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Thermal Energy Release Measurement with Thermal Camera: The Case of La Solfatara volcano (Italy). *(Supplementary materials)*

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Abstract: Quiescent volcanoes dissipate a large part of their thermal energy through hot soils and ground degassing mainly in restricted area called Diffuse Degassing Structures. La Solfatara crater represents the main spot of thermal release for the Campi Flegrei volcano (Italy) in spite of its reduced dimensions with regards to the whole caldera. The purpose of this study is to develop a method to measure thermal energy release extrapolating it from the ground surface temperature. We use imaging from thermal cameras at short distances (1 meter) to obtain a mapping of areas with thermal anomalies and a measure of their temperatures. We have built a conceptual model of the energy release from the ground to atmosphere which well fits the experimental data taken in the La Solfatara crater. Using our model and data we can estimate the average heat flux in a portion of the crater as $q_{avg} = 220 \pm 40\,\mathrm{W/m^2}$ compatible with other measurements in literature.

Keywords: Thermal flux measurement; IR camera; La Solfatara volcano.

Appendix S. Extended data analysis

Appendix S.1. Heat flow on full dataset

As stated in sections 3.1.1, 3.1.2, 4, 5 and 6 of main part of the work, we only used points sampled during night time to estimate the heat flux in La Solfatara crater. This is because daytime measurements may be affected by errors due to solar irradiation. In order to estimate this error we have repeated all the analysis made in section 3.2.1 even for the whole dataset of direct gradient points (see 3.1.2) regardless the acquisition hour. In figure S1 we show the comparison between shallow gradient extrapolation at zero depth and the measured surface temperature, as done in figure 4.

The result of the fit of q_{soil} of equation (1) using also these points is shown in figure S2. The value for k_{soil} coming from this fit gives out the value of $0.81 \pm 0.09\,\mathrm{WK^{-1}m^{-1}}$ that is congruent to which we obtain only from nightly points. The a parameter of eq.(20) has a value of $100 \pm 40\,\mathrm{W/m^2}$, in this case. The fact that this value is not congruent with zero tells us that we are probably not considering some part of the energy balance of equation (1) during daytime. This has the net effect of an overestimate of the heat flow and may be related to two effects that we are not considering in our model:

1. sun heat reflected by the soil
2. temperature alteration due to solar irradiation

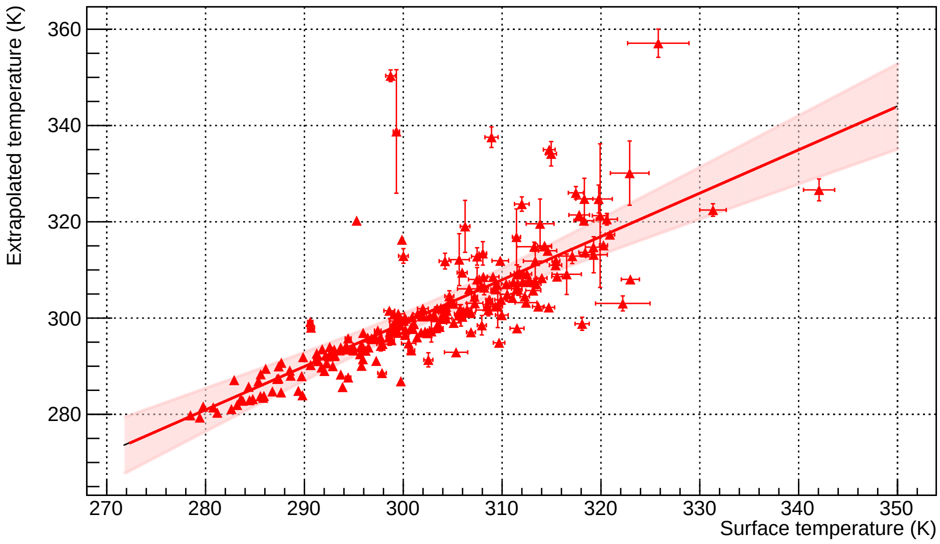

Figure S1. Gradient extrapolation at zero depth vs measured surface temperature for the whole shallow dataset. This is the same plot shown in figure 4. The results of the fit give $30 \pm 14\,K$ for the intercept and 0.90 ± 0.05 for the angular coefficient, correlation factor is about 0.78 over 230 points.

