

GEOTHERMAL ENERGY AND MASS RELEASE AT VULCANO, AEOLIAN ISLAND, ITALY

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ABSTRACT. — A preliminary estimation of Vulcano's geothermal potential by directly measuring the fumaroles gaseous output and by calculating the amount of energy associated has been done. The method and the special device used for measuring the output are here described. Based on the data registered in 1979 during the rapid thermal evolution of Vulcano's system, and in agreement with the model proposed by CARAPEZZA, NUCCIO and VALENZA (1981), the depth of the geothermal reservoir has been calculated and a rough estimation of its volume has been obtained.

The reservoir results as being at a depth of approx. 1.6-2 kms. and its volume, which is probably of the order of 0.1 km^3 , is decidedly small.

RIASSUNTO. — Attraverso la misura diretta della quantità di gas emessi dalle fumarole e calcolando la quantità di energia ad essa associata, è stata effettuata una stima preliminare del potenziale geotermico dell'isola di Vulcano. Vengono descritti il metodo e lo speciale apparato usato per la misura della quantità di vapore emesso. Sulla base dei dati registrati nel 1979, durante l'evoluzione del sistema di Vulcano e, in accordo con il modello proposto da CARAPEZZA, NUCCIO e VALENZA (1981), è stata calcolata la profondità del serbatoio geotermico ed è stata effettuata una stima orientativa del suo volume.

Tale serbatoio risulta essere posto ad una profondità di circa 1,6-2 km ed il suo volume, che è probabilmente dell'ordine di $0,1 \text{ km}^3$, è decisamente piccolo.

Introduction

In the last few years there has been a renewed interest in the geothermal exploration of Vulcano. In this respect the Italian companies AGIP, ENEL and EMS have developed a geothermal energy utilization program that aims at making the islands of Vulcano, Lipari and Salina self-sufficient as far as energy and water are concerned. In

1956 AGIP bored two wells near the «Fraglione di levante» finding at a depth of about 200 meters a thermal aquifer having a temperature close to 200°C .

Later geochemical studies (TONANI, 1970) suggested that there was a deeper geothermal reservoir. According to CARAPEZZA, NUCCIO and VALENZA (1981) the fluids present in this reservoir determine a liquid-vapour biphasic system with temperatures of $320\text{--}350^\circ \text{C}$.

The vapour phase reaches the surface feeding the fumarolic manifestations at the crater rim.

In this paper we present the results of the measurements of the total output of mass and energy at the surface.

Using data recorded in 1979 during the rapid evolution of the fumarolic activity, we were also able to make a rough estimation of the volume and of the depth of the geothermal reservoir.

Composition of fumarolic gases

The composition of the fumarolic gases was determined through the use of appropriate sampling methods and by their subsequent analysis.

The aether condenser method

This method was used to determine the gas/ H_2O ratio and is based on the volume of dry gas pumped and on the weight of the collected condensate.

