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Multifractal IDW interpolation and fractal filtering method in environmental studies: an application on regional stream sediments of (Italy), Campania region

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Abstract

In recent years environmental geochemical mapping has assumed an increasing relevance and separation of background values to evaluate pollution is, probably, even more critical than the separation between background and anomalies in mineral prospecting studies. The recognition of background values assumes particular relevance as a function of national environmental legislation, which fixes intervention limits for some elements, such as the harmful ones (e.g. As, Cd, Hg, Pb). In this paper a recently developed multifractal IDW interpolation method and a fractal filtering technique are applied to separate natural background and anthropogenic values for the compilation of environmental geochemical mapping from stream sediment samples of Campania region (Italy), where no mineralization occurs. To discuss the application of these recently developed techniques the elements Pb and U were selected because they show two completely different situations, the high Pb values being mostly of anthropogenic origin and high U values being mostly of geogenic origin. The new fractal filtering method works well in both extreme situations.

1. Introduction

Regional sampling of stream sediments has been widely used in geochemical prospecting aimed at mineral exploration. In recent years the use of geographic information systems (GIS) has greatly enhanced the capability of drawing geochemical maps containing large amounts of data critical for mineral exploration. A basic task of geochemical exploration, and hence of the derived maps, is to try to classify geochemical samples into groups reflecting different geochemical processes, separating anomalies associated with mineralization from background values which result from regional geological processes (Cheng et al., 1996). In this process it is also critical to separate anomalies related to natural processes (mineralization) from the ones related to contamination. In recent years environmental problems have become increasingly important, and environmental geochemical mapping is assuming an increasing relevance (Darnley et al., 1995; Plant et al., 2001), where the separation of natural background from anthropogenic values is, probably, even more critical than the separation between background and natural anomaly (mineralization) in mineral prospecting studies.

In this paper, maps interpolated by a multifractal IDW (Inverse Distance Weighted) method and a fractal filtering technique, studied by Cheng et al. (1999, 2000) and Cheng (2001), have been used for separating natural geogenic background from anthropogenic values with an application to stream sediment environmental samples of Campania region (Italy), where no mineralization occurs. Correct identification of background values can be useful to discriminate the natural background values, by taking into account the basic geological

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characteristics of the region. Background values assume particular relevance as a function of environmental legislation, which fixes intervention limits for elements, such as the harmful ones (e.g. As, Pb, Cd and Hg). Under Italian legislation, for example, if the intervention limits are exceeded, remediation of the contaminated land becomes mandatory, whereas concentrations above the fixed intervention limits are allowed only in situations where the investigated area is characterized by natural background values higher than the intervention limits. For this reason, it is important to separate efficiently background from anthropogenic anomalies at the regional level.

For geochemical anomaly separation various statistical methods have been used (Cheng et al., 1996) including probability graphs, univariate and multivariate analysis (Sinclair, 1974, 1976, 1991; Govett et al., 1975; Miesch, 1981; Stanley, 1988; Garrett, 1989; Stanley and Sinclair, 1989).

The method used for environmental geochemical mapping of the Campania region is a fractal filtering technique, a recently developed technique, as described in detail by Xu and Cheng (2001).

2. Geological outlines and stream sediments geochemistry of campania region

The Campania region (Fig. 1) covers about 13,600 km^2; it is the second most populous region in Italy (about six million inhabitants), with more than 50% being concentrated in the Naples metropolitan area. Morphologically Campania is made up, in its eastern sector, by the Apennine mountains oriented roughly NE–SW and on the west, by two coastal plains: Campania and Sele plains, occupied respectively by the Volturno and Sele rivers drainage basins. The Apennine chain consists of a pile of nappes formed during the Miocene, overthrusting towards N–NE, and it is structured in several blocks in contact with one another along tectonic discontinuities. Lithologies consist mostly of sedimentary and volcanic rocks, spanning from the Triassic to the recent age (Fig. 1).

The sedimentary rocks include: stratigraphic Mesozoic units, made up of limestones, dolostones, siliceous schists and terrigenous sediments (clays, siltstones, sandstones, conglomerates), which characterize mostly the external Apennine domains; the neogenic units,

