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Landscape reaction, response, and recovery following the catastrophic 1918 Katla jökulhlaup, southern Iceland

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Abstract One of the largest recorded glacier outburst floods (jökulhlaups) occurred in 1918, generated by the last major subglacial eruption of Katla volcano in southern Iceland. Using digitized historical topographic surveys and field observations from the main proglacial outwash plain (Mýrdalssandur), we document the reaction of Mýrdalssandur to the 1918 event and subsequent response and recovery. Our analysis highlights the longevity of elevated topography, over the recovery period, and the complete reorganization of the main perennial meltwater channel system, both of which will affect and condition the flow routing and impact of future jökulhlaups. The jökulhlaup deposited approximately 2 km^3 of sediment onto Mýrdalssandur immediately after the event and extended the coastline by several kilometers. However, 80% of this material by volume has since been removed by surface and subsurface water flow on the main sandur and by marine reworking at the coast. By 2007, the surface elevation at specific locations on the outwash plain and the position of the coastline were similar to those in 1904, indicating near-complete recovery of the landscape. Despite this, the Mýrdalssandur coastline has experienced net advance over the past 1000 years. Using our calculated characteristic landscape response and recovery values following the 1918 event (60 years and 120 years) we deduce that the landscape has been in a dominant state of transience, with regard to forcing frequency and timescale of recovery, over the past 1000 years, which has facilitated long-term landscape growth.

1. Introduction

The Katla volcano lies under the center of the Mýrdalsjökull ice cap and constitutes the most southerly portion of the Katla Volcanic System (Figure 1) [*Larsen*, 2000]. The ice-filled Katla caldera, which is 10–15 km in diameter and 600–700 m deep [*Björnsson et al.*, 2000], is host to the Katla fissure and the Katla central volcano. The central volcano is the second most active volcano in Iceland, being the locus of predominantly basaltic volcanic activity over the past 200,000 years [*Larsen*, 2000]. Katla eruptions are highly explosive and rapidly generate large volumes of meltwater, resulting in the sudden onset of sediment-enriched glacier outburst floods or jökulhlaups [*Thórarinsson*, 1957; *Roberts*, 2005]. Jökulhlaups accompanying Katla eruptions have historically been routed onto the Mýrdalssandur through the Kötlujökull outlet glacier (Figure 1) [*Larsen*, 2000; *Russell et al.*, 2010].

The last major eruption of Katla volcano in 1918 generated a sediment-enriched jökulhlaup that inundated an approximately 400 km^2 area of central Mýrdalssandur, bordered to the west by volcanic bedrock and to the east by the Blautakvísl River and lava flow units [*Jónsson*, 1982; *Maizels*, 1992; *Tómasson*, 1996]. The jökulhlaup had an acceleration rate on the rising limb of the flood hydrograph of 7 m^3 s^{-2}, one of the highest recorded in Iceland [*Roberts*, 2005], mean flow velocity of approximately 6–12 m s^{-1} [*Duller et al.*, 2008], and a maximum discharge of approximately 2.5–4.0 × 10^5 m^3 s^{-1} [*Tómasson*, 1996], making it one of the largest and most powerful floods observed. Katla has experienced a number of major eruptions with an average recurrence interval of 45 ± 24 years spanning 1179 Common Era (C.E.) to 1955 C.E. [*Elíasson et al.*, 2006]. Each eruption was accompanied by a jökulhlaup, the magnitude of which is positively correlated with eruption magnitude [*Jónsson*, 1982; *Tómasson*, 1996; *Elíasson et al.*, 2006; *Russell et al.*, 2010]. Using a combination of eyewitness accounts and historical topographic data, *Tómasson* [1996] completed a comprehensive investigation of the 1918 jökulhlaup and the immediate effect it had on the Mýrdalssandur coastal landscape (hereafter "landscape"). However, the broad-scale landscape response to this event, the pattern and