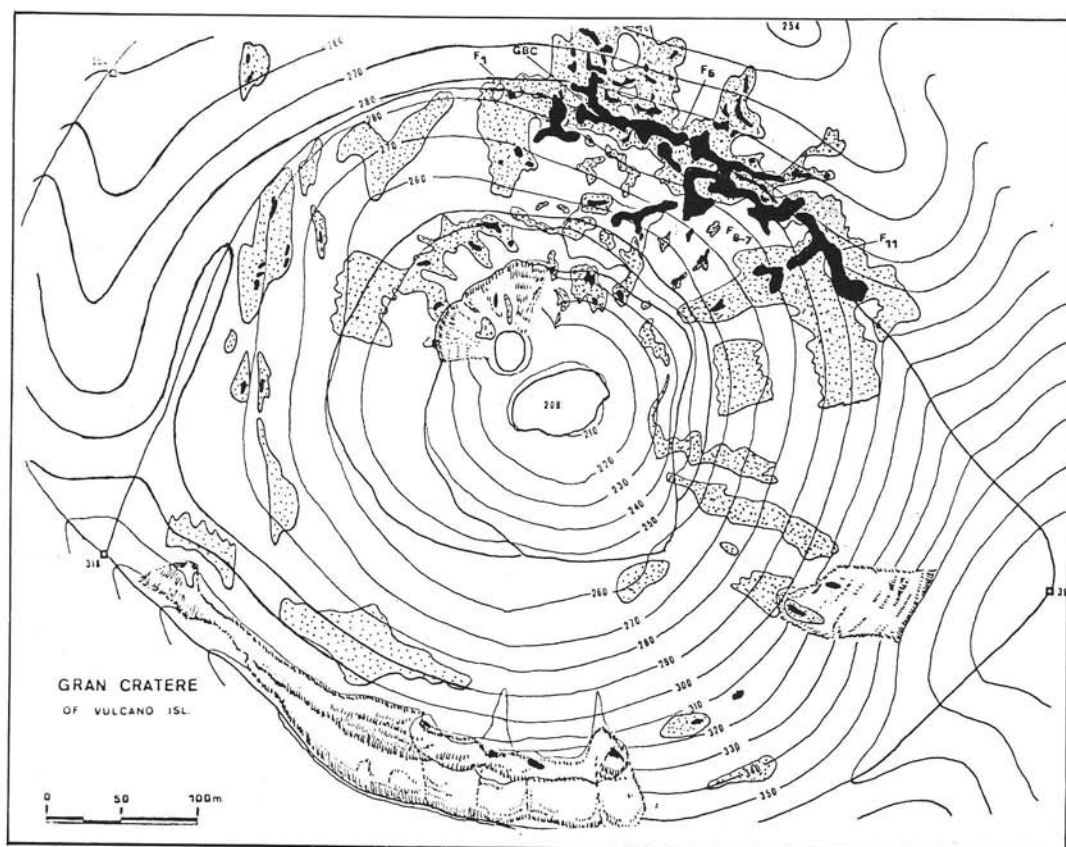


Fig. 1. — Mapping of the fumarolic fields on the Gran Cratere area. - Dotted area: diffused fumarolic manifestations. Black area: more intense fumarolic manifestations with visible gaseous release.

The quantities of Na^+ , K^+ , Mg^{2+} , Fe^{2+} , etc. in the condensate were determined by means of atomic absorption spectrophotometry; the HCl by means of volumetric titration of the chlorides present; the HF by means of ion-selective determination and the H_3BO_3 by means of spectrophotometry. The dry gases were analyzed by gas-chromatography.

The absorption of fumarolic gases in an NH_4OH solution containing AgNO_3

This method, already used by SICARDI (1952), was employed in the determination of the H_2S and SO_2 content. The analytical results relative to the composition of the fumarolic gases of Vulcano are given in table 1.

Output of fumarolic gases

Some methods already exist in literature to estimate the quantity of volcanic gases emanated into the atmosphere. The applicability of a method often depends on the type of emanation and on environmental problems. In the case of Vulcano, considering the easy access to the fumarolic fields, we preferred to use a direct method based on measurements of the emanating area and of the gaseous output.

This output is calculated using the following equation:

$$Q = \sum_{i=1}^n A_i \Phi_i$$

where: Q = total mass in the unit of time; A_i = emanating surface of the « i » fumarole; Φ_i = average output of the « i » fumarole per unit of surface.

TABLE 1

Analysis of fumarolic gases of the crater area expressed in vol. %

Species	%	Species	mmols/l
H ₂ O	77.8		
Dry gases	22.2		
CO ₂	90.1	Cl ⁻	586.00
SO ₂	3.5	H ₃ BO ₃	18.30
H ₂ S	2.1	Na ⁺	0.68
HCl	3.5	K ⁺	0.09
HF	0.1	Ca ⁺⁺	0.31
N ₂	0.8	Fe ⁺⁺	0.07
O ₂ +Ar	0.1	Mg ⁺⁺	0.08
CO	2.0 · 10 ⁻³		
H ₂	4.0 · 10 ⁻³		

The ionic species in the condensate are expressed in mmols/litre.

An accurate mapping of the fumarolic fields was made (fig. 1) and the actual emanating area *A* was measured as was the temperature of each fumarole.

