

ENVIRONMENTAL STUDIES

Permafrost thawing under overlaying salt water

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Thawing of permafrost substantially affects the local environment and global energy balance. When salt water overlays permafrost, Rayleigh-Darcy (R-D) instability emerges because of the density mismatch and regulates melting (thawing) dynamics. Contrary to expectations that a higher Rayleigh number (R) would amplify instability, our experiments revealed fingering and stable melting fronts at low and high R , respectively. We attribute the occurrence of the two melting patterns to the interplay between two competing flow structures: local circumfluence modulated by front perturbation and transversal chaotic mixing. We propose theories that rationalize the melting pattern transition and finger-scale evolution. In addition, the classic mass transport theory for R-D convection drastically underestimates the melting rate and misses key variable(s). The presence of fingering patterns and accelerated dynamics may have led to earlier penetration of the permafrost layer than previously anticipated. These findings have implications for understanding similar processes in magma migration, carbon sequestration, and subsurface energy recovery.

INTRODUCTION

Overlying salt water melts the ice in the permafrost layer (subterranean persistent frozen layer) after sea level rise and salt lake expansion (1, 2). As salinity reduces the melting point (3), melting occurs below 0°C, which may amplify global climate change by releasing underground methane (4–8) and threaten the coastal structures and ecosystem (9, 10). In addition, groundwater pollution is known to result from the melting and penetration of high-salinity wastewater into the permafrost layer (11, 12). Despite these environmental and climatic consequences, the dynamics of the melting of ice in porous media caused by overlying salt water remain unclear. Macroscopic modeling must adopt simplified and empirical correlations (1, 9, 13).

The melting of bulk ice immersed in bulk seawater has been extensively studied (14–18), wherein the salinity contrast highly complicates the dynamics. When high-salinity (high-density) water is positioned above low-salinity (low-density) water, convective instability (19, 20) emerges and destabilizes the melting ice interface into a saw-like topology (21–23). This convective instability is characterized by the Rayleigh number (R), defined as the ratio of the gravity-driven advection flux to the static molecular diffusion flux (24–26); it is initiated when the R value exceeds a threshold of approximately 10^{1-2} (25). Experiments and simulations have indicated that a higher R value results in stronger interface instability in bulk seawater (19, 25, 27, 28).

However, the melting of ice in porous media is distinct from that in bulk fluids. In porous media, advection follows Darcy's law (29), which reshapes the gravitational convective instability into Rayleigh-Darcy (R-D, or Horton-Rogers-Lapwood) instability (26, 30). Moreover, scale- and velocity-dependent mechanical dispersion (31) largely

modifies convective mixing in porous media (32). Unfortunately, despite the numerous studies on the transport behavior transfer in porous media with R-D instability (26–30, 33–37), how it shapes melting dynamics is still largely unexplored owing to the lack of direct experimental observations and limitations of computational capacities (33).

In this study, we conducted visualization experiments in a porous Hele-Shaw cell to provide a direct physical picture of ice melting in porous media overlaid with salt water. We aimed to answer two major questions: (i) how the melting front morphology evolves in response to the mechanical, fluidic, and transport behaviors that regulate it; and (ii) how fast the ice melts, which is required to evaluate the environmental energy balance. A numerical simulation was conducted to demonstrate the details of fluid flow and mass transfer, and theories were proposed to rationalize the experimental observations.

RESULTS

Visualization experiments

We prepared a permafrost (MP) model using a glass bead pack that was presaturated with water and prefrozen. Subsequently, we fixed the temperature of the system at -5°C , filled the space above the porous medium with precooled salt water, and recorded the melting process. The experimental setup and corresponding dimensions are shown in Fig. 1. We assume isothermal conditions during the melting process, as rationalized in Materials and Methods; thus, salinity is the only driving force of melting and sole origin of the fluid density contrast. Sodium chloride (NaCl) was used to adjust brine density. In addition, 5 wt % copper sulfate (CuSO_4) and 2.5 wt % hydrogen chloride (HCl) were added in every experiment to enhance visualization. Here, “salinity” is only referred to the weight percentage of NaCl for clarity.

The initial saltwater density (ρ_b , corresponding to salinity c_b) is higher than that of salt water in equilibrium with ice under the experimental temperature (denoted by ρ_{eq} , corresponding to salinity c_{eq}); thus, R-D instability is expected at an adequately large R value. We define the terminate Rayleigh number as $R = Hu / \phi D$ (33), where H is the height of the porous medium, u is the characteristic fluid velocity, $\phi = 0.42$ is the porosity of the porous medium, and $D = 2.29 \times 10^{-10} \text{ m}^2/\text{s}$ is the salt molecular diffusion coefficient in

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water (38, 39). Equivalent salinity c_{eq} is measured as 5.2 ± 0.5 wt %. The characteristic velocity u can be estimated by Darcy's law as $u = k\Delta\rho g/\mu$, where g is the gravitational acceleration, $\Delta\rho = \rho_b - \rho_{eq}$ is the global density contrast, $\mu = 1.79 \times 10^{-3}$ Pa·s is the fluid viscosity, and k is the permeability of the porous medium calculated by the Carman-Kozeny equation as $k = d^2\phi^3 / 108(1 - \phi)^2$ (40), with the bead diameter denoted by d . Notably, ρ_b (thus $\Delta\rho$) mildly reduces during melting owing to dilution, which can be calibrated by mass conservation. The change of ϕ is negligible during freezing and the porous structure does not change during melting, as shown in fig. S1 and presented in section S2 in the Supplementary Materials.

We varied R across multiple orders of magnitude in our experiments from 3113 to 175,880 as presented in Table 1. We measured the evolution of the melting ratio S , which is defined as the ratio of the melted porous zone to the total porous area.

Description of melting patterns

Melting patterns were visually identified. With a small bead size and low salinity (Exp. 1, $d = 0.1$ mm and $c_b = 10$ wt %), prominent fingers emerge and grow, as shown in Fig. 2A. Conversely, with a large bead size and high salinity (Exp. 9, $d = 0.5$ mm and $c_b = 20$ wt %), the melting front remained horizontally stable with some fluctuation, as shown in Fig. 2B. We recorded the evolution of the temporal melting front for all the experiments in Fig. 2C, which shows a clear trend: Increasing the bead size and salinity suppressed the development of the fingering melting front. In particular, the melting front unstably and stably evolved at low and high R , respectively.