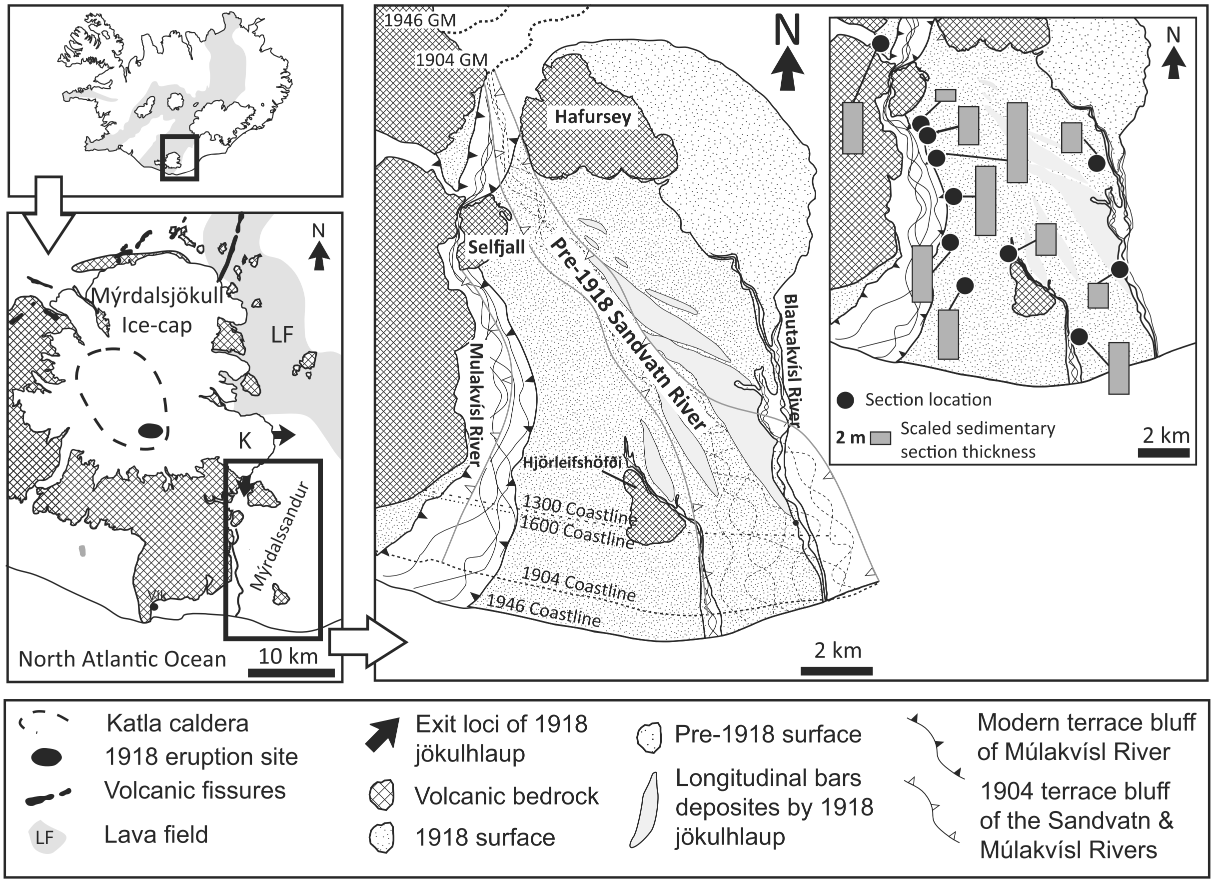

Figure 1. Location map showing the area of data collection on Mýrdalssandur and highlighting past and present geomorphological attributes of the sandur that are referred to in the main text. GM, glacier margin. K, Kötlujökull. Figure based in part on *Larsen* [2000] and *Maizels* [1992]. Coastline positions of 1300 and 1600 are from *Nummedal et al.* [1987].

timescale of sandur landscape recovery over the last century, and the conditioning of the landscape for routing and behavior of future jökulhlaups remain unquantified. Here we describe the reaction (immediate response of the prejökulhlaup landscape) and response (immediate response of the post jökulhlaup landscape) to and subsequent recovery from the 1918 jökulhlaup by highlighting relevant patterns of landscape change from field and historical data sets, with emphasis on timescale involved.

2. Methods

We examined a set of 20 m interval contour topographic maps of Mýrdalssandur for the years of 1904, 1946, 1960, 1975, and 2007, obtained from the digital archives of the National Land Survey of Iceland [*Landmælingar Íslands*, 2011]. This data set was coregistered and the elevations digitized in ArcGIS to create digital terrain models (DTMs). DTMs were used to generate surface difference maps (SDM) of Mýrdalssandur between 1946–1904, 1959–1904, and 2007–1904. Significant geodetic differences were reconciled prior to DTM construction and data analysis. Although localized and transient morphological phenomena exist in the data set, due to inaccuracies in the original topographic data (1904 to 2007) and interpolation between the digitized contours, our primary focus concerns broad-scale surface elevation changes of Mýrdalssandur. Measured thicknesses of the 1918 sedimentary succession change across Mýrdalssandur (2005, 2006, and 2007) are compared against SDMs to confirm amounts of net surface elevation.

