BOLLETTINO DI GEOFISICA TEORICA ED APPLICATA VOL. XXXIV, N. 136 - DECEMBER 1992

A. TABBAGH

SHALLOW CONDUCTIVE HEAT FLOW AT A SITE ON MOUNT ETNA FOR THE PERIOD SEPTEMBER 1984 - SEPTEMBER 1986

Abstract. Temperature data recorded on vertical profiles at several locations on Mount Etna allow calculation of the flux, its transient variations and also its steady values over an annual cycle. At Torre del Filosofo station the flux transient variations are of climatic origin. However, the steady flux is important in that it implies the presence of heat sources in the summit region. A network of shallow vertical temperature profiles would be a useful tool to study the structure of a volcano.

INTRODUCTION

The energy balance at the surface of a volcano is an important parameter in characterizing its midterm activity. In "hot areas" the transfer corresponds to a convective flow of gas (air, CO_2, water vapor...) through the permeable superficial layers; but elsewhere, impermeable formations stop the fluid motion, and the conductive heat flux may contain an upward term corresponding to a continuous energy release. In areas where convection dominates, the upward heat flux can be directly deduced from superficial temperature values (Sekioka and Yuhara, 1974); in other cases, temperature measurements at several points of a vertical profile are necessary. The possibilities now offered by satellite - borne systems, such as Argos, to transmit and record the data anywhere on the earth allow non - expensive and quick flux determinations.

As established in a preceeding paper (Tabbagh and Trézéguet, 1987) the analysis of shallow vertical profiles in the ground allows calculation of both the steady and unsteady parts of the heat flux, and recognition of their climatic or internal origin. These quantities are then determined at one, or a small number of points, which is the main limitation; but mapping of the surface temperature with airborne or satellite borne infra-red radiometers (Friedman et al., 1982; Tabbagh et al., 1987) may be used to increase the representativity of the measurement points.

This paper presents the results obtained on Mount Etna at Torre del Filosofo station (T.D.F. hereafter) in the near summit southern area (2900 m).

RESULTS OBTAINED OVER YEARLY CYCLES

The temperature profile is located in the summit area, sixty metres NE of the T.D.F. teletransmission station. Measurements are taken at four depths, 3 cm, 30 cm, 80 cm and 120 cm with 0.1° C sensitivity; the sampling rate is between 6 and 7 measurements per day. An

---

Manuscript received November 9, 1990; accepted November 13, 1992.

Université de Paris 6, Département de Géophysique Appliquée and Centre de Recherches Géophysiques, CNRS, Garchy 58150, France.

