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Controls on glacier surging in Svalbard

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ABSTRACT. The geographical distribution of surge-type glaciers worldwide displays a remarkably non-random pattern. Surge-type glaciers tend to be concentrated in certain glacierized areas and to be completely absent in others. This observation suggests that special conditions are required for surges to occur. However, the factors controlling the spatial occurrence of surge-type behaviour are not known. To investigate this problem we performed probability statistical analysis on a sample population of 615 glaciers in Svalbard. The probability that a glacier in the sample population is surge-type is 36.4%. Within the sampled area there is a spatial variation in the concentration of surge-type glaciers. Several geometric and environmental factors associated with glaciers in the sample population were measured and tested to determine if they are related to the probability of surging. Of the geometric factors tested (length, slope, elevation, orientation and presence or absence of tributaries), only glacier length is related to surging, with surge probability increasing with increasing length. Elevated probabilities of surging were also found for glaciers associated with sedimentary subglacial rocks and sub-polar thermal regimes. The distributions of related factors were used to predict the spatial distribution of surge-type glaciers. However, in each case the individual factors were unable to reproduce the observed pattern of surge-type glacier distribution.

INTRODUCTION

The spatial distribution of surge-type glaciers is enigmatic. A non-random geographic pattern (Raymond, 1987) is characterised by concentrations of surge-type glaciers in certain glacierized areas of the world and their complete absence in others. Large numbers of surge-type glaciers are found, for example, in southeast Alaska and the Yukon (Post, 1969; Clarke and others, 1986), the Pamirs (Dolgushin and Osipova, 1975), central West Greenland (Weidick, 1992), Iceland (Thórarinsson, 1969) and Svalbard (Liestøl, 1993). Yet, no known reports describe surges of glaciers in the European Alps, mainland Scandinavia, New Zealand or the Rocky, Cascade and Coast mountains of North America. This pattern suggests that certain environmental controls are required for surges to occur, although what these controls are is not yet known. Elucidating these controls is important since they are likely to constrain the possible mechanisms by which glaciers can surge. Furthermore, the exact nature of the surge mechanism itself has yet to be resolved (Clarke and others, 1984; Kamb, 1987).

Several studies have already attempted to identify the factors controlling the distribution of surge-type glaciers (Post, 1969; Glazyrin, 1978; Clarke and others, 1984; Wilbur, 1988). With the exception of Post (1969), all these studies involved statistical analysis. Post found that surge-type glaciers had no special geometric requirements and that climatic variations or seismicity were not related to surging in western North America. He did, however, speculate that certain bedrock types might be related to surging, noting that surge-type glaciers were rare in areas of predominantly granitic rocks. Glazyrin (1978) worked with a sample of 62 glaciers (surge-type and non-surge-type) in Central Asia. He found that surging appeared to be related to the ratios of accumulation-zone area to ablation-zone area, and accumulation-zone area to width of the glacier tongue. This latter ratio, according to Glazyrin, represented the "damming" of the firn zone. Clarke and others (1986) conducted a statistical analysis of 2356 glaciers in Canada's Yukon Territory. Several morphometric and topographic parameters were examined, but only glacier length was found to be related to surging. Why long glaciers should have an increased probability of being surge-type has not been fully explained (Raymond, 1987). The study carried out by Wilbur (1988) used a sample of 146 glaciers in Alaska and the Yukon. He concluded that surging tends to occur in glaciers with concave surface profiles and a greater proportion of area at lower altitudes (described by Wilbur as "bottom-heavy" hypsometries). Wilbur suggested that the ultimate control on the distribution of surge-type glaciers is geology, since glacier hypsometry is inherited from mountain hypsometry. Support for this hypothesis came from the observation that hypsometric curves tended to be non-randomly distributed.

None of the above studies has identified firmly what controls the spatial distribution of surge-type glaciers. With the aim of shedding more light on this problem, a statistical analysis was performed on a sample of glaciers on Svalbard.

DATA SOURCES

The high Arctic archipelago of Svalbard has approximately 2100 ice masses, of which a substantial number are known or believed to be of surge type (Liestøl, 1969, 1993; Dowdeswell and others, 1991). It was likely, therefore, that the islands would yield statistically representative sample populations of normal and surge-type glaciers.

Data on individual glaciers were collected specifically for this study. The principal sources of information were Norsk Polarinstitutt's (NP) topographic and geologic map series and aerial photographs of the 55 1:100 000 map sheets. Because of time considerations the study was restricted to glaciers found on ten of the map sheets. The ten selected map sheets were produced in colour. On black-and-white maps the contrast between glaciers and ice-free terrain is often indistinct, which made accurate data compilation more difficult. There are 18 colour maps covering various parts of Svalbard; eight were not used because, individually, they contain very few glaciers.

All of the selected map sheets were located on the island of Spitsbergen (Fig. 1a). The glaciers shown on these maps formed the primary data set. A total of 615 glaciers were in this data set, representing approximately 30% of the total glacier population of Svalbard.

All glaciers on these map sheets were sampled, with two exceptions. The first exception was bodies of ice less than 1 km in length. Examination of these features on small-scale aerial photographs (1:18 000) showed that they are invariably remnant ice patches and not true glaciers. The second exception was plateau ice caps, which were excluded from the sampling because they lacked a single and distinct flow direction. The following data were recorded for each sampled glacier: glacier length, width and area (using a digitizer); maximum and minimum elevations; the presence or absence of tributaries; and compass orientations of the upper and lower regions (corresponding roughly to accumulation and ablation zones).

Geological information on the bedrock underlying each glacier was also recorded for ice masses in the sample population. Geological maps were available for eight of the ten sampled sheets used in this study. Geological data for glaciers located on the remaining two sheets were obtained from an NP 1:500 000 scale geological map.

Because data relating to the thermal regime of all 615 glaciers were not available, an analysis of the relationship between thermal regime and glacier surging was carried out for a smaller data set consisting of 136 glaciers. Yu. Ya. Macheret (personal communication, 1991) provided information concerning the thermal structure of these glaciers, based on the interpretation of radio-echo sounding profiles.

ESTABLISHING A SURGE INDEX

The data recorded for each glacier were completed by assigning a value representing the likelihood that a particular glacier is of surge type (the surge index). The Canadian Glacier Inventory (CGI), from which Clarke and others (1986) obtained their sample population, uses a six-point surge index which describes various degrees of certainty that a glacier is of surge type. In recent work this index has been modified. Clarke (1991) simplified the six-point index to a dichotomous scheme in which glaciers were classified as either surge-type or normal. Wilbur (1988) used the same six-point scheme, but included glaciers in the type 4 category that have been observed to surge but whose surges were minor events. Thus, his type 5 category was reserved for glaciers which had experienced high-magnitude surges. Eventually, Wilbur reduced the index to a threefold classification of normal, intermediate and surge-type categories. In the present study, it was considered that the differences between several of the classes in the CGI were indistinct. Therefore, a modified version of this index, comprising four classes (0–3), was defined. The surge index (i) is described as follows;

$i = 0$: glacier most likely to be normal (no features diagnostic of surging)

$i = 1$: possibly surge-type (1–2 surge-type features)

$i = 2$: probably surge-type (>2 features, and/or historical report of surging)

$i = 3$: most likely to be surge-type ("contemporary" observation).

