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NIVATION: AN ARCTIC–ALPINE COMPARISON AND REAPPRAISAL

By COLIN E. THORN*

(Department of Geography, University of Maryland, College Park, Maryland 20742, U.S.A.)

and KEVIN HALL

(Institute for Environmental Sciences, University of the Orange Free State, Bloemfontein, South Africa)

ABSTRACT. Nivation is a collective noun identifying a set of geomorphic processes, comprised of an indeterminate number of elements and of unknown relative importance, for which there is little likelihood of ever producing a precise definition. Instead, attention should first be directed towards the relationships between snow-packs and individual geomorphic processes. The relationship between freezing amplitude in the bedrock, snow cover, and aspect at an Arctic site in northern Norway and an alpine site in the Front Range, Colorado, U.S.A. is complex. Comparison of field data and laboratory criteria permit several conflicting interpretations. If oscillations across 0°C, regardless of freezing amplitude, are critical, the alpine site is potentially a more active freeze–thaw weathering regime, with a primary springtime peak and a secondary fall peak. If a freezing amplitude of $-5°$C is required for effective freeze–thaw weathering then the alpine site is largely inactive and the Arctic active (but with only a single fall peak). Chemical weathering is much more important at snow-patch sites than has traditionally been recognized. Mass wasting at colluvial sites subject to snow patches is dominated by interaction between overland flow and solifluction when the site is unvegetated, and by solifluction when it is vegetated. Given contemporary knowledge of snow and glacial geomorphology, there appears to be no threshold, only differences of intensity. Resolution of the disruptive mechanism associated with bedrock freezing and its constraining temperature and moisture requirements is the most pressing present problem in the field of snow geomorphology.

RÉSUMÉ. *Nivation: une comparaison arctique–alpine et une réestimation.* La nivation est une appellation collective désignant un ensemble de processus géomorphologiques composé d'un nombre indéterminé d'éléments d'importance relative inconnue, pour lequel il est très peu probable qu'on parvienne jamais à une définition précise. On devrait plutôt apporter en premier lieu son attention aux relations entre le manteau neigeux et chaque processus géomorphologique individuel. La relation entre l'intensité du gel du lit rocheux, le manteau neigeux et l'exposition dans un site arctique en Norvège septentrionale et dans un site alpin dans le Front Range, Colorado, États-Unis est complexe. La comparaison entre les données du terrain et les résultats du laboratoire autorise plusieurs interprétations opposées. Si les oscillations autour de 0°C indépendamment de l'intensité du gel, sont critiques, le site alpin peut être soumis à un régime d'alternance gel–dégel plus actif avec un maximum primaire au printemps et un maximum secondaire à l'automne. Si une intensité de gel de $-5°$ cest nécessaire pour que se manifeste une dégradation réelle par le gel–dégel, alors le site alpin est surtout inactif et le site arctique actif (mais seulement avec un seul maximum à l'automne). La désagrégation chimique est beaucoup plus importante sur les sites où subsistent des congères de neige qu'il n'est traditionnellement reconnu. La dégradation de masse sur les sites colluviaux sujets aux accumulations de neige est dominée par l'interaction entre les écoulements superficiels et la solifluction lorsque le site n'est pas végétalisé, et par la solifluction lorsqu'il est végétalisé. Les données de la connaissance contemporaine sur la géomorphologie nivale et glaciaire fait apparaître qu'il n'y a pas de seuil tranché mais seulement des différences d'intensité. La compréhension du mécanisme de rupture associé au gel du lit rocheux et ses exigences contraignantes de température et d'humidité est le problème actuellement le plus urgent dans le domaine de la géomorphologie de la neige.

ZUSAMMENFASSUNG. *Nivation: ein Vergleich Arktis–Hochgebirge und eine Neueinschätzung.* Nivation ist ein Kollektivbegriff für eine Reihe von formbildenden Vorgängen; er umfasst eine unbestimmte Zahl von Elementen, deren relative Bedeutung unbekannt ist, weshalb nur geringe Wahrscheinlichkeit dafür besteht, dass sich je eine genaue Definition finden lässt. Stattdessen sollte die Aufmerksamkeit zunächst auf die Beziehungen zwischen Schneeanhäufungen und einzelnen formbildenden Vorgängen gerichtet sein. Die Beziehung zwischen der Amplitude des Bodenfrostes, der Schneedecke und dem Aussehen einerseits an einem arktischen Platz in Nordnorwegen, andererseits an einer Hochgebirgsstelle in der Front Range von Colorado, U.S.A., ist komplex. Der Vergleich zwischen Feldmessungen und Laborkriterien lässt mehrere widersprüchliche Deutungen zu. Wenn Schwankungen um 0°C ohne Rücksicht auf die Frostamplitude massgeblich sind, dann weist die Hochgebirgsstelle ein potentiell aktiveres Frostwechsel-Verwitterungsregime mit einem primären Höhepunkt im Frühling und einem sekundären im Herbst auf. Wird dagegen eine

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* Present address: Department of Geography, 220 Davenport Hall, University of Illinois, Urbana, Illinois 61801, U.S.A.

Frostamplitude von −5°C für eine effektive Frostwechsel-Verwitterung benötigt, dann ist die Hochgebirgsstelle weitgehend inaktiv und die arktische aktiv (jedoch mit nur einem Höhepunkt im Herbst). Chemische Verwitterung ist an Stellen mit Schneeflecken weit wichtiger als traditionsgemäss angenommen wurde. Die Massenbewegung an Anhäufungsstellen von Colluvium unter der Wirkung von Schneeflecken wird vom Wechselspiel zwischen Rutschungen und Solifluktion bestimmt, wenn das Gelände vegetationslos ist, von der Solifluktion allein im bewachsenen Gelände. Nach dem derzeitigen Wissensstand in der Schnee- und Eisgeomorphologie scheint hier keine Schwelle zu bestehen, höchstens Unterschiede in der Intensität. Die Klärung des Abrissmechanismus, der mit Frost am Felsbett verbunden ist, und der dafür notwendigen Bedingungen für Temperatur und Feuchtigkeit ist das gegenwärtig dringendste Problem auf dem Gebiet der Schneegeomorphologie.

