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Common geophysical characteristics of Campi Flegrei, Rabaul and Usu: Three volcanic events

Giovanna Berrino* and Izumi Yokoyama

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Resumen

Durante periodos de actividad existen varios tipos de relación entre las deformaciones vulcanogénicas y la sismicidad volcánica. Las intrusiones de magma o de otros fluidos geotérmicos bajo los volcanes pueden causar deformaciones graduales o rápidas de la superficie. La energía mecánica de las intrusiones se convierte en energía de deformación y sismos, y bajo ciertas condiciones, también en explosiones. La partición entre estos tres tipos de energía provee valiosa información sobre los procesos internos y sugiere la naturaleza de sus orígenes. Desde este punto de vista, se discuten las deformaciones que acompañaron a la sismicidad en los Campi Flegrei, Rabaul y Usu con base en los datos publicados. Para correlacionar cuantitativamente las deformaciones y la sismicidad, tratamos las derivadas temporales de los cambios de elevación y de la liberación de energía sísmica, que están relacionados energéticamente. La correlación entre esas derivadas es moderada en Campi Flegrei, algo mayor en Rabaul y alta en Usu, aunque es necesario considerar que la calidad de los datos no es siempre la misma. Los volúmenes deformados son diferentes entre los tres volcanes, y para homologarlos, se comparan las energías sísmicas liberadas por unidad de volumen de cada deformación. Se encuentra que la energía sísmica específica se incrementa de Campi Flegrei a Rabaul y de allí a Usu. Las diferencias entre los comportamientos de las sismo-deformaciones en esos tres volcanes se interpretan en términos de distintos mecanismos de actividad volcánica y diferentes propiedades físicas de los medios involucrados.

Palabras clave: deformación, sismicidad, energía relevar, depósitos de caldera.

Abstract

Volcanogenic deformations during periods of unrest are related to volcanic seismicity in various ways. Magmas or geothermal fluids intrude beneath volcanoes and cause deformations at the surface gradually or rapidly. Mechanical energies of the intrusions are converted to deformation energy, earthquakes, and also explosions under certain circumstances. Partition among the three kinds of energies provides information of the internal processes and yields a clue to their origin. From the above standpoint, deformations accompanying seismicity at Campi Flegrei, Rabaul and Usu are discussed with the aid of published data. To quantitatively correlate the deformations and the seismicity, we discuss the time-derivatives of uplift and release of seismic energy, which are energetically interrelated. The correlation between them is moderate at Campi Flegrei, somewhat higher at Rabaul and high at Usu, but the data sets are not always equal in quality. The deformation volumes are also different among the three volcanoes. In order to standardize the volumes, seismic energies released by unit volume of each deformation are compared. The specific seismic energy is found to increase from Campi Flegrei through Rabaul to Usu. Such different behavior in seismo-deformations among the three volcanoes is interpreted as differences in the mechanism of volcanic activity, and in physical properties of the mediums involved.

Key words: deformation, seismicity, energy release, caldera deposits.

G. Berrino*
Istituto Nazionale di Geofisica
e Vulcanologia–Sezione di Napoli
Osservatorio Vesuviano
Via Diocleziano, 328,
80124, Napoli, Italy
Tel: + 39 081-6108307
fax: +39 081-6108351
*Corresponding author: giovanna.berrino@ov.ingv.it

I. Yokoyama
Usu Volcano Observatory
Hokkaido University
Sapporo 060-0810 Japan

Introduction

Volcanogenic deformations appear as uplift, subsidence, tilt, collapse and doming, which are generally gradual, and are caused by subsurface magma movements. The relationships between volcanogenic deformations and seismicity may be very close, or somewhat imprecise. During some volcanic activities, we observe a clear correlation between deformation and seismicity showing stick-slip movements. The difference in the correlativity mainly derives from mechanisms of the volcanic activity and from physical properties of the mediums concerned, i.e. magmas, caldera deposits and host rocks.

In the case of tectonic earthquakes, fault movements are usually instantaneous, and sometimes earthquake swarms are also simultaneously accompanied by ground deformations. On the other hand, volcanogenic deformations are generally gradual or sporadic and usually accompanied by seismic activity, small or large in magnitude. We will discuss such examples below.

The activities of the three volcanoes, Campi Flegrei (1982~1984), Rabaul (1981~1984) and Usu (1977~1979) manifested different features of volcanogenic deformations: Campi Flegrei was abrupt ground uplift after secular depression at the center of a caldera, Rabaul was movements of caldera floor enclosing active cones, and Usu was a local uplift of the summit part of an active volcano accompanying phreatomagmatic explosions.

The consequences of the three activities are as follows: Campi Flegrei has repeated rises and falls in activity, but no surface eruption has occurred in recent times. Rabaul finally developed into eruptions after 10 years (in 1994). The activity of Usu declined gradually after the early paroxysms and ended after 5 years (in 1982).

The earthquake data on the three volcanoes discussed in the present paper are originally acquired and properly analyzed by each volcano observatory (e.g. Osservatorio Versuviano, 1984; Seino, 1983). Completeness of their seismic data in the period concerned was kept at high standard of those days according to their publications.

Background

In some volcanic areas, we observe gradual secular movements of the ground with low or no seismicity: these are regarded as anomalous. Yokoyama and Nazzaro (2002) adduced Campi Flegrei in Italy, Iwojima Island and Aira caldera in Japan as examples. On the other hand, deformations on and around volcanoes simultaneous with magma movements, shallow or deep, are usually interpretable in terms of mechanical models. In the present paper, a kind of seismo-geodetic coupling shall be considered.

The secular changes in the height above the sea level of "Serapeo" (ruins of a Roman market) that is located at the center of Campi Flegrei caldera, have been documented since the Roman period. Oliveri del Castillo and Quagliariello (1969) concluded that Serapeo would tend to subside monotonously due to self-loading compaction of the caldera fill, and that it would change to upheaval instantly or elastically when major local earthquakes occurred. In 1969, Serapeo changed to uplift from the secular subsidence, and fostered various researches on its origins. Later we will refer to some results of the recent studies.

The Rabaul activities for 1981~1984 were also remarkable in deformations and seismicity within the caldera. McKee *et al*. (1984) and Mori *et al*. (1989) monitored the developments in uplift at the caldera bottom and in seismicity of the volcano, and determined the sources of deformations, earthquake magnitudes and mechanisms. Berrino and Gasparini (1995) compared the activities of Campi Flegrei and Rabaul, and noted that the acceleration of deformation rates with increasing numbers of earthquakes was less at Campi Flegrei than at Rabaul.

The 1977 eruption of Usu began with violent explosions at the summit crater, and thereafter a part of the summit continued to uplift accompanied by incessant microearthquakes. The uplifts were generated by stick-slip motions along fault zones. Yokoyama (2006) tentatively concluded that the discharge rates of seismic energy are directly proportional to the upheaval rates in cases of the 1983-1984 Pozzuoli event and the 1977~1979 Usu eruption.

On the other hand, McGarr (1976) discussed theoretically the relationship between seismicity and related volume changes, and exemplified tremors in mines, man-made earthquakes, earthquake swarms and a caldera collapse. He concluded that the seismic energies ranged from 0.2 to 3% of the total energy in the examples cited. The necessary condition for his conclusion is that the deformations should be accommodated by seismic failure. In the present paper, this conclusion is confirmed by the coincidence of occurrences between seismicity and deformation, and by the distribution of the hypocenters directly related to the deformations, and by the focal mechanisms. The seismic activities of the volcanic events studied are summarized in relation to their deformations.

When volcanogenic uplifts are closely correlated with seismicity, we may consider the energy partition between earthquakes and volcanogenic uplifts. The former can be estimated while the latter is not always determinable, but should be proportional to uplift rates. We treat this problem, therefore, using time-derivatives of seismic energy release and uplift.

