INFLUENCE OF ROCK JOINTING ON THE ASYMMETRIC FORM OF THE PTARMIGAN GLACIER VALLEY, SOUTH-EASTERN ALASKA

Matti Seppälä

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Jointing of rocks is concluded to be the main factor affecting the asymmetric form of the Ptarmigan Glacier valley. Fault lines control the general direction of the valley.
In the paper the general influence of joints on the valley forms is also discussed. The most suitable conditions for the formation of a symmetric U-shaped glacial valley exist when the dipping of the predominant joint sets is close 0°, 45° or 90° and the strike is parallel to the axis of the valley.

Matti Seppälä, Department of Geography, University of Oulu, SF-90100 Oulu 10, Finland.

Introduction

Glaciers are able to form valleys into very regular U-shaped or parabolic cross-sections (*e.g.* Embleton & King 1968, p. 160; Doorkamp & King 1971, p. 276) but not all glacial valleys are so regularly parabolic that their shape can be presented in the form of mathematical formula (*cf.* Svensson 1959, p. 362).

Twenhofel and Sainsbury (1958) inferred fault control for almost all prominent linear topographic features in southeastern Alaska, but did not exclude the possibility that some of the features could be joint controlled.

It has been shown very clearly that ice-eroded linear topographic features parallel the general strike of foliation and several joint sets, but are locally controlled by faults in the southern part of Baranof Island (Brew *et al.* 1963) in south-eastern Alaska about 250 km south of Juneau.

These two studies deal with the macroforms of landscapes in large areas of Alaska and usually in a two-dimensional way. For example, Brew *et al.* (1963) excluded all joints dipping less than 35° from their analysis of linear topographic features, because they probably have relatively little effect on orientation.

In the Taku Glacier valley and adjoining highlands some 20 km NE of the Ptarmigan Glacier valley Miller (1963, p. 30) has pointed out that »It is noteworthy that the most prominent fractures appear as strike and dip-joints which are more or less parallel to the average anticlinal axis and direction of regional foliation. This is significant for the geomorphological interpretations since the longitudinal directions of the main glacial valleys and fiords, as well as the trend of the major cirque walls in this district, invariably parallel the strike of the first and second order jointing sets which have been noted.»

The present study is a detailed quantitative experiment to investigate the three-dimensional influence of all joint sets on the form of a small glacial valley. The question is how the inclination and orientation of slopes is controlled by the jointing of rocks in the Ptarmigan Glacier valley about 7 km north of Juneau (about 58°22′N, 134°23′W). Because of its small size the valley is especially suitable for this type of work.

Methods of study

Using a geological compass measurments were taken of the attitudes of 100 joints in four different small areas (approx. 25 m²) on the ridges of the Ptarmigan Glacier valley (P-1 — P-4 in Fig. 1). Points 1 and 2 are on the Cairn-Vesper-Gismo (Topless) ridge to the east of the valley and points 3 and 4 on the Ptarmigan Ridge to the west of the valley (Fig. 1).

Also the attitude of foliation was measured in each area. Foliation measured in the metamorphic rocks usually includes the schistosity.

All the measurments were plotted on a stereographic plane projection using Lambert's equal area plate and then transformed into contour diagrams (Fig. 5). In drawing special attention has been given to the magnetic declination of 30° to the east between true north and magnetic north in the region.

The topography and form of the valley was observed in the field using a clinometer, and the topographic map 1 : 250 000 (U.S. Department of The Interior, Geological Survey, Sheet Juneau, Alaska N 5 800—W 13 400/60×120), and a simplified topographic map with an approximate scale of 1 : 17 500 drawn by Austin Helmers.

