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TECHNICAL REPORT
ES-6

CASCADE ALP SLOPES AND GIPFELFLUREN AS CLIMA-GEOMORPHIC PHENOMENA

QUARTERMASTER RESEARCH & ENGINEERING CENTER
EARTH SCIENCES DIVISION

JANUARY 1963 NATICK, MASSACHUSETTS

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Technical Report
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CASCADE ALP SLOPES AND GIPFELFLUREN AS CLIMA-GEOMORPHIC PHENOMENA

Will F. Thompson, Ph. D.
General Environments Branch

Project Reference:
7X83-01-008

January 1963

FOREWORD

This study of fundamental aspects of relationships between landscape and climate in a Pacific Coast mountain range was made as a basis for comparisons with other mountain ranges, some known to be similar (the Alps) and others quite different (New England mountains, analyzed in an earlier study). Homogeneity of alpine landscapes in such regions is held to be due in large part to regional climatic homogeneity; such homogeneity may provide a sound basis for extension of local logistical experience to whole regions. Environmental description of such regions, based on criteria developed in studies such as this, will permit comparison of mountain regions, and determination of analogy between them, and thus be useful in world-wide logistical planning.

Mountains tend to restrict the size and scope of military operations, and for this reason the strategic significance of operations in such terrain has often been considerable. Because rugged terrain makes massive counter-operations difficult, mountains of one sort or another have been the typical base for guerilla and other limited warfare which has been so costly to us in the last 15 years. Criteria for environmental evaluation developed in studies such as this can be applied not only to logistical problems, but also in forestry, hydrology, and other non-military fields.

First presentation of this study was at the AAAS meetings at Denver, December 1961. It was published in 1962 in Erdkunde, a geographical journal in Bonn, Germany. Requirement for additional copies has made this edition necessary.

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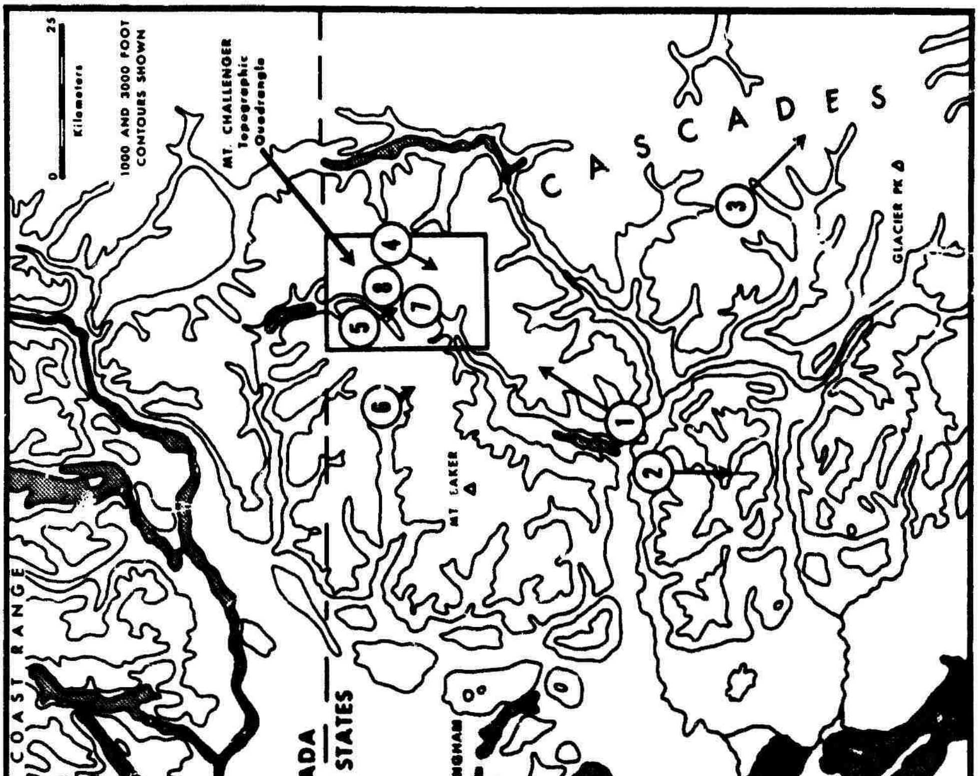
ABSTRACT

Certain topographic forms and relationships, and the processes which have caused them, are found to characterize the Cascades and other mid-latitude mountains, including the Alps, which have similar climates dominated by westerly winds off the sea. The relative frequency of summits at certain heights relative to timberline (gipfelfluren), and the occurrence of a certain kind of moderated surface (alp slope) at timberline, are found to be closely related to and indicative of regional climate. It is thus possible to determine the degree of climatic consistency which exists in the Cascade or similar regions, and to compare their climates with those of regions having similar, or consistently different, landscapes. Present climate in the Cascades is found to approximate that normal during Pleistocene interglacial times. However, warmer periods are shown to have occurred.



