On the mechanics of caldera resurgence of Ischia Island (southern Italy)

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Abstract: A model of caldera resurgence was applied to the Island of Ischia to explain uplift, volcanic activity and tectonics on Mount Epomeo, as well as historical seismicity and slow ground movements recorded for the past 2000 years. A two-dimensional mechanical model was utilized for the crust, which was considered to be an elastic plate overlying a laccolith. Geometric dimensions and mechanical parameters were constrained using geological, geophysical and geochemical data.

We propose that a laccolith, with a diameter *L* of *c.* 10 km, and a depth of up to 1 km in the centre of the island, triggered the caldera resurgence after the Mount Epomeo Green Tuff eruption forming the caldera (55 000 a BP). A bending phase and a punched laccolith phase are thought to have caused the observed deformations in the caldera. These processes control the tectonics at the boundary of the Mount Epomeo resurgent structure, volcanic activity and dynamics of the island.

The island of Ischia is a 46 km^2 volcanic field emerging at the western edge of the Bay of Naples (Fig. 1). This field represents the emergent part of a more extensive volcanic area developed mainly to the west of the island (Vezzoli 1988; Bruno *et al*. 2002). It consists of volcanic rocks deriving from a number of eruptive centres which have been largely destroyed or covered by subsequent activity and can now be identified only in part. The oldest outcrops date back to about 150 000 a BP, while the most recent eruption occurred in 1301–1302 AD in the eastern sector of the island (Vezzoli 1988; Civetta *et al.* 1991). During this period, five phases of activity have been distinguished and grouped in an older cycle and a younger cycle, whose transition is defined by the great alkali-trachytic ignimbrite eruption of the Mount Epomeo Green Tuff (MEGT) (55 000 a BP) which was accompanied by a caldera collapse (Table 1). Although the boundaries of the caldera are ill-defined, it has an approximately elliptical shape 10×7 km^2 (Fig. 2), with the longer axis trending east–west (Tibaldi & Vezzoli 1998). The caldera depression was filled – at first in sub-aerial and subsequently in submarine conditions – by the MEGT, the tuffs of the Citara Formation (CF) (about 44 000–33 000 a BP) and subaqueous epiclastic and pyroclastic deposits, Colle Jetto Formation (CJF). These deposits were involved in an uplift process starting between 33 000 and 28 000 years ago, forming the Mount Epomeo block. Total uplift, deduced from the present height of marine deposits and eustatic variations, is 710 m on the southern flank and 920–970 m on the northern flank, with an average uplift rate of 2.3 and 3 cm a^{-1} respectively (Barra *et al*. 1992; Tibaldi & Vezzoli 2004). This resurgence of the central part of the island is thought to be associated with the input of new magma at shallow depths, which from 28 000 to 18 000 a BP produced volcanic deposits of significantly different composition from those of previous eruptions (Civetta *et al.* 1991; Petrini *et al*. 2001). The resurgent block of Mount Epomeo, dominating the central sector of the island, is roughly square, with sides about 4 km long. The edges of the block are marked by a system of faults with NW–SE, NE–SW and N–S strikes (Fig. 2). The faults on the northern side of Mount Epomeo have been active over the last 800 years as seismogenetic sources, as testified by historical data. Furthermore, the horseshoeshaped structure of Mount Epomeo, open towards the southeast, and the large hummocky deposits off the south coast of Ischia, recently recognized by marine surveys, are consistent with an avalanche involving the summit of the Mount Epomeo resurgent block and the southern onshore caldera flank (Luongo *et al*. 1995; Cubellis & Luongo 1998; Marsella *et al*. 2001;

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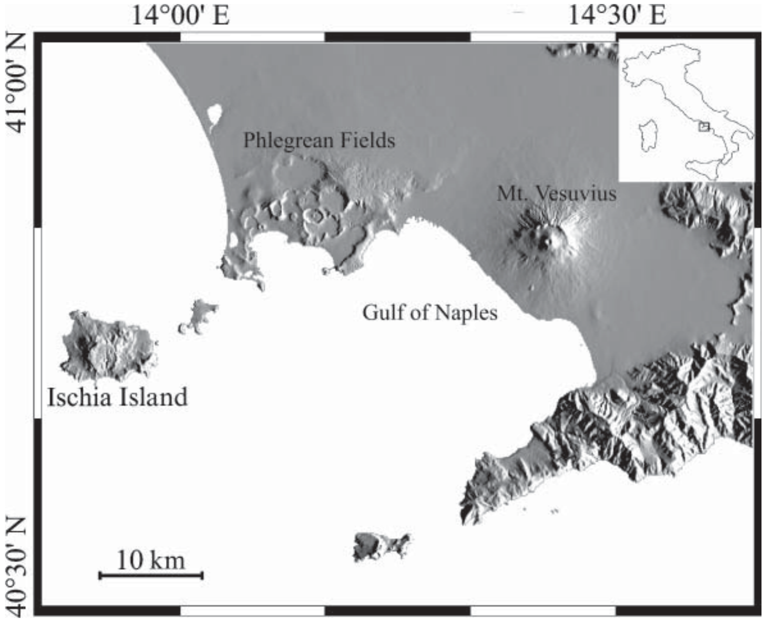

Fig. 1. Digital terrain model (DTM) image of the Bay of Naples. Ischia Island is located in the western sector.

Table 1. *Volcanic activity phases of Ischia*

Older cycle Pre-Mount Epomeo Green Tuff activity	Phase 1 > 150 000 a BP	Older major pyroclastic activity
	Phase 2 50 000–75 000 a BP	Lava dome emplacement
Younger cycle Mount Epomeo Green Tuff Citara Formation	Phase 3 55 000–33 000 a BP	Younger major pyroclastic activity
	Phase 4 29 000–18 000 a BP	Explosive and effusive activity in the southwestern and southestern sector
	Phase 5 10 000 a BP to 1302 AD	Prehistoric and historical activity

Chiocci *et al.* 2002; Cubellis *et al.* 2004; De Alteriis *et al.* 2004; Tibaldi & Vezzoli 2004; Carlino & Cubellis 2005).

