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Climatic control on Icelandic volcanic activity during the mid-Holocene

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ABSTRACT

Human-induced climate change is causing rapid melting of ice in many volcanically active regions. Over glacial-interglacial time scales changes in surface loading exerted by large variations in glacier size affect the rates of volcanic activity. Numerical models suggest that smaller changes in ice volume over shorter time scales may also influence rates of mantle melt generation. However, this effect has not been verified in the geological record. Furthermore, the time lag between climatic forcing and a resultant change in the frequency of volcanic eruptions is unknown. We present empirical evidence that the frequency of volcanic eruptions in Iceland was affected by glacial extent, modulated by climate, on multicentennial time scales during the Holocene. We examine the frequency of volcanic ash deposition over northern Europe and compare this with Icelandic eruptions. We identify a period of markedly reduced volcanic activity centered on 5.5–4.5 ka that was preceded by a major change in atmospheric circulation patterns, expressed in the North Atlantic as a deepening of the Icelandic Low, favoring glacial advance on Iceland. We calculate an apparent time lag of ~600 yr between the climate event and change in eruption frequency. Given the time lag identified here, increase in volcanic eruptions due to ongoing deglaciation since the end of the Little Ice Age may not become apparent for hundreds of years.

INTRODUCTION

The link between large-scale ice mass decline and an increase in volcanic eruptions at the end of the last glacial period, ca. 12 ka, is well established (Jull and McKenzie, 1996; Maclennan et al., 2002). A number of questions remain regarding the sensitivity and response time of volcanoes to smaller changes in ice mass, such as those that occur over shorter time scales (e.g., during the Holocene; Tuffen, 2010; Schmidt et al., 2013). The loading and unloading of glaciers change surface pressure and stress relationships in the crust and upper mantle (Schmidt et al., 2013). Numerical models suggest that glacial unloading increases mantle melt production at depth and alters the storage capacity in the crust (Hooper et al., 2011). Even small changes in surface loading can alter the stress field around shallow magma chambers, increasing or decreasing the likelihood of eruptions at ice-covered volcanoes (Albino et al., 2010).

Examining past trends in the frequency of eruptions using proximal records (e.g., tephra layers and lava flows) is often complicated by reworking or burial of evidence by more recent eruptions (Global Volcanism Program, http://volcano.si.edu/). However, evidence of past volcanic eruptions can also be recorded by far-traveled cryptotephra shards, which eventually fall out from ash clouds, forming invisible layers in peatlands and lakes (Swindles et al., 2011, 2013; Watson et al., 2016). Cryptotephra layers provide a record of explosive volcanism unaffected by many of the issues that can confound proximal records of volcanic activity. In Europe, the majority of cryptotephras are intermediate to silicic in nature. For the first time, we examine records of Icelandic eruptions alongside records of distal volcanic ash (tephra) deposition from northern Europe (referred to here as the NEVA, northern European volcanic ash, record; Figs. 1

