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Swarm Theory, Hydraulic Fracturing, and the Emergence of Natural Spacing within Dyke Swarms

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Like all swarming behavior in Nature, the self-organization expressed by the emergence of a natural spacing among a swarm's members should be considered its most fundamental characteristic, and grasping the mechanics governing the swarming behavior is synonymous with grasping the drivers that lead to the emergent spacing. This presentation will tell the story of a recent research effort aimed at finding the ingredients required for swarming behavior to occur in systems of fluid-driven cracks such as dykes and hydraulic fractures.

At first one might expect relatively analogous behavior between swarms of dykes and swarms of man-made hydraulic fractures. After all, the mathematical models used to describe these processes are strikingly similar (e.g. Lister, 1990 compared with e.g. Khristianovic and Zheltov, 1955). However, the typical observed behaviors of the natural and manmade systems are substantially different. One the one hand, hundreds to thousands of dykes often cluster together as swarms, possibly with many dykes growing at the same time so that the number of dykes exceeds the number of discrete magma pulses. On the other hand hydraulic fractures tend to localize to one or two dominant strands and, in the absence of mechanical isolation of already-fractured regions, subsequent pulses of injection are not typically found to produce spatially-distributed swarms-like collections of hydraulic fractures.

Hydraulic fracturing has an extensive history of applications including quarrying/mining (since the 1890s), gas and oil extraction (since 1949), and Enhanced Geothermal Systems ("EGS", since the early 1970s). With perhaps only one notable exception, the Barnett Shale in Texas, this experience points to a mechanical system that tends to favor localization of fracture growth to one or two dominant hydraulic fractures rather than propagation of many simultaneous branches. This is in spite of four decades of attempts to generate complex networks of hydraulic fractures for EGS applications and more than a decade of efforts to generate Barnett-like networks of hydraulic fractures in other shale gas reservoirs. Man-made hydraulic fractures seem highly prone to localization.

On the other hand, there are more than 400 known examples of giant dyke swarms on Earth, Venus, and Mars (e.g. Ernst et al., 1995). These stunning features comprise hundreds to thousands of subparallel to radiating dykes that originate from a common source region and that potentially have grown in episodes involving multiple, and possibly concurrently-growing dykes. So, in contrast to man-made systems, these natural systems of fluid (magma)-driven cracks appear to favor swarming dynamics rather than localization.

In this presentation we will argue that swarming behavior in systems of dykes and hydraulic fractures requires the same three ingredients found in any system that exhibits swarming. These are (Reynolds, 1987): 1)

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Alignment force, 2) Avoidance force, and 3) Attraction force.

It has long been understood that the alignment of dykes is driven by the predominant in-situ stress field. The avoidance force has also been previously related to the stresses induced by dyke intrusion, leading to a tendency for dykes to avoid growing in close proximity to one another. We propose that the missing ingredient has been a basic understanding of the attractive force in these systems, that is, why fluid-driven cracks would have any mechanical impetus to grow near one another in the first place. Here we show that this key element of the system depends on geometry and the relative importance of viscous energy dissipation in the context of the energy balance of the system (Bunger et al., 2013). By understanding these fundamental drivers, future studies of dyke swarm morphology will provide insight into the mechanical properties of the crust and magma at the time of emplacement, as well as for application of dyke swarm theory to the optimization of industrial hydraulic fracturing.

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