INTRODUCTION

Traditionally, snow-patches have been distinguished from glaciers by identification of the former as static and the latter as mobile. Evidence of snow-pack mobility (Costin and others, 1973; Mathews and Mackay, 1975) obscures the established glaciological distinction. A parallel problem exists in separating the geomorphic impact of snow-patches and glaciers. In many ways "nivation" (a collective noun used to summarize all snow-pack-derived erosion) confounds the issue.

Matthes (1900) coined the term "nivation" after a reconnaissance study in the Big Horn Mountains of Wyoming, U.S.A. Unfortunately, the term became entrenched in the literature prior to any comprehensive process studies designed to identify individual components and their relative importance. That nivation remains a rather loose concept and lacks a uniform definition is shown by the literature review summarized in Table I.

TABLE I. ELEMENTS OF NIVATION ACCORDING TO MOST WIDELY CITED REFERENCES

			Frost weathering			*Sheet-wash*			
Author	*Date*	*Snow-pack mobile*	*At margin*	*Under snow*	*Solifluction dominant*	*Transport*	*Erosion*	*Chemical weathering*	*No vegetation*
Matthes	1900	No	Yes	No	—	Yes	No	—	Yes
Ekblaw	1918	—*	Yes	—	Yes	Yes	—	—	—
Lewis	1936, 1939	No	Yes	Yes	Yes	Yes	No	—	Yes
McCabe	1939	No	Yes	Yes	—	No	—	—	—
Roth	1944	—	Yes	—	Yes	—	—	—	—
Boch	1946, 1948†	Yes	Yes	No	Yes	Yes	—	Yes	Yes
Paterson	1951	Yes	Yes	—	Yes	—	No	Yes	Yes
Henderson	1956	—	Yes	—	Yes	Yes	—	—	—
Cook and Raiche	1962	—	Yes	No	Yes	Yes	—	—	—
Nichols	1963	—	Yes	No	—	Yes	Yes	—	—
Lyubimov	1967	No	Yes	No	Yes	Yes	Yes‡	Yes	—
St Onge	1969	—	Yes	—	—	—	—	—	—

* Means "not mentioned".
† Boch (1948) specifically corrects some errors in Boch (1946).
‡ Under longitudinal snow-patches only.

Faced with such an amorphous concept, two recent and independent studies (Hall, unpublished; Thorn, 1976, unpublished) have attempted to verify quantitatively the existence and characteristics of nivation. This paper is a *post hoc* comparison of the two studies and provides a comparison between nivation in Arctic maritime (Hall, unpublished) and temperate alpine regimes (Thorn, 1976, unpublished). The individual findings and methodologies of the two studies are not discussed exhaustively, rather the emphasis is upon the comparisons and contrasts and their significance for refining the understanding of nivation.

STUDY SITES

Arctic site

The Arctic site lies on a north-facing slope of the east–west trending valley of Austre Okstinbredal in the Okstindan region of northern Norway (Fig. 1). The north-facing valley wall rises from 725 m, through a series of benches, to a maximum elevation of 1 916 m a.s.l. Only 80 km from the sea, the area is relatively maritime; integration of a partial local climatic record with data from Hattsfjelldal, some 50 km south, suggests a mean annual temperature of approximately −3°C. Mean annual precipitation is 1 120 mm and snow covers the ground for 180 d of the year.

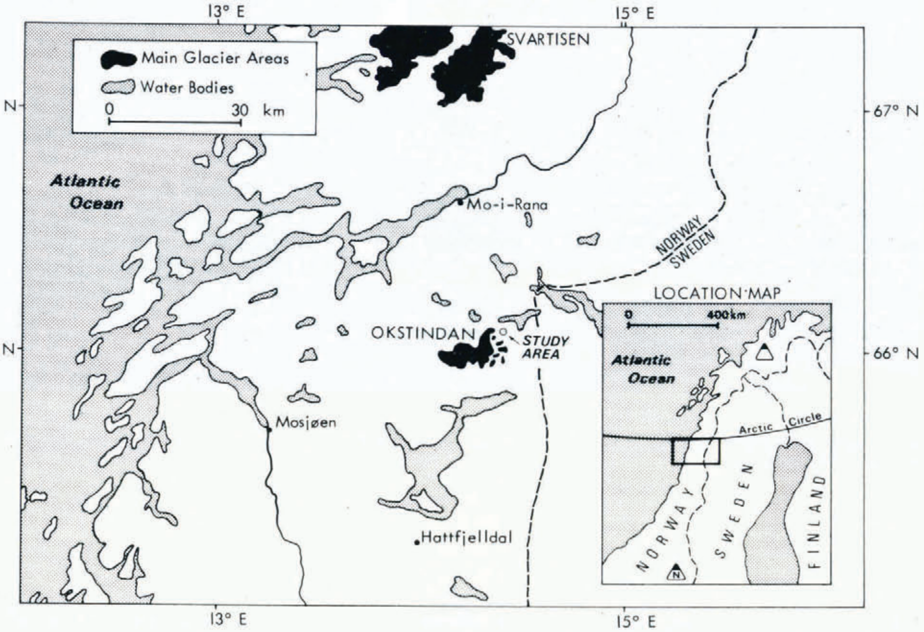

Fig. 1. Regional location of the Arctic research site. The map is modified with permission from The Times atlas of the world. Mid-century edition. Vol. 3. Northern Europe. *London, The Times Publishing Co., Ltd., 1955, plate 52.*

The study site lies mainly at 800 m a.s.l. Overall the semi-permanent snow-patch comprises an upper transverse section and a longitudinal section which drops to the valley bottom (Fig. 2). The transverse section has a maximum width across slope of 150 m, and a maximum down-slope extent of 100 m; the longitudinal section is only 20–30 m wide, but nearly 250 m in length. Only the transverse snow-patch was studied in detail.