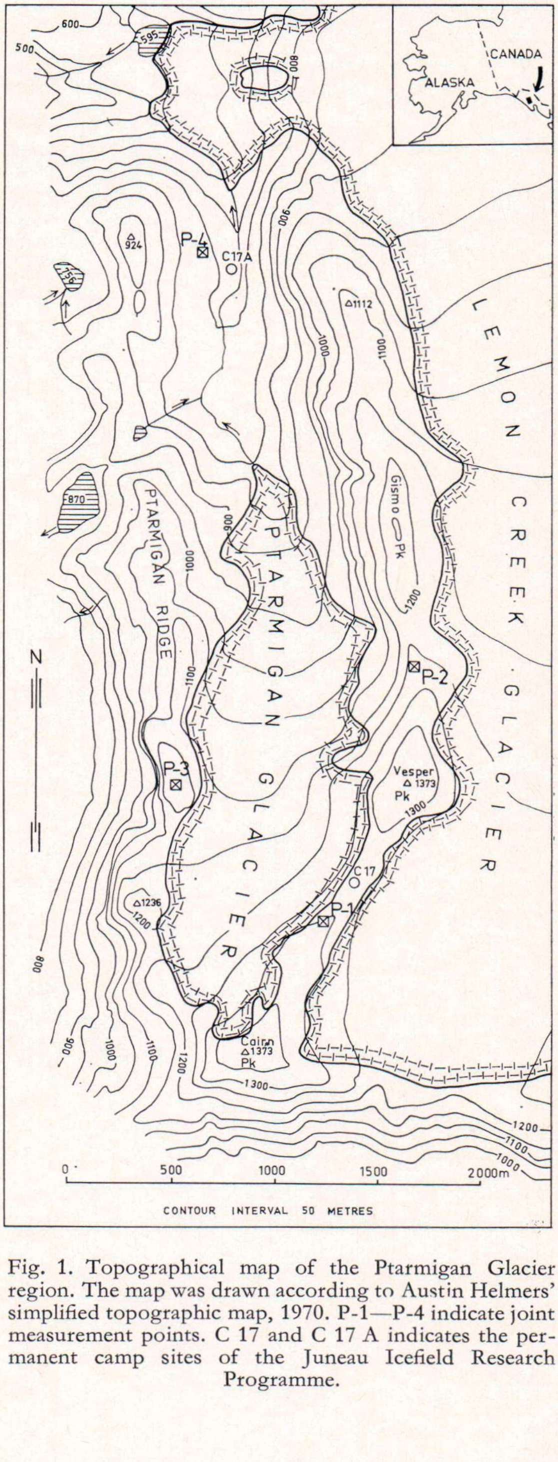

Fig. 1. Topographical map of the Ptarmigan Glacier region. The map was drawn according to Austin Helmers' simplified topographic map, 1970. P-1—P-4 indicate joint measurement points. C 17 and C 17 A indicates the permanent camp sites of the Juneau Icefield Research Programme.

Fig. 2. General view looking south up the Ptarmigan Glacier valley photographed from an old end moraine ridge. July 18, 1971. Note the asymmetric slopeform of the valley. All photographs by the author.

General location and topography of the area

The Ptarmigan Glacier valley is a separate drainage system (Fig. 2). The glacier is less than 3 km long and has a maximum width of about 900 m. East of it lies the Lemon Creek Glacier, about 6 km long and 1 300 m across at its widest point. Between these two glaciers is a bare rock ridge forming an arête called Cairn-Vesper-Gismo (Topless) ridge from which the Gismo Peak rises to about 1 350 m a.s.l. and Vesper Peak to 1 373 m a.s.l. (Fig. 1).

The Lemon Creek Glacier flows down from about 1 240 m to 550 m through an icefall at the edge of the Ptarmigan Glacier valley (Fig. 1). Both glaciers extend northwards and the lower course of Lemon Creek Glacier turns westwards (Fig. 6).

The ridge west of Ptarmigan Glacier valley is called Ptarmigan Ridge with its highest point 1 236 m a.s.l. To the west of it occurs a deep U-shaped asymmetric valley formed earlier by a valley glacier (Fig. 3).

Ptarmigan Glacier is quite steep having an average surface gradient of about 180 m/km. Snow covers the lower portion of Ptarmigan valley only during winter and early spring. Despite the small size and slow movement of the glacier, large crevasses constitute major surface features in late summer (Naff 1969, p. 111). The upper course of the glacier surface dips to the NW (Fig. 1) because of snowdrifting winds blowing from SE (Seppälä 1973, p. 270).

Geology of the area

The Juneau Icefield region is geologically situated in the Coast Range batholith which lies between the Pacific Plate in the west and the volcanic belt of British Columbia in the east (Stacey 1974, Fig. 1). The Coast Range starts

Fig. 3. Dry asymmetric valley west of Ptarmigan Ridge. A view to the SW from Ptarmigan Ridge. July 18, 1971. See Fig. 11.

from Vancouver B.C. and runs up to Skagway, Alaska (Buddington 1927, p. 226).

