STONE ROUNDNESS OF MORAINES CONNECTED WITH TAKU GLACIER, SOUTHEASTERN ALASKA

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The roundness and flatness (Cailleux's indices) of granodioritic stones from three different moraines in contact with Taku Glacier were measured. Mean roundness of talus material was 60, of late Wisconsin moraine material 240 and of push moraine material 370. Flatness of stones decreased in the same order.
Results were statistically evaluated and the differences were identified also by analysis of variance.
By comparing the stone size and roundness it was concluded that the original forms of stones determine their final forms. Flat and small stones cannot be rounded as easely as cubical and bigger blocks by glacial and glaciofluvial processes.

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Introduction

The aim of this paper is to describe the influence of glacial and glaciofluvial processes on the roundness of stones in the area of an active valley glacier.

A problem here is the procedure by which the stones were transported and rounded before reaching their present location. Since there are fewer possibilities in the case of a valley glacier, it is easier to study the problem in these conditions than in other cases *e.g.* moraines of the continental ice sheets.

The Taku Glacier in southeastern Alaska was chosen as a suitable research area (Fig. 1). Samples were taken from: 1) a granodiorite mound of stones (talus moraine) situated on the slope of a nunatak in the middle part of the glacier, 2) a moraine of late Wisconsin date lying near the previous site and situated on the slope of Icy Basin, a small tributary glacier of the Taku Glacier, where the till is subjected to quite active solifluction, and 3) a push moraine at the foot of the Taku Glacier on the seashore, where the material is washed glaciofluvial sand, silt and gravel.

Methods

The method of measuring roundness used in this study was that of Cailleux *(e.g.* Blenk

1960, p. 203). Stones with a diameter of more than 20 mm and less than 140 mm (*cf.* King and Buckley 1968, p. 202) were taken and their maximum length (L), the maximum width (1) at right angles to the length and the thickness (E) at right angles to both of these measured. In addition the minimum radius (r) of curvature in the principal plane L1 at its sharpest point was taken. With the aid of these measurements an index of roundness $2r/L \times 1000$ and an index of flatness $(L + 1)/2E \times 100$ was calculated for the stones. An increase in the index of roundness indicates a higher degree of roundness in the stone. A decrease in the value of E means a higher index of flatness and the higher the value, the flatter is the stone. When the value for the index of flatness approaches 100, it means that the values for L, 1 and E are the same as in a cube or a sphere.

The number of stones measured at each sampling location varied between 20 and 91. Only granodioritic stones were selected for measurement. The results were processed statistically and the means ($\bar{x}$), standard deviations (s), coefficients of variability (v), and standard errors of the mean (m) calculated for each of the three sites. The significance of the statistical differences between the samples was studied with the aid of analysis of variance (Table 1).

Stone roundness

As might have been expected the least rounded stones were found in the talus moraine (sample 1, Figs. 1, 2 and 4, Table 1). The mean index of roundness for stones from this sample was only 60 and the maximum value 160 (Table 1). Approximately 68 per cent of the stones in sample 2 and over 90 per cent of those in sample 3 had an index of roundness higher than the maximum value for sample 1 (Fig. 4). In sample 2 the mean index of roundness was 240 and the standard