BRITISH COLUMBIA COAST RANGE
CASCADES
CANADA
UNITED STATES
VANCOUVER
VICTORIA
BELLINGHAM
MT. BAKER
GLACIER PK
MT. CHALLENGER Topographic Quadrangle
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CASCADE ALP SLOPES AND GIPFELFLUREN AS CLIMA-GEOMORPHIC PHENOMENA

1. Introduction

In a report published in 1896, the pioneer Canadian geologist, G.M. Dawson, noted that a remarkable number of summits rise to altitudes of about 8,000 feet, both where he was working on the east flank of the southern British Columbia Coast Range and in the nearby northern Cascades. Nevertheless, very few non-volcanic peaks within the area of his observations rise much higher, and those rise only to about 9,000 feet. In the Alps such an accordance of alpine summits is called a "peak plain" (gipfelflur). Later students of the phenomenon in the Cascades thought, as Dawson did, in terms of a single level of accordance. They reported that it extends far to the south in that range; in studies published between 1900 and 1906 I.C. Russell, Bailey Willis, G.O. Smith, and F.C. Calkins, all of the U.S. Geological Survey, described it as a peneplain.

In 1912 Reginald Daly challenged the peneplain explanation and supported Dawson's prior theory, yet he may never have noticed Dawson's gipfelflur. His work was done within the northern fringes of the high Cascades, where only a few peaks approximating 8,000 feet can be seen at once. Dawson's theory, as stated, drew his attention to the well-defined accordance at timberline (about 6,000 feet) in that area. He presumably dismissed as an error the 8,000 foot elevation given by Dawson. To explain the accordance they described, Dawson and Daly both cited a great difference in rates of weathering and erosion above and below timberline, observable throughout the region. However, Dawson's description of the accordance he saw in the Cascades from across the Fraser lowland makes it clear that the elevation given was correct and that he was looking at the high gipfelflur of that range, 2,000 feet above timberline. From that distance, Daly's 6,000-foot accordance was probably obscured by haze.

The true explanation of Dawson's gipfelflur seems to be a fairly simple variant of his original one but the issue has long been confused for various other reasons discussed in this paper. Neither alpine peneplains or Dawson and Daly's observations have ever been completely accepted as solutions of the problem of alpine accordances, either in this country or in the Alps, though alpine peneplains long had many advocates among geologists working in the Rockies. The problem has been discussed only occasionally in recent decades. It is revived here because of the usefulness of such clima-geomorphic features in defining climatic regions in mountains.

Our concern with alpine clima-geomorphology is even wider than that, however. Whether one's interest in mountains is esthetic, scientific, economic, conservational, or military, it is well to understand how such landscapes are organized and the significance of their elements. Various climate-related landscape elements, such as the alp slopes and accordant summits discussed here, play consistent roles as summit follows summit and gorge follows gorge across a mountain region. Regional unity in climatically homogeneous mountains is thus like that created by repetition of complex pattern-units in a very boldly printed fabric. Because regional climatic homogeneity can never be complete, however, climate-induced consistency of landscape elements is always imperfect and is less in broad regions than in sub-regions. Nevertheless, it is very real and worthy of attention.

2. Dawson's Gipfelflur

One of the best places to see Dawson's gipfelflur is in and around the Picket Range, a part of the northern Cascades covered by the Mount Challenger 15-minute quadrangle. The Pickets are like most of the high Cascades in having local relief of more than a mile throughout. Total relief in the quadrangle is almost 8,000 feet. The Pickets are deeply and completely dissected by steep-walled glacial gorges, as are the rest of the northern Cascades. No significant summit upland exists near or above the 8,000 foot level anywhere in the range. One gorge enters the quadrangle at an altitude of about 1,000 feet only $2\frac{1}{2}$ miles from a 7,860-foot summit. Five other valleys enter below the 2,600-foot level. Most of the big valley-head cirques have floors at about 3,500 feet, though the floor of the McMillan Creek cirque, between the two Picket Range serrate crests, is at about 2,800 feet. Several large cirques near Mt. Redoubt have floors above 4,000 feet.

Within the small sector of the range covered by the Mt. Challenger quadrangle, fourteen summits carry spot heights between 7,450 and 8,450 feet; the map shows about fifty unsurveyed peaks and minor pinnacles in that range of altitude also. Only one peak in the quadrangle rises higher, to 8,957 feet. On it the map shows one secondary pinnacle rising to about 8,800 feet. The gipfelflur thus forms a very distinct, though not absolute, ceiling on summit heights in the Picket Range. The same is true of non-volcanic peaks throughout the northern Cascades, very many of which approximate 8,000 feet but only a thin scattering of which exceed 9,000 feet, and those by only a few hundred feet. The Mount Terror massif in the Picket Range is a 2-mile serrate ridge, all summits of which are between 7,600 and 8,157 feet high. The three-mile Challenger-Fury ridge is closely similar and has five surveyed peaks 8,045 to 8,292 feet high. The precarious sharpness of those two serrate crests, and the presence nearby of a number of accordant or moderately sub-accordant peaks now isolated from them by convergence of erosion on flanking valley walls, strongly suggests that they are remnants of much more extensive even-crested ridges which have been dismembered by erosion to form the present topography.