The number of glaciers in each category is shown in Table 1. Several features were considered to be an indication of surge-type behaviour. These features included looped moraines, anomalous and/or widespread crevassing, pronounced ice ramps, stagnant ice (Meier and Post, 1969) and potholes (Sturm, 1987; Sturm and Cosgrove, 1990). The principal documentary sources of information used in the compilation of the surge index were Liestøl (1993) and Lefauconnier and Hagen (1991). Further references to the behaviour of individual glaciers were contained in scientific papers, theses and historical reports. However, most of the glaciers in the sample population have not featured in the literature on

Table 1. Surge-index distribution and probability scheme for the Svalbard primary data set. The surge probability for the data set is 36.4%

i	n_i	p_i	$p_{s\|i}$	$n_{s\|i}$
0	393	0.639	0.051	20
1	141	0.229	0.894	126
2	26	0.042	0.923	24
3	55	0.089	0.980	54
Total	615	1.000		224

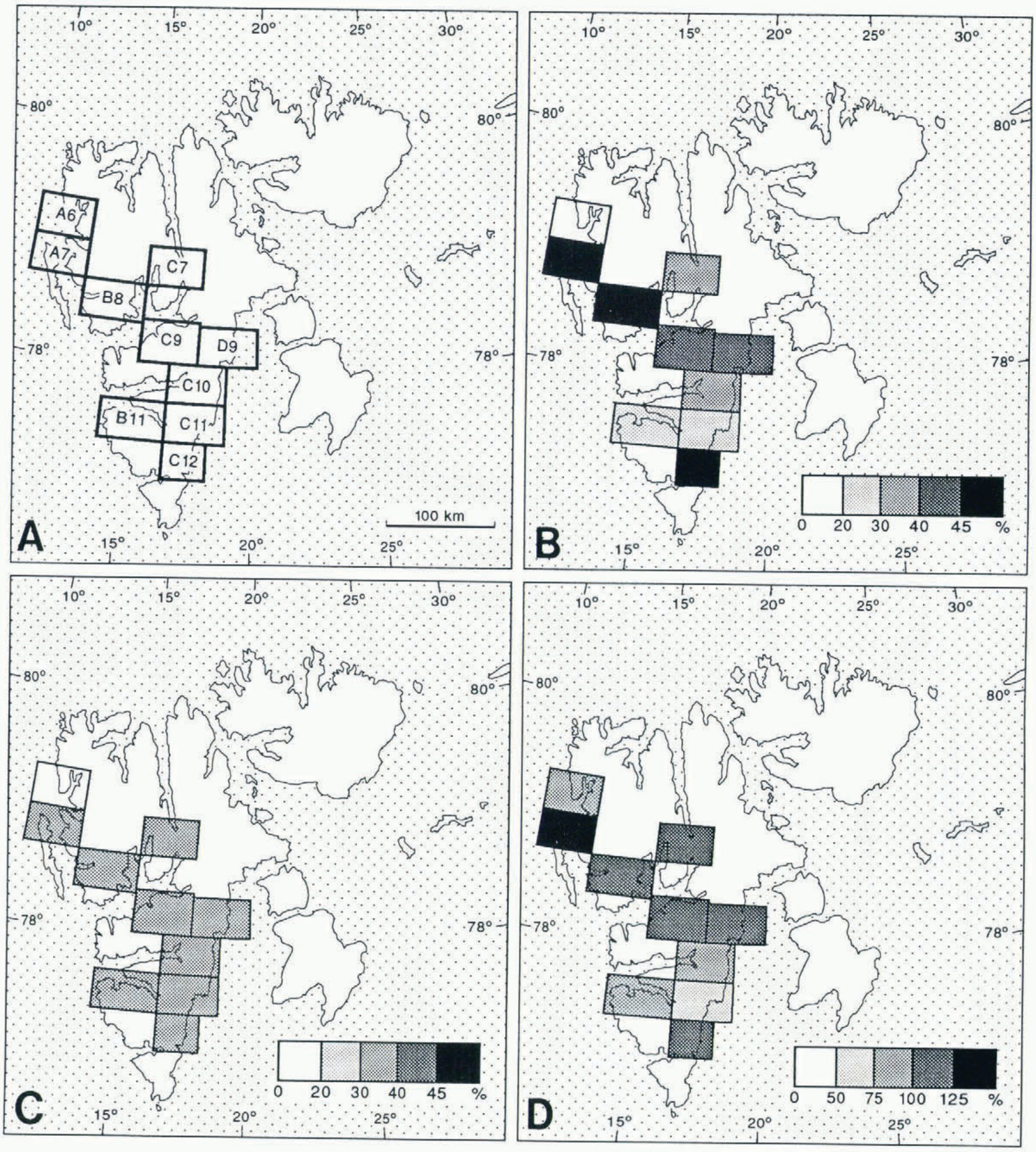

Fig. 1. (a) Location and code numbers of the map sheets used to derive the primary data set. (b) Geographic variation in concentrations of surge-type glaciers in the sampled map sheets. The degree of shading represents calculated values of $p_{s|m}$, with the dark shades indicating areas where the probability of surging is particularly high. (c) Geographic variation of geologically predicted surge probabilities for the primary data set, using a threefold geological classification scheme. Glaciers underlain by sedimentary rocks have the highest probability of being surge-type. This scheme is unable to differentiate between regions of high and low concentrations of surge-type glaciers, because large areas of sedimentary rocks were located on each map sheet. This suggests that if surging is geologically controlled, individual rock types are likely to be more important than petrographic categories. (d) Geographic variation of surge probabilities for the primary data set. The influence of the bedrock geology has been removed by computing the ratio $r^*_{s|m(g)}$. This is similar to the observed distribution of surge-type glaciers (b) (Spearman's rank correlation coefficient 0.93).

Svalbard. Therefore, a substantial amount of information was obtained from aerial photographs.

The NP aerial-photograph archive contains images of Svalbard from the following years: 1936, 1938, 1948, 1956, 1960, 1961, 1966, 1969, 1970, 1971, 1977 and 1990. The first four missions obtained oblique photography. The remaining photography is vertical, at scales ranging from 1 : 15 000 to 1 : 50 000. The whole of Svalbard was covered by the 1936 and 1938 imagery combined. For other years, photographic coverage is restricted to certain areas of the archipelago. Each glacier in the sample population was photographed in 1936 or 1938 and, in general, on at least four subsequent occasions.

