EUG XI

Symposium VPP2

Non-Linear and Chaotic Dynamics in Igneous Petrology

Convenor

Giampiero Poli

Thursday AM Session

VPP2 : THam02 : G7
Self-Organizing Complex Phenomena in Petrology

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Many phenomena in petrology are complex. A signature of self-organizing complex phenomena is a power-law (fractal) statistical distribution and such phenomena often display deterministic chaos. A general requirement is that the governing equations be nonlinear. A classic example of self-organizing complex phenomena is the diffusion limited aggregation (DLA) model. This is a model for dendritic structures. Recent advances have been made in classifying these structures using both primary branching statistics and side-branching statistics. Clustering and growth are other examples that can exhibit self-organized complexity. Under some conditions clustering and growth can be treated as an inverse cascade process that leads to 'self-organized criticality' and fractal distributions. Distributions of minerals are examples of self-organizing complex phenomena. A strong case can be made for the applicability of fractal tonnage-grade statistics for ore deposits. One explanation for this type of distribution is Rayleigh distillation. Another signature of a self-organizing complex system is a spatial distribution of mineral composition that has spatial correlations associated with fractional Brownian walks or fractional Gaussian noises. One explanation for these distributions is the applicability of a stochastic diffusion equation (i.e., the Langevin equation).

VPP2 : THam03 : G7
Illegitimate Pyroxenes or Chaotic Dynamics? The Role of Flow Fields in the Petrogenesis of Igneous Rocks

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Disequilibrium textures of mineralogical phases are ubiquitous in igneous rocks. From a general point of view, changes of physical and chemical conditions within magmatic systems can be adequate to explain minerals disequilibrium textures. However, detailed petrographical and mineralogical observations evidence that crystals of the same mineralogical phase reacted differently in response to physicochemical changes and now they occur at short distance even in the same thin section. Evidence of this intriguing petrological phenomenon can be found on pyroxenes occurring in mildly alkaline basalts from Mt. Etna. Pyroxene show a variety of textures: un-zoned euhedral Cr-Al-diopside, anhedral resorbed cores of Cr-Al-diopside with a rim of variable thickness of Al-Fe^{+3}-diopside composition, and un-zoned euhedral Al-Fe^{+3}-diopside.

Crystallographycal analyses suggest that this textural and chemical variability cannot be attributed to abrupt variation in pressure conditions of crystallization. On the other hand, geochemical constraints suggest that magmatic interaction processes between magmas having similar rheology and geochemical characteristic may have played a key role in the development of these disequilibrium textures.

The thickness of the Al-Fe^{+3}-diopside rim has been measured on a large number of pyroxenes having approximately the same size. Such measures can be considered strictly related to the degree of disequilibrium suffered by pyroxenes. Statistical analysis show that this parameter has a gaussian distribution.

Such occurrence are difficult to reconcile with a homogeneous and widespread propagation of the disequilibrium conditions. Then, a prototypical mixing chaotic system in which two magmas interact and where pyroxenes crystallize is used. Such system is characterized by the contemporaneous occurrence of both well mixing and isolated regions. An initial configuration in which nuclei of pyroxene are dispersed uniformly within the system is considered. The growth of pyroxene rims is then modelled taking into account the amount of compound available in their neighbourhood. Within well mixing regions the growth of rims around pyroxenes is strongly enhanced. In this kinematic regime, in fact, pyroxenes are transported through large volumes of magma and the probability that they encounter fertile regions for their growth is high. On the contrary, isolated regions behave as closed systems and in this kinematic regime, the growth of rims is reduced since pyroxenes remain persistently within discrete volumes of magma in which mass transfer processes are inhibited. Statistical analysis of the amount of rim grown around pyroxenes nuclei during the simulation evidence that rim distribution is gaussian. The agreement between rim thickness measurements of pyroxenes in lava flows and in the simulated system suggests that chaotic flow fields during magma mixing may be responsible for the non-homogeneous propagation of the compositional disequilibrium conditions within the system.