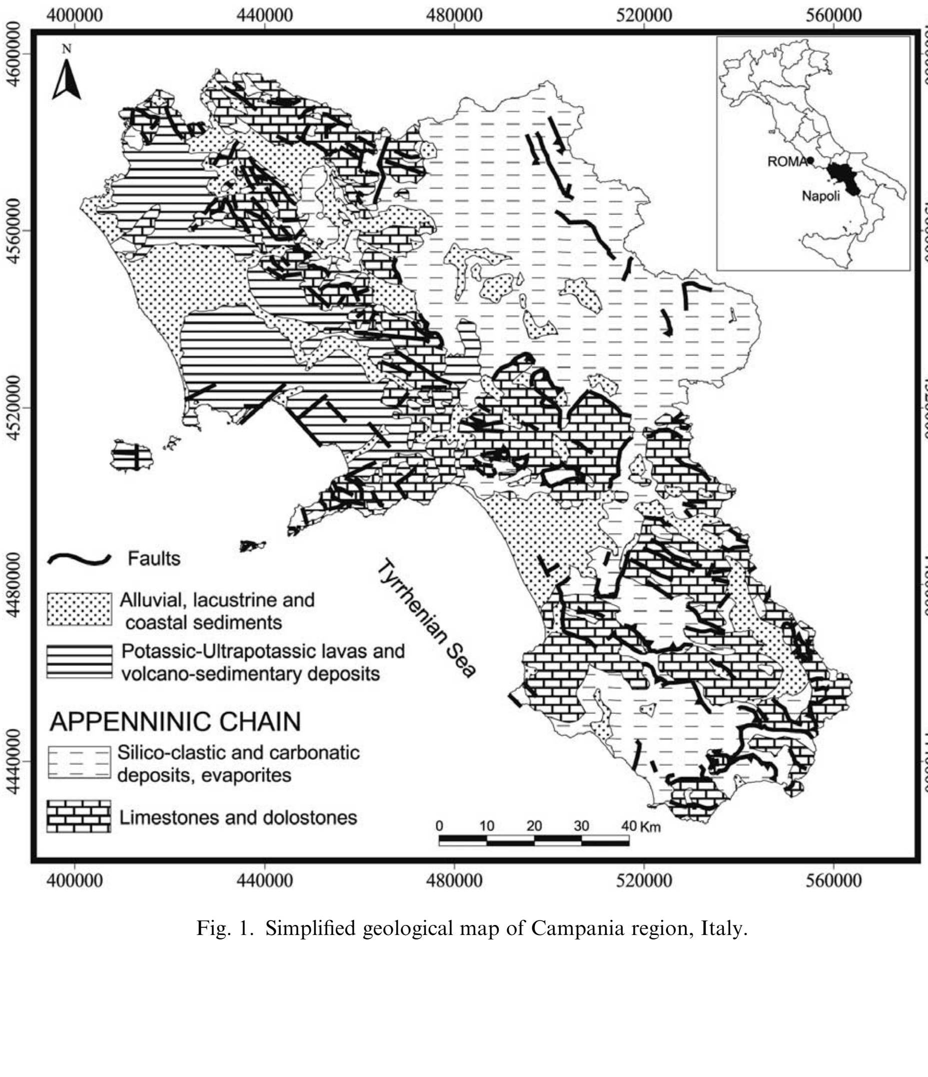

Fig. 1. Simplified geological map of Campania region, Italy.

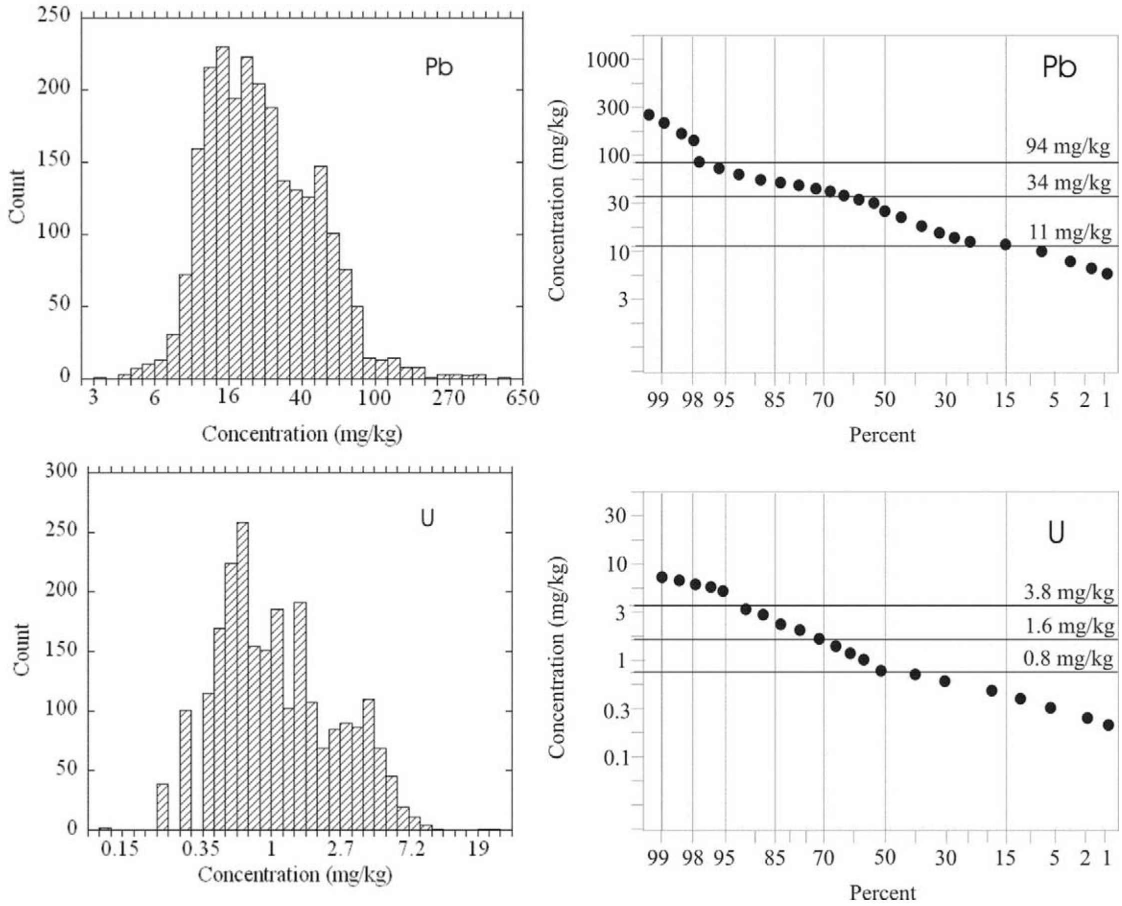

Fig. 2. Pb and U log-transformed values histograms and cumulative frequency curves.

made up mostly of silico-clastic, carbonatic and evaporitic sediments; Quaternary sediments, which occur mostly in the Campania plains and are made up of lacustrine, alluvial and evaporitic sediments.

The volcanic rocks (dated from about 600 ka to present) are represented by potassic/ultrapotassic rocks (lavas and pyroclastics) of different volcanoes: Roccamonfina, in the northwestern sector of the region; Mt. Somma-Vesuvius, Campi Flegrei and Ischia, along the western border of the region; and a fissural activity (Campanian Ignimbrites) related to fractures activated in the Campanian plain from > 315 to 18 ka. The ignimbrites cover the whole Campanian plain, and also occur on the Apennine mountains (De Vivo et al., 2001).

Industrial activities are developed mostly around the metropolitan areas of Naples and of the other main cities (Avellino, Benevento, Caserta and Salerno) of the region, whereas in the other portions of the territory agricultural activities prevail. No economic mineral deposits occur in Campania; only a few minor bauxite mineral occurrence—of no economic relevance—are situated in the Mesozoic rocks of Mt. Matese in the Apennine mountains.