THE PRIMARY DATA SET AND GEOGRAPHICAL ANALYSIS

Initial analysis of the primary data set of Svalbard glaciers involved calculating the probability that a glacier

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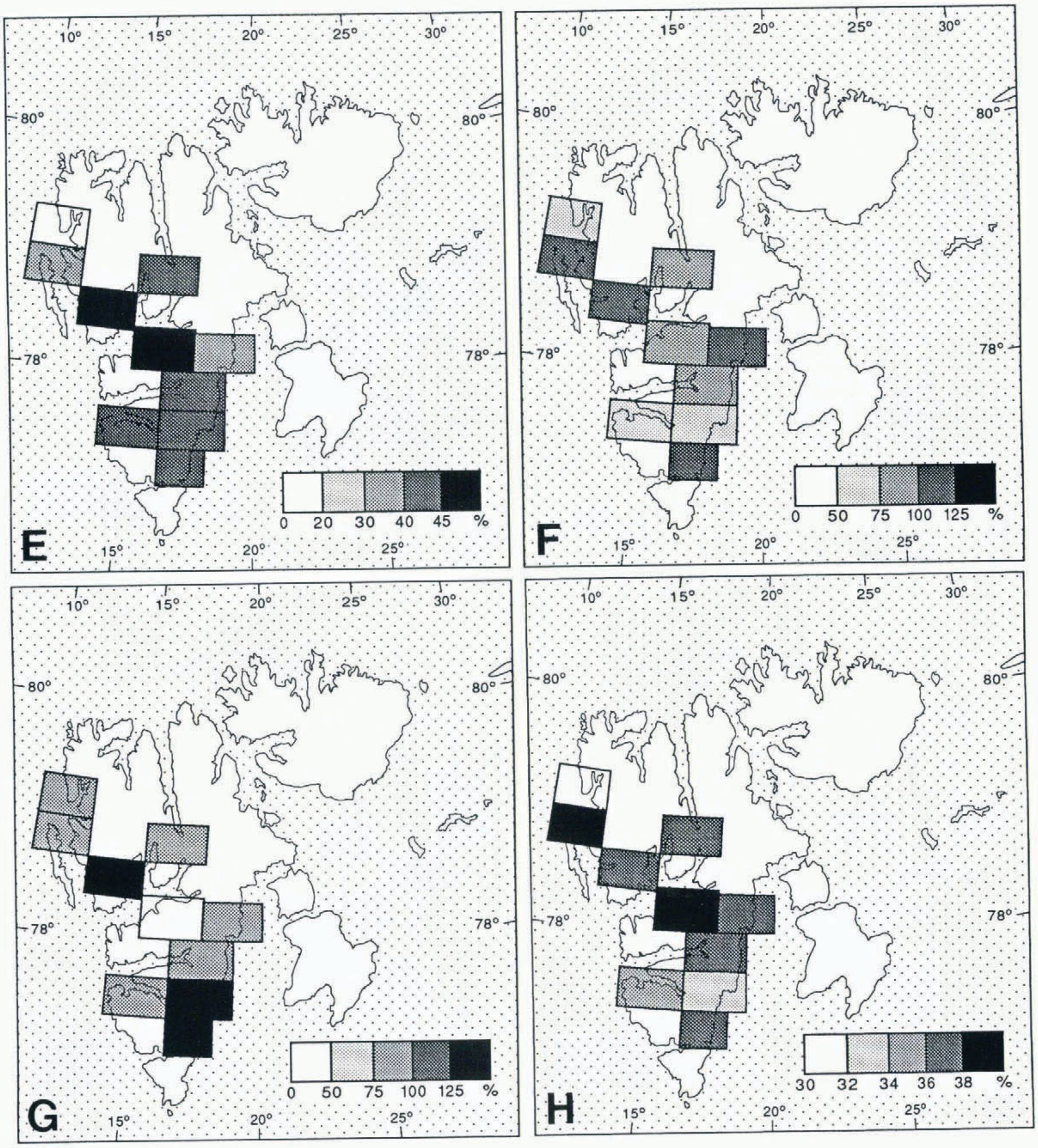

Fig. 1. (e) Geographic variation of surge probabilities for the primary data set predicted using the revised geological classification scheme. Comparison with the observed distribution (b) of surge-type glaciers is qualitatively better than that between (d) and (b). This suggests that the more detailed lithological classification scheme is a better predictor of surge-type behaviour. However, a Spearman's rank correlation coefficient of 0.2 indicates only weak agreement between this prediction and the observed pattern. (f) Geographic variation of surge probabilities for the primary data set. The influence of the revised geological classification scheme has been removed by computing the ratio $r^*_{s|m(\text{lith})}$. There is reasonable agreement with the observed distribution of surge-type glaciers (b) (Spearman's rank correlation coefficient 0.855). However, this ratio cannot identify map sheets with abnormal concentrations of surge-type glaciers, which suggests that the revised geological classification scheme was partly successful in predicting the spatial variation of surging. (g) Geographic variation of length-predicted surge probabilities ($p^*_{s|m(l)}$) for the primary data set. Long glaciers have a greater probability of being surge-type (Fig. 4). Lengths of glaciers on each map sheet were analyzed and the data used to predict the distribution of surge-type behaviour. Comparison with (b) shows that the length-predicted pattern of surge-type glacier distribution does not match the observed pattern. This difference was confirmed by a low Spearman's rank correlation coefficient between observed and length-predicted surge distributions. (h) Geographic variation of surge probabilities for the primary data set. The length influence has been removed by computing $r^*_{s|m(l)}$. Comparison with (b) shows close agreement (Spearman's rank correlation coefficient 0.87), suggesting that length does not influence the spatial distribution of surge-type glaciers.

in the sample is surge-type. The surge probability was calculated first for the entire sample population and then for individual geographical areas. Much of the methodology is taken from Clarke and others (1986), who conducted a similar study in the Yukon Territory, Canada. The probability statistics are based on the classical work of Laplace (Stuart and Ord, 1987). The general expression for the probability of an event, x, occurring in a sample population, N is $p_x = n_x/N$, where n_x is the frequency of x. If the probability of an event, x, is certain, then $p_x = 1$ (or 100%).

Surge probability for the primary data set

The primary data set is composed of 615 glaciers sampled from ten map sheets. The surge probability for this sample population was calculated from the surge-index data recorded for each glacier. The number of glaciers in each class "i" is denoted n_i. The probability that a particular glacier is "i-type", p_i, was found from $p_i = n_i/N$, where N is the total number of glaciers in the data set. The surge index is a qualitative description of the likelihood that a glacier is of surge type. It was, therefore, necessary to quantify this index to provide a measure of the probability that a glacier surges, given that it is i-type, $p_{s|i}$. This was achieved by estimating the number of incorrect identifications associated with each i category. This is a subjective estimate by the person carrying out the classification of glaciers in the sample and, therefore, lacks any rigorous mathematical justification. The estimate would most likely vary if another person were to perform the exercise with the same data. In this study, the classification of glaciers into i categories was performed entirely by G.S.H.

