

Interactive comment on “The ring-shaped thermal field of Stefanos crater, Nisyros Island: a conceptual model” by M. Pantaleo and T. R. Walter

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RC: This paper is well presented, however it needs to better address the structural controls on Nisyros to determine that it is indeed surface permeability which is affecting the distribution of thermal anomalies. For example a fault is reported to run through Stefanos crater, but little mention is made to this and how it may affect the observations (e.g. see Caliro et al, 2005; Tibaldi et al, 2008).

REPLY: We agree to better address the role and contribution of the structures to determine the pattern of the thermal anomalies. However we disagree with the fact that Caliro et al. (2005) or Tibaldi et al. (2008) recognize a fault in the Stefanos crater. We answer this and other connected comments by adding and rephrasing the sections 5.2 Conceptual model and 5.3.3 Discussion (5.3.3) as follows:

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Section 5.2 - PAGE 2025 line 13 is rephrased: “The thermal anomalies associated with the mud pools and the diffuse heating along the northeastern flank (p and g Fig. 3-5) require, however, an explanation alternative to the pure lithological control. We speculate that both the thermal features can be addressed by a complex volcanotectonic control locally overprinting the soil texture control. Indeed several structural data and CO₂ flux measurements suggest that tectonics exert a strong control on fluid path at Nisyros (Caliro et al., 2005). Whereas there are no direct or indirect observations indicating the presence of faults running through the crater, we speculate that inactive buried structures facilitate the drainage of soil (i.e. fine soil) increasing the permeability and allowing the rising of hot gasses. At larger extent the drainage causes the development of the mud pools, at minor extent causes subtle permeable channels connecting different permeable layers, i.e. the bottom rim anomaly with the anomaly (g) along the flank (Fig. 7). Such fault-driven erosional process is not unexpected on Nisyros. Indeed Caliro et al. (2005) detected, during the unrest, a long linear anomaly of the CO₂ flux in the Lakki plain where later a long fissure opened (Galanopoulos et al., 2005; Lagios et al., 2005; Vougioukalakis and Fytikas 2005) (Fig. 1). Apparently the opening of the fissure in 2001-2002 was not accompanied by vertical or lateral deformations (Vougioukalakis and Fytikas 2005), which exclude active tectonic processes.”

Section 5.3.3 - PAGE 2027 line 16 is added: “At Nisyros caldera the elongation of the crater major axis, the structural data and the CO₂ flux measurements indicate that tectonics exert a strong control on fluid path (Caliro et al., 2005). Fractures are identified crosscutting the southern flank of the Stefanos crater (Caliro et al., 2005), nevertheless these features did not seem to strongly affect the distribution of the CO₂ flux. Indeed the gas flux measured in 1999-2001, during the unrest, appeared almost homogeneously distributed on the crater (Caliro et al., 2005), which may result from the enhanced activity level. We observed that the wider thermal features lie parallel to the fracture direction but we do not recognize a well-defined linear thermal pattern, which actually may be overprinted by the lithological control (cf. 5.2). Nevertheless there are two more clues, i.e. the boiling ponds and the anomaly along the northern flank (p and

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g in fig. 3, 4, 7 respectively), suggesting the existence of fractures in the subsurface and their local influence on the thermal field (cf. 5.2)."

RC: The main mud pools in the centre of Stefanos crater apparently cannot be explained by the permeability model presented and thus alternative controls need to be addressed in more detail. Page 2028 – line 5: Need to expand on faults as an alternative control.

REPLY: We answer this and other connected comments by adding and rephrasing some concepts. See (above) improved sections 5.2 Conceptual model 5.3.3 Discussion (5.3.3).

RC: A word of caution must also be made with regard to linking thermal imagery of April 2010 with the soil samples of January 2013: The thermal activity in Stefanos crater and distribution of sediments varies on a day-to-day basis, and is particularly influenced by rainfall and changes in the local water table. Is the period of study truly representative? Given the difference between the 'flooding in the crater' in January vs none in April – can these data sets be compared? Analysis on just one day would not necessarily be reflective of the activity in Stefanos. How long was the analysis done for? It is not clear if the paper is based on a single day of measurements during each field trip.

REPLY: We comment and clarify how we can justify the use of single day measurements, how the surveys can be compared, despite the time separation, and be considered representative in the sections 3.1 Method and 5.1 Limitation, that were improved as follows:

Section 3.1 - PAGE 2011 line 16 reads: "in April 2010 during a single day at day and night time".

