RESTUDY OF RED ROCK ICE CLIFF  
NUNATARSSUAQ, GREENLAND  

Richard P. Goldthwait  

August 1971  

CORPS OF ENGINEERS, U.S. ARMY  
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY  
HANOVER, NEW HAMPSHIRE  

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PREFACE

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Dr. Arthur J. Brandenberger helped in planning the photogrammetric operations, and John Splettstoesser reviewed the manuscript.

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THE PROBLEM

Purpose

This study was undertaken in 1965 to provide a 10-year coverage in the rheological knowledge of a land-based marginal ice cliff and to answer such questions as: Why do 10- to 40-m ice cliffs develop at the margins of great continental ice sheets? Exactly where do they develop? Do they advance suddenly or erratically enough to destroy installations? What causes their degradation and disappearance?

Ice cliffs present a barrier to vehicle access and to communication and fuel lines. They make travel or work along the ice margin hazardous and endanger structures near the ice edge. Predicting their future height and rate of advance, slow or rapid, is critical for any occupation or installation in their vicinity.

Comprehensive initial studies were made a decade ago of 1) the vegetation- and deposit-recorded history of a rather static Red Rock Ice Cliff, 2) all aspects of its motion, 3) the structure and thermal conditions of the ice including the 40-m-deep base, and 4) the local regimen of mass balance as it is affected by inflow and losses of ice or by deluges of meltwater. This follow-up study was intended to time-test the earlier findings and to detect other slow changes which seem to occur. The scope of this restudy was limited to mapping the position of the ice surface and studying the effects upon vegetation. It must assume some aspects of internal motion and structure, or water budget, discovered and measured earlier.

Earlier studies

In 1954, spurred by the need to get men, supplies and machinery up onto the Greenland Ice Cap, the U.S. Army Corps of Engineers (Snow, Ice and Permafrost Research Establishment) contracted for a short reconnaissance study of the nature of the northwestern edge of the Greenland Ice Cap. The 10% which is gently sloping ramp had already been studied in 1953 (Goldthwait et al., 1954; Schytt, 1955). Approximately 15% of this long, crenulate margin proved to have a vertical ice cliff. Another 10% was ice cliff in water and 30% was steep, wedge-shaped ice slope on land. To discover why these cliffs develop, and whether one form changes to another, detailed studies were carried out in 1955 and 1956 at Red Rock Ice Cliff (Fig. 1) at the northern tip of the glacier-surrounded land called Nunatarssuaq.

The geological history, climatological influences on tundra plants, and the mass balance of the small (2.2-km²) ice drainage basin above Red Rock Ice Cliff were determined. The key studies were a theodolite triangulation of absolute ice motion and photogrammetry to map net changes in the cliff itself (Goldthwait, 1956). By second, third, and fourth triangulation of stakes we sought
Figure 1. Red Rock area, northern Nunatarssuaq, Greenland.
to find the absolute motion and ablation along 500 m of Red Rock Ice Cliff through a second summer season (1956). By terrestrial photogrammetry producing 25-cm contours along 280 m of the vertical ice cliff we sought to find the net changes occurring over periods of a summer month and a year. Detailed studies were made of the thermal regime and petrographic nature of the ice, especially in a tunnel under the cliff. These were all analyzed and reported (Goldthwait, 1960). Simultaneous studies of the junction of the ice caps just to the east were reported (Nobles, 1964), and a revisit to study deformation at Red Rock Ice Cliff in June 1957 was reported by Hilty (in Goldthwait, 1960).

Current study

After a decade, in July 1965, this restudy of Red Rock Ice Cliff was made. The surface of the drainage basin was remapped by plane table showing 5-m contours (Appendix A). The vertical face of the cliff was remapped with 25-cm contours, and the 1955 map was replotted with the Wild A7 plotter to use identical matching methods (Appendix B). To see whether the environment next to the cliff was changing, a botanical study was made of the same quadrats observed in 1955 (Appendix C). An analysis and conclusions concerning the changes in this ice cliff and the small feeding ice basin are the objectives of the first part of this report. A hypothesis concerning the growth and demise of an ice cliff is presented.

The studies concentrated on a section of ice cliff up to 4.0 m high along the southeast edge of North Ice Cap (Fig. 1), just west of where it touches and overrides the main Greenland ice sheet (76°54'N, 66°57'W). This sector is part of a broad symmetrical semicircle of ice cliff which faces south where studied, but swings southwest and south 1.5 km over Survey Hill. South of this for 4 km the same cliff, not over 20 m high, faces east and is draped across small valleys and Botanist Flats.

This cliff was selected because it was high, had easy access to open ground, and appeared to be advancing. Well-developed polygonal soil patterns with ice wedge structures pass beneath the cliff at many points. A 20-m tunnel into the cliff, with shafts to the frozen drift floor, revealed that permafrost was indeed beneath. Moss from shear planes in the cliff dated less than 200 years before the present (W-532), indicating recent ice advance. Thus this cliff is believed to have developed through the advance of this edge of North Ice Cap. Surficial geology studies bore this out (Goldthwait, 1960).

ICE SURFACE CHANGES

Lowered surface

The ice drainage basin has lowered in a decade by at least 5 m. Figure 2 shows the remapping of a sample square kilometer within the 2.2-km² ice drainage basin in back of the cliff. Five-meter contours have been displaced just one contour interval in ten years and at first glance the 1955 map (Goldthwait, 1960, Fig. 57) and 1965 map look alike. The comparison at 378 accurately located grid points gives an average lowering of 5.6 m. The equilibrium line, or last year’s snow limit, fell lower in mid-July 1965 (892 m elevation) than it did in July 1955 (904 m elevation) (Goldthwait, 1960, p. 21). This combined lowering and protection by snow covering can only mean a drainage of ice into the ice cliff that exceeds the supply of ice from the high accumulation zone on North Ice Cap. The hydrologic budget calculated from the outflow of Red Rock Lake in 1955 and 1956 indicated an excess of 563,500 m³ and 439,504 m³ of measured outflow each year over and above the measured ablation (inflow). Instead of being due to errors in photographic measurement of snowdrift size, as was thought earlier (Goldthwait, 1956, 1960), or melting losses from permafrost in nearby land (which was not observed anywhere), it now appears that the whole ice surface is lowering by 0.5 m per year. The loss of ice, which must total 500,000 m³/year in this small basin, has been finding its way into Red Rock Lake.
Irregularity of change

It is notable that this settling of the surface is not at all uniform in the western half of the area. Centers of excessive loss are marked by the large numbers -7, -9, -10 on Figure 2. Nine such centers are outlined on the basis of 3 to 34 grid point values, and four centers of minimal loss (-2, -3, -4) are noted.
The five spots which dropped 8 m or more in a decade total about 6% of the square kilometer mapped. Why should the ice surface have dropped so irregularly? Maximal surface ice depression occurred along the western half of the ice basin over a uniform 12 to 13% eastward land slope. The gravity and seismic surveys of 1956 (Goldthwait, 1960, Fig. 53) give no hint of small topographic irregularities which might generate these spots. That they occur along a notable slope at 660 to 680-m elevation over underlying land rather than over the flat land to the east at 600-m elevation may be significant in this small sample.

