Comparing Episodes of Volcanic Unrest at Campi Flegrei Caldera, Italy

Mungyeom Kim

UCL

1. INTRODUCTION

Campi Flegrei is a volcanic area in Naples (Italy) which has been marked by alternating periods of long-term quiescence and short-term unrest[1]. Its caldera (a depression created when magma reservoirs are partially-evacuated, with a resurgence of the sunken floor)[2], experiences unrest due to a matrix of factors, including magmatic activity, crustal stress, and hydrothermal fluids[1,3]. The area (depicted in Figure 1), has many fumaroles and vents, including the Bocca Grande and Bocca Nuova fumaroles, as well as the Pisciarelli fumarolic field[4], and is neighboured by volcanoes (Vesuvius and Ischia) that exhibit similar patterns of long-term quiescence and short-term unrest[1].

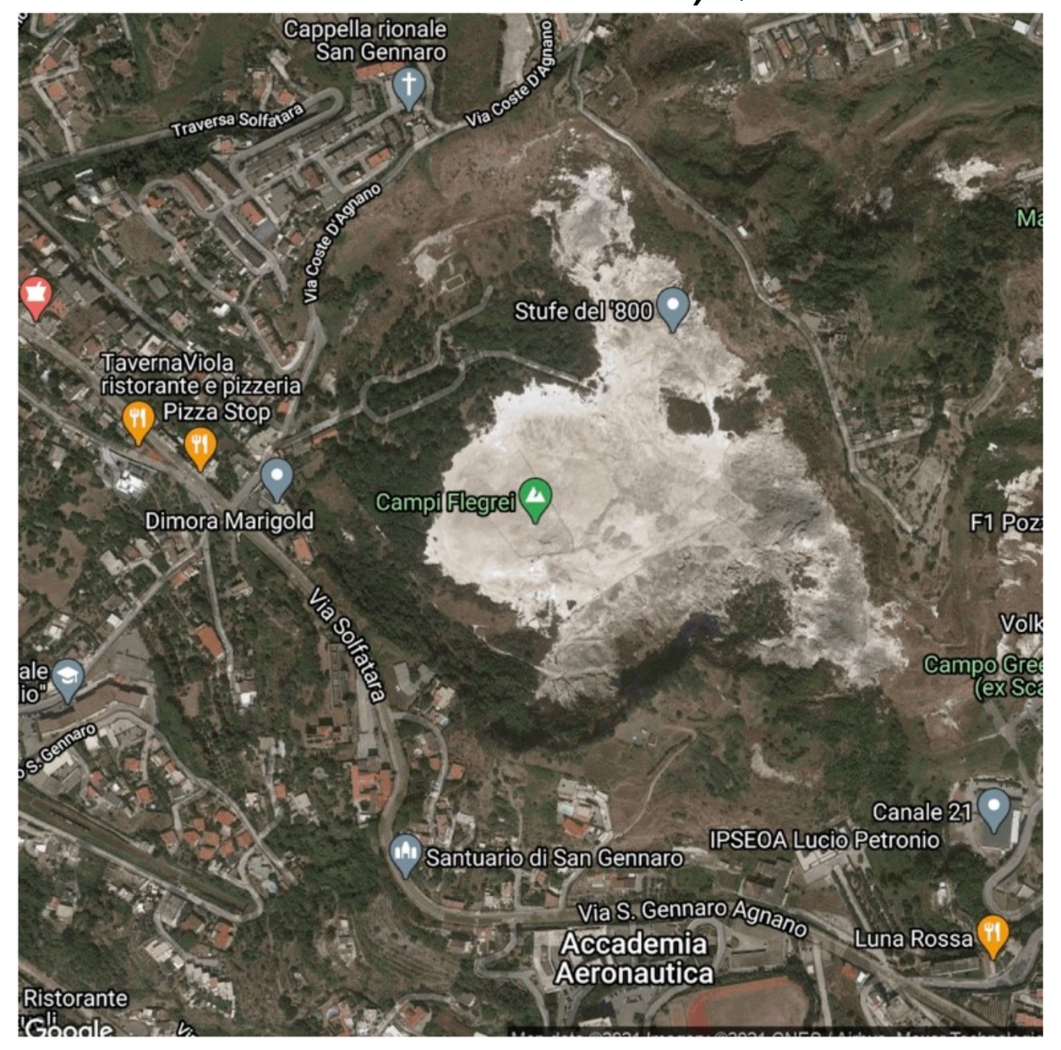

Figure 1: Map of Campi Flegrei.*

2. AIMS AND OBJECTIVES

Between 1982-1984, there was a period of large unrest (**First Unrest Period**), followed by quiescence, and recent ongoing unrest (**Second Unrest Period**)[3]. Whilst it is agreed that there was higher uplift and seismicity in the First Unrest Period, geochemical interpretations disagree as to the cause of unrest of each period: some studies find that deep hydrothermal perturbations resulted in the First Unrest Period, with shallow magmatic intrusions causing the Second Unrest Period[5], whilst other studies find the opposite[6]. Extensive hydrothermal systems complicate discrimination between the two factors, meaning both may contribute to an extent[7].