Stream sediment samples numbering 2389 were collected in the region (Figs. 3 and 4) with a density of one sample per 5 km^2, for the purpose of compiling an environmental geochemical map. In the metropolitan area of Naples, because of the lack of drainage, top soils have been collected; the soil data have been studied separately from stream sediment data (De Vivo et al., 2003a). In addition to elemental analysis, at each sampled site pH and conductivity were measured; partial and total radioactivity using a portable Scintrex GRS-500 were also measured. The project has been undertaken as part of a more general one, aimed, in the near future, at the compilation of an environmental geochemical map covering the whole of Italy, with the same sample density as used for the Campania region.

For the compilation of such environmental maps it is critical to separate background from anomaly values, because, as explained previously, the recognition of background levels is critical for establishing the intervention limits of inorganic elements.

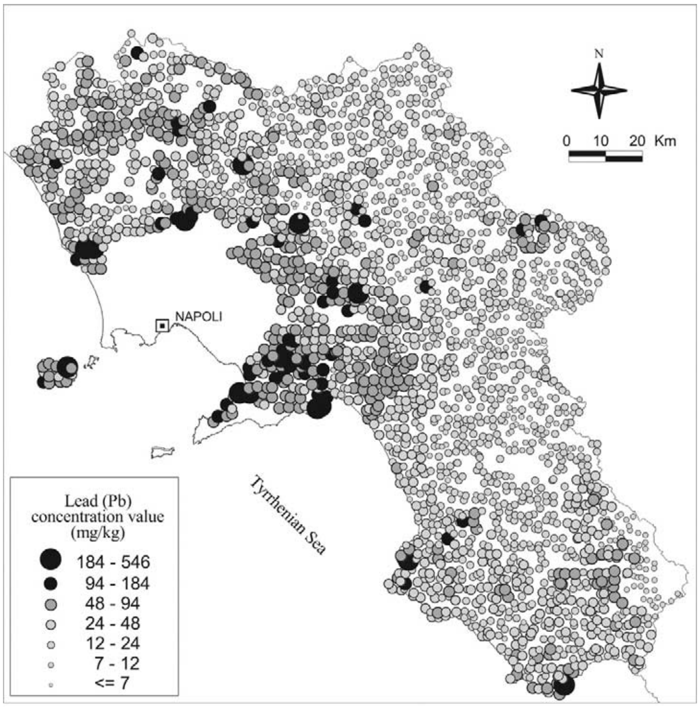

Fig. 3. Stream sediments (2389 samples) dot map showing Pb distribution. Class intervals are antilogarithms of $\bar{x} \pm ns$ ($n = 1, 2, 3$).

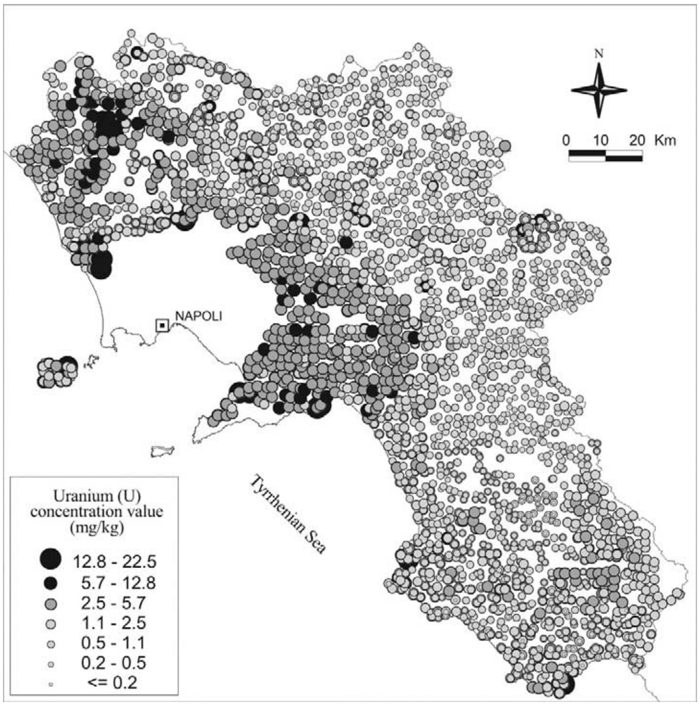

Fig. 4. Stream sediments (2389 samples) dot map showing U distribution. Class intervals are antilogarithms of $\bar{x} \pm ns$ ($n = 1, 2, 3$).

All the stream sediments and the soil samples were sieved, and the <150 μm fraction was retained for ICP-MS analysis for 37 elements (Ag, Al, As, Au, B, Ba, Bi, Ca, Cd, Co, Cr, Cu, Fe, Ga, Hg, K, La, Mg, Mn, Mo, Na, Ni, P, Pb, S, Sb, Sc, Se, Sr, Te, Th, Ti, Tl, U, V, W and Zn). Specifically, a 15 g split of pulp was digested in 45 ml of Aqua Regia (equal quantities of HCl, HNO_3 and distilled water) at 90 °C for 1 h. The solution was taken to a final volume of 300 ml with 5% HCl. Aliquots of sample solution were aspirated into a Jarrel Ash Atomcomp 975 ICP-Emission Spectrometer and a Perkin Elmer Elan 6000 ICP-Mass Spectrometer. The analyses were carried out at ACME Analytical Laboratories (Vancouver, Canada). The precision (calculated as relative percent difference) is 4.7 and 6.3% for Pb and U respectively, whereas the accuracy is 2.7% for Pb and 3.8% for U (Table 1). Precision is calculated on three in-house replicates and two blind duplicates submitted by the authors. Accuracy is calculated on ACME's in-house reference material (DS2) (HMTRI, 1997).

