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Reconstructing glacial outburst floods (jökulhlaups) from geomorphology: challenges, solutions, and an enhanced interpretive framework

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ABSTRACT

Glacial outburst floods (jökulhlaups) have been significant drivers of landscape change across Earth throughout the Quaternary and are a contemporary hazard in Arctic and alpine regions worldwide. Geomorphologic evidence is a foundation for reconstructing past and contemporary flood events and using additional analytical methods such as geochronology and paleohydraulics. Yet, accurate interpretation of jökulhlaup landforms and depositional sequences poses a persistent challenge due to complex controls on flood hydraulics and landscape evolution. Researchers have developed numerous strategies to reduce or resolve these challenges, but a comprehensive, globally applicable model to interpret flood evidence outside of sedimentary environments is lacking. This article synthesizes existing case studies to describe jökulhlaup geomorphologic interpretive challenges, discuss strategies to resolve them, and present a conceptual model of flood landform assemblages to illustrate hydraulic and environmental controls on resultant geomorphologic impacts. This enhanced interpretive framework aids researchers in identifying, interpreting, and testing geomorphologic evidence to reconstruct past jökulhlaups and predict future flood impacts as robustly as possible at a global, landscape-wide scale. Understanding jökulhlaup geomorphology yields insight into glacial lake

and ice margin dynamics, the role of extreme events in landscape evolution, and interactions between climate, ice sheets, and hydrology. Moreover, it is increasingly important as glacial outburst floods may become more frequent due to climate-driven ice retreat, advancing predictive capacities to mitigate societal risk downstream.

1. INTRODUCTION

Glacial outburst floods (jökulhlaups) have occurred across Earth throughout the Quaternary—and during earlier glaciations—and are a significant contemporary hazard in Arctic and alpine regions worldwide (Baker, 2013; Carrivick and Tweed, 2013, 2016; Ghienne et al., 2010; Harrison et al., 2018). These sudden meltwater drainage events are triggered by subglacial volcanic eruptions or dam failure or overtopping at ice-contact lakes (Björnsson, 2002; Evans and Clague, 1994; Tweed and Russell, 1999). Jökulhlaups can modify landscapes far beyond the proglacial source region and leave a legacy that can persist for millennia, eroding bedrock, redistributing sediment, and—in the case of the largest events—influencing ocean circulation and global climate (Baynes et al., 2015b; Carling, 2013; Clarke et al., 2004; Cook et al., 2018; Russell et al., 2005). Since floodwaters recede relatively quickly and are difficult to measure in real-time, geomorphologic and sedimentologic impacts are often the only lines of evidence to reconstruct both past and contemporary floods (Baker, 2008; Carrivick and Rushmer, 2006; Carrivick et al., 2013a; Clague and Evans, 2000). The overall aims of this paper are to assess the interpretive challenges in using geomorphologic data to reconstruct past jökulhlaups, discuss strategies to resolve them, and introduce an enhanced jökulhlaup geomorphologic interpretive framework.

1.1. Previous work

Scientists have long debated the evidence for jökulhlaups, tracing back to J Harlen Bretz’s promotion of a catastrophic glacial flood hypothesis for the formation of the Channeled Scabland in Washington State, U.S.A. (Baker, 2009b; Baker and Bunker, 1985; Bretz, 1923). A century later, controversial reconstructions of flood occurrence, chronology, and hydraulics show that geomorphologic interpretation is still disputed (i.e. Baynes et al., 2015a, 2015b; Carrivick et al., 2013b; Herget, 2005; Howard et al., 2012; Larsen and Lamb, 2016; O’Connor et al., 2020; Stucky de Quay et al., 2019; van der Bilt et al., 2021). Numerous studies have discussed the challenges and solutions to interpreting geomorphologic evidence and establishing process–form relationships (Lang and Glade, 2008; Schumm, 1991). One interpretive strategy is to group landforms into assemblages that develop under similar environmental conditions, as has been defined for glacial landsystems, for example (Ballantyne, 2002; Benn and Evans, 2006; Evans et al., 2006; Möller and Dowling, 2018; Shaw, 2010; Storrar et al., 2020). Yet, while researchers have promoted this approach for jökulhlaup landscapes, studies have been largely limited to megaflood sedimentary deposits (Carling, 2013; Carling et al., 2009a), sediments on sandurs (glacial outwash plains) (Maizels, 1997; Marren, 2002, 2005, 2016; Marren and Schuh, 2009), and individual case studies (Table 1—supplementary information). No previous publication has addressed jökulhlaup geomorphologic interpretation or developed jökulhlaup landform assemblages at a comprehensive, global scale.

1.2. Rationale and objective

Correctly identifying and interpreting jökulhlaup geomorphologic evidence is crucial for reconstructing past flood events, predicting future landscape impacts, and effectively using additional reconstructive methods such as geochronology and paleohydraulic calculations. Flood geomorphologic reconstruction yields insight into the role of extreme floods in bedrock erosion, sediment transport, and landscape evolution. Additionally, it helps reconstruct glacial lake and ice margin dynamics, advancing understanding of the links between climate, ice response, and hydrology in polar and alpine regions across the globe. Yet, accurate geomorphologic interpretation presents a unique, persistent, and current challenge. We tackle this problem by: 1) identifying and describing issues that pose an interpretive challenge when reconstructing jökulhlaups from geomorphologic evidence; 2) discussing strategies to resolve these challenges; and 3) presenting an enhanced interpretive framework for reconstructing flood geomorphologic evidence at a global, landscape-wide scale. Our overarching goal is to provide a methodology to aid researchers in identifying, interpreting, and testing geomorphologic evidence in a modern landscape to reconstruct past flood events as robustly as possible.

2. CHALLENGES IN JÖKULHLAUP GEOMORPHOLOGIC INTERPRETATION

Due to their high-magnitude stream power and competence, jökulhlaups are capable of performing more geomorphologic “work” than normal river flow or seasonal floods, creating a distinctive geomorphologic record (Benito, 1997; Carrivick, 2007; Carrivick and Rushmer, 2006; Cenderelli and Wohl, 2003; Wolman and Miller, 1960). Each jökulhlaup landform or depositional sequence is the product of a unique set of hydraulic and environmental conditions that are controlled by a complex array of interdependent factors, including flood stream power, triggering mechanism, hydrograph shape, dam characteristics, sediment availability, drainage

route topography and lithology, base level, and channel geometry. These parameters can vary significantly over the course of a single flood and between different flood events (Carrivick, 2011; Carrivick et al., 2013a; Cenderelli and Wohl, 2003; Clague and Evans, 2000; Kershaw et al., 2005; Korup and Tweed, 2007; Maizels, 1997; Marren, 2005, 2016; Roberts, 2005; Rushmer, 2006; Russell et al., 2005; Tomczyk et al., 2020; Tweed and Russell, 1999). Thus, jökulhlaups can generate some, all, or none of the same landforms, even if floods have similar hydraulic conditions or drain across the same landscape (Clague et al., 2021; Herget, 2005). The resultant geomorphologic record can be distinctive (diagnostic of jökulhlaup provenance) or ambiguous (not clear enough to definitively establish process–form relationships). These complexities introduce numerous challenges in jökulhlaup geomorphologic interpretation, including equifinality, preservation, absence of evidence, complex relationships between geomorphology and hydrology, and linking landforms to specific flood events. The following section discusses how these challenges arise, and Table 2 (supplementary information) describes them for individual jökulhlaup landforms and sediments.

2.1. Equifinality

Equifinality (convergence)—where different processes create a similar landform—presents one of the most significant challenges in geomorphologic interpretation (Möller and Dowling, 2018; Phillips, 2009; Schumm, 1991; Storrar et al., 2020). Though some landforms and depositional sequences are only generated by jökulhlaups, many resemble those formed by other processes, particularly glaciation and normal river activity, which typically operate in the same environment. Moreover, some jökulhlaup features are simply “scaled-up” versions of those generated by lower-magnitude fluvial processes (Marren and Schuh, 2009). Closer

geomorphologic investigation of landform or sediment morphology, orientation, composition, sorting, and stratigraphy may unravel process–form relationships (Carrivick and Rushmer, 2006; Maizels, 1997; Marren, 2002, 2005; Marren and Schuh, 2009; Russell et al., 2005). Landform scale or spatial extent may also resolve equifinalities as some features are sufficiently large or widely distributed to only result from jökulhlaups (Carling, 2013; Carling et al., 2009a; Carrivick et al., 2004a; Marren, 2002; Marren and Schuh, 2009).

Equifinality can present a challenge for interpreting individual landforms, such as boulder erratics that may have been deposited by glaciers, high-magnitude floods, or mass wasting events (i.e. Carrivick et al., 2013b); trimlines that could have been eroded by floodwaters or formed by mass wasting on canyon walls (i.e. Cenderelli and Wohl, 2001); or bedrock grooves, which can appear similar when eroded by jökulhlaup, glacial, or fluvial activity (i.e. Baynes et al., 2015a). It also applies at a landscape scale, with different sequences of events generating similar suites of landforms or sediments (Schumm, 1991). Sandurs offer an excellent example, as glaciers, proglacial rivers, and jökulhlaups repeatedly erode, deposit, and rework material to produce a similar set of landforms and depositional sequences (Maizels, 1997; Marren, 2005, 2016; Marren and Schuh, 2009). For example, hummocky terrain on the sandur at Breiðamerkurjökull outlet glacier, south Iceland, can be formed either by the melting of glacier ice covered by glaciofluvial outwash sediment or by jökulhlaup-deposited ice blocks melting beneath flood sedimentation (Evans and Twigg, 2002; Russell et al., 2005).

2.2. Preservation

Variability in landform or sediment preservation also poses specific challenges in interpreting jökulhlaup geomorphologic evidence. Landscapes are palimpsests, sculpted by a complex sequence of natural (and sometimes anthropogenic) processes, and jökulhlaup landforms and sediments may be removed, modified, or obscured to leave an incomplete geomorphologic record of the flood event (Carrivick and Tweed, 2019; Marren, 2016; Schumm, 1991). Landform and sediment preservation depends on a complex array of factors (Carling, 2013; Maizels, 1997; Marren, 2005). Generally, the more time elapsed, the more a jökulhlaup landscape will change through erosion or sediment accumulation (Wolman and Gerson, 1978; Duller et al., 2014).