The Ptarmigan Glacier region belongs to the Western Marginal Belt, which includes migmatic crystalline schists (Forbes 1959, p. 4). Most batholith rock types along the mainland date back to the Middle Jurassic — Lower Cretaceous age (Forbes 1959).

The bedrock geology of the Juneau Icefield area has been studied in detail by Forbes (1959) in his unpublished Ph. D. thesis (Fig. 4). The rocks have a fairly high metamorphic grade according to Forbes (1959) (*cf.* Naff 1969, p. 110). In the upper course of Ptarmigan Glacier close to Cairn Peak there are amphibolites, marbles and lime silicate rocks. The strike of schistosity planes of these rocks is to the NW approximately, and the NE dip averages about 40° and ranges from 8° to 70° (Forbes 1959, p. 4).

Amphibolites occur also west of Vesper Peak and on the western slope of the valley in the southern part of Ptarmigan Ridge (Fig. 4).

Migmatic gneisses as quartz diorites and/or granodiorites are characteristic of Ptarmigan Ridge and the ridge between Vesper and Gismo (Topless) Peaks. The strike of schistosity is from NW to SE and approaches a W—E direction in the lower course of the glacier on Ptarmigan Ridge. The dip of schistosity is about 50°, more or less to the NE (Fig. 4).

Alumina-rich schists are to be found on both sides of the lower course of Ptarmigan Glacier forming the steep west-facing slope of the Ptarmigan Glacier valley. Another place with alumina-rich schists is near Vesper Peak (Fig. 4).

Thin layers of quartzites and micaceous quartzites are to be found on Ptarmigan Ridge (Fig. 4).

In the Cairn ridge a controversy has developed over homoclinal versus folded structures. The longitudinal fold axes in the Cairn Ridge Sequence consistently plunge to the SE at an angle 20° to 40°. The longitudinal folds are overturned to the SW and axial planes are parallel to the S which also represents the axial plane of the large-scale folds. Large-scale folds also plunge to the SE (Forbes 1959).

High-angle normal faults occur near the summit of Cairn Peak. The strike is approximately east-west and the dip from 70°N to vertical (Fig. 4). The faults cut all previous structures. The Cairn Peak fault is one of several step faults which cut the Cairn Peak — Topless Peak ridge (Fig. 4).

Gismo (Topless)-Vesper-Cairn Ridge has several high-angle normal faults. It is interesting to note that faults occur in the area of culmination as indicated by the reversal of plunge. This seems to provide a explanation for the localization of the step faulting, as secondary tensional stresses were probably greater in the area of maximum curvature (Forbes 1959, p. 152).

The strike of some fault lines is parallel to Ptarmigan Glacier valley. This valley is transverse to many structures and may in general be faultcontrolled (Fig. 4).

In the region there are numerous small-scale folds which are usually overturned to the southwest (Forbes 1959).

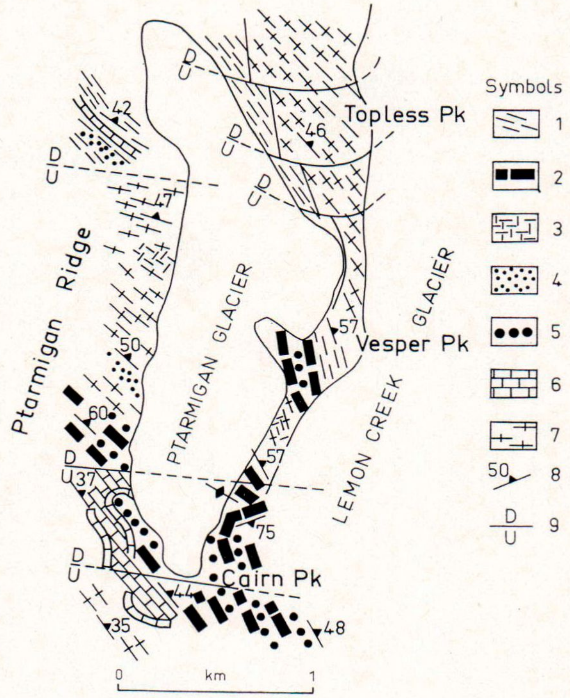

Fig. 4. Geological map of the Ptarmigan Glacier region. Redrawn from Forbes' (1959) appended map. Key to symbols: 1. alumina-rich schists; 2. amphibolites; 3. massive amphibolite; 4. quartzites and micaceous quartzites; 5. lime silicate rocks; 6. marbles; 7. migmatic gneisses (quartz dioritic and/or granodioritic); 8. strike and dip of schistosity; 9. high-angle normal faults; relative movement indicated with U-upwards and D-downwards.