The geochemical data have been analyzed by means of a GIS (Cheng, 2001; Cheng et al., 2001; GeoDAS, 2001) to compile an environmental geochemical atlas of the Campania region (De Vivo et al., 2003b). In this paper the authors report only the results obtained by the multifractal IDW interpolation and by the spatial and spectral analysis (S–A) method to separate background and anomaly values for Pb and U (Cheng et al., 1996, 2000), as an example of the application of these methods in environmental studies. To discuss the application of concentration–area (C–A) and spectral analysis (S–A) methods for the Campania data two elements were selected, namely Pb and U, because they show two completely different situations: the spatial distribution of high values of Pb is mostly of anthropogenic origin, whereas the distribution of high U values is mostly geogenic. It will be shown that the new fractal filtering method works well in both extreme situations.

Table 1
Pb and U statistical parameters of 2389 stream sediment samples from Campania Region

mg/kg	Pb	U
Mean	31.7	1.6
Median	22.4	0.9
Geometric mean	24.5	1.1
Mode	Multiple	0.7
Minimum	3.3	0.1
Maximum	546	22.5
25th percentile	14.5	0.6
75th percentile	39.5	1.9
Standard deviation	32	1.6
Variance	1014	2.4
Skewness	5.9	3.3
Kurtosis	59	26
Detection limit	0.01	0.1
Accuracy (%)	2.7	3.8
Precision (%RPD)	4.7	6.3

Precision is calculated as %RPD (Relative Percent Difference).

3. Statistical analysis of Pb and U concentration values

Univariate statistical analysis has been performed on the 2389 Campania region stream sediment data. Table 1 shows Pb and U statistical parameters. The frequency distributions of Pb and U concentrations were evaluated using traditional methods such as histograms and probability plots. Fig. 2 shows the Pb and U histograms and the plot of % cumulative frequency versus concentrations (log-transformed values) on probability paper. For both Pb and U the data show a tendency towards a lognormal distribution; the histograms do not help to characterise the population distribution, whereas this distribution becomes quite clear using cumulative frequency plots. Cumulative frequency curves for both Pb and U show the existence of three data populations: one with excess of low values (<11 and <0.8 mg/kg for Pb and U respectively), one with anomalous values (>94 and >3.8 mg/kg for Pb and U respectively), and a mixed data population falling between 11 and 94 mg/kg for Pb and between 0.8 and 3.8 mg/kg for U. By means of this statistical frequency analysis the threshold values, for the separation of anomaly from background, could be fixed at an intermediate level of the mixed population for Pb and U respectively (at 34 mg/kg for Pb and 1.6 mg/kg for U). Using this method has some disadvantages. The selected single threshold may not work well at a regional scale (e.g. Campania), because the background values show significant variations due mostly to lithological variations. The value distributions are not sufficient to divide the data set into different populations, because they show an overlap, and give no idea of the spatial distribution and geometry of the geochemical anomalies. Statistical frequency is currently the most popular technique for processing local and regional geochemical data, but the new fractal filtering technique (Cheng et al., 1999) seems to offer a promising method that is more efficient in separating anomalies from the background. Figs. 3 and 4 show dot maps for Pb and U respectively; class intervals are antilogarithms of the mean and ±1, 2, 3 standard deviations.

4. Pb and U geochemical maps generated by multifractal IDW interpolation method

The stream sediment geochemical maps of Campania have been interpolated by multifractal IDW using the GeoDas 2001 program (Cheng et al., 1999, 2000; Cheng, 2001).

Fig. 5A shows a Pb geochemical map of Campania performed by ArcView GIS, generated by kriging with an exponential semivariogram model. Search distance is

