Radiocarbon dating of mid-Holocene megaflood deposits in the Jökulsá á Fjöllum, north Iceland

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Abstract: Two megafloods in the canyon of the Jökulsá á Fjöllum, the major northern routeway for glaciovolcanic floods from Vatnajökull, have been closely dated by ^{14}C AMS dates from *Betula* macrofossils within peat immediately below beds of flood-deposited sand. Ages of *c.* 4415 and *c.* 4065 yr BP (5020 and 4610 cal. yr BP) are consistent with the presence of the Hekla 4 tephra (*c.* 3830 yr BP) resting on the upper surface of the younger flood sand. These sediments are correlated across the Jökulsà à Fjöllum canyon with the upper flood sands in a stack recording around 16 flood events. Deposits on both sides of the canyon were trimmed by the last megaflood after the Hekla 3 tephra fall at *c.* 2900 yr BP, and the highest Holocene flood stages were at the culmination of a series peaking at *c.* 3500 yr BP. These floods have wider palaeoclimatic significance because they require the formation of large subglacial reservoirs below Vatnajökull. Therefore, the dated floods indicate that a large composite ice cap covered volcanoes in the southeastern highlands through the early and middle Holocene, and that flood routeways largely switched to the south after *c.* 3500 yr BP.

Key words: Jökulhlaups, radiocarbon dating, slackwater sediment, megafloods, mid-Holocene, Iceland.

Introduction

The sedimentary record left by glaciovolcanic megafloods along the route of the Jökulsà à Fjöllum, northern Iceland, is important as a record of flood history and, by proxy, of the development of the major Vatnajökull ice cap, which is the source of the floodwaters. A chronology of megafloods in the Jökulsà à Fjöllum will allow inferences about the timing and scale of the volcanogenic subglacial reservoirs from which such floods are sourced. It is not known if Vatnajökull has maintained its large composite form throughout the Holocene, or whether it has previously melted and reformed. The ice cap has been comparatively stable under twentieth century climates. However, if destroyed it would not regain its present form simply as a result of a return to twentieth century conditions, because only *c.* 10% of the subglacial topography lies above the modern ELA. Therefore, short-lived climate change could result in its persistent absence. Megaflood production probably requires Vatnajökull to exist as a composite mountain ice cap of dimensions comparable with the present day, because very large subglacial reservoirs are a necessity for generating the peak discharges of $>4.0 \times 10^6$ m^3/s that have been reconstructed for the largest floods in the Jökulsà à Fjöllum. A 'megaflood' in the Icelandic context is defined by a peak discharge $>10 \times 10^5$ m^3/s (Tómasson, 2002).

Previous tephrochronological research has led to three different versions of flood history being proposed. (a) The so-called '2500 yr BP' flood was the only Holocene megaflood to leave preserved deposits (Thórarinsson, 1960; Tómasson, 2002). (b) Major floods at *c.* 4600 yr BP, 3000 yr BP and 2000 yr BP followed an early (pre-canyon?) Lateglacial flood (Elíasson, 1977). (c) A series of many (16?) mid-Holocene floods culminated with the largest being the most recent at *c.* 2500 yr BP (Waitt, 2002).

All authors agree that the most recent megaflood occurred *c.* 2000–2500 yr BP, and was responsible for all landform assemblages that are not covered by the *c.* 2900 yr BP Hekla

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3 tephra. However, this flood is poorly dated: the present authors have not been able to identify the '2000 year old' tephra (which Tómasson (2002) ascribes to Thórarinsson (1960) as constraining the minimum age of this flood) either in soil profiles in the field or in translation of Thórarinsson's paper. Many smaller floods have been contained within the present canyon (Knudsen and Russell, 2002). Dating of megafloods has been limited to minimum ages of water-eroded surfaces using tephra layers within overlying aeolian soils (Thórarinsson, 1960; Elíasson, 1977). Thus, Tómasson (2002) states that, 'the question of whether or not there has been more than one catastrophic flood cannot be answered by tephrochronology'.