In general, the models used to interpret resurgence processes for large calderas – the thrust of the magma in a shallow source due to an increase in pressure or due to vesiculation; regional detumescence; or heat transfer from the magmatic basin to the surface aquifer system (Smith & Bailey 1968; Marsh 1984; Luongo *et al.* 1991; De Natale *et al.* 2001) – appear inadequate to explain resurgence in calderas of modest size, as in the case of the island of Ischia. The complexity of the problem also emerges from analysis of the models proposed since the early twentieth century. Indeed, Rittmann (1930) proposed volcano-tectonic horst mechanism, i.e. uplift by the intrusion of a shallow laccolith, to explain the structure of Mount Epomeo. More recently, Fusi *et al.* (1990) and Tibaldi & Vezzoli (1998) proposed that the resurgent process of Ischia was produced by volumetric variations in the subsurface magma body. Orsi *et al.* (1991) suggest a simple-shear stress for the resurgence, in which the source mechanism is an increase in magmatic pressure in the upper part of a shallow magma chamber. Luongo *et al.* (1995) and Cubellis & Luongo (1998) used a punched laccolith mechanism to model the uplift of Mount Epomeo. Acocella *et al.* (1997, 1999) and Molin *et al.* (2003), according to similar experimental models, proposed that the resurgent doming of Mount Epomeo is due to a trapdoor uplift mechanism, with a hinge in the southeastern part of the island.

To remove the arbitrariness of the above solutions for the resurgence of Ischia we impose

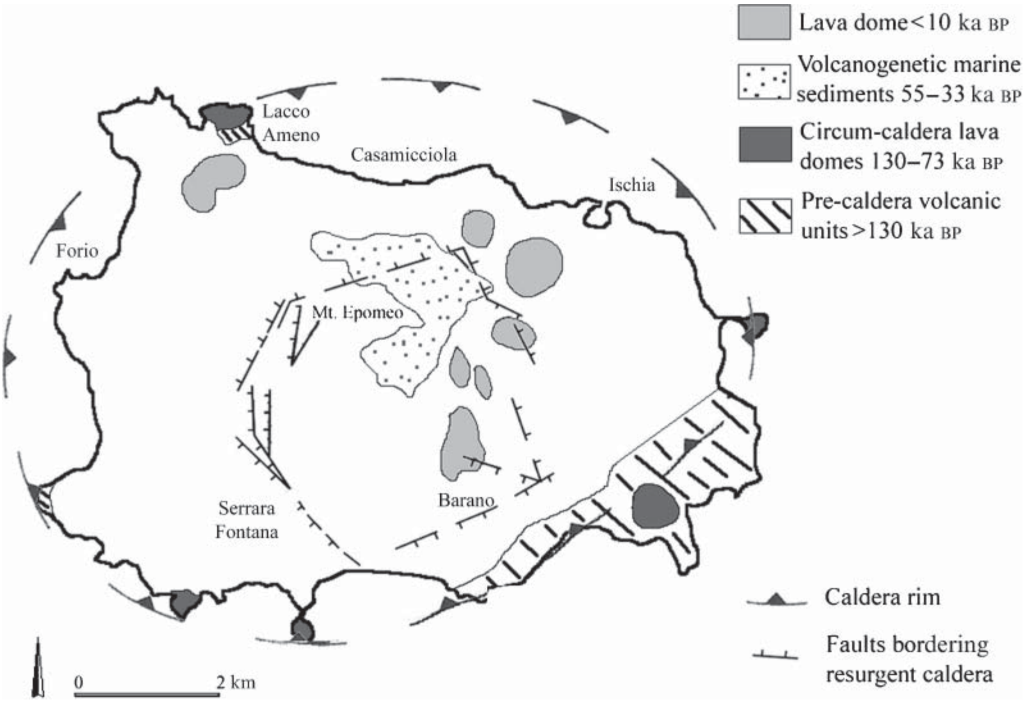

Fig. 2. Sketch map of Ischia, showing major structural and volcanological features related to resurgence (adapted from Tibaldi & Vezzoli 1998).

geological boundary conditions within the solution to the problem of the ground deformation. General and specific boundary conditions are deduced by high-quality field-mapping data and geochemical and geophysical surveys of the island.

The bending model for Mount Epomeo resurgence

The analytical Mount Epomeo resurgence model proposed in this work assumes that the source of stress is a laccolith located at shallow depths in the central zone of the island (Rittmann 1930; Luongo *et al.* 1987; Cubellis & Luongo 1998). The evolution of calderas such as the Christmas Mountain caldera complex (Texas) has already been interpreted using a model of laccolith emplacement and growth (Henry *et al.* 1989, 1997). For Ischia, the resurgence process will be quantified through the theory of the bending of an elastic plate subjected to thrust from laccolith resurgence (Johnson & Pollard 1973; Pollard & Johnson 1973; Corry 1988; Kerr & Pollard 1998; Turcotte & Schubert 2001) (Fig. 3). The boundary conditions used in model quantification are the thickness of the layer subjected to deformation; the lateral extent of block uplift; the distance of the faults that border the Mount Epomeo block from the centre of maximum uplift – as the expression of maximum shear strain produced by the bending process; the caldera's dimensions; and the mechanical properties of the covering rocks.

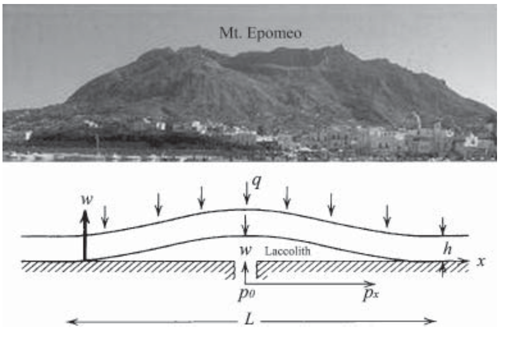

Fig. 3. Bending of an elastic plate of load q and thickness h subject to the thrust of a laccolith of diameter L. w is the uplift and p_0 is the maximum pressure (bottom sketch). Profile of Mount Epomeo viewed from the west of the island. The structure of the resurgent block is delimited by faults (top sketch).