This work uses geophysical and geochemical data (temporal trends in gas geochemistry, seismicity, and ground deformation) to **(i)** ascertain the onset of the Second Unrest Period, **(ii)** compare and contrast the two unrest periods; and **(iii)** determine the cause of each unrest period.

Data at each of Bocca Grande (**BG**), Bocca Nuova (**BN**), and Pisciarelli (**Pisc**) will be assessed where possible, with the caveat that only BG has been actively monitored since 1983, meaning data is sometimes limited and may be aggregated across Campi Flegrei.

3. TEMPERATURE CHANGES

Several geophysical and geochemical processes assessed here are temperature-dependent (e.g. N_2 production, water evaporation)[3]. High temperatures are observed in the First Unrest Period in BG, increasing at each site after **2005/ 2006**.

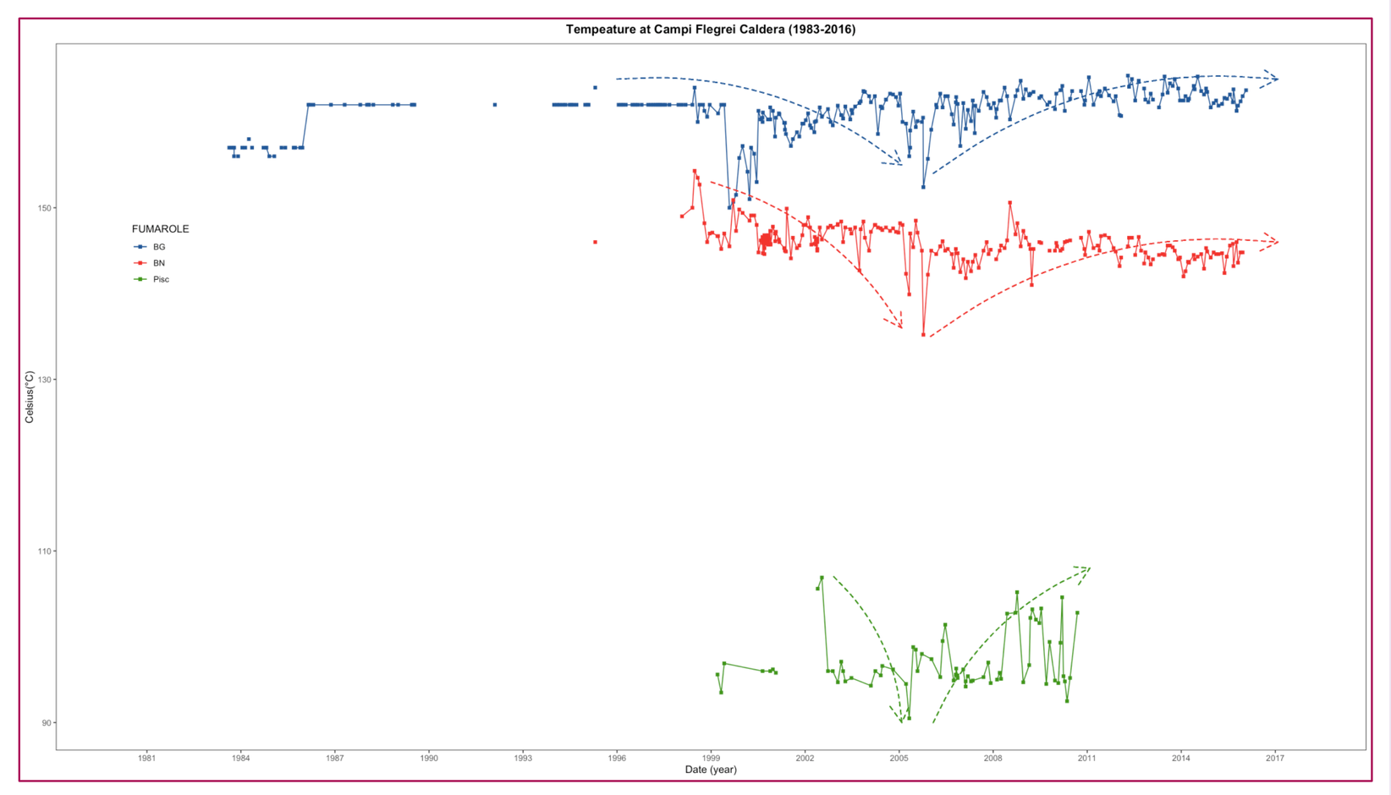

Figure 2: Temperature changes at Campi Flegrei.*

4. GEOPHYSICAL ANALYSIS

As part of the geophysical analysis undertaken, **(i)** VT seismicity and **(ii)** deformation were assessed.

(i) Volcanic Tectonic (VT) seismicity (Figure 3)

The First Unrest Period shows a high peak of monthly VT seismicity. While VT seismicity can be observed beginning in **2005-2006** (and subsequently), the First Unrest Period peak is approximately 5x the Second Unrest Period's peak.

