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Application of the Wiener filter to magnetic profiling in the volcanic environment of Mt. Etna (Italy)

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Abstract
The frequency-domain Wiener filtering was applied to magnetic anomalies in the volcanic area of Mt. Etna. This filter, under suitable conditions (additive noise, linear processing and mean-square error criterion), can furnish an effective tool for discriminating the geologic feature of interest (the signal) from the noise. The filter was first tested with synthetic data. Afterwards it was applied to a magnetic profile carried out across the principal fault system of the Mt. Etna volcano, that hosted the dykes feeding both the 1989 and the 1991-93 eruptions. The magnetic anomalies linked to the volcanic section and those linked to the contact between the clay basement and the lava coverage show significant spectral overlap. Thus by estimating the power spectrum of the signal, obtained resolving the forward problem, a least-squares Wiener filter has been designed. In such context, it was possible to verify the effectiveness of Wiener filters, whereas traditional band-pass filtering proved inadequate. In fact, analysis of the noise showed that all the meaningful components of the observed magnetic field were resolved. The results put further constraints on location and geometry of the shallow plumbing system of Mt. Etna.

Key words *Wiener filter – magnetic anomalies – Mt. Etna*

1. Introduction

Magnetic prospecting data gathered in volcanic environments are often highly contaminated by noise originated, among others, by the intrinsic uncertainty of measurements and magnetic heterogeneity typical of surface lavas. Regions where igneous rocks predominate, like Mt. Etna, usually exhibit complex magnetic variations. Deep features are frequently hindered by high frequency magnetic effects originating near the surface. In practice it is rare to observe isolated simple anomalies whereas in most cases the magnetic field can be seen as a stack of anomalies resulting from different sources located at various depths and showing complex shapes.

Magnetic surveying on the ground along profiles almost always consists of total field measurements $t(x)$ which usually can be described as the sum of the effects linked to the geologic feature of interest (the useful signal, $s(x)$) and of the interfering magnetic effects produced by the structures of no interest together with data error (the noise, $n(x)$):

$$t(x) = s(x) + n(x). \qquad (1.1)$$

Then, the major problem in magnetic interpretation is that of separating the useful signal from the noise. Traditional techniques of numeric processing of experimental data give a good separation of the signal and noise components when these occupy different frequency bands. Actually, as often happens, the signal and the noise display overlapping spectra, and any attempt to remove the noise through conventional band-pass filters can result in a worsening of the signal properties. For example, let us assume the presence of a signal linked to a process of the Gauss-Markov type and of white noise; their spectral densities are shown in fig. 1. In this case a band-pass filter, at whatever optimisation level, is unable to separate the signal from disturbing noise.

In order to overcome this drawback, the optimum-filter theory by Wiener (1949) was used. This filter allows the detection, in any signal, of the presence of a component of known form, and represents an interesting alternative to the conventional band-pass filters because geologic information can be used in a more extensive manner, when defining the filter transfer function. The crucial point of Wiener filtering, however, is the definition of the filter transfer function, an operator determined in practice by the ratio of the power spectra of the signal and the observed data (Shanmugan and Breipohl, 1988). The specification of this operator is often subjective because of the incomplete knowledge of the spectral properties of the signal. In the case of processing a gravity contour map, Pawlowski and Hansen (1990) proposed a method which provides, through direct modeling of the known geological features, an «objective» estimate of the signal power spectrum required to define the transfer function of the filter. The purpose of the present paper is to apply this method to magnetic profile data collected on the volcanic area of Mt. Etna, characterised by the presence of rocks with high susceptibility values.

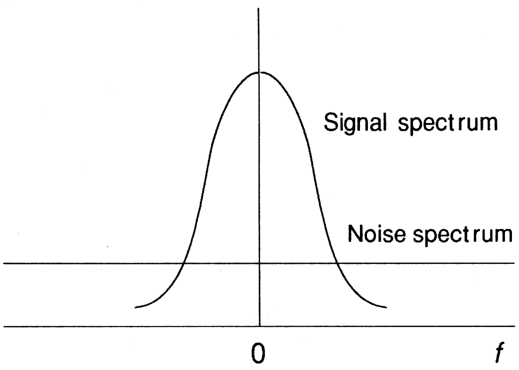

Fig. 1. Spectral densities of Gauss-Markov signal and white noise.

2. Wiener's optimum-filter theory

Here is a brief description of the Wiener optimum filter theory. If the spectral characteristics of an additive combination of signal and noise are known, then the Wiener filter theory simply states what the filter's frequency response should be in order to give the best possible separation of the signal from the noise, that is, how the filter characteristics should be chosen in order to enhance the signal while minimising the noise. When Wiener's optimum-filter theory is used to separate the magnetic anomalies, it is necessary for Wiener filter $h(x)$ applied to the measured signal $t(x)$ to produce a signal $\check{s}(x)$, the actual filter output, which is represented by the convolution $t(x) * h(x)$. This is as close as possible to the uncorrupted signal $s(x)$, which represents the desired or ideal output of the filter. In other words, in the frequency domain (f), we will estimate the true signal S by:

$$\check{S}(f) = T(f)\ H(f) \tag{2.1}$$

and the sense in which $\check{S}$ will be close to S is that they minimise the mean-square error, *i.e.*:

$$\begin{aligned} e &= \langle | \check{s}(x) - s(x) |^2 \rangle = \\ &= \langle | \check{S}(f) - S(f) |^2 \rangle = \text{minimum}. \end{aligned} \tag{2.2}$$

In eq. (2.2), angle brackets denote the mean, or expected value (averaged over all points x, of the sample space), and $\check{S}$, H, N and T are the Fourier transforms of $\check{s}$, h, n and t. The mean-square error criterion, used in Wiener's original work (1949), weighs large errors heavily while ignoring smaller ones: on the other hand, it offers some mathematical advantages. The quantity e can be defined in terms of the unit-impulse response of the filter and of the statistical characteristics of the input and output waveforms (Kulhanek, 1976).

