Seismic Coda Q and Turbidity Coefficient at the Phlegraean Fields Volcanic Area: Preliminary Results

M. CASTELLANO
E. DEL PEZZO
G. DE NATALE
A. ZOLLO

Osservatorio Vesuviano, 80056 Ercolano (Napoli), Italy

ABSTRACT

Digital recordings of microearthquake codas from shallow seismic events in the Phlegraean Fields region (south-central Italy) were used to calculate the attenuation factor Q_c.

A quite unusual frequency dependence was found for the coda attenuation comparable to Hawaii pattern of Q_c. This is interpreted as due to the presence of magma that increases the amount of anelasticity. Amount of scattering at Phlegraean Fields was estimated through the «turbidity» coefficient (Dainty model), that shows a high degree of scattering due to inhomogeneities as compared to Hawaii. Probably this is due to the greater crustal thickness of Phlegraean Fields with respect to Hawaii that produces more scattering.

INTRODUCTION

Attenuation is an important property of the medium from which useful information on the Earth's structure can be inferred. Moreover its evaluation is the first step for eliminating path effects from spectra made from field data for having a correct source spectral shape.

The evaluation of the so called quality factor Q ($Q^{-1} = \Delta E/E$, where E is the fraction of energy lost in a wave cycle) is very important in volcanic areas where the presence of magma presumably influences the properties of seismic wave propagation.

Another peculiar feature of volcanic areas and in general of all the active zones is the strong hetereogeneity in the geological structures as compared to tectonically stable zones. This nonuniformity do not allow one to use deterministic models to explain high frequency seismograms because of the many parameters required.

To overcome this difficulty the scattered waves that are generated in the zone in which the primary waves encounter strong variations in elastic properties, for example a small fault or crack or a local and sudden variation of density of the rocks, have been used in this study.

The scattered waves in the short period range (1-30 Hz) compose the part of the seismogram that follows the S-wave train, the so called *coda* of the earthquake.

In general the behaviour of the seismic coda is described by the average decay of its envelope, rather than by the amplitude of a particular phase in its wavetrain (AKI and CHOUET, 1975; AKI, 1980). It means that stochastic processes are assumed, for wave propagation and consequently we have no possibility to describe the Earth's structure in detail, but we can well determine the average attenuation properties of the crust and the upper mantle.

On this basis, the attenuation of the Phlegraean Field area was investigated using scattered waves.

METHOD AND ANALYSIS OF DATA

The coda method is not sensitive to the particular path hypocenter-station, but is a smoothed measurement of the average Q of the zone (AKI and CHOUET, 1975; AKI, 1980). Coda waves are presumed to be shear waves, single scattered by random and uniformly distributed heterogeneities. The S wave and the single scattering assumptions are in principle rather restrictive, but verified in first approximation by experimental results (see *e.g.* AKI, 1980). This model leads to the following relationship:

$$A(w/t) = S(w)\ t^{-1}e^{-wt/2Q} \qquad (1)$$

where $A(w/t)$ is the moving Fourier spectrum of the coda depending on the angular frequency, w, and the time elapsed from the origin time of the earthquake, t. $Q(w)$ is the quality factor of the medium and $S(w)$ is the so called «Source Coda Factor».

$Q(w)$ takes into account the energy lost by pure anelasticity as well as the energy lost by scattering. To evaluate separately these two effects a scattering model is necessary. In this paper we used the model developed by DAINTY (1981) that is expressed by

$$Q^{-1} = Q_A^{-1} + gv/w \qquad (2)$$

where Q is the measured quality factor, g is the so called turbidity coefficient, Q_A is the pure anelastic Q and v is the seismic velocity of the medium. g expresses the energy lost by pure scattering for unit distance.

The procedure used to compute Q from experimental data is described in DEL PEZZO *et al.* (1984*b*). Here only a brief outline of this method will be given. $A(w/t)$ of eq. (1) is experimentally evaluated by calculating the Fourier Transform of a sample of the seismogram around a given time t measured from origin time. With