Crustal model of the island

The shallow crustal structure of the island is defined using geological, deep-drillings, geophysical and geochemical data. Furthermore, the deep wells, stratigraphy and temperature gradients allow us to define the rheology of the shallow crust down to about 2 km depth (Penta 1963; Penta & Conforto 1951; Maino & Tribalto 1971; Carrara *et al*. 1983; Nunziata & Rapolla 1987; Orsi *et al*. 1999; Lima *et al*. 2003). From the 1930s to the 1950s, many geothermal boreholes were drilled on the island, down to a maximum depth of 1150 m. These stratigraphic data help in constraining the interpretation of gravity and magnetic surveys. Maino & Tribalto (1971) interpreted a relative maximum in the Bouguer anomaly in the southwestern sector of Ischia as a magma body at shallow depth. A more detailed model of the island's shallow structures was proposed by Carrara *et al*. (1983) and Nunziata & Rapolla (1987) on the basis of gravimetric and magnetic surveys. A Bouguer gravity anomaly along a NNW–SSE profile across the island is interpreted as the contribution of the basement structure whose top is situated in the southwestern part of the island, at 1.0 km in depth, and deepens more steeply towards the south, at a depth of about 3 km, than in the north where it reaches a depth of about 2 km (Fig. 4). There is no direct evidence for the composition of the basement. However, Nunziata & Rapolla (1987) and Orsi *et al.* (1999) support the hypothesis that the basement is of igneous composition, with a low magnetic susceptibility. The low value of susceptibility is interpreted to be the consequence of high temperatures due to the presence of hot magmatic bodies at shallow depths.

Furthermore, the high geothermal gradients registered on the island (180 °C/km); the absence of sedimentary lithics in the pyroclastic products; and the presence of a hydrothermal reservoir fed by an inferred shallow magma system deduced from the geochemical data (Tedesco 1996; Chiodini *et al*. 2004), are all elements supporting the volcanic nature of the basement. In fact, given that the island of Ischia is located over thinned continental crust the sedimentary basement may be assumed to be deeper or to have been dismantled by large explosive eruptions.

The presence of a shallow magma body beneath the island supports the hypothesis of the resurgence of Mount Epomeo due to the thrust of a laccolith intrusion. In addition, the emplacement of the laccolith would produce the observed anomalous thermal state of the overburden

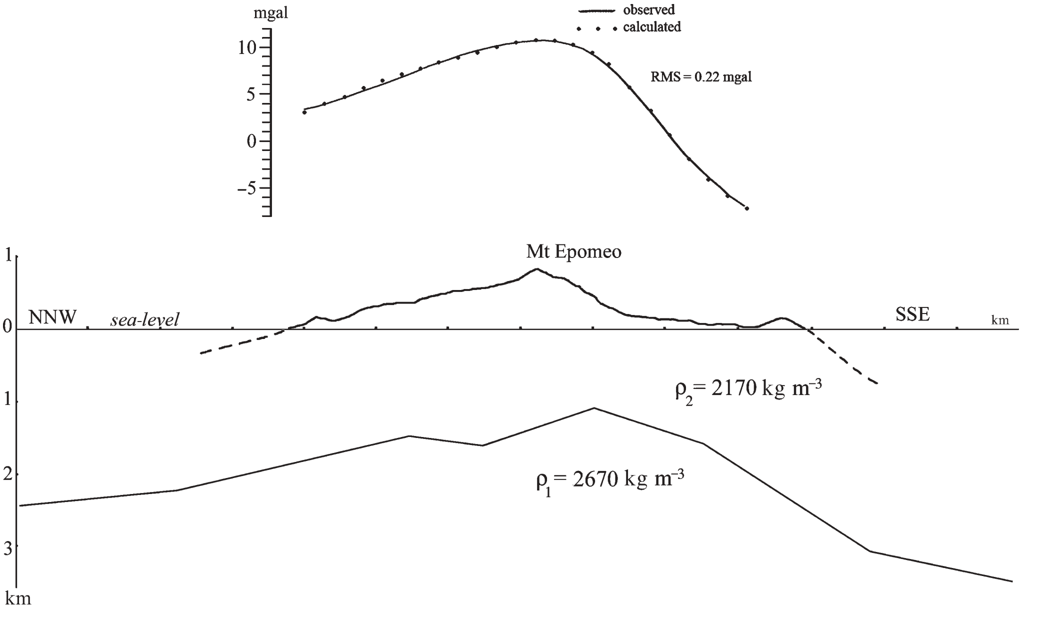

Fig. 4. Structural model deduced from the gravimetric anomalies and topographic profile of Ischia along a NNW–SSE traverse (adapted from Carrara *et al.* 1983 and Nunziata & Rapolla 1987). Rocks with a density of 2170 kg m^{-3} rest on a basement with a density of 2670 kg m^{-3}. This shows a peak at 1 km roughly below the peak of Mount Epomeo and sinks to a low about 3 km offshore. The ratio between vertical and horizontal distance is 1:1. The dotted line indicates the trend in the island's bathymetry.

rocks. The geothermal gradients measured in the deep drillings (in the southern and southwestern sectors of the island), allow the brittle–ductile boundary beneath this area to be defined. Ord & Hobbs (1989) inferred that, for wet conditions and a pressure of 50 MPa, the temperature of the brittle–ductile transition is about 350 °C. For a geothermal gradient of 180 °C km^{-1}, this transition is found at *c.* 2 km depth.

