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Evaluation of detrital thermochronology for quantification of glacial catchment denudation and sediment mixing

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ABSTRACT

Thermochronometric methods have been applied successfully on bedrock samples as well as detrital material to study exhumation processes in mountain belts. The access to exposed bedrock can be a limiting factor in remote and rugged mountainous regions, or areas covered by ice. The analysis of detrital material provides an integrated signal of rock cooling from sediment source areas in a catchment. One advantage of detrital thermochronology is that the source areas can include regions that are inaccessible for bedrock dating, such as beneath glaciers. In this study we investigate the suitability of various detrital thermochronometer sampling approaches at the glacier terminus including sediments from the pro-glacial fluvial outwash, the ice-cored terminal moraine, and older moraines. Specifically we analyzed the detrital apatite fission track ages of sand-size material collected from the Tiedemann and Scimitar Glaciers that drain the eastern and northern flanks of Mt. Waddington British Columbia, Canada, respectively. We present 935 new apatite fission-track ages and compare the grain-age distributions of the various detrital sites among each other and with published bedrock ages from the Tiedemann Glacier catchment. We show that detrital apatite fission-track thermochronometry is a viable and powerful tool to obtain a robust cooling age distribution of a catchment or region that can elucidate age populations originating from those parts of the catchment that are covered by ice and therefore remain undetected by bedrock studies. We also show that sampling the ice-cored terminal moraine is an alternative sampling approach to the pro-glacial river sediments that provides cooling age distributions representative of the sediments sourced by the entire catchment including sub-glacially eroded material. Finally, samples collected from the modern glacial systems and terminal moraines of different ages are compared to assess temporal variations in the distribution of glacial erosion over the Late Holocene.

1. Introduction

Throughout the Quaternary glaciers have shaped most mountain belts on Earth, and as a consequence these regions are characterized by glacial erosion and their remnant landforms today. Erosion processes acting over million of years result in the exhumation of rocks from progressively deeper structural levels. Rock exhumation can be quantified using low-temperature dating techniques such as fission-track (FT) and (U–Th)/He analysis of apatite and zircon. These methods are powerful tools for quantifying the cooling history of rocks in the upper crust, and interactions between tectonic and surface processes (e.g., Reiners et al., 2005; Bernet and Garver, 2005; Hodges et al., 2005; McQuarrie et al., 2008). Thermochronometric methods can be applied to bedrock samples as well as detrital material. Although bedrock dating has the advantage of recording the cooling of rocks at a specific location, the access to exposed bedrock can be a limiting factor in difficult to access mountainous regions. The analysis of detrital material provides a spatially integrated cooling signal of an entire catchment where sediment is sourced. Detrital material can also provide indirect access to unreachable locations such as under glaciers themselves. The analysis of apatite (U–Th)/He ages from detrital material was successful in quantifying the spatial distribution of erosion in formerly glaciated catchments of the Sierra Nevada, California (Stock et al., 2006), and in the Tiedemann Glacier catchment in British Columbia (Ehlers et al., 2015). In contrast to the (U–Th)/He dating technique, the FT dating approach has the advantage that large numbers of measurements are possible, which is crucial for a statistical robust analysis of detrital age distributions. The FT dating approach is therefore valuable for both regional and detailed local studies. For example, in the St. Elias Mountains in southeast Alaska, massive glaciers and ice fields obstruct the study of rock exhumation by means of bedrock thermochronology. Detrital zircon and apatite FT dating of sediment derived from more than 50 glacial catchments was able to reveal the spatial and temporal pattern of rock exhumation across the entire mountain range (Enkelmann et al., 2008, 2009, 2015; Falkowski et al., 2014).

Erosion in a glacial catchment occurs through several processes, some of them act under the glacier and others above on the ice-free mountain ridges. Erosion processes under the glacier include abrasion,

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plucking, and those associated with melt water under the glacier, whereas periglacial erosion processes, particularly landslides, deliver debris to the glacier surface, where it is carried along and becomes mixed with the subglacial sediments towards the terminus (Syvitski, 1989; Hallet, 1996; Hunter et al., 1996; Arsenault and Meigs, 2005; Hallet and Roche, 2010). Melt water transports sediment through and underneath the glacier facilitating bedrock abrasion and glacial flow. Freezing can cause blockage of the fluvial system and pressure can build up underneath the ice that can be released suddenly in outburst floods of large amounts of sediment-laden water (Raymond, 1987; Paterson, 1994; Lingle and Fatland, 1998; Headley et al., 2013). All these transport processes in glaciers raise the question of how representative are sediment samples collected at the glacier terminus to record the source of sediment of the entire catchment? The terminus of a glacier is often characterized by hundreds of meters to kilometers long debris covered glacier and ice-cored terminal moraine until the main subglacial channel emerges and forms the pro-glacial river. Applications of detrital thermochronology for quantifying glacial erosion would benefit from answering the following questions: how well mixed is a detrital sample from glacial outwash and where is the best sampling location at the glacier terminus to collect material suitable for the study of catchment-wide erosion processes?