In view of the considerable relief and complete dissection of the high Cascades, and the great number and sharpness of those of its peaks which comprise Dawson's gipfelflur, that accordance can hardly be considered a peneplain or other uplifted ancient graded surface. On the crest of the central Wind River Range in Wyoming which, because it stands on a high plateau, has somewhat less local relief than the Cascades, there is a strongly rolling felsenmeer-mantled graded summit upland at roughly 12,000 feet which, though not a peneplain, is sufficiently like one for purposes of discussion. Converging glacial cirques have divided it into tablelands with precipitous walls. A considerable number of very sharp pinnacles, often accordant with the upland, are associated with the tablelands but are not found remote from them. Many such spires have been formed in the past at the expense of the tablelands as cirques approached intersection in various places, but they have not retained either their steepness or their accordant status. None of those now in existence will long remain accordant with the big tablelands, since the flanks of the two classes of peaks seem to be attacked about equally vigorously and the pinnacles have relatively little substance to lose.

As the tablelands gradually dwindle, the number of new accordant spires formed from them will dwindle, and none can long survive the last remnant of the summit upland. The 12,000-foot accordance in the Wind Rivers will then be gone. Any accordance due to a peneplain in the Cascades must have had a similar history, yet the peaks of Dawson's gipfelflur, attacked on their flanks at least as vigorously as are the Wind River spires, nevertheless persist in accordance in impressive numbers. Many peaks of the high gipfelflur, like those in the Picket Range, even retain some ridge-continuity.

Unlike the peneplain hypothesis, Dawson's explanation of accordance in the Cascades as due to different rates of weathering and erosion on timbered subalpine and open alpine slopes allows us to assume development of his gipfelflur late in the history of the range, after the mountain mass had become completely dissected. Long survival of precariously sharp alpine ridges thus need not be assumed. However, Dawson's 8,000-foot gipfelflur is 2,000 feet above the present timberline and its previously much more continuously accordant ridges are now being dismembered. Thus, it seems a relic of times past and in that sense not related to modern timberline. The known variability of Pleistocene timberline levels has long been the leading objection to Dawson's explanation of alpine accordance. Study of the Cascades may allow us to answer that objection at the same time that we explain Dawson's gipfelflur.

3. Daly's Accordance

Brink has pointed out (1959) that the present climatic timberline in the southern British Columbia Coast Range lies somewhat above the lower-lying meadows of the accordance Daly studied and that it has recently been rising. The same is presumably true in the Cascades. Nevertheless, wherever it occurs along the northwest coast of North America, Daly's accordance currently remains the upper limit of dense, continuous, timber. It is not primarily an accordance of summits but rather one of moderated slopes, close to the present upper limit of tree growth, which are kept more or less clear of timber by soil disturbance, avalanches, and in many places by persistence of heavy snowdrifts through much of the growing season. The relatively moderate slopes of its timberline meadows are consistently in strong contrast with steep gorge walls, stabilized by the root-mat of their heavy timber, in the subalpine zone immediately below. Such timberline meadows in the Cascades have not been intensively grazed, nor have their clustered trees been much cut for fuel. In other respects, however, they are entirely equivalent to typical alp slopes in European ranges, which are likewise closely and consistently associated with the existing timberline (Boesch, 1946).

Daly's accordance does include a great many summits, and thus becomes a gipfelflur, on the flanks of the northern Cascades, throughout the central and southern Cascades including those of Oregon, and in the Olympic Mountains, wherever peaks and ridges have commonly been truncated by headward expansion of alp slopes. Cascade trails often run for many miles along ridges thus truncated, climbing only to low summits and descending only into shallow cols. Daly pointed out in 1912 that the same accordance is present as a belt of alp slopes on the faces of higher peaks even in the more rugged parts of the northern Cascades, where it has been unable to truncate enough crests to form a gipfelflur at timberline. He considered its role there incompatible with interpretation of its gipfelflur phase as a peneplain. Its alp slopes are closely overshadowed there by alpine crests much too spectacularly youthful in aspect to be considered monadnocks. Also, alp slopes so located were subject to strong undercutting by Pleistocene valley glaciers and have maintained themselves only because processes similar to those now active on them have constantly renewed their surfaces and caused them to migrate headward at the expense of the high ridges above. The alp slopes which have truncated and brought to accordance the lesser summits which form the gipfelflur phase of Daly's accordance support similarly vigorous processes. As forms thus in dynamic equilibrium with their environment, they can hardly be considered "fossil" features.