The present paper will discuss comparatively and synthetically the three events, Campi Flegrei, Rabaul and Usu, from the standpoint of correlation between deformations and seismicities from the available published data. In all the three events, we will mainly treat with movements of the maximally deforming points, and volume of the media concerned shall be taken into consideration. On the other hand, at present, real-time and continuous two-dimensional measurements of volcanogenetic deformations are accessible by using networks of GPS and EDM, as carried out on Kilauea, Hawaii by Hooper *et al*. (2002).

Campi Flegrei

The Campi Flegrei is located in the western part of the Gulf of Naples and occupies the major part of a caldera measuring 15 km in diameter which contains several monogenetic cones and fumaroles. A sketch map of its topography is shown in Figure 1 (a) where the roughly southern half of the caldera is Pozzuoli Bay bounded by three shallow banks. It was formed about 39,000 years B.P. as a result of the eruption of 80 km^3 of the Campanian Tuff. The Bouguer gravity anomalies observed there, both on-land (Cassano and La Torre, 1987) and off-shore (Berrino *et al*., 2008), indicate that the caldera is funnel-shaped and that its center coincides with the town of Pozzuoli. The caldera deposits are ignimbritic tuffs and pyroclastic rocks, which have a lower density than the basement rocks (carbonatic and/or thermo-metamorphic rocks). According to Fedi *et al*. (1991) and Berrino *et al*. (2008), the low-density material fills the caldera to a depth of about 2 to 3 km at the center.

Secular ground deformation at Serapeo, Pozzuoli

Since 1969 a remarkable uplift of the ground has been noticed in the Pozzuoli area in the center of Campi Flegrei and micro-earthquakes have been recorded. As for the ground deformations in this area, we can refer to historical documents of the secular changes in the height of "Serapeo" which is a ruined Roman market near the shore in the town of Pozzuoli. Several reconstructions of the crustal-related sea-level change in Pozzuoli since Roman time have been done as shown in Figure 2 (e.g., Parascandola, 1947; Casertano *et al*., 1976; Dvorak and Mastrolorenzo, 1991; Mohrange *et al*., 2006). Here we consider the reconstruction made by Parascandola (1947) who drew a trend of the secular vertical deformation at Serapeo, as shown in Figure 2 (a) where the arrows with the letters VE, SO, IS and MN indicate major eruptions of Vesuvius, Solfatara,

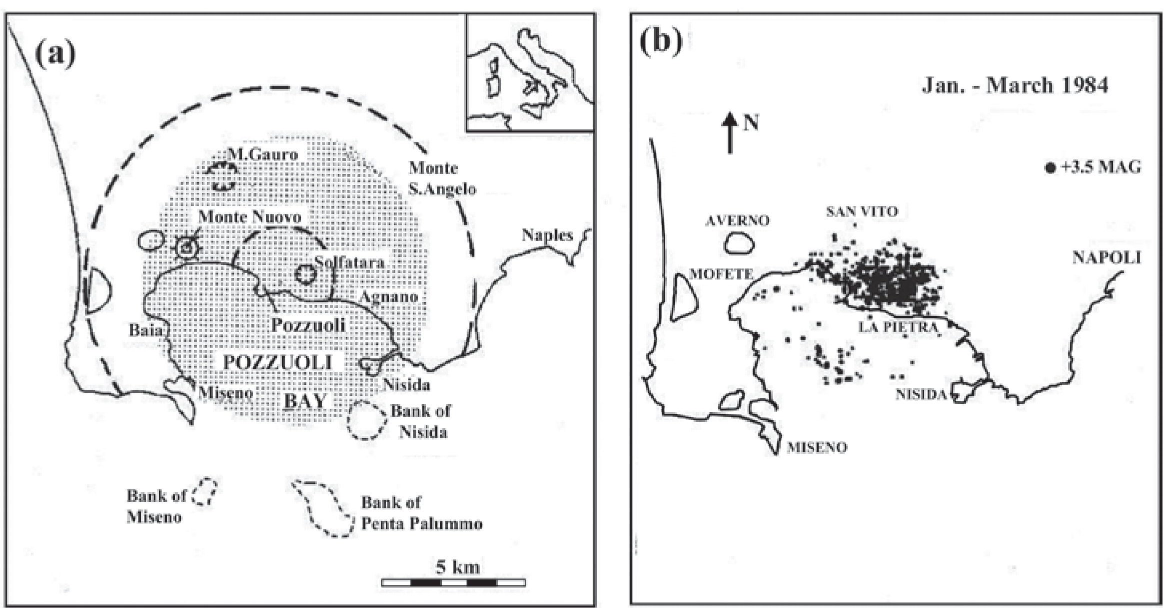

Figure 1. (a) Topographic sketch map of Campi Flegrei. The outer arc indicates the limit of the deformation and the inner one represents a contour of 50% of the maximum upheaval at the center. The dotted area (r = 5 km) indicates an assumed area of upheaval in a circular cone centered at Pozzuoli: (b) Distribution of epicenters during Jan.~March 1984. Focal depths range from 0 to 4 km (after Orsi *et al*., 1999).

Ischia (about 15 km west of Miseno) and Monte Nuovo (Figure 1(a)), respectively, and the bars indicate major earthquakes in Campania. Those with the letter P are earthquakes in the Pozzuoli area. In the 10th century, the pattern changed to upheaval and was especially marked at about the time of the 1538 eruption of Monte Nuovo. After 1538, it again subsided until 1969 (Oliveri del Castillo, 1960; Corrado and Palumbo, 1969). According to Dvorak and Gasparini (1991), it is probable that no uplifts larger than a few meters occurred during the period between 1538 and the 1820's when sea level measurements near Pozzuoli were made for the first time. Serapeo subsided at an average rate of 1.4 cm/yr between the 1820's and 1969 (Berrino *et al*., 1984). In Figure 2, the relationships between the uplifts of Serapeo and macroearthquakes are not clear, but we may infer that Serapeo rose during a short period due to local earthquakes or nearby volcanic events.

Oliveri del Castillo and Quagliariello (1969) concluded that Serapeo would tend to subside monotonously due to self-loading compaction of the caldera fill, and that it would change to upheaval instantly or elastically when major local earthquakes occurred, as in A.D. 63, 1536-1538 etc., and also when major eruptions broke out such as the A.D. 79 and the 1631 eruptions of Vesuvius, the 1302 eruption of Ischia and the 1538 eruption of Monte Nuovo. Such behavior of Serapeo is due to the viscoelastic properties of the caldera fills. This compaction model can account for the increasing subsiding velocity from the borders to the center (Figure 1a).

The secular subsidence of Campi Flegrei can be interpreted by the compaction model, and this characteristic of the caldera deposits has a strong effect on the deformations. This is discussed later.

The 1969-1985 activity of Campi Flegrei

In 1969, the Pozzuoli area began to rise suddenly, probably as a result of magma or steam intrusion beneath Campi Flegrei caldera (Yokoyama, 1971). After 1969, precise levels have been repeated around Pozzuoli. Oliveri del Castillo and Quagliariello (1969) found, from mareographic observations on February 5, 1970, that Pozzuoli had uplifted about 94 cm since 1953. This recent uplift probably began in 1969 (Corrado *et al*., 1976/77). On this assumption, the area may

