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Did rock avalanche deposits modulate the late Holocene advance of Tiedemann Glacier, southern Coast Mountains, British Columbia, Canada?

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ABSTRACT

Most glaciers in western North America with reliable age control achieved their maximum Holocene extents during final advances of the Little Ice Age. Tiedemann Glacier, a large alpine glacier in western Canada, is an enigma because the glacier constructed lateral moraines that are up to 90 m higher, and extend 1.8 km farther downvalley, than those constructed during the Little Ice Age. Our data show that the activity of the glacier is more complex than originally documented and that the glacier advanced many times during the past six thousand years. Surface exposure dating and radiocarbon ages of stumps beneath till demonstrate that the glacier achieved its maximum Holocene extent at about 2.7 ka. We hypothesize that one or more rock avalanches delivered surface debris to the glacier and caused the 2.7 ka glacier advance to be much larger than can be explained by climate forcing. To test our hypothesis, we developed and used a surface debris advection routine coupled to an ice dynamics model. Our results show that even a moderately sized rock avalanche (10×10^6 m^3) delivered to the top of the ablation zone could cause the glacier to thicken and advance far beyond its Little Ice Age limit.

1. Introduction

With few exceptions, glaciers in western North America achieved their maximum Holocene extents during the final centuries of the Little Ice Age. Many moraines that lie outside Little Ice Age limits, initially believed to be Holocene landforms, are now known to be latest Pleistocene in age (Osborn and Luckman, 1988; Davis et al., 2009). Denton and Karlén (1977) documented several mid-to-late Holocene (Neoglacial) terminal moraines in the Saint Elias Mountains in Yukon Territory that extend beyond Little Ice Age deposits, but these glaciers surge or have unusually thick debris cover that complicates the relation between climate and glacier response (Denton and Karlén, 1977; Yde and Paasche, 2010).

Porter and Denton (1967) first described regional evidence for an advance of North American alpine glaciers about 2700 years ago. Tiedemann Glacier, located in the southern Coast Mountains of British Columbia, advanced well beyond its Little Ice Age limit during this regional advance. In particular, the stratigraphic and geomorphic evidence for the late Holocene 'Tiedemann Advance' at its type locality is compelling. Lateral moraines associated with this advance occur along the lower 12 km of the ablation zone of the glacier, rise up to 90 m above the Little Ice Age moraine crest, and extend 1.8 km downvalley from the outermost Little Ice Age terminal moraine. Glacier downwasting during the 20th century exposed lateral moraines composed of multiple tills, glaciofluvial sediments, and subfossil wood. Fulton (1971) obtained radiocarbon ages on bulk samples of organic sediments just above and below a thin layer of outwash in a bog just outside the Tiedemann north lateral moraine. These ages constrain the age of the Tiedemann Advance to 2.16–3.33 ka (2σ range) (kilo calendar yrs BP). Arsenault et al. (2007) narrowed this age range to 2.18–2.75 ka based on radiocarbon ages on conifer needles from the lower and upper contact of the outwash. Radiocarbon ages from wood in the north Tiedemann lateral moraine suggest that the Tiedemann Advance began about 3.30 ka and that the glacier remained in an advanced position until 1.90 ka, after which it retreated (Ryder and Thomson, 1986).

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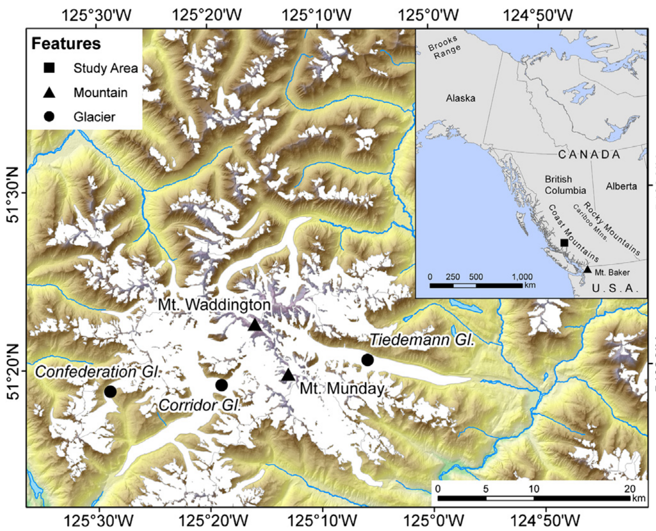

Fig. 1. Color shaded relief map of the study area.

