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The "breathing" Earth (la terra che respira) at Solfatara-Pisciarelli (Campi Flegrei, southern Italy) during 2005-2024: Nature's way of attenuating the effects of bradyseism through gradual and episodic release of subsurface pressure.

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Abstract

Campi Flegrei (CF) is a large volcanic complex west of Naples, in a densely populated region at high volcanic risk due to recurrent ground uplift and subsidence (bradyseism) that has been ongoing since at least Greek-Roman times. We compare the current period of unrest beginning in 2005 with that of the bradyseism crisis of 1982-84. Despite the similarity in the quasi-radially symmetric pattern of ground deformation suggesting a similar source location and overpressure, the current uplift rate is about 8 times lower, and the seismic release energy is an order of magnitude lower than in 1982-84, and mainly located in isolated regions below the Solfatara-Pisciarelli area. We interpret the recent earthquake swarms at Solfatara-Pisciarelli as a reflection of the activation of a fault system that was inactive during previous bradyseism crises. Furthermore, the increase of Solfatara-Pisciarelli fumarole mass flux is the manifestation of fluid discharge that significantly reduces the uplift rate of the ongoing bradyseism event. As a result, the effects of bradyseism in the CF system have self-attenuated through increased fluid expulsion ("*breathing or exhalation*") from the deep lithostatically-pressured reservoir. Having gained a clear understanding of the causes of bradyseism at CF, we suggest that modern geoengineering approaches developed to exploit high-temperature geothermal reservoirs may be employed to manage

fluid flow and reduce the pressure exerted by geothermal fluids in the Solfatara-Pisciarelli area with the aim of minimizing the risk of phreatic eruptions and, concomitantly, reducing uplift and seismicity. This approach requires concerted and cooperative efforts between geoscientists, engineers, government officials, and the general public.

1. OVERVIEW OF THE CF VOLCANIC SYSTEM

Lima et al. (2021) previously described the “bradyseism signature” at Campi Flegrei (CF) as the ensemble of cyclical phenomena associated with ground deformation. CF is an area of very high volcanic risk, and it is therefore critical to be able to distinguish between uplift or deformation that may be a precursor to an eruption, as occurred in 1538 preceding the Monte Nuovo event, and ground deformation showing the “bradyseism signature” and which does not presage an eruption. The unrest at CF beginning in 2005 and continuing today shows a typical "bell shaped" spatial pattern of ground deformation (Fig. 1) in which the magnitude of uplift and subsidence decay rapidly with distance from the central location of maximum uplift/subsidence, with the epicenter located at the town of Pozzuoli.

De Vivo and Lima (2006) noted that the magmatic and hydrothermal systems at CF are similar to those associated with formation of porphyry copper deposits. In subsequent years, quantitative conceptual models were developed (Bodnar et al., 2007, Lima et al., 2009; 2021) to show that bradyseism could be related to the transition from magmatic to hydrothermal conditions in a subvolcanic environment based on the model of Fournier (1999). The subsurface at CF is composed of three fluid reservoirs, separated by two relatively impermeable horizons. The deepest reservoir contains magmatic fluids (mostly CO_2 and H_2O) generated by exsolution from a deeper magma body as it cools, crystallizes and expels fluid. The fluids in this deep reservoir are separated from those in the overlying hydrothermal reservoir by the relatively impermeable crystallized outer portion of the magma body (layer A; Fig. 2A) that Burnham (1979) refers to as the "crystallized rind". Episodically, impermeable layer A fractures, allowing magmatic fluids to migrate into the overlying reservoir (Fig. 2B). A critical component of bradyseism at CF is the presence of a second impermeable layer B (claystone/siltstone cap; Fig.2) that separates and maintains the deeper hydrothermal system without substantial variations for centuries (Vanorio and Kanitpanyacharoen, 2015). As such, impermeable layer B acts as a throttling valve between the deep hydrothermal system and the shallow hydrostatically-pressured aquifer. This valve operates on short time scales (1-10^2 years) decoupled from the longer timescale associated with magma cooling, crystallization, and fluid expulsion. The valve cyclicity (open vs. shut) causes conditions in the deeper reservoir to alternate between lithostatic and hydrostatic pressure (Fig. 2A and 2C). Connectivity between the shallow hydrostatic and deeper lithostatic reservoirs is episodically turned on and off, perhaps related to cycles of deposition from hydrothermal solutions (permeability decrease) and new phases of fracture formation (permeability increase), causing alternating periods of uplift and subsidence, depending on the temporal evolution of the permeability field and associated thermo-poroelasticity of the host rocks. Earthquake swarms are the manifestation of formation of hydrofractures in the impermeable layer. These fractures allow fluid decompression and expansion, transport and mineral (e.g., silica) precipitation that leads to sealing of cracks and isolation of the two reservoirs (Fig. 2D).

