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Investigating groundwater flow paths within proglacial moraine using multiple geophysical methods

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SUMMARY

Groundwater that is stored and slowly released from alpine watersheds plays an important role in sustaining mountain rivers. Yet, little is known about how groundwater flows within typical alpine geological deposits like glacial moraine, talus, and bedrock. Within the Lake O'Hara alpine watershed of the Canadian Rockies, seasonal snowmelt and rain infiltrates into a large complex of glacial moraine and talus deposits before discharging from a series of springs within a relatively confined area of a terminal moraine deposit. In order to understand the shallow subsurface processes that govern how groundwater is routed through this area, we have undertaken a geophysical study on glacial moraine and bedrock over and around the springs. From interpretations of several seismic refraction, ground-penetrating radar (GPR), and electrical resistivity tomography (ERT) profiles, we delineate the topography of bedrock beneath moraine. Although the bedrock is generally flat under central parts of the terminal moraine, we suggest that an exposed slope of bedrock on its eastern side and a ridge of shallow bedrock imaged by ERT data underneath its western margin serves to channel deep groundwater toward the largest spring. Low-electrical-resistivity anomalies identified on ERT images within shallow parts of the moraine indicate the presence of groundwater flowing over shallow bedrock and/or ice. From coincident seismic refraction, GPR and ERT profiles, we interpret an ca. 5-m-thick deep layer of saturated moraine and fractured bedrock. Despite their relatively small storage volumes, we suggest that groundwater flowing through bedrock cracks may provide an important contribution to stream runoff during low-flow periods. The distinct deep and shallow groundwater flow paths that we interpret from geophysical data reconcile with interpretations from previous analyses of hydrograph and water chemistry data from this same area.

1. Introduction

More than one-sixth of the Earth's population relies either directly or indirectly on glaciers or seasonal snowpacks for their fresh water supplies (Barnett et al., 2005). Alpine regions form the headwaters of many major river systems and hydrological processes within these areas play an influential role in the rate and timing of runoff to mountain rivers. Reliable estimates of the response of mountain rivers to future climate warming will therefore require a thorough understanding of how rain and melt water from ice and snow is stored and transported within alpine watersheds.

Over the past two decades, new insights have been gained into the role of groundwater in sustaining runoff from alpine watersheds. Williams and Melack (1991) and Denning et al. (1991) first hypothesized that strong changes in the geochemistry of snow melt entering mountain streams were a result of that melt water being flushed through soil. Although soil layers can be relatively thin in alpine regions compared to other areas, several studies have shown that a large percentage of the snow melt and rain that falls within an alpine catchment travels through the ground before it enters streams (e.g. Campbell et al., 1995; Sueker et al., 2000; Liu et al., 2004) and lakes (Gurrieri and Furniss, 2004; Hood et al., 2006; Roy and Hayashi, 2008).

Thick overburden materials like glacial moraine and talus have the potential to store significant amounts of melt water and can slow the rate at which it enters mountain streams (Caballero et al., 2002; Clow et al., 2003). Consequently, in snow-dominated alpine watersheds, groundwater flowing from these types of deposits helps sustain stream flow well after the seasonal snowpack has melted (Clow et al., 2003; Hood et al., 2006). Recent work