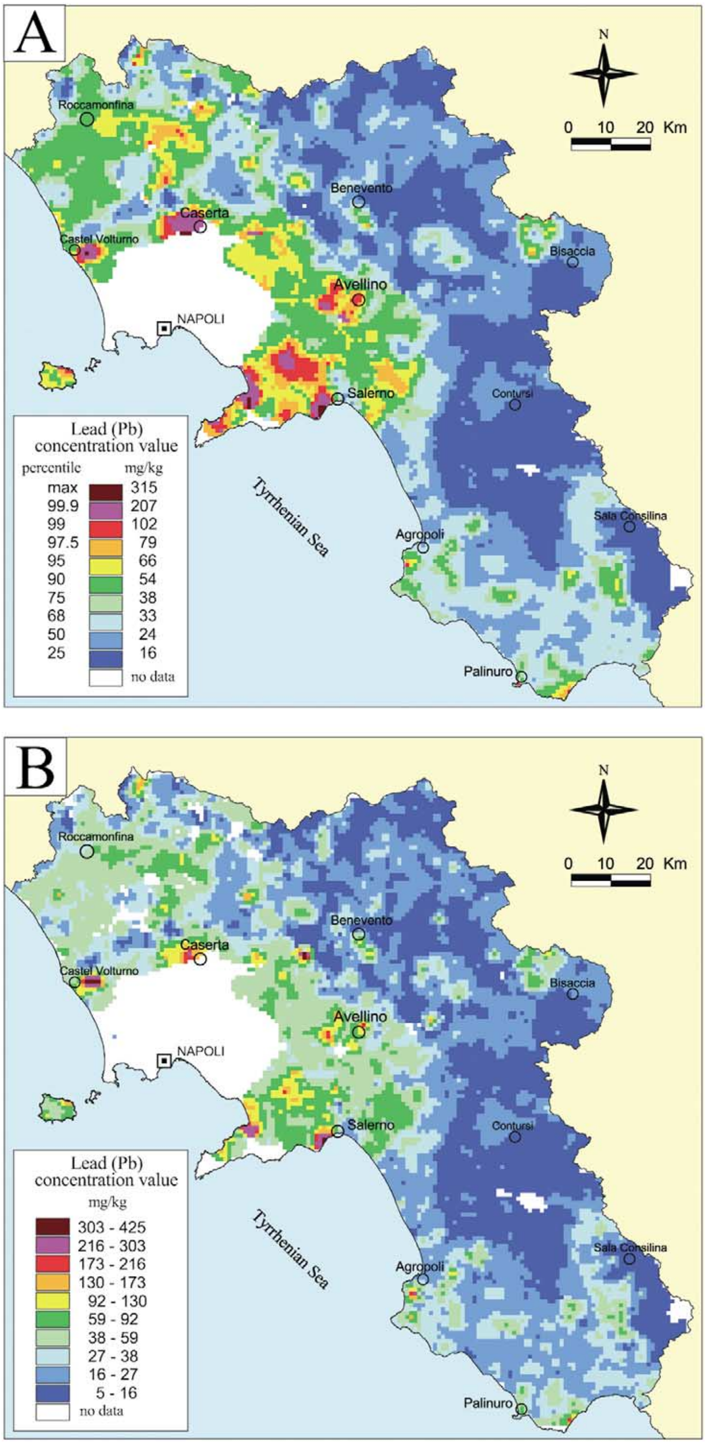

Fig. 5. (A) Pb stream sediments (2389 samples) geochemical map generated by kriging interpolation method. Search distance is 3.5 km and map resolution 1 km. Pixel values have been reclassified by percentile. Note that the maximum pixel Pb concentration value is 315 mg/kg. (B) Pb geochemical map compiled using multifractal-IDW interpolation method (GeoDas). Search distance is 3.5 km and map resolution 1 km. Pixel values have been reclassified by fractal concentration–area (C–A) plot based on the frequency distribution of pixel values (Fig. 7). In this case, for comparison, the number of the classes are the same as in (A).

3.5 km, maximum number of neighborhood points is equal to 12, and map resolution is 1 km. Fig. 5B shows the same geochemical map generated by multifractal IDW, with search distance and map resolution similar to those used for kriging. A conventional weighted average technique such as kriging and ordinary IDW smooth the local variability of the geochemical data, whereas multifractal IDW creates a geochemical map in which information about the local variability is retained. If the fractal IDW map of Pb (Fig. 5B) is compared with the Pb dot map (Fig. 3) it can be seen that they are similar for large patterns; this is important in enhancing geochemical anomalies for anomaly-background separation.

Multifractal interpolation is a new method that preserves high frequency information, which is lost in any conventional moving average methods such as kriging and ordinary IDW. The method (Cheng, 1999; Cheng et al., 1999) takes into account both spatial association and local singularity. Singularity is an index representing the scaling dependency from a multifractal point of view, which characterizes how the statistical behavior of a spatial variable changes as the measuring scale changes. Spatial association represents a type of statistical dependency of values at separate locations; his indexes (covariance, autocorrelation and semivariogram) have been used to characterize the local structure of surfaces and, in kriging, for data interpolation.

Spatial association and scaling are two different aspects of local structures and surfaces. Both should be taken into account in data interpolation and surface mapping of geochemical variables. Ordinary moving average methods (including kriging) can be considered a special case of the multifractal data interpolation method (for more details see Cheng, 1999 and Xu and Cheng, 2001). Fig. 6 shows the U geochemical map generated from the Campania region stream-sediment data by multifractal IDW, with search distance and map resolution similar to those utilized for the Pb map.

In order to assign a classification for the Pb geochemical maps generated by kriging (Fig. 5A), the pixel values have been reclassified by percentile; note that the maximum pixel value has a Pb concentration of 315 mg/kg, whereas in the dot map (Fig. 3) the maximum Pb concentration is 546 mg/kg, the difference being caused by spatial averaging.

The classification in the multifractal IDW interpolated maps of Figs. 5B and 6 was assigned using the fractal concentration–area (C–A) method. This methods allows images to be subdivided into components for symbolizing distinct image zones representing specific features on the ground. The pixels of the image were classified by means of the fractal C–A plot. Fig. 7 shows the C–A plots for Pb and U (Cheng et al., 1994); they plot the pixel concentration values against the cumulative

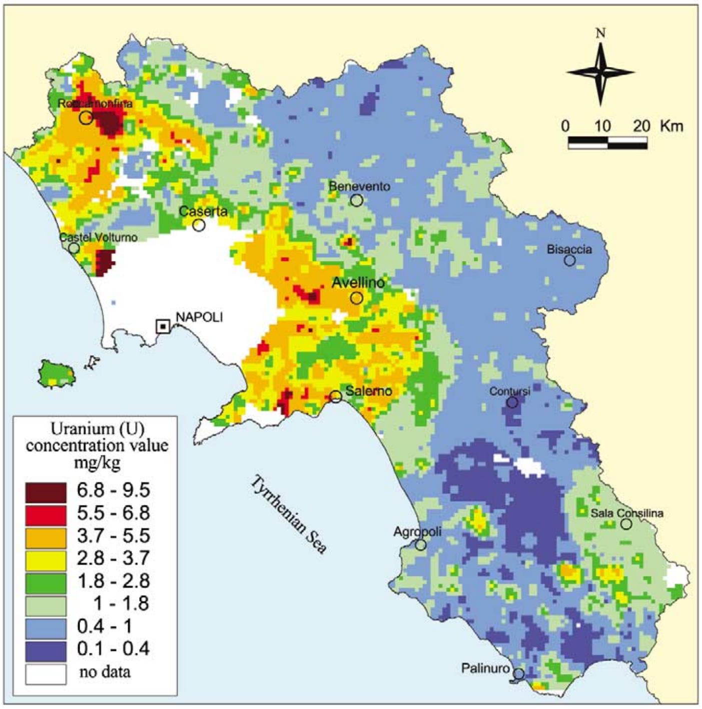

Fig. 6. U geochemical map compiled using multifractal-IDW interpolation method (GeoDas Sofware). Search distance is 3.5 km and map resolution 1 km. Pixel values have been reclassified by fractal concentration–area (C–A) plot (Fig. 7) based on the frequency distribution of pixel values (see text).