Thus, pressure slowly builds up within the hydrothermal reservoir beneath impermeable layer B (Fig. 2) until the pressure is reduced by permeability increase due to fracture propagation concomitant with the expulsion of fluids from the deeper reservoir into the shallower one. The processes operating in the subsurface at CF are not unlike those responsible for the regular eruptions of Old Faithful Geyser in Yellowstone National Park, USA, whereby constrictions (i.e., permeability barriers) in the deep plumbing system prevent water from moving from depth to the surface until sufficient pressure builds up to allow water to pass through the constrictions and escape to the surface.

The seismogenic zone at CF is bounded by two impermeable layers. The shallower one (layer B in Fig. 2) has greater elasticity (Vanorio and Kanitpanyacharoen, 2015; Ahmed, 2018; Sayed et al., 2018; Heap et al., 2020) compared to the deeper one (Layer A in Fig. 2). Additionally, fault systems around the lateral margins are truncated by an anticline that allows the hydrothermal system to be preserved without variation for millennia. Danesi et al. (2024) generally confirm this pattern through a detailed study of seismic data recorded during the period 1982-2023.

The current period of bradyseism unrest began in 2005. However, despite the commonality of the quasi-radial symmetric pattern of ground deformation, suggesting a similar source location and overpressure, the uplift rate, the spatial distribution of seismicity, and the seismic energy release show quantitatively significant differences for the two periods (1982-84 and 2005-24). For the current unrest, the uplift rate is about 8 times slower than in 1982-84, and earthquakes below the point of maximum uplift and the released seismic energy are an order of magnitude smaller than in 1982-84 and mainly located in isolated regions below the Solfatara-Pisciarelli area (Tramelli et al., 2022; Danesi et al., 2024).

2. **EVOLUTION IN INTERPRETATION OF CAUSES OF BRADYSEISM AT CF**

Various models have been put forward to explain the bradyseism at CF (see also Lima et al., 2021) and they can be divided into three groups. The first group of models interprets CF unrest to be the result of intrusion of magmas to shallow depths of ~3 km, such that input of new magma in the subsurface leads to deformation at the surface (e.g., Woo and Kilburn, 2010, Amoruso and Crescentini, 2011). Through analysis of deformation and microgravity data, parameters characterizing the magmatic source, such as shape, petrophysical properties (rigidity modulus, Poisson's ratio) the change in volume and hence pressure are estimated. These models fail to explain subsequent subsidence that always follows an uplift phase. In fact, uplift induced by a magmatic intrusion varies very little over short (on the order of a year) timescales. The timescale of a magmatic event is quite long since magma volume is not removed (no eruptions before, during or after recent bradyseism crises). The explanation of the 80 cm of subsidence that occurred in the subsequent 20 years following the 1982-1984 unrest (Del Gaudio et al., 2010) is better explained by the implications of the cyclic model and related thermo-poroviscoelastic effects that accompany the movement of crustal fluids.

