The 1969-1985 Pozzuoli event and active volcanisms

By Izumi YOKOYAMA, M.I.A.†

(Contributed by Izumi YOKOYAMA, M.I.A.)

Abstract: Pozzuoli is located at the center of the Campi Flegrei caldera, near Naples and is famous for its anomalous subsidence and upheaval documented since the Roman period. Its secular and gradual subsidence can be interpreted as self-loading compaction of the caldera fills while abrupt upheavals are geologically suspected to be caused by magmatic movements or steam forces. In order to interpret the origin and the process of the Pozzuoli upheavals, they are compared with active volcanisms represented by the 1977-1982 eruption of Usu volcano in Hokkaido.

Usu volcano outburst in 1977 in major pumice eruptions and repeated magmatic and phreatomagmatic eruptions, and manifested remarkable ground deformations accompanying earthquake swarms. In 1969, the ground of Pozzuoli began to upheave with increases in seismicity but finally failed to cause any eruptive phenomena at the surface; nevertheless there are common characteristics of their motives and processes between the two events. The motive of the Usu deformation is clearly due to magma movements while that of the Pozzuoli upheaval has not been completely settled. A quantitative relationship between seismicity and deformation gives a clue for discussing the motive of the Pozzuoli deformations. The discharge rates of seismic energy and the deformation rates are compared between the two events and a certain similarity is found. This suggests that the origin of the Pozzuoli event may be partly magmatic as well as the Usu eruption, but its behavior largely depends on the property of the caldera deposits. When their deformation volumes are taken into consideration, their characteristics become quantitatively conspicuous. The ground at Pozzuoli is much more easily deformed by the upward motive force than Usu volcano. This is due to the rheological property of the caldera deposits of Campi Flegrei, and agrees to the theory that interprets the secular subsidence observed in historical times, as self-loading compaction. It is interesting that there is a point of contact between anomalous movements of the ground along the seashore in Italy and remarkable magmatic movements at the active volcano in Japan.

Key words: Pozzuoli; Usu volcano; bradisismi; deformation; seismicity.

1. Introduction. Pozzuoli is located along the shore of the Pozzuoli Bay, the western part of the Gulf of Naples and at the center of Campi Flegrei caldera that is proved by gravity anomalies there. The secular changes in the height above the sea level of “Serapeo” which is the ruins of a Roman market near the shore at Pozzuoli have been documented from time to time since the Roman period. Such secular changes are named “Bradisismi” which means slow movements unaccompanied with seismicity. The last event began as an abrupt upheaval of the ground noticed at the Pozzuoli port in 1969. It was not accompanied with remarkable earthquakes or volcanic eruptions in this district. The upheaval reached a peak in 1973 and after some stagnation, reached another high peak in 1985, and thereafter gradual subsidence is continuing (cf. Fig. 5). After 1970, various geophysical discussions on this event have been published such as special issues on the Bulletin of Volcanology, vol. 47 (1984, Eds. F. Barberi, D. Hill, F. Innocenti, G. Luongo and M. Treuil) and on the Journal of Volcanology and Geothermal Research, vol. 48 (1991, Eds. G. Luongo and R. Scandone). They include 20 and 15 papers, respectively.

†) Higashi, 1-17-7-1304, Kunitachi, Tokyo 186-0002, Japan (iyokoya@aol.com)
Usu volcano is located in the southern part of Hokkaido, and has erupted frequently in its history. Its actual magmas are dacitic and liable to cause earthquake swarms and to produce lava domes and mounds or remarkable crustal deformations. During the 1977-1982 eruption of Usu volcano, the frequent seismic activities were accompanied with small dislocations, upheaval and lateral ones at its summit part and finally have resulted in remarkable deformations. The activities of this eruption gradually decreased and eventually stopped in 1982. Geophysical researches on the 1977-1982 eruption were reported by Yokoyama et al. and Okada et al., and three eruptions of the 20th century were summarized by Yokoyama and Seino.

The origin of the Usu deformation is clearly magmatic while that of the Pozzuoli deformation has not been established. In the present paper, probable origin of the Pozzuoli upheaval and property of the medium shall be discussed in relation to accompanied seismicities and in comparison with the behavior of the Usu eruption.