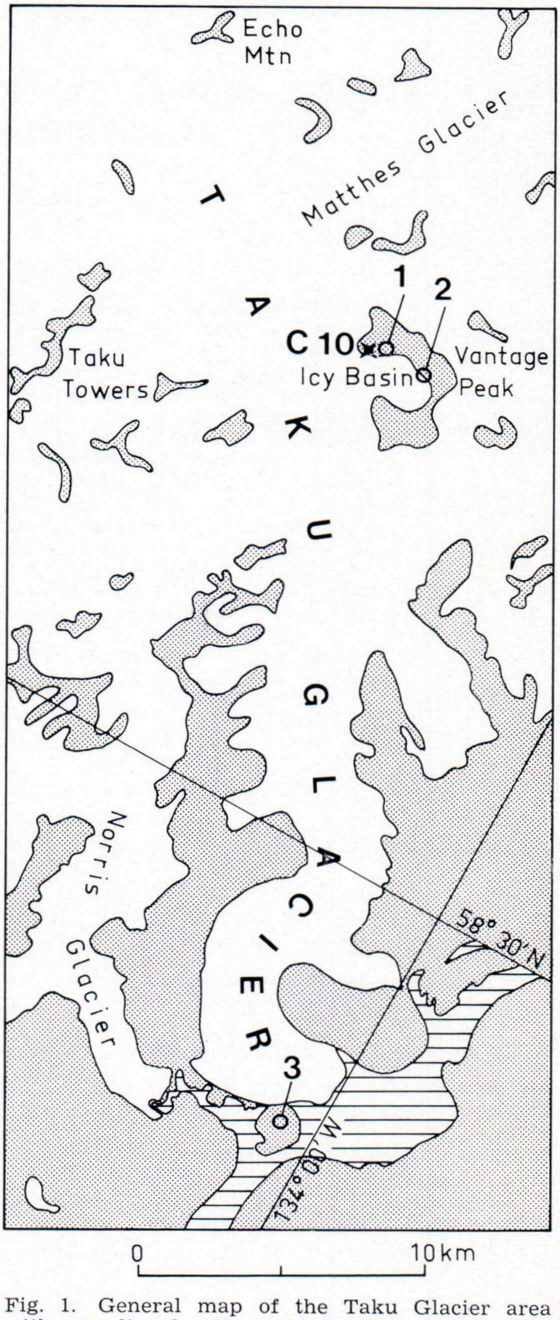

Fig. 1. General map of the Taku Glacier area with sampling locations (1—3). C 10 is the main camp on the Juneau Icefield. The hatched area is Taku Inlet.

Table 1. Roundness and flatness distributions of studied samples. Explanation of symbols in text.

Sample	n	Roundness $\frac{2r}{L} \cdot 1000$					Flatness $\frac{L+1}{2E} \cdot 100$				
		Range	$\overline{x}$	s	v	m	Range	$\overline{x}$	s	v	m
1	20	3 — 160	60	40	60.33	8.93	142 — 929	236	168	71.26	37.6
2	25	80 — 520	240	120	49.49	2.35	106 — 344	185	50	26.77	9.92
3	91	70 — 700	370	150	40.82	15.6	106 — 215	147	21	13.94	2.14
		F = 45.106 dfl = 2 df2 = 134 $p < 0.001$					F = 14.805 dfl = 2 df2 = 134 $p < 0.001$				

deviation 120 or, in other words, considerably larger than in sample 1 but somewhat smaller than in sample 3 (s = 150) (Table 1). The standard error of the mean index of roundness was largest in sample 3 (Table 1).

More than 16 per cent of the stones from the push moraine were more rounded than any single stone in the other samples. The stones in this sample were also on average more rounded than others ($\overline{x}$ = 370). The range (70—700) was by far the greatest (Table 1). The cumulative curve for the indices of roundness in sample 3 was consequently gentler than for the other samples (Fig. 4).

When testing statistical differences in the indices of roundness of the samples by means of analysis of variance, a variance ratio (F = 45.106) was obtained, which is significant below the 0.1 % risk level ($p < 0.001$) (Table 1).

Flatness

The highest values for the index of flatness were obtained for stones from the talus material ($\overline{x}$ = 236). In sample 2 stones were less flat ($\overline{x}$ = 185). The stones with the most even proportions were found in the push moraine sample ($\overline{x}$ = 147) (Table 1 and Fig. 4). The standard deviation (s), which gives an indication of variations within the sample, also decreased in the same way (Table 1). This same regularity was also followed by the coefficient of variability and the standard error of the mean (Table 1).

In the cumulative curves drawn for the indices of flatness the influence of the rounding of the stones can also be seen (Fig. 4). The steepest curve is that for the most rounded push moraine material and the flattest that of the slightly or not at all rounded talus material.

A variance analysis was also carried out in the case of the three samples on the basis of flatness. This gave a similar result to the one obtained from the analysis of the indices of roundness. The variance ratio for the three samples (F = 14.805) is significant

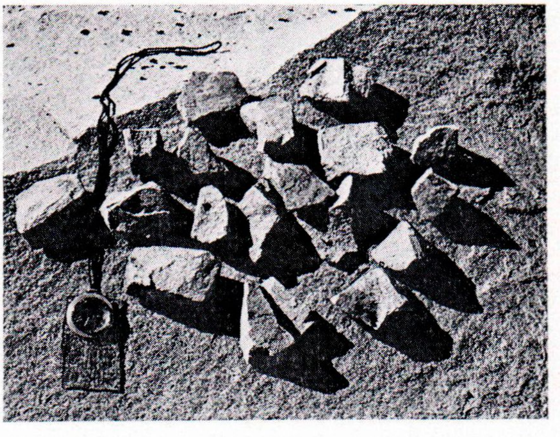

Fig. 2. Angular stones from the talus material (Sample 1). The longer side of the compass is 11 cm in length. Photographs by the author.