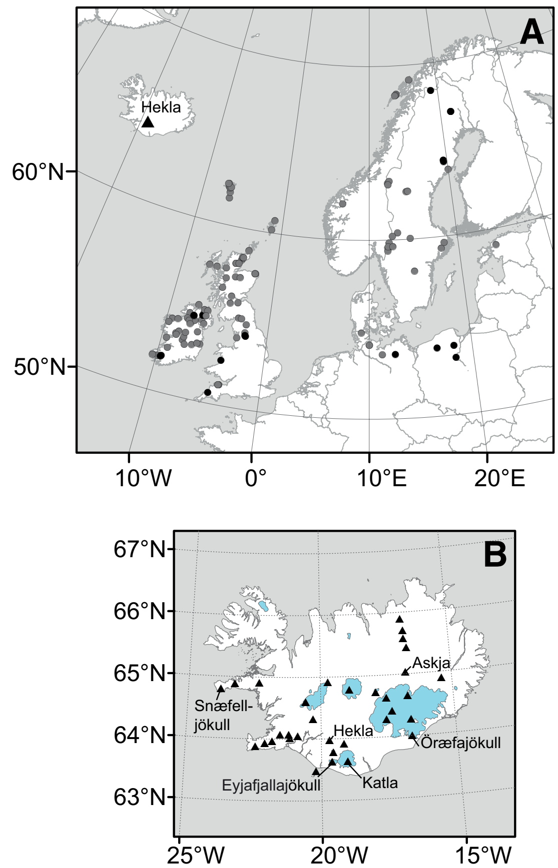

Figure 1. A: Map of northern Europe showing the location of sites where Holocene cryptotephra layers have been identified; gray circles indicate sites included in the original database compiled by Swindles et al. (2011); black circles indicate new data added to the database (see Watson et al., 2017). B: Map of Iceland indicating Holocene volcanoes and the location of large ice masses (blue shading).

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and 2; Table DR1 in the GSA Data Repository[1]). We use these data sets to examine whether there is evidence for changes in volcanic activity related to climate-driven changes in ice cover over Holocene time scales.

METHOD

The NEVA record (originally compiled by Swindles et al., 2011) was updated and quality checked as of March 2017 (Figs. 1 and 2; Table DR1). Tephra layers with a known source eruption outside of Iceland were removed from the database prior to analysis (see Table DR1). Data for Icelandic eruptions based on the proximal geological record were taken from the Smithsonian Global Volcanism Program Database (Global Volcanism Program, http://volcano.si.edu/). In addition, high-resolution tephrostratigraphic data derived from Icelandic soils east of the Katla volcano (Óladóttir et al., 2008), around the Vatnajökull ice cap (Óladóttir et al., 2011), and from marine core MD99–2275 from the North Icelandic shelf (66°33.06′N, 17°41.59′W; 440 m water depth) (Gudmundsdóttir et al., 2012) were investigated. Unless otherwise stated all ages are reported as calibrated yr before A.D. 2000. Cross-correlation analysis was conducted on Na^+ data from the Greenland Ice Sheet Project 2 (GISP2) ice core, a proxy for the depth of the Icelandic Low (Mayewski et al., 1997), and Icelandic eruption and NEVA data, which were split into 100 yr bins; the Na^+ data were averaged into 100 yr bins. Cross-correlation was conducted using the ccf function in R version 3.1.1. (R Core Team, 2014). The period 7.0–1.5 ka was used for numerical analysis to ensure that only data derived from the geological record were used, not a combination of the geological and historical and/or observational records.

RESULTS AND DISCUSSION

An apparent general decrease in the frequency of volcanic eruptions during the mid-Holocene in Iceland was previously identified (e.g., Óladóttir et al., 2011). Here we identify a pronounced ~1 k.y. period of decline in the frequency of known Icelandic eruptions in the mid-Holocene and a corresponding period of absolute quiescence in the NEVA record centered on 5.5–4.5 ka (Fig. 2). The repose interval for eruptions with a Volcanic Explosivity Index (VEI) ≥ 3 during this period (1800 yr; 6.1–4.3 ka) represents a major departure from the average return interval (507 yr; Watson et al., 2017). There is also a reduction in the volume of lava erupted from multiple Icelandic volcanoes including Grímsvötn, Bárðarbunga, and Kverkfjöll between 5 and 2 ka (Hjartarson, 2003; Óladóttir et al., 2011), indicating a change in the rate of effusive volcanism. Identification of a corresponding period of decline in all terrestrial Icelandic and the NEVA records (Fig. 2) suggests that this period reflects genuine changes in the frequency of eruptions in Iceland rather than periods of poor preservation in the geological record.

