The possible role of extensional faults in localizing magmatic activity: a crustal model for the Campanian Volcanic Zone (eastern Tyrrenian Sea, Italy)

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Abstract: Three crustal geological sections of the Campanian Volcanic Zone (Italy) were reconstructed by integrating basin architecture and deep well stratigraphies. In addition, mapping of the fault system and of large-volume ignimbrites was carried out. A linked fault system has been identified, which was responsible for asymmetric subsidence contemporaneous with the eruption of ignimbrites. Late Quaternary extension is characterized by a WNW–ESE stretching axis, NNE–SSW normal faults and reactivation of inherited structures. Structural, stratigraphic and palaeogeographical analyses reveal evidence for up to 750 m of subsidence, which has occurred at a mean rate of up to 4.9 mm a⁻¹ over the past 154 ka. These rates suggest that extensional tectonics was responsible for the regional subsidence. A 6 km deep seismic reflector was associated with a magmatic reservoir underlying Campi Flegrei. By matching the structural and stratigraphic architecture with published geophysical and geochemical data a crustal tectonomagmatic model was constructed that displays high-angle faults that root into a low-angle detachment, which in turn roots into a deep sill-like magma reservoir. This model suggests the possible role of extensional faults in localizing magmatic activity, as faults controlled magma rise from deep to shallow reservoirs and to the surface during ignimbrite eruptions.

Supplementary material: Seismic reflection profiles and interpretations are available at http://www.geolsoc.org.uk/SUP18451.

The interplay between lithospheric extension and magmatism affects magma migration within the crust and regulates the frequency, volume and location of volcanic eruptions (e.g. Gudmundsson 1995; Singh et al. 2006; Ferguson et al. 2010). During continental extension, decompression of the asthenosphere beneath the rift triggers partial melting in the mantle leading to the emplacement of magma bodies at the base of or within the crust (Ruppel 1995). Extensional faults, owing to their high permeability, can tap crustal magma bodies and are a preferred site of magma migration from the reservoir to the surface (Lara et al. 2006). Knowledge of the architecture of the fault system feeding volcanic eruptions, and of the location of crustal magma chambers, permits the volcano-tectonic evolution of an active volcanic region to be defined and allows the site of future eruptions to be predicted (Ferguson et al. 2010).

An ideal place to investigate the interplay between lithospheric extension and magmatism is the Campanian Volcanic Zone (Italy), which features a complex magmatic system within an active extensional tectonic setting. In the Campanian Volcanic Zone, corresponding to the Campanian Plain and the Bay of Naples (Fig. 1), volcanic activity over the last 290 ka has built the volcanoes of Campi Flegrei, Ischia, Procida and Vesuvius and involved the eruption of many large-volume trachytic ignimbrites (Rosi & Sbrana 1987; Santacroce 1987; Vezzoli 1988; De Vivo et al. 2001). The Campanian Volcanic Zone is one of the most high-risk volcanic areas in the world and a better understanding of the relationship between tectonics, magma chambers and volcanism is crucial for hazard assessment studies.

Previous structural and stratigraphic studies of this region have analysed the basin infill and fault patterns (e.g. Ippolito et al. 1973; Milia & Torrente 1997, 1999; Milia 1999; Acocella & Funiciello 2006), and the link between extensional tectonics and eruptive vents (Milia & Torrente 2003, 2007; Rolandi et al. 2003; Bellucci et al. 2006; Torrente et al. 2010). Although a wealth of geophysical and geochemical information (e.g. Ferrucci et al. 1989; Belkin & De Vivo 1993; Zollo et al. 1996, 2008; Wholetz et al. 1999; Auger et al. 2001; Della Vedova et al. 2001; Pappalardo et al. 2002, 2008; De Astis et al. 2004; Piochi et al. 2006; De Natale et al. 2006; Marianeli et al. 2006; Lima et al. 2007; Piana Agostinetti & Chiarabba 2008; Scaillet et al. 2008; Nunziata 2010) has provided the fundamental constraints for the construction of a tectonomagmatic model of the Campanian Volcanic Zone, a holistic view of the crustal system of this region taking into account the fault architecture, magma reservoirs and ignimbrite eruptions has yet to be produced.

The Campanian Volcanic Zone was studied using an integrated geological–geophysical database (Fig. 2). Here we show results from an integration and reanalysis of structural, stratigraphic, geochemical and geophysical data supporting evidence of a link between lithospheric extension and magmatism in the Campanian Volcanic Zone. Three crustal geological sections were reconstructed and a mapping of the fault system and the large-volume ignimbrites, with special focus on the crucial Campi Flegrei area, was produced.

Dataset and methods

The Campanian Volcanic Zone has been investigated by seismic reflection, offshore in the Bay of Naples, and a combination of geological survey, outcrop stratigraphy and borehole data, collected from drilling companies, local authorities and the
literature (e.g. Ippolito et al. 1973; Rosi & Sbrana 1987; Bellucci 1998; Brocchini et al. 2001), for the subaerial part (Fig. 2).

