A Crustal Damage Model for Coupling the Magmatic and Hydrothermal System and the Control on Ground Movements at Campi Flegrei Caldera, Italy

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Helping the Vulnerable Protect Themselves

1. Campi Flegrei

Campi Flegrei, Southern Italy (**Fig.1**) has been in a state of episodic unrest since 1950. Similar behaviour was last recorded before the caldera's only historical eruption in 1538.

Uplift is the result of magma intrusion and changes in pore pressure in the hydrothermal system. To improve eruption forecasts, it is essential to distinguish deformation signals caused by hydrothermal behaviour from those produced by intrusions.

The potential for eruption depends on the cumulative effect of previous unrests [1]. Here we consider how progressive changes in the crust may have influenced the hydrothermal system and its contribution to observed ground deformation.

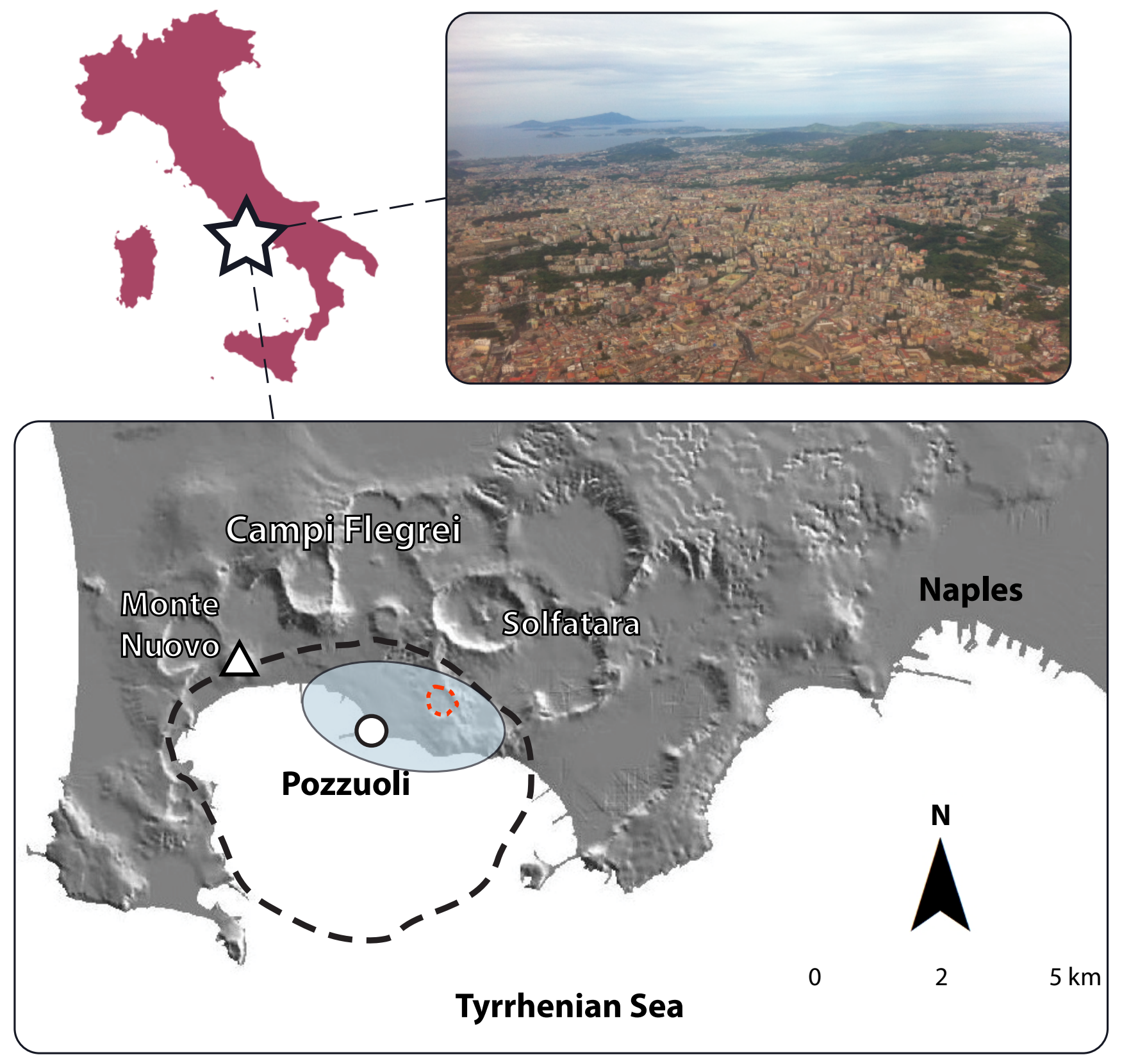


Figure 1. Location map. The black line marks the main collapse and the blue ellipse highlights the main hydrothermal basin. The town of Pozzuoli coincides with the centre of ground deformation, whilst Solfatara is the primary site of hydrothermal activity at the surface. Monte Nuovo is the site of the last eruption. **Inset**: Campi Flegrei looking southwest. The caldera has a population of c. 360 000 (photo: D. Charlton, 2015)

2. Essential Features of the Magmatic-Hydrothermal System

1. The Magmatic System (Fig. 2)

- Primary magma reservoir (7-9 km) and a zone of preferential sill intrusion (3-4 km)
- Reservoir of supercritical magmatic fluids (3-4 km) [2].

Permeability is low ($<10^{-17}$ m²) and pore fluid pressures are super-hydrostatic.

2. The Hydrothermal System

- Fractured reservoir where magmatic and non-magmatic fluids mix (2-3 km) [3]
- Cap rock of low-temperature alteration clays
- Fractured vertical structure connecting the main reservoir to the surface [4]. We propose that this structure has a key role in regulating pressure in the hydrothermal system.

Permeability (10^{-17} m² -10^{-13} m²) is high enough to permit a near-hydrostatic pressure gradient [5].

The primary controls on pore fluid pressure in the hydrothermal system are: i) permeability; and ii) the rate of fluid flux from the magmatic system.

