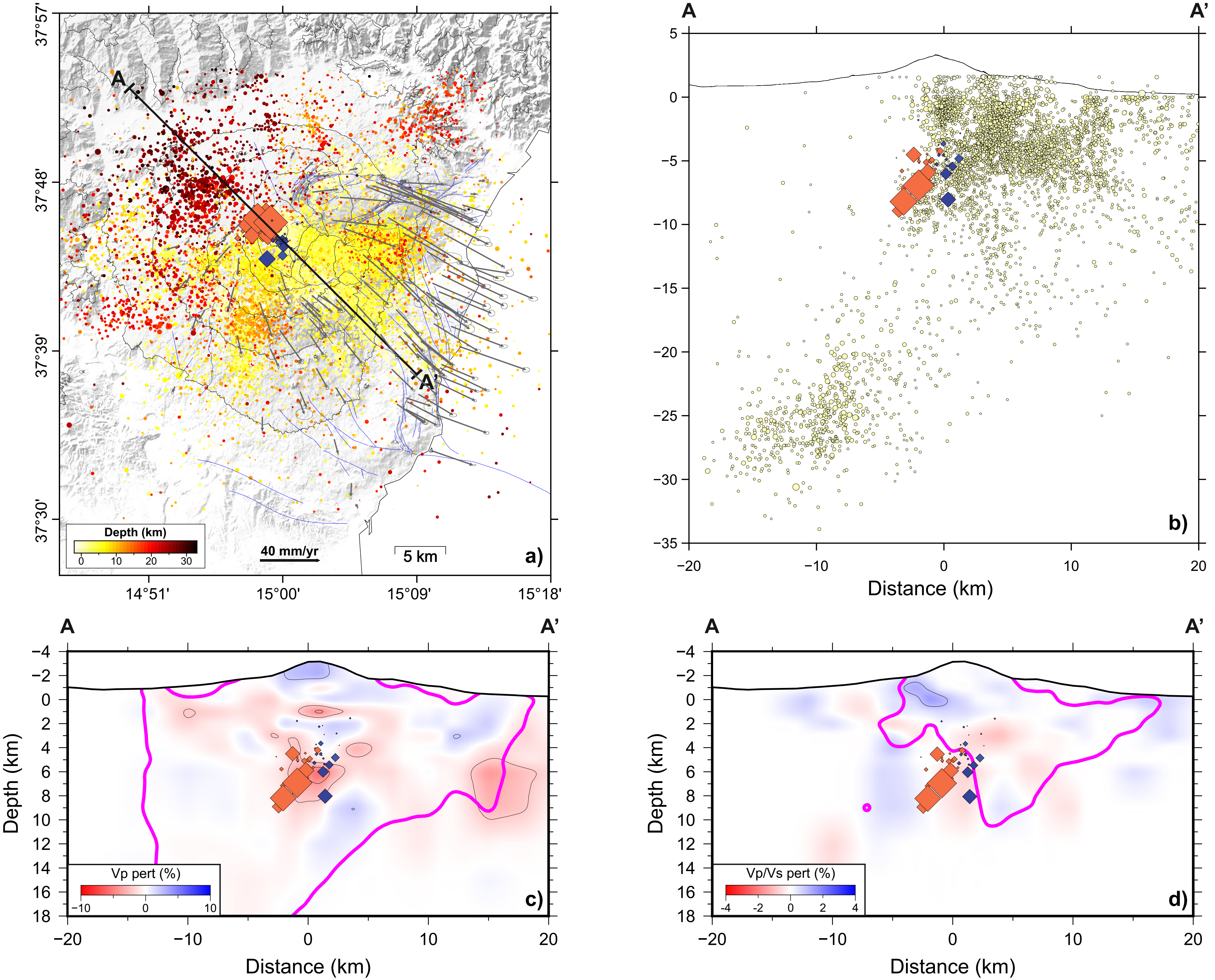
c)
14°51'
15°00'
15°09'
15°18'



Eruptions
Infla./Defla.
EDAM-ESLN baseline (m)
a)
Cumulative volume (106 m3)
10.7 x 10^6 m^3/yr
7.4 x 10^6 m^3/yr
3.3 x 10^6 m^3/yr
b)
Depth (km)
30
c)
Height variation (mm)
d)



37°57'
37°48'
37°39'
37°30'
14°51'
15°00'
15°09'
15°18'
A
A'
Depth (km)
0 10 20 30
40 mm/yr
5 km
a)
b)
Distance (km)
Depth (km)
Vp pert (%)
−10 0 10
c)
Vp/Vs pert (%)
-4 -2 0 2 4
d)