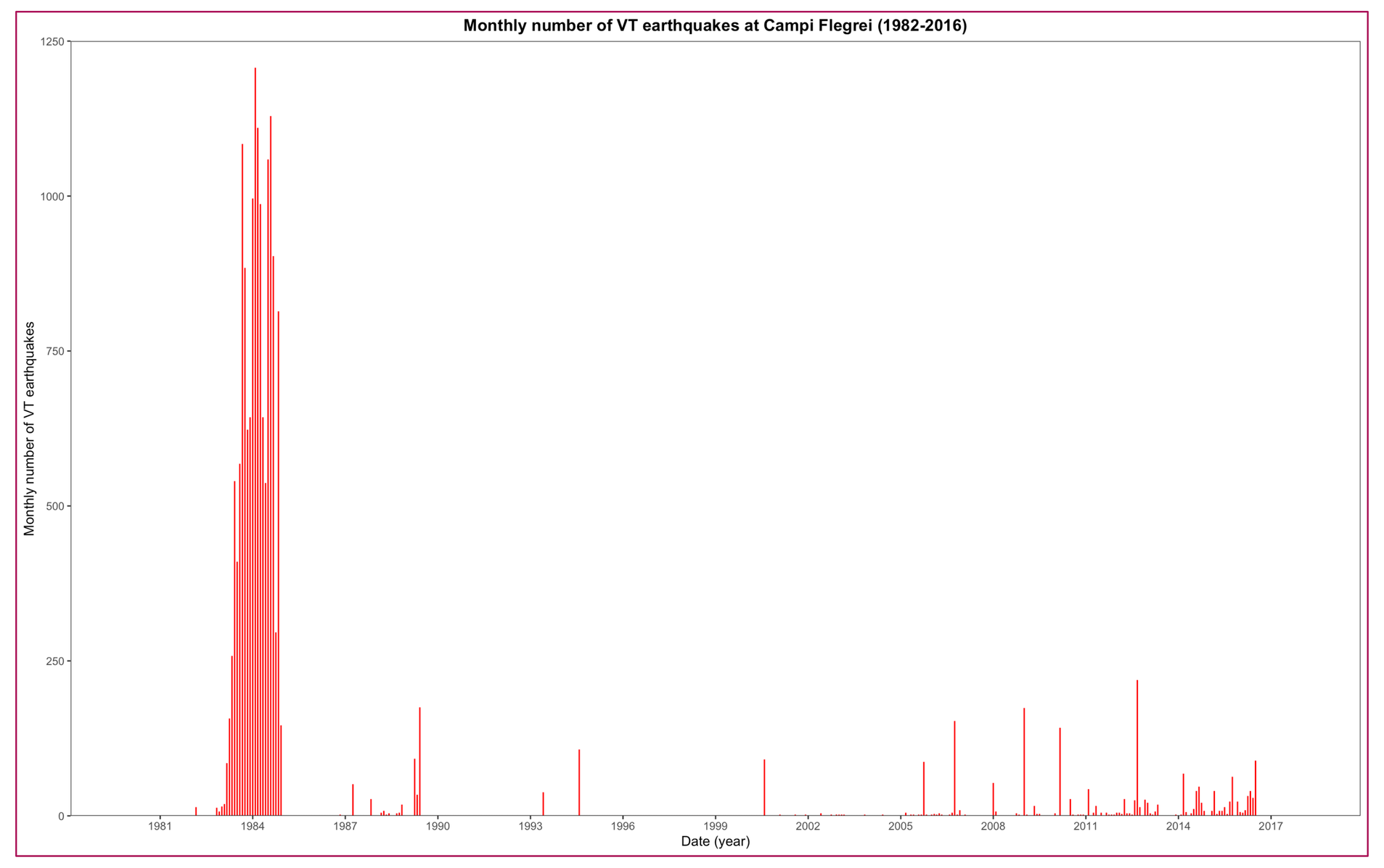

Figure 3: Monthly VT earthquakes at Campi Flegrei.*

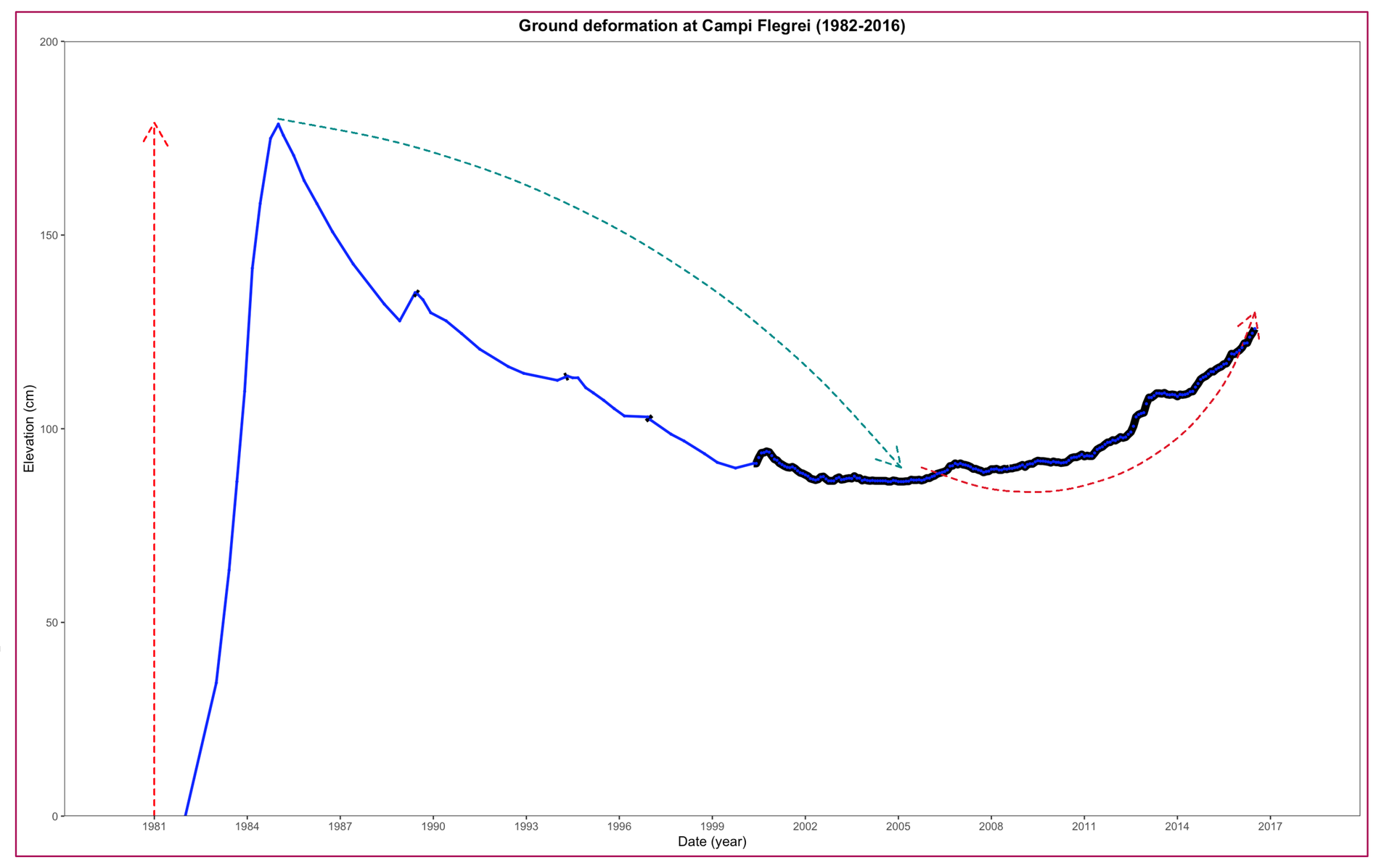

Figure 4: Ground deformation at Campi Flegrei.*

(ii) Deformation (Figure 4)

There is sharp ground elevation in the First Unrest Period (179cm), with a subsequent depression of 80cm during a period of quiescence. In **2005**, ground uplift ensues once again (gradually), at a smaller uplift than the First Unrest Period (126cm).

(iii) Relationship between average VT and average deformation (Figure 5)

Changes in VT seismicity are more minimal in the Second Unrest Period than changes in elevation, and both are more minimal in the Second Unrest Period as compared to the First Unrest Period.