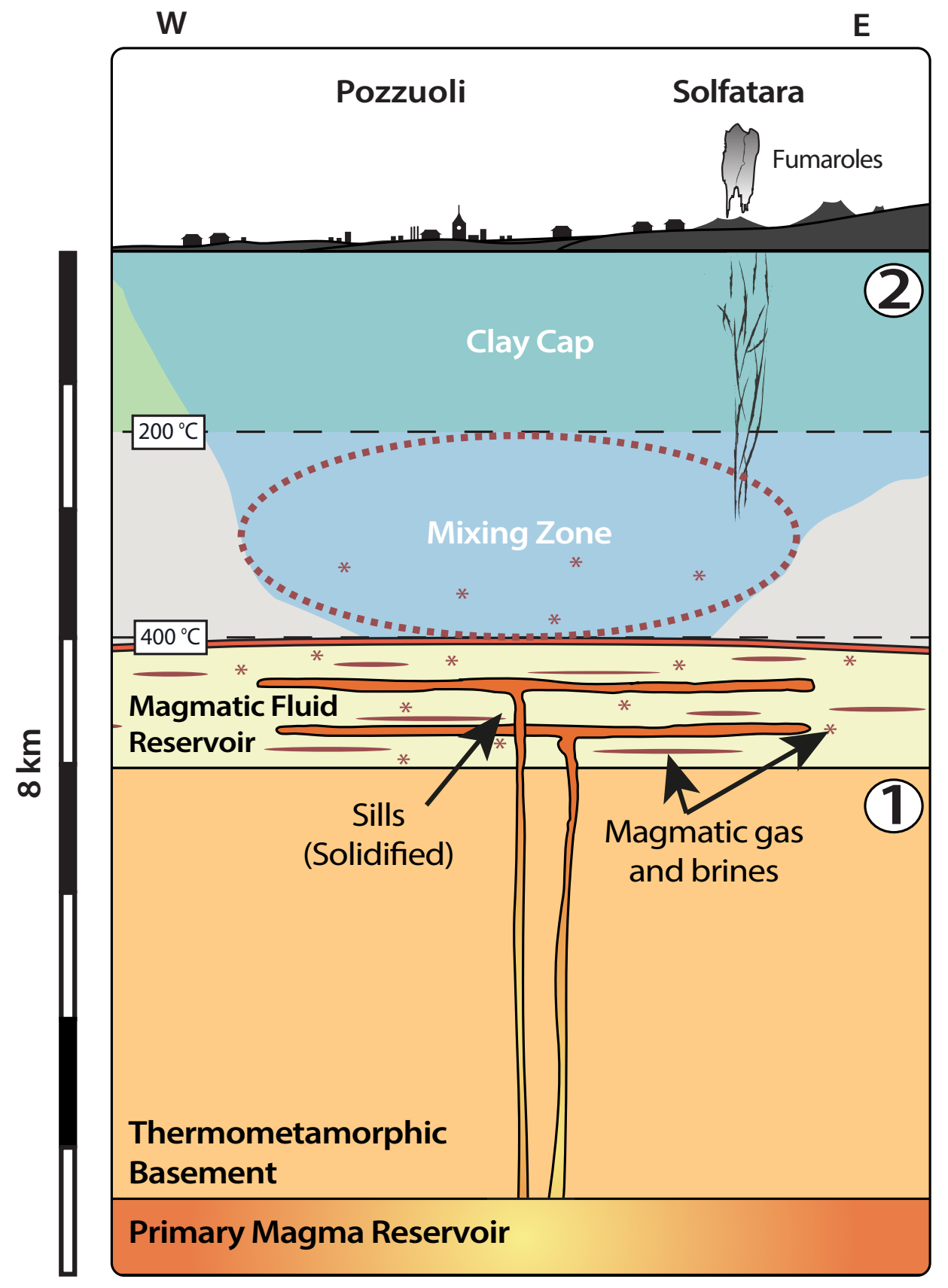


Figure 2. Schematic of the magmatic-hydrothermal system. In the magmatic system heat transfer is dominantly via conduction, whereas advection is the dominant mode in the hydrothermal system. The hydrothermal basin overlies the location of sill intrusion.

3. Unrest Since 1950

Removal of a background rate of subsidence from the deformation profile (**Fig. 3**) reveals that Pozzuoli has been permanently raised c. 3.6 m by sill intrusions in 1950-1952 (0.76 m), 1969-1972 (1.66 m) and 1982-1984 (1.22 m) [1]. Rates of Volcano-Tectonic (VT) seismicity accompanying the uplifts also increased over time suggesting that the crust has become progressively damaged.

After 1984 the caldera entered a phase of slow, aseismic subsidence (0.6 m), additional to background rates, until 2000 that was followed by a largely aseismic uplift (c. 0.6 m) that continues to the present.

