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Planetary Science

C004
Volcanism and the Mantle

Campi Flegrei

1. Introduction

Location:

Lat: 40°49’43”
Long: 14°23’37”

Campi Flegrei is a nested caldera complex located in the Campanian plain region of south central Italy and forms part of the Roman co-magmatic province which is a volcanic chain that characterises the western coast of the country.

The Campanian Plain

Fig 1. Map of Italy

1.1 Tectonic setting

The Campanian plain is contained within a graben bounded by Mesozoic carbonate platforms which formed via back arc rifting during the Pliocene and Pleistocene (Barberi *et al.* 1991) in response to the cessation of south-west dipping subduction in the Ionian arc to the east of Italy.
The plain has been volcanically active for at least the last 50 000 years (according to potassium/argon dating of lava domes) with the activity concentrated in Campi Flegrei, on the island of Procida and at Vesuvius.

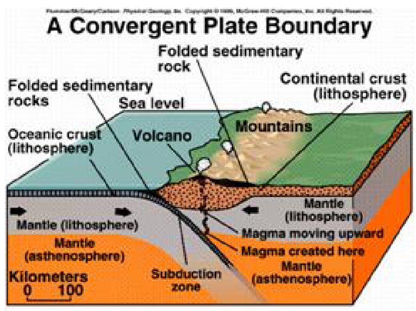

Fig 2. A convergent plate boundary.

1.2 Morphology

The main caldera at Campi Flegrei is 12 – 15km across and is thought to have been formed during an eruption which produced a deposit referred to as the Campanian Ignimbrite. It lies half onshore and half offshore, centred on the town of Pozzuoli and contains within it the products of all subsequent eruptions.
The floor of the crater is pock-marked with smaller calderas and cones from other, later eruptions and these are clearly visible in from space in satellite images.

1.3 Geology visible today

The geological map below shows the extent of mapable geology visible today. This is a heavily populated area of central Italy which helps to obscure the deposits present.
By far the best preserved of the eruptions in Campi Flegrei in terms of outcrop are the Neopolitan Yellow Tuff deposits, mostly seen in the north of the area. Material older than this is hard to come by and is generally only visible along the coast and in the Neopolitan Yellow tuff caldera walls where a thin veneer has been preserved.
Several products from more recent eruption have been preserved and are found locally to their eruptive centres as would be expected.

