Re-calibration of the magnitude scales at Campi Flegrei, Italy, on the basis of measured path and site and transfer functions

S. Petrosino [(1)], L. De Siena [(1)], E. Del Pezzo [(1)]

(1) Istituto Nazionale di Geofisica e Vulcanologia, sezione di Napoli " Osservatorio Vesuviano"

The quantification of the seismic energy of earthquakes occurring in volcanic regions is of great importance to better understand the dynamics of the volcanoes. The amount of the released energy and its variation during seismic crises can be considered as an indicator of the source processes acting inside the volcano. In this context, the effect of the propagation in attenuative media should be considered to correct for path effects and to properly estimate the seismic energy released at the source. Moreover, to allow a comparison with the dynamic processes occurring in different volcanic areas, the use of magnitude scales as homogeneous as possible is strongly recommended. In this framework, new duration-based Local (M_l) and Moment (M_w) magnitude scales are obtained for the Campi Flegrei area (southern Italy), by analysing a data-set of local volcano-tectonic earthquakes. First the S-wave quality factor for the investigated area was experimentally calculated and then the distance-correction curve, log*A0*(r), to be used in the Richter formula M_l = log*Amax* − log*A0*(r), was numerically estimated by measuring the attenuation properties and hence propagating a synthetic S-wave-packet in the earth medium. The Local magnitude scale was normalized in order to fit the Richter formula valid for Southern California at a distance of 10 km. M_l magnitude was estimated by synthesizing Wood-Anderson seismograms and measuring the maximum amplitude. For the same data-set, Moment magnitude from S-wave distance and site corrected displacement spectra was obtained. Comparisons between Local and Moment magnitudes determined in the present work, and the old Duration magnitude (M_d) routinely used at the INGV - Osservatorio Vesuviano are presented. Moreover, relationships between M_l and M_w calculated for two reference sites, Solfatara and Astroni, are also derived.

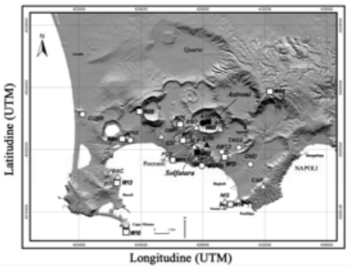
Instruments and dataset

The present seismic monitoring network of the Campi Flegrei volcanic complex managed by INGV-Osservatorio Vesuviano is composed of 9 analogue stations and 8 digital stations recording in situ. To calibrate the magnitude scales, we used the recordings from the stations located in the Solfatara area and in the Astroni crater:

1) 83 local earthquakes occurred from March 2005 to December 2006 with low M_d (up to 1.2), recorded at the three-component short period (1-Hz) analogue station STH and at the three-component broad-band (20-s) digital station ASB2.

2) 57 local earthquakes collected during the 1984 bradyseismic crisis with M_d between 0.9 and 3.2, recorded at the three-component short period (1-Hz) digital stations W12 and W03.

The final full dataset consists of 140 earthquakes with hypocentral distances ranging from 0.2 to 8 km, and depths ranging from 0 to 5 km.



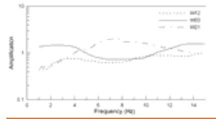
Attenuation properties and quality factor determination

The amplitude spectrum for the S waves as the product of source, path and site effects can be written as:

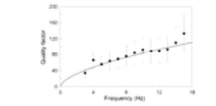
$$A_{ij}(f,r) = S_i^A(f)T_j(f)\exp(-\pi f k_0)G_{ij}(r)\exp(-\pi f \frac{t_{ij}(r)}{Q(f)})I_j(f)$$

A_{ij} is the high-frequency amplitude spectrum;
f is the frequency of the S-wave radiation emitted by the source;
S_i^A is the amplitude spectrum at the source;
T_j is the site amplification function;
exp($-\pi f k_0$) is the site-dependent attenuation term or diminution operator;
G_{ij} is the geometrical spreading term;
exp($-\pi f\, t_{ij}(r)/Q(f)$) is the path-dependent anelastic attenuation term;
t_{ij} is the travel time along the ray with coordinate ;
I_j is the instrument transfer function.

Using the known site-dependent attenuation terms and the site amplifications, and estimating the amplitude spectrum for the earthquakes recorded at the stations W12, W03 and W21, we determined the quality factor Q in different frequency bands, obtaining $Q(f)=21f^{0.6}$



Site amplification functions for stations W12, W03 and W21.



Q values obtained from the attenuation analysis in the 3-15 Hz frequency range (circles), and the functional dependence on the frequency (line).

