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THE INCIDENCE OF GLACIER SURGING IN SVALBARD: EVIDENCE FROM MULTIVARIATE STATISTICS

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Abstract—Surge-type glaciers switch between long periods of slow flow and short periods of fast flow. The spatial distribution of surge-type glaciers is markedly non-random. The clustering of surge-type glaciers in certain glaciated regions and their complete absence from other regions, suggests that environmental factors control surging. To identify factors that control surging, the relationship between surging, glacial variables and geological environment was tested using logit regression models. In the analysis we used 132 surge-type and 372 normal glaciers identified from the literature and aerial photographs in the High Arctic archipelago of Svalbard. We calculated that approximately 13% of the glaciers of Svalbard are of surge-type. In the analysis we used 13 variables collected from glacier inventories and geology maps. Variables that are significantly associated with surging in Svalbard are glacier length, surface slope and the lithology of the underlying bedrock. Multivariate analyses show that long glaciers overlying shale or mudstone with steep surface slopes have the highest probabilities of surging. Surge-type glaciers are significantly less likely to overlie rocks older than Devonian. These findings do not support Kamb's linked cavity theory of surging but lend some support to soft-bed surge theories. © 1998 Elsevier Science Ltd. All rights reserved

Code available at http://www.iamg.org/CGEditor/index.htm

Key Words: Glacier surging, Logit regression model, Multivariate statistics, Svalbard, GLIM.

INTRODUCTION

Surge-type glaciers show a semi-regular cyclic flow instability, in which slow flow during a long period of quiescence is followed by fast flow (10–1000 times faster) during a relatively short surge phase. The typical period of quiescence is 15–100 years and the typical active phase is 1–10 years (Meier and Post, 1969; Dowdeswell, Hamilton and Hagen, 1991). Less than 1% of the glaciers around the world exhibit surge-type behaviour; according to our literature survey about 700 of more than 100 000 glaciers world-wide. Despite their rarity, surge-type glaciers are of vital importance in the understanding of ice flow dynamics. The existence of a two-phase velocity regime indicates different glacial processes control slow flow and fast flow (Clarke, 1987).

Surges of ice sheets can have catastrophic effects, discharging very large volumes of ice into the ocean and on land. Such surges of the Laurentide ice sheet may have produced the repetitive glaciomarine layers in Pleistocene ocean cores known as Heinrich events (Alley, 1991). Furthermore, surging is associated with natural hazards such as outburst floods (Bruce and others, 1987). Major glacier advances associated with surging can also cause damage to constructions in the proglacial area.

From observational evidence during the active phase of surging glaciers, glaciologists have suggested that the fast flow results from motion at the glacier bed rather than creep instability within the glacier ice (Kamb and others, 1985). Fast basal motion during surging is facilitated by water trapped at pressure beneath the ice (Paterson, 1994). Dichotomous views of the process of fast flow have emerged, dependent on whether the glacier is underlain by hard and impermeable bedrock or soft and permeable sediments. The *hard-bed* view states that fast flow is promoted by water trapped in linked cavities at the glacier bed (Kamb, 1987). In this hypothesis, the surge mechanism is a morphological switch between an efficient channelised water evacuation system and the inefficient linked cavity system (Kamb, 1987). The *soft-bed* view is that the surge is promoted by enhanced deformation of sediments underlying the glacier (Boulton, 1979), possibly caused by destruction of drainage paths through these subglacial sediments (Clarke, Collins and Thompson, 1984). The linked cavity theory is easy to test, because it predicts that surge-type glaciers will preferentially have low surface slopes (Kamb, 1987). However, the soft-bed theory is much less easy to test, as a mathematically rigorous treatment has yet to be developed.

Surge behaviour has been identified and examined since the early 20th century (e.g. Tarr and Martin, 1914) and has been identified in a wide variety of type and size of glacier. However, the spatial distribution of surge-type glaciers is markedly non-random, on both a global and regional scale (Clarke and others, 1986). Some areas are devoid of surge-type glaciers, but clusters have been recorded in Alaska, Canada, the Andes, the Tien Shan, Pamir and Karakoram, Iceland, Greenland and Svalbard (Paterson, 1994). Research into the factors controlling the distribution of surge-type glaciers has been performed at regional scales using qualitative observations (Post, 1969) and univariate statistical analysis methods (Glazyrin, 1978; Clarke and others, 1986; Wilbur, 1988; Hamilton, 1992; Hamilton and Dowdeswell, 1996). Most studies indicate that a univariate approach is unable to explain the distribution of surging and therefore that multivariate analyses are required. However, only one multivariate analysis has been performed to date (Clarke, 1991).

The non-random geographical distribution of surge-type glaciers implies that environmental factors control surge behaviour (Post, 1969). Distinguishing these factors may provide vital clues to the surge mechanism, and allow testing of glacier surge theories. In this paper we present the results from an analysis which distinguishes between surge-type and normal glaciers in Svalbard using a number of glacier and geological variables. Some of these variables are continuous (e.g. glacier length) while others are categorical (e.g. lithology type). Conventional statistical correlation procedures are unable to cope with mixtures of data types. To overcome this problem, we use a multivariate logit regression analysis to examine the independent and combined effects of a number of explanatory variables on the incidence of glacier surging in Svalbard and thus identify the major factors that influence surging in this region. In our analysis we build upon the research performed in the Yukon Territory (Clarke and others, 1986; Clarke, 1991) and in Spitsbergen (Hamilton, 1992; Hamilton and Dowdeswell, 1996). The study region analysed by Hamilton covered about 50% of the island of Spitsbergen (the largest island of the Svalbard archipelago) and this region is also encapsulated in our study. However, Hamilton used univariate area statistics based on map sheets, whereas in this paper we apply a multivariate regression approach using data collected for individual glaciers.