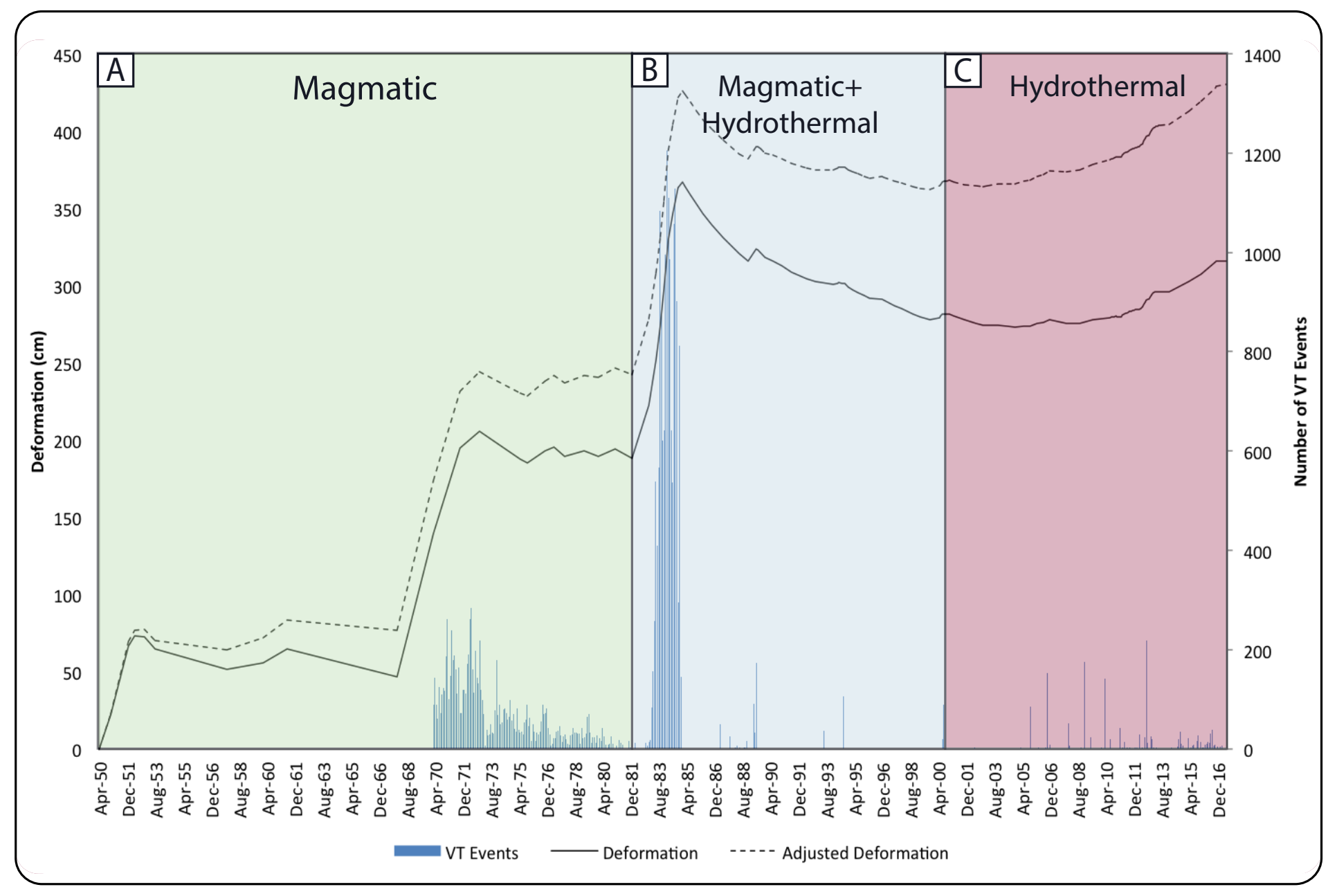


Figure 3. Uplift at Pozzuoli and VT event rate since 1950. Uplift has been recorded from levelling data (1950-2000) [6] and GPS measurements (2000-Present) [7]. Blue bars represent VT events. The two curves for deformation show the measured trend and the trend adjusted. adjusted for a background rate of subsidence of c. 17 mm yr⁻¹ [1]. Boxes A, B. C highlight different phases in behaviour and the change in the source over time.

The uplift has progressed at a mean rate of c. 0.04 m yr^{-1}, similar to the magnitude of the preceding subsidence. This is 15 times slower than the 1982-1984 uplift and so unlikely to be driven by a shallow intrusion. A more likely control on the post-1984 ground movements is the loss and subsequent recovery of pore pressure in the hydrothermal system.

A key question is: which of the primary controls changed in 1982-1984 and in 2000?

4. Conceptual Models for Unrest Since 1950

Increasing crustal damage over successive unrests favours an increase in permeability and hence, changes in pore pressure in the hydrothermal system.

