ENTROPY AND THE SELF-REGULATION OF GLACIERS IN ARCTIC AND ALPINE REGIONS

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Everything tends toward reconciliation (T.S. Eliot)

INTRODUCTION

The geomorphologist working in arctic-alpine areas is often confronted with problems concerning present or past glaciation which require appreciation of the dynamics and the physics of glacier flow. These subjects involve the rigorous mathematical approach of the engineering and materials sciences in which many geomorphologists have not been especially trained. Similarly, the ice physicist and materials science engineer have not usually been exposed to the total systems geological and environmental outlook which geomorphology represents.

For this reason, it is appropriate to consider some basic principles shared by these disciplines toward a clearer understanding of field problems. Such an overview suffers the danger of boring some and confusing others but, because of its geomorphic implications, it may kindle a feed-back to the theoretician and assist him in establishing more helpful mathematical models.

This paper will attempt to consider these needs and pose some special geomorphic and glacio-climatological questions.

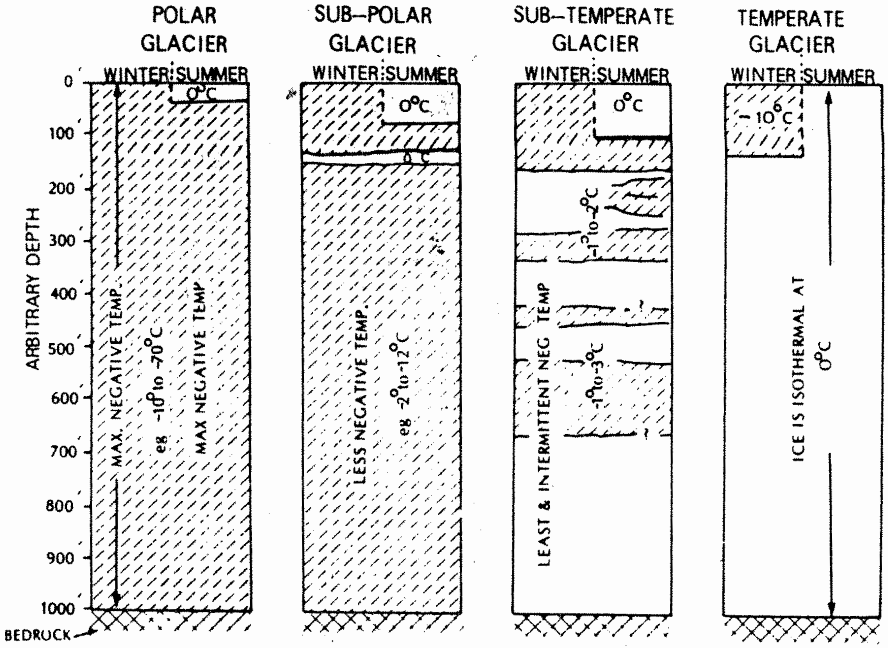
THE MODULAR APPROACH

The writer appreciates that it is impossible to prove any fact in nature just by eludicating first principles. Too many variables affect the processes of evolution along the way. But in the field of geomorphology, some anomalous relationships in the broadest sense may be seen not as inexplicable mysteries, but rather as phenomena which are integral parts of a total unit and represent necessary repetitions in the normal evolution of a mass-energy system.

Investigations in glaciology in recent years have revealed the complexity of glacier behavior, particularly in the arctic or high alpine areas where geophysically Polar conditions pertain. Glaciothermal Polar or sub-Polar ice, as depicted in the classification chart (Figure 1), is less responsive to load stress changes than Temperate ice because of the great sensitivity of creep rates to changes in englacial temperature, especially when close to the freezing point. This relationship is well illustrated by the tabulation of load-temperature effects from Glen's early (1955) laboratory experiments, which show that in the power law of glacial flow $\dot{\epsilon} = \kappa\tau^{n}$, the minimum rate of strain ($\dot{\epsilon}$) of ice under constant stress (τ, i.e. 6 kg cm^{-2}) varies with the temperature (τ) in the ratio:

t	$\dot{\epsilon}$ as a proportion of the value at 0°C.
-1.5°C	13.5%
-6.7°C	4.7%
-13.0°C	1.0%