The second set of models relate uplift to magmatic intrusions but additionally focuses on developing more convincing explanations for the subsidence that invariably follows (e.g. Troise et al., 2019; Chiodini et al., 2021; Giacomuzzi et al., 2024). The subsidence is generally interpreted due to hydrothermal processes in the subsurface, but a detailed explanation of how the transition from uplift to subsidence occurs is not provided. During unrest the involvement of shallow magma intrusions is based on the decreasing H_2O/CO_2 ratio in the Solfatara volcano fumaroles as a result of addition of magmatic CO_2 to the fumaroles (Chiodini et al., 2015). Recently, Giacomuzzi et al. (2024) concluded that evidence for the presence of magma bodies at shallow depths is lacking, based on a detailed seismic tomography analysis.

The third group of models explains unrest at CF to be the result of hydrothermal fluid migration in three intermittently isolated fluid reservoirs, as discussed above (see Fig. 2), with *no* addition of new magma to the magma body at depth. The latter hydrothermal model works well for the interpretation of bradyseism and has been supported by more recent studies asserting that magmatic intrusions are not required to explain bradyseism. These workers (e.g. Nespoli et al., 2021; 2023) apply a physical model that considers that a Thermo-Poro-Elastic (TPE) inclusion, with an assigned geometry, is responsible for deformation induced by mechanical effects of both pore pressure and temperature changes of the fluids which pervade a poroelastic region, embedded in an elastic matrix. Based on tomography studies, layer B (Fig. 2) with time dependent permeability below the shallow aquifer has been recognized (e.g., Calò and Tramelli, 2018; Nespoli et al., 2021; Danesi et al., 2024) to play an important role in bradyseismic events. Vanorio and Kanitpanyacharoen (2015) stress the importance of the claystone/siltstone impermeable layer that acts as a caprock affording the capability to accommodate the strain as fluids accumulate and pore fluid pressure increases until a critical threshold is exceeded.

The models that ascribe bradyseism to be the result of shallow magmatic intrusions cannot explain the repetitive cyclical signals without substantial variations over time, as well as the constancy of the seismogenic volume during a bradyseismic episode. The maximum uplift is always centered at Pozzuoli. In addition, the results of both seismic tomography (Zollo et al., 2008; Calò and Tramelli, 2018; Giacomuzzi et al., 2024) and the density model built using a new 3-D inversion of the available high-precision gravity and deformation data (Amoruso et al., 2008; Capuano et al., 2013; Amoruso and Crescentini, 2022) also exclude the presence of magma at shallow levels.

3. WHAT IS THE DRIVING FORCE OF BRADYSEISM AT CF?

The ultimate heat engine that drives bradyseism at CF is the deep magmatic system at >7.5 km depth. The surrounding deep fluid environment proximal to the cooling magma body is similar to that documented in magmatic-hydrothermal ore deposit systems associated with porphyry copper deposits (e.g., Burnham, 1979; Fournier, 1999; Becker et al., 2019) (Fig.2). *Bradyseism is a cyclical phenomenon that can last for millennia and is not a precursor to a volcanic eruption because it is driven by the transient connection between the deeper lithostatic reservoir and an overlying more permeable hydrostatic one, and does not require new magma to have been added to the deeper magmatic system.* In the magmatic-hydrothermal model of Lima et al. (2021), the ultimate driver of bradyseism includes heat and fluid from the deeper reservoir; the addition of magma from the very deep crust or mantle to shallow depth is *not* an integral feature. Indeed, the mechanism proposed is driven by the geothermal environment, and is not dependent on addition of new magma.

In the hydrothermal model two different processes operate - each at a unique timescale; one is the 10^4-10^5 years timescale associated with magma solidification (and associated magmatic fluid generation and expulsion) (Ingebritsen et al., 2010; Cox et al., 2001). During this long timescale process the brittle-ductile transition migrates downward as magma cools and crystallizes (see Becker et al. 2019, their Fig. 2). The second shorter timescale (1-10^2 years) is intrinsically episodic and associated with fluid migration and concomitant transient fracture propagation events that compromise the mechanical integrity of layer B, connecting the lower lithostatic reservoir with the upper hydrostatic one (Fig. 2B and 2C). Connectivity between the reservoirs is enhanced or is dampened by opening of fractures to increase permeability or by mineral precipitation (e.g., deposition of silicates, sulfates. carbonates, and sulfides) and, hence, permeability decrease (Fig. 2D). The pervasive zoning of the epidote supergroup minerals observed in drill cores records the episodic nature of hydrofracturing and the pulsing of geothermal fluids (Belkin and De Vivo, 2023).