Id	Time Interval	Notes	East (m)	North (m)	Depth (m)	Pressure (10^8 Pa)	Long axis (m)	Aspect ratio	Strike (°)	Plunge (°)	ΔV ($m^3 \cdot 10^6$)
T01	12.01.2001 - 26.04.2001	Inflation	498327 ± 341	4181155 ± 284	-8329 ± 407	4.31 ± 0.41	1649 ± 84	0.23 ± 0.01	56 ± 18	124 ± 9	13.11 ± 5.34
T02	26.04.2001 - 12.07.2001	Deflation	500937 ± 311	4177318 ± 215	-2843 ± 314	-2.40 ± 0.09	764 ± 66	0.35 ± 0.01	47 ± 9	30 ± 5	-1.60 ± 0.62
T03	12.07.2001 - 13.07.2001	Dyke intrusion	----	----	----	----	----	----	----	----	----
T04	13.07.2001 - 18.07.2001	Deflation	499016 ± 364	4180040 ± 111	-1800 ± 581	-1.74 ± 0.39	912 ± 43	0.35 ± 0.01	29 ± 9	69 ± 3	-1.97 ± 0.90
T05	18.07.2001 - 15.08.2001	Deflation	498512 ± 313	4176242 ± 237	-8037 ± 671	-4.14 ± 0.32	1228 ± 60	0.41 ± 0.01	83 ± 5	10 ± 2	-15.36 ± 5.49
T06	15.08.2001 - 20.12.2001	weak deflation	501196 ± 293	4175984 ± 183	-1572 ± 472	-1.88 ± 0.32	807 ± 50	0.40 ± 0.01	122 ± 12	148 ± 10	-1.90 ± 0.80
T07	20.12.2001 - 26.10.2002	Inflation	498864 ± 218	4179855 ± 301	-6940 ± 482	3.86 ± 0.29	1719 ± 72	0.36 ± 0.01	198 ± 8	60 ± 5	30.83 ± 10.69
T08	26.10.2002 - 27.10.2002	Dyke intrusion	----	----	----	----	----	----	----	----	----
T09	27.10.2002 - 23.01.2003	Deflation	500052 ± 161	4176584 ± 474	-4837 ± 256	-3.09 ± 0.36	1279 ± 78	0.33 ± 0.01	180 ± 11	50 ± 3	-8.66 ± 4.01
T10	23.01.2003 - 07.09.2004	Inflation	497046 ± 78	4178586 ± 154	-4517 ± 183	2.86 ± 0.41	1528 ± 83	0.35 ± 0.01	37 ± 10	115 ± 3	15.25 ± 7.63
T11	07.09.2004 - 10.03.2005	Deflation	500147 ± 129	4177396 ± 249	-5450 ± 495	-3.52 ± 0.33	817 ± 46	0.64 ± 0.01	58 ± 4	29 ± 2	-8.72 ± 2.62
T12	10.03.2005 - 12.11.2005	weak inflation	497404 ± 59	4178427 ± 341	-4804 ± 514	3.00 ± 0.26	821 ± 66	0.38 ± 0.01	45 ± 6	120 ± 7	2.84 ± 1.10
T13	12.11.2005 - 06.03.2006	Inflation	499484 ± 196	4178087 ± 144	-4223 ± 396	2.96 ± 0.32	1125 ± 55	0.37 ± 0.01	88 ± 5	111 ± 1	6.97 ± 2.23
T14	06.03.2006 - 04.04.2006	weak deflation	----	----	----	----	----	----	----	----	----
T15	04.04.2006 - 10.10.2006	Inflation	498101 ± 298	4178271 ± 346	-5118 ± 316	3.23 ± 0.21	1333 ± 62	0.25 ± 0.01	35 ± 4	123 ± 2	6.09 ± 3.06
T16	10.10.2006 - 16.12.2006	Deflation	499609 ± 247	4177853 ± 209	-3663 ± 238	-2.66 ± 0.18	1012 ± 72	0.40 ± 0.01	140 ± 14	77 ± 3	-5.26 ± 2.24
T17	16.12.2006 - 20.03.2007	Inflation	499123 ± 323	4178001 ± 139	-4090 ± 351	2.75 ± 0.38	936 ± 59	0.32 ± 0.01	51 ± 16	105 ± 1	2.85 ± 1.23
T18	20.03.2007 - 16.11.2007	Inflation	496405 ± 264	4179595 ± 247	-8907 ± 235	4.86 ± 0.30	1699 ± 67	0.21 ± 0.01	96 ± 14	97 ± 1	13.60 ± 4.65
T19	16.11.2007 - 01.12.2007	Deflation	499475 ± 322	4177503 ± 229	-2186 ± 178	-1.97 ± 0.19	551 ± 40	0.48 ± 0.01	178 ± 9	49 ± 7	-0.88 ± 0.33
T20	01.12.2007 - 01.01.2008	no deformation	----	----	----	----	----	----	----	----	----
T21	01.01.2008 - 12.05.2008	Inflation	497729 ± 395	4178692 ± 243	-5041 ± 486	3.12 ± 0.26	1072 ± 53	0.27 ± 0.01	74 ± 9	110 ± 7	3.54 ± 1.79
T22	12.05.2008 - 13.05.2008	Dyke intrusion	----	----	----	----	----	----	----	----	----
T23	13.05.2008 - 05.08.2008	Deflation	500275 ± 111	4178698 ± 145	-2276 ± 174	-2.01 ± 0.19	553 ± 59	0.77 ± 0.02	71 ± 8	90 ± 10	-2.16 ± 1.13
T24	05.08.2008 - 30.04.2009	weak inflation	496141 ± 209	4178997 ± 250	-5799 ± 580	3.55 ± 0.32	1213 ± 81	0.23 ± 0.02	45 ± 8	113 ± 2	4.31 ± 3.03
T25	30.04.2009 - 20.07.2010	Inflation	498590 ± 296	4178585 ± 205	-5910 ± 271	3.61 ± 0.33	2226 ± 73	0.18 ± 0.01	65 ± 6	108 ± 2	16.93 ± 7.22
T26	20.07.2010 - 24.04.2011	weak inflation	495618 ± 266	4178297 ± 127	-7161 ± 437	3.97 ± 0.23	1359 ± 68	0.21 ± 0.01	32 ± 7	102 ± 1	5.70 ± 1.90
T27	24.04.2011 - 16.07.2011	Inflation	499369 ± 98	4178489 ± 185	-5652 ± 242	3.56 ± 0.18	1296 ± 81	0.17 ± 0.01	198 ± 3	15 ± 2	2.96 ± 1.65
T28	16.07.2011 - 08.09.2011	Deflation	499633 ± 181	4177472 ± 163	-2933 ± 316	-2.33 ± 0.22	910 ± 72	0.19 ± 0.01	196 ± 6	172 ± 4	-0.83 ± 0.39
T29	08.09.2011 - 21.04.2012	weak inflation	496341 ± 383	4179795 ± 220	-4770 ± 409	3.05 ± 0.13	918 ± 84	0.18 ± 0.01	59 ± 20	96 ± 3	1.00 ± 0.65
T30	21.04.2012 - 18.02.2013	Inflation	498873 ± 311	4179360 ± 195	-6540 ± 227	3.81 ± 0.47	1643 ± 94	0.27 ± 0.01	49 ± 5	106 ± 1	15.53 ± 6.04
T31	18.02.2013 - 30.04.2013	Deflation	499569 ± 149	4178308 ± 133	-4549 ± 351	-3.26 ± 0.32	885 ± 47	0.35 ± 0.01	16 ± 1	181 ± 2	-3.37 ± 1.13
T32	30.04.2013 - 25.10.2013	weak inflation	498210 ± 150	4179790 ± 255	-7313 ± 481	3.98 ± 0.30	1115 ± 87	0.24 ± 0.01	201 ± 3	36 ± 7	4.06 ± 1.73
T33	25.10.2013 - 20.03.2014	Deflation	500432 ± 381	4178256 ± 227	-5384 ± 420	-3.56 ± 0.35	715 ± 71	0.38 ± 0.01	74 ± 4	43 ± 3	-2.26 ± 1.06
T34	20.03.2014 - 14.06.2014	Inflation	499379 ± 104	4177980 ± 107	-4166 ± 218	2.76 ± 0.30	572 ± 30	0.59 ± 0.01	80 ± 12	124 ± 11	2.01 ± 0.62
T35	14.06.2014 - 20.06.2014	no deformation	----	----	----	----	----	----	----	----	----
T36	20.06.2014 - 11.07.2014	no deformation	----	----	----	----	----	----	----	----	----
T37	11.07.2014 - 20.08.2014	Deflation	499393 ± 154	4178182 ± 229	-3748 ± 520	-2.65 ± 0.35	581 ± 67	0.48 ± 0.01	69 ± 4	32 ± 13	-1.38 ± 0.78
T38	20.08.2014 - 25.12.2014	Inflation	499711 ± 184	4178005 ± 291	-4554 ± 362	3.09 ± 0.47	1195 ± 75	0.20 ± 0.01	29 ± 11	106 ± 2	2.75 ± 1.44
T39	27.12.2014 - 29.12.2014	Dyke intrusion	----	----	----	----	----	----	----	----	----