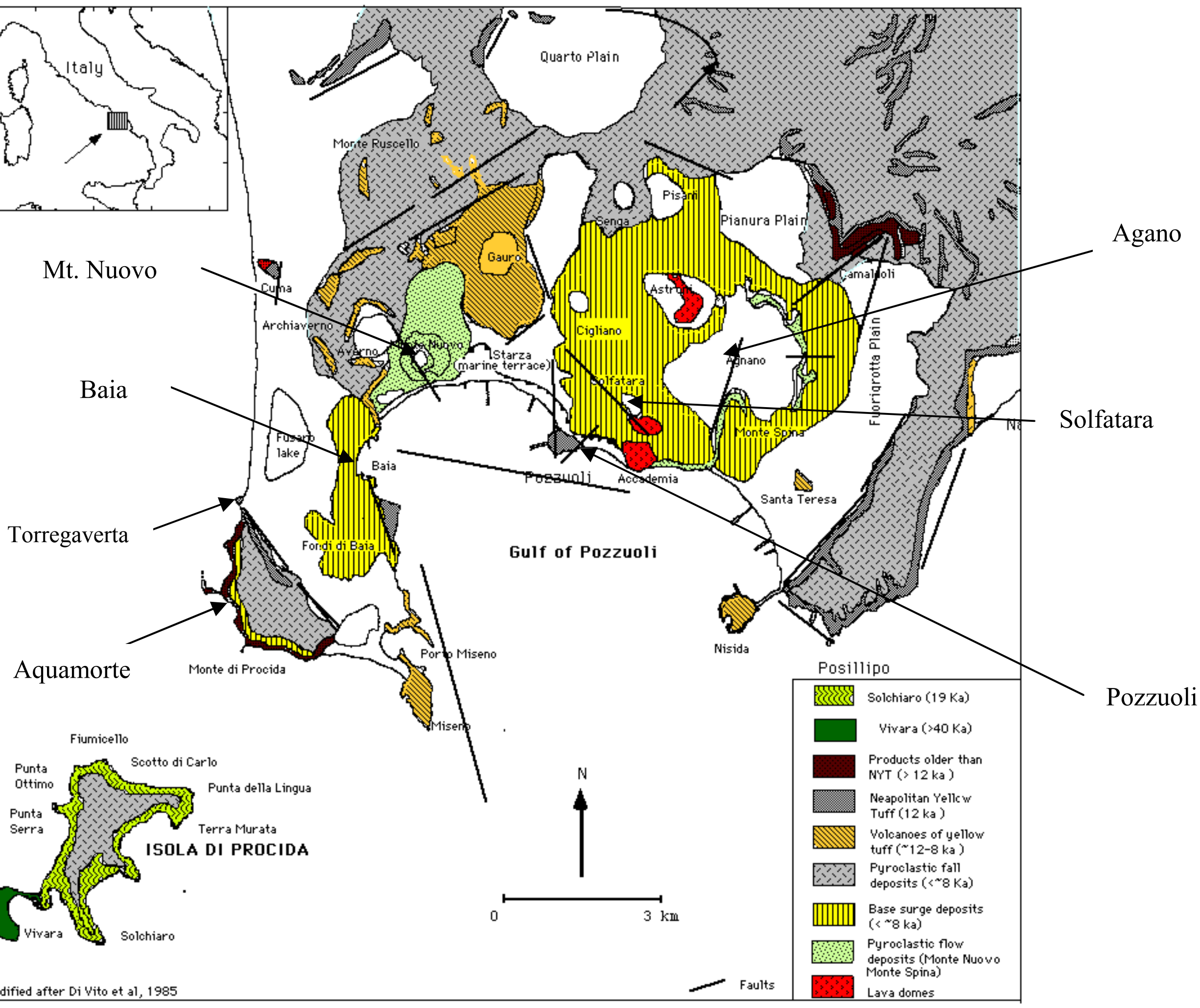

Fig 3. Geological map of Campi Flegrei. (after Di Vito *et al.* 1985)

1.4 Structural theories

Over the time that Campi Flegrei has been studied there have been several theories put forward as to the structure which lies beneath the caldera. The current favoured theory is summarised by Rosi *et al.* 1983 and Kilburn 1986:

This theory uses the following evidence deduced from deposits of previous eruptions, their volume, appearance, distribution and the age of the crystal and soil components between the eruptions. They conclude that there have been intermittent eruptions for the last 50,000years with a dominant sequence of events approximately 34,000 years ago which have produced all together over 250,000million tonnes of debris spread over an area of 1.5million km^2 , producing the Campanian Ignimbrite and the outer caldera structure we see today.

Since then intensity of eruptions has decreased with time and the vent locations have also drifted over this period from the edge of the caldera, to the current centre directly below the town of Pozzuoli. This is interpreted as a shrinking of the magma chamber below Campi Flegrei without replenishment as it cools which can be seen in the magma chemistry. The magma chemistry suggests a magma chamber with a hotter interior of trachybasalt (~1200C) enclosed by a cooler zone of filial trachytic melts. (~850) It is the upper layers of these from which the primary eruption products are derived.
This postulates a current magma chamber which is very currently small, perhaps only 3km across which therefore may not have been detected with modern geophysical techniques as it is simply too small to be resolved by current techniques.
The geophysical data has been used by several workers to theorise a caldera fed through a ring fracture which attaches to the magma chamber via a cone sheet structure.(Barberi et al. 1991)

2. Eruptive history

The activity in Campi Flegrei is characterised by explosive eruptions with effusive activity only contributing a minor part to the overall eruption products. In general the volume of material produced by a single eruption event has decreased with time as can be seen from the table below.
The eruptions are Plinian and Strombolian in style and strength with the Plinian eruptions producing the largest volumes of material and distributing them over the largest areas. The area is also an example of a system dominated by phreatomagmatic eruptions in which magma interacts with surface water, primarily sea water or deep aquifers beneath the caldera and there is evidence that activity in the area changed from submarine to subaerial shortly before the eruption of the campanian ignimbrite.
The plinian eruptions follow the same sequence of events as the eruptions of Vesuvius with basal surges and fall units, the final ash unit being formed when water invades the magma chamber.