It is clear that the replicated pattern in the NEVA and terrestrial tephra data sets is not mirrored in marine core MD99–2275, although there is a decline in the number of tephras from ca. 6 ka. The record from

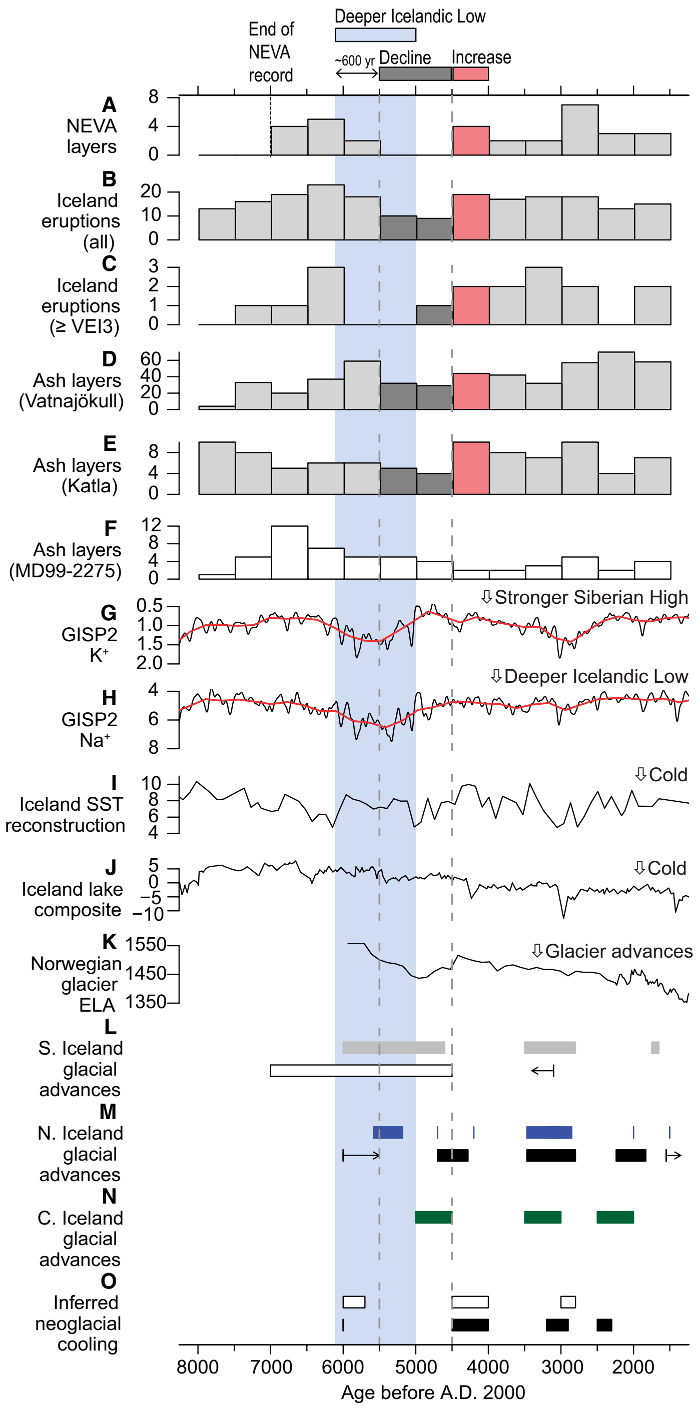

Figure 2. Histograms (500 yr bins). A: Number of NEVA (northern European volcanic ash) events. B: Number of Icelandic eruptions of all magnitudes. C: Number of Icelandic eruptions with a Volcanic Explosivity Index (VEI) ≥ 3. D: Number of tephra layers in Icelandic soils around the Vatnajökull ice cap (Óladóttir et al., 2011). E: Number of tephra layers in Icelandic soils east of the Katla volcano (Óladóttir et al., 2008). F: Number of tephra layers in marine core MD99-2275 from the North Icelandic shelf (Gudmundsdóttir et al., 2012). G: 200 yr Gaussian smoothed Greenland Ice Sheet Project 2 (GISP2) potassium (K^+) concentrations (μg L^{-1}) (Mayewski et al., 1997). H: 200 yr Gaussian smoothed GISP2 sodium (Na^+) concentrations (μg L^{-1}) (Mayewski et al., 1997). The red lines in G and H are locally weighted smoothing functions. I: Sea-surface temperature (SST) reconstruction (°C) from the North Icelandic shelf (Bendle and Rosell-Melé, 2007). J: Icelandic lake composite record (Geirsdóttir et al., 2013). K: Folgefonna glacier (Norway) reconstructed equilibrium line altitude (ELA; Bakke et al., 2005). L: Glacial advances in southern Iceland: Kvíárjökull (gray) (Kirkbride and Dugmore, 2001); Sólheimajökull (outline) (Dugmore, 1989). M: Glacial advances in northern Iceland: Tröllaskagi (Stötter et al., 1999) (blue), Tröllaskagi (black) (Gudmundsson, 1997). N: Glacial advances in central Iceland (Kirkbride and Dugmore, 2006). O: Periods of inferred neoglacial cooling Iceland based on lake (white) and marine (black) records (Geirsdóttir et al., 2009). Dashed gray lines bracket the mid-Holocene decline in volcanic activity. Blue bar indicates the period of deeper Icelandic low. Gray histogram bars indicate the mid-Holocene decline in volcanic activity; pink histogram bars indicate the subsequent increase in volcanic activity. The ~600 yr lag between the phase of deeper Icelandic low and decline in volcanic activity is also illustrated.

[1]GSA Data Repository item 2018010, Table DR1 (the new Holocene tephra database for northern Europe used here), is available online at http://www.geosociety.org/datarepository/2018/ or on request from editing@geosociety.org.

MD99–2275 needs to be considered with some caution, because (1) it is based on only a single core; (2) it only contains ash that traveled in a northern direction from Iceland, and thus is less comprehensive than the other data sets; (3) it is likely to be more sensitive to subtle changes in atmospheric circulation than the NEVA and terrestrial Icelandic data sets as it is a single point in space; and (4) some key markers are clearly missing from this record (e.g., Askja 1875, Hekla-Selsund tephra).

