Terrestrial volcanism in the framework of complex network theory

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Many Earth systems exhibit dramatic emergent organization, as processes that occur over many orders of magnitude in time and space interact. Evidence for extreme events is common in the rock record, and spatio-temporal organization is also often inferred from seismic and geochemical studies of the Earth’s interior. In volcanology, these extreme events come in two forms, spatial and temporal.

Large single eruptions, such as those preserved in Large Igneous Provinces like the Columbia River plateau, USA, or caldera forming eruptions such as at Yellowstone National Park, USA, represent a catastrophic end member of a complex network of magma transport that starts in the Earth’s upper mantle as a broad distribution of partial melt along mineral grain boundaries. This melt migrates through the crust, directed by tectonic stresses, overpressure and buoyancy forces, coalescing as it rises and sometimes stalling in large reservoirs known as magma chambers. The formation and spatial organization of this plumbing system represents interaction between processes that occur on scales over $10^{12}$ orders of magnitude in space (nanoscale grain boundary melting to kilometers of transport through dikes) and $10^{10}$ orders of magnitude in time (hour-long volcanic eruptions to melt generation over millions of years).

A second kind of emergent organization in volcanology is temporal. At every loci of volcanism, the time-averaged output of lava is unsteady, and there are generally periods of enhanced eruptions representing pulses of magma moving through the system or variable external forcing. These pulses of magmatism are recognized through isotopic dating as occurring over million-year timescales in ancient volcanic belts such of the Sierra Nevada batholith in California and the San Juan volcanic field, Colorado, or on thousand year time-scales as at Mount Mazama (Crater Lake), Oregon [e.g., 1]. Historic volcanoes also display episodicity and variability in the time-evolution of their eruptive products. For example, Hekla volcano in Iceland erupts with a 10-year period lava whose composition reflects rapid transit through the crust, however it also erupts material that shows evidence of longer-term storage with a larger eruptive period [2].

It is safe to say that neither type of emergent organization is well understood. Data is incomplete due to erosion of surface rocks over time and incomplete dating. And the physics of volcanic processes are themselves poorly constrained, coupling reactive multiphase fluid flow, heat transfer and solid mechanics over a broad range of spatial and time scales. We have a solid understanding of the pathways by which rocks melt, and the equilibrium thermodynamics of magma evolution. However, large-scale melt transport is always a non-equilibrium process in some sense, making classical theory an approximation at best. As many of the geologic structures observed on the Earth’s surface are integrated frozen records of melt transport, a mechanistic understanding of volcanologic processes is a prerequisite for deep understanding of geologic deposits. As it stands, we do not understand how even granodiorite, the most common rock type exposed on continents, arises because we do not understand the physics of the magma bodies that freeze to make this rock.
Most current theoretical work in understanding the processes magma transport in the crust utilizes the toolbox of continuum mechanics, which often involves finding numerical solutions to coupled nonlinear partial differential conservation equations [e.g., 3]. This work is important, as it helps to define the most important parameters and processes, and provides models that can be tested against field observations and laboratory experiments. However, the framework of continuum mechanics is insufficient to deeply understand the emergent dynamics of integrated magmatic systems, because of the incredible stiff differential equations that govern processes that interact over such a large range of space and time.

We are developing a complex networks approach to this problem as a way to study the consequences of interactions between components of the magmatic system as a whole. This approach provides a way to connect volcanologic field data in a probabilistic way to theory, and by so doing study the episodic nature of large volcanic events throughout Earth’s history. We utilize data from the Western United States, the so-called Navdat database [4], which contains locations, dates, as well as major and trace element composition information for volcanic rocks that span the last 60 million years. This dataset, while still fraught with preservation issues and sampling biases, is currently the most complete record of volcanism at a continental scale. We initially focus on the last 5 million years (the Pliocene Epoch) to minimize data gaps (Figure 1), and will also focus on geographic subsets of the entire Navdat database that are particularly well-sampled: the cascade volcanoes in the NW United States, and the Yellowstone hotspot track in Idaho and Wyoming.

This study is still in a preliminary phase, following two different approaches. The first, an inference-type model, utilizes the network inference methods developed by Gomez-Rodriguez et al. [5], whose initial application was studying information diffusion in social networks. This approach will be used to test genetic relationships between volcanoes that have well-documented timeseries, and will be used to infer the topological evolution of the volcanic plumbing system over million-year timescales. The network inference algorithm (detailed in [5]) will be supplemented by geologic models for the probability distribution of pairwise interaction between each volcano considered. These distributions will take into account data on the pathways chemical evolution of the magma at each volcano, the volume of erupted magma, and the physical separation between volcanoes.

The second approach is a “forward-type” model, in which we construct a network where nodes are state-changes in the magmatic system: transitions from reactive melt channels to elastic fractures, or to magma chambers that store melt for a period of time before erupting to the surface through volcanic conduits. These state changes form a kind of irreversible Markov process, in which a certain ensemble of states is available to choose from at different depths and times within the Earth’s crust. Local thermodynamic conditions and the local stress field determine the state chosen by the magmatic system. Transport times are calculated using simple parameterizations of flow processes, such as magma transport in elastic-walled cracks. Both may be cast into a cascade model similar to [6]. In this way, we include well-studied physics of particular space and time scales in the magmatic system, but are free from the numerical limitations of a fully coupled conservation of mass, momentum and energy for the entire transport problem. This type
of model may also be constrained by observed surface eruptions, but we can study a broader range of possible dynamics as well.

By any definition, volcanism on Earth or other planets is a complex system. Magma transport is a highly dissipative, nonlinear process, so it is natural to look for cyclic behavior, chaos, and other emergent dynamics that are difficult to identify in the rock record or so uncommon that we have little basis for understanding them. A complex networks modeling approach that is well grounded in the geochemistry, physical volcanology and tectonics that form the basis of our general understanding of this phenomena seems to hold great promise.

**Locations of Pleocene volcanism in the Western United States**

![Maps showing locations of Pleocene volcanism](image)

Figure 1. Distribution of volcanism throughout the Pliocene Epoch, taken from the Navdat database. Data preservation is clearly an issue in the older time intervals.


