The influence of subglacial hydrology on the flow of Kamb Ice Stream

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Introduction

RATIONALE:

- Subglacial hydrology and till influences the flow of ice, but it is not known whether it drives the stagnation or speed up of ice streams.
- In the past, numerical models have estimated that the Siple Coast ice streams, Antarctica, (Figure 1) oscillate between fast and slow flow on time scales of 1000s of years (MacAyeal, 1992; Parizek and others, 2003; Payne, 1995).
- However, recent evidence from boreholes beneath Kamb Ice Stream (KIS) indicates that this ice stream may in fact be subject to cycles of stagnation and reactivation that are an order of magnitude faster (Vogel and others, 2005).

AIMS:

- To investigate how subglacial hydrology affects the flow of KIS, ignoring external forcing.
- To determine whether the surface velocity of KIS is capable of oscillating in time.
- If oscillations are found to occur, to isolate what mechanisms drive them and the time scales on which they occur.

METHODS:

- Develop a numerical model that couples ice thermodynamics, subglacial hydrology and till.
- Conduct tests in which different magnitudes of subglacial water are discharged into the ice stream at the onset.

Kamb Ice Stream (KIS)

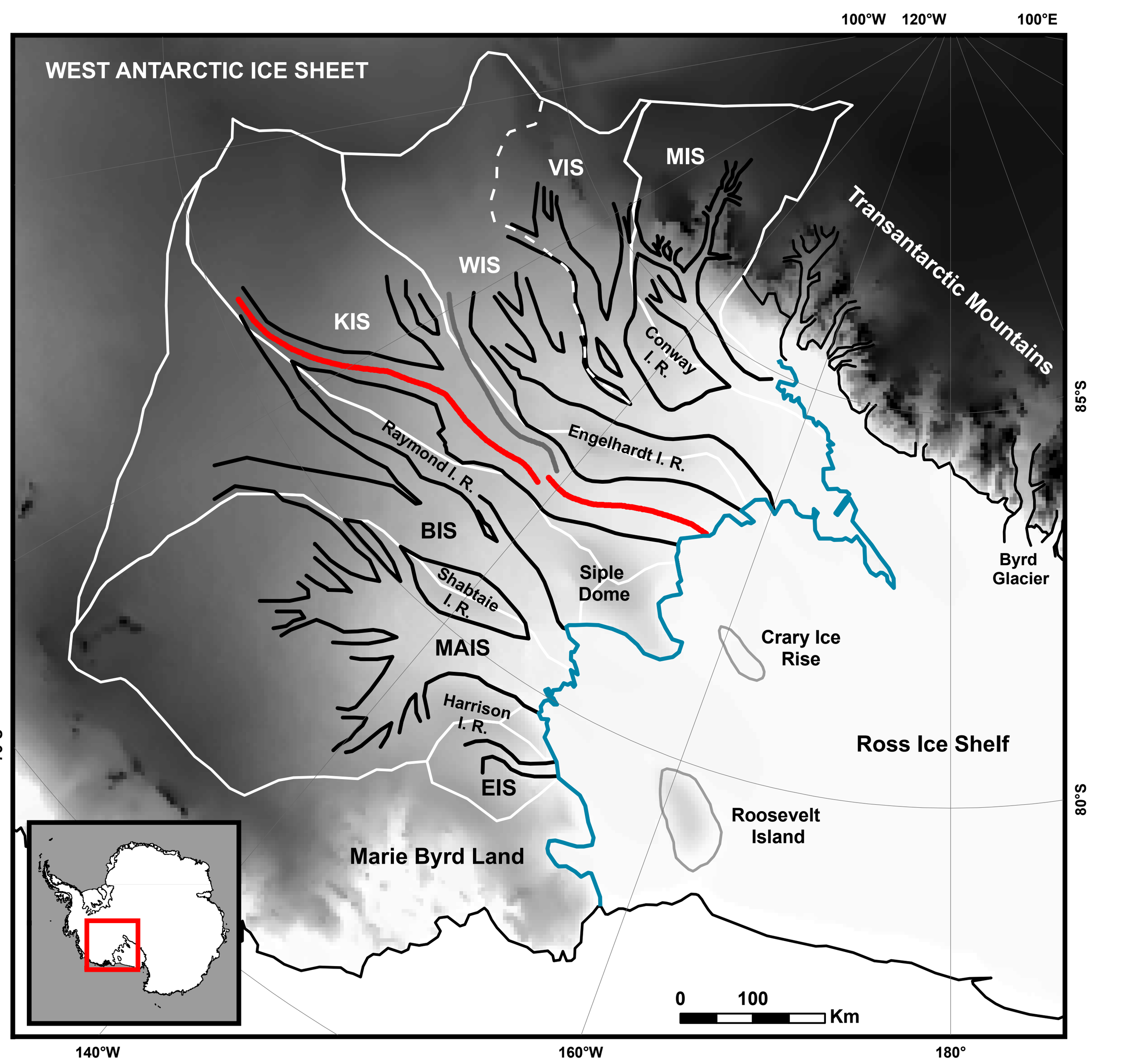