A series of closely spaced single-channel and multi-channel seismic reflection profiles were collected in the Bay of Naples. The single-channel profiles were acquired using a 16 kJ Multi-spot Extended Array Sparker (MEAS) system, a 1 kJ Surfboom system, and a 0.2 kJ multi-electrode Sparker system. All seismic sections were recorded graphically using a continuous paper feed with vertical recording scales of 0.25 s for the multielectrode Sparker; 0.25 and 0.5 s for the Surfboom; and 1 and 2 s for the MEAS. Ship positioning was determined using LORAN C for MEAS, Micro-Fix Racal for the Surfboom (with a positional accuracy of 1 m), and a differential global positioning system (GPS) system (with a positional accuracy of 1 m) for the multi-electrode Sparker. The best vertical resolution was c. 6 m for MEAS data, and 1 m for the Surfboom and multi-electrode Sparker data. Multi-channel seismic lines were acquired using a double water gun and a 24-trace streamer. The maximum

Fig. 1. Structural map of the Campanian Volcanic Zone also showing the location of volcanic vents, crustal sections and deep boreholes mentioned in the text. Fine black line marks the present shelf edge of the Bay of Naples; the yellow dotted line corresponds to the palaeo-shelf edge before ignimbrite emplacement; GB, Gaia Bank; MB, Miseno Bank; PB, Pia Bank; PP, Penta Palummo volcano; DB, Mt. Dolce dome; NB, Nisida Bank; BF, Breakaway fault; GF, Gauru fault; CaF, Camaldoli fault; AF, Agnano fault; CoF, Coastal fault; VF, Vesuvius cone fault; TC, Trecase well; SV1, San Vito1 well; SV3, San Vito3 well; CF23, CF23 well; AR, Arenella well; PR, Palazzo Reale well; VO, Volta well. Submarine volcanoes after Milia & Torrente (2003) and Milia (2010). The inset shows a schematic structural map of Italy and Campanian Volcanic Zone location; TS, Tyrrhenian Sea; NAA, Northern Apennine Arc; SAA, Southern Apennine Arc; AF, Adriatic Foreland; the red arrow displays the migration of the SAA over the last 700 ka.
recorded length was 4.5 s two-way travel time (TWT), and the fold coverage was 1200% or 2400%. The data processing sequence included deconvolution, velocity analysis, normal moveout (NMO) stacking, and time migration. These multi-channel profiles were characterized by a high signal–noise ratio with the best vertical resolution being 10 m. Raster image of seismic profiles were converted to segy format and then collected in a dedicated geographic information system (GIS) environment. Line drawing, interpretation of profiles and 3D reconstruction of geological surfaces were performed using Kingdom® software (copyright Seismic Micro-Technology). Seismic stratigraphic analysis was performed using the sequence stratigraphy approach (e.g. Posamentier & Vail 1988; Thorne & Swift 1991), allowing the identification of fourth-order depositional sequences (100 ka), forecast depositional settings, and lithologies. Volcanic and sedimentary units were determined on the basis of the termination of strata and internal and external seismic configurations (Mitchum et al. 1977). The thickness of the volcanic units recognized on seismic reflection profiles was calculated assuming a mean velocity of 2000 m s\(^{-1}\) for tuffs and tuffites during the depth conversion process, as reported from sonic logs of wells that were drilled in Campi Flegrei (Chelini & Sbrana 1987).

**Structural and volcanological framework**

The Tyrrhenian Sea is a Neogene back-arc basin formed by extensional tectonics within the overriding plate of an eastward migrating subduction system, giving rise to the arcuate fold and thrust belt running from the central–southern Apennines to Sicily (lower inset of Fig. 1). Its evolution has been mainly attributed to the rollback of the subducting Apulian–Ionian plate towards the SE (Malinverno & Ryan 1986; Faccenna et al. 1996).

The Campanian Volcanic Zone displays the typical characteristics of a lithospheric extensional zone: thinned continental crust (Ferrucci et al. 1989), normal faults (Milia & Torrente 1997, 1999, 2003; Acocella & Funiciello 2006), high heat flow (Della Vedova et al. 2001), crustal magma reservoirs, and high-K and normal-K volcanic rocks (Campi Flegrei, Vesuvius and post-290 ka ignimbrites).

The Campanian Volcanic Zone is characterized by NW–SE, NE–SW, NNE–SSW and east–west faults (Fig. 1) that are the product of three extensional events. (1) In the Early Pleistocene, NW–SE normal faults gave rise to symmetrical horst and graben structures (De Rita & Giordano 1996; Milia & Torrente 1997). (2) In the Middle Pleistocene (after 700 ka) NE–SW normal faults gave rise to half-grabens filled with clastic deposits and tilted blocks dipping towards the NW (Mariani & Prato 1988; Milia & Torrente 1997, 1999); two remarkable examples of NE–SE fault blocks are the ridge of the Sorrento Peninsula and the Banco di Fuori high, characterized by a maximum vertical slip rate of 4.3 mm a\(^{-1}\) in the time interval 700–400 ka (Milia & Torrente 1999). (3) During the late Quaternary the extension direction rotated counterclockwise by c. 20° (Milia & Torrente 2003; Torrente et al. 2010). This WNW–ESE-trending extension was associated with NNE–SSW normal faults, east–west transfer faults and the reactivation, as oblique-normal faults, of NE–SW and NW–SE inherited structures.