In the northern sector of the island, the frictional behaviour of the shallow layer could be inferred by the evaluation of seismicity cut-off depth. Indeed, the earthquakes recorded in the last 800 years, in this sector, were very shallow, which is consistent with a high epicentral intensity with respect to the moderate released energy. The same scenario was observed for the catastrophic earthquake of 1883. Total collapse of buildings was observed in a small area between Casamicciola and Lacco Ameno, accompanied by strong attenuation of seismic energy, as inferred from macroseismic data. These effects are linked to a small seismic source in the shallow crustal layer at a depth of 1–2 km (Cubellis & Luongo 1998; Cubellis *et al.* 2004). This depth represents the seismicity cut-off depth, below which the behaviour of the crust is predominantly ductile (Kobayashi 1977; Chapman 1986; Ito 1993) (Fig. 5). Seismicity is thought to be generated in the northern sector at a lower geothermal gradient where the brittle–ductile transition is deeper and hence the brittle layer has greater thickness. By contrast, its thinning in the southern sector promotes slow-slip phenomena that do not cause earthquakes.

According to the above data, for our model, we consider a 2 km thick brittle plate overlapping the laccolith with prevalently ductile behaviour. The value of the geothermal gradient could indicate that the top of laccolith (at 1 km depth) represents the cold part, which shows brittle behaviour, of a more extensive ductile magmatic body at depth.

Deformation of strata overlying the igneous intrusion

The overburden of an elastic plate of thickness h is bent upwards by the pressure p of the magma that goes to form the laccolith. In a two-dimensional analysis, the plate deflection is governed by the general equation (Jaeger & Cook 1976; Turcotte & Schubert 2001):

$$D\frac{d^4w}{dx^4} = q(x) - P\frac{d^2w}{dx^2} \qquad (1)$$

where w = deflection of the plate; $q(x)$ = downward force per unit area; P = horizontal force; $D = Eh^3/12(1-\nu^2)$ is flexural rigidity with: E = Young's modulus and ν = Poisson's ratio. The displacement of the plate can be determined by integrating the equation according to the boundary condition $P = 0$:

$$D\frac{d^4w}{dx^4} = q(x) \qquad (2)$$

where $q = \rho gh - p$, is the lithostatic pressure reduced by the upward pressure p of the magma. If we assume L as the length of the laccolith, and if we take $x = 0$ at the centre of the laccolith (Fig. 3), the solution of the equation (2) that

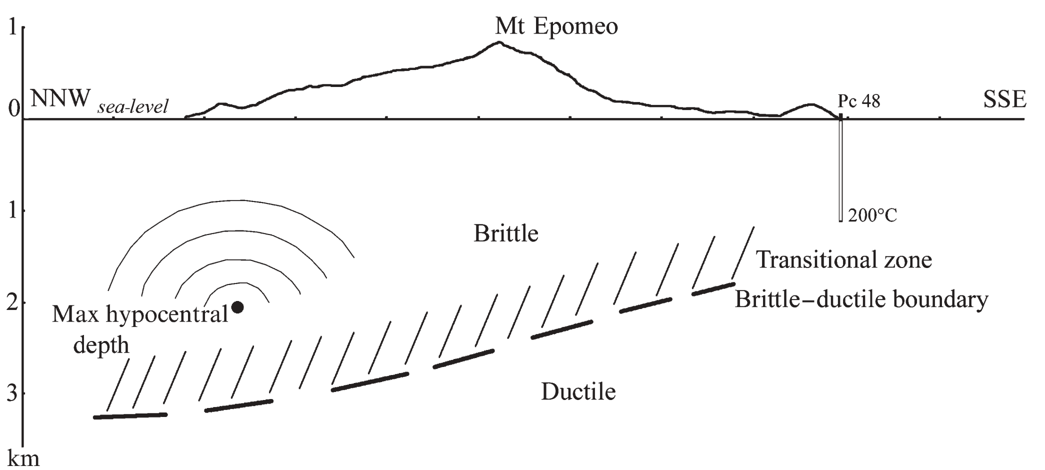

Fig. 5. Trend of the brittle–ductile transition deduced from geothermal gradients and from seismicity on the island of Ischia. The seismogenetic volume is located in the northern sector of the island, where lower geothermal gradients are observed. The ratio between the vertical and the horizontal distance is 1:1.

satisfies the following boundary conditions $w = dw/dx = 0$ for $x = \pm L/2$, $d^2w/dx^2 = 0$ for $x = \pm L/2$ is:

$$w = -\frac{(p - \rho g h)}{24D}\left(x^4 - \frac{L^2x^2}{2} + \frac{L^4}{16}\right) \quad (3)$$

The pressure in the laccolith is variable as a function of x; for $x = 0$, $p = p_0$ (maximum pressure value), while for $x = \pm L/2$, $p = 0$. Kerr & Pollard (1998) proposed the solution:

$$p(x) = p_0\left\{1 - \left(\frac{x}{a}\right)^n\right\} \quad (4)$$

where $a = L/2$, and n is a parameter that depends on the rheology of the magma; for $n = 1$ the drop in pressure from the feeder towards the periphery is linear (Newtonian fluids). For $x = 0$ eq. (3) becomes:

$$w_0 = -\frac{(p_0 - \rho g h)}{384D}L^4 \quad (5)$$

Furthermore, using the equation of plate deflation and the $p(x)$ function, Kerr & Pollard (1998) obtained a solution for the maximum pressure as a function of overburden q_0 for the different rheological behaviour of magma:

$$p_0 = \left\{\frac{(n+1)(n+3)}{(n+1)(n+3) - 3}\right\}q_0 \quad (6)$$

where $q_0 = \rho g h$. For a Newtonian fluid, we obtain $p_0 = 8/5\ q_0$.

The above solutions for w and p were utilized to quantify the resurgence process of Mount Epomeo.

