Fluid transport in Antarctic sea ice

K. M. Golden[1*], A. Gully[1], and J. L. Tison[2]

[1]University of Utah, Department of Mathematics
155 S 1400 E RM 233, Salt Lake City, UT 84112-0090 USA

[2]Laboratoire de Glaciologie, CP 160/03, Université Libre de Bruxelles
50, av. F. D. Roosevelt, 1050 - Bruxelles, Belgium

*To whom correspondence should be addressed; E-mail: golden@math.utah.edu.

Fluid flow through porous sea ice mediates a broad range of processes which are critical to predictions of climate change, and the response of polar ecosystems. We have made the first measurements of fluid permeability in Antarctic pack ice, and find that the granular sea ice there leads to strikingly different fluid transport behavior than in the Arctic. In particular, granular ice exhibits a percolation threshold, the on−off switch for fluid transport, for brine volume fractions around 10% or higher, rather than 5% observed in columnar ice which dominates the Arctic. Our findings shed new light on key processes such as snow-ice formation, melt pond evolution, CO_2 exchanges, and nutrient replenishment, and their parameterizations in global climate and biogeochemical models.

The polar sea ice packs form a key component of Earth's climate system, and are sensitive indicators of climate change (*1, 2*). They also host extensive algal and bacterial communities which sustain life in the polar oceans (*1, 3*). While global climate models generally predict declines in polar sea ice, they have significantly underestimated the dramatic losses observed in the summer Arctic ice pack (*4, 5*). On the other hand, Antarctic sea ice has increased overall, along with some significant regional losses (*6, 7*).

Our focus here is on key sea ice processes which must be better understood to improve the predictions of climate models and the future of the polar ice packs, as well as the microbial communities that live there. In particular, fluid flow through porous sea ice helps control the evolution of melt ponds and ice pack albedo (*8*), brine drainage and the evolution of salinity profiles (*9, 10*), snow-ice formation, where sea water floods the ice surface and then freezes (*11, 12*), ocean-ice-atmosphere CO_2 exchanges (*13*), convection-enhanced thermal transport (*14, 15*), and biomass build-up fueled by nutrient fluxes (*1, 3, 16, 17*). For example, it is believed that ice-albedo feedback has played a significant role in the declines observed in the Arctic (*18*). Snow-ice formation, on the other hand, may have helped in thickening the Antarctic sea ice pack (*11, 12*), and may become more important in the Arctic with increased precipitation and thinning ice, so that it is more susceptible to flooding.

The fluid permeability of sea ice, which depends strongly on its brine microstructure, plays a key role in understanding such processes, and in parameterizing them in large-scale models. To date, columnar microstructures have received disproportionate attention, mostly due to their prevalence in Arctic sea ice and their importance in undisturbed ice growth (*9, 10, 19*). However, granular microstructures, which lack intragranular inclusions and exhibit a film of brine enveloping individual grains, are particularly important for processes which are relevant to climate studies. For example, granular ice is common in surface layers in the Arctic (*20*), which directly underly the melt ponds controlling ice albedo. Examination of the crystalline structure in sea ice from a recent trans-Arctic survey (*20*) showed a striking increase in overall granular ice fraction, of just over 40% compared to previous observations of around 10% (*21*). In the Antarctic it has long been observed that granular ice (*11, 22–24*), accounts for a fraction of up to around 40% of the sea ice pack. Snow-ice in particular, with granular microstructure itself, accounts for over a quarter of the ice found in the Southern Ocean, with much higher fractions in some regions (*25*). An accurate accounting of sea ice processes involving fluid flow in climate and biogeochemical models relies on knowledge of the fluid permeability of granular ice.

In (*26*) it was observed that for brine volume fractions ϕ below about 5%, columnar sea ice is effectively impermeable to fluid flow, yet is increasingly permeable for ϕ above 5%.