The Bay of Naples Quaternary depositional sequences form
aggrading and prograding stacking patterns bounded by tectonically enhanced unconformities (Milia 1999; Milia & Torrente 1999). Changes in the stacking pattern record variations in accommodation space that in turn are the result of the tectonic subsidences. During the activity of the NE–SW normal faults a transgressive succession was deposited (Sequence Set B), forming a NE–SW-trending prograding wedge contemporaneously with the north-westwards tilting of the footwall block. Later, a regressive succession (Sequence Set C) partially filled the Bay of Naples, forming a continental shelf in the southeastern bay passing to a slope-basin toward the NW. Based on a sequence stratigraphic approach combined with a tectonic study of the area and the ages of the stratigraphic units cropping out along the coast, Milia & Torrente (1997, 1999) reconstructed a chronostratigraphic framework and proposed the following ages for the Bay of Naples seismic units: Early Pleistocene for Unit A, early Middle Pleistocene for Set B (between c. 700 and 400 ka), and late Middle Pleistocene for Set C (c. post-400 ka).

The relationship between volcanism and extensional tectonics in the Campanian Volcanic Zone has been addressed by several researchers (Milia & Torrente 2003, 2007; Rolandi et al. 2003; Acocella & Funicello 2006; Bellucci et al. 2006; Milia et al. 2006; Milia 2010). For example, the location of both the 150 ka Gaia Bank and Pia Bank volcanoes together with the Monte Dolce dome was strictly controlled by a NE–SW normal fault swarm (Milia & Torrente 2003; Milia 2010) (Fig. 1). Several trachytic ignimbrites were emplaced across the Campanian Volcanic Zone and the Apennine valleys as distal ash flows in the last 290 ka (De Vivo et al. 2001). The Campanian Ignimbrite is the product of a large explosive eruption that occurred at 39 ka (De Vivo et al. 2001) with an estimated total volume of 200 km³ Dense Rock Equivalent (DRE) (Rolandi et al. 2003). In the southern Campanian Plain the products of the Campanian Ignimbrite are overlain by the Somma–Vesuvius volcanic complex (25 ka–AD 1944 lava and pyroclastic deposits; Santacroce 1987). The second large-volume pyroclastic deposit of the Campanian Volcanic Zone is the Neapolitan Yellow Tuff, which erupted 15 ka ago (Deino et al. 2004), with an estimated total volume of 49.3 km³ DRE (Scarpati et al. 1993) from a source area located near Posilippo (Scarpati et al. 1993). Isopach maps of the Pre-Campanian Ignimbrite tuffs, the Campanian Ignimbrite and the Neapolitan Yellow Tuffs have been produced for the whole Campanian Volcanic Zone, apart from the Campi Flegrei area (Milia & Torrente 2007; Torrente et al. 2010). The relationship between regional faults, as opposed to calderas, and the emplacement of the Late Pleistocene ignimbrites of the Campanian Plain is highly controversial (see the review by Torrente et al. 2010). Previous volcanological and geophysical investigations (Nunziata & Rapolla 1981; Rossi & Sbrana 1987; Orsi et al. 1996; Zollo et al. 2003; Beauducel et al. 2004; Acocella 2007) proposed that the Campanian Ignimbrite and/or the Neapolitan Yellow Tuff eruptions triggered the collapse of a caldera located in Campi Flegrei and in the northern part of the Bay of Naples (Pozzuoli Bay). On the other hand, the occurrence of a caldera in Campi Flegrei has been questioned by some workers (Milia 2000; Milia & Torrente 2003, 2007; Rolandi et al. 2003; Bellucci et al. 2006; Milia et al. 2006; Nunziata 2010), who have proposed a structural control by regional faults on ignimbrite emissions in the Campanian Volcanic Zone. Recently, Torrente et al. (2010) documented that during ignimbrite eruptions the regional faults were active, with ignimbire vents located along NE–SW and NW–SE faults and asymmetrical volcano-tectonic subsidences occurring along normal faults near Vesuvius and north of Campi Flegrei.

**Stratigraphy**

Depositional sequence mapping is a powerful technique that assists the interpretation of basin evolution on passive continental margins. This method may be used to establish a tectonic and stratigraphic framework, and produces realistic stratigraphic predictions in areas of sparse well control (Hubbard et al. 1985). By contrast, the detailed geometry and sequence of movements on the linked fault system directly controls the dip and strike development of the sedimentary fill, its facies, and the second-order faulting within the sediments. Conversely, the linked fault geometry and its movement history can be deduced by applying balanced-section techniques to the stratigraphic section. Accordingly, either structure or stratigraphy can be predicted in a systematic way if either of the two is known (Gibbs 1989; Schlische 1992).

Our approach in the construction of crustal geological sections across the Campanian Volcanic Zone was to integrate our knowledge of basin architecture (depositional sequence sets and tectonically enhanced unconformities (Fig. 3), the fault geometry and deep well stratigraphy (Fig. 4).