Indeed, assuming that the signal and noise are uncorrelated (this is the definition of what is meant as noise), and substituting eqs. (1.1) and (2.1) on the right-hand side of eq. (2.2) we obtain

$$\langle |[S(f)+N(f)]H(f)-S(f)|^2\rangle =$$

$$=\langle |S(f)|^2|1-H(f)|^2+|N(f)|^2|H(f)|^2\rangle. \qquad (2.3)$$

Obviously eq. (2.3) will be a minimum if and only if the integrand is minimised with respect to $H(f)$ for any value of f. We shall look for a solution where $H(f)$ is a real function. Differentiating with respect to H, and imposing the result equal to zero we have:

$$H(f)=\frac{|S(f)|^2}{|S(f)|^2+|N(f)|^2} \qquad (2.4)$$

or

$$H(f)=\frac{|S(f)|^2}{|T(f)|^2}. \qquad (2.5)$$

This is the formula for optimal filter $H(f)$. Since $S(f)$ and $T(f)$ are real functions of the frequency, $H(f)$ represents a distortionless phase filter.

The theory of Wiener's filters, that allows the extraction of a random signal from a background of additive random noise, assumes that both signal and noise of the magnetic field are random stationary and ergodic processes. Stationarity implies that the spectral properties of the magnetic field are invariant under a translation of space, while the ergodic assumption entails that a sample of the magnetic field, randomly chosen, contains all possible statistical variations of the process.

Experience shows that in many cases the Wiener filter theory has provided acceptable solutions (Gordin and Mikhailov, 1977; Meskò, 1984), particularly in seismic methods (Robinson and Treitel, 1980). The Wiener filter has also been applied to gravity and magnetic methods (Clarke, 1969; Gunn, 1972; Hansen and Pawlowski, 1989) and resistivity sounding (Koefoed and Dirks, 1979).

The major practical difficulties in the design of least-squares filters are linked to the estimate of correlation or spectral characteristics of the useful signal and the noise. To determine the optimal filter from eq. (2.5) we need some way of estimating separately $|S|^2$ and $|N|^2$. Obviously, there is no way to do this from the measured signal T alone without some other information, or some assumptions or guessing (that is why the signal and the noise are generally assumed to be noncorrelated). For the estimate of the signal power spectrum, we followed an approach suggested by Pawlowski and Hansen (1990). The approach consists in solving the forward problem using the available geologic and geophysical information to obtain, through Fourier's transform of the modeled signal response, a more objective estimate of the magnetic field's signal power spectrum. In this way we will consider the signal $s(x)$ known and our objective is to establish the presence or absence of $s(x)$ in the observed process $t(x)$. The noise $n(x)$ is a random process with known properties.

Pawlowski and Hansen (1990) already emphasised that the procedure of constructing a filter from the modeled magnetic signal and then utilising the same filter to separate the actual signal from the observed magnetic field evidently has a circular character. However, it is worth stressing that, when the available information is reliable, the modeled signal can be sufficient to construct suitable models of the magnetic signal power spectrum. In this way the available information on the useful signal is fully utilised without the variations of the noise properties affecting the obtained results too strongly (Strakhov, 1977). It is worth noting that the filter response at any frequency f has a weight proportional to the signal/noise ratio at that frequency. The filter's transfer function can be seen as a weighting function that establishes how the input values should be weighted in order to determine the output values, that is the optimal estimate (Brown and Hwang, 1992).

The implementation of the zero-phase Wiener filtering involves different steps. First of all, a grid representation of the observed magnetic field $t(x)$ is necessary, in correspondence with which the modeled magnetic signal

$s(x)$ is evaluated by resolving the forward problem using all available geologic and geophysical information. Then, the mean values have to be removed from the observed field and the modeled signal, extrapolated to the periphery of the area of interest. This step is usually necessary because the presence of a linear trend in the data can seriously distort the calculated spectrum (Papoulis, 1977). To this end Fourier transforms $T(f)$ and $S(f)$ of the observed field and modeled signal are computed, and irregularities smoothed out (Gibbs' phenomena) in the power spectra. Finally, the zero-phase Wiener filter is constructed from the smoothed power spectra by use of eq. (2.5), and the frequency-domain Wiener filter is applied to the Fourier transform of the observed magnetic field $t(x)$. The inverse Fourier transformation of this frequency-domain multiplication yields the space-domain representation of the filtered field which is then taken again to the original dimensions and added to the mean value of the original magnetic data.

3. Application to synthetic data

To check the performance and applicability of the Wiener filter to a case of volcanic source, an artificially constructed data set was employed. Thus a model simulating structures that are often observed on volcanoes was assumed. The geological model (fig. 2) consists of four layers labeled L1-L4, and one shallow body intrusion B1. Within each layer and in the body the susceptibility is assumed to be constant. Synthetic magnetic fields in this study were calculated using a 2½D model