When a hydrous melt becomes saturated in H_2O and exsolves a magmatic H_2O phase, the volume of the system (crystals + melt + fluid) increases significantly at constant pressure. At pressures of 100-200 MPa, the system volume change can be 50% or greater, and even at 0.6 GPa (roughly 20 km depth) the volume of the system (crystals + melt + H_2O) will increase by about 10% (Burnham, 1972, 1985), owing to the large difference between the partial molar volume of H_2O in the melt compared to the molar volume of the separated magmatic H_2O phase. If the system is unable to expand to accommodate the volume increase (as in the case of magma that is surrounded by impermeable and rigid crystallization products), pressure increases. In an isochoric process, large amounts of mechanical energy are stored in the magma chamber (Fig. 3). This energy leads eventually to fracturing (via hydrofracturing) allowing the magmatic aqueous phase and, in some cases, magma, to escape into the overlying rocks (Bodnar et al., 2007; Lima et al., 2009; Lima et al., 2021). The decrease in H_2O /CO_2 ratio of fumarolic fluids (Chiodini et al., 2015; 2021) is interpreted to represent addition of magmatic CO_2 to the hydrothermal system and indicates that fluids do indeed escape. Because the magmatic fluids expelled are quite hot, a sharp temperature front is present and migrates at a speed on the order of Darcy flow rate of order $v \sim \frac{\rho_f K g \alpha_f \Delta T}{\eta}$ where ρ_f, K, **g**, α_f, ΔT, and η represent the fluid density, permeability, acceleration due to gravity, fluid isobaric expansivity, characteristic temperature difference between upper and lower reservoirs and fluid viscosity, respectively. Adopting typical values for H_2O at 0.1GPa (~3 km depth) and 400 ℃ (Haar et al., 1984) of 693 kg/m^3, 10^{-3} K^{-1}, and 8x10^{-5} Pa s for density, expansivity and viscosity, respectively, and setting $\Delta T = 400\,K$ and K = 10^{-13}m^2 gives a percolation (Darcy) velocity of $v \approx 110\,m/year$. This shows that ground deformation takes place on a timescale consistent with observed uplifts of a few years and not on the magmatic timescale on the order of many thousands of years. Quantitatively, Bonafede (1991) has noted the thermo-poroelastic deformation associated with the advection of superheated steam can easily provide uplifts on the order of 1 meter on a short timescale, consistent with observations. Finally, it is noted that if fluid escape is very efficient, the volume change associated with magma crystallization is negative since solid (crystals), being denser, occupies less volume than melt and detumescence (collapse) rather than tumescence (uplift) occurs. The value of permeability (10^{-13} m^2) used to determine the above characteristic Darcy velocity is a mean value typical of geothermal areas (e.g., Nield and Bejan, 1992). However, on shorter spatial and time scales precipitation and/or dissolution of hydrothermal phases due to decompression and cooling of expelled fluids will ensure a complex permeability field that evolves both spatially and temporally, a topic for future work.

4.WHY IS THE RECENT UPLIFT RATE SLOWER THAN THAT IN 1982-1984?

The current unrest shows an uplift rate that is about 8 times lower than in 1982-84, and the seismically released energy, located in a restricted region below the Solfatara-Pisciarelli area (Danesi et al., 2024), is an order of magnitude lower than in 1982-84. As discussed above, if the CF magmatic-hydrothermal system is completely closed, the mechanical energy associated with magma crystallization (Fig. 3) would be capable of generating a maximum uplift of 40 m (Lima et al., 2009). It is very unlikely that a natural system such as CF that is extensively fractured including numerous lateral faults (Capuano et al., 2013) could be closed with respect to fluid loss. Indeed, the presence of active fumaroles and hot springs in the region (Scotto di Uccio et al., 2024) is *prima facie* evidence for open system behavior. When fluid is allowed to escape, the amount of uplift is reduced in proportion to the amount of fluid leakage from the deep reservoir, recharged by fluids that are exsolving from the magma (second boiling). Chiodini et al. (2015; 2021) highlighted that fumarolic activity in the Solfatara-Pisciarelli area (Fig. 1) since 2005 has significantly increased, with fumarolic gases showing the presence of elements and compounds of magmatic origin, such as CO_2. This is consistent with the advection of hot fluids and associated thermo-poroelastic deformation discussed above. In addition, Danesi et al. (2024) show that seismicity occurred west of Solfatara in 2005-2023, with the cluster of events developing at depths of 2-3 km beneath