Regional tephra layers in the area are few, with three main prehistoric Hekla tephras providing isochrones at *c.* 2900 yr BP (Hekla 3), *c.* 3800 yr BP (Hekla 4) and *c.* 6000 yr BP (Hekla 5). Flood sediments can be broadly dated to the intervals between these isochrones, but not more precisely than this. To date, no radiometric dating of flood deposits has been carried out.

This report presents four ^{14}C AMS dates from organic material intercalated with flood-deposited sand beds, providing bracketing ages to within a few decades on the two highest Holocene floods at a site on the east of the Svinadalur–Vesturdalur sector of the canyon (Figure 1). The dates presented here provide precise constraints on a key part of the megaflood chronology, with implications for the significance of changes in the temporal pattern of very high flood stages during the Holocene.

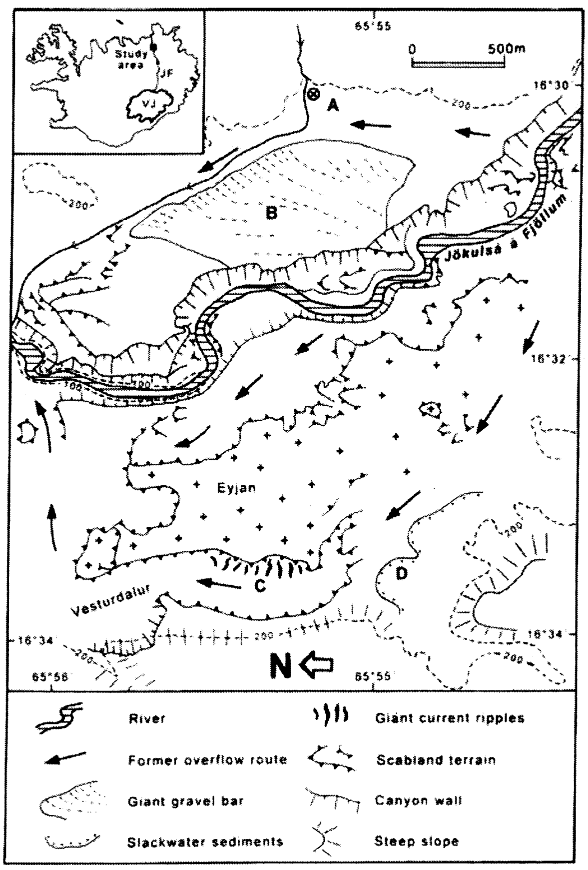

Figure 1 Site location and geomorphology. A, marginal embayment floored by flood sediments; B, giant bar; C, megaripple train; D, location of the Vesturdalur section (Figure 2) described by Waitt (2002); ⊗, location of ^{14}C-dated section in embayment A. The 'upstream' and 'downstream' profiles are the logged parts of the same stream-bank section (see text). Inset: location of the study site within Iceland relative to Vatnajökull (VJ) and the Jökulsà à Fjöllum (JF)

Geomorphology

In contrast to the sandur-dominated southern flood routeways from Vatnajökull, the northern megaflood routeways are dominated by erosion of lava plateaux, and landform assemblages are reminiscent of the Channelled Scabland in the USA (Tómasson, 2002). The Jökulsà à Fjöllum becomes incised into a canyon at 135 km from the ice cap margin. Spectacular lateral deposits occur along the flood corridor in places where flood waters spilled out of the canyon, providing the potential for constructing a sediment-based flood chronology.

The Jökulsà canyon passes through a 2-km-wide valley in the area of Svinadalur–Vesturdalur (Figure 1). The wide sector contains intracanyon lavas erupted at around 9000 yr BP and later rapidly incised (Tómasson, 2002; Waitt, 2002). The canyon must therefore predate the present Interglacial period, and peak flood stages will have been influenced by local changes in canyon cross-section in the early Postglacial period. In the valley centre, these lavas have been eroded into distinctive scabland topography, while slackwater sediments have been deposited in low-energy marginal embayments where flood waters were shallow (A, Figure 1). Huge gravel bars and megaripples laid down in the last megaflood form major landforms in this sector (B and C, Figure 1), though most of the wetted perimeter comprises sculpted scabland. The present canyon floor lies *c.* 90 m below the highest flood level reached during the Holocene.