VPP2 : THam04 : G7
Power-Law Olivine Size Distributions in Refractory Mantle

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Olivine crystal size distributions have been obtained in three suites of mantle xenoliths found in alkaline basalts from Canary Islands-Africa, Victoria Land - Antarctica and Pali Aike - South America. Samples are Spinel- and Garnet-bearing harzburgites, textures vary form coarse and mosaic-equant to porphyroclastic. Samples derive from lithospheric mantle, from depths ranging from 80 to a few km. Data have been collected with a simple method, processing digital images get at crossed polars and in normal light. Image processing has been performed developing procedures based on VISILOG 5.2 package. Acquisition method is based on low-cost high-resolution color scanner that allows to collect data from the whole section with a resolution up to 10 mm/pixel. The data set has been obtained with the working resolution of 1500 dpi, resolving crystals larger than about 100 mm. 2-D data from binary images have been converted in 3-D data applying stereological corrections (Armienti et al., 1994) based on the Schwartz-Saltykov algorithm, accounting for the crystal form factors (Higgins, 2000, Sahagian and Proussevitch, 1998). Volumetric data have been reported in bi-logarithmic diagrams, plotting the crystal number density (crystal number per unit size per unit volume (mm^{-4}) versus characteristic lenghts). Both linear and geometric class scales have been accounted for, to optimize the count statistics of larger grains or reveal the details of distribution at smaller sizes. Strikingly, all samples show scale invariance of size distributions over two orders of magnitude of olivine sizes from 0.2 to 20 mm. Truncation effects are easily recognizable at smaller and larger size and are respectively due to the resolution and to the sample size. Crystal size distributions show a power-law distribution that in bi-logarithmic coordinates yields linear arrays with slopes varying around -3. This scale invariance corresponds to fractal dimensions of the data arrays varying from 2.5 to 3.5, a range of values observed for distributions of fragment sizes in a variety of geological contexts. A fragmentation model seems to explain the observed distributions with fractal dimensions around 2.6, that correspond to equilibrated mosaic textures. Linear distributions with slopes smaller than -3 are typical of porphyroclastic and cataclastic samples. A detailed inspection of distributions reveals the occurrence of slight bends in the linear arrays that suggest selective crushing of crystals with size larger than 1 mm, whose number decreases, thus feeding smaller classes. This corresponds to an increase in the average slope of the resulting distribution. Olivine is an essential constituent of the upper mantle and its size distribution constraints the estimates of grain-boundary areas per unit volume, a parameter influencing both the attenuation mechanisms of seismic wave propagation and re-equilibration of fluids percolating in the mantle

Armienti P, Parschi MT, Innocenti F & Pompilio M, *Contribution to Mineralogy and Petrology*, **115**, 402-414, (1994).
Higgins MD, *American Mineralogist*, **85**, in press, (2000).
Sahagian DL & Proussevitch AA, *Journal of Volcanology and Geothermal Research*, **84**, 173-196, (1998).

VPP2 : THam05 : G7
Fractals, Chaotic Dynamics and Chemical Diffusion during Magmatic Interaction Processes: Fast Engines for Fast Hybridisation of Magmas

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Magmas can mix in different environments the most important being magma chambers, conduits and sub aerial channels. A lot of works exist in the literature concerning both numerical and analogical simulations of magmatic interaction processes using various geometries. Nevertheless, the basic physics of magma mixing processes is still poorly understood. In this work, structures of magma mixing from three different lava flows cropping out on the islands of Lesbo (Greece), Vulcano and Salina (Italy) have been analysed using methods coming from the field of chaos theory. Results evidence the contemporaneous occurrence in the same system of well mixed and poorly mixed regions. The chaotic nature of magma mixing is demonstrated calculating the fractal dimension of the attractors of the magma mixing structures and measuring the Lyapunov exponents of the same structures. Moreover, the entity of mixing has been quantified by means of fractal analyses. Since fractal structures are the fingerprint of chaos and magma mixing processes are chaotic, a chaotic dynamical system consisting of stretching and folding processes between interacting magmas is used as prototype for natural magma mixing. Results suggest that natural fractal structures have been produced by chaotic dynamics between interacting magmas and that the intensity of magma mixing can be quantified.

Since physical dispersion of one magma inside another through stretching and folding processes and chemical exchanges between magmas are strictly related, we perform numerical simulations of chaotic advection coupled with chemical diffusion. Results show good agreement between the computed structures and the structures occurring in nature. In particular it is shown that chaotic stretching and folding processes reduce dramatically the distances between the interacting magmas and produce fractal structures that propagate inside the magmatic masses from the macro-scale to the micro-scale favouring chemical exchanges. This occurrence suggests that chemical diffusion processes, even if acting on small volumes of magma during the life time of magmas, can propagate quickly through larger volumes thanks to the fractal nature of the structures produced by stretching and folding processes. From this point of view, the chaotic nature of magmatic interaction processes can be considered a very powerful engine to promote very efficient chemical exchanges between interacting magmas leading to high degree of hybridisation in relatively short times.

Our analysis evidence that the study of chaotic dynamical systems as prototypes magma mixing systems are powerful techniques that are useful to better understand the complex dynamics involved in this petrological process.

VPP2 : THam07 : G7
Chaos, Disequilibria, Fractals, and Replacement in Earth

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Disequilibrium reactions prevail in the open systems of Earth (Prigogine, 1997). Reactions are driven by excess energy along gradients in temperature, pressure and composition in Earth's electromagnetic and gravitational fields.