From this we see that at an ice temperature of only -1°C, the flow rate may be expected to be reduced to approximately 1/5 that expected at 0°C. At about -10°C the internal creep should be less than 1/25 of that



ARBITRARY DEPTH AND TEMPERATURE VALUES CITED IN EACH CROSS–SECTION AS SAMPLES TO SHOW SEASONAL VARIATIONS

NOTE THAT CROSS–HATCHED SECTION CONNOTES "COLD" SUB–FREEZING ICE: WHEREAS PLAIN SECTION DENOTES "WARM" (0°C) ICE.

FIGURE 1. Thermal classification of glaciers.

under the same stress at 0^oC. With these proportions pertaining under conditions of unchanging stress, they should be considered only qualitatively. For example, because the heat of deformation cannot escape from the interior of a Temperate glacier, it may be generally assumed that there is local melting with a consequent weakening of crystal structure. It follows that the flow behavior of glaciers will depend somewhat on its flow history which, in turn, suggests that one field case may not be directly comparable with another. This is one of the difficulties in relating mathematical models formed on a set of simplifying assumptions. And it is one of the reasons why probably no field case will ever exactly agree with a modular explanation.

ENERGY LEVELS AND MODES OF FLOW

In a general systems analysis of the normal behavior of glaciers, the term "normal" needs to be defined. For our purposes, parabolic and rectilinear flow (plug or Block-Schollen flow) are included in the "normal" range. "Anomalous" or "abnormal" flow involves surging glaciers and the possibility of kinematic waves. Surges relate to catastrophic and often chaotic glacier advances and kinematic waves to a theoretical concept of spontaneous energy release through a glacier system up to 100 times as fast as normal mass discharge (Weertman, 1951). In terms of the increased energy levels involved, these categories provide a sequence not dissimilar to the flow stages in fluid (stream) dynamics, i.e., from low velocity *laminar flow,* to *streaming flow* (the low-velocity range of turbulent flow) to high velocity plunging or *shooting* (catastrophic) *turbulent flow.* The latter has a limiting critical maximum velocity of 23.4 m/sec., above which all extra free energy ceases being used in the work of transportation and converts to the work of erosion. Figure 2 is a diagrammatic representation of the glacial and fluvial categories, comparing the respective intensities of energy in each mode.

That some glaciers experience seemingly "abnormal" surges was first observed by the writer while involved in a regional Alaskan glacier study in 1946–48. While surveying the glaciers of Yakutat and Icy Bay in the St. Elias Mountains, he found evidence of catastrophic, sudden-slip glacier flow and abnormal increases in crevassing even on glaciers whose termini were retreating (Miller 1948, 1958). This situation had been well documented in that region by Tarr and Martin (1914) while engaged in a similar National Geographic Society survey some 60 years ago. Glaciologists have now become very concerned about the scientific implications of this phenomenon, usually referred to as "surging" flow.

Recently several authors have mathematically analyzed the theoretical conditions involved in glacier surges: Nye (1963, 1965, 1969, 1971); Weertman (1962); Campbell and Rasmussen (1969), Robin and Barnes (1969), Robin and Weertman (1973). Others have attempted to relate or otherwise apply theoretical conditions to field cases: e.g., Post (1960), Meier and Tangborn (1965), Meier and Post (1969), Kamb (1970) and Miller (1973).

FLOW DYNAMICS AND ENTROPY

The most appropriate attempts to explain the behavior of cold ice (Polar) as an elasto-plastic material (Temperate ice may be defined as visco-plastic) are in the realm of continuum mechanics and involve the establishment of stress-strain models in mass-energy systems in which