Figure 1: Map of the Siple Coast showing ice stream outlines (black) and drainage basins (white) based on RAMP imagery and Joughin and Tulaczyk (2002). Ice streams are: Mercer Ice Stream (MIS), van der Veen Ice Stream (VIS), Whillans Ice Stream (WIS), Kamb Ice Stream (KIS), Bindschadler Ice Stream (BIS), MacAyeal Ice Stream (MAIS) and Echelmeyer Ice Stream (EIS). The red line is the approximate centreline of KIS, following the northern upper tributary. The centreline of the southern upper tributary is marked in grey. The coastline is adapted from the ADD v3, available from the Scientific Committee on Antarctic Research (www.add.scar.org). The blue line is the position of the grounding line (GL), from RADARSAT-1 Antarctic Mapping Project (RAMP) imagery and Horgan and Anandakrishnan (2006). The red box on the inset map shows the location of this map in Antarctica.

- Location: Siple Coast, West Antarctica (Figure 1).
- Ice thickness: 4.1 km at the onset and 2.7 km at the grounding line (GL) (Figure 2).
- Ice stream length: 745 km from onset of northernmost tributary to the GL.
- Ice stream width: 2 km at the onset and 37 km at the GL.
- Mean annual ice surface temperature: -30.2°C at the onset and -27.7°C at the GL. (RACMO2/ANT model data, van den Broeke (2008)).
- Mean accumulation rate: 0.21 m a^{-1} i. e. at the onset and 0.08 m a^{-1} i. e. at the GL (Arthern and others, 2006).
- Subglacial till: Not many measurements, but thought to be several metres thick (Anandakrishnan and others, 1998)
- Subglacial hydrology: Borehole water data suggests a hydrological system of localised canals that are ~1 m wide and ~0.1 m deep (Engelhardt and Kamb, 1997).
- Temporal change: Main trunk of KIS stagnated ~150 years ago (Rose, 1979).