Icelandic volcanism is controlled by complex interactions between rifting, mantle plume activity, and environmental factors such as ice loading. Eruption frequency is episodic over short (centennial) time scales and is associated with rifting events at the plate boundary (Larsen et al., 1998). Although the underlying cause of periodic activity over these time scales remains unknown, changes in rifting rates have previously been linked to alterations in magmatic activity and upwelling (Sigmundsson, 2006; Sigmundsson et al., 2015). Pulses in mantle plume activity (e.g., Jones et al., 2002) may be the cause of longer term (multimillennial) decreases in eruption frequency at the Grímsvötn, Bárdarbunga, and Kverkfjöll subglacial volcanic centers (Óladóttir et al., 2011; Sigmundsson et al., 2015). Although changes in the magma supply rate due to this effect cannot be completely discounted as a reason for the period of reduced volcanic output we identify, it appears unlikely that such pulses would result in a simultaneous period of pronounced decline spanning ~1 k.y. across multiple volcanic systems in Iceland. A more plausible scenario is that an external driver, for example, changing ice load, might have had an impact on eruption frequency during the period of decline we identify. Icelandic glaciers are known to respond actively to climatic fluctuations (Caseldine and Stötter, 1993; Flowers et al., 2008). Recent models of magmatic systems suggest that a significant alteration to the local and regional stress regimes, such as deglaciation, may lead to a rapid increase in the likelihood of volcanic destabilization (Sparks and Cashman, 2017).

Multiple paleoclimate records indicate changing conditions in Iceland and in the surrounding oceans (Arctic and Atlantic) prior to the period of decline in volcanic activity. Records from both the Icelandic shelf (ca. 7.4–6.2 ka) and North Atlantic (post–6 ka; Bendle and Rosell-Melé, 2007) indicate oceanic cooling (Fig. 2). Furthermore, reduced productivity in lake records from Iceland suggests a cooling event ca. 6.4 ka, with the onset of long-term summer cooling from 5.7 to 5.5 ka (Geirsdóttir et al., 2013; Blair et al., 2015). The concentration of sodium (Na^+) in the Greenland ice core shows a major deviation in the period 6.2–5 ka, indicating a deeper Icelandic Low (Mayewski et al., 1997). The Icelandic Low influences both temperature and precipitation in the North Atlantic, two of the dominant controls on the size of glaciers in Iceland (Caseldine and Stötter, 1993; Flowers et al., 2008). These climatic changes in Iceland correspond to the timing of a global and rapid climate changes centered on 6–5 ka (Mayewski et al., 2004).