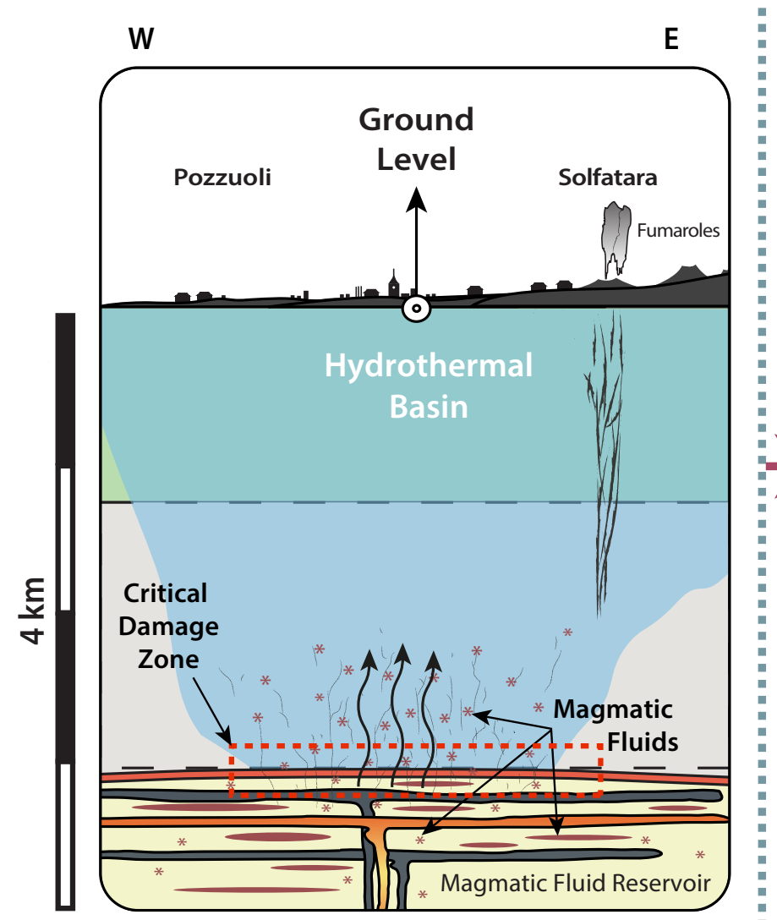
No additional subsidence was observed following the 1950-1952 and 1969-1972 uplifts, suggesting that there was no loss of pore pressure in the hydrothermal system. A critical change in the crust must therefore have occurred in 1982-1984.

Two end-member scenarios for the post-1984 deformation sequence can be recognised depending on whether equilibrium conditions were reflected by the ground level maximum in 1984, or the minimum in 2000. In both cases the sequence is triggered by the mechanical effect of the third sill intrusion. This increases permebility in a Critical Damage Zone (CDZ), the preferred location of which is scenario dependent.