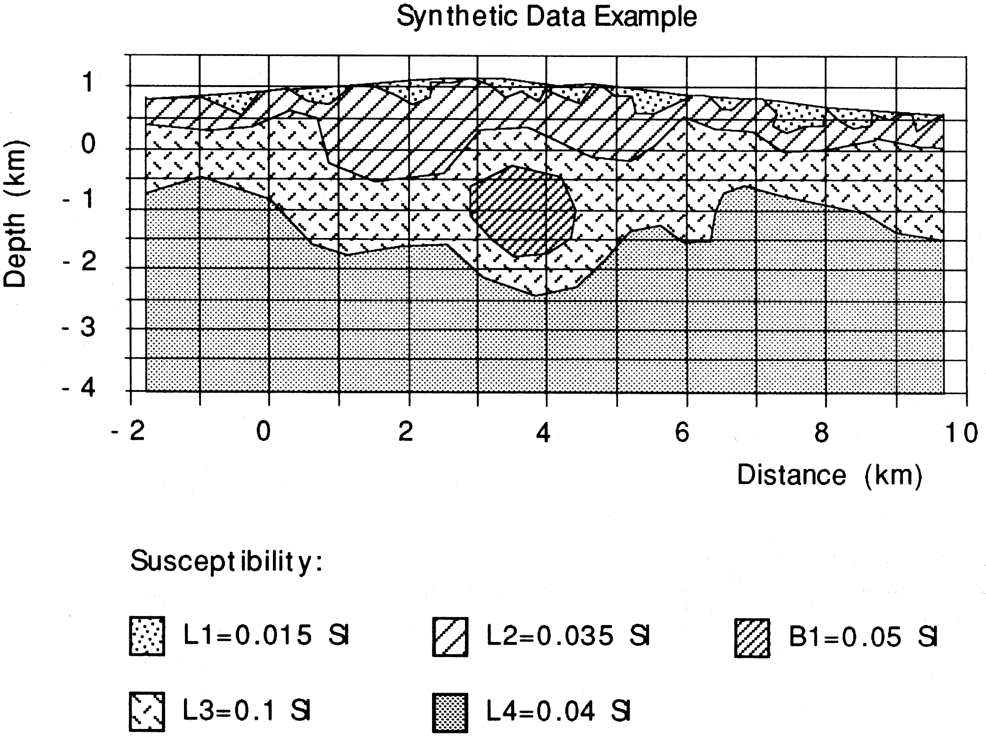

Fig. 2. Cross-section through the geological model from which the synthetic magnetic field was computed.

(Shuey and Pasquale, 1973; Fedi, 1990) so that we can consider, if only partially, the finite dimension of the sources in an orthogonal direction to that of the profile. Then, a Wiener filter is applied to the computed magnetic response (fig. 3a) of the geological model. The target of filtering is that of separating the magnetic signal (desired output of the Wiener filter; fig. 3b) generated from the susceptibility contrast occurring between layers L2 and L3 and the body B1, from the noise field (fig. 3c) produced by geologic sources which are both shallower and deeper than the feature of interest.

Figure 4c shows the Wiener filter transfer function designed on the basis of eq. (2.5) from the total power and signal power spectra (fig. 4a,b). The Wiener filter's transfer function is characterised by a filter response that is never equal to zero, where the noise is dominant, or unity, where the noise is negligible, albeit that it usually tends toward one or both of these extremes (Press *et al.*, 1987). The intermediate dependence given by eq. (2.5) is the optimum way of varying between these two extremes.

Fig. 5a shows the magnetic field after Wiener filtering compared with the desired filter output. The comparison shows that the performance of the Wiener filter is satisfactory along the entire profile. Note that the short wavelength components arising from the shallower noise sources were smoothed in the filtered profile, and likewise the intermediate scale noise was almost completely removed.

Before applying the frequency domain Wiener filter it was necessary to taper the data. Indeed, the original profile was extrapolated to outside the investigated area, in order to reduce the edge effects, using recursive filters derived from Burg's Maximum Entropy Spectral Analysis algorithm (MESA; Burg, 1975). The Wiener filter is shown in fig. 5b, in application to the case in which the original data were not extrapolated. Comparison with the desired filter output shows that the performance of the Wiener filter worsens considerably toward the edges.

Another step in the construction of the Wiener filter is the smoothing of the spectra of the observed field and modeled signal. This

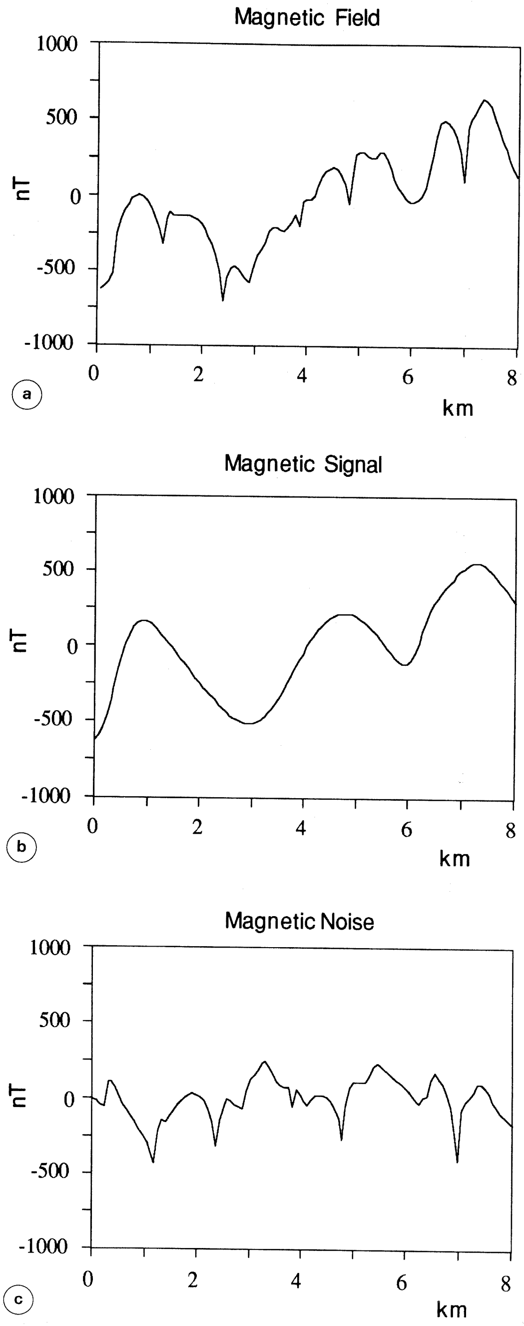

Fig. 3a-c. a) Synthetic magnetic field; b) magnetic signal; c) magnetic noise.