Geologic structure and history of past uplift are by no means consistent in the various Pacific Coast ranges in which Daly's accordance occurs, yet it rises gradually and regularly, as timberline rises, from Alaska to California. In Prince William Sound, Alaska, it is about 1,000 feet above the sea; in the high Sierras both timberline and the alpine meadows reach 10,000 feet. The Sierras are much less dissected than the ranges in which Daly's accordance occurs further north. Their subalpine slopes are often too gentle to contrast sharply with the alp slopes at their timberline, yet Daly's accordance seems quite distinct, for example, at about 9,000 feet on summits in the Carson Range east and northeast of Lake Tahoe.

Because, in a regional sense, timberline is very closely controlled by climate, Daly's accordance is also, even though both are somewhat influenced by local structural geomorphic considerations. Thus, the accordance not only rises southward as temperature rises, but also rises from west to east across the northern Cascades as maritime climatic influence diminishes. Timberline and Daly's accordance are at about 5,000 feet on the seaward flank of the range, at about 6,000 feet in its inner parts, and at about 7,000 feet on its continental flank. The rise inland is due to warmer mid-summer temperatures at any given level away from the sea, and also to reduced snowfall permitting longer growing seasons. The attitude of Dawson's gipfelflur is not as easy to determine away from the crest of the high Cascades as is that of Daly's accordance because of the scarcity of high peaks on the range flanks. The two accordances seem closely parallel as far as can be seen; however, the one is consistently about 2,000 feet higher than the other.

4. Firn Glaciation of Alp Slopes; Richter's Hypothesis

Another important objection to the peneplain hypothesis as an explanation of alpine accordance is the fact that processes dominant at alpine levels invoke not only great gravitational energy but also great climatic energy because of their altitude (Albrecht Penck, 1886-87). In the Cascades alpine climatic energy is expressed geomorphically mostly as frost riving, solifluction, avalanches, and glacial erosion. Because alpine gradients are seldom low over any considerable area, and above the alp slopes are often extreme, wastes from alpine processes are for the most part rapidly carried away downslope instead of clogging their action. Any really ancient surface at alpine levels must therefore have been destroyed long ago (Russell, 1933; Mackin, 1947).

One of the most distinctive features of the higher Cascades is an abundance of hanging glaciers (firn fields), mostly lying on the alp slopes. This is especially noteworthy in view of the present rarity of valley glaciers in the non-volcanic Cascades, where such trunk glaciers have done great work in the past. Pleistocene firn-glaciation of Cascade alp slopes seems to have been universal, producing great numbers of moraines, roches moutonees, small cirques with floors at alp-slope levels, and ice-gouged alpine ponds. It would be easy to conclude from such evidence that glaciation had been the primary process forming the alp slopes and that mass wasting (solifluction and related processes) had been secondary. Thus, similar evidence of glacial erosion on the alp slopes (fjelds) of Norway led the Austrian student, Eduard Richter, to describe them in 1896 as having been formed by the action of firn-glaciers such as commonly persist on them now.

Guided by Penck's very reasonable hypothesis (1886-87) that climate limits the height of mountains, Richter decided that firn-glaciers had truncated and reduced to accordance many summits of Norwegian mountains. He would have reached the same conclusion in the Cascades, since existing firn-glaciers are quite generally limited to the alpine zone in both regions and mass wasting was little understood in his time. Richter's critics seem to have cited the variability of the climatic controls of glaciation during the Pleistocene and the altitudinal irregularity of the lower limit of present glacial erosion in ranges such as the Alps where glaciers are still doing really significant work. Present alpine glaciers in the Cascades sometimes carry downslope a good deal of debris riven from cliffs above by frost; otherwise they seem to be eroding very little. If they were big enough to do much work, they would cease to be limited mostly to the alp slopes. If alp slopes had not initially been present at accordant levels in the Cascades and Norway, no altitudinal control is known which would induce glaciers to form such an accordance of moderated slopes, much less produce the close correlation between Daly's accordance and timberline on the northwest coast of North America which has been described above.

5. Mass Wasting of Alp Slopes

Penck's concept of climatic limits on the height of mountains seems to have fallen from favor some years before mass wasting was much studied, perhaps partly because of criticism stirred up by Richter's paper. Thus, the way was cleared in that respect for widespread acceptance, shortly after the turn of the century, of W.M. Davis' very instructive system of geomorphology which ignored altitudinal differentiation of processes. Davis did not deny or attempt to minimize such differentiation. He was presumably aware of the problems involved in discussing it at that time and for that reason simply avoided considering it. In alpine geomorphology, however, simplicity is not gained at that price. Furthermore, we know more about climate-sensitive geomorphic processes such as solifluction than was known at the turn of the century.

The key to the geomorphology of the high Cascades is the fact that their prevailing winds are onshore westerlies which greatly moderate their alpine frost climate by limiting the range of thermal variation between day and night, and between winter and summer. Seasonal freeze and thaw are therefore relatively shallow even on high wind-swept ridges which have permafrost. At timberline, solifluction of soil which is protected in winter by the heavy snowpack characteristic of the Cascades is plainly very effective, both because of the frequency with which freeze and thaw alternate there in spring and early summer, and because of the abundance of fines in such soils. (See Williams, 1949, on chemical weathering, producing fine-textured soil, at alpine levels on the Pacific Coast.) Nevertheless, such solifluction is so shallow as to be decisively checked by the roots of timber, as Dawson and Daly observed.