Within the period of the Holocene Thermal Maximum (HTM, ca. 8.0–5.5 ka; Caseldine and Stötter, 1993; Geirsdóttir et al., 2013), geomorphic evidence suggests that Iceland was mostly ice free between 8 and 7 ka. Coinciding with climatic changes, there is evidence of glacial advances in the south (7–4.5 ka), center (4.5–5 ka), and north (before 5 ka) of Iceland (Dugmore, 1989; Gudmundsson, 1997; Stötter et al., 1999; Kirkbride and Dugmore, 2001). Some glaciers may have advanced to their maximum Holocene extent, exceeding Little Ice Age (LIA) limits (Kirkbride and Dugmore, 2001). However, there is no evidence for substantial expansion of the Langjökull ice cap prior to 5.5 ka (Wastl et al., 2001), perhaps revealing that smaller glaciers, which respond rapidly to climate forcing, accounted for the majority of glacial expansion following the HTM (Kirkbride and Dugmore, 2006). There is also evidence for further late Holocene glacial advances in Iceland (cf. Dugmore, 1989; Gudmundsson, 1997; Stötter et al., 1999; Kirkbride and Dugmore, 2001, 2006).

Although there is evidence for the advance of glaciers in the period preceding the reduction in eruption frequency, there are no quantitative reconstructions of glacier volume that we can compare with our eruption

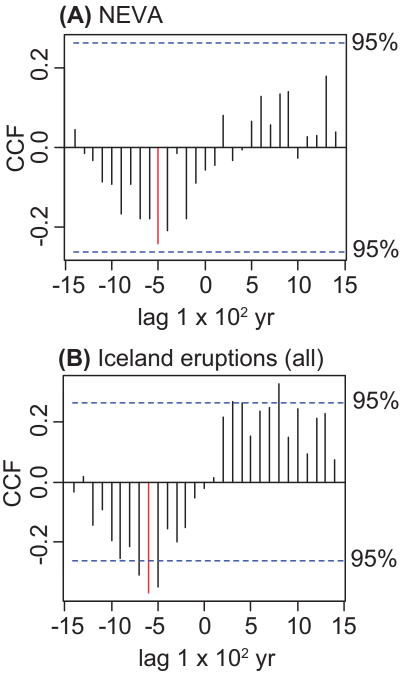

Figure 3. Plots showing the results of cross-correlation analysis. (A) Between Greenland Ice Sheet Project 2 (GISP2) Na^+ and northern European volcanic ash (NEVA) frequency. (B) GISP2 Na^+ and Icelandic eruption frequency from 7.0 to 1.5 ka. Dashed blue lines indicate 95% confidence intervals. Red bars highlight the strongest correlations. CCF—cross-correlation function.

frequency estimates (Watson et al., 2017). Therefore, we conducted a cross-correlation analysis on the GISP2 Na^+ record (depth of Icelandic Low) with the NEVA record and Icelandic eruption frequency data for the period 1500–7000 yr ago. Cross-correlation analysis shows the strongest lags at 600 yr (all Icelandic eruptions; $p < 0.05$), and 500 yr (NEVA; $p < 0.10$) (Fig. 3). Visual inspection of the data sets also reveals an ~600 yr lag between the climate event and the mid-Holocene decline in volcanic activity, lending support to the results from statistical cross-correlation analysis (Fig. 2).