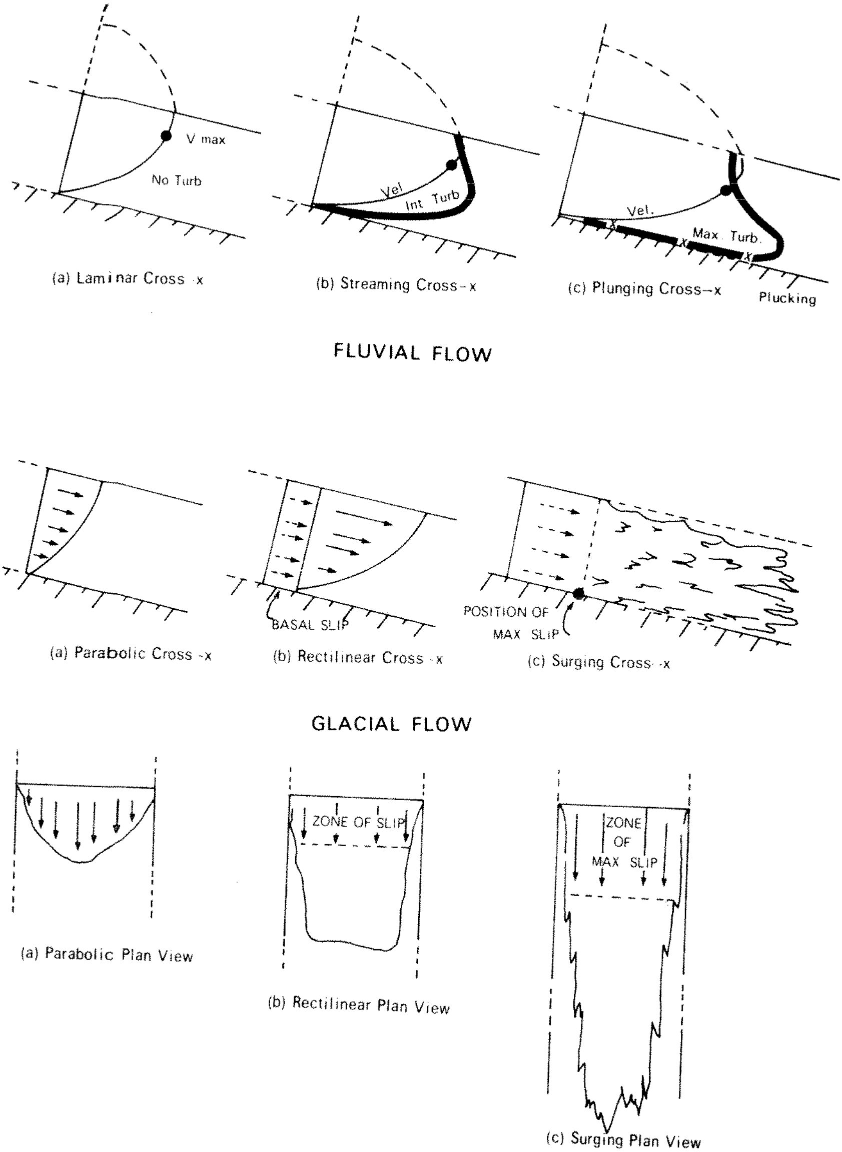


FIGURE 2. Comparison of energy levels in fluvial and glacial systems.

equilibrium conditions can be identified and described and appropriate equations of equilibrium invoked. Divergences from equilibrium, if they are to be analyzed mathematically, necessitate instability solutions, using constitutive equations and the mathematical framework of appropriate boundary conditions for the particular material involved.

An empirical approach can also help by relating actual field information to the modular concepts. The systemic approach also includes the second law of thermodynamics and the concept of entropy. These involve consideration of the energy distribution in an open mass-energy system which, in the process of dynamic natural self-regulation, is constantly striving towards equilibrium. In this a glacier is an excellent prototype, as is also a river. The *first law of thermodynamics* states the principle of conservation of energy when heat is involved, while *the second law,* in its simplest interpretation, states that in every natural system, when the full system is considered (i.e., treated as an isolated or closed system), there is an increase in entropy signifying a corresponding decrease in available energy for useful work. Thus, whatever work is put into a system becomes, in effect, negentropy.