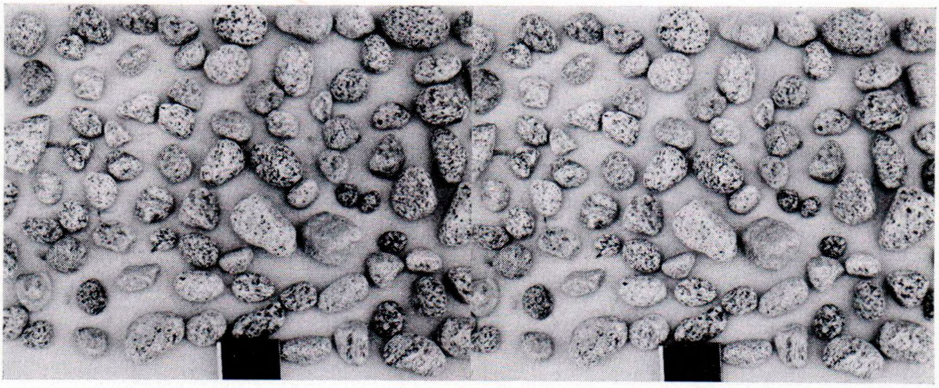

Fig. 3. Rounded stones from the push moraine (Sample 3). The longer side of the matchbox is 5 cm in length. Stereogram.

below the 0.1 ‰ risk level ($p < 0.001$) (Table 1).

Relationship between roundness and flatness

The indices of flatness become smaller as the stones become more rounded (Figs. 4 and 5).

In Fig. 5 the indices of roundness and flatness are shown together. The stones of sample 1 are to be found in the lower part of the grid and the area within which the values lie extends to the right. The area representing sample 2 lies higher up on the grid and lies farther to the left than the first even though it, too, is rather elongated because of a single stone. Sample 3 provides a roundish area lying even farther to the

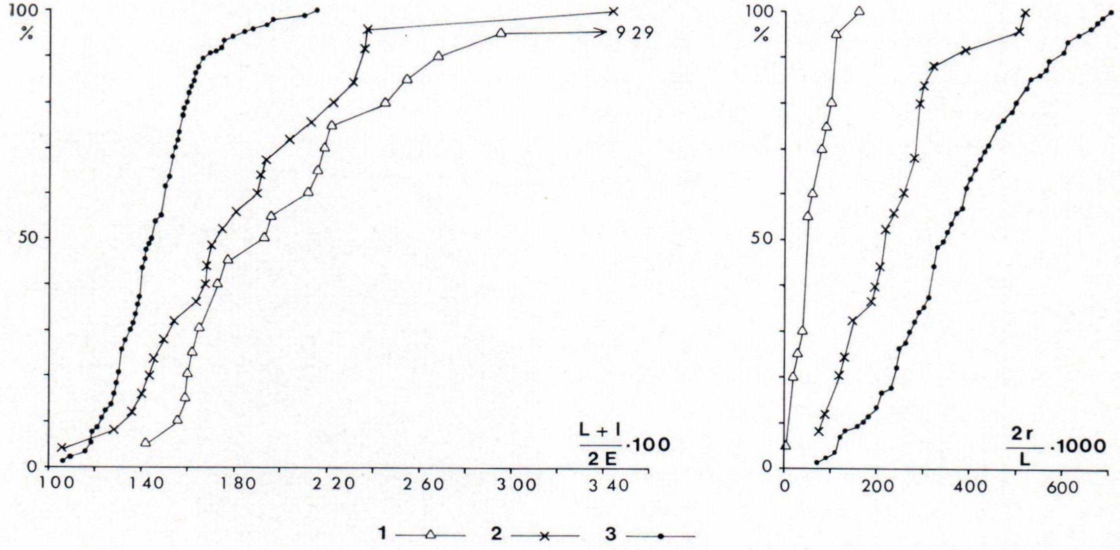

Fig. 4. Percentage cumulative curves of the flatness $(L + l)/2E \times 100$ and roundness $2r/L \times 1000$ of the studied samples. Key to symbols: 1. talus material, 2. Late Wisconsin moraine and 3. push moraine stones (see Fig. 1.).