3. Results: Landscape Reaction and Response to the 1918 Jökulhlaup

The reaction [sensu *Brunsden and Thornes*, 1979] of the landscape to the jökulhlaup (1904 to 1946) was one of net aggradation, increasing down system from the glacial terminus to the southern Mýrdalssandur coastline

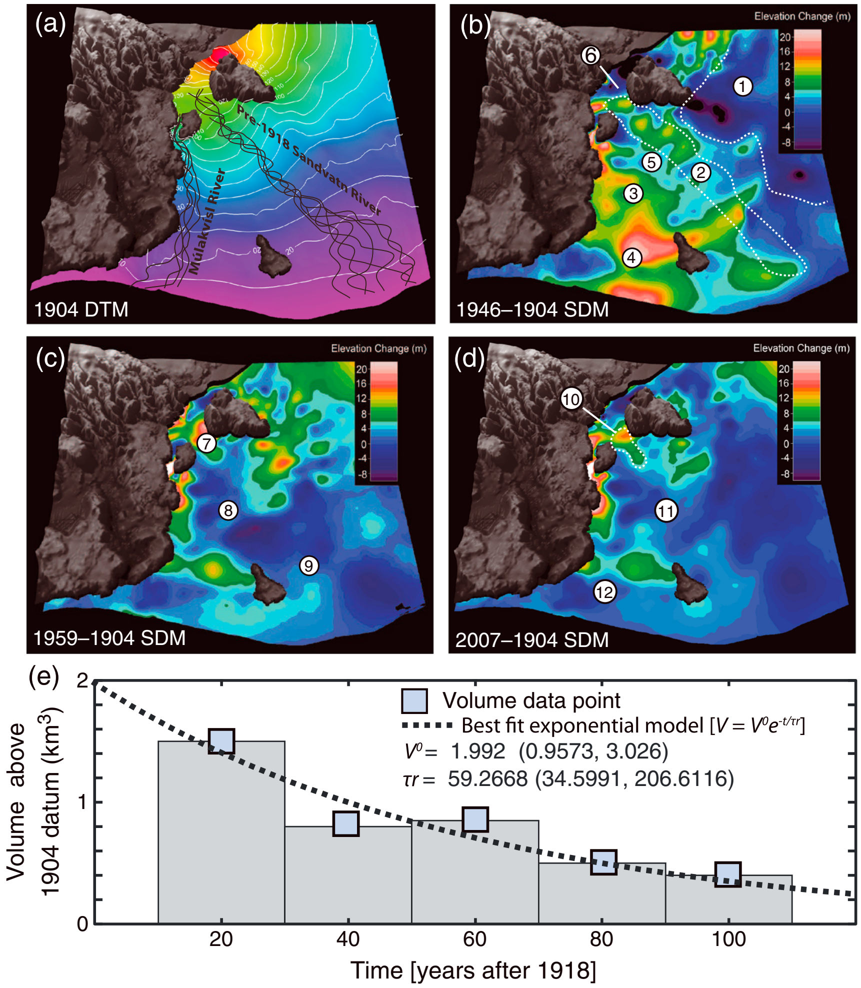

Figure 2. (a) Digital terrain model (DTMs) of Mýrdalssandur in 1904 generated from topographic maps. (b–d) Surface difference maps (SDMs) of Mýrdalssandur between 1946–1904, 1959–1904, and 2007–1904. Features of interest are highlighted by encircled numerals 1–12: (1) Region of minimal surface elevation change; (2) strip of sandur with positive surface elevation change coincident with the position of the pre-1918 Sandvatn River; (3) positive surface elevation change on central Mýrdalssandur; (4) maximum amount of positive surface elevation change at distal regions; (5) negative surface elevation change on central Mýrdalssandur; (6) negative surface elevation change in proximal sandur regions; (7) area of positive surface elevation change; (8) negative surface elevation change over the larger area of central Mýrdalssandur; (9) negative surface elevation change at distal regions where most initial aggradation took place; (10) continued presence of positive topography between Hafursey and Selfjall; (11) continued negative surface elevation change over large parts of central Mýrdalssandur; and (12) negative surface elevation change of coastal swath of Mýrdalssandur. (e) Graphical representation of sediment volume above the 1904 surface datum for a nearly a century following the jökulhlaup. Values of coefficients are shown (with 95% confidence bounds). The estimate of material volume immediately after the event is based on calculations from *Tómasson* [1996].