Joint systems

The rock type at P-1 (Fig. 8) and P-2 (Fig. 9) is migmatic gneiss with granodioritic character, at P-3 garnetiferous mica schist (Fig. 10) and at P-4 micaceous schist and migmatic gneiss.

At P-1 were found four strong joint sets (Fig. 5). The predominant set strikes N15°W—N40°W and dips range from 30° to 60° approximately to the NNE. Joint sets corresponding to these can be also seen at all the other measuring points. The second important joint set at P-1 strikes from N to N20°W and dips 80—90° to the E or W. No corresponding joints can be found in the other areas. The third joint set which ought to be mentioned strikes from N50°E to N75°E and dips from 90° to 60° to the NNW. This is one of the predominant joint sets in the region and similar can be found at P-2, 3 and 4, too. It is almost perpendicular to the first-mentioned joint set. The fourth joint set strikes from N80°E to N70°W and dips 20°—45° southwards. Corresponding joints can be found in other areas but they are normally perpendicular to the first mentioned.

At P-2 (Fig. 5) the predominant joint set strikes from N30°W to N15°E and it dips from 25° to 60° to the east. The second joint set is more diffuse, striking from N60°E to N80°E and dipping from 70° to 90° to NNW or SSE. The third concentration of joints is almost striking the first mentioned and is approximately perpendicular to it.

At P-3 (Fig. 5) two joint sets strike between N20°W and N70°W and the angle between their