Vent Location	Deposited volume (km3)	Age (BP)
Monte Nuovo	0.02	460
Senga	0.06	2431
Astroni	0.5	3298
Cupi di Monte Olibano	0.08	3472
Monte Senga (Fossa Lupara)	0.15	3800
Astroni + Senga	0.29	3830
Pigna, St Nicola, Monte Spina	0.08	3958
Capo Miseno, Baia, Fondi di Baia	0.4	3958
Agano-Monte Spina	0.18	4065
Solfatara	0.01	4500
Monte Olibano (Accademia)	0.29	4500
Montagna Spaccata, Concola, Fondo Riccio	0.16	5903
Minopoli	0.01	6944
Archiaverno	0.3	7639
Sartania, Fondi di Baia	0.1	8600
Pomici Principali	0.5	9722
Gauro	0.7	10069
Vivara	0.01	10500
Minopoli	0.01	11050
Neapolitan Yellow Tuff	40	12847
Solchiaro	0.5	16701
Campanian Ignimbrite	100	32813
Fiumicello, Terra Murata	0.1	38889
Vivara	0.06	40000

2.1 Pre Caldera Activity

There is evidence for volcanic activity in the Campanian Fields from 49,000 years ago to the present with the earliest evidence in the form of lava domes. An example of this can be seen at Aquamorte where there is a small lava dome overlain by later pyroclastic units seen in fig. 5. This is typical of the pre caldera activity.

Lava
Dome

Fig 4. A trachytic pre caldera dome overlain by pyroclastic material from the Campanian Ignimbrite eruption.

Geothermal wells and outcrop suggest that the pre-caldera activity at Campi Flegrei consisted of mainly trachytic and latitic lavas, tuffs and tuffites interbedded with silty and marly sediments. (Rosi et al. 1991)

2.2 The Campanian Ignimbrite Eruption.

The first major eruptive event that we have evidence for occurred 34,000 years ago with the eruption of the Campanian Ignimbrite which formed the largest of the calderas we can see today and marks the outer bounds of Campi Flegrei. This was to date the largest eruption at Campi Flegrei, producing approximately 100km3 of pumice alone.

The Campanian Ignimbrite has the average composition of an evolved trachyte with some spatial variation in the composition of scoria and pumice suggesting a zoned magma chamber with the later products becoming steadily more mafic.
There are lateral facies variations in the form of a colour change from a poorly welded grey deposit to a more welded yellow deposit.(Scandone *et al*. 1991) – this is explained as being due to secondary mineralisation and zeolitization.
In general the deposit is composed of pumice, scoria and small amounts of lithics embedded in an ashy matrix which becomes more welded as you travel down through the deposit.

The Campanian Ignimbrite deposits outcrop in only a few places, one of which is Torregaveta on the coastal road between Pozzuoli and Miseno.

Fig 5. Campanian Ignimbrite deposits at Torregaveta.

The Campanian Ignimbrite can be summed up very generally as a yellow tuff.
The oldest units of the Campanian Ignimbrite are called the Torrefranco tuffs which are a sequence, 50m thick, of ash beds showing cross laminations and alternating layers of pumice and scoria interbedded by palaeosols. (Scandone *et al.*1991)

Above these is the Piperno-Museum breccia formation, famously named and studied by Johnson – Lavis. This is an unwelded, poorly sorted breccia containing welded piperno scoria layers within in. There is an abundance of coarse (up to 1m) lithic blocks of varying composition most of which are composed of lava with some hydrothermally altered blocks.

