Geothermal Energy Release at the Solfatara of Pozzuoli (Phlegraean Fields): Phreatic and Phreatomagmatic Explosion Risk Implications

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ABSTRACT

The H_2O, CO_2 and H_2S outputs at the Solfatara of Pozzuoli have been measured and a map of the exhaling areas has also been made. The energy released at the surface by the fluids has been estimated to be 10^{19} ergs/day.

The presence of aquifers at Phlegraean Fields increases the phreatic and phreatomagmatic explosion risk.

Our results suggest that even if an uprising magma may interact with water at depth, an explosion could occur only at the shallow levels of a few hundred meters. Since the tranfer of energy toward the surface is favoured by the presence of fractures, a detailed analysis of the deep fracture network would help to evaluate the risk levels of the various areas of Phlegraean Fields.

INTRODUCTION

Phlegraean Fields make up the floor of an impressive caldera, about 12 km in diameter, that was formed approx. 35,000 years ago by the emission of more than 80 km^3 of pyroclastic products. All eruptions since then have tended to decrease both in energy and on volume (ARMIENTI *et al.*, 1983).

This area has continually undergone alternating phases of uplift and subsidence of the ground. According to both historical reports and evidence left by lithodomi on Roman ruins these phenomena date back at least 2,000 years. Before the last eruption in 1538, which formed Monte Nuovo, the ground rose up about 7 meters. During the last century was a gradual subsidence, then in the summer of 1969 a rapid uplift began which in 1972 reached 170 cm (OSS. VESUVIANO, 1983).

Between 1972 and 1974 the ground subsided again about 20 cm, and there after, up to 1982, the situation remained fairly stable.

Beginning in the summer of 1982 the ground rose again, gaining another meter by January 1984. Therefore between 1969 and January 1984 there was a total rise of about 2.50 meters.

Most of the knowledge in our possession regarding the Phlegraean stratigraphy comes from information obtained by AGIP during their geothermal explorations. The geothermal drillings tap, besides shallow aquifers, other productive levels at a depth between 1,400 and 3,046 meters, having a maximum temperature of more than 400°C (SAFEN, 1955; CIOPPI, 1981). These levels are often intercalated by rocks sealed by the saline deposits precipitated from thermal fluids.

The energy flux associated with the fluids emitted by the Solfatara of Pozzuoli was evaluated by a mixed group of researchers from the Istituto di Mineralogia, Petrografia e Geochimica of the University of Palermo and from the Istituto di Geochimica dei Fluidi of C.N.R., during the program of geochemical surveillance of volcanic activity.

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The aim of this evaluation was to plot, over a period of time, the variations in the energy flux so as to evaluate the probability of a volcanic explosion.

THE EXHALING AREAS

Mapping of the exhaling areas was carried out in this area. The various zones were identified by topography and structure as well as by exhalation characteristics. They are shown in Fig. 1 and are briefly described as follows:

1. *The Soffione Area* – This area takes its name from very active fumarole (also known as Forum Vulcani or Elliptical fumarole) situated in the southern part of the crater.

This fumarole, although its exhaling area is only 0.2 m^2, gives a relatively high contribution of energy to the total output of the Solfatara, its flux of condensed water being approx. $1.6 \cdot 10^{-2} \cdot \mathrm{cm}^3 \cdot \mathrm{sec}^{-1} \cdot \mathrm{cm}^{-2}$ (STP).