T40	29.12.2014 - 30.01.2015	weak inflation	----	----	----	----	----	----	----	----	----
T41	30.01.2015 - 24.02.2015	weak deflation	----	----	----	----	----	----	----	----	----
T42	24.02.2015 - 10.05.2015	Inflation	498812 ± 231	4178875 ± 398	-4479 ± 494	2.86 ± 0.23	1312 ± 56	0.17 ± 0.01	237 ± 3	64 ± 3	2.55 ± 1.00
T43	10.05.2015 - 16.05.2015	Deflation	501501 ± 161	4179692 ± 171	-4499 ± 379	-2.77 ± 0.28	1306 ± 40	0.18 ± 0.01	220 ± 10	110 ± 3	-2.63 ± 1.02
T44	16.05.2015 - 02.12.2015	Inflation	498829 ± 122	4178627 ± 178	-5661 ± 360	3.52 ± 0.32	1279 ± 68	0.29 ± 0.01	216 ± 5	72 ± 1	7.71 ± 2.65
T45	02.12.2015 - 09.12.2015	Deflation	499099 ± 193	4178083 ± 236	-5273 ± 230	-3.23 ± 0.28	619 ± 29	0.68 ± 0.01	1 ± 18	86 ± 5	-3.91 ± 1.06
T46	09.12.2015 - 17.05.2016	Inflation	498915 ± 113	4178595 ± 176	-5029 ± 393	3.15 ± 0.33	1503 ± 88	0.20 ± 0.01	223 ± 2	65 ± 4	5.63 ± 2.34
T47	17.05.2016 - 19.05.2016	Deflation	499903 ± 253	4177832 ± 341	-4910 ± 414	-3.08 ± 0.37	824 ± 47	0.33 ± 0.01	184 ± 14	68 ± 6	-2.35 ± 0.88
T48	19.05.2016 - 22.06.2016	no deformation	----	----	----	----	----	----	----	----	----
T49	22.06.2016 - 14.03.2017	Inflation	498518 ± 187	4178975 ± 168	-6298 ± 350	3.70 ± 0.30	1594 ± 77	0.25 ± 0.01	211 ± 11	79 ± 1	11.84 ± 3.97
T50	14.03.2017 - 01.04.2017	Deflation	500111 ± 456	4178250 ± 516	-4640 ± 434	-3.24 ± 0.24	438 ± 43	0.68 ± 0.01	227 ± 3	0 ± 5	-1.38 ± 0.57
T51	01.04.2017 - 26.05.2017	Inflation	498092 ± 285	4178919 ± 128	-5147 ± 312	3.06 ± 0.17	939 ± 131	0.25 ± 0.02	237 ± 12	34 ± 7	2.01 ± 1.76
T52	26.05.2017 - 09.06.2017	Deflation	501122 ± 195	4177068 ± 264	-3820 ± 304	-2.71 ± 0.22	674 ± 98	0.26 ± 0.02	179 ± 6	120 ± 7	-0.71 ± 0.57
T53	09.06.2017 - 28.06.2018	Inflation	498934 ± 234	4179257 ± 288	-7048 ± 195	3.97 ± 0.20	2067 ± 121	0.21 ± 0.01	219 ± 11	79 ± 9	20.01 ± 9.29
T54	28.06.2018 - 23.12.2018	Inflation	499592 ± 279	4178981 ± 247	-4935 ± 326	3.08 ± 0.18	1647 ± 79	0.18 ± 0.01	11 ± 8	104 ± 5	5.84 ± 2.81
T55	24.12.2018 - 24.12.2018	Dyke intrusion	----	----	----	----	----	----	----	----	----
T56	02.02.2019 - 21.11.2019	Inflation	498312 ± 115	4179406 ± 221	-6810 ± 371	4.01 ± 0.32	1717 ± 85	0.26 ± 0.01	30 ± 8	121 ± 10	17.38 ± 7.30
T57	21.11.2019 - 15.02.2021	Inflation	497531 ± 215	4180136 ± 196	-8200 ± 190	4.21 ± 0.28	1956 ± 55	0.26 ± 0.01	48 ± 7	109 ± 10	26.96 ± 9.25
T58	15.02.2021 - 02.04.2021	Deflation	499963 ± 123	4177878 ± 186	-6016 ± 478	-3.60 ± 0.21	1287 ± 63	0.35 ± 0.02	40 ± 11	15 ± 14	-11.60 ± 5.68