SURGE-TYPE GLACIERS IN SVALBARD

Svalbard (latitude 74–81°N, longitude 10–35°E) is an archipelago in the European high Arctic where surging appears to be a common occurrence (Liestøl, 1969). Glacier data from this region are relatively well documented and a large number of surge events have been recorded. The glacier data used in our analysis are mainly derived from a glacier inventory of Svalbard (Hagen and others, 1993), although additional information was retrieved from aerial photographs and geology maps published by the Norsk Polarinstitutt.

For this study glaciers were divided into surge-type and normal categories. The definition "surge-type" means that either one or multiple surges have been recorded in a glacier, or that the morphological characteristics of a glacier show strong enough evidence to assume that a surge has occurred in the past and might occur again. Surge-type glaciers were identified from published data (e.g. Croot, 1988; Lefauconnier and Hagen, 1991; Liestøl, 1993). The majority (102) of the glaciers described as being surge-type have documented surges. The classification of surge-type glaciers without recorded surges was verified by means of air photo interpretation of morphological evidence of surging. The result of this "double check" of surge-type glaciers was the discovery that a number of glaciers were probably mis-classified as surge-type in earlier reports (e.g. Croot, 1988). The maximum extent of these glaciers, which is marked by terminal moraine complexes, is not due to a surge advance, but rather reflects the maximum extent during the Little Ice Age, which occurred about 1900 in Svalbard (Lefauconnier and Hagen, 1991).

The Svalbard archipelago has a total of 2229 glaciers of which 1029 are larger than 1 km^2 (Hagen and others, 1993). In our data analysis we used 504

Table 1. Statistics of surge-type glaciers in Svalbard

	Glaciers used in the analysis
No. of glaciers	504
Surge-type glaciers	132
Observed surge-type glaciers	102
Percentage surge-type glaciers	26.2%
Area glaciated by surge-type glaciers	48.3%

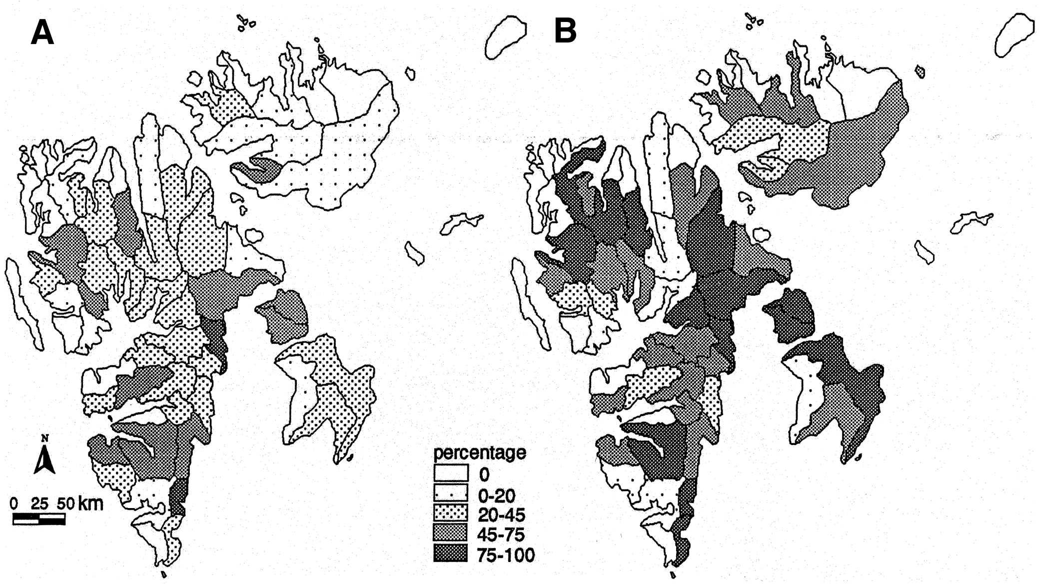

Figure 1. Spatial variation of surge-type glaciers in Svalbard used in our analysis. Grey-scale shading for both figures is identical. (A) Percentage of surge-type glaciers and (B) percentage of glaciated area covered by surge-type glaciers.

of these 1029 glaciers (Table 1), as data on geometry, orientation, elevation, glacier-type, frontal characteristics or activity were incomplete for the remaining glaciers. The vast majority of the excluded glaciers are smaller than 4 km^2 and of "normal" type.

In total, 136 of all glaciers larger than 1 km^2 (1029) have been classified as surge-type (13.4%), although the limited data available for the glaciers excluded from this study may make this figure unreliable. Of the 504 glaciers used in our analysis, 132 (26.2%) were classified as surge-type and there are large variations in the percentage of surge-type between the different drainage basins (Fig. 1a). We also calculated the glaciated area covered by surge-type glaciers, expecting this percentage to be higher, because surge-type glaciers are generally larger than normal glaciers (Clarke and others, 1986; Hamilton, 1992). Of the total glaciated area (36598 km^2) (Hagen and others, 1993), 46.5% is occupied by surge-type glaciers, whereas for our sample of 504 glaciers (34195 km^2), 48.3% of the area is so occupied. There are also large variations in the percentage of the area glaciated by surge-type glaciers between the different drainage basins (Fig. 1b).

These figures compare poorly with the often quoted estimation that 90% of the glaciers in Svalbard are surge-type (Lefauconnier and Hagen, 1991). We believe that this estimate of 90% is an overestimation unless typical quiescent phases are significantly longer than the length of observation in the archipelago, and towards the upper end of the range 50–500 years suggested by Dowdeswell, Hamilton and Hagen (1991). If this is the case it would be possible that we have failed to detect glaciers as "surge-type". The period of observation started locally around the mid 1800s and glaciers with quiescent phases longer than 100–200 years might not be identified as surge-type because the morphological evidence of a surge becomes less clear with time.