The study section (circled cross in embayment A, Figure 1) is the bank of a local stream crossing a shallow, sediment-floored marginal embayment at an altitude of 190–220 m a.s.l. Sediments are intermittently exposed over several hundred metres and represent the eastward-tapering edges of thin depositional wedges deposited close to peak stages when waters flooded the embayment floor. The downslope margin of the sediment infill is the trimmed bank of a younger spillway channel formed by the '2500 yr BP' megaflood. This spillway is part of a giant bar complex (0.4 km^2) formed by overspill from the main canyon immediately to the west. Sediments exposed in the embayment are black flood sands interbedded with peat soils containing *Betula* roots and stems, tephra and pale diatomaceous silt in fine lenses and in surface ponds. The logged profile (Figure 2) comprises an upper 1.0 m exposure located 30 m upstream from the lower 2.1 m of the profile. The land surface above the profile is waterlogged and poached, and younger sediments, if they were ever deposited, have been eroded away.

Stratigraphy and dating

The profile contains two thick medium-to-coarse black sand layers that are identical in texture and composition to flood-laid sands described by Waitt (2002) at a section to the west side of the canyon (D in Figure 1). The lowest exposed unit in the stream bed is a peat containing woody debris of *Betula pubescens*. Roots, twigs and stems up to 50 mm in diameter are concentrated at the upper surface of the peat in sharp contact with the overlying sand. The size of the stems is indicative of the taller woodland that characterized many lowland areas of Iceland in the 'Early Bog Period' of *c.* 2500 to 1000 yr BP

(Einarsson, 1961, 1963). The lower 0.55-m-thick flood sand contains several fine gravel layers and is bounded by sharp upper and lower contacts. Above, 0.26 m of interlayered thin peats and grey silts separate it from the 0.8-m-thick upper flood bed. The main sand unit comprises crudely bedded medium to coarse sand with centimetre-scale fining-upward units. Fine gravel layers grade up from sharp bases into coarse sand. This unit continues 30 m up the stream bank, where it is overlain by traces of organic material, immediately below the distinctive couplet of fine-grained white and black Hekla 4 tephra. Electron-probe microanalysis has provided geochemical confirmation of this diagnosis (Figure 3). Above the tephra are thin beds of peaty sand, peat and silt.

Two pairs of samples were collected for radiometric dating. Two samples of bark (SUERC-2785 and SUERC-2786) from the *Betula* stems at the contact between the lowest peat and the lower flood sand provide as close a date as possible for the onset of the lower flood, given that the birch woodland had been destroyed by the flood waters and deposition of the flood sand. SUERC-2789 was a woody macrofossil extracted from the peat at the lower contact of the upper flood sand, and SUERC-2791 a sample of the peat in contact with the sand. Together, these samples date the deposition of the upper flood sand.

Samples were digested in 2M HCl (80°C for 8 h), washed in distilled water to remove mineral acid then digested in 1M KOH (80°C for 2 h). The digestion was repeated until no further humics were extracted. The residue was rinsed free of alkali, digested in 1M HCl (80°C for 2 h) then rinsed free of acid, dried and homogenized. The total carbon in a known weight of the pre-treated sample was recovered as CO_2 by heating with CuO in a sealed quartz tube. The gas was converted to graphite by Fe/Zn reduction.

The two dates within each pair are indistinguishable at the one sigma confidence level (Table 1). They date the earlier flood to 4432 ± 32 yr BP (SUERC-2785) and 4397 ± 29 yr BP (SUERC-2786) and the later flood to 4085 ± 30 yr BP (SUERC-2789) and 4044 ± 30 yr BP (SUERC-2791), providing mean dates of 4415 yr BP and 4065 yr BP for the two floods. These are consistent with the age of 3834 ± 15 yr BP for the Hekla 4 tephra (Dugmore *et al.*, 1995), which was deposited upon vegetation that had colonized the surface of the upper flood sand. Calibrated ages of the two flood sands are 5020 and 4610 cal. yr BP (Table 1) based on version 5.0 of the Stuiver and Reimer (1993) program using the calibration data set of Reimer *et al.* (2004).