It is postulated that this is a natural counterpart of the attenuated “turbulent” flow demonstrated in 1955-56 (Goldthwait, 1960) by 1) aberrant motion of stakes, a few of which moved backward with respect to the ground, or 2) folded basal dirt structures in the low ice cliff across the summit slope of Survey Hill (Goldthwait, 1956, Fig. 5.332B). Whether this is true turbulence, in the solid flow of such a viscous material, may be argued.

**Changes in the Ice Cliff Itself**

*Vertical area*

Nine to ten years after the initial detailed survey, the outstanding change in the high ice cliff was a 30% reduction in the area of exposed cliff (between 140 m and 420 m on the grid of Figures 3 and 4). This loss of vertical cliff face is due to three changes. If the ice surface in the basin dropped 5.6 m (Appendix A) then the top of the cliff lowered a significant amount. Figures 3 and 4 show this, and lines have been added to Figure 4 showing that the high eastern cliff face (320- to 420-m grid) has lost nearly 3 m of its top. Farther west on the slope (140 to 240 m grid) the lowering averaged 4.5 m. These correspond to the average surface lowering of 3.5 m and 4.5 m shown in the proximity of the ice cliff on the surface contour map (Fig. 2).

A second loss of vertical cliff face, all along the high eastern portion, has resulted from a rise in the top of the sloping ice toe at the base of the cliff. In 1955 (Fig. 3) the upper limit of the toe varied from 67 to 76 m, the average being 72.7 m; but in 1965 (Fig. 4) it was 76 to 81 m, or an average of 78.3 m. This 100-m-long portion of cliff lost 5.6 m of its height right at the base. Or to put it another way, the stagnant basal sloping "toe" ice had thickened from 12 m to over 17 m. Indicative of what was going on is the fact that the dirty ice toe surface inclined at 33\(^\circ\) in 1955 but a decade later it averaged 54\(^\circ\) from horizontal. Ablation had ceased, for most of the ice toe was covered with snow, and it slowly tipped to a steeper incline. This change was limited to the high cliff area because on the lower cliff up the hill slope to the west no ice toe showed at all above the snowdrifts in 1965 and by comparison this means it averaged at least 0.7 m lower than in 1955 when it did show.

The outstanding third loss in the mappable area of the ice cliff was due to flanking snowdrifts getting much higher. These drifts have grown in spite of annual packing and partial melting each summer. When the area was first inspected in August 1954 north of base line station 14, the snow was less than 2 m deep. In 1955 photogrammetry showed it to be 8 m deep, in 1956 10 m deep (a warm summer), and by 1965 it was 16 m deep. This drift, well out in front of the high section of ice cliff and separated from it by a hollow, grew at least 8 m higher on the average in the decade (between grid positions 320 and 420, Fig. 4). It obscured much of the ice toe (e.g. the old tunnel site) in 1965 photogrammetry and buried base line stakes 12, 13, 14, and 15 where the drift extended southward (Appendix B).

Up the slope to the west (Fig. 4, grid positions 140 to 240 m) the snowdrifts have always been banked in high ridges oblique to the ice cliff. In 1955 these averaged 8.5 m deep up and down the slope; a decade later they averaged 14 m deep, from the photogrammetry.
Ablation

Of the total net ablation of this ice basin, when appraised in 1955-56, 98% occurred on the sloping top surface and 2% on the vertical ice cliff itself. The cliff represented the most dynamic exposure, however, involving several types of ice loss, such as "dry calving" (Table I), not found in the ice surface up to the equilibrium line. The annual total loss on the cliff averaged 2.0 m depth in the 1955 ablation season and 2.5 m in 1956, whereas the measured average loss over the ice basin surface above was only 0.54 m and 1.1 m respectively.

Inasmuch as the ice cliff area decreased 30% in a decade the available surface for the "double rate" ablation losses peculiar to ice cliffs (i.e. dry calving plus melting) is drastically reduced. The calculations in Table I are based upon 1955-56 measurements. It is assumed that the relative proportions of different types of ablation are the same today as they were in 1955-56 but that the areas of application and gross amounts have changed. The role of the ice cliff in disposing of ice has decreased from about 2% of the ice to less than 1%.

Table I. Annual losses of ice from Red Rock Ice Cliff

<table>
<thead>
<tr>
<th>Year: June to June</th>
<th>1955-1956</th>
<th>1965-1966</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drainage basin below snow line (sloping)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum area of melting ice</td>
<td>3,183,000 m²</td>
<td>1,924,000 m²</td>
</tr>
<tr>
<td>Depth ablation loss by melt*</td>
<td>0.54 m</td>
<td>0.35 m</td>
</tr>
<tr>
<td>Volume total ablation loss</td>
<td>1,719,000 m³</td>
<td>673,000 m³</td>
</tr>
<tr>
<td>Movement of surface ice, inferred</td>
<td>-0.012 m</td>
<td>-0.21 m</td>
</tr>
<tr>
<td>Net change in surface position</td>
<td>-0.55 m</td>
<td>-0.56 m</td>
</tr>
<tr>
<td>(by mapping): volume</td>
<td>-1,751,100 m³</td>
<td>-1,077,000 m³</td>
</tr>
</tbody>
</table>

Ice cliff fringing basin (vertical)

| Area of melting cliff ice | 9,500 m²| 6,650 m² |
| Depth of loss by melting and sublimation | 2.72 m | = 2.25 m |
| Thickness of dry calving | 0.95 m | = 0.75 m |
| Volume of total ice losses | 34,900 m³ | = 19,950 m³ |
| Movement forward of cliff ice | 4.64 m | -3.0 m |
| Net change in cliff position | +1.27 m** | +0.14 m |
| (by photogrammetry): volume | +12,000 m³ | +1,330 m³ |

* No sublimation due to snow cover.
† Double the cliff mapped by photogrammetry since it was selected as a sample half of the total cliff.
** Only 0.53 m from August 1955 to August 1956 due to severe 1956 ablation season.

Net movement of the position of the ice cliff

Inasmuch as the area of ice cliff suffering the outstanding rapid ablation has been reduced almost 30% we might expect some forward creep of the front due to less exposure. From the average net movement of the cliff face position (+0.53 m) measured photogrammetrically in 1955-56, we would have projected a forward motion of at least 5 m in a decade also. Nothing like these motions occurred, let alone the sum of them.
The net change measured for 890 grid points on the vertical cliff is +1.42 m of ice advance southward. To be sure, some portions of cliff face, mostly in the moderately high portion resting on the lower hill slope, did move 5 to 9 m forward (Fig. 5, areas at 200 to 270 m, 290 to 340 m). But net recession of 2 to 5 m is shown by top-to-bottom point averages where the cliff is highest and near the sloping west end (Fig. 5, 150 to 185 m, 390 to 420 m). Close study of Figure 4 suggests that these areas of net recession are where ice converges most into the cliff front (1955-56 measurements), for there it suffers the most vigorous dry calving, much like the nine zones plotted in 1957 (Hilty, in Goldthwait, 1960, Fig. A6). The portions with maximum net advance are broad monolithic portions which overhang a little more and probably came off in 1966. But the total picture is very close to that of a static position for the cliff itself.