The correlation of seismic stratigraphy with Trecase well data (Brocchini et al. 2001) permitted us to define the age, lithology, depositional environments and depositional sequences of the basin fill. The Mesozoic carbonate rocks of the substrate are covered by 300 m thick subaerial conglomerates overlain by 200 m thick marine siltstones and calcarenites (with samples dated at 1240 and 980 ka) correlated to the Lower Pleistocene (A in Fig. 4). The U0 unconformity (Fig. 4) corresponds to the boundary between the oldest marine deposits (Unit A) and the continental deposits, and marks the beginning of the basin subsidence in a marine environment. The upper boundary of Unit A corresponds to the U1 angular unconformity (Fig. 3), which formed when the NE–SW normal faults produced uplift and subaerial erosion of the footwall blocks and subsidence of the hanging-wall blocks of the Trecase well. The Lower Pleistocene siltstones and calcarenites are overlain by 80 m thick clays of a deep-marine environment (corresponding to Sequence Set B in Fig. 3) deposited between 700 and 400 ka when the basin reached its maximum water depth and underwent a period of strong tectonic subsidences controlled by the NE–SW-oriented normal faults. These deep-marine clays are overlain by 400 ka old lavas, followed by a succession of marine to subaerial sandstones and siltstones with interbedded lavas and tuffites and stratified sands (C in Fig. 4). The latter sequence corresponds to Sequence Set C, deposited between 400 and 106 ka, and is a thick regressive succession displaying a progradational stacking pattern. The U2 unconformity affects the top of the Sequence Set C (Fig. 3) corresponding to a rapid increase in the accommodation space. The upper part of the stratigraphic succession of the Trecase well includes two pyroclastic deposits (with the 39 ka old Campanian Ignimbrite at the top) covered by the post-25 ka Somma–Vesuvius products. This volcanic succession is part of the latest depositional sequence (D in Fig. 4) and is late Quaternary in age.

In Naples, a 465 m deep well at Palazzo Reale was drilled in 1859. The detailed stratigraphic description of the well made by D’Erasmo (1931) permits us to recognize, from older to younger, a siliciclastic and calcareous unit, two trachytic tuffs interlayered by sandstones rich in marine mollusc fragments, the Campanian Ignimbrite and the Neapolitan Yellow Tuff (Fig. 4). The eulist succession comprises 9 m of coarse sands followed by 100 m of mudstones, clays and sandy clays, 26 m of sandstones, 48 m of alternating sandy clays, mudstones and siltstones rich in fossil...
fragments and benthonic foraminifers, and 28 m of sandstones. This stratigraphic succession displays an upward thickening of the sandstone strata. It shows a regressive trend typical of successions deposited during a lowering of sea level. We correlate the younger of the two trachytic tuffs underlying the Campanian Ignimbrite with the 106 ka tuffs present in the Trecase well, and date the older tuffs at 154 ka after comparing them with the succession in the subsurface north of Campi Flegrei (Santangelo et al. 2010). An age of 154 ka corresponds to Oxygen Isotopic Stage 6, which was a sea-level lowstand characterized by the deposition of a regressive succession.

West of Naples, Ippolito et al. (1973) described a succession of 850 m of tuffs overlying siliciclastic marine deposits in the CF23 geothermal well (Fig. 4) located near the coast at Campi Flegrei. These tuffs were tentatively correlated to the ignimbrite units mapped in the Bay of Naples because the CF23 well is close to the boundary of a seismic line (Fig. 5) showing three superimposed wedge-shaped seismic units: Pre-CI Tuffs, Campanian Ignimbrite and Neapolitan Yellow Tuff (Milia & Torrente 2007). Towards the NW the SVI well cuts through 1800 m of tuffs and a low-permeability cap rock (top of unit B) at a depth of 2800 m (Bodnar et al. 2007; Lima et al. 2009). We separated the pre-CI tuffs and the Campanian Ignimbrite onshore on the basis of the architecture of these units in the adjacent marina area.

Based on the recognition of the depositional environments (seismic interpretation) and the sedimentary facies (well stratigraphy) it was possible to reconstruct the palaeogeography that preceded the ignimbrite eruptions. Before the ignimbrite eruptions, the physiography of the Campanian Volcanic Zone was characterized by complex lateral variations in the depositional environment ranging from shelf to deep marine, and a recon-
struction of the shelf edge position led to the identification of a palaeo-basin in the Campi Flegrei area (Fig. 1). Indeed, the toplap surface of the Middle Pleistocene deposits formed as lowstand systems tracts during glacial maximum periods at a palaeo-water depth of 130 m (Milia & Torrente 1999). These deposits form a continental shelf in the southeastern part of the Bay of Naples, with a slope dipping c. 4° toward the WNW to form a basin in the region of the present Campi Flegrei (Milia & Torrente 2007). Further evidence of different palaeogeographical settings, from shallow- to deep-water environments, is the sedimentary facies change of the pre-ignimbrite Middle Pleistocene deposits from sandstones and conglomerates (TC well) and sandstones (VO well) in the Vesuvian area to fine graded sands, marls and clays along the Naples coast (PR well) to coarse sands in Naples (AR well).