Discussion

In a recent review of the history of megafloods in the Jökulsá á Fjöllum, Waitt (2002) presents a section through 9 m of

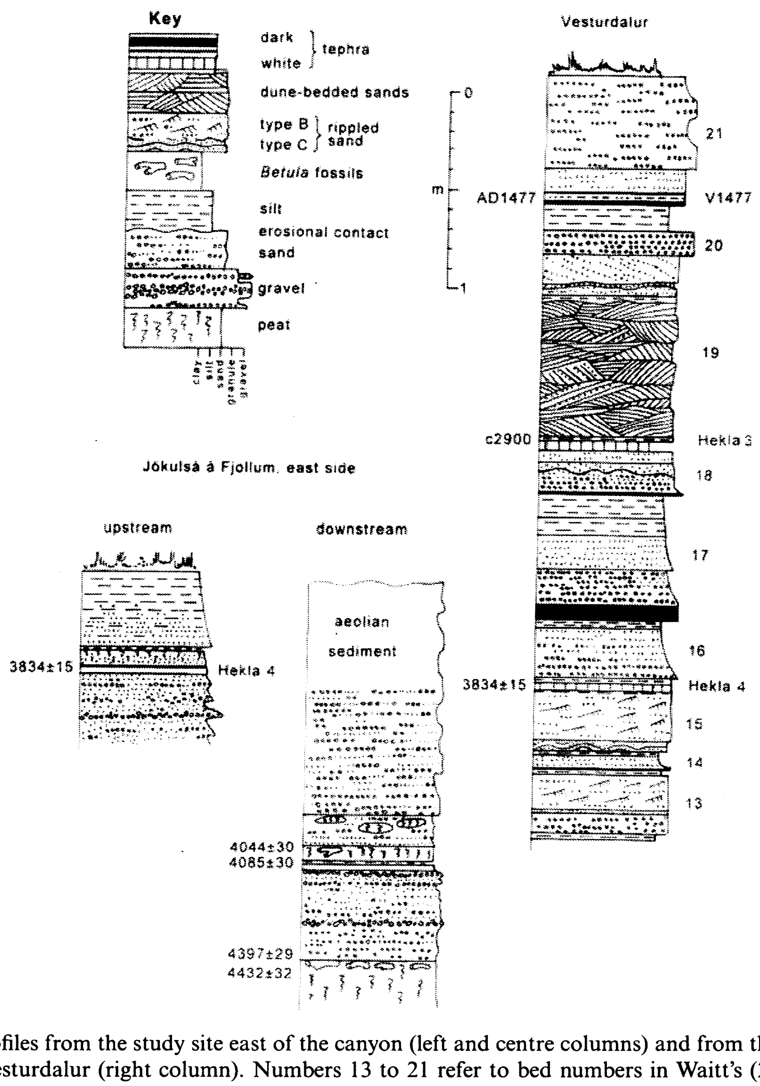

Figure 2 Measured profiles from the study site east of the canyon (left and centre columns) and from the upper part of the 9 m section west of the canyon above Vesturdalur (right column). Numbers 13 to 21 refer to bed numbers in Waitt's (2002) log of the same section, cross-referenced with the 2003 survey according to tephra layers. The location of radiocarbon dates on wood fragments and peat macrofossils is shown in the central column. All dates are ^{14}C years BP except for the historical AD 1477 tephra