Some locations have higher preservation potential than others. For example, subsequent flood or fluvial activity is more likely to modify jökulhlaup evidence in the center of a drainage channel than material at or beyond channel margins (Benito, 1997; Carling, 2013; Marren, 2005; Marren and Schuh, 2009; Roberts et al., 2003); buried boulders are less likely to be weathered than clasts exposed at the surface (Ehlmann et al., 2008); and fine-grained sediments are usually preserved better in lake basins than in terrestrial contexts (Geirsdóttir et al., 2000; Roberts et al., 2003). Weathering can also alter jökulhlaup evidence; for example, freeze-thaw activity may fracture flood-deposited boulders or flood-scoured bedrock, and fluvial or aeolian processes can erode finer particles to armor jökulhlaup bar surfaces or remove sand and silt deposits (Carrivick et al., 2013a; Russell et al., 2005). Additionally, ephemeral jökulhlaup impacts—such as ice blocks, englacial ice tunnels, or supraglacial ice-walled canyons—are among the most diagnostic flood evidence in the days to years following a jökulhlaup, but they rarely survive on geological

time scales and must be reconstructed from indirect evidence like kettle holes or englacial sediment deposits (Marren, 2005; Russell and Knudsen, 1999; Russell et al., 2005, 2006).

Moreover, even if a jökulhlaup leaves a distinct, well-preserved geomorphologic signature, landforms and depositional sequences may not be visible or accessible for study. Flood evidence may be buried by lava flows or fluvial or aeolian sediments, concealed by vegetation cover, or submerged by sea level transgression, forcing researchers to rely on limited exposures or subsurface geophysical imaging to study stratigraphic sequences (Carrivick and Rushmer, 2009; Maizels, 1997; Marren and Schuh, 2009; Marren et al., 2009). Evidence for past floods may also lie in lake or marine environments only visible through bathymetric surveys, coring, or geophysical imaging (Geirsdóttir et al., 2000; Kehew et al., 2009).

2.3. Absence of evidence

Given the complex controls on jökulhlaup landscape impact, floods do not always leave a distinctive geomorphologic signature or create diagnostic landforms or sedimentary deposits (Carrivick and Rushmer, 2006; Carrivick et al., 2004a, 2013b). Thus, spatial distribution of flood features may not accurately reflect inundation area, and a lack of evidence does not necessarily help define the limits of flood extent or indicate that a jökulhlaup did not occur (Cenderelli and Wohl, 2001). If floodwaters are sediment-starved—for example, if they drain across a landscape where previous floods have removed material—they will leave little depositional evidence, regardless of their competence (Carling, 2013; Carrivick et al., 2013a; Maizels, 1997). Similarly, high-magnitude floodwaters will have little erosional impact if they do not cross geomorphic thresholds required to initiate erosion due to lithologic constraints of resistant bedrock or

topographic constraints of existing valleys or unconfined plains (Benito, 1997; Bull, 1979; Kehew et al., 2009; Kirkbride et al., 2006; Schumm, 1979; Whipple et al., 2000). These interactions can be complex. At Jökulsárgljúfur canyon, northeast Iceland, for example, floods drained through an existing canyon with resistant bedrock, but basalt jointing structure and pre-existing knickpoints resulted in significant canyon incision where local stream power exceeded rock strength (Baynes et al., 2015a, 2015b).

2.4. Complex relationships between geomorphologic evidence and hydraulic conditions

Jökulhlaup landforms and sediments can provide valuable information for reconstructing flow magnitude, stream power, velocity, depth, and shear stress. Researchers have derived quantitative relationships between feature characteristics and hydraulic parameters, including megaripple dune geometry (Baker, 1973; Bohorquez et al., 2019; Carling, 1996; Herget, 2005); obstacle mark dimensions and morphology (Herget, 2005; Herget et al., 2013); run-up sediment height (Herget, 2005; Carling et al., 2020); streamlined hill length-to-width ratios (Baker, 1978a; Komar, 1984); boulder dimensions (Costa, 1983; Clarke, 1996; Stokes et al., 2012; Williams, 1983); and columnar basalt toppling thresholds and knickpoint retreat rate during canyon formation (Baynes et al., 2015b; Lamb and Dietrich, 2009; Lamb et al., 2014; Stucky de Quay et al., 2019). Studies have also quantified hydraulic boundary condition “envelopes” for some flood landforms (Benito, 1997; Carrivick, 2007).

Despite their utility, these relationships are not always simple. Higher-magnitude floods do not necessarily perform more geomorphologic work or generate larger landforms or depositional sequences, with sediment supply and local lithological conditions critical to the

resulting flood impact. Moreover, researchers must interpret flood evidence in the context of all controlling factors; for example, cataracts formed by floods of similar magnitudes may have different sizes due to differences in substrate erodibility or land surface slope rather than hydraulic conditions. One notable example of this complexity comes from the 2010 subglacial eruption beneath Eyjafjallajökull ice cap, south Iceland, where a series of ~140 small-scale jökulhlaups deposited a greater volume of sediment than two previous floods with discharges of one to two orders of magnitude larger (Dunning et al., 2013).

Flood-transported boulders also illustrate the complexity associated with geomorphologic evidence and hydraulic conditions, as their use for paleohydraulic reconstruction often underestimates peak flow competence. Such boulders may have been deposited during flood waning stages, or their size is limited by an absence of larger clasts along the drainage route due to local bedrock jointing controls (Baynes et al., 2015a; Carrivick, 2007; Carrivick et al., 2013a; Dugmore et al., 2013; Kershaw et al., 2005; O'Connor, 1993; Stokes et al., 2012). Boulder size can also lead to overestimates of peak discharge when floodwaters transport clasts in a traction carpet rather than completely mobilizing them, or when particles are buoyed by high sediment concentrations in floodwaters (Carrivick and Rushmer, 2009; Kershaw et al., 2005; O'Connor, 1993).

Jökulhlaup sedimentary deposits present another example of geomorphologic evidence that may not scale to flood magnitude. Transported material depends on sediment availability, which may change over the course of a single flood or between different events. Floodwaters may be hyperconcentrated and behave as non-Newtonian flows—for example, if there is

abundant sediment along the drainage route or if subglacial eruptions have generated large quantities of tephra or volcanogenic material. Alternatively, jökulhlaups may contain low sediment concentrations if the drainage route is sediment-starved—for example, if previous floods have flushed material from the system. Thus, larger floods do not necessarily deposit greater quantities of material (Dunning et al., 2013; Maizels, 1997; Marren, 2005, 2016; Westoby et al., 2014).

Non-scalar relationships also extend to paleohydraulic reconstructions from canyon geometry. Researchers have used dimensions of flood-eroded canyons in the Channeled Scabland, Washington State, U.S.A., to calculate peak jökulhlaup discharges on the order of $1 \times 10^7 \text{ m}^3 \text{ s}^{-1}$ (Baker, 1973, 2009a; O'Connor et al., 2020). However, other studies have argued that peak discharge was more than an order of magnitude smaller because floodwaters did not necessarily fill canyons to the brim, and canyons were likely deepened during and after flood events (Larsen and Lamb, 2016; Perron and Venditti, 2016). Conversely, modern-day canyon dimensions in the Altai Mountains, Siberia, and Nostetuko River valley, British Columbia, Canada, underestimated peak jökulhlaup discharge by not accounting for during- and post-flood sedimentary infill and aggradation in the channel (Herget, 2005; Kershaw et al., 2005).

2.5. Linking landforms to specific flood events

Another persistent challenge in jökulhlaup geomorphologic interpretation is directly linking a landform or depositional sequence to the flood event that formed it, which is important for quantifying the geomorphologic effectiveness of a single flood (Benito and Thorndycraft, 2020; Herget, 2005; Marren, 2005). Multiple floods often drain along the same routes, resulting

in “landsystem overprinting” (Evans, 2016), so a landscape may only reflect the geomorphologic impact of the largest or most recent event (Benito and O’Connor, 2003; Herget, 2005; Kershaw et al., 2005; Westoby et al., 2014). Sandurs are excellent examples, where jökulhlaups repeatedly drain across the same outwash plain and add new sediments while reworking previous deposits, challenging researchers to tease apart the depositional sequence of each event (Maizels, 1997; Marren, 2005, 2016; Russell and Knudsen, 1999). Canyons can also challenge chronological reconstruction, as a larger jökulhlaup may remove evidence of previous, smaller floods, while a subsequent, lower-magnitude event may drain through a gorge formed by a larger flood without leaving an erosional trace (Carling, 2013; Kehew et al., 2009; Kershaw et al., 2005; Kirkbride et al., 2006).

Some jökulhlaups have complex drainage sequences with multiple hydrograph peaks, challenging researchers to distinguish between landforms and sediments generated by a pulsed flood versus separate flood events (Carling, 2013; Dunning et al., 2013; Herget, 2005; Maizels, 1997). Multiple discharge peaks—also termed “hydropeaking” (Carrivick et al., 2013a)—can occur when ponded floodwaters are released from lake basins, proglacial trenches, tributary valleys, upstream of topographic constrictions, or behind blocked drainage channels (Björnsson, 2002; Kershaw et al., 2005; Maizels, 1997; Marren et al., 2009; Russell and Knudsen, 1999; Russell et al., 2005, 2006). This complexity is exemplified by the Glacial Lake Missoula flood rhythmites in Washington State, U.S.A., where researchers have long debated whether each rhythmite was deposited by a unique flood or pulses from backponded water release (Baker and Bunker, 1985; Benito and O’Connor, 2003). A multi-peaked hydrograph can also result from a complex triggering sequence, as seen during subglacial geothermal meltwater drainage followed

by ice-marginal lake spillover at Sólheimajökull outlet glacier, south Iceland (Roberts et al., 2003; Russell et al., 2005), and lake drainage via an overtopping wave followed by moraine dam incision at Queen Bess Lake, British Columbia, Canada (Kershaw et al., 2005).

3. STRATEGIES TO RESOLVE INTERPRETIVE CHALLENGES

Despite the challenges in identifying and interpreting jökulhlaup geomorphologic evidence, there are strategies to reduce or resolve them. These approaches are not mutually exclusive and can be employed concurrently to reconstruct a flood event as robustly as possible (Figure 1).