If each surge-type glacier in the sample is identified correctly, then $p_{s|i=3} = 1$ and $p_{s|i\neq 3} = 0$. However, given the large sample population size it is likely that some glaciers were assigned to incorrect i categories. For the data set discussed here, we are confident that all but one of the glaciers we identified as type 3 are of surge type. Therefore, $p_{s|i=3} \approx 0.980$, or, in other words, if a particular glacier is classified as type 3 there is a 98% probability that it is surge-type. Similarly, for type 2 glaciers we estimate that only two might be wrongly classified, giving $p_{s|i=2} \approx 0.923$. For type 1 glaciers there was greater scope for error because of the increased n_i and the lack of corroborating evidence suggesting surge-type behaviour. In this group we estimate 15 incorrectly classified glaciers. Thus $p_{s|i=1} \approx 0.894$. The largest errors were associated with type 0 glaciers. Again, this was partly a result of the increased n_i. It was also a reflection of the long quiescent-period length (>100 years) of many surge-type glaciers in Svalbard (Dowdeswell and others, 1991). For example, a glacier with a very long quiescent phase may not develop surge-type features over the period for which aerial photography is available (a maximum of 54 years). Such a glacier will have escaped identification as being surge-type during the analysis of the photographs. For the type 0 category we estimate 20 possibly incorrect identifications, giving $p_{s|i=0} \approx 0.051$.

Once $p_{s|i}$ had been quantified, it was possible to calculate the number of surge-type glaciers in each category, $n_{s|i}$, from the product of n_i and $p_{s|i}$. The surge probability for the primary data set was computed from the expression:

$$p_s = \sum_{i=0}^{3} p_{s|i} p_i \,. \tag{1}$$

The calculated values of n_i, $p_{s|i}$ and $n_{s|i}$ for the primary data set are shown in Table 1. In the sample population, 224 glaciers were estimated to be of surge type. This represents a surge probability for the sample of 36.4%. Clarke and others (1986) calculated a surge probability for their Yukon sample population of 6.4%.

Geographical analysis

The purpose of the geographical analysis was to examine whether spatial variations in the concentration of surge-type glaciers exist in Svalbard. In this case, the regions were taken to be the ten map sheets used for sampling (Fig. 1a).

Map sheets were defined by the subscript "m". The i-distribution of each sheet, $n_{i|m}$, was determined, and from this the probability that a particular glacier in a map area, m, is i-type was calculated from $p_{i|m} = n_{i|m}/n_m$. This enabled the surge probability on each map to be computed from:

$$p_{s|m} = \sum_{i=0}^{3} p_{i|m} p_{s|i} \,. \tag{2}$$

Map surge probabilities are expressed as percentages. Map sheets with higher than average concentrations of surge-type glaciers are those with surge probabilities greater than p_s for the primary data set, i.e. 36.4%. The values range from 15.8% for sheet A6 (Krossfjorden) to 46.8% for sheet B8 (St Jonsfjorden) (Table 2). The spatial variation of $p_{s|m}$ is represented graphically by different shading of the sampled areas (Fig. 1b).

Three map sheets were found to contain particularly high concentrations of surge-type glaciers. These clusters are located in sheets A7, B8 and C12 (Fig. 1b). High concentrations are also found in maps C9 and D9. The area with the greatest deficiency of surge-type glaciers was sheet A6. Low concentrations were also found in maps B11 and C11. Thus, the clustering of surge-type glaciers observed at the global scale is reflected at the regional scale in Svalbard.

Sample size is not constant between the various map sheets (see n_m in Table 2). To test the null hypothesis that the i-distribution of each map sheet does not differ significantly from that of the primary data set, χ^2 calculations were made. At a 95% significance level, only map B11 fell below the rejection limits. The χ^2 values for all other areas exceeded the critical limit at this level. Therefore, the null hypothesis is rejected and the differences in i-distribution between these map areas and the primary data set can be attributed to non-random variation with 95% certainty.

A spatial variation in the concentration of surge-type glaciers on Svalbard has now been established. We seek to explain this variable distribution. The first stage in this process is to analyze factors associated with glaciers to identify characteristics that appear to be related to the occurrence of surge-type behaviour. If a relationship can be established the spatial distribution of this factor can be used to predict where surge-type glaciers are likely to be located. The closer a predicted pattern is to the observed distribution (Fig. 1b) the greater the probability that the factor concerned is in some way connected with surging.

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Table 2. Various stage probability statistics for the primary data set arranged by map sheet. The columns headed Lithology I and Lithology II use the threefold geological classification scheme and the revised geological classification scheme, respectively. Variations are shown graphically in Figure 1

Map sheet	n_m	Geographic $n_{s\|m}$	$p_{s\|m}$	Lithology I $p^*_{s\|m(g)}$	$r^*_{s\|m(g)}$	Lithology II $p^*_{s\|m(\mathrm{lith})}$	$r^*_{s\|m(\mathrm{lith})}$	Length $p^*_{s\|m(l)}$	$r^*_{s\|m(l)}$
A6	56	7.9	15.8	19.3	82	19.3	82	35.4	45
A7	36	16.3	45.3	34.0	133	38.7	117	34.1	133
B8	56	26.2	46.8	38.7	121	45.6	103	38.2	122
B11	76	22.0	28.9	37.0	78	43.7	66	34.9	83
C7	72	27.4	38.1	35.9	106	43.2	88	34.9	109
C9	98	40.0	40.8	39.8	103	45.1	90	31.4	130
C10	98	36.7	37.4	39.8	94	44.3	84	35.5	105
C11	50	13.7	27.4	39.8	69	43.3	63	40.7	67
C12	42	19.5	46.4	39.8	117	41.3	112	38.9	119
D9	31	13.1	42.3	39.8	106	36.7	115	35.9	118

SURGE PROBABILITY AND SUBGLACIAL GEOLOGY

There is general agreement amongst glaciologists that the nature of the ice/bed interface is a significant component of the surge mechanism. An unresolved issue is whether surging takes place on an essentially rigid and impermeable bed (e.g. Kamb, 1987) or if deformation of subglacial sediments is the surge trigger (Clarke and others, 1984) or a combination of bed types is involved. The geological characteristics of bedrock beneath glaciers are, therefore, likely to be a key factor in determining the surge mechanism.

Initial geological classification and surge probability

Data obtained from geological maps were reorganised to find the i-distribution for each lithological type. It was usually not possible to specify a single rock type on which an individual glacier is resting, for two reasons. First, the geological maps of Svalbard tend to assign several different, although lithologically similar, rock types to a given shaded area. There is insufficient detail available concerning regional geology to enable a more precise classification. Secondly, glaciers often cross geological boundaries and are underlain by more than one lithology. In total, 41 different combinations of rock type were noted.