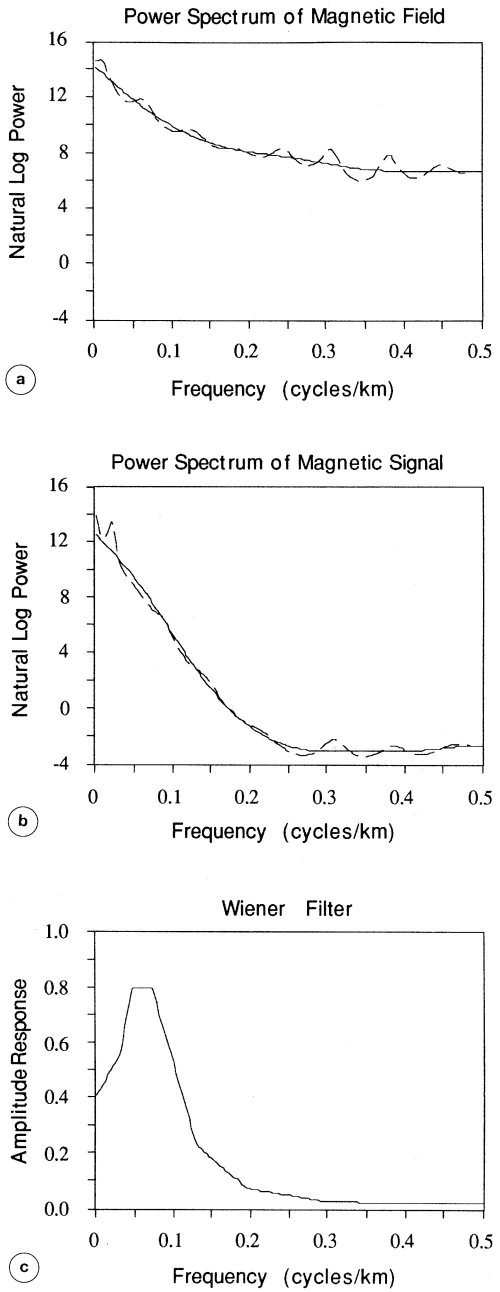

Fig. 4a-c. a) Log-power spectra for synthetic magnetic field and b) magnetic signal. Continuous curves in (a) and (b) define smoothed spectra from which a zero-phase Wiener filter (c) was constructed according to eq. (2.5).

operation was performed by first removing the linear trend and then applying a Fast Fourier Transform to low-pass filter the data (Press *et al.*, 1987). The linear trend is reinserted at the end. Fig. 5c shows the Wiener filter in the case in which the spectra were not smoothed. The comparison with the desired filter output shows that the behaviour of the Wiener filter worsens significantly and is more complex.

4. Application to Mt. Etna data

The Mt. Etna volcano, situated on the eastern margin of Sicily, is characterised by an alkaline and tholeiitic volcanism (Barberi *et al.*, 1973). The volcano built up on an intricate and heterogeneous substratum which is made up of Quaternary marine deposits and by nappes of the Apenninic-Maghrebian chain (Lentini, 1982). Two major structural lineaments at a regional scale, intersecting beneath Mt. Etna, affect the basement and the volcanic edifice. The first trends SSE-NNW and parallels the passive margin, normal-fault system known as the Malta escarpment (*e.g.*, Chester *et al.*, 1985; Cristofolini *et al.*, 1985). The second, with approximate NE-SW strike, is characterised by left-lateral transcurrence where it borders the volcano (*e.g.*, Ghisetti and Vezzani, 1982). Because of these complex conditions, the structural framework of the basement of the Mt. Etna volcanic system is not yet well defined, and the location and the geometry of the shallow plumbing system still calls for explanation (Cosentino *et al.*, 1982; Ferrucci *et al.*, 1993).

The presence of basic lava with high susceptibility values (Tanguy, 1980), superimposed on a non-magnetic basement made up prevalently of clays, relatively superficial and strongly dislocated (Cristofolini *et al.*, 1979), prompted us to use the magnetic method to execute a structural investigation centred on basement morphology. Taking advantage of the near-quiescent state of Mt. Etna and of the consequent absence of magnetic noise sources linked to activity of large magma masses at shallow depth, in the course of the summer of 1993 a ground survey line of the total intensity