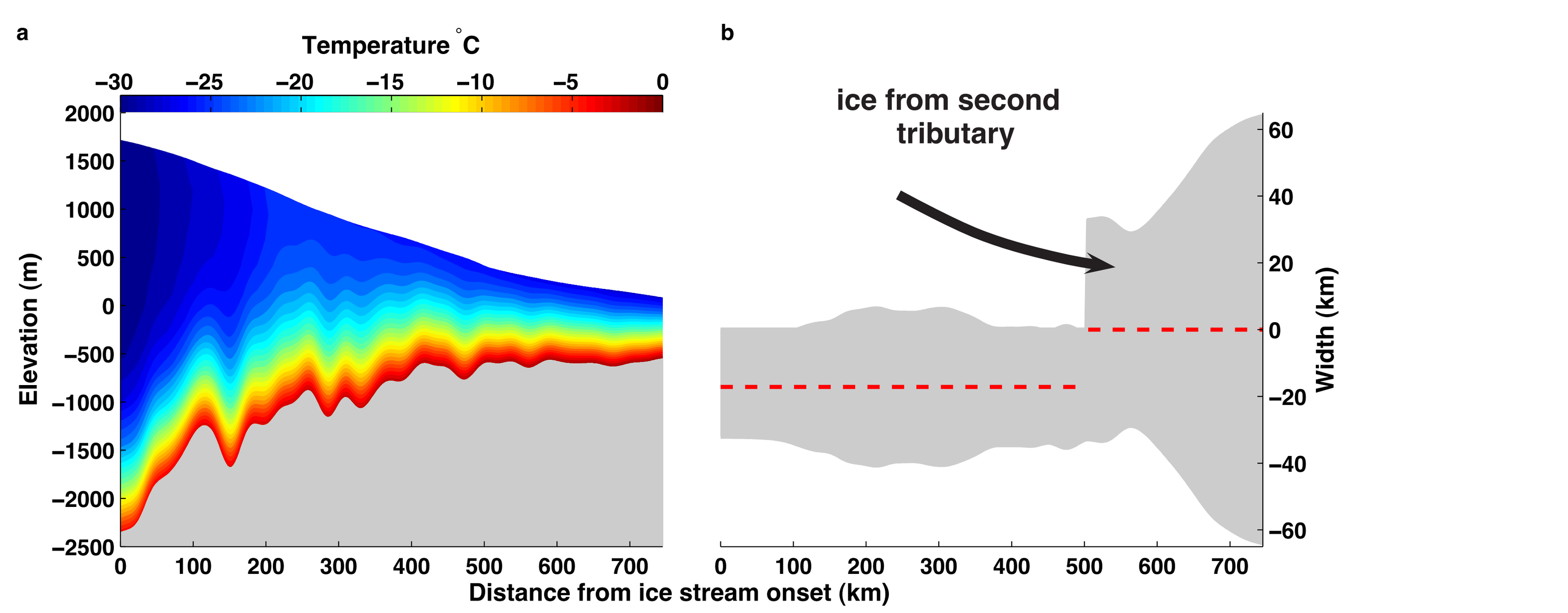

Figure 2: Initial conditions of Kamb Ice Stream. (a) Surface and bed elevation and ice temperature. (b) ice stream width. The red dashed line is the model flowline.

The Hydrology, Ice and Till (HIT) model

The HIT model is a 2D flowline model that couples ice thermodynamics, subglacial hydrology and till (Figure 3). It is an extension of previous modelling work by Tulaczyk and others (2000a,b) and by Bougamont and others (2003a,b) and is discussed in more detail in Baker (2012).

ICE, Figure 4a

- Surface flow by internal ice deformation and shallow till deformation.
- Shallow till deformation occurs when the till strength < the driving stress.
- Ice thickness evolution is according to conservation of mass.
- Glacial isostatic adjustment is included.
- Bed assumed to be at the pressure melting point.
- Column averaged ice temperature.
- No climate forcing.

TILL, Figure 4b

- Assumes till erosion = deposition, no sediment transportation.
- Till porosity/void ratio varies with water content.
- Mixing of till layers depends on surface velocity and till porosity.
- Assumes that the effective pressure of the till is a function of its void ratio.
- Assumes that till strength is a function of its effective pressure.

HYDROLOGY, Figure 5

- Water available from basal melt/freeze and from transportation of water through conduits at the ice-till interface from upstream.
- Vertical and horizontal porous water flow through till (Darcy flux) driven by the hydraulic potential.
- Subglacial conduits are assumed to be elliptical (eccentricity of ~0.995).
- Conduits open by melt and close by ice creep.
- Conduits can open faster in response to high discharge events when effective pressure is ~zero (hydraulic jacking).