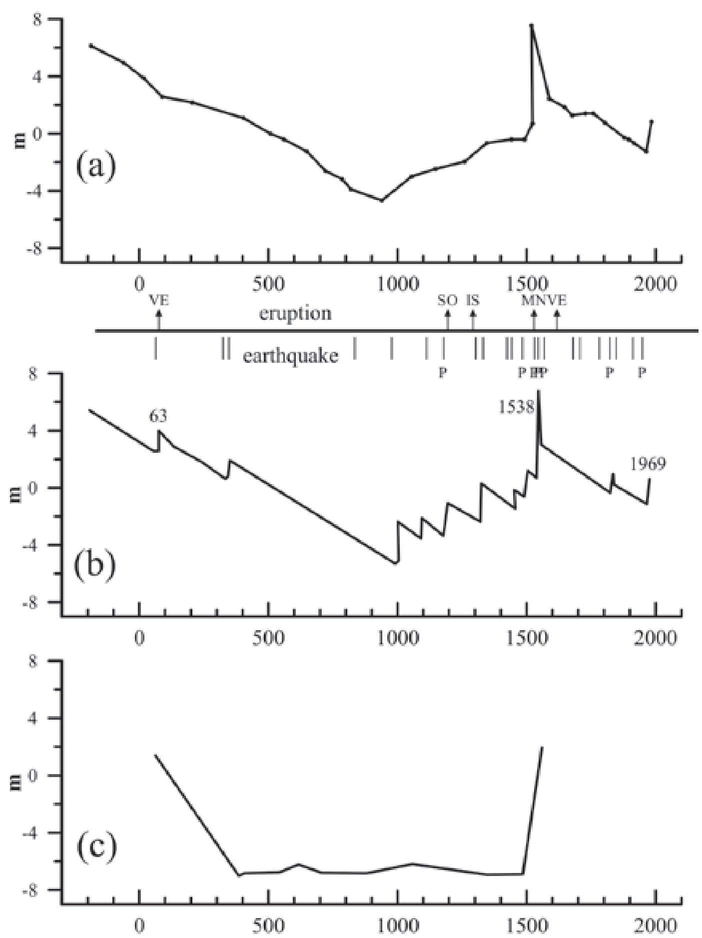

Figure 2: Deformation trends of Serapeo, Pozzuoli: (a) after Parascandola (1947), (b) after Casertano *et al.* (1976). In between, arrows and bars mark eruptions and earthquakes, respectively. For the notations, refer to the text. (c) after Morhange *et al*. (2006).

have subsided continuosly, at a rate of 1.4 cm / yr, for 16 years from 1953 to 1969. If we assume that Pozzuoli subsided 22 cm (= 1.4 cm/yr × 16 yr) in this interval, we may conclude that it had uplifted 116 cm (= 94 cm + 22 cm) over a period of nearly 4 months; this rate is approximately 3.5 m/yr. Such a rapid uplift may have ever been perceptible along the seashore without instruments (Yokoyama, 1971). No earthquakes felt at Pozzuoli during these four months were reported: the seismic activity may have been microseismic.

Since the end of February 1970, a seismometric network has been installed in Campi Flegrei, and the seismicity has been recorded continuously. During the period (1982-1984) analyzed in the present paper, vertical ground movements have been monitored continuously by mareographic observations at 5 tide-gauges, located one in Napoli and four in the Gulf Pozzuoli, and intermittently by precise leveling on a network of 124 benchmarks covering the whole Campi Flegrei area (Berrino *et al*., 1984). Berrino (1998) analyzed sea-level changes in the Neapolitan area and obtained the two diagrams, monthly numbers of earthquakes and variation of the sea level, shown in Figure 3. Discussing the correlation between the two diagrams, Berrino and Gasparini (1995) pointed out that the seismic activity follows the beginning of the uplift of the ground some months later.

Hypocenters of the earthquakes related to the upheaval

An example of the distribution of the epicenters related to the Pozzuoli uplifts for the period January to March 1984 is shown in Figure 1 (b) after Orsi *et al.* (1999, Figure 15). They cluster roughly around the center of the caldera, and their focal depths range from 0 to about 3 km. Seismic activity occurred through earthquakes with magnitude ranging from 0.1 to 4.2 and several swarms. The major swarms occurred on 13 October 1983 (when 315 shocks with magnitude ranging between 0.2 to 3.0 were recorded in 4 hours) and the greatest on 1st April 1984 (when 513 shocks were recorded in 6 hours). A detailed description of the seismic activity from 1970 to 1997 is given in Orsi *et al*. (1999).

During the 1983-1984 activity, the seismicity varied with time, but its general tendency remained the same. Dvorak and Berrino (1991) discussed ground movement, seismic activity and near-surface fractures around Pozzuoli, and proposed a structural model of Campi Flegrei caldera, in which the Pozzuoli upheaval was caused by a resurgent dome measuring about 4 km in diameter, centered at Pozzuoli (Dvorak and Berrino, 1991, Figure 12).

Earthquake mechanism

The focal mechanisms of the 1982-1984 earthquakes in Campi Flegrei were discussed by Zuppetta and Sava (1991) who concluded that NNE extensional tectonics coupled with doming can account for the seismic pattern during the period, and that the spatial distribution of the normal fault related to the seismic activity was controlled by a pre-existing regional, quasi-conjugate, fracture system. The earthquake mechanisms are consistent with the doming beneath Campi Flegrei caldera.

Deformations and seismic energy

In order to examine the relationship between the deformation and the seismicity quantitatively, the rate of seismic energy release and the upheaval rate are compared with each other for the period from January 1982 to December 1984, the most active period of seismicity and uplift in Figure 3. On the principle of energetics, deformation

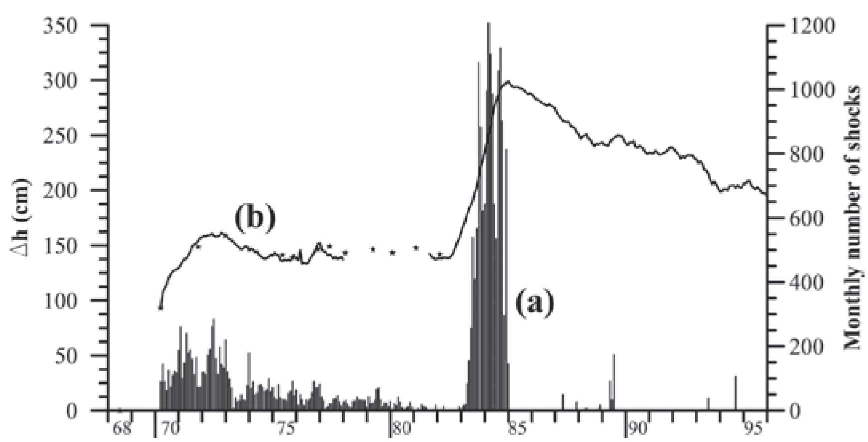

Figure 3: Activities in Campi Flegrei during the period 1970~1995 (Berrino, 1998): (a) Monthly numbers of earthquakes (0.1≤ML≤ 4.2) in Campi Flegrei, (b) Upheaval trend at Pozzuoli determined by mareographic observations.

energy released by uplift per unit time may be expressed as:

(uplift / unit time) × (quasi-constant resisting force + gravitational force).

Thus, uplift rates are proportional to release rates of deformation energy that can be compared with release rates of seismic energy.

Here we analyze the upheaval rate of the maximum uplift point recorded at a benchmark presently named No. 25, located west of Pozzuoli town along the coastline. More detailed data and a new reconstruction of the temporal elevation change at the benchmark No.25 from 1905 to 2009 are given in Del Gaudio *et al*. (2010).

Orsi *et al*. (1999) gave the maximum uplift rate calculated from precise levels (Berrino *et al*., 1984; Dvorak and Berrino, 1991) in the Pozzuoli area (benchmark No. 25) for eight unequal intervals ranging from two to 12 months during the period. We calculate the monthly uplift rates at the benchmark No. 25 for these eight intervals. The monthly discharge rates of seismic energy are calculated from the earthquake magnitudes given by the Osservatorio Vesuviano (1984). During the period, earthquakes of local magnitude ranging from 0.1 to 4.2 were recorded.

Both of these sets of results are shown in Figure 4. The correlation coefficient between the two diagrams for the eight stages of the precise levels is shown as 0.55. This suggests that in a significant extent deformations were accommodated by seismic failure.

