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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.

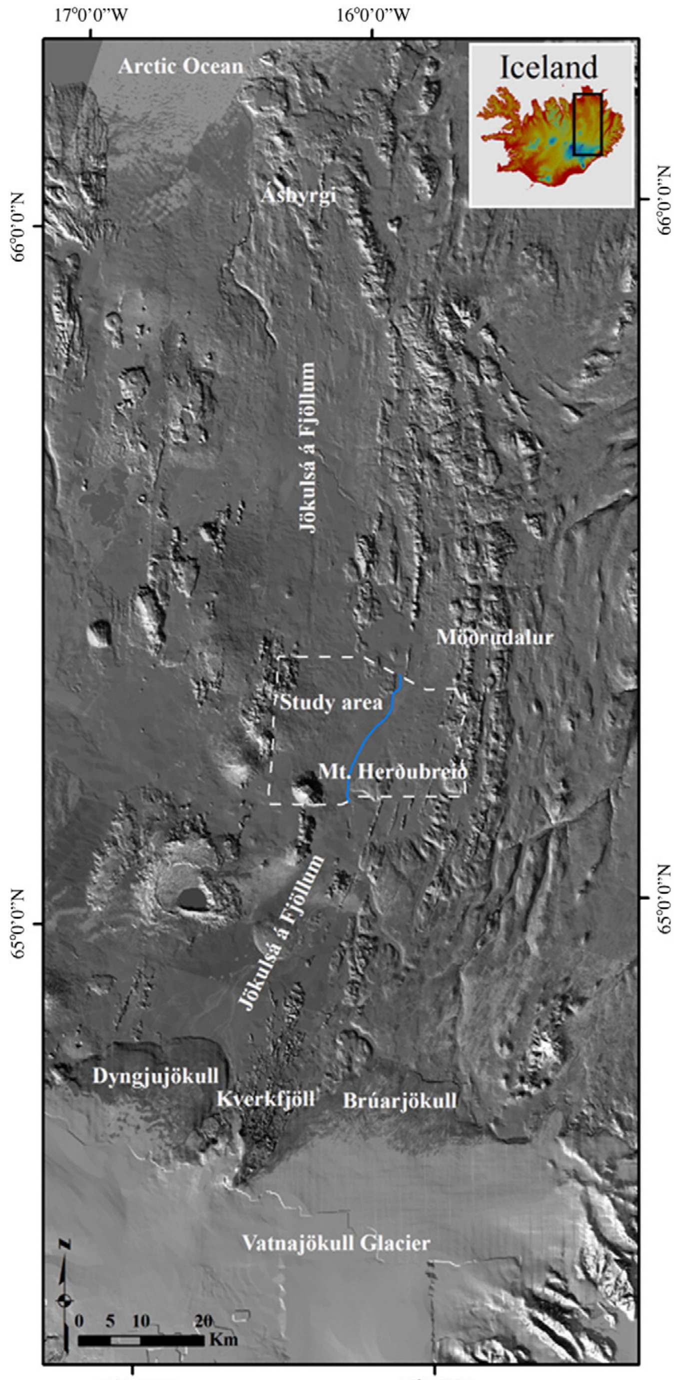

Fig. 1. Jökulsá á Fjöllum channel at Vatnajökull, Iceland. The inset overview shows the bounding area. Jökulsá á Fjöllum flows from south to north, from Vatnajökull to the Arctic Ocean. The white dashed line outlines the study area. The image is Landsat ETM + panchromatic (band 8) overlain on a digital 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 events in the central highlands since the last glaciation and therefore glacial deposits are rare (Geirsdóttir et al., 2007).

Our field study was conducted in 2008 and extended from the current channel convergence at 65°10′46.6″ N, 16°12′17.5″ W about 3.5 km south of Mt. Herðubreið campground to Ferjufjall at 65°20′1.6″ N, 16°0′23.6″ W, for a total reach length of approximately 22 km (Fig. 2). Our intent was to support the work of Alho et al. (2005) by filling in the field gap between Upptyppingar and Möðrudalur reaches of the channel and use their field evidence to extend our spatial coverage.

3. Methodology

3.1. Remote sensing data

Topographical data for the hydraulic model were derived from two European Remote Sensing Satellite Synthetic Aperture Radar (ERS-SAR) image pairs from the Interferometric Synthetic Aperture Radar (InSAR) instrument. The image pairs were used to generate the 25 × 25 × 1 m resolution digital elevation model used in this study. Landsat ETM + multispectral and panchromatic imagery at 25 and 15 m spatial resolution, respectively, were also used for basemaps and feature location and identification in the field. 1:50,000 scale Iceland topographic maps (Unknown, 1950) were used for general geologic mapping and field evidence locations.

3.2. Field investigation

Our field work included mapping erosional and depositional fluvial geomorphological evidence of catastrophic flooding and estimating channel and overbank surface roughness (Manning's n). We estimated Manning's n using previous field observation experience and standard references as a guide (Chow, 1959; Barnes, 1967; Arcement and Schneider, 1989). We field-validated DEM-derived channel geometry and geomorphology through geologic mapping and surveying using a handheld Global Positioning System (GPS), Brunton compass, clinometer, and laser rangefinder. Trimline heights and erosional and depositional landforms were mapped and entered into a GIS Geodatabase for use in the hydraulic model. We recognize that our Garmin GPSMAP 60CSx may produce location and elevation inaccuracies even in differential GPS mode on the order of 3–5 m; however, we used the altimeter function (calibrated barometer) to assist in vertical GPS error correction (Garmin GPSMAP 60CSx Owner's Manual, 2007).

3.3. One versus two-dimensional flow models

One-dimensional open-channel flow models are the most readily available models used for hydraulic modeling. Two-dimensional models exist (TELEMAC-2D, HIVEL2D, and RMA2) but are rarely used in paleoflood studies (Alho and Aaltonen, 2008). In a review of studies that examine the sensitivity of 1 and 2-dimensional model parameters (e.g. Manning's n) and the overall accuracy of the numerical model, results are inconclusive as to whether the added complexity of a 2-dimensional model is worth its use (Miller and Cluer, 1998). There is indication that 2-dimensional hydraulic models, based on finite element and finite volume numerical methods are less sensitive to surface roughness coefficients (Miller and Cluer, 1998); therefore it is of interest to pursue these models for Mars research given that surface roughness is difficult to assess remotely. Recent work by Alho and Aaltonen (2008) demonstrates that 1-dimensional

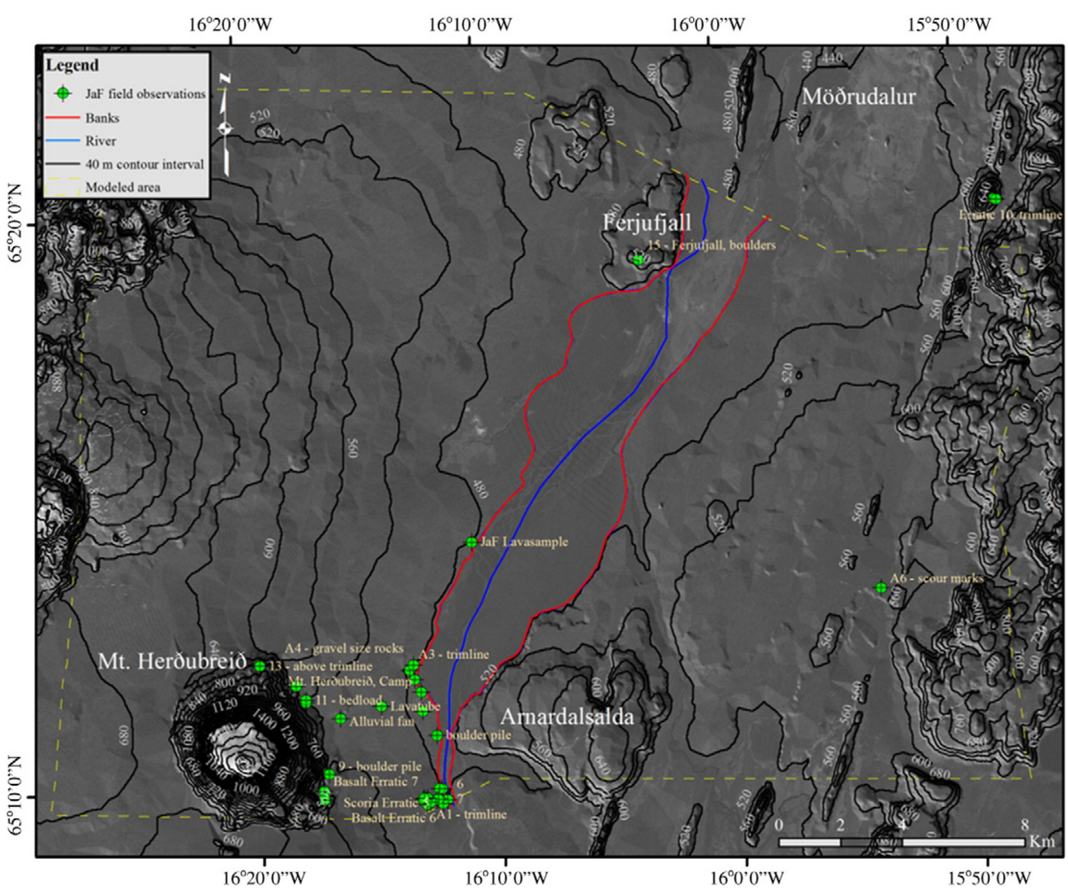

Fig. 2. Jökulsá á Fjöllum channel study reach. The paleoflood flowed from south to north. Field observations are indicated by the cross circles. The GIS delineation of the stream (blue line) and the left and right overbanks (red lines) assisted in quantifying the surface roughness assignments for bed and overbank areas. North is to the top of the image.

modeling of jökulhlaup outburst floods provides generally similar results to 2-dimensional models.