We thank both reviewers for their useful and constructive comments which greatly improved the quality of this manuscript. We carefully addressed them in the revised version of the manuscript. In agreement with their suggestions we provided also a supplementary file showing for each of the modelled phases the observed and the expected ground deformation patterns.

Reviewer#1 (Federico Galetto)

This manuscript is a very comprehensive analysis of all deformations occurred at Mt. Etna in the last 20 years. It is not common to see so long time series of deformation and the associated modelling results in one paper and I appreciated the fact that the Authors not only show their modelling results, but they also tried to discuss the geological implications of their results. I think that this paper is appropriate for Communications Earth & Environment, since I see a potential high impact of their results, and I support its publication. However, before that manuscript can be accepted, I think that some moderate changes have to be made, since I think that the Authors could valorize their results better, expanding their discussion. In addition, there are some points that seem incorrect in the way they are written and that therefore have to be corrected (but the Authors can easily make these changes). Below I report my detailed reviews. I also attached an annotated version of the manuscript with further changes and comments.

Main points:

In the abstract and in the discussion section you wrote that "About 28.5% of this magma contributed to the effusive activity, the remaining 71.5% fed the endogenous volumetric growth of the plutonic crystallized mush and promoted the lateral spreading of Mt. Etna." This sentence, written in this way, seems not correct since the ΔVi you estimated (10.7 x 10^6 m^3/yr) are lower than the eruptive rates at Etna (~25x10^6 m^3/year; Bonaccorso and Calvari, 2013). This result is consistent with what has been observed in many other volcanoes of the World, where similar differences between the pre-eruptive new volume of magma accumulated in the reservoir, estimated from the inversion of deformation with elastic models, and the erupted volume have been observed. These differences can be ascribed by many complications that usually are not considered in the modelling (e.g. compressibility). The 28.5% represents the difference between the ΔVi and the ΔVo you estimated with elastic models and not the difference between the ΔVi and the erupted volume (if you wrote "about 28.5% of this magma contributed to the effusive activity" it seems that only the 28.5% of ΔVi has been erupted, but the true erupted volume is about the double that your ΔVi). You should change this sentence in the abstract, as well as similar sentences in the discussion, to better explain what you have done and what the data from your analysis means.

> **Reply: we rearranged the sentence clarifying that it refers to the geodetically estimated volumes. Along the manuscript we clarify that these estimations must be considered as minimum estimations (see lines 193-195 and 416-417). Moreover, we improved the comparison with other independent estimations (Bonaccorso and Calvari, 2013; Calvari et al., 2020) in the discussion section.**

Volume estimation and magma compressibility: This section represents the most important part of your manuscript. I think it should be expanded and rewrote to address the following points: 1) I think would be important to add and/or expand the discussion about the comparison between your results (ΔVi and ΔVo) and the erupted volumes. Mt. Etna is known to be usually characterized by regular eruptive rates (~25x10^6 m3/year; Bonaccorso and Calvari, 2013; Calvari et al., 2020). Every time that Etna erupts less magma than that expected from its average eruptive rates, it is supposed that the volcano is accumulating magma (Bonaccorso and Calvari, 2013; Calvari et al.,

2020) and your results agree well with this. For example, from 2016 to 2020 Etna erupted much less magma than that expected (Calvari et al., 2020) and you found and important increase in the modelled ΔVi, providing a proof that effectively the volcano was in a phase of strong accumulation of magma. You should better highlight this in your discussion, as well as you should expand this discussion also at the other periods you analysed (e.g. lines 161-164, where the "quasi-cyclic recharge" is supported also by the regular eruptive rates occurred in that time span). 2) You are using elastic models and therefore ΔVi and ΔVo are minimum estimations (would be equal to the true ΔVi and ΔVo only if the system is incompressible). For example, the difference between the ΔVo (3.3 ± 0.3 x 10^6 m3/yr) with the eruptive rates (~25x10^6 m3/year; Calvari et al., 2020) can be explained by the compressibility of the reservoir. Since the compressibility of the system is unknown and can change over the time (especially during an eruption), the comparison of the ΔVi with the ΔVo might be not necessarily correct (not sure that the sentence at line 176 is correct). I think you should better explain somewhere how your modelling results (ΔVi and ΔVo) could be affected by the compressibility (and other parameters).

Bonaccorso, A., & Calvari, S. (2013). Major effusive eruptions and recent lava fountains: Balance between expected and erupted magma volumes at Etna volcano. Geophysical Research Letters, 40(23), 6069-6073. https://doi.org/10.1002/2013GL058291

Calvari, S., Bilotta, G., Bonaccorso, A., Caltabiano, T., Cappello, A., Corradino, C., et al. (2020). The VEI 2 Christmas 2018 Etna eruption: A small but intense eruptive event or the starting phase of a larger one? Remote Sensing, 12(6), 905. https://doi.org/10.3390/rs12060905

Reply: we rearranged the section following the reviewer's suggestions. We explained that such a discrepancy has been observed at other active volcanoes and is related to the compressibility of the system (lines 238-245). We improved the discussion about our results and the ones reported in literature. See lines 252-263 in the revised manuscript.