With so many lithological combinations it was inevitable that some of these groups contained very few glaciers. In such cases, the sample populations would have been too small to permit a valid statistical analysis. Thus, in order to obtain viable populations, the data were regrouped. This regrouping took the simple form of classifying the rock types according to the major petrological categories: igneous, metamorphic and sedimentary. Igneous rocks ($g = 1$) in the sample were granites, migmatite and gabbro. The metamorphic category ($g = 2$) contained quartzite, pelite, schist, gneiss and slate. Tillites, limestone, sandstone, Old Red Sandstone, shale and conglomerate were classified as sedimentary ($g = 3$).

The i-distribution for each geological category was determined, from which the probability that a glacier overlying lithology g is i-type was calculated as $p_{i|g} = n_{i|g}/n_g$. The surge probability of each petrological group was computed from:

$$p_{s|g} = \sum_{i=0}^{3} p_{i|g} p_{s|i} \,. \tag{3}$$

Table 3 presents the results of the above calculations. If the rock type beneath glaciers does not influence surging, then $p_{s|g}$ should be roughly equal for each category. In the Svalbard sample population this is not the case. Igneous rocks have a surge probability of 5.1%. This value matches the surge probability for type $i = 0$ glaciers because no glaciers from any other i category were found overlying igneous rocks. Admittedly, the number of glaciers in the sample population with igneous subglacial rocks was fairly small (Table 3). Metamorphic rocks have a much greater surge probability (27.5%). The highest surge probability was found for glaciers overlying sedimentary rocks (39.8%).

The above analysis demonstrates a marked association between subglacial geology and the probability of surging. There might, therefore, exist a geological control on the geographical distribution of surge-type glaciers. To test this hypothesis, the geological variability of each map sheet was examined. The probability that a glacier in map sheet m is resting on bedrock g was found from $p_{g|m} = n_{g|m}/n_m$, where $n_{g|m}$ is the number of glaciers above rock type g in map m. The geologically predicted

Table 3. Surge probability statistics for the three petrological categories derived from the primary data set

Lithology	n_g	p_g %	$p_{s\|g}$ %
Igneous	18	3.0	5.1
Metamorphic	82	13.0	27.5
Sedimentary	515	84.0	39.8

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surge probability for each map sheet was then calculated from:

$$p^*_{s|m(g)} = \sum_{g=1}^{3} p_{g|m} p_{s|g} \,. \tag{4}$$

The map surge probability predicted by geology was lowest for sheet A6 (19.3%). All the glaciers on this map were observed to be overlying igneous and metamorphic rocks. In comparison, maps C9, C10, C11, C12 and D9 had a $p^*_{s|m(g)}$ of 39.8% (Table 2). These areas were entirely composed of sedimentary rocks. Figure 1c shows that this geological analysis is unable to identify those map sheets which have an observed concentration of surge-type glaciers (Fig. 1b). Only sheet A6 stands out as an area with a low surge probability. χ^2 calculations showed that this map sheet was the only one to differ at the 95% significance level, in terms of geological variability, from the primary data set.

The influence of geology on the surge probability can be removed by computing the probability ratio:

$$r^*_{s|m(g)} = p_{s|m} / p^*_{s|m(g)} \,. \tag{5}$$

According to Clarke and others (1986), this ratio provides a measure of the difference between the observed surge probability and the factor-predicted surge probability, in this case geologically predicted. The probability measure $r^*_{s|m(g)}$ was computed for each map to assess the magnitude of the difference between actual and geologically predicted surge probabilities (Table 2). The minimum ratio was obtained for sheet C11 ($r^*_{s|m(g)} = 68.8\%$). This map had an actual map surge probability of 27.4%. However, because all glaciers on this map are underlain by sedimentary rocks, the probability of surging predicted by geology is 39.8%. The maximum ratio was calculated for sheet A7 ($r^*_{s|m(g)} = 133.2\%$). In the original calculation of $p_{s|m}$ this map had the second highest surge probability, at 45.3%. When geology was used to predict the probability of surging, the value for A7 dropped to 34.0%. The comparatively low result is due to a large proportion of glaciers on this map being based on metamorphic rocks. Figure 1d illustrates the map probability ratios calculated from the geology predictions. Comparison of this figure with Figure 1b shows some similarity.

Surge probabilities associated with individual rock types

The above examination suggests that subglacial geology does have an influence on the probability of surging. However, geology cannot account for the geographical distribution of surge-type glaciers (as shown by comparison of Figure 1b and c). The analysis performed above considered subglacial geology in terms of only three petrological groups. It is possible that by grouping many different rock types into just three categories some significant information was lost. Individual lithologies probably play a more important role than petrological classes in influencing surge-type behaviour. This hypothesis was tested.

It was demonstrated that glaciers overlying sedimentary rocks have the highest probability of being surge-type. Approximately 80% of the primary data set was composed of glaciers overlying sedimentary rocks. It was considered that the individual lithologies within this group provided sufficient sample numbers to justify a statistical analysis of the influence of each. The sample sizes associated with the igneous and metamorphic groups were too small to permit a similar examination.

The following lithologies were analysed individually: tillites, limestone, sandstone, Old Red Sandstone, shale and conglomerate. The number of glaciers underlain by each lithology was denoted n_{lith} and the probability that a glacier has a certain subglacial geology was p_{lith}. Over half the glaciers in the sample were underlain by shale. Limestone was the least frequently occurring rock type. The i-distribution for each rock type was established. The number of i-type glaciers resting on that lithology was denoted $n_{i|\mathrm{lith}}$ and the probability that a glacier with a certain subglacial geology is i-type was $p_{i|\mathrm{lith}} = n_{i|\mathrm{lith}}/n_{\mathrm{lith}}$. The probability that a glacier surges given its subglacial geology was then found from:

$$p_{s|\mathrm{lith}} = \sum_{i=0}^{3} p_{i|\mathrm{lith}} p_{s|i} \,. \tag{6}$$

Values ranged from 62.5% for limestone to 35.0% for conglomerate (Table 4). The sedimentary petrology of each map sheet was examined in more detail and the frequency of individual rock types noted, from which values of $p_{\mathrm{lith}|m}$ were calculated. This cleared the way for new estimates of map surge probabilities to be predicted from the revised geological classification using a modified Equation (4). Table 2 summarizes the results of this analysis, and Figure 1e illustrates the differences between the map sheets graphically.

New values of the probability ratio $r^*_{s|m(\mathrm{lith})}$ were obtained to compare the revised geologically predicted surge probabilities with the actual probabilities. Table 2 lists the calculated values. The maximum and minimum ratios were found, once again, to occur on map sheets A7 and C11, respectively. The probability ratios were plotted (Fig. 1f) and compared with other maps showing different measures of surge probability.