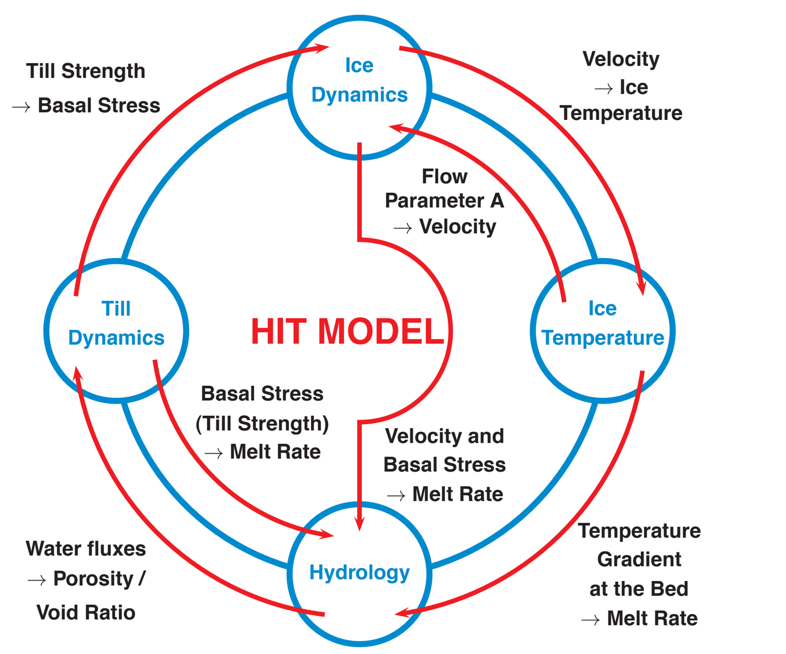

Figure 3: Structure and coupling of the HIT Model. Blue lines link the four components of the HIT model. Red arrows show key variables that link the components. The notation is: variable 1 → variable 2, where variable 1 is used in the calculation of variable 2.