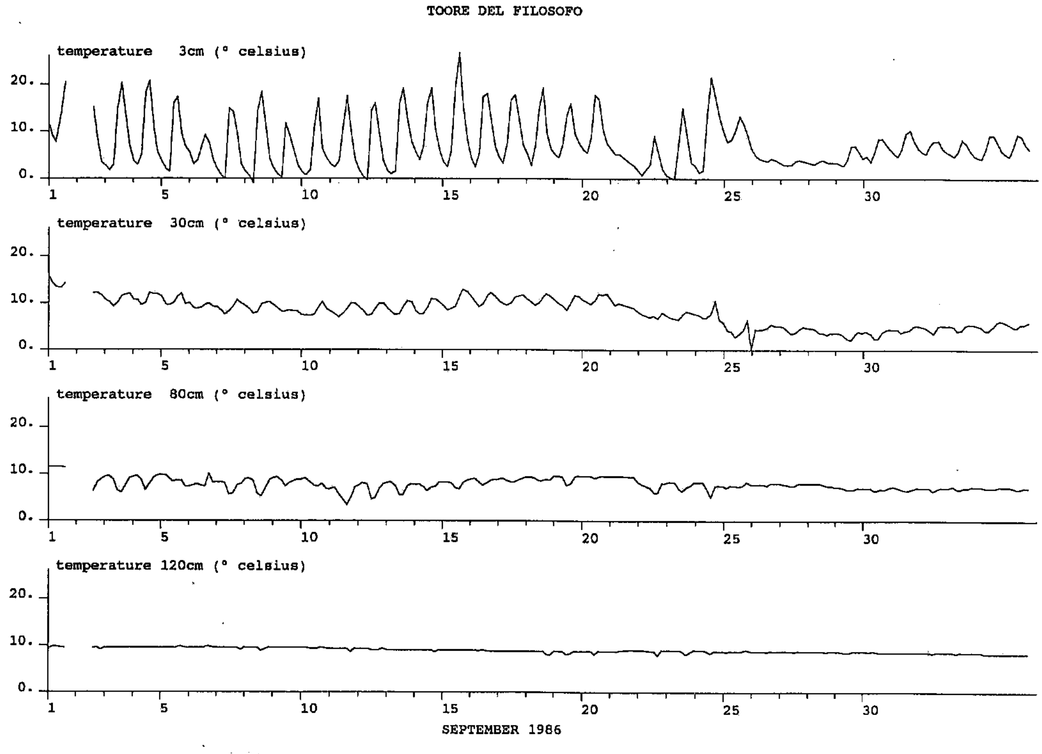

Fig. 1 — Example of temperature records at T.D.F. on September 1986.

example of the raw temperature data for September 1986 is presented in Fig. 1. We separated the studied period into two year-long cycles, September 1984 - August 1985 and October 1985 - September 1986 because of a change in transmission procedure and data format in September 1985. All the data were collected and preprocessed by the CTIV ("Centre de Télétransmission Informatisée des Volcans"). As for the November 1982 - November 1983 (Tabbagh and Trézéguet, 1987) cycle, the data were resampled at one - day steps by averaging the data collected over a smooth part of the daily variation curve, between 1 a.m. and 6 a.m. (local time). Several criteria were defined to eliminate erroneous data: for depths greater than 30 cm, the temperature had to be in the range -7° C to 18° C; the time variation in temperature had to be lower than 9° C/day at 3 cm, 4° C/day at 30 cm, 0.7° C/day at 80 cm and 0.5° C/day at 1.20 m; at 30 cm the value had to be in the range ± of the average of the 3 cm and 80 cm values; at 80 cm between ± 1.5° C of the 30 cm and 1.20 m average values. The missing values were linearly interpolated at a later stage from neighbouring data at the same depth. The sensors were all copper thermistors, and as the flux was always determined by differences (in time and/or depth) possible long term shifts would have a very small influence.

Thermal properties of the ground

The calculation of flux from temperature data necessitates knowledge of the ground thermal properties: diffusivity Γ and conductivity k in the conduction transfer case, volumetric flow rate of the fluid in case of convection transfer. At T.D.F. the conduction tranfer largely predominates, as can be seen from the agreement between the calculations in the conduction case and the data (see later). Thermal property measurements were made in July 1983 by J.P. Décriaud and D. Trézéguet using the method described by Tabbagh (1985). The diffusivity was 0.64 10^{-6} m^2/s and the conductivity 0.53 W/ (m.K). The diffusivity values can be controlled by the damping with depth of the modulus of the annual variation or by the phase shift with depth. For the first cycle, we obtained 0.63 10^{-6} m^2/s from the phase shift and by averaging the six possible depth combinations; for the second cycle the values had a greater spread: 0.51 10^{-6} m^2/s between 3 cm and 1.20 m, and 0.75 10^{-6} m^2/s between 80 cm and 1.20 m. The-