(Figures 2b and 3b). The similarity between measured thicknesses of complete 1918 jökulhlaup sedimentary successions (Figure 1) and values of net vertical aggradation (1904 to 1946) indicates that landscape modification by the 1918 jökulhlaup was broadly constructional. Surface elevation changes are constrained between the Blautakvísl River in the east and the volcanic bedrock topography in the west (Figure 2b). The most areally extensive region of net sediment aggradation (approximately 15 m) occurred at the southern portion of Mýrdalssandur in a swath of terrain that parallels the coastline (Figure 2b) and within a approximately 2 km wide zone from the western margin of Hafursey to the border of the Blautakvísl River in the south (Figure 2c). Through subtraction of the 1946 and 1904 DTMs we have calculated that that a minimum of 0.8 km^3 of sediment was added to Mýrdalssandur during this time. This is considerably less than the reported approximately 2.0 km^3 of material added immediately after the event in 1918, suggesting

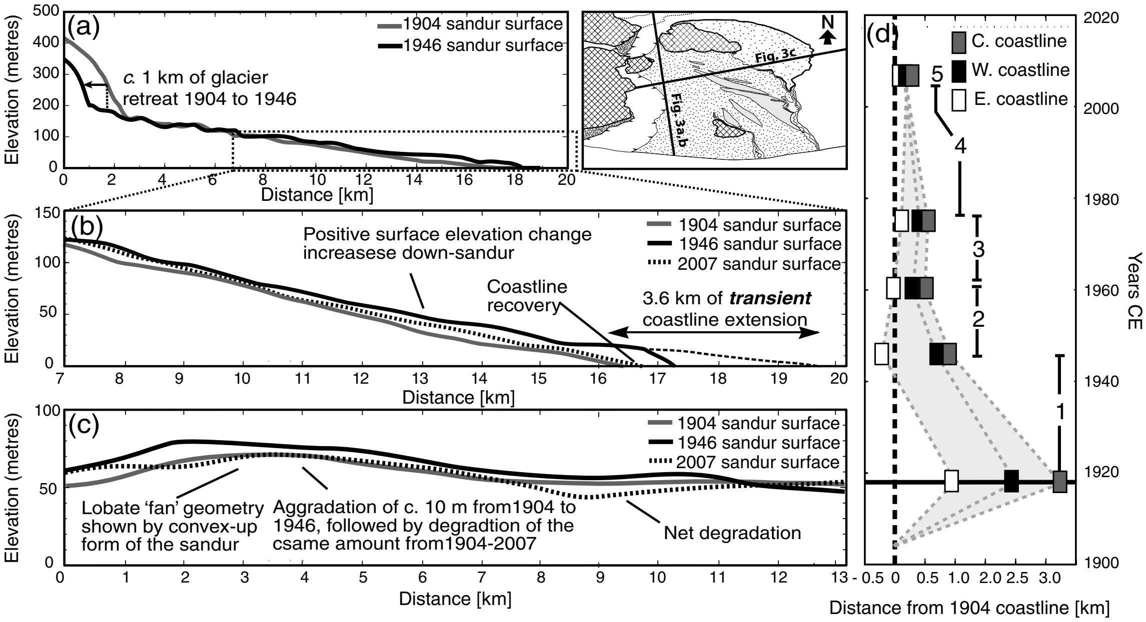

Figure 3. (a, b) Topographic profiles of Mýrdalssandur in 1904, 1946, and 2007, taken from a down-system transect. (c) Topographic profiles in a cross-system transect. (d) Coastline position from 1904 to 2007. (1) Initial coastline retreat post event at 55 Myr^{-1}. (2) Retreat of the western and central coastline at 28 Myr^{-1} and advance of the eastern coastline at 13 Myr^{-1}. (3) Coastline advance at 6 Myr^{-1}. (4) Retreat of western and central coastline at 10 Myr^{-1}, with advance of the eastern coastline at 3 Myr^{-1}. (5) Convergence of data to a position coinciding with the pre-jökulhlaup 1904 coastline position.

significant evacuation of sediment during the years following the jökulhlaup [*Tómasson*, 1996]. From comparison between the 1946 and 2007 topographic data sets we calculate a volume loss of approximately 0.4 to 0.6 km^3 (Figure 2e).