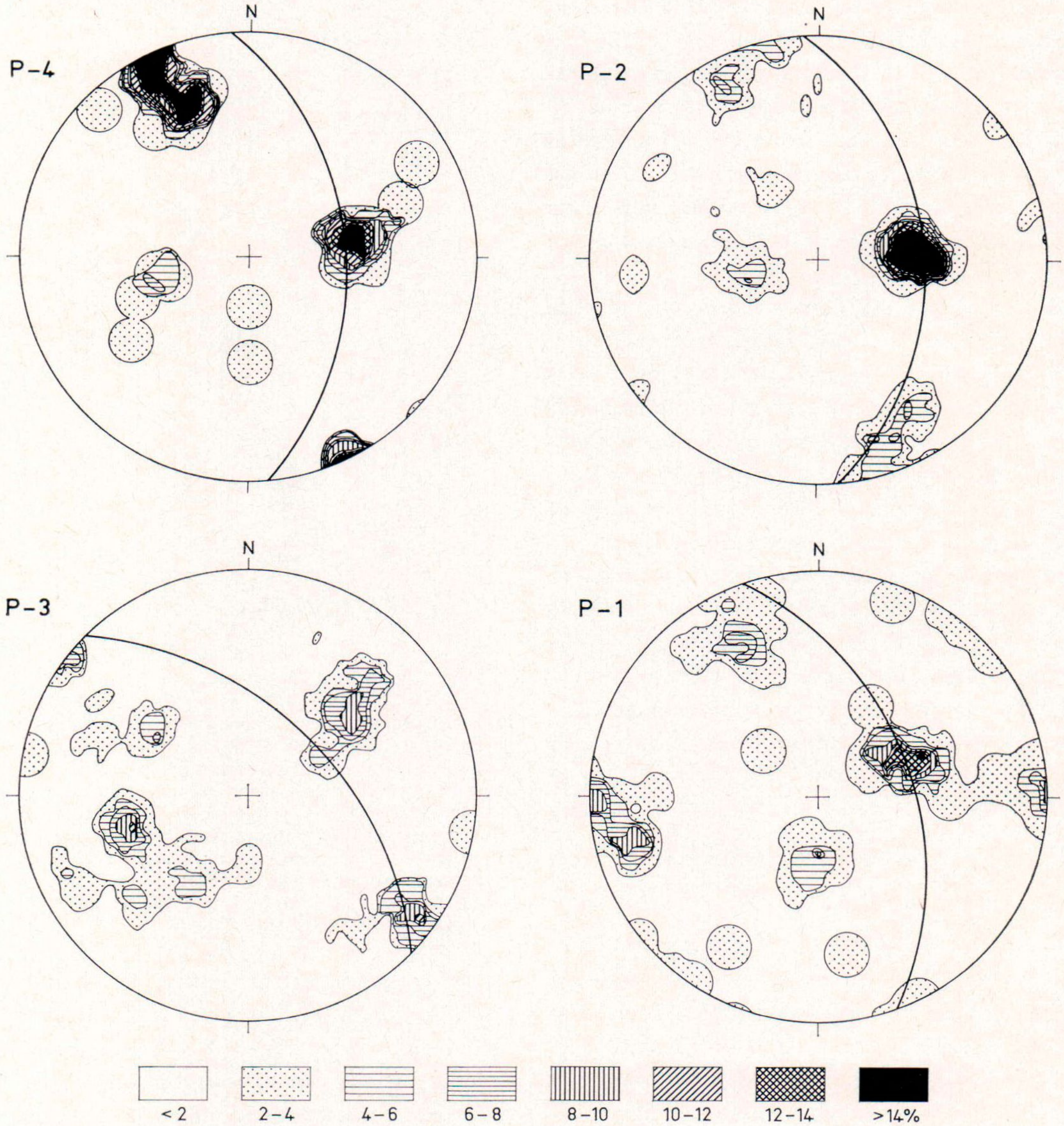

Fig. 5. Stereographic joint diagrams. For P-1—P-4 see Figs. 1, 8, 9 and 10. Curving lines indicate foliation in each measured area.

dips ranges from 70° to 145°. The third joint set is approximately plumb and strikes to NE and SW.

At P-4 (Fig. 5) the first joint set strikes between N15°W and N5°E and it dips from 45° to 60° to the east. The other joint set which, in this case, is the predominant one, strikes between N55°E to N75°E. This means that these two are approximately at right angles to each other. The dips of these joints range between vertical and 65° to the NNW. The third, less important joint set is approximately parallel to the first and dips between 40° and 55° to the NNE.

Fig. 6. View to the NE of steep west-facing slope of the Ptarmigan Glacier valley with talus. In the background the icefall of the Lemon Creek_Glacier. July 18, 1971.

Fig. 7. View to the NW of the east-facing slope of the lower part of the Ptarmigan Glacier valley. Note the saw tooth-like forms on the slope. July 18, 1971.

Fig. 8. Tongue of rock jutting out into the upper eastern side of the Ptarmigan Glacier close to P-1 (Fig. 1). Rock surface indicates one small fault dipping to the NNW. July 16, 1971.

The previous predominant joint set is approximately parallel to the foliation of the rocks (Fig. 5).

The joint sets form a fairly well developed cross joint system which controls frost weathering.

Relief features of the valley

The cross-section of the Ptarmigan Glacier valley is asymmetric. The slope facing west is much steeper (max inclination 70°) than that facing east (max 35°) (Figs. 2 and 6). The same feature can be seen in Lemon Creek Glacier valley and in the dry valley west of Ptarmigan Ridge (max inclination approx. 90°) (Fig. 3).

From the topographic map (Fig. 1) it can be seen that, in general, the western side of the Ptarmigan Glacier is much straighter than the highly winding eastern side where sharp tongues of rock jut towards the glacier from the arête (Figs. 8 and 9).

On both sides of the Cairn-Vesper-Gismo ridge can be seen (Figs. 1 and 4) linears running NW—SE and NNE—SSW. These slopes may be controlled by the strike of fault lines (Fig. 8) parallel with the linears. To some extent these follow the two main joint sets, too.

The effect of faults on the relief of the valley is clearly seen on the slope west of Gismo Peak (Figs. 3 and 6). Lines can be seen on the slope as deeper cuttings dipping to the north and partly filled with snow (Fig. 6).

On the slope of Ptarmigan Ridge the micro-relief shows the effect of some small faults. Ridge-like patterns can be seen on the slope (Fig. 7) with a fairly flat surface which partly follows the schistosity of the rock.

A similar even slope surface has developed on the east-facing wall of the dry valley west of Ptarmigan Ridge (Fig. 4).

Fig. 9. Frost-weathered migmatic gneiss with granodioritic character at P-2 (Fig. 1) facing north. July 16, 1971.

Fig. 10. Frost-weathered garnetiferous mica schist at P-3 (Fig. 1). View facing north. July 18, 1971.