METHODOLOGY

From the data available in the glacier inventory (Hagen and others, 1993) we selected a set of variables to test against the prevalence of surging (Table 2). For the statistical analysis we assigned a binomial surge potential, S, to the glaciers in the inventory ($S = 0$ for normal glaciers; $S = 1$ for surge-type glaciers). Most of the continuous vari-

Table 2. Variables used in data analysis. Most variables are listed in glacier inventory (Hagen and others, 1993)

Continuous variables	Categorical variables
Log glacier length	Orientation of accumulation zone (8)
Log glacier area	Orientation of ablation zone (8)
Maximum altitude	type of glacier front (6)
Mean altitude	*Petrological category (3)
Minimum altitude	*Geological age (8)
Equilibrium line altitude	*Lithology type (25)

*Log mean surface slope.
Asterisked variables were assigned by the authors. Categorical variables have the number of categories indicated in brackets.

ables (Table 2) were directly available from the glacier inventory of Svalbard. We added mean surface slope, calculated from maximum and minimum glacier altitude and glacier length as a continuous variable. Where the relationship between glacier surging and the continuous variables was non-linear, log transformations were used. Two categorical variables came from the glacier inventory: glacier orientation (expressed in compass octants), and frontal characteristic (six types: normal, piedmont, expanded, lobed, calving and confluent).

Geology-related variables were based on geological maps from the Norsk Polarinstitutt at scales 1:100 000 and 1:500 000. From these maps it appears that the majority of glaciers in Svalbard cross geological boundaries and therefore overlie more than one lithology. However, to simplify the analysis, the "dominant" lithology for each glacier was identified. The "dominant" lithology is the bedrock beneath more than 50% of the glacier base. In cases where multiple lithologies were present, the bedrock underlying the majority of the lower region of the glacier was assigned. As geology maps only show outcrops beyond glacier margins, visual interpolation was used to estimate the location of geological boundaries beneath glaciers. This can be problematic in highly glaciated areas, particularly for the outlets of the Nordaustlandet icecap. With this method we identified 25 "dominant" lithology-types each belonging to one of the three main petrological categories. Finally, we denoted geological age of these lithologies in eight classes, ranging from Precambrian to Tertiary age.

Multivariate logit regression analysis

Multivariate logit regression models can be fitted as generalised linear models (Nelder and Wedderburn, 1972) in packages such as the generalised linear interactive modelling (GLIM) system. Francis and others (1993) describe the package and its capabilities in detail. Logit regression models are directly analogous to standard multiple regression models, but the dependent variable is categorical with a value of 0 for "failures" (non-surging glaciers) and a value of 1 for "successes" (surging glaciers). These models allow the independence of a set of explanatory variables, which may be continuous, categorical, or a mixture of the two as in this example, to be assessed while controlling for the influence of the remaining variables. Thus, we can disentangle the primary factors influencing glacier surging.

In a logit model it is assumed that the dependent variable is binomially distributed, with the binomial parameter being related to a linear function of a set of dependent variables. The general form of the logit model is

$$P_i = \frac{\exp\,(f(X_i))}{1 + \exp\,(f(X_i))} \tag{1}$$

where

$$f(X_i) = \alpha + \sum_{k=1}^{K} \beta_k X_{ik} \tag{2}$$

and P_i is the probability of success for the ith observation, X_{ik} is the value of the kth explanatory variable for the ith observation and α and β are parameters to be estimated. When fitted as a generalised linear model, the logit transformation is used, meaning effectively that the analysis is equivalent to a multiple linear regression of the log-odds ratio (the logarithm of the odds that an individual is a "success") on the explanatory variables.

The resulting "model deviance" is a measure of fit which is useful for comparing the relative ability of different explanatory variables, although it does not tell us whether the model fitted could have generated the observed data. By comparing the reduction in the deviance from the null model (the simplest model where no explanatory variables are included) with the associated loss of degrees of freedom (DF) using the χ^2 value at the appropriate significance level (95% was used in this study), it is possible to assess the most important explanatory variables. A stepwise strategy of model fitting is then used so that the effect of individual variables, variables in combination and interactions between variables, can be assessed logically. The significance of the individual parameters can be determined by comparing them with their associated standard errors. At the 95% significance level a parameter is significant when its value is approximately twice the standard error. A tutorial explanation of the use of logit modelling in the context of geomorphology is given in Atkinson and others (1997).

DESCRIPTIVE RESULTS

Simple data visualisation (plotting data in histograms, scatter plots, etc.) can aid in the detection of variables that distinguish surge-type glaciers from normal glaciers. Initial ideas about patterns were tested using simple statistical methods such as χ^2 tests. This exploratory data analysis also aids the decision about how to reduce the number of categories of each categorical variable in the logit analysis. Whereas for normally distributed samples the mean and standard deviation are a good measure to represent the central tendency, these statistics cannot be used for data that are not normally distributed. None of the continuous variables used in our analysis were normally distributed. We therefore use the "median value" to quantify the central tendency. The length and slope data in the histograms (Figs 2 and 3) are plotted on a log-normal scale in order to show that, after transformation, the data distribution is approximately normal. The log-transformed data for length, area and slope were used in the logit analysis, providing significantly better results than the non-transformed data.

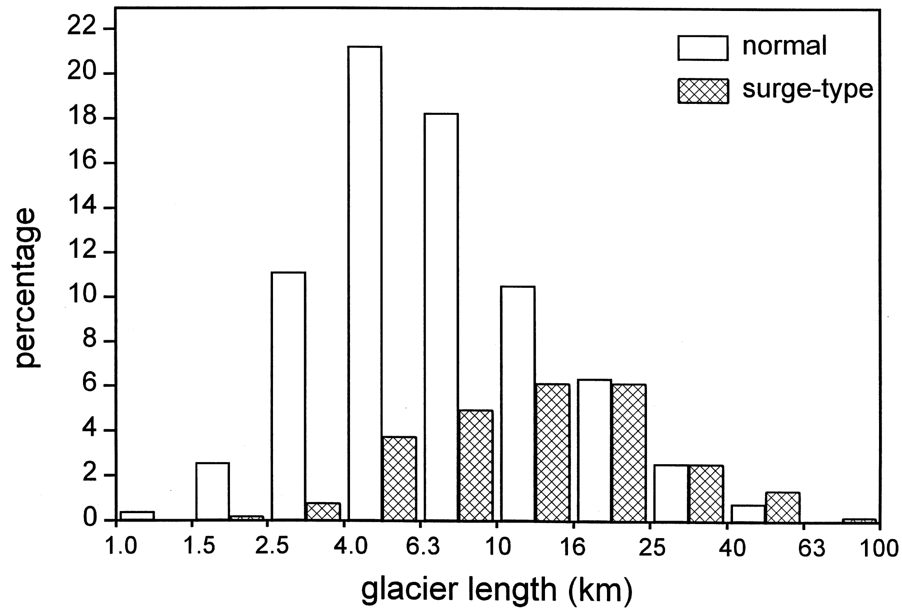

Figure 2. Length distribution of surge-type and normal glaciers expressed in percentage of total glacier population in data analysis. Note that length-scale is log-normal.

