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Field evidence and hydraulic modeling of a large Holocene jökulhlaup at Jökulsá á Fjöllum channel, Iceland

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ABSTRACT

Field investigation and hydraulic modeling of the Jökulsá á Fjöllum outflow channel in the northern highlands of Iceland suggest a larger than previously modeled jökulhlaup catastrophic release of glacial floodwaters probably occurring just after early Holocene deglaciation. Although earlier investigations described a similar large paleoflood event, our hydraulic model parameter estimates and floodplain inundation maps correlate with new field evidence presented here. Due to its temporal and voluminous outflow we consider potential jökulhlaup sources and mechanisms and also its relevance as an Earth analog to Mars fluvial geomorphology and processes. In this study, we reconstruct this large jökulhlaup event using HEC-GeoRAS to extract three-dimensional channel geometry and the HEC-RAS hydraulic model. Depositional and erosional landforms across the 435–485 km^2 flood inundation area provide field evidence of high water lines (trimlines) required for hydraulic model constraints. Hydraulic modeling results related to this field evidence and the unambiguous inundation of Ferjufjall along the Mt. Herðubreið reach gives a conservative peak discharge rate of 2.2×10^7 m^3 s^{-1} and a mean flow velocity of 14.9 m s^{-1}. By comparison, this is larger than the 1.8×10^7 m^3 s^{-1} peak discharge of the Kuray paleoflood in the Altai Mountains of Siberia, which is the largest previously documented paleoflood on Earth. This study suggests that this paleoflood through the Jökulsá á Fjöllum channel is the largest known on Earth.

1. Introduction

This paper presents new field evidence and hydraulic modeling for a large Holocene jökulhlaup in the northern highlands of Iceland. We also compare how this paleoflood relates to other catastrophic outbursts and to important issues in paleoflood hydrology. Jökulhlaup is the Icelandic term that describes any abrupt release of massive amounts of water generated by glacial–volcanic interactions and climate change (Björnsson, 2009). They are typically of short duration with high magnitude water and sediment outflows much greater than normal discharge (Carrivick and Rushmer, 2006). The objective of this research was to develop a method to model catastrophic discharge on Earth using remote sensing data that can be applied to analogous locations on Mars. Two field sites were initially chosen, Eddy Narrows, Montana, which is the conduit for all Pleistocene Glacial Lake Missoula (GLM) floodwaters on its way through the Channeled Scablands of the pacific northwestern United States (Pardee, 1942; Alt, 2001), and Jökulsá á Fjöllum channel in Iceland, which has experienced episodic jökulhlaups over recent geologic time (Saemundsson, 1973; Björnsson, 2002; Waitt, 2002; Carrivick et al., 2004a,b; Alho et al., 2005; Björnsson, 2009). Each site was previously hydraulically modeled and its fluvial geomorphology described in the field and subsequently compared to Mars outflow channels (Baker and Milton, 1974; Malin and Eppler, 1981; Rice and Edgett, 1997). The focus of our paper is on Iceland hydraulic modeling results validated by new field evidence and to offer a model to apply to Mars fluvial systems. To that end, we are fortunate to use the extensive research by others on the Glacial Lake Missoula paleofloods (Pardee, 1910; Bretz, 1925; Pardee, 1940, 1942; Baker, 1973; Baker and Milton, 1974; Benito, 1997; Alt, 2001; Carling et al., 2003) as well as our previous work there. We also rely on extensive research that addresses the use of hydraulic models and fluvial geomorphological interpretation of paleofloods related to both Earth and Mars fluvial systems (Costa, 1983; Baker et al., 1988; House et al., 2002; O'Connor et al., 2002; Carling et al., 2003; Herget, 2005; Carrivick and Rushmer, 2006).

One important application of this work is to offer insight into the volumes of water necessary for jökulhlaup-type outburst events that produced the massive fluvial geomorphological features observed on Mars (Howard, 2008, 2010 unpublished data). Applying these hydraulic models to Mars outflow channels serves to test hypotheses about water conveyance and if water sources were from air-fall precipitation contained in source basins, or if water was derived from subsurface aquifers beneath a confining cryolithic ground-ice layer, or through groundwater

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sapping (Hanna and Phillips, 2005). In this paper we will briefly discuss the applicability of our model to Mars fluvial processes.