For a typical bulk salinity of 5 ppt, this critical brine volume fraction $\phi_c \approx 5\%$ corresponds to a critical temperature $T_c \approx -5^\circ$ C, which is known as the *rule of fives*. The critical brine volume fraction was explained in terms of the *percolation threshold* in a continuum model for compressed powders which was has been used to understand the behavior of stealthy or radar absorbing materials. In (*27*) a comprehensive theory for the vertical fluid permeability $k(\phi)$ of columnar sea ice was developed, and validated experimentally with laboratory and Arctic field data. Micro-scale imaging methods based on X-ray computed tomography (CT) and pore structure analysis were also developed to provide detailed pictures of the brine microstructure and the evolution of its connectivity with temperature (*27, 28*).

During September and October of 2007, we measured the fluid permeability of first year Antarctic pack ice as participants in the Australian Sea Ice Physics and Ecosystem Experiment (SIPEX), aboard the icebreaker *Aurora Australis*. The study area was located off the coast of East Antarctica, between 115° E and 130° E, and 64° S and 66° S. Permeability measurements were made at 8 of the 15 ice stations along the cruise track of the *Aurora*, and we obtained 38 data points covering a range of depths, temperatures, salinities, and ice types. Full length cores were taken nearby by our colleagues, usually within a few meters of our location, and were later subjected to crystallographic and other analyses. When we separated out the permeability data which was likely being influenced primarily by granular microstructures, we found that the critical threshold for fluid flow had effectively doubled to around $\phi_c \approx 10\%$. For a typical salinity of around 5 ppt, the corresponding critical temperature is around $T_c \approx -2.5^\circ$ C (*29*). Moreover, as predicted by our percolation theoretic analysis in (*27*), we find here that the *universal* lattice critical exponent of about 2 for columnar ice in the Arctic still accurately describes the take-off of $k(\phi)$ above the threshold ϕ_c for granular sea ice in the Antarctic.

The novel behavior we find in the percolation threshold for fluid transport in granular ice is explained in terms of the compressed powder model (*30, 31*). By measuring the relative

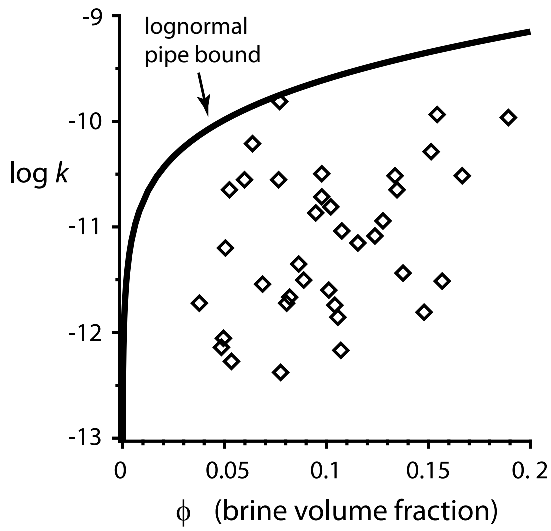

Figure 1: Comparison of *in situ* data on k (m^2) for Antarctic sea ice (37 diamonds) with the lognormal pipe upper bound.

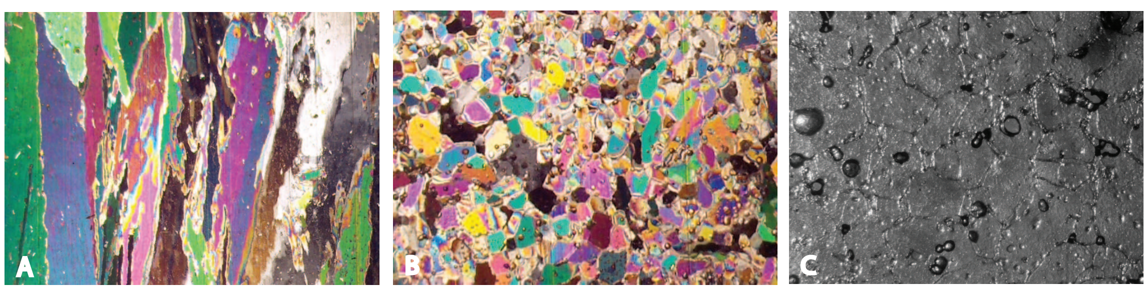

Figure 2: (A) Columnar and (B) granular microstructures. (C) Granular snow-ice.

dimensions of the ice grains and the fluid inclusions in photomicrographs of granular sea ice, we obtain a percolation threshold of around 10%, with the possibility of even higher thresholds for more finely grained microstructures.