Four small-scale elements may be identified within the transverse patch. These are: (1) a near-vertical bedrock back-wall; (2) a stone pavement dissected by rock outcrops, particularly well developed at the eastern end; (3) a lower vegetated area; (4) a gully which bisects the entire site (the gully is headed at the back-wall by a waterfall and below the transverse snow-patch becomes the location of the longitudinal snow-patch). The back-wall ranges from 2–10 m high and averages about 4 m; it is composed of various types of schist and basal niches are prominent. Coarse gravel and cobbles in a matrix of fines forms the stone pavement which is unvegetated and dissected at its eastern end by a series of bedrock outcrops ("rockbands") up to 1.5 m high and parallel to the slope. Vegetation gradually increases down-slope, culminating in a continuous cover, dominated by billberry (*Vaccinium myrtillus*), dwarf birch (*Betula nana*) and *Carex* spp.

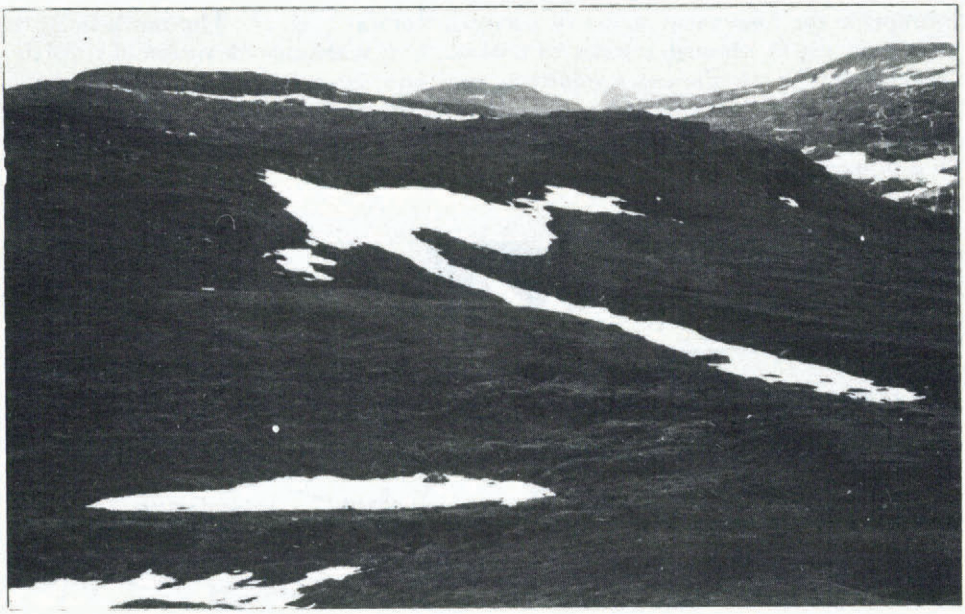

Fig. 2. A view looking approximately south-west across the Arctic research site. Note the waterfall at the top of the transverse section of the snow-patch.

Alpine sites

Two snow-patches on the south face of Niwot Ridge, Colorado Front Range, U.S.A. (Fig. 3) were the focus of the alpine study. The bedrock, or "longitudinal", snow-patch (Fig. 4) is approximately 3 590 m a.s.l. It is a seasonal snow-patch which accumulates to depths of 4–5 m against the western wall of a narrow gully dissecting a cliff. The bedrock is gneiss and at the up-slope end of the gully there is evidence of hydrothermal alteration (Thorn, unpublished).

The larger ("Martinelli") snow-patch (Fig. 5) ranges through the tundra–forest ecotone at elevations above 3 450 m a.s.l. Maximum extent is approximately 175 m across slope and 450 m down-slope. Syenite colluvium underlies the snow patch which accumulates along the down-wind edge of a till lobe. As the ablation season progresses the snow-patch divides into an upper, circular snow patch and a lower, longitudinal one; the upper patch rarely ablates totally, but the lower patch is destroyed annually.

Core areas of both Martinelli patches are unvegetated, but peripheral areas are partially vegetated and discontinuous tundra cover occurs beyond the upper basin and sub-alpine meadow beyond the lower basin.

Mean annual air temperature on the crest of Niwot Ridge is −4°C with annual precipitation of 1 021 mm (Barry, 1973). Wintertime wind speeds are high; mean monthly averages from October through March exceed 11 m/s. As a result the landscape is divided into zones of high and low effective precipitation, as snow-fall is rapidly redistributed.