The approximately 2 km wide zone of net aggradation, from the western margin of Hafursey to the border of the Blautakvísl River in the south (Figure 2c), coincides with the position of the main pre-1918, perennial glacial outwash on Mýrdalssandur, the Sandvatn River (Figures 2a and 2b). Remarkably, there are no features apparent on post-1918 topographic maps nor are there features that can be observed in the field that record the former existence of the Sandvatn River, thus demonstrating the effectiveness of the 1918 jökulhlaup to reorganize the morphometry of the proglacial landscape. A proximal stack of 1918 sediments between Selfjall and Hafursey, marking the position of the paleo-Sandvatn River course outlet (Figures 1 and 2a–2d), represents a long-lived geomorphic feature. This is demonstrated both by minimal change of SDMs from 1946 to 2007 and by the preservation of soil and vegetation cover at this location, visible in the field and from satellite images [*Warner and Farmer*, 2010].

Comparison of the historical coastline data shows that the Mýrdalssandur coastline (1904 to 1946) advanced southward by 1 km following substantial sandur aggradation during the 1918 jökulhlaup (Figures 3b and 3c), which is in contrast to eyewitness observations that suggest that the coastline advanced by approximately 3–4 km [*Jónsson*, 1982; *Tómasson*, 1996] during the event. This apparent discrepancy is resolved upon oceanward extrapolation of the 1946 longitudinal profile, using a second-order polynomial fit to the elevation data, which implies that the coastline immediately after the 1918 event was 3.6 km ($R^2 = 0.98$) southward of the 1904 coastline position. The longitudinal profile of the 1946 DTM exhibits a steep gradient of 0.02 within 500 m of the coastline, compared to 0.007 for the main sandur (Figure 4b). This higher gradient represents a coast-parallel knickpoint generated by continued long-shore current and winter storm erosion since 1918. Overall, the central sector of the south Mýrdalssandur coastline retreated by 3 km from 1918 to 1946 at a time-averaged rate of 55 m yr^{-1} and by a farther 1 km from 1946 to 2007 at a time-averaged rate of 10 m yr^{-1} (Figure 3d). Overall, the surface gradient of central Mýrdalssandur decreased in response to the 1918 jökulhlaup from a value of 0.012 in 1904 to 0.009 in 1946 and has since returned to a value of 0.012 (2007 DTM).

Landscape degradation after the 1918 event, as shown by the set of DTMs from 1946 to 2007, occurred in several main regions: the immediate proglacial region, a narrow region of the sandur that parallels and