3.4. Hydraulic model

Current approaches to hydraulically modeling catastrophic outburst channels on Earth primarily use the Chézy and Manning's equations. However, simplifying assumptions are made to the geometry of the channel and assigned values for Manning's n coefficient vary widely. We used an approach that employs high resolution digital elevation models of the surface to derive channel cross-sectional area, wetted width, gradient, and the appropriate number of cross-sections that accurately represent the channel geometry and geomorphology. To derive the channel geometry we used the ArcGIS geospatial tool HEC-GeoRAS (Hydrological Engineering Center Geographical River Analysis System) (Ackerman, 2005). The reach cross-section geometry is input into the HEC-River Analysis System (HEC-RAS) hydraulic model to iteratively estimate peak discharge, mean flow velocity, power, and shear stress of the channel reach until the field-observed trimline height is achieved. We assessed Manning's n in the field and assigned a range of surface roughness coefficients to the channel bed and overbank areas. A more refined predictive-method of assigning Manning's n to account for smoothing of the channel bed and banks with increasing flow stage was not used but may be explored in future models.

3.4.1. HEC-GeoRAS

To prepare data for use in HEC-RAS, the Hydrological Engineering Center collaborated with Environmental Systems Research Institute, Inc. (ESRI) under a Cooperative Research and Development Agreement to develop an ArcGIS extension to process geospatial data for that purpose (Ackerman, 2005). HEC-GeoRAS is a set of ArcGIS tools that uses digital elevation models, imagery, feature-classes, and tables to prepare channel geometry required by HEC-RAS. We created stream centerline, bank, and flow line vectors and channel cross-sections through manual and semi-automated steps that were then output to a format that is directly read by HEC-RAS. HEC-GeoRAS then reads the HEC-RAS output file for further analysis and to map inundation and delineate floodplains (Ackerman, 2005).

3.4.2. HEC-RAS

The U.S. Army Corps of Engineers Hydrologic Engineering Center River Analysis System, HEC-RAS, was used exclusively for this modeling study. HEC-RAS was developed to perform one-dimensional steady and unsteady flow hydraulic calculations and sediment transport modeling (Brunner, 2006). Under steady flow, HEC-RAS calculates water surface profiles based on the input geometry, gradient, and Manning's n for any number of discharge rates. Water surface profiles referenced in the software are equivalent to trimlines, wash limits, or peak-flow water heights. The system is capable of modeling channel networks or a single reach, and provides modeling of subcritical, supercritical, and mixed (a computation accounting for a mixture of subcritical, critical, and supercritical flow) flow regimes (Brunner, 2006).

HEC-RAS calculates water surface profiles of successive channel cross-sections by solving the energy equation in a scheme called the standard step-backwater method. Conveyance, channel velocity, and energy loss are accounted for by Manning's equation. To use HEC-RAS effectively for steady flow in natural channels the following assumptions are made: 1) flow is steady, 2) flow varies gradually through the reach, 3) flow is one-dimensional, and 4) the channel slope is small (<10%) (Brunner, 2001).

3.5. Errors and uncertainties

Bedrock channels such as Jökulsá á Fjöllum have irregular channel boundaries, which cause energy losses due to channel geometry expansions and contractions. These irregularities are due to erosion and deposition along the channel reach that causes channel bed undulations such as knickpoints, potholes, and longitudinal grooves (Miller and Cluer, 1998). Errors caused by not accurately adjusting for these irregularities may be problematic. However, sensitivity to the expansion and contraction coefficients used is minimal unless they are grossly over or under estimated (Miller and Cluer, 1998). HEC-RAS allows for adjusting expansion and contraction coefficients, but recommends using the default values of 0.1 for contraction and 0.3 for expansion for straight channel reaches, and is consistent with the approach used here. The straight nature of the modeled channel presents minimal variability to the model accuracy.

Errors also arise from the choice of flow regime of the steady flow model used. Selecting subcritical, supercritical, or mixed flow regimes for water surface modeling and the ability of the numerical model to accurately depict the surface profile both introduce potential sources of error. In general, unless there is justification for supercritical or a mixed flow regime, apparent by highly irregular channel bed or wall conditions, the subcritical flow regime should be used. Using the subcritical flow regime does not preclude occasional transition to supercritical flow. We used the subcritical flow regime in our model to be consistent with previous work along Jökulsá á Fjöllum (Alho et al., 2005), although we did run the supercritical and mixed flow regimes for comparison. Our results, using the subcritical flow regime, consistently produced the best fit to the observed water surface profiles even under fully turbulent conditions ($Re>4000$).

The largest source of potential error in hydraulic modeling is the selection of Manning's n, the surface roughness coefficient. The literature for selecting Manning's n is vast, and different methods of selecting coefficients produce varied results. The method used here was based on field assessment of the channel bed, banks, and overbank roughness characteristics using field observation experience and standard references as a guide (Chow, 1959; Barnes, 1967; Arcement and Schneider, 1989).

Uncertainties of model results may also be due to inaccurately mapping trimline heights. Geologic interpretation of paleoflood peak-flow height can be difficult, but guidelines can be followed to provide a range of peak-flow conditions. Our approach was to use a range of trimline heights that bound our observations in the field. Uncertainties of exact trimline heights may be due to jökulhlaup bore and initial run-up that are above the average trimline. Additionally, uncertainties may be introduced due to GPS and DEM vertical error at field locations.

Assumptions of input parameters in the model also result in outcome uncertainties. Parameter assumptions include cross-sectional area, averaged Manning's n across or longitudinally down reach, and averaged gradient along the reach. To minimize these errors we used the HEC-GeoRAS tool to define the channel geometry more accurately and therefore provide better geomorphic representation. The hydraulic model uses the geometry to assess discharge, velocity, power and shear stress at any point along the reach.

4. Results and discussion

4.1. Field evidence

The present channel reach begins as a basalt bedrock bed in the first 3 to 4 km and then becomes mostly gravel filled for the 18–19 km downstream. The channel bed is lined with basalt sand, cobbles, and boulders. Most channel-fill material is well rounded from fluvial transport. Boulders vary in size up to 3 m in diameter. Boulders are imbricated, in random piles, or aligned longitudinally or perpendicular to the flow direction, and stand alone as erratics (Fig. 3A). The channel banks from the main channel bed to the lateral margins of the valley floor are layered with rough pahoehoe and àà basalt flows. Lava tubes and domes are present with deep localized

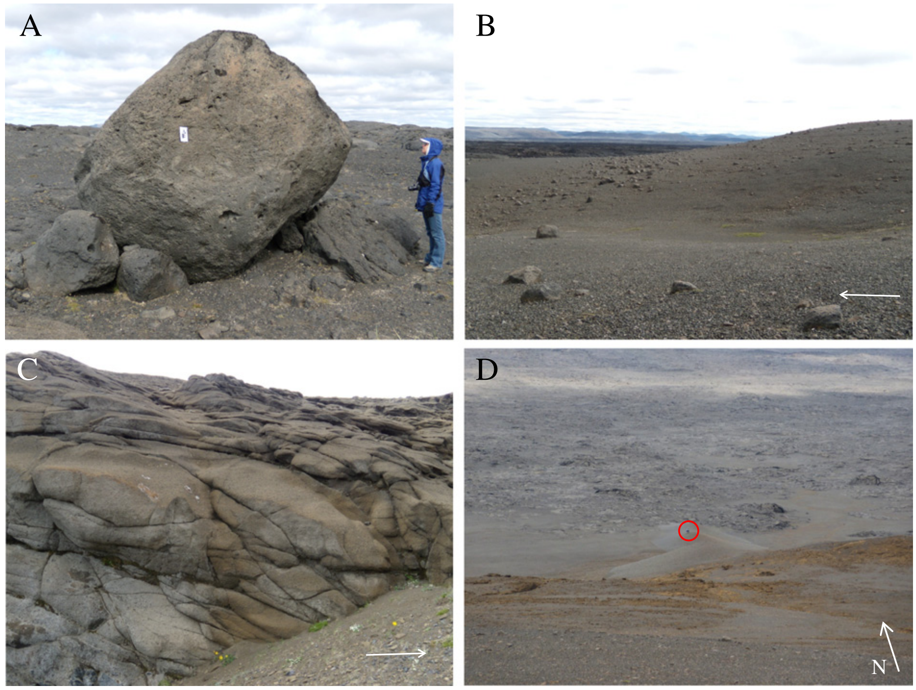

Fig. 3. Jökulhlaup field evidence along Mt. Herðubreið reach. A) Basalt boulder erratic and imbricated boulder pile. Boulder is approximately 9.5 m circumference around the short axis and 3.3 m high. B) Eastern side of Mt. Herðubreið showing boulder field beyond crest of hill. During peak flow larger material was carried over the tops of the submerged hills and dropped from suspension upon dispersion of water where the water column depth increases. Flow direction is indicated by the white arrow. C) Exposure of hydroclastic rock along the northeastern side of Mt. Herðubreið. The photograph illustrates evidence of fluvial erosion. Notice the undulating surface. Flow direction is indicated by the white arrow. Light colored flowers on ground are about 3 cm for scale. D) Prominent bar feature at the northern most point of Mt. Herðubreið. Field geologists circled for scale.

collapse structures throughout. Air-fall deposits of volcanic ash and pumice from recent eruptions of the nearby Áskja lava field are evident. The channel is flanked by hyaloclastite ridges and tuyas (exhumed subglacial volcanoes) from subglacial fissure eruptions.