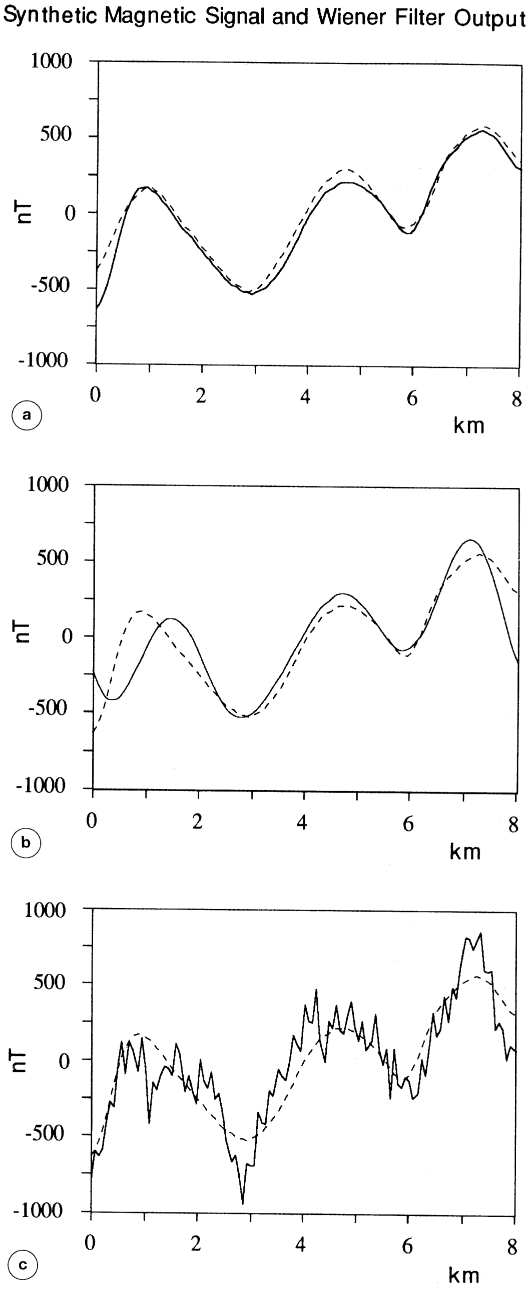

Fig. 5a-c. a) Synthetic magnetic field after Wiener filtering (continuous curve) compared with the desired filter output (dashed curve); b) Wiener filter in the case in which the original data were not extrapolated; c) in the case in which the spectra were not smoothed.

of the magnetic field across Etna was carried out (fig. 6). The profile is *ca.* 40 km long and has approximate strike west-east. The highest altitude, *ca.* 1900 m, is reached at Rifugio Sapienza. The easternmost end of this profile is on the shoreline of the Ionian sea, *ca.* 15 km east of Zafferana Etnea.

The data were gathered using a nuclear precision magnetometer Geometrics G-856 (typical resolution: 0.1 nT). The measurement points are spaced by 20 m only, which accounts for 2302 data. The data were reduced with respect to the normal field using the reference magnetic field IGRF 1990.0 (IAGA, 1991). We did not correct the field by the time variations of the Earth's Magnetic Field (EMF), since variations of the order of a few tens of nanoTeslas are negligible with respect to the observed spatial magnetic heterogeneity (thousands nT).

In a volcanic area with basic lava, magnetizations are very high (from 0.1 to 10 A/m) and the spatial gradients of the field can reach several hundred nanoTeslas per meter at ground level. It is well known that, when the field is too heterogeneous, the measurements are more contaminated by noise, the shallower the magnetised structures. Observed data, shown in fig. 7a, emphasise the presence of high-frequency noise generated by the magnetic heterogeneity typical of surface lavas. However, on Mt. Etna the contact between the clay section that makes up the basement and the thick sequence of volcanic rocks that covers it corresponds to the most significant susceptibility contrast. In particular, it is possible to identify two long wavelength anomalies which distinguish the profile (fig. 7a). The strongest (*ca.* 2500 nT) is located in the central part of the profile (Rifugio Sapienza), the second some 10 km to the east of it. The anomalies correspond with the fault system located on the western-southwestern flank, and near the Ionian shoreline.

A Wiener filter was designed to isolate the magnetic effect resulting from the large susceptibility contrast across the contact lava coverage and the sedimentary basement (the signal) from the observed magnetic anomaly. The power spectrum of the signal was estimated by modeling (via the technique of Shuey and