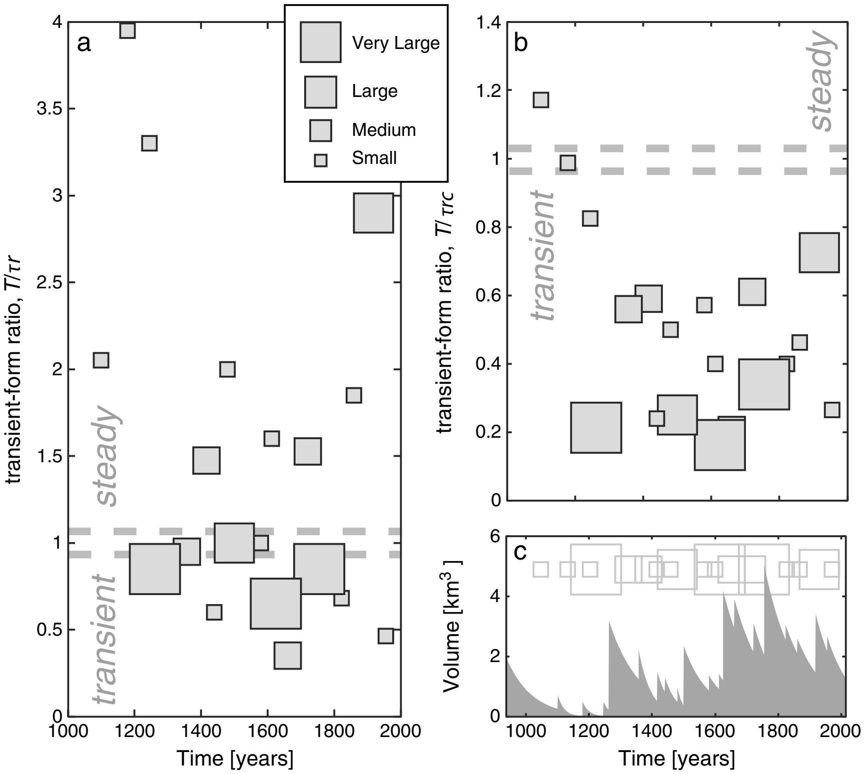

Figure 4. (a, b) Landscape state (transient or steady) of Mýrdalssandur over the past circa 10^3 years calculated from the known characteristic response [$\tau r \sim 60$ years] and recovery [$\tau rc \sim 120$ years] timescales of Mýrdalssandur following the 1918 jökulhlaup, corrected for historical jökulhlaup magnitude. (c) Calculated cumulative impact (frequency and magnitude) of historical jökulhlaups on the landscape, stated in terms of gross volume change, over the past 1000 years. Note that the general growth of the landscape over this time. T, time elapsed since the last major, geomorphologically effective event, τr, τrc, characteristic timescales of landscape response and recovery.

includes the coastline, and, to a more limited extent, the central sandur region (Figures 2b–2d). Field observations in the immediate proglacial region indicate that the 1918 jökulhlaup succession has been incised by up to 20 m over a width of 200 m [*Russell et al.*, 2010], in agreement with results from DTMs presented here (Figure 2). A large portion of this incision likely occurred in the weeks following the 1918 event [*Tómasson*, 1996; *Russell et al.*, 2010], but relatively small (10^3 m^3 s^{-1}) jökulhlaups in 1955, 1966, 1975, and 2011 are potentially significant agents of landscape dissection. A negative surface elevation change of approximately 5 to 10 m experienced by central Mýrdalssandur (Figures 2c and 2d) is notable since it has been unaffected by running surface water since the 1918 event. Subterranean groundwater channels, which feed several sapping channels, are the most likely mechanism responsible for this negative surface elevation change since 1946, and low-density volcanic material is easily remobilized by tranquil water flow. The possibility also exists that large and small ice fragments, transported by the 1918 jökulhlaup and subsequently buried by sediment, may have taken decades to melt, causing broad deformation of the surface over decadal timescales [*Everest and Bradwell*, 2003; *Dunning et al.,* 2013].

4. Discussion: Landscape State and Landscape Development

The reaction of the landscape to the 1918 jökulhlaup was constructional, i.e., aggradation and progradation, which reorganized the surface routing of the main perennial meltwater system. However, the data uniquely illustrate the mechanics and timescales of landscape response and recovery. Granular landscape surfaces react to pulsed changes in fluid flow conditions through erosion and deposition, recovering during interevent periods over timescales commensurate with the physiohydraulic conditions of a given landscape. The routing of future catastrophic floods and their geomorphic effectiveness [*Wolman and Gerson*, 1978] will depend strongly on the conditioning of that landscape [*Anderson and Calver*, 1977]. The 1918 jökulhlaup caused significant, nonuniform, elevation change across Mýrdalssandur, which will act to mediate the impact of the next major jökulhlaup. For instance, the reorganization of main routing of perennial surface meltwater from the central sandur (pre-1918 Sandvatn River) to the western sandur (Múlakvísl River), the presence of a region of persistent elevated topography between Selfjall and Hafursey, and the continued degradation of the glacier-proximal region, amplified by the retreat of the outlet glacier, to the north are conducive to the partial containment of floodwaters during the next major jökulhlaup, which may serve to suppress the down-system hazard and geomorphic impact of the initial catastrophic flood wave (e.g., 1996 jökulhlaup at Skeiðarárjökull) [*Russell and Knudsen*, 1999]. By contrast, the pre-1918 topography was conducive to immediate flood water evacuation and complete inundation of the western and central sandur along the pre-1918 Sandvatn River course.