Trimlines determined by our GPS field survey range in elevation from 495 to 670 m above mean sea level. Trimline heights were also found for what are presumably lower discharge paleofloods at elevations between 495 and 525 m. Our modeled results suggest that the lower trimline heights correspond generally to the peak discharge estimated by Alho et al. (2005). They reported a peak discharge of 9.0×10^5 $m^3\,s^{-1}$ for the "largest Holocene" jökulhlaup within Jökulsá á Fjöllum channel based on wash limits and observations of scoured topography, bedrock gorges, streamlined hills, boulder fields, and longitudinal bars (Alho et al., 2005).

Beyond these lower wash limits, our GPS field survey established higher trimlines based on many of the same field observations as Alho et al. (2005). At the base of Mt. Herðubreið a new lower boundary trimline was observed at approximately 548 m where fluvial-glacial erratic boulders were deposited on top of longitudinal hills that flank the eastern side of the tuya. It is apparent that fluvial processes deposited the well rounded erratic boulders as suspended or wash load to this elevated position. Additionally, rocks appear to have experienced fluvial push-up due to high velocity flow and are piled up just before the crest of the hill. Larger boulders are found preferentially deposited just beyond the hill's high point where the flow lost energy and the heaviest waterborne debris fell out of suspension when the water column depth increased (Fig. 3B). Mapping the trimline around to the north of Mt. Herðubreið shows evidence of extreme fluvial erosion along the base of the tuya where more easily erodible hydroclastics crop out (Fig. 3C). On the north flank of Mt. Herðubreið the trimline appears to taper out at about 670 m above mean sea level. This is evidenced by the gradual texture difference on the north-facing slope where talus gives way to lower fluvial deposited debris in the "shadow zone" of the tuya. Also a prominent bar feature is found at the northern most point of Mt. Herðubreið (Fig. 3D). Our interpretation of the feature, considering that it is on the leeward side and flood waters would have been impeded by the tuya, is that the flood wave was probably attenuated and allowed for suspended sediment deposition (Maizels, 1997) during this large paleoflood event. This bar's presence suggests that significant flow would have come from both sides of Mt. Herðubreið.

At Ferjufjall, an undulating tear-drop shaped hill at the downstream end of the modeled reach, there appears to be no evidence of an unambiguous trimline. Our interpretation is that this once streamlined hill was apparently overrun by a large jökulhlaup. Ferjufjall exhibits fluvial erosion creating smooth undulating topography similar to landforms in the Channeled Scablands (Baker, 1973), and the surface layer is overlain by rounded to sub-angular pebble, gravel, and cobble sized rocks. Additionally, rounded and sub-angular boulders are found at the highest point of the hill at 558 m. These boulders have also been eroded by aeolian processes (ventifaction) indicating a long period of immobile exposure at the surface. As observed from the hill's apex, Ferjufjall appears to have been submerged in order for the floodwater to sculpt the present-day topography (Björnsson, 2009). Also, at the furthermost downstream end of the modeled reach the hyaloclastite ridges southeast of Möðrudalur provided evidence of boulder erratics to a height of approximately 670 m. This field evidence of a higher trimline at Möðrudalur also suggests that Ferjufjall was inundated during the highest peak discharge.

Observed within the channel are glacial grooves and striations that were once overlain by glacial diamictons (glacial drift from moraines) (Boggs, 1995). Due to Holocene jökulhlaup outbursts proglacial depositional features have been mostly reworked by fluvial processes and glacially carved bedrock surfaces have been exhumed. Additionally, tuyas (i.e., Mt. Herðubreið) and hyaloclastite ridges created by subglacial volcanic eruptions are exposed (Björnsson, 2002). In general, the floodplain landscape is barren of vegetation and the channel overbank areas are covered by basaltic lava flows.

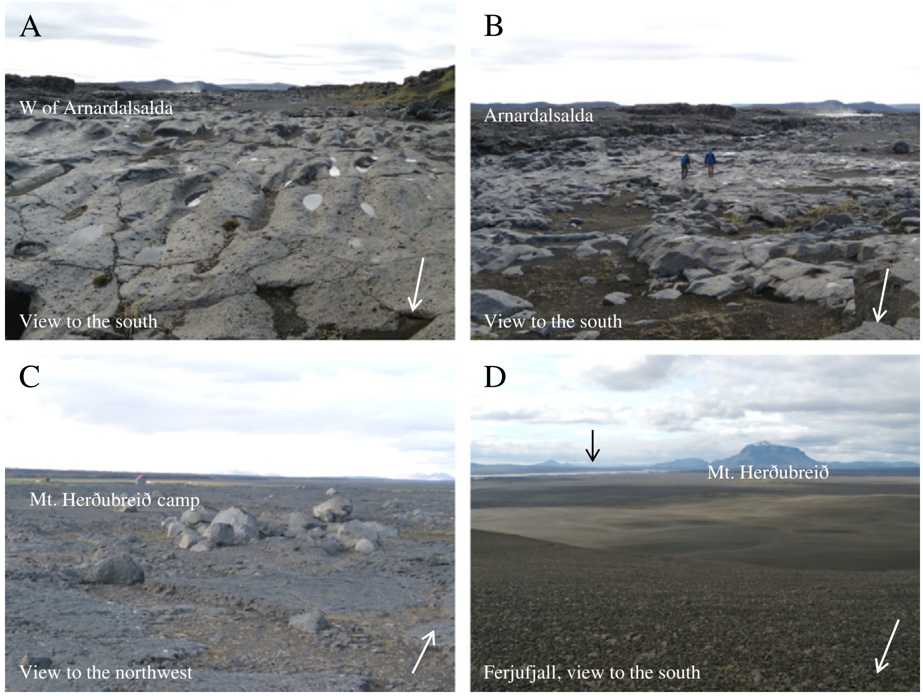

Fig. 4. Field evidence of jökulhlaup outburst floods in Jökulsá á Fjöllum channel, Iceland. A) Fluting near the present channel, B) extreme channel bedrock scouring, C) boulder pile on scoured bedrock, D) smooth undulating topography viewed from Ferjufjall at the end of modeled reach. Black arrow in D indicates Dyngjujökull glacier. Flow direction is indicated by white arrows.

The field evidence represents erosional and depositional landforms associated with catastrophic outbursts including scoured, grooved and fluted bedrock surfaces, remnant streamlined hills, longitudinal bars, gravel bars, longitudinal and perpendicular boulder piles, imbricated boulders, fluvial–glacial erratics, ripples, scabland topography, and deep canyons (Fig. 4) (Björnsson, 2002; Waitt, 2002; Alho et al., 2005). These observed landforms also allow comparison to fluvial geomorphology observed on the Martian landscape (Baker and Milton, 1974; Rice et al., 2002; Carling et al., 2009).

Based on previous field evidence where the highest noted trimlines at Upptyppingar and Ferjufjall are 40 m above the channel floor (Waitt, 2002), and on prehistoric paleoflood descriptions (Saemundsson, 1973; Alho et al., 2005; Björnsson, 2009) these trimline elevations are consistent with our field surveyed trimlines where Upptyppingar is estimated at 618 m and Ferjufjall at 558 m. This new field evidence and the cited literature of relative ages of paleofloods evidence (Saemundsson, 1973; Waitt, 2002; Alho et al., 2005; Björnsson, 2009) suggests a much larger jökulhlaup paleoflood may have occurred between 9000 and 7100 BP.

4.2. Hydraulic model

HEC-GeoRAS was used to create 21 initial topographic cross-sections over the approximately 22 km reach. The channel bed and overbank boundaries were digitized to provide flexibility in the assignment of different surface roughness coefficients (Manning's n) based on rock and sediment size and shape (Chow, 1959; Barnes, 1967). Cross-sections spanned approximately 31 km width to cover the hypothesized lateral extents of the reach. Additional cross-sections were interpolated in HEC-RAS to better define the channel geomorphology, totaling 130 for the entire reach (Brunner, 2006). The geometry was then imported into HEC-RAS. The slope of the reach was estimated from the DEM at 0.0016 m m^{-1} and was used as the model's initial boundary conditions. The default contraction and expansion coefficients of 0.1 and 0.3 were used (Brunner, 2006). The initial Manning's n coefficients were set to 0.065 for left and right overbank areas, and 0.035 for the channel bed based on our field assessment.

Manning's n was estimated throughout the channel bed and overbank areas, varying from 0.03 in the channel bed to 0.075 in the overbank areas (Fig. 5). Manning's n was estimated on the basis of particle

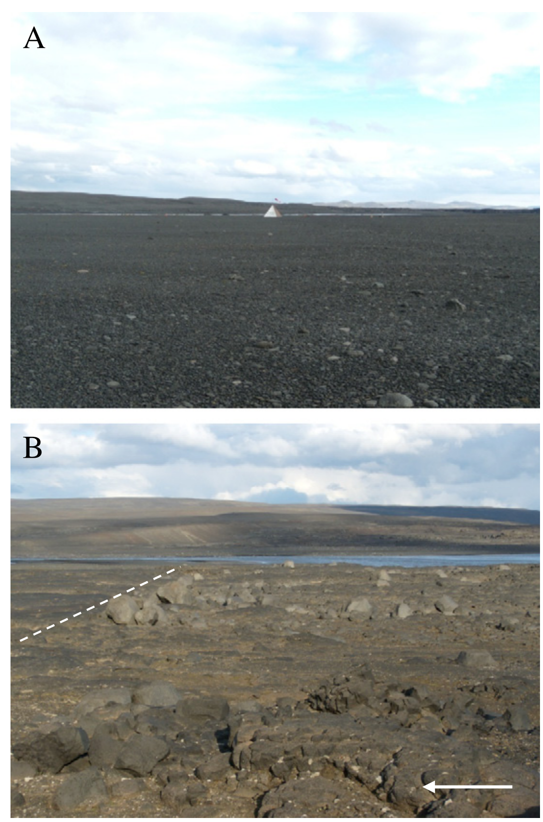

Fig. 5. Channel bed materials used for surface roughness estimation. A) River materials of gravel and cobble size. B) Bedrock with erratic boulders up to 2 m across. The boulders are aligned perpendicular to flow (dotted line) in this photo. Flow direction is indicated by the white arrow.