**Detailed change in topography**

Two sorts of change in the details of topography are apparent from the six separate photogrammetric representations of the vertical ice cliff by 25-cm contours: 1) the short annual march of changes is exhibited by the four maps of 1955 and 1956 made by Kelsh plotter and published in 1960 (Goldthwait, Fig. 57, 58); and 2) long range changes are exhibited by comparison of the two July maps of 1955 and 1965 as made by Wild A7 plotter and published here (Fig. 3, 4).

After one year (June 1956) the 10 or more vertical couloirs cut by streams which had been so prominent in August 1955 left only three old residual channels cut 1 to 5 m deep in the cliff face, and these were badly deformed by 10 months of irregular ice motion (June 1956, 190 m, 255 m, and 273 m grid). Secondly, in June 1956, the lower 1- to 3-m strip of the vertical cliff was sharply undercut for at least 100 m of its total length (260 m). In short, the massive bulging cliff in early June overhung for 40% of its length as a result of a concentrated shearing just above the ice toe, and this was not sloughed off by late June. A third feature consisted of three fresh, nearly vertical and slightly curved "steps" a meter or so deep representing places where large unstable ice slices peeled off the face of the ice cliff even before June 1956 (at 217 m, 385 m, and 394 m grid).

By late August 1956 all the contours were smoother even though they were all made on the same Kelsh plotter by the same operator. The stream couloirs were more numerous than in June (six or seven) and fell straight downward from recent meltwater action. The zone under the overhang was broader (2 to 5 m) and rose higher on the cliff. This was probably due to grain by grain ablation enlargement which undermines upward from the overhang in the radiation-melt season. The earlier steps, facing westward, were sloping, irregular, blunted and hard to identify, because ablation resulting from radiation-convection had dulled and changed the whole surface after the June dry calving.

The July maps one decade apart (1955 and 1965, both by Wild A7 plotter and identical operator) show less difference in detailed character of contour than do those of the one season. Some steps caused by dry calving and the overhang caused by shearing appear in each decade. To be sure, all vertical stream couloirs and steps (breaks) were in entirely different places after 10 years. However, the clearly contoured stream cuts were much more numerous (3 deep, 14 shallow) on the high 1955 ice cliff compared to the lower 1965 ice cliff (1 deep, 3 shallow). To some extent this might be due to completion of photography two weeks earlier in the 1965 season before seasonal waterfalls had accomplished much. So many cuts are perennial, however, that this difference must reflect less water and less height of fall as well. The inference is that there was diminished snow melt and glacier ice ablation in the 1963-64-65 years as compared to 1953-54-55.
Figure 5. Profile of net advance and retreat of the cliff in a decade.
Ice motion

Measuring absolute motion of the ice in the cliff was not a recognized part of the 1965 mission. Obviously, with the marked changes in cliff shape and size just noted, it would be useful to know whether and how ice motion had changed. No differences in activity on the cliff between 1955 and 1965, such as dry calving, suggest any change in motion. However, the only stake carefully mapped in 1956 that lasted in place until 1965 was a long aluminum pipe sunk very deep in 1955 to hold the ablatograph. It moved 24 m southeast (about 16 m south and 18 m east) in 9 years. Its specific motion had not been determined in 1955-56 but ablation stake no. 14, 220 m to the west, moved 4.53 m in 321 days which should project to 46 m in 9 years. The nearest cliff face stake, 15A (grid 418 m), was moving in 1955 at a rate which would carry it 42 m south and 10 m east. The ablatograph pipe may represent a more easterly motion because it lies farther east, but it does represent slowing down to about half speed.

Mass budget of the ice cliff

Unfortunately there has been no survey of the mass budget of any large part of North Ice Cap, especially in the accumulation area critical to this small Red Rock Drainage Basin. The draping of the ice cliff edge over hills and into valleys for 20 km south of Red Rock, plus gravity soundings checked by several seismic profiles in 1956 (Goldthwait, 1960, Fig. 53), suggest that this is a relatively thin highland ice sheet flowing irregularly into broad basins like Red Rock Lake. The maximum ice thickness established in 1955 was about 245 m. In 1965 measurements made by reconnaissance radar soundings from a helicopter were in close agreement with the 1955 value (Amory Waite, private communication, Institute for Exploratory Research, ECCM, Ft. Monmouth, N.J.).

Evidently the supply of ice, or the present wave of supply from this thin, topographically controlled ice sheet, is completely inadequate to maintain the 1955 ice thickness with the reduced movement and reduced ablation found at the cliff in 1965. If movement has reduced the supply of ice by nearly 50%, and ice surface ablation has been reduced up to 50% by a lower equilibrium line (snow line), and if cliff ablation-calving area is reduced 30%, then each parameter has scaled down to meet less favorable conditions and the cliff position has changed an insignificant amount to accommodate the new regime.

CHANGES OVER THE LAND AREA

The botanical studies in Appendix C were intended to show whether significant changes in the environment had occurred. Wolfe showed in 1955 (in Goldthwait, 1960) that wind exposure and insolation were reflected most by the blooming dates of plants, and that meltwater from cold snowdrifts reflected the health of the plant community rather than the proximity of the ice cliff as such. Einarsson's study (Appendix C) of the same plots a decade later shows clearly that the principal changes reflect more snowdrifts near the ice cliff, as for example covering cairn 16 on Survey Hill, and deeper flooding in Red Rock Lake, which implies more snow and no drainage south from the lake. The 1955-56 lake-gauging station and the old Jamesway huts at either end of Red Rock Lake are both lost under snow; the upper 2 m of one building did melt out. In 1953 Colton and Holmes (in Goldthwait et al., 1954) and in 1955 Wolfe (in Goldthwait, 1960, p. 93) saw evidence in the wide gray zone of lichen-free rocks around snowdrifts that the perennial snow was less than it had been one to four decades earlier. Evidently, in Red Rock Basin this trend has now been reversed and many snowdrifts have grown bigger and deeper.
Five cogent observations may be read from an additional 75 overlapping 35 mm photographs made in both 1955 and 1965 from the cairns along 6 km of curving ice cliff which rises and falls from the junction with the main Greenland Ice Cap (1 km east of Red Rock base to Botanist Flats 4 km south of that base). 1) The highest vertical cliff faces lie across relatively broad, low, flat land surfaces. These are places of convergent and rapidly moving ice. 2) The only gaps in the ice cliff are steep wedge-shaped edges over the tops of underlying hills. 3) Sloping "ice toes" below the vertical cliff rise and thicken toward each hilltop margin. 4) Flanking snowdrifts grow most over lower slope and valley areas. 5) The thinnest toe ice (under 2 m) is on flat land (Botanist Flats) where ice has sheared sharply over the dead toe ice burying it.

**CONCLUSIONS**

**Changes at Red Rock Ice Cliff**

1) Red Rock Ice Cliff is suffering a slow demise. Its "metabolic rate" is decelerating decisively (confirmed for the main ice cap junction just to the east by Nobles, 1964).

2) The sloping toe ice base is rising, thickening, and steepening at the expense of vertical ice cliff in many places, especially under high ice cliffs on flat land.

3) From its structures it seems that the toe ice incorporates former snowdrift turned to ice along with layers of dirt ablated from the cliff (Goldthwait, 1960; Hooke, 1970). This toe ice is slowly rolled, steepened, or overturned forward yet it is almost stagnant ice.

4) Only sometime prior to 1954 at Red Rock Ice Cliff, or 1953 and earlier at Botanist Flats, was there rapid monolithic advance of the ice cliff over low masses of toe ice and low snowdrifts.

