Introduction to the Topical Volume “Fractals and Dynamic Systems in Geoscience”

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1. Introduction

Chaotic dynamic systems and nonlinear processes, together with the resulting fractals and multifractals, are becoming increasingly fundamental for analyzing data and understanding processes in the Earth and environmental sciences. Many processes and phenomena, poorly known only a few years ago, can now be studied and understood with the help of conceptual models from the fields of fractals and dynamic systems. This represents a bold step towards the aim of understanding how the planet Earth works.

The focal point of this volume is the use of fractals and dynamic systems in analyzing and studying a variety of geological and geophysical processes. The aim is to provide the reader with a collection of papers highlighting the usefulness of concepts and methods belonging to fractals and chaotic dynamic systems in understanding geological processes that would be otherwise very hard or even impossible to study using only classical conceptual approaches.

This volume contains some contributions to the 6th International Conference on Fractals and Dynamic Systems in Geoscience, held in Perugia (Italy), September 30–October 2, 2013.

This forum was dedicated to recent developments in the application of fractals and dynamic systems to Earth systems, with emphases on predictability of geological risks, natural resources, and climate change.

The 21 papers presented in this volume cover well the wide range of applications of fractals and dynamic systems to the Earth and planetary sciences. As a whole, they represent the leading-edge research dedicated to the understanding of the mechanisms and processes responsible for the nonlinear dynamics triggering and characterizing geological processes.

The papers are divided into five main groups, including petrology/volcanology, seismology, geomorphology, space science, and other topics. The many fields covered by the works presented in this volume testify to the unique multi- and transdisciplinary character of the conceptual models belonging to fractal geometry and dynamic systems, spanning virtually the entire constellation of geological disciplines and beyond.

2. Petrology/Volcanology

Soesoo and Bons provide measurements of migmatitic leucosomes and granitic veins in drill cores. The authors show that the cumulative width distribution of the studied leucosomes/granitic veins follows a power law with exponents between 0.7 and 1.8. The authors also focus on fractal statistics of granitoid pluton sizes: the cumulative sizes follow power-law distributions with exponents between 0.6 and 0.8. These results support the model that the crust develops a self-organized critical state during magma generation. In this state, magma batches accumulate in a noncontinuous, stepwise manner to form ever larger accumulations. The authors suggest that there is no characteristic length or time scale in partial melting or its products and that the smallest melt segregations and km-scale plutons form the end-members of a continuous chain of mergers of magma batches.

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The study by Albert et al. is focused on examination of magma mingling and mixing, expressed as basanitic enclaves within a phonolitic host lava. The authors report that the morphology of enclaves varies from rounded to complex finger-like structures that can be quantified by fractal geometry methods. It is shown that the logarithm of the viscosity ratio between the phonolitic magma and the basanitic enclaves ranges between 0.39 and 0.81, with most values clustering around 0.49. This allowed the authors to constrain the water content of interacting magmas. The usefulness of fractal analyses to determine preeruptive conditions of magmas is highlighted in this study.

De Campos focuses on the mixing between basalt and granite in a deep plutonic environment. The description of flow patterns and measurements of their fractal dimensions, and the evaluation of geochemical data from a Cambro-Ordovician granitic pluton are presented and discussed. Measurements of fractal dimension of flow patterns are performed at different scales. The author suggests that the compositional variability and the flow patterns of the studied pluton are greatly controlled by the onset of nonlinear dynamics that triggered chaotic mixing between a granitic and a basaltic end-member.

El Omari et al. examine numerically the cooling of a basaltic melt undergoing chaotic advection in a two-dimensional (2D) cavity with moving boundary. It is shown that different cooling rates can be obtained during thermal mixing of a single basaltic magmatic batch and that this process can induce complex temperature patterns inside the magma chamber. Results indicate that the emergence of chaotic dynamics strongly modulates temperature fields over time and greatly increases the cooling rates. This mechanism has implications for the thermal lifetime of the magmatic body and may favor the appearance of chemical heterogeneities in the igneous system as a result of different crystallization rates. The authors suggest that results from this study can provide explanations for some natural features that, to date, have received unsatisfactory explanations such as the production of magmatic enclaves, compositional zoning in mineral phases, and the generation of large-scale compositional zoning observed in many plutons worldwide.

The work of Buccianti focuses on the study of the multivariate nature of geochemical data. The author proposes an approach that can be used to investigate the shape of the frequency distribution of multivariate geochemical indices. The approach is based on the use of the transformations of the log-ratio family. The methodology proposed by the author shifts attention to the modeling of the frequency distribution of more complex indices, linking all the terms of the composition to better represent the dynamics of geochemical processes. The application to the chemistry of 616 ocean-floor basaltic glasses from the Abyssal Volcanic Glass Data File is presented.