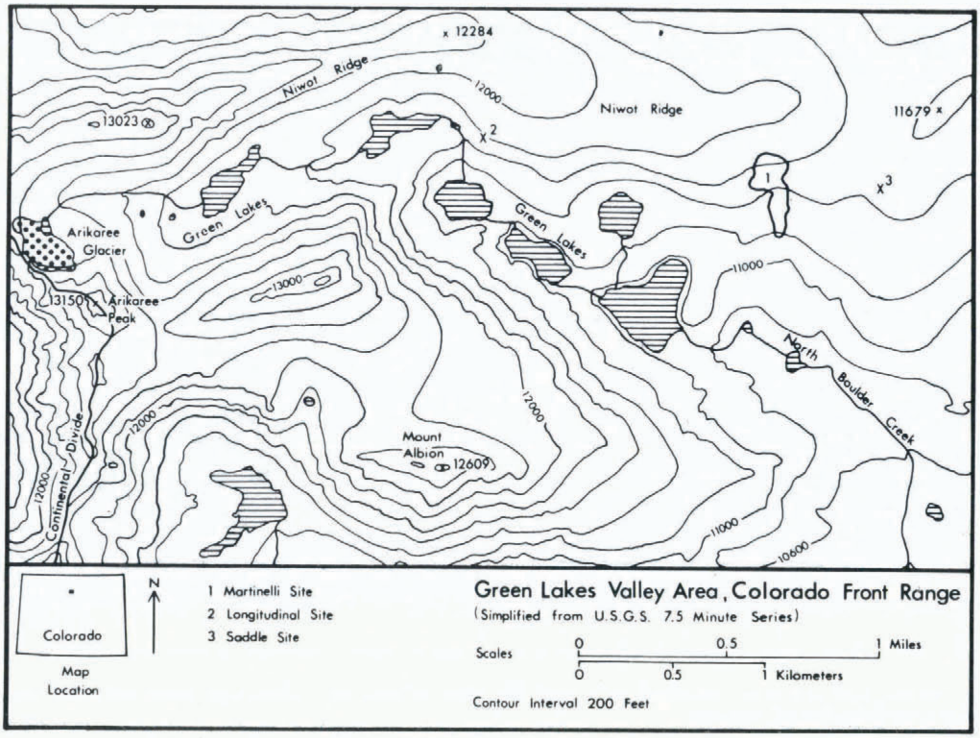

Fig. 3. Location of the three alpine research sites. The longitudinal site is the source of bedrock data; Martinelli site is the primary colluvial site; Saddle site is the subsidiary colluvial site briefly mentioned in the text. Contour interval is approximately 61 m.

Fig. 4. Looking north-west across the longitudinal site. The early June 1973 photograph shows the snow-patch near its maximum extent against the wall. The large snow-free buttress to the right of the person served as the control site.

Fig. 5. Looking north-east across Martinelli snow-patch (the alpine colluvial site). Photograph shows subdivision into upper and lower basins during melt-out.

METHODOLOGIES

The two methodologies contain fundamental similarities while differing substantially in detail. Comprehensive methodological descriptions are provided in Hall (unpublished) and Thorn (unpublished); the discussion herein is restricted to essentials.

Both studies attempted to verify nivation by testing the research hypotheses that nivation promotes: (1) mechanical weathering, (2) mass wasting, (3) chemical weathering. Each hypothesis was investigated by monitoring individual geomorphic processes. A fundamental component in the research design for the alpine program was that all measures were comparative. Each snow-patch measurement was matched by identical measurements at adjacent snow-free locations. This approach was intended to recognize nivation as a concept of intensification, rather than one of unique properties.

In both studies a bedrock freeze–thaw cycle (a purely thermal event) was accepted as a surrogate measure for a geomorphologically effective freeze–thaw cycle. In reality, there are important distinctions between the two as the latter is normally considered to be subject to important moisture constraints, in addition many researchers also envisage important freezing-intensity and/or freezing-duration constraints. However, it is not presently possible to monitor bedrock moisture content remotely, and therefore moisture conditions must be inferred.

At the Arctic site, multichannel recorders, with 2 h and 6 h sampling intervals, were attached to thermistors cemented to the bedrock face in a variety of micro-environments. The multichannel recorder at the alpine bedrock site produced spot readings at two-hourly intervals from thermistors inserted into holes drilled into the bedrock to depths of 10, 20, 30, and 50 mm (only those at 10 mm are discussed in this paper). Both records are discussed in terms of Hewitt's (1968) terminology which describes a freeze–thaw cycle and its component parts as a wave form.

Mass wasting at snow-patch sites would appear to be dominated by solifluction, overland flow, and frost creep (Hall, unpublished; Thorn, unpublished). A variety of other processes are possible, or probable, but do not appear to be quantitatively important. Amongst these are the snow-dependent processes of sub-snow creep, produced by a mobile snow-pack, and supra-snow movement, resulting from material free-falling and then rolling or sliding, or being included in surface avalanches.

At Martinelli snow-patch, overland flow was comprehensively monitored using small sediment traps (Thorn, 1976). These traps, with a catching edge of 100 mm, were distributed in groups of five and left at the site during the winter. Direct measurement of solifluction was not undertaken at Martinelli snow patch. A combination of Rudberg pillars and polythene tubes was used to monitor solifluction at Austre Okstinbredal. The hollow tubes bent with down-slope movement. Deflection was measured by inserting test tubes filled with warm jello which was allowed to cool and harden; upon removal, the angle between the jello surface and the horizontal may be used to calculate down-slope deflection. An incremental approach permits reconstruction of vertical profiles (Hall, unpublished, p. 237–46).

Both studies investigated chemical weathering by chemical analysis of snow and melt-water solutes. Arctic samples were subject to analysis by atomic absorption spectrometer; alpine samples to analysis by colorimeter. In addition, rock samples from the Arctic were examined microscopically for signs of chemical weathering, while the spatial variation in weathering-rind thickness was mapped at Martinelli snow-patch (Thorn, 1975).

Mechanical weathering

A geomorphically effective freeze–thaw cycle, that is one which disrupts bedrock, is still an uncertain concept. This is because the precise nature of the disruptive forces remains undetermined (see Hall, unpublished, and Thorn, 1979, for discussions). Most laboratory experiments have consisted of freezing rocks to varying degrees, then thawing them and noting the degree of breakdown, without investigating the mechanics of the breakdown process(es). All laboratory researchers (e.g. Fukuda, 1972; Potts, 1970; Latridou, 1971) identify rock saturation as a prerequisite, but the necessary freeze-phase amplitude remains uncertain. Potts (1970) favors the frequency with which 0°C is crossed, regardless of intensity, as the controlling factor. Most other researchers cite a specific freezing amplitude: Fukuda (1971), −4°C; Fukuda (1972), −5°C; Dunn and Hudec (1966), −6 to −10°C. Latridou (1971), summarizing the results of many workers at Caen, suggests both an amplitude of −5°C and a duration of at least 9–10 h. Finally, Battle (1960) and Mellor (1973) emphasize freezing-rate, Battle stating that a minimum cooling-rate of 0.1 $\mathrm{deg/min^{-1}}$ is necessary.