5) The ice surface above the cliff suffers somewhat less ablation now than in most summers a decade ago, yet it is lowering at ½ m/year.

6) Snowdrifts flanking the ice cliff are rising against the lower ice toe and even onto the cliff in places. After several decades of decrease in the size of snowdrifts in Nunatarssuaq generally, the patches of snow in Red Rock Basin increased notably from 1955 to 1965.

7) The growth of snowdrifts greatly reduces the ablation of dirty ice which was 5% of all ice-cliff losses in 1955-56.

8) Ablation by melting, sublimation, or calving on the vertical ice cliff is probably reduced another 30% by simple reduction of the cliff area.

9) Motion in the 1965 ice may be only half that of 1955. It is slightly convergent toward the highest ice cliff on low flat areas at roughly 3 m/year.

10) Active ice shears sharply upward onto the prism of dirty stagnant toe ice which serves as a partial dam. It projects over it with some overhang in nearly half its length.

11) Ice sags and bulges in the middle of the vertical ice cliff, creating tension fractures and slight slump blocks with forward, downward motion vectors.

12) Eventually the failure in ice produces "dry calving," most of which takes place from mid-May to mid-July after long winter overhang.
Hypothesis for ice cliff growth or decay

A fully grown active ice cliff, stably maintained, as in the middle of Figure 6, must have an ice supply by forward-upward motion into the surface equal to surface ablation (convection-radiation-sublimation) as well as forward and downward motion equal to cliff ablation plus dry calving. This means that the ice toe, which is a stagnant ice obstruction, is moderately low (8 m). Since toe ice is dark with fallen debris on it, its ablation is 20% to 30% greater than the ice above. The sharp shear zone just above the toe of the cliff allows a deep, sharp, narrow overhang, and creates the loss of support which engenders dry calving.

Recession profiles are shown by lines 5 to 7 (bottom Fig. 6). The dirty or yellow ice zone rises ever higher in the ice mass of the cliff and the zone of maximum shearing rises. Below it the wedge of nearly stagnant dirty ice thickens, receives "new" dirt by ablation of the lower cliff, adds ice grains and snow cover annually when drifts cover it, and slowly dips more steeply forward. Whether drifts increase markedly, as they did here, and are necessary adjuncts, is not certain but it is certain that they adhere to and preserve frozen ground structures beneath and become incorporated into the overriding ice above.

The true advancing cliff situation (Fig. 6A) was not measured in these studies, but it seems to be modeled near Botanist Flats. Starting with the traditional sloping ice wedge some kinetic wave or great climatic impetus must disturb the regular motion gradient to the edge. Shearing concentrates above dirty old ice. The upper part steepens, overrides and soon becomes a small cliff advancing down its own stagnant toe or wedge (profile 3 on Fig. 6A). If the impetus increases, the maximum shear zone lowers with some overridden ice or old snowdrift in the wedge moving off with the advancing cliff. As the ice cliff gets higher, dry calving, granulation by radiation and wind, and stream waterfalls are added to ablation mechanisms. The monolithic front will plow into drift materials if the edge advances on the thaw zone in summer. Since we know from extensive tunnel exposure that Red Rock ice is not sliding at its base, but is frozen tight to the ground, this is probably how solid debris gets introduced into lower ice. Since there was a sharp shear gradient right at the base 20 m back of Red Rock Ice Cliff the final active high cliff is just like a vertical exposed section, maintained half a kilometer back of the wedge-shaped ice edge.

General deductions

Some general aspects of high land-based ice cliffs along the margin of a continental ice cap can be deduced from this pair of studies a decade apart when coupled with deductions from many other recent studies of the physics of glacier behavior.

1. Ice cliffs on land are the product of the advancing ice margin, possibly surging rapidly initially in response to kinetic waves down the ice surface.

2. The cliffed edge develops only where basal motion is vastly reduced below upper ice motion, i.e. with a strong plastic shear zone near the base. It overrides itself. This shearing is especially notable in the Red Rock example because it advanced "kilometers" over deeply frozen ground and adhered by freezing solidly to the base.*

3. No ice cliff will maintain itself more than 30 to 50 m high, inasmuch as the plausible stresses of forward motion cannot exceed the rate of vertical closure due to the creep rate in thick ice. "Dry calving" (a new term in these studies) becomes a potent factor limiting cliff height; it occurs primarily in late spring after maximum winter overriding.

* Note than another common cause for ice cliff edges is undermining by a contiguous water body. This is not a land-based ice cliff and may indeed constitute a floating ice shelf if summer temperature is below 0°C.
Figure 6. Diagrammatic sketch of advance and retreat of an ice cliff.
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APPENDIX A: MAPPING AND CALCULATIONS
by
Henry H. Brecher and Steven P. Wrestler

Ice drainage basin

A topographic map (Fig. 2) of the ice drainage basin above Red Rock Ice Cliff was drawn on a plane table using a Kern RK self-reducing alidade at a scale of 1 in. = 50 m (about 1:2000). Eight plane table stations and 151 rod stations were used to cover an area of about 1 km². The table stations were established by means of theodolite triangulation from the photo base line. Five-meter contours were plotted with the 1955 elevation of base line stake 15 as datum. This is 630 ±3 m above sea level (Goldthwait, 1960, p. 2). The central portion of the cliff edge was delineated on the plane table map from the photogrammetric map of the cliff face. The remainder of the edge was sketched in from photographs and made to fit the central portion and an intersected point at each end.

The precision of elevation differences obtained is about ±0.1 to 0.2 m, and the precision in planimetry is estimated to be ±2 to 3 m.

A remarkably close match of the shape of the drainage basin and the position of the cliff edge on the 1955 and 1965 maps is apparent when the maps are superimposed, but the 1965 surface is one contour (5 m) lower over virtually the whole mapped surface. The correspondence of shape is so close that one is in fact led to suspect a 5-m error in one of the maps. A careful check of the 1965 work fails to show any such error, however.

The comparison of the two surveys, 1955 and 1965, was also made on a statistical basis with a grid. This grid of 50-m squares was laid over the 1955 map of Merrill and Dresser (Goldthwait, 1956, Fig. 5.311A*) and the 1965 map of Brecher and Weissman (Fig. 2) and elevations interpolated to the nearest meter at each of 352 intersections. Subtraction yields the somewhat erratic values of points shown (Fig. 2). Only the 4-, 6-, and 8-m isopleths are shown. All values are negative; that is, in a decade there was net loss of ice at every point. The average net loss for all 352 points is 5.6 m. The large negative numbers (-7, -9, -10) indicate areas of greatest lowering. At the south margin of the ice sheet the 18 points nearest the ice cliff also average 5.6 m loss of height, which is nearly double that of the 14 points used in the computations from the photogrammetric map of the cliff face. This is due to major zones of depression at both the east and the west ends of the cliff beyond the photogrammetric maps.

Comparison of 1955 and 1965 ice cliff surfaces

The following calculations are based on two 25-cm contour maps of the vertical face of Red Rock Ice Cliff, one for July 1955 (Fig. 3), and the second for July 1965 (Fig. 4). All contours represent distances, Y, perpendicular to a 460-m-long base line established in 1955 approximately parallel to the ice cliff. The base line is the horizontal, X, axis of an arbitrary local coordinate system. Details regarding camera locations and the coordinate system are given by Jury (1956) and Weissman (Appendix B).