Neither glaciation or any other process likely to form alp slopes is as sensitive to the presence of timber as solifluction is in such a climate. The clear-cut correlation which exists between alp slopes and timberline on the northwest coast of North America and in western Europe (Boesch, 1946) may therefore be considered evidence that alp slopes have been developed there primarily by mass wasting (frost-caused solifluction and associated processes) and that the role of firn-glaciation has been secondary. However, we must still explain how the present situation can have developed in the presence of a varying timberline.

The statement made above about the shallowness of freeze and thaw on high, wind-swept ridges in the Cascades is based on the modest size of boulders upsorted to form felsenmeers in such sites. At high levels on Redface Mountain in the Picket Range and Ruth Mountain near Mt. Shuksan there are felsenmeers of stones only 4 to 8 inches across. The south ridge of Luna Peak in the Pickets (8,285 feet) has the coarsest felsenmeer observed in the central northern Cascades; its stones are probably 2 to 4 feet across. Throughout the Cascades and Olympics alpine frost-sorting of stony soil, though often active, is shallow except in sites (generally very restricted) which are subject to non-climatic intensification of soil frost.

What seemed to be an exception to that rule was found on Silver Star Mountain in the Methow drainage, in the part of the eastern flank of the northern Cascades most protected from marine influence. Coarse boulders on the northern face of that peak are subject to mass wasting by felsenmeer creep (Thompson, 1960-61) and even by rock glacier flow (Warhaftig and Cox, 1959). The latter phenomenon implies the presence of permafrost in the silty, stony, soil which makes up the greater part of huge felsenmeer-mantled glacier-like masses of detritus. Such deep frost is due to refrigeration of the subsoil beneath the felsenmeer by Balch ventilation comparable to that which forms ice in caves (Balch 1897, 1900). Air cooled by radiation on adjacent surfaces during the winter seeps down into the crevices among the boulders and chills them, displacing crevice air which, at that season, is warmer than the air outside. In summer the chill is retained because air in the crevices is cool, heavy, and thus stable.

It is noteworthy, however, that the uncreviced surface of stony, silty, alpine soil over which felsenmeers and rock glaciers are advancing downslope on Silver Star shows little evidence of upsorting of its own stones by frost, even though it is continuously in the shadow of the mountain for several months each winter. Formation of felsenmeer on Silver Star is not due primarily to frost heave but rather to sorting-out of coarse boulders by free fall from the cliffs above. The larger boulders roll further than smaller rockfall debris and thus accumulate as open-jointed blockfields, subject to Balch ventilation. The mobility of such surfaces on Silver Star is thus due entirely to non-climatic intensification of soil frost, as in the rest of the Cascades, though because the Cascades shelter the Methow region from the sea, intensification occurs more readily and on a larger scale there than elsewhere in the range.

Troll (1943-44) showed that the horizontal dimensions of frost polygons, stripes, and other frost patterns in alpine and arctic soil vary with the duration and intensity of freeze and thaw, being very small in tropical mountains where the alternation typically occurs daily and very large in the arctic where the alternation is annual. Because of its frequency, the cumulative effect of frost seems about as great in some of Troll's tropical mountain landscapes as in arctic topography. (Dresch, 1958, should be read from this point of view.) In the Cascades the dimensions and character of frost patterns are very like those Troll describes for the Alps. Solifluction terraces and various kinds of garland soils are very common. Polygons and stripes occur only in favorable sites; their wider prevalence in the Alps seems to be due to destruction of vegetation by grazing on soils favorable to frost sorting.

6. Weathering and Erosion of Alpine Crests

The relationships between processes on Cascade alp slopes and processes on sharpened alpine ridges and towers standing above them are of considerable interest. On the alp slopes gradients are low enough so that, though soils are very mobile, soil does form and vegetation grows. However, removal of soil by solifluction keeps a great deal of bedrock within reach of weathering at all times. The mobile soil of the alp slopes, which is generally quite thin where it lies directly on bedrock, actually seems to accelerate weathering in such places, partly by retaining, in contact with the substratum, moisture essential to active chemical and physical weathering, and partly because solifluction is able to pick up moderately coarse blocks and carry them away mixed with finer materials, instead of leaving them to protect unweathered materials beneath.

Since the alp slopes of the Cascades seem to have been formed primarily by mass wasting, they must once have been quite well-graded. Locally they are still well-graded, in spite of having been glaciated, and are again completely dominated by mass wasting. A graded slope is one on which there is an equilibrium between detritus available at any given point and the capacity of processes active there to move the detritus. A continuing deficiency of detritus exposes bedrock to rapid weathering at the surface; an excess aggrades the slope. Heavily glaciated alp slopes are thus ordinarily a mosaic of bare bedrock knolls and pockets of aggrading soil or talus, with gradation beginning at the margins of the outcrops. Complete gradation removes such irregularities. A graded slope under fairly uniform thick soil is often eroded only slowly at any given point because almost all of the detritus which can be handled by processes at that point is supplied from upslope. Where the soil is thin but nevertheless continuous, on the other hand, much of the detritus load of active processes must be derived from local bedrock, which is consequently wasted down evenly but relatively rapidly.