The 1977-1982 eruption of Usu volcano shall be firstly described because it may be exemplary for the 1969-1985 Pozzuoli event.

2. The 1977–1982 Usu eruption. Usu volcano has erupted eight times in historical period, four of which occurred in the 20th century and were studied rather well with the standard instruments of each time. The 1977-1982 eruption of Usu is the first example observed by a telemeterized and computerized observation system in Japan. The characteristic activities of Usu volcano in seismicity and deformation derive from its viscous dacitic magmas.

The 1977 eruption of Usu volcano took place at the summit with a vigorous pumice explosion and successively formed 3 craterlets by magmatic explosions and then 14 by phreatomagmatic explosions (Fig. 1a). During the period, 1977-1979, the summit part of the volcano had upheaved approx. 160 m and displaced 180 m northeastward by upward pressure of the intruded magma as shown in Fig. 1b where a U-shaped block had tilted at an angle of roughly 11 degrees. Volcanic earthquakes were closely related to ground deformations. Yokoyama et al. found that the rate of seismic energy release is proportional to the rate of deformation (upheaval rate) as shown in Fig. 2; The seismic energy of volcanic earthquakes of magnitude $\approx 3.1$ was estimated by the seismograms observed at Sapporo ($\Delta = 70$ km), and the daily discharge rates are averaged for every 5 days. The upheaval of a peak at the summit (OY in Fig. 1) was monitored by a theodolite from a fixed point at a distance of about 8 km south from the peak and the daily upheaval rates are averaged around each observation period. Such trends of seismicity and deformation with time were useful for medium-term predictions of volcanic activities.

From the proportionality between the two quantities shown in Fig. 2, we may know that a release of seismic energy of $2 \times 10^{11}$ J/day roughly corresponds to an
upheaval rate of 0.3 m/day. By these two values, the seismic energy accompanied with 1 m upheaval of the peak is obtained as $6.7 \times 10^{11}$ J. In fact, the upheaval of the peak should be necessarily accompanied with an upheaval of a block of the ground which is defined as a wedge-shape square of 1 km-by-1 km, sharpening toward NE, shown by dotted part in Fig. 1b. Now we assume that a volume of $1 \text{ km} \times 1 \text{ km} \times 1 \text{ m} \times 1/2$ was upheaved accompanying a release of seismic energy $1.3 \times 10^6$ J/m$^3$. In other words, the magma beneath Usu volcano pushed up the block of the summit and a part of mechanical energy was released into seismic energy at a certain rate. Yokoyama et al.\(^1\) estimated the energy partition among an explosion, earthquakes and deformation, based on the observation fact that both earthquake and deformation activities interrupted for several days after a major explosion; The three kinds of energy have a constant amount in total, and the seismic energy may be about one tenth as large as the deformation energy. At present, we can not determine the mass of the deformed medium but the present author surmises that its depth may have been roughly 1 km (Yokoyama and Seino,\(^3\) Fig. 11).

**Coseismic deformations.** Yokoyama et al.\(^1\) pointed out that the deformations at the summit part, upheaval and northeastward thrust (Fig. 2b) are closely related to volcanic earthquakes; The deformations did not progress at a uniform rate but discontinuously, relating with individual earthquakes, and the amount of strain step was dependent on the magnitude and the hypocenter of earthquakes.

**Mechanisms of the earthquake families.**

Takeo\(^4\) discussed a quantitative relation between the large earthquakes and the doming deformation during the period, 1979~1981, in terms of the source mechanisms obtained by analysis of the near-field displacements. The magnitudes of the earthquakes were 3.8~4.3 and the hypocenter depths were 1.5 km at the maximum. The cumulative seismic deformation caused by these earthquakes is consistent with the N-NW component of the observed doming deformations. It is suggested that the two large earthquake families occurring at the two sides of the U-shaped fault zone open to the northeast, were caused by stick-slip motions.