Glacier length

Glacier length in our data set ranges from a minimum of 1.5 km to a maximum of 68.4 km, with a range of 1.5 to 47 km for normal glaciers and 2.0 to 68.4 km for surge-type glaciers. From the observed frequency curves we expected length to be log-normally distributed, and normality tests confirmed this observation. The median length of surge-type glaciers is 13.1 km and the median length of normal glaciers is 6.5 km. Histograms of the length of normal and surge-type glaciers, Figure 2, show that surge-type glaciers tend to be longer than normal glaciers.

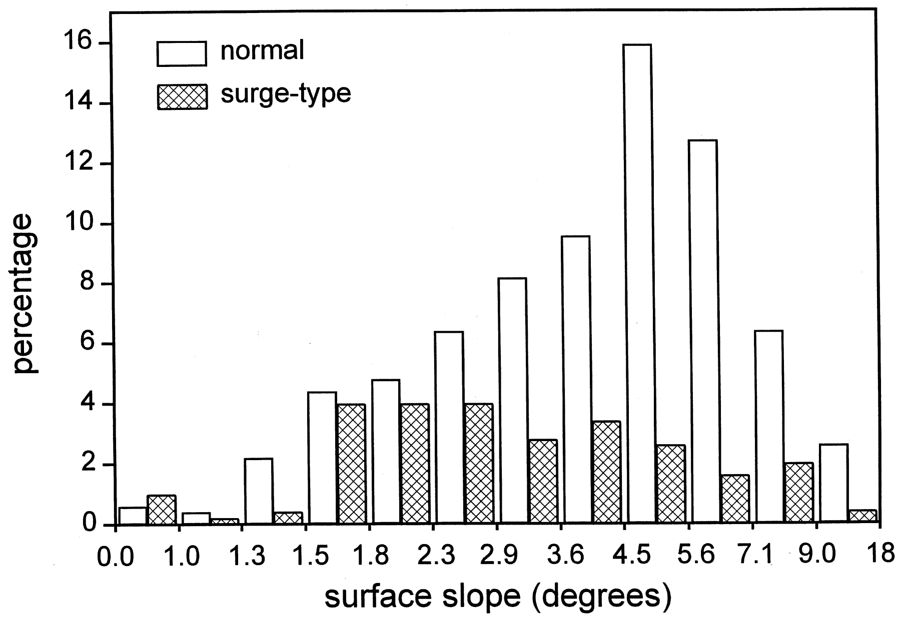

Figure 3. Surface slope distribution of surge-type and normal glaciers expressed in percentage of total glacier population in data analysis. Note that slope-scale is log-normal.

Glacier area

Glacier area ranges from 1.8 to 1270 km^2 for surge-type glaciers and from 1.8 to 720 km^2 for normal glaciers. As glacier area is directly linked to glacier length ($R^2 = 0.79\%$) the relation between glacier area and surging is similar to that of glacier length and surging: surge-type glaciers tend to have larger areas than normal glaciers. This relationship is significant using χ^2 tests at 95% significance level. The median area for surge-type glaciers is 49 km^2 and for normal glaciers 14 km^2. The four largest glaciers in the database with an area of more than 1000 km^2 are all of surge-type.

Mean surface slope

Thesurface slope of the glaciers in our data set varies between 0.7° and 18.4° and this parameter is also log-normally distributed. The range for normal glaciers lies between 0.8 and 18.4° and for surge-type glaciers between 0.7 and 14°. The median surface slope for surge-type glaciers is 3.1° and for normal glaciers it is 5.1°. Qualitatively the distribution of surface slopes, Figure 3, suggests that surge-type glaciers have low surface slopes.

Glacier elevation

The maximum altitude (elevation of the highest point of a glacier) for surge-type glaciers ranges from about 400 to 1700 m above sea level (asl) and for normal glaciers between about 200 to 1350 m asl. The minimum altitude (elevation of the glacier snout) for surge-type glaciers varies between 0 and 400 m asl and for normal glaciers the range is between 0 and 500 m asl. Mean altitude (elevation of the point midway up the glacier) for both glacier types varies between about 150 and 1050 m asl and equilibrium line altitude ranges between 100 and 800 m asl.

It is difficult to differentiate between surge-type and normal glaciers using elevation data as the altitude ranges overlap considerably. However, the elevation span of surge-type glaciers is larger as they are found up to 350 m higher than normal glaciers whereas the minimum altitude for both is at sea level. It should be noted that the distribution of the equilibrium line altitude across the archipelago varies according to latitude and distance from the ocean. The lowest values are found in the southern and western areas of Spitsbergen and the highest values appear in the central northern part of Spitsbergen.

Glacier orientation

The orientation of accumulation area and ablation areas of the glaciers in our data set are expressed in octants. The rose-diagrams in Figure 4 show that 51% of the surge-type glaciers have their accumulation area facing in easterly directions (NE, E, SE), whereas only about 36% of the normal glaciers do. For the ablation area the percentages are 49 and 37%, respectively. This would suggest that surge-type glaciers have a higher probability of facing in easterly directions than normal glaciers. However, many of the east orientated surge-type glaciers in Svalbard are located in south-east Spitsbergen and also have calving fronts (Lefauconnier and Hagen, 1991). To disentangle possible relationships between glacier surging, orientation and type of glacier front a multivariate analysis is necessary.