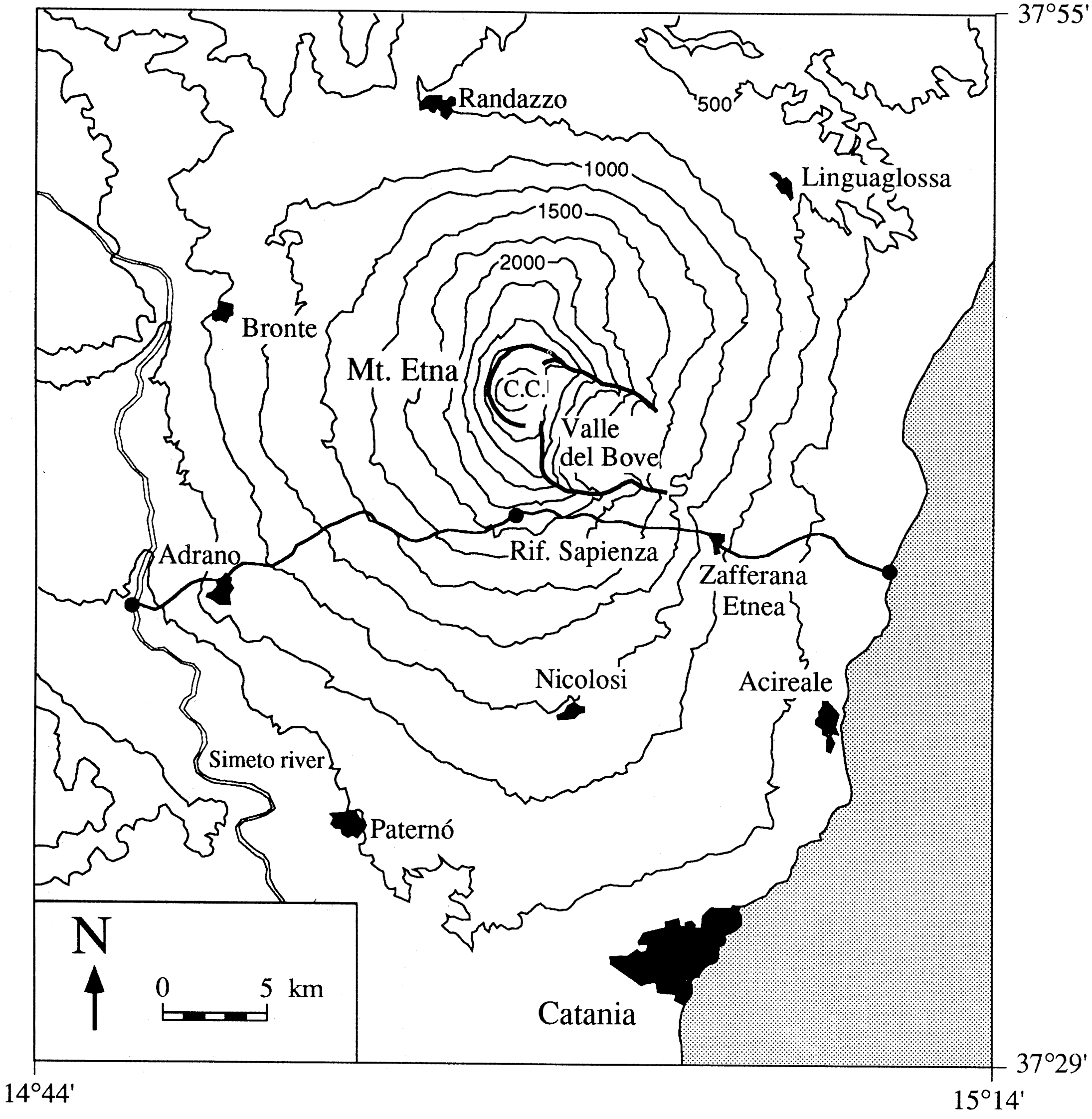

Fig. 6. Location map for Mt. Etna study area.

Pasquale, 1973) the magnetic effect and calculating the power spectrum of the computed response.

The sedimentary structure was modeled accounting for all the available geologic and geophysical information, with reference to the basement top values obtained from the data of drillings carried for water supplying the Etna area (Aureli, 1973; Ferrara, 1975). These data allow us to state that the thickness of the lava exceeds 1000 m in the central sector, while in the peripheral belt it never exceeds 200 m. In the model (fig. 7c) a susceptibility contrast of 0.2 S.I. (Tanguy, 1980) between the volcanic products and the underlying clay layer was adopted. This simple model considered a dis-

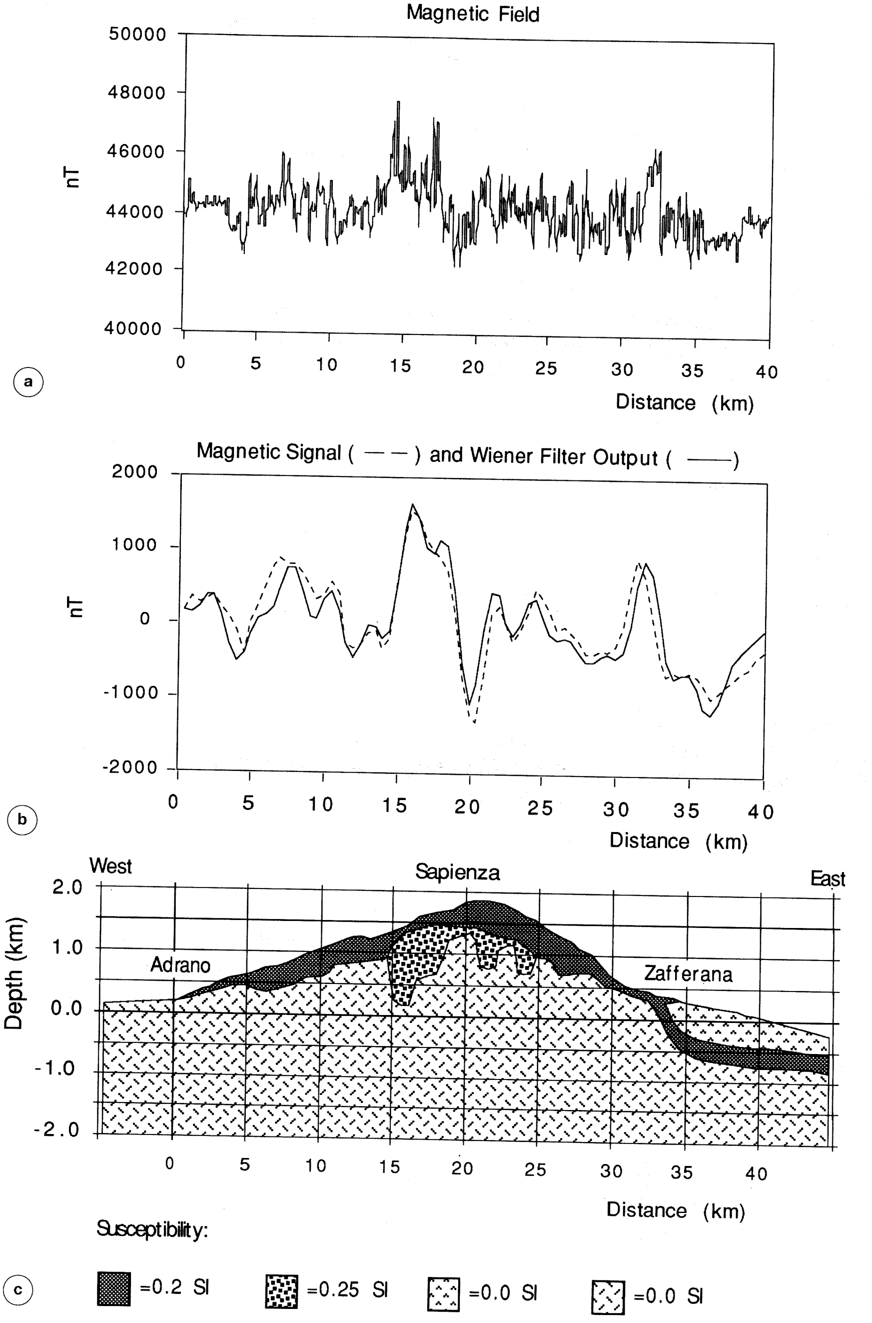

Fig. 7a-c. Mt. Etna profile: a) observed field; b) Wiener-filtered output (continuous curve) compared to the modelled signal (dashed curve); c) cross-section through the geological model from which the modelled signal was computed.

