Hydraulic Fracture along Glacier Beds by Turbulent Flow of Meltwater

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The problem of hydraulic fracture has been studied extensively, with focus ranging from enhanced hydrocarbon flow to boreholes, to water-driven glacial cracking, to magma eruption through Earth's crust. Although some of this work has addressed fast-flowing fracture, the work applied to glaciers has, so far, focused either on static or relatively long timescale conditions. However, glaciological observations suggest that the fluid-induced fracture process may occur quickly, possibly driven by turbulently flowing water during crack growth. Here, we take the approximation of a fully turbulent flow into an elastic ice medium with small fracture toughness to derive an approximate expression for the crack-tip speed. We accomplish this by first showing that a Manning channel model for wall resistance to turbulent flow leads to the same mathematical structure as for resistance to laminar flow of a power-law viscous fluid. We then make use of the asymptotic crack solution for that case by Desroches et al. [Proc. R. Soc. Lond. A, 1994], and finally estimate the pressure scale appropriate for a finite crack. Comparison of this estimated solution with an exact self-similar solution of Adachi and Detournay [Int. J. Numer. Anal. Meth. Geomech., 2002] validates the approximation. To apply this model, we use parameter values thought appropriate for a basal crack driven by the rapid drainage of a surface meltwater lake near the margin of the Greenland Ice Sheet (Das et al. [Science, 2008]). Thus, we take a maximum excess crack inlet pressure of 0.9 MPa, corresponding to neglect of any hydraulic head loss in flow from the glacier surface to crack entry at the bed, a horizontal basal crack length of 1 km, and a wall roughness scale for flow resistance of 10 mm, and hence estimate a crack-tip speed of about 8 m/s. Loss of ten percent of the surface head on descent to the bed would reduce that speed by slightly more than ten percent. Making various plate theory and linear elastic fracture mechanics approximations perhaps relevant to this setting, we additionally model both vertical and horizontal surface displacements and find rough agreement with the meter-scale displacements observed through GPS by Das et al. [Science, 2008].