Given the range of response times exhibited by Icelandic glaciers to changing climate (10–1000 yr; Wastl et al., 2001) and uncertainties involved in the time taken for new melt produced in the mantle to reach the surface (Maclennan et al., 2002), a lag time of ~600 yr between climate forcing and a reduction in the frequency of volcanic activity would support the argument for the modulation of climatic forcing by glacial expansion. A significant increase in mantle melt production (100%–135%) due to deglaciation between A.D. 1890 and 2010 was modeled in Schmidt et al. (2013). The rate of ice accumulation between the HTM and 5 ka may have been of a magnitude similar to (or slower than) the current rate of ice loss since the LIA. If this was the case, the same model would predict extremely reduced or even a complete shutdown of mantle melt production between the HTM and 5 ka, assuming that the spatial distribution of changes in ice mass between the HTM and 5 ka was not significantly different from that between A.D. 1890 and 2010. The renewal of volcanic activity was most likely driven by a change in climate and subsequent glacier retreat. There is evidence for a weakening of the Icelandic Low and a reduction in ice-rafting events in the North Atlantic preceding the resumption of greater volcanic activity following the mid-Holocene decline (Bond et al., 2001). The most recent glacial advances in Iceland occurred during the LIA, ca. A.D. 1600–1880. Although some glaciers reached their maximum Holocene extent during the LIA (Caseldine and Stötter, 1993), the magnitude of changes in the Icelandic Low is smaller than at 6–5 ka. Climate warming driven by human activity may also have curtailed ice expansion in the 20th century.

We conclude that there was a reduction in the frequency of volcanic eruptions between 5.5 and 4.5 ka, and that climate-forced changes in glacier extent provide a plausible explanation for this event. Our results may support modeling results that suggest that moderate to small changes in ice volume, such as those that have occurred and continue to occur during the Holocene, can affect mantle melt production rates. Given the lag time between climate forcing and changes in eruption frequency, the impact of post-LIA deglaciation on volcanic eruption frequency may not be discerned for hundreds of years.

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REFERENCES CITED

Albino, F., Pinel, V., and Sigmundsson, F., 2010, Influence of surface load variations on eruption likelihood: Application to two Icelandic subglacial volcanoes, Grímsvötn and Katla: Geophysical Journal International, v. 181, p. 1510–1524, https://doi.org/10.1111/j.1365-246X.2010.04603.x.

Bakke, J., Lie, Ø., Nesje, A., Dahl, S.O., and Paasche, Ø., 2005, Utilizing physical sediment variability in glacier-fed lakes for continuous glacier reconstructions during the Holocene, northern Folgefonna, western Norway: The Holocene, v. 15, p. 161–176, https://doi.org/10.1191/0959683605hl797rp.

Bendle, J.A.P., and Rosell-Melé, A., 2007, High-resolution alkenone sea surface temperature variability on the North Icelandic Shelf: Implications for Nordic Seas palaeoclimatic development during the Holocene: The Holocene, v. 17, p. 9–24, https://doi.org/10.1177/0959683607073269.

Blair, C.L., Geirsdóttir, Á., and Miller, G.H., 2015, A high-resolution multi-proxy lake record of Holocene environmental change in southern Iceland: Journal of Quaternary Science, v. 30, p. 281–292, https://doi.org/10.1002/jqs.2780.

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., and Bonani, G., 2001, Persistent solar influence on North Atlantic climate during the Holocene: Science, v. 294, p. 2130–2136, https://doi.org/10.1126/science.1065680.

Caseldine, C., and Stötter, J., 1993, 'Little Ice Age' glaciation of Tröllaskagi peninsula, northern Iceland: Climatic implications for reconstructed equilibrium line altitudes (ELAS): The Holocene, v. 3, p. 357–366, https://doi.org/10.1177/095968369300300408.

Dugmore, A., 1989, Tephrochronological studies of Holocene glacier fluctuations in south Iceland, *in* Oerlemans, J., ed., Glacier fluctuations and climatic change: Glaciology and Quaternary geology Volume 6: Dordrecht, Kluwer, p. 37–55, https://doi.org/10.1007/978-94-015-7823-3_3.

Flowers, G.E., Björnsson, H., Geirsdóttir, Á., Miller, G.H., Black, J.L., and Clarke, G.K.C., 2008, Holocene climate conditions and glacier variation in central Iceland from physical modelling and empirical evidence: Quaternary Science Reviews, v. 27, p. 797–813, https://doi.org/10.1016/j.quascirev.2007.12.004.