Replacement operates under diversive geological conditions, at intergranular to Earth scales, and results from coupled dissolution-precipitation reactions (Ortoleva, 1994). Host minerals being replaced are destabilized by energies released at interfaces of simultaneously growing replacing phases.

Replacement at granular scales is exemplified by growth of porphyroblasts with locally supplied constituents in a consolidated pluton with minerals sparsley coated with fluid at Papoose Flat, California in response to excess energy of stress (Dickson, 1996). Intermediate scale replacement is typified by selectively dolomitized limestone beds. Earth-scale replacement by reaction cells passively emplace intrusive rocks: liquefaction energies cycle between endothermic dissolution of country rocks at cell tops and exothermic crystallization of minerals at cell bases (Dickson, 2000).

Prigogine, I, *End of Certainty. Free Press, New York*, (1997).
Ortoleva, PJ, *Geochemical Self-Organization. Oxford University Press, New York*, (1994).
Dickson, FW, *In: Coyner, A. R. and Fahey, P. L. , (Eds.), Geology and Ore Deposits of the American Cordillera: Geol. Soc. Nevada Symposium Proceedings, Reno/Sparks, Nevada*, 909-924
Dickson, FW, *J. of Geodynamics*, **30**, 475-487

VPP2 : THam10 : G7
The Mechanism Concentration of Impurities Melts at Formation of Reefs Intrusions

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The calculations have shown that the quantity of latent heat during the crystallization of pyroxene and olivine makes up more than a third of their heat contents within the range from melt temperature to standard condition (for plagioclase, this value is about two time lower). At escape heat in crystallization system and deleted heat in an environment have among themselves defined correlation. Their ratio sets a level of a positive feed-back, which is determined by a heat, accelerating the process crystallization, and the negative feed-back carries on to a drop of a velocity crystallization through variations of temperature. From a position of principles of a nonequilibrium thermodynamics the process crystallization magmatic melt flows past under some distinct from equilibrium scheme. The periodicity of the process creates in a system conditions of oscillations of a velocity crystallization and temperature. The conditions of selected heat play a role of the amplifier of oscillations. Thus the velocity crystallization is inspected by a velocity heat to derive, and the recurring of such oscillations will flow past by that more often, than above velocity of outflow of heat from a system. In accordance with promoting front crystallization tear a way of a molecule of impurities in melt the gradually is created a stratum of their increased concentration. The mechanism of this process is exhibited in a drop of a velocity crystallization because of creation on interphase of a surface enriched impurities of a stratum from minor components, hampering pass of basic molecules melt. The thickness and structure of a created stratum of impurities depends on a velocity crystallization melt. The appropriate conditions for creation of a periodic chemical heterogeneity in the field of front crystallization are determined by a relation of velocities crystallization melt and outflow of heat through containing breeds in an environment. Therefore selective character concentration of impurities before front crystallization, as a rhythmic recurring of a series of minerals (including EPG), should flow past longly in time, with periodic capture them in defined places of volume intrusions agrees of conditions of outflow of heat and character of a thermal conduction of containing breeds. It is obvious, that shaping layered such as a Merensky Reef, J-M of a reef, Skaergaard Intrusion etc. were carried out according to explained of the mechanism.

VPP2 : THam11 : G7
Fractal Analysis of Mingled-Mixed Calc-alkaline Magmas

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A lava sample from Aeolian Islands (Italy) displays textural and compositional heterogeneities due to different degrees of interaction between a basalt and a dacite. A fractal analysis of the interfaces between the different mingled magmas has been carried out using the box-counting technique. Results indicate that the interface of the mafic and salic end-members shows a fractal geometry. Basalt and dacite have a fractal dimension (D) in the range 1.53-1.63 whereas intermediate compositions have D between 1.62 and 1.81. The calculated D values suggest linear and/or low degrees of fingering of the end-members and higher fingering in the intermediate compositions. We propose that end-members represent a steady state in the mixing process, whereas compositions reflecting low degrees of mixing are transient (i. e. fractal mixing). Hybrid compositions result from a homogeneization process. Our results apparently contrast with those of previous studies on chaotic mixing (Ottino et al., 2000). However it must be noticed that chaotic mixing starts from an initial layering and evolves towards the fractal mixing, whereas our study starts from fractal mixing towards homogeneization. Our results are consistent with those from numerical models in mixing of non-newtonian and newtonian fluids (Ten et al., 1997). We conclude that in calcalkaline magmas an increase of D reflects the transition fractal mixing- transient- homogeneization.

Ottino JM, DeRoussel P, Hansen S & Khakhar RDV, *Adv. Chem. Engineer*, **25**, 105-204, (2000).
Ten A, Yuen DA, Podlachikov YY, Larsen TB, Pachepsky E & Malenvsky AV, *EarthPlanet. Sci. Lett*, **146**, 401-414, (1997).