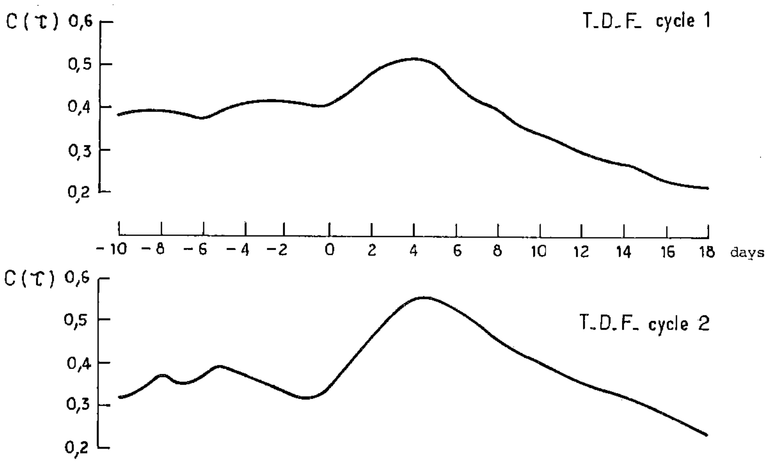

Fig. 2 — Correlation function between the flux at 0 m and the flux at 1.2 m at T.D.F. for the two annual cycles.

refore, we adopted the 0.64 10^{-6} m^2/s and 0.53 10^{-6} m^2/s values for both cycles.

Transient flux analysis

The transient flux variations can be calculated from transient temperature variations at the different measurement depths. Two methods exist for this calculation (Tabbagh and Trézéguet, 1987). In the first, the flux is considered as a series of step functions of amplitude Δq_i which are calculated from the flux values and the temperature variations of the given day. One may consider one flux origin at the ground surface, or two flux origins, one at the surface, the second beneath the deeper sensor. In this latter case, considering the time lag between flux at the surface and flux at depth, it is possible to determine the direction of the conduction and the time lag between the surface and the depth. The second method is the finite element one in which each vertical interval between adjacent measuring points forms an element. On each element, the temperature variation with depth is approximated by a linear expression, and we use the Galerkin process to obtain the matrix expression corresponding to this variation. For the time variation, we use an iterative process by calculating the temperature at time t from that at t–iδt. In the first analytical method, we use the temperature response to step variations of the flux of amplitude q_0 at $z=0$ and q_1 at $z=h$, in homogeneous layer of thickness h, conductivity k and diffusivity Γ:

$$\theta_u\,(z,t)=\frac{2\sqrt{\Gamma}}{k}\,(q_0\cdot f_0\,(z,t)-q_1 f_1\,(z,t)\,),$$

with

$$f_0\,(z,t)=\sqrt{t}\sum_{n=0}^{\infty}\left\{ierfc\,\frac{2nh+z}{2\sqrt{\Gamma t}}+ierfc\,\frac{2\,(n+1)\,h-z}{2\sqrt{\Gamma t}}\right\},$$

and

$$f_1\,(z,t)=\sqrt{t}\sum_{n=0}^{\infty}\left\{ierfc\,\frac{(2n+1)\,h+z}{2\sqrt{\Gamma t}}+ierfc\,\frac{(2n+1)\,h-z}{2\sqrt{\Gamma t}}\right\},$$

ierfc being the integral of the complementary error function. At each depth, the temperature for any time $n\delta t$ is calculated by summing the effects of the foregoing flux variations:

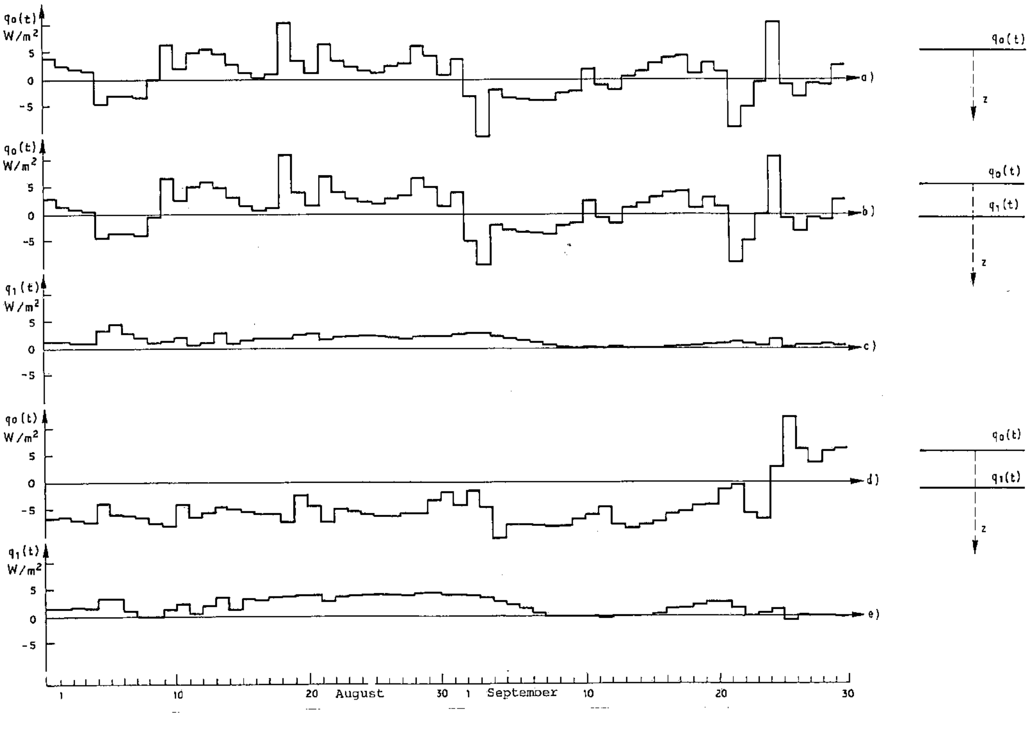

Fig. 3 — Transient flux variations at Torre del Filosofo during August and September 1986.

$$\theta\,(z,n\delta t)=2\,\frac{\sqrt{\Gamma}}{k}\left\{\sum_{i=2}^{n-1}\left[q_0\,(i\delta t)-q_0\,(\,(i-1)\,\delta t)\,\right].f_0\,(z,\,(n-i)\,\delta t)+\right.$$
$$+q_0\,(\delta t)\,.f_0\,(z,\,(n-1)\,\delta t)-q_1\,(\delta t)\,.f_1\,(z,\,(n-1)\,\delta t)+$$
$$\left.+\sum_{i=2}^{n-1}\left[q_1\,(i\delta t)-q_1\,(\,(i-1)\,\delta t)\,\right].f_1\,(z,\,(n-i)\,\delta t)\right\}.$$

We have a linear relation between θ and successive flux values, which can be calculated step by step. If we have more than two depths of measurement, the least square method allows us to take all of them into account in the calculation.

For the two cycles, the results corroborate and confirm those already obtained for the 1982 - 1983 cycle (Tabbagh and Trézéguet, 1987). The correlation functions, (Fig. 2), show maxima of 0.5 and 0.6, and a delay of 4 days between the surface flux and the flux at 1.20 m. This delay corresponds to a value of $h^2/4\Gamma t$ equal to 1.63, h being equal to 1.2 m, in perfect agreement with a conduction transfer. Fig. 3 shows the transient flux variations during August and September 1986 calculated using both methods and taking into account a conductive transfer. From the analytical calculation, the flux at the ground surface is identical (with only a small offset) to the model where there is only a source at the surface, curve (a), and the model with a source at depth also, curve (b). At 1.20 m depth, the flux is small even during the volcanic activity between the 20th and the 30th of September. During this period, the important external variations could be related to the eruption by the reduction in solar radiation followed by an air temperature increase. The finite element method, curves d) and e), corroborates the results of the analytical one. Fig. 4 shows the complete results for the two annual