Figure 1. Conceptual visualization of jökulhlaup geomorphologic interpretive challenges and strategies. Multiple strategies can be employed to reduce or resolve each challenge, as demonstrated by rotating the outer circle (strategies) and inner circle (challenges) to test each combination.

3.1. Multiple working hypotheses

Chamberlin's (1890) concept of "multiple working hypotheses" has become a foundational approach in scientific research, including in interpreting jökulhlaup geomorphologic evidence (Baker, 2009b). There are numerous potential pathways to generate a single landform or suite of landforms, and the best explanation is often found in a complex combination of events and processes. Accurate geomorphologic interpretation requires developing and testing hypotheses at a corresponding level of complexity as the processes of formation, from assessing equifinality of an individual landform or sediment sequence, to reconstructing landscape evolution over multiple flood events, to testing scenarios of glacial lake volume and drainage dynamics (Chamberlin, 1890, 1897; Schumm, 1991).

Given the complexity of many jökulhlaup landscapes, hypothesis testing may hinge on rejecting incorrect hypotheses and provisionally accepting jökulhlaup provenance by process of elimination rather than the presence of enough definitive evidence (Marren, 2002, 2005). In his pioneering jökulhlaup study, J Harlen Bretz (1923: 621) argued that the Channeled Scabland was sculpted by catastrophic floods—not glaciers, as was widely accepted by the geoscience community at the time—on the basis that "All other hypotheses meet fatal objections" (Baker, 2009b; Baker and Bunker, 1985). In a more recent example, Carrivick et al. (2004a) rejected glacial and volcanic equifinalities in the Kverkfjallarani region, central highlands, Iceland, by concluding that only jökulhlaups could explain observed landform characteristics, scale, and spatial distribution.

3.2. Map flood geomorphologic evidence at a variety of spatial scales

Flood landforms span a wide range of spatial scales, typically categorized into microforms (sub-meter to meters), mesoforms (meters to kilometers), and macroforms (tens of kilometers) (Baker, 2009a; Carling et al., 2009a; Carrivick et al., 2004a; Munro-Stasiuk et al., 2009). Different landforms are optimally identified and mapped at different spatial scales using a variety of methods. A single landform or depositional sequence can also yield diverse information when interpreted at multiple resolutions; for example, satellite imagery may be used to delineate sandur extent, but field investigation is necessary to study sandur sediment stratigraphy (Chandler et al., 2018; Thorndycraft et al., 2016).

Remote sensing, including aerial photographs, satellite imagery, and lidar, is most effective for identifying potential field sites and mapping meter-to-kilometer-scale landforms like megaripple dune fields and anastomosing bedrock channel networks (Chandler et al., 2018; Roering et al., 2013; Thorndycraft et al., 2016). Of particular interest for Arctic glacial environments is the ArcticDEM dataset, which provides a digital elevation model (DEM) of the entire Arctic at two-meter resolution, improving flood mapping in locations such as Iceland and Greenland (Carrivick and Tweed, 2019; Porter et al., 2018). At a more local scale, photogrammetry methods such as Structure-from-Motion and Terrestrial Laser Scanning are ideal for generating centimeter-scale DEMs or three-dimensional models of individual landforms (Chandler et al., 2018; Westoby et al., 2012; Wilson et al., 2019). Notable examples include mapping sandur evolution after jökulhlaups from the 2010 Eyjafjallajökull subglacial eruption in south Iceland (Dunning et al., 2013; Harrison et al., 2019) and river channel changes from glacial outburst floods in the Nepal Himalayas (Cook et al., 2018) and northeast Greenland (Tomczyk et al., 2020). Additionally, these imaging tools can be mounted on drones or unmanned aerial

vehicles (UAVs) to provide a relatively affordable, portable, self-operable, and spatially tailored mode of data collection (Chandler et al., 2018; Tomczyk and Ewertowski, 2020).

Despite the expanding toolbox of remote sensing techniques, on-the-ground field mapping is indispensable for accurate jökulhlaup interpretation. Accurate studies of some flood features, such as bedrock scour marks, boulder morphology, and sediment stratigraphy, can only happen at a sub-meter scale. Field mapping is also often necessary to assess landform and sediment equifinality and preservation (Thorndycraft et al., 2016).

3.3. Determine spatial and chronological associations with other flood landforms

Accurate jökulhlaup geomorphologic interpretation hinges on determining landform spatial, temporal, and stratigraphic “association” with other lines of flood geomorphologic evidence along the drainage route (Baynes et al., 2015a; Carling, 2013; Carling et al., 2009a; Carrivick et al., 2013b; Dugmore et al., 2013; Marren and Schuh, 2009). First, a jökulhlaup landform or depositional sequence must be accurately located within both the flood channel and the overall drainage path. For example, calculating flow paleocompetence from a boulder deposited at a channel margin will underestimate peak discharge compared to a clast in the channel thalweg; and a boulder deposited near the flood source may represent peak discharge more accurately than one deposited several kilometers downstream where flow energy has dissipated (Stokes et al., 2012).

Second, jökulhlaup evidence needs to be interpreted within its chronological context, with each landform or depositional sequence linked to the flood event that formed it. Assigning

“time stamps” to individual features enables researchers to trace the geomorphologic impact of a single flood across a landscape. This task can be complex since subsequent floods often drain along the same routes, superimposing and modifying landforms and sediments (Maizels, 1997; Marren, 2005; Rushmer, 2006; Russell et al., 2006). Moreover, each drainage path has a unique hydrograph magnitude and shape, so different geomorphologic impacts occur concurrently at different reaches; for example, floodwaters may incise a bedrock canyon in the central drainage channel at the same time as they deposit slackwater sediments in a marginal tributary valley.

Finally, different contextual framings can lead to differing interpretations of geomorphologic evidence. For example, Baynes et al. (2015a, 2015b) integrated observations of flood landforms, canyon morphology, cosmogenic nuclide exposure dates on strath terraces, and a model of bedrock block toppling at waterfalls to conclude that Jökulsárgljúfur canyon, northeast Iceland, primarily formed during three periods of extreme flooding in the mid-Holocene. In another study, Stucky de Quay et al. (2019) interpreted additional exposure dates to suggest that the canyon formed via gradual fluvial knickpoint retreat. Though the studies used similar quantitative methods, Baynes et al. (2015a, 2015b) interpreted results in spatial and stratigraphic relation to other lines of jökulhlaup geomorphologic evidence in the area, situating canyon formation within the overall flood landscape context rather than studying the gorge as an isolated unit.

3.4. Interpret flood evidence within broader environmental context

Researchers should also interpret jökulhlaup geomorphologic evidence within the broader regional environmental context (Carling, 2013; Marren and Schuh, 2009). Some geologic

processes operate at a larger spatial and temporal scale than a given jökulhlaup landscape and must be factored into geomorphologic reconstruction, such as the role of regional base level change or isostatic adjustment in driving post-flood canyon incision rates (Schumm, 1979). Jökulhlaup geomorphology must also be interpreted in the context of climatic conditions, which may have operated differently in the past, leading to potential changes in weathering rates, river discharge, sediment availability, or vegetation cover over time, all of which can influence flood landform generation and post-flood preservation (Marren, 2005). It is also important to consider jökulhlaup source and, where relevant, ice margin position. Although these variables can be challenging to reconstruct due to lake drainage and glacier change, estimated flood drainage routes and hydraulics must fit with realistic scenarios of lake location and volume, respectively (Baker and Bunker, 1985; Carrivick et al., 2013b; Høgaas and Longva, 2018; Pardee, 1942; Regnéll et al., 2019).

4. JÖKULHLAUP GEOMORPHOLOGY: AN ENHANCED INTERPRETIVE FRAMEWORK

The existing jökulhlaup geomorphologic classification system describes landforms by spatial scale (micro-, meso-, and macroforms) or by erosional versus depositional context (Baker, 2009a; Baynes et al., 2015a; Carrivick et al., 2004a). However, not all features will occur in all types of landscapes, and this categorization yields little insight into flood hydraulic or environmental conditions. This section introduce an enhanced interpretive framework using jökulhlaup landform assemblages to advance flood geomorphologic reconstruction across a range of landscapes at a global scale.

4.1. Jökulhlaup landform assemblages

The presence of a single jökulhlaup landform or depositional sequence does not provide enough information to reconstruct a flood event. However, individual landforms can be grouped into a suite or assemblage that represents a similar set of hydraulic and environmental conditions, which may be a more functional geomorphologic interpretive unit (Baynes et al., 2015a; Carling et al., 2009a; Carrivick et al., 2013b; Marren and Schuh, 2009). Landform assemblages have been defined for proglacial environments, with features (elements) grouped together to form land facets (units), which in turn make up landsystems, each of which represents a specific set of glacial conditions (i.e. surging, debris-covered, or active temperate glaciers) (Evans, 2005, 2014, 2016; Evans and Twigg, 2002). While previous studies have highlighted the importance of applying this approach to jökulhlaup settings, it remains limited to sandur sedimentary deposits, where sediment sequences are grouped into facies assemblages, which compose landsystems formed by unique glaciofluvial magnitude–frequency regimes (Carrivick and Rushmer, 2009; Glasser and Hambrey, 2002; Maizels, 1997; Marren, 2002, 2005, 2016; Marren and Schuh, 2009; Marren et al., 2009), and megaflood sedimentary deposits, where individual sediment beds or facies are grouped into sequences reflecting hydraulic conditions at a given hydrograph point (Carling, 2013). However, research on landform assemblages in non-sedimentary jökulhlaup settings is mostly limited to individual case studies (i.e. Benito and Thorndycraft, 2020; Carrivick et al. 2004a).

Figure 2 synthesizes observed jökulhlaup geomorphologic evidence from case studies in Table 1 (supplementary information) to create a conceptual model of flood pathways and landform assemblages. Figure 2a defines landform assemblages by grouping features that form

under similar hydraulic conditions, as controlled by flood stream power, substrate erodibility, and geomorphic thresholds. It plots these assemblages along five unique flood pathways based on observed drainage route lithologic and topographic characteristics. Two pathways are sedimentary environments with different drainage route topographies: unconfined and confined sandur plains. The other three pathways are in bedrock terrain, divided into unconfined topography (i.e. broad plains), confined topography (i.e. river channels or valleys), and lithology with strong structural controls (i.e. stacked basalt lava flows) where erosion is often dominated by plucking and/or toppling.