The melting front morphology is analyzed using fast Fourier transform (FFT), where we extract amplitude (e_i) for each frequency (f_i) component and calculate the dominant wavelength ($\lambda = \sum e_i^2 / \sum f_i e_i^2$) and maximum wave amplitude (e_{max}) of the

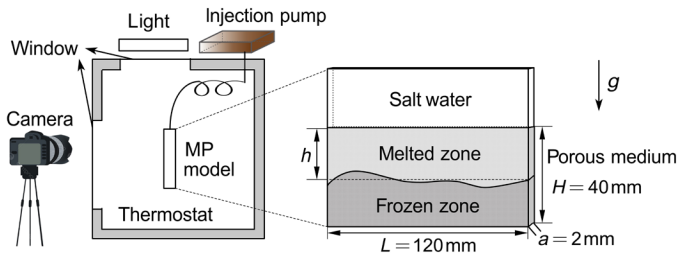


Fig. 1. Experimental setup. Light is placed outside the thermostat to avoid its thermal effect. At the beginning of the experiment, 17 ml of saline water in the precooled tube was injected at once into the permafrost (MP) model using an injection pump. A camera is used to record the melting process.

wavy front. We present the detailed wavelength analysis and data acquisition method in Materials and Methods. Figure 2D shows the evolution of e_{max} with the melt depth (h) for small R values (Exps. 1, 2, 3, and 4), showing a nearly exponential increase in e_{max} . In contrast, the increase in e_{max} with h in the high R experiments (Exps. 5, 6, 7, 8, and 9) was limited, as shown in Fig. 2E. Their qualitatively distinctive behaviors are as follows: Although all experiments show the emergence of front morphology fluctuation at the beginning, the maximum amplitude e_{max} of fingers in Exps. 1 to 4 continues to grow in a near exponential mode, whereas finger growth in Exps. 5 to 9 is “frozen” when the melting depth further increases.

Notably, this trend is in contrast to that characterizing R-D convection, wherein instability is enhanced with higher R . It is also distinct from bulk ice melting in that increasing R amplifies the melting front instability (22). In section S3 of the Supplementary Materials, we also eliminate the possibility of finite-size effect in presenting the “stable” front.

Identification of flow structures through numerical simulation

We used numerical modeling to identify the mechanisms underlying this counterintuitive melting pattern transition. A comprehensive simulation of ice melting in porous media is technically challenging. A recent numerical simulation reproduces the fingering pattern at a low R end (41); however, increasing R requires an extremely high computational cost. Fortunately, the pseudo-steady-state assumption is valid in this process (see the Materials and Methods section). This allows the melting front to be fixed as the bottom boundary and solves only the mass flux in the melt zone. Steady-state mass flux helps determine how the perturbation further increases or diminishes.

Pseudo-steady-state simulations were conducted using the COMSOL software. We set the bottom boundary of the melted zone as a sine wave with a wavelength of $\lambda = 1.25 \times 10^{-2}$ m and amplitude of $e = 5 \times 10^{-4}$ m. This morphology was extracted from typical experimental observations for demonstration. The concentration at the bottom boundary is fixed at c_{eq} with density ρ_{eq} ; the right and left boundaries are periodic; the upper boundary is fixed at c_b with density ρ_b . The initial concentration in the domain is c_b with density ρ_b . The R value was varied by adjusting the permeability k . The flow field was captured at a statistically steady state. Simulation details are presented in section S4 of the Supplementary Materials. Two distinctive flow structures at low and high R values are identified:

- 1) When $R = 10$, a regular and stable local circumfluence emerged at the bottom boundary when a perturbation was present (Fig. 3A),

Table 1. Experiment numbers and parameters.									
Exp. #	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 6	Exp. 7	Exp. 8	Exp. 9
d (mm)	0.1	0.1	0.1	0.3	0.3	0.3	0.5	0.5	0.5
c_b (wt % NaCl)	10	15	20	10	15	20	10	15	20
k (10^{-11} m ²)	2.04	2.04	2.04	18.4	18.4	18.4	51.0	51.0	51.0
$\Delta\rho$ (kg/m ³)	89.9	131.1	174.2	89.9	131.1	174.2	89.9	131.1	174.2
R	3113	5030	7035	28,015	45,268	63,317	77,820	125,745	175,880

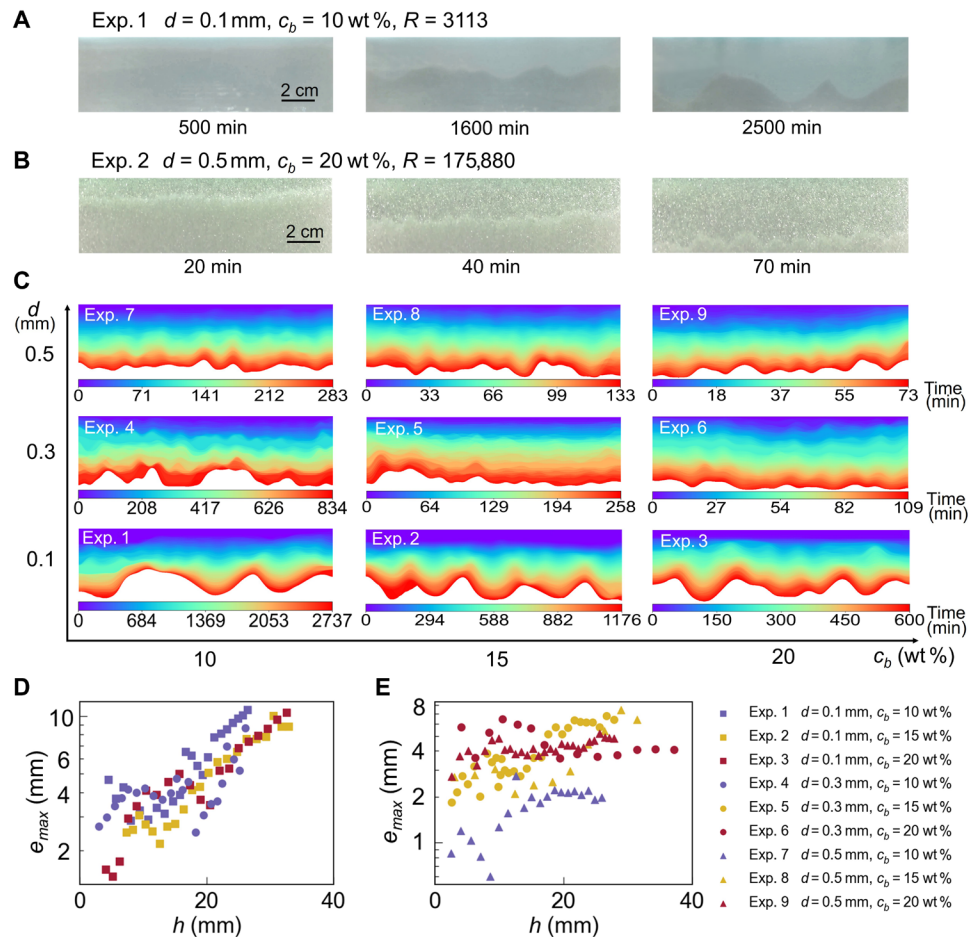


Fig. 2. Melting front patterns. (A) Front development of fingering melting in Exp. 1, when the bead size is 0.1 mm and salinity is 10 wt %, corresponding to $R = 3113$. (B) Stable melting front development in Exp. 9, when the bead size is 0.5 mm and salinity is 20 wt %, corresponding to $R = 175,880$. (C) Temporal evolution of the melting front for all experiments. Notably, the finger magnitude decreases with higher salinity and larger particle size. (D) Evolution of maximum amplification $e_{\max}$ with melted depth h for Exps. 1 to 4 (low R); a nearly exponential increase is observed. (E) Evolution of maximum amplification $e_{\max}$ with melted depth h for Exps. 5 to 9 (high R). This indicates fluctuation emergence at the beginning but no further growth in the latter stage.

whereas no flow was observed if the bottom boundary was straight (Fig. 3B). The absence of convection at low R values for a straight boundary aligns with the classic R-D instability theory.

