Veðurstofa Íslands
Report

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Return period for avalanches on Flateyri

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CONTENTS

ABSTRACT

The return period corresponding to the runout of the avalanche on 26.10.1995 on Flateyri is estimated to be approximately 150 years using a Gumbel distribution to model the statistical distribution of runout of avalanches from Skollahvilft. Different assumptions regarding the frequency of relatively short avalanches and different statistical methods for the treatment of the avalanche runout data lead to a variation in the estimated return period of avalanches, reaching the runout of the 26.10.1995 avalanche, ranging from 80 to 310 years. If a similar analysis is carried out with the 26.10.1995 avalanche omitted from the dataset, the return period estimate changes to 310 years. An avalanche reaching about 200 m longer than the main front of the 26.10.1995 avalanche, *i.e.* essentially to the ocean on the far side of the reef, is determined to have a return period of approximately 1150 years.

1. INTRODUCTION

The return period of avalanches on Flateyri has been estimated by several different methods. Þorsteinn Jóhannesson (1997) applied Gumbel statistics to the snow thickness in the starting zone and used a physical model to compute the runout distance. He determined the parameters in the statistical distribution by fitting them to the dataset of recorded runout distances. He found the return period of the 26.10.1995 avalanche to be approximately 120 years and a return period corresponding to the tip of an avalanche reaching all the way to the ocean on the far side of the reef was found to be between 500 and 1000 years.

David M. McClung (1996) used a different approach involving a simulation model based on extreme value statistics and an application of the estimated frequency of avalanches on Flateyri. He found the return period corresponding to the runout of the 26.10.1995 avalanche to be approximately 140 years. The return period corresponding to an avalanche reaching about 150 m further or approximately to the ocean on the far side of the reef was found to be approximately 350 years.

Cristopher J. Keylock (1996) also used extreme value statistics and an application of the estimated frequency of avalanches on Flateyri to derive both return period and risk as a function of distance from the mountain above Flateyri. He found the return period of the 26.10.1995 avalanche to be less than 100 years and estimated a risk of a fatal accident of about 0.001 per year for inhabitants in the area where the avalanche terminated,

Investigation of avalanches on Flateyri after the catastrophic avalanche on 26.10.1995 has brought to light more information about past avalanches than was available when the above studies were made. Avalanches in 1936 and 1953 appear to have reached further than previously assumed and avalanches that fell in 1919, 1938-40, 1955, 1958, 1960 and 1963-65 were missing from the archives of reported avalanches until recently. In the present report, the currently available information about runout distances of avalanches from Skollahvilft are summarised and a return period analysis based on Gumbel statistics is presented. The report is meant to serve as background material for the appraisal of avalanche defences for Flateyri which has been prepared by VST and NGI (1996). Avalanches from Innra-Bæjargil are not considered here, but will be analysed in the same manner in a follow-up report. A forthcoming report about the avalanche history of Flateyri contains descriptions of the individual avalanches and maps of the avalanche outlines (Haraldsdóttir, in press).

2. DATASET

There are 23 recorded avalanches from Skollahvilft in the avalanche archives of the Icelandic Meteorological Office (Haraldsdóttir, 1997). Several avalanches are reported for some of the years, some of the smaller avalanches did not reach the mounds, which are located below Skollahvilft at 30-35 m a.s.l. and information about two avalanches is incomplete and their runout cannot be estimated. The following table lists the longest avalanche of each year in the order of decreasing runout distance, x, omitting years when avalanches did not reach the mounds. The runout distance in the table is measured from the estimated rupture zone of the 26.10.1995 avalanche along a profile labeled "flat02ab" in the profile archives of the IMO. The runout distances in the table do not represent the outermost tip of the avalanches. Rather, they represent the distance to a point, where the width of the tongue has become much less than the width of the main tongue as further discussed below.

Table 1: Recorded snow avalanches on Flateyri 1919-1995 with the longest horizontal reach of each year.

Date	"Average" runout distance of the main tongue, x (m)
26.10.1995	1835
02.04.1953	1715
20.03.1936	1715
1963-65	1665
1938-40	1665
11.02.1974	1655
10.11.1969	1585
14.03.1958	1585
1955	1585
about 1919	1585
29.11.1979	1560
1960	1535
12.11.1991	1495
01.04.1987	1485

For comparison with the runout distances in the table, the distance to the ocean from the estimated rupture zone along the profile "flat02ab" is 2035 m, and the distance to the β-point (10°-point) along the profile is 1365 m. The distance along the profile to the top of the breaking mounds located at 30-35 m a.s.l. is approximately 1335 m. The location of the $(\alpha - \sigma)$-point of an α/β-model for Icelandic avalanches, $\alpha = 0.85\beta$, $\sigma_{\Delta\alpha} = 2.2°$ (Lied and Bakkehøi, 1980; Jóhannesson, 1998), for this profile is at approximately 1930 m and a similar model for Norwegian avalanches, $\alpha = 0.93\beta$, $\sigma_{\Delta\alpha} = 2.1°$, leads to an $(\alpha - \sigma)$-point at 1720 m.