Figure 2b superimposes this conceptual model over time, indicating the relative position of landform assemblages along each pathway over the duration of an “idealized” flood with uniformly increasing and decreasing stream power. Figure 2c provides a “real-world” example of the pathways and landform assemblages of a hypothetical jökulhlaup draining across a landscape, illustrating many of the challenges and solutions in interpreting flood geomorphology. Taken together, Figure 2 provides an enhanced conceptual model to interpret flood geomorphologic evidence by: 1) illustrating links between landforms and their hydraulic, lithologic, and topographic controls; 2) tying together diverse case studies from landscapes worldwide to facilitate more direct comparison; and 3) narrowing the list of potential lines of geomorphologic evidence in a flood landscape, helping to reconstruct paleofloods and predict future flood impacts.

Figure 2. Conceptual models for jökulhlaup geomorphologic interpretation.

a) Conceptual model of jökulhlaup landform assemblages (circled numbers) and flood pathways (arrows), as defined by stream power, substrate and topographic controls, and geomorphic thresholds.

b) Conceptual model of jökulhlaup landform assemblages and flood pathways superimposed over time (flood duration) for an idealized, single-peaked flood hydrograph. Numbered circles and arrows correspond to landform assemblages and flood pathways, respectively, in Figure 2a.

c) Example of geomorphologic impact for a hypothetical jökulhlaup, showing location of flood landform assemblages (numbered circles) and pathways (arrows) corresponding to key in Figures 2a and 2b. This model illustrates the spatial and chronological complexity of feature formation and demonstrates the potential for diverse topographic, lithologic, and hydraulic conditions along a flood drainage route.

4.2. Discussion

Figure 2 guides flood reconstruction by indicating which lines of geomorphologic evidence we expect to see—or could possibly exist—in different contexts. However, as with any conceptual model, real-world application can be complex. Some flood pathways are continuous, some interrupted; some have simple trajectories, others have multi-stranded, bifurcating, or reconnecting drainage routes. Given the complex factors controlling resultant geomorphologic impacts, not every landform assemblage will be present along each pathway; and, conversely, a pathway may include features that are not listed in an assemblage. The presence of a single line of jökulhlaup evidence does not unequivocally diagnose a flood landscape or reject other provenances; instead, landforms and sediments must be interpreted in their geomorphologic context.

Moreover, this conceptual model is derived from geomorphologic evidence reported in case studies (Table 1—supplementary information), which may be biased by landform and sediment preservation potential. For example, finer-grained sediments are more easily eroded, possibly underrepresenting lines of evidence such as slackwater deposits in the geologic record. Interpretive bias may also exist between different flood pathways, since most studies of sandurs have occurred on a time scale of days to decades after a flood event, while bedrock terrain sculpted by Pleistocene and Holocene megafloods has been modified by millennia of geologic activity before its study. This highlights the importance of monitoring contemporary floods real-time, mapping pre- and post-flood landscapes, and conducting flume experiments to directly

observe and quantify jökulhlaup geomorphologic impact (Baynes et al., 2018; Harrison et al., 2019).

While Figure 2 demonstrates the relative links between flow hydraulics and drainage route characteristics, it does not indicate landform or sediment spatial or chronological context; in other words, it cannot predict where or when features will form on a landscape. Lithology, topography, sediment supply, and flow dynamics can vary along the drainage path over the course of a flood event, so stream power will not increase and decrease at a uniform rate on flood rising and waning stage, respectively, across an entire landscape. For example, floodwaters may incise cataract and canyon systems in a central channel, while stream power is only great enough to erode overlying sediment or scour bedrock in marginal channels (Carrivick et al., 2004a). Slackwater sediments may settle in ponded areas behind topographic constrictions such as moraines near the flood source where stream power is expected to be highest (Russell et al., 2005). Similarly, waning stage floodwaters or subsequent pulses or events may only drain along certain routes, aggrading or reworking sediments in some channels while leaving others abandoned (Baynes et al., 2015b; Maizels, 1997; Marren, 2005; Russell et al., 2006).

A single location may also transition through multiple pathways over the course of a flood or between different events, resulting in a complex sequence of landform assemblages. For example, the first jökulhlaups in the Channeled Scabland, Washington State, U.S.A., drained across loess-covered terrain, sculpting streamlined residual hills and initiating bedrock erosion, while subsequent floods flowed through and further incised existing basalt canyons (Baker, 2009a; Benito, 1997). Additionally, a single flood route may contain multiple pathways, as

illustrated in Figure 2c. An excellent example is the Jökulsá á Fjöllum River, northeast Iceland, where floods drained from the Vatnajökull ice cap margin across a sandur, over relatively unconfined hyaloclastite and basalt terrain, through a columnar basalt canyon, and over another sandur before reaching the coast, leaving a different suite of landforms and depositional sequences in each reach (Alho et al., 2005; Baynes et al., 2015a; Carrivick et al., 2004a, 2013a; Marren et al., 2009). To tackle these challenges, researchers can divide a flood route into expected pathways based on lithology and topography, hypothesize which landform assemblages will occur along each pathway, and estimate how hydraulic and environmental conditions changed before, during, and after a flood event.

Jökulhlaups may also generate other landforms or depositional sequences beyond those included in this conceptual model. Figure 2 focuses on geomorphologic evidence in terrestrial landscapes because these data are reported most frequently and consistently in the literature. However, jökulhlaup evidence also exists in subglacial, englacial, and supraglacial settings (i.e. eskers, ice tunnels, and ice canyons) (Russell et al., 2005, 2006), lacustrine and marine environments (i.e. turbidites and submarine channels) (Garcia-Castellanos et al., 2020; Geirsdóttir et al., 2000), and extra-terrestrially on Mars (Baker et al., 2015; Warner et al., 2013). Floods can also trigger secondary geomorphologic processes, generating debris flow deposits, mass movement scars from channel bank destabilization, or aeolian dunes formed from fine-grained flood deposits (Benito and Thorndycraft, 2020; Cenderelli and Wohl, 2001; Korup and Tweed, 2007).

Finally, presenting a conceptual model raises the critical question: what is its practical use and how can we test our geomorphologic interpretation within this framework? There will be gaps in most, if not all, datasets due to variable landform or sediment preservation, post-flood landscape modification, and the impracticability or impossibility of mapping all evidence; and some features will more definitively (less ambiguously) indicate flood provenance than others. Nonetheless, this model provides a starting point for geomorphological analyses of landscapes that may have been impacted by jökulhlaups. The maximum number of lines of evidence across a greater spatial area with a higher interpretive confidence will more strongly support a flood hypothesis; in other words, the more complementary lines of jökulhlaup confirmation, the better (Carling, 2013). While this conceptual model guides jökulhlaup geomorphologic reconstruction, it should be most effective when used in conjunction with the interpretive challenges and strategies previously discussed, following a methodological framework summarized in Figure 3.

Figure 3. Methodological flowchart for reconstructing jökulhlaup geomorphology. Research progresses through four stages: 1) formulating hypotheses; 2) identifying jökulhlaup landforms and sediments; 3) interpreting geomorphologic evidence; 4) developing conclusions and additional research questions to test, at which point it cycles back to repeat the workflow.

4.3. Limitations of geomorphologic evidence

Despite our best interpretive efforts, some jökulhlaup parameters are particularly challenging—or impossible—to reconstruct from geomorphologic evidence alone. It is best to recognize limitations and identify where interpretive uncertainty lies to avoid extrapolating false or misleading conclusions from evidence. First, landforms and sediments rarely preserve information about flood source. Mapped jökulhlaup evidence can help constrain lake dam location, and flood-deposited sediments may provide geochemical fingerprinting to reconstruct drainage routes (Herget, 2005; Lang et al., 2013). However, without pre-flood lake measurements or evidence—such as paleoshorelines or lacustrine sediments—reconstructing characteristics of a drained or emptied lake can be challenging at best (Carrivick and Tweed, 2013; Høgaas and Longva, 2018; Mangerud et al., 2004; Montgomery et al., 2004; Pardee, 1942; Regnéll et al., 2019; Thorarinsson, 1939; Tómasson, 1993). Moreover, this evidence is largely limited to subaerial lakes, since subglacial and englacial lakes rarely preserve shorelines or sediments due to subsequent ice movement.

Jökulhlaup geomorphologic evidence also provides few clues to dam characteristics and flood triggering mechanism (Carling et al., 2010; Korup and Tweed, 2007). Some impoundments, particularly bedrock rims, may be partially or completely preserved following lake drainage, enabling researchers to compute breach incision rates (Garcia-Castellanos and O'Connor, 2018). However, most dams are modified or destroyed by subsequent

geomorphologic activity, particularly when lake-impounding glaciers retreat or moraine dam breaches become permanent drainage outlets (Clague and Evans, 2000; Costa and Schuster, 1988; Herget, 2005; Kershaw et al., 2005; Korup and Tweed, 2007; O'Connor and Beebee, 2009; Westoby et al., 2014). Dam material also disaggregates during flood transport, providing few clues to its original structure, though some deposits (particularly landslide and debris flow dams) may be identifiable in the geologic record as hummocky terrain (Korup and Tweed, 2007; O'Connor and Beebee, 2009). Moreover, even when geomorphologic evidence seems to provide clues to flood triggering process, it may be subject to equifinality; for example, tephra in flood deposits does not necessarily indicate a volcanogenic jökulhlaup, as these sediments may have been remobilized from sediment stores in ice marginal lakes or along flood routes (Dugmore et al., 2013).

Finally, jökulhlaup geomorphologic evidence often provides little insight to pre-flood topography. Quantifying the landscape change during a single flood event enables researchers to calculate bedrock erosion rates, geomorphic thresholds, and hydraulic parameters. However, extracting this information from a modern-day landscape poses a significant challenge (Carrivick et al., 2004a; Cenderelli and Wohl, 2001; Duller et al., 2014; Kershaw et al., 2005; Larsen and Lamb, 2016; Westoby et al., 2014). Some jökulhlaups leave behind evidence of pre-flood topography—for example, by abandoning fluvially-scoured strath terraces during canyon incision to leave a remnant imprint of pre-flood river elevation, as seen in Jökulsárgljúfur canyon, northeast Iceland (Baynes et al., 2015a, 2015b), and the Río Baker valley, Patagonia (Benito and Thorndycraft, 2020). However, other events (or subsequent geologic processes) can remove or obscure pre-flood geomorphologic traces, prompting most studies to input modern

topographic data and note its potential error in flood paleohydraulic reconstruction (Alho et al., 2005; Westoby et al., 2014). Some researchers have attempted to resolve this challenge by modeling landscape evolution at various stages during a single flood or between multiple events, as conducted in the Channeled Scabland, Washington State, U.S.A. (Larsen and Lamb, 2016), and the Kverkfjallaráni region, central highlands, Iceland (Carrivick et al., 2004a, 2004b).