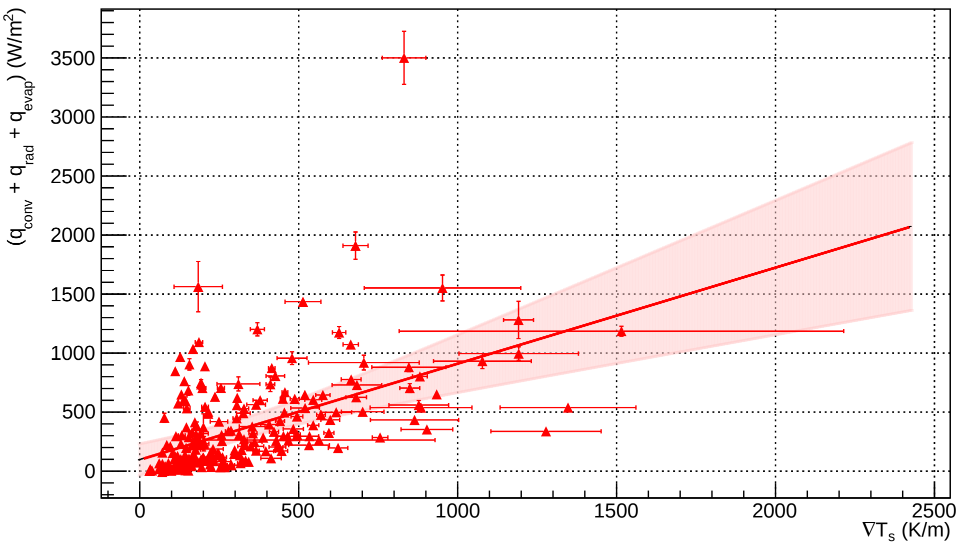

Figure S2. This is the same plot shown in figure 6 for the whole shallow gradient dataset. Fit results: $k_{soil} = 0.81 \pm 0.09\,W/(K \cdot m)$, intercept: $100 \pm 40\,W/m^2$.