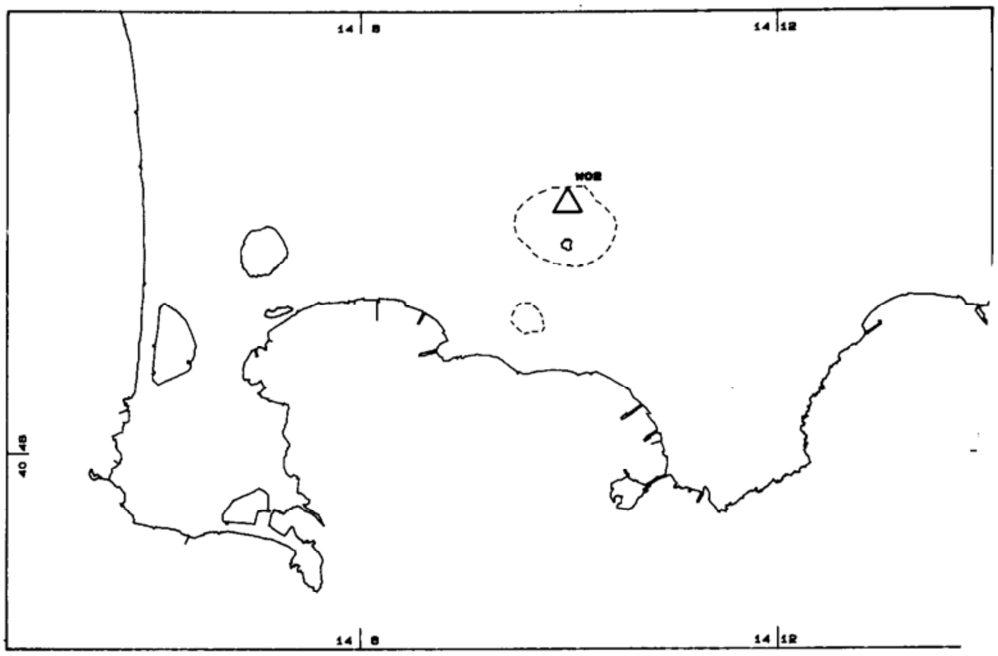

FIG. 1 - Map of the Phlegraean Fields zone. WO2 (triangle) is the station used in the pres study.

repeating this procedure for an increasing t along the coda of the seismogram we have the experimental estimate of $A(w/t)$. Taking the natural logarithm of both sides of eq. (1) we obtain

$$\ln A(w/t) \cdot t = \ln S - (w/2Q) \cdot t \quad (3)$$

Using the calculated $A(w/t)$ it is possible to have a least square fit of eq. (3) for different frequency bands centered in w. The slope is $w/2Q(w)$, so it is possible to estimate the frequency dependence of Q. Using this last estimate the turbidity g is the least square evaluated from (2).

An interesting remark about the results of this method applied in various regions in the world is that the pattern of Q as a function of the frequency depends on the investigated area.

A particular frequency dependence of Q was calculated for example in Hawaii (AKI, 1980), as compared to other active areas as California. This result led the author to hypothesize an attenuation mechanism for Hawaii influenced by the presence of magma that produces a substantial energy decay by anelasticity as compared to other tectonic areas in which the scattering is the most important factor governing the attenuation.

The data used in the experiment at Phlegraean Fields were collected with a portable digital three-component seismic station located in the crater of Astroni (Fig. 1). This type of station has 106 dB dynamical range and is controlled by a microprocessor. Seismograms are recorded in a 60 sec time window after the triggering. Triggering is obtained by comparison of long term average with short term average of the signal.

A set of about 150 earthquakes recorded in the period August-September 1983 was examined. Selection of the best recorded codas restricted the sample to 43 seismograms. The distance was evaluated by the S-P times. Because the used method is not sensitive to the relative position of the earthquake and the station (SATO, 1977) no locations were evaluated for these earthquakes. The range of the values of the S-P times shows that the utilized events originate very probably from the zone of Solfatara crater in which most of the earthquakes of Phlegraean Fields are located (DE NATALE *et al.*, 1984).

The beginning of the coda was chosen at the point in which the amplitude of the seismogram begins to decay regularly. The coda is stopped when it reaches about twice the amplitude of the noise

TABLE 1

Campi Flegrei						
Freq.Band centered at	1.7	3.0	6.0	12.0	16.0	
Q averaged on earthq.	135	225	265	326	433	**Q averaged on freq.=277
standard deviation	27	53	93	112	131	
sample variance	10	20	21	23	36	
Hawaii (Chouet,1976)						
Freq. band centered at	1.5	3.0	6.0	12.0	24.0	
Q averaged on earthq.	266	296	281	519	455	
Last sq. error	16	15	10	21	47	

measured before the beginning of the seismogram. It is worth noting that often the noise at Phlegraean Fields is very high, and this shortens the length of the useful coda interval. We examined a portion of coda lasting from 15 to 30 seconds.