2) When $R = 100,000$, chaotic and fluctuating convection occurred globally, regardless of whether geometric perturbations existed (Fig. 3, C and D). In particular, convective envelopes considerably smaller than λ are observed at the bottom boundary, as shown in Fig. 3C, indicating that the perturbation loses its regulation on convection.

The local circumfluence at low R brings high salinity water down to the trough, where salt water becomes diluted and subsequently flows to the crest along the bottom boundary: The liquid at the crest (point a* in Fig. 3E) and trough surfaces (point b* in Fig. 3E) is at an equilibrium with the ice (thus, of lower density ρ_{eq}), whereas that above the trough at the same latitude as the crest (point c* in Fig. 3E) is of higher density. This local density contrast drives convection from point C to B and subsequently to point A along the bottom boundary. Consequently, the trough has a stronger mass transfer flux than the crest. Thus, the perturbation is amplified and the fingers develop.

In contrast, the global chaotic convection at high R values largely homogenizes the horizontal concentration field, as illustrated in Fig. 3F. This uniform mass flux along the bottom boundary limits the development of perturbation, and the fingers are suppressed.

Spatial variation in the bottom boundary flux supports this physical picture. We quantified the local time-averaged dimensionless mass flux at the bottom boundary, $J_d = \frac{dc}{dy} / \frac{c_b - c_{\text{eq}}}{H}$, and investigated its correlation with the relative position of each sine wave. As shown in Fig. 3G, when $R \leq 3000$, J_d correlates with the location, being higher and lower near the trough and crest, respectively. When $R = 10,000$, J_d becomes spatially uniform and irrelevant to the position. At even larger R , J_d at the crest can be even larger than that at the trough, which implies the trend of flattening the wavy bottom.

Hypothesis

On the basis of experimental and numerical observations, we hypothesized that the transition of the melting front pattern from unstable to stable with increasing R is determined by that of the flow

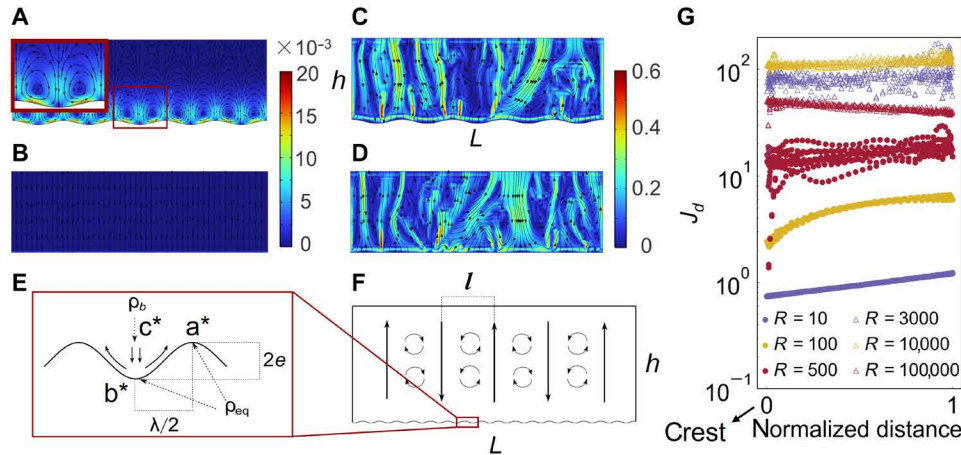


Fig. 3. Fluid flow patterns and mass transfer under different R values captured from pseudo-steady-state numerical simulation. (A) Normalized velocity field when $R = 10$ in the presence of melting interface perturbation. In all velocity field figures, velocity is normalized by u . (B) Normalized velocity field when $R = 10$ when the melting interface is straight. (C) Velocity field when $R = 100,000$ in the presence of melting interface perturbation. (D) Velocity field when $R = 100,000$, with a straight melting interface. (E) Schematic demonstration of the local circumfluence at the melting interface in the presence of bottom boundary perturbation. Point a^* is the crest, b^* is the trough, and c^* is positioned above the trough at the same latitude as the crest. (F) Schematic demonstration of global R-D convection. (G) Dimensionless mass transfer flux at the bottom boundary, from crest to trough under different R values.

pattern from being regulated by the bottom boundary perturbation that amplifies the fingering to perturbation-irrelevant global chaotic convection that homogenizes the melting front.

Setup and key variables for the theories

To validate this hypothesis of pattern transition and establish the theory of finger development, we consider the moment that the melting front achieves depth h , and a sinusoidal perturbation at the bottom boundary with wavelength λ and amplitude e is set to emerge. We set y as the vertical axis pointing upward and $y = 0$ at the bottom. We define the instantaneous R as $R_h = k\Delta\rho gh / \mu D$.

The flow structure during quasi (statistically)–steady-state R-D convection comprises upward- and downward-flowing streams (Fig. 3F), with characteristic velocity u . The distance between neighboring countercurrent streams is denoted by l . The upward (rising; density denoted by ρ_{rise}) and downward (falling; density denoted by ρ_{fall}) streams exchanges mass with the transversal dispersion coefficient D_T .

Effective density contrast

We consider the mass exchange between neighboring countercurrent streams under R-D convection at a steady state. Mass conservation equations of two streams are expressed as $ul \frac{d\rho_{\text{rise}}}{dy} = D_T \frac{\Delta\rho_{\text{local}}}{l}$ and $ul \frac{d\rho_{\text{fall}}}{dy} = D_T \frac{\Delta\rho_{\text{local}}}{l}$. The boundary conditions are set as $\rho_{\text{rise}}(y=0) = \rho_{\text{eq}}$ and $\rho_{\text{fall}}(y=h) = \rho_b$; we determined that local density contrast ($\Delta\rho_{\text{local}} = \rho_{\text{fall}} - \rho_{\text{rise}}$) is a constant smaller than $\Delta\rho$, wherein the exact solution is $\Delta\rho_{\text{local}} = \Delta\rho / \left(1 + \frac{h^2}{l^2} \frac{D_T}{D} R_h^{-1}\right)$.