During the period of 1982~1984 in Figure 4, the mean discharge of seismic energy was 3.0×10^{10} J/month, and the mean uplift was 5.6×10^{-2} m/month. Thus one gets the release of seismic energy accompanying an uplift of 1 m of the benchmark as 5.3×10^{11} J/m. To standardize energy releases among volcanoes, we need to evaluate volume of the ground concerned. The Pozzuoli deformation extends outward radially from the center of the caldera as shown in Figure 1 (a), where the outer circle (r = 6.8 km) roughly indicates zero-uplift, and the inner one (r = 2.3 km) marks 50% of the maximum uplift following Berrino and Corrado (1991, Figure 2). We approximate the uplifted volume as an inverted circular cone with base radius 5 km, and get the volume change of 1 m uplift as 2.6×10^{7} m^3. Thus, the release of seismic energy related to ground uplifts of a unit volume is obtained as 2.0×10^{4} J/m^3. In other words, magma intruded into the caldera deposits beneath Campi Flegrei, and the mechanical energy was converted into deformations and earthquakes, although we do not know the exact partition of the energy. The above value is a measure of seismo-deformations of the ground. Later we will compare the values among the three volcanoes.

After 1985, the deformation at Pozzuoli changed to subsidence with the exception of a small uplift lasting from 1989 to 2009, according to Del Gaudio *et al.*, (1998, 2010). The recent Campi Flegrei crises have not caused any eruptive phenomena at the surface, up to the present time.

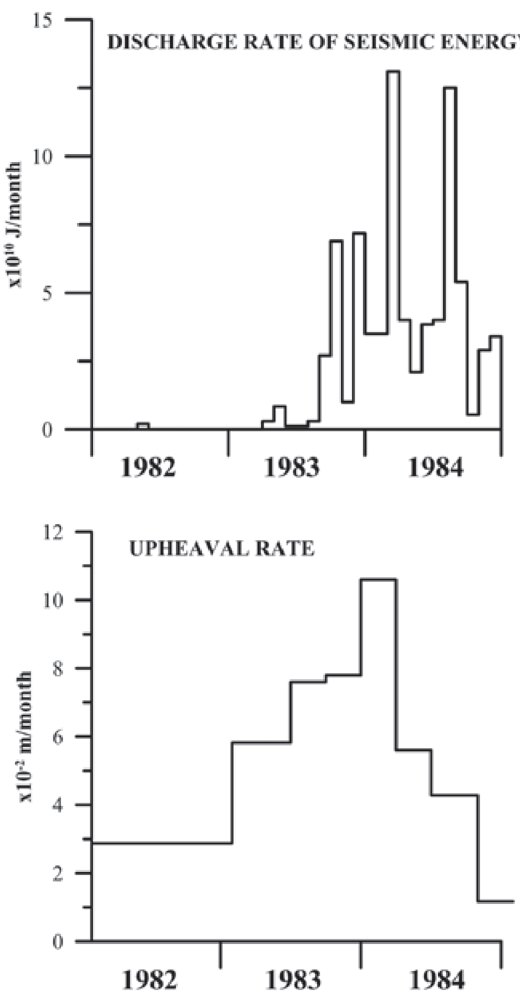

Figure 4: Activities in Campi Flegrei in the period 1982~1984: discharge rate of seismic energy (original data after Osservatorio Vesuviano, 1984) and upheaval rate at BM 25 near the Pozzuoli Port in 1982 ~ 1984 (original data after Orsi *et al*., 1999).

The 1981-1985 activity of Rabaul

Rabaul caldera is located on the NE end of New Britain Island in Papua New Guinea, and measures 15 km in the N-S and 9 km in the E-W directions, opening to the sea on the eastern side (Figure 5). The hypocenter distribution suggests an outward-dipping ring-fault structure (Mori and McKee, 1987). In 1997, seismic tomographic imaging was carried out by Finlayson *et al*. (2003), and detected a 30~35 km^3 low-velocity region at a depth of 3~6 km beneath the center of the caldera.

According to McKee *et al*. (1984), only Tavurvur and Vulcan (Figure 5 (a)) have erupted in historical times. Both vents were simultaneously active in 1878 and 1937, and Tavurvur was active in 1941-1942 and 1943. In 1967 a permanent short-period seismic network began to operate. Throughout the 1970's, seismic swarms tended to have increasing numbers of earthquakes, and a seismo-deformational crisis occurred from September 1983 through to July 1985. Later, in 1994, Rabaul volcano erupted through both vents, Tavurvur and Vulcan.

Hypocenters of the earthquakes related to the upheavals

Mori *et al.* (1989) obtained the distribution of over 2,500 hypocenters for the period September 1983 to July 1985, which were related to the central upheavals of the caldera as shown in Figure 5 (b). Their focal depths range from 0 to about 4 km, and the hypocenters outline a ring-fault system. Mori *et al.* (1989) interpreted the caldera subsidence into movements occurring on this ring-fault system. They suspected that the earthquakes took place there in response to stresses created by magma intrusions into the central block, with increased magma pressure at the base of the block. In other words, they assumed that the Rabaul uplifts in the 1980's were caused by increases in magma pressure at the base of the caldera.

Earthquake mechanisms

McKee *et al*. (1984) and Mori *et al*. (1989) discussed the focal mechanisms of the larger events during the period 1983 to 1985, and obtained predominantly normal faulting. They

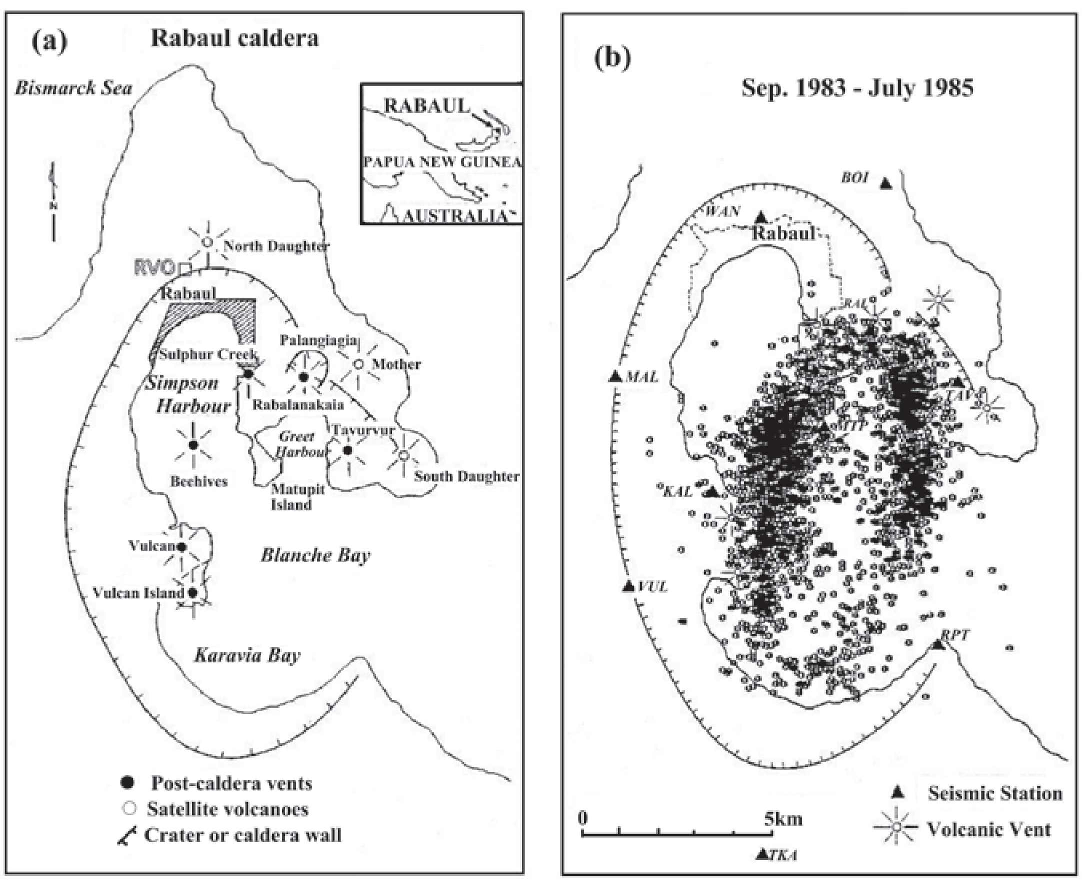

Figure 5. Rabaul caldera and its seismic activity. (a) A topographic sketch map of Rabaul caldera. (b) Distribution of epicenters during Sept. 1983 ~ July 1985. Focal depths range from 0 to 4 km (Mori *et al*., 1989).

assumed that the outward-dipping nodal planes were the fault planes. This assumption implies that the region bounded by the ring structure moved upwards relative to its surroundings. This mechanism is rather similar to that of Usu, as shall be described later.