Solfatara starting in 2005, with clusters of shallow earthquakes extending from depths of 0.5-1 km toward Pisciarelli.

The current uplift rate can be interpreted to reflect the activation of a fault system in the Solfatara-Pisciarelli area (Scotto di Uccio et al., 2024) that allows the CF hydrothermal system to discharge energy by escape of fluids and preventing the buildup of high poro-elastic pressures and associated enhanced ground deformation. In previous bradyseism crises these fractures were not active (Danesi et al., 2024), and uplift was greater than in the current crisis. This is the only difference between the former and present bradyseism events so far recorded. The cyclic nature of the ongoing bradyseism is closely related to the complex geological, tectonic, and stratigraphic upper crustal structures that govern spatial and temporal variations of the subsurface permeability and distribution of fluid pressure associated with migration of fluids. Earthquake swarms in the Solfatara-Pisciarelli area and the increase of fumarole outflows are the manifestation of enhanced fluid discharge (compared to 1982-84) from the hydrothermal reservoir contained between impermeable layers A and B that significantly reduces the uplift rate of the ongoing bradyseism event.

The rate of subsidence is a function of the extent of brecciation (fracturing) of the impermeable layer B. The extent of fracturing does not represent a competition between fluid escape and injection rates because the release of magmatic fluid is continuous over time. In the shallow hydrothermal reservoir, seawater and meteoric water can mix with the magmatically-derived fluids intermittently, thereby introducing another layer of complexity. In 1985 (Fig. 2C), extensive fracturing of the impermeable barrier occurred, and subsidence resulted. In the immediate future, it is much more likely that the uplift will continue for some years at a rate that can vary depending on the efficiency of fluid discharge at Solfatara Pisciarelli. Thus, in a completely natural way, the CF system is "*breathing*" and has self-attenuated the effects of bradyseism.

5.IMPLICATIONS

Having gained an understanding of the processes that lead to bradyseism at CF - that is, the rate and extent of uplift and subsidence is controlled by a natural valve system at depth that is represented by impermeable layer B (Fig. 2) as well as the presence of subsurface conduits (faults) that allow fluids to migrate laterally. As such, it may be possible to control the flow of fluids in the Solfatara-Pisciarelli area with the aim of minimizing future periods of ground deformation and seismicity. By drilling boreholes that penetrate impermeable layer B, high permeability zones that allow continuous transfer of fluids from the deeper to more shallow reservoirs can be introduced. As such, pressure would not build up (or, at least, the extent of pressure build up would be reduced) beneath layer B and thermo-elastic deformation would be limited. Targeted pumping of subsurface fluids would facilitate drainage of the system and minimize hydrofracturing and seismic activity in general. Considering that the input of rainwater increases seismic tremor activity (Scafetta and Mazzarella, 2021), it is clear how important drainage is in the surface aquifer as well.