2. *Friedländer Observatory Area* – A wide fumarolized area, 500 m^2, partially

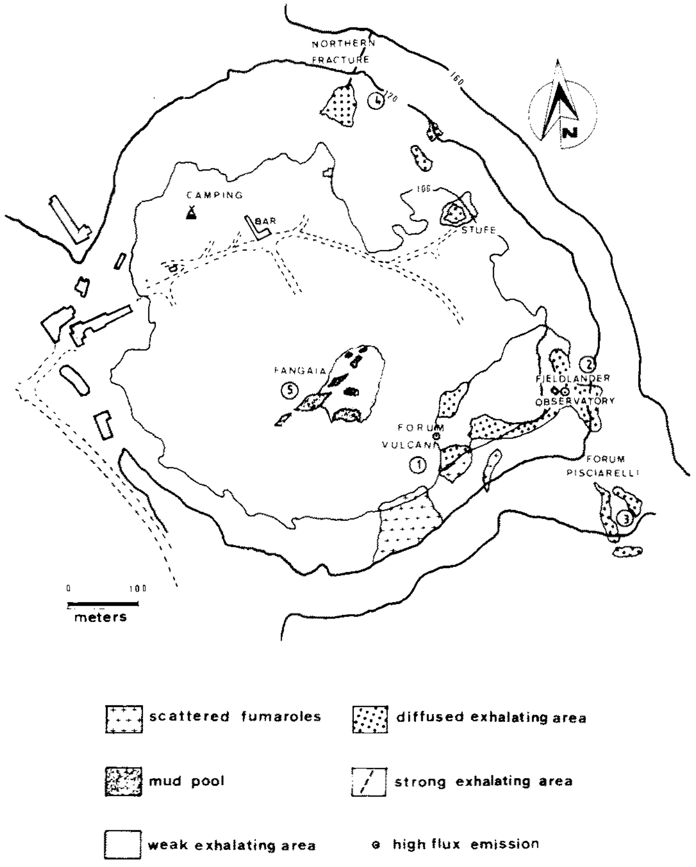

FIG. 1 – Sketch map of the Solfatara crater showing exhaling areas having different flux intensities.

covering the internal wall of the crater behind the Friedländer Observatory. The intensity of the steam exhalations vary from place to place, with H_2O flux values between $1.3 \cdot 10^{-5}$ and $2.8 \cdot 10^{-4}$ $cm^3 \cdot sec^{-1} \cdot cm^{-2}$; the «Bocca Grande» fumarole, showing a very high H_2O flux value ($0.8 \cdot 10^{-2} \cdot cm^3 \cdot sec^{-1} \cdot cm^{-2}$), is the hottest point with a temperature of 158°C.

3. *The Forum Pisciarelli Area* – This fumarolized area, covering 600 m^2, except for a few high emission points (*e.g.* Fumarole A), generally gives low H_2O flux values between $7.8 \cdot 10^{-5} \cdot cm^3 \cdot sec^{-1} \cdot cm^{-2}$. This area is clearly located along a fracture with a NW-SE direction.

4. *Northern Fracture Area* – A fracture system having a NE-SW direction lies along the northern wall of the crater. On the high side of the wall, open fractures extend for about 40 meters, while on the lower side they are concealed by detritic materials. A few fumaroles are developing on the crater floor destroying the vegetation. The steam flux measured along the open fracture, is slower when the exhalation becomes diffused over an extensive area.

5. *Fangaia* – This is an extensive exhaling area consisting of low H_2O flux fumaroles ($1.6 \cdot 10^{-6} \cdot cm^3 \cdot sec^{-1} \cdot cm^{-2}$) and of hot mud pools (75°C – 80°C).

The pools are about two meters deep with their area varying from a few square meters to more than 500 m^2. They are arranged along an E-W fracture. At the end of 1983 a new mud pool appeared, growing in a month, to a length of 12.5 meters and an average width of 0.5 meters.

This event indicates the intense activity of this fracture, which has already undergone similar phenomena in the past (OLIVIERI DEL CASTILLO and QUAGLIARELLO, 1970). Besides this new mud pool, Fangaia consists of the following features:

— a mud pool of about 360 m^2, having a CO_2 flux of the order of $4.5 \cdot 10^{-1} \cdot cm^3 \cdot sec^{-1} \cdot cm^{-2}$, surrounded by a weak fumarolized area;

TABLE 1 – Extent of exhaling areas and relative H_2O output.

SITE	Emanating area (m^2)	H_2O output (10^3 Kg/day)
Soffione area	0.2	3
Fieldlander Observatory area	500	30
Forum Pisciarelli area	600	90
Northern fracture area	1200	100
Stufe area	150	8
Weak fumarolized S-E side	94	1.5
Southern scattered fumaroles	--	0.8
Fangaia (fumaroles)	7500	0.7
Fangaia (mud pools)	650	n.d.
	10,694.2	234

TABLE 2 – Gas ratios at the various fumaroles expressed in wt.%.

