BUDD: There has been considerable longitudinal strain from the inland ice sheet to the Lambert Glacier. This would thin the cold isotope layer substantially so that the considerable melt expected while travelling down the Lambert could then remove it.

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THERMO-PHYSICAL CHARACTERISTICS OF GLACIERS—TOWARD A RATIONAL CLASSIFICATION

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ABSTRACT. Forty years ago, Ahlmann considered the thermo-physical character of ice masses as a basis for differentiating glaciers into two broad geophysical groups: (1) *polar* and (2) *temperate*. About the same time, Lagally sub-divided glaciers into corresponding thermodynamic categories: (1) *kalt* and (2) *warmen*. By this it was understood that the temperature of a polar, or "cold", glacier was perennially sub-freezing throughout, except for a shallow surface zone which might be warmed for a few centimeters each year by seasonal atmospheric variations. Conversely, in a temperate, or "warm", glacier, the temperature below a recurring winter chill layer was consistently at the pressure melting point. As these terms are thermodynamic in connotation, glaciers of the polar type may exist at relatively low altitudes if their elevations are sufficiently great. Temperate glaciers may be found even above the Arctic Circle at elevations low enough that chilling conditions are not induced by the lapse rate.

In these distinctions, it is implied that regardless of geographical location a glacier's mean internal temperature represents an identifiable characteristic which can be shown critically to affect the mass and liquid balance of ice masses and significantly to relate climatic influences to glacier regimes. The importance of these implications, and the fact that they are based on a gross, sometimes changing, and always difficult to measure, thermo-physical characteristic, makes some explicit terminology desirable.

To some extent Ahlmann addressed this problem by introducing a subordinate classification, *sub-polar* glaciers. In these, the penetration of seasonal warmth involved only a shallow surface layer at 0°C, but still to a depth substantially greater than the superficial warming experienced in summer on polar glaciers. Lagally also recognized an intermediate type which he called "transitional", characterized by a relatively deep penetration of 0°C englacial conditions during the summer. These pioneering efforts reflect Ahlmann's experience with glaciers in the high Arctic and Lagally's with the Alpine glaciers of southern Europe. Although some confusion has resulted from alternate application of these different terms, both definitions can be useful. Further to refine the classification, a modified terminology is suggested by the writer. This involves introducing a fourth category, substituting the term *sub-temperate* for Lagally's "transitional" type on the basis that it is etymologically more consistent with the

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Ahlmann terminology which has remained most commonly in use. Thus, two distinct transitional categories are identified. These categories, sub-polar and sub-temperate, typify ice sheets during changes from fully polar to fully temperate englacial conditions—a situation pertaining during the waning and waxing stages of deglaciation and reglaciation.

A review of the literature reveals further problems. Flint and others have considered geophysically temperate glaciers as most typical of the inland glaciation which covered much of Europe, northern North America and Siberia during the expanded phases of the Pleistocene, whereas others including Ahlmann have suggested that the massive continental glaciers of the Pleistocene were geophysically polar. Thus, the latter advocates consider that present-day Antarctic and Greenland ice sheets represent conditions comparable to those which pertained in the Laurentide and Cordilleran ice sheets. New insights have developed, however, through deep drilling and englacial temperature measurements carried out in a number of different geographical locations in recent years. Such research has shown that each of the geophysical categories can pertain in a glacier system if there is sufficient range of latitude, area and elevation for the requisite climatological factors to pertain.

Because of the foregoing considerations, it is probable that *polar*, *sub-polar*, *sub-temperate* and *temperate* thermal conditions coexisted in different parts of continental glaciers during the Pleistocene maxima. At times of greatest extension, the ice sheet's peripheries could have been thermo-physically polar and sub-polar, as on the margins of today's Greenland ice sheet. But in their most regressive phases, the lower latitude margins were more than likely temperate, with only high interior sectors remaining "cold". Such combined conditions characterize a fifth thermo-physical category, which in the geophysical sense may be termed *polythermal*. To some extent all glaciers are polythermal, except in the final wasting temperate phase when they are fully isothermal.

To elucidate the characteristics of each of these five categories and to identify prototypes with suggested thermal parameters, selected field studies on existing glaciers are discussed and thermal measurements and characteristics illustrated. From the sampled data, arbitrary englacial temperature limits are suggested: for the main body of *polar glaciers* (-10 to -70°C); for *sub-polar glaciers* (-2 to -10°C); for *sub-temperate glaciers* (-0.1 to -2°C); for *temperate glaciers* (in summer, 0°C throughout); and for *polythermal glaciers* (a range across at least two of the foregoing temperature zones). The significance of thermal anomalies, temperature sandwich structures, diagenetic ice zones, and measured shifts in thermodynamic characteristics over a number of years are considered as they aid in the interpretation of ice morphology, glacier regimes, and climatic change.

Type thermo-physical examples are briefly compared from the following areas: the Antarctic and Greenland ice sheets (polar and polythermal), the Nepal Himalaya, Svalbard (polar to sub-polar), Lapland (sub-polar), sub-Arctic Norway (sub-temperate), the Alps (polythermal to temperate), the Canadian Rockies (sub-temperate), the Juneau Icefield, Alaska (sub-temperate to temperate), the Alaskan–British Columbian coast (temperate), glacier systems on Mount Rainier, Washington State (polythermal), and icefields in the St Elias Mountains, Yukon Territory (temperate to polythermal).