4.4. Enhancing geomorphologic interpretation with additional reconstructive techniques

When morphological evidence alone is insufficient to reconstruct a flood event, we can draw on additional methods, each of which relies on accurately identifying and interpreting jökulhlaup landforms and sediments. First, geochronology can constrain flood timing and recurrence interval and chronologically link different lines of jökulhlaup evidence. Effective sample selection hinges on accurately connecting flood evidence with the dating method under consideration. Bedrock surfaces must be aptly preserved for cosmogenic nuclide exposure dating (Cockburn and Summerfield, 2004; Heyman et al., 2011). Stratigraphic context needs to be clearly established for tephrochronology and organic material for radiocarbon dating (Dugmore et al., 2013; Kirkbride et al., 2006). Even direct dating of flood deposits with optically stimulated luminescence (OSL) requires a careful linkage of sediment sequence to overall flood event stratigraphy (Herget, 2005; Herget et al., 2020; O'Connor et al., 2020). In some cases, geochronological results do not yield a high enough resolution to distinguish between separate flood events, which may occur on an annual or decadal time scale (Kershaw et al., 2005; Maizels, 1997). Nonetheless, these methods can constrain periods of flood activity within a few hundred years (Baynes et al., 2015b; Kirkbride et al., 2006).

Paleohydraulic reconstructions can yield critical insight into flood source location, routing, volume, hydrograph shape, and triggering mechanism, providing information that geomorphologic evidence alone cannot. However, accurate results rely on robust interpretation of jökulhlaup landforms and reconstruction of pre-flood topography (Benito and Thorndycraft, 2020; Carrivick, 2007; Klimeš et al., 2014; Westoby et al., 2014). Boulder paleocompetence calculations require correct identification of flood-deposited clasts (that may be confused with glacial erratics), and slope–area equations depend on accurate reconstruction of channel geometry at the time of a flood (Carrivick, 2007; Cenderelli and Wohl, 2001; Rushmer, 2006; Stokes et al., 2012). Hydraulic modeling simulations test jökulhlaup drainage routes, sources, inundation depths, and flow conditions against the location and elevation of geomorphologic field evidence, which serve as paleostage indicators (PSIs) (Baker, 1978b, 2008; Carrivick, 2007; Cenderelli and Wohl, 2001). However, interpretation can be challenging since PSIs can under- or overestimate maximum floodwater elevation. For example, bars are typically formed from suspended sediment deposited below the water surface, while emplaced boulders may protrude above water level (Cenderelli and Wohl, 2001; Herget, 2005; Benito et al., 2021); and trimlines may overestimate water surface elevation if they form from mass movement events on flood-destabilized slopes (Cenderelli and Wohl, 2001).

Additionally, ice sheet modeling can bolster jökulhlaup reconstruction by simulating possible ice margin positions, meltwater lake volumes, and dam locations, especially when calibrated against observed jökulhlaup and glacial geomorphologic field evidence. However, though various modeled scenarios may be helpful, they cannot precisely define past ice margins (Flowers et al., 2007). While none of these methods can reconstruct all aspects of a jökulhlaup

event, integrating geomorphologic, geochronological, hydraulic, and modeling techniques provides additional interpretive confidence by cross-checking results.

5. CONCLUSION

In the century since J Harlen Bretz's pioneering study on glacial outburst floods in the Channeled Scabland, researchers have identified myriad jökulhlaup landscapes across the globe. Despite technological advances in flood mapping, dating, and modeling techniques, interpreting jökulhlaup geomorphologic evidence continues to ground these methods and present a significant challenge. A complex array of dynamic, interdependent factors controls flood landscape impact, and evidence is often fragmentary and obfuscated by millennia of subsequent natural and anthropogenic modification. Scientists employ numerous strategies to resolve these interpretive challenges, but research gaps remain. We have synthesized existing case studies to present an enhanced conceptual model of jökulhlaup landform assemblages for reconstructing flood geomorphologic evidence at a global, landscape-wide scale that goes beyond the existing classification based on spatial (micro-, meso- or macro-) scale or erosional versus depositional environment. Taken together, these interpretive challenges, solutions, and conceptual model provide an improved geomorphological methodology for reconstructing flood events as robustly as possible.

Understanding jökulhlaup geomorphologic impacts has important implications for reconstructing paleofloods and predicting impacts of future events. Defining jökulhlaup landform assemblages and improving interpretative approaches helps to identify and reconstruct past flood landscapes and advances knowledge of the role of extreme events in landscape

evolution (Baynes et al., 2015b). This is increasingly important as glacial outburst floods may become more frequent due to climate-driven meltwater lake expansion and flood triggering events due to permafrost thaw and slope destabilization (Anaconda et al., 2015; Carrivick and Tweed, 2013; Evans and Clague, 1994; Haeberli et al., 2017; Harrison et al., 2018; Shugar et al., 2020; Tweed and Carrivick, 2015). Determining flood geomorphologic impact based on known topographic and hydraulic conditions—in other words, predicting which landforms will likely form in which parts of a drainage route—will inform infrastructure engineering, construction zoning, and evacuation plans, mitigating societal risk from future floods (Anaconda et al., 2015; Carrivick and Tweed, 2016). Accurate interpretation of jökulhlaup geomorphologic evidence anchors our understanding of both past events and future impacts, presenting a multifaceted challenge that demands an equally complex approach.

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TABLE 1 (*supplementary information*). Selected case studies focusing on jökulhlaup geomorphologic impacts.

	Location	Flood event/source	Selected references
EUROPE	Germany	Ice-dammed marginal lake drainage, Scandinavian Ice Sheet	Lang et al. (2019); Meinsen et al. (2011); Winsemann et al. (2016)
	Sweden	Ice-dammed marginal lake drainage, Scandinavian Ice Sheet	Regnéll et al. (2019)
	Norway	Ice-dammed marginal lake drainage, Nedre Glomsjø lake, Scandinavian Ice Sheet	Høgaas and Longva (2016)
	Iceland	Subglacial volcanic eruptions beneath Vatnajökull ice cap, drainage along Jökulsá á Fjöllum River	Alho et al. (2005); Baynes et al. (2015a, 2015b); Carrivick et al. (2004a, 2004b, 2013b); Howard et al. (2012); Marren et al. (2009); Rushmer (2006); Tómasson (1973); Van der Bilt et al. (2021); Waitt (2002)
	Iceland	Subglacial volcanic eruptions beneath Mýrdalsjökull ice cap	Duller et al. (2008, 2014); Roberts et al. (2003); Russell et al. (2010); Smith and Dugmore (2006); Tómasson (1996)
	Iceland	Subglacial volcanic eruptions beneath Vatnajökull ice cap	Magilligan et al. (2002); Russell and Knudsen (1999, 2002); Russell et al. (2005, 2006)
	Iceland	Subglacial volcanic eruptions beneath Eyjafjallajökull ice cap	Dunning et al. (2013); Harrison et al. (2019)

	Iceland	Rock fall onto Steinsholtsjökull glacier and proglacial lake, Eyjafjallajökull ice cap	Kjartansson (1967)
	Iceland	Ice-dammed lakes and subglacial volcanic eruptions at Vatnajökull ice cap, drainage along Þjórsá-Kaldakvísl-Tungnaá, Skjálfandi-Fnjóskadalur, and Jökulsá á Brú Rivers	Van Vliet-Lanoë et al. (2020)
	Iceland	Ice-dammed lake drainage along Hvítá River	Tómasson (1993, 2002)
	Greenland	Ice-dammed marginal lake drainage, Russell Glacier	Carrivick et al. (2013a); Russell (2009); Russell et al. (2011)
	Greenland	Ice-dammed lake drainage, Zackenberg River	Tomczyk and Ewertowski (2020); Tomczyk et al. (2020)
	United Kingdom	Marginal lake drainage, Palaeolake Milfield, British-Irish Ice Sheet	Thorndycraft et al. (2016)
	Switzerland	Marginal lake drainage and/or englacial meltwater release, Alps	Haeberli (1983)
	Mediterranean Basin	Atlantic Ocean water flowing into Mediterranean Basin through Strait of Gibraltar (<i>not glacial source</i>)	Garcia-Castellanos et al. (2020)
	English Channel	Proglacial lake drainage through English Channel, Fennoscandian and British Ice Sheets	Gupta et al. (2007)
SOUTH AMERICA	Chile; Argentina	Moraine/ice-dammed lake drainage, Patagonia	Anaconda et al. (2015); Dussaillant et al. (2010); Harrison et al. (2006); Hauser (1993); Jacquet et al. (2017); Wilson et al. (2019)
	Chile	Ice-dammed marginal lake drainage, Río Baker, Patagonia	Benito and Thorndycraft (2020); Benito et al. (2021)
	Peru	Moraine-dammed lake drainage, Cordillera Blanca	Klimeš et al. (2014); Lliboutry et al. (1977); Vilímek et al. (2015)
	Bolivia	Moraine-dammed lake drainage, Andes	Hoffmann and Weggenmann (2013); Kougkoulos et al. (2018)
NORTH AMERICA	Washington State, U.S.A.	Ice-dammed marginal lake drainage, Lake Missoula, Laurentide Ice Sheet	Baker (1973, 1978a, 2009a); Baker and Bunker (1985); Benito and O'Connor (2003); Bretz (1923); Larsen and Lamb (2016); O'Connor et al. (2020)
	Washington State, U.S.A.	Subglacial/englacial meltwater release, Mount Rainier	Driedger and Fountain (1989); Walder and Driedger (1994)
	Idaho, U.S.A.	Ice-dammed lake drainage, Big Lost River, Box Canyon	Lamb et al. (2008); Rathburn (1993)
	Idaho, U.S.A.	Lava-dammed river diversion, Malad Gorge (<i>not glacial source</i>)	Lamb et al. (2014)
	Northwestern U.S.A.	Pluvial lake basin overflow, Lake Bonneville (<i>not glacial source</i>)	O'Connor (1993)
	Alaska, U.S.A.	Ice-dammed marginal lake drainage, Glacial Lake Atna, Matanuska Valley	Reger et al. (2011); Wiedmer et al. (2010)