Fig. 6. Jökulsá á Fjöllum channel distal overbanks. This photo shows the extreme rocky, clinkery, and undulating surface. Two geologists for scale (1.65 and 1.86 m).

size and irregularity of the channel floor and overbank area surfaces. Estimates of Manning's *n* from the channel bed varied little due to consistent bed material composition and distribution. The small variations that exist are attributed to boulder fields and their linear alignments, and the scoured, grooved, and plucked basalt bedrock exposed at the erosional sections of the channel (knickpoints, falls, and steps). These small scale variations change the estimate of surface roughness locally, but the average longitudinal roughness varies little and in any case increases the channel bed coefficient to between 0.035 and 0.04.

The channel walls were extremely scoured and plucked where the present river flows. Terraces from more recent flooding also exhibit rough surfaces caused by wash load scouring. The overbank areas nearest the current channel are highly scoured and grooved (Fig. 4A and B) from hyperconcentrated flows (flows with high percentage sediment load) but the surface roughness is less than that of the lateral margins of overbank areas. Given the evidence of the highest trimline surveyed in this work, the overbank areas are enormous due to the floodplain's gentle slope. Estimated Manning's *n* for the overbank areas ranges from 0.05 to 0.075, based on the extremely rocky, clinkery, and undulating topography (Fig. 6). Manning's *n* for the bed and overbank areas was varied in the hydraulic model to best agree with the observed surface roughness.

The HEC-RAS steady flow model was run for a subcritical flow regime using 30 discharge rate profiles that bound the previously estimated peak discharge of $9.0\times10^5\ m^3\ s^{-1}$ (Alho et al., 2005). We assumed steady state flow (i.e., flow discharge rate and velocity are assumed constant in time) in that the time taken for a fluid element to traverse the length of the modeled domain is short compared to the expected duration of a catastrophic flood. To calibrate our model, we used the estimated discharge rate from Alho et al. (2005) to generate a paleoflood inundation and floodplain map. The modeled water surface heights generally match the field surveyed lower trimline of approximately 524 m at Arnardalsalda (65°11′29.5″ N, 16°4′ 59.0″ W) at the upstream end of the reach, and approximately 474 m at Ferjufjall. The inundation map we produced (Fig. 7) matches that of Alho et al. (2005, Fig. 3) for this section of the reach. For the modeled channel reach using the Alho et al. (2005) peak discharge rate, mean flow velocity averaged 7 $m\ s^{-1}$, power per unit area varied from 735 to 6747 $W\ m^{-2}$ with a reach average of 2221 $W\ m^{-2}$, and shear stress varied accordingly from 164 to 704 $N\ m^{-2}$ with a reach average of 357 $N\ m^{-2}$. The Froude number for all cross-sections is less than 1, indicating that flow remained subcritical for the modeled

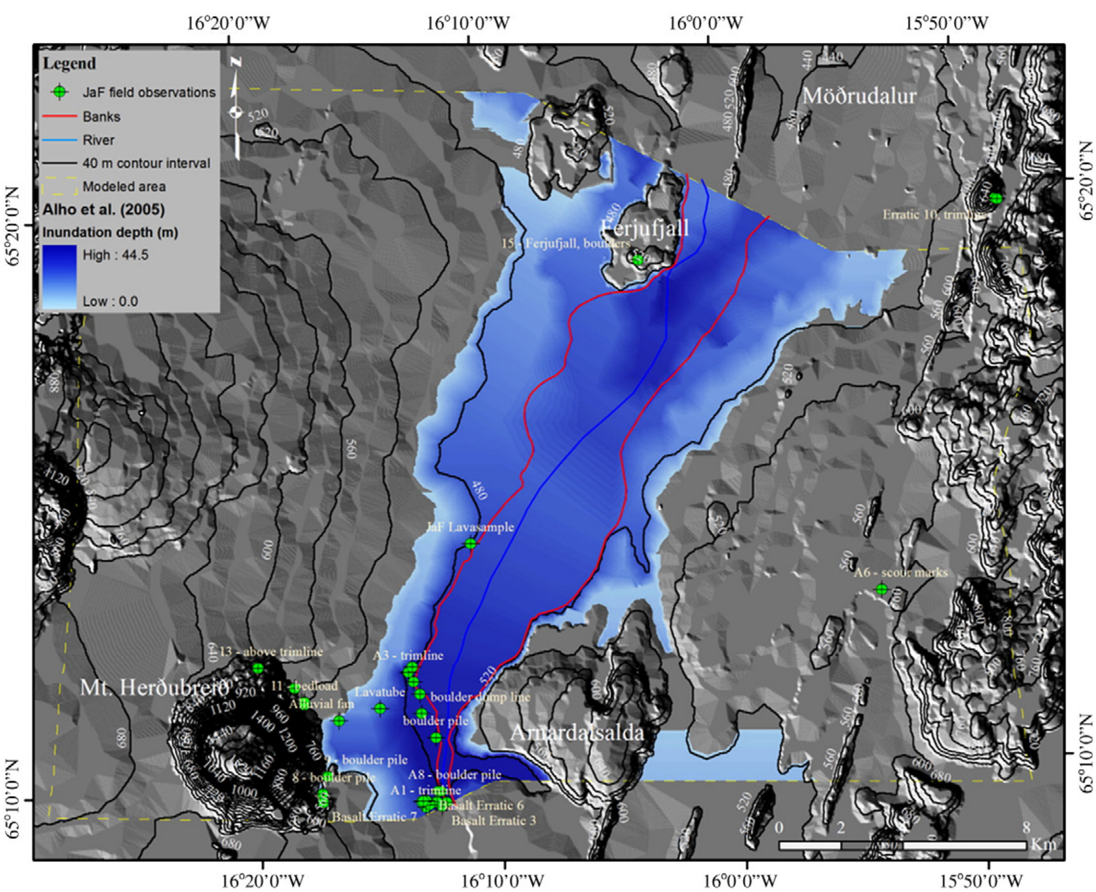

Fig. 7. Jökulsá á Fjöllum inundation map at $Q_P = 9.0\times10^5\ m^3\ s^{-1}$. This inundation map matches Alho et al. (2005, Fig. 3) inundation map along Mt. Herðubreið reach where lower flow trimline evidence is observed. Local variations exist possibly due to dissimilar digital elevation model processing or Manning's *n* assignments.

Fig. 8. Fluvial landscape viewed from Ferjufjall. Smooth undulating topography with evident ripples in the background left. White arrow indicates approximate flow direction. View is to the north.

reach. Calculated Reynolds numbers show that the flow was fully turbulent ($Re>4000$). Local variations exist possibly due to dissimilar digital elevation model processing or Manning's *n* assignments. Unfortunately, since Alho et al. (2005) focused on Vaðalda, Upptyppingar, and Möðrudalur sections along Jökulsá á Fjöllum we are unable to directly compare estimated hydraulics along Mt. Herðubreið reach. However, the modeled peak discharge and the match of paleoflood inundation produced here corroborate their work and our new field data provide additional hydraulic flow parameters to those already reported.

To achieve the topographically higher trimlines from our new field evidence and supported by evidence cited in the literature (Waitt, 2002), a much larger outburst probably occurred just after deglaciation between 9000 and 7100 BP (Saemundsson, 1973; Björnsson, 2002; Waitt, 2002; Björnsson, 2009). Unfortunately there is little discussion in the literature about the spatial extent or related discharge rates of this larger paleoflood. Our field survey suggests evidence for higher trimlines based on 1) boulder fields and fluvial erosion of hydroclastic units at higher elevations, 2) inundation of Ferjufjall and Arnardalsalda in the paleoflood's floodplain, and 3) fluvial-glacial erratics at higher elevations than previously observed. The inundation map of Alho et al. (2005) shows that Ferjufjall and Arnardalsalda were not inundated; however, Ferjufjall at the lower end of the modeled reach shows no signs of unambiguous trimlines around the base of the hill as their inundation map suggests. As discussed above, our field survey at Ferjufjall suggests complete flood inundation, given the presence of approximately 1 m diameter rounded to sub-angular boulders at the peak of the hydroclastic bedrock hill, approximately 558 m above mean sea level. Moreover, Ferjufjall and the surrounding terrain exhibits smooth undulating topography and distinct ripples recognized in the Channeled Scablands (Fig. 8) (Bretz, 1923, 1925; Bretz et al., 1956; Baker, 1973; Baker et al., 1988; Alt, 2001; O'Connor et al., 2002; Björnsson, 2009).