The gaseous flux Φ was measured by means of a specifically developed device. It was made of a portion of tube, of an established diameter, aimed at intercepting the fumarolic gases. The vapour condensed on the walls of an externally refrigerated cone, and, by means of an open, duct the condensate was collected in a graduated container.

The quantity of H₂O vapour emanated daily by the entire fumarole was calculated by means of the following formula:

$$Q = \frac{VA}{ST} 86,400$$

where: *V* = the volume of the collected condensate; *A* = the measured surface of the emanating area of the fumarole; *S* = the intercepting area of the device; *T* = the time, in seconds, in which the condensate is collected; 86,400 = the number of seconds in one day.

The measurements were repeated at least three times consecutively in each point of measurement and the average flux was found. In some cases we repeated the operation in different points of the same fumarole.

The results are given in table 5.

In a few cases the measurements were not taken, either because the vapour was insufficient or because the fumarole itself had a very particular morphology, and we were anyway convinced that the estimate of the total output would not be appreciably altered.

A different method was used for measuring the output of the fumaroles of the isthmus that links Vulcano to Vulcanello and those of the fumaroles in the sea. In these two cases the gas was collected with an aluminum funnel having a diameter of about 30 cm and was carried through a rubber tube to an upsidedown bottle of known volume full of water. As the gas enters the bottle the water is pushed out, and by measuring the time to empty the bottle, the CO₂ output was deduced.

Since the CO₂ represents about 1 % of the H₂O vapour in these fumaroles which have temperatures near 100° C, the quantity of H₂O, which makes up 99 % of the gaseous emanation, was deduced. The result are given in table 2.

Output measurements of some of the species we considered, were made on Vulcano by FAIVRE PIERRET et al. (1980), table 3.

These measurements were made on samples of air taken at a distance of approximately 400 m from the fumarolic field where a source of SF₆ had been placed with the aim to determining the dilution ratio to be applied to all the species considered.

TABLE 2

Total output of CO₂ measured in the fumaroles at the seaside

SITE	CO ₂	H ₂ O
Fumaroles of the isthmus	0.35 tons/day	35 tons/day
Subaqueous fumaroles	0.15 tons/day	15 tons/day
TOTAL	0.5 tons/day	50 tons/day

The H₂O output was calculated taking into account that the CO₂ content is 1 % and H₂O is 99 %.

This method however doesn't take into account the different ways in which each single species is diffused in the air, which

TABLE 3

Output of some gases measured at the crater in 1980 by FAIVRE PIERRET et al. (1980)

SPECIES	tons/day
SO ₂	2.3 ± 0.4
HCl	6.4 ± 0.4
HF	0.11 ± 0.03

• From R.F. PIERRET et al., 1980.

depends on their specific chemical properties and on possible interactions in the atmosphere. Oxidation reduction reactions have a great effect on the sulphuretted species and can cause the formation of solid sulphur, which, at a certain distance from the point of discharge, might no longer be found under the form of SO₂ or H₂S.

We can therefore conclude that there is probably a considerable error in the measurements made on Vulcano by FAIVRE PIERRET et al.

In fact the ratio between the various species measured does not coincide with the ratio deduced from the analysis of the same gases taken directly from the fumarole. HCl and HF do not undergo the same fractionation phenomena which SO₂ is subjected. If we consider that these two gases have similar chemical properties and that their ratio respects that of the gases directly measured in the fumarolic condensate, we can assume that the quantities of HCl and HF measured by FAIVRE PIERRET et al. are probably quite close to that emanated by the fumaroles.

On the basis of the quantities of HCl and HF given by FAIVRE PIERRET et al. (1980) and taking into consideration the analytical ratio between these gases and the other fumarolic species it is possible to obtain the corrected quantities for all species and they are given in table 4. These values are in good agreement with our estimates, especially considering that the measurements were made with completely different methods.