Geirsdóttir, Á., Miller, G.H., Axford, Y., and Ólafsdóttir, S., 2009, Holocene and latest Pleistocene climate and glacier fluctuations in Iceland: Quaternary Science Reviews, v. 28, p. 2107–2118, https://doi.org/10.1016/j.quascirev.2009.03.013.

Geirsdóttir, Á., Miller, G.H., Larsen, D.J., and Ólafsdóttir, S., 2013, Abrupt Holocene climate transitions in the northern North Atlantic region recorded by synchronized lacustrine records in Iceland: Quaternary Science Reviews, v. 70, p. 48–62, https://doi.org/10.1016/j.quascirev.2013.03.010.

Gudmundsson, H.J., 1997, A review of the Holocene environmental history of Iceland: Quaternary Science Reviews, v. 16, p. 81–92, https://doi.org/10.1016/S0277-3791(96)00043-1.

Gudmundsdóttir, E.R., Larsen, G., and Eiríksson, J., 2012, Tephra stratigraphy on the North Icelandic shelf: Extending tephrochronology into marine sediments off North Iceland: Boreas, v. 41, p. 719–734, https://doi.org/10.1111/j.1502-3885.2012.00258.x.

Hjartarson, Á., 2003, Postglacial lava production in Iceland in the Skagafjörður unconformity, North Iceland, and its geological history [Ph.D. thesis]: Copenhagen, Denmark, University of Copenhagen, 248 p.

Hooper, A., Ófeigsson, B., Sigmundsson, F., Lund, B., Einarsson, P., Geirsson, H., and Sturkell, E., 2011, Increased capture of magma in the crust promoted by ice-cap retreat in Iceland: Nature Geoscience, v. 4, p. 783–786, https://doi.org/10.1038/ngeo1269.

Jones, S.M., White, N., and Maclennan, J., 2002, V-shaped ridges around Iceland: Implications for spatial and temporal patterns of mantle convection: Geochemistry, Geophysics, Geosystems, v. 3, p. 1–23, https://doi.org/10.1029/2002GC000361.

Jull, M., and McKenzie, D., 1996, The effect of deglaciation on mantle melting beneath Iceland: Journal of Geophysical Research, v. 101, p. 21,815–21,828, https://doi.org/10.1029/96JB01308.

Kirkbride, M.P., and Dugmore, A.J., 2001, Timing and significance of mid-Holocene glacier advances in northern and central Iceland: Journal of Quaternary Science, v. 16, p. 145–153, https://doi.org/10.1002/jqs.589.

Kirkbride, M.P., and Dugmore, A.J., 2006, Responses of mountain ice caps in central Iceland to Holocene climate change: Quaternary Science Reviews, v. 25, p. 1692–1707, https://doi.org/10.1016/j.quascirev.2005.12.004.

Larsen, G., Gudmundsson, M.T., and Björnsson, H., 1998, Eight centuries of periodic volcanism at the center of the Iceland hotspot revealed by glacier tephrostratigraphy: Geology, v. 26, p. 943–946, https://doi.org/10.1130/0091-7613(1998)026<0943:ECOPVA>2.3.CO;2.

Maclennan, J., Jull, M., McKenzie, D., Slater, L., and Grönvold, K., 2002, The link between volcanism and deglaciation in Iceland: Geochemistry, Geophysics, Geosystems, v. 3, p. 1–25, https://doi.org/10.1029/2001GC000282.

Mayewski, P.A., Meeker, L.D., Twickler, M.S., Whitlow, S., Yang, Q., Lyons, W.B., and Prentice, M., 1997, Major features and forcing of high-latitude Northern Hemisphere atmospheric circulation using a 110,000-year-long glaciochemical series: Journal of Geophysical Research, v. 102, p. 26,345–26,366, https://doi.org/10.1029/96JC03365.