	Northern U.S.A.-Southern Canada	Ice-marginal lake overspill, Lake Agassiz, Laurentide Ice Sheet	Fisher et al. (2020); Kehew and Lord (1986); Kehew et al. (2009); Teller (2013)
	British Columbia, Canada	Moraine-dammed lake drainage	Clague and Evans (2000); Evans and Clague (1994); Kershaw et al. (2005)
	British Columbia, Canada	Ice-dammed marginal lake drainage, Fraser River valley	Clague et al. (2021)
	Yukon, Canada	Ice-dammed lake drainage, Glacial Lake Alsek	Clague and Rampton (1982); Clarke (1989)
	Nunavut, Canada	Supraglacial lake drainage, Axel Heiberg Island	Maag (1969)
	Alberta, Canada	Ice-dammed lake drainage, Lake Algar	Norris et al. (2019)
ASIA	Siberia, Russia	Ice-dammed lake drainage, Kuray-Chuya Lakes, Altai Mountains	Agatova et al. (2020); Baker et al. (1993); Carling et al. (2002, 2009c); Herget (2005); Herget et al. (2020); Rudoy (2002)
	Siberia, Russia	Ice-dammed lake drainage, Glacial Lake Vitim	Komatsu et al. (2016); Margold et al. (2011, 2018)
	Siberia, Russia	Ice-dammed lake drainage, Barents-Kara Ice Sheet	Komatsu et al. (2016); Mangerud et al. (2004)
	Nepal	Moraine-dammed lake drainage, Himalayas	Byers et al. (2019); Cenderelli and Wohl (2001, 2003); Cook et al. (2018); Richardson and Reynolds (2000); Vuichard and Zimmermann (1987)
	Nepal	Englacial meltwater release, Khumbu region, Himalayas	Rounce et al. (2017)
	Tibet	Ice-dammed lake drainage, Tsangpo River Gorge, Himalayas	Lang et al. (2013); Montgomery et al. (2004)
	Pakistan	Glacier- and/or landslide-dammed lake drainage, Karakoram Himalayas	Hewitt (1982)
OCEANIA	New Zealand	Subglacial/englacial meltwater release, Franz Josef Glacier	Carrivick and Rushmer (2009); Davies et al. (2003); Goodsell et al. (2005)
ANTARCTICA	Antarctica	Subglacial lake drainage, Dry Valleys	Lewis et al. (2006); Sugden et al. (1991)
MARS	Mars	Subsurface aquifer release and/or surface lake basin overspill (<i>not glacial source</i>)	Baker et al. (2015); Burr et al. (2009); Coleman (2013); Goudge and Fassett (2018); Warner et al. (2010, 2013)

TABLE 2. (*supplementary information*) Jökulhlaup geomorphologic feature descriptions, equifinalities, interpretive challenges, and selected case studies.

Landform (erosional)	Description	Equifinalities	Additional geomorphologic evidence to support jökulhlaup formation	Interpretive challenges for jökulhlaup landform	Selected case studies
Gorges/ canyons	Canyons formed by incision, knickpoint retreat, and/or columnar basalt plucking	<ul style="list-style-type: none"> • Fluvial • Tectonic (fault) • Glacial (eroded valley) 	<ul style="list-style-type: none"> • Box-shaped (vs. V-shaped = fluvial or U-shaped = glacial) • Presence of underfit stream (or no stream) • Too large to have been formed by fluvial incision • Oriented parallel to hypothesized flow direction 	<ul style="list-style-type: none"> • Canyon may have been incised or aggraded during or post-flood, so using modern-day dimensions and morphology could overestimate or underestimate flow magnitude, respectively (Carrivick, 2007; Carrivick et al., 2004a; Kershaw et al., 2005; Larsen and Lamb, 2016) • Floodwaters may not have filled canyon to brim, so dimensions could overestimate flow magnitude (Carrivick, 2007; Larsen and Lamb, 2016) • Canyon may contain different lithologies and thus different erosional mechanisms and rates, so same flood event could produce different morphologies in the same canyon (Carling et al., 2009b; Larsen and Lamb, 2016; Richardson and Carling, 2005; Whipple et al., 2000) • River discharge may have been larger than present-day flow, so modern underfit stream does not necessarily indicate extreme flood erosion (Baynes et al., 2015a; Garcia-Castellanos and O'Connor, 2018) 	<ul style="list-style-type: none"> • <i>Iceland</i>: Alho et al. (2005); Baynes et al. (2015a, 2015b); Carrivick et al. (2004a); Tómasson (1993) • <i>Lake Bonneville, U.S.A.</i>: O'Connor (1993) • <i>Altai Mountains, Siberia</i>: Herget (2005); Rudoy (2002) • <i>Big Lost River, Idaho, U.S.A.</i>: Lamb and Dietrich (2009); Lamb et al., (2008, 2014) • <i>British Columbia, Canada</i>: Kershaw et al. (2005) • <i>Channeled Scabland, Washington State, U.S.A.</i>: Baker (1978a); Larsen and Lamb (2016) • <i>Tsangpo River Gorge, Tibet</i>: Montgomery et al. (2004) • <i>Patagonia, Argentina</i>: Benito and Thorndycraft (2020); Benito et la. (2021) • <i>British-Irish Ice Sheet, U.K.</i>: Thorndycraft et al. (2016)
Cataracts	Dry waterfalls or bedrock steps/headcuts carved by knickpoint retreat and/or	<ul style="list-style-type: none"> • Fluvial • Glacial (plucking) 	<ul style="list-style-type: none"> • Amphitheater-shaped • Presence of underfit stream (or no stream) • Too large to have been formed by fluvial incision 	<ul style="list-style-type: none"> • River discharge may have been larger than present-day, so modern underfit stream may not indicate extreme flood erosion (Baynes et al., 2015a; Garcia-Castellanos and O'Connor, 2018) 	<ul style="list-style-type: none"> • <i>Iceland</i>: Baynes et al. (2015a); Carrivick et al. (2004a); Russell et al. (2005)

	columnar basalt plucking		<ul style="list-style-type: none"> In active volcanic rifting zones, eroded along lava flow layers (termed “lava step”) (Carrivick et al., 2004a) 		<ul style="list-style-type: none"> <i>Big Lost River, Idaho, U.S.A.:</i> Rathburn (1993); Lamb et al. (2008, 2014) <i>Channeled Scabland, Washington State, U.S.A.:</i> Baker (1978a, 2009a)
Spillways	Passes, cols, or saddles between flood channels, formed when water overtops one channel and flows into another	<ul style="list-style-type: none"> Glacial (eroded saddle) Fluvial 	<ul style="list-style-type: none"> Flood-scoured or abraded bedrock on spillway floor Adjacent valleys contain flood evidence May end in a cataract leading into a neighboring valley 	<ul style="list-style-type: none"> Spillway was not necessarily brim-full during flood event due to during- or post-flood incision and floor lowering (overestimates flow magnitude) (Kehew et al., 2009) 	<ul style="list-style-type: none"> <i>Iceland:</i> Carrivick et al. (2004a) <i>Glacial Lake Agassiz, Canada-U.S.A.:</i> Fisher (2020); Kehew and Lord (1986); Kehew et al. (2009) <i>Channeled Scabland, Washington State, U.S.A.:</i> Baker (1978a, 2009a) <i>Altai Mountains, Siberia:</i> Herget (2005); Rudoy (2002) <i>Patagonia, Argentina:</i> Benito and Thorndycraft (2020); Dussailant et al. (2010) <i>Lake Algar, Alberta, Canada:</i> Norris et al. (2019) <i>Glacial Lake Vitim, Siberia:</i> Komatsu et al. (2016); Margold et al. (2011, 2018)
Anastomosing bedrock channels	Eroded bedrock channels that form an anastomosing pattern	<ul style="list-style-type: none"> Fluvial 	<ul style="list-style-type: none"> Typically dry/abandoned Presence of underfit stream (or no stream) Individual channels often contain cataracts, plunge pools, scoured bedrock, and/or gravel- to boulder-sized infill deposits Channels are often separated by streamlined linear residual forms 		<ul style="list-style-type: none"> <i>Iceland:</i> Carrivick et al. (2004a) <i>Channeled Scabland, Washington State, U.S.A.:</i> Baker (1973, 1978a, 2009a) <i>Glacial Lake Agassiz, Canada-U.S.A.:</i> Kehew and Lord (1986)

