Simulating Subglacial Sediment Transport using a Semi–Lagrangian Method

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Introduction

Temperate ice sheets have the capacity to erode, transport and deposit large quantities of sediments. These products of past ice sheet activity can be observed in the geological record. Simulating the sediment record, therefore, helps constrain reconstructions of past ice sheets.

Two methods of sediment transport are considered here:

- sediments can be transported in a thin basal ice layer
- transport can occur within a deforming layer of sediments below the ice bed.

The amount of sediments transported within these layers depends on their rheology and the thermal conditions at the ice base.

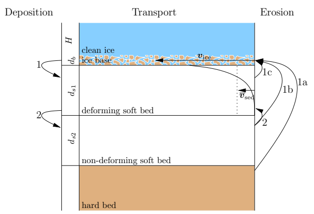
A three–dimensional, thermo–mechanically coupled ice sheet model using the *shallow ice approximation* is used. The model employs a simple binary sliding law. Basal décollement only occurs when the ice base has reached the pressure melting point of ice. Basal velocities are assumed to be proportional to the gravitational driving stress

$$v_{\text{sliding}} \propto \left[H\nabla_{\text{H}}(H+h)\right]^n, \tag{1}$$

where H is the ice thickness, h the bedrock elevation and $n=3$.

The ice sheet model is used to simulate the evolution of the Fennoscandian ice sheet during the last glacial cycle. Initially a uniform sediment distribution of 5m is assumed.

Sediment Transport, Erosion and Deposition



Three layer approximation to the sediment erosion/deposition/transport problem. The arrows indicate sediment transfer.

The system is divided into 3 layers with 2 boundaries accross which sediment transfer occurs:

1. **Basal ice layer:** A thin layer of ice which carries debris gained by regelation processes. The layer is assumed to have a uniform thickness over the entire ice sheet of a few centimetres.
2. **Deformable soft bed:** A layer of deformable sediments may accumulate below the ice sheet. The thickness is assumed to be proportional to the basal ice velocity.
3. **Non–deformable soft bed:** A layer of soft sediments which is not deforming.

Sediment erosion, deposition and transport arise from the basal ice velocity and are assumed:

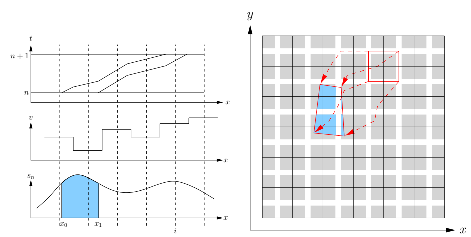
1. **Erosion:** Two mechanisms are considered: i) Abrasion/plucking, erosion rate is assumed to be proportional to the basal ice velocity, i.e. $\dot{E} \propto |\boldsymbol{v}_{\text{sliding}}|$. ii) The deformable soft bed layer might grow, since its thickness is assumed to be also proportional to the basal ice velocity.
2. **Deposition** is a consequence of the sediment carrying capacity of the layers being exceeded.
3. **Transport** of sediment can occur in the dirty basal ice (transport velocity is equal to basal ice velocity) and in the deforming soft bed layer (transport velocity is assumed proportional to basal ice velocity).

Theory

The sediment transport problem reduces to solving the advection equation

$$\frac{\partial s}{\partial t} + \boldsymbol{\nabla}_H \cdot (s\boldsymbol{v}) = \dot{S}, \tag{2}$$

where s is the sediment thickness, $\boldsymbol{v}$ the transport velocity and $\dot{S}$ sediment erosion/deposition. Numerical problems can be avoided by using a semi–Lagrangian approach to solving the advection equation. The approach taken here is outlined in the Figure below.

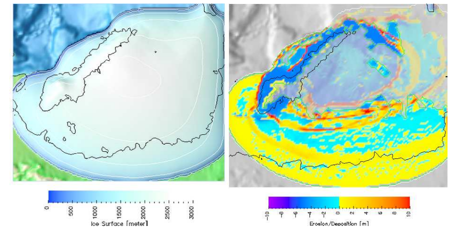


The new sediment distribution s_{n+1} at time $t=n+1$ is sought given the velocity field v and the present sediment distribution s_n. In one dimension (left panel), s_{n+1} is found by tracing back particles injected at the cell edges and integrating the old sediment distribution between x_0 and x_1 and dividing by Δx. The right panel shows how this method is extended to two dimensions.

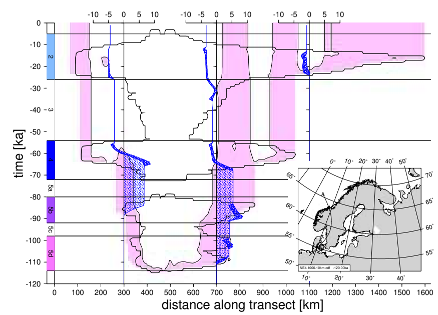
Results

The output produced by the model outlined above is phenomenologically rich. The following plots demonstrate output of the same simulation of the Fennoscandian ice sheet during the last glacial cycle.

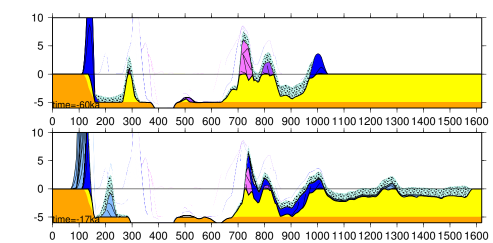
The ice sheet pushes sediments quickly to the margin where they accumulate. These ridges are then partly eroded during subsequent ice readvances.



Plan view of the simulated ice sheet at the last glacial maximum (left panel). The right panel shows cummulative sediment erosion (cold colours) and sediment deposition (warm colours). Greyed–out colours indicate inactive areas (i.e. the ice sheet is no longer occupying this area or frozen to the bed).



Time–distance diagram showing the extent of the simulated ice sheet through the last glacial cycle along the profile indicated by the inset. Pink areas show regions of sediment deposition. The vertical graphs show the sediment evolution at locations 300km, 700km and 1100km along the profile. Dark blue areas indicate active sediment transport.



Two snapshots at 60ka and 17ka ago of the sediment distribution along the profile described above. Brown indicates the hard bedrock horizon, yellow the inital soft sediment distribution. The remaining colours correspond with the colour code of the stadials of the time–distance diagram. The black lines are paleo–surfaces and the patterned layer indicates the active sediment layer.