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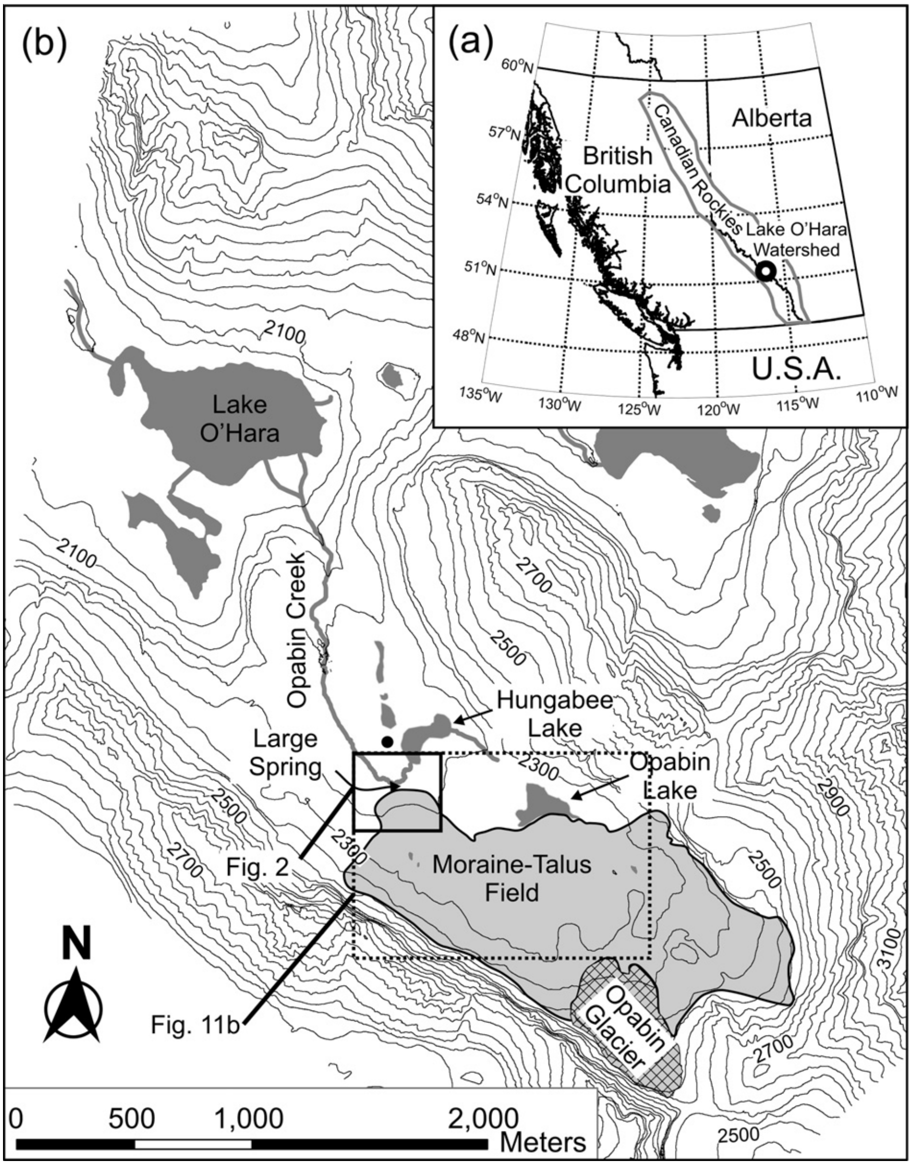

Fig. 1. (a) Location of the Lake O'Hara watershed within the Canadian Rockies. (b) Topographic map of the Lake O'Hara watershed and Opabin sub-watershed showing the location of the moraine-talus field (light gray body). Surface water lakes and streams are plotted in dark gray. Black square indicates the location of the geophysical surveys around the groundwater springs shown in Fig. 2. Dotted black rectangle outlines the map area shown in Fig. 11b. Black dot denotes the location of an automatic weather station. Contour interval is 50 m.

by Roy and Hayashi (2009), in the Lake O'Hara alpine watershed within the Canadian Rockies (Fig. 1a), suggests that the groundwater flow within these unconsolidated sediments can be complex. Most of the groundwater discharging from a large (ca. 1500 × 1000 m) complex of moraine and talus deposits, which covers a high alpine plateau in this watershed, emanates from a large spring (hereafter referred to as the Large Spring), with several smaller springs also occurring in the same relatively confined ca. 100 × 100 m area (Fig. 2a). The chemical composition of water discharging from the large and small springs in the area showed a strong spatial variation that suggests that multiple, distinct groundwater flow paths exist within the moraine-talus field. Analysis of the discharge hydrograph of groundwater contributed by these springs to the upper Opabin Creek indicated at least two different responses to precipitation and melt inputs: a rapid and possibly local response and a slow response correlated (with a delay of 12–24 h) with the water-level hydrograph of an alpine lake, which is at a higher elevation and ca. 500 m away from the Large Spring (Opabin Lake; Fig. 1b). This latter finding along with a link in water chemistry suggests that the two features are connected by subsurface flow paths.

The Lake O'Hara watershed is typical of many alpine watersheds in the Canadian Rockies in that there is no road access to the site and it is an ecologically sensitive area. Consequently, conventional hydrogeology techniques such as drilling and piezometer installation are rarely feasible in these environments. Thus, it is difficult to gather information on the groundwater storage capacity and the nature of potentially complex groundwater flow paths within glacial moraine and talus deposits. However, near-surface geophysical techniques can provide a non-invasive alternative for characterizing internal structures within talus and moraine deposits (e.g. Degenhardt and Giardino, 2003; Schrott et al., 2003; Sass, 2006, 2007; Maurer and Hauck, 2007). By imaging differences in subsurface physical properties within these deposits there is potential to infer hydrological characteristics, including debris volumes, the extent of wet and dry areas and internal structures that may control the flow of groundwater (e.g. Clow et al., 2003; McClymont et al., 2010).