3. Seismology

Șuțeanu performed analysis on multiple sets of earthquake networks created for the Hawaii volcanic system. The author indicates that the scale-free behavior of the connectivity distribution along the spectrum of the minimum weight values can be used to discern the interrelated earthquakes from the rest of the data set. It is highlighted that the patterns in the distributions of temporal and spatial intervals between earthquakes are similar from large to small networks. Moreover, similarities are found between the variation of the network clustering coefficient, and the variation of the exponents of the connectivity distribution and of the weight distribution. The author suggests that the synchronous variation over successive temporal windows can be related to changes in seismicity and in the life of the volcanic system.

The work by Nelson et al. focuses on understanding how a layered basalt sequence affects the propagation of a seismic wave. The authors construct detailed realistic models of basalt sequences, using fractal properties derived directly from outcrop analogues including roughness of basaltic lava flows, the latter captured using terrestrial laser scanning and satellite remote sensing. Synthetic lava flow surfaces were reconstructed using a von Karman power spectrum. P-wave velocity data were then added, and the resulting model was used to generate synthetic seismic data. The resulting stacked section shows that the ability to resolve the internal structure of the lava flows is quickly lost due to scattering and attenuation

by the basalt pile. A further result from generating wide-angle data is that the appearance of a lower-velocity layer below the basalt sequence may be caused by destructive interference within the basalt itself.

The work by Matcharashvili et al. investigates the dynamical features of seismic activity in Central Asia, where strong electromagnetic (EM) soundings were performed, revealing the impact of strong electromagnetic discharges on the microseismic activity of the investigated area. Using a variety of time series analysis techniques, such as wavelet transformation, Hilbert–Huang transformation, detrended fluctuation analysis, and recurrence quantification analysis, the authors show that manmade high-energy EM irradiation essentially affects the dynamics of the seismic process in the investigated area in its temporal and spatial domains.

Michas et al. use a multifractal approach to study the time dynamics of the recent earthquake activity in the Corinth rift. The results indicate a heterogeneous clustering degree and correlations acting at all time scales, suggesting a strongly non-Poissonian behavior. In addition, the authors show that the multifractal analysis in different time periods indicates that the degree of multifractality exhibits strong variations with time, which are associated with the dynamic evolution of the earthquake activity in the rift and the transition between periods of high and low seismicity.

The work of Papadakis et al. presents analysis of the earthquake magnitude distribution for the period 1990–1998, in a broad area surrounding the epicenter of the 1995 Kobe earthquake. The authors perform a frequency–magnitude distribution analysis in the context of nonextensive statistical physics. The nonextensive parameter q_M , which is related to the frequency–magnitude distribution, is found to highlight the presence of long-range correlations and is used as an index of the physical state of the studied area. The authors report a significant increase of q_M some months before the strong earthquake (on April 9, 1994), indicating the start of a preparation phase towards the Kobe earthquake.

In order to disclose the inner time properties of complex seismograms, Telesca et al. analyze the time dynamics of P-waves of seismograms of tsunamigenic earthquakes and nontsunamigenic events, using the

Fisher–Shannon method and multifractal detrended fluctuation analysis. Using jointly these two methods, the authors define a classifier, whose performance was tested by means of the receiver-operating characteristic curve that plots the true positive rate versus the false positive rate. It is shown that the classifier shows a discrimination power that can be useful for early warning of tsunami events.

Polyakov et al. explore the possibility of earthquake prediction, proposing an approach based on analysis of common short-term candidate precursors with subsequent processing of brain activity signals generated in rats. They report that the candidate precursors are observed as synchronized peaks in the nonstationarity factors, introduced within the flicker-noise spectroscopy framework for signal processing, for the high-frequency component of time series. Moreover, the authors hypothesize that these peaks correspond to the local reorganizations of the underlying geophysical system, which are believed to precede strong earthquakes. They suggest that the rodent brain activity signals could be selected as potential “immediate” (up to 2 weeks) deterministic precursors for earthquakes.

4. Geomorphology

Liucci et al. focus on the fractal analyses of landslides with an attempt to identify a possible structure in their spatial pattern. The authors apply the box-counting algorithm to maps of landslide triggering points and landslide areas and identify a scale-invariant structure. They recognize two distinct types of fractal behavior, separated by a scale value of 1 km and characterized by capacity dimensions of 1.35–1.76, in the ranges of 25 m to 1 km and 1–16 km, respectively. The authors show that the higher capacity dimension describes the spatial distribution of landslides, whereas the lower one contains information about their geometries. They also suggest that the contribution of each causal factor (i.e., predisposing and triggering factors) for the occurrence of landslide events and their spatial development could be different in the two ranges of scales identified, depending on its spatial variability at the local and the regional scale.