Characteristic mass transport length

Theories on R-D convection without bottom boundary perturbation indicates that l reduces with increasing R_h as $l = l_0 R_h^{-c}$, with c being estimated as 5/14 and 1/2 for two-dimensional (2D) and 3D cases, respectively, when $R_h > 10^3$ (35, 42). We expect that this negative correlation will still hold at an adequately high R_h when a bottom boundary perturbation is present. However, at low R_h with bottom boundary perturbation, convection is regulated by the perturbation wavelength (λ) as $l \sim \lambda$.

Dispersion coefficient

For experimental and practical conditions when $R_h \gg 1$, advection dominates over molecular diffusion in mass transfer. In addition, two geometric length scales exist in the system: bead size and depth. Therefore, we formulate the transversal dispersion coefficient as $D_T / D = \alpha_T (ud/D) = \alpha (h/d)^\beta (R_h d/h)$, where $\alpha_T = \alpha (h/d)^\beta$ is the transverse dispersivity (29, 43, 44), with $0 < \beta \leq 1$ being the scale-dependent index that is reported to be close to 1 (45–49).

Bottom flow velocity

For $\lambda \gg e$, the characteristic distance of perturbation-induced flow is approximately $\lambda/2$ and the hydrostatic pressure difference is $2\Delta\rho_{\text{local}}ge$; thus, the Darcy velocity of bottom flow is $u_{\text{bottom}} = \frac{k}{\mu} \frac{2\Delta\rho_{\text{local}}ge}{\lambda/2} = 4DR_h \left(\frac{\Delta\rho_{\text{local}}}{\Delta\rho}\right) \frac{e}{\lambda h}$.

Effective Peclet number for bottom flow

We define $Pe_{\text{bottom}} = u_{\text{bottom}}\lambda / D_T$ as the effective Peclet number for bottom flow. This characterizes the relative importance of Darcy advection and mechanical dispersion at the perturbed bottom boundary. We can easily prove that $Pe_{\text{bottom}} \propto e / (h^\beta d^{1-\beta} + \alpha h^{1+2\beta} d^{2-2\beta} l^{-2})$ is negatively correlated with R_h . This negative R_h dependency of Pe_{bottom} is physically plausible: increasing h enhances dispersion but suppresses bottom flow by decreasing $\Delta\rho_{\text{local}}$; increasing d ($\propto k^{1/2}$) simultaneously reduces flow and dispersion resistance; reducing l (by increasing R_h) enhances dispersion. Pe_{bottom} is infinitely large when h or d (and thus R_h) are close to zero, and approximately zero when h , d , or R_h approximates infinity. In summary, stronger gravitational convection increases the relative importance of dispersion over advection for mass transport.

Theory on pattern transition

The characteristic times of the two flow structures were compared. For perturbation-modulated local circumfluence, the characteristic time to flow across half the wavelength is estimated as $\tau_{\text{lc}} = \lambda / u_{\text{bottom}}$. For horizontal mixing, the characteristic time τ_{mix} is estimated using the classical diffusive timescale, $\tau_{\text{mix}} = l^2 / D_T$. Subsequently, we obtain

$$\frac{\tau_{lc}}{\tau_{mix}} = \frac{\lambda^2}{l^2} P e_{bottom}^{-1} \quad (1)$$

We can prove that τ_{lc}/τ_{mix} is positively correlated with R_h . Our hypotheses and observations are well rationalized with Eq. 1:

1) At adequately small R_h , h , and d , $\tau_{lc}/\tau_{mix} \ll 1$ because $P e_{bottom} \rightarrow 0$ and $l \sim \lambda$. Under this condition, the perturbation-modulated circumfluence dominates the global R-D convection and therefore amplifies the perturbation.

2) At adequately high R_h , h , and d , $\tau_{lc}/\tau_{mix} \gg 1$ because $P e_{bottom} \rightarrow +\infty$ and $l \propto R_h^{-c}$. Under this condition, global horizontal mixing dominates and homogenizing the melting front.

Notably, the magnitude of τ_{lc}/τ_{mix} is also sensitive to the perturbation amplitude, e . Larger e results in higher $P e_{bottom}$ and thus smaller τ_{lc}/τ_{mix} . Therefore, a finger may develop even at large R_h , h , and d from a previously stable melting front if a major perturbation or heterogeneity occurs.

Theory on the finger scale

We assume that λ corresponds to the fastest growing wavelength of the perturbation (50, 51). At melt depth h and any small amplitude e , the finger growth strength can be characterized by advection mass transport along the local circumflex (Fig. 3E), which is estimated as $J_{finger} = u_{bottom} \Delta \rho_{local} = \frac{4eD}{\Delta \rho} R_h h^{-1} \lambda^{-1} \Delta \rho_{local}^2$. Here, we only consider the wavelength at the low R_h regime, such that the perturbation does regulate the global convection structure and $l \sim \lambda$. The dominant wavelength can thus be calculated by $dJ_{finger}/d\lambda = 0$ as

$$\lambda = \left(3 \frac{D_T}{D} \frac{h^2}{R_h} \right)^{\frac{1}{2}} = \sqrt{3\alpha} h^{\frac{1+\beta}{2}} d^{\frac{1-\beta}{2}} \quad (2)$$

The performance of Eq. 2 in predicting the melting finger wavelengths:

1) As expressed in Eq. 2, λ increases with increasing h with the scaling of $(1+\beta)/2$. This scaling was measured to be ~ 1 for the experiments with a fingering front (Fig. 4A). This implies that β is close to 1. No clear scaling was identified in the experiments with a stable melting front (Fig. 4B).

2) We derive that $\Delta \rho_{local}/\Delta \rho = 3/4$ under a dominant wavelength; thus, $J_{finger} \propto h^{-\frac{1+\beta}{2}} k^{1-\frac{1-\beta}{2}} \Delta \rho^2 e$. As $J_{finger} \propto \frac{de}{dt}$, subsequently, we obtain $\frac{de}{dt} \propto k^{1-\frac{1-\beta}{2}} \Delta \rho^2 h^{-\frac{1+\beta}{2}} e$. Assuming constant $\Delta \rho$, $\beta = 1$, and a constant melting rate (supported by the measurement presented in next section), we obtain $\ln e \propto \ln t$. This linear correlation was observed in experiments with a fingering front (Fig. 4C), where we use e_{max} to characterize e . This was not observed in experiments with a stable front (Fig. 4D).