SITE	RATIOS	
	CO_2/H_2O	H_2S/H_2O
Soffione area	0.237	$2.3\ 10^{-3}$
Fieldlander Observatory area	0.266	$3.5\ 10^{-3}$
Northern fracture area	0.327	$1.0\ 10^{-3}$
Forum Pisciarelli area	0.358	$3.6\ 10^{-3}$

— an amygdaloidal mud pool of about 140 m^2 partially filled by water, extending along the E-W fracture.

— a pool of very dense mud about 50 m^2, connected with the previous pool by an open fracture.

— a pool of about 10 m^2 situated between the amygdaloidal pool and the largest one.

OUTPUTS OF H_2O, CO_2 AND H_2S

The gaseous output was calculated using the following equation:

$$Q = \sum_{1}^{n} i\, A_i\, Ø_i$$

where Q = total mass output per unit time;

A_i = extent of exhaling area;

$Ø_i$ = average output of the «i» fumarole per unit of time and area.

The specific flux of condensed steam was measured by the methods already tested on the island of Vulcano, Aeolian Islands, (ITALIANO *et al.*, 1983), using a stainless steel condenser.

The value obtained for each site is the arithmetical mean of three measurements. The reproducibility of the measurements is better than 5%; whereas the uncertainty of the final estimates is of the order of 20%. Table 1 shows the daily output of H_2O for each sampled area.

A different method was used for measuring the CO_2 output at the mud pools: the gas was collected in a stainless steel funnel and was carried through a rubber tube to an upsidedown bottle full of water, having a known volume. As the gas entered the bottle, the water was pushed out, and by measuring the time it took to empty the bottle, the specific flux of CO_2 was calculated. The surface area of the degassing mud pools were also measured and the total CO_2–output was calculated.

In the fumarolized area the CO_2 and the H_2S outputs were calculated using both the condensed steam measurements, and the CO_2/H_2O and H_2S/H_2O concentration ratios measured at the various fumaroles (Tables 2 and 3).

GEOTHERMAL ENERGY OUTPUT

The energy brought to the surface by the geothermal exhalations was computed. As more than 99% of the gases is H_2O vapour and CO_2, the calculations were based on these two species.

The temperature of the emissions was always near 100°C except for the Soffione

TABLE 3 - Daily CO_2 and H_2S outputs of the various areas.

SITE	CO_2 output (10^3 Kg/day)	H_2S output (10^3 Kg/day)
Soffione	1	$7\ 10^{-3}$
Fieldlander Observatory area	7	$98\ 10^{-3}$
Forum Pisciarelli area	30.5	$305\ 10^{-3}$
Northern fracture area	32.5	$97.5\ 10^{-3}$
Stufe area	2.8	$8\ 10^{-3}$
Weak fumarolized area S-E side	0.4	$1.15\ 10^{-3}$
Southern scattered fumaroles	0.1	$0.4\ 10^{-3}$
Fangaia (fumaroles)	0.2	$0.5\ 10^{-3}$
Fangaia (mud pools)	85	n.d.
	15.5	$517.5\ 10^{-3}$

fumarole (~ 145°C), and the «Bocca Grande» (~ 158°C). Therefore the excess energy of the fluids with respect to the mean ambient temperature of 25°C was calculated.

As we are dealing with a process that takes place under a constant pressure of 1 atmosphere, the energy is equal to the enthalpy variation of the entire process, which we have schematized as follows:

$$\underset{100^\circ C}{H_2O\ \text{vapour}} \xrightarrow[\text{condensation}]{\Delta H_1} \underset{100^\circ C}{H_2O\ \text{liquid}} \xrightarrow{\Delta H_2} \underset{25^\circ C}{H_2O\ \text{liquid}}$$

$$\underset{100^\circ C}{CO_2\text{gas}} \xrightarrow{\Delta H_3} \underset{25^\circ C}{CO_2\text{gas}}$$

The value ΔH_1 relative to the condensation of the H_2O at 100°C is a known value equal to 9,717 cal/mole.

$$\Delta H_2 = C_s \ \Delta \ T$$

where C_s is the specific heat of liquid H_2O at a constant pressure of 1 atm.

$$\Delta H_3 = \int_{t=100^\circ C}^{t=25^\circ C} C_p(co_2)\, d\, T$$

C_p (co_2), expressed as cal · mol^{-1}, can be substituted by the empirical equation: $a + bT + cT^{-2}$, T being the absolute temperature and the constants, $a = 6.21$, $b = 10.40\ 10^{-3}$, $c = -35.45\ 10^{-7}$ (LEWIS and RANDALL, 1961).