The essentiality of this increase in entropy leads to the *irreversibility* of the process. Although by the first law total energy cannot be destroyed and, in fact, remains constant (straight line at top of Figure 3), the rate of entropy increase in the system serves as an index of its irreversibility. This rate can start rapidly and diminish, start slowly and accelerate (as noted in the upwardly convex and concave heavy line curves depicting entropy in Figure 3), or can achieve a variety of other variations during the course of the system's regime; but it can never reverse. Corresponding to the entropy curves, but with opposite trends, are the negentropy curves idealized in the figure as representations of changes in available free energy. These should not be considered as mirror image curves, other than in a graphical sense, because the first law connotes that energy cannot be destroyed, whereas entropy can be. Theoretically, in an isolated system, entropy (hence also negentropy) can remain approximately constant and still satisfy the second law, such a condition connoting stability. The extent to which order or stability is present in the system represents its level of entropy. As hinted above, entropy may be discharged although never via a step-by-step reversal. Because of the irreversibility principle, "reductions" in entropy, even minor ones, must derive from an appropriate spontaneous process or sudden change which frees energy again to be applied to stabilization of the system. If this change is large it can appear to be catastrophic (right hand termination of curves in Figure 3). This illustrates how entropy, unlike energy, is not conserved. The inferences are fascinating with respect to glaciers, but to be sustained they must be verified by field observations and tests. The approach involves a critical view of fundamental philosophical and scientific premises relating to all processes in geomorphology.

The second law, because it is derived from what, in effect, are theoretically closed thermal systems, is not easily applied to glaciers because here mechanical energy (the kinetic category) is involved. Its application to open geomorphic systems, however, has been defended on empirical and heuristic grounds by Leopold and Langbein (1962). It has been shown by Scheidegger (1970) that this application has deep significance and is justified "because the statistical basis for both systems is the same". Scheidegger considers that when a system linearly combines fluctuating components, and when a

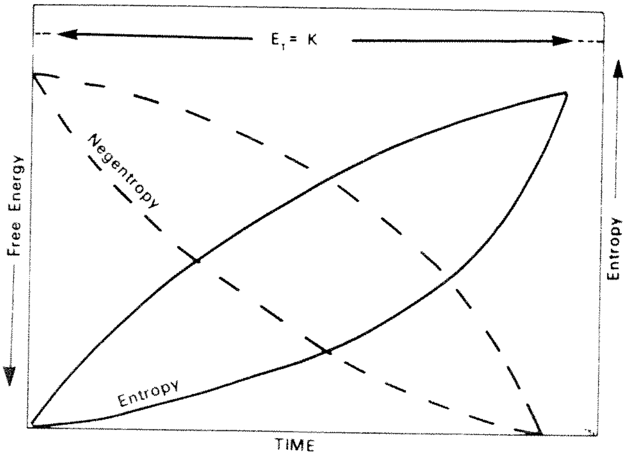


FIGURE 3. Idealized representation of entropy and negentropy showing significant rate curves in total time.

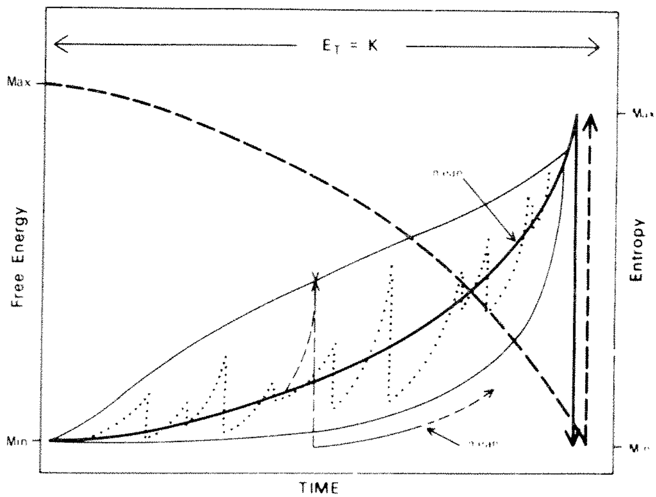


FIGURE 4. Self-regulation within positive and negative boundary limits prescribed for an ideal system in which entropy increases to maximum.