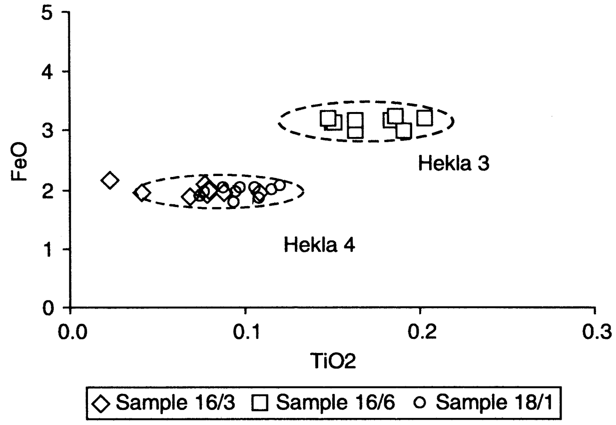

Figure 3 FeO/TiO_2 plot of samples from the two silicic tephras in the section above Vesturdalur (diamonds, squares) and from the silicic layer of the couplet in the radiocarbon-dated profile east of the canyon (open circles). The dashed lines show the fields for the Hekla 3 and Hekla 4 tephras based on reference data from the Tephrabase website (http://tsunami.geo.ed.ac.uk/~tephra/, last accessed 23 March 2006).

Holocene sediments above Vesturdalur (Figure 1). This spectacular section includes *c.* 16 beds of flood sands, the youngest immediately above the Hekla 4 tephra. The section is at a similar altitude (*c.* 190 m a.s.l.) and directly across the widest part of the canyon from the study site reported here (D in Figure 1) and the upper 5 m were re-measured in detail in July 2003 (Figure 2). The Hekla 4 tephra allows precise correlation between the two sites, indicating that the upper and lower flood sands on the eastern margin represent the same floods as beds 14 and 15 in Waitt's profile.

The Vesturdalur section (Figure 2) contains five distinct facies, (1) to (5), the disposition of which shows a trend from flood-dominated sedimentation lower in the section to aeolian-dominated resedimentation above. (1) Grey/black rippled flood sands are the characteristic units making up the lower section. Individual flood units contain multiple fining-up sequences. (2) Locally resedimented flood sands occur in association with some of the main flood units. (3) Thin aeolian orange-brown silty sands mark periods of background sedimentation at very low rates between floods, and in places contain (4) primary airfall tephras. Basaltic ashes of unknown age, derived from local volcanoes, contrast with the silicic Hekla 3 and 4 tephras and the blue-grey Veiðivötn AD 1477 tephra, which provide age constraints. (5) The upper units are dominated by grey/black aeolian sands whose internal structures include dune-bedding and whose transport directions contrast with those of the primary flood deposits. These upper sands were apparently blown from exposed faces along the eroded face of the sediment stack to be redeposited on the terrace surface.

What is clear by correlation between the eastern and western profiles is that the two floods dated in this paper are nearly the last in a long sequence that dominated sedimentation throughout the first half of postglacial time (about 9000 years in this area). Only two flood units overlie the Hekla 4 tephra above Vesturdalur, and apparently only one of these is represented east of the canyon. Older flood sediments presumably lie beneath the topographic floor of the embayment at the study site.

The radiometric ages accord with the tephrochronological date and show that flood peaks ceased to reach 190 m a.s.l. shortly after 4000 yr BP. The only later flood of comparable stage was the post-Hekla-3 flood at *c.* 2000–2500 yr BP, described by Elíasson (1977) at Ásbyrgí and by Waitt (2002) throughout the canyon. This flood was responsible for deposition of surviving giant bars and megaripples (Figure 1), and clearly trimmed the scarps of the preserved sediment stacks in high lateral positions. The flood peak must therefore have been a few metres below those of the early and mid-Holocene floods, but this was sufficient to prevent slackwater deposition on the surfaces of embayment fills.

Our observations raise three questions for discussion. Could the floods have been clustered in time rather than distributed over several millennia? Why was the last flood such an isolated occurrence? And why has the frequency of the really large megafloods suddenly decreased?