The geothermal industry has demonstrated that it is possible to drill geothermal wells to at least 5,000 m and to temperatures up to 500°C (Rivera and Carey, 2023) including operations in supercritical geothermal systems (Reinsch et al., 2017). Drilling deep geothermal wells can be accomplished at a cost that is much less than the cost of damage, and risk to human health and safety, associated with periods of unrest at CF. In the 1970-80s, numerous boreholes were drilled in CF to explore for geothermal resources (Fig. 1). For example, well SV1 reached a total depth of 3,040 m (AGIP, 1987; De Vivo et al., 1989). The risk linked to drilling can be managed with modern technologies that have been developed to exploit very high temperature (≤500°C) geothermal reservoirs (c.f., Rivera and Carey, 2023), and the proposed objectives would not require the re-location of residents of CF. Bradyseism could be managed and controlled by careful geoengineering. In any case, concerted efforts are needed to bring together geoscientists, engineers, government officials, and the general public to address and solve this ongoing problem using existing knowledge and tools. Through dedicated efforts it is possible to manage the forces of nature, and with a cost/benefit ratio that is very favorable for the many thousands of people living within the CF volcanic complex.

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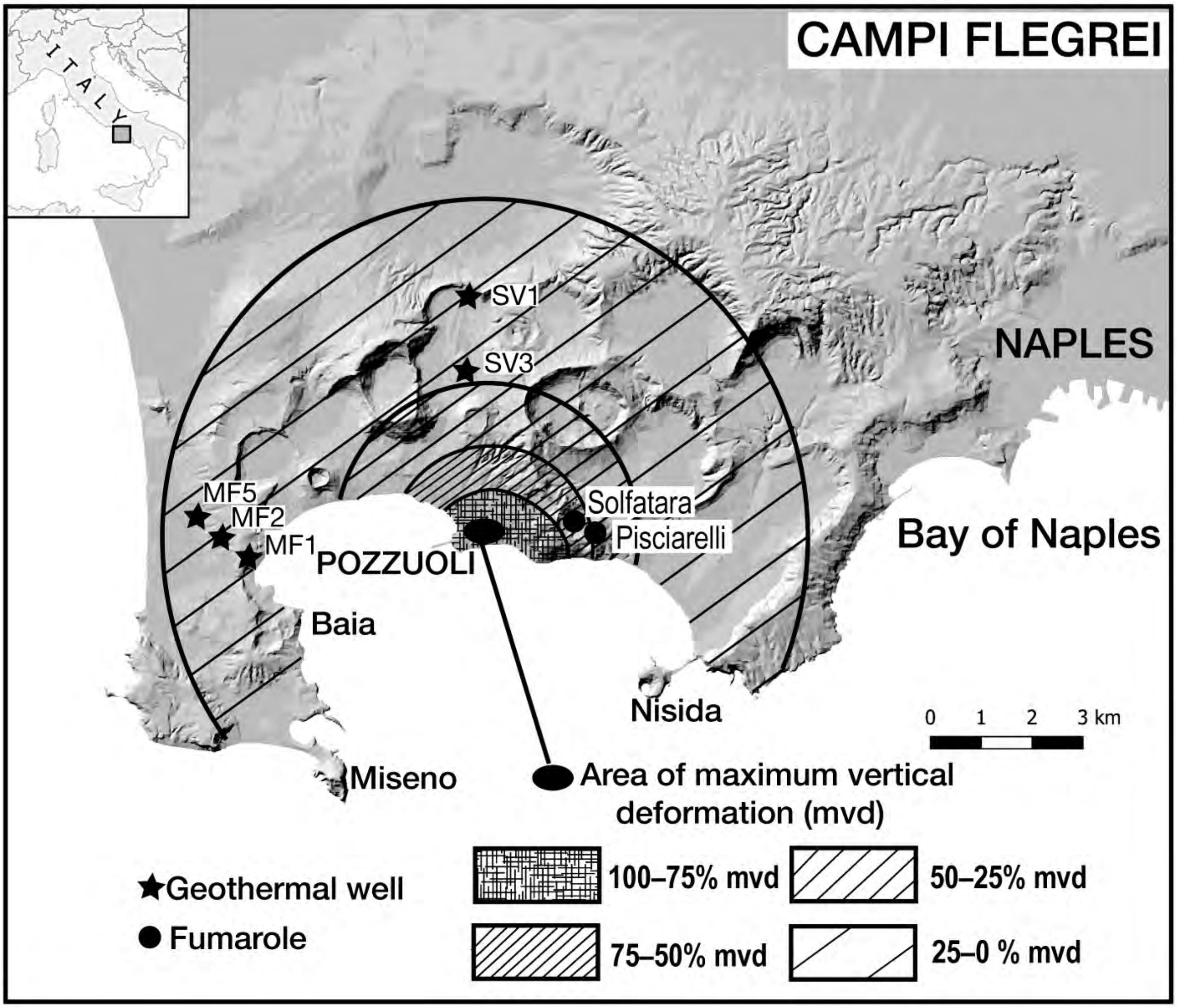