In part this variability reflects uncertainty as to the exact process of disruption. Principal possibilities are pressure due to direct expansion upon freezing (Mellor, 1973), oriented ice-crystal growth (Connell and Tombs, 1971), and the growth of macroscopic crystals in large pore spaces (Everett, 1961). The thermodynamics of the situation is only known in very general terms (Everett, 1961). Hudec ([1973]) has produced a series of papers which provide substantial evidence that in the majority of instances freeze–thaw weathering is, in reality, weathering by wetting and drying. Domination by one process or the other is primarily dependent upon pore size and its distribution within the bedrock. The critical problem is that in the most widely cited geomorphic literature on freeze–thaw weathering the experimental designs do not permit separation of the two weathering processes.

Data

Only the fall freeze and spring melt periods may be compared; even these must be evaluated in general terms as data are for different years, and of uncertain representativeness.

TABLE II. FALL AND EARLY-WINTER FREEZE-PHASE AMPLITUDES AT THE ARCTIC SITE (ROCKBAND 6), 13 SEPTEMBER–9 DECEMBER 1973

Cycle number	*Freeze-phase duration*	*Maximum freeze amplitude* °C
1	21–22 September	−4.4
2	4– 8 October	−9.0
3	10–12 October	−6.4
4	12–19 October	−11.0
5	24–26 October	−6.9
6	1– 3 November	−7.4
7	4–17 November	−13.5
8	17–28 November	−14.8
9	28 November–6 December	−16.5

TABLE III. FALL AND EARLY-WINTER FREEZE-PHASE AMPLITUDES AT ALPINE MICROSITES, 1971*

Low-amplitude cycles (freeze-phase amplitude $\leqslant -3.9$°C)

Thermistor	*Cycle total*	*Average duration* h
11[a]	26	6.9±5.0
19[b]	26	5.1±4.2
23[c]	5	6.6±3.9
25[d]	8	5.3±4.6

High-amplitude cycles (freeze-phase amplitude $\geqslant 4.0$°C)

Thermistor	*Cycle number*	*Freeze-phase duration* h	*Maximum freeze amplitude* °C
11	1	46	−8.2
	2	13	−5.5
	3	14	−4.1
19	—	—	—
23	1	69	−10.3
	2	16	−5.0
	3	17	−4.6
	4	16	−6.8
	5	41	−8.2
	6	22	−6.2
	7	18	−8.8
	8	19	−11.2
	9	42	−14.2
	10	16	−6.5
25	1	16	−5.0
	2	20	−4.6
	3	19	−6.8
	4	44	−8.6
	5	25	−6.6

* Precise record periods are: 14 September 1971 to 17 October 1971; 24 October 1971 to 27 October 1971; 15 December 1971 to 22 December 1971.

[a] Thermistor 11 is at the foot of the bedrock wall; snow buried in winter, easterly aspect.

[b] Thermistor 19 is at the foot of the bedrock wall in the absolute cove accumulation area; snow buried in winter, easterly aspect.

[c] Thermistor 23, exposed southerly face of buttress; always snow-free.

[d] Thermistor 25 exposed westerly face of buttress; always snow-free.

The clearest contrasts between the two bedrock sites during freeze-up appear to be the higher frequency of low-amplitude cycles at the alpine accumulation site, and the greater freeze amplitude of the late freeze-up cycles in the Arctic (Tables II and III). The former must be viewed cautiously as it is certainly in part a reflection of sampling interval (two hours in the alpine versus six hours in the Arctic). High inter-annual variations in seasonal frequency at alpine accumulation sites (thermistor 19, Table IV) reflect the difference between a dry fall with late establishment of the winter snow-pack (1971) and one with numerous temporary accumulations (1972).

Snow-free alpine sites experience wintertime freeze-phase amplitudes equal to, or exceeding, Arctic fall cycles. This is not generally true of snow-buried sites, where insulation precludes such freezing amplitudes; however, April 1972 was one of record cold, and even snow-buried sites had temperatures as low as −20°C, although without the intervening thaw phases which produce complete cycles.

Comparison of melt-out periods reveals a contrast between the two regimes. In the Arctic, sub-snow temperatures remained just below freezing, upon melt-out bedrock temperatures rose quickly without recording freeze–thaw cycles. Sub-snow bedrock temperatures in the alpine situation exhibited as many as sixty low-amplitude cycles (freeze-phase amplitude $\leqslant -1.6$°C) of brief duration throughout a six-week period preceding melt-out. Those thermistors which melted out in May experienced up to six low-amplitude (freeze-phase amplitude $\leqslant -5.2$°C, commonly much less) diurnal cycles after melt-out; those melting out in June recorded a single post-melt-out cycle at most.

Individually, the alpine record illustrates the insulating role of the snow-pack which, thereby, redistributes the seasonal pattern of cycle occurrence (Table IV). A further facet is that high-amplitude freeze phases are also precluded at snow-pack accumulation sites.

Table IV. Seasonal distribution of freeze–thaw cycle frequency at the alpine bedrock site

	1971				*1972*									*1972*		
Month	*Sept.*	*Oct.*	*Nov.*	*Dec.*	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*Jun.*	*Jul.*	*Aug.*	*Annual total*	*Sept.*	*Oct.*	*Nov.*
Days on record	16	21	0	7	0	6	19	11	19	30	16	9	154	23	22	14
Thermistor 11*	17	12	—	0	—	0	0	0	45	27	1	0	102	10	17	2
Thermistor 19	7	19	—	0	—	0	0	0	7	9	1	0	43	14	48	7
Thermistor 23	5	6	—	4	—	2	17	6	9	1	0	0	50	5	9	10
Thermistor 25	5	8	—	0	—	1	14	6	6	1	0	0	41	n.d.†	n.d.	n.d.