Strath terraces	Bedrock platforms on canyon sides that mark former flood or fluvial surfaces and are abandoned when canyon is further incised	<ul style="list-style-type: none"> • Fluvial 	<ul style="list-style-type: none"> • Flood-scoured bedrock on terrace surfaces • Terraces are often paired (occur at same elevation on each side of canyon) 	<ul style="list-style-type: none"> • Individual terrace levels do not necessarily correspond to unique flood events 	<ul style="list-style-type: none"> • <i>Iceland</i>: Baynes et al. (2015a, 2015b); Tómasson (1993) • <i>Patagonia, Argentina</i>: Benito and Thorndycraft (2020)
Streamlined residual hills	Hills eroded into a hydraulically efficient, lemniscate (teardrop) shape as floodwaters trim material from the sides and deposit it downstream in the lee of the hill to create a “tail”	<ul style="list-style-type: none"> • Glacial (drumlins or streamlined whaleback features) 	<ul style="list-style-type: none"> • Oriented parallel to flow direction; “tail” is on downstream end • Usually composed of easily erodible material, such as loess or hyaloclastite 		<ul style="list-style-type: none"> • <i>Iceland</i>: Alho et al. (2005); Carrivick et al. (2004a) • <i>Channeled Scabland, Washington State, U.S.A.</i>: Baker (1978a, 2009a); Bretz (1923); Komar (1984) • <i>Big Lost River, Idaho, U.S.A.</i>: Rathburn (1993) • <i>Glacial Lake Agassiz, Canada-U.S.A.</i>: Kehew and Lord (1986); Kehew et al. (2009) • <i>Scandinavian Ice Sheet, Germany</i>: Lang et al. (2019); Meinsen et al. (2011) • <i>Glacial Lake Atna, Alaska, U.S.A.</i>: Wiedmer et al. (2010)
Plunge pools	Bedrock depressions at the base of cataracts carved by force of cascading water	<ul style="list-style-type: none"> • Fluvial 	<ul style="list-style-type: none"> • Presence of underfit stream (or no stream) • Often contain a push bar immediately downstream • Too large to have been formed by fluvial erosion 		<ul style="list-style-type: none"> • <i>Iceland</i>: Baynes et al. (2015a) • <i>Big Lost River, Idaho, U.S.A.</i>: Rathburn (1993) • <i>Scandinavian Ice Sheet, Germany</i>: Meinsen et al. (2011)
Scoured bedrock	- <i>Grooves</i> : troughs in bedrock that are elongate parallel to flow direction	<ul style="list-style-type: none"> • Fluvial • Glacial (abrasion or subglacial) 	<ul style="list-style-type: none"> • Orientation of grooves and flutes corresponds to flow direction • Feature scale is too large to have been formed by fluvial erosion 	<ul style="list-style-type: none"> • Type of erosional mechanism (i.e. plucking vs. scouring) is controlled by lithology, so same flow magnitude may form scour marks with different scales and morphologies on different rock surfaces (Carrivick et al., 2004a) 	<ul style="list-style-type: none"> • <i>Iceland</i>: Alho et al. (2005); Baynes et al. (2015a, 2015b); Carrivick et al. (2004a); Russell et al. (2005)

	<p>-<i>Flutes</i>: scalloped depressions in bedrock that are open in downstream direction</p> <p>-<i>Potholes</i>: roughly circular depressions in bedrock</p>	meltwater erosion)			<ul style="list-style-type: none"> • <i>Channeled Scabland, Washington State, U.S.A.</i>: Baker (1973, 1978a, 2009a) • <i>Big Lost River, Idaho, U.S.A.</i>: Rathburn (1993) • <i>Scandinavian Ice Sheet, Germany</i>: Lang et al. (2019); Winsemann et al. (2016)
Trimlines	Lines on hillsides or canyon walls that mark the upper limits of floodwater scouring	<ul style="list-style-type: none"> • Fluvial • Glacial • Mass wasting (rockfall scars) • Paleolake shorelines 	<ul style="list-style-type: none"> • Can be traced continuously at same elevation (or floodwater depth) throughout canyon or across landscape • Trimline elevation is too high to have formed from fluvial or seasonal floods 	<ul style="list-style-type: none"> • May overestimate flow depth if trimlines formed by mass wasting on canyon walls triggered by flood destabilization (Cenderelli and Wohl, 2001) • Trimline elevation may only reflect largest jökulhlaup since larger events may erase trimlines from smaller, previous floods (Westoby et al., 2014) 	<ul style="list-style-type: none"> • <i>Himalayas, Nepal</i>: Cenderelli and Wohl (2001) • <i>Iceland</i>: Carrivick et al. (2013b); Howard et al. (2012) • <i>New Zealand</i>: Davies et al. (2003) • <i>Greenland</i>: Carrivick et al. (2013a); Russell et al. (2011)
Obstacle marks	Crescent-shaped scour marks that wrap around the upstream sides of flow obstacles such as hills, boulders, and ice blocks	<ul style="list-style-type: none"> • Fluvial • Aeolian (erosional blowouts) 	<ul style="list-style-type: none"> • Scour marks are on upstream side of paleoflow direction, with deposited material in downstream “shadow” 		<ul style="list-style-type: none"> • <i>Greenland</i>: Russell (1993) • <i>Iceland</i>: Carrivick et al. (2004a); Fay (2002a, 2002b); Maizels (1997); Marren and Schuh (2009); Russell et al. (2005, 2006, 2010) • <i>Altai Mountains, Siberia</i>: Herget (2005); Herget et al. (2013) • <i>Scandinavian Ice Sheet, Norway</i>: Høgaas and Longva (2016)
Erosional forms in soft sediments/ channel incision or widening in	Channels, erosional megaripples, and/or remnant bedforms incised into sandur, outwash fans, or	<ul style="list-style-type: none"> • Fluvial 	<ul style="list-style-type: none"> • Too large to have formed by fluvial erosion • Often terraced (abandoned surfaces on channel sides mark formerly active surfaces) 		<ul style="list-style-type: none"> • <i>Iceland</i>: Carrivick et al. (2004a); Harrison et al. (2019); Magilligan et al. (2002); Marren et al. (2009); Russell and Knudsen (1999)

unconsolidated material	talus slopes; channel deepening and/or widening in unconsolidated material				<ul style="list-style-type: none"> • <i>British Columbia, Canada:</i> Clague and Evans (2000); Kershaw et al. (2005) • <i>Scandinavian Ice Sheet, Norway:</i> Høgaas and Longva (2016) • <i>Alps, Switzerland</i> Haeberli (1983) • <i>Karakoram Himalayas, Pakistan:</i> Hewitt (1982) • <i>Greenland:</i> Russell (2009); Tomczyk et al. (2020) • <i>Andes, Bolivia:</i> Hoffmann and Weggenmann (2013); Kougkoulos et al. (2018) • <i>Cordillera Blanca, Peru:</i> Klimeš et al. (2014); Vilímek et al. (2015) • <i>Patagonia, Argentina:</i> Harrison et al. (2006); Wilson et al. (2019) • <i>Mount Rainier, Washington State, U.S.A.:</i> Walder and Driedger (1994) • <i>Himalayas, Nepal:</i> Byers et al. (2019); Cenderelli and Wohl (2001, 2003); Cook et al. (2018); Vuichard and Zimmermann (1987)
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Landform/ sediment sequence (depositional)	Description	Equifinalities	Additional geomorphologic evidence to support jökulhlaup formation	Interpretive challenges for jökulhlaup landform/sediment sequence	Selected case studies
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Boulder erratics	Boulders that stand in isolation (not part of a boulder cluster, bar, berm, or terrace)	<ul style="list-style-type: none"> • Glacial • Mass wasting deposits • Fluvial • Erosional remnants from moraine, till, and/or mass wasting deposits • In-situ exhumed bedrock slabs (eroded/ weathered) 	<ul style="list-style-type: none"> • Too large for fluvial or seasonal flood transport • Well-rounded • No hillslopes, mass wasting sources, or moraines nearby • Allochthonous lithology • May contain obstacle mark on upstream end of flow direction 	<ul style="list-style-type: none"> • Deposited on waning stage of hydrograph (dimensions underestimate flow magnitude) (Stokes et al., 2012) • Ice-rafted/embedded in glacier ice during flood transport (dimensions over- or underestimate flow magnitude) • Large enough clasts are not available along drainage route and/or bedrock jointing patterns preclude larger clast generation (dimensions underestimate flow magnitude) (Carrivick, 2007; Dugmore et al., 2013; Kershaw et al., 2005; Stokes et al., 2012) • Boulders are transported in a “traction carpet” and are not fully mobilized, move only a short distance, or occur in situ and are not moved by flood (dimensions overestimate flow magnitude) (Kershaw et al., 2005) • Boulders are “buoyed” by high sediment concentrations (dimensions overestimate flow magnitude) (Carrivick and Rushmer, 2009; Westoby et al., 2014) • Post-flood weathering (i.e. fluvial/flood reworking; freeze-thaw fracturing; ventifaction) modifies boulder size and morphology (dimensions underestimate flow magnitude) • Boulder is partially subsumed, leading to minimum dimension measurements (underestimates flow magnitude) (Baynes et al., 2015a; Stokes et al., 2012) • If ice-rafted, boulder may be protected from rounding/erosion during transport (Rathburn, 1993) 	<ul style="list-style-type: none"> • <i>Iceland</i>: Carrivick (2007); Carrivick et al. (2013b); Howard et al. (2012); Maizels (1997); Roberts et al. (2003); Russell et al. (2010) • <i>British Columbia, Canada</i>: Kershaw et al. (2005) • <i>Big Lost River, Idaho, U.S.A.</i>: Rathburn (1993) • <i>Channeled Scabland, Washington State, U.S.A.</i>: Baker (1973)
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				<ul style="list-style-type: none"> • Boulder could be transported by floodwaters only a short distance, retaining angular shape (Rathburn, 1993) • Lithology will not accurately trace provenance if regional bedrock has homogenous composition; and boulder with allochthonous lithology may be deposited by non-flood processes (i.e. glacier) • Boulder location may indicate minimum flood depth since typically transported as bed load (Rathburn, 1993) • Boulders could have broken into smaller pieces during flood transport (underestimates flow magnitude) (Stokes et al., 2012) 	
Bars	Deposits classified by particle composition and size (i.e. boulders, cobbles, gravel, sand) formed in a variety of flow condition settings and orientations (longitudinal bars; expansion bars; pendant bars; eddy bars)	<ul style="list-style-type: none"> • Fluvial • Mass movement deposits • Glacial moraines • Erosional remnants (moraines, till, or mass movement deposits) 	<ul style="list-style-type: none"> • Dimensions are too large to have formed by fluvial activity • Bar orientation matches flow direction • Clast size is too large to have been transported by fluvial activity • Well-sorted • Clasts are imbricated • Jökulhlaup stratigraphic sequences as described by Maizels (1997); Marren (2002, 2005); and Marren and Schuh (2009) 	<ul style="list-style-type: none"> • Flood may be sediment-starved (i.e. material removed by previous flood event or stage), so deposit thickness, clast size, and/or spatial extent may under-represent flood magnitude • Bar elevation may over- or underestimate flood water surface elevation (i.e. boulders protrude above water surface when deposited; gravel is deposited as bed load) (Cenderelli and Wohl, 2001) • Sorting may be due to post-flood erosional processes (i.e. winnowing of smaller clasts from moraine or mass wasting deposits) • Material is often reworked or modified on flood waning stage or during subsequent pulses or events 	<ul style="list-style-type: none"> • <i>Iceland</i>: Alho et al. (2005); Carrivick et al. (2004a); Maizels (1997); Marren (2005, 2016); Russell et al. (2005) • <i>Channeled Scabland, Washington State, U.S.A.</i>: Baker (1973, 1978a, 2009a); Benito and O'Connor (2003) • <i>Lake Bonneville, U.S.A.</i>: O'Connor (1993) • <i>Himalayas, Nepal</i>: Cenderelli and Wohl (2001, 2003) • <i>Glacial Lake Agassiz, Canada-U.S.A.</i>: Kehew et al. (2009) • <i>Altai Mountains, Siberia</i>: Carling (2013); Carling et al. (2009c); Herget et al. (2005) • <i>British Columbia, Canada</i>: Clague et al.