Figure 1. Map of Campi Flegrei showing the area of maximum vertical deformation (mvd), the areas of decreasing vertical deformation around Pozzuoli, and locations of geothermal wells (M1, M2, M5, SV1, SV3) drilled by AGIP-ENEL (AGIP, 1987) (modified from Todesco and Berrino, 2005).

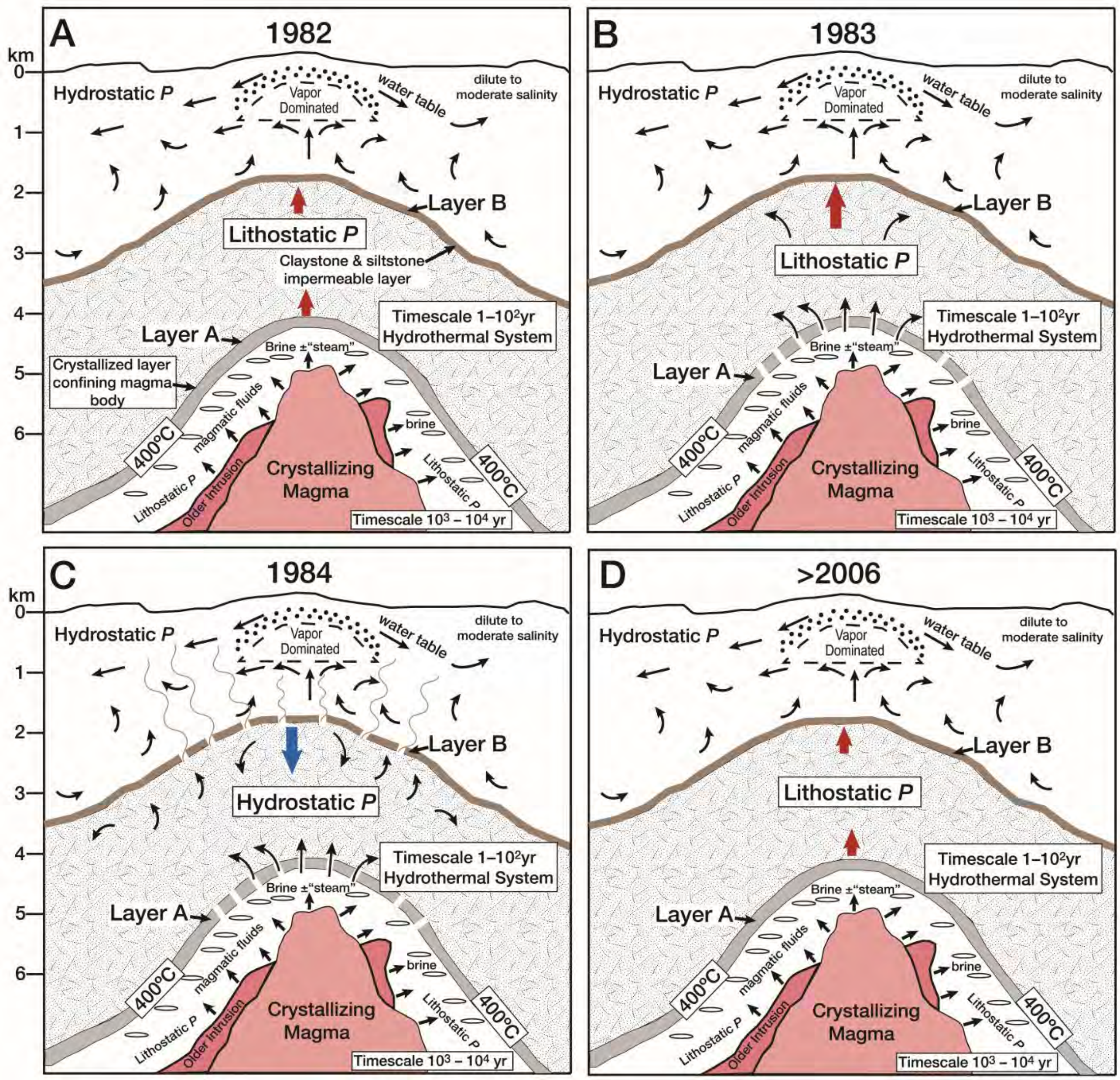

Figure 2. Layer A marks the "brittle-ductile transition zone" that separates the magmatic system (at a depth> 5 km) from the overlying hydrothermal system which, in turn, is confined by impermeable layer B at a depth of about 2.5-3 km (see Lima et al. 2009 Fig. 3). When the system is closed and fluids are retained at depth, uplift