Section 5.1 - PAGE 2021 addition at line 4 reads: "We surveyed the site during a single day in 2010 and for 2 days in 2013, in both cases collecting images at day and night time. During this interval Nisyros Island was quiescent and we decided to test whether

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some long term changes might have occurred at the hydrothermal system. Despite seasonal changes (affecting the air temperature and the water table level) may occur and affect the magnitude and pattern of the thermal anomalies, however Teschner et al. (2007) reported seasonal changes in the order of $\sim 5^{\circ}\text{C}$. This suggests that the changes are negligible for our purpose. Moreover at Nisyros the fumarole temperature outlet does not change on a day-to-day basis (Teschner et al., 2007), at least when the volcano is quiescent. Consequently we consider that the IR data, based on single day recording, are representative of the site and of the activity during the encompassed period. Beside, we observe that the geothermal field appeared (in the IR data) almost identical in 2010 and 2013. Therefore we are confident to relate IR data collected in 2010 with the soil analysis of samples collected in 2013. Indeed, considering the deposition processes, we do not observe geological/geomorphological clues indicating clear changes in sedimentation, nor at fast rate (e.g. recent slumpings) or slow rate (e.g. upward grain-size changes) (Fig. 5). Also nearby the mud pools we do not expect changes in sedimentation because the pits drain the surface runoff rather than acting as springs. Despite the flooding of this area prevents to image the ground, we expect temporary cooling of the water and the soil at the pits because of the mixing of rising hot gasses with large volumes of cold rain water."

RC: The title would benefit from including reference to the permeability side of the study – for example 'a conceptual model linking surface permeability (or soil properties etc) and the spatial distribution of thermal flux'.

REPLY: We agree, and actually it was similar. However we were asked to shorten for editing reasons.

RC: It is not clear over what period the IR measurements were made.

REPLY: We surveyed the site during a single day in 2010 and for 2 days in 2013, in both cases collecting images at day and night time (See improved Section 3.1 and 5.1 given above).

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RC: Activity in Stefanos crater varies day to day and particularly after rainfall - did you make repeat measurements over a few days to ensure a representative dataset or do the data represent just 2 days (April + January)? This needs addressing in Pages 2012-2013.

REPLY: No, we did not repeat the measures and we had not rainy days during the surveys. Thermal variations related to rainfall and seasonal changes were observed by Teschner et al. (2008) consisting in few degrees. Such an effect may influence the detection of transition zones, between the sites hosting the vents and the vent-free sites, but do not modify substantially the main fumarole field (See improved Section 5.1 given above).

RC: PAGE 2013 "it was partially flooded", what is the effect. How could rainfall influence the heat output and sediment recorded at surface?

REPLY: As above, we could not observe directly the effect of rainfall. However previous authors report of minor changes in the fumarole outlet temperature (See improved Section 5.1 given above).

RC: The mud pools frequently overflow and distribute fine sediments and this could influence the soil analysis you did?

REPLY: No, the mud pools are not expected to distribute lots of fine sediments because they drain the surficial runoff and are not behaving as springs (See improved Section 5.1 given above). Very few amount of material can be ejected, nearby the pits, because of the bubbling when the mud is at shallow level.

RC: Can you compare the data of April 2010 and January 2013 given these extra variables?

REPLY: Yes, the thermal data are very similar, except for the impossibility to image the flooded area (See improved Section 5.1 given above).

RC: In particular are the samples collected in January actually representative of ground

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conditions during April? This needs to be addressed. Page 2018 – lines 25-27: The flooded area could make a difference to the sediment sampled and comparison with thermal data for period when it wasn't flooded (e.g. April).

REPLY: Yes, they are. Indeed we do not observe in the field, especially in the sampling pits, any features that may suggest recent changes in the deposition style or rate (See improved Section 5.1 given above).

RC: Page 2019 – line 10-11: If you can attribute cool areas as being from the 'cooling effect of the rain' – how can you verify that your trends are representative of the soil properties, and comparable over different time periods?

REPLY: Previous authors showed minimum seasonal variations in the temperature trend. Moreover we found that the thermal map were very similar despite the site conditions were different during the two surveys. Consequently we are confident that the observed patterns relate to geological conditions and soil properties. (See improved Section 5.1 given above).

