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A theoretical model of drumlin formation based on observations at Múlajökull, Iceland

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Theoretical models of drumlin formation have generally been developed in isolation from observations in modern drumlin forming environments—a major limitation on the empiricism necessary to confidently formulate models and test them. Observations at a rare modern drumlin field exposed by the recession of the Icelandic surge-type glacier, Múlajökull, allow an empirically-grounded and physically-based model of drumlin formation to be formulated and tested.

Till fabrics based on anisotropy of magnetic susceptibility and clast orientations, along with stratigraphic observations and results of ground penetrating radar, indicate that drumlin relief results from basal till deposition on drumlins and erosion between them. These data also indicate that surges cause till deposition both on and between drumlins and provide no evidence of the longitudinally compressive or extensional strain in till that would be expected if flux divergence in a deforming bed were significant. Over 2000 measurements of till density, together with consolidation tests on the till, indicate that effective stresses on the bed were higher between drumlins than within them. This observation agrees with evidence that subglacial water drainage during normal flow of the glacier is through channels in low areas between drumlins and that crevasse swarms, which reduce total normal stresses on the bed, are coincident with drumlins.

In the new model slip of ice over a bed with a sinusoidal perturbation, crevasse swarms, and flow of subglacial water toward R-channels that bound the bed undulation during periods of normal flow result in effective stresses that increase toward channels and decrease from the stoss to the lee sides of the undulation. This effective-stress pattern causes till entrainment and erosion by regelation infiltration (Rempel, 2008, JGR, 113) that peaks at the heads of incipient drumlins and near R-channels, while bed shear is inhibited by effective stresses too high to allow deformation. During surges lower effective stresses on the bed and distributed drainage prevent the intimate ice-bed contact that regelation infiltration requires and cause shear deformation of the bed, assumed to occur with zero flux divergence as suggested by the fabric data. This deformation generates a heat flux sufficient to melt basal ice and deposit, by lodgment, till layers of up to $\sim$2 m in thickness during a single surge. 1-D analytical solutions illustrate that with multiple surge cycles drumlins grow in height, owing to the net effect of spatially variable erosion between surges and till deposition during them, and that drumlins migrate downglacier, with resultant stratigraphy in broad agreement with observations. 2-D numerical calculations reinforce these results. The model, if taken at face value, implies that drumlins formed by non-surge-type glaciers should be dominantly erosional.