**Crustal sections**

To reveal the crustal architecture and quantify the subsidence of the Campanian Volcanic Zone we combined three crustal geological sections into a fence diagram (Fig. 6a). The construction of these cross-sections is based on the recognition and
mapping of the geological units in the overall seismic dataset offshore and in borehole stratigraphies onshore. Nine stratigraphic units (overlying the crystalline basement) were traced across these geological sections; the pre-volcanic substrate corresponds to Mesozoic carbonates and Lower and Middle Pleistocene marine and transitional deposits.

Sections 1 and 3 (Fig. 6a) reveal that the area of the Campi Flegrei is characterized by two NE–SW high-throw normal faults: the Breakaway and Gauro faults. These structures formed a prominent half-graben and a structural depression of the substrate at a depth of c. 5 km in the hanging-wall block. The Breakaway fault displays a listric shape and its hanging wall includes a synthetic fault (Gauro fault) and a rollover anticline. The throw of the Breakaway fault is 1800 m and 900 m for the top of the substrate and Middle Pleistocene sediments respectively; higher throws for older stratigraphic markers together with an abrupt thickness change across the structure suggest a Middle Pleistocene activity for this structure. In contrast, the Gauro fault displays a throw of 900 m for both the top of the substrate and Middle Pleistocene sediments, thus implying a post-Middle Pleistocene fault activity. We believe that the Breakaway fault was active until the end of the Middle Pleistocene. The physiography of the Campi Flegrei Basin is characterized by (Fig. 6b): an 1150 m high fault scarp, an asymmetrical 1250 m deep half-graben basin, a gentle rollover anticline in the hanging-wall block and a 100 m deep shelf area in the footwall block.

The pyroclastic units of pre-CI tuffs and Campania Ignimbrite thicken toward the NW (Campi Flegrei) and form a wedge up to 1800 m thick (1050 m of pre-CI tuffs and 750 m of Campania Ignimbrite) bounded by the Gauro fault (Section 1); the base of this wedge reaches a maximum depth of 2000 m in the hanging-wall block. These ignimbrites, in contrast, form a low-angle wedge that attains a maximum thickness of 1000 m in the hanging-wall block of the Breakaway fault. We interpret these different wedge geometries within the hanging-wall blocks as a reflection of the contrasting behaviour of the Gauro and Breakaway faults; that is, during ignimbrite emplacement the activity of the listric fault mainly developed on the Gauro fault segment.

**Fig. 5.** Multichannel seismic section P1–P2 and its interpretation. Vertical scale is two-way travel time in seconds. Section location is shown in Figure 2. SSC, Sequence Set C; Pre-CI, pre-Campanian Ignimbrite tuffs; CI, Campanian Ignimbrite; NYT, Neapolitan Yellow Tuff; LQ, Late Quaternary marine deposits; G, fluid-bearing rocks; T, top of the thermo-metamorphic zone; M, magmatic chamber. Modified from Milia & Torrente (2007).
(asymmetric subsidence) whereas the Breakaway fault segment slowed its movement (filling of the previous depression). Accordingly, an amplification of the rollover anticline occurred.

The structural depression of Campi Flegrei is also characterized by two steep NW–SE-trending normal faults (Agnano and Camaldoli faults) (Section 3) and bounded at the base by the NE–SW listric fault. As the Agnano and Camaldoli faults feature an equal throw of the top of the substrate and Middle Pleistocene sediments (400 m and 250 m respectively) their activity postdates the Middle Pleistocene and is coeval with ignimbrite emission. The ignimbrite units of the pre-CI tuffs and Campanian Ignimbrite form a wedge at Campi Flegrei and pinch out toward the Bay of Pozzuoli; they reach a maximum thickness of 900 m (600 m of pre-CI tuffs and 300 m of Campanian Ignimbrite) in the hanging-wall block of the Agnano fault.

The Vesuvian region has two NW–SE-trending normal faults that are located on the coast and volcano crater (Coastal and Vesuvius cone faults; Section 2). The Coastal fault has a throw of 650 m and 145 m of the top of the substrate and Middle Pleistocene sediments respectively. It was consequently active during the Middle Pleistocene. In contrast, the Vesuvius cone fault has a constant throw of 100 m for both the top of the Mesozoic carbonates and Middle Pleistocene sediments, implying that its activity started during ignimbrite emission. The pre-CI tuffs and Campanian Ignimbrite are relatively thin in the Vesuvian region; they form a 140 m thick wedge in the hanging-
wall block of the Coastal fault and pinch out toward the Bay of Naples.

The Campanian Ignimbrite and pre-CI tuffs were mapped in the Bay of Naples and in the Campanian Plain by earlier workers (Milia & Torrente 2007; Torrente et al. 2010) who left the Campi Flegrei area unmapped. New isopach maps of the Campanian Ignimbrite and pre-CI tuffs, which cover the whole Campanian Volcanic Zone including Campi Flegrei, are shown in Figures 7 and 8. These isopach maps confirm that several thickness maxima in the Campanian Volcanic Zone were controlled by the activity of NE–SW and NW–SE normal faults. Furthermore, these maps show that ignimbrite source areas occur on faults extending over a large part of the Campanian Volcanic Zone (Torrente et al. 2010). The striking feature of both isopach maps is the occurrence of the three largest maxima (1050 m, 650 m and 600 m for the pre-CI tuffs; 750 m, 350 m and 300 m for the Campania Ignimbrite) at Campi Flegrei, which may be related to the activity of NE–SW (Gauro and Breakway faults) and NW–SE (Agnano fault) normal faults.