1.1. Background

Jökulhlaup outbursts create fluvial channels with unique geomorphologic features that are observed at various locations on Earth and in the enormous fluvial channels observed on Mars. Jökulhlaups are studied extensively on Iceland to understand paleofloods and modern floods due to glaciovolcanic interactions and climate change (Gomez et al., 2000; Björnsson, 2002; Magilligan et al., 2002). Recent volcanic eruptions (March and May 2010) beneath the Eyjafjallajökull glacier in southern Iceland released tremendous volumes of ash, lahars, and glacial melt-water that devastated local communities and halted European airline travel for days, underscoring that jökulhlaups are a significant topic of modern geological hazards research (Berninghausen et al., 2010). Of particular interest to our study is the groundbreaking research of Alho et al. (2005), Carrivick et al. (2004a,b), and Carrivick (2007) in that their work describes the geomorphology and hydraulics of Jökulsá á Fjöllum channel at Vatnajökull glacier. Additionally, Björnsson (2002, 2009) describes the formation mechanisms and heat sources for marginal and subglacial lakes required for jökulhlaups to occur. Previous field work at Jökulsá á Fjöllum channel describes in detail many of the glacial deposits and fluvial features such as pendant bars, streamlined hills, boulder fields, and slackwater deposits (Malin and Eppler, 1981; Rice et al., 2002; Waitt, 2002; Carrivick et al., 2004a, b; Alho et al., 2005; Carrivick, 2007). Alho et al. (2005) conducted the most quantitative hydraulic study and proposed a peak discharge and mean flow velocity for the channel's largest Holocene outburst primarily from aerial photography and field evidence at Vaðalda, Upptyppingar, and Möðrudalur reaches (Fig. 1).

Based on previous HEC-RAS hydraulic modeling of paleofloods in GLM (Benito, 1997; O'Connor et al., 2002) and at Jökulsá á Fjöllum (Alho et al., 2005) and the minimal quantitative differences between one and two-dimensional models (Miller and Cluer, 1998; Alho and Aaltonen, 2008), we adopted a one-dimensional standard step method hydraulic model for the estimation of catastrophic outburst parameters. A discussion of hydraulic model differences is presented in Section 3.3. Jökulhlaup-type Earth-analog sites at Eddy Narrows, Montana, and Jökulsá á Fjöllum channel in Iceland were used to refine and calibrate the model and to assess correlations between channel hydraulics and fluvial morphology. Glacial Lake Missoula research is relevant because of its catastrophic outflow across a large area that has similar geomorphology to outflow channels found on Mars (Pardee, 1910; Bretz, 1923, 1925; Pardee, 1940, 1942; Bretz et al., 1956; Baker, 1973; House et al., 2002; Gregory and Benito, 2003). The adopted hydraulic model uses remote sensing imagery, digital elevation models (DEM), and geographic information system (GIS) feature classes to create an accurate hydraulic profile of the outflow channel. The profile of the channel, derived from GIS, is input to the hydraulic model where subcritical to supercritical regimes are used under steady flow conditions to estimate peak discharge, mean flow velocity, shear stress, and power of the flood.