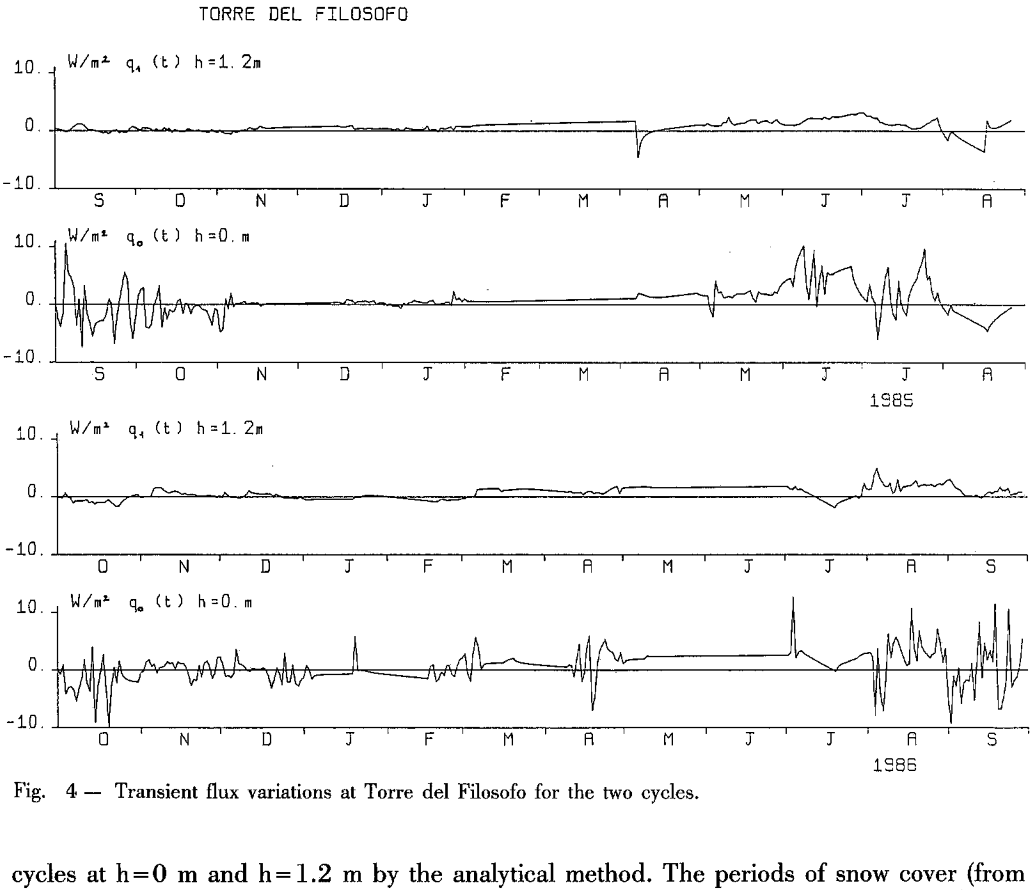

Fig. 4 — Transient flux variations at Torre del Filosofo for the two cycles.

cycles at h=0 m and h=1.2 m by the analytical method. The periods of snow cover (from November to April) in the summit zone appear clearly. These results confirm those already established at T.D.F.: there is no convective transfer, and all the transient variations originated in the atmospheric conditions, so it is possible to calculate the steady component of the flux from the conduction equation.

Steady flux analysis

The study of the 1982-1983 data led us to a very important result: the upward conductive flux averaged over one year between 0.8 m and 1.2 m was slightly over 0.7 W/m^2. This value is clearly higher than the climatic variations between one year and the next, which are inferior, in absolute value, to 0.1 W/m^2 (Tabbagh and Trézéguet, 1987). We had, therefore, a real abnormal value of the geothermal flux originating in the volcano itself. this value includes an error of around 10% or 15% due to possible (and unkown) climatic variations, but is fairly good and comparable to most of those obtained on land in drill holes. This method for obtaining the abnormally high geothermal flux is cheap and simple and could be used for as long as the teletransmission and the sensors functioned.