* An error of about 20° in the north arrow appears to be due to the use of a magnetic north compass.
The following procedure was used. First a grid representing 2-m squares on the ice cliff was drawn at map scale (1:250). Then the contour map of 1955 was placed under the grid and values of $Y$, distance from the base line, at each intersection on the grid, were obtained by interpolation. The procedure was repeated with the same grid superimposed on the contour map of 1965 (Fig. 4). From these two values for each of 940 points, the difference in distance $Y$ was found at each point and an isopleth map at 0.25-m intervals of net change in the ice cliff was drawn at the same scale as the contour maps. Of the 940 points, 578 advanced toward the base line an average distance of 3.28 m; 320 receded an average of 1.55 m from the base line; 42 remained unchanged. Average movement of the 940 points was 1.49 m advance.

The upper limit of the ice toe, the 40° to 50° sloping apron of dirty ice projecting forward from the base of the vertical ice cliff, is shown where visible on Figure 4 for both 1955 and 1965. This limit was determined by sketching on the two original contour maps the upper margin of the closely packed contours extending right and left along the ice cliff face. This was plotted on Figure 4 by tracing from the contour maps.

Figure 5 is a projection in the horizontal plane of the average change in position of the ice cliff between 1955 and 1965. The values of change in ice cliff position at each vertical line were averaged. This average was plotted above the straight ("no-movement") base line if negative (retreat), and below the base line if positive (advance), to show the average horizontal displacement of the ice cliff at every 2 m of its length over the 10-year period.
APPENDIX B: PHOTOGRAMMETRIC MAPPING

by

Simha Weissman

Reconnaissance

A base line was established in 1955 when 15 stakes were set 30 m apart along an approximately straight line 420 m long in an east-west direction. The west end of the base (stake 1) is about 40 m higher than the east end (Stake 15). The 1965 party recovered stakes 1-11, but stakes 12-15 were under the snow and ice which had accumulated during the intervening 10 years. Stake 15 was about 2.4 m below the surface, and attempts to dig down and recover the stations failed when the digging reached water. Moreover, since the exact location of the buried stations was not known, wide holes were needed which, in turn, would not allow setting the instrument above them. Therefore, new stakes 12-15 had to be established, and any future comparisons in regard to the base will probably have to be made using stakes 1-11 only.

On observing the base line stakes from stake 1, it was found that the base line was no longer straight, but that the deviations were very small. Therefore, for all practical purposes the base can be assumed to be a straight line.

In 1955, two targets were established south of the base line and were assumed to be fixed points. A triangulation connected the base to these targets to serve as a check for any possible future displacement of the base. However, because of lack of the original field notes, these two targets were not identified until the end of the 1965 season. After analyzing the observations it was found that the base movement was smaller than could be detected from the observations of these two points.

During the intervening 10 years, snowdrifts had accumulated near the base of the cliff so that in 1965 only about half of the cliff height was visible, particularly at the west end (Fig. 4). Thus, only partial comparisons can be made regarding the face of the cliff. Moreover, during the period of field work (15 June to 15 July, 1965) a considerable amount of snow still remained on the cliff. This fact must be considered in comparing this work with the previous work.

In 1955, photographs were taken from stakes 1-15 but only those taken from stakes 6-15 were used for plotting. The area of glacier margin covered by photographs taken from stakes 1-5 is a moderate slope rather than a cliff, occupying only a small portion of the photographs which, therefore, could not be properly oriented. Since the same situation existed in 1965 and since the aim is to compare this work with work done in 1955, photographs were taken only from stakes 6-15. Figure B1 is a graphical representation of the stereoscopic coverage as arranged in the field. This figure is projected on the horizontal X-Y plane and the line connecting the odd-numbered targets would represent roughly the top edge of the cliff.
Preparations for field measurements

New base line stakes 12-15 were established by setting stakes aligned by a theodolite from stake 1. These stakes, being on snow and ice, were not as firmly fixed as the other stakes and served only for the 1965 work.

Circular wooden targets 30 cm in diameter were used to provide easy identification on the photograph and maximum convenience during photogrammetric operations.

The general arrangement of targets provided four control points for each model. Generally, three controls are the minimum requirement for photogrammetric needs but the additional point provides an accuracy check and reveals possible model deformation. The controls were arranged so as to appear in the overlap of successive models and a total of 13 targets provided sufficient control for the entire area covered by five models.

Measurements

A closed loop was run using an engineer's level, starting from stakes 1-11 and closed back on stake 1. Another closed loop was run from stakes 11-15 and back to stake 11. The elevation differences at each station were averaged and, giving stake 1 the arbitrary elevation of 100 m (in accordance with the 1955 work), the other elevations were computed accordingly. Actually, altimeter measurements and Army Map Service contours show stake 1 at about 670.5 m above sea level.

Table B1 contains the 1955 and 1965 elevations of the base stakes and the elevation differences between the two sets of observations. This comparison is made only between stakes 1 and 11. The elevation differences between old stakes 12-15 and the new ones would indicate approximately how deep the old targets were buried below the snow in 1965.
APPENDIX B

Table BI. Base stake elevations

<table>
<thead>
<tr>
<th>Base stake</th>
<th>Elev, 1965 (m)</th>
<th>Elev, 1955 (m)</th>
<th>Elev diff (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100.000*</td>
<td>100.000*</td>
<td>0.0</td>
</tr>
<tr>
<td>2</td>
<td>95.069</td>
<td>95.086</td>
<td>-1.7</td>
</tr>
<tr>
<td>3</td>
<td>90.353</td>
<td>90.360</td>
<td>-0.7</td>
</tr>
<tr>
<td>4</td>
<td>85.489</td>
<td>85.491</td>
<td>-0.2</td>
</tr>
<tr>
<td>5</td>
<td>81.604</td>
<td>81.608</td>
<td>-0.4</td>
</tr>
<tr>
<td>6</td>
<td>78.407</td>
<td>78.425</td>
<td>-1.8</td>
</tr>
<tr>
<td>7</td>
<td>73.353</td>
<td>73.353</td>
<td>0.0</td>
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<tr>
<td>8</td>
<td>69.480</td>
<td>69.477</td>
<td>+0.3</td>
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<tr>
<td>9</td>
<td>67.820</td>
<td>67.816</td>
<td>+0.4</td>
</tr>
<tr>
<td>10</td>
<td>66.524</td>
<td>66.513</td>
<td>+1.1</td>
</tr>
<tr>
<td>11</td>
<td>63.900</td>
<td>63.819</td>
<td>+8.1</td>
</tr>
<tr>
<td>12</td>
<td>62.481†</td>
<td>60.596</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>61.832†</td>
<td>59.792</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>62.022†</td>
<td>59.756</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>61.801†</td>
<td>59.511*</td>
<td></td>
</tr>
</tbody>
</table>

* Old stake 15 was determined by altimeter to be 630 ± 3 m above sea level which places stake 1 at about 670.5 m above sea level.
† New stakes on snow.

Distances were measured using a Wild T2 theodolite and 2-m Invar subtense bar. For a length of 30 m (the approximate distance between stakes) this method gives an accuracy of about ±3 mm. (see Table BII, col. A). As a check, the distances between stakes 1 and 11 were taped with an uncalibrated steel tape (col. B). The results did not indicate any gross error in the distances determined by subtense methods which were taken as final.