The microrelief features are mostly made up of frost-weathered bare rock surfaces (Figs. 9 and 10). The nature of the broken rock surfaces differs depending on the rock type. For example, schists with steep dipping produce thin plates and sharp relief forms (Fig. 10) while granodiorite breaks into more cubical blocks and forms smooth microrelief forms (Fig. 9).

There are very few roches moutonnées in the lower part of the valley because it is filled with valley train and moraine materials, which may cover glacially eroded rock surfaces.

Rock surfaces on the eastern slope of the valley are more or less furrowed into an uneven surface (Fig. 6). The western slope consists of more even surfaces following the predominant joint plates and foliation (Fig. 7).

Discussion and conclusions

In the formation of Ptarmigan Glacier valley the first phase was the Tertiary folding which resulted from metamorphizing of the batholith rock types of the Middle Jurassic-Lower Cretaceous age to form the Coast Range. Different strains of the tectonic movements caused fracturing, faults and joints in the rocks.

It may be supposed that before the glacier accumulated in the valley it was subject to subaerial weathering processes. Primary determining factors were then the weakness zones of rocks, fold axes, fault and rupture lines, jointing patterns and qualitative differences in rock layers. Chemical and physical weathering formed the valley first and drift material was transported to the lower levels by mass wasting, nivation, fluvial and eolian processes. This may have developed on a peneplain-like surface which was later rejuvenated by epeirogenic uplifts and the erosion processes reactivated. The erosion type might have been so-called »down-dip lateral erosion» (term by von Engeln 1942, p. 119) which caused a asymmetric slope profile. At the beginning of Pleistocene glaciation the valleys of the region were filled with valley glaciers and later also the top parts of the mountains were covered by the ice sheet. This can be concluded from the erratic boulders on the upper ridges and in the cols of the arêtes (Naff 1969). During the Holocene the valley was at times filled by glacier. The role played by the glacier in forming the valley has been to cause bottom erosion which has overdeepened the valley and effectively transported the drift material falling from the sides of the valley downwards. The effect of the glacier as a result of the development of the valley has been principally to purge it from drift material which new fresh rock surfaces became the object of subaerial erosion processes.

In south-eastern Alaska the most effective type of weathering is periglacial frost weathering (Hamelin 1964) on the nunataks. The type of drift material produced by frost weathering is determined by the fracturing of the rocks. Several students have shown that the asymmetric slope form is caused by exposure factors *i.e.* how the slopes are facing to the sun. In asymmetric valleys found in sedimentary materials the south- and west-facing slopes are usually steeper than those facing east or north according to Ollier and Thomasson (1957, p. 71). French (1971, p. 721), however, has found on the Beaufort Plain that the steeper slope was oriented towards the southwest.

Jahn (1947, p. 96) writes: »A characteristic feature for almost all the ridges and longitudinal valleys, (parallel to the fjords), in the region of Arfersiorfik, western Greenland, is their asymmetrical transversal section. The asymmetry of the valleys corresponds exactly to the position and the inclination of the layers of gneiss. The exposition is here of no importance, as the steep slopes of the valleys are exposed as well toward the north, as towards the south.» The present author also holds the view that it is the structure of rocks that primarily determines the form of glacial valleys.

To interpret the fracturing effect on the geomorphic forms studies must be made of the

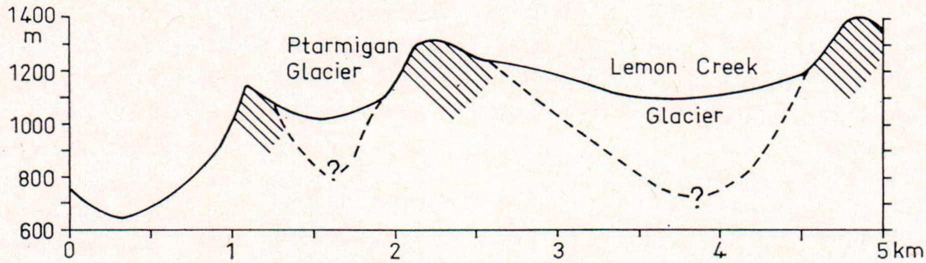

Fig. 11. Sketchy profile from W to E across the dry valley (Fig. 3), the Ptarmigan Glacier and Lemon Creek Glacier. Thickness of the ice is unknown. Parallel lines indicate the approximate dips of predominant joints.

directions in which and the intervals at which small faults, joints and foliation occur. This was done by measuring all fractures (at least 100 joints) in small areas.