In the abstract you wrote that there are "two partially overlapping reservoirs located beneath the summit area in the 4-9 km (inflation sources) and in the 3-6 km (deflating sources) depth ranges". I think you arrive to this conclusion because the inflating and the deflating sources are located in different places. However, the discussion section lacks a discussion about it. I think this is one of your main results, since it is surprisingly that all inflation sources are placed NW with respect to all deflating sources, and this should be properly shown and discussed both in the result section (you do not mention this result in the result section) and in the discussion section. Here you should try to explain why you get this result and how you interpret it (e.g. by writing something like: the different location of the inflating and deflating sources might suggest the existence of two different reservoirs …). Instead of limiting to speak about two magma reservoirs, I think it is better to talk about the existence of a complex magmatic system that can have multiple reservoirs (e.g., Sparks et al., 2019; Edmonds et al., 2019), which can respond in different ways during the different inflation/deflation events. You can also try to check if there might be a geological explanation of why your deflating sources are placed SE respect to the inflating sources (e.g., any evidence that it is easier to drain magma from that part? Is this area further from the eruptive vents and therefore the subsidence in that area is not masked by the deformation of the propagating dikes?).

Sparks, R. S. J., Annen, C., Blundy, J. D., Cashman, K. V., Rust, A. C., & Jackson, M. D. (2019). Formation and dynamics of magma reservoirs. Philosophical Transactions of the Royal Society A, 377. https://doi.org/10.1098/rsta.2018.0019

Edmonds, M., Cashman, K. V., Holness, M., & Jackson, M. (2019). Architecture and dynamics of magma reservoirs. https://doi.org/10.1098/rsta.2018.0298

Reply: We improved the discussion about the spatial separation between the inflation and the deflation sources and provided a plausible explanation behind it. We explained that the continuous south-eastward motion of the unstable flank presumably led to a decrease in the confining pressure and an increase in host-rock porosity beneath the summit area and along the S-Rift and NE-Rift. This mechanism would enable the formation of new pathways/reservoirs in the very shallow crust, providing also a plausible explanation for the south-eastward migration of shallow deflation sources. We added also some general concepts on complex magmatic systems as the one depicted at Mt. Etna by quoting the suggested papers in the discussion section. See lines 180-186.

Minor reviews:

Abstract: I do not think that the estimation of the "location and quantitative estimation of the eruptible magma" is the most effective way to assess volcanic hazard. I think it is better to rewrite the first sentence (something like: "The location and the quantitative estimation of the eruptible magma provide an important tool to assess the volcanic hazard").

Reply: We modified the sentence accordingly.

Line 60-61: I think that other valuable examples of cycles of inflation-eruption-deflation, whose deformation has been measured and modelled, are: Krafla (e.g. Ewart et al., 1991); Axial Seamounts (Nooner and Chadwick, 2016); Sierra Negra and Fernandina (Gregg et al., 2018, 2022; Bagnardi and Amelung, 2012; Galetto et al., 2023); Piton de la Fournaise (Peltier et al., 2008). All these volcanoes are basaltic (like Etna) and their volcanic activity is similar to that of Etna, so I think it would be a good idea to quote at least some of them.

Ewart, J. A., Voight, B., & Björnsson, A. (1991). Elastic deformation models of Krafla Volcano, Iceland, for the decade 1975 through 1985. Bulletin of Volcanology, 53, 436-459.

Nooner, S. L., & Chadwick Jr, W. W. (2016). Inflation-predictable behavior and co-eruption deformation at Axial Seamount. Science, 354(6318), 1399-1403.

Gregg, P. M., Le Mével, H., Zhan, Y., Dufek, J., Geist, D., & Chadwick Jr, W. W. (2018). Stress triggering of the 2005 eruption of Sierra Negra Volcano, Galápagos. Geophysical Research Letters, 45(24), 13-288.

Gregg, P. M., Zhan, Y., Amelung, F., Geist, D., Mothes, P., Koric, S., & Yunjun, Z. (2022). Forecasting mechanical failure and the 26 June 2018 eruption of Sierra Negra volcano, Galápagos, Ecuador. Science advances, 8(22), eabm4261.

Bagnardi, M., & Amelung, F. (2012). Space-geodetic evidence for multiple magma reservoirs and subvolcanic lateral intrusions at Fernandina Volcano, Galápagos Islands. Journal of Geophysical Research: Solid Earth, 117(B10).

Galetto, F., Reale, D., Sansosti, E., & Acocella, V. (2023). Implications for shallow magma transfer during the 2017 and 2018 eruptions at Fernandina (Galápagos) inferred from InSAR data. Journal of Geophysical Research: Solid Earth, 128, e2022JB026174.

Peltier, A., Famin, V., Bachèlery, P., Cayol, V., Fukushima, Y., & Staudacher, T. (2008). Cyclic magma storages and transfers at Piton de La Fournaise volcano (La Réunion hotspot) inferred from deformation and geochemical data. Earth and Planetary Science Letters, 270(3-4), 180-188.

Reply: We added some of the suggested papers.

Lines 78-79: If you have space, here you might specify the geodynamic setting better, since it is the reason of why Mt. Etna is one of the most active volcanoes of the world. You could quickly mention that it is placed nearby the Malta escarpment, which is a fault system separating the thinner Ionian oceanic lithosphere to the thicker continental crust of the African foreland, and that this fault system creates an asthenospheric window promoting a mantle upwelling below Etna (Gvirtzman and Nur, 1999).

Reply: We slightly expanded the geodynamic setting by mentioning the debate about the origin of Etna. See lines 79-85.

Lines 89-90: You have to explain what it is the EDAM-ESLN baseline. You should not assume that all the reader are familiar with the Etna ground monitoring system. It would be a good idea to show the EDAM-ESLN baseline on Figure 1.