3) As expressed in Eq. 2, λ is unaffected by the driving force ($\Delta \rho$) and is only weakly affected by the bead size (d) with the scaling of $(1-\beta)/2$. Notably, $(1-\beta)/2 \sim 0$ if $\beta \sim 1$. These inferences are supported by the experimental measurement shown in Fig. 4 (E and F), wherein λ has no clear dependency on $\Delta \rho$ and d .

We emphasize that the aforementioned theory is valid only when $e \ll h$ and when R is below a critical point, such that $l \sim \lambda$.

Analysis on melting dynamics

We quantified the melting rates (evolution of S with time t) in all experiments, as shown in Fig. 5A. We observed nearly proportional

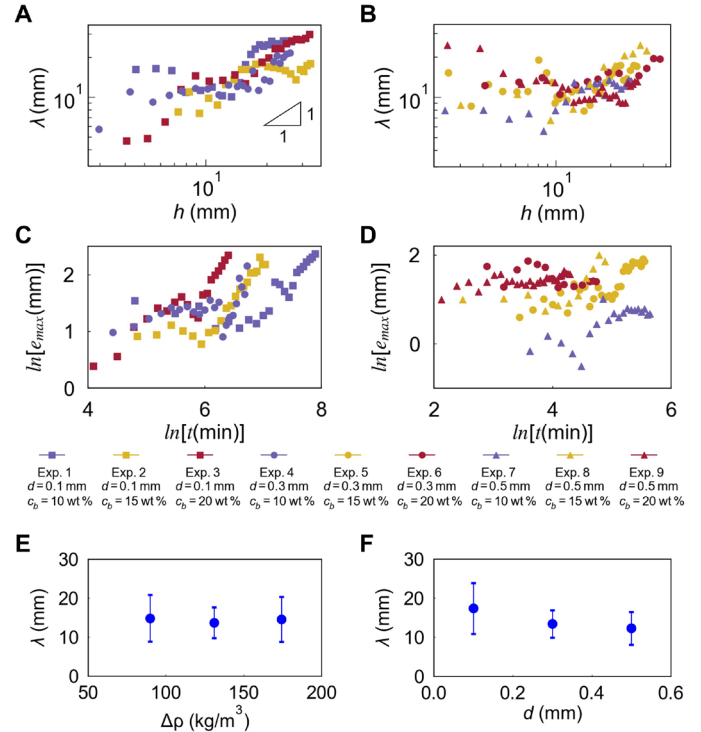


Fig. 4. Finger-scale analysis. (A) Wavelength λ evolution with melted depth h in Exps. 1 to 4, showing low R and an unstable melting pattern. A statistical proportional correlation can be identified. (B) Wavelength λ evolution with melted depth h in Exps. 5 to 9, showing high R and a stable melting pattern. (C) Temporal evolution of maximum amplitude e_{max} in Exps. 1 to 4, where we can identify near-linear correlation. (D) Temporal evolution of maximum amplitude e_{max} in Exps. 5 to 9, where no clear trend is identified. (E) Statistics of wavelength λ with different density contrasts $\Delta \rho$, where no convincing dependency can be identified. (F) Statistics of wavelength λ with different bead sizes d , where no convincing dependency can be identified.

S - t curves in all cases, regardless of the melting pattern. We subsequently characterize the mass transfer dynamics by the Sherwood number $Sh = F_c/F_d$, where $F_c = \phi \frac{dS}{Ldt} c_{eq}$ and $F_d = \phi D \frac{c_b - c_{eq}}{h}$ are the experimentally measured salt flux and equivalent salt diffusion flux in the absence of convection, respectively. Recent theoretical and numerical investigations of R-D instability with straight bottom boundaries claim that Sh/R_h at statistically steady-state continuously declines smoothly with increasing R_h and converges to a constant at high R_h (27, 28, 33, 42).

However, straight-boundary theories failed to match our experimental data, as shown in Fig. 5B. The value of Sh/R_h in every experiment is only similar to that in the straight-boundary theories (28, 42) at the very beginning and subsequently increases by an order of magnitude. Notably, Sh/R_h is no longer a declining single-variable function of R_h . Instead, the data were divided into three groups corresponding to the three permeability values. This indicates that additional variables besides R_h are required to determine the melting dynamics under R-D convection.

We introduce Darcy's number, $Da = k/h^2$, which characterizes the ratio of two length scales in the system (29); we found that $Sh \propto R_h Da^{-1/3}$ works satisfactorily, as shown in Fig. 5C. This proportionality matched every single experiment, and the data for all

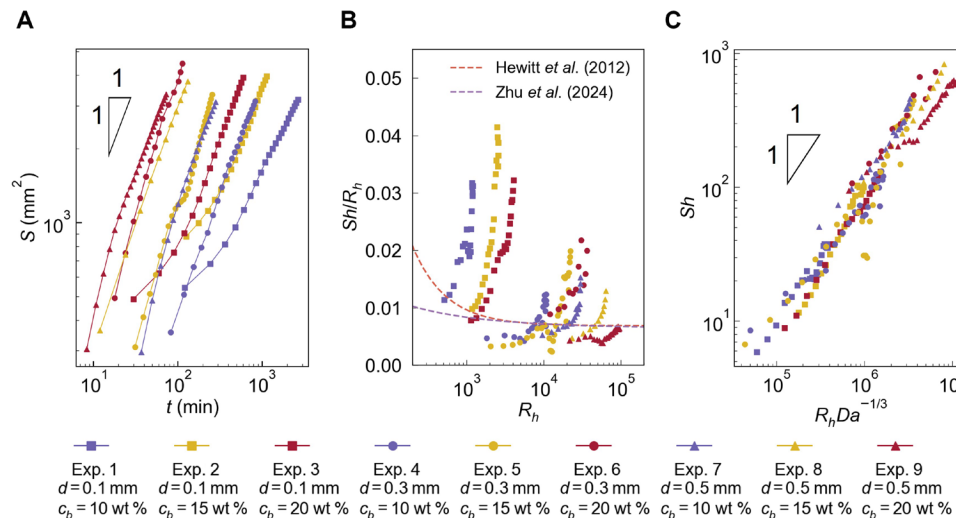


Fig. 5. Quantitative analysis of melting rates. (A) Evolution of melting area S with time t , where both axes are in the log scale. (B) Correlation between Sh/R_h and R_h (33, 42), where data fall into three distinct groups based on permeability k and qualitatively deviate from those predicted by classical correlations assuming a straight boundary (28, 42). (C) Correlation between Sh and $R_h Da^{-1/3}$. Data fall into one straight line corresponding to a proportional relationship, regardless of the melting pattern.

experiments collapsed into one line. This correlation may imply that the current theory overlooks mechanical dispersion (32), which is sensitive to $\Delta\rho$ and is scale dependent. Further theoretical and experimental studies are required to fully resolve the melting dynamics and rationalize the experimental observations.