The relationship of thermal anomalies is clarified and illustrated within the defined framework of each category. It is noted how these are manifest by deformation irregularities, differing salinities, and varying heat capacities within the ice. Also discussed is the relationship of changes in thermo-physical characteristics to the sensitivity of ice flow, revealed by changes in entropy and negentropy of glacier systems and by observable shifts from *parabolic* to *rectilinear* to *surging flow*. Finally considered is the long-term implication of secular changes in climate and their influences on englacial thermal regimes which affect the hydrological capacity and fluvial discharge of glaciers as well as their terminal fluctuations. The strong interdependence of all these factors and the total systems analysis which they represent underscore the mandate for a rational thermo-physical classification of glaciers.

DISCUSSION

J. W. Glen: I recognize that there are great complications in special cases; however, there are situations which are different from each other and for which it is worth finding a terminology to express the difference, as is the case for polar, sub-polar and temperate glaciers. This is surely helpful (e.g. for school textbooks). Just because there are blurred boundaries we do not cease to use the concepts of solid, liquid, and gas (for example, because such things as bouncing putty exist)!

For our purposes, however, it seems undesirable to try to categorize a large glacier which has various zones. Is it not better to follow Benson and discuss *facies* so that one glacier has various facies at various levels—and may have relics of other facies deeper down?

M. M. Miller: Thank you for your comment that blurred boundaries need not preclude generalization of categories. As for the *polythermal* category, it is suggested only for general reference, and specifically in cases where insufficient information is in hand to delineate facies. Certainly the *polythermal* term must connote the existence of thermal or even water-content facies, and in the definition this should be well explained.

If we back up for a moment and look at this in a broader context, we can be reminded that the facies concept has been widely applied in geology, especially stratigraphy, for the handling of lateral, and to some extent vertical, changes in the lithologic character of sandstones, shales, limestones, etc. Such facies changes have considerable environmental significance with respect to provenance of the clastics involved. So, traditionally, I have had little difficulty in applying the environmental rationale to the thermal and physical "stratigraphy" of glaciers. Therefore, as in geology where the recognition and classification of rock facies do not vitiate reference to the main lithologic unit, why not in glaciology use a term which is applicable to the whole glacier unit, especially if one of our other suggested categories does not readily apply? In other words, if there is not a *dominantly polar* or *dominantly temperate* situation, call it *polythermal*, with all of the environmental, geophysical and orographical connotations. Such an application would simply recognize that indeed the unit comprises a *whole system of facies*, which actually is quite complex. (The separate identification of facies would then be left as a study in itself.) Perhaps one refinement could be to apply the *polythermal* terms only to those cases which bridge the full range from polar to temperate, and not use it where the thermal range is less.

Again the aim has been to suggest a relatively simple classification, one which tries to remain consistent with previous terms yet which hopefully succeeds in identifying the dominant thermal character of the glacier system *as a whole*. If complications and uncertainties do not warrant this, then of course the segmental or facies concept could be more rigorously applied. And so the plea is not to overcomplicate the situation but, instead, through a rationally induced classification, to improve communication between scientists on these seemingly simple but at heart rather complex matters.

L. Lliboutry: We need different classifications according to the goal in view. (For instance for case histories, an alphabetical classification would be the best one.) Thus I favour two distinct classifications: one, for studies of mass balance, relations with meteorology, etc., according to the thermal conditions in the firn (as developed by Shumskiy, F. Müller and others, etc.); and another, for glacier dynamics, where the bulk of the glacier (not the firn or a superficial thin layer getting cold in winter) is considered; namely, a temperate glacier with liquid water in it, and cold glaciers with a cold glacier–bedrock interface (no sliding), with a glacier–bedrock interface at the melting point, and with a temperate layer at the bottom. (I doubt whether this last case is Lagally's transitional glacier.)

Miller: There certainly may be merit in some kinds of climatologically related studies to consider the firn pack as a separate entity from the main underlying mass of glacial ice, but I have endeavoured to avoid invoking unusual complications in the terminology. Instead, I have followed the idea of a classification which can connote *mutually affected* characteristics of both the firn pack and its underlying ice as a stress-influenced *total system*. (The stress here could be climatological or kinetic, or both.) As for strict considerations in glacier dynamics the main interest would be in deformation and mass transfer of the deep ice. I believe that the suggested classification does indeed lend itself to this, with any pertinent subsidiary characteristics, say in the bottom zone, being best considered not by single terminology but by appropriate modifying comments to be appended to the framework categories of the suggested classification.

G. K. C. Clarke: I would like to speak on behalf of preserving a certain vagueness in terminology. It seems to me that the use of highly specific terms to describe the thermal structure of a glacier can be abused to imply that you have more information than your measurements support.

Miller: I agree, to the extent that the classification which I have discussed does retain a certain desired looseness. As for implying more information than one has, this danger is implicit in the use of any descriptive phraseology. There will always be a need for scientific integrity in any reporting endeavour. But I am not too concerned about the danger of muddying the scientific waters too much here because after all the presentation of facts is what is judged. Perhaps if we are not sure at all of what the thermal character of a glacier system is we could indeed call it "crypto-thermal"!

THE SPEED OF GLACIERIZATION OF CANADA DURING THE WISCONSIN ICE AGE

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Abstract. A three-dimensional, time-dependent numerical model of ice sheets, developed by Mahaffy (unpublished), has been applied to the general problem of the speed of ice-sheet inception and development over Canada during the last major glaciation. Ice sheet development is assumed to begin due to a lowering of the equilibrium-line altitude with a resulting increase in the accumulation over Baffin Island and Laborador in Canada. This leads to the development of large snow fields over the high plateau areas of this region. Preliminary results are given for the areal extent and the water volume of the ice sheets possible after a period of 10 000 years from the initiation of glaciation.

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DISCUSSION

J. W. Glen: How was the sea-level change calculated? Did you assume no changes in ice volume anywhere else in the world?