Instability of an infiltration-driven dissolution-precipitation front with a nonmonotonic porosity profile

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Infiltration of a rock by an external fluid very often drives it out of chemical equilibrium. As a result, alteration of the rock mineral composition occurs. It does not however proceed uniformly in the entire rock volume. Instead, one or more reaction fronts are formed, which are zones of increased chemical activity, separating the altered (product) rock from the yet unaltered (primary) one. The reaction fronts propagate with velocities which are usually much smaller than those of the infiltrating fluid. One of the simplest examples of such alteration is the dissolution of some of the minerals building the primary rock. For instance, calcium carbonate minerals in the rock matrix can be dissolved by infiltrating acidic fluids. In such a case the product rock has higher porosity and permeability than the primary one. Due to positive feedbacks between the reactant transport, fluid flow, and porosity generation, the reaction fronts in porosity-generating replacement systems are inherently unstable. An arbitrarily small protrusion of the front gets magnified and develops into a highly porous finger-like or funnel-like structure. This feature of dissolution fronts, dubbed the "reactive-infiltration instability" [1], is responsible for the formation of a number of geological patterns, such as solution pipes or various karst forms. It is also of practical importance, since spontaneous front breakup and development of localized highly porous flow paths (a.k.a. "wormholes") is favourable by petroleum engineers, who apply acidization to oil-bearing reservoirs in order to increase their permeability.

However, more complex chemical reactions might occur during infiltration of a rock by a fluid. In principle, the products of dissolution might react with other species present either in the fluid or in the rock and reprecipitate [2]. The dissolution and precipitation fronts develop and and begin to propagate with equal velocities, forming a single dissolution-precipitation front. The porosity profile is not monotonic as in the case of pure dissolution, but it typically has a minimum in the vicinity of the front. Additionally, the porosity difference between the initial rock far-downstream and the well-developed secondary rock far-upstream can be either negative or positive, which either destabilizes of stabilized the front.

We propose a theoretical model of a simple infiltration-driven dissolution-precipitation system and find the morphology of the resulting planar reaction front. By performing linear stability analysis of the stationary planar solutions we show that the front can be unstable for a wide range of control parameters, even if the porosity of the secondary rock is lower than the porosity of the primary rock. Next, by numerical simulations of the full nonlinear model we present the long-term evolution of the system.

[1] D. Chadam et al., IMA J. Appl. Math. 36, 207-221, 1986.
[2] A. Putnis, Rev. Mineral. Geochemistry, 70(1), 87–124, 2009.