Deformations and seismic energy

During the period November 1973 to May 1984, eight precise levels were repeated along the main route in the northern part of the caldera, and the results are reproduced in Figure 6, from McKee *et al.* (1984, Figure 2). In the figure, the reference point is BM 21, and the center of the uplift is assumed to be around Matupit Island. McKee *et al*. (1984) determined the location of a point source model applied to the NE part of the caldera as 2 km deep. They also from the results of tilt measurements in that area, determined a possible source near Vulcan as 3 km deep.

In the present paper, the relationship between the deformation and the seismicity for the period 1981-1984 is discussed on the basis of the published data. Following the previous discussion on Pozzuoli, the release rates of seismic energy are compared with the uplift rates for the period from 1981 to 1984. We select three periods I, II and III when the precise levels were repeated, as shown in Figure 6. The monthly discharge rates of seismic energy for the periods corresponding to the leveling intervals are approximately estimated from the seismic data given by Mori *et al*. (1989, Table 2; in which the magnitudes (M_L) range from 2.0 to 5.1). The activity in period I was very low and the largest earthquake in the period was M_L 5.1 in March 1982 (Mori *et al*., 1989, p. 432). The monthly uplift rates for the three periods are obtained from the results of precise leveling at BM 15 where the largest uplift occurred (Figure 6). The two rates are shown in Figure 7: they are broadly similar, although the samples are only three in number. The similarity indicates that the Rabaul uplift was probably accommodated by seismic failure, and that the origin of the uplifts may have been magmatic, since the post-caldera vents, Tavurvur and Vulcan, erupted in 1994. To compare the two rates in Figure 7, we deal with the mean values of both the rates for the three stages, I, II and III. One is about 6.3×10^{10} J/month, and the other is about 0.016 m/month. Cancelling the time terms, one gets the seismic energy release related to a ground upheaval of 1 m as 3.9×10^{12} J. Considering that the deformation decreases radially within a radius of about 3 km from the center as shown in Figure 6 (inset), we roughly approximate the deformed volume as an inverted circular cone with base circle of the same radius: This encloses an area of 28.3 km^2. Thus, with the above approximation, an uplift of 1 m at the center of the caldera produces an increase of volume of the ground of about 9.4×10^6 m^3. Hence, the release of seismic energy related to a ground uplift of a unit volume is 4.1×10^5 J/m^3 in order of magnitude.

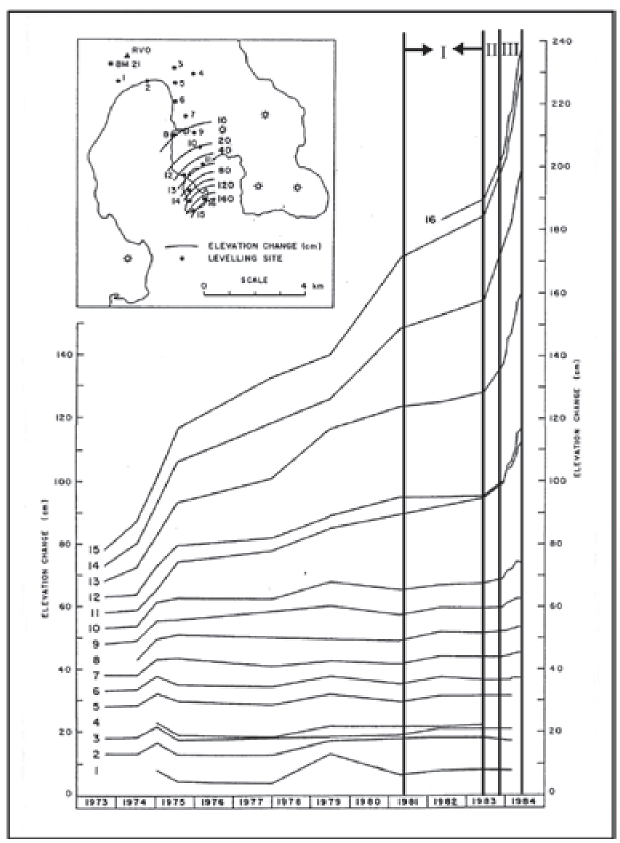

Figure 6. Vertical deformation at Rabaul caldera referred to BM 21 (McKee *et al.*, 1984). I, II and III indicate the periods for which earthquake energy is estimated.

The 1977-1982 eruption of Usu

The eruption of Usu was different from the previous examples: its summit part uplifted about 160 m after magmatic eruptions. Usu is located in the southern part of Hokkaido, Japan, and has erupted eight times in the historic period. Four of these eruptions occurred in the 20th century and were studied rather well, with instruments that were state-of-the-art in each period. Its magmas are dacitic and usually give rise to earthquake swarms and remarkable ground deformations with lava domes and mounds. A topographic sketch map of Usu volcano as of 2009 is shown in Figure 8. The Usu Volcano Observatory of Hokkaido University was established just before the outburst of the 1977-1982 eruption. By the eruption, the summit part of the volcano was deformed, uplifted and thrust

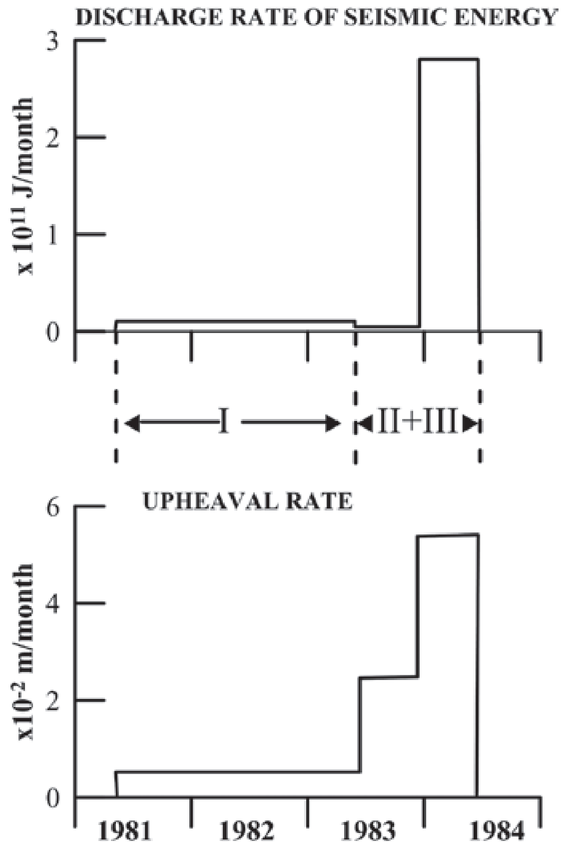

Figure 7. Monthly discharge rate of seismic energy and monthly upheaval rate of BM 15 (original data after Mori *et al.*, 1989). Periods I, II and III are the same as those in Figure 6.

northeastward, but the magma had remained at a depth of over 1 km. Later, in 2000, another eruption with phreatomagmatic explosions took place at the NW base of the volcano, and formed several craterlets and a few mounds (Figure 8).