DISCUSSION

We experimentally investigated the melting of ice in porous media induced by overlaying high-salinity water, where R-D convection controlled the melting dynamics. We discovered unstable and stable fingering melting fronts under low and high R values, respectively, which is contrary to those in R-D convection, where a higher R results in stronger instability. We attribute this observation to the dynamic interplay between two distinct flow structures when a perturbation emerges at the melting front: (i) perturbation-modulated stable bottom circumfluence that amplifies fingers and (ii) global convective horizontal mixing that suppresses fingers. The former and latter dominated at low and high R values, respectively. We further propose a finger-scale theory that effectively predicts the evolution of the wavelength with increasing melt depth.

With this previously unknown fingering melting, the frozen layer may have penetrated without complete thawing. Consequently, the hydrodynamic pathway connecting the surface environment and subpermafrost zone can be established much earlier than previously anticipated. This has led to unexpected environmental and climatic concerns. In addition, the melting rate can be up to four times faster than that predicted by the mass transfer theory for straight-boundary R-D convection. Models for energy exchange between the permafrost layer and environment require recalibration.

Such fingering liquid-solid transition fronts shaped by gravitational convection may also occur in other critical geological scenarios, such as volcanic evolution, carbon subsurface sequestration, and heavy oil recovery, as discussed in section S5 of the Supplementary Materials.

MATERIALS AND METHODS

Experimental design

The experiments were conducted using a VT6003 thermostat. We used Camera Ordoro AC7 for visualization, and a light-emitting diode is positioned at the top. The porous region had a width L of 6 cm, height H of 4 cm, and thickness a of 2 mm. The glass wall thickness of the Hele-Shaw cell is $b = 1$ mm. Each experiment was conducted in the following three steps:

1) MP model preparation: Deionized water is saturated into a package of spherical glass beads (porosity $\phi = 0.42$) in a Hele-Shaw cell. Subsequently, the system is frozen at -5°C . We vary the glass bead diameter d to adjust the permeability of porous media according to the Carmon-Kozeny equation as $k = \frac{\phi^3}{108(1-\phi)^2} d^2$ (40).

2) Melting experiment: We maintain the environment at -5°C and fulfill the overlaying nonporous region in the Hele-Shaw cell with salt water of a desired salinity. Subsequently, melting is initiated. The amount of overlaying salt water (17 ml) was greater than that required to melt all the ice in the cell. We vary saltwater salinity c_b to adjust its density ρ_b . Notably, c_b decreases during the melting process and can be calibrated based on mass conservation.

3) Image analysis: The evolution of the melting front (interface between melted salt water and ice) is identified by a grayscale contrast of captured images using the ImageJ software. Details are available in fig. S2 and section S6 of the Supplementary Materials. We quantify the melted ratio, S , defined as the ratio between the melted porous zone to total porous area. We also measure the melting front length at a resolution of 3 pixels/mm.

Reynolds number Re and Darcy's number Da

Reynolds number $Re = u\rho_b d/\mu$ in all experiments are listed in Table 2. $Re \ll 1$ in all experiments; thus, inertial effects can be ignored. Darcy's number $Da = k/L^2$ in all the experiments are listed in Table 3. $Da \ll 1$ in all experiments; thus, Darcy's law is valid in this study.

Table 2. Reynolds number Re in all experiments.

	$d = 0.1 \text{ mm}$	$d = 0.3 \text{ mm}$	$d = 0.5 \text{ mm}$
$c_b = 10 \text{ wt } \%$	6.182×10^{-4}	1.669×10^{-2}	7.727×10^{-2}
$c_b = 15 \text{ wt } \%$	9.351×10^{-4}	2.525×10^{-2}	1.169×10^{-1}
$c_b = 20 \text{ wt } \%$	1.289×10^{-3}	3.481×10^{-2}	1.612×10^{-1}

Table 3. Darcy's number Da in all experiments.

	$d = 0.1 \text{ mm}$	$d = 0.3 \text{ mm}$	$d = 0.5 \text{ mm}$
Da	1.42×10^{-9}	1.28×10^{-8}	3.54×10^{-8}

Isothermal assumption

The melting is considerably slow, and we can assume that it is isothermal. The following presents a simple estimate used to validate the assumption.

The heat absorbed by melting ice is $q = \gamma A L \phi \rho_i u_{\text{melt}}$, where $\gamma = 3.35 \times 10^5 \text{ J/kg}$ is the latent heat of ice (52), u_{melt} is the measured melting front velocity, and $\rho_i = 917.5 \text{ kg/m}^3$ is the ice density at -5°C . Assuming that heat transfer mainly occurs along the thinnest dimension, we can calculate the temperature contrast using $q = \frac{2A\Delta T}{\frac{1}{\kappa} + \frac{b}{f}}$, where A is the cooling area, $\kappa = 200$ to $1000 \text{ W/(m}^2\cdot\text{K)}$

(53) is the convective heat transfer coefficient of salt water in the buffer where the cell immerses in, $f = 0.77 \text{ W/(m}\cdot\text{K)}$ is the thermal conductivity of glass, and b is the thickness of the glass wall. $A \sim H'L$ where $H' = 9 \text{ cm}$ is the height of the cooling surface of the glass model.

The temperature control accuracy of the setup is 0.1 K . Even for the fastest case in the experiment that $u_{\text{melt}} = 8.3 \times 10^{-6} \text{ m/s}$, we can obtain $\Delta T = 0.025$ to 0.1 K , which is below the temperature control accuracy; for the second fastest case, $\Delta T < 0.06 \text{ K}$; for the slowest case, $\Delta T < 0.003 \text{ K}$. Therefore, the melting of ice in this study can be considered isothermal.

Pseudo-steady-state assumption for the simulation

The actual melting time t_m measured by the experiment is considerably longer than the convective relaxation time t_c , which is calculated as the ratio of H over Darcy velocity $u = k\Delta\rho g/\mu$, as shown in Fig. 6.

Therefore, we propose a pseudo-steady-state hypothesis: The flow field of the melted zone develops to a steady state (or completely developed state with time-averaged features unchanged) before the melting front moves. Thus, we do not need to consider the dynamics of the initialization and development of R-D convection (54) for the demonstrative numerical simulation and can focus only on the “ultimate regime” (28, 33), with a constant density contrast.