Figure 1e shows that using the revised geological

Table 4. Surge probability statistics prepared using the revised geological classification scheme. The figures for the metamorphic and igneous groups remain as before. The additional data were obtained by subdividing the lithologies comprising the original sedimentary group

Lithology	n_{lith}	p_{lith} %	$p_{s|\mathrm{lith}}$ %
Tillite	52	8.5	47.5
Limestone	9	1.5	62.5
Sandstone	61	9.9	50.6
Old Red Sandstone	36	5.9	47.5
Shale	337	54.8	36.7
Conglomerate	20	3.3	35.0
Metamorphic	82	13.3	27.5
Igneous	18	2.9	5.1

classification scheme to predict surge-type behaviour results in closer agreement with the pattern of actual surge probabilities (Fig. 1b) than does the original approach using geology (Fig. 1c). However, it tends to overpredict slightly the likelihood of surging in maps B11 and C11, and underpredict that for map A7. Nonetheless, it correctly identifies sheets A6 and B8 as areas with extremely low and high concentrations, respectively, of surge-type glaciers. When the revised probability ratios are plotted (Fig. 1f) there is slight reorganisation of the probability distribution to a pattern broadly similar to that of the actual surge probabilities (Fig. 1b). This ratio cannot, however, identify map sheets with extreme values.

INTERNAL REFLECTING HORIZONS, GLACIER THERMAL REGIME AND SURGE PROBABILITY

Thermal instabilities have been considered as trigger mechanisms for glacier surges (e.g. Robin, 1955; Clarke, 1976), although they can only explain surges of glaciers where there is an element of basal freezing (Paterson, 1981). Schytt (1969) speculated that parts of ice caps in eastern Svalbard surged when an inner core of ice at the melting point broke through an annulus of colder ice frozen to the bed.

Schytt (1969) based his hypothesis on limited field data. Since then, more evidence has been obtained on the thermal characteristics of glaciers and ice caps in Svalbard. Much of this information has been derived from the results of radio-echo sounding programmes. A persistent feature of many echo returns is the presence of internal reflecting horizons (IRHs) giving the appearance of two-layered glaciers. Bamber (1987) reported the presence of continuous horizons, situated at a depth of 100–200 m below the ice surface, on approximately 60% of the glaciers surveyed by the Scott Polar Research Institute in 1983. The distribution of glaciers with such horizons exhibits a clear geographical trend (Bamber, 1987; Macheret and others, 1991; Fig. 2), which Bamber (1987) attributed to variations in climate over the archipelago.

Two-layered glaciers are inferred to have a sub-polar thermal regime characterised by cold surface ice overlying temperate basal ice (also called a polythermal regime by Blatter and Hutter (1991)). An IRH marks the boundary between the two conditions. Thermistor measurements in boreholes in several Svalbard glaciers support this hypothesis (Hagen and Sætrang, 1991; Hagen, 1992; Ødegård and others, 1992; Bjørnsson and others, In press). Borehole temperature measurements enabled Holmlund and Eriksson (1989) to make a similar interpretation for the presence of a reflecting horizon in radar surveys of Storglaciären, northern Sweden. The connection between IRHs and a two-layered thermal structure has not, however, been shown beyond doubt. In most of the above studies, temperature measurements were not made below the depths of the IRHs; the presence of warmer ice at depth was based on extrapolation.

Yu. Ya. Macheret (personal communication, 1991) provided information, obtained during Russian radio-

Fig. 2. Location of glaciers in Svalbard where internal reflecting horizons (IRH) have been recorded during radio-echo sounding. The dashed lines show echo-sounding flight paths. Based on Bamber (1987) and Macheret and others (1991).

echo sounding programmes, on the thermal regime of 136 glaciers in Svalbard. Several of the ice masses in his sample are included in the primary data set, although, in addition, the Russian sample contains glaciers in north-east Spitsbergen and Nordaustlandet.

Macheret organised his data set in two ways. First, he was able to classify most of the sample glaciers according to thermal regime on the basis of radio-echo sounding results (cf. Macheret and others, 1993). The three categories of thermal regime used are "cold", "relatively warm" and "two-layered", corresponding to polar, temperate and sub-polar (polythermal) thermal regimes, respectively. For a few glaciers, a thermal regime could not be specified, giving a fourth category. Secondly, Macheret organised his data into a dichotomous surge classification scheme in which glaciers were either surge-type or normal. This was done using information reported by Liestøl (1993), which lists as surge-type only those glaciers which have been observed to surge this century. It is likely that some of Macheret's 'normal' glaciers are actually surge-type but were not included in Liestøl's list because they have not been observed to surge.

Using Macheret's sample population we were able to do a simple analysis of the relationship between surging and thermal regime. The probability that a glacier in the Russian sample is surge-type is $p_{s|\mathrm{Russian}} = 23.5\%$. This is less than the $p_s = 36.4\%$ for the primary data set, probably because the Russian sample contains surge-type glaciers incorrectly classified as normal. The probability that a glacier is surge-type given its thermal regime was estimated as $p_{s|therm} = n_{s|therm}/n_{therm}$, where $n_{s|therm}$ is the number of surge-type glaciers, and n_{therm} is the total number of glaciers, in a particular thermal category. Table 5 summarises the data and the results of this simple analysis. Note that two-layered (sub-polar) glaciers have the greatest probability of being surge-type (45.7%). Neglecting glaciers which could not be classified by thermal regime, cold glaciers have the second highest surge probability, but the figure is much lower (13.2%). Temperate glaciers have 4.3% probability of being surge-type. The proportion of two-layered glaciers in the Russian sample is 65.6%, which is consistent with the proportion of two-layered glaciers in a sample reported by Bamber (1987).

Table 5. Surge probability statistics for the Russian sample (data from Yu. Ya. Macheret, personal communication, 1991)

Thermal regime	n	$n_{s\|therm}$	$p_{s\|therm}$ %
Cold	38	5	13.2
Two-layered	46	21	45.7
Relatively warm	23	1	4.3
Not specified	29	5	17.2

The possibility that previous surges have altered the thermal regime of some glaciers, causing, for example, the non-appearance of reflecting horizons in several glaciers in the sample, has not been considered here. There is also a possibility that the occurrence of IRHs is length-related. Hagen and Sætrang (1991) reported that IRHs occur more frequently in long glaciers than in short glaciers. Length is shown later to be associated with increased surge probabilities. The potential bias introduced by length into the relationship of IRHs and surging has not been removed in this study.