tinction between intrusive rocks and lavas. We stated the susceptibility is greater in intrusive rocks of Etna than in the lavas. Although no measurements of susceptibility exist to support this hypothesis, the constant presence of high magnetic values along the rift zones of Etna provides strong evidence that intrusions can be highly magnetic.

The Wiener filter transfer function (fig. 8c), calculated as the spectral ratio between the modeled signal (fig. 8b) and the real data (fig. 8a), was applied to the observed anomaly. The Wiener-filtered output is compared to the expected anomaly in fig. 7b. The comparison with the desired signal shows the suitability of the assumptions as well as the number and locations of constraints taken into account in the hypothesised schematic model.

It is possible to obtain an important control of the quality of the filtering by removing the Wiener-filtered output from the observed magnetic field. In this way the noise component as shown in fig. 9a is evidenced. The noise does not present specific anomalies, although its amplitude along the whole profile shows some kind of spindle trend. In particular, greater amplitudes are observed in the central part, corresponding to a more disturbed field when the crater zone was grazed, in comparison to the tips of the profile. The absence of meaningful anomalies is pointed up even more clearly by the power spectrum of the noise (fig. 9b) which has the characteristics of a white spectrum (an amplitude spectrum nearly constant at all frequencies, see fig. 1). It is worth noting that the presence of meaningful sources in a power spectrum is easily recognised by marked changes that take place in the spectral decay rate (Spector and Grant, 1970). Therefore, the application of the Wiener filter resolved all the meaningful components of the observed magnetic field. The filter was successful and the Mt. Etna model assumptions employed to design the Wiener filter were satisfactory. The analysis of the noise confirms that if there is significant overlap in signal and noise spectra an efficient signal-noise separation is possible when the *a priori* available information on the nature of the modeled signal can be incorporated extensively in the definition of the filter transfer function.

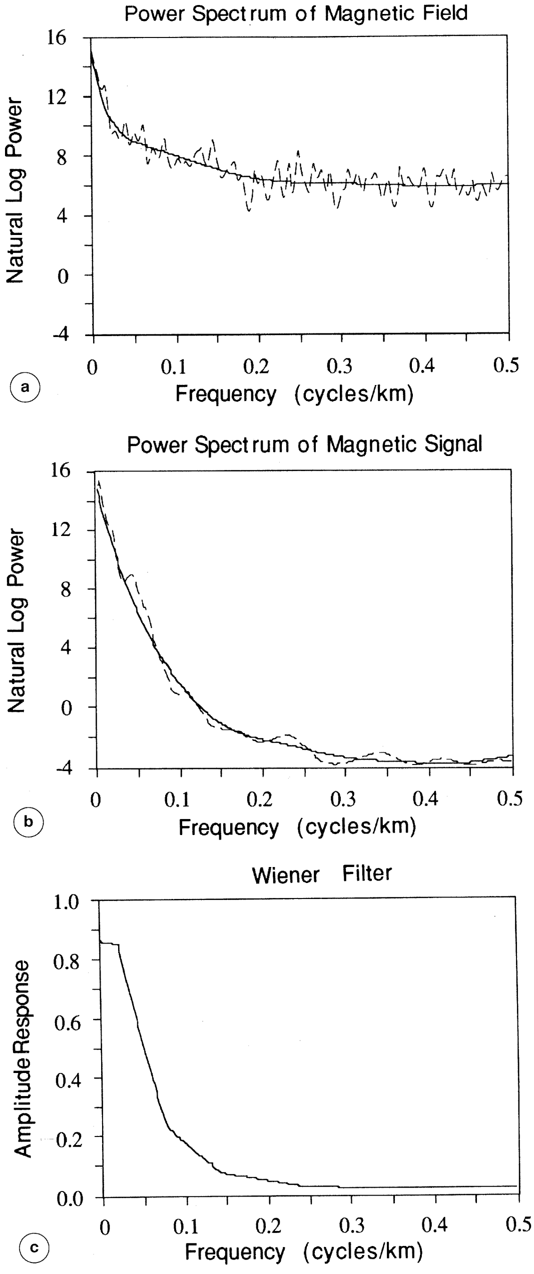

Fig. 8a-c. a) Log-power spectra for Mt. Etna observed magnetic field; b) modeled magnetic signal. Continuous curves in (a) and (b) define smoothed spectra from which a zero-phase Wiener filter (c) was constructed according to eq. (2.5).