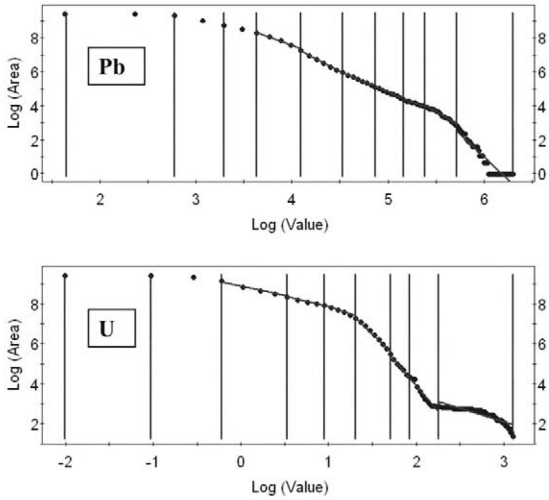

Fig. 7. Fractal concentration-area plots (C-A method) for Pb and U. The vertical axis represents cumulative pixel areas A(ρ), with element concentration values greater than ρ, and the horizontal axis the values itself (ρ). Breaks between straight-line segments and corresponding values of ρ have been used as cut-offs to reclassify pixel values in the multifractal-IDW interpolated map (Figs. 5B and 6).

area on log–log paper. These plots characterize not only the frequency distribution of pixel values, but also the spatial and geometrical properties of the features reflected by pixel zones in the image. Area concentration $[A(\rho)]$ with element concentrations greater than ρ show a power-law relation. If the geochemical surface is fractal, a single straight line relationship would occur, whereas for a multifractal surface, values will fall on several straight lines. The breaks between straight-line segments on this plot and the corresponding values of ρ, have been used as cut-offs to separate geochemical values into different components, representing different causal factors, such as lithological difference and geochemical processes (e.g. mineralizing events, surficial geochemical element concentrations, surficial weathering) (for more details see Cheng et al., 1994).

5. U and PB decomposed geochemical maps generated by fractal filtering technique (S–A) method

Maps showing background Pb and U values (Figs. 8 and 9) and maps showing Pb and U anomalies (Figs. 10 and 11) have also been obtained using the recently proposed S–A method.

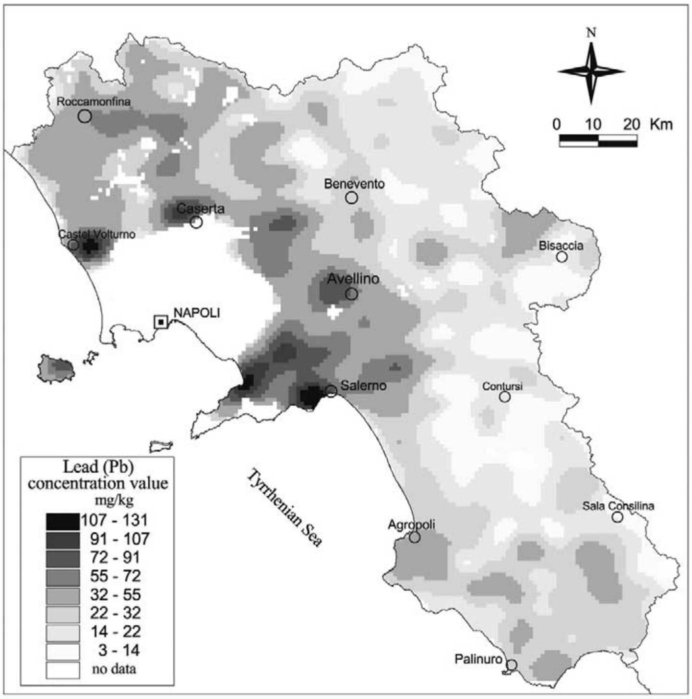

Fig. 8. Pb background map compiled using spatial and spectral analysis (S–A method). Pb values have been obtained by decomposition of the Pb geochemical map (Fig. 5A) into separate components using the fractal filters selected on the S–A plot (Fig. 12). Pb background map is generated only with signals with power spectrum (E) <15713 (selected cutoff in Fig. 12). Pixel values have been reclassified by fractal C–A plot (see text).

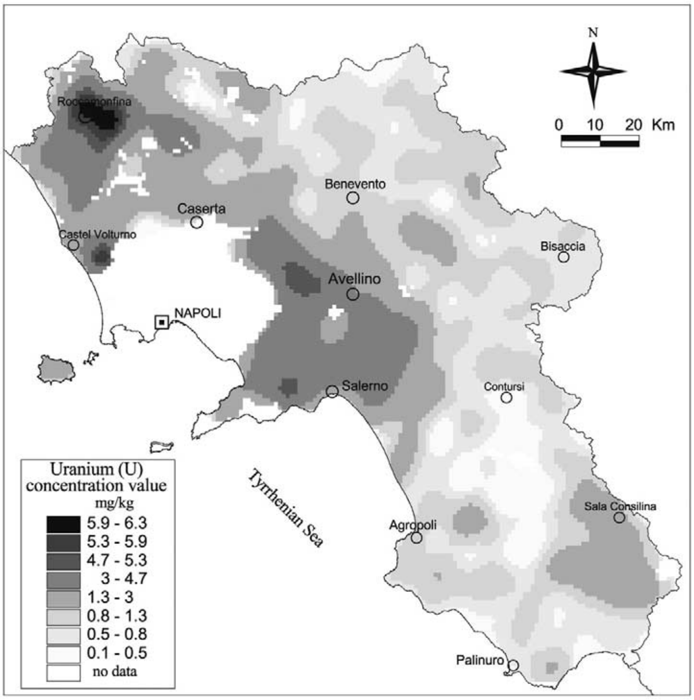

Fig. 9. U background map compiled using spatial and spectral analysis (S–A method). U values have been obtained by decomposition of the U geochemical map (Fig. 6) into separate components using the fractal filters selected on the S–A plot (Fig. 12). U background map is generated only with signals with power spectrum $(E) < 706$ (selected cutoff in Fig. 12). Pixel values have been reclassified by fractal C–A plot (see text).