RC: Page 2008 - Geological background: It is the African plate that subducts northwards below the Aegean-Anatolian plate, not the Mediterranean plate. It is perhaps better to refer the island as being in the South Aegean Active volcanic arc?

REPLY: Yes. We rephrase, line 20-24 read "Nisyros is a volcanic island in the South Aegean Active volcanic arc related to the northward subduction of the African plate below the Aegean plate. The island is sub-circular in plan-view with a diameter of ~ 7 km and morphologically appears like a truncated cone."

RC: Page 2012: Formula and all components need to be in italics, including T_v , T_b , T_{atm} , T_{obj} .

REPLY: Ok, we modify here and everywhere else.

RC: Page 2025 – line 13: 'the depositional processes, however cannot explain the mud-pools at the center of the crater' – surely this is the one of the most important features

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of Stefanos crater and so needs to be accommodated by the model? An expansion on alternative controls would be beneficial here, rather than simply alternatively attributing these features to 'a complex volcano-tectonic control'. Is such a volcano-tectonic control more influential in Nisyros than the sediment permeability?

REPLY: We explain better how the tectonic control acts to generate the thermal anomalies corresponding to the mud pools. We also clarify that this process is spatially confined to few sites. (See improved Section 5.2 given above).

RC: Page 2026 – line 6: - changes in thermal anomalies between measurements do not necessarily represent permanent changes in the system - just a change between repeated measurements, which further stresses the need to justify comparison of the April and January datasets.

REPLY: Referring to previous authors (Teschner et al., 2008) we can exclude drastic temperature changes due to seasonal cycles. Besides we observed very similar IR results from the two surveys. (See improved Section 5.1 given above). Consequently the lack of thermal anomalies observed several years before, and at short distance from the unrest period, can be considered as permanent.

RC: Page 2007-line 25: dubitably - perhaps use 'alternatively' instead.

REPLY: Accepted and changes made.

RC: Page 2008 – line 1 – “The testing the stratigraphic” – word missing.

REPLY: Actually it is “testing the stratigraphic”.

RC: Page 2008 – line 20 – should be 'Plan view'.

REPLY: Accepted and changes made.

RC: Page 2008 – line 23 – Should be African plate below Aegean, not Mediterranean.

REPLY: Corrected “African plate underneath the Aegean plate”.

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RC: Page 2008 – line 24: 'the volcanic edifice developed through 5 stages' – this is somewhat controversial. See for example Vougioukalakis 2008, Francalanci et al 1995; 2005, Tomlinson et al, 2012, Kinvig, 2012.

REPLY: We do not agree. Indeed we note that less stages are proposed following earlier studies (i.e Francalanci et al., 1995 following Di Paola 1974) which use a coarser distinction, whereas 5 stages refer to finer distinction of events and are widely accepted by most recent authors (e.g the cited ones and the suggested Tomlinson et al., 2012).

RC: Page 2009 – line 12-25: The depths of the permeable layers should be referenced to the drill reports of Geotermica Italiana.

REPLY: Yes, we agree.

RC: Page 2009 – line 16: No permeable zone 'was found' in...

REPLY: We agree, we corrected “is found”.

RC: Page 2009 – line 18: delete 'but' from 'but at 1000-1300m...'

REPLY: We agree, we thought to emphasize the depth difference respect to W1.

RC: Page 2009 – line 22: Coming from what “depths”?

REPLY: These fluids come from the magmatic body. The depth of the magma body is at unknown depth (Caliro et al. 2005). Only Sykioti et al. (2003) indicate a depth of ~ 5 km inverting geodetic data of the 1996-2001 unrest. We prefer not to give any number as the unrest condition is a particular one and might be not fully representative.

RC: Page 2010 – line 6: Add Tibaldi et al, 2005 and 2008.

REPLY: OK, we add Caliro et al., 2005 and Tibaldi et al., 2008.

RC: Page 2010 – line 14: Fluctuates by 'a'few...

REPLY: Corrected “fluctuates by a”

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RC: Page 2010 – line 14: You don't need to repeat the general temperatures of the fumaroles (see line 1)

REPLY: We agree, we avoid repetition of fumarole temperature at line 13.

RC: Page 2010 – line 19: Incomplete sentence – 'inferred to instabilities of' – add 'be related to/attributed to'?