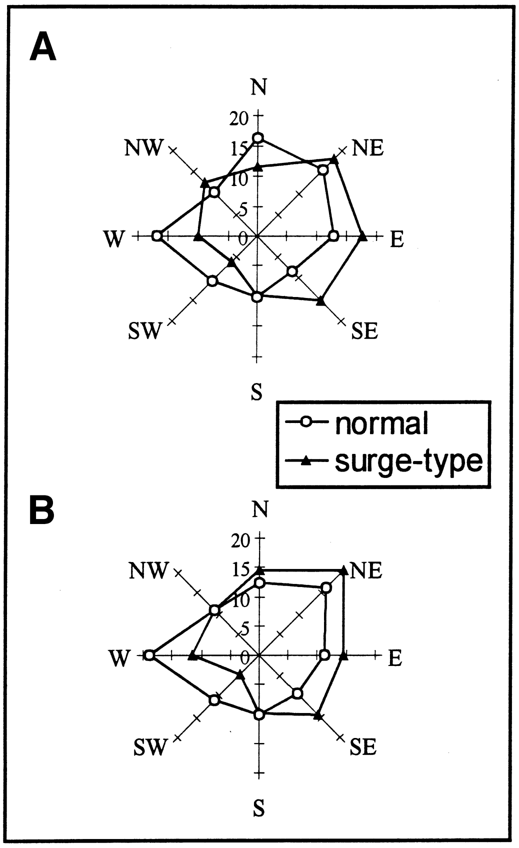

Figure 4. Orientations of (A) accumulation areas and (B) ablation areas of surge-type and normal glaciers expressed in percentages.

Type of glacier front

The glaciers in the glacier inventory were divided into six glacier front types: normal, piedmont, expanded, lobed, calving and confluent (Hagen and others, 1993). As shown in Figure 5, the majority (59%) of non-surge-type glaciers have normal/valley type fronts, whereas for surge-type glaciers, calving fronts (39%) and normal fronts (41%) are almost

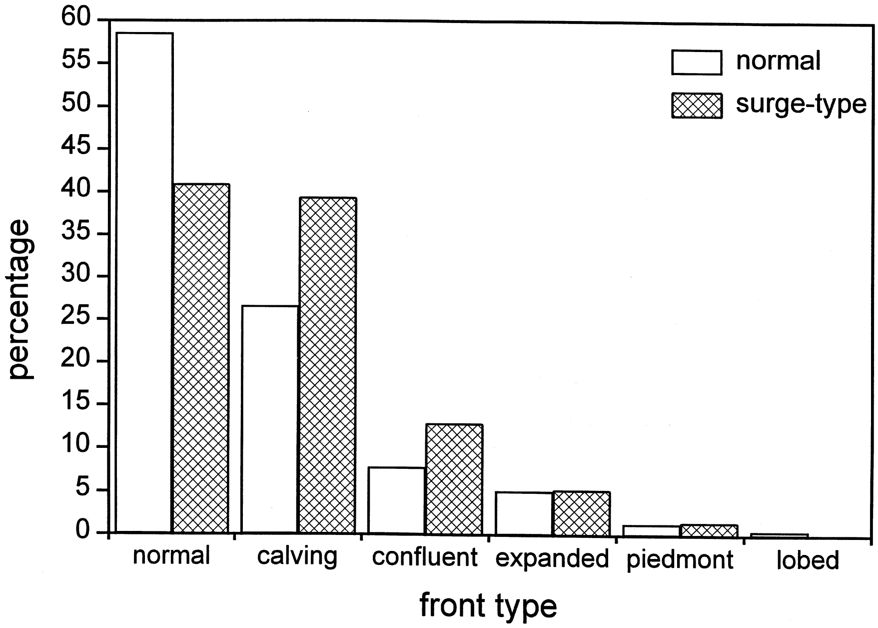

Figure 5. Distribution of glacier-front types of surge-type and normal glaciers expressed in percentages.

equally present. Moreover, the percentage of confluent front types in the surge-type glacier population (13%) is almost double that for normal glaciers (7.5%).

Geology

In our data set 74.6% of all glaciers predominantly overlie sedimentary bedrock (13.5% shale/mudstone, 60.1% other sedimentary), 18.6% overlie metamorphic bedrock and only 6.8% overlie igneous bedrock. As Figure 6 shows, surge-type glaciers are more likely to overlie shale/mudstone lithologies (29%) and less likely to overlie metamorphic rocks (13.6%).

Lithological age

The percentage of surge-type glaciers overlying Cretaceous (26%) and Permian (12%) aged litholo-

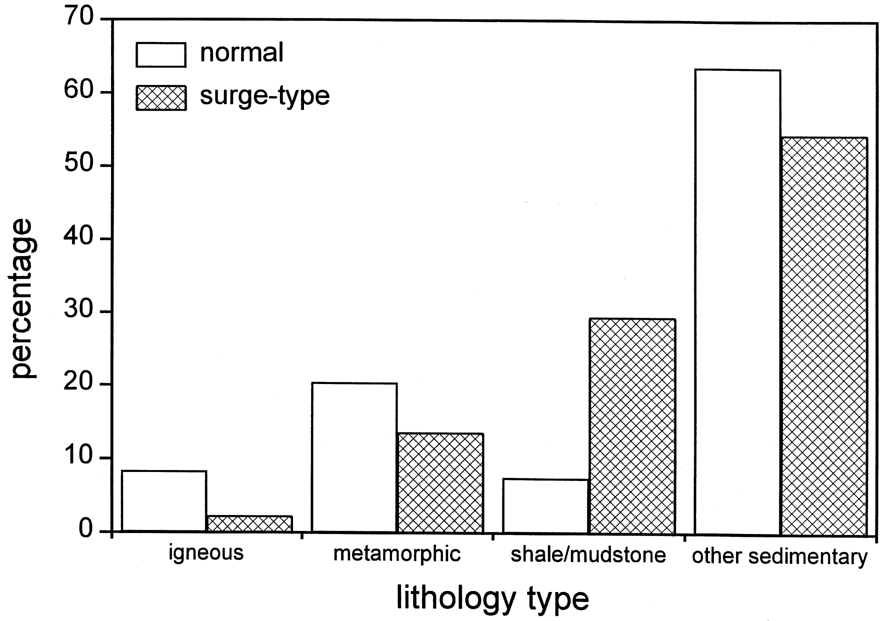

Figure 6. Distribution of lithology types underlying surge-type and normal glaciers expressed in percentages.