Wavelength analysis

Raw data

The melting front morphology was captured by image processing. We analyzed the front using FFT and obtained the frequency-amplitude correlation. Amplitude is made dimensionless by

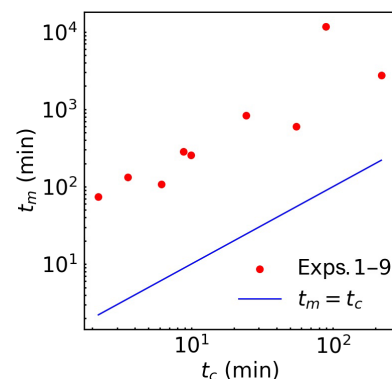


Fig. 6. Validation of the pseudo-steady-state assumption. Experimental melting time t_m for all experiments are recorded and plotted against the characteristic convective relaxation time t_c . We found that $t_m \gg t_c$. The blue line represents the reference line of $t_m = t_c$.

normalization with the cell length, L . For each frequency f_i with amplitude $e_{i, \text{raw}}$, the corresponding wavelength is calculated as $\lambda_i = 1/f_i$. For wavelength λ_i , the corresponding “wave energy” is defined as $f_i e_{i, \text{raw}}^2$, which is an analog from signal processing technologies. We eliminate data for $\lambda_i \geq L$.

Denoising

The discretization of the front morphology into pixels results in long-tail noise at the high-frequency end, which falsifies the wavelength analysis. To quantify the noise, we analyze the high-frequency information ($n_i > 200$) and indicate that $f_i e_{i, \text{raw}}^2$ at high frequency randomly fluctuates around an average P value, with an SD of δE . We subsequently obtain denoised e_i by solving Eq. 3; the details are shown in figs. S3 and S7 in the Supplementary Materials

$$f_i e_i^2 = \begin{cases} 0, & \text{if } P + \delta E \geq f_i e_{i, \text{raw}}^2 \\ f_i e_{i, \text{raw}}^2 - P, & \text{if } P + \delta E < f_i e_{i, \text{raw}}^2 \end{cases} \quad (3)$$

Average wavelength and maximum amplitude

The average wavelength λ is calculated by $\lambda = \frac{\sum e_i^2}{\sum f_i e_i^2}$. We defined the maximum among all e_i values as e_{max} to represent the magnitude of the front instability.

Supplementary Materials

The PDF file includes:

Supplementary Text

Figs. S1 to S3

Legends for movies S1 to S11

Other Supplementary Material for this manuscript includes the following:

Movies S1 to S11

REFERENCES AND NOTES

- J. A. Guimond, A. A. Mohammed, M. A. Walvoord, V. F. Bense, B. L. Kurylyk, Saltwater intrusion intensifies coastal permafrost thaw. *Geophys. Res. Lett.* **48**, e2021GL094776 (2021).
- K. M. W. Anthony, S. A. Zimov, G. Grosse, M. C. Jones, P. M. Anthony, F. S. Chapin, J. C. Finlay, M. C. Mack, S. Davydov, P. Frenzel, S. Frolking, A shift of thermokarst lakes from carbon sources to sinks during the Holocene epoch. *Nature* **511**, 452–456 (2014).
- S. Olson, M. F. Jansen, D. S. Abbot, I. Halevy, C. Goldblatt, The effect of ocean salinity on climate and its implications for earth's habitability. *Geophys. Res. Lett.* **49**, e2021GL095748 (2022).
- E. A. G. Schuur, A. D. McGuire, C. Schädel, G. Grosse, J. W. Harden, D. J. Hayes, G. Hugelius, C. D. Koven, P. Kuhry, D. M. Lawrence, S. M. Natali, D. Olefeldt, V. E. Romanovsky, K. Schaefer, M. R. Turetsky, C. C. Treat, J. E. Vonk, Climate change and the permafrost carbon feedback. *Nature* **520**, 171–179 (2015).
- G. Whiteman, C. Hope, P. Wadhams, Vast costs of Arctic change. *Nature* **499**, 401–403 (2013).
- E. A. G. Schuur, J. Bockheim, J. G. Canadell, E. Euskirchen, C. B. Field, S. V. Goryachkin, S. Hagemann, P. Kuhry, P. M. Lafleur, H. Lee, G. Mazhitova, F. E. Nelson, A. Rinke, V. E. Romanovsky, N. Shiklomanov, C. Tarnocai, S. Venevsky, J. G. Vogel, S. A. Zimov, Vulnerability of permafrost carbon to climate change: Implications for the global carbon cycle. *Bioscience* **58**, 701–714 (2008).
- U. Mishra, G. Hugelius, E. Shelef, Y. Yang, J. Strauss, A. Lupachev, J. W. Harden, J. D. Jastrow, C.-L. Ping, W. J. Riley, E. A. G. Schuur, R. Matamala, M. Siewert, L. E. Nave, C. D. Koven, M. Fuchs, J. Palmtag, P. Kuhry, C. C. Treat, S. Zubrzycki, F. M. Hoffman, B. Elberling, P. Camill, A. Veremeeva, A. Orr, Spatial heterogeneity and environmental predictors of permafrost region soil organic carbon stocks. *Sci. Adv.* **7**, eaaz5236 (2021).
- T. Wang, D. Yang, Y. Yang, S. Piao, X. Li, G. Cheng, B. Fu, Permafrost thawing puts the frozen carbon at risk over the Tibetan Plateau. *Sci. Adv.* **6**, eaaz3513 (2020).
- A. A. Mohammed, V. F. Bense, B. L. Kurylyk, R. C. Jamieson, L. H. Johnston, A. J. Jackson, Modeling reactive solute transport in permafrost-affected groundwater systems. *Water Resour. Res.* **57**, e2020WR028771 (2021).
- R. Margesin, Ed., *Permafrost Soils*, vol. 16 of *Soil Biology* (Springer Berlin Heidelberg, 2009).
- I. C. Burkow, R. Kallenborn, Sources and transport of persistent pollutants to the Arctic. *Toxicol. Lett.* **112–113**, 87–92 (2000).
- L. D. Dyke, Contaminant migration through the permafrost active layer, Mackenzie Delta area, Northwest Territories, Canada. *Polar Rec.* **37**, 215–228 (2001).
- J. G. H. De Bruin, V. F. Bense, M. J. Van Der Ploeg, Inferring permafrost active layer thermal properties from numerical model optimization. *Geophys. Res. Lett.* **48**, e2021GL093306 (2021).
- D. L. Feltham, N. Untersteiner, J. S. Wettlaufer, M. G. Worster, Sea ice is a mushy layer. *Geophys. Res. Lett.* **33**, L14501 (2006).
- D. Notz, M. G. Worster, Desalination processes of sea ice revisited. *J. Geophys. Res.* **114**, C05006 (2009).
- D. L. Feltham, M. G. Grae Worster, Flow-induced morphological instability of a mushy layer. *J. Fluid Mech.* **391**, 337–357 (1999).
- M. G. Worster, J. S. Wettlaufer, Natural convection, solute trapping, and channel formation during solidification of saltwater. *J. Phys. Chem. B* **101**, 6132–6136 (1997).
- M. G. Worster, Natural convection in a mushy layer. *J. Fluid Mech.* **224**, 335–359 (1991).
- R. Guo, H. Sun, Q. Zhao, Z. Li, Y. Liu, C. Chen, A novel experimental study on density-driven instability and convective dissolution in porous media. *Geophys. Res. Lett.* **48**, e2021GL095619 (2021).
- Y. Du, Z. Wang, L. Jiang, E. Calzavarini, C. Sun, Sea water freezing modes in a natural convection system. *J. Fluid Mech.* **960**, A35 (2023).
- C. Cohen, M. Berhanu, J. Derr, S. C. Du Pont, Buoyancy-driven dissolution of inclined blocks: Erosion rate and pattern formation. *Phys. Rev. Fluids* **5**, 053802 (2020).
- B. Favier, J. Purse, L. Duchemin, Rayleigh–Bénard convection with a melting boundary. *J. Fluid Mech.* **858**, 437–473 (2019).
- M. Mondal, B. Gayen, R. W. Griffiths, R. C. Kerr, Ablation of sloping ice faces into polar seawater. *J. Fluid Mech.* **863**, 545–571 (2019).
- L. Rayleigh, LIX. On convection currents in a horizontal layer of fluid, when the higher temperature is on the under side. *Lond. Edinb. Dublin Philos. Mag. J. Sci.* **32**, 529–546 (1916).
- G. Schubert, J. M. Straus, Three-dimensional and multicellular steady and unsteady convection in fluid-saturated porous media at high Rayleigh numbers. *J. Fluid Mech.* **94**, 25–38 (1979).
- C. W. Horton, F. T. Rogers, Convection currents in a porous medium. *J. Appl. Phys.* **16**, 367–370 (1945).
- M. De Paoli, S. Pirozzoli, F. Zonta, A. Soldati, Strong Rayleigh–Darcy convection regime in three-dimensional porous media. *J. Fluid Mech.* **943**, A51 (2022).
- D. R. Hewitt, J. A. Neufeld, J. R. Lister, Ultimate regime of high Rayleigh number convection in a porous medium. *Phys. Rev. Lett.* **108**, 224503 (2012).
- M. De Paoli, Convective mixing in porous media: A review of Darcy, pore-scale and Hele-Shaw studies. *Eur. Phys. J. E Soft Matter* **46**, 129 (2023).
- E. R. Lapwood, Convection of a fluid in a porous medium. *Math. Proc. Camb. Philos. Soc.* **44**, 508–521 (1948).
- F. Molz, Advection, dispersion, and confusion. *Groundwater* **53**, 348–353 (2015).
- Y. Liang, B. Wen, M. A. Hesse, D. DiCarlo, Effect of dispersion on solutal convection in porous media. *Geophys. Res. Lett.* **45**, 9690–9698 (2018).
- S. Pirozzoli, M. De Paoli, F. Zonta, A. Soldati, Towards the ultimate regime in Rayleigh–Darcy convection. *J. Fluid Mech.* **911**, R4 (2021).
- B. Wen, L. T. Corson, G. P. Chini, Structure and stability of steady porous medium convection at large Rayleigh number. *J. Fluid Mech.* **772**, 197–224 (2015).
- M. De Paoli, F. Zonta, A. Soldati, Influence of anisotropic permeability on convection in porous media: Implications for geological CO₂ sequestration. *Phys. Fluids* **28**, 056601 (2016).
- J. Lasser, J. M. Nield, M. Ernst, V. Karius, G. F. S. Wiggs, M. R. Threadgold, C. Beaume, L. Goehring, Salt polygons and porous media convection. *Phys. Rev. X* **13**, 011025 (2023).
- H. Lagzi, M. Bezzazi, Robin boundary effects in the Darcy–Rayleigh problem with local thermal non-equilibrium model. *Transp. Porous Media* **129**, 701–720 (2019).
- D. R. Caldwell, Thermal and Fickian diffusion of sodium chloride in a solution of oceanic concentration. *Deep-Sea Res. Oceanogr. Abstr.* **20**, 1029–1039 (1973).
- M. Vancoppenolle, H. Goosse, A. de Montety, T. Fichefet, B. Tremblay, J. L. Tison, Modeling brine and nutrient dynamics in Antarctic sea ice: The case of dissolved silica. *J. Geophys. Res.* **115**, C02005 (2010).
- P. C. Carman, Permeability of saturated sands, soils and clays. *J. Agric. Sci.* **29**, 262–273 (1939).
- M. Magnani, S. Musacchio, A. Provenzale, G. Boffetta, Convection in the active layer speeds up permafrost thaw in coarse-grained soils. *Phys. Rev. Fluids* **9**, L081501 (2024).
- X. Zhu, Y. Fu, M. De Paoli, Transport scaling in porous media convection. *J. Fluid Mech.* **991**, A4 (2024).
- S. V. Patankar, Numerical Heat Transfer and Fluid Flow, Series in Computational Methods in Mechanics and Thermal Sciences (McGraw-Hill, 1980) [u.a.].
- B. Bijeljic, M. J. Blunt, Pore-scale modeling of transverse dispersion in porous media. *Water Resour. Res.* **43**, W12S11 (2007).
- T. Menand, A. W. Woods, Dispersion, scale, and time dependence of mixing zones under gravitationally stable and unstable displacements in porous media. *Water Resour. Res.* **41**, W05014 (2005).
- J. F. Pickens, G. E. Grisak, Modeling of scale-dependent dispersion in hydrogeologic systems. *Water Resour. Res.* **17**, 1701–1711 (1981).
- L. Pang, B. Hunt, Solutions and verification of a scale-dependent dispersion model. *J. Contam. Hydrol.* **53**, 21–39 (2001).
- E. J. Peters, Advanced Petrophysics: Geology, Porosity, Absolute Permeability, Heterogeneity, and Geostatistics (Live Oak Book Company, 2012).
- A. Arya, T. A. Hewett, R. G. Larson, L. W. Lake, Dispersion and reservoir heterogeneity. *SPE Reserv. Eng.* **3**, 139–148 (1988).
- P. Saffman, G. Taylor, The penetration of a fluid into a porous medium or Hele-Shaw cell containing a more viscous liquid. *Proc. R. Soc. London Ser. A Math. Phys. Sci.* **245**, 312–329 (1958).
- D. A. DiCarlo, Stability of gravity-driven multiphase flow in porous media: 40 years of advancements. *Water Resour. Res.* **49**, 4531–4544 (2013).
- P. Schwerdtfeger, The thermal properties of sea ice. *J. Glaciol.* **4**, 789–807 (1963).
- R. B. Bird, W. E. Stewart, E. N. Lightfoot, *Transport Phenomena* (John Wiley & Sons, rev. ed. 2, 2006).
- M. De Paoli, D. Perissutti, C. Marchioli, A. Soldati, Experimental assessment of mixing layer scaling laws in Rayleigh–Taylor instability. *Phys. Rev. Fluids* **7**, 093503 (2022).

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