Local magnitude determination

The original definition of Local magnitude introduced by Richter is based on the equation:

$$M_l = \log A - \log A0(r)$$

where A is the maximum amplitude of the Wood-Anderson trace in millimetres, and log*A0*(r) is the distance-correction curve, which is defined with respect to a reference earthquake and needs to be experimentally determined. Due to the restricted number of stations recording the same event and to the short distance range of our observations (0.2 to 8 km), it is difficult to experimentally derive the maximum amplitude decay with distance in the Campi Flegrei area. To overcome this difficulty, we numerically simulated an S-wave train generated by a Haskell-like source, for a suitable source-distance range, propagating in a medium with known attenuation properties. The amplitude spectra were multiplied for the site amplification factors of the two sites of Solfatara and Astroni. The path- and site-corrected spectra were transformed into time domain via inverse FFT, and the maximum amplitudes corresponding to each distance r were fitted to the relationship:

$$-\log A_{0j} = a\cdot\log(r) + b\cdot r + c + \sum_{l=1}^{N_s} s_l\delta_{lj}$$

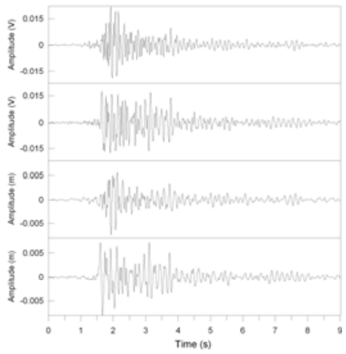
where δ_{lj} is the Kronecker delta and N_s is the number of stations. The system of equations was inverted under the constraint that the station correction sum is equal to zero. The value of the constant c was constrained assuming that at the distance of 10 km an earthquake of magnitude 3 would have the same amplitude as in Southern California on a Wood-Anderson seismometer.

Therefore the Local magnitude scale for Campi Flegrei is given by:

M_l=log$A$+0.95log(r)+0.09r-0.1+s_j

$s_{Solfatara}$= 0.12 ±0.03 $s_{Astroni}$= -0.12 ±0.03

Using this scale, we estimated the local magnitudes for the earthquakes of our dataset, by calculating the Fourier Transform of the two horizontal components and correcting them for the complex instrument transfer function. The corrected displacement spectra were then multiplied by the complex Wood-Anderson transfer function. We used the standard Wood-Anderson transfer function, with magnification of 2800, damping factor of 0.8, and natural period of 0.8 s. The synthetic Wood-Anderson seismograms were obtained by applying the inverse FFT algorithm, the zero-to-peak maximum amplitudes were measured on both of the horizontal components, and the two values were averaged.



Seismogram for a local VT earthquake. The first upper panels represent the E-W and N-S components of the original velocity seismogram recorded at station ASB2. The lower two panels are the synthesized Wood-Anderson seismograms for the E-W and N-S components, respectively.

Moment magnitude determination

We calculated the Moment magnitude from the seismic moment M_0 using the formula of Hanks and Kanamori:

$$M_w = \frac{\log M_0}{1.5} - 10.73$$

To estimate the seismic moment M_0 of the 140 earthquakes recorded at the STH, ASB2, W12 and W03 stations, we selected a 2.5-s-long time window around the S-wave onset, and we calculated the amplitude spectrum of the displacement and corrected it for the geometrical spreading 1/r, for the path-dependent anelastic attenuation term , for the diminution factor and for the frequency-dependent site amplification. We averaged the corrected spectra of the two horizontal components, and evaluated the spectral Ω level below the corner frequency. The scalar seismic moment associated to the double couple mechanism was calculated by:

$$M_0 = \frac{4\pi\rho v_s^3 r\Omega_0}{FY_{\theta,\phi}}$$

where r is the hypocentral distance, v_s is the S-wave velocity, ρ is the average density, Ω_0 is the low-frequency level of the S-wave displacement spectrum, F is the free surface operator and Y is the radiation pattern term.

