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Salinity-induced melting of underlaying permafrost

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The rise of sea levels and the expansion of plateau salt lakes are among major consequences of the ongoing climate change[1]. When saline water overlays above permafrost (ice in porous soil), ice may melt because salinity reduces the melting/freezing point. Permafrost melting may alter the mechanical properties of the soil and affect the safety of coastal structures[1], and even may induce the release of underground methane gas into the atmosphere[2]. Therefore, studying the kinetics of salinity-induced melting of underlaying permafrost is of great environmental significance.

We conducted visualized experiments to study the kinetics of permafrost melting induced by overlying saline water. Water in bead-pack is first frozen to mimic permafrost and then is immersed under excessive saline water at -5℃. Glass bead diameter varies from 0.1mm to 0.5mm, and salt concentration varies from 10wt% to 25wt%. Melting front (ice-water interface) in porous media can be visually identified (Figure 1(a)) and recorded by camera. As the dilute saline water at the melting front is of lower density than the overlying saline water, Rayleigh-Darcy convection is induced in the porous medium[3,4], so we use Rayleigh number (ratio of gravitational-induced flux over diffusion), Ra, to characterize the mass transfer in liquid-saturated porous layer[5].

Surprisingly, we found two distinct melting patterns: 1) when Ra is high, the melting front is flat and moves down stably; 2) when Ra is low, "fingers"emerge and develop at melting front. This seems to be different from the previous research results that greater Ra implies higher instability[6–8].

We theoretically show that the melting pattern is a result of interplay between local circumflux shaped by the melting front perturbation and the global Rayleigh-Darcy convection (Figure 1(b)). When a perturbation emerges at the front, density contrast induces local convection from the trough to the peak, that further enlarge the perturbation (Figure 1(c)). This local convection is proportional to Ra. Meanwhile, global Rayleigh-Darcy convection enhances lateral mixing which compress the development of the perturbation. This lateral mixing is proportional to Ra^(1.5~2). As a result, when Ra is low, melting is dominated by the local circumflux and fingers grow; when Ra is high, strong lateral mixing homogenizes concentrations along the solid-liquid interface and results in flat melting front. Numerical simulations further support the above theory and match the experiments well. When the melting front is flat, the melting rate can be predicted by classical Rayleigh-Darcy convection theory. However, when a fingering melting front forms, the melting rate is one order of magnitude slower than classical theory prediction. Moreover, fingering melting front implies penetration of permafrost layer before melting all ice, that may induce unexpected groundwater pollution and subsurface methane release.

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Primary author: WANG, Yumin

Co-author: Dr XU, Ke (Peking University)

Presenter: WANG, Yumin

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