The return period of avalanches may be given as a function of the distance along the path from the rupture zone or from some other convenient reference point. A return period based on the location of the snout of the avalanches would not directly give the return period of avalanches hitting buildings at the specified distance, because the tip of avalanches is often narrow and only a fraction of the width of the tongue somewhat upstream. The runout distances in Table 1 are measured along profile "flat02ab" to a point near the end of the avalanche outline where the width of the avalanche is still "appreciable". This is done so that the runout distance represents a location where the avalanche hits a significant fraction, say on the order of one half, of buildings that are approximately at this distance along the profile. With the exception of the 1960 avalanche and avalanche reported around 1980 with an unknown runout, long avalanches from Skollahvilft tend to be wide enough to cover much of the runout area above a stopping position defined in this way. Long, very narrow avalanches covering only a small fraction of the width of the runout area are not relevant for Flateyri in this connection. Therefore, a more elaborate treatment of the width of the area covered by the avalanche is not justified. The return periods derived from the data in Table 1 should thus to a first approximation represent return periods of avalanches hitting buildings at the corresponding runout distance. For comparison, the runout distance to the tip of the 26.10.1995 avalanche was approximately 1925 m, *i.e.* 90 m longer than the runout given in Table 1.

The recorded avalanches are from the period 1919 to 1997. Two relatively short avalanches are recorded during the last decade of the period, but before that time only avalanches long enough to reach about 10 m a.s.l. or lower, or to the sea in the "Bót" region to the east of Flateyri, are recorded. This is due to a more systematic registration of avalanches in recent years compared with the earlier part of the period, when the uppermost buildings of the village were not located as close to the mountain as in recent decades.

The lack of recorded, relatively short avalanches before approximately 1987 is certainly not because no such avalanches fell before this time. It is estimated that longest yearly avalanches reaching $x \approx 1500$ m have occurred once or twice per decade on average (such avalanches are recorded in 1987 and 1991 but not before that time), and that longest yearly avalanches reaching into the mounds at $x \approx 1365$ m have occurred 3-5 times per decade (Jón Gunnar Egilsson, Magnús Már Magnússon and Svanbjörg H. Haraldsdóttir, personal communication; my own subjective judgement from the scarce data that exist and from discussions with people from Flateyri). We assume here that the two avalanches with an unknown runout in the archives of IMO may be taken into account through this estimate of unreported avalanches before 1987.

Another "problem" with the data in Table 1 is that the period 1919-1997 has the very long avalanche on 26.10.1995 near the end, and the timing of the analysis presented here may in a certain sense be considered caused by the release of this avalanche. Similarly, the start of the period in 1919 is determined by the avalanche recorded in that year. A return period analysis should preferably be based on data from a time window which is independent of the data. This nature of the data can be treated in a more satisfactory way using maximum likelihood methods, but here it will be assumed that the recorded avalanches span the nine decades from 1908 to 1997. One may expect some lack of reported avalanches in the early decades of the period, in particular before 1936, when no avalanches are reported, except for the avalanche in 1919. However, very long avalanches in the period between 1908 and 1936 might have been reported had they occurred, and the effect of a possible lack of avalanches before 1936 on the analysis may be partly compensated by the end effects discussed above.

3. GUMBEL STATISTICS

A Gumbel distribution will be fitted to the longest reported runout distance of each year as tabulated in Table 1 in order to determine the return period as a function of distance along the path. Although the table does not show the longest avalanche of every year in the time period 1908 to 1995, it is possible to use the data in the table by assuming that it contains the longest yearly avalanches beyond a given reference distance during the period.

The Gumbel distribution or type I extremal distribution (Kite, 1988) is given by

$$D(x) = e^{-e^{-(x-a)/b}} \quad , \quad d(x) = D'(x) = e^{-e^{-(x-a)/b}} e^{-(x-a)/b}/b \quad , \tag{1}$$

where x is the horizontal reach of an avalanche, $D(x)$ is cumulative probability, $d(x)$ is the probability density and a and b are parameters.

Given values for the parameters a and b, one may compute the horizontal reach, x_T, corresponding to a specified return period T (in years)

$$x_T = a + b(-\log(-\log((T-1)/T))) \quad , \tag{2}$$

and the return period, T_x, corresponding to a specified runout distance x as

$$T_x = 1/(1 - e^{-e^{-(x-a)/b}}) \quad . \tag{3}$$

Several methods for determining the parameters in the distribution given by eq. (1) exist, for