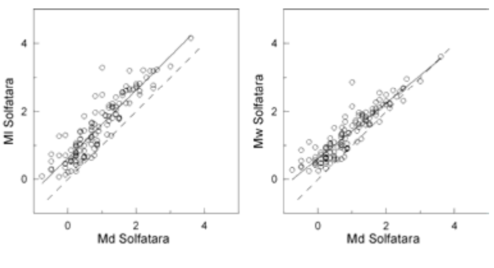
Regression and new magnitude scales (I)

We compared Local and Moment magnitudes obtained using the new scales for the reference site of Solfatara, with the Duration magnitude routinely calculated at the INGV-Osservartorio Vesuviano using the formula M_d=-2.46+2.82log(τ)

The relationships between M_l, M_w and M_d were derived from the linear fit:

M_l=0.63(±0.05)+1.00(±0.05)M_d

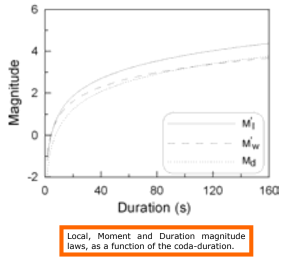
M_w=0.61(±0.04)+0.82(±0.03)M_d



The duration-based Local and Moment magnitude scales for the Solfatara site that can be used for practical purposes were obtained by linear regression on the logarithm of the coda-duration:

M_l=-1.8(±0.1)+2.8(±0.1)log(τ)

M_w=-1.4(±0.1)+2.3(±0.1)log(τ)

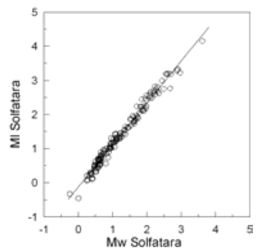


Local, Moment and Duration magnitude laws, as a function of the coda-duration.

Regression and new magnitude scales (II)

The relationship between M_l and M_w for the Solfatara site was obtained by a linear regression:

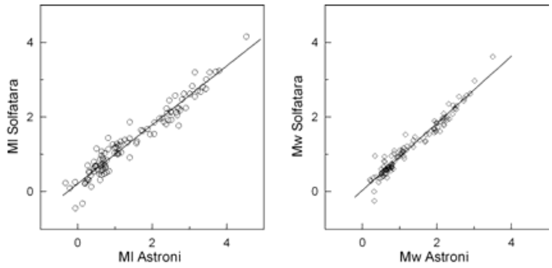
M_l=-0.12(±0.02)+1.23(±0.01)M_w



To give alternative magnitude scales to be used in case of a malfunction of the STH reference station without loosing the catalogue coherency, we derived the relationships for the Local and Moment magnitude between the Astroni and Solfatara sites. The relationships that relate the magnitudes calculated at the two sites are:

$M_{l,Solfatara}$=0.21(±0.04)+0.79(±0.02)$M_{l,Astroni}$

$M_{w,Solfatara}$=0.028(±0.03)+0.90(±0.02)$M_{w,Astroni}$



Therefore, Local and Moment magnitudes can be also evaluated for earthquakes recorded at the ASB2 station, using the new calibrated Local scale or from the seismic moment, respectively, and then this value can be corrected using the previous formulas, to minimize possible bias introduced by different local site responses and to make it consistent with the seismic catalogue for the reference station STH.

References: Petrosino S., De Siena L., Del Pezzo E., 2008. Re-calibration of the magnitude scales at Campi Flegrei, Italy, on the basis of measured path and site and transfer functions. Bulletin of the Seismological Society of America, in press.

Conclusions

We calibrated new duration-based magnitude scales for the Campi Flegrei area, that are particularly suitable for real-time applications. The advantage of calculating Local (or Moment) magnitudes from the coda-duration, instead of making amplitude measurements, is that problems related to the saturation of the seismic traces that often occur with the most energetic earthquakes and that usually affect low-dynamic gain analogue stations are fully overcome. This is particularly important for the routine magnitude estimates of the local earthquakes, because the reference station STH used at the INGV-OV is a low-dynamic analogue instrument.

On the other hand, if duration-based magnitude evaluations at the reference station STH are not possible, for the following reasons:

1) A malfunction of the station;
2) In case occurrence of seismic swarms, when the very close temporal occurrence of the earthquakes prevents an estimation of the correct coda-duration;
3) The amplitude of the seismic noise (or volcanic tremor) is high enough to mask the real coda-duration of low-energy earthquakes;

then, the Local and Moment magnitudes can be evaluated for the Astroni site, where the ASB2 digital station is located and, using the presented relatioships, traced back to the Solfatara site, to ensure the catalogue homogeneity and consistency.

A final consideration concerns the Moment magnitude scale that represents the most objective way of estimating the earthquake energy, because it depends on the value of the seismic moment, and unlike the Local scale, it does not depend on a normalization distance. Therefore the use of this scale is strongly recommended.

Due to its volcanological history, its geographic setting and its high degree of urbanization, the Campi Flegrei caldera is potentially one of the most high-risk volcanic areas in the World. Correct and reliable magnitude estimates are therefore necessary for quantitative evaluations of the volcano dynamics, and are more urgent considering the recent 2004-2006 unrest episode.