The geothermal energy released in 24 hours at the varous sites was then calculated and the results are shown in Table 4.

Figure 2 shows both the H_2O vapour and CO_2 output expressed as the percent-

TABLE 4 – Daily geothermal energy release comuted from the steam and CO_2 outputs.

SITE	H_2O energy 10^{18} ergs	CO_2 energy 10^{16} ergs
Soffione area	0.7	0.4
Fieldlander Observatory area	0.8	3.9
Forum Piscitelli area	2.3	11.65
Northern fracture area	2.55	13
Stufe area	0.15	1.4
Weak fumarolized area S-E side	0.03	0.2
Southern scattered fumaroles	0.02	0.05
Fangaia (fumaroles)	0.01	0.1
Fangaia (mud pools)	n.d.	41.3
	6.56	72

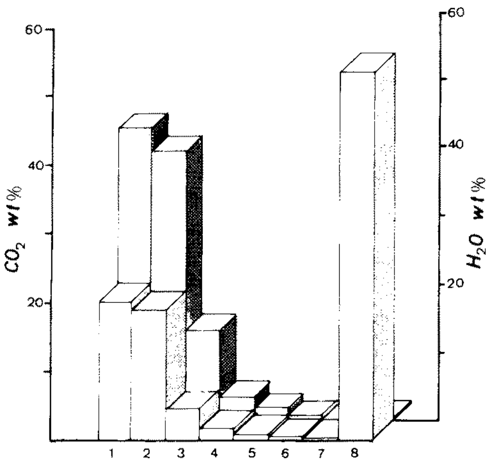

FIG. 2 – Output of H_2O and CO_2 of the single areas, expressed in weight % of the total output.

1 - Northern Fracture;
2 - Forum Pisciarelli area;
3 - Friedländer Observatory area;
4 - Stufe area;
5 - Soffione area;
6 - Weak fumarolized area (S-E side);
7 - Scattered fumaroles (south side);
8 - Fangaia area.

age of the total outputs at the Solfatara of Pozzuoli. It is possible to see that the maximum contribution of the H_2O vapour output is given by Forum Pisciarelli area, whereas the mud pools of Fangaia give more than 59% of the total CO_2 output.

Assuming that the mud pools are fed by the same fluids emitted by the fumaroles, their CO_2 output (Table 3) suggests that more than $200 \cdot 10^3 kg \cdot day^{-1}$ of steam condenses in the water table existing in the Fangaia area. That means that the total steam reaching the surface will double, then the extimate of the geothermal energy carried by the fluids shoulds also double.

ENERGY IMPLICATION ON VOLCANIC RISK

Historical reports and vulcanological data indicate that Phlegraean Fields are characterized by a high volcanic risk. The presence of aquifers increases the phreatic and phreatomagmatic explosion risk. NUCCIO and VALENZA (1983) indicate that the essential conditions for a volcanic explosion are:

— a thermal source of energy, generally magma;