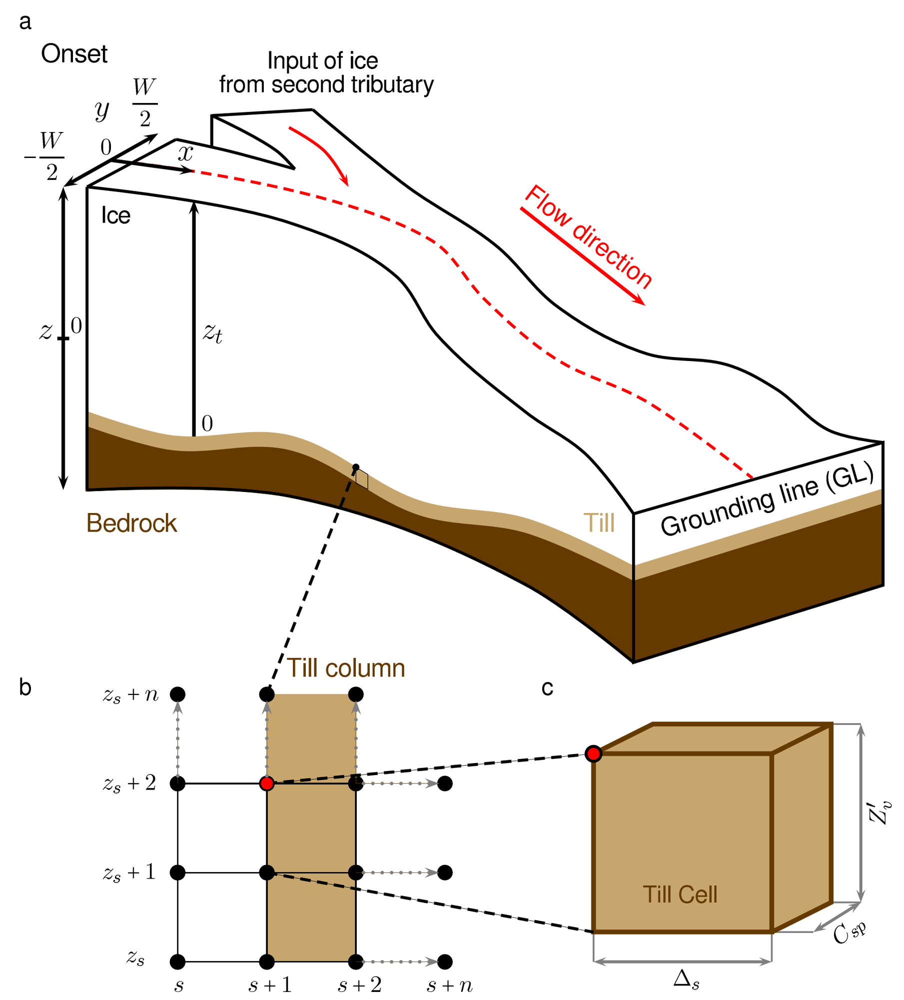

Figure 4: Schematic of ice and till geometry. (a) is the ice geometry, (b) is the till matrix, showing the coordinate system of a till column and (c) depicts a single till cell. C_{sp} is the conduit spacing and Z_v^i is the thickness of a till cell.

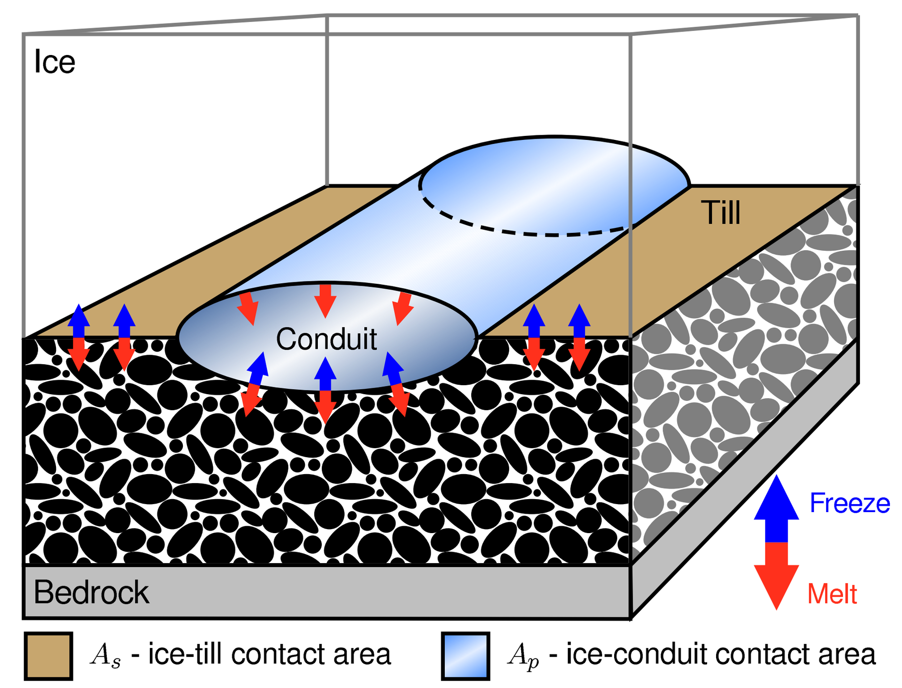

Figure 5: Schematic of a conduit at the ice-till interface. Arrows represent water movement into and out of the till as a result of melt (red arrows) and freeze (blue arrows).

Results

TESTS:

We conducted three tests with different volumetric fluxes at the onset, as given in Table 1.

MAIN FINDINGS:

- Oscillations were generated at the GL of the ice stream and depended on the basal water availability and thermal conditions there.
- When the volumetric flux at the onset was low (KIS1), water supply at the GL was dictated by basal melt/freeze and the subglacial conduit did not extend to the GL (Figure 6a).
- This confirms the theoretical model of Tulaczyk and others (2000a), which stated that internal oscillations in ice stream dynamics are thermally driven.
- For KIS1, changes in till porosity were small near the GL and surface velocities changed rapidly (Figure 7a-d).
- Amplitudes in the surface velocity were higher (higher maximum and lower minimum, Table 2) and periods were faster for KIS1 than for KIS2 (Table 1).
- When the volumetric flux at the onset was higher (KIS2-3), water supply at the GL was dictated mainly by water transportation from upstream and the subglacial conduit extended to the GL (Figure 6b-c).
- In KIS2 changes in the till porosity were large near the GL and surface velocities changed gradually (Figure 7e-h).
- In KIS3 water availability at the GL was high enough that the till remained at high porosity and oscillations in the surface velocity ceased.
- Once a conduit was permanently open at the GL, an increase in the water flux had very little additional effect on ice flow.