Energy estimations

From the analysis of the gaseous species emanated by the fumaroles it is evident that

TABLE 4

Total output of fumarolic species at the crater

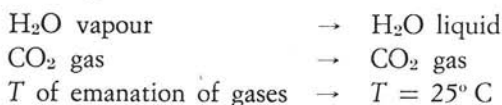
Species	This work	Modified values based on the data acquired by Faivre Pierret et al.		
H ₂ O	252.00 tons/day	296.00	- 336.00	tons/day
CO ₂	124.00 tons/day	146.00	- 164.00	tons/day
SO ₂	8.88 tons/day	10.40	- 11.80	tons/day
H ₂ S	2.75 tons/day	3.20	- 3.70	tons/day
HCl	5.10 tons/day	6.0	- 6.80	tons/day
HF	0.08 tons/day	0.08	- 0.14	tons/day
N ₂	0.81 tons/day	1.00	- 1.10	tons/day
CO	0.20 tons/day	0.24	- 0.27	tons/day
H ₂	0.03 tons/day	0.03	- 0.04	tons/day
H ₂ BO ₃	0.26 tons/day	0.31	- 0.35	tons/day

Also on the basis of some geochemical considerations we recalculated output values on the FAIVRE-PIERRET et al. (1980) data.

approx. 98 % of the fluid is made up of H₂O vapour and CO₂.

In this respect our computation of the total energy output is based on these two species.

The calculated energy is the excess of energy of fumarolic gases with respect to the environmental temperature (25° C). This energy is equal to the enthalpy variation of the process schematized as follows:



The enthalpy variation (ΔH) has been calculated using these equations:

$$\Delta H = \int_{T_1}^{T_2} C_p dT \quad (1)$$

$$C_p = a + bT + c/T^2 \quad (2)$$

$$\Delta H = \int_{T_1}^{T_2} (a + bT + c/T^2) dT \quad (3)$$

where the constants a , b and c have the following values (LEWIS and RANDALL, 1961):

for H ₂ O	for CO ₂
$a = 7.25$	$a = 6.21$
$b = 2.3 \cdot 10^{-3}$	$b = 10.40 \cdot 10^{-3}$
$c = 2.8 \cdot 10^{-7}$	$c = -35.45 \cdot 10^{-7}$

TABLE 5
Energy release at the crater.

Data on the temperature, surface and output of CO₂ and of H₂O are also shown

FUMAROLES	t°C	Emanating Surface (m ²)	CO ₂ (tons/day)	H ₂ O Vapour Output (tons/day)	ENERGY RELEASE MW	
					H ₂ O	CO ₂
F ₁	212	0.34	0.29	0.60	1.82 10 ⁻²	2.9 10 ⁻⁴
F ₂	212	0.21	0.18	0.36	1.15 10 ⁻²	1.8 10 ⁻⁴
F ₃	112	0.46	0.39	0.80	2.30 10 ⁻²	4.1 10 ⁻⁵
F ₄	243	5.50	6.50	13.30	4.30 10 ⁻¹	8.4 10 ⁻³
F ₅	253	5.30	5.96	12.20	4.00 10 ⁻¹	7.8 10 ⁻³
F ₆	226	2.50	1.46	3.00	1.00 10 ⁻¹	9.2 10 ⁻³
F ₇	183	1.00	2.15	4.40	1.40 10 ⁻¹	1.8 10 ⁻³
F ₈	210	0.35	0.29	0.60	2.00 10 ⁻²	2.9 10 ⁻⁴
F ₉	198	0.20	0.73	1.50	4.80 10 ⁻²	6.3 10 ⁻⁴
F ₁₀	210	4.50	2.25	4.60	1.45 10 ⁻¹	2.2 10 ⁻³
F ₁₁ {	a	224	5.60	12.70	4.10 10 ⁻¹	7.8 10 ⁻³
	b	112	9.80	13.80	4.10 10 ⁻¹	8.1 10 ⁻⁴
	c	265	27.46	141.20	4.70	0.1
F ₁₂	112	0.10	0.06	0.13	3.80 10 ⁻³	6.3 10 ⁻⁶
GBC {	a	260	7.80	30.00	1.00	2.1 10 ⁻²
	b	112	0.13	0.16	5.00 10 ⁻³	8.5 10 ⁻⁶
scattered fumaroles in the crater:						
High flux	108	0.30	0.27	0.55	3.60 10 ⁻¹	2.8 10 ⁻⁵
Low flux	126	3.13	5.91	12.10	1.60 10 ⁻²	1.8 10 ⁻²
Total		74.68	123.88	252.00	8.24	1.8 10 ⁻¹