A pyroclastic flow origin is suggested for this unit because:

1. The deposit thickens in topographic depressions.

2. The deposits show lamination and cross bedding.

3.There are fumarolic piles.

(Scandone *et al.* 1991)

From these and other petrographic and chemical data the Breccia Museo has been interpreted as a proximal facies of the Campanian Ignimbrite erupted from a ring fracture system and the variety of lithic fragments suggests that a wide range of pre caldera rocks were included in the Breccia Museo. However there is some evidence from the carbon isotope dating that this may be a later small tuff eruption but there is still some debate on this subject. (Lirer *et al.* 1991)

2.3 Post caldera activity

There were 3 periods of activity at Campi Flegrei post the formation of the main caldera structure.

1. 35 – 10 500 years ago

After the main caldera forming event the caldera was flooded by the sea and gradually filled up with a sequence of submarine lavas and tuffites, the last of which was erupted approximately 11,000 years ago. The deposits are mainly yellow hydroplinian tuffs. A large proportion of the material from this period has been hydrothermally altered and so it is difficult to date these deposits using radiometric methods.

The second major eruption occurred around 12,000years ago in the south of the main caldera and produced a smaller caldera 6km across, centred on the modern town of Pozzuoli, and erupting the Neapolitan yellow tuff deposit.

Neopolitan Yellow Tuff.

The eruption which formed this deposit was phreatoplinian in style and consists of alternating layers of pumice and ash overlain by a sequence of surges and pyroclastic flows.
Outcrops of this material are found much more abundantly than deposits from any older event, especially in the caldera wall and within the caldera itself.
This eruption marks the end of volcanic activity outside the caldera margins.

There is some controversy about the origin of the Neopolitan yellow tuff. There is still a debate as to whether it is a deposit from a single vent or the product of several shallow marine vents located around the rim of the caldera.

2. 10 500 – 8000 years ago

More recently the eruptions have all been subaerial. In this period the activity was concentrated in two main areas around Baia and Agano. (Scandone *et al.* 1991) The largest event in this period was an eruption at Agano in which a plinian style event lead to the formation of the small 3km Agano crater.
This period also saw the migration of the vents of subsequent eruptions across the caldera floor from the rim toward the centre which is roughly at Pozzuoli. The exceptions to this were centres which produced the lesser basaltic units rather than the main bulk of the deposits which are the trachytic products of the more central vents.

3. 4500 – present

This period was preceded by uplift in the vicinity of Pozzuoli as apparent from the level of the Roman harbour which now lies 2m above current sea level. This period was also characterised by two main eruptive zones, primarily eruptions in Mt Nuovo and Solfatara. It is thought that for at least some of this period there was a shallow lake in the caldera floor which lead to hydromagmatic processes being even more common than in previous times.

The eruption of Astroni during this period produced a classic structure seen in Campi Flegrei, a tuff ring. The deposits found here are composed for the most part of pyroclastic surges with a few lesser fall units in association.
The products are composed of vesiculated tuffs, glass fragments and accretionary lapiili.

The formation of Mt Nuovo is the most recent and only recorded eruptive event in Campi Flegrei and it occurred in 1538 AD producing the structure visible in fig. 7 There was approximately 10m of uplift in the century immediately preceding the eruption. Mt Nuovo was a strombolian event and the main deposit is made up of welded scoria and pumice which have an overall K – Phonolitic composition.
The eruption killed 32 people living locally in the town of Tripegole which was completely buried, mainly because there was little warning of the imminent eruption, no seismic activity was detected until two days prior to the eruption – this may simply be because there was not the means to detect the levels of earthquake magnitude and so the eruption prediction has become easier or may be a sign that eruption prediction in Campi Flegrei may be more problematic than first anticipated.

Scoria
The scoria deposits of Mt Nuovo are black in colour and formed of large clasts (up to 10s of cm sized) in a matrix of poorly sorted and well cemented sand sized particles which weather to a blue/grey colour.