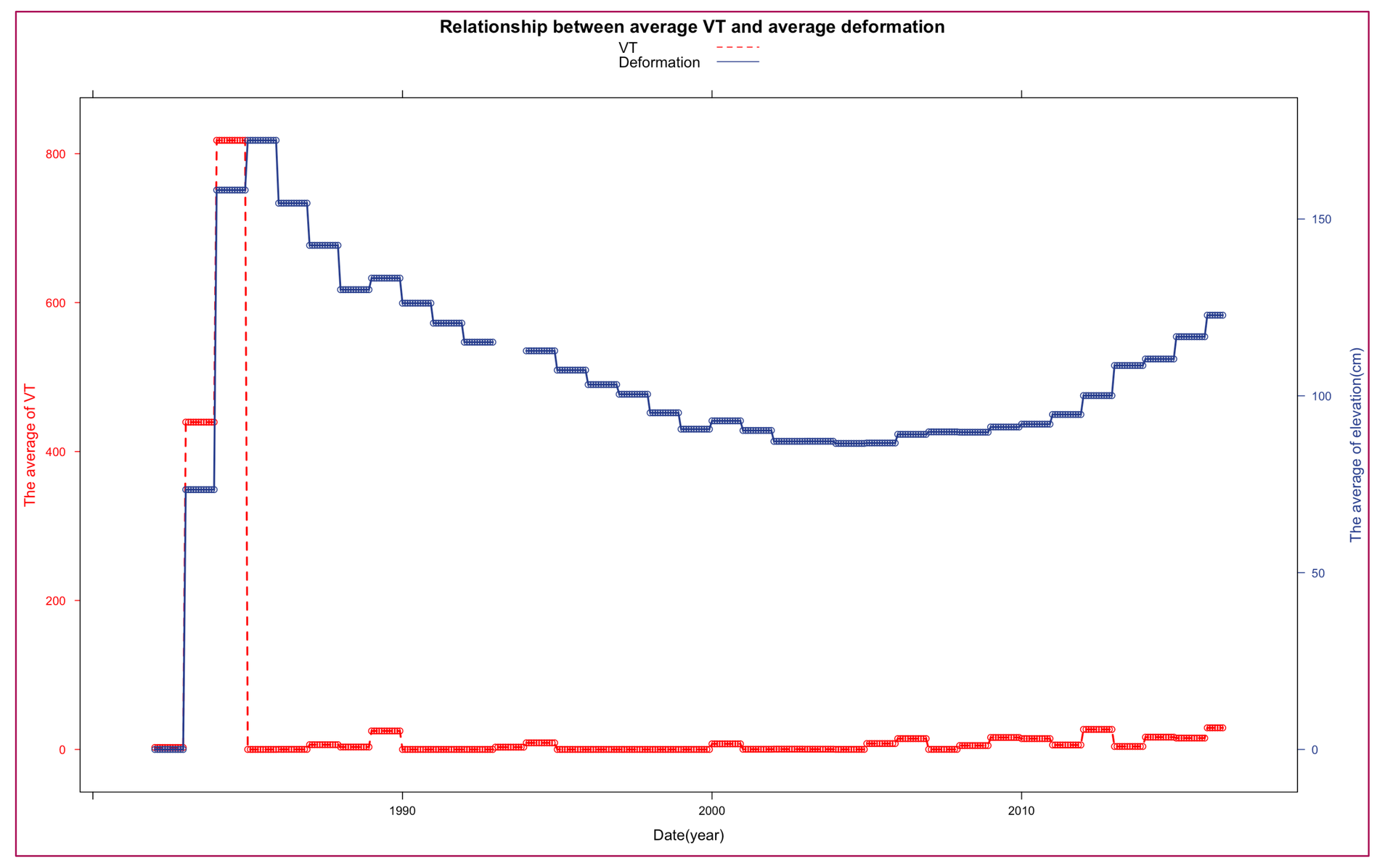

Figure 5: Average VT and average deformation at Campi Flegrei.*

5. GEOCHEMICAL ANALYSIS

As part of the geochemical analysis undertaken, **(i)** CO_2/CH_4, CO_2/H_2S, and CO_2/H_2O ratios, **(ii)** the N_2/CO_2 ratio, and **(iii)** CO_2 and N_2 Z scores were studied.

(i) CO_2/CH_4, CO_2/H_2S, and CO_2/H_2O (Figure 6)

A general ascending trend of these ratios, beginning in **2005**, is observed. The increase in CO_2-rich oxidising gases, coupled with a correlative decrease in H_2 (i.e. via chemical reduction) suggests oxidising conditions, likely due to injections of magmatic fluids in deep hydrothermal systems[3,6]. This is supported by an increase in the CO_2/H_2O ratio over time, which suggests steam condensation from hydrothermal sources[3,6].

