

# Hydrochemical coupling of a glacial borehole–aquifer system

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**ABSTRACT.** Measurements of the electrical conductivity of subglacial water provide a useful complement to measurements of pressure and turbidity. In the summer season, fluctuations of conductivity can be attributed to changes in water transport, water provenance and subglacial residence time. These explanations are unlikely to apply during the winter season because surface melt sources are not active and the subglacial water system is predominantly unconnected. Thus, fluctuations in water conductivity during the winter months seem paradoxical. To introduce a quantitative basis for comprehending such phenomena, we develop an interpretative model of the hydrochemical interaction between a water-filled borehole and a subglacial aquifer. The electrical conductivity of water near the borehole–aquifer contact is affected not only by diffusion but also by advective transport of solute between the two reservoirs in response to pressure forcing of the system. Using records of ice strain, water pressure and electrical conductivity from unconnected boreholes in Trapridge Glacier, we demonstrate that changes in borehole geometry caused by ice-strain events provide a plausible mechanism for at least some of the observed fluctuations of electrical conductivity. Conductivity records provide information regarding advective coupling of the borehole–aquifer system that is not available from pressure records alone.

## INTRODUCTION

Spatial and temporal measurements of the electrical conductivity of subglacial and englacial water provide useful indicators of hydrological conditions. Interpretation of these data requires a framework for analyzing the coupling between a borehole, containing one or more conductivity sensors, and the subglacial water–sediment system with which it chemically and hydraulically interacts. The purposes of this paper are to explore this interaction and, guided by a theoretical model, to interpret field observations from Trapridge Glacier, Yukon Territory, Canada, where year-round measurements of subglacial hydraulic properties have been collected since summer 1988 (Stone, 1993; Stone and others, 1993; Stone and Clarke, 1996).

In holes that are well connected to the subglacial hydraulic system, temporal variations in water conductivity observed near the ice–bed contact can largely be explained in terms of the subglacial residence time of the water. A lumped-element model to describe this situation was elaborated in Clarke (1996). In holes that are unconnected or weakly connected, the explanation of temporal variations is less clear. For example, during the winter season, we occasionally observe rapid changes of water conductivity in unconnected holes. Because these fluctuations cannot be attributed to the operation of an active hydraulic system, other explanations must be sought. We propose that some of these puzzling fluctuations result from ice- or bed-deform-

ation events that drive water exchange between the borehole and subglacial bed. During these events, advection, rather than diffusion, can become the dominant mechanism for chemical transport. Figure 1 illustrates possible hydrological and chemical responses when a sealed, water-filled borehole is subjected to sudden deformation (negative longitudinal strain rate corresponds to compression of the hole). As the hole is pressurized, downward water flow flushes comparatively unmineralized water from the borehole to the subglacial bed. Upon termination of a strain event, water flow ceases and ion diffusion from the bed to the borehole eventually restores chemical concentrations to their former state.

We begin by developing a physical model that describes solute transport in a borehole–aquifer system. The utility and limitations of the model are assessed by using it as a tool for interpreting electrical conductivity variations beneath Trapridge Glacier.

## PHYSICAL MODEL

We assume that the glacier rests upon water-saturated unlithified permeable sediment that can be regarded as a somewhat permeable aquifer, a situation that is thought to apply to Trapridge Glacier (Stone and Clarke, 1993; Waddington and Clarke, 1995). The aquifer is taken to be tabular and underlain by an impermeable boundary. A quasi-cylindrical borehole, coaxial with the  $z$  axis and having cross-sectional area  $A$  and water column height  $L$ , is in hydrological and chemical contact with the subglacial aquifer; for geometrical simplicity, the borehole is assumed to completely penetrate the subglacial aquifer (Fig. 2). Balance relations for this coupled borehole–aquifer system are developed below.

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