* See Table III for description of thermistor microsites.
† No data from this channel.

Analysis

Evaluation of the relative potential for freeze–thaw weathering at the two sites is dependent upon the thermal criterion selected (accepting the additional critical factors of bedrock porosity and adequate rock-moisture content). If simple oscillations across 0°C, without regard to freezing amplitude, are effective, then clearly the alpine environment is more vigorous. It would also appear to have a strong seasonal rhythm, with a principal springtime maximum, and a secondary fall peak, which is particularly well developed during falls with frequent, temporary snow-pack accumulations.

Selection of any of the cited freezing amplitude criteria appears to come close to eliminating freeze–thaw weathering at the alpine site (Table V). The snow-patch probably supplies the necessary moisture, but snow-pack insulation precludes high freeze-amplitude cycles. Conversely, snow-free sites experience adequate freeze-phase amplitudes, but would seem likely to lack adequate moisture. Thus, the Arctic would be a more effective freeze–thaw weathering regime climatically. Furthermore, the season of optimal conditions shifts from the spring to the fall and early winter. This rather simple contrast is probably subject to substantial modification.

Table V. Seasonal distribution of freeze–thaw cycle-frequency with freeze-phase amplitude $\geqslant -5.0$°C at the alpine bedrock site*

	Fall†	*Winter*†	*Spring*†	*Total*
Days on record	37	43	65	145
Thermistor‡				
11	3	0	0	3
19	0	0	0	0
23	6	26	0	32
25	5	13	0	18

* Such cycles meet Fukuda's (1972) criterion and, in addition, all met Latridou's (1971) duration criterion.

† Fall is September through November 1971; winter is December 1971 through April 1972; spring is May through July 1972.

‡ See Table III for description of thermistor microsites.

Relationships between a number of factors probably control the location of effective freeze–thaw weathering in both Arctic and alpine regimes. Bedrock porosity is the dominant control, for without suitable porosity either wetting and drying weathering will prevail or rocks will be "sound" (Hudec, [1973]), that is resistant to weathering. Further constraints are imposed by snow-pack distribution in response to prevailing wintertime winds, as without snow melt adequate moisture is unavailable. These are the two fundamental controls which create the presence or absence of freeze–thaw cycle weathering; its intensity is modified by additional relationships.

Freeze–thaw weathering intensity in any region would appear to be dependent upon the interplay between freezing amplitude, snow-pack insulation, and total direct solar radiation; all of which vary seasonally. Snow-pack depths vary the insulation afforded the underlying bedrock; in general, any moderate to deep accumulation will obliterate all diurnal variations and most synoptic fluctuations. Therefore, such sites do not exhibit wintertime cycles; certainly neither site in the present studies did so. Radiation can penetrate snow to a depth of approximately one meter (Geiger, 1961), so even if cold waves penetrate the snow-pack there is no potential for sub-snow melt once the snow-pack exceeds this depth and residual ground heat has been exhausted. Even if totally sub-zero temperature changes can exert stresses on the rock, they will occur very slowly beneath a snow-pack.

Optimum conditions are likely to be associated with deep accumulation sites in fall and/or spring, and with temporary and/or shallow accumulation sites in winter. In either case a southerly or easterly aspect is likely to maximize the weathering regime. The absence of sub-snow cycles during melt-out at the Arctic site is probably due to its northerly aspect, rather than its latitude; conversely, the easterly aspect of the alpine site undoubtedly maximized the frequency of sub-snow cycles. A further point to appreciate is that optimal conditions of high moisture and low insulation also occur immediately down-slope of melting snow-patch sites.

Widespread association between snow-patches and basal niches, such as at the Arctic site, may possibly depend upon wetting and drying cycles, or salt weathering, rather than upon freeze–thaw weathering. Location of such niches at the base of steep faces locates them in zones of maximum snow-pack accumulation, and therefore of maximum insulation and belated melt-out. Both of these factors tend to minimize high-amplitude freezing frequency. In contrast, such locations experience optimal moisture supply as water percolates downward through the rock. It is even possible that the snow produces a perched water table by maintaining freezing temperatures in the abutting bedrock, thereby directing water along an impervious surface. Given the data herein, such an hypothesis compares favorably with the classic idea that such locations experience optimal freeze–thaw weathering regimes. This latter argument would appear to be valid only if cycle frequency, regardless of freezing amplitude, is dominant.

A final point is that comparative studies at both sites indicate the inadequacy of air-temperature data as an indicator of bedrock freeze–thaw frequency, form, or amplitude. Such features in bedrock tend to be dominated by aspect and snow cover, and only the most generalized relationships can be established between air and bedrock temperatures (Thorn, 1979).

Chemical weathering

Traditionally chemical weathering has been assumed to be very low in cold environments. This is based primarily on the assumption that reactions are temperature dependent and therefore slowed in cold regimes. Tamm (1925) presented evidence that between +2 and +15°C reaction rates are invariant. Furthermore, Reynolds and Johnson (1972) propose that water and hydrogen-ion supply, not temperature, are the limiting factors. Most researchers appear to have accepted the temperature-dependency hypothesis and consequently chemical activity has received relatively little attention. Just how misleading this may be was clearly established by Rapp (1960) when he found that in Kärkevagge, Swedish Lappland, solute load was the foremost denudational process.