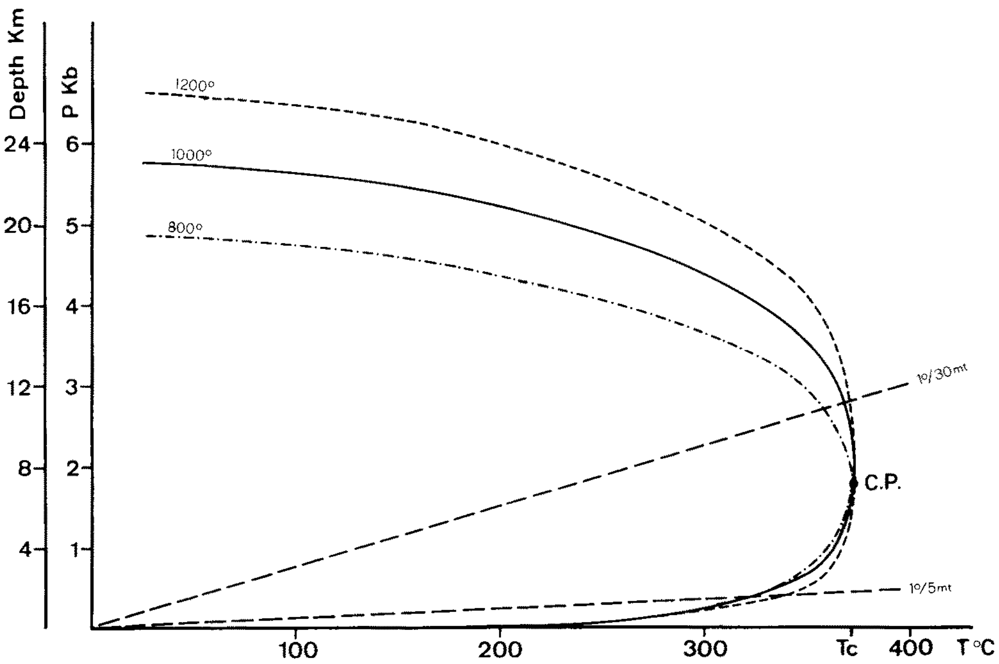

FIG. 3 - Overpressure obtained by heating at constant volume water (upper curves) or steam (lower curves), having an initial temperature indicated in the abscissa.
The three curves were calculated for three different final temperatures. The geothermal gradients of normal area and of a volcanic area are also reported (dotted lines).

— the presence of fluids, generally water vapour, at depth, having a pressure at least equal to the overburden;

— a sufficient amount of energy generated by the expansion of fluids to break and lift the rocks.

These conditions imply that the more likely centers of explosion will be located at the level of the aquifers.

The geothermal well CF-23, drilled near the Solfatara, tapped some aquifers at about −200 m and −1,600 m. The deepest aquifer in the area was reached at −3,000 m, by the well S. Vito 1.

The most probable volcanic events are:

— a phreatic explosion, following an accumulation of energy in the aquifers;

— a phreatomagmatic explosion, caused by a sudden energy transfer from the magma to the water.

The consequence of each of these events is obviously different, the most dangerous conditions being attained in the latter case, as the magma is an almost infinite source of energy.

Figure 3 shows the overpressure obtained by vaporization of water having different initial temperatures at various magmatic temperatures. The temperature of the aquifer located at −1,600 meters is 320°C, so we can expect an overpressure of about 4-6 kbars resulting from the vaporization of water taking place at constant volume and magmatic temperature (Fig. 3). This overpressure is one order of magnitude more than the overburden. This implies that the second instability condition may easily be reached.

We calculated third instability condition of the aquifers at −200 m, −1,600 m and −3,000 m using the graph shown in Fig. 4. In