Application of the bending process on Mount Epomeo

Mean laccolith diameter (L) can be estimated with eq. (5), using field data supplied by the referenced works. According to this solution, based on elastic plate theory the relation between the diameter and other parameters of the laccolith should be:

$$|L| = \left(\frac{w_0 384D}{p_0 - \rho g h}\right)^{1/4} \quad (7)$$

Different values of L can be obtained according to: $w_0 = 800$ m, uplift of Mount Epomeo as determined using field data; $h = 2000$ m; $\rho = 2100$ kg m^{-3}; p_0 values, obtained by eq. (6) for magma with different rheologies; and the assumed values of the material properties, namely Poisson's ratio $\nu = 0.25$ and Young's modulus $E = 10$ GPa. In addition, eq. (6) gives the following values of p_0: 66 MPa, 96 MPa, 156 MPa, 342 MPa versus $n = 1$, 0.5, 0.25 and 0.1, respectively. Hence, the corresponding laccolith diameters are: 17 km, 14 km, 11.7 km and 9.2 km. The largest value corresponds to the magma with rheological properties of a Newtonian fluid.

Some researchers (Petrazzuoli *et al.* 1993; De Natale *et al.* 2000) have suggested values of Young's modulus of 2.5–4.5 GPa for the volcanoes of the Bay of Naples, lower than those that we assumed when employing eq. (7). The last values of Young's modulus provide laccolith diameters of 9–10 km. Such values are consistent with the geological and geophysical data, particularly with the long-wavelength gravity anomalies which are high in the southwestern part of the island with an E–W maximum extension of about 9 km (Nunziata & Rapolla 1987). Scaled analogue models of laccolith diameter versus thickness of brittle overburden (Berdiel *et al.* 1995) also provide a value of about 10 km for Ischia (Fig. 6).

The bending–lifting model for Mount Epomeo resurgence

The process of bending does not produce sufficient shear stress to fracture the rocks to

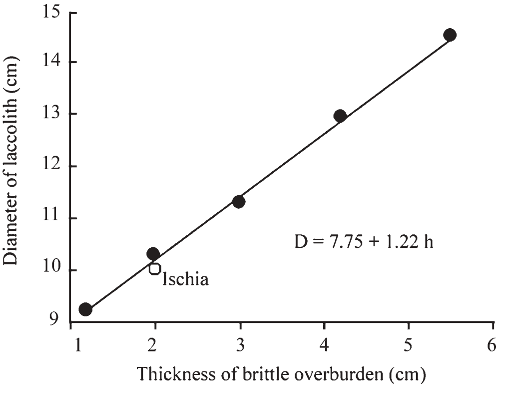

Fig. 6. Linear law between laccolith diameter and overburden thickness (adapted from Berdiel *et al.* 1995). In the linear equation, D is the laccolith diameter and h is the thickness of the overburden. The full circles indicate values obtained from analogue models. The scale of the lengths is 10^5 (1 cm = 1 km). The values of D and h hypothesized for Ischia, at the same scale, fit the law well (*empty circles*).

form a resurgent block bordered by faults, as we observed at Mount Epomeo. Hence, we suppose an evolution of the bending process producing the failure of the overburden. A similar process was proposed by Paige (1913) for the Black Mesa intrusion (Henry Mountains, USA) whose evolution was interpreted by proposing two different stages: bending and faulting (Fig. 7). The bending stage is due to sill intrusion and its thickening. As the laccolith forms, the intrusion fails to lengthen, because there is the rapid increase in viscosity resulting from crystallization at the periphery (Fig. 8). During this process, the section of the active pushing mass decreases and consequently increases the effective pressure on the overburden till it experiences faulting, delimiting a central block (faulting stage). When the pressure overcomes the overburden load, the block is uplifted along the faults as a ‘punched laccolith’ according to Corry (1988) (Fig. 9). Furthermore, as the pressure decreases from the centre to the periphery, according to eq. (4), there will be a point between $x=0$ and $x=a=L/2$, where pressure $p(x)$ is equal to the loading of the overburden q_0 (Fig. 10). Therefore, the active zone of the laccolith is that in which the pressure is higher than the overburden loading. This mechanism is also consistent with Paige’s hypothesis of the reduction in the size of the active section of the laccolith. Using equations (4) and (6), for Mount Epomeo, we found that the distances at which $p(x)=q_0$ are: 1800 m, 4000 m, 4600 m, 5000 m, according to the various values of n and p_0, i.e. $n=1$ and $p_0=66$ MPa, $n=0.5$ and $p_0=96$ MPa, $n=0.25$ and $p_0=156$ MPa, $n=0.1$ and $p_0=342$ MPa, respectively. The value of 1800 m, for which $p(x)=q_0$, corresponds to the distance of the faults bordering the block of Mount Epomeo from the centre of the block itself. This distance could represent the radius of the active section of the laccolith during the Mount Epomeo uplift.

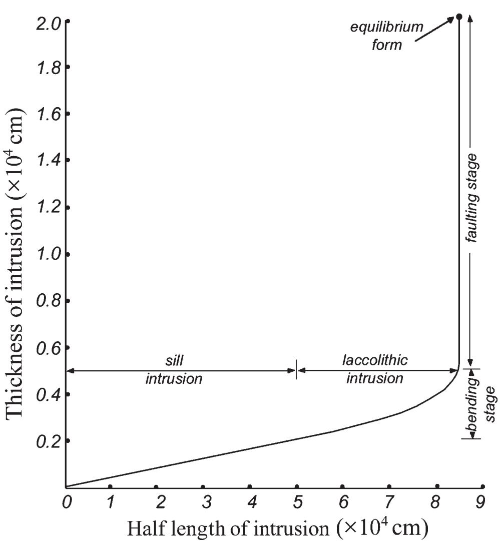

Fig. 7. Relation between maximum thickness and lateral expansion of the laccolith at Black Mesa (Henry Mountains, USA) (Pollard & Johnson 1973). The bending stage produced by the growth of the laccolith is followed by the uplift of the overburden along peripheral faults.