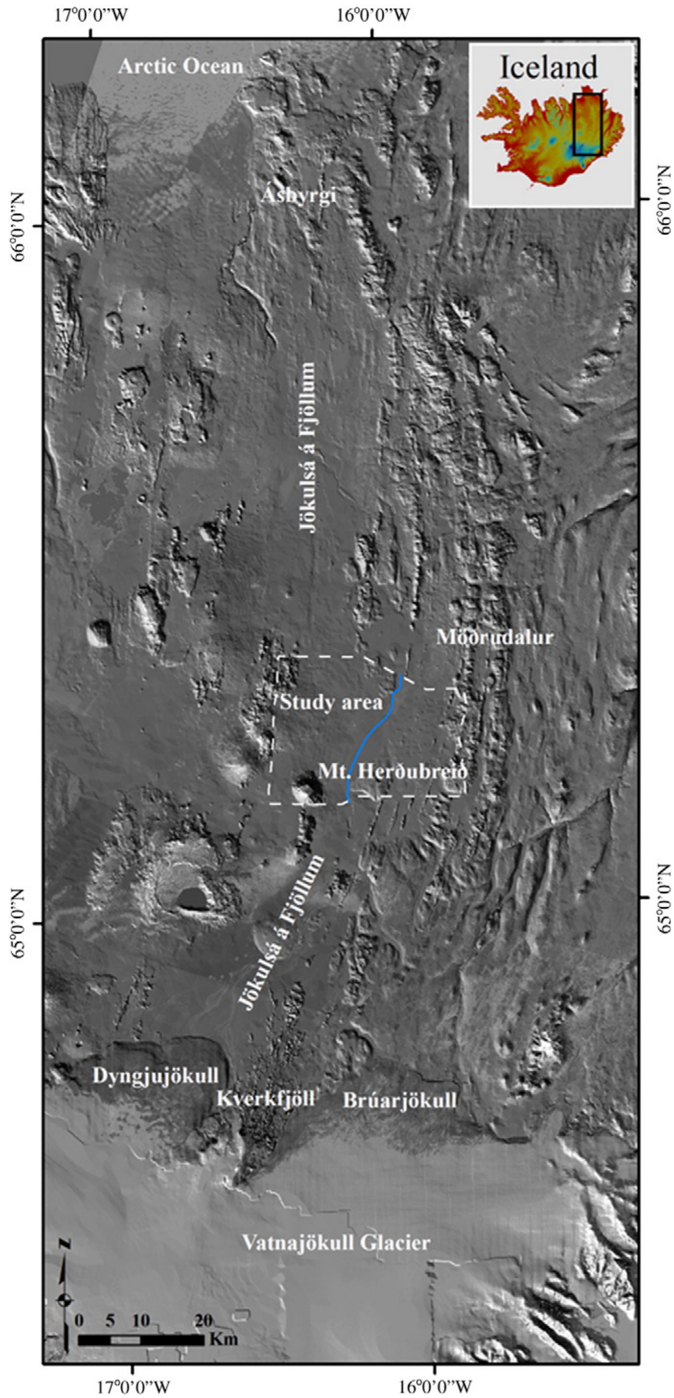

Fig. 1. Jökulsá á Fjöllum channel at Vatnajökull, Iceland. The inset overview shows the bounding area. Jökulsá á Fjöllum flows from south to north, from Vatnajökull to the Arctic Ocean. The white dashed line outlines the study area. The image is Landsat ETM + panchromatic (band 8) overlain on a digital elevation model derived from ERS-SAR InSAR data. The Landsat image source is USGS EOSDIS, and Iceland elevation data are courtesy of the Institute of Earth Sciences, University of Iceland.

2. Field area

Jökulsá á Fjöllum channel, Iceland (Fig. 1) located at 16°08′02.94″ W, 65°15′08.15″ N, is a basalt bedrock fluvial channel that experienced prehistoric periodic jökulhlaup outbursts from Vatnajökull glacier due to 1) subglacial volcanic activity and 2) accumulation of marginal lakes as a result of Pleistocene ice-cap recession (Björnsson, 2002, 2009). Located in the highlands of northeastern Iceland, the channel is the only conduit north of Vatnajökull for jökulhlaup discharge. Jökulsá á Fjöllum is the second longest river in Iceland, extending 206 km from Vatnajökull glacier to Ásbyrgi canyon in northern Iceland. The channel follows the active Mid-Atlantic Ridge Northern Volcanic Zone (NVZ) (Carrivick et al., 2004b) and was covered by a late Pleistocene (Weichsel Period) ice-cap that extended into the Arctic Ocean (Björnsson, 2002; Waitt, 2002; Geirsdóttir et al., 2007). Iceland experienced glacial retreat from the Bølling/Allerød interstadial through the Younger Dryas stadial. Since the Late Preboreal Period the glacial coverage of Iceland was not much different from its current glacial areal extent (Ehlers and Gibbard, 2007; Geirsdóttir et al., 2007). The literature suggests that constructive (volcanic) processes have exceeded erosional processes except for jökulhlaup