HEC-RAS model runs produced water surface profiles that also matched the higher observed trimlines at elevations ranging between 548 and 670 m. Although we observed trimline evidence between

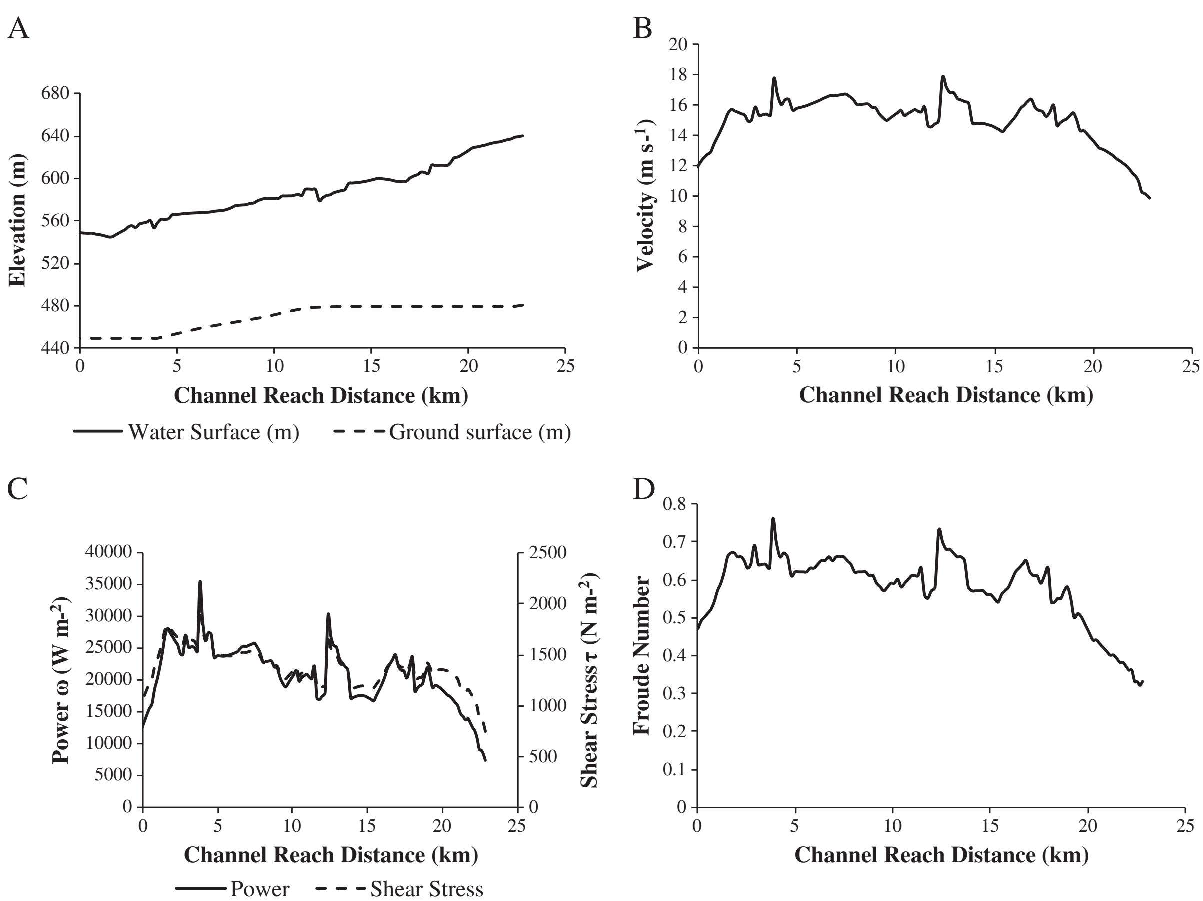

Fig. 9. Mt. Herðubreið hydraulic modeling results for $Q_P = 2.2\times10^7$ m^3 s^{-1}. A) Water surface profile. This water surface profile best fits the range of field surveyed trimlines with complete inundation of Ferjufjall. The water surface height at the upstream end is 640 m at Arnardalsalda and inundates Ferjufjall at 558 m at the downstream end of the reach. B) Average mean flow velocity is 14.9 m s^{-1}. C) Power and shear stress profiles. Power and shear stress are correlated to stream geomorphology by erosional and depositional processes. The power and shear stress are highest at knickpoints and steps where erosion potential is highest. D) Froude number. The Froude number for all cross-sections is <1 indicating that flow remained subcritical for the modeled reach.

these elevations, a conservative lowest trimline height, assuming complete inundation of Ferjufjall at its peak elevation (558 m), was initially used for the model. To inundate Ferjufjall the modeled surface water height (Fig. 9A) requires a peak discharge of 2.2×10^7 $m^3\ s^{-1}$ and mean flow velocity of 14.9 $m\ s^{-1}$ (Fig. 9B, Table 1). The model power per unit area and shear stress averaged 20,680 $W\ m^{-2}$ and 1248 $N\ m^{-2}$, respectively, along the reach (Fig. 9C). Froude numbers for reach cross-sections remained <1, indicating subcritical flow for Mt. Herðubreið reach (Fig. 9D). The inundation depth at Arnardalsalda at the upstream end of the modeled reach is approximately 629 m, which does not completely submerge the entire hill (Fig. 10). We were unable to validate this trimline elevation due to our field season time constraints.

The model was run subsequently to account for field evidence of the highest trimline height at approximately 670 m above mean sea level, which inundates Arnardalsalda almost completely and allows the

Table 1
Summary of Jökulsá á Fjöllum modeled flow hydraulics.

Model run	Trimline (WS_1 Elevation) (m)	Manning's *n* LOB_2	Channel	ROB_2	Peak discharge, Qp ($m^3\ s^{-1}$)	Mean velocity, v ($m\ s^{-1}$)	Power, ω ($W\ m^{-2}$)	Shear stress, τ ($N\ m^{-2}$)	Hydraulic depth (m)	Froude number range	Reynolds number (Re)	Notes
Jökulsá á Fjöllum channel	498	0.065	0.035	0.065	9.0E+05	7.0	2221	357	17	0.35–0.79	1.3E+11	Alho et al.'s Qp and lowest trimline evidence - using modeled channel geometry (Alho et al., 2005)
Mt. Herðubreið reach	587	0.065	0.035	0.065	2.2E+07	14.9	20,680	1248	70	0.32–0.76	3.5E+11	Assumed Ferjufjall inundation at 558 m
Mt. Herðubreið reach	627	0.065	0.035	0.065	4.5E+07	18.5	38,411	1936	101	0.35–0.71	4.3E+11	Used the highest trimline evidence at 670 m at Mt. Herðubreið and Möðrudalur

1. WS is water surface average along the reach.
2. LOB and ROB are left and right overbanks used in HEC-RAS.
Note that all steady flow model runs resulted in subcritical flow (Froude numbers below 1.0) and are fully turbulent (Re>4000).

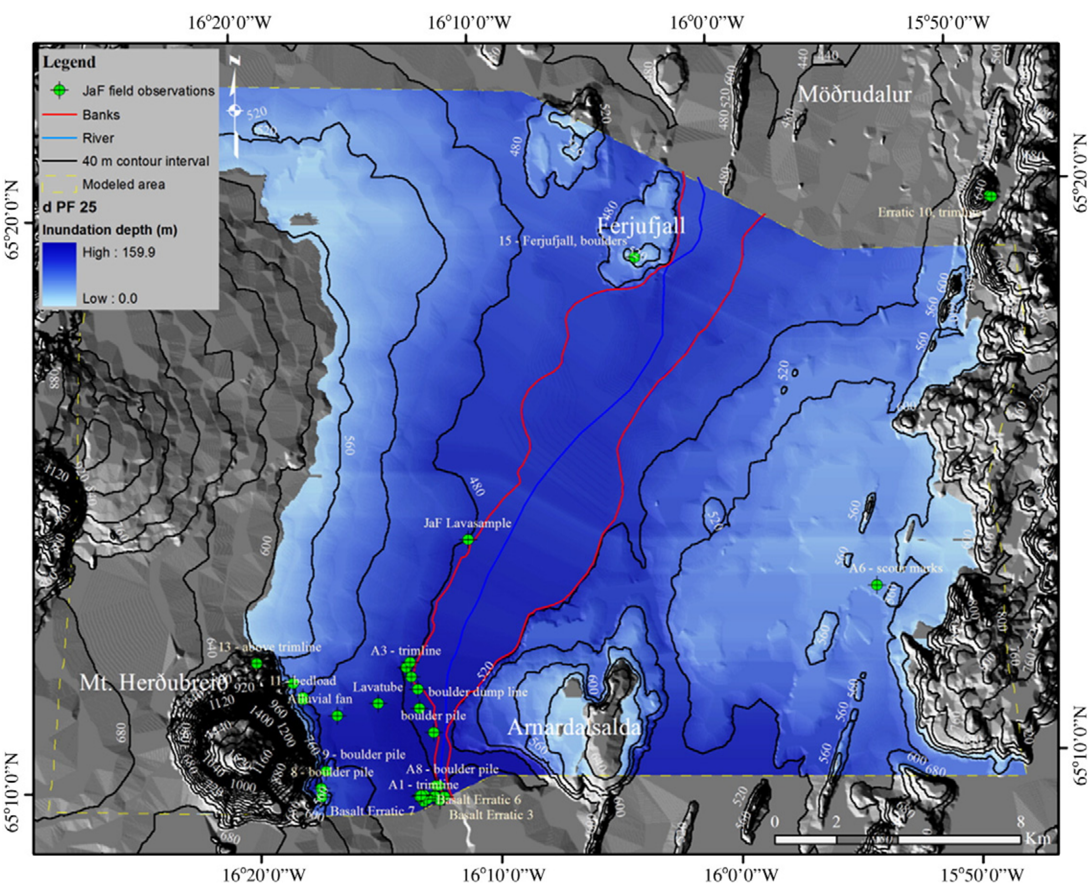

Fig. 10. Jökulsá á Fjöllum inundation map at $Q_P = 2.2 \times 10^7$ $m^3\ s^{-1}$ along Mt. Herðubreið reach. This modeled inundation shows Ferjufjall submerged at the lower end of the reach and supports field surveyed trimline heights at Möðrudalur and Mt. Herðubreið.

paleoflood to flow around Mt. Herðubreið (Fig. 11). Using these upper limits peak discharge is estimated at 4.5×10^{7} $m^{3}\ s^{-1}$, with a mean flow velocity of 18.5 $m\ s^{-1}$. The modeled power per unit area and shear stress averaged at 38,411 $W\ m^{-2}$ and 1936 $N\ m^{-2}$, respectively (Fig. 12, Table 1). It is apparent from Landsat ETM + 15 m per pixel panchromatic imagery that there is a tonal contrast difference that generally follows this larger modeled inundation boundary, however further investigation is necessary to confirm this observation.