Reply: We added some generic sentences about the use of baseline time-series to detect magma motion along the plumbing system of active volcanoes. These sentences, along with the remaining text should provide a clear picture about the significance of the EDAM-ESLN baseline. The baseline has been reported in Figure 1. See lines 96-101 and 342-353 of the revised manuscript.

Line 91: "throughout the investigated time interval". Before this sentence, you have never defined what time interval you investigated. Please specify.

Reply: Done.

Lines 94-95: "By dividing the time-series into piecewise linear segments with no uniform duration". You have to specify how you divided the segments (I guess every time that the deformation changed from uplift to subsidence). This is poorly defined also in the Method section. So, you should better define how you divided the time-series in at least one of the two sections. If you specify it in the methods, remember to recall the method section at the end of the sentence reported at lines 94-95, by writing "…By dividing the time-series into piecewise linear segments with no uniform duration (see Methods)".

Reply: Added some few sentence to better explain the adopted approach. See lines 342-353 of the revised manuscript.

Lines 95: here you wrote you "detected a total of 58 different ground deformation phases consisting in 28 inflation phases, 21 deflation phases, 5 magmatic intrusions and 4 periods with no significant deformation", while in the Methods you report "59 different ground deformation phases consisting in 29 inflation phases, 21 deflation phases, 5 magmatic intrusions and 4 periods with no significant deformation". Please be consistent. One of them is reported erroneously.

Reply: The correct number of detected ground deformation phases is 57. We corrected the mistake in the revised version of the manuscript.

Results section: At the end of the Results section, you quote the figures where you show your results, but you do not describe any of your results. Even though the Figures are very good, you should dedicate few lines to describe what your figures show. For example, you can briefly summarize your results about the depth of your sources and their location (the fact that the subsidence sources seem shifted with respect to the inflating sources).

Reply: We slightly expanded the end of the Results section by briefly described some of the achieved results. See lines 129-139 of the revised manuscript.

Discussion: Is there an explanation of why all your inflating sources are plated at NW and all your deflating sources are placed at SE respect to the crater? I am not wonder by the fact that the modelled sources are placed in slightly different locations, since it is normal that when you run the inversion, solutions converge for slightly different locations. For example, in Galápagos volcanoes every time that you model the deformation due to the inflation/deflation of the reservoir, the location (lon-lat) and the geometry of the sources representing the reservoir are always slightly different each other (especially at Fernandina). However, here at Etna your modelling results show that the sources are not randomly oriented as in Galápagos, but you have a trend (all the inflating sources on one side and all the deflating sources on the other side), which should be explained/motivated, since it is a very interesting result.

Reply: We explained that the continuous south-eastward motion of the unstable flank presumably led to a decrease in the confining pressure and an increase in host-rock porosity beneath the summit area and along the S-Rift and NE-Rift. This mechanism would enable the formation of new pathways/reservoirs in the very shallow crust, providing also a plausible explanation for the south-eastward migration of shallow deflation sources. See lines 180-186.

Lines 144-145: if you used elastic models, the estimated volume is a minimum estimation since you consider an incompressible material (for both the host rock and the magma in the reservoir). For the same reason, the volume lost by the deflating sources is a minimum estimation, since you are considering an incompressible medium (host rock and magma in the reservoir). I think it would be better to specify that these estimations are minimum estimates. This is important for the sentence you wrote at lines 147-149.

Reply: Thank you for this useful comment. We added a sentence to clarify this point.

Lines 158-160: To be considered as “re-equilibrium episodes” the volume of new magma added by these two periods of inflation should be similar (or lower) to the volume lost by the two eruptions. You should check if it is true. Otherwise, if the volume added during the inflation is higher than the volume lost by the previous eruption, it means that a certain point the “re-equilibrium phase” ended.

Reply: The term re-equilibrium is inappropriate, therefore we rearranged the sentence.

Lines 212-214: Where EINT and EMEG are placed? On figure 1b, you show only EPLU. Please add the location of EINT and EMEG on Figure 1b or Figure 1c.

Reply: All these stations have been placed in Figure 1b and 1c.

Figure 2. Panel b: on the y axis please do not write 106 m3, but 10^6 m^3. Panel c: in the grey box you have to specify the size (you simply write 30, but I think they are 30x10^6 m^3). I hope these reviews can help you.

Reply: Corrections done.

Reviewer#2 (Anonymous)

With the accumulation of decades-long geodetic data, it has become possible to investigate the long-term evolutionary behavior of volcanoes. This paper analyzed and inverted 20 years of GPS observations of the Etna volcano. The authors found 59 different deformation phases of the Etna volcano and inverted those with significant ground deformation. The inversion results show differences in the location of inflation and deflation sources. The interesting results of two partially overlapping magmatic reservoirs and the continuous magma supply are found. These results help answer the magma budget and plutonic growth of Mt. Etna.

The authors discussed key magma parameters such as magma chamber volume change and magma compressibility, as well as the contribution of magma accumulation to flank growth through time-series variations in the location of the source. This paper provides an excellent view of the effects of continued magma replenishment and eruption on volcanic growth. However, many issues in this paper must be corrected to make it easier for the reader to understand the authors' contributions.
My main concern is the separation of the deformation time interval. How do you "divide the time-series into piecewise linear segments with no uniform duration", most of them seems to be 6 month or 8 months, and others are short. Please write the principle of time interval separation, and make a visible figure to show the time Interval. Moreover, the eruptions were also unclear, what is 2002-2003 eruption and what is 2004-2005 eruption? My suggestion is to make a table to show these eruptions.