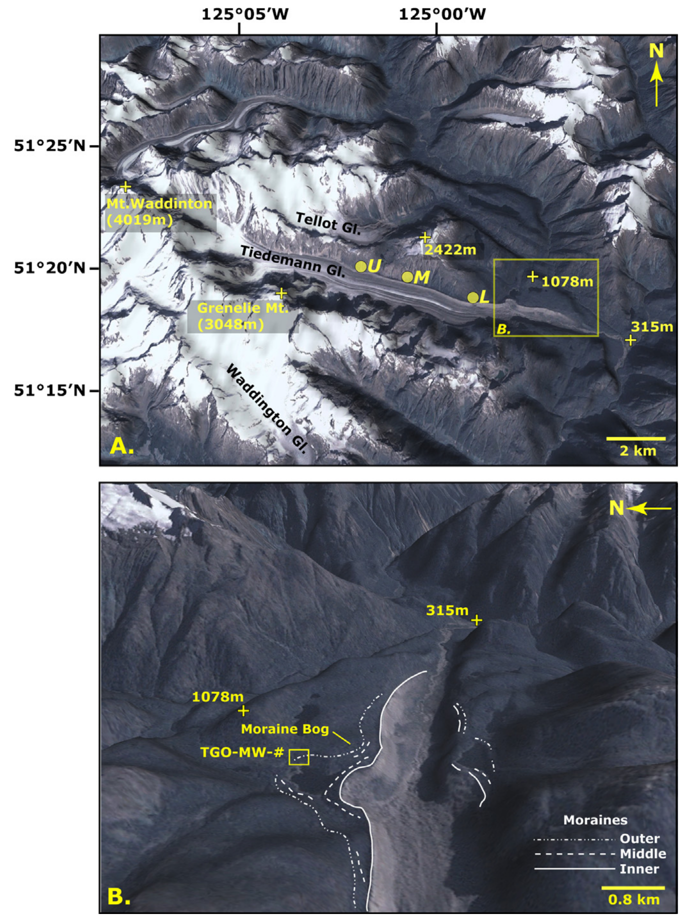

Fig. 2. Oblique aerial photograph overlain with Landsat7 imagery of the southern Coast Mountains near Mount Waddington and Tiedemann Glacier. The yellow box indicates the area from which blocks were collected for surface exposure dating. The relief is vertically exaggerated 1.5 times to improve clarity (distance scale is approximate). Image generated with NASA World Wind 1.4. Labels U, M, and L, respectively, denote "upper", "middle", and "lower" stratigraphic sections. "TGO-MW" denotes the sampling site for surface exposure ages. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

Given the unusual behavior of Tiedemann Glacier during the middle Neoglacial, we reexamined the stratigraphy and moraine record of the glacier. Our motivation was two-fold. First, we sought to obtain additional stratigraphic and chronological information that might reveal additional details about the behavior of Tiedemann Glacier during the period 3.3–1.9 ka. Continued mass wasting of the lateral moraines and thinning of the glacier by several tens of meters since Ryder and Thomson (1986) visited the glacier in 1977 and 1978 offered the possibility that we could examine new stratigraphic sections. Second, we wished to verify the age of the outermost moraines at Tiedemann Glacier because it is one of only a few sites in western Canada where Holocene moraines lie outside Little Ice Age moraines.

In this paper, we present new stratigraphic and chronologic evidence for the timing of fluctuations of the Tiedemann Glacier between 5.89 ka and 0.32 ka and offer an explanation for its idiosyncratic behavior. We first describe the study area and the methods used to temporally constrain the activity of the glacier. We then describe the stratigraphy of the north lateral moraine and present surface exposure ages that confirm the age of the Tiedemann Advance. Finally, we use a coupled ice dynamics and surface debris advection model to investigate the possibility that surface debris cover may explain the unusual behavior of the glacier.

2. Study area and methods

Tiedemann Glacier (Figs. 1 and 2) flows 23 km east from Mount Waddington (4019 m asl) to its terminus at 360 meters above sea level (m asl). The lower 17 km of the glacier, which lies in the ablation zone, has a width of 1–1.5 km. The net mass balance of Tiedemann Glacier was strongly negative during the latter half of the 20th century — the glacier thinned, on average, 25 m and lost 1.67 ± 0.17 km^3 of ice (water equivalent) over the period 1949–2009 (Tennant et al., 2012). In 2005, debris covered about 27% of the glacier surface, primarily its lowest 8.5 km. Sequential aerial photographs indicate that this debris cover increased in extent as the glacier thinned over the past 60 years.

The upper portion of the glacier is bordered by steep slopes with relief up to 1000 m, whereas the lower part and its associated Neoglacial moraines extend across an area of subdued relief (Figs. 1 and 2). The Little Ice Age moraine, termed the "inner moraine" by Ryder and Thomson (1986), is a prominent single- or multiple-crested ridge that reaches up to 100 m above the glacier surface and impounds two lakes (Fig. 2). The maximum Holocene extent of the glacier is delineated by a conspicuous blocky lateral moraine, the "outer moraine" of Ryder and Thomson (1986). The outer lateral moraine on the north side of the glacier is continuous over a distance of almost 10 km. A correlative moraine is present along the south side of the glacier, but it is poorly preserved and is only continuous over a distance of less than 4 km. About 3 km above the terminus, on the north side of the glacier, the "outer moraine" comprises three separate ridges (Fig. 2). Mature forest and a well-developed soil on these ridges contrast with the sparse vegetation and lack of soil development on the "inner moraine," suggesting a significant difference in the age of the features.

2.1. Lateral moraine stratigraphy

We documented the stratigraphy of the north lateral moraine of Tiedemann Glacier at three sites during the summers of 2005 and 2006. Exposed sediment sections were steep, difficult to access, and subject to rockfall. For safety reasons, our stratigraphic work thus focused on determining the general sediment character and broad stratigraphic relationships exposed in the north lateral moraine.

A hand-held GPS was used to record section locations. We determined relative elevations with a barometric altimeter and tied readings to several base stations at the edge of the glacier. The absolute elevations of the base stations were determined from a