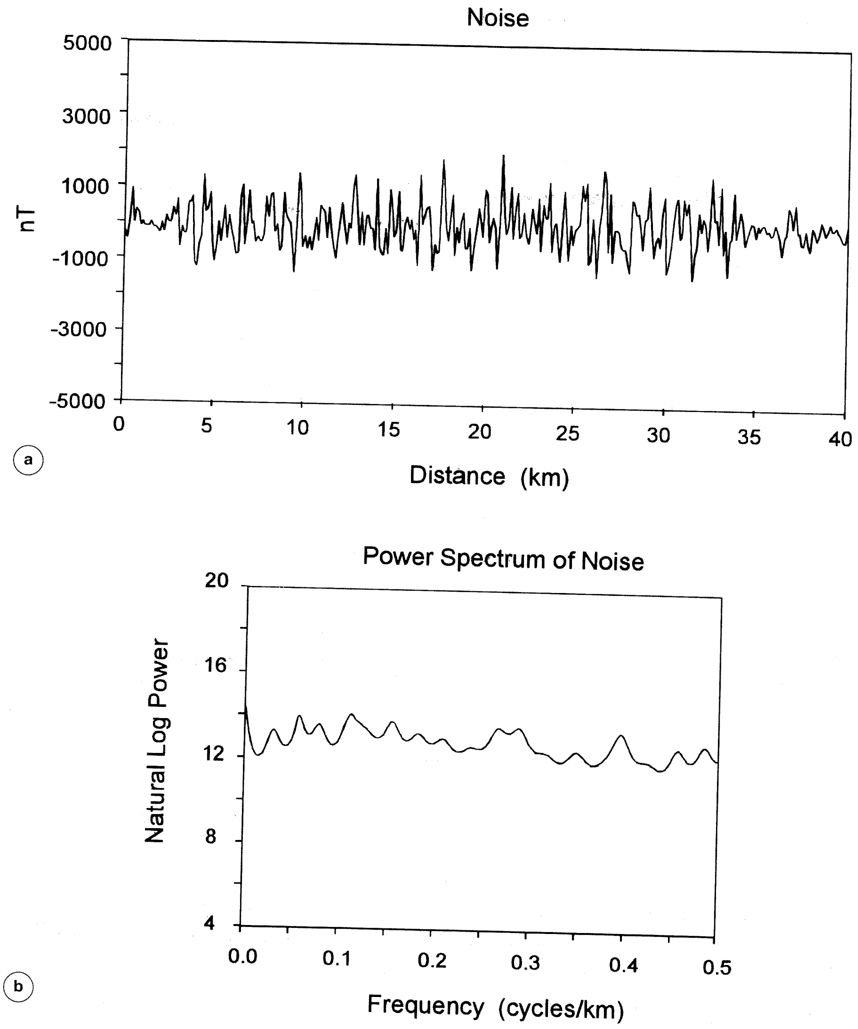

Fig. 9a,b. Mt. Etna profile: a) noise component obtained by removing the Wiener-filtered output from the observed magnetic field; b) log-power spectra of noise.

The magnetic features contained in this profile are crucial for the spatial definition of the shallow plumbing system on Mt. Etna. The major magnetic structures across the southern branch of the plumbing system, which hosted the dykes feeding both the 1989 and the 1991-93 eruptions, were outlined. The signature of the 0.25 S. I. body was limited to a narrow strip (*ca.* 10 km) running *ca.* S-N, which contains most of the eruptive fractures and adventive cones located on the volcanic edifice. Such magnetic character is lacking west of Rifugio Sapienza and definitely vanishes some 7-8 km east of it, thus defining the zone of repeated intrusive activity witnessed by exposed dykes in the southern Valle del Bove and by the spatial trends of (among others) the fracture system opened in 1989 and active in 1991-1993. Further east (from Zafferana to the coast), the observed magnetic field is fitted by a model accounting for the presence of a basement sunk by as much as -400 m, covered by loose, null susceptibility materials (the «Chiancone» fan). Even though the present results are influenced by the *a priori* knowledge based upon the surface evidence and the sparse geophysical data available today, the reliability of this model is supported by the large amplitude of the anomaly of fig. 7b (dashed line) located between km 15-22 of the profile, and corresponding uphill to the plexus of dykes as above. As for the second largest peak near km 33 (figs. 7a, b), the shape of the anomaly is consistent with the typical signature of steep fault scarps, also consistent with the fault scarp of the *ca.* NNW-SSE trending normal fault located at the immediate west of Zafferana.

5. Conclusions

The Wiener filter theory was used for magnetic anomaly separation on the Mt. Etna volcano where the field is highly contaminated by noise. The technique is similar to the one described by Pawlowski and Hansen (1990), but applied to profile data. The examples presented, both artificial and real, confirm that a successful separation of the useful signal from the interference is obtained when the *a priori* available information on the nature of the modeled signal is fully used. Since *a priori* information is incorporated completely in the definition of the Wiener filter's transfer function, this technique is very appealing when geologic or geophysical information is available and reliable.

In the case of Mt. Etna data, the power spectrum of the noise component, obtained by removing the Wiener-filtered output from the observed magnetic field, approximately showed the characteristics of a white spectrum. This points out that filtering was successful, all the meaningful components of the observed magnetic field were resolved, and the Mt. Etna model assumptions were acceptable. The Wiener filtering was calibrated to separate the signal (*i.e.*, the real magnetic anomaly) from the magnetic effect due to the contact between bodies with very different susceptibility properties (lavas against basement). The bedrock was modelled taking into account the whole of its known (or inferred) geophysical and geometrical properties. A susceptibility contrast of 0.2 S. I. between the volcanic products and the underlying clay layer was adopted. It is worth noting that a significant susceptibility contrast between intrusive rocks and lavas is stated too. The 2½D susceptibility model agrees, both in geometry and in the inferred properties of the subsurface layers, with the 2D density and resistivity models obtained by previous gravity and geo-electrical surveys (Loddo *et al.*, 1989). The survey line conducted across the principal fault system of Mt. Etna emphasises a dramatic increase in susceptibility when crossing a narrow strip from west-to-east corresponding to its surface trace (which trends *ca.* NNW-SSE). Such evidence for strong lateral susceptibility variations east-west allows the sharp definition of the spatial limits of subsurface frozen magmas and supports other seismic and gravity evidence recently published (Rymer *et al.*, 1993; Ferrucci and Patanè, 1993).

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