The 1977 eruption of Usu began at the summit with a vigorous pumice explosion and went on to form three craterlets with magmatic explosions, and then 14 with phreatomagmatic explosions (Figure 9 (a)). During the period, 1977-1979, the summit part of the volcano was uplifted about 160 m and displaced 180 m northeastward as a result of the upward pressure of the intruded magma, as shown in Figure 9 (b). A U-shaped block at the summit tilted at an angle of roughly 11 degrees. Yokoyama and Seino (2000) estimated the depth of the intruded magma as about 1 km, judging by the topographic sectional changes. Volcanic earthquakes were closely related to ground deformations. Seino (1983) estimated the seismic energies using the seismograms recorded at Sapporo (Δ = 70 km).

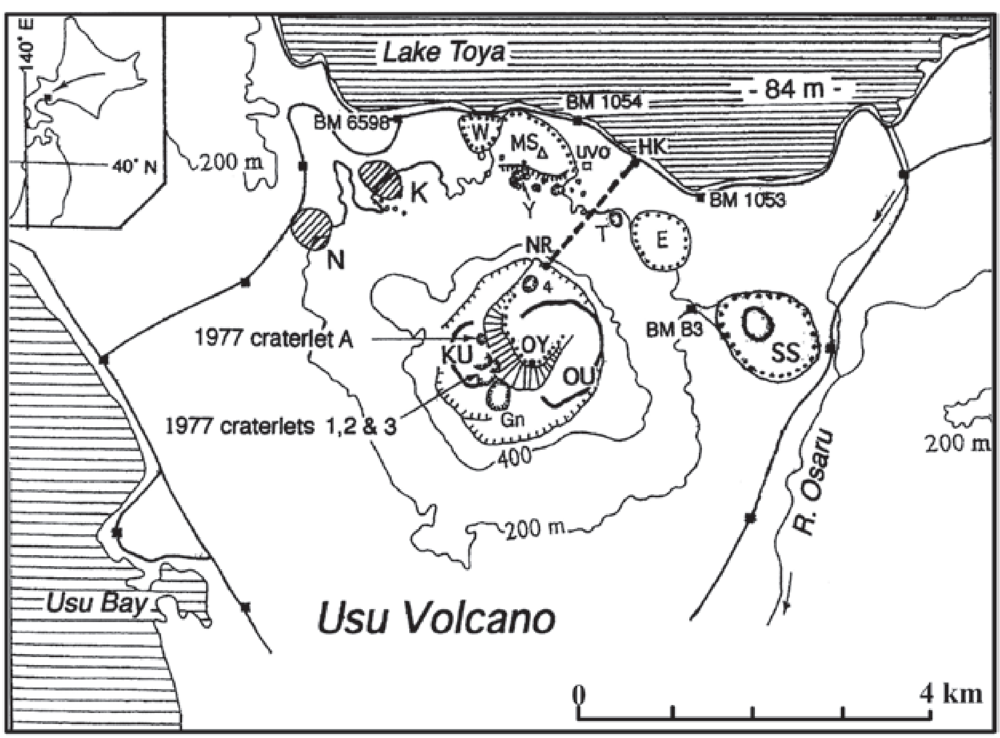

Figure 8. Topographic sketch map of Usu, as of 2009. Thick lines indicate lava domes; KU, the 1769 lava dome; OU the 1853 lava dome; and MS, the 1910 mound, with Y and T, the 1910 craterlets. E and W are the mounds of unknown ages. SS is the 1944 lava dome, and OY a benchmark on the rising block in 1977~1979. The NR-HK line is an EDM survey line. K and N are the craterlet areas of the 2000 eruption.

Their magnitudes ranged between 3.1 and 4.3. Yokoyama *et al.* (1981) found that the rate of seismic energy release was proportional to the uplift rate, as shown in Figure 10. In the figure, the daily discharge rates are averaged for every 5 days.

The uplifts of a target at the summit (OY in Figure 9 (a)) were measured with a theodolite from a fixed point at a distance of about 8 km to the south, and the daily uplift rates were averaged around each observation period. Topographic changes of the summit part, on the other hand, were monitored by aerial photogrammetric surveys (Figure 9 (b)). Although the uplift resulted from tilts of a summit block (Yokoyama and Seino, 2000), we may assume that the summit uplifts represent upward magma movements. The magma provoked phreatomagmatic explosions forming several craterlets (A~N) along a fault line in Figure 9 (a). Such systematic and gradual trends of seismicity and deformation shown in Figure 10 were useful for forecasting the behavior of the volcano in the medium-term. The 1977-1982 eruption of Usu finally ended in February 1982 when the deformations totally ceased.

Earthquakes related to the uplifts

An example of the epicenter distribution for one particular period is shown in Figure 9 (c) (after the Usu Volcano Observatory). The epicenters cluster around a U-shaped fault zone open to the NE, and clearly belong to several earthquake families, with focal depths ranging from 0 to 2 km. During the 1977-1982 eruption, the seismicity varied with time in the location, number of earthquakes and magnitude, but its general tendency remained roughly the same. As seen in Figure 9 (c), each earthquake family has a predominant magnitude; i.e. they do not satisfy the Gutenberg-Richter formula. This is a characteristic of stick-slip mechanisms.

Mechanisms of the earthquake families

Takeo (1983) discussed a quantitative relationship between the large earthquakes (M_L 3.8~4.3) and the doming deformation during the period 1979~1981, in terms of the source mechanisms obtained by analysis of the near-field displacements. The cumulative seismic deformation caused by these earthquakes is consistent with the N-NW component of the observed surface deformations. Hence, the two earthquake families of larger magnitude occurring on the two sides of the U-shaped fault zone may have been generated by stick-slip motions along the fault zone.

Deformations and seismic energy

Here, we deal with the time-derivatives of the deformation and the seismic energy release, as we did for the previous examples. The correlation coefficient between the monthly mean values of the two diagrams of discharge rate of seismic energy and uplift rate, shown in Figure 10, is calculated for the 13 months as 0.97, and from that we derive a release of seismic energy of 2×10^{11} J/day, which corresponds to an uplift rate of 0.3 m/day. From these two values, the seismic energy released by 1 m uplift of the peak is obtained as 6.7×10^{11} J. The uplift of the peak was accompanied by an elevation of a summit block, defined as a wedge-shape, 1 km square, tapering toward the northeast, as shown by the dotted part in Figure 9 (b). Thus, 1 m uplift of the peak produces a volume uplift of (1 km×1 km ×1 m×1/2) = 0.5×10^6 m^3. We therefore get a release of seismic energy related to a ground uplift of a unit volume as 1.3×10^6 J/m^3.

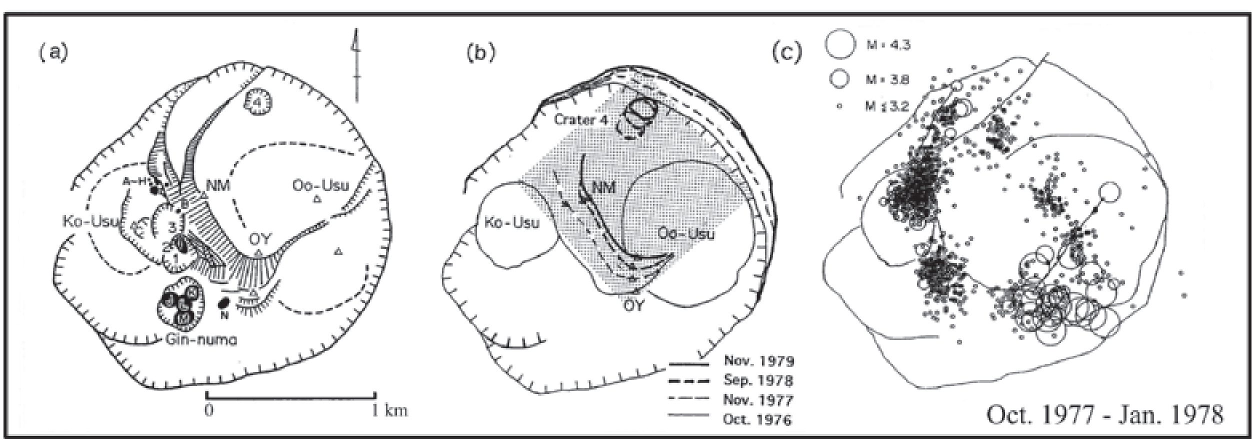

Figure 9. (a) Topographic sketch map of the summit crater of Usu as of 1982. 1 ~ 4, A~N, and Gn are craterlets formed in the 1977 eruption. (b) Horizontal deformations: the OY-point was raised about 185 m; its vertical deformations are shown in Figure 10 (bottom). The dotted area indicates deformed ground (roughly 1 km square). (c) Distribution of epicenters during Oct. 1977 ~ Jan. 1978. Focal depths range from 0 to 2 km.