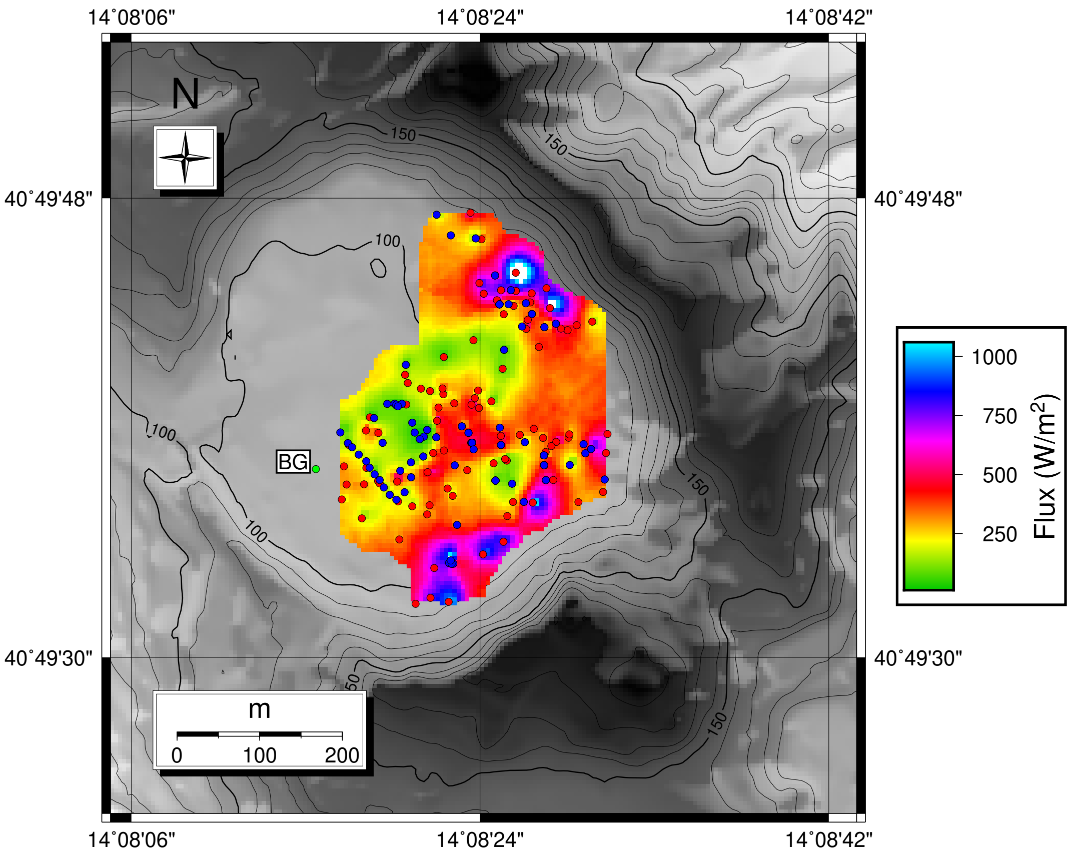

Figure S3. Map of the calculated heat flux distribution over the whole investigated area using all points with a direct thermal profile (red and blue points in figure 2) taken both during daytime and nighttime. Side scale is the same of figure 7.

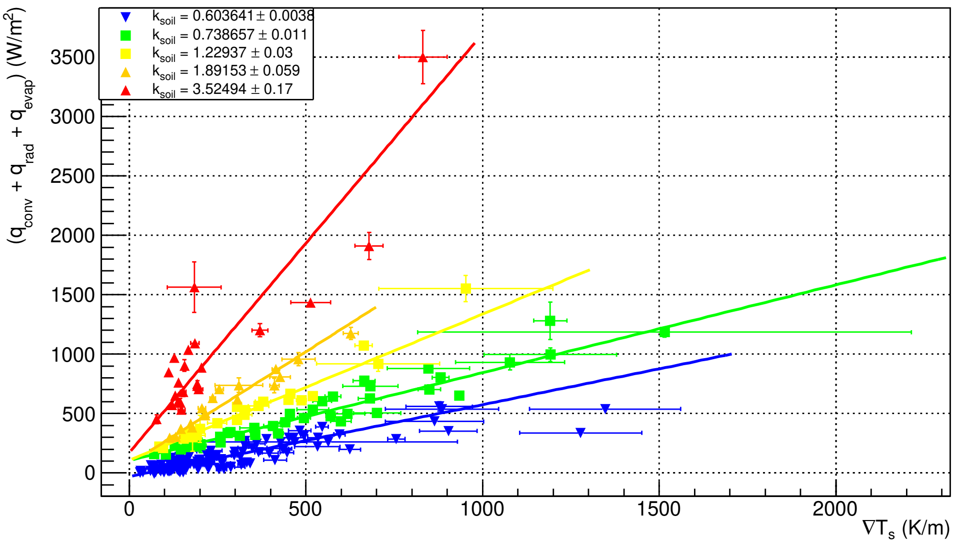

Figure S4. Separation of the sampled points with their $\nabla T_s / q_{soil}$ ratios. Each family has been fitted towards eq.(20) giving the results for the different k_{soil} shown in the top box.

We will investigate in these directions in order to understand if, making some modifications, the method could also be applied using daytime thermal images. We applied the procedure described in section 4 to estimate the total energy release from the investigated surface. In figure S3 there is the same result shown in figure 7 only calculated on all the direct gradient points. The estimate of the