The differences between the 1955 and 1965 observations (col. D) are small indeed for stations set on a permafrost slope during a whole decade. Clearly stake 11 moved the most of all the eleven relocated stakes (2.7 cm eastward and 8.1 cm upward). The negligible differences in elevation (Table BI) and distance (Table BII) between the 1955 and 1965 observations indicate that the base was practically undisturbed during this period of time. The fact that neither distances nor elevations changed considerably is sufficient indication that the base is fixed. Slight shifts en bloc cannot affect the accuracy of the work; therefore, the stations were taken as unchanged and along a straight line which is the X-axis of the arbitrary rectangular coordinate system, with the origin at base stake 1.

Cliff targets

Base stakes 6 and 11 were selected as ends of the base for the determination of the coordinates of the cliff targets. The length of this base is the sum of the distances between stakes 6 through 11 (Table BII). The directions to all cliff targets were observed from stakes 6 and 11. Three sets of observations were made at each of these stakes and averaged. Target elevations and coordinates were calculated and are given in Table BIII (see Fig. B1 for location).
APPENDIX B

Table BII. Distances between base stakes

<table>
<thead>
<tr>
<th>Base stakes</th>
<th>A Dist, 1965 (m)</th>
<th>B Dist check with tape, 1965 (m)</th>
<th>C Dist, 1955 (m)</th>
<th>D Diff A-C (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2</td>
<td>29.604</td>
<td>29.609</td>
<td>29.585</td>
<td>+1.9</td>
</tr>
<tr>
<td>2-3</td>
<td>29.541</td>
<td>29.545</td>
<td>29.637</td>
<td>-9.6</td>
</tr>
<tr>
<td>3-4</td>
<td>29.586</td>
<td>29.593</td>
<td>29.588</td>
<td>-0.2</td>
</tr>
<tr>
<td>4-5</td>
<td>29.735</td>
<td>29.744</td>
<td>29.751</td>
<td>-1.6</td>
</tr>
<tr>
<td>5-6</td>
<td>29.877</td>
<td>29.870</td>
<td>29.844</td>
<td>+3.3</td>
</tr>
<tr>
<td>6-7</td>
<td>29.665</td>
<td>29.657</td>
<td>29.652</td>
<td>+1.3</td>
</tr>
<tr>
<td>7-8</td>
<td>29.640</td>
<td>29.647</td>
<td>29.661</td>
<td>-2.1</td>
</tr>
<tr>
<td>8-9</td>
<td>29.961</td>
<td>29.960</td>
<td>29.961</td>
<td>0.0</td>
</tr>
<tr>
<td>9-10</td>
<td>29.943</td>
<td>29.953</td>
<td>29.949</td>
<td>-0.6</td>
</tr>
<tr>
<td>10-11</td>
<td>29.903</td>
<td>29.907</td>
<td>29.876</td>
<td>+2.7</td>
</tr>
<tr>
<td>11-12</td>
<td>32.982</td>
<td></td>
<td>29.824*</td>
<td></td>
</tr>
<tr>
<td>12-13</td>
<td>27.508</td>
<td></td>
<td>29.997*</td>
<td></td>
</tr>
<tr>
<td>13-14</td>
<td>27.712</td>
<td></td>
<td>30.018*</td>
<td></td>
</tr>
<tr>
<td>14-15</td>
<td>30.561</td>
<td></td>
<td>30.010*</td>
<td></td>
</tr>
</tbody>
</table>

* Stakes buried in snow by 1965 and not reused.

Table BIII. Final target coordinates, 1965

<table>
<thead>
<tr>
<th>Target no.</th>
<th>X(m)</th>
<th>Y(m)</th>
<th>Z approx elev (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-11.628</td>
<td>185.112</td>
<td>104.052</td>
</tr>
<tr>
<td>2</td>
<td>-20.949</td>
<td>127.831</td>
<td>98.667</td>
</tr>
<tr>
<td>3</td>
<td>47.372</td>
<td>138.751</td>
<td>99.477</td>
</tr>
<tr>
<td>4</td>
<td>31.757</td>
<td>111.990</td>
<td>93.309</td>
</tr>
<tr>
<td>4a</td>
<td>55.274</td>
<td>114.145</td>
<td>84.528</td>
</tr>
<tr>
<td>5</td>
<td>91.324</td>
<td>145.691</td>
<td>98.044</td>
</tr>
<tr>
<td>6a</td>
<td>101.964</td>
<td>135.147</td>
<td>86.263</td>
</tr>
<tr>
<td>7</td>
<td>163.018</td>
<td>149.104</td>
<td>94.574</td>
</tr>
<tr>
<td>8</td>
<td>161.993</td>
<td>130.956</td>
<td>77.294</td>
</tr>
<tr>
<td>9</td>
<td>223.629</td>
<td>152.508</td>
<td>96.830</td>
</tr>
<tr>
<td>10</td>
<td>218.573</td>
<td>128.098</td>
<td>74.576</td>
</tr>
<tr>
<td>11</td>
<td>288.006</td>
<td>154.468</td>
<td>98.508</td>
</tr>
<tr>
<td>12</td>
<td>275.284</td>
<td>152.733</td>
<td>77.398</td>
</tr>
</tbody>
</table>

Photography and photogrammetry

The photographs were taken with the Wild Phototheodolite No. P30-229. The nominal focal length of this camera is 165.07 mm and aperture is f/12. One photograph was taken from each of the base stakes 6-15 with the camera axis perpendicular to the base line (X-axis). The stereo
models were planned to be formed from the following pairs of photos: 6-7, 8-9, 10-11, 12-13, and 14-15. The targets were distributed as shown in Figure B1 and were checked by viewing through the ground glass inserted in the camera before each exposure. This planning ensured a complete stereoscopic coverage of the cliff with an adequate base/distance ratio of about $\frac{1}{3}$. To reduce the effect of the nonlinearity of the base line upon the perpendicularity of the camera axis, the phototheodolite was oriented with respect to each individual base; thus at stake 6 and stake 7 the camera axis was at a 90° angle with base 6-7. Right angles were taken similarly from bases 8-9, 9-10, 10-11, etc. No tilts were necessary and the normal case with horizontal camera axis was used at all stations. The photos were taken between 1000 and 1400 because it was noticed that before and after this part of the day large portions of the face of the cliff were covered by shadows.

The 1955 and 1965 maps were plotted by photogrammetric means in which the cliff face was projected onto an XZ vertical plane with contour lines of equal Y distance. The contour interval is 25 cm and the lines were numbered according to their actual distance from the base line. The 1955 map, originally plotted using the Kelsh plotter, was replotted using the Wild A7 plotter, making the 1955 and 1965 maps directly comparable graphically.
APPENDIX C: BOTANICAL INVESTIGATIONS

by

Eythor Einarsson

Objectives

The objectives of the botanical investigations were:

1. To restudy the ecology of 16 quadrats which were marked by cairns on Survey Hill 10 years before and thoroughly investigated botanically at that time.

2. To compare these studies with the results obtained 10 years before and thus try to determine the successional changes, if any, which had occurred in the vegetation of these plots.