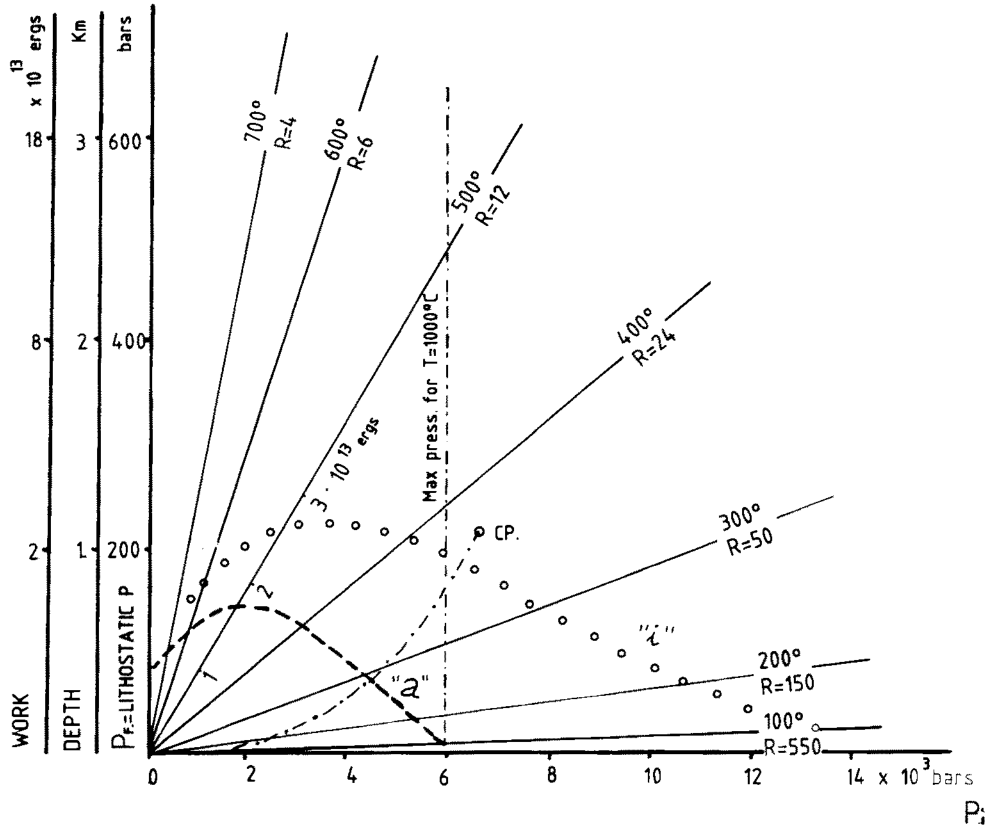

FIG. 4 – Work done during expansion of steam to lift a given rock columns.
On the ordinate are shown:

– Work necessary to lift a rock column (d = 2) of a given height, with 1 cm^2 cross section, so that its base reaches ground level.

– Depth of the hypothetical explosion center, equivalent to the height of the rock column.

– Final pressure (P_f) of the expansion process, equivalent to the lithostatic pressure on the hypothetical explosion center.

On the abscissa is shown: initial pressure (P_i) of steam occurring after the vaporization of water at 1,000°C (from Fig. 3).

The segments cut off by the « a » curve on the lines indicating various final temperatures (700-100°C) are proportional to the work developed by the adiabatic expansion of 100 moles of steam.

The segments cut off by the « i » curve on the lines indicating various P_i/P_f ratios (R = 4-R = 550), are proportional to the work developed during the isothermal expansion of 100 moles of steam.

Below the dotted « CP » curve (boiling point curve of water) steam condenses, limiting the final temperature of the adiabatic expansion process.

To the right of the maximum intial pressure line (for t = 1,000°C) all the Pi values are unattainable.

TABLE 5 – Water colums, with equivalent aquifer vertical thickness expressed in meters, that must be converted to steam at magmatic temperatures to able to do the work necessary to lift the overhanging rocks in the hypotheses of explosion centers respectively located at –200 m, –1600 m and –3000 m. The data regarding the isothermal expansion at –3000 m gives either unattainable values of initial pressure, or unreasonable vertical thickness of the aquifers.

	ADIABATIC EXPANSION (Tf = 500°C)			ISOTHERMAL EXPANSION (Pi/Pf = 12)		
- Depth of hypothetical explosive centers expressed in m	-200	-1600	-3000	-200	-1600	-3000
- Moles of expanding steam per cm^2 of exploding surface (see fig.4)	50	312.5	1125	30	190	--
- Height in meters of the equivalent water column, having 1 cm^2 cross section	9	56	202.5	5.4	34.2	--
- Equivalent vertical thickness of the saturated aquifer in m, assuming a porosity of 10%	90	560	2025	54	342	--

this graph we can read, on the ordinate, the work required to lift a rock column ($\delta = 2$) having a 1 cm^2 cross section and a height equal to the depth of the explosion center being considered.

The work done by the expansion of the steam following the vaporization of the water, is estimated to be $0.8 \cdot 10^{13}$ ergs for an explosion center situated at –200 m.

Although the expansion process is most likely to be mainly adiabatic, we considered the two extreme cases: all adiabatic and all isothermal expansions.

We assumed here that the process takes place between 1,000°C (Ti) and 500°C (Tf). We can read, on the 500°C (Tf) line in Fig. 4, that the work done by 100 moles of steam expanding adiabatically, is $2 \cdot 10^{13}$ ergs (curve « a »). Therefore the moles of steam necessary to lift the rock column under consideration are:

100 moles: $1.6 \cdot 10^{13}$ ergs = N moles: $0.8 \cdot 10^{13}$ ergs N = 50 moles

50 moles of vapour are equivalent to 900 g of H_2O and therefore to a column of water (δ (H_22O) = 1) 9.0 m high with a 1 cm^2 cross section.