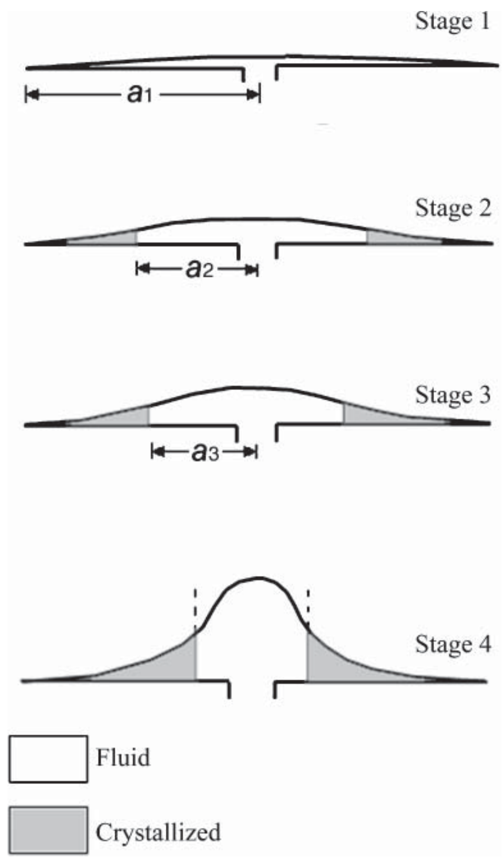

Fig. 8. Stages of intrusion, as drawn by Paige (1913). As the magma is injected, the intrusion does not lengthen, due to crystallization of the periphery. Paige suggested that the central portion would bulge upward. a_1, a_2 and a_3: represent the radius of the laccolith at different stages.

In order to quantify the contributions to uplift of the bending (w_{0b}) and punched processes (w_{0p}), we can set the laccolith diameter at 10 km, as inferred from the diameter of the Ischia Caldera and the wavelength of the Bouguer gravity anomalies. Then we can calculate the uplift of w_{0b} using equation (5) and the value of

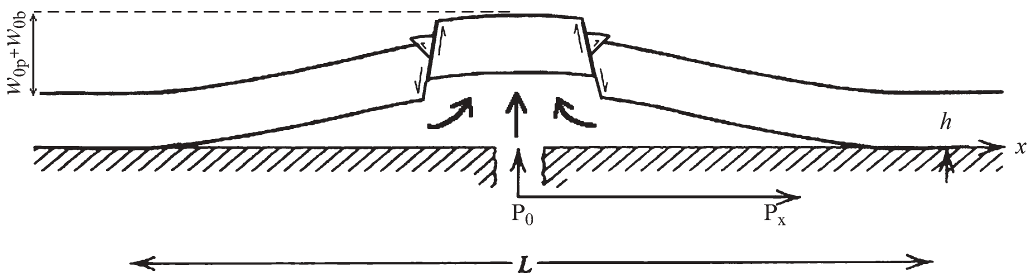

Fig. 9. Scheme of evolution of the bending process towards the formation of a punched laccolith. The process is accompanied by both the formation of normal faults, along which the resurgent block is defined, and smaller reverse faults. The total uplift is $w_{0b}+w_{0p}$ (w_{0b} = bending uplift; w_{0p} = punched uplift).

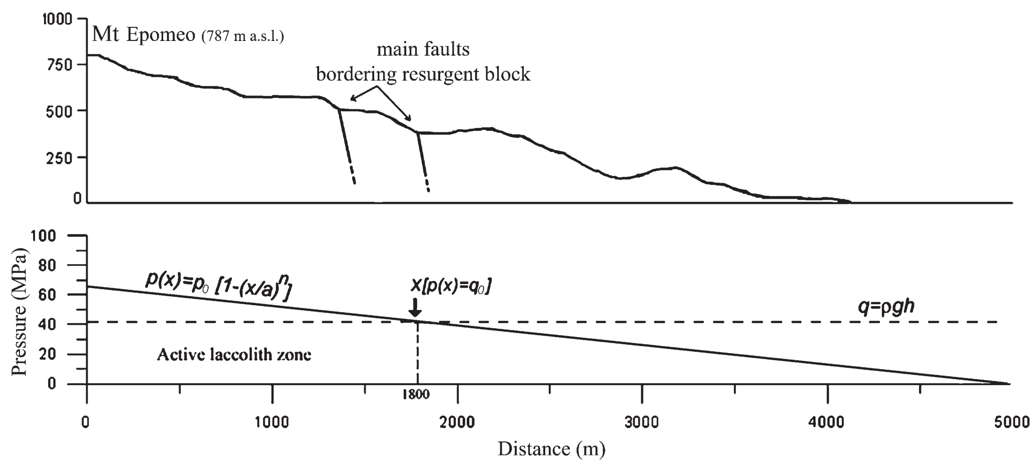

Fig. 10. Trend in the pressure $p(x)=p_0\{1-(x/a)^n\}$ from laccolith thrust (calculated for a Newtonian fluid $n=1$) (bottom sketch). Note that the active part of the laccolith has a radius of about 1800 m where the thrust pressure exceeds the load of the overburden ($q=\rho gh$, *dotted line*). At this distance, calculated from the centre of Mount Epomeo, the main faults that border the block are located (NW–SE topographic profile) (top sketch).

w_{0p} inferred from the difference between the total uplift of Mount Epomeo (w_{0T}) and w_{0b}. According to geological data $w_{0T}=w_{0b}+w_{0p}=800$ m. Using eq. (5) we found the w_{0b} solutions for different pressures (p_0) and rheologies (E, n) of the overburden (Table 2). Using total uplift, the w_{0p} values are obtained for different values of w_{0b} (Table 3).The w_{0b} values which exceed the total uplift of Mount Epomeo (800 m) will not be used for these analyses.