The work by Donadio et al. is based on an estimate of the fractal dimension of the drainage network of three large watercourses having different geologic context and tectonic styles. Their aim is to better understand the morpho-evolutionary processes of these fluvial morphotypes, to classify hydrographic patterns, and finally to compare fractal degree with some geomorphic quantitative indexes. It is suggested that, according to the geological setting and geomorphic indexes of these basins, the lower fractal dimension indicates a prevailing tectonic activity, whereas the higher fractal dimension appears to be related to stronger erosion processes on inherited landscapes.

Paliaga examines by fractal analysis the triangular facets that arise in different geomorphic systems characterizing three river basins. It is shown that the spatial dispersion of erosional facets in the subbasins, corresponding to equally distributed closure sections along the main riverbed, follows power-law distributions. The author suggests that the number of facets is related to the hydrographical network structure and reflects the way erosion cycles, induced by base level changes, behaved in the catchment.

5. Space Science

Mancinelli et al. use the data gathered during the Mariner10 and MESSENGER missions on Mercury to classify impact craters into four classes related to four main geochronological units. They show that, for each crater class, size frequency distributions show a fractal behavior. The fractal dimension is different for each crater distribution, and this allows the authors to advance a new hypothesis for the crustal structuring of Mercury due to a complex interplay between endogenic and exogenic processes.

Based on fractal geometry methods, Hossain and Kruhl studied the shock-induced fragmentation structures of basement rocks and their limestone cover in and around the Ries impact crater (Germany). Quantification was performed by automated procedures and in areas of square centimeters to square decameters. In 2D and on all scales, the fragmentation structures form complex, statistically self-similar patterns highlighting that three different

power-law relationships exist, which might reflect the effect of three fragmentation processes. Moreover, the authors show that fracture patterns are anisotropic and inhomogeneous over large areas. It is suggested that the approach proposed in their work could shed new light on impact-related fragmentation processes.

Chang et al. review a recent method, rank-ordered multifractal analysis (ROMA), explicitly constructed to analyze the intricate details of the distribution and scaling of intermittent structures. The authors apply this method to the analyses of selected examples related to the dynamical plasmas of the cusp region of the Earth's magnetosphere, velocity fluctuations of classical hydrodynamic turbulence, and the distribution of the structures of the cosmic gas obtained through large scale, moving mesh simulations. It is suggested that the ROMA method can be successfully applied to study the similar multifractal processes in extreme environments of near-Earth surroundings.

6. Other Topics

Based on fractal statistics, Blenkinsop examines lode gold deposits, geothermal wells and volcanoes, and conventional and unconventional gas wells. The author shows that mass dimensions and scaling exponents generally increase from the lode gold through geothermal wells to gas data sets, reflecting decreasing degrees of clustering. The author argues that, as all the natural resources in his study are formed by fluid fluxes in the crust, the percolation theory is an appropriate unifying framework to understand their significance. Following this idea, it is shown that none of the percolation networks that formed the studied deposits reached the percolation threshold.

The work by Şuşteanu is focused on the analysis of daily minimum and maximum surface air temperature time series from 15 high-latitude Arctic stations from Canada, Norway, and the Russian Federation. The author applies a range of analysis methods. Statistical L-moments were determined for temporal windows of different lengths. L-skewness was found to change towards more positive values, reflecting an enhancement of warm spells. In addition, Haar wavelet analysis was applied both to the entire time series and to running windows.

Persistence diagrams were generated, based on running windows advancing through time and on local slopes of Haar analysis graphs. It is suggested that this approach offers a more nuanced view on variability by reflecting its change over time on a range of temporal scales. In the light of the obtained results, the author suggests that explanations for the discrepancy between variability perception and results of pattern analysis need to be explored using an integrative approach to weather variables such as air temperature, cloud cover, precipitation, and wind.

The work of Czechowski focuses on the microscopic mechanisms that can be responsible for elongation of tails of cluster size distributions, using cellular automata. The author shows that only the appropriate forms of rebound function can lead to inverse-power tails if densities of the grid are small or moderate. For larger densities, correlations between clusters become significant and lead to elongation of tails and flattening of the distribution to a straight line on log–log scale. The author suggests that the

microscopic mechanism, given by the rebound function, included in simple one-dimensional (1D) random domino automaton (RDA), can be projected on the geometric mechanism which favors larger clusters in 2D RDA.

As guest editors, we would like to thank all the authors for their efforts and patience regarding this topical volume. We also wish to acknowledge the input of these and all the other participants in making the 6th International Conference on Fractals and Dynamic Systems in Geoscience in Perugia a success. We express our appreciation for the work of the reviewers, and Editor-in-Chief for Topical Issues, Dr. Renata Dmowska, who greatly helped in managing this volume, and Mrs. Priyanka Ganesh for her patience and help with the several problems we encountered in managing submitted manuscripts with the online submission system.

(Received January 28, 2015, accepted January 28, 2015, Published online February 12, 2015)