The S–A method is a fractal filtering technique, based on a Fourier spectral analysis (Cheng et al., 1999; Cheng, 2001), used to separate anomalies from background values. It also uses both frequency and spatial information for geochemical map and image processing. The basic geological assumption for the S–A method is that a geochemical field or image generated by specific geological processes may be discriminated in terms of its fractal properties. The scale invariant property of most geological processes (e.g. erosion processes, mineralizing events, magnetic field of the earth's crust, distribution of earthquakes and volcanic eruption) often show ''self-similarity'' or ''self-affinity''. These properties can be measured in both the frequency and the spatial domain (Turcotte, 1997). In the spatial domain, scaling properties are related to the spatial geometry of patterns, the histogram distribution of values, and the changes in shape corresponding to changes in value, as used in the multifractal IDW interpolation method described earlier. In the frequency domain, such properties can be represented by means of power spectra (Lewis et al., 1999; Cheng et al., 2000). The fractal filter to be used is defined on the basis of the power-law properties of a power spectrum in the frequency domain (Fig. 12). The purpose of this is to divide the power spectrum into components characterized by similar scaling properties. It is an irregularly shaped filter, due to the anisotropic and usually complex intrinsic structure of the geochemical data. The filter can be used to identify anomalies from the background, and to extract other meaningful patterns from the original map (see Xu and Cheng, 2001 for more details). The S–A method is different from the well known SG (Spector and Grant, 1970) filtering model (used mostly in the field of regional geophysical data processing) since S–A involves the use of the following relationship:

$$A(\geqslant E)\alpha\ E^{-\beta}$$

where A represents the area enclosed by contours which have values greater than or equal to E and β is an exponent which may assume different values estimated by plotting values of A $(\geqslant E)$ vs log E for various ranges of E, based on which filters can be constructed (Cheng, 1999).

Fractal filters are defined in Fourier space by applying the fractal C–A model (Cheng et al. 1994) to the power spectrum of the processed geochemical field.

2-D Fourier transformation and inverse Fourier transformation provide the foundation for converting the geochemical field (map) between spatial and frequency

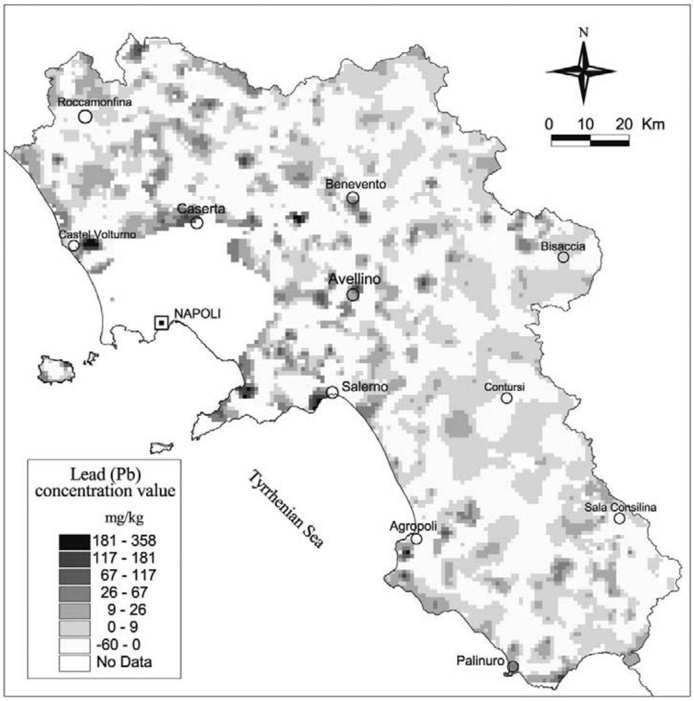

Fig. 10. Pb anomaly map compiled using spatial and spectral analysis (S–A method). Pb values have been obtained by decomposition of the Pb geochemical map (Fig. 5B) into separate components using the fractal filters selected on the S–A plot (Fig. 12). Pb anomaly map is generated only with signals with power spectrum (E) >15718 (selected cutoff in Fig. 12). Note that negative values in legend means that background values are greater than the interpolated value (Fig. 5B). Pixel values have been reclassified by fractal C–A plot (see text).

domains. Fourier transformation can convert geochemical values into a frequency domain in which different patterns of frequencies can be identified. The signals with certain ranges of frequencies can be converted back to the spatial domain by inverse Fourier transformation.

Fig. 12 shows S–A plots for Pb and U. Lead and U multifractal IDW maps have been converted by means of 2-D Fourier transformation into the frequency domain; the power spectrum values were calculated and plotted on log–log paper. The relationship between area A ($>E$), on the power spectrum plane with spectral values above a threshold E, and the power spectrum E value may show power–law relationships. In each plot, two (or more in some cases) straight lines were fitted by means of least squares to different portions of the plot; this implies two subsets of frequencies: high and low frequency power-spectra. The vertical line on each plot (Fig. 12) marks the cutoff (15 713 for Pb and 706 for U) applied in order to generate the corresponding filter based on the power spectrum. Applying these filters to the Fourier transformed signals and converting them back to the space domain yield two different images. The one with the high power-spectrum filter applied will represents the background geochemical patterns whereas the other with the lower power-spectrum filter applied represent the anomalous signals. The GeoDas program in its default setting removes 2.5% of values from both sides of the plot. In the present case, the setting has been changed only for the right side of the plot, avoiding the 2.5% removal of high values. After some tests the break on the plot has been selected based on its significance. This explains the reason why the other two breaks, visible on the right half of the Pb plot (Fig. 12), have not been considered.

In order to break Pb and U background and anomaly images into components and assign colors or patterns to distinct image zones representing known specific features on the ground, once again the fractal C–A method was used, as described before.

The Pb anomaly map (Fig. 10), as opposed to the U anomaly map (Fig. 11), shows a random distribution of high values, because the latter are not related to geological or geochemical patterns, preserving the very high values shown on the dot map (Fig. 3).