For the two annual cycles under consideration, we refined the calculation by fitting at each measurement depth the sum of a constant value and a sinusoid of annual period to the actual data. This gave a better estimate of the steady temperature value and could also be applied where we do not have a whole annual cycle. The phase and amplitude of the sinusoid can also be used to check the diffusivity value (see above). Using the finite element method, it is also possible to average the flux at 1.20 m. For the first annual cycle, we found -2.07 W/m^2 (the minus sign corresponds to an upward transfer) for the average of the flux value calculated by the finite element method, and -2.05 W/m^2 from the constant values at 0.8 m and 1.2 m depth. For the second annual cycle, the corresponding values were -1.40 W/m^2 and -1.41

W/m ^{2}. The two cycles have clearly different results and both are higher than the flux during the 1982-1983 period. Considering the causes of error that could explain this difference, one should note:

1) As the natural climatic variations remain inferior to 0.1 W/m ^{2} in modulus, its maximum possible effect on the difference between two cycles is 0.2 W/m ^{2}.

2) The fluxes are determined from both temperature and conductivity measurements. An error in conductivity introduces an error in the absolute value of the fluxes but does not affect the relative variations between one cycle and the other. The temperatures are determined from daily values using a least square process, which limits very efficiently the possible influence of errors. The were no changes of sensors during the two cycles and the copper thermistors are very reliable.

We can assert then that at T.D.F. the steady internal flux varied from one cycle to the other and was due to the volcanic activity. Nevertheless, with only one point at our disposal it is difficult to go further in the interpretation: the representativity of the point on the volcano's surface is not established and we need other points to determine the size or the location of any possible source of heat. It can only be said that one or several heat sources changed in intensity or location in the vicinity of T.D.F.

CONCLUSION

Grouping together the temperature profile data remotely recorded on Mount Etna for the 1984-1986 period and the preceeding results for the 1982-1983 period leads to the following conclusion: the steady flux of internal origin, an abnormal geothermal flux, is important in Torre del Filosofo and variable from one year to the next. The preparation of a "geothermal flux" map, from a network of remotely recorded temperature profiles could be considered. Such a network would involve major work but would provide valuable information about the inner structure of a volcano: the location of stable sources of heat, and mean term evolution of these sources (over several years). This could be an important help in monitoring.

Aknowledgements. The calculations presented in this paper were funded by the "Centre de Recherches Volcaniques" (Clermont-Ferrand, France). All the temperature data were transmitted and recorded by the "Centre de Téléobservation Informatisée des Volcans" (C.R.G. Garchy, France) as part of the PIRPSEV program (C.N.R.S., France).

REFERENCES

Friedman J. D., Williams D. L. and Franck D.; 1982: *Structural heat flow implications of Infrared anomalies at Mt Hood, Oregon, 1972-1977.* J. Geophys. Res., **87-B4**, 2793-2803.

Sekioka M. and Yuhara K.; 1974: *Heat flux estimation in geothermal areas based on the heat balance of the ground surface.* J. Geophys. Res., **79-B4**, 2053-2058.

Tabbagh A.; 1985: *A new apparatus for measuring thermal properties of soils and rocks in sity.* IEEE transactions Geos. Remote Sensing, GE **23-6**, 896-900.

Tabbagh A. and Trezeguet D.; 1987: *Determination of sensible heat flux in volcanic area from ground temperature measurement along vertical profiles: the case study of Mount Etna (Sicily, Italy).* J. Geophys. Res., **92-B5**, 3634-3644.

Tabbagh A., Tabbagh J. and Dechambenoy C.; 1987: *Mapping of the surface temperature of Mount Etna and Vulcano Island using and airborne scanner radiomter.* J.V.G.R., **34**, 79-88.