3. To survey the vegetation of the Red Rock area as a whole and to try to relate the vegetational pattern to microclimatic conditions and possible fluctuations of the ice front.

The investigations were carried out from 30 June to 22 July 1965. Phenological conditions were noted during the whole period. Climatological observations were made, mainly during the last two weeks, of wind, cloud cover, precipitation, and temperature. Samples of the vegetation types were collected from the quadrats on Survey Hill. All the vascular plants found in the area were collected and studied. Most of the species have been identified. Bergthor Johannsson (Department of Botany, Museum of Natural History, Reykjavik) identified most of the mosses.

Quadrats

In 1955 J.N. Wolfe set out 16 quadrats marked by cairns in a line from the western edge of Red Rock Lake to the steep edge of North Ice Cap on Survey Hill (Goldthwait, 1956). The vegetation of these quadrats, with the single exception of number 16, the one nearest the ice cliff, was thoroughly investigated. Cairn 16 was still covered with snow when the investigations were finished on July 22. The distance between cairn 13 and cairn 14 was 30 m, not 20 m as stated by Wolfe in his report (Goldthwait, 1956). Quadrats of 4 m² were set out around the cairns. The cairn was at the center of the quadrat except in places where boulders around the cairns made this arrangement impossible. During the three weeks, each quadrat was visited and the vegetation investigated almost every day. To make the investigation more complete, the strips between the quadrats were also examined. Thus, a 2-m-wide strip from the level of Red Rock Lake to the edge of North Ice Cap was investigated. The numbers of the quadrats are the same as the cairn numbers. Table CI contains a summary of the investigations of the vegetation in the quadrats and between quadrats.

Successional changes in the vegetation

There are some minor difficulties in directly comparing the results of the investigations made in 1965 with the results obtained in 1955, but it is obvious that some successional changes have occurred around the cairns on Survey Hill during the 10 years.
### Table CI. Vegetation cover in and between quadrats, 1965

<table>
<thead>
<tr>
<th>Vascular Plants</th>
<th>Mosses</th>
<th>Lichens</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potentilla vahliana</td>
<td>Pogonatum capillare</td>
<td>Sphaerophorus fragilis</td>
</tr>
<tr>
<td>Potentilla hyparctica</td>
<td>Polytrichum hyperboreum</td>
<td>Sphaerophorus globosus</td>
</tr>
<tr>
<td>Saxifraga nivalis</td>
<td>Polytrichum piliferum</td>
<td>Solorina crocea</td>
</tr>
<tr>
<td>Saxifraga foliolosa</td>
<td>Psilopilum cavifolium</td>
<td>Cladonia pyxidata</td>
</tr>
<tr>
<td>Saxifraga cernua</td>
<td>Amphidium lapponicum</td>
<td>Cetraria nivalis</td>
</tr>
<tr>
<td>Saxifraga hyperboria</td>
<td>Ceratodon purpureus</td>
<td>Cladonia sp.</td>
</tr>
<tr>
<td>Saxifraga caespitosa</td>
<td>Rhacomitrium lanuginosum</td>
<td>Cladonia sp.</td>
</tr>
<tr>
<td>Saxifraga oppositifolia</td>
<td>Pohlia cruda</td>
<td>Stereocalon sp.</td>
</tr>
<tr>
<td>Papaver radicatum</td>
<td>Pohlia proligera</td>
<td>Umbilicaria sp.</td>
</tr>
<tr>
<td>Draba subcapitata</td>
<td>Conostomum tetragonum</td>
<td>Parmelia saxatilis</td>
</tr>
<tr>
<td>Draba lactea</td>
<td>Gymnomitrium corallioides</td>
<td>Cetraria nivalis</td>
</tr>
<tr>
<td>Draba nivalis</td>
<td>Cephaloziella sp.</td>
<td>Dactylina ramulosa</td>
</tr>
<tr>
<td>Draba sp.</td>
<td>Cardamine bellidifolia</td>
<td>Alectoria ochroleuca</td>
</tr>
<tr>
<td>Cardamine bellidifolia</td>
<td></td>
<td>Alectoria minuscula</td>
</tr>
<tr>
<td>Salix arctica</td>
<td></td>
<td>Buellia sp.</td>
</tr>
<tr>
<td>Cerastium alpinum</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sagina intermedia</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minuartia rubella</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Melandrium triflorum</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silene acaulis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Luzula confusa</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Luzula arctica</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carex nardina</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Festuca brachyphylla</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poa arctica</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hierochloe alpina</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

At cairn 1, or in quadrat 1, some species of mosses were growing in 1965, but none at all in 1955, and the vascular plant clusters seemed to be larger. In 1965 the first rock lichens were found on rocks midway between cairns 1 and 2, but in 1955 no rock lichens were found lower than cairn 5, quadrat 5. The distance between these places is about 70 m and the difference in elevation about 13 m. But even in 1965 rock lichens did not become prominent lower than just below quadrat 5. Mosses and soil lichens seemed to be more prominent in many of the quadrats in 1965 than in 1955 although the same species seemed to be the dominating ones. Lichens like Solorina crocea and Cetraria nivalis, which were common along the line transect in 1965, are not mentioned at all in Wolfe's report.

In many of the quadrats more species were found in 1965 than in 1955 although the most prominent species seem to be the same. Species of Saxifraga were much more prominent in 1965 than in 1955 when Saxifraga is only listed at cairn 2. Cardamine bellidifolia, which was common along the line transect in 1965, is not mentioned in the 1955 investigations and neither are Carex nardina, Luzula arctica, Festuca brachyphylla, Minuartia rubella, Silene acaulis or Sagina intermedia. Cardamine bellidifolia could perhaps have been present but mistaken for Draba, and Luzula arctica was probably also present in 1955 but not distinguished from the more common Luzula confusa which is dominant in most parts of the area. Potentilla vahliana was not distinguished from the much more common Potentilla hyparctica in 1955 and only two different species of Draba were mentioned, but according to the 1965 investigations there are at least four.
When Wolfe has listed more species at some of the cairns in 1955 than we found around these same cairns in 1965, it is probably because he used larger quadrats.

**Age of vegetation on Survey Hill**

Wolfe reported (Goldthwait, 1956, p. 132) that the shores of Red Rock Lake were devoid of vegetation, probably because of their youth. In 1965, however, although the shore still looked very young, especially nearest the lake, it was no longer devoid of vegetation. It had been colonized by a few species of vascular plants and mosses which were growing scattered in the gravel and between the boulders. The pioneer species were *Luzula confusa* and *Papaver radicatum*; the mosses *Polytrichum piliferum*, *Psilopilum cavifoium* and *Pogonatum capillare* invaded later.

On 7 July it was observed that some of the vascular plants growing on the western shore of Red Rock Lake were almost submerged by the lake, the level of which was rising continuously from day to day. To find out how long these plants could endure complete submersion without being killed, the changes of the lake level were measured daily from 9 July through 22 July at small cairns set up on the shore. During this 15-day period the daily increase of the level of Red Rock Lake ranged from 1.5 to 25 cm; the total increase was 174.5 cm. The outlet was blocked by snow-drifts all the time and did not open at all. More and more plants were submerged by the lake, most of them *Luzula confusa* and *Papaver radicatum*, some in flower, but none of them became dry again during this period. Therefore, no results were obtained as to how long a submersion the plants could endure. It is obvious, however, as at least some of these plants were several years old, that if the lake level changes in the same way every year, these plants have to be able to endure at least 15 days of complete submersion during the short growing season. Otherwise they could not survive on the shore.