We must consider that many jökulhlaup outbursts would have occurred since the early Holocene (Björnsson, 2002; Waitt, 2002; Alho et al., 2005); therefore the erosion rate along Jökulsá á Fjöllum was probably quite high. Country-wide, Iceland Holocene erosion rates have varied from 5 to 70,000 $cm\ ka^{-1}$ (Ehlers and Gibbard, 2007; Geirsdóttir et al., 2007); however, a recent study suggests an average of about 5 $cm\ ka^{-1}$ based on the shelf sediment record and glacial sediment accumulation in Hvítárvatn (Geirsdóttir et al., 2007). Although their study did not take into account extreme events such as jökulhlaups, erosion from glacial rivers with sources from Vatnajökull and Mýrdalsjökull range from 100 to 300 $cm\ ka^{-1}$ (Geirsdóttir et al., 2007). Currently, denudation and erosion rates remain unclear for Jökulsá á Fjöllum channel north of Vatnajökull from the Preboreal Period through the end of large episodic jökulhlaups occurrences in the Early Subatlantic Period. Furthermore, although fluvial erosion rates due to hyperconcentrated flow during jökulhlaup events are not well understood, down-cutting relationships in bedrock channels will help to calibrate our hydraulic model, to refine our discharge estimates, and to reconstruct this large jökulhlaup event (Costa, 1983; Miller and Cluer, 1998; Tinkler and Wohl, 1998; Jansen et al., 2006).

Taken into perspective, the modeled conservative discharge of 2.2×10^{7} $m^{3}\ s^{-1}$ along Mt. Herðubreið reach is larger than the 1.8×10^{7} $m^{3}\ s^{-1}$ peak discharge of the Kuray paleoflood in the Altai Mountains of Siberia (Baker et al., 1993; Herget, 2005), which is the largest previously documented paleoflood on Earth. Our study presents new lines of evidence that suggests a large paleoflood occurred through Jökulsá á Fjöllum channel in Iceland, the largest known early Holocene paleoflood on Earth.

5. Jökulsá á Fjöllum jökulhlaup sources

Based on age determinations from Hekla volcanic tephra, post-glacial jökulhlaups originating from Vatnajökull occurred during the Holocene (between 9000 and 2000 BP) (Waitt, 2002). These jökulhlaups are attributed to subglacial lakes associated with glaciovolcanic processes and seasonally accumulated glacier-marginal lakes. The largest eruptions are thought to have occurred just after deglaciation between 9000 and 7100 BP (Waitt, 2002; Björnsson, 2009), with peak discharges on the order of 10^{6} $m^{3}\ s^{-1}$. Limited field evidence for these larger floods is cited in the literature (Saemundsson, 1973; Waitt, 2002; Alho et al., 2005; Björnsson, 2009) and only subsequent smaller Holocene paleofloods have been modeled. Jökulhlaup outburst eruptions through Jökulsá á Fjöllum originate from volcanic sources beneath the three northern lobes of Vatnajökull glacier, Dyngjujökull, Kverkfjöll, and Brúarjökull (Alho et al., 2005; Björnsson, 2009) (Fig. 1). Evidence suggests that the largest and probably most catastrophic paleoflood sources were from ice-filled calderas of Bardarbunga and Kverkfjöll (Björnsson, 2002). There are currently six major thermal sources that contribute to glacial meltwater and the formation of subglacial lakes beneath Vatnajökull with heat capacities indicating possible activity during the Preboreal Period. Another probable water source is from marginal lakes that also formed at the end of the Younger Dryas when glacial retreat re-accelerated and these lakes filled at the boundaries of Vatnajökull. We suggest that in order to produce

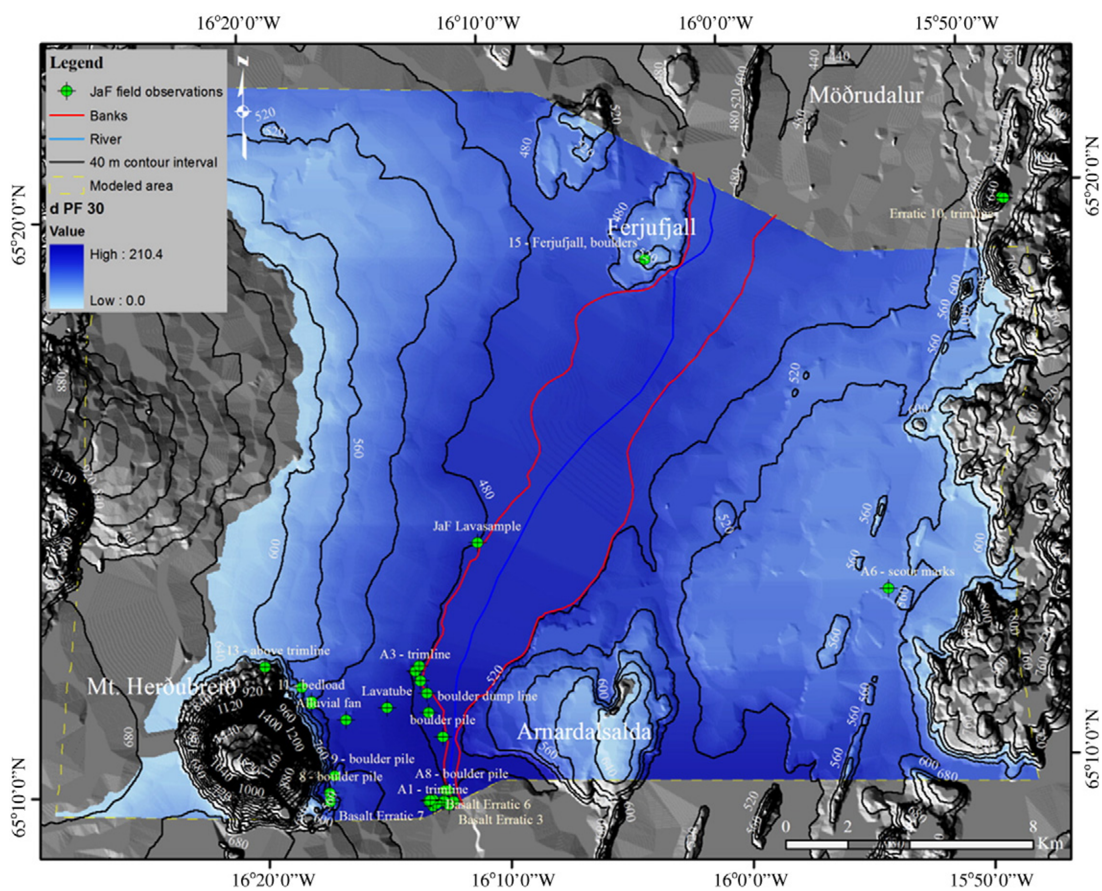

Fig. 11. Jökulsá á Fjöllum inundation map at $Q_P=4.5\times10^{7}$ $m^{3}\ s^{-1}$ along Mt. Herðubreið reach. This model inundation map supports the upper limits of the field surveyed trimline heights at Möðrudalur and Mt. Herðubreið.