TABLE 1

Various terms defining system characteristics at idealized entropic levels

LOW LEVEL	INTERMEDIATE LEVEL	HIGH LEVEL
Irregular distribution of energy	Regular distribution of energy	Nearly perfect regularity in distribution of energy, but prime for change
Rapidly decreasing instability	Stability	Tending to instability
Imbalance	Dynamic balance	Tending to imbalance
Disequilibrium	Dynamic equilibrium	"Unstable" equilibrium
Low sensitivity	Intermediate sensitivity	High sensitivity, fragility
High level of internal energy, optimum available free energy	Intermediate level of internal energy	Low level of internal energy, least available free energy; ready for release of maximum free energy
Inefficient	Dynamically efficient	Overly efficient (delicate)
Disorder and randomness	Order	Nearly perfect order; high potential for spontaneous disruption and decay, toward disorder and randomness
Low potential energy	Strong mechanical energy (potential plus kinetic)	High potential energy
Low kinetic energy	Intermediate kinetic energy	High gain in kinetic energy

ck

certain quantity of available energy is a non-negative constant of the motion, the energy quanta are distributed among the components when the system is in equilibrium. When conditions do not lend themselves to equilibrium (assuming linear regression of the fluctuations) this energy is diffused with a symmetric diffusivity tensor. From this, Scheidegger defines corresponding entropies (S) of thermodynamic and geomorphic systems in accordance with the equation $dS = dQ/T \longleftrightarrow dM/h$. In this, Q is the quantity of heat energy, T is the temperature in Cartesian coordinates (x,y), M is the mass involved and h is the height (x,y) of the geomorphic feature above a designated base level. This follows from the analogs suggested by Leopold and Langbein that $T \longleftrightarrow h$ and $dQ \longleftrightarrow dM$. In other words, even though closed systems cannot exist in the actual world of nature, concepts derived from their analysis can be useful in developing potential energy and mass analogs which are helpful in understanding why certain process changes take place in the ever present open systems in nature.

Thus, in applying the second law to glacier systems, *entropy is seen as a function of availability and distribution of energy and not as a function of the total energy in the system.* It therefore relates to the degree of order or disorder which the system expresses and hence to the probability or improbability of the observed state. As Brilbuin has pointed out (in Leopold and Langbein, 1962, citing Bell, 1956, p. 159):

> *Entropy and probability are practically synonymous for the physicist who understands the second principle of thermodynamics as a natural tendency from improbable to more probable structures.*

Stated in another way, the relationship expresses the degree of stability or instability of a system and hence its equilibrium or disequilibrium. Some define this as the extent of order or disorder in a system or the regularity or irregularity of its energy distribution. These and various other expressions which describe system characteristics at different entropic levels from minimum to maximum (Figure 3) are presented in Table 1.

DYNAMIC SELF-REGULATION

Although a few of the descriptive characteristics in the above tabulation are somewhat synonymous, they represent sufficiently different shades of meaning to warrant use. In later discussion, application of the alternate terms in selected situations will become clear. For example, the intermediate to high entropy characterized by *dynamic equilibrium* indicates more than a simplistic balance. It involves continuing minor reductions in entropy as organized adjustments take place in response to short-period stress acceleration within a system. This kind of pattern is represented by small-scale interruptions in the entropy curve in Figure 4. Only in this way can the amounts of energy and mass stored within a system, and the rates at which energy and mass enter and leave, remain constant with time. Such a system is in a *steady state.* It is dynamic because the affecting quanta are constantly being transported and transformed, absorbed or released. Whenever the input or output rates significantly change, the system strives to achieve a new dynamic equilibrium, toward *a new steady state.* This helps us to appreciate how a glacier can experience different levels of mass-energy storage and why small glaciers may return to equilibrium more quickly than large ones. Because their storage capacity is less, they are more sensitive to changes in input, a complication which can also affect periodicities in their energy regime.