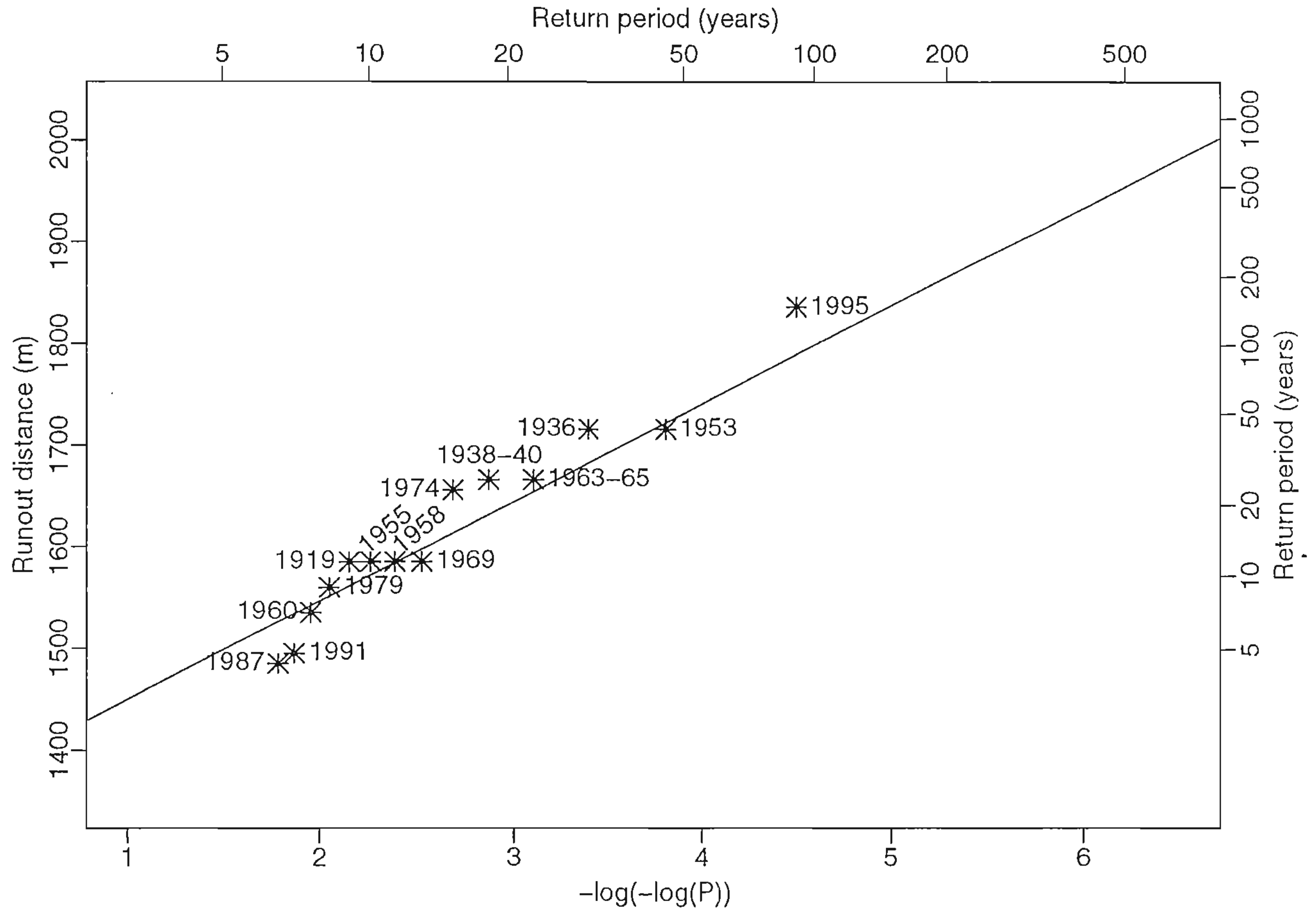

Figure 1. Recorded horizontal runout distance of longest yearly avalanches from Skollahvilft in the period 1908-1997 plotted against the Weibull plotting positions $-\log(-\log(P)) = -\log(-\log(i/(n+1)))$, where P is cumulative probability, i is the index of the avalanches after the they have been ordered according to runout distance and n is the total number of years (see text for explanation). The line represents a Gumbel distribution estimated with the maximum likelihood method based on avalanches reaching as far as or further than the avalanche in 1979. The return period axis on the right is computed from this line.

example the maximum likelihood method, the method of moments and a simple graphical least squares method (*cf.* Chow, 1964; Kite, 1988). In Appendix A, it is shown how the maximum likelihood method and the simple graphical method can be used to estimate the model parameters a and b in eq. (1) from the longest avalanches of each year which reach beyond a given reference distance. The maximum likelihood method will be used in this report since it gives the best parameter estimates and eliminates the need for using a somewhat arbitrary formula for computing so-called plotting positions (*cf.* Appendix A).

The Gumbel distribution is widely used in the analysis of extremes in hydrology and meteorology, in addition to log-normal and log-Pearson distributions. Examples of the use of these distributions in for extreme analyses by Icelandic scientists can be found in Guðmundsson (1993) and Jónsson (1995).

Analysis of extreme events is usually based on one of two possible methods. The first method, which is applied here, is to choose the longest or most extreme event within each of subsequent time periods of a fixed length. The time periods are usually one year long, but their length may be different depending on the problem. The other method is based on choosing all extremes above a certain base value (sometimes called the partial duration method). The first method has the advantage of being simpler and it is also sometimes better suited to engineering aspects of a problem since repeated loss due to floods or other extreme events is often not relevant unless a certain time passes between the events. The second method has the advantage that less data is left out of the analysis, *i.e.* two or more extreme events in the same year are all used. It has been shown that computed return periods of extreme events are not much affected by the choice of the method as long as the return period is appreciably longer, say 5-10 times longer, than the length of the time period which is used in the first method (Kite, 1988).