Pumice
The pumice is white with no obvious glass shards. There are lithic fragments in the pumice layers which along with the pumice are well rounded.

Both these layers are interpreted as being flows with the more vesiculated pumice layer being erupted first. There was also some water interaction at this eruption with eye witnesses reporting heavy falls of mud (Paracsndola 1946) in the area.

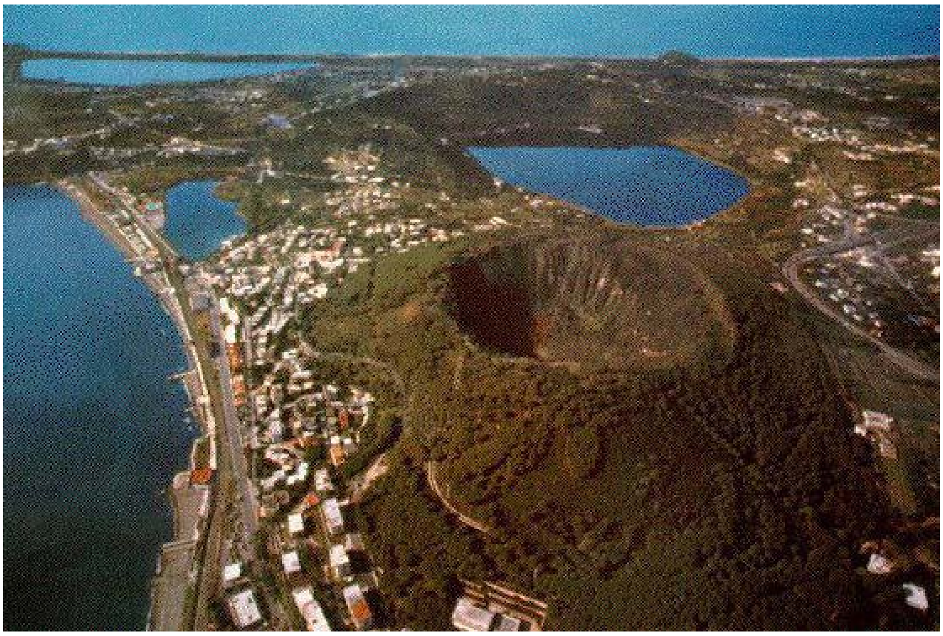

Fig 6. Mt Nuovo –The most recent eruption in Campi Flegrei.

Solfatara

Solfatara formed between 3.7 and 4.6 thousand years ago and is a hydrothermally altered tuff cone which then suffered a typical post eruption caldera collapse. It is the only currently active centre in Campi Flegrei.

It is quite wide for its height which has been taken as evidence for shallow hydrothermal activity in Campi Flegrei.
In the caldera there are active fumaroles, the biggest of which is the "Bocca Grande". In the centre is a mud pool with a fissure from which meteoric water and clay material combine to form the mud. The elemental compositions of the mud suggests that it originates at temperatures of around 170 – 250C. It contains trace amounts of Barium, Sodium, Magnesium, Vanadium, Arsenic, Zinc, Antimony, Iodine, Rubidium amongst others and Bocca Grande is surrounded by deposits of rare Sulphur compounds including Realgar, Cinnabar and Orpiment.

Solfatara is also the home for several colonies of extremophile bacteria in the form of the green and grey algae Bacillus acidocaldarius and Sulfolobus which only live at temperatures above 90C.

Solfatara has been used throughout history to exploit its volcanic products, the Romans used it as a sauna and thought that that the waters of Solfatara had healing properties. They called it Forum Vulcani.

In the 1700s it was mined to produce the locals with a supply of Alum and as far back as 1900 the activity was being measured by the Freidlaender observatory which was destroyed, somewhat ironically, by an earthquake. Today the Vesuvius observatory has several stations set up to measure the seismic and fumarolic activity in the area as part of the ongoing hazard monitoring in the Phlegraean fields.