Two explanations might account for the statistical relationship between two-layered glaciers and surge-type glaciers. One interpretation is based on the observation by Hagen and Sætrang (1991) of an englacial channel in Austre Broggerbreen, Svalbard, at a depth corresponding to a measured reflecting horizon. Bamber (1987) suggested that the presence of cold, impermeable ice above and warmer, more permeable ice below might be important in controlling the vertical position of these englacial conduits. We suggest that during the quiescent phase of a two-layered surge-type glacier a large proportion of water drains through englacial channels. Hamilton (1992) found little evidence of subglacial drainage beneath Bjuvbreen, a quiescent surge-type glacier in Svalbard. Englacial channels are maintained by a balance between frictional heating of the ice walls by flowing water and creep closure caused by internal deformation of the glacier, as suggested by Röthlisberger (1972). As a glacier approaches its active phase, increased overburden pressure and enhanced creep deformation might succeed in closing the englacial channels. Water will be driven down through the permeable lower layers of the glacier and could accumulate at the base where there are no efficient drainage pathways. A linked-cavity drainage system might develop (Kamb, 1987) or unlithified subglacial sediments could begin to deform (Clarke and others, 1984), both of which are suggested surge mechanisms. Alternatively, the water might accumulate in lower ice strata leading to an increase in creep deformation. This explanation does not advocate a thermal instability mechanism for surges, nor does it imply that only glaciers with a two-layered thermal structure are able to surge. Instead, the presence of a two-layered thermal regime serves to "encourage" surging, rather than being the primary cause.

G. K. C. Clarke (personal communication, 1993) offers an alternative explanation for the link between IRHs and surging. He notes that very high subglacial water pressures commonly associated with actively surging glaciers cause ice quakes. These events create networks of small fault planes. Impure basal water under high pressures propagates upward along these faults but freezes quickly because of the cold surrounding ice. The upper limit of water propagation appears as a dielectric boundary in radio-echo sounding profiles due to the presence of impurities carried up from the bed. This explanation implies that IRHs are a product of glacier surges and not a cause of surges.

We are unable to evaluate which explanation is more likely, because of the lack of detailed, long-term studies of surge-type glaciers in Svalbard.

INFLUENCE OF GEOMETRY AND TOPOGRAPHY ON GLACIER SURGING

Various morphometric and topographic parameters associated with each glacier in the sample population were analyzed to determine whether any of these factors are related to the occurrence of surging. The parameters analyzed were glacier length, elevation and slope, orientation and the presence or absence of tributaries. The only factor which showed a statistical relationship with surging was glacier length (described below). The analyses demonstrated that surge-type glaciers do not have special elevation, slope, orientation or tributary requirements (Hamilton, 1992). Similar conclusions were reached by Clarke and others (1986) in their study of Yukon glaciers.

The influence of glacier length

Clarke and others (1986) found that surge probability increased with glacier length in their Yukon sample population, although the glaciological significance of this discovery was not apparent (Raymond, 1987). The present analysis tested the hypothesis that, in the Svalbard data set, long glaciers have an increased probability of being surge-type.

Ice masses in the Svalbard sample population have lengths, L, in the range $1.0 > L \leq 35$ km. These glaciers were organised into one of nine length bins defined by various length limits (Table 6). The probability that a glacier will fall into bin l, p_l, was calculated from $p_l = n_l/N$, where n_l is the number of glaciers in that

Table 6. Length limits for each of the length bins, the probability that a glacier in the sample population will fall into a given bin and surge probabilities for each length bin

Length bin, l	*Length limits* km	p_i %	$p_{s\|l}$ %
1	1–2	14.1	20.4
2	2–3	25.7	27.9
3	3–4	20.7	36.2
4	4–5	10.9	32.4
5	5–6	7.8	37.1
6	6–8	7.6	42.4
7	8–10	3.9	50.7
8	10–15	5.4	50.8
9	15–40	3.9	75.1

length bin. Figure 3 illustrates that glaciers have the highest probability of falling into bin $l = 2(2 < L \leq 3\,\text{km})$.

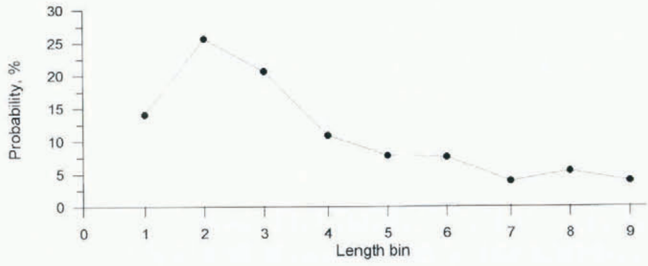

Fig. 3. Distribution of glacier lengths for the Svalbard sample population. Plotted values represent the probability that a glacier has certain length limits.

Next, the influence of glacier length on the probability of surging was examined. The number of i-type glaciers in each length bin, $n_{i|l}$ was established and, from that, the probability that a glacier in bin l is i-type was found from $p_{i|l}, = n_{i|l}/n_l$. The glacier surge probability for each length bin was then computed using the expression:

$$p_{s|l} = \sum_{i=0}^{3} p_{i|l} p_{s|i} \,. \tag{7}$$

If there is no relationship between glacier length and surging, then $p_{s|l}$ should be roughly equal for each length bin. Figure 4 illustrates that this is not the case. Instead, we observe an almost monotonic upward trend in the probability of surging with increasing glacier length. Values of $p_{s|l}$ range from 20.4% for $l = 1$ to 75.1% for $l = 9$ (Table 6). This trend suggests that, in the sample population, long glaciers have a greater probability of surging than do short ones. The analysis does not reveal distinct peaks of $p_{s|l}$. This could have been the case if short glaciers surged by one mechanism and long glaciers by another. The results obtained using the Svalbard data set are similar to those obtained by Clarke and others (1986) for the Yukon glacier population, although Post (1969),

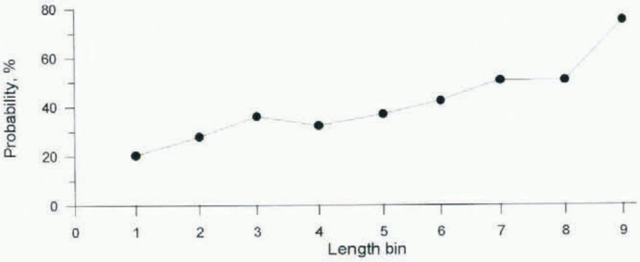

Fig. 4. Influence of glacier length on the probability of surging. There is an almost monotonic increase in surge probability with glacier length, indicating that long glaciers are much more likely to be surge-type.

using a much smaller data set, found no qualitative relationship between glacier length and surging. Weertman (1969) demonstrated theoretically that surges were more likely in large glaciers (roughly >10 km long). According to Weertman, glaciers draining a large area would be able to accumulate a layer of subglacial water thick enough to reduce bed friction.

The relationship between glacier length and surging may be a product of the sampling process. It is unlikely that surge-type features associated with long glaciers ($\sim> 6$ km) would go unrecorded, although it is conceivable that similar characteristics on short glaciers were missed during observations. If so, we would expect at least 75.1% of the glaciers in the sample population to be surge-type. This is almost double the figure calculated from the original data. It is unlikely that such a considerable number of short surge-type glaciers went unrecorded. Therefore, it is concluded that length does influence the probability of surging.