as occurred in 1982 and 2005 takes place. Conversely, when brecciation occurs and fluids migrate upwards via a fracture permeability, subsidence occurs. The engine that controls bradyseism is always the deep magmatic system where heat is converted to mechanical energy by fluid expansion as shown in Figure 3 (modified from Lima et al., 2021).

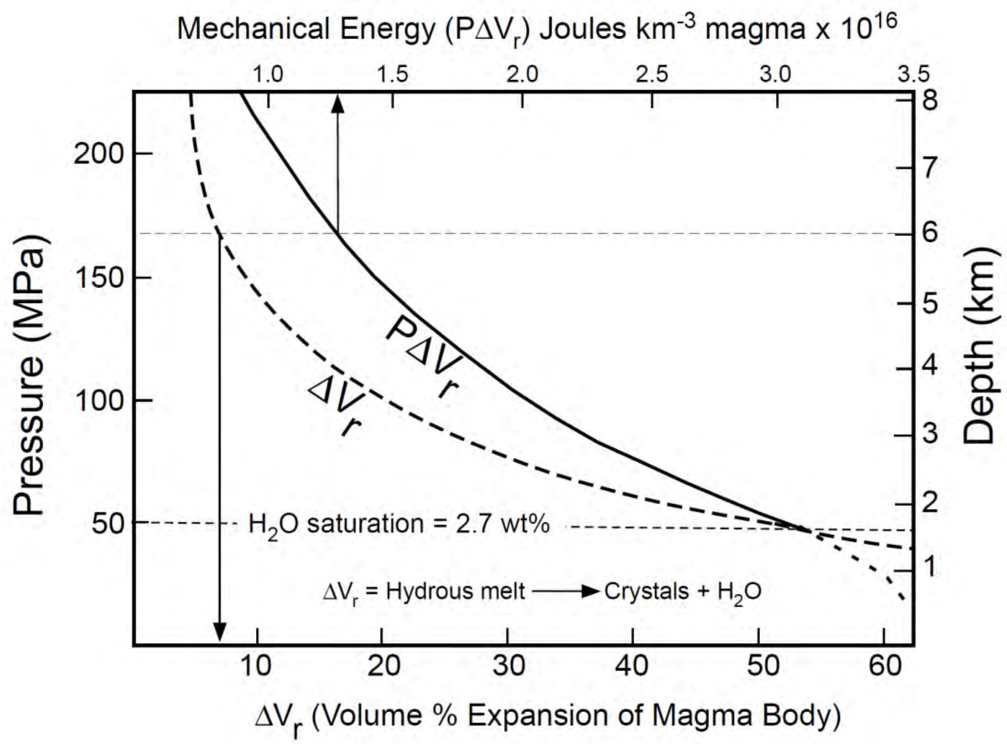

Figure 3. Volume change (ΔVr) and mechanical energy (PΔVr) associated with crystallization of an H_2O-saturated melt and exsolution of an H_2O magmatic fluid. The calculated values assume a closed system (Bodnar et al., 2007, modified after Burnham, 1972, 1985).