Data

Snow pH measurements at both sites fell into the range 4.5–5.5, which is a normal measurement for snow (Clement and Vadour, 1968). Comparisons of snow solute concentrations with those in melt waters are given in Table VI (Arctic) and Table VII (alpine). It should be noted that the alpine data are for the colluvial site. Despite the absence of overlap in measures, the data produce a unified picture of rapid solution, but of moderate intensity. Sodium at the Arctic site is assumed to be wholely atmospheric and to result from proximity to the sea. Clearly the high calcium values in melt waters indicate weathering of the calc-schists and impure marbles which outcrop at the site. The three alpine melt-water sites exhibit a trend of increasing solute load with increasing distance travelled underground. This statement, however, is based on careful surficial examination and not upon tracer studies (Thorn, unpublished).

Table VI. Solutes (p.p.m.) from precipitation, snow-pack, and melt waters at the Arctic site

Sample	*Ca*	*Mg*	*Fe*	*K*	*Na*
Rainfall	0	0.006	0	0	0.208
New snow	0.072	0.03	0	0.75	0.729
Snow-pack at 1 m depth	0.192	0.138	0	0	1.66
Waterfall, gully top	4.1	—	—	0.4	0.55
Melt water below rockband 1	7.6	0.72	0	1.8	0.833
Melt water below rockband 2	4.35	—	—	0.7	0.55
Melt water below wall (section 10)	4.8	0.42	0	1.05	0.469

TABLE VII. SOLUTES (p.p.m.) FROM SNOW-PACK AND MELT WATERS AT THE ALPINE COLLUVIAL SITE

	Aluminum			*Silica*			*Total hardness*			*Total dissolved solids*		
	n	x	s	n	x	s	n	x	s	n	x	s
Dirty snow	18	0.11	0.14	18	0.10	0.31	17	2.00	3.39	18	5.27	4.03
Zero readings*	9			16			11			0		
Clean snow	16	0.08	0.00	16	0.12	0.33	15	1.20	2.36	16	3.53	2.60
Zero readings*	8			14			11			0		
Melt-water sites												
X1	23	0.20	0.10	23	6.69	1.25	23	20.86	8.23	23	26.54	1.42
X2	19	0.18	0.10	19	4.36	0.75	19	12.94	3.96	19	15.43	1.47
X3	26	0.19	0.10	26	2.03	0.76	26	7.53	5.63	26	6.48	2.34

Note: n = number in sample, x = sample mean, s = sample standard deviation.
* Zero readings indicate the number of occasions when the specified material was absent.

Microscopic examination of thin sections from Arctic bedrock samples showed staining indicative of chemical weathering. Furthermore, surface staining was widely evident in the field. A comprehensive mapping of weathering rind thickness on surficial debris was undertaken at the alpine colluvial site (Thorn, 1975). It revealed a distinct hiatus between the nearby snow-free control site and the snow-patch. Rinds were two to three times thicker within the confines of the nivation hollow, and showed distinct peaks in zones where melt-water concentration was apparent.

Analysis

Overall data suggest that snow-patch sites exhibit high regional relative rates of chemical weathering, although these may be low by absolute world-wide standards. On *a priori* grounds melt waters are likely to be inefficient in comparison to rainfall. Snow-fall is concentrated in a chemically inert state (there being no geomorphic equivalents to sheet-wash and through-flow during concentration of the snow-pack), and then released over a small portion of the landscape. This simple reduction in water–ground surface-area contact is probably the major contributor to reduced chemical weathering-rates. Certainly ground-surface temperatures quickly enter Tamm's (1924) +2 to +15°C range after melt-out.

A final point is consideration of the relative importance of mechanical and chemical denudation. A ratio of approximately one to one was determined at the alpine colluvial site, which suggests that while chemical rates may be low in absolute terms, it is possible that mechanical rates have traditionally been overestimated.

MASS WASTING

Traditionally, the mass-wasting component of nivation is assumed to be dominated by solifluction. Overland flow is normally assigned a secondary role, although McCabe (1939) found no evidence of its presence. Unfortunately, the present studies provide little common ground for discussion.

Hall (unpublished) undertook qualitative investigation of the transport role of sub-snow overland flow and rivulets. He found anastomosing networks on unvegetated surfaces, which apparently shifted too frequently to permit entrenchment. On vegetated surfaces small channels became entrenched and exhibited a dendritic pattern. Particles up to coarse sand sizes were observed moving and upon melt-out sinuous ridges of fines were observed; presumably marking the locations of sub-snow channels, or transport on the snow surface.

At the alpine colluvial site, groups of miniature sediment traps were set so that they lay beneath the snow patch during the winter (Thorn, 1976). Sediment totals indicated some sub-snow transport, but a distinct peak occurred shortly after melt-out. Overland flow was dominant within a 5–10 m distance down-slope of the retreating snow margin or for a maximum of 3–7 d after melt-out. Particle sizes up to granules were transported, but competence was commonly limited to coarse sand. Within the nivation hollow sheet-wash transport-rates were one to two orders of magnitude higher than on the nearby snow-free control site; rates appeared to be independent of slope and dependent dominantly upon overland flow frequency. At a subsidiary colluvial site a continuous vegetation mat prevented overland flow, except along a frost crack.

The combined processes of frost creep and solifluction produced down-slope movement which averaged 0.02 m year^{-1} in the top 0.35 m of the Arctic debris surface. Even a sparse vegetation cover depressed the zone of maximum movement to depths of 0.05 to 0.10 m below the surface. Movement of Rudberg Pillars clearly established the presence of discrete shearing and irregular variation of movement with depth. Rates of movement were moisture, rather than slope, dependent.

A variety of other movement processes were examined at one or both sites. Snow-pack creep (Thorn, unpublished) and deflation of the unvegetated area after melt-out (Hall, unpublished) were both verified as present, but are not considered quantitatively significant. Rock fall across the Arctic snow-patch was common, although it is not possible to establish this as a nivation process *per se*.