6. Results and discussion

If the geological map (Fig. 1) of the Campania region is compared with Pb (Fig. 5B) and U (Fig. 6) multifractal

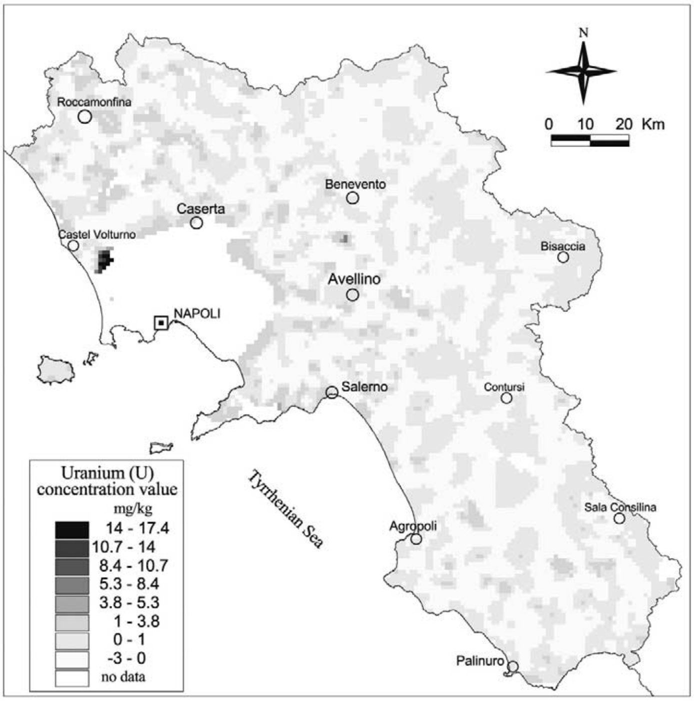

Fig. 11. U anomaly map compiled using spatial and spectral analysis (S–A method). U values have been obtained by decomposition of the U geochemical map (Fig. 6) into separate components using the fractal filters selected on the S–A plot (Fig. 12). U anomaly map is generated only with signals with power spectrum (E) >706 (selected cutoff in Fig. 12). Note that negative values in legend means that background values are greater than the interpolated value (Fig. 6). Pixel values have been reclassified by fractal C–A plot (see text).

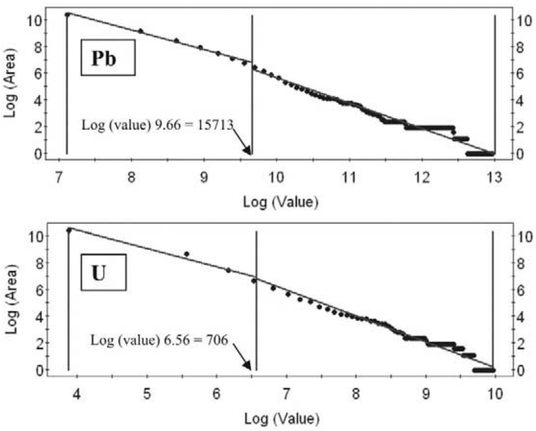

Fig. 12. Spectrum–area plots (S–A method) for Pb and U. The vertical axis represents log Area A ($\geqslant E$) and the horizontal axis the log-transformed power spectrum value itself (E). After some experiments two straight-line segments have been fitted by means of least square; this implies that two subsets of frequencies may exist in terms of distinct scaling properties: high and low frequency power-spectrum components. The cutoff indicated by the vertical line on each plot were applied to generate the corresponding filter used for background and anomaly separation.

IDW interpolated maps, it can be seen that the distribution of high Pb values reflects both a lithological and an anthropogenic control, whereas U reflects mostly a lithological control. Lead values, between 38 and 92 mg/kg (Fig. 5B) are located within the potassic–ultrapotassic volcanic rocks of Roccamonfina, Mt Somma-Vesuvius and Ischia along the western border of the region. In contrast the highest Pb concentrations (up to 425 mg/kg) are located in urban areas mostly around the big cities, and where human activities are more intense. This situation is perfectly outlined by the Pb background map (Fig. 8). The Pb anomaly map (Fig. 10) has been obtained by decomposition of the Pb IDW multifractal interpolated geochemical map (Fig. 5B) and generated only with signals with power spectrum (E) >15718 (selected cutoff in Fig. 12). The map shows no anomalies in the volcanic area (Roccamonfina, Ischia, south-east and east of Naples), meaning that Pb background values (Fig. 8) in these areas are similar to the interpolated values (Fig. 5B) and that they are due exclusively to the occurrence of potassic volcanic lithology. High Pb values (>117 mg/kg) occurring in small areas of the anomaly map (Fig. 10) are interpreted as anomalous values of anthropogenic origin. This conclusion based on the obtained Pb multifractal maps is confirmed as well by the fact that the Pb content in Campanian volcanic rocks has an average value of 64 mg/kg (Paone et al., 2001). It can be concluded therefore that Pb values >91 mg/kg in volcanic areas do not reflect natural baseline values, but reflect pollution (Fig. 8).

Uranium maps (Figs. 9 and 10) show a different situation. With the exception of the area SE of Castelvolturno which might represent pollution caused by illegal waste disposal, a close relationship can be observed (Fig. 9) between the U background values and the different lithologies of the Campania region, with the highest values occurring in the Roccamonfina potassic volcanic area, and the lowest values in the sedimentary carbonate rocks. Based on the high background values of the volcanic areas, the U anomaly map (Fig. 11) shows no anomalies in volcanic areas, whereas the only significant U anomaly occurs SE of the Castelvolturno area, confirming the interpretation that this anomaly is real, reflecting possibly some illegal waste disposal in the area.

In conclusion, it is emphasized that geochemical maps generated by multifractal IDW for environmental purposes, show a more realistic data distribution reflecting in detail the geolithological formations. By applying the C–A method, the user may interact with the software in order to choose the cut-offs that separate geochemical values into different components, and to discriminate areas with similar features. Background maps, obtained by the S–A filtering method along with C–A method, are useful for environmental purposes, where the discrimination of background values is particularly important because of legislative reasons. Maps interpolated by kriging (e.g. Pb map, Fig. 5A) represent an intermediate stage between multifractal IDW interpolated maps (e.g. Pb map, Fig. 5B) and background maps (Pb map, Fig. 8). The background map (Fig. 8) integrates information about various geolithological and environmental features. This case study of Pb and U distribution in the Campania region successfully delimits polluted areas, and allows natural background values to be assigned with more confidence.

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