To summarize, the magma beneath Usu pushed up the summit block and part of the mechanical energy was released as seismic energy. Yokoyama *et al.* (1981) found that both the seismic activity and the deformation became quiet for a few days to as long as a week, immediately after a major explosion. This means that explosions would release pressure and cease deformations and seismicity. Yokoyama *et al.* (1981) also discussed the energy partition between explosions, earthquakes and deformations, the first two being estimated from the observations. They concluded that the seismic energy is approximately one tenth as large as the deformation energy. At present, we cannot determine exactly the original volume of the deformed medium. However, from the distribution of the hypocenters, and a sectional diagram of the tilt movements (Yokoyama and Seino, 2000, Figure 11), and from stick-slip movements in the deformation of Usu, we suggest that its depth may have been more than 1 km. In December 1977, semi-continuous measurements of the distance between the north rim NR and a base station HK (Figure 8) were carried out using an electronic-distance-meter for 44 hours. The measurements were able to detect changes in the distance with an accuracy of ±1 cm. From these measurements, it was found that the summit block moved coseismically northeastward in a stick-slip manner. This indicates that a magmatic force uplifted the summit block in stick-slip movements against the surrounding rocks. This is due to characteristic property of the surrounding medium, and would not occur in unconsolidated caldera deposits. Earthquake families of stick-slip mechanism have been recognized during doming activities of some other volcanoes; for example, in the 1944 eruption of Usu, a solidified magma extruded forming the Showa-Shinzan lava dome (SS in Figure 8), and the doming was accompanied by an earthquake family, some events of which showed stick-slip motions. The family was named "C-type earthquakes" by Minakami *et al*. (1951). Such earthquakes were characterized by similar forms and phases of the seismic waves, and had similar magnitudes, all smaller than 3.9. Minakami *et al.* (1951) correctly inferred that this earthquake family had close connections with the enormous forces that acted on the subterranean base of the lava dome.

Similarly, during the 1990-1995 eruption of Unzen, Kyushu, a number of volcanic earthquakes of similar waveform and roughly constant magnitude occurred successively at the doming stage of dacitic magma (Nakada *et al*., 1999). In contrast, such stick-slip motions have not been observed in both Campi Flegrei and Rabaul because these two volcanic events were deformation of the caldera floors unrelated to any movements of a particular volcanic block.

Discussion

The three volcanoes discussed here are characterized as regards their volcanic activity as follows; at Campi Flegrei, no surface activities have taken place so far in recent years; at Rabaul, two post-caldera vents within the caldera erupted in 1994, 10 years after a major seismo-deformational crisis, and at Usu, during the period of uplift, phreatomagmatic explosions took place intermittently.

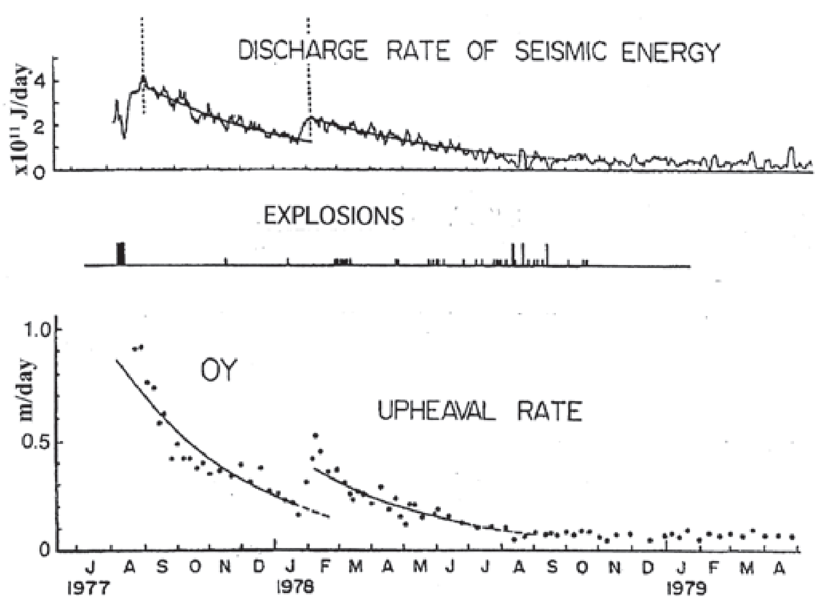

Figure 10. Daily discharge rate of seismic energy ($M_S \geq 3.0$) and daily upheaval rate of the OY-point in the eruption of Usu during 1977~1979. Explosion magnitudes in the center are shown in arbitrary scale.

The areas of the uplifted regions differ among the three volcanoes. The two calderas measure 10~15 km in diameter, and the upheaval at Usu took place in a 1 km square area. The deformation rates of the three cases examined also differ: 0.1 m/month at Campi Flegrei, 0.05 m/month at Rabaul, and 9 m/month at Usu, at their peak periods. Thus it is clear that volcanic activities were more strongly focused at Usu than at the two calderas.

The origin of the remarkable deformations manifested at the summit of Usu is clearly magmatic: part of the summit was pushed up in stick-slip motions by dacitic magmas located at a depth of 1 km. The origin of the uplifts at Campi Flegrei is due to a resurgent doming at the center. At Rabaul, the uplifts were caused by an increase of magma pressure at depth, and accelerated towards the eruptions in 1994.

All the upheavals at the three volcanoes correlate, to a greater or lesser extent, with the seismic energy released during each sequence. To summarize, we get seismic energy releases related to an uplift of unit volume for the three volcanoes, to within one order of magnitude, as follows:

- Campi Flegrei (1983~1984): 2.0×10^4 J/m^3: uplift at the center of the caldera,

- Rabaul (1981~1984): 4.1×10^5 J/m^3: ditto,

- Usu (1977~1979): 1.3×10^6 J/m^3: uplift at the summit of the volcano.

The results, to an order of magnitude, vary according to the resistance to deformation of the mediums in each area. The differences among the three volcanoes are due to different subsurface structure, and different physical properties of the mediums affected, caldera deposits or summit block. In the above active periods of Campi Flegrei and Rabaul, both did not cause any eruptions while Usu erupted intermittently in the period. At Usu, by the agency of these explosions, Yokoyama *et al*. (1981) concluded that the seismic energy was approximately one tenth as large as the deformation energy. Such energy partition between seismicity and deformation at the other two volcanic activities may be analogized.

The caldera deposits of Campi Flegrei deform much more readily than those of Rabaul. This is compatible with the suggestion that the secular subsidence of Serapeo at Pozzuoli is due to self-loading compaction of the poorly consolidated caldera deposits, which are mainly composed of pyroclastics and behave viscoelastically. Rabaul caldera is somewhat resistant to deformation by magmatic forces, probably as a result of the existence of several active post-caldera volcanoes within the caldera. Berrino and Gasparini (1995) compared the activities of Campi Flegrei and Rabaul, and noted that the acceleration of deformation rates with increasing numbers of earthquakes was less at Campi Flegrei than at Rabaul. They concluded that Rabaul has a more brittle environment than Campi Flegrei. This is consistent with our results.

The uplifts at the summit of Usu were accompanied by greater releases of seismic energy than at the two calderas because the surrounding rocks there were highly resistant to uplifts, which took place as stick-slip motions at the fault boundaries. This is characteristic of dome formation of dacitic magmas. In short, the differences of behavior among the three volcanic events are due to those of the mediums involved, although their ultimate motives may be similar. This suggests that the origin of the Pozzuoli uplift is probably magmatic also.