3. Geophysical studies of Campi Flegrei

3.1 Gravity and Magnetics

Extensive gravity studies have been carried out in the Campi Flegrei. The largest survey utilised 770 ground stations and 500 sea stations deployed over the entirety of the caldera. The gravity surveys have shown a residual negative bouger anomaly (10mGal) in the floor of the caldera centred on Pozzuoli, a mass deficit interpreted as, a residue of the caldera collapse. (Nunziata and Rapolla 1981)
There is also a positive anomaly found to lie along the caldera edges due to the isolated lava bodies.

An aerial magnetic survey of Campi Flegrei was carried out in 1985.
The pre caldera volcanic rocks produce the largest positive anomalies as they have the highest magnetic susceptibility. The caldera structure is less evident from the magnetic data as there is not much of a contrast between these rocks and the pre caldera volcanics.

3.2 Seismicity and ground movement.

Between 1982 and 1985 there was a period of prolonged seismic unrest. There were earthquakes in the coastal region around Pozzuoli which were all contained within the caldera boundaries. These earthquakes had depths ranging from a few 100m to 5km and a maximum magnitude of 4 on the Richter scale.
Most of the earthquakes were single events but there were some swarms to the west of Pozzuoli which were the shallowest of the earthquakes to occur during this period.
The deepest and highest magnitude earthquakes occurred in the east.

In 1988 Aster and Meyer carried out seismic tomographic studies and found that the centre of the caldera had a high Vp/Vs ratio and generally low Vs and Vp values, suggesting that the area is underlain by a highly fractured incompetent medium saturated with water thought to be brecciated material which aggregated in caldera formation. They also found what they have interpreted as a ring fault.

Fig. 7 The Temple of Serapis, Pozzuoli.

Campi Flegrei is an area which suffers from bradyseismicity, this was most famously illustrated by Lyell using the Roman columns in the "Temple of Sepapis" in Pozzuoli.

Since 1800 the whole region of Campi Flegrei has been sinking with the maximum rate of subsidence concentrated at Pozzuoli.
In 1970 the area began to rise forming a dome centred on Pozzuoli and this continued until the end of the period of unrest in1986. Campi Flegrei is currently sinking again.

4. Volcanic Hazards

It is thought that the Campi Flegrei caldera is still magmatically active and that the caldera may erupt again in the near future.
At the present time the caldera is subsiding overall but the area outlined by the Neopolitan Yellow Tuff caldera is currently resurging. (Orsi *et al.* 2001)

There have been 2 recent periods of unrest 1969 -72 and 1982 – 4 which are thought to be the result of interaction between ductile expansion and deflation of the geothermal system and brittle fracturing of the shallow crust above the magma chamber due to the arrival of small batches of magma in the chamber which are hotter than the resident magma.

The most recent period of unrest started in 1984 and lasted 18 months coming to a close in the January 1985. A bulge 1.8m high at its peak appeared over an area of 80km^2 centred on Pozzuoli. It was feared that the unrest at this time may be an indication of the filling of the magma chamber which lies under Pozzuoli. During this time the harbour became shallower leading to a decline in fishing and tourism in the area also suffered.
The ground movement prompted the regional authorities to build Monte Ruscello, a new community 5km from Pozzuoli where half the population where evacuated to, which may seem a little bit close, designed for 20,000 and has now effectively increased the population by this much thereby increasing the risk from an eruption somewhat unnecessarily.

Currently 350 000 people live in the active portion of the caldera with a further 1 million in the neighbouring Naples area which of course increases the hazard of the caldera and the difficulty of clearing the area in the event of an eruption.

The caldera is continually monitored by a system of sensors which monitor seismicity, subsidence and hydrothermal water temperature amongst other things. These are maintained by the Vesuvius Observatory.

A major problem in the detection of future eruptions in the Campi Flegrei area is that magma movement in the area seems to be aseismic and so one of the forecasting tools at the disposal of hazards experts may not be available in this case and so an eruption time cannot be accurately defined but we can hypothesise the structural conditions necessary to allow the passage of magma to the surface.

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