As shown by the above results, the different contributions of bending and punched mechanisms are controlled by the rigidity of the overburden (the higher the Young's modulus, the less the bending), and by the rheology of the magma. Overall, the punched mechanism provides the chief contribution to the uplift of the block (Fig. 10). According to this mechanism, in response to pressure p_0, laccolith thickness increases in the zone below the block delimited

Table 2. *Uplift due to bending (w_{0b}) obtained for different pressures and rheologies (E, n) of the rocks*

n		1			0.5			0.25			0.1	
p_0 (MPa)		66			96			156			342	
E (MPa)	10	4.5	2.5	10	4.5	2.5	10	4.5	2.5	10	4.5	2.5
w_{0b} (m)	88	195	368	198	439	827	418	927	1746	1100	2441	4596

Table 3. *Different values and percentage (%) contributions to uplift (metres) of bending and punched processes*

w_{0b} Bending		w_{0p} Punched		Rheology of Magma
(m)	%	(m)	%	
88	11	$w_{0p1} = 712$	89	
195	24	$w_{0p2} = 605$	76	Newtonian
368	46	$w_{0p3} = 432$	54	
198	24	$w_{0p4} = 602$	76	
439	55	$w_{0p5} = 361$	45	Non-Newtonian
418	52	$w_{0p6} = 382$	48	

by faults, which will be raised by the quantity w_{0p}, equal to its thickness. As the block may be raised, pressure p_0 must exceed the sum of the weight of the overburden and the shear resistance in the fractured zone, i.e. $p_0 > q_0 +$ shear stress. From Amonton's Law (Byerlee 1977; Lay & Wallace 1995) we obtain the shear stress $\tau_s = f_s \sigma_n$, where f_s is the coefficient of static friction and σ_n is the normal stress at the slip plane (Fig. 11). Let σ_n be the lithostatic pressure (ρgh), for $h = 2000$ m and $f_s = 0.7$. Then:

$$p_0 > \rho gh + \tau_s = \rho gh + f_s \sigma_n = 70 \text{ MPa}$$

The shear stress (τ_s) decreases in the presence of water, as may be hypothesized in the resurgence area of Mount Epomeo, where there is an extensive hydrothermal system. In this case the normal active stress will be given by the difference between normal stress (σ_n) and pore pressure (p_w). If a free aquifer system is considered, then the water pressure will be equal to hydrostatic pressure $p = \rho_w gh$. With $h = 2000$ m and $\rho_w = 1000$ kg m^{-3}, we obtain:

$$p_0 > \rho gh + \tau_{sw} = \rho gh + f_s\,(\sigma_n - p_w) = 56 \text{ MPa}$$

Furthermore, during resurgence, the block of Mount Epomeo has undergone dismantling episodes attributed to avalanching, as testified by the study of subaerial and submerged deposits south of the island and from the horseshoe shape in the mountain's southern sector (Fig. 12). These episodes appear to have produced a decrease in load q_0, in response to which the laccolith reached a more superficial level, with additional uplift of the block. The volume lost after avalanching and dismantling is estimated as about 3 km^3 (Chiocci *et al.* 2002; De Alteriis *et al.* 2004; Tibaldi & Vezzoli 2004). If we approximate the uplifted block (prior to dismantlement) to a parallelepiped of dimensions $4 \times 4 \times 2$ km^3, the loss of volume would be about 12% of the volume of the undeformed block, with a decrease in lithostatic load of about 5 MPa. It is likely that the dismantling of Mount Epomeo was followed by an explosive eruption. Indeed, pressurized dome rocks decompressed above a critical threshold in the range 2 to 5 MPa will explode (Alidibirov & Dingwell 1996).

As we can see in the proposed mechanism, the punched stage followed the bending stage with fracturing of the overburden and further uplift of the Mount Epomeo block. Taking into account the eruptive history of Ischia after the Green Tuff eruption, which had three active periods: 43 000–33 000 a BP, 29 000–18 000 a BP

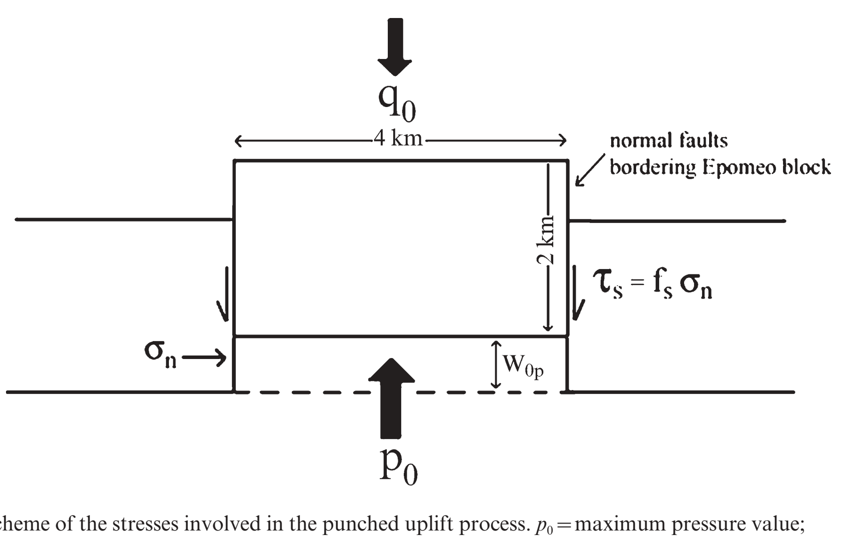

Fig. 11. Scheme of the stresses involved in the punched uplift process. p_0 = maximum pressure value; q_0 = overburden loading; σ_n = horizontal stress; τ_s = shear stress; w_{0p} = punched uplift.