The method above described was applied to this restricted set of data. The running spectra of eq. (1) were averaged in 5 frequency bands centered at $f_c = 1.7, 3, 6, 12, 16$ Hz with bandwidths of $0.6\ f_c$. By fitting the data with eq. (3) in the least square sense we accepted the data with correlation coefficient greater than 0.85. A Q averaged over the earthquakes was obtained for each frequency band (see Table 1).

Because the duration of the codas used in this study are in the range 15-30 seconds, the maximum travel distance of the back-scattered waves is of the order of 15-30 km assuming a V_S velocity of 2.0 km/sec. It means that if it is assumed to disregard the hypocentral distance as compared to this distance, the investigated zone has the dimension of a hemisphere with a radius of about 20 km. So, no information about the attenuation in the upper mantle is obtained.

TABLE 2 – Values of «Turbidity» in different areas of the world.

Area	turbidity g(1/km)	method	reference
Kanto district Japan area A	1.5Hz 0.022 3.0Hz 0.02 6.0Hz 0.04 12.0Hz 0.06	S and coda method (direct) S waves	Aki, 1980
Kanto district	0.012	Dainty mdl Qs pattern	Dainty, 1981
Kanto district	0.012	Coda method Coda waves	Sato, 1978
Central Asia	0.0047	Dainty mdl Qs pattern	Dainty, 1981
Friuli Italy	0.02	Dainty mdl coda waves	Rovelli, 1982
New England USA	crust 0.014 mantle 0.005	Dainty mdl coda waves	Pulli, 1984
Hawaii USA	0.0044	Dainty mdl coda waves	This paper
Campi Flegrei Italy	0.024	Dainty mdl coda waves	This paper
Stone Canion USA	1.0Hz 0.14 24.0Hz 0.002	Coda method coda waves	Aki and Chouet, 1975
Oishivama st. Japan	1.0Hz 0.003 12.0Hz 0.001	Coda method coda waves	Aki and Chouet, 1975
Tsukuba st. Japan	1.0Hz 0.001 24.0Hz 0.003	Coda method coda waves	Aki and Chouet, 1975
Norcia Italy	0.05	Dainty mdl coda waves	Del Pezzo and Zollo, 1984
Aeolian Islands Italy	1.0Hz 0.0008 2.0Hz 0.0007 4.0Hz 0.012 8.0Hz 0.017	Coda method coda waves	Del Pezzo and Zollo, 1984
Aeolian Islands Italy	0.02	Dainty mdl coda waves	Del Pezzo and Zollo, 1984

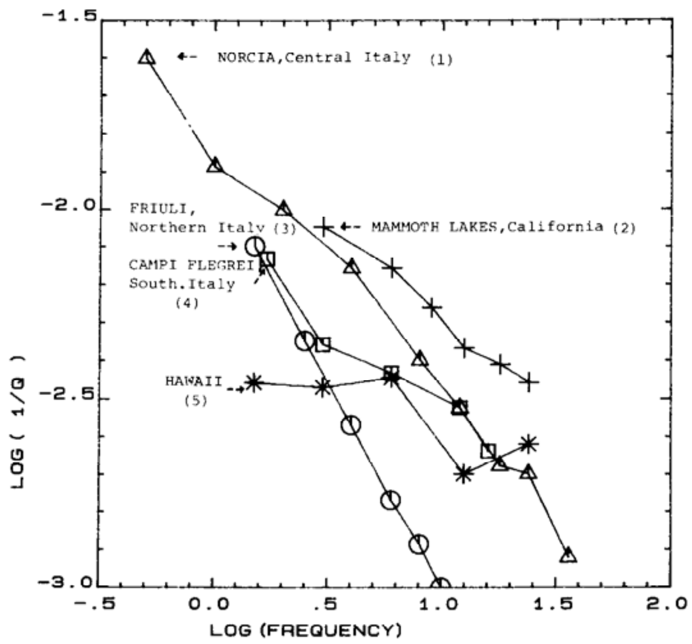

FIG. 2 – Q pattern as a function of the frequency in several tectonic and volcanic areas: (1) DEL PEZZO and ZOLLO, (1984*b*); (2) AKI, personal comunication (1984); (3) ROVELLI (1982); (4) This paper; (5) CHOUET (1976).