Subsidence rates

The reconstruction of the palaeogeographical setting preceding a major volcanic eruption is a fundamental step in the evaluation of the volcano-tectonic subsidence of a region. Our basin analysis reveals the existence of a palaeo-basin in the Campi Flegrei area before the ignimbrite eruptions. During the Middle Pleistocene, the palaeowater depth (assuming the present sea level as datum) of the continental shelf was between 0 and 150 m, and that of the Campi Flegrei deep basin reached a maximum of c. 1250 m (Fig. 6b). The NE–SW and NW–SE faults produced asymmetric subsidence within the basin, resulting from the cumulative effect of multiple syn-ignimbrite deformation episodes. To yield quantitative data on subsidence we first determine the cumulative subsidence, and then estimate the mean rate of hanging-wall subsidence in the areas of Campi Flegrei and Vesuvius (Table 1). The NE–SW and NW–SE normal faults bounding the Campi Flegrei basin affect different palaeogeographical environments (Figs 1 and 6b) but involve similar hanging-wall subsidence. The NE–SW-trending faults show hanging-wall subsidence of 750 m (2000 m of pre-CI base depth (Section 1) minus 1250 m of palaeobasin water depth (Fig. 6b)) whereas the NW–SE-trending faults show hanging-wall subsidence of 700 m (1050 m of pre-CI base depth (Section 3) minus 350 m of palaeoslope water depth (Fig. 6b)). In contrast, offshore from Vesuvius, the NW–SE-trending normal faults are characterized by hanging-wall subsidence of 300 m, which equals the value of the pre-CI base depth (Section 2). This is because the depth of the continental shelf remained approximately in the same position before and after the ignimbrite emplacement (Milia et al. 2006).

Our calculation of the mean rate of hanging-wall subsidence in the areas of Campi Flegrei and Vesuvius is based on the assumed age of the pre-CI tuffs (Table 1). A well drilled a few

![Fig. 7. Isopach map of the Campania Ignimbrite displaying sources, syn-ignimbrite faults and fissures. Contour interval is 50 m. Modified from Milia & Torrente (2007) and Torrente et al. (2010).](image-url)
kilometres north of Campi Flegrei encountered two ignimbrite deposits dated at 105 ka and 150 ± 10 ka (Santangelo et al. 2010). In addition, the pre-CI tuffs reach their maximum thickness (1050 m) in the Campi Flegrei area and correspond to several ignimbrites emplaced on the Campania margin. We maintain that these tuffs correspond to two eruptions (a 105 ka ignimbrite and a 154 ka ignimbrite). Consequently, the duration of the period that encompassed the ignimbrite eruptions associated with the asymmetric subsidence at Campi Flegrei is post-154 ka. Therefore the mean hanging-wall subsidence is 4.9 mm a⁻¹ for NE–SW faults and 4.5 for NW–SE faults. An ignimbrite deposit close to Sorrento was dated at 106 ka and underlies the Campania Ignimbrite in the area between Vesuvius and the Sorrento Peninsula. Assuming that only this ignimbrite corresponds to the pre-CI tuffs, the inferred magnitude of the subsidence rate in the Vesuvian fault is 2.8 mm a⁻¹.

Table 1. Subsidence values and subsidence rates

| Faults                  | Section | Ignimbrites base (m) | Palaeo-depth (m) | Subsidence (m) | Ignimbrite age (ka) | Hanging-wall subsidence rate (mm a⁻¹) |
|-------------------------|---------|----------------------|-----------------|----------------|--------------------|---------------------------------------|
| Campi Flegrei faults (NE–SW) | 1       | 2000                 | 1250            | 750            | 105 and 154        | 4.9                                   |
| Campi Flegrei faults (NW–SE) | 3       | 1050                 | 350             | 700            | 105 and 154        | 4.5                                   |
| Vesuvius faults (NW–SE)    | 2       | 300                  | 0               | 300            | 106                | 2.8                                   |

The syn-ignimbrite rate of subsidence ranges between 2.8 and 4.9 mm a⁻¹. These subsidence rates can be linked to extensional processes that affected the Campanian Volcanic Zone during the Quaternary because an analogous vertical slip rate value was estimated (4.3 mm a⁻¹; Milia & Torrente 1999) in the Bay of Naples for the Middle Pleistocene.