Where graded alp slopes head under cliffs, the latter condition, implying rapid erosion, is usual on their upper parts, though the mantle covering the graded surface of bedrock may be mostly rockfall debris rather than a well-developed soil. Under such circumstances, any soil, coarse or fine, tends to creep away from the base of the cliff and leave bedrock thinly covered at that point. Because snow generally accumulates and lies late at the cliff base, melt-water is abundant there in spring and early summer. At that time, furthermore, a gap several feet wide develops between the cliff and the snow, within which conditions are similar to those in a bergschrund or a felsenmeer crevice. That is, the gap traps the lowest, coldest layers of the downslope flow of air chilled by night radiation on surfaces upslope. On clear, calm nights in particular, the trapped cold air freezes the rock and causes severe riving of the moist cliff-base. A sharp knick-point is therefore normal between the upper margin of a graded alp slope and the cliff above it; it may even develop into a recess like the ones often carved by waves in the bases of sea-cliffs. (Compare Spreitzer, 1960.)

Even in the absence of firn-glaciation, which generally acts powerfully to the same end, there is thus a strong tendency for alp slope processes to undercut and steepen the cliffs above them, consequently sharpening and eventually truncating the high alpine summits. Generally speaking, firn glaciation tends to simplify the boundary between alp slopes and cliffs. Other alp slopes tend to render it intricate, so that it runs upslope into avalanche gullies (couloirs) and downslope around ridges. In any case, the high ridges are eventually truncated.

Destruction of the high alpine ridges does not take place from the top down, however. The higher ridge-crests and summits seem too dry, in effect, to support frost riving and weathering comparable to that on their flanks, though their temperatures are more severe than those on alp slopes and they probably get as much precipitation. Snow blows off them or falls away as avalanches. Rain and meltwater promptly seep into bottomless joint systems which lead the moisture down to cliff-faces and alp slopes below. The escaping water often carries with it any soil formed on the summits, leaving nothing but a heavy cover of black lichens on the rocks. Soil and even fairly coarse rock fragments may also be picked up and carried away by wind. Many high alpine crests are thus a mass of coarse blocks of bedrock approximately in place, though generally dramatically riven. The slowness of the riving, because of lack of moisture, is expressed by the completeness and maturity of lichen cover on the stones. Clean surfaces are common only on cliff margins, from which stones fall away freely. Slow riving and erosion of alpine summits are also expressed by the long persistence of the high peaks of the range in Daly's accordance in spite of the steepness and rapid wasting of their rockfall-swept faces.

7. Accordances as Records of Varying Timberline Levels

Opposition to Dawson's concept of the origin of alpine accordances at timberline has been based to a large extent on the argument that since timberline is climate-controlled and must vary in altitude as climate varies, its geomorphic effect during the Pleistocene must have been diffused over so wide a zone of mountainsides as to have had no significant effect at any one level. To point in rebuttal to the regularity and consistent coincidence of Daly's accordance and timberline on the northwest coast of North America does not in itself solve the problem. However, observations in the Cascades indicate that, rather than being imperceptible, the geomorphic effect of timberline is visible not only within the present timberline zone but at many higher levels. The observations in question include extensive photographic flights and several weeks of study on foot in the northern Cascades and Olympics during the summer of 1961. About 350 aerial oblique photographs and a very large number of ground photographs were taken on which to check the field observations.

If Daly's accordances were the only level at which the Cascade timberline had ever controlled the truncation of higher alpine crests, summits above that level should tend to be sharp (Matterhorn peaks) instead of being continuous ridges. Only timberline, controlled by climate, could have inhibited the differential erosion of alpine crests so sharply at certain levels as to produce the even-crested ridges which are very common in the northern Cascades even above timberline. If we consider the region as a whole, the prevalence of even-crested ridges seems to diminish only gradually upward. Except locally, isolated sharp peaks become the dominant summit form only as we approach the level of Dawson's gipfelflur. There are numerous more or less continuous ridges even in the gipfelflur, such as the serrate crests in the Picket Range. It may thus be said that the alpine geomorphology of the Cascades and similar ranges indicates strong variation of timberline levels during interglacial and recent time, though the fluctuation was not so rapid as to keep timberline from leaving its mark in many places above the level of Daly's accordance. If the indicated timberline levels were due simply to differences in temperature, they demonstrate the occurrence of interglacial climate about 7 degrees warmer than that of the present time, that many degrees being the temperature difference required to sustain timberline at the level of Dawson's gipfelflur.