The contribution of CO₂ to the total ΔH was calculated simply by substituting in the equation (3) the values of the above constants and the temperature values. As far as the contribution of H₂O is concerned, the calculation of ΔH is made as follows:

$$\left| \begin{array}{c} \text{H}_2\text{O vapour} \\ T \text{ of fumarole} \end{array} \right| \xrightarrow{\Delta H_1} \left| \begin{array}{c} \text{H}_2\text{O vapour} \\ T = 100^\circ \text{C} \end{array} \right| \xrightarrow{\Delta H_2} \left| \begin{array}{c} \text{H}_2\text{O liquid} \\ T = 100^\circ \text{C} \end{array} \right| \xrightarrow{\Delta H_3} \left| \begin{array}{c} \text{H}_2\text{O liquid} \\ T = 25^\circ \text{C} \end{array} \right|$$

where: ΔH_1 is calculated between the T of emanation and 100°C ; ΔH_2 (the latent heat of condensation) has a value of 9,717 cal/mole; ΔH_3 is calculated from the expression $\Delta H = C_s \Delta T$, with C_s as the specific heat of liquid H₂O (18 cal/mole).

The table 5 shows the energy values, expressed in MW, of the fumaroles of the

crater rim. As far as the fumaroles of the « Forgia Vecchia » and the other groups of the « Fossa » are concerned, which we weren't able to make output tests on, we estimated their global contribution, to be about 1.5 MW.

The fumaroles at the seaside release about 50 tons/day of H₂O, equal to 2.1 tons/h. Considering that the enthalpy of condensation at 100°C is 540 cal/gr and that another 75 cal/gr are released due to its cooling down to 25°C , a total of 615 cal/gr are obtained.

Therefore the energy released by these fumaroles is:

$$E = 2.1 \times 10^6 \text{ (gr/h)} \times 615 \text{ (cal/gr)} \times 1.16 \times 10^{-9} \text{ (MWh/cal)} = 1.5 \text{ MW}$$

Therefore, taking into account the release of energy measured at various fumarolic area and the estimated contribution of those areas

TABLE 6

Surface leakage of geothermal energy at various sites of Vulcano

SITE	MW
Crater rim (measured)	8.24
Other fumaroles at the crater (estimated)	1.50
Seaside fumaroles (measured)	1.50
Other fumaroles at the seaside (estimated)	0.20
TOTAL	11.44

that it was impossible to measure, we have been able to evaluate the total energy output at Vulcano as being near to 11.5 MW (table 6).

Volume and depth estimation of Vulcano's geothermal reservoir

Volume

By using the energy output values acquired, and the data relative to the evolution of the fumarolic activity registered between August and October 1979, we arrived at a rough estimation of the volume of Vulcano's geothermal reservoir.

After a period of absolute costancy a regular increase in temperature of the fumarolic gases, was observed, which, on August 15th 1979 was 303°C and which by October 8th had reached 318°C.

At the same time variations in other parameters were observed, such as changes in the composition of the gases, an increase in the gaseous flux and the extension of the fumarolic area. The increase of about one order of magnitude in the total output of gas has been estimated. The data and assumption used to estimate the volume of the reservoir are summarized below.

The data are:

- initial temperature of the fumarolic gases (t_i) = 303°C;
- final temperature of the fumarolic gases (t_f) = 318°C;
- duration of the evolution = 54 days;
- variation in the gaseous flux measured at fumarole F5 $\approx$ 50 %;
- estimated increase of the total gas output = 1 order of magnitude;
- thermal capacity 0.66 cal/cm³ of a brine with 10 wt% NaCl at T of about 310°C.