Fault architecture

Extension in the upper crust is achieved mainly by brittle deformation, changing at greater depths to ductile deformation where localized deformation may lead to the formation of mylonites (Sibson 1986; Karato 2008). Such a trend is consistent with the depth variation of seismicity (Sibson 1986). Because lithosphere rheology is strongly temperature dependent, high geothermal gradients are critical in determining the depths of
detachment levels. With surface heat flow of 80 mW m\(^{-2}\) large stresses are concentrated in the top 10 km of the lithosphere (Kuszmar & Park 1987). In regions of lithospheric extension, low-angle normal faults are active between 4 and 20 km depth in the Basin and Range Province (Eaton 1980; Anderson et al. 1983; Ferrill et al. 1995) and between 7 and 14 km depth in the Suez rift (Perry & Schamel 1990).

We suggest that the Campanian Volcanic Zone presents a pattern typical of extensional zones: shallow earthquakes and a detachment level at a depth of 9–12 km. The depth of this décollement surface is based on the presence of a seismic low-velocity zone below Vesuvius and Campi Flegrei (Zollo et al. 1996; Auger et al. 2001) and of the magnetic basement inferred by a semi-quantitative interpretation of aeromagnetic data (Mostardini & Merlini 1986). Focal depths are very shallow in the active volcanic areas of the Campanian Volcanic Zone (<5 km at Vesuvius, Presti et al. 2004; <6 km at Campi Flegrei, Beauducel et al. 2004). This vertical seismicity distribution, combined with very high heat flow values (Della Vedova et al. 2001), suggests a shallow position of the brittle–ductile transition in the Ischia–Campi Flegrei area. Our crustal sections (Fig. 6) reveal an asymmetrical style and high-angle faults rooting into a low-angle detachment at a depth of 12 km. In detail, a main listric normal fault and an associated rollover fold formed starting at 700 ka at the Campi Flegrei, and this NE–SW-trending half-graben extends within the Campania Plain near Acerra. In the late Quaternary the extension direction was WNW–ESE, inducing a reactivation, as oblique-normal faults, of the NE–SW and the NW–SE inherited structures; this tectonic event produced asymmetrical subsidence at Campi Flegrei and Vesuvius (Figs 6 and 9).

**Magma chambers**

As for other volcanoes world wide, the Campanian magma storage in the crust was inferred on the basis of seismic and petrological data revealing deep (>10 km) and shallow (<10 km) reservoirs underlying the active volcanoes of Mount Vesuvius and Campi Flegrei (Ferrucci et al. 1992; Belkin & De Vivo 1993; Zollo et al. 1996, 2003, 2008; Wholletz et al. 1999; Auger et al. 2001; Pappalardo et al. 2002, 2008; De Astis et al. 2004; Presti et al. 2004; De Natale et al. 2006; Marianelli et al. 2006; Nunziata et al. 2006; Piochi et al. 2006; Lima et al. 2007, 2009; Piana Agostinetti & Chiarabba 2008; Scaillet et al. 2008; Nunziata 2010). We have summarized the inferences on magma reservoir depths in the region in a subsurface sketch (Fig. 10) that includes sill-like magma bodies inferred by many researchers (e.g. Auger et al. 2001; Pappalardo et al. 2008; Zollo et al. 2008). This picture of the magmatic system underlying the Campi Flegrei volcanic area (Fig. 10) was enriched using multi-channel seismic reflection. We identified on a seismic reflection profile (Fig. 5) three deep seismic reflectors: reflector G at 1.4–1.8 s TWT (corresponding to high-amplitude bright spots), reflector T at 2.0–2.2 s TWT and reflector M at 3.5 s TWT. Stacking velocities from the time sections were averaged; interval velocities for each layer were obtained from the averaged stacking velocity using the Dix equation (Dix 1955). Calculated depths of reflectors were as follows: G between 2 and 2.7 km, T about 3.5 km, and M about 6 km. Interpreting our deep seismic reflectors in the framework of the Lima et al. (2009) magmatic–hydrothermal model of Campi Flegrei, which is consistent with geological, geochemical and geophysical data, we propose that the 2–2.7 km deep zone G is an extended fluid-bearing rock formation, the 3.5 km deep reflector T is the top of the thermometamorphic zone (overlying a magmatic body) and the 6 km deep reflector M is the top of a crustal magmatic chamber consistent with that inferred by Zollo et al. (2008).