The maximum state of entropy is equated to the state of a full-blown balloon just before it bursts . . . or a glacier as it is about to surge. The prime quality is fragility, a high potential for instability. Once the surge takes place, it involves transformation of the maximum potential energy of position to the maximum kinetic energy of motion. Thus, in changing the system to a disordered state, the surge shifts the intensity level to that of low entropy, with the kinetic energy becoming dissipated as the surge progresses. Because glaciers are not closed systems, maximum entropy represents the state experienced just prior to such a spontaneous change, while minimum entropy represents the state achieved after dissipation of the potential energy to produce maximum release of free energy expressed by the surge. Before total reduction in entropy occurs, free energy (since it cannot be destroyed), has been locked up and made totally unavailable. With sudden decay of the system and final release of this energy, the system's regime starts all over again from its new low-entropy state. Recurrences of this sequence take place either in a periodic fashion (cyclic or rhythmic) or in a non-periodic manner (random fluctuation). The predictability and unpredictability of this regularity and irregularity depend upon constraints in the system (Figure 5).

The large-scale decay and rejuvenation of regimes are also examples of self-regulation. Thus we must question the validity of referring to glacier surges as "anomalies", because they can be manifestations of "normal" self-regulation in the sense of dynamic open systems. In nature both rivers and glaciers combine sub-systems which may have all the characteristics of decay, and also of cyclicity and of random-fluctuation. The proportion and predictability of these characteristics should define the extent of "normalcy" in the total system. The probable relationship to changing glacial regimes and hence to climatological events is not difficult to grasp, although characteristics of a given glacier which might be representative of each entropic state are not as easily inserted into this descriptive model.

As energy is the capacity to do work, application of the concept of entropy to glacier systems involves the gain in kinetic energy within the glacier as well as on its bed. Conceptually, this can be related to the work=energy theorem $W = m\,2d = 1/2\,mv^2 - 1/2\,mv_o^2$, in which $1/2\,mv^2$ is kinetic energy, $v^2 = v_o^2 + 2\,ad$, and a is the acceleration, m the mass and d the frictional displacement. The Force (ma) and Distance (Displacement) parameters are determined by the glaciologic head (potential energy) or integrated elevation of mass above immediate base level. This can be expressed by the summation of the potential energy of all points on the glacier bed. In terms of the work to be accomplished (total force X distance), the base datum for any one point is the bed at that point. The long profile of a glacier manifests the spatial distribution of myriads of such points of mechanical energy (potential plus kinetic) throughout the system, each point having a different level of energy available for work. For the glacier, the base datum is its terminus. If the glacier is in equilibrium, there is a relatively more equal distribution of energy from point to point throughout its length . . . but with the force tensors in somewhat opposing directions above and below the névé-line. Variations in the long profile then relate only to changes in load due to accumulation and/or ablation and to those variations in bed slope which produce changes in englacial shear stress in accordance with the well-known formula: $\tau = D\rho g \sin \alpha$ where: τ = shear stress; D = primary variant depth; α = primary variant slope; ρ = ice density, and g = acceleration of gravity.