The state of a landscape at any given time is dictated by the magnitude and frequency of sediment delivery by major jökulhlaups and by the rate of redistribution of this sediment in the years following a major jökulhlaup. For the short term (hours to days) the rate of sediment delivery to the coast by major jökulhlaups far exceeds the rate of sediment redistribution by coastal processes, leading to the observed transient coastline advance following the 1918 jökulhlaup. However, for the longer term (10^2 to 10^3 years), the historical state of a landscape can be expressed in terms of characteristic timescales of response and recovery, versus the time elapsed since the last major, geomorphologically effective event, T. This relationship is the "transient-form ratio" of *Brunsden and Thornes* [1979].

Assuming that landscapes respond exponentially to a step-change perturbation [*Allen*, 2008], we use $V(t) = V^0 e^{-t/\tau r}$ to model this response, where V^0 is the volume contributed by the initial perturbation from steady state, t is time, τr is a characteristic response time (mean lifetime or scaling time) defined as the time it takes for the perturbation to decay to $1/e$ (36.8% of its initial value), and $\tau\mathrm{rc}$ is a characteristic recovery time defined as the time it takes for the perturbation to decay to $1/e^2$ (13.5% of its initial value). We must emphasize that τr is the only independent parameter in an exponential decay law, and therefore, the value of $\tau\mathrm{rc}$, as defined here, is linearly dependent on the value of τr as both define the same exponential decay curve. The values of τr and $\tau\mathrm{rc}$ are dependent on the physiohydraulic properties of a particular landscape system, conditions that are usually captured by a diffusion coefficient, a constant parameter value for a given landscape system [*Paola et al.*, 1992]. By inference, we assume that these physiohydraulic properties of the Mýrdalssandur landscape remained roughly constant when averaged over a 10^3 year timescale. From the above, if $T < \tau r$ (and hence $T < \tau\mathrm{rc}$), the state of landscape system is defined as transient, and if $T > \tau\mathrm{rc}$ (and hence $T > \tau r$), the state of the landscape system is defined as steady [*Brunsden and Thornes*, 1979; *Allen*, 2008]. In nature, an abrupt transition between these landscape states is unlikely to exist as components of the landscape system have different response timescales [*Brunsden and Thornes*, 1979]. The present analysis is based on total landscape volume as a measure of change, so the timescales of behavior of landscape system components are subsumed into our analysis. Transient systems are conducive to longer-term landscape growth (aggradation and progradation) since sediment mass addition to a landscape is greater than sediment mass removal from a landscape, whereas steady systems inhibit longer-term landscape growth.

A limitation of this approach when applied to historical landscape development is that, for the present case, the volume of material remaining after times τr and $\tau\mathrm{rc}$ [$V^{\tau r}$,$V^{\tau\mathrm{rc}}$] is unrelated to the absolute magnitude [V^0] of the jökulhlaup or magnitude of step change. Clearly, this must be accounted for when assessing long-term landscape state and development. Therefore, we define a metric to define response and recovery using the volume remaining at τr and $\tau\mathrm{rc}$ for the 1918 event: $V^{\tau r} = V^0 e^{-1} = 0.56 \times 10^6$ m^3; $V^{\tau\mathrm{rc}} = V^0 e^{-2} = 0.21 \times 10^6$ m^3. Using our quantitative information of sandur volume decay, supplemented by coastline and spatial landscape data, during the 100 year period following the 1918 event, we determine that the Mýrdalssandur landscape has a τr value of 60 years and a $\tau\mathrm{rc}$ value of 120 years. Using historical information of eruption and jökulhlaup magnitude [*Jónsson*, 1982; *Tómasson*, 1996; *Elíasson et al.*, 2006] we are able to make an informed assessment of the magnitude of historical jökulhlaups that affected Mýrdalssandur, given that a positive correlation ($R^2 = 0.75$) has been found to exist between eruption magnitude and jökulhlaup magnitude [*Elíasson et al.*, 2006]. We use $\tau r = \ln\left(V_{1918}^{\tau r}/V^0\right)\tau r_{1918}\left[\tau\mathrm{rc} = \ln\left(V_{1918}^{\tau\mathrm{rc}}/V^0\right)\tau\mathrm{rc}_{1918}\right]$ to calculate τr and $\tau\mathrm{rc}$ values for the landscape affected by different jökulhlaup magnitudes. Our definitions and timescales are as follows: small jökulhlaup magnitude ($V^0 < 0.5 \times 10^3$ m^3; $\tau r = 20$ years, $\tau\mathrm{rc} = 80$ years), medium ($V^0 < 1 \times 10^3$ m^3; $\tau r = 40$ years, $\tau\mathrm{rc} = 100$ years), large ($V^0 < 2 \times 10^3$ m^3; $\tau r = 80$ years, $\tau\mathrm{rc} = 140$ years), and very large ($V^0 < 3 \times 10^3$ m^3;