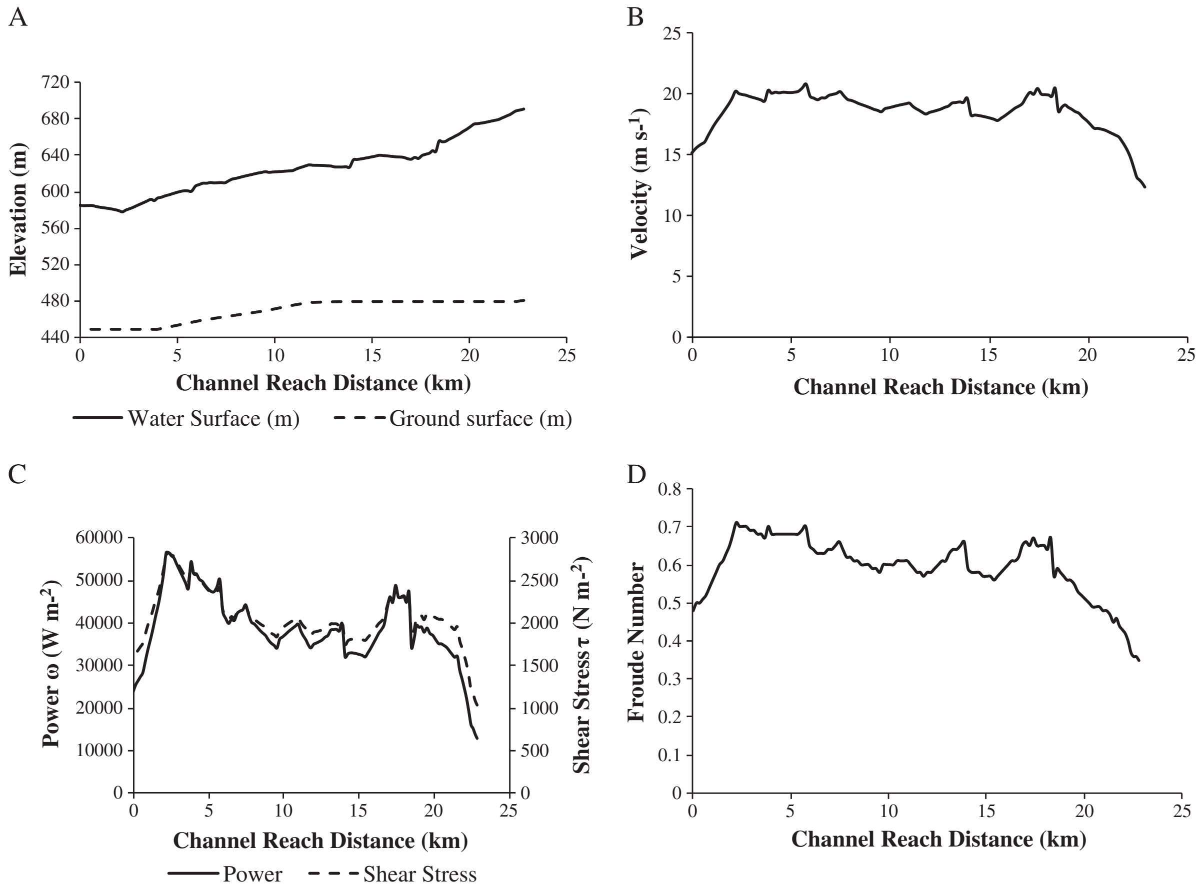

Fig. 12. Hydraulic results at $Q_P = 4.5 \times 10^7$ m^3 s^{-1} along Mt. Herðubreið reach. A) Represents the water surface profile, B) represents the mean flow velocity with an average of 18.5 m s^{-1}, C) represents the power per unit area and shear stress, averaged 38,411 W m^{-2} and 1936 N m^{-2}, respectively, and D) represents the Froude number along the paleoflood path.

the volumes of water required to create enormous jökulhlaups along Jökulsá á Fjöllum, a combination of these sources was necessary. Evidence suggests that during the Preboreal Period westward volcanic migration occurred beneath Bardarbunga and Kverkfjöll (Fig. 1) (Geirsdóttir et al., 2007) while large subglacial lakes formed due to the relatively thick ice-cap overburden. These sources in combination with marginal lakes produced enough water volume for massive jökulhlaups.

6. Applicability to Mars fluvial processes

Similarities between Earth and Mars outflow channels were identified in the early 1970s (Baker and Milton, 1974) and have been actively compared since then (Masursky et al., 1977; Carr, 1979; Komar, 1979; Malin and Eppler, 1981; Rotto and Tanaka, 1991; Rice and Edgett, 1997; Anguita et al., 2000; Malin and Edgett, 2000; Williams et al., 2000; Carling et al., 2003; Burr et al., 2004; Manga, 2004; Coleman, 2005; Gupta et al., 2005; Baker, 2009; Carling et al., 2009). The primary difference is that Mars' fluvial features are generally much larger than those on Earth. Additionally, to apply our hydraulic model to Mars we would have to take into account the difference in gravitational acceleration and its effect on Manning's *n*, and the specific weight of water. Accordingly, we altered the HEC-RAS software code and successfully applied this model to Aram Chaos channel on Mars (Howard, 2008). Jökulsá á Fjöllum presents an Earth analog site that resembles Martian fluvial geomorphology and representative hydraulic output (Howard, 2008, 2010 unpublished data). For comparison, Jökulsá á Fjöllum created similar peak discharges and power per unit area to Mangala Valles (Komar, 1979), Kasei Valles (Williams et al., 2000) and reaches of Ares Vallis. Additionally, fluvial geomorphological features were previously studied within Jökulsá á Fjöllum such as antidunes and transverse ribs south of Möðrudalur for comparison with Mars (Rice et al., 2002). It is apparent from the hydraulics and fluvial geomorphology presented here that Jökulsá á Fjöllum is a promising Earth analog for Mars fluvial processes.

7. Conclusions

We hydraulically modeled Mt. Herðubreið reach along the Jökulsá á Fjöllum channel and collected field evidence to provide input to the model and to verify the model's results. Our results support the following conclusions.

1. Our field survey suggests new evidence for higher trimlines based on a) boulder fields and fluvial erosion of hydroclastic units at higher elevations, b) inundation of Ferjufjall and Arnardalsalda in the paleoflood's floodplain, and c) fluvial-glacial erratics at higher elevations than previously observed.
2. Our hydraulic modeling results correlate well with previous peak discharge estimates and floodplain inundation maps, providing good calibration of our model.
3. The hydraulic modeling results, using new field evidence that Ferjufjall was completely inundated, give a conservative estimated peak discharge of 2.2×10^7 m^3 s^{-1}, with a mean flow velocity of 14.9 m s^{-1}. Estimated power per unit area and shear stress averaged 20,680 W m^{-2} and 1248 N m^{-2}, respectively.
4. Hydraulic modeling results for the highest trimline field evidence at Mt. Herðubreið and Möðrudalur estimated an upper limit peak discharge of 4.5×10^7 m^3 s^{-1}, with a mean flow velocity of 18.5 m s^{-1}.

5. One dimensional hydraulic modeling is probably sufficient for estimating such large catastrophic outbursts; however, future work will entail using rock-size to stream power and flow depth methods to validate our results.
6. Erosion and denudation rates along the channel are not well understood and may have an impact on our reconstructed hydraulic parameters. However, to assume and use current channel-bed elevation as base-level in the model is consistent with other paleoflood studies. Our intent is to incorporate temporal erosion rates into future runs of our model.
7. The fluvial geomorphology and hydraulic results are comparable to Mars outflow channels and Jökulsá á Fjöllum is a representative Earth analog.
8. Our study presents new lines of evidence that suggest a large paleoflood occurred through Jökulsá á Fjöllum channel in Iceland, probably the largest known early Holocene paleoflood on Earth.

Our intent is to continue this field work in and beyond the Mt. Herðubreið reach to support our new lines of evidence, further validate our discharge estimates using methods such as boulder size to unit stream power calculations (Costa, 1983), and to apply cosmogenic nuclide age-dating techniques to date this and sequential jökulhlaups.

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References

Ackerman, C.T., 2005. HEC-GeoRAS: GIS Tools for support of HEC-RAS using ArcGIS, Version 4. U.S. Army Corps of Engineers. (204 pp.) .

Alho, P., Aaltonen, J., 2008. Comparing a 1D hydraulic model with a 2D hydraulic model for the simulation of extreme glacial outburst floods. Hydrological Processes 22, 1537–1547.

Alho, P., Russell, A.J., Carrivick, J.L., Kayhko, J., 2005. Reconstruction of the largest Holocene jokulhlaup within Jokulsa a Fjollum, NE Iceland. Quaternary Science Reviews 24, 2319–2334.

Alt, D., 2001. Glacial Lake Missoula and Its Humongous Floods. Mountain Press Publishing Company, Missoula. (197 pp.).

Anguita, F., Babin, R., Benito, G., Gomez, D., Collado, A., Rice, J.W.J., 2000. Chasma Australe, Mars: structural framework for a catastrophic outflow origin. Icarus 144, 302–312.

Arcement, G.J., Schneider, V.R., 1989. Guide for selecting manning's roughness coefficients for natural channels and flood plains U.S. geological survey. Water-supply Paper, 2339 (67 pp.).

Paleohydrology and sedimentology of Lake Missoula flooding in Eastern Washington. In: Baker, V.R. (Ed.), The Geological Society of America, Boulder, Special Paper, 144 (79 pp.).

Baker, V.R., 2009. Overview of megaflooding: Earth and Mars. In: Burr, D.M., Carling, P.A., Baker, V.R. (Eds.), Megaflooding on Earth and Mars. Cambridge University Press, Cambridge, pp. 1–12.

Baker, V.R., Milton, D.J., 1974. Erosion by catastrophic floods on Mars and Earth. Icarus 23, 27–41.

Baker, V.R., Kochel, R.C., Patton, P.C. (Eds.), 1988. Flood geomorphology. Wiley, New York (503 pp.).

Baker, V.R., Benito, G., Rudoy, A.N., 1993. Paleohydrology of Late Pleistocene superflooding, Altay Mountains, Siberia. Science 259, 348–350.

Barnes Jr., H.H., 1967. Roughness Characteristics of Natural Channels. U.S. Geological Survey Water-Supply Paper. (213 pp.) .

Benito, G., 1997. Energy expenditure and geomorphic work of the cataclysmic Missoula flooding in the Columbia River Gorge, USA. Earth Surface Processes and Landforms 22, 457–472.

Berninghausen, W.H., Einarsson, P., Gudmundsson, A.T., Gudmundsson, M.T., Larsen, G., Hoskuldsson, A., Gylfason, A.G., Jakobsson, S.P., Johannesson, H., Saemundsson, K., Sigmundsson, F., Pedersen, Sapper, K., Steinthorsson, S., Thordarson, T., 2010. Eyjafjallajökull, Global Volcanism Program — SI/USGS Weekly Volcanic Activity Reports. Smithsonian Institution / US Geological Survey, Washington DC http://www.volcano.si.edu/world/volcano.cfm?vnum=1702-02=&volpage=weekly#Apr2010.

Björnsson, H., 2002. Subglacial lakes and jökulhlaups in Iceland. Global and Planetary Change 35, 255–271.