The structural and stratigraphic architecture of the Campanian Volcanic Zone has been matched with its crustal magmatic system to investigate the role of extensional faults on pathways for magma ascent. Within the crustal sections, large and deep crustal magmatic chambers were identified in the crystalline basement, the tops of which lie at a depth of 10–12 km and 20 km (Figures 9 and 10). This is consistent with seismic evidence for a low-velocity zone that might represent melt, interpreted as a magmatic sill, in the upper crust beneath Mount Vesuvius and Campi Flegrei. The late extensional stress field is characterized by WNW–ESE \(\sigma_3\) (large white arrows), NNE–SSW normal faults, and NE–SW and NW–SE transtensional oblique-slip faults. Deep and shallow crustal magma reservoirs are as in Figure 10: hypothesized pattern of magma rise (red arrows) and ignimbrite sources (red spots) are shown. The ignimbrite units are omitted for clarity. Colour legend is as for Figure 6.
Vesuvius and Campi Flegrei (Zollo et al. 1996; Auger et al. 2001; Nunziata 2010). Evidence for the widespread presence of this reservoir beneath the Campania area includes the isotopic imprints of magmas from the Campi Flegrei and Procida volcanic rocks (Pappalardo et al. 2002, 2008; De Astis et al. 2004), which indicate magma storage at 11–22 km, with melt inclusions in Vesuvius xenoliths suggesting a magma chamber at a depth of 12 km (Lima et al. 2007). Isotopic data (Pappalardo et al. 2002) suggest that deep crustal magmatic chambers located in the crystalline basement fed ignimbrite eruptions. Several small shallow magma reservoirs of the Campanian Volcanic Zone are, in contrast, imaged at a depth of 4–8 km within the Mesozoic rocks approximately below the active volcanoes of Campi Flegrei and Vesuvius (Figs 6 and 9). The occurrence of a small shallow magma chamber located at 6–7 km depth beneath Campi Flegrei is supported by geochemical, petrological (Pappalardo et al. 2002) and seismic reflection data (this study; Zollo et al. 2008). Geochemical studies also support small magmatic chambers (diameter <1 km) at depths of 4–8 km beneath Vesuvius (Belkin & De Vivo 1993; Piochi et al. 2006; Lima et al. 2007; Piana Agostinetti & Chiarabba 2008; Scaillet et al. 2008), which are confirmed by the depth termination (5 km) of local seismicity at Vesuvius, corresponding to a peak of the seismic moment release (Presti et al. 2004).

**Interplay between extension and magmatic system**

Our tectono-magmatic model (Fig. 9) supports the evidence of a link between continental extension and magma pathway in the Campanian Volcanic Zone, as magma rise from deep to shallow reservoirs was controlled by faults. Indeed, the detachment zone matches the 10–12 km deep magma reservoir that is linked by faults to shallower and smaller sill-like reservoirs at Vesuvius (8–9 km deep) and Campi Flegrei (6–7 km deep). The Campi Flegrei shallow magma reservoir is tapped by both NE–SW listric faults and NW–SE steep faults, whereas the Vesuvius shallow magma reservoir is tapped only by NW–SE steep faults (Figs 6 and 9). A magma migration from a deeper reservoir (periodically refilled by less evolved magma) located in the crystalline basement to a shallower one is confirmed by isotopic data from Campi Flegrei (Pappalardo et al. 2002). Further evidence (Fig. 9) of the interaction between continental extension and magma system is the control that faults exert on the rise of magma during ignimbrite eruptions of the Campanian Volcanic Zone. This control is indicated by the multiple ignimbrite source areas and the ignimbrite thickness maxima both being located on the faults. We believe that the Campanian Volcanic Zone ignimbrites were erupted according to a mechanism of fissure emission as previously reported for the ignimbrites of the highly extended Basin and Range province (Aguirre-Diaz & Labarthe-Hernandez 2003; Andrews et al. 2008). It is worth mentioning that a similar volcano-tectonic link between normal faults, magma chambers and large eruptions has also been proposed in Scotland and Afar (Moore & Kokelaar 1998; Acocella 2010). In Scotland, Moore & Kokelaar (1998) documented that a normal fault controlled the emplacement of a voluminous ignimbrite and gave rise to a half-graben and differential collapse of the magma chamber roof. Alternatively, in Afar Acocella (2010) proposed that the structures of the grabens resulted from the collapse of the surface induced by magma withdrawal of kilometre-thick volcanic sequences.

Our research results are inconsistent with the conventional caldera model that has been postulated at Campi Flegrei in several ways. First, the reconstructed 3D fault architecture does not display fault segments within a presumed caldera. Second, ignimbrite vents are not located at the boundary of the caldera

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**Fig. 10. Sketch of the magma system of the Campanian Volcanic Zone as reconstructed by recent geophysical and petrological studies. Depth ranges of the magma bodies inferred by various researchers are shown together with reference papers. Based on De Natale et al. (2006).**
but also occur outside Campi Flegrei (Torrente et al. 2010), and mapped distributions of pre-CI tuffs and Campanian Ignimbrite reveal that these ignimbrites occur only in the eastern part of Pozzuoli Bay, thus excluding the occurrence of a caldera throughout the Pozzuoli Bay area. In contrast, thickness maxima occur throughout the Campanian Volcanic Zone and this study shows that also at the Campi Flegrei they are related to NE–SW and NW–SE faults. In addition, our palaeoearthquake reconstruction suggests that Campi Flegrei was a deep basin before ignimbrite volcanism, so the estimated total subsidence (700–750 m related to the eruptions of both pre-CI tuffs and Campanian Ignimbrite) was much lower than the presumed collapse associated with the Campanian Ignimbrite caldera (e.g. Orsi et al. 1995; Acocella 2007) and the calculated subsidence rates up to 4.9 mm a−1 can be linked to regional extension.

The results of our study contribute to a crustal picture and a tectonomagmatic model of the Campanian Volcanic Zone outlining a direct link between the regional fault network and the magma migration pattern. Furthermore, the knowledge of this link is an essential element in the correct volcanic hazard evaluation of one of the most densely populated and high-risk volcanic areas of the world.

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