gies is significantly higher than the percentage of normal glaciers in these categories (11 and 5%), whereas the percentage of normal glaciers overlying Precambrian (37%), Devonian (10%) and Carboniferous (8%) is significantly higher than that of surge-type glaciers (30, 3 and 5%). The percentages of surge-type and normal glaciers overlying Triassic, Jurassic and Tertiary bedrock are almost equal. From these raw data it appears that "older bedrock" is not favourable for surging.

RESULTS FROM THE LOGIT ANALYSIS

The logit analysis was performed in two stages. First, the relationship between each variable and the incidence of surging was examined individually. However, during these analyses certain relationships may be misinterpreted because the confounding effect of other variables is ignored. Consequently, the second stage involves fitting multivariate models where each variable is incorporated in a step-wise fashion to account for these combined effects.

For these analyses we reduced the number of classes in each of the categorical variables orientation, lithology and geological age systematically in order to optimise each model. The glacier orientation was reduced from eight octants into two orientation clusters: (1) north-west, north, north-east, east, south-east and (2) south, south-west, west based on the descriptive results of Figure 5. Of the surge-type glaciers, 75% have orientations in the first category compared to only 60% of the normal glaciers. The 25 lithology-types were reduced into four categories: igneous, metamorphic, shale/mudstone and sedimentary lithologies other than shale/mudstone. Finally the eight age classes were reduced into five categories (Precambrian, Devonian, Permian/Carboniferous, Triassic/Jurassic/Cretaceous, Tertiary).

Univariate models

The models resulting from the separate fitting of each independent variable are provided in Table 3. For a loss of one DF the critical χ^2 value at a significance level of 95% is 3.84. Of the continuous

Table 3. Results of logit regression with each variable fitted separately

Variable	Subgroup	Estimate	Standard error	Deviance	Degrees of freedom
Null model				579.64	503
Glacier length	intercept	–3.695	0.3912	516.74	502
	log length	1.186	0.1605		
Glacier area	intercept	–2.854	0.3099	533.03	502
	log area	0.5320	0.08131		
Surface slope	intercept	0.2563	0.256	550.30	502
	log slope	–0.9580	0.1818		
Maximum altitude	intercept	–2.566	0.3367	554.61	502
	max alt	0.001995	0.0004052		
Mean altitude	intercept	–1.773	0.2918	572.20	502
	mean alt	0.001637	0.0005957		
Minimum altitude	intercept	–0.8098	0.1328	573.22	502
	min alt	–0.002612	0.001069		
Equilibrium line altitude	intercept	–1.786	0.3142	573.09	502
	ela	0.001975	0.0007683		
Orientation accumulation area	S, SW, W	–1.408	0.1912	573.63	502
	NW, N, NE, E, SE	0.5420	0.2259		
Orientation ablation area	S, SW, W	–1.471	0.1901	571.03	502
	NW, N, NE, E, SE	0.6442	0.2254		
Type of glacier front	normal	–1.396	0.1520	564.84	498
	piedmont	0.4792	0.8504		
	expanded	0.3970	0.4675		
	lobed	–4.164	6.951		
	calving	0.7516	0.2290		
	confluent	0.8614	0.3412		
Lithology	igneous	–2.335	0.5949	539.87	500
	metamorphic	0.8944	0.6500		
	shale/mudstone	2.631	0.6099		
	other sedimentary	1.148	0.6055		
Geological age	Precambrian	–1.224	0.1797	566.31	499
	Devonian	–0.9732	0.5523		
	Carboniferous/Permian	0.3765	0.3340		
	Triassic/Jurassic/ Cretaceous	0.4797	0.2330		
	Tertiary	–0.5108	0.6514		

variables, glacier length caused the largest reduction in the deviance (63) from the null model. The parameter estimate (1.186) shows that the odds of being surge-type increases with length. Glacier area reduced the null model deviance by 46, and the parameter estimate was smaller (0.532) despite the relationship between area and length. Surface slope is, with a reduction in model deviance of 29 and an estimate of –0.958, significantly and negatively related to surging; univariate models suggest that glaciers with shallow slopes are more likely to surge. All four groups of glacier altitude data are significantly related to surging. Of these, maximum altitude, with a model deviance reduction of 25, is most significant but the parameter estimate of 0.001995 is very small.

Categorical variables are fitted in GLIM as "factors". The parameter for the first level of each factor is used as a baseline and the parameters for subsequent levels of the factor are expressed as differences from this base. Of the categorical variables, the reduction in the null model deviance for orientation of the ablation area (8.6) is larger than for the orientation of the ablation area (6.0). The positive parameter estimates for both ablation and accumulation area for the north-west to south-east orientations demonstrate that the odds of surging are significantly higher in these directions.

Among the categorical variables, lithology causes the largest reduction in the null model deviance (39.77), for the loss of only three DF. The highest positive parameter estimates for shale/mudstone (2.631) and other sedimentary lithologies (1.148) show that the odds of surging are highest for glaciers overlying these types of bedrock. The odds are lowest for glaciers overlying igneous lithologies, with a parameter estimate of –2.335. The parameter estimate for metamorphic lithologies is not significantly different from the base category of igneous rocks as its value is less than twice its standard error.

The results for geological age show that only geology of the Triassic/Jurassic/Cretaceous age has a significantly different effect to the Precambrian base category. The type of glacier front reduced the null deviance by 14.8, which is significant for the loss of five DF, but small compared to the other categorical variables. The positive and significant parameter estimates for confluent (0.8614) and calving glaciers (0.7516) indicate an increased likelihood of surging compared to the normal glacier fronts.