4. ESTIMATION OF RETURN PERIODS

Figure 1 shows a double logarithmic plot of the avalanches tabulated in Table 1 assuming that they are the longest maximum yearly events of a 90 year period. The 1987 and 1991 avalanches, and perhaps also the 1960 avalanche, fall below a trend defined by the other points as would be expected if many avalanches of similar lengths to these avalanches are missing from the dataset. This indicates that one should either omit the avalanches from 1960, 1987 and 1991, or add an appropriate number of similar avalanches to the dataset, before a maximum likelihood model is estimated or a least squares line is fitted through the points. Figure 1 also shows a line representing the maximum likelihood Gumbel distribution based on avalanches reaching as far as or further than the avalanche in 1979. The model parameter estimates a = 1354 and b = 97 for this model were derived as described in Appendix A using x_{min} of 1550 m, which corresponds to runout between the runout of the 1960 and 1979 avalanches (*cf.* eq. (A1)). The model indicates that the return period corresponding to the runout of the 26.10.1995 avalanche is equal to 146 years. The statistical uncertainty of this estimate is discussed in Appendix A where it is concluded that the range 80 to 310 years represents the 25% and 75% quartiles of the statistical distribution of the return period estimate.

The following table lists runout distances corresponding to a sequence of return periods estimated with the maximum likelihood model shown in Figure 1. Figure 2 shows the locations corresponding to the runout tabulated in Tables 1 and 2 on a map of Flateyri together with the measured outline of the avalanche on 26.10.1995.

Table 2: Runout distance corresponding to different return periods for a maximum likelihood Gumbel distribution with a = 1354 and b = 97 (*cf.* Figure 1).

Return period T_x (years)	Runout distance x (m)
5	1498
10	1571
20	1641
50	1731
100	1798
200	1865
500	1954
1000	2021
2000	2088

The runout distances corresponding to 1000 and 2000 year return periods do of course represent an extreme extrapolation of the data in the 90 year time frame, on which the analysis is based, and must be considered to be highly uncertain. The random sampling from a Gumbel distribution described in Appendix A indicates that the statistical uncertainty of the runout estimates for the 100 and 1000 year return periods is ±50 and ±100 m, respectively (estimated from the location of the 25% and 75% quartiles as for the return period of the 26.10.1995 avalanche above).

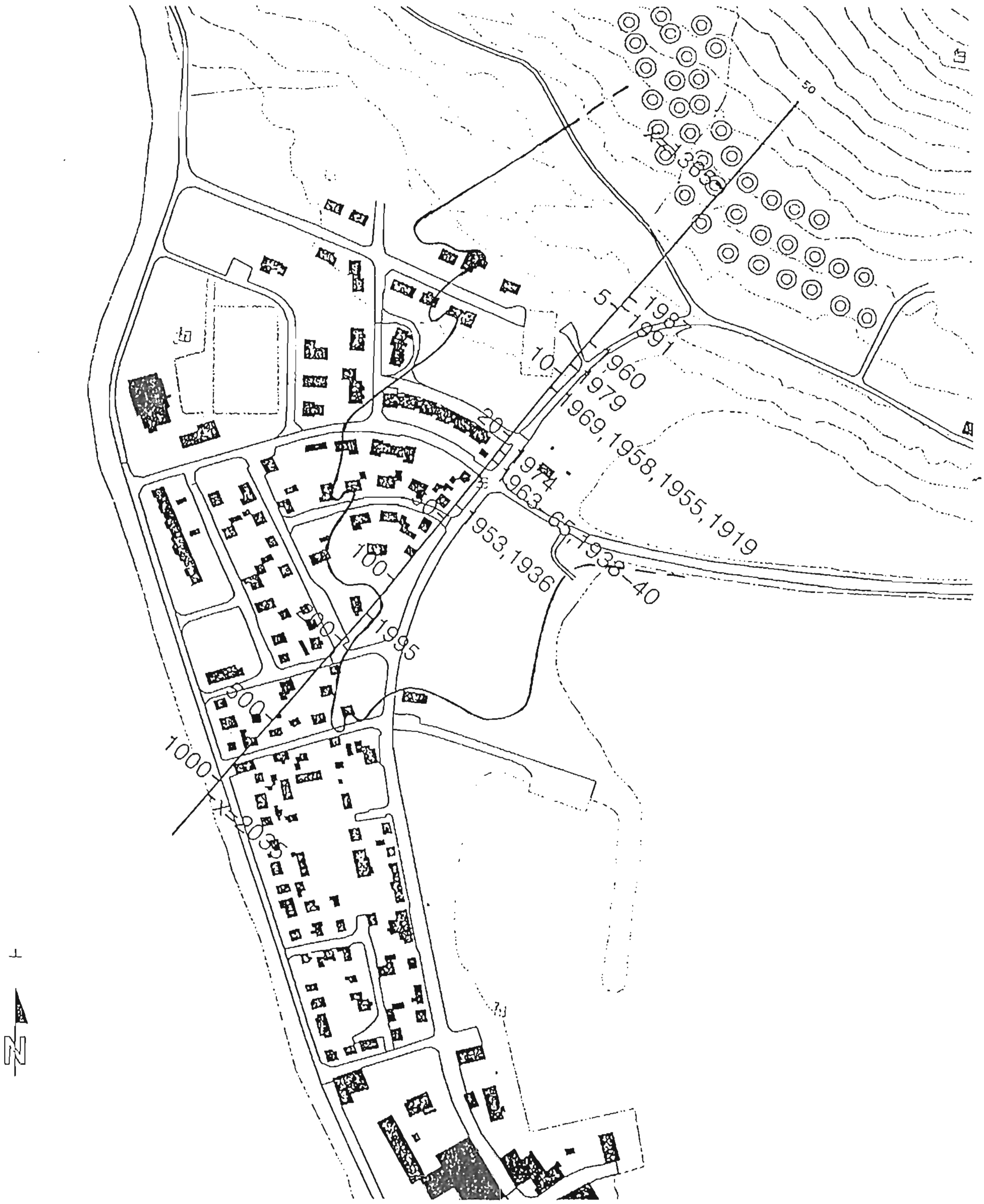

Figure 2. Runout distance corresponding to different return periods tabulated in Table 2 plotted along profile "flat02ab" on a map of Flateyri. Return periods are indicated with labels to the left of the profile. "Average" runout of recorded avalanches is labeled with the corresponding date to the right of the profile. The map also shows the measured outline of the avalanche on 26.10.1995.