VPP2 : THam12 : G7
Reconstruction of Magma Mixing Structures in 3D by Serial Slices: Visualizing Chaotic Dynamics during Magmas Interaction

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A great deal of works concerning magmatic interaction processes exist in the literature. However, most of these works are focused on the petrological interpretation of magma mixing and only few efforts have been made to asses the role of magma mixing structures as markers to decipher the dynamics occurred inside the magmatic masses. In this work we analyse magma mixing structures in 3D in order to understand the dynamics to which magmatic masses underwent during their history. We analyse mixing structures in lava flows because they offer the opportunity to follow the life of the process thank to the rapid cooling of magmas. To visualise and analyse the magma mixing structures in 3D, parallel serial slices have been cut from cubes of volcanic rocks. Subsequently, slices have been scanned using a high resolution scanner and imported into a software able to perform digital serial slices reconstruction. This method allowed to visualize and analyse volumes of rock instead of focusing on pure 2-dimensional pictures giving the opportunity to observe 'virtually' the real spatial distribution of magma mixing structures.

A great variety of structures can be observed using this kind of technique. In particular, large stretched and folded surfaces between the interacting magmas are found to coexist with coherent volumes of magmas that did not underwent strong deformation. These occurrences relate well to the structures that can be observed in both numerical and analogical simulations of fluid mixing where the mixing process is strongly related to the onset of chaotic dynamics inside the system. From this point of view, we interpret kinematically the stretched and folded structures as unstable manifolds associated to hyperbolic orbits within the system and produced by vigorous stretching and folding dynamics occurred between the interacting magmas. On the other hand, we consider the coherent volumes of magmas as invariant tori associated to elliptic orbits where the stretching and folding process has been inhibited thank to the closed structures of the flow fields.

VPP2 : THam13 : G7
Magma Interaction in the Elba Island Pluton, Tuscan Archipelago, Italy: A Fluid-Dynamic Approach using Numerical Modeling

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The Monzogranite pluton of the Monte Capanne, Elba Island, was emplaced at ca. 6.8 Ma (Ferrara & Tonarini, 1985; Juteau et al., 1984), and is related to the post-collisional phase of the Apennine orogeny. Mafic microgranular enclaves (MME) are ubiquitous throughout the pluton, exhibiting dark-grey colour, ellipsoidal shape and occasionally schlieren-like trails. Their size ranges from a few centimetres up to 10 meters. Composition varies from tonalite to monzogranite. Petrological and geochemical data demonstrate that the monzogranite magma of Monte Capanne formed through mingling-mixing processes, between a crustal peraluminous melt, and a mantle-derived magma(Poli,1992; Bussy,1991). A variety of interaction phenomenologies have been observed between the host-rocks and the enclave magma, possibly recording the different degrees of evolution of the basic magma (e.g. composite enclaves characterised by a fine-grained inner zone and a medium grained outer zone). MME have a continuous variation in texture and mineral assemblage from inner to outer zones.

Intensive parameters have been calculated using geothermobarometry, in order to elucidate the dynamic evolution of the studied system. The monzogranite pluton yields a temperature of ca. 770°C, while enclaves yield 940-840°C. The mineral assemblage of highly refractory metamorphic crustal xenoliths, dispersed within the monzogranite pluton, record a pressure >2.5 kbar. This estimate is the upper limit of the crustal source region of the monzogranite.

The efficiency of mixing depends on several thermo-mechanical parameters such as viscosity, density, and temperature contrasts between interacting magmas, their relative volumes, and velocity fields. Campbell & Turner (1985) have carried out a series of analogue laboratory experiments to investigate the fluid-dynamic behaviour of melts during interaction, highlighting the importance of the injection velocity of basic magma and the viscosity of the rhyolitic magma in controlling mixing. Sparks & Marshall (1986) pointed out that the physical state of magmas after thermal equilibrium plays a major role during mixing events. In order to assess quantitatively the relative role of the thermo-mechanical parameters, a numerical model simulating the injection of basaltic magmas into a rhyolitic magma chamber will be presented.

Bussy F, *Enclaves and Granite Petrology, Elsevier*, 167-178, (1991).
Campbell IH & Turner JS, *J. Petrol*, **27**, 1-30, (1986).
Ferrara G & Tonarini S, *Rend. Soc. It. Miner. Petrol*, **40**, 111-124, (1985).
Juteau M, Michard A, Zimmermann JL & Albarède F, *J. Petrol*, **25**, 532-545, (1984).
Poli G, *J. Petrol*, **100**, 41-56, (1992).
Sparks SRJ & Marshall LA, *J. Volcanol. Geotherm. Res*, **29**, 99-124, (1986).