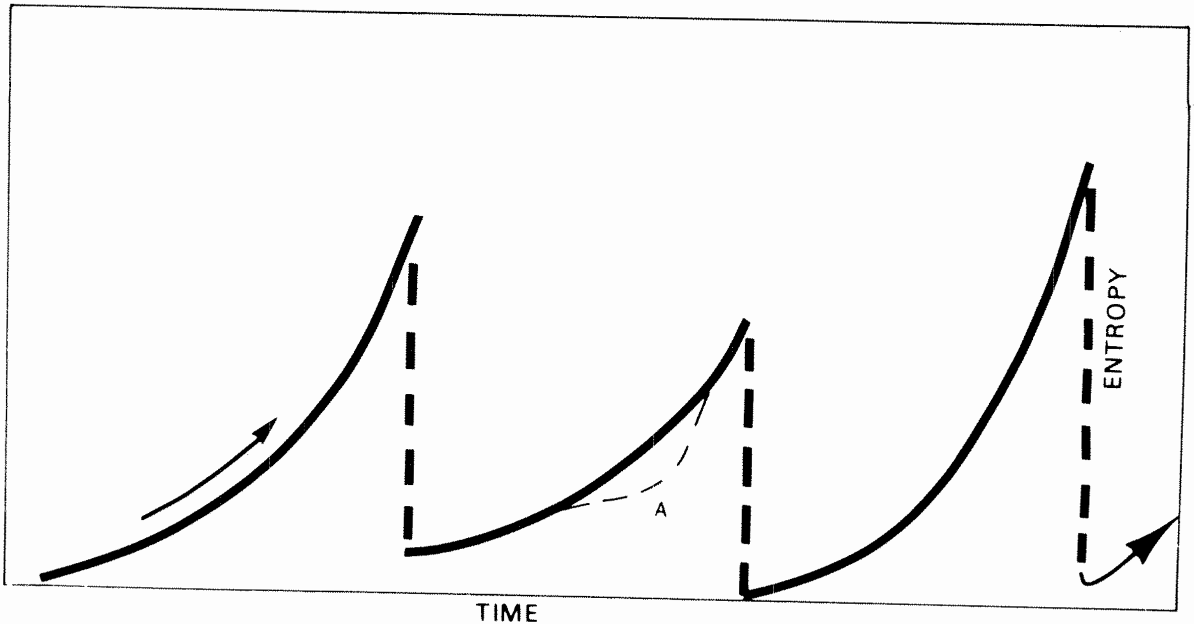


FIGURE 5. Generalized sketch of a series of rejuvenated entropy curves in a simple open system showing differing rates during successive regimes.

We can be further guided by reference to the mass-energy relationships in a *dynamically balanced river, a graded stream* that is consistently striving for a steady state in which the downstream rate of production of entropy per unit mass remains relatively constant. Such a river develops a *beautiful* sequence of meanders on the surface of the land, which by definition must be relatively flat. Fluvial down-cutting in some segments is balanced by fluvial deposition in others, the river thus adequately coping with the stresses upon it. In this "most probable state", individual meanders tend to follow sine-generated curves which ideally provide an equal distribution of energy in each segment. This also expresses the most efficient of all stream geometries and is the one for which all streams continually strive. It is the balanced condition of self-regulation in an open system in dynamic equilibrium. As the mass inputs and outputs vary each year, the stream is continuously attempting to re-distribute its energy evenly and smoothly. Unusual constraints introduced into the system, however, do render this difficult and whenever disequilibrium (unequal energy distribution) takes place there are resultant instabilities.

BOUNDARY LIMITATIONS IN GLACIER REGIMES

Instabilities characterize even well-graded systems whenever an unequal distribution of energy results from temporary increases in mass or energy through inputs which a segment of the system cannot contain. When this happens in a glacier, it too strives to adjust to these perturbations through corresponding outputs leading to development of a more efficient over-all profile. *Because of this, any segment or even a large portion of the whole* glacier may undergo necessary changes to maintain the equilibrium. Also it should be noted that a glacier, as a river, adjusts within prescribed boundary limits (illustrated by the hypothetical boundary lines drawn in Figure 4). These limits are wide during the intermediate (growing) phase, but as maximum entropy is approached the system's fragility is exposed by the narrowing of its boundary limits. Upon reverting to low-entropy, the system retains close boundary limits until the stability of intermediate entropy is achieved again.

The critical parameters are always the energy storage capacity of the ice (its "flow strength" which is a function of age, previous flow history, etc.) and the glacier's thickness. If the mass increase suddenly becomes too large for the system's usual flow capability to handle, its storage capacity is exceeded and much of the energy available for useful work ceases to be efficiently applied. Because of the irreversibility principle, this leads to instability and the spontaneous reduction of entropy, be it small or large, with the consequent release of free energy. In glaciers, small imbalances in *a part of the system can produce dislocations such as the annual* pulsations which produce seasonal and annual (washboard) moraines.

A surge exemplifies such imbalance and instability on a large scale affecting *all of the system*. It is therefore defined as a disorganized self-regulation in a total system which has come out of balance. Once this overall adjustment occurs, the ice again reverts to normal discharge with its characteristic striving for production of a constant entropy rate. The situation is comparable to sudden change-overs in a fluvial system from dry season (laminar) to temperate season (streaming) to flood season (turbulent) flow and back again to laminar flow. However, use of the common hydrological term "streaming flow" for a second energy level of