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Toward a unified dynamic model for dykes and cone sheets in volcanic systems

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Igneous sheet intrusions, such as dykes and cone sheets, represent various geometries of magma channels through the crust. In many volcanoes, they coexist as parts of complex plumbing systems and are likely fed by common sources. How they form is fundamental regarding volcanic hazards, but yet no dynamic model simulates and predicts satisfactorily the diversity of sheet intrusions observed in volcanic systems. Here we present scaled laboratory experiments that reproduced dyke and cone sheet intrusion geometries under controlled conditions. Combined to a parametric study, a dimensional analysis shows that two dimensionless numbers $\Pi 1$ and $\Pi 2$ govern the formation of these intrusions. $\Pi 1$ is geometrical and describes the geometry of the magma source; $\Pi 2$ is dynamical and compares the local viscous stresses in the flowing magma to the host-rock strength. Plotting our experiments against these two numbers results in a phase diagram evidencing a dyke and a cone-sheet field, separated by a sharp transition that fits a power law. This result shows that dykes and cone sheets correspond to two distinct physical regimes of magma emplacement in the Earth's crust. Cone sheets preferentially form when their source is shallow relative to their size, when the magma influx (or viscosity) is large, or when the host rock is weak. In addition, both dykes and cone sheets may form from the same source, the shift from one regime to the other being then controlled by magma dynamics, i.e. different values of $\Pi 2$. We compare our phase diagram to geological data and show that the extrapolated empirical dyke-to-cone sheet transition predicts the occurrence of dykes and cone sheets in various natural volcanic settings. This study thus provides a unified dynamic model of sheet intrusions emplacement and captures fundamental mechanisms of magma transport in the Earth's crust.