A few meters from the shore the species became more numerous and some soil lichens, especially *Stereocaulon* sp., were found among the mosses, but there were no rock lichens on the boulders lower than approximately the same elevation (i.e. just below quadrat 5) as on the line transect. There were exceptions on very few rather small, round boulders having small clusters of lichens which were found closer to the shore. These boulders could easily have rolled down from the rock lichen-covered upper part of the slope. Some narrow solifluction tongues with fine sand surfaces extended down almost to the lake level about 50 m north of the transect, where the slope is steepest. On these tongues the vegetation was not as sparse as in the gravel. *Luzula confusa* and the mosses *Psilopilum cavifoium* and *Polytrichum piliferum* were the most prominent species, but *Papaver radicatum*, *Cerastium alpinum*, *Luzula arctica*, *Draba* sp., *Saxifraga nivalis*, *S. cernua*, *S. foliolosa*, *Poa arctica* and even *Salix arctica* on one of the tongues, were also found together with the lichens *Stereocaulon* sp. and *Solorina crocea*. On the upper part of some of these tongues *Psilopilum cavifoium* and *Stereocaulon* sp. completely dominated the vegetation. In the troughs between the tongues the mosses *Rhacomitrium lanuginosum*, *Polytrichum piliferum*, *Psilopilum cavifoium* and *Pohlia cruda* were found. As a whole, the question of vegetation near the shore of the lake seems also to be a question of soil and moisture because shallow depressions in this area where some moist soil was found were the parts most densely covered with vegetation. They could easily be seen from far away because of their darker color due mostly to soil lichens.

Patterned ground became gradually more and more prominent as the slope was ascended. Large polygons a few meters in diameter with deep troughs between them were found almost everywhere. The surfaces of the polygons were often covered mostly with soil and vegetation, and the boulders and rocks of the troughs were colored almost black due to rock lichens. This upper part of the slope seemed to be the oldest vegetated part of Survey Hill and has probably been exposed for centuries. Some of the troughs between the polygons were partly filled with soil and almost
covered by vegetation. Along the edges of such stabilized polygons and troughs, where the soil is covered with snow during the winter, was found the most developed plant community of the area, i.e. the Cassiope tetragona heath which was sometimes mixed with Salix arctica and even Dryas integrifolia. As Dryas prefers calcareous soils it was rather rare on Survey Hill. Salix was also occasionally found almost in the middle of the polygons together with other vascular plants and many mosses and soil lichens, but Cassiope was found only where the polygon edges slope down into the troughs. The lichens growing on the rocks in some of the troughs seemed to be rather old. A foliose Parmelia-like lichen was found on the southern side of a fairly large rock at approximately the same elevation as cairn 7, and it is assumed that it was several centuries old, perhaps older than 1000 years. The diameter of the colony was close to 120 mm and its center was dead and decayed. According to Beschel (1961, p. 1044-1047) the growth rate of various lichen species is very different and individual plants of the same species even grow at very different rates, but the Parmelia-like individual looked very old compared to the lichens mentioned by Wolfe (Goldthwait, 1956, p. 134-137).

Some of the patches of Salix arctica observed in this part of Survey Hill were of a considerable size; the most extensive patch observed had a diameter of 90 cm. According to Beschel and Webb (1963) diameters of Salix arctica patches have proved useful indicators of age in glacier forelands of the Alps and in west Greenland, but on Axel Heiberg Island no correlation between the age and the diameter of patch was found. It is therefore difficult to determine the exact age of these patches of creeping Salix arctica, but for this patch with a diameter of 90 cm an age of some decades can be assumed. However, this Salix arctica patch was found growing a few meters south of, and at about the same elevation as, cairn 4, i.e., just below the main trim line on Survey Hill mentioned by Wolfe (Goldthwait, 1956, p. 138). If this was the first generation of Salix arctica below the trim line then certainly many Salix generations have been growing above it since Survey Hill became exposed. The vegetation above the trim line, which is without doubt much older than the vegetation below the trim line, must therefore be at least several centuries old, and perhaps even more than 1000 years old. It depends on the speed of plant succession at this elevation and northerly latitude; this is not known but is supposed to be very slow.

As mentioned above, the snowdrift in front of the ice cliff on the top of Survey Hill was so thick that cairn 16 was completely covered with snow on 22 July 1965, and so was a 15- to 40-m-wide strip nearest the cliff. It was therefore impossible to investigate the vegetation in this strip close to the glacier, but nearest the snowdrift the vegetation did not seem to differ very much from the vegetation in the middle part of the slope. Large polygons and deep troughs with boulders and rocks almost black because of the lichen cover were observed and in some of the troughs even Cassiope tetragona was found. In spite of the long snow cover on this part of the slope and the meltwater which makes the substrate very wet during the growing season, most of the species common in other parts of Survey Hill were also found here. Species like Hierochloe alpina, Luzula arctica and Solorina crocea are more prominent here than elsewhere, probably because of the moisture and the long snow cover. However, as a whole, vascular plants were not as prominent here as on the middle part of the slope, probably also because of the meltwater and the snow cover. The vegetation in this uppermost part of Survey Hill, therefore, seems to be of about the same age as the vegetation in the middle part of Survey Hill. The glacier, therefore, probably has not retreated for centuries, but as the vegetation close to the ice cliff could not be investigated it is difficult to say if the glacier is advancing or if it is relatively stable (see Wolfe in Goldthwait, 1956; Benninghoff and Robbins in Goldthwait et al., 1954).

It is obvious from the main trim line that the lowest part of Survey Hill has been exposed for a much shorter time than the part above the trim line. This part must have become exposed gradually and the shore only very recently. The cause of this trim line must be the snow cover since
it is not at all horizontal and therefore it cannot be due to water cover. The part above the trim line has all been exposed for about the same number of years and the differences in the vegetation in this upper part of Survey Hill must be due primarily to topographical factors and soil formation and to the factors resulting from the topography, such as snow cover, moisture, exposure to winds and sunshine, i.e. microclimatological conditions.
A follow-up study of Red Rock Ice Cliff was undertaken in summer 1965 to test findings of more comprehensive studies in 1955 and 1956. Work was limited to mapping the ice cliff face and a portion of the ice drainage basin above it and to studying the effects upon vegetation. A total ice loss of 500,000 m³/year was calculated for the small 2.2-km² ice drainage basin whose surface dropped 5 m in a decade. Five regions, totaling 6% of the 1 km² mapped, dropped by 8 m or more. Ice loss from the ice cliff decreased from about 2% to less than 1%, due largely to a 30% reduction in the area of exposed cliff. The overall position of the cliff remained unchanged. There was less difference in cliff face detail in the two July maps ten years apart than in the several maps over one season. From a comparison of the positions of a long aluminum pipe near the cliff edge which survived in place from 1955 to 1965, it appears that motion has slowed to one-half the 1955-56 speed. Botanical studies indicate that principal changes reflect more snow drifts near the ice cliff and deeper flooding in Red Rock Lake which implies more snow and no drainage. Several hypotheses and deductions for ice cliff growth and decay are presented.

Key Words
Glacial features  Glaciers  Glaciology  Land ice