Ridges and upland surfaces more or less accordant with one another exist on the fringes of the northern Cascades below the level of Daly's accordance but do not seem related to timberline. The amount of valley glaciation in the range indicates that glacial climates were as severe there as elsewhere, yet slopes within the range below the alp-slope accordance provide no evidence of low stands of timberline. It therefore seems probable that the critics of Dawson and Richter were correct with respect to glacial periods during the Pleistocene, though not with respect to interglacial periods, in arguing that the geomorphic effects of timberline must have been too greatly diffused to be obvious today.

Old erosion surfaces below alp slope levels, seen in the summer of 1961 west of the Cascades, are too broad to be due to ridge truncation at a lower timberline. They seem to be portions of old floors of the Puget Sound Basin. On the eastern flank of the Cascades the crests of several ranges which run from the high Cascades southeastward to the Columbia between the mouths of the Wenatchee and Methow Rivers descend quite regularly in that direction to form an accordance sloping eastward. It cannot be related to timberline, since timberline rises slowly in that direction as far as there are crests high enough to reach it. The accordance was described by Willis as the "Entiat Surface," the eastern margin of his Cascade peneplain. Aerial photographs of the Twisp River Valley, north of Lake Chelan, show similarly accordant ridges descending northward toward that basin. Willis' hypothetical peneplain can hardly descend to the Twisp as those ridges do, yet they are just as accordant as the crests on which he based his "Entiat Surface." Daly discussed various possible origins of such accordances in 1905; his discussion of the effect of regular stream spacing and uniform slope development may apply in this instance.

8. <u>Cascade Alp Slopes and Gipfelfluren as Regional Characteristics Related to Climate</u>

The forms and surface patterns of peaks in the Cascades have great individuality. Such distinctions are particularly evident to people traveling among them on foot because they have good views of only a few summits at a time. From the air, on the other hand, the more or less accidental characteristics which make each peak distinctive are subordinate to similarities among them which create a strong sense of regional unity. The accidental features are generally due to local geologic structure. The similarities are in large part responses to regional climate such as we have discussed in this study. Except as they are affected by local geological situations, all the various features of summits, cliffs, glaciers, cirques, alp slopes, timberline, subalpine forests and slopes, and of the gorges between the peaks, thus conform to rules such as those we have been discussing, not only with respect to altitude but also with respect to exposure, gradient, and relationship with adjacent features.

Regular as are the circumstances in which such features occur and recur, however, there is a progressive change in the aspect of the Cascades as one flies from their western flank to their eastern flank. The forest becomes more open and less tall. Bedrock crops out more generally on alpine meadows and subalpine slopes. Southfacing slopes become more sharply folded into gullies and ridges. Alp slopes are less continuous on the faces of high peaks and may be entirely absent on southern exposures, as on Silver Star Mountain. The gipfelflur phase of Daly's accordance is widely present but the mountains which compose it are truncated by alp slopes developed on north faces only; south faces are steep to their crests. The same thing happens locally west of the Cascades but is not the rule. The easternmost Cascades are thus a distinct subregion within the range with respect to alpine climate. The subregion is probably best exemplified on the Methow watershed because that area is especially sheltered from marine influence.

The more westerly parts of the Idaho Rockies, such as the Sawtooth Range, may have an alpine climate and landscape quite like that of the Methow peaks; further study there is desirable. Field studies in the Lost River Range, the Sawtooths, and intervening mountains during 1961 and 1962 indicate that the much discussed "Idaho Peneplain" is closely correlated with timberline throughout that region and is thus an eastward extension of Daly's accordance. Even on the face of the Lost River Range east of Mackay, which is so dry that it has only a fringe of pines well above the valley floor, a series of spurs projecting from the mountain front have crests very regularly accordant at timberline. How much further into the Rockies the accordance might be followed is hard to say, perhaps as far as the winter westerlies deposit a really heavy winter snow cover.

Contrasts between the Cascade alpine landscape and that of New England mountains (Thompson, 1960-61) have been mentioned earlier. They are greater than would be guessed by a person comparing the lowland climates of the two regions. Anyone who has spent much time in both the Cascades and the Presidentials can vouch for the much greater violence of alpine winds in the latter. Differences in frost regime are mostly due to the fact that the alpine winds blow off the continent in New England, but are accentuated by the fact that westerly winds remove most of the snow from New England alpine uplands. Regionally speaking, western timberlines are closely controlled by temperature and growing season, but those of New England are very sensitive to wind. Observation of such climate-sensitive characteristics of the mountains of the world may eventually provide a sound basis for studying the regional physical geography of mountains and will also contribute substantially to related sciences.

9. Summary

The explanation of summit accordance in the northern Cascades advanced by G.M. Dawson (1896) and supported by Reginald Daly (1912) is confirmed with some modification. Hypothetical peneplains in that range are found invalid. Erosion by mass wasting, much more vigorous above timberline than below, has formed alp slopes (Daly's accordance) at timberline throughout the Cascades, in coastal ranges from Alaska to California, and in the Idaho Rockies. They are considered an indicator of maritime climatic influence at alpine levels. Analysis of their development is based on a description of the alpine clima-geomorphology of the region which will also be useful as a basis for climatic and environmental comparisons with other mountain regions.