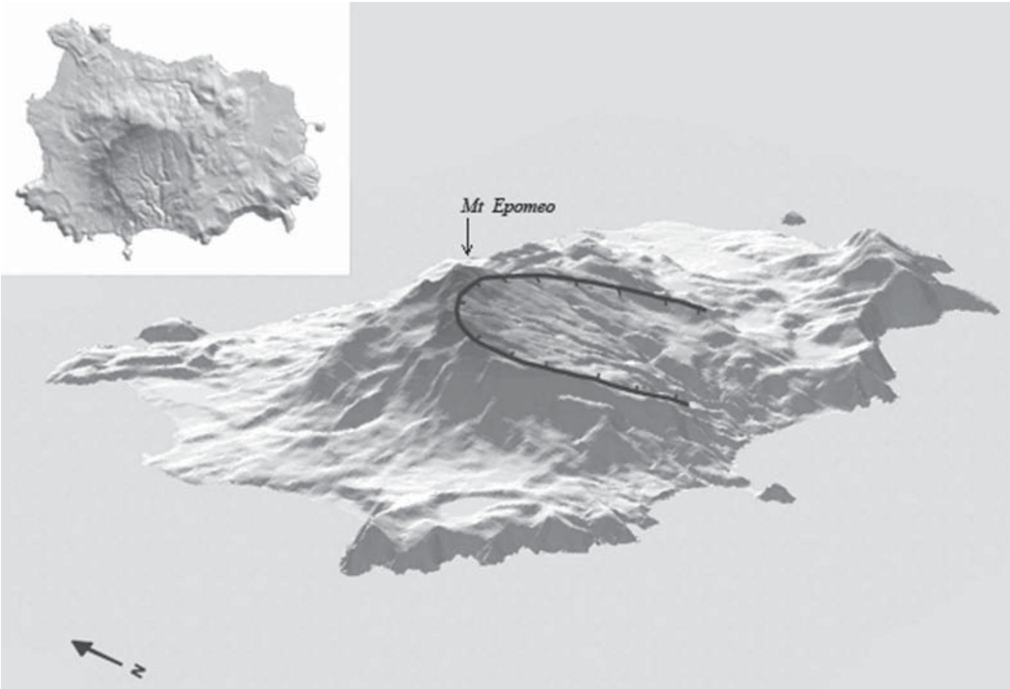

Fig. 12. Digital terrain model of the island of Ischia (CGR 2000). Note the structure of Mount Epomeo, with the edge of the dismantled area shown as a *solid line*.

and 10 000 a BP to 1302 AD, it may be reasonably hypothesized that the uplift of Mount Epomeo occurred at steps during the time intervals of quiescence, i.e. 55 000–43 000, 33 000–29 000 and 18 000–10 000 a BP. In this case the block's resurgence rate was 3.3 cm a^{-1}.

Conclusions

In various studies on the evolution and dynamics of the island of Ischia, two structures are frequently considered:

(1) deformation of the overburden, known as a volcano-tectonic horst (Rittmann 1930) and resurgence recorded by the succession of marine terraces and by fractures, faults and earthquakes at the edges of Mount Epomeo;
(2) the source of the volcanism, like the laccolith proposed by Rittmann (1930) or the surface magmatic sources used to account for the evolution of the composition of erupted products.

To these structural elements we can add the results produced by analogue models to interpret resurgence, but those available are generally poorly constrained or qualitative.

Our study takes its cue from the two original observations made by Rittmann, namely the uplift of Epomeo and the presence of a laccolith, supported by more recent works. Geological constraints have been introduced to quantify the resurgence process. The bending model thus constructed supplies significantly lower uplift data than the constraints obtained from field observations. In particular, once the caldera dimensions and reliable stress values have been defined, bending supplies only a percentage of the uplift. Besides, the caldera dimensions and the pressures required to reach the uplift value observed are unlikely, in so far as they are not consistent with the geological and geophysical data ($L = 17$ km, $p = 342$ MPa). Instead, the bending–lifting mechanism which produced a punched laccolith and the resurgence of Mount Epomeo appears more likely, because it is consistent with geological and geophysical data. A resurgent process starts with the bending of the overburden, but when the uplift reaches large values with a constant lateral dimension of the strata it is necessary to invoke overburden lifting along peripheral faults (Paige 1913; Johnson & Pollard 1973; Pollard & Johnson 1973; Kerr & Pollard 1998).

Along the faults of the northern side of Mount Epomeo, seismic energy was released during historical times up until 1883. Since that time, a seismic silence has been observed on the island, while a general subsidence has occurred. We hypothesized that the upheaval is accompained by an intense seismicity, but, on the contrary, the subsidence develops without seismicity. A similar process was observed in recent times at Campi Flegrei's resurgent caldera. During the unrest episode, De Natale *et al.* (1997) and Troise *et al.* (2003) showed the relevant effect of faults concentrating uplift, by analysing of the seismicity in correspondence with faults bordering the uplifted area.

In the bending phase, volcanic activity is limited, due to the lack of significant fracturing that would allow the magma to rise to the surface. On the basis of the island's volcanic history, this phase appears to have developed between 55 000 and 43 000 years ago, with an uplift rate of about 3.3 cm a^{-1} (calculated with 400 m of uplift). In the interval 55 000–43 000 a BP we may hypothesize the establishment and development of the laccolith, with subsequent eruptive activity lasting about 10 000 years. There follows a stasis in volcanic activity, during which a punched laccolith is thought to have formed. This raised Mount Epomeo along the faults at its margins, and these faults become feeder dykes for eruptive activity between 29 000 and 18 000 a BP, in the western part of the island. During the eruptive phase the uplift stopped, because the magma had found feeder dykes and no longer exerted pressure exceeding the overburden. At the end of this phase, uplift was to begin once again, reaching its maximum before 10 000 years ago when the island's last eruptive phase began.

Archaeological and precise levelling data, which began to be collected in the early twentieth century, show a general lowering of Ischia over the past 2000–2500 years (Luongo *et al.* 1987; Pingue *et al*. 2005). This would confirm the hypothesis of a stasis or regression in the uplift of Mount Epomeo during eruptive cycles, while uplift occurred in the phases of the eruptive inter-cycle (tumescence–detumescence).

The average uplift rate in the past 30 000 years during the punched phase is thought to amount to about *c.* 1.5 cm a^{-1}. However, if we allow for stasis in Mount Epomeo's eruptive periods, the volcano was uplifted discontinuously for no longer than 12 000 years. In this case, the average rate is very close to that of bending, a result which appears quite reasonable given the rheological properties of the medium and the stress fields at work. This idea of resurgence evolving in fits and starts is supported by the formation and age of marine terraces.

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