Björnsson, H., 2009. Jokulhlaups in Iceland: sources, release and drainage. In: Burr, D.M., Carling, P.A., Baker, V.R. (Eds.), Megaflooding on Earth and Mars. Cambridge University Press, Cambridge, pp. 50–64.

Boggs Jr., S., 1995. Principles of Sedimentology and Stratigraphy. Prentice-Hall, Inc., Englewood Cliffs, N.J.. (774 pp.).

Bretz, J.H., 1923. The channeled scablands of the Columbia plateau. Journal of Geology 31, 617–649.

Bretz, J.H., 1925. The Spokane flood beyond the channeled scablands. Journal of Geology 33, 97–259.

Bretz, J.H., Smith, H.T.U., Neff, G.E., 1956. Channeled scabland of Washington; new data and interpretations. Geological Society of America Bulletin 67, 957–1049.

Brunner, G.W., 2001. HEC-RAS River Analysis System. Army Corps of Engineering. (262 pp.).

Brunner, G.W., 2006. HEC-RAS, River Analysis System User's Manual, Version 4.0 Beta. U.S. Army Corps of Engineers. (420 pp.) .

Burr, D.M., Carling, P., Beyer, R.A., Lancaster, N., 2004. Flood-formed dunes in Athabasca Valles, Mars: morphology, modeling, and implications. Icarus 171, 68–83.

Carling, P., Kidson, R., Cao, Z., Herget, J., 2003. Palaeohydraulics of extreme flood events: reality and myth. In: Gregory, K.J., Benito, G. (Eds.), Palaeohydrology. Understanding Global Change, Wiley, Hoboken, N.J., pp. 325–336.

Carling, P., Burr, D.M., Johnsen, T.F., Brennand, T.A., 2009. A review of open-channel megaflood depositional landforms on Earth and Mars. In: Burr, D.M., Carling, P., Baker, V.R. (Eds.), Megaflooding on Earth and Mars. Cambridge University Press, Cambridge, pp. 33–49.

Carr, M.H., 1979. Formation of Martian flood features by release of water from confined aquifers. Journal of Geophysical Research 84, 2995–3007.

Carrivick, J.L., 2007. Hydrodynamics and geomorphic work of jokulhlaups (glacial outburst floods) from Kverkfjoll volcano, Iceland. Hydrological Processes 21, 725–740.

Carrivick, J.L., Rushmer, E.L., 2006. Understanding high-magnitude outburst floods. Geology Today 22, 60–65.

Carrivick, J.L., Russell, A.J., Tweed, F.S., 2004a. Geomorphological evidence for jokulhlaups from Kverkfjoll volcano, Iceland. Geomorphology 63, 81–102.

Carrivick, J.L., Russell, A.J., Tweed, F.S., Twigg, D., 2004b. Palaeohydrology and sedimentary impacts of jökulhlaups from Kverkfjöll, Iceland. Sedimentary Geology 172, 19–40.

Chow, V.T., 1959. Open-Channel Hydraulics. McGraw-Hill, New York. (680 pp.).

Coleman, N.M., 2005. Martian megaflood triggered chaos formation, revealing groundwater depth, cryoshpere thickness, and crustal heat flux. Journal of Geophysical Research 110, E12S20. doi:10.1029/2005JE002419.

Costa, J.E., 1983. Paleohydraulic reconstruction of flash-flood peaks from boulder deposits in the Colorado Front Range. Geological Society of America Bulletin 94, 986–1004.

Ehlers, J., Gibbard, P.L., 2007. The extent and chronology of Cenozoic Global Glaciation. Quaternary International 164–165, 6–20.

Geirsdóttir, Á., Miller, G.H., Andrews, J.T., 2007. Glaciation, erosion, and landscape evolution of Iceland. Journal of Geodynamics 43, 170–186.

Gomez, B., Smith, L.C., Magilligan, F.J., Mertes, L.A.K., Smith, N.D., 2000. Glacier outburst floods and outwash plain development: Skeidararsandur, Iceland. Terra Nova 12, 126–131.

Gregory, K.J., Benito, G. (Eds.), 2003. Palaeohydrology, Understanding Global Change. Wiley, West Sussex (396 pp.).

Gupta, S., Collier, J., Potter, G., Palmer-Felgate, A., 2005. Year. Catastrophic flood geomorphology in the English Channel compared with Martian outflow channels. Geophysical Research Abstracts 7, 10803.

Hanna, J.C., Phillips, R.J., 2005. Hydrological modeling of the Martian crust with application to the pressurization of aquifers. Journal of Geophysical Research 110, E01004. doi:10.1029/2004JE002330.

Herget, J., 2005. Reconstruction of Pleistocene ice-dammed lake outburst floods in the Altai Mountains, Siberia, Special Paper. Geological Society of America, 386 (118 pp.).

Ancient Floods, Modern Hazards, Principles and Applications of Paleoflood Hydrology. In: House, P.K., Webb, R.H., Baker, V.R., Levish, D.R. (Eds.), Water Science and Application. American Geophysical Union, Washington D.C (385 pp.).

Howard, D.A., 2008. Quantitative hydrologic and hydraulic models for Jokulhlaup-type outflow channels on Mars : application of Earth analogues, comparative geomorphology, and remote sensing. Ph.D., George Mason University, 2008, Fairfax, Virginia. (202 pp.) .

Jansen, J.D., Codilean, A.T., Bishop, P., Hoey, T.B., Persano, C., 2006. Channel sinuosity: another angle on steady state and transient response in bedrock rivers draining active mountain belts, European Geosciences Union. (8 pp.).

Komar, P.D., 1979. Comparisons of the Hydraulics of Water Flows in Martian Outflow Channels with Flow of Similar Scale on Earth. Icarus 37, 156–181.

Magilligan, F.J., Gomez, B., Mertes, L.A.K., Smith, L.C., Smith, N.D., Finnegan, D., Garvin, J.B., 2002. Geomorphic effectiveness, sandur development, and the pattern of landscape response during jokulhlaups: Skeietharársandur, southeastern Iceland. Geomorphology 44, 95–113.

Maizels, J., 1997. Jökulhlaup deposits in proglacial areas. Quaternary Science Reviews 16, 793–819.

Malin, M.C., Edgett, K.S., 2000. Evidence for Recent Groundwater Seepage and Surface Runoff on Mars. Science 288, 2330–2335.

Malin, M.C., Eppler, D.B., 1981. Catastrophic floods of the Jokulsa a Fjollum, Iceland. Reports of Planetary Geology Program - 1981 (NASA Technical Memorandum 84211). Government Printing Office, Washington D.C (272–273 pp.).

Manga, M., 2004. Martian floods at Cerberus Fossae can be produced by groundwater discharge. Geophysical Research Letters 31, L02702. doi:10.1029/2003GL018958.
Masursky, H., Boyce, J.M., Dial, A.L., Schaber, G.G., Stobell, M.E., 1977. Classification and time formation of Martian channels based on Viking data. Journal of Geophysical Research 82, 4016–4038.
Miller, A.J., Cluer, B.L., 1998. Modeling Considerations for Simulation of Flow in Bedrock Channels. In: Tinkler, K.J., Wohl, E.E. (Eds.), Rivers over rock: fluvial processes in bedrock channels. American Geophysical Union, Washington D.C., pp. 61–104.
O'Connor, J.E., Grant, G.E., Costa, J.E., 2002. The Geology and Geography of Floods. In: House, P.K., Webb, R.H., Baker, V.R., Levish, D.R. (Eds.), Ancient floods, modern hazards: principles and applications of paleoflood hydrology. : Water Science and Application. American Geophysical Union, Washington D.C, pp. 359–385.
Pardee, J.T., 1910. The Glacial Lake Missoula. Journal of Geology 18, 376–386.
Pardee, J.T., 1940. Ripple marks (?) in glacial Lake Missoula, Montana. Geological Society of America Bulletin 51, 2028–2029.
Pardee, J.T., 1942. Unusual currents in glacial Lake Missoula, Montana. Geological Society of America Bulletin 53, 1569–1599.
Rice, J.W., Edgett, K.S., 1997. Catastrophic flood sediments in Chryse Basin, Mars, and Quincy Basin, Washington: application of sandar facies model. Journal of Geophysical Research 102, 4185–4200.
Rice, J.W., Parker, T.J., Russell, A.J., Knudsen, O., 2002. Morphology Of Fresh Outflow Channel Deposits On Mars, Lunar and Planetary Science XXXIII (2002). LPSI, Houston, TX.
Rotto, S., Tanaka, K.L., 1991. Geologic History and Channeling episodes of the Chryse Planitia Regions of Mars. Lunar and Planetary Science Conference, XXII, pp. 1135–1136.
Saemundsson, K., 1973. Straumrakadar klappir i kringum Asbyrgi. Natturufaedingurinn 43, 52–60.
Tinkler, K.J., Wohl, E.E. (Eds.), 1998. Rivers Over Rock, Fluvial Processes in Bedrock Channels. American Geophysical Union, Washington D.C (323 pp.).
Unknown, 1950. Iceland Topographic Map Series, 1:50,000 scale. AMS Series C762. Army Corps of Engineers, Washington DC.
Waitt, R.B., 2002. Great Holocene floods along Jokulsa a Fjollum, north Iceland. In: Martini, P.I., Baker, V.R., Garzon, G. (Eds.), Flood and megaflood processes and deposits: recent and ancient examples. : Special Publications of International Association of Sedimentologists. Wiley-Blackwell, Oxford, pp. 37–51.
Williams, R.M., Phillips, R.J., Malin, M.C., 2000. Flow rates and duration within Kasei Valles, Mars: implications for the formation of a martian ocean. Geophysical Research Letters 27, 1073–1076.