

Episodic tectonic behaviour from crystal-plasticity to seismicity

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The purpose of this paper is to emphasise that deforming, chemically reacting systems in the Earth operate as nonlinear dynamical systems held far from equilibrium by the influx of energy and mass. The nonlinear behaviour leaves its mark as apparently stochastic distributions of mineral assemblages, mineralisation, structures and seismic activity. However these irregular (apparently random) distributions are deterministic and, in principle, contain all the information required to understand the dynamics of the underlying mechanisms.

Tectonic systems in common with most large nonlinear systems such as weather and ocean circulation systems are characterised by being forced to evolve by energy supplied at a large spatial scale; in order to do so mechanisms of evolution are adopted that involve dissipation of energy at finer and finer spatial scales. The coupling of deformation and mineral reactions in tectonic systems is one mode of cooling for the planet Earth. Thus, plate tectonic motions driven by cooling of the Earth at a global scale drive the development of through-going lithospheric faults and associated damage zones that focus mantle derived fluids. Energy is dissipated by these deformation processes and by the flow of fluids through the deformed regions. Energy continues to be dissipated by exothermic chemical and deformation processes such as hydrothermal alteration, fracturing and sliding on faults. These processes occur at increasingly finer scales until ultimately any energy in the system is either stored by endothermic reactions such as melting, the deposition of sulphides (such as pyrite), non-hydrous silicates (such as K-feldspar) and metals (such as gold) or is dissipated by heat conduction and advection to the surface of the Earth. Processes of dissipation at finer and finer scales resemble energy cascades which are multifractal in their energy distribution. Thus tectonic systems are multiscale dynamical systems and need to be studied using the insights and tools developed to study such systems over the past 50 years or so. This involves knowledge gained from statistical mechanics and the thermodynamics of chaotic systems.

Episodic behaviour in the deformation of the Earth has been described at length scales from asthenospheric shear flow to nano-scales in crystal plasticity and at time scales ranging from 100' s of millions of years in metamorphic complexes to milliseconds in seismic events. We discuss such episodic behaviour in the context of energy cascades and their associated scaling laws as the systems approach criticality. The processes that dissipate energy in the global energy cascades almost always involve coupling between exothermic processes, such as fracturing, brecciation, sliding on faults and hydrothermal alteration of fault zones, and endothermic processes, such as melting and deposition of anhydrous silicates and of carbonates in hydrothermal systems or fault zones.

By considering the energy and mass balances for these systems one can show that coupling between processes that compete for energy and/or mass results in the episodic behaviour of temperature and/or chemical composition and the response can be periodic or chaotic depending on a range of parameters we will discuss. We explore the phase space for these interactions and illustrate the transitions between different modes of operation with different attractors in phase space. The chaotic behaviour of these systems means that the outputs are multifractal both in time and space. We discuss fast efficient ways of analysing the multifractal nature using wavelet transforms. Finally, the complexity of these systems can be fully quantified both in space and time using various versions of recurrence plots. These plots (given

sufficient data) enable the attractor to be derived for a given system along with estimates of the predictability of system behaviour. We illustrate these analytical procedures with data from deformed rocks, hydrothermal systems and from seismic events.