Variation of timberline during Pleistocene interglacial time is found to have caused alp slope formation at various higher levels. The alp slopes have truncated alpine summits at those levels and have thus formed many ridges with considerable continuity of crestline and altitude. A well-defined peak-plain (Dawson's gipfelflur) at about 8,000 feet throughout the northern Cascades is believed to represent a stand of timberline when interglacial climate was about 7 F° warmer than at present. Few non-volcanic summits rise much higher. Minor summits in the Washington and Oregon Cascades and in Idaho have been truncated uniformly at timberline over wide areas by the alp slopes of Daly's accordance. No stand of timberline at lower levels seems to have lasted long enough to have topographic effects still visible within the Cascades.

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Figure 1. Accordances in the Northern Cascades

Dawson's gipfelflur appears here at a height of about 8,000 feet on the skyline of the Picket Range, seen to the northeast from over the lower Skagit Valley. The forested ridges in the foreground are part of Daly's timberline accordance, here at about 5,000 feet. Alp slopes on the forested ridges are confined to their higher crests and in this photograph are out of sight on their northern slopes (compare Fig. 2). Considerable ridge-continuity at levels intermediate between the two accordances is evident on the peaks in the middle distance.

Figure 2. Daly's Accordance on the Western Flank of the Cascades

In the zone on the western flank of the Cascades most completely dominated by Daly's accordance, only the higher crests retain alp slopes, evident here as snowfields. Peaks forming part of Dawson's gipfelflur are roughly 2,000 feet higher than the timberline accordance at their immediate bases, carry glaciers and broad snowfields, and are common only to the extreme left of the picture near the crest of the Cascades. Peaks of intermediate height are common in a transition zone. All peaks which stand above Daly's accordance (timberline) carry alp slopes. The Puget Sound lowland lies to the right beyond the last level ridges of the range. Mount Rainier is about 110 miles south; in that distance the general level of the western fringes of Daly's accordance rises from about 5,000 to nearly 6,000 feet.

Figure 3. Dawson's Gipfelflur around the Margins of the Suiattle Watershed

Dawson's gipfelflur is especially well developed between the 48th and 49th parallels in the northern Cascades. Figures 1, 4, and 5 were taken not far from the 49th parallel; Figure 3 shows a region near the 48th parallel. A few non-volcanic Cascade peaks, including Mts. Bonanza and Dome on the skyline to the left, approximate 9,000 feet but none reach 9,500 feet. The gipfelflur as a whole is at about 8,000 feet. (View southwest over Mt. Buckindy.)

Figure 4. Dawson's Gipfelflur in the Picket Range

This picture shows the characteristic form of its peaks. Their summits are nowhere of sufficient area to be interpreted as a peneplain or other ancient surface now uplifted. (The "Terror Group" and Mts. Luna and Fury.)

Figure 5. Accordance at Multiple Levels within the High Cascade.

Dawson's gipfelflur (about 5,000 feet) is visible on and beyond the summits of the Picket Range (center). Some of the peaks in Figure 3 form part of the distant skyline at far right. More or less continuous ridges at levels intermediate between 8,000 feet and timberline, such as Easy Ridge (center right), have been truncated during stands of Pleistocene interglacial timberline intermediate in height between the present forest limit and the ancient interglacial timberline which determined the level of the high gipfelflur. Because the Picket Range summits are much too bulky to have yet been truncated at the present level of timberline, Daly's accordance is represented among them by an accordance of moderated slopes (alp slopes) immediately above timberline, rather than by an accordance of summits as in Figure 2. (View southeast over Brush Creek in the Picket Range.)

Figure 6. The Nooksack Cirque on Mt. Shuksan

Wisconsin and recent glaciation have been especially vigorous at the head of this representative cirque in the northern Cascades, yet alp slopes remain intact there at the same level as on the other walls of the valley. Present climate and timberline are believed to correspond to those which have controlled alpine mass wasting, and thus the development of alp slopes, during a considerable part of Pleistocene interglacial time; present conditions may probably be considered as nearly normal for the Pleistocene as any climate could be in such a variable epoch. Persistence of present climate may permit timberline to eventually regain a continuity lost in this and similar localities because of local glaciation extending below timberline during the last few thousand years (the Little Ice Age of Matthes).

Figure 7. Patterned Ground in the Picket Range

Such patterns in the Cascades are believed to have dimensions controlled by thermal and frost regimes. Analogy of form and dimension with patterns in some parts, at least, of the Alps is considered an indication of similar regional climate.

Figure 8. Nivation in the Picket Range

Diurnal freeze and thaw over many years in moist ground beneath this snowfield has caused weathering and mass wasting, resulting in the advance of a tongue of debris over heather sod downslope. Note similar creeping debris below the snowfield in the background.

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