In Ptarmigan Glacier valley the predominant joint sets dip to the E and NE and strike is approximately parallel to the axis of the valley. The second, weaker jointing dips about 90° to the predominant jointing. As foliation also almost follows the predominant joints it has provided a suitable erosion basis for valley formation. The third effective joint set strikes about 90° to the two others and dipping is very steep. This has had its influence on the shape of the valley, especially on the west-facing slope, by forming the peninsulalike rock tongues which make the valley side winding. The tongues may represent walls of former small cirques. The development of cirques is controlled by rock structure according to several investigations (*e.g.* Embleton & King 1968, p. 190—191).

The development of the Ptarmigan Glacier valley as well as the valleys on both sides of it has been asymmetric because the predominant joint set dips diagonally to the flow direction of the glacier (Fig. 11).

The phenomenon can be examined theoretically by constructing simple models of different joint sets and of their influence on the valley form. Very often the surface of the predominant joint set conforms to one slope of the valley. If the second, weaker joint set dips 90° to the predominant one, then asymmetric valley will form if the dip of the predominant joint set is close to 0°, 45° or 90° (Fig. 12). This basic situation gives the best possibilities for the formation of a regular U-shaped glacial valley. In the other cases (A and B in Fig. 12), the valley would have a more or less asymmetric cross-section. A more complicated picture is obtained if the different joints are not perpendicular to each other. Glaciers of course erode these asymmetric valleys to shape them into their characteristic form of

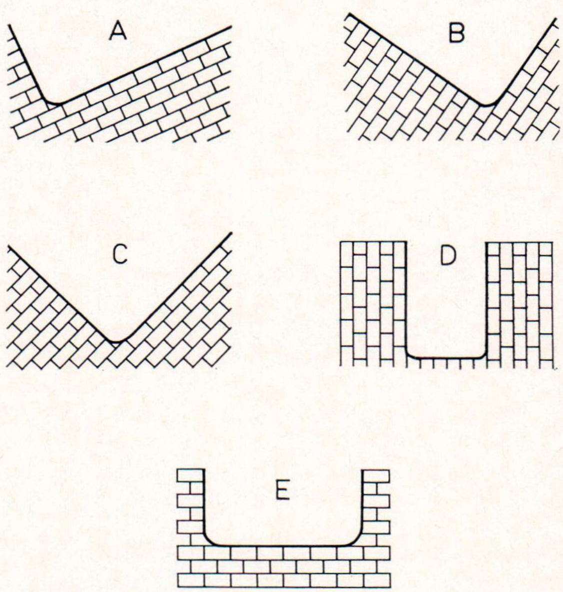

Fig. 12. Diagrammatic cross-sections of the influence of two perpendicular joint sets on the form of valley. In figure A dip of the predominant joints is less than 45°, in B more than 45°, in C 45°, in D the vertical joint set and in E the horizontal joint set is predominant.

a glacial trough but it must be borne in mind that ice is a plastic mass which follows the topography and most of the erosion power is directed to the bottom parts of the glaciated valley and to zones of weakness.

The influence of different rock types on the valley form has been small. Amphibolites, lime silicate rocks and migmatic gneisses may have been somewhat more resistant to wearing so they have formed most of the rock tongues on the eastern side of the valley (Figs. 1 and 4). The influence of rock types has been mostly on the microrelief forms of the arêtes.

In conclusion the author would like to emphasise that the jointing of rocks controls the asymmetry of the Ptarmigan valley and most important eroding factor (also controlled by joints) in this type of climate is frost weathering. This influence of the bedrock structure can be seen in the glacial troughs and fjords of, for example, New Zealand and Norway, as the author has been able to note subsequent to his visit to Alaska.[1])

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[1]) Since this manuscript was accepted for publication it has come to my knowledge that a similar study in many respects has been made of the Ptarmigan Glacier area [Egan, Christopher Paul (1971). Contribution to the Late Neoglacial history of the Lynn Canal and Taku valley sector of the Alaskan Boundary Range. Unpublished Ph. D. thesis. Michigan State University.] The author of that study has also come to the conclusion that the structure of the bedrock has been of decisive importance in determing the strongly asymmetric form of the valleys in the region.