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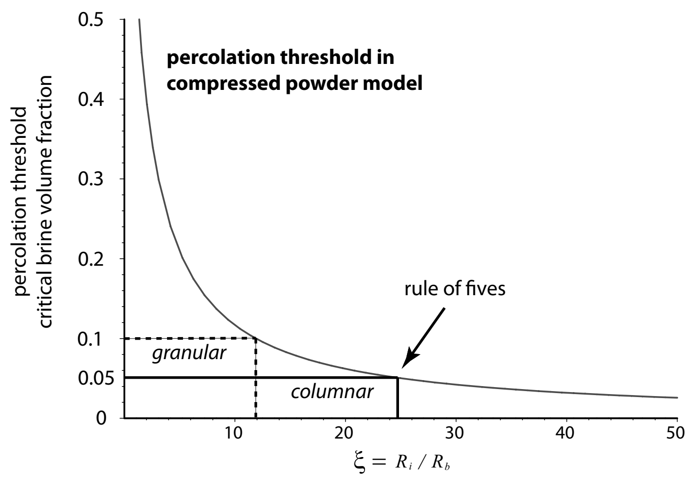

Figure 3: Percolation threshold in the compressed powder model as a function of the ratio of the particle radii.

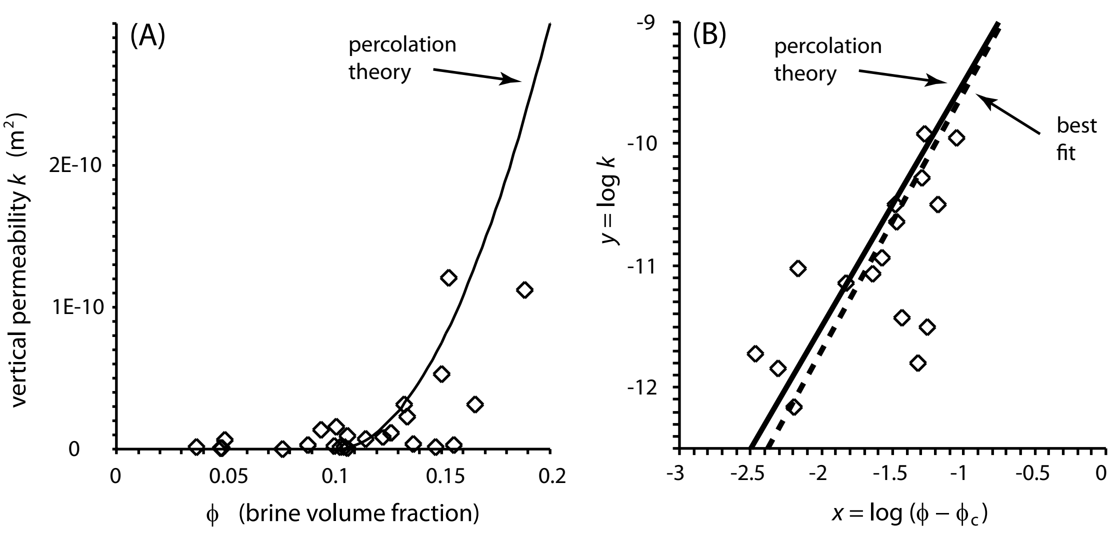

Figure 4: Comparison of *in situ* data on k (m^2) for Antarctic sea ice with percolation theory, displayed on a linear scale in (A) and on a logarithmic scale in (B), where a statistical best fit (dotted line) of the data is shown along with the prediction of percolation theory with $\phi_c \approx 0.1$.

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