From univariate model results we can conclude that all tested variables are significantly related to surging when fitted separately, with glacier length, area, surface slope and lithology causing the greatest reductions in model deviance respectively. However, it is important to check whether these relationships are consistent in multivariate models.

Multivariate models

All of the variables listed in Table 2 were tested in the multivariate models; variables that are not discussed below made no significant improvement to the model results. The best model fit included the variables length, slope, orientation of the ablation area, lithology and geological age (Table 4). Parameters with the highest estimates compared to their standard errors are those which effect the likelihood of surging most.

Many of the findings from the univariate analysis are confirmed by the multivariate analysis. However, a number of the variables are not independent, and these dependencies affect the relationships in the multivariate analysis. For example, glacier slope is inversely related to surging when fitted in a univariate model but, when glacier length is added to the model, the relation between slope and surging becomes significantly positive (Table 4). This indicates that with increasing length and increasing slope the probability of surging increases. The multivariate analysis therefore revealed that, once length is accounted for, the relationship between slope and surging is reversed.

According to this model, the ablation zones of surge-type glaciers tend to be orientated in a broad arc, clockwise from the north-west to the south-east

Table 4. Optimal model using multivariate logit regression

Variable	Subgroup	Estimate	Standard error	Deviance	Degrees of freedom
Intercept		–13.42	1.799	425.23	493
Glacier length	log length	3.224	0.4556		
Surface slope	log slope	2.268	0.4953		
Aspect	NW, N, NE, E, SE	0.6911	0.2642		
Lithology	metamorphic	0.4630	0.7175		
	shale/mudstone	3.034	0.7382		
	other sedimentary	1.338	0.6788		
Geological age	Devonian Permian/	–1.411	0.6553		
	Carboniferous	0.3170	0.4606		
	Triassic/Jurassic/Cretaceous	0.5153	0.4000		
	Tertiary	–0.8827	0.7747		

although the parameter estimate is not very large (0.6911) indicating that surging probability is weakly increased in glaciers with orientations in this arc. However, as suggested in the qualitative description, there was a need to test whether this association results from a relationship between surging and calving glaciers, which are locally predominantly eastward orientated (Lefauconnier and Hagen, 1991). We removed calving glaciers from the analysis and this resulted in a decrease in the significance of the relationship between orientation of the ablation zone and surging. Even so, the inclusion of this variable did result in a significant reduction in the model deviance. Thus, "orientation of the ablation area" was retained in the final multivariate model.

As in the univariate model, the multivariate model shows that glaciers predominantly overlying shale/mudstone have a high positive parameter estimate (3.034), followed by other sedimentary rock types, with an estimate of 1.338. The estimate for metamorphic rock types was not significantly different to the base category. Geological age is the last variable retained in the final multivariate model and bedrock of Devonian age has a significant negative estimate (−1.411). Surging was not significantly related to either orientation or frontal type in the multivariate model.

DISCUSSION

A major problem in large-scale research such as ours is the availability, accuracy and form of the data in glacier databases. These problems manifest as missing data, data of different and incompatible formats and inaccurate data. For the purposes of this analysis all glaciers with missing data have been excluded, a process which is valid only if these excluded data are randomly distributed. This is not the case, as the missing data relate mainly to small glaciers of normal type, assuming that their classification is reliable. This means that the glacier sample we selected (504 of 2229 glaciers) may be biased. However, it is likely that our results for glacier length and slope would have been strengthened if the remaining 1725 could have been included, as of the excluded glaciers only 2 were surge-type and more than 95% of these glaciers have areas smaller than 4 km^2. A second potential problem is the misclassification of glaciers as surge-type or normal-type as our analysis assumes that all glaciers have been correctly classified. However, by analysing the residuals from the final model we can identify "outliers" in the population of surge-type glaciers. This may elucidate mis-classification errors or help predict surge-type glaciers which have not been identified as surging glaciers before. This analysis is the topic of a paper in preparation.

From our analysis it appears that length, lithology, geological age, slope and orientation of the ablation zone influence surging, and that length and lithology are by far the most important variables. The results show the advantages of using a multivariate logit regression analysis over conventional methods which have been used previously to analyse the distribution of surge-type glaciers. Multivariate analysis can deal with multicollinearity in the findings and the use of a generalised linear modelling approach allows the combined analysis of continuous and categorical explanatory variables.

In both univariate and multivariate models "glacier length" is the variable most strongly related to glacier surging. This finding is consistent with those of previous research (Clarke and others, 1986; Hamilton, 1992; Hamilton and Dowdeswell, 1996). A number of possible explanations have been suggested for the relationship. Clarke and others (1986) noted that the larger a glacier becomes the more vulnerable its subglacial drainage system is to instability. Long glaciers also have greater likelihood of traversing lithological boundaries and thus experiencing a change in substrate, which may in turn affect the stability of the subglacial drainage system. Furthermore, glacier length could be a proxy for other attributes such as glacier thickness or mass, which could have critical thresholds at which a surge could be initiated. However, at this point there is not enough information available to test these variables statistically.

Clarke (1991) states that for glaciers in the Yukon Territory "slope has no explanatory value not accounted for by the correlation between length and surge tendency". Similar results were found for Spitsbergen glaciers, essentially a subset of the Svalbard glaciers in this study (Hamilton, 1992; Hamilton and Dowdeswell, 1996). However, both studies show a slight but not statistically significant positive correlation between slope and surging. In contrast, our study which uses multivariate models shows a significant and positive correlation between surging and surface slope even after controlling for other explanatory variables: glaciers with steep slopes are more likely to be of surge-type. Clarke used his null finding to argue against the Kamb (1987) linked cavity theory of surge behaviour because this theory predicts that glaciers with low surface slopes are most likely to be of surge-type (Clarke, 1991). Our results argue against Kamb's theory even more strongly Clarke's and our results thus lend no support to the linked cavity mechanism of glacier surging being prevalent in Svalbard.