Scenario 1

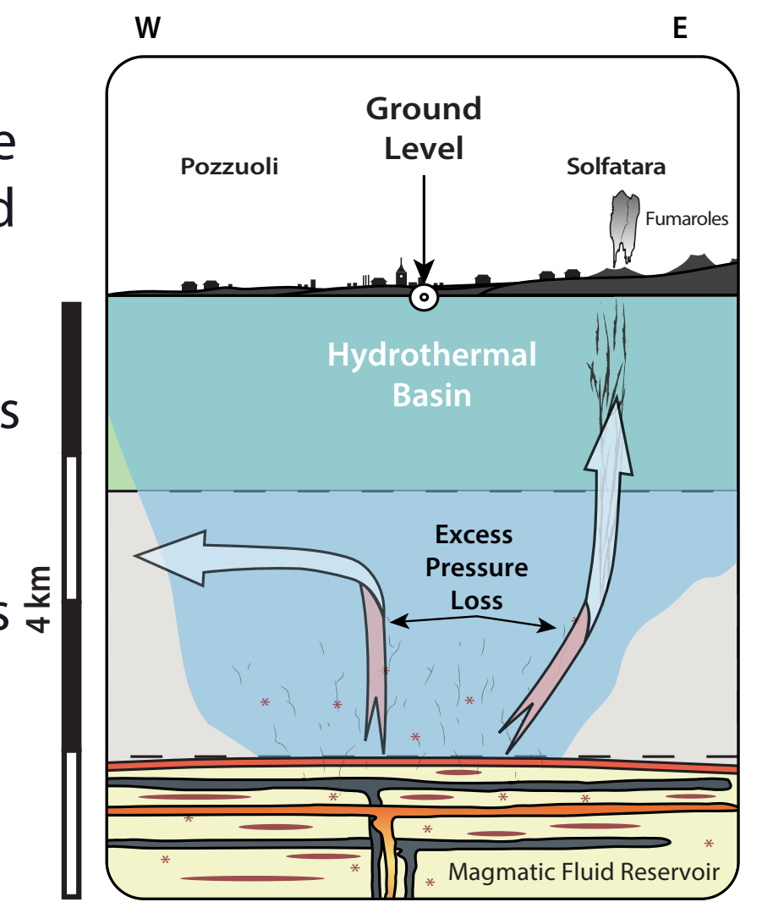
1982-1984

The CDZ was located at the transition between the magmatic and hydrothermal systems increasing the connectivity between them. The increase in permeability enhanced the supply of magmatic fluids into the hydrothermal system, raising pore pressures and causing an uplift of 0.6 m that was additional to that from the sill (1.2 m)



1985-2000

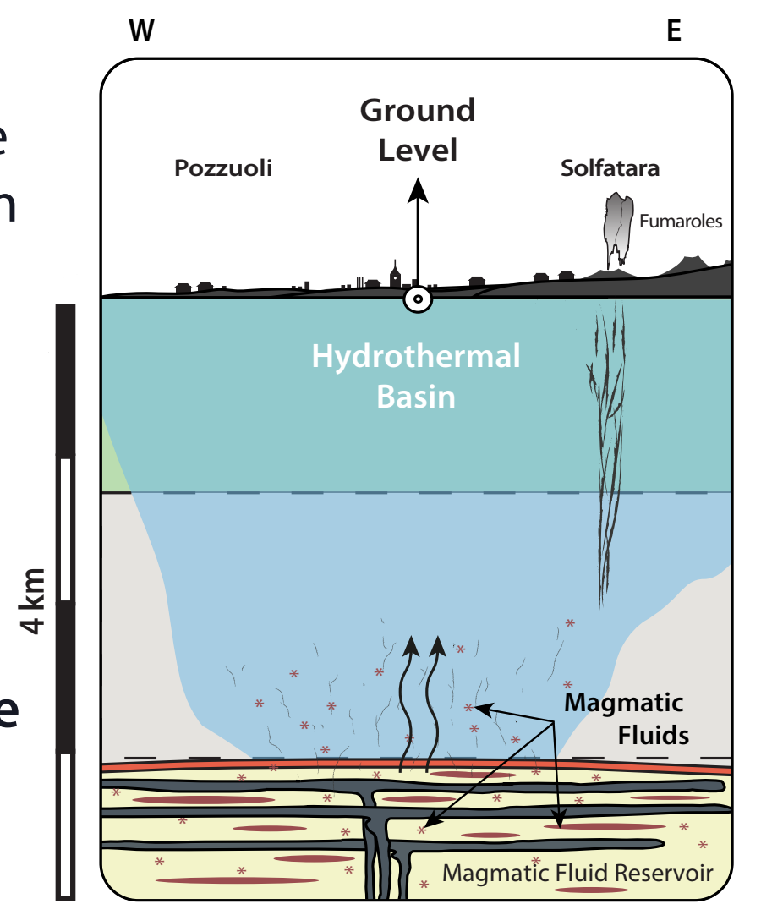
Following uplift, the enhanced permeability at the CDZ could not be maintained and the supply rate of magmatic fluids returned to background levels. The excess pore pressure in the hydrothermal system was removed by circulating fluids causing the subsidence, which ended once the equilibrium pressure was restored in 2000.