Mayewski, P.A., et al., 2004, Holocene climate variability: Quaternary Research, v. 62, p. 243–255, https://doi.org/10.1016/j.yqres.2004.07.001.

Óladóttir, B.A., Sigmarsson, O., Larsen, G., and Thordarson, T., 2008, Katla volcano, Iceland: Magma composition, dynamics and eruption frequency as recorded by Holocene tephra layers: Bulletin of Volcanology, v. 70, p. 475–493, https://doi.org/10.1007/s00445-007-0150-5.

Óladóttir, B., Larsen, G., and Sigmarsson, O., 2011, Holocene volcanic activity at Grímsvötn, Bárdarbunga and Kverkfjöll subglacial centres beneath Vatnajökull, Iceland: Bulletin of Volcanology, v. 73, p. 1187–1208, https://doi.org/10.1007/s00445-011-0461-4.

R Core Team, 2014, R: A language and environment for statistical computing: Vienna, Austria, R Foundation for Statistical Computing, https://www.R-project.org/.

Schmidt, P., Lund, B., Heironymus, C., Maclennan, J., Árnadóttir, T., and Pagli, C., 2013, Effects of present-day deglaciation in Iceland on mantle melt production rates: Journal of Geophysical Research, v. 118, p. 3366–3379, https://doi.org/10.1002/jgrb.50273.

Sigmundsson, F., 2006, Plate tectonics: Magma does the splits: Nature, v. 442, p. 251–252, https://doi.org/10.1038/442251a.

Sigmundsson, F., et al., 2015, Segmented lateral dyke growth in a rifting event at Bárðarbunga volcanic system, Iceland: Nature, v. 517, p. 191–195, https://doi.org/10.1038/nature14111.

Sparks, R.S.J., and Cashman, K., 2017, Dynamic magma systems: Implications for forecasting volcanic activity: Elements, v. 13, p. 35–40, https://doi.org/10.2113/gselements.13.1.35.

Stötter, J., Wastl, M., Caseldine, C., and Häberle, T., 1999, Holocene palaeoclimatic reconstruction in northern Iceland: Approaches and results: Quaternary Science Reviews, v. 18, p. 457–474, https://doi.org/10.1016/S0277-3791(98)00029-8.

Swindles, G.T., Lawson, I.T., Savov, I.P., Connor, C.B., and Plunkett, G., 2011, A 7000 yr perspective on volcanic ash clouds affecting northern Europe: Geology, v. 39, p. 887–890, https://doi.org/10.1130/G32146.1.

Swindles, G.T., Savov, I.P., Connor, C.B., Carrivick, J., Watson, E.J., and Lawson, I.T., 2013, Volcanic ash clouds affecting northern Europe: The long view: Geology Today, v. 29, p. 214–217, https://doi.org/10.1111/gto.12026.

Tuffen, H., 2010, How will melting of ice affect volcanic hazards in the twenty-first century?: Royal Society of London Philosophical Transactions, ser. A, v. 368, p. 2535–2558, https://doi.org/10.1098/rsta.2010.0063.

Wastl, M., Stötter, J., and Caseldine, C., 2001, Reconstruction of Holocene variations of the upper limit of tree or shrub birch growth in northern Iceland based on evidence from Vesturárdalur-Skíðadalur, Tröllaskagi: Arctic, Antarctic, and Alpine Research, v. 33, p. 191–203, https://doi.org/10.2307/1552220.

Watson, E.J., Swindles, G.T., Stevenson, J.A., Savov, I., and Lawson, I.T., 2016, The transport of Icelandic volcanic ash: Insights from northern European cryptotephra records: Journal of Geophysical Research, v. 121, p. 7177–7192, https://doi.org/10.1002/2016JB013350.

Watson, E.J., Swindles, G.T., Savov, I.P., Lawson, I.T., Connor, C.B., and Wilson, J.A., 2017, Estimating the frequency of volcanic ash clouds over northern Europe: Earth and Planetary Science Letters, v. 460, p. 41–49, https://doi.org/10.1016/j.epsl.2016.11.054.

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