Avalanches that reach the ocean on the far side of the reef (x=2035 m) have a return period

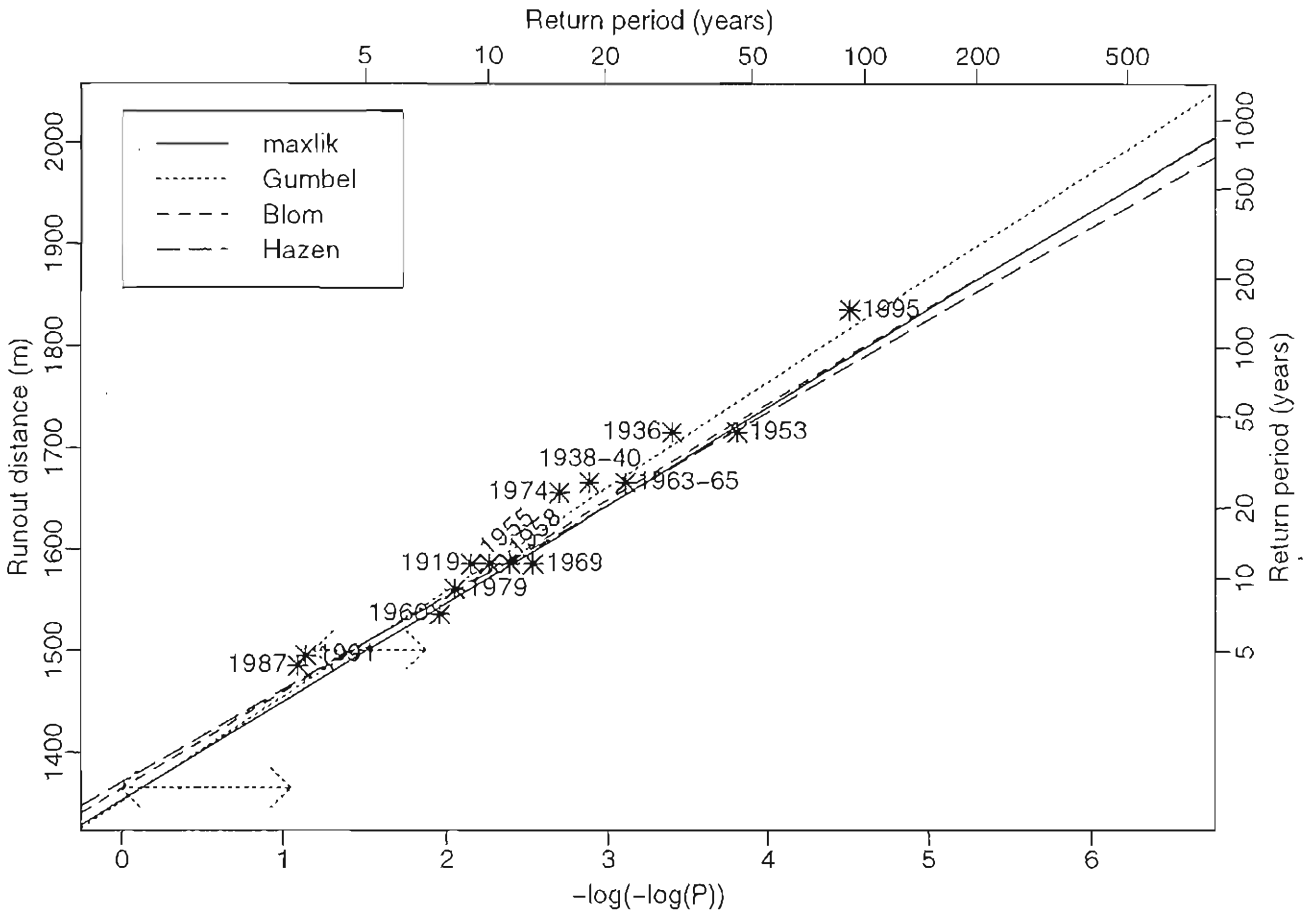

Figure 3. Recorded horizontal runout distance of longest yearly avalanches from Skollahvilft in the period 1908-1997 (symbols) including an estimated number of relatively short avalanches (indicated with dashed arrows) plotted against the Weibull plotting positions $-\log(-\log(P)) = -\log(-\log(i/(n+1)))$ in the same way as in Figure 1. The solid line shows a maximum likelihood Gumbel distribution based on avalanches reaching as far as or further than the avalanche in 1979 (the same model as in Figure 1). The dashed and dotted lines represent Gumbel distributions derived with the least squares method for three different choices of plotting positions (see text). The return period axis on the right is computed from the maximum likelihood model shown as a solid line.

approximately equal to 1150 years.

One may ask to what extent the above estimates depend on the occurrence of the 26.10.1995 avalanche and the fact that it reached as far as it did. If this longest avalanche is omitted from the dataset together with the 1960, 1987 and 1991 avalanches, then the maximum likelihood estimate of the return period corresponding to the runout of the 26.10.1995 avalanche becomes about 310 years. Therefore, the conclusion that avalanches reach far into the populated area on Flateyri on a time-scale of one to a few centuries is not critically dependent upon this single event.

Another possibility is to take missing avalanches, shorter than approximately 1500 m, into account by adding the expected number of such avalanches to the dataset before the statistical analysis. As mentioned above, it is expected that longest yearly avalanches reaching $x \approx 1500$ m occur once or twice per decade on the average and longest yearly avalanches reaching the mounds at $x \approx 1365$ m occur in approximately 3-5 out of every ten years. Judging from the recent additions to the records of long avalanches on Flateyri it is very likely that some avalanches longer than 1500 m from the time period after 1908 are still missing from the records, but the data given in Table 1 are the best currently available.

Figure 3 shows a double logarithmic plot of the avalanches tabulated in Table 1 together with arrows indicating added 1500 m and 1365 m long avalanches which are assumed to have been longest yearly avalanches before 1987 (1.5 per decade = 12 avalanches with x = 1500 m and 4 per decade = 32 avalanches with x = 1365). The figure also shows the maximum likelihood Gumbel distribution from Figure 1 as a solid line. Three Gumbel distributions derived from the amended dataset with the least squares methods for different choices of plotting positions are shown as dashed and dotted lines. Since the estimates of the missing avalanches must be considered more uncertain than the information from Table 1, each group of added avalanches was weighted in the least squares computations such that it entered the dataset with a combined weight corresponding to only one of the avalanches from Table 1. The added 1500 m long avalanches were, thus, given the weight 1/12 and the added 1365 m long avalanches were given the weight 1/32. Each group of added avalanches is spread over a range of plotting positions as shown in Figure 3, but the group only affects the statistical models as the equivalent of one avalanche due to the weighting. The return periods corresponding to the runout of the 26.10.1995 avalanche according to the three least squares Gumbel models in Figure 3 are 108, 144 and 164 years for the Weibull, Blom and Hazen plotting positions, respectively. These models do therefore not lead to very different results compared with the maximum likelihood model in Figure 1. The Weibull plotting positions lead to the shortest return period estimate and the Hazen positions to the longest estimate (see the return period axis at the top of the figure) as expected from the bias observed in random samples from a Gumbel distribution in Appendix A.

5. DISCUSSION

Several different methods for estimating the return period of avalanches from Skollahvilft on Flateyri yield a return period of about 150 years for a location corresponding to the main tongue of the 26.10.1995 avalanche. The number of long avalanches reaching to or beyond the foot of the slope at Skollahvilft is sufficiently high that this estimate changes only by a factor of approximately two when the longest avalanche in the dataset is omitted from the analysis. Statistical uncertainty associated with the small number of available data points indicates that the return period estimate is uncertain by approximately a factor of two.

The runout lengths corresponding to return periods longer than 100 years are of course more uncertain, but the conclusion that avalanches from Skollahvilft may be expected to reach the ocean on the far side of the reef on a time-scale of 500 to 1000 years is common for all analyses of this problem that have been performed.

In a draft version of this report from 1996 (draft VÍ-R96014-ÚR14), the return period corresponding to the runout distance of the avalanche on 26.10.1995 was estimated to be about 100 years. The improved dataset considered here leads to longer return periods for long runout distances and somewhat shorter return periods for short runout distances due to the previously unknown avalanches with intermediate runout length which have been added to the dataset.

6. ACKNOWLEDGEMENTS

Svanbjörg H. Haraldsdóttir provided information about avalanches from Skollahvilft from a preliminary version of a report about the avalanche history of Flateyri. David McClung and Þorsteinn Jóhannesson supplied their estimates for the return periods of avalanches on Flateyri. Guðmundur Guðmundsson gave helpful advise in the derivation of the likelihood function of the maximum likelihood analysis.

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APPENDIX A: Estimation of the parameters in a Gumbel distribution

Maximum likelihood parameter estimates are derived by maximising a likelihood function which is the product of the probabilities of the events that are observed. When longest yearly runout distances are drawn from the Gumbel distribution defined by eq. (1), the likelihood function for the observation of events longer than a specified minimum runout distance, $x_{\min}$, over a period of n years, is given by

$$L(a,b) = (\prod_{i=1}^{m} d(x_i))D^{n-m}(x_{\min}) = (\prod_{i=1}^{m} e^{-e^{-(x_i-a)/b}} e^{-(x_i-a)/b}/b)(e^{-e^{-(x_{\min}-a)/b}})^{n-m} \quad , \tag{A1}$$

where $d(x)$ and $D(x)$ are defined by eq. (1) and m is the number of observations.

Estimates of the parameters a and b are derived by equating the partial derivatives of the likelihood function with respect to the parameters to zero. This leads to the equations

$$\sum_{i=1}^{m} x_i e^{-x_i/b} + (n-m)x_{\min} e^{-x_{\min}/b} - (\mu - b)(\sum_{i=1}^{m} e^{-x_i/b} + (n-m)e^{-x_{\min}/b}) = 0 \quad , \tag{A2}$$

where $\mu = (1/m)\sum_{i=1}^{m} x_i$, and

$$a = b\log(m/(\sum_{i=1}^{m} e^{-x_i/b} + (n-m)e^{-x_{\min}/b})) \quad , \tag{A3}$$

which must be satisfied by the parameters a and b. The above system of equations cannot be solved analytically, even in the simplest case when observations are available for all years ($m = n$). The system of equations can, however, be solved numerically with a computer with a small computational effort.

The simplest method for determining the parameters a and b in eq. (1) is based on fitting a least squares line to a plot of the longest horizontal reach of each year, x_i, against the Weibull plotting positions which are used in Figure 1. The Weibull positions are given by $-\log(-\log(P)) = -\log(-\log(i/(n+1)))$, where P is cumulative probability, i is the index of the avalanches after they have been ordered according to x_i such that $i = n$ for the longest avalanche and n is the total number of years (*cf.* Gumbel, 1958; Kite, 1988). The coefficients a and b are then given as the intercept and slope of the least squares line. The years when no avalanches are reported are taken into account by using the total number of years in the observation period, n, in the computations of the plotting positions, rather than the number of reported avalanches, m, assuming that these are the m longest among the maximum yearly avalanches released during the period. Since the plot is linear in x, it does not make a difference whether the y-ordinate of the plot is the horizontal reach x, distance from the β-point or the runout ratio as used in McClung (1996).

Computing the values of the abscissa for x_i as $-\log(-\log(P)) = -\log(-\log(i/(n+1)))$ as done in Gumbel (1958) and Kite (1988) is somewhat arbitrary and leads to significant bias in the parameter estimates derived from the least squares line. The bias is particularly severe when only the longest events in the time period are recorded as in the problem considered here. In this case only the upper range of the cumulative probabilities are plotted and bias near the upper end of the probability range becomes relatively more important (*cf.* Chow, 1964). Cumulative probability plots are often made using the cumulative probability or plotting positions $(i-0.5)/n$ or more generally $(i-c)/(n+1-2c)$, where c is a number between 0 and 1 (*cf.* Becker, Chambers and Wilks, 1988). Typical values for c are 0, 0.375 and 0.5, which are traditionally termed Weibull, Blom and Hazen plotting positions, respectively (Chow, 1964). The Weibull plotting positions $-\log(-\log(i/(n+1)))$ used in Figure 1 correspond to $c = 0$. Yet another possibility for the choice of plotting positions is $-\log(-\log((i-0.4)/n))$ which is used by McClung, Mears and Schaerer (1989), McClung and Mears (1991) and Keylock (1996) for an analysis of avalanche runout. McClung and Mears (1991) argue

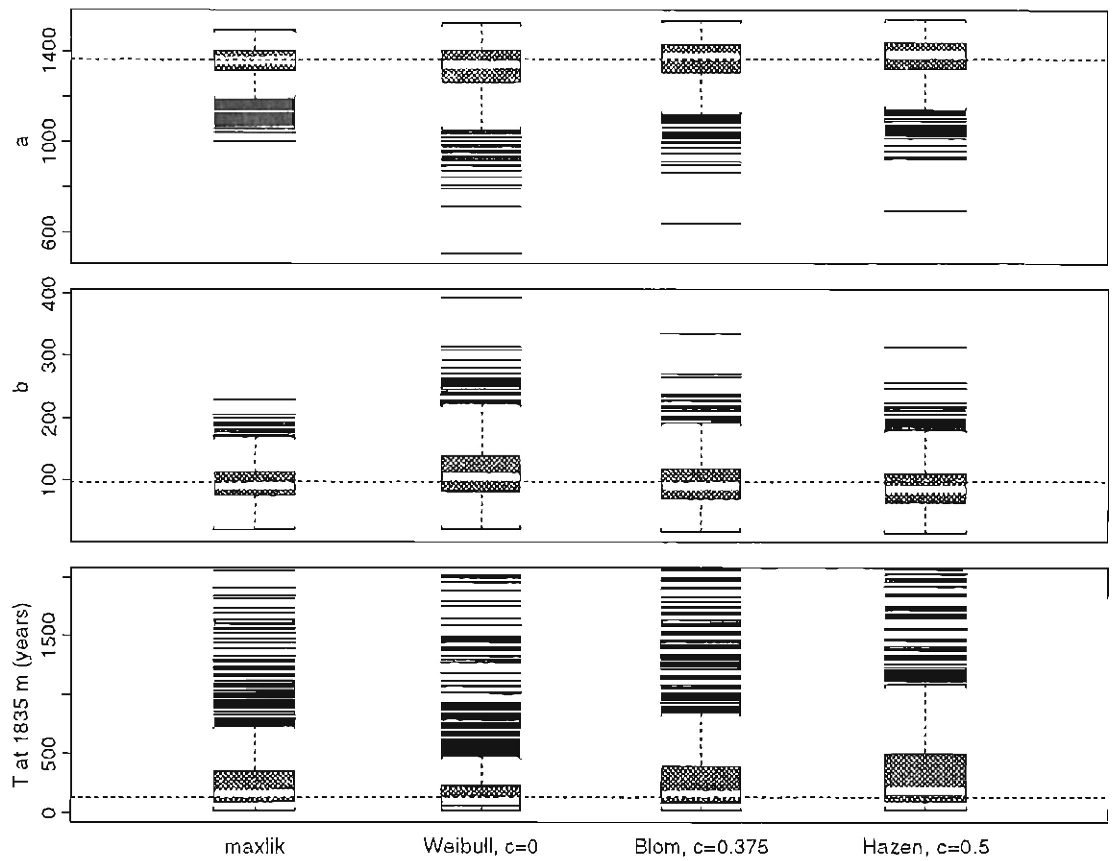

Figure A1. Parameter estimates and an estimate of the return period, T_{1835}, corresponding to the 26.10.1995 avalanche determined for random samples from a Gumbel distribution with $a = 1354$ and $b = 97$. Observations larger than 1550 m are selected from sets with 90 random samples and used for estimating the parameter. The plot shows the results of 1000 such sets. The estimates are computed with the maximum likelyhood method and the least squares method with three different choices for the plotting positions, the Weibull, Blom and Hazen positions. The shaded box with a white line indicates the interquartile range and the median of the estimates and whiskers are drawn to the nearest data point not beyond 1.5 times the inter-quartile range. The horizontal dashed lines correspond to the correct values of a, b and T_{1835}. Several outliers beyond $T_{1835} = 2000$ years are not shown in the lowest panel. The quartiles of a dataset are the points that split the ordered dataset into four sub-sets with the same number of points each. The median is equal to the 50% quartile. The interquartile range is the range between the 25% and the 75% quartiles.

that this choice of plotting positions is superior to other choices of plotting positions, especially for small, censored datasets.

Figure A1 shows estimates of the parameters a and b and an estimate of the return period T_{1835}, which corresponds to the 26.10.1995 avalanche, determined for random samples from a Gumbel distribution with $a = 1354$ and $b = 97$. These values for a and b were found for the Skollahvilft path in a maximum likelihood analysis of the data in Table 1 in the main text. Observations with longer runout than 1550 m were selected from sets with 90 random samples each and used for estimating the parameters with the methods described above. This procedure generates random samples of runout data which correspond to the situation encountered in Skollahvilft where only the largest events during a 90 year period are known. The boxplots in Figure A1 show the distribution of the parameter estimates derived from 1000 such sets. These plots can both be used to assess the uncertainty of the parameter estimates and also to compare the different methods for estimating the parameters.

The lowest panel in Figure A1 shows that approximately 50% of the return periods estimated with the maximum likelihood method are in the range 80 to 310 years, with a median close to $1/(1-e^{-e^{-(x-1354)/97}}) = 146$ years, which corresponds to the a and b values used to generate the datasets. The figure also shows that there is a large number of outliers in the estimates of a, b and T_{1835}, which fall far away from the interquartile range indicated with the shaded boxes. A similar analysis of parameter estimates derived from the uncensored datasets shows that such outliers are not nearly as common when the entire dataset is used (not shown in Fig. A1). This indicates that estimating model parameters or return periods from observations near the extreme end of a dataset, as done here, is associated with a substantial uncertainty.

Comparison of the results for the different methods in Figure A1 shows that the distribution of the least squares estimates of a and b is wider than for the maximum likelihood estimates. The interquartile range of a and b estimated with the least squares methods is 20-70% wider than for the maximum likelihood estimates. In addition, the figure shows that estimates of a, b and T_{1835} corresponding to the Weibull ($c = 0$) and Hazen ($c = 0.5$) plotting positions, which are most often used in practice, are biased. The parameter estimates derived with the maximum likelihood method are not much affected by bias and this is achieved without the somewhat arbitrary choice of c in the definition of the plotting positions. The Blom ($c = 0.375$) plotting positions produce parameter estimates with almost as small bias as the maximum likelihood method. A similar analysis of the plotting positions $-\log(-\log((i-0.4)/n))$ (not shown in Fig. A1), which are suggested by McClung and Mears (1991), indicates that they lead to comparable bias as the Hazen plotting positions.

Table A1 shows the model parameter and return period estimates derived from the avalanches in Table 1 reaching as far as or further than the avalanche in 1979 (*cf.* Figure 1) derived with the four different methods discussed above (using $x_{min} = 1550$ m, which corresponds to runout between the runout of the 1960 and 1979 avalanches, in the maximum likelihood analysis *cf.* eq. (A1)).

Table A1: Model parameters and return period T_{1835}, corresponding to the 26.10.1995 avalanche, estimated with the maximum likelihood method and with the least squares method for three different choices of plotting positions.

Method	a	b	T_{1835}
Maximum likelihood	1354	97	146
Weibull ($c = 0$)	1345	105	104
Blom ($c = 0.375$)	1377	91	152
Hazen ($c = 0.5$)	1390	86	181

The return period estimates in the last column of the table differ from each other by a factor up to 1.7. These differences are, however, smaller than the statistical uncertainty indicated by Figure A1 since the different methods all yield T_{1835} estimates within the interquartile range of the results of the maximum likelihood method which may be considered the best method.

The above considerations indicate that the return period corresponding to the runout of the 26.10.1995 avalanche is in the range 80 to 310 years with a best estimate of approximately 150 years. The range should be interpreted as the locations of 25% and 75% quartiles of the statistical distribution of the return period estimate.