2000-Present

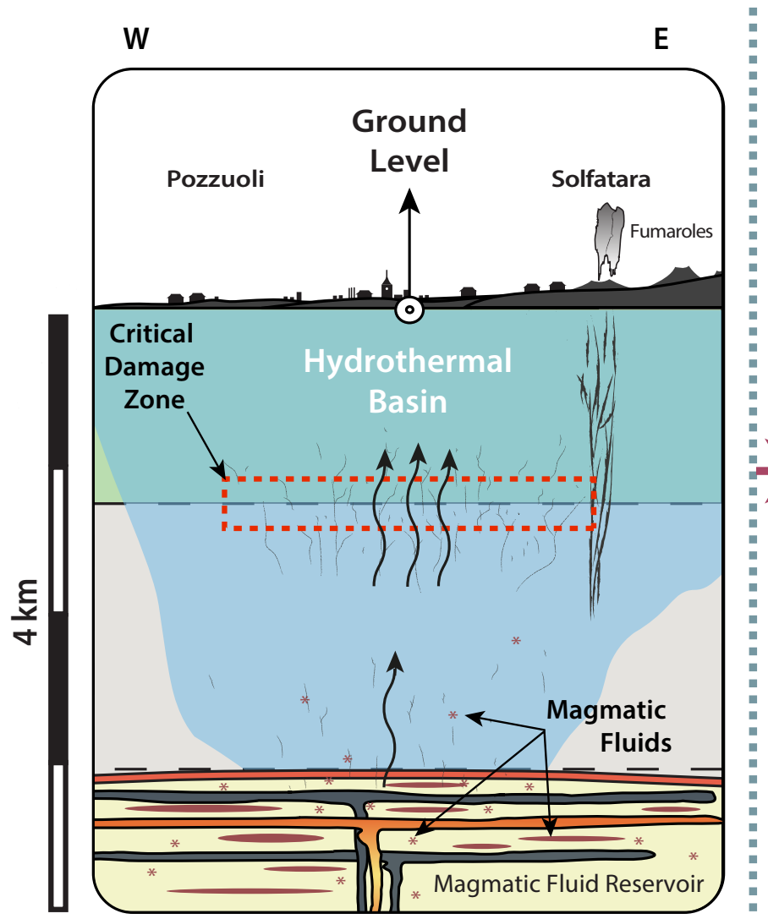
Pore pressures in the hydrothermal system have progressively increased since 2000. Without evidence for an intrusion this is most simply attributed to an increase in supply rate of volatiles from depth.

Uplift will end once the volatile supply returns to background rates and will be followed by a period of subsidence as excess pressure is removed.

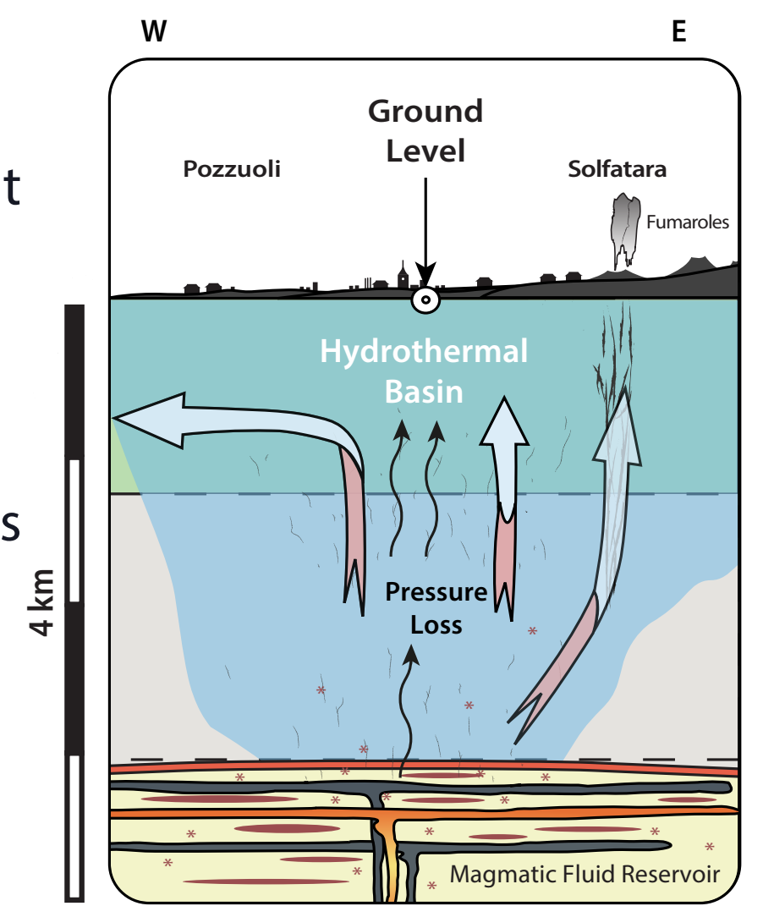


Scenario 2

The CDZ was located at the top of the mixing zone and the lower margin of the cap rock. Pore pressure within the hydrothermal system remained unchanged and so