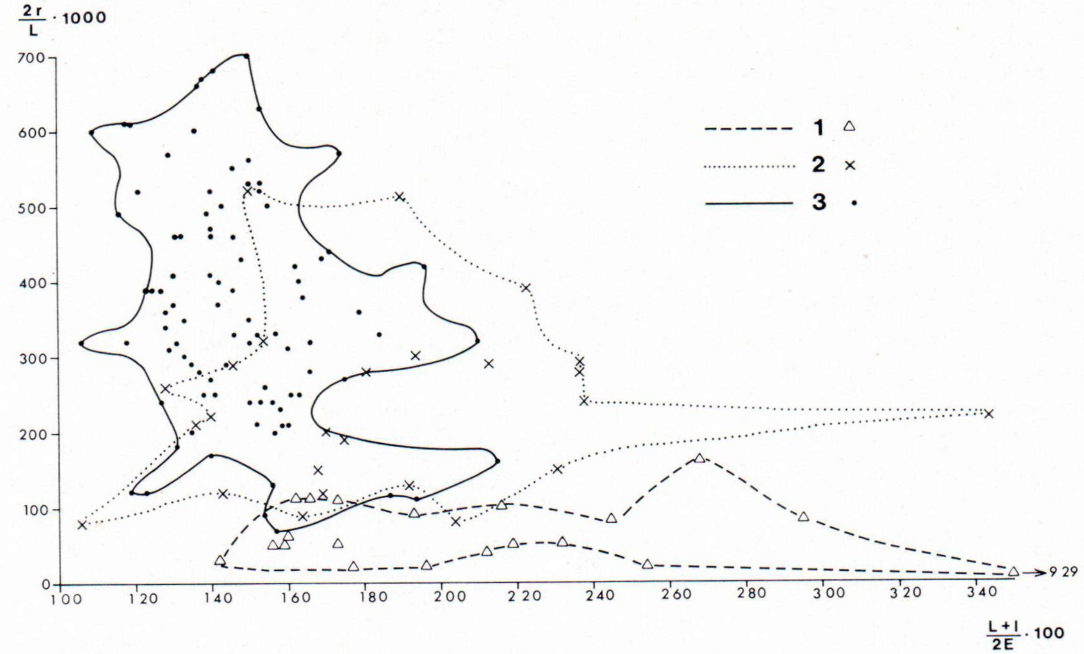

Fig. 5. Relationships between roundness and flatness of stones in different moraines. Key to symbols: see Fig. 4.

left and higher on the grid than the two previous samples. The greater the degree of erosion and roundness of the stones, the farther to the left and the higher up the grid the clusters of values for the indices lie.

Relationship between stone size and roundness

To illustrate the size of the stones the length of the longitudinal axis (L) of stones was chosen (*cf.* King and Buckley 1968). When this was compared with the index of roundness of the stones it was noticed (Fig. 6) that large stones, which were most frequent in the talus material, were generally less rounded than small stones, which had undergone different abrasion processes. This observation is rather natural since the size of the stones decreases as they are worn and rounded. However, no clear statistical correlation was obtained for the whole material.

If Fig. 6 is studied more closely, there can

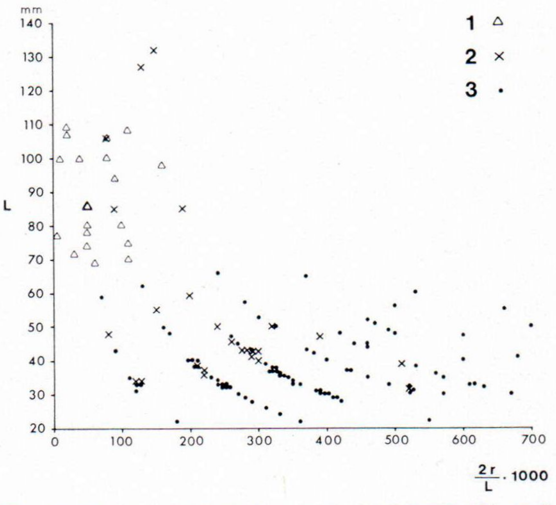

Fig. 6. Relationship between stone length (L) and roundness (2r/Lx1000) of stones in different moraines. Key of symbols in Fig. 4.

be seen some interesting hyperbolic lines formed by the points from the samples. From this the guess might be hazarded that a stone of a certain shape when it has been loosened from the rock undergoes a certain development process in the course of its becoming rounded. In other words, the final form of a stone is determined primarily by its original shape when crumbled away from the rock and secondarily by the processes through which it subsequently passes (*cf.* King and Buckley 1968). In Fig. 6 it is possible to follow five or six different hyperbolic roundness generation lines. Two of the lines are not very clear because of the small material used and the fact that the largest stones were not measured but they appear only in the section of the figure illustrating more rounded stones. The stones are clearly not crushed in the course of the fluvial processes and therefore they follow the roundness development lines rather closely. On the other hand, the glacier can crush stones which have already been rounded (*cf.* Holmes 1960, p. 1648). As a result of this new stones are formed which in turn are subjected to the abrasion activity of the rounding processes.

Discussion

As general rule it may be said that the degree of roundness of stones is determined by the process and the distance they are transported.