Different volumetric strain energy released as seismic energy among the three events may be interpreted into differences in mechanism of the volcanic activity and those in physical properties of the mediums concerned.

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Bibliography

Berrino G., 1998, Detection of vertical ground movements by sea-level changes in the Neapolitan volcanoes. *Tectonophysics, 294*, 323-332.

Berrino G., Corrado G., 1991, Tidal signal in the recent dynamics of Campi Flegrei caldera (Italy), *J. Volcanol. Geotherm. Res., 48,* 93-101.

Berrino G., Corrado G., Luongo G., Toro B., 1984, Ground deformation and gravity changes accompanying the 1982 Pozzuoli uplift. *Bull. Volcanol. 47,* 187-200.

Berrino G., Corrado G., Riccardi U., 2008, Sea gravity data in the Gulf of Naples. A contribution to delineating the structural pattern of Phlegraean Volcanic District, *J. Volcanol. Geotherm. Res., 175*, 241-252.

Berrino G., Gasparini P., 1995, Ground deformation and caldera unrest, *Cahiers du Centre European Geodynamique et de Seismologie, 8,* 41-55.

Casertano L., Oliveri Del Castillo A., Quagliariello M.T., 1976, Hydrodynamics and geodynamics in the Phlegrean fields area of Italy. *Nature, 264,* 161-164.

Cassano E., La Torre P., 1987, Geophysics, in Santacroce R. (editor), Phlegrean Fields. *Quad. Ric. Sci. CNR,* 103-133.

Corrado G., Guerra I., Lo Bascio A., Luongo G., Rampoldi R., 1976/77, Inflation and microearthquake activity of Phlegrean Fields, Italy. *Bull. Volcanol., 40,* 169-188.

Corrado G., Palumbo A., 1969, Osservazioni sul bradisisma flegreo, *Bull. Soc.Nat., Napoli, 78,* 11-16.

Del Gaudio C., Ricciardi G.P., Ricco C., Sepe V., Berrino G., Riccardi U., D'Errico V., La Rocca A., 1998, Ground deformations, in Phlegrean fields (Eds), *Acta Vulcanol., 10*, 103-106.

Del Gaudio C., Aquino I., Ricciardi G.P., Ricco C., Scandone R., 2010, Unrest episodes at Campi Flegrei: a reconstruction of vertical ground movements during 1905-2009, *J. Volcanol. Geotherm. Res.,* 195, 48-56.

Dvorak J., Berrino G., 1991, Recent ground movement and seismic activity in Campi Flegrei, Southern Italy: episodic growth of a resurgent dome. *J.Geophys. Res., 96,* 2,309-2,323.

Dvorak J., Gasparini P., 1991, History of earthquakes and vertical movement in Campi Flegrei caldera, Southern Italy: comparison of precursory events to the A.D. 1538 eruption of Monte Nuovo and activity since 1968. *J. Volcanol. Geotherm. Res., 48,* 77-92.

Dvorak J., Mastrolorenzo G., 1991, The mechanism of recent vertical crustal movements in Campi Flegrei caldera, southern Italy, *Geol. Soc. Am., Special Paper, 263*, 47p.

Fedi M., Nunziata C., Rapolla A., 1991, The Campania-Campi-Flegrei area: a contribution to discern the best structural model from gravity interpretation. *J. Volcanol. Geotherm. Res., 48*, 51-59.

Finlayson D.M., Gudmundsson O., Itikarai I., Nishimura T., Shimamura H., 2003, Rabaul volcano, Papua New Guinea: seismic tomographic imaging of an active caldera. *J. Volcanol. Geotherm. Res., 124,* 153-171.

Hooper A., Segall P., Johnson K., Rubinstein J., 2002, Reconciling seismic and geodetic models of the 1989 Kilauea south flank earthquake. *Geophys. Res. Lett. 29,* 2062, doi:10.1029/2002GL016156.

McGarr A., 1976, Seismic moment and volume changes. *J. Geophys. Res., 8,* 1,487-1,494.

McKee C., Lowenstein P.L., De Saint Ours P., Talai B., Itikari B., Mori J., 1984, Seismic and ground deformation crisis at Rabaul caldera: Prelude to an eruption?, *Bull. Volcanol., 47*, 397-411.

Minakami T., Ishikawa T., Yagi K., 1951, The 1944 eruption of Volcano Usu in Hokkaido, Japan, *Bull. Volcanol., 11*, 45-157.

Mori J., McKee C., 1987, Outward-dipping ring-fault structure at Rabaul caldera as shown by earthquake locations, *Science, 235*, 193-195.

Mori J., McKee C., Itikarai I., Lowenstein P., De Saint Ours P., Talai B., 1989, Earthquakes of the Rabaul seismo-deformational crisis September 1983 to July 1985: Seismicity on a caldera ring fault, In Volcanic Hazards (Ed.) J. H. Latter, 430-462.

Morhange C., Marriner N., Laborel J., Todesco M., Oberlin C., 2006, Rapid sea-level movements and noneruptive crustal deformations in the Phlegrean Fields caldera, Italy, *Geology, 34*, 93-96.

Nakada S., Shimizu H., Ohta K., 1999, Overview of the 1990-1995 eruption at Unzen Volcano. *J. Volcanol. Geotherm. Res., 89*, 1-22.

Oliveri del Castillo A., 1960, Studio del bradisisma flegreo mediante osservazioni mareografiche, X Meeting of Italian Geophysical Society, Rome, 18-19 November.

Oliveri del Castillo A., Quagliariello M.T., 1969, Sulla genesi del bradisismo Flegreo, *Atti Ass. Geofis. Ital., 18º Convegno*, 557-594.

Orsi G., Civetta L., Del Gaudio C., De Vita S., Di Vito M.A., Isaia R., Petrazzuoli S.M., Ricciardi G.P., Ricco C., 1999, Short-term ground deformation and seismicity in the resurgent Campi Flegrei caldera (Italy): an example of active block-resurgence in a densely populated area, *J. Volcanol. Geotherm. Res., 91*, 415-451.

Osservatorio Vesuviano, 1984, Bradisismo Flegreo, Rapporto Sorveglianza Gen. 1982 – Gen. 1984. Internal Report, pp. 93.

Parascandola A., 1947, I fenomeni bradisismici del Serapeo di Pozzuoli, Napoli, pp. 1-115.

Seino M., 1983, Seismic activity accompanying the 1977-1978 eruption of Usu volcano, Japan. *Paper Met. Geophys., 54,* 105-141.

Takeo M., 1983, Source mechanisms of Usu volcano, Japan, earthquakes and their tectonic implications, *Phys. Earth Planet. Interiors, 32*, 241-264.

Yokoyama I., 1971, Pozzuoli event in 1970, *Nature, 229,* 532-533.

Yokoyama I., 2006, The 1969-1985 Pozzuoli event and active volcanisms, *Proc. Japan Acad., Ser. B, 82,* 121-126.

Yokoyama I., Yamashita H., Watanabe H., Okada Hm., 1981, Geophysical characteristics of dacite volcanism. The 1977-1979 eruption of Usu volcano, *J. Volcanol. Geotherm. Res., 9*, 335-358.

Yokoyama I., Seino M., 2000, Geophysical comparison of the three eruptions in the 20th century of Usu volcano, Japan, *Earth Planets Space, 52*, 73-89.

Yokoyama I., Nazzaro A., 2002, Anomalous movements with low seismic efficiency — Campi Flegrei, Italy and some examples in Japan, *Ann. Geophys., 45,* 709-722.

Zuppetta A., Sava A., 1991, Stress pattern at Campi Flegrei from focal mechanisms of the 1982-1984 earthquakes (Southern Italy), *J. Volcanol. Geotherm. Res., 48,* 127-137.