Table 1: Prescribed volumetric flux (Q) at the onset and amplitude/period of surface velocity at the grounding line

Test	Q at the onset ($m^3\ s^{-1}$)	Oscillation in surface velocity: amplitude (m)	period (years)
KIS1	4.5×10^{-3}	947.2	265.8
KIS2	6.0×10^{-2}	676.7	537.5
KIS3	1.5×10^{-1}	no oscillation	no oscillation

Table 2: Modelled surface velocity (m a^{-1}) of KIS

	Onset			Grounding line		
	min	max	mean	min	max	mean
KIS1	69.8	71.0	70.2	7.4	1040.2	454.2
KIS2	72.6	80.4	76.7	39.9	1721.9	498.6
KIS3	-	-	78.7	-	-	561.0

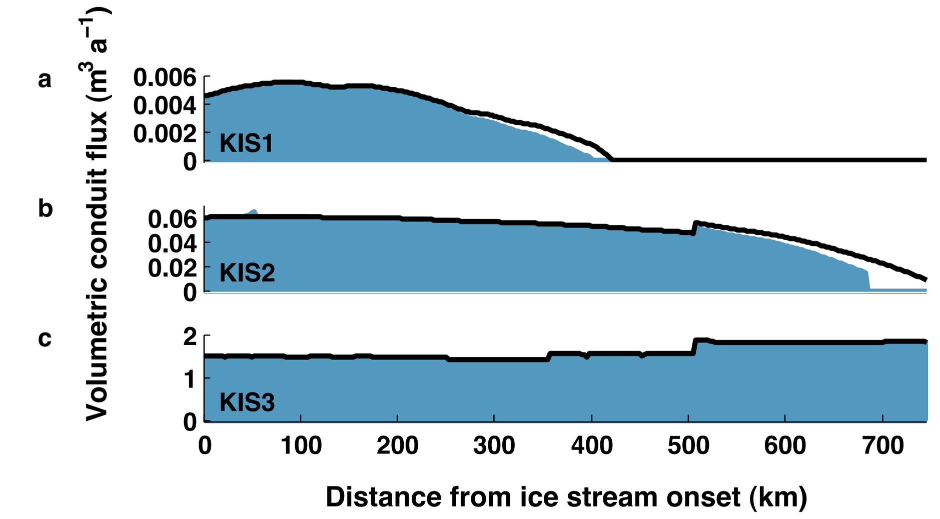

Figure 6: The volumetric conduit flux of model runs KIS1-3. The black line is maximum size and extent along the ice stream of the conduit. The area in blue is the minimum size and extent of the conduit. The increase at 507.5 km downstream of the onset in b and c is where additional water from the second upper tributary is added at the junction. Note the different vertical scales.