> **Reply: We provided a more detailed description on how the different deflation and inflation phases have been defined. See lines of the revised version .... We provided also a supplementary file showing for each of the modelled phases the observed and the expected ground deformation patterns; at the top of each figure the modelled time interval is reported. We provided an additional table for the eruptions.**

Comments for figures and table:

Figure 1: Please add the full descriptions of AMC and ME in Fig.1a, as well as the faults in Fig.1c; The captions of Fig.1 b and c do not correspond to the figures; Key GPS stations cited in Fig.2 (e.g., EDAM, ESLN, etc.) are not found in Fig.1, and I suggest that the authors add a list of GPS stations or label important GPS stations; Please draw the range of Fig.1b in Fig.1c; The captures of the elements in Fig.1c don't match the actual figure, the city area is only black (no yellow-to-black gradient), and the white diamonds seem to be GPS? What's the red dot?

> **Reply: We added some missing elements on Figure and rearranged also the caption.**

Figure 2: I suggest the authors directly label the meaning of the three lines, Δvi, Δvo, and Δvb, in Fig.2b. In Fig.2d, label the names of the GPS stations, and label these stations in Fig.1; What is the meaning of the yellow line in Fig.2b?

> **Reply: We added the requested labels and removed the yellow lines.**

Figure 3: The circles in Fig.3 a and b represent earthquakes, and should be labeled with the magnitude size corresponding to the circle size. If necessary, it should be focused on highlighting earthquakes with larger magnitude. Add the description of Fig.3c and d. What is the meaning of the purple line?

Reply: Done. We also added the meaning of the purple line in the figure caption.

Table1:
The authors claim to have detected 59 different phases of deformation, so why are only 58 shown in the Table 1;

Reply: The correct number of detected ground deformation phases is 57. We corrected the mistake in the revised version of the manuscript.

The authors inverted some of the weak inflation and weak deflation phases in addition to the 26 inflation and 14 deflation phases, and Δv of these 'weak' events was even larger. Please explain in detail the specifics and logic of the processing of GPS data;

Reply: we understand that the term "weak" can be misleading, therefore we removed it. We provided a more detailed description on how the GPS data have been used to define the different deflation and inflation phases.

Add a column to show the duration of each phase, which could be in days. There are many hidden results remains to describe. For instance, why the higher ratio (Aspect ratio>0.5) often associated with deflation. Moreover, I suggest the magma ratio (Volume/year) added behind the delta V.

Reply: We expanded Table 1 by adding the duration of each phase (in days) and the magmatic volume change (Volume/year). Table 1 was moved to the supplementary material as Table S1. We extended the "Results" section by describing the most significant of the hidden results.

Comments for the paper:

Line 42, 27 instead of 26?

Reply: Correction done.

Line 65: The authors emphasized the eruptive cycle paradigm of volcanoes several times in the paper and found that the Etna volcano has a replenishment phase that precedes all eruptions. The authors should have presented this cycle better, e.g., by dividing all the deformation phases into different cycles in Fig.2c. In addition, whether there is consistency between replenishment and eruption in different cycles is a question worth exploring, and the present results tell us that magma accumulation is close to linear on longer time scales, but the consistency between different cycles seems ambiguous.

Reply: By considering the overall recharge/discharging phases during the investigated time-interval, we grossly defined 19 eruptive cycles. We added this information in Table S1. We slightly improved the description of the different cycles.

Line 80, Please draw the third rift zone.

Reply: Done.

Line 90, is it Fig. 2b?

Reply: Correction done.

Result: It would have made the results more convincing if the authors could have shown all the observations, the inverted model values, and the residuals in an appendix.

Reply: We added as supplementary figures, a panel consisting of multiple figures for each modelled phases. In particular, each panel shows the time-series of volcanic activity and baselines used to define the deformative stage (on the top) as well as the observed and modelled ground deformation field (on the bottom). Residual values can be easily deduced by comparing observed and modelled patterns.

Line 127-129: From Fig. 2c, it seems the deflating source is always shallower than the inflating source. Please explain the difference in location between the inflating and deflating sources.

Reply: We highlighted better this difference and suggested a plausible mechanism to explain it. See the revised manuscript at lines 180-186.

Line 150-158: There seems to be a T55.5 between T55 and T56 (24.12.2018 - 02.02.2019) and seems like an Inflation event, why you missed it? Is the data missing or may affect the discussion?

Reply: We thank the editor for pointing out this mistake. We properly corrected it in our table (and consequently in the related figures).

Line 195-197: Please explain in detail the process of CO_2 exsolved in the volcano.

Reply: we added some sentences to explain the process of CO_2 exolution beneath the volcano.

Line 200: What is the value of "our estimations"?

Reply: the sentence has been rearranged

Line 208-211: According to the conclusion, the contribution of the replenishing magma to the overall vertical deformation of the volcano is limited, contributing mainly to the horizontal movement of the eastern flanks of the volcano. However, with this inference, the authors did not take into account the effect of the horizontal movement of the volcano's eastern flanks in their inversion, which would have significantly biased the estimate of the volcano's supplemental magma volume. Please explain it;

Reply: we explained that sites located on the middle-to-upper portion of the unstable flank of the volcano have been included in the inversion: while they provide a better geometry to constrain the parameters of the modelled source, the expected deformation at their location is generally lower than the observed one, resulting in a poor fit of the model. By using these stations, a possible bias of the parameters of the modelled source would be introduced, however by considering the general good fit at the stations located externally from the unstable flank of the volcano (see the Supplementary material), we believe that such a bias can be certainly considered negligible.

Line 212-213: "EINT" and "EMEG" are not found in Fig.1;

Reply. We added the missing stations.

Line 213: What does "dowlift" mean?

Reply. We corrected the mistake. We used the term “subsidence”.

Line 255-256: Highlighting these earthquakes in Fig.3 can help the reader understand the importance of the work;

Reply. These earthquakes have magnitude larger than 4, so we reported them in Figure 3 as colored stars.

Method: Since not all GPS stations are available from 2001 to 2021, the authors should give details of the availability of GPS stations and describe in detail the basis for judging the different phases. For example, which GPS stations did the authors use to determine significant changes in magma replenishment rates during continuous inflation phases?