REPLY: We agree, corrected as "inferred to reflect instabilities".

RC: Page 2010 – line 23: Pantaleo 2013 is not in the reference list – it needs adding to ref' list or removing from paper.

REPLY: Added Pantaleo to reference list.

RC: Page 2010 – line 26: 'at crater scale because' – replace 'because' with 'due to'?

REPLY: Accepted and changes made.

RC: Page 2011 – line 16: IN April, not ON April. Specify when – and how long for.

REPLY: Accepted and changes made.

RC: Page 2012: Formulae and all components need to be italicised, including T_v , T_b , T_{atm} , T_{obj} :

REPLY: Formula will be italicised as well as all the components in the following text.

RC: Page 2014 – line 1-3: Remove sentence "Finally...reasons".

REPLY: We agree, removed line 1-3 "Finally . . . reasons. However".

RC: Page 2014 – line 11 & 17: Weighted should be 'weighed'.

REPLY: Accepted and changes made.

RC: Page 2014 – line 18: Suggest rewording to 'We used four sieves, which allowed the separation of gravel and coarse sand fraction ... etc' - i.e. remove 'with

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mesh....0.064mm'.

REPLY: Accepted and changes made.

RC: Page 2015 – line 8 & 24: replace 'side' with 'size'.

REPLY: In our opinion size suggests an area and giving the areal value of the pixel is – in these cases - of difficult handle for the reader.

RC: Page 2017 – line 12: Needs a reference e.g. Tibaldi et al, 2005; 2008.

REPLY: OK, we add Caliro et al., 2005 and Tibaldi et al., 2008.

RC: Page 2020 – line 6: change 'stronger expressed' to 'expressed more strongly'.

REPLY: Accepted and changes made.

RC: Page 2021: Put all formulae components in italics, e.g. T_{atm} . Page 2022: Put all formulae components in italics, e.g. T_{atm} .

REPLY: Accepted and changes made.

RC: Page 2024 – line 9: Reference e.g. Tibaldi et al, 2005; 2008.

REPLY: OK, we add Caliro et al., 2005 and Tibaldi et al., 2008.

RC: Page 2025 – line 10: Caliro et al, 2005.

REPLY: Accepted and changes made.

RC: Page 2025 – line 13: Incomplete sentence – 'it is also possible a combination...'. 'Possible that'?

REPLY: No, we mean the deposition and faults may coexist and control.

RC: Page 2026 – line 6: - changes in thermal anomalies between measurements do not necessarily represent permanent changes in the system - just a change between repeated measurements, which further stresses the need to justify comparison of the

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April and January datasets.

REPLY: See improved Section 5.1 given above.

RC: Page 2026 – line 22-23: 'A scoria layer and an ash layer' or make plural – layers.

REPLY: Accepted and changes made.

RC: Page 2027 – line 7: add word 'of' or 'in'? 'overpressure of/in the hydrothermal system'.

REPLY: Accepted and changes made.

RC: Page 2028 – line 3: Nisyros has an extensional stress regime.

REPLY: PAGE 2028 line 3 reads: Nisyros has an extensional regime. Yes, but we are talking about the stress field expected at the Stefanos crater as indicated in line 3.

RC: Page 2028 – line 4: 'that observed' or 'what is observed'.

REPLY: Accepted and changes made.

RC: Page 2028 – line 11: Repeat surveys would be crucial at Nisyros as the thermal activity can be seen to change dramatically with the local water table and rainfall. ?

REPLY: The data acquired by us is campaign mode data and does not allow more inference or speculations on temporal changes.

RC: Page 2029 – line 3: Capital I for Island – keeps it consistent with earlier in text.

REPLY: Accepted and changes made.

RC: Page 2028 – line 5: Need to expand on faults as an alternative control.

REPLY: See improved Section 5.2 and 5.3.3 given above.

RC: Page 2030 – line 2: 'A few centimetres'.... References: Add Pantaleo 2013, change Caliro et al 2004 to 2005.

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REPLY: We state that "we observe". No information found in Caliro et al. (2005).

RC: Page 2037 – line 4: 'From' SW to NE?

REPLY: Accepted and changes made.

RC: Page 2042 – line 6: Change 'it results cooler' to 'it appears cooler'.

REPLY: Accepted and changes made.

Interactive comment on Solid Earth Discuss., 5, 2005, 2013.

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