3. **The 1969-1985 Pozzuoli event.** Campi Flegrei is a caldera measuring approx. 15 km in diameter and containing multiple phreatic craters, monogenetic cones and fumaroles. Its topographic sketch map is shown in Fig. 3 where the southern half of the caldera is bounded by three shallow banks in the bay. It was formed approx. 35000 years B.P. by the eruption of the Campanian tuff of 80 km$^3$. Judged from the Bouguer gravity anomalies there, the caldera is funnel-shaped and its center coincides with the town of Pozzuoli. The caldera deposits are the tuff and the fallback which have lower density than the basement rocks (carbonatic and/or thermo-metamorphic rocks). According to Fedi et al.\(^5\) the low density material ($\Delta \rho = -200 \text{ kg/m}^3$) fills the caldera to a depth of approx. 2 km at the center.
Secular deformation at Serapeo. The height of Serapeo has been documented from time to time since the Roman period with respect to the sea level. In fact, it is rather difficult to establish the exact trend of deformation at Serapeo, especially during the ancient periods. Parascandola\textsuperscript{6) drew a trend of the secular vertical deformation at Serapeo as shown in Fig. 4a where the arrows with the letters VE, SO, IS and MN indicate major eruptions of Vesuvius, Solfatara, Ischia and Monte Nuovo, respectively, and those with the letter P do earthquakes in Campania (the southwestern part of the Italian Peninsula), and those with the letter P do earthquakes in the Pozzuoli area. Then we can infer a relationship between the deformation and the events probably capable to effect Pozzuoli: Serapeo subsided monotonously for approx. 9 centuries since the Roman period, with the exception of short stagnation of subsidence related to the 63 earthquake beneath Vesuvius and the two major earthquakes in Campania in the 4th century. In the 10th century, the trend turned to upheave and sharply did in case of the 1538 eruption of Monte Nuovo. After 1538, it again subsided till 1969.

Oliveri Del Castillo and Quagliariello\textsuperscript{7) proposed an idea that Serapeo would have a tendency to subside monotonously due to self-loading compaction of the caldera deposits, and that it would turn to upheave instantly when major local earthquakes occurred such as in 63, 1488, 1536-1538, and so on, and also when major eruptions broke out such as the 79 and the 1632 eruptions of Vesuvius, the 1198 eruption of Solfatara, the 1301 eruption of Ischia, and the 1538 eruption of Monte Nuovo. This compaction model can account for the variation of subsiding velocity from the borders to the center of the caldera. Furthermore, Casertano et al.\textsuperscript{8) discussed hydrodynamics and geodynamics in Campi Flegrei and modified the Parascandola's diagram as shown in Fig. 4b. In this figure, the height of Serapeo increased instantly with a high rate when triggered by major local shocks or nearby volcanic activities, and recovered viscoelastically.

The recent activity at Pozzuoli. Oliveri Del Castillo and Quagliariello\textsuperscript{7} in October 1969, determined the subsiding rate of Serapeo between the period 1800-1960 as 1.3 cm / year by the mareographic data, and in February 1970, incidentally found by mareographic observations that Pozzuoli had upheaved approx. 94 cm since 1953, contrary to the preceding trend of subsidence. Oliveri Del Castillo and Quagliariello\textsuperscript{7} assumed the recent upheaval of Pozzuoli began in 1969, and estimated the upheaval in 1969 as the sum of the subsidence since 1953 and the upheaval referred to 1953, namely $1.3 \text{ cm} / \text{yr} \times 16 \text{ yr} + 94 \text{ cm} = 115 \text{ cm}$. In other words, Pozzuoli upheaved 115 cm over a period of several months before February 1970. The upheaval was first noticed in late 1969 by people of Pozzuoli who found that bridges and wharves along the shore had uplifted with respect to the sea level. This upheaval was not accompanied with any strong earthquakes or volcanic eruptions in this region (Yokoyama\textsuperscript{9}).

After 1969, the precise levels have been repeated around Pozzuoli, and since February 1970, a seismometric network has been installed in Campi Flegrei. Berrino and Corrado\textsuperscript{9) and Berrino\textsuperscript{10) discussed the temporal trends of vertical ground movements obtained from the mareographic data at the port of Pozzuoli and seismicity in Campi Flegrei during the period 1970-1995. The monthly number of earthquakes is shown in Fig. 5a, and the mareographic data are actually fluctuating and a smoothed curve is shown in Fig. 5b. Fig. 5 suggests that the deformation may be closely related with the seismic activity.