Reply: We thank the reviewer for this useful point. We improved the description about the use of some baseline data (i.e. the slope distance between two stations) to determine significant changes in magma replenishment rates. The baselines of stations closed to the summit area are generally subject to shortening/lengthening in response to magma movement along the plumbing system. We emphasized that among the available baselines, we considered the EDAM-ESLN one since it shows very few data gaps over the April 2001 - April 2021 period. To properly define some deformative phases on periods no adequately covered by the EDAM-ESLN baseline we considered also two additional baselines as the EDAM-EMGL and EDAM-EMAL ones. See lines 96-101 and 342-353 of the revised manuscript.

Line 320-321: it is suggested that different symbols be used in Fig.1 to mark these unused GPS stations.

Reply: We used different colors to distinguish between the stations used to constrain the elastic models elastic models discussed in this study with respect to the remaining ones.

19th Jan 24

Dear Dr Palano,

Your manuscript titled "Magma budget, plutonic growth and lateral spreading at Mt. Etna" has now been seen by our reviewers, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment under the open access CC BY license (Creative Commons Attribution v4.0 International License).

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewers. At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

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REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

The revised version is significantly improved, and I support the publication of this manuscript. I have only a couple of very minor comments, but the Authors can apport these changes also during the proof correction. In general, I support the publication of this article.

Abstract
Line 47: here the Authors forgot to clarify that the 28.5% is the volume lost estimated from the inversion of geodetic data and not the true erupted volume. Please clarify this concept better.

Introduction
Line 59: “eruptive cycles” (plural)

Line 64-65: add references?

Lines 194-195: change as “…we consider an isotropic elastic half-space medium with a Poisson’s ratio of 0.25”.

Lines 232-266: I found that discussion extremely important. It is well done, but in some volcanoes another possible explanation for the discrepancy between the erupted volumes and geodetic estimated volumes is that during eruptions the shallow reservoirs are fed by new inflow of magma from deep sources that partially (or totally) balancing the magma lost by the shallow reservoir (or the deep magma is directly erupted explaining why the shallow reservoirs lost less magma that that erupted). This explanation is usually put as one of the two possibilities to explain the discrepancies between the geodetic volumes and the erupted volumes (the other possibility is the compressibility of the shallow reservoir that is already well explained by the Authors at lines 232-266). I do not know if for Mt. Etna exist petrological studies that exclude the possibility that part of the erupted magma directly comes from deep reservoirs that do not contribute to the observed deformation, or that the modelled shallow reservoirs could be fed by new magma during eruptions partially explaining why the modelled ΔVo is lower than the ΔVi (and why ΔVi is lower than the erupted magma). If these explanations could be possible for Etna, the Authors could add a couple of lines to the discussion to suggest these other possible explanations that, together with the compressibility, could explain the discrepancies between the geodetic volumes and the true erupted volumes.

Line 307: unrest in English is a singular word (does not exist the word unrests). If you want to use the plural change as “unrest episodes”.

Figure 1 caption: the caption of figure 1b is actually referred to figure 1c and vice versa.

Reviewer #2 (Remarks to the Author):

Etna volcano has been very active in recent years. It is important to understand the magma budget and storage system. The authors have done a good job to answer my comments. I enjoyed reading the revised version and recommend publication.

Reviewer #1:

The revised version is significantly improved, and I support the publication of this manuscript. I have only a couple of very minor comments, but the Authors can apport these changes also during the proof correction. In general, I support the publication of this article.

REPLY: We thank the reviewer for his useful comments.

Line 47: here the Authors forgot to clarify that the 28.5% is the volume lost estimated from the inversion of geodetic data and not the true erupted volume. Please clarify this concept better.

REPLY: we clarify the concept. See the revised version of the manuscript.

Line 59: “eruptive cycles” (plural)

REPLY: Done

Line 64-65: add references?

REPLY: We added a general reference

Lines 194-195: change as “…we consider an isotropic elastic half-space medium with a Poisson’s ratio of 0.25”.

REPLY: Correction done

Lines 232-266: I found that discussion extremely important. It is well done, but in some volcanoes another possible explanation for the discrepancy between the erupted volumes and geodetic estimated volumes is that during eruptions the shallow reservoirs are fed by new inflow of magma from deep sources that partially (or totally) balancing the magma lost by the shallow reservoir (or the deep magma is directly erupted explaining why the shallow reservoirs lost less magma that that erupted). This explanation is usually put as one of the two possibilities to explain the discrepancies between the geodetic volumes and the erupted volumes (the other possibility is the compressibility of the shallow reservoir that is already well explained by the Authors at lines 232-266). I do not know if for Mt. Etna exist petrological studies that exclude the possibility that part of the erupted magma directly comes from deep reservoirs that do not contribute to the observed deformation, or that the modelled shallow reservoirs could be fed by new magma during eruptions partially explaining why the modelled ΔVo is lower than the ΔVi (and why ΔVi is lower than the erupted magma). If these explanations could be possible for Etna, the Authors could add a couple of lines to the discussion to suggest these other possible explanations that, together with the compressibility, could explain the discrepancies between the geodetic volumes and the true erupted volumes.

REPLY: We thank the reviewer for this suggestion. We added some lines in the revised manuscripts. See lines 242-247 lines of the revised manuscript.

Line 307: unrest in English is a singular word (does not exist the word unrests). If you want to use the plural change as “unrest episodes”.

REPLY: Correction done

Figure 1 caption: the caption of figure 1b is actually referred to figure 1c and vice versa.

REPLY: Correction done

Reviewer #2:

Etna volcano has been very active in recent years. It is important to understand the magma budget and storage system. The authors have done a good job to answer my comments. I enjoyed reading the revised version and recommend publication.

REPLY: We thank the reviewer for his useful comments and are happy that him appreciated our work.