As the relationship between log-transformed length and log-transformed slope is linear, the definition of "steep slope" is not straightforward. Overall surface slope decreases with glacier length and the slope of the regression line determines the average length/steepness relationship. Hence, "steepness" of the surface slope depends on the length of a glacier: for a glacier of 7 km in length, the average surface slope is 4.5°, for glaciers of 10 km in length the average surface slope is 3.5° and for glaciers of 25 km in length the average surface slope is 1.8°. A glacier with a "steep slope" is one with a surface slope steeper than this average.

The multivariate logit analysis shows a significant correlation between bedrock lithology and surging. Our results show that surge-type glaciers in Svalbard are most likely to overlie shale, mudstone or other sedimentary rocks and least likely to overlie igneous lithologies. These differ from the findings of previous research in Spitsbergen where limestone was found to be the lithology most strongly related to glacier surging (Hamilton and Dowdeswell, 1996). There is a discrepancy between the distribution of surge-type glaciers and normal glaciers on different lithologies between Spitsbergen and the other islands of the Svalbard archipelago. In the regions of Spitsbergen investigated by Hamilton (1992), surge-type glaciers mainly overlie limestone. However, in the additional regions included in our analysis the majority of surge-type glaciers overlie shale/mudstone and a relatively large number of normal glaciers overlie limestone/carbonate. The size and location of a regional study may restrict the environmental setting and it is therefore necessary to take into account the scale of the research before making statements about the relationship between surging and geology.

Relationships between geology and surging are complex to interpret. Geology reflects many factors including bed roughness, permeability, erodibility, sediment properties and geothermal heat flux. Most of these parameters can only be measured in the field, and on a local scale, so that for a statistical analysis of a large glacier population, geology must necessarily be used as a proxy for them. The strong relationship between surging and lithology must imply that one or more of these derived factors is a strong influence on glacier surging.

Compact sedimentary lithologies and especially shales and mudstones, tend to produce fine-grained sediments and the rocks themselves are relatively impermeable (Freeze and Cherry, 1979). The occurrence of fine sediments overlying an aquitard has been suggested to be particularly favourable for unstable deformation of basal sediments (Boulton, 1979). Limestone, which is not favourable to surging in Svalbard according to our results, can be much more permeable, thus preventing the build-up of high basal water pressures. Igneous and metamorphic bedrock are generally of lower permeability than sedimentary bedrock, because they have fewer interconnected pore spaces, and would therefore be favourable to the building up of high basal water pressures. They are more resistant to erosion than sedimentary rocks so that any sediment layer may be thinner beneath the glacier, although in Greenland surge-type glaciers appear to be clustered on igneous bedrock (Weidick, 1988). These results suggest some support for soft-bed rather than hard-bed views of glacier surging, although this is equivocal. Furthermore, as our research into the incidence of glacier surging is a regionally based study, and because the glaciers in Svalbard are low altitude glaciers and often overlie thick sequences of fjord sediments, our support for a soft bed surge mechanism may not hold in other regions.

Our results show a weak but negative relationship between geological age and glacier surging; surge-type glaciers preferentially overlie young rocks. Mean heat flow, water circulation, orogenesis and related uplift and erosion rates are suggested to vary with geologic age of the crust (Sclater and others, 1980; Stacey, 1992), which may in turn be related to variations in subglacial conditions.

SUMMARY AND CONCLUSIONS

The results of our study show the advantages of using a multivariate logit regression approach over conventional statistical methods previously used in the analysis of the distribution of surge-type glaciers. The logit analysis allows the combined analysis of continuous and categorical explanatory variables and the identification of the independent effects of variables whilst controlling for the confounding effects of other variables. Provided the data are appropriate the method will identify the primary factors related to the probability of surging.

From our analyses the following conclusions may be drawn:

(1) From a literature survey and aerial photograph interpretation roughly 13.4% of the total glacier population of Svalbard are surge-type. These surge-type glaciers cover approximately 46.5% of the total glaciated area of the archipelago.

(2) Of the glacial and geological variables, glacier length and lithology appear to be most strongly related to surging if the variables are analysed in univariate models (Table 3). These variables resulted in the highest reductions in model deviance (63 and 39.77, respectively). The positive relationship between glacier length and surging is consistent with findings from previous research (Clarke and others, 1986; Hamilton and Dowdeswell, 1996).

(3) Of the glacial and geological variables tested in the multivariate logit analysis (Table 4), glacier length, surface slope, lithology, geological age and aspect of the ablation area caused a significant reduction in the model deviance. The relatively high parameter estimates for glacier length, surface slope and the lithology category "shale and mudstone" indicate that long glaciers with steeper slopes overlying shale or mudstone have the highest probability of being surge-type. Geological age is

marginally significant in our final model and the negative parameter estimates for Devonian and Precambrian lithologies suggest that surge-type glaciers are less likely to overlie geologies older than approximately 360 Ma.

Our observation that long glaciers are more likely to be of surge-type is in accordance with previous studies (Clarke and others, 1986; Hamilton and Dowdeswell, 1996). However, the positive and significant result from our multivariate analysis for glacier slope (Table 4) do not match the conclusions of previous research, where no significant positive relationship between surging and surface slope was detected while controlling for glacier length (Clarke, 1991; Hamilton and Dowdeswell, 1996). The observation that glaciers with relatively steep slopes are more likely to be of surge-type lends no support to Kamb's (1987) theory of linked cavity mechanism of surging on a hard bed. This conclusion is even stronger than that of Clarke (1991).

The relationship between surging and sedimentary rocks, particularly fine-grained lithologies, suggests that surging may be related to the erodibility, deformability and permeability of the substrate. A possible explanation for the relation between surge potential and geological age is the overall higher geothermal heat flux in younger rocks, or variations in water circulation, orogenesis or related uplift and erosion rates (Sclater and others, 1980). Combined with the results for glacier slope these results for lithology argue in favour of a soft-bed surge mechanism acting in the Svalbard archipelago.

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