In order to quantitatively discuss the relationship between the deformation and the seismicity, the rates of seismic energy release are compared with the upheaval rates for the period from January to December 1983. The monthly discharge rate of seismic energy is calculated from the seismic data given by the Osservatorio Vesuviano\textsuperscript{12) (Tables I and II) and the monthly upheaval
rate is obtained from the mareographic data given by the same observatory (Table V), as shown in Fig. 6. The upheaval rates shown in the figure fluctuate irregularly and not precise because they were monitored by the tidal records, not by precise levels in this period. In Fig. 6, we may say that the trend of deformation rate is roughly similar to that of the discharge rate of seismic energy as well as the Usu eruption (Fig. 2).

The similarity means qualitatively that the Pozzuoli upheaval was also accommodated by seismic failure and that its origin may have been magmatic. For the period of 1983, in Fig. 6, the mean value of the discharge rate of seismic energy is approx. $2.5 \times 10^{10}$ J/month, and that of the upheaval rate is approx. 0.07 m/month, both by rough estimates which may have no serious effect on the following discussion. Canceling the time terms, one gets the energy release accompanying an upheaval 1 m of the ground as $3.6 \times 10^{11}$ J. Here, we take into consideration that some volume of deformation, not only the central point. The Pozzuoli deformation decreases outward radially from the center as shown in Fig. 3 where the outer circle ($r = 6.8$ km) roughly indicates the zero upheaval and the inner one ($r = 2.3$ km) does 50% limit of the maximum upheaval after Berrino and Corrado (Fig. 2). It is noticeable that the deformed area in Campi Flegrei is much larger than that of Usu volcano.

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**Earthquake mechanisms.** The focal mechanisms of the 1982-1984 earthquakes in Campi Flegrei were discussed by Zuppetta and Sava. They conclude that a 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 with seismic activity was at least controlled by a preexisting regional, quasi-conjugate, fracture system. The earthquake mechanisms are consistent with the doming beneath Campi Flegrei.

**Gravity changes.** When there is a good correlation between gravity and elevation changes and any particular source model is not assumed, the Bouguer gradient is generally expressed by
where \( \rho, G \) and \( \beta \) denote the crustal density relating to the deformations, gravity constant, and the vertical gradient of gravity, respectively. If \( \rho \) is zero, \( \Delta g / \Delta h = -\beta \) and is called the free-air gradient. Berrino et al.\textsuperscript{14} discussed relationship between the ground deformation and gravity changes accompanying the 1982 Pozzuoli event and expressed the change by the following formula:

\[
\Delta g (\text{mgal}) = -0.001 - 0.215 \Delta h (\text{m}), \quad r = -0.9
\] \[2\]

And \( \beta \) is experimentally observed in Campi Flegrei by Berrino et al.\textsuperscript{14} as 0.29 mgal / m. Then, substituting the known values into [1], we get \( \rho = 1.8 \times 10^3 \) kg / m\(^3\). This means that the material related to the anomalous upheavals at Pozzuoli is probably the caldera deposits or a mixture with volcanic gases.

On the other hand, at Usu volcano, gravity measurements were repeated at the benchmarks for precise levels at the foot of the volcano, but were impossible at the deformed region at the summit because of the eruption activities.

4. Concluding remarks. The discharge rates of the seismic energy and the upheaval rates are found to be parallel in both the Pozzuoli event and the Usu eruption. It means that both the upheavals were accomodated by seismic failure. The actual deformation rates of the two events are rather different: 10 cm / month at the former and 30 cm / day at the latter, in their highest periods. When we take their deformation volumes into consideration, we reach a conclusion that the caldera deposits of Campi Flegrei are much easier to deform than the dacitic magma of Usu volcano, and may be viscoelastic. This supports an interpretation that the secular subsidence of Serapeo was caused by self-loading compaction of the caldera deposits. Gravity changes around Pozzuoli suggest that the upheaval may have been caused by movements of the caldera deposits or their mixture with gases while the remarkable deformations at the summit of Usu volcano clearly derive from dacitic magma. It is clarified that the upheaval process of Pozzuoli are influenced by viscoelastic property of the caldera deposits, and the origin of the upheavals may be partly magmatic.

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