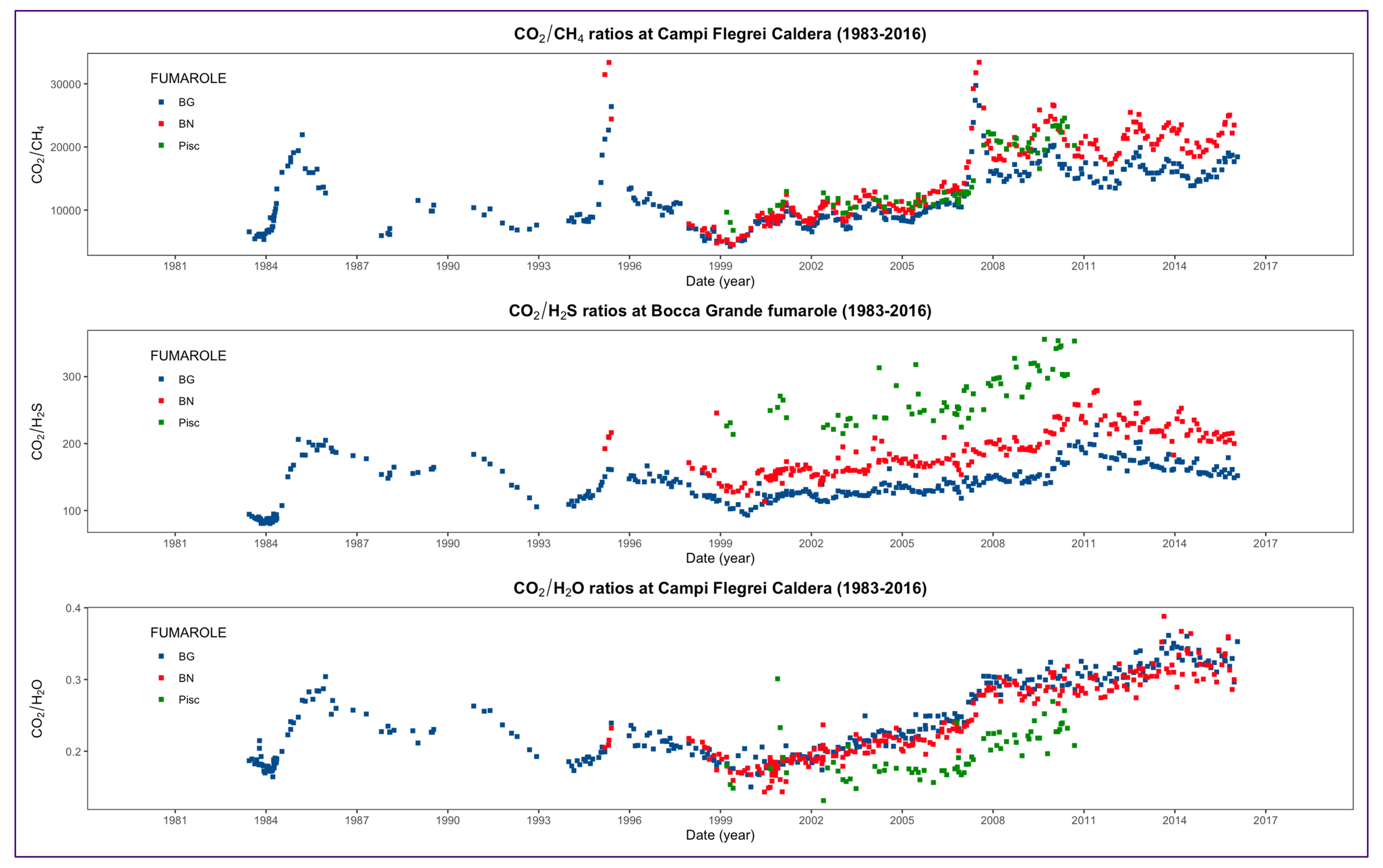

Figure 6: CO_2/CH_4, CO_2/H_2S, and CO_2/H_2O ratios at Campi Flegrei.*

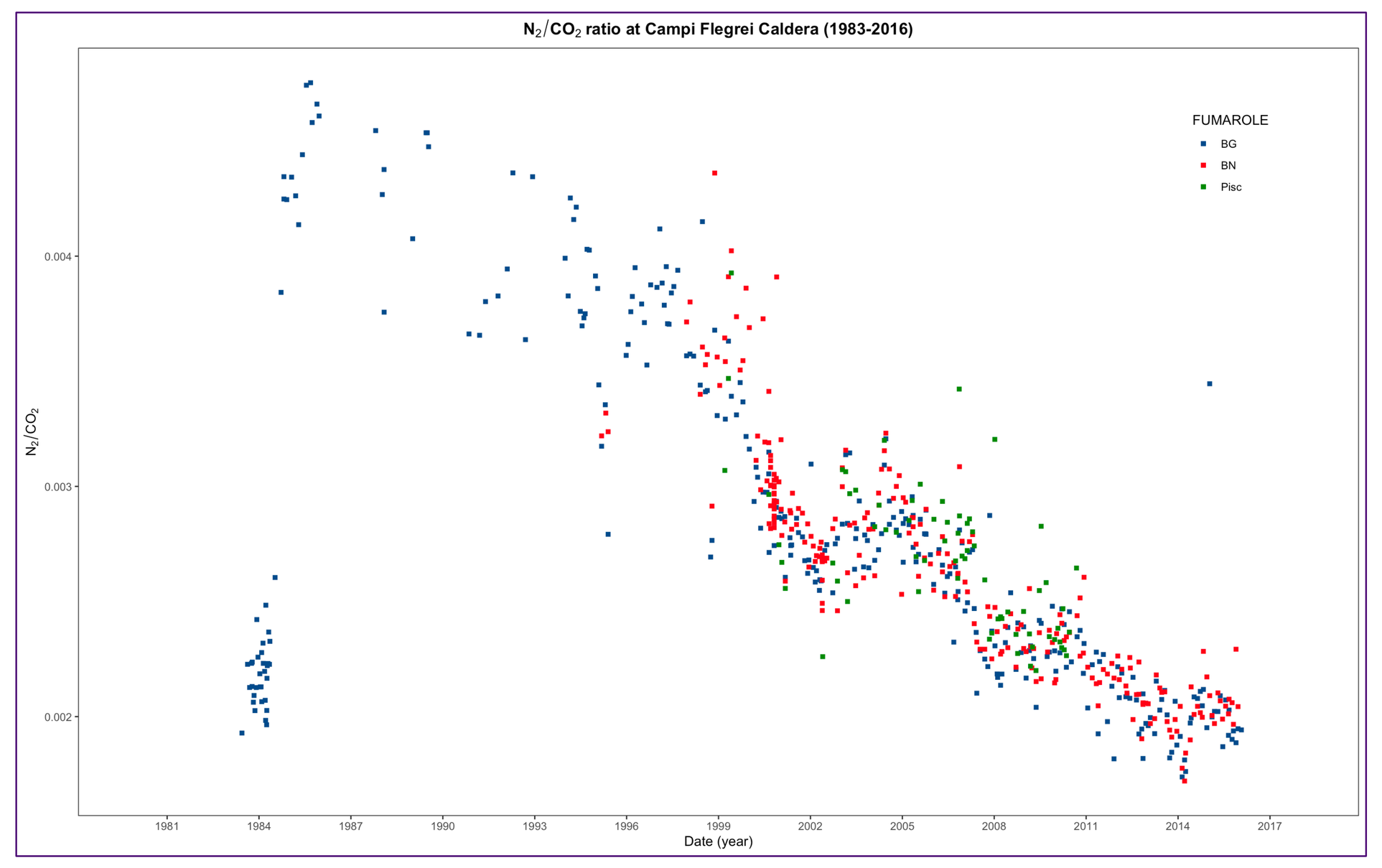

Figure 7: The N_2/CO_2 ratio at Campi Flegrei.*

(ii) N_2/CO_2 (Figure 7)

The N_2/CO_2 ratio clearly decreases over time, with a slight peak in **2005** and sharp decline thereafter. This suggests injection of N_2-depleted deep geothermal gases in the Second Unrest Period, as compared to the First Unrest Period's peak (likely caused by magma emplacement/ release of heat causing N_2-NH_3 inter-conversion)[3].