In this study we analyze detrital apatite FT data from the Tiedemann and Scimitar Glaciers that drain the eastern and northern flanks of Mt. Waddington, British Columbia, Canada, respectively (Fig. 1). We collected sediment of primarily sand size (0.06–2 mm) and pebble size of <2 cm at different locations with respect to the glacier terminus. Sample locations include the modern deposit of the pro-glacial river, two terminal moraines from 1600 A.D. and 2900 B.C., and a profile of samples collected across the ice-cored terminal moraine (Figs. 1 and 2). We present new apatite fission track (FT) ages and compare the grain-age distributions of the samples from the various sites with results from 9 published bedrock ages from the Tiedemann Glacier catchment.

2. Background

2.1. Thermochronology

Thermochronometric dating techniques quantify the cooling of rocks through temperatures that are typical in the upper crust. The FT and (U–Th)/He analysis can be applied to uranium-bearing minerals like apatite and zircons, and each of these thermochronometric systems is sensitive to different temperature ranges. The concept of the closure temperature is a convenient way to compare dates from different thermochronometric systems. Assuming monotonic cooling through the temperature range where the radiogenic daughter products (i.e., fission tracks or helium) are partially retained in the mineral grain, the thermochronometric cooling age provides the time when the sample cooled below its closure temperature (Dodson, 1973). Thermochronometric methods like (U–Th)/He and FT on apatite refer to closure temperatures of 55–75 °C and 100–120 °C (e.g., Shuster et al., 2005; Green et al., 1986), respectively, and are often referred to as low-temperature thermochronometers. These methods are able to record processes that affect the upper 2–6 km of the crust, depending on the geothermal gradients. Many studies have successfully identified patterns of cooling ages across a region that could be interpreted with respect to tectonics, erosion, landscape evolution, and climate (e.g., Armstrong et al., 2003; Reiners et al., 2007; Huntington et al., 2007; Barnes et al., 2012).

Most studies use thermochronometry on bedrock samples but the use of detrital samples has been shown to be a powerful tool and became increasingly popular (e.g., Enkelmann et al., 2009, 2011, 2015; Stock et al., 2006; Rahl et al., 2007; Vermeesch, 2007, 2013; Whipp et al., 2009; Avdeev et al., 2011; Thomson et al., 2013). Although there is a general loss of the spatial information of where the cooling age is sourced within the catchment, there are several advantages that come with dating detrital material: (1) the age distribution of a detrital sample can provide an integrated picture of the cooling age pattern for the entire catchment, (2) using detrital thermochronometry on sedimentary strata of known depositional age allows quantification of changes in either the source rock exhumation rates, or catchment area through time (e.g., Bernet and Garver, 2005; Bernet et al., 2009), and (3) detrital samples can provide age information from regions that may be otherwise inaccessible for bedrock sampling due to thick vegetation cover, lacking infrastructure, political reasons, landscapes that are too steep, or ice coverage. This latter reason is of particular interest because glaciers cover the valley bottoms of many mountain belts and prevent sampling at low elevations. Those low-elevation bedrock samples are however those where we generally expect the youngest cooling ages, because the distance from the closure isotherm to Earth surface is shorter in the valleys than on the mountain tops resulting in younger cooling ages at low elevations and older ages for rocks at higher elevations (see Fig. 3A). Presumably the valleys are also the locations where

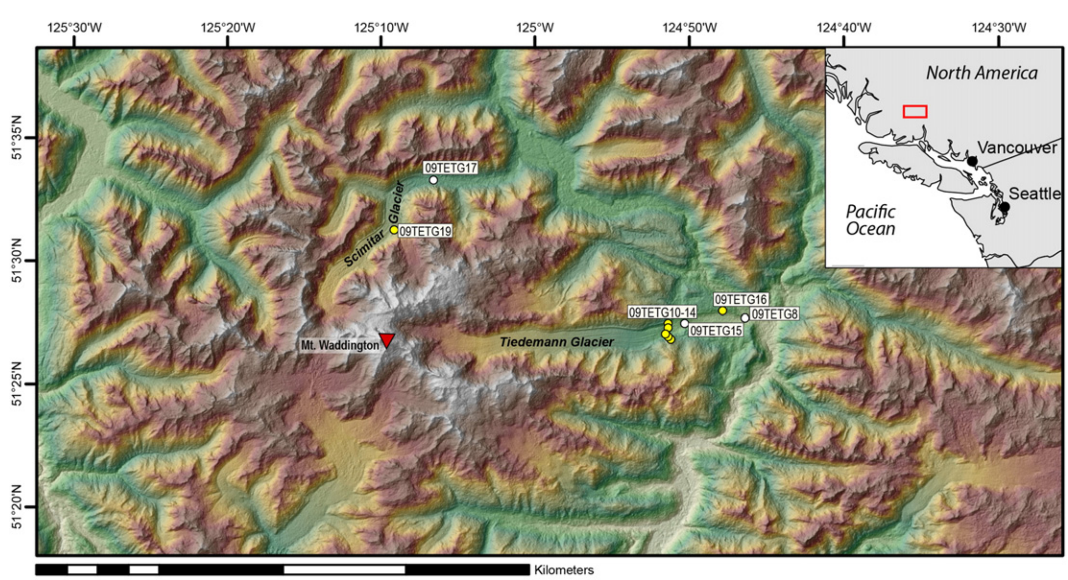

Fig. 1. Digital elevation model of the study area with sample location for detrital thermochronology. Inlet map shows as red box the study region in the western part of North America.