The work done by 100 moles of steam expanding isothermally, is a function of the ratio (R) between the initial and final pressures (curve « i »). The final pressures, equivalent to the lithostatic pressure at each explosion center, are shown on the ordinate on Fig. 4. Considering again an explosion center situated at –200 m, the isothermal expansion of 100 moles of steam develops $2.6 \cdot 10^{13}$ ergs if the initial pressure is at least 12 times the final pressure. Therefore:

100 moles: $2.6 \cdot 10^{13}$ ergs = N moles: $0.8 \cdot 10^{13}$ ergs

N = 30 moles which is equivalent to 540 g of H_2O.

In Table 5 the results for each explosion center considered are shown.

Whatever the true expansion process is, our study suggests that it is reasonable to expect the most likely explosion centers to be located at shallow depths.

CONCLUSIONS

The geochemical surveillance of volcanic activity aims at identifying both indicators of rising magma and variances in depth conditions. In particular, the estimates of the energy output carried by the fluids, if related to other chemical, physical and geological data, give some useful indications about possible accumulation of energy at depth, and could help to evaluate the amount of energy implicated in an impeding explosion. For a correct evaluation of volcanic explosion risk, all the available data must be interpreted together.

In spite of the numerous sealed levels intercepted by the AGIP geothermal drillings, our results indicated a considerable amount of energy carried by the fluids towards the surface. This energy is about 10^{19} ergs/day at the Solfatara, which is close to the potential energy accumulated in the Phlegraean caldera by the ground uplift in the last 15 years. This estimate ($6.0 \cdot 10^{14}$ ergs $\mathrm{day}^{-1} \cdot \mathrm{m}^{-2}$) is in the same order of magnitude of that made using the ammonia output data (DALL'AGLIO *et al.*, 1972) for the whole Pozzuoli bay: 1,000 - 10,000 H.F.U. ($3.6 \cdot 10^{13}$ ergs $\cdot \mathrm{day}^{-1} \cdot \mathrm{m}^{-2}$—$3.6 \cdot 10^{14}$ ergs $\cdot \mathrm{day}^{-1} \cdot \mathrm{m}^{-2}$). This convective flux of energy is several orders of magnitude greater than a conductive flux in a normal area. Therefore any model of the evolution of the Phlegraean magmatic reservoir or interpretation of the bradyseism, must take into account the important role played by the fluids.

In Phlegraean Fields, we can expect both phreatic and phreatomagmatic explosions. The former may be as a consequence of a slow accumulation of energy in the aquifers or following a rapid upward energy transfer; the latter due to a magma-water contact. In this case, our results (Table 5) show that:

— for a deep explosion center the vertical thickness of the aquifer involved in the vaporization process is so large as to be almost unrealistic;

— in the hypothesis of a shallow explosion center situated at a few hundred meters, the vertical thickness of the aquifer necessary for an explosion is quite reasonable.

We would like to point out that in our computations we only considered the energy required to lift the rocks, whereas the energy implicated in a real explosion process is almost double.

On the basis of our results and taking into account the hydrological, geothermal and structural data on Phlegraean Fields, we think a deep phreatomagmatic explosion is unlikely, whereas the probability of a shallow explosion is relatively high.

The destructive strength of a volcanic explosion is strictly related to the kinetic energy dissipated during the explosion itself. Contrary to the statement made by ROSI *et al.* (1983) that «*the degree of primary fragmentation of magma coming into contact with water is the main factor in controlling the degree of transformation of thermal into kinetic energy*», we would like to argue this point since the kinetic energy is only the excess of mechanical energy dissipated in breaking and lifting the over-hanging rocks (NUCCIO and VALENZA, 1983).

An explosion process as a consequence of a deep magma/water interaction, can be outlined as follows:

— the vaporization of the deep water;

— an energy transfer by fluids towards shallower levels, at which all explosive conditions are verified and the explosion occurs.

As this process is mainly dependent on the uprising fluids, we can expect that higher risk areas can be defined by the deep fracture network. In this respect a more detailed structural analysis should help to evaluate the risk levels.

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