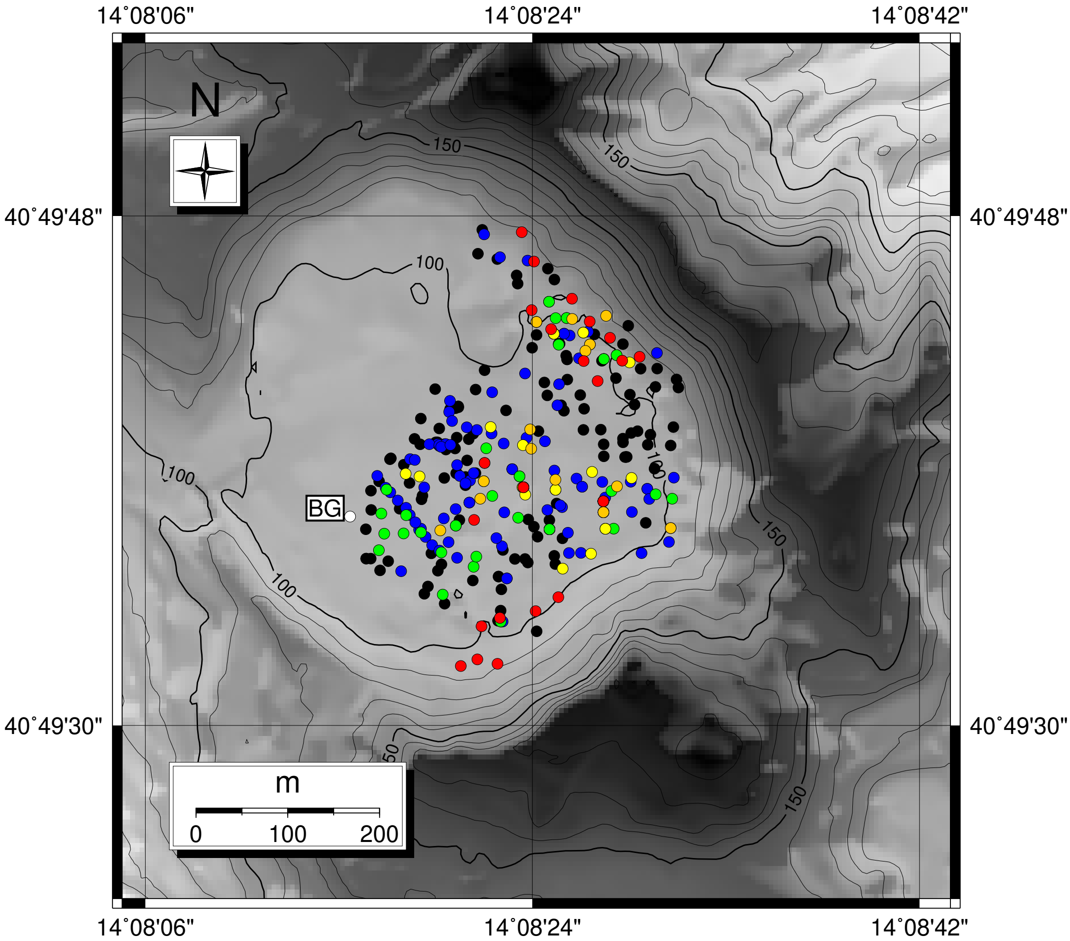

Figure S5. Distribution of the five families inside the La Solfatara crater, colors of the dots corresponds to those of figure S4. Black dots are those with an inverted gradient (Fig. 3(c)), while the white one corresponds to the background point.

total power released from the surface leds now to $Q_{tot} = 37 \pm 5\,\mathrm{MW}$ and to an average heat flux of $q_{avg} = 360 \pm 50\,\mathrm{W/m^2}$. If we subtract the actual value of a parameter obtained from the fit, we got a rough removal of the introduced bias. In this way we obtain a value of $q_{avg} \simeq 260 \pm 90\,\mathrm{W/m^2}$ still in accordance with Chiodini *et al.* [1].

Appendix S.2. Thermal conductivity separation

It is interesting to note that if we try to fit eq.(20) keeping the value of the a parameter fixed to zero on the whole dataset of direct gradients, we obtain a value of $k_{soil} \simeq 1.00 \pm 0.06\,\mathrm{WK^{-1}m^{-1}}$ which is near to that used in Chiodini *et al.* [2]. We have found that there is a weak statistical separation for the values of the $\nabla T_s / q_{soil}$ ratios in our dataset allowing to roughly divide it in the five families shown in figure S4. Here we observe that separately fitting these families we can identify five different values of the k_{soil} parameter ranging from about 0.06 to 3.5 $\mathrm{WK^{-1}}m^{-1}$.

In figure S5 we have shown the spatial distribution of the five separated families inside the investigated area. While they are quite uniformly distributed over the whole area, it is possible to note that points with an higher value of k_{soil} roughly corresponds to higher heat flux zones. This could be related to a different soil characteristics such as porosity/density or to the different temperature conditions or to a different water amount in the soil.

References

1. Chiodini, G.; Frondini, F.; Cardellini, C.; Granieri, D.; Marini, L.; Ventura, G. CO_2 degassing and energy release at Solfatara volcano, Campi Flegrei, Italy. *J. Geophys. Res.* **2001**, *106*, 16213–16221.
2. Chiodini, G.; Granieri, D.; Avino, R.; Caliro, S.; Costa, A.; Werner, C. Carbon dioxide diffuse degassing: implications on the energetic state of a volcanic hydrothermal systems. *J. Geophys. Res.* **2005**, *110*, B08204. doi:10.1029/2004JB003542.