At present there are two types of material which are transported by the ice and waters of Taku Glacier. First, there is material deposited on the peaks and slopes of mountains during the Wisconsin glaciation and, second, material recently broken off the rocks as a result of periglacial weathering processes (Hamelin 1964).

It is not known how far the first type of material has been transported and what stages it has passed through before being deposited on the nunataks. The originally fluvial material may have been carried by continental ice from different drainage areas to the new surroundings. In studing material that may have been transported by the continental ice it is therefore necessary to be extremely careful in drawing conclusions about rounding that has resulted from glacial and glaciofluvial processes.

The stones from the Wisconsin glaciation moraine on the Taku Glacier are noticeably more rounded than stones taken from the talus sample. These moraines are small in size and their material moves only slowly down the slope under the influence of solifluction. Consequently the amount of material moved now is very small when compared with the material that crumbles away by frost weathering and is transported by the glacier and its waters.

Sedimentation on the coasts of Alaska is extremely rapid at the terminus of glaciers (*cf.* Jordan 1962). Stones of the push moraine of the Taku Glacier which lie close to the surface at the edge of the glacier have presumably been transported there only a few years earlier.

The maximum straight-line distance over which material can have been transported from the source of the Taku Glacier to its present foot is 60 kilometres, and the direction of transport is downwards along the glacier valley. The stones have been carried either frozen into the glacier or glaciofluvially by meltwaters. In this case the method by which this material has arrived at its present site may be termed a one-way transportation system.

On the basis of one rock type the source of which is known it is possible to arrive at a fairly reliable picture of the rounding qualities of the stones and thus arrive at an idea of how great a distance they would have had to travel to become completely rounded.

It is, of course, impossible to measure under natural conditions the total distance the stones travelled before being deposited. In this study we know only the place in which the stones have been deposited: we do not know how long a stone might have been rolled back and forth on one spot, for example, in a glacier moulin. There are plenty of granodioritic rocks in the Taku Glacier area, in the batholiths of the Coast Range (Forbes 1959), so that the stones could have originated from several different sources along the sides of the glacier.

By selecting only granodioritic stones for the measurements it was possible to keep one variable (rock type) constant (*cf.* King and Buckley 1968, p. 200).

Sample 1 is representation of those stones that have loosened from the rock in the course of periglacial weathering processes. The results of measurements indicate that a considerable number of flat stones break away and become talus material. The granodioritic rock has one predominant direction of fissuring and two others at roughly right angles to the first but at different angles to each other. This character has its effect on the original shape of the stones.

The degree of roundness of the stones of the second sample is much the same as that observed by King (1969, p. 294) in analyses made on Baffin Island of moraines of different ages. Unfortunately King does not reveal which types of rock she used in her measurements.

In glacial meltwater streams material does not need to be transported very great distance for rapid rounding to take place because of the efficacy of the turbulent, running water of such streams (*cf.* King and Buckley 1968, p. 211). Large stones become rounded more rapidly than small ones (*cf.* King and Buckley 1968, p. 209) since they tend to be rolled along the bottom of meltwater channels in the course of transport. This can be seen in Fig. 6 where the best rounded stones are not the smallest ones.

The largest number of measurements of stones was taken in the third sample (Table 1). These stones have possibly undergone all the different transport and abrasion phases connected with the glacier. Therefore the most rounded stones and the greatest variation in material are to be found in this sample. A small proportion of the material may have carried on the surface of the glacier so that it has not been abraded at all.

We do not know exactly what effect tidal waters have had on the roundness of stones in the Taku Inlet area, where there are strong tidal currents (*cf.* Slatt and Hoskin 1968, p. 434—435), nor the significance of outwash processes in proglacial streams (Alimen 1961 according to Flint 1971, p. 168). These processes may have affected the degree of roundness to some extent before the push moraine was formed.

Conclusions

Compared with the material broken off the original rock and the stones deposited earlier during the glacial phase the roundness of stones increases very considerably in the course of their being transported by the Taku Glacier to its margin. In general it may be said, therefore, that the rounding effect of a temperate valley glacier and its waters on the material it transports is very great, even when the distance over which the material is transported is short.

Perhaps the most important observation made in this study is that the roundness of the stones depends on their original shape and size in which they loosened from the rock face. Of course, the final shape of the stones depend also on the rock type and erosional processes to which they are subjected (*cf.* Blenk 1960).

It is intended later to study experimentally, with the aid of a ball mill-like device, changes in the shape of stones, and so follow the rounding of stones of a given shape as they pass through different rounding processes (*cf.* Kuenen 1959).

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