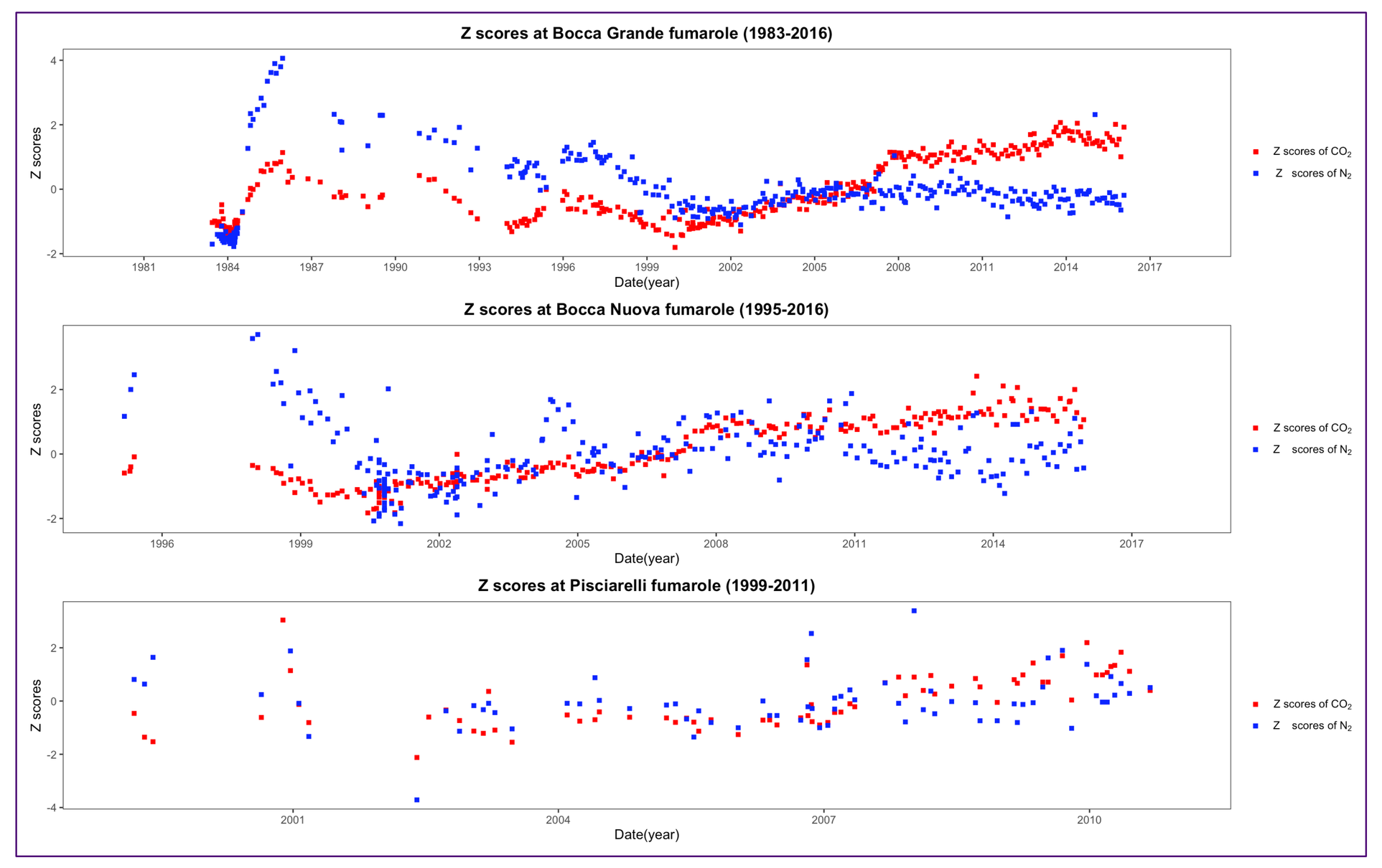

Figure 8: Z scores of N_2 and CO_2 at Campi Flegrei.*

(iii) Z scores (Figure 8)

Normalising N_2 and CO_2 by calculating Z scores confirms that, in the First Unrest Period there were many values of N_2 above the mean (suggesting shallow magmatic activity), whereas values of CO_2 above the mean increased starting in **2005** (suggesting hydrothermal activity).[3]

6. SUMMARY COMPARISON

Parameter	First Unrest Period	Second Unrest Period
VT	High increase (peak of 1206)	Moderate increase (peak of 218)
Deformation	Sharp ground elevation (peak of 179cm)	Gradual ground elevation (peak of 126cm)
CO_2/CH_4, CO_2/H_2S, CO_2/H_2O	Lower CO_2-rich gases and significantly lower CO_2/H_2O ratio	Increase in CO_2-rich oxidising gases, decrease in H_2, and significantly higher CO_2/H_2O ratio
N_2/CO_2	High N_2 content	Low N_2 content
Z Scores	Values of N_2 > mean. Values of CO_2 ≤ mean	Many values of CO_2 > mean. Values of N_2 ≤ mean
Source	Likely to be magmatic	Likely to be hydrothermal

Figure 9: Summary comparison table of First Unrest Period and Second Unrest Period.*

7. CONCLUSIONS

(1) *Onset of Second Unrest Period*. Increased deformation, VT seismicity, and temperature indicate that the Second Unrest Period began in **2005**, as do concurrent rises in CO_2 and decreases in N_2.

(2) *Different Causes*. There are marked differences between the two unrest periods, especially geochemically: increased CO_2-rich gases and a decrease in N_2-rich gases suggest that the Second Unrest Period is caused by changes in hydrothermal systems, whereas the First Unrest Period was caused by magmatic perturbations. This explains anomalous results noted in geochemical studies[5] and stresses the importance of holistic approaches (which support our identification of source mechanisms)[3,6]. Other studies using techniques like wave field characterisation reach the same conclusion that current activity is at the hydrothermal reservoir level[4].

(3) *Further Research*. It would be helpful to assess not just the locus of the source mechanism, but also magmatic migration paths, to fully account for the interaction of hydrothermal systems and magma transfers (e.g. through emplacement and lateral transfers)[8]. Such studies have already revealed a more complicated picture than the binary presented in the literature thus far[8,9].

8. REFERENCES

*All asterisked figures and tables have been created by the author using R Programming.

1. Scandone, R. & Giacomelli, L. Eruptions, earthquakes and geothermal resources at Campi Flegrei and Ischia. *Annals of Geophysics* **61,** (2018).
2. Galetto, F., Acocella, V. & Caricchi, L. Caldera resurgence driven by magma viscosity contrasts. *Nature Communications* **8,** (2017).
3. Moretti, R., De Natale, G. & Troise, C. A geochemical and geophysical reappraisal to the significance of the recent unrest at Campi Flegrei caldera (Southern Italy). *Geochemistry, Geophysics, Geosystems* **18,** 1244-1269 (2017).
4. Giudicepietro, F. et al. Insight Into Campi Flegrei Caldera Unrest Through Seismic Tremor Measurements at Pisciarelli Fumarolic Field. *Geochemistry, Geophysics, Geosystems* **20,** 5544-5555 (2019).
5. Chiodini, G. et al. Evidence of thermal-driven processes triggering the 2005–2014 unrest at Campi Flegrei caldera. *Earth and Planetary Science Letters* **414,** 58-67 (2015).
6. Moretti, R., Arienzo, I., Civetta, L., Orsi, G. & Papale, P. Multiple magma degassing sources at an explosive volcano. *Earth and Planetary Science Letters* **367,** 95-104 (2013).
7. Todesco, M., Chiodini, G. & Macedonio, G. Monitoring and modelling hydrothermal fluid emission at La Solfatara (Phlegrean Fields, Italy). An interdisciplinary approach to the study of diffuse degassing. *Journal of Volcanology and Geothermal Research* **125,** 57-79 (2003).
8. Di Vito, M. et al. Magma transfer at Campi Flegrei caldera (Italy) before the 1538 AD eruption. *Scientific Reports* **6,** (2016).
9. Rivalta, E. et al. Stress inversions to forecast magma pathways and eruptive vent location. *Science Advances* **5,** eaau9784 (2019).