					<p>(2021); Kershaw et al. (2005)</p> <ul style="list-style-type: none"> • <i>Patagonia, Argentina</i>: Benito and Thorndycraft (2020); Benito et al. (2021) • <i>Scandinavian Ice Sheet, Norway, Sweden, and Germany</i>: Høgaas and Longva (2016); Lang et al. (2019); Regnéll et al. (2019); Winsemann et al. (2016) • <i>Lake Algar, Alberta, Canada</i>: Norris et al. (2019) • <i>Greenland</i>: Russell (2009); Tomczyk et al. (2020) • <i>British-Irish Ice Sheet, U.K.</i>: Thorndycraft et al. (2016) • <i>Glacial Lake Vitim, Siberia</i>: Margold et al. (2018)
Ice blocks and kettle holes	Ice blocks transported by floodwaters during sub-, en-, or supraglacial drainage; often buried by subsequent sedimentation, leaving a depression called a kettle hole following melt. Often results in hummocky topography.	<ul style="list-style-type: none"> • Glacial (kettle/kame topography) • Melt-out of buried stagnant glacial ice 	<ul style="list-style-type: none"> • Ice block or kettle hole size decreases with increasing distance from glacier terminus; has “radial” spatial pattern where flow expands and deposits ice blocks • Ice blocks occur in trains, with larger blocks upstream and smaller blocks deposited in their lee • Glacier-deposited blocks are likely in a random spatial pattern 	<ul style="list-style-type: none"> • Ice blocks do not necessarily become smaller downstream (smaller ones may be grounded in lower-velocity shadow of larger ones) (Russell et al., 2005) 	<ul style="list-style-type: none"> • <i>Iceland</i>: Evans and Twigg (2002); Fay (2002b); Harrison et al. (2019); Maizels (1997); Marren and Schuh (2009); Russell and Knudsen (1999); Russell et al. (2005, 2006, 2010) • <i>Greenland</i>: Russell (1993) • <i>Scandinavian Ice Sheet, Norway</i>: Høgaas and Longva (2016)
Megaripple dunes	Giant current ripples or dunes	<ul style="list-style-type: none"> • Crevasse fill ridges 	<ul style="list-style-type: none"> • Regular spacing 		<ul style="list-style-type: none"> • <i>Channeled Scabland, Washington State</i>,

	formed by floodwaters; usually consist of sand, gravel, and pebble-sized clasts.	<ul style="list-style-type: none"> • Fluvial • Moraines (erosional remnants) • Aeolian dunes (for sand ripples) 	<ul style="list-style-type: none"> • Well-sorted/stratified layers • Orientation perpendicular to flow direction 		<p><i>U.S.A.:</i> Baker (1973, 1978a, 2009a)</p> <ul style="list-style-type: none"> • <i>Altai Mountains, Siberia:</i> Herget (2005); Rudoy (2002) • <i>Iceland:</i> Maizels (1997); Marren (2005) • <i>Glacial Lake Atna, Alaska, U.S.A.:</i> Wiedmer et al. (2010) • <i>Glacial Lake Alsek, Yukon, Canada:</i> Clague and Rampton (1982); Clarke (1989) • <i>British Columbia, Canada:</i> Clague et al. (2021)
Slackwater deposits/ rhythmites	Flood deposits (typically sand/silt/clay) in zones of low flow energy (i.e. tributary valleys; backponded areas upstream of topographic constrictions)	<ul style="list-style-type: none"> • Fluvial • Lacustrine 	<ul style="list-style-type: none"> • In tributary valleys, clast size and deposit thickness generally decrease up-valley as larger particles settle out first as flow velocity drops 	<ul style="list-style-type: none"> • Finer-grained material has a lower preservation potential • Proglacial environments are often poor in fine-grained sediments (clays and silts), so may not exist in some jökulhlaup environments • One layer or rhythmite does not necessarily correspond to one flood event (may be multiple pulses during a single flood) 	<ul style="list-style-type: none"> • <i>Iceland:</i> Carrivick et al. (2004a, 2004b); Maizels (1997); Russell and Knudsen (1999); Russell et al. (2005); Van der Bilt et al. (2021); Waitt (2002) • <i>Altai Mountains, Siberia:</i> Carling (2013); Rudoy (2002) • <i>Lake Bonneville, U.S.A.:</i> O'Connor (1993) • <i>Channeled Scabland, Washington State, U.S.A.:</i> Baker (1973); Baker and Bunker (1985); O'Connor et al. (2020) • <i>Patagonia, Argentina:</i> Benito and Thorndycraft (2020) • <i>Tsangpo River Gorge, Tibet:</i> Lang et al. (2013)
Rip-up clasts	Pieces of frozen, ice-embedded sediment ripped	<ul style="list-style-type: none"> • Fluvial (subglacial or proglacial) 	<ul style="list-style-type: none"> • Formed during subglacial or englacial jökulhlaup drainage 		<ul style="list-style-type: none"> • <i>Iceland:</i> Maizels (1997); Marren (2005); Marren and Schuh (2009);

	off the glacier bed or tunnel walls during subglacial or englacial drainage. Ice eventually melts, leaving behind a cohesive mass of poorly sorted, coarse-grained sediment.	<ul style="list-style-type: none"> meltwater drainage) Armoured mudballs 			Russell and Knudsen (1999); Russell et al. (2005, 2006)
Channel/ cataract infill or aggradation	Deposits on a channel or cataract floor; typically cobble- or boulder-sized clasts	<ul style="list-style-type: none"> Fluvial Mass movement deposits from channel sides 	<ul style="list-style-type: none"> Clast size is too large to have been deposited by fluvial activity Clasts are well-sorted, imbricated, and rounded (evidence against mass movement deposition) 	<ul style="list-style-type: none"> Post-flood sediment reworking by fluvial processes or subsequent floods in the channel Mass wasting deposits may be well-sorted due to winnowing/removal of smaller clasts by other processes (equifinality) 	<ul style="list-style-type: none"> <i>Iceland</i>: Carrivick et al. (2004a) <i>British Columbia, Canada</i>: Clague and Evans (2000); Kershaw et al. (2005) <i>Scandinavian Ice Sheet, Germany</i>: Meinsen et al. (2011) <i>Mount Rainier, Washington State, U.S.A.</i>: Walder and Driedger (1994) <i>Himalayas, Nepal</i>: Byers et al. (2019); Cenderelli and Wohl (2001, 2003); Vuichard and Zimmermann (1987) <i>Cordillera Blanca, Peru</i>: Klimeš et al. (2014)
Sand/silt drape	Fine-grained sediment (sand/silt) deposited as suspended load; typically mark high water level on channel sides	<ul style="list-style-type: none"> Aeolian Fluvial 	<ul style="list-style-type: none"> Can be traced at same elevation along channel 	<ul style="list-style-type: none"> Finer-grained sediments have a lower preservation potential 	<ul style="list-style-type: none"> <i>Iceland</i>: Roberts et al. (2003) <i>Himalayas, Nepal</i>: Byers et al. (2019); Cenderelli and Wohl (2001) <i>Greenland</i>: Russell et al. (2011) <i>Cordillera Blanca, Peru</i>: Klimeš et al. (2014) <i>Mount Rainier, Washington State</i>,

					<p><i>U.S.A.:</i> Walder and Driedger (1994)</p> <ul style="list-style-type: none"> • <i>British Columbia, Canada:</i> Clague and Evans (2000)
Sediment fans	Fan-shaped deposits of sediment at points of sudden flow expansion (i.e. valley floors or ends of topographic constrictions)	<ul style="list-style-type: none"> • Fluvial • Aeolian 	<ul style="list-style-type: none"> • Clast size decreases with increasing distance from beginning of fan deposit • Thickness and spatial extent are too large to have been deposited by fluvial processes 		<ul style="list-style-type: none"> • <i>Channeled Scabland, Washington State, U.S.A.:</i> Baker (2009a) • <i>Iceland:</i> Dunning et al. (2013); Harrison et al. (2019); Magilligan et al. (2002); Marren et al. (2009); Russell et al. (2010) • <i>British Columbia, Canada:</i> Clague and Evans (2000); Kershaw et al. (2005) • <i>Scandinavian Ice Sheet, Germany:</i> Winsemann et al. (2016) • <i>Patagonia, Argentina:</i> Harrison et al. (2006); Wilson et al. (2019) • <i>Glacial Lake Agassiz, Canada-U.S.A.:</i> Fisher (2020); Kehew and Lord (1986)
Boulder clusters/bars/berms/terraces	Boulder deposits grouped in cluster, bar, berm, or terrace formations	<ul style="list-style-type: none"> • Glacier moraines (erosional remnants) • Mass wasting deposits • Fluvial 	<ul style="list-style-type: none"> • Well-sorted • Deposit is too thick to have been deposited by fluvial activity • Well-rounded • Clasts decrease in size downstream 		<ul style="list-style-type: none"> • <i>Iceland:</i> Baynes et al. (2015a); Carrivick et al. (2004a); Marren et al. (2009); Russell et al. (2010) • <i>Channeled Scabland, Washington State, U.S.A.:</i> Baker (1973) • <i>Lake Bonneville, U.S.A.:</i> O'Conner (1993) • <i>Scandinavian Ice Sheet, Sweden:</i> Regnéll et al. (2019)

					<ul style="list-style-type: none"> • <i>New Zealand</i>: Carrivick and Rushmer (2009); Davies et al. (2003) • <i>Greenland</i>: Russell (2009) • <i>Cordillera Blanca, Peru</i>: Vilimek et al. (2015) • <i>Patagonia, Argentina</i>: Dussaillant et al. (2010); Harrison et al. (2006) • <i>Glacial Lake Agassiz, Canada-U.S.A.</i>: Fisher (2020) • <i>British Columbia, Canada</i>: Clague et al. (2021)
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