In Table 2 are reported the results obtained with fitting eq. (2) with the set of Q values as a function of frequency for the volcanic zones of Hawaii and Phlegraean Fields and for tectonic areas investigated with the same method (New England USA; and Friuli, Italy). In the same Table are reported many other results about « turbidity »obtained with methods different from that used in the present paper. An intrinsic Q of 500 and a scattering coefficient of 0.02 km^{-1} are found for Phlegraean Fields. A dissipative Q of 500 is very low as compared to the value of 2.000 found in the seismic active areas of Kanto district, Japan (AKI, 1980) and Friuli, Italy (ROVELLI, 1982). Unfortunately, it is impossible to compare directly the turbidity values of every tectonic zone reported in Table 2 with the values obtained in the present paper because of the different adopted methods. Notwithstanding it seems that the turbidity coefficient for Phlegraean Fields is not appreciably different from other values reported in the literature for non volcanic areas. For this reason it would be necessary a check with a direct method for a turbidity evaluation (AKI, 1980).

CONCLUSIONS

The coda method was applied to the volcanic area of Phlegraean Fields to investigate the average properties of the attenuation of seismic waves in the short period range.

A weak frequency dependence of Q was found as compared to other tectonic zones investigated with the same method. Moreover a comparison with the area of Hawaii was carried out and a similarity of these two volcanic areas was noted in the different increase of Q with frequency as compared to other tectonic zones. This different frequency dependence suggests that for Phlegraean Fields and Hawaii the mechanism of attenuation is partly different from that of tectonic zones. For the tectonic zones it has been demostrated that scattering is the predominant mechanism in the energy absorption (AKI, 1980). This is evidenced when the Dainty model [eq. (2)] is applied to Q patterns with a frequency calculated for the tectonic zones, where intrinsic Q greater than 2000 are obtained (PULLI, 1984; ROVELLI, 1982).

This is substantially different from what is found in Phlegraean Fields and Hawaii that show intrinsic Q as low as about 500. In Hawaii the turbidity coefficient, that is the factor controlling directly the amount of scattering, is about five times lower than in Phlegraean Fields. This may be due to the different crustal thickness of these two volcanic zones; the mantle under Kilauea is about 7 km (ELLSWORTH, 1977), and under Phlegraean Fields it reaches a depth approximately two or three times more. If, as it is reasonable, the mantle is less heterogeneous than the crust from the scattering point of view, a turbidity at Phlegraean Fields stronger than in Hawaii is explained.

ACKNOWLEDGEMENTS

This paper is based on the first digital data collected at Phlegraean Fields during the summer 1983 by the staff of the University of Wisconsin. We are grateful to the whole staff for making these data fastly available. We thank also Robert Meyer for the helpful discussions and for critically rewiewing the manuscript.

Keiiti Aki is gratefully aknoweledged for the helpful suggestions and for making unpublished data available to us.

REFERENCES

AKI, K., 1980, *Scattering and Attenuation of Shear Waves in the Lithosphere.* J. Geophys. Res., *85*, p. 6496-6504.

———, CHOUET, B., 1975, *Origin of Coda Waves: Source, Attenuation and Scattering Effects.* J. Geophys. Res., *80*, p. 3322-3342.

CHOUET, B., 19.., *Source, Scattering and Attenuation Effects on High Frequency Seismic Waves.* Mass. Inst. Techn. Ph. D. Thesis.

DAINTY, A.M., 1981, *A Scattering Model To Explain Seismic Q Observations in the Lithosphere Between 1 and 30 Hz.* Geophys. Res. Letters., *8 (11)*, p. 1126-1128.

DEL PEZZO, E., ROVELLI, A., ZONNO, G., 1984*a*, *Seismic Coda Q and Site Response in Central Italy.* Annales Geophysicae, 1984*a* (in press).

———, ZOLLO, A., 1984*b*, *Attenuation of Coda Waves and Turbidity Coefficient in Central Italy.* Bull. Seism. Soc. Am., (in press).

DE NATALE, G., ZOLLO, A., DEL GAUDIO, C., RICCIARDI, G.P. and MARTINI, M., *Error Analysis in the Hypocentral Locations at Phlegraean Fields.* Bull. Volcanol., this issue.

ELLSWORTH, L.W., KOYANAGI, R.Y., 1977, *Three Dimensional Crust and Upper Mantle Structure of Kilauea Volcano, Hawaii.* J. Geophys. Res., *82 (35)*, 5379-5393.

PULLI, J.J., 1984, *Attenuation of Coda Waves in New England.* Bull. Seism. Soc. Am., *74*, p. 1149-1166.

ROVELLI, A., 1982, *On the Frequency Dependence of Q in Friuli from Short Period Digital Records.* Bull. Seism. Soc. Am., *72*, p. 2369-2372.

SATO, H., 1978, *Mean Free Path of S Waves under the Kanto District of Japan.* J. Phys. Earth, *26*, p. 185-198.

Ms. received March 1984. Revised ms. received Sept. 1984.