The orange-brown aeolian layers of facies (3) are intercalated throughout the flood sands in the lower part of the section, and indicate quite long intervals between floods. In Waitt's (2002) profile, 14 aeolian silt layers below the Hekla 4 tephra have a total thickness of *c.* 1 m. If this thickness represents the minimum background aeolian accumulation (because of possible flood erosion of some layers), it gives an accumulation rate of $\geq$ *c.* 0.2 mm/yr over *c.* 5000 years. For comparison, rates of aeolian deposition are characteristically 0.1–0.3 mm/yr in the lowlands of pre-settlement Iceland (Dugmore *et al.*, 2000). Therefore the estimated rate in the Vesturdalur section is consistent with floods fairly evenly distributed throughout the early and mid-Holocene.

If the *c.* 16 large floods represented by the Vesturdalur stack were distributed over about five millenia, a mean frequency of similar peak stages is estimated to be one flood per three centuries. The two ^{14}C-dated floods were four centuries apart. Subsequently, there has been apparently only one similar flood at *c.* 2000–2500 yr BP. The peak flow of this last flood has been variously estimated at 4.0 to 7.0 $\times 10^5$ m^3/s (Tómasson, 1973, 2002; Waitt, 2002). The flood frequency recorded by the Vesturdalur stack represents a level of risk to the present population that is an order of magnitude greater than floods post *c.* 3500 yr BP, making it important

Table 1 Calculation of mean calibrated age for each pair of radiocarbon samples.

Sample code	Conventional age (yr BP $\pm 1\sigma$)	Calibrated age range at 2σ (yr BP)[a]	Calibrated age
SUERC-2785	4432 ± 32	4875–5276	5080
SUERC-2786	4397 ± 29	4878–5045	4960
Mean calibrated age			5020
SUERC-2789	4085 ± 30	4445–4807	4630
SUERC-2791	4044 ± 30	4424–4782	4600
Mean calibrated age			4610

[a]Based on the calibration data set of Reimer *et al.* (2004).

to understand whether preserved sediments faithfully record actual flood frequency.

Four possible causes of a reduction in the frequency of peak megaflood stages can be identified: (i) a reduction in the frequency and/or scale of subglacial eruptions in the Kverkfjöll–Grimsvotn area; (ii) a reduction in ice cover over the volcanoes, preventing formation of km^3-scale subglacial reservoirs; (iii) a re-routing of floods to the south coast; or (iv) an enlargement of the canyon cross-section sufficient to reduce peak flood stages relative to the threshold of the canyon rim. The first two would reduce actual peak discharges; the second two would reduce the frequency and/or magnitude of peak stages. It is perhaps most likely that ice-divide evolution on Vatnajökull, combined with volcanogenic changes in subglacial topography, have directed more recent floods to the south and southeast (such as the 1996 Gjalp event, Guðmundsson *et al.*, 1997). Modest cross-section enlargement of the Jökulsá canyon will also have occurred in the last few millennia, though not to the extent that peak stages would have been abruptly and dramatically reduced so that evidence of very large floods has not been preserved. There is no evidence for a reduction in either volcanic activity over the mantle plume, or in ice cover. In fact Vatnajökull has probably increased in volume and extent in recent millennia. A cautionary note is that no observed or historically recorded floods are of the same order of magnitude as those which deposited the sediments described in this report, so risk assessments based on data from the last *c.* 1200 years may not be a realistic guide to the potential flood hazard.

Conclusions

Four radiocarbon dates provide precise dates of 4415 yr and 4065 yr BP (5020 and 4610 cal yr BP) on the Holocene maximum flood stages in the Jökulsá á Fjöllum. The younger flood is (or very nearly is) the last in a sequence of about 16 megafloods for which sedimentary evidence is preserved. An approximate frequency of one flood per three centuries characterized the five millennia up to *c.* 4000 yr BP for peak flows exceeding 7.0×10^5 m^3/s. More recent megafloods have been rare, possibly because changes to Vatnajökull have redirected flood routeways to the south coast of Iceland.

The Jökulsá á Fjöllum flood chronology indicates that very large subglacial reservoirs formed beneath Vatnajökull during repeated volcanic eruptions in the early to mid-Holocene, consistent with the continuous presence of a large composite icecap over the southeastern highlands throughout the post-glacial period.

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