$\tau r = 100$ years, $\tau rc = 160$ years). We note that values for V^0 for each jökulhlaup magnitude are estimates calibrated from the known value of V^0 from the 1918 jökulhlaup, which is classified as large jökulhlaup magnitude. With these timescales we assess landscape state over the past 1000 years (Figure 4). From the above it is clear that larger, more frequent events will have the greatest impact on the landscape. The data show that the landscape is, historically, transient in state when taking both τr (Figure 4a) and τrc (Figure 4b) as the characteristic timescales, which promotes long-term landscape growth. This long-term behavior, over the past 1000 years, is calculated and shown graphically in Figure 4c.

Historical coastline data indicate that a steady state, as observed between the 1904 and 2007 coastline position (Figure 3d) and the 1300 and 1600 coastline position (Figure 1), has not always been achieved. Since 1600 C.E. the southern Mýrdalssandur coastline has experienced a net advance of approximately 3 km (Figure 1) [*Nummedal et al.*, 1987], suggesting that multiple jökulhlaups during this time had an additive effect on the landscape. Historic accounts suggest that the jökulhlaups of 1625 and 1755 were greater in magnitude than the 1918 jökulhlaup and that the jökulhlaups of 1660 and 1721 were of similar magnitude [*Larsen*, 2000; *Elíasson et al.*, 2006]. Given this and a known average value of *T* from 1660 to 1904 of 51 ± 15 years, we deduce that the landscape was in a constant and strong state of transience and growth over this time (Figure 4c). Therefore, it is not surprising that the coastline experienced a phase of rapid advance (3 km) from 1600 to 1904.

Landscape state at the time of perturbation determines landscape sensitivity, which in turn conditions the geomorphic effectiveness of the perturbation, in our case the catastrophic release of sediment-enriched floodwaters. In addition, topographic irregularities and landscape gradient will affect the behavior, hydraulics, and impact of these events, the absolute value of which is dependent on when in the recovery cycle the landscape is affected by the next jökulhlaup. Therefore, the routing of future catastrophic floods and their geomorphic effectiveness [*Wolman and Gerson*, 1978] will depend strongly on the conditioning of that landscape [*Anderson and Calver*, 1977]. Our analysis highlights the importance of understanding long-term landscape state and its relationship with physical landscape development over the long term (Figure 4c). The approach used here is accessible and suitably generic so that it can be applied to a range of landscapes over a range of timescales to perform a first-order approximation of past and future landscape development and sediment mass redistribution [cf. *Phillips*, 1995]. This can be done if the characteristic response timescale and perturbation magnitude can be determined.

5. Conclusions

The 1918 jökulhlaup from Katla volcano caused up to approximately 4 km of coastline advance and contributed up to 2 km^3 of sediment to the landscape of Mýrdalssandur in little more than several hours. Time series analysis of historical topographic surveys over a 90 year period following the jökulhlaup identifies regions of persistent topography that are likely to have an effect on flow routing of future jökulhlaups and also highlights the complete reorganization of the main perennial meltwater channel. Following landscape reaction to the 1918 jökulhlaup, we calculate a characteristic landscape response time ($1/e$ of initial value) of 60 years and a characteristic landscape recovery time ($1/e^2$ of initial value) of 120 years. Using historical data on jökulhlaup frequency and magnitude we are able to deduce that Mýrdalssandur is a dominantly transient landscape, which has facilitated long-term landscape growth over the past 1000 years. Our analysis highlights the role of historical landscape state in governing long-term landscape development, therefore providing a quantitative and qualitative framework for short-term and long-term landscape development in regions affected by the catastrophic release of floodwaters, and also the role it has in conditioning the sensitivity of the landscape for the next major jökulhlaup, which can provide a broad perspective on hazard assessment and mitigation. The generality of the approach used here means that it can be used to assess landscape development in a range of settings and over a range of spatial scales.

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