If we assume that:

- the increase in the input of energy E was applied with constant intensity, from the beginning of the evolution;
- the evolution occurred between two steady states, as the temperature plateaus before and after the thermal evolution suggest;
- the energy output measured in July 1980 and that at the beginning of the August-October 1979 evolutions are comparable, seeing that the temperature of the gases was the same ($t = 303^\circ\text{C}$);
- the energy output directly measured at the surface in geothermal areas is equal to 1/5 - 1/10 of the total (MUFFLER, 1975);
- the maximum temperature of the fumarolic gases measured at the surface can be correlated with that of the reservoir, following the model proposed by CARAPEZZA et al. (1981);
- the porosity of the rocks forming the reservoir is $\epsilon = 0.1$;
- the density of the rocks forming the reservoir is $\delta = 2$;
- the thermal capacity of the reservoir (rocks + water) is 0.4-0.50 cal/cm³ °C.

The volume of the geothermal reservoir is determined by means of the following expression:

$$V = Qe/Cr\Delta t \quad (4)$$

where: Qe = the quantity of energy, expressed in calories, needed by the reservoir to increase its own temperature from the original value to the final value; Cr = the thermal capacity of the reservoir (rocks + water $\approx$ 0.425 cal/cm³); $\Delta t = t_f - t_i = (318 - 303) = 15^\circ\text{C}$.

Since the evolution took place between two steady states, the increase in the energy input is equal to that of the estimated energy output. The regular increase in temperature of the fumaroles suggests that the increased energy input was constantly applied to the system and the increased energy input E_i must have been used, in reasonably comparable quantities, both by the reservoir to increase its own temperature, and partially dissipated by the output increase. The quantity of energy Qe stored in the reservoir during the evolution is therefore:

$$Q_e = \frac{(E_i \times \text{length of time of evol.})}{2} \quad (5)$$

where $E_i \approx 10 E_o = 11.5 \times 10 = 115$ MW and taking into account that the superficial leakage is 1/10 of the total we have:

$$Q_e = \frac{(115 \times 10 \text{ MW}) \times 24^h \times 54^d}{2 (1.16 \cdot 10^{-9} \text{ MWh/cal})} = 6.42 \times 10^{14} \text{ cal}$$

and from eq. 4 we have:

$$V = \frac{(0.425 \text{ cal } ^\circ\text{C}^{-1} (\text{cm}^3)^{-1}) \times 15^\circ \text{C}}{6.42 \times 10^{14} \text{ cal}} = 10^{14} \text{ cm}^3 = 0.1 \text{ km}^3$$

We must point out that this value is only to be considered as an order of magnitude and is referred to the central part of the reservoir, where the more active convective circulation produces a rapid thermal re-equilibration.

Depth

The model proposed by CARAPEZZA et al. (1981) postulates the existence of a pressurized geothermal reservoir located above a metamorphic basement, in the carbonatic-sedimentary and volcanic levels.

The evolution of such a system from a liquid-vapour biphasic to a mono-phase can take place:

- because it reaches its critical temperature, which for a brine, with 10 wt% NaCl is about 480°C ;

- because the internal vapour pressure at the bottom of the reservoir equals the hydrostatic pressure.

This latter condition was attained in 1979 when evolution towards the mono-phase system was observed (NUCCIO, VALENZA, CARAPEZZA, 1980). The maximum temperature of the fumaroles at that time was 303°C , corresponding to temperature of the boiling aquifer which was about 340°C and to the vapour pressure which was about 180 atm (± 20 atm.).

Therefore the bottom of the geothermal reservoir must be at a depth equal to the hydrostatic pressure of 180 ± 20 atm., and that is, at 1.6-2 km below sea level.

Concluding remarks

The total output of energy measured in July 1980 at Vulcano is of the order of 11.5 MW. The experiences made on other geothermal areas suggest that this value, associated to the natural superficial leakage, represents 1/5 - 1/10 of the natural flux of energy towards the surface.

We can therefore conclude that the actual geothermal energy available on Vulcano is of the order of 100 MW.

Finally, the exiguity of the order of magnitude of the geothermal reservoir's estimated volume, results as being in good agreement with the indications given by the rapid geochemical variations in the composition of the fumarolic gases observed during the evolution of the system in the last few years.

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