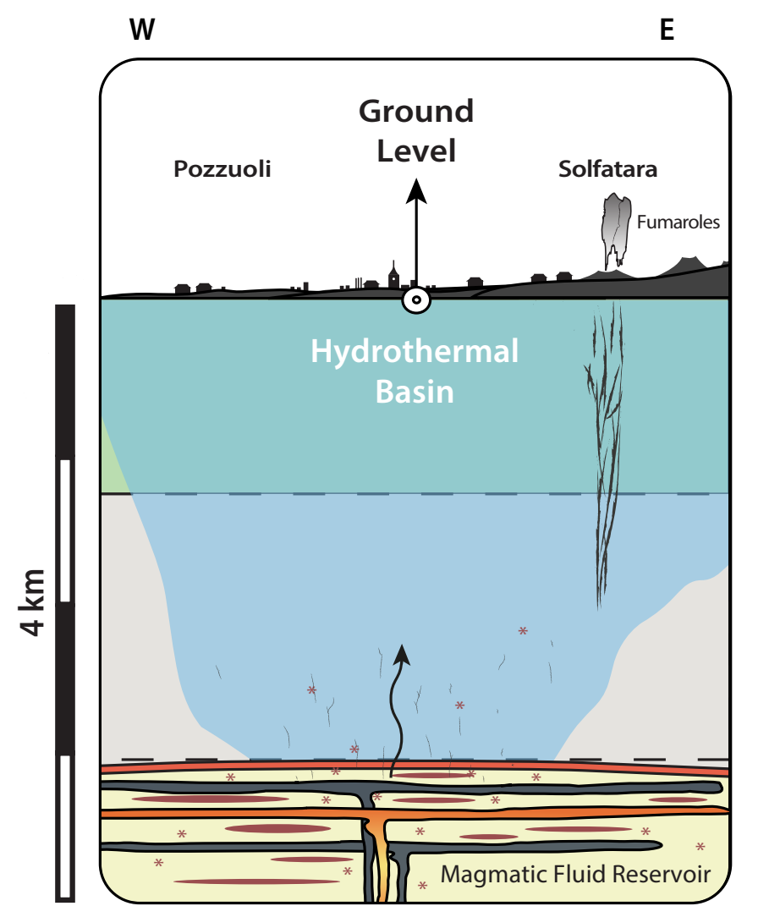


The enhanced permeability at the CDZ caused a flux of fluids into the overlying formation and elevated discharge through the Solfatara structure. The excess loss of pore pressure controlled the subsidence phase.



Background supply of magmatic fluids increased pore pressures over time, driving uplift without an increase in the flux from the magmatic system.

Uplift will end when the equilibrium pore-pressure distribution is restored. This condition would be expected once the ground level returns to that of 1984.



5. Conclusions

- The 1985-2000 subsidence can be attributed to an increase in permeability at either the base or the top of the mixing zone of the hydrothermal reservoir. A critical strain must therefore have been exceeded during the uplift in 1982-1984.
- For equilibrium conditions to be restored, background rates of either magmatic fluid supply or hydrothermal fluid discharge, must be recovered. This requires a self-sealing mechanism to recover permeability in the CDZ.
- Uplift since 2000 may represent a return to equilibrium conditions or a departure from them. Establishing which is the case is essential to improving assessment of the volcanic hazard.

6. Future Work

To better understand how the hydrothermal system will behave in future unrest by:

- Establishing the stress field in the hydrothermal system during intrusions to identify the preferred location of the CDZ.
- Testing scenarios of past unrest against multiple monitoring parameters.

6. References

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