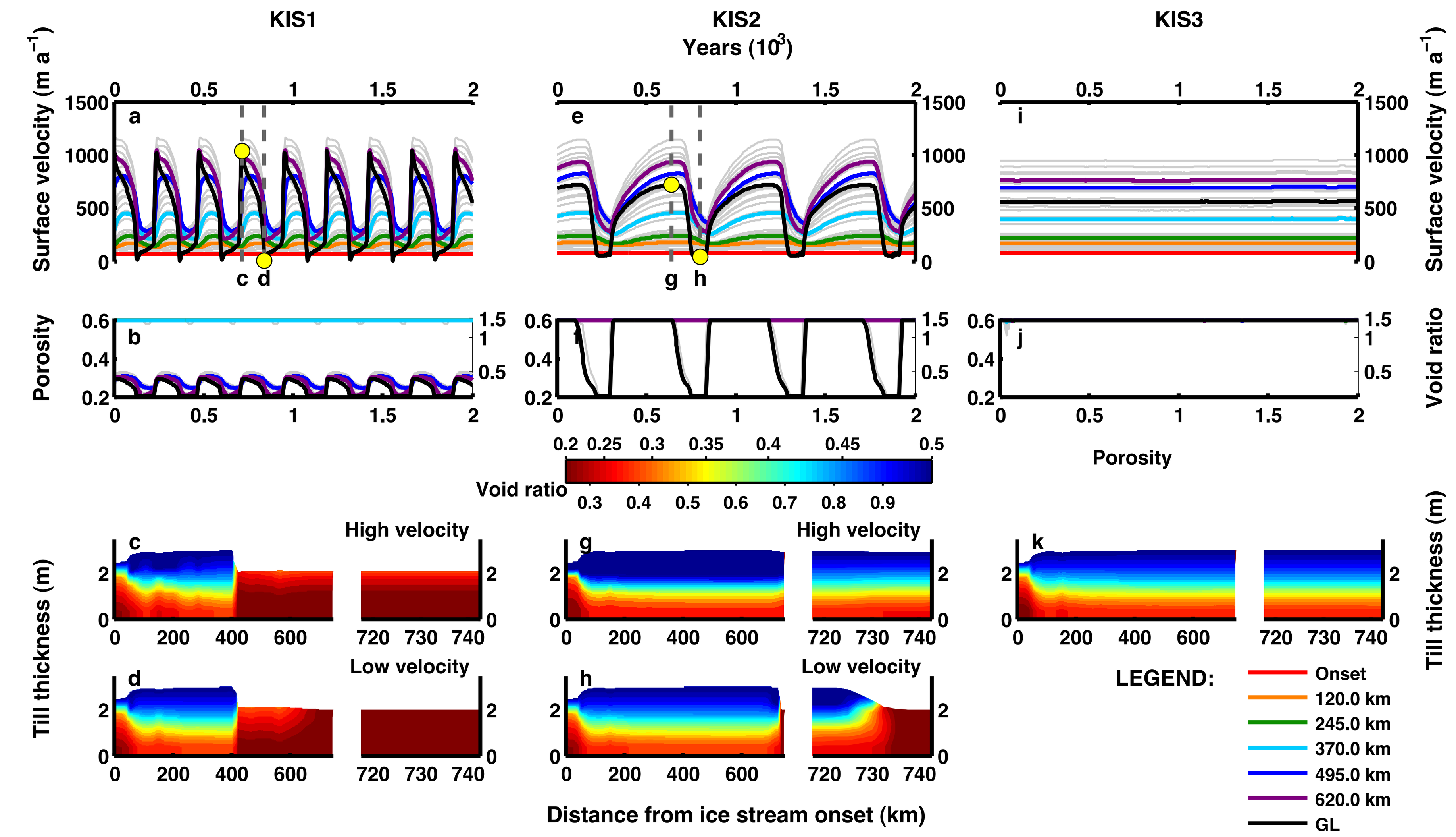

Figure 7: Surface velocity, till porosity and till thickness of KIS1-3. a, e and i give the surface velocity. The location of coloured lines is given in the legend and light gray lines are spaced 22.5 km apart. Gray dashed lines and yellow dots indicate years of maximum and minimum surface velocity at the GL displayed in c, d, g and h. b, f and j give the porosity and void ratio of the top layer of the till. Line colours correspond to those of the legend where visible. c and g give the till profile at maximum and d and h at the minimum surface velocity. For KIS3 till porosity and thickness are constant in time (k). For c, d, g, h and k, the LHS figure gives the full ice stream profile and the RHS figure shows the last 25 km of the ice stream in greater detail.

Conclusions

- KIS can either reach a stable state or can oscillate on periods of hundreds of years, depending on water availability at the GL.
- Oscillations can be driven by either basal melt/freeze at the GL (thermal condition) or by a change in hydrological conditions due to water transportation to the GL from upstream.

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