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Rheological nonlinearity and pattern formation in basal ice flow

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Exposed glacier beds often have a furrowed appearance due to the presence elongated sediment ridges or ‘flutes’ aligned in the former direction of ice flow. Measurements of the orientation of elongated rock fragments in these flutes have previously been interpreted as indicative of spiral flows in basal ice, with a component of velocity transverse to the mean flow direction which tends to move sediment from the troughs of flutes to their crests. The potential origins of such spiral flows are unclear: at the low Reynolds numbers typical of glacier and ice sheet flow, commonly employed rheological models such as Glen’s law preclude their formation. Secondary, transverse flows are however possible if the deviatoric stress tensor is not parallel to the strain rate tensor alone, but depends also on the contraction of the strain rate tensor with itself. This rheological effect occurs in a number of complex (Reiner-Rivlin) fluids, where it accounts for such phenomena as rod climbing and the generation of deviatoric normal stresses in simple shearing flows. Here, we review the evidence for this effect occuring in ice, and explore its implications in terms of flute formation. Our results indicate that rheologically induced spiral flows can explain the formation of flutes, and that flute spacing depends on both, the rheology of ice and the specifics of sediment transport mechanism involved.