Analysis

It is not possible to make direct comparison of the relative importance of overland flow and solifluction, either on an intra- or inter-site basis; however, some synthesis of the data may be attempted. Hall (unpublished) postulates a temporal shift in which overland flow or solifluction dominates, with overland flow dominant upon melt-out, but giving way to solifluction as the ground thaws. This may be coupled with the observation from the alpine site that solifluction lobes were generally absent from the unvegetated core area of the nivation hollow, more common at the partially vegetated down-slope margin of the hollow, and most common in a continuously vegetated zone at the extreme down-slope margin of the snow-patch. Such a sequence appears to be a spatial analog of Price's (1974) model of the self-limiting growth of solifluction lobes. Lobes grow thereby providing sheltered sites on their down-wind side which promote snow-patch development, as the lobe continues to extend so does the snow-patch; eventually the snow-patch is so large and its melt-out so belated that vegetation is precluded. At this time solifluction is superseded by overland flow and the lobe eroded.

Both temporal and spatial shifts are envisaged for the interrelationship between overland flow and solifluction. Where a continuous vegetation cover is present solifluction, dominates at all times because overland flow is all but absent. When vegetation is discontinuous or absent overland flow predominates immediately after melt-out but gives way to solifluction when the snow-patch no longer supplies adequate moisture. In the unvegetated, or sparsely vegetated zone, dominance by overland flow or solifluction is dependent upon the duration of overland flow versus the rapidity with which thaw penetrates and thereby limits solifluction. Temporally, overland flow precedes solifluction regardless of the relative importance between them. This entire picture is undoubtedly refined by the texture of the fine material available (a characteristic which may change through time as fines are transported). As overland flow is a more rapid process than solifluction, temporary storage is likely along the transition zone where overall domination by overland flow gives way to overall domination by solifluction. This phenomenon, plus the concavity associated with overland flow as compared with the convexity associated with solifluction, probably accounts for the marked low-angle apron zone immediately up-slope of a distinct convexity which is commonly found at the down-slope margin of nivation hollows.

Conclusions

These two process studies may be contrasted with the largely reconnaissance and morphological studies which produced the traditional view of nivation. As such they indicate that the concept merits further attention and some fundamental reappraisal.

First, a caveat is appropriate: nivation is not a concept which is ever likely to be constrained by a precise definition. It appears that geomorphic processes associated with a snow-patch vary in absolute terms (presence or absence of individual elements), in the relative importance of individual processes, and that both absolute and relative characteristics vary temporally at and between sites. Therefore, the term nivation should be accepted as an imprecise concept and attention focussed upon the role of snow as a driving mechanism for individual geomorphic processes.

Chemical weathering is clearly important at all snow-patches, its relative importance is very high and it may attain significant levels by world-wide absolute rates. Bedrock and surficial colluvial temperatures may be quite high during exposure to melt waters and therefore exhibit rates of chemical weathering which seem inappropriate to what is intuitively considered to be a cold environment. Conversely, snow melt waters would appear to be inherently less efficient than an equivalent amount of rainfall because they are in contact with a smaller portion of the landscape for a shorter period.

Mechanical weathering is probably controlled by bedrock porosity. If porosity is such that the rock weathers by wetting and drying cycles the significance of the snow-patch is reduced. This is because such rocks saturate from high humidity conditions alone, and do not require addition of "bulk water" (Hudec, [1973]). Rock with porosity appropriate to freeze–thaw weathering will experience optimal conditions in association with some sort of snow cover. Available data suggest that the relative mixture of seasonal freezing amplitude, seasonal snow-cover insulation and seasonal radiation receipt may produce a bewildering array of freeze–thaw weathering intensities. Some salient points do emerge from the present studies.

Fall periods which exhibit late establishment of the winter snow-pack preceded by frequent temporary accumulations probably produce optimal freeze–thaw-cycle weathering conditions. A secondary peak is likely to occur in early spring on those sites which have southerly and easterly aspects and melt-out at that time. Aspect is probably as important as snow cover in maximizing freeze–thaw weathering. Indeed, data herein may be interpreted as indicating that shallow snow accumulations, and not deep ones, are optimal for freeze–thaw weathering. The widespread idea that freezing and thawing is frequent immediately beyond a retreating snow-patch margin is not supported by the field data. Combination of available laboratory data and freezing patterns reported herein produce a conundrum. Apparently micro-environments exhibit critical shifts across laboratory defined thresholds; however, until temperature–moisture interaction during freezing is precisely known, freeze–thaw weathering remains a topic for conjecture.

The mass-wasting role of snow-patches is a much simpler topic than their role as weathering agents. A realistic view requires the integration of overland flow and solifluction in a spatially and temporally shifting symbiosis when the snow-patch precludes a continuous vegetation cover; where it does not, solifluction prevails. The transport of fines by overland flow from unvegetated core areas to peripheral, vegetated areas enhances solifluction by delivery of particle sizes most susceptible to the process.

Secondary transport mechanisms are present at snow-patch sites, although they appear to be of limited quantitative importance. The exception, at some sites, is rock fall across the snow-patch surface, but it is extremely difficult to establish that rock fall from a high cliff is directly related to the erosive action of the snow-patch at the base.

Snow-pack mobility, with associated basal stresses (Costin and others, 1973), and an appreciation of the limited worth of the nivation concept would seem to place snow geomorphology into closer proximity with glacial geomorphology; while the intensity may vary dramatically it is difficult to identify a threshold which separates the two geomorphically. Perhaps weathering-limited snow-patch sites and glacial sites are more readily distinguished from transport-limited snow-patch sites than anything else. Possibly the glacial environment is geomorphically dominated by mechanical processes, rather than balanced between mechanical and chemical processes, or showing chemical bias, as in the snow regime. It appears that the situation will be most successfully resolved by comprehensive work on individual processes and abandonment of the collective term "nivation"; although "nivation" might be resurrected if a more substantive definition is possible. Certainly the greatest effort must be directed toward identification of the precise mechanism(s) responsible for freeze–thaw weathering.

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