If this conclusion is correct, it suggests that the concentration of surge-type glaciers in certain geographical areas could be a function of the distribution of long glaciers. We now investigate this possibility.

Employing the notation used earlier, $n_{l|m}$ is defined as the number of glaciers in length bin l in map sheet m. If n_m is the number of glaciers in a given map sheet, then the probability that a particular glacier in map m is in bin l is $p_{l|m} = n_{l|m}/n_m$. The length-predicted surge probability for each map sheet can thus be calculated from:

$$p^*_{s|m(l)} = \sum_{l=1}^{9} p_{l|m} p_{s|l} \,. \tag{8}$$

Table 2 lists the values of length-predicted surge probabilities for each map sheet. It can be seen that the variation in $p^*_{s|m(l)}$ between the different areas is not great. The calculated values range from 31.4% for sheet C9, which has a large proportion of short glaciers, to 40.7% for map C11, which has a large proportion of long glaciers. The length-predicted surge probability for the primary data set was 33.3%. The l-distribution for each map sheet was analyzed using the χ^2 statistic. This tested the null hypothesis that the l-distribution for a particular map sheet did not differ significantly from that for the primary data set. At the 95% significance level, sheets A6, C11, C12 and D9 had different l-distributions from the primary sample, but for different reasons. Sheet A6 has a

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higher number of glaciers in bin $l = 4$ and a deficit in bin $l = 5$, C11 has slightly more glaciers in bins $l > 6$, and C12 has a greater proportion of mid-length glaciers. Map D9 is characterised by a noticeable peak of glaciers in bin $l = 9$ (Hamilton, 1992, p. 68). Maps with high χ^2 percentile values are not necessarily those with concentrations of surge-type glaciers. For example, sheet D9 is an area with an apparent deficit of surge-type glaciers (Fig. 1b), despite its favourable l-distribution. In addition, map B8 has a large length-predicted concentration of surge-type glaciers, but χ^2 calculations do not support the hypothesis that it has a significantly different l-distribution from the primary sample. Figure 1g illustrates the geographical distribution of $p^*_{s|m(l)}$. This figure shows that there is some reorganisation in the distribution of "surge clusters" when length is used to predict probabilities, compared to the actual probabilities (Fig. 1b).

The influence of length on the surge probability can be removed by computing the probability ratio:

$$r^*_{s|m(l)} = p_{s|m} / p^*_{s|m(l)} \, . \qquad (9)$$

These values are compared in Table 2. The ratios range from a high of 133% for map A7 which has a number of short glaciers which are surge-type, to a low of 45% for A6 which has several long glaciers which are not surge-type. When the ratios are plotted graphically (Fig. 1h) there is a redistribution of the areas where surge-type glaciers are clustered, relative to Figure 1g. This reorganisation produced a broadly similar pattern to that found when original values of $p_{s|m}$ were plotted (Fig. 1b). Thus, the areas with the highest concentrations of surge-type glaciers, calculated with the length influence removed, are A7 and C9. Surge probability also remains high in map sheets B8, C7, C10, C12 and D9. If the various measures of surge tendency for each map are ranked (Table 7), the same map sheets appear in the top five of both $p_{s|m}$ and $r^*_{s|m}$, although in slightly different order. The Spearman's rank correlation coefficient for $p_{s|m}$ and $r^*_{s|m(l)}$ is 0.867. In contrast, the correlation coefficient for $p_{s|m}$ and $p^*_{s|m(l)}$ is only 0.091, indicating a very weak correlation between the actual and length-predicted surge probabilities for each map sheet. We conclude that glacier length cannot fully explain the observed concentration of surge-type glaciers in certain map sheets.

SUMMARY

The work described in this paper reveals several characteristics of surge-type glaciers in Svalbard. These can be summarised as follows:

The proportion of surge-type glaciers in the sample population is relatively high, at 36.4%. It contrasts with a lower surge probability of 6.4% found for glaciers in the Yukon (Clarke and others, 1986), indicating that conditions favourable for surging occur more frequently in Svalbard.

Certain areas of the archipelago have higher than average concentrations of surge-type glaciers, while in

Table 7. Various measures of surge probability, arranged by map sheet and ranked in order, with greatest first. Comparison of the columns headed $p_{s|m}$ and $r^*_{s|m(l)}$ shows that the same map sheets occur in the top five of both, although the order is slightly different. A Spearman's rank correlation coefficient of 0.87 for these two columns indicates statistically that they are very similar

Rank	$p_{s\|m}$	$p^*_{s\|m(l)}$	$r^*_{s\|m(l)}$
1	B8	C11	A7
2	C12	C12	C9
3	A7	B8	B8
4	D9	D9	C12
5	C9	C10	D9
6	C7	A6	C7
7	C10	C7	C10
8	B11	B11	B11
9	C11	A7	C11
10	A6	C9	A6

other areas surge-type glaciers are rare. This non-random geographical distribution is a local reflection of a global pattern.

Factors such as glacier slope, elevation, orientation and the presence or absence of tributaries do not have a significant influence on the probability of surging. These findings agree with Clarke and others (1986) and Post (1969).

Glacier length was found to have an influence on the probability of surging, in agreement with Clarke and others (1986). Recent work by Clarke (1991) confirmed that, of length, slope and width, length was the dominant variable correlated with surging, and that slope and width influences were derived from this association. Length by itself was not completely successful at predicting the location of surge clusters. This must be the case, since not all long glaciers in Svalbard are of surge type. Furthermore, there are long glaciers in the European Alps, the New Zealand Alps and the Coast Mountains of British Columbia, areas where surge-type glaciers do not occur.

Glaciers possessing an internal reflecting horizon in radio-echo sounding profiles have an elevated probability of being surge-type. IRHs might be an indication of a sub-polar thermal regime. One interpretation is that a sub-polar thermal regime could serve as a kind of encouragement to a glacier already close to being surge-type. An alternative interpretation is that surges cause a glacier to develop an IRH.

The probability of surging is greatly increased for glaciers underlain by sedimentary rocks. This connection between lithology and surging was first proposed, qualitatively, by Post (1969). Further evidence of a geological control on glacier surging was provided by Weidick (1992) who noted that surge-type glaciers in central West Greenland occur on predominantly basaltic rocks. The interpretation is that some sedimentary rocks, and other softer rocks, are eroded to form potentially deformable beds. This supports surge mechanisms involving deforming beds (e.g. Jones, 1979; Clarke and others, 1984). The geological data used in this study were not detailed enough to identify which particular lithologies are most related to surge-type glaciers.

None of the factors analyzed in conjunction with surging of Svalbard glaciers was able to explain, on its own, the distribution of surge-type glaciers in the archipelago. This implies that surging is probably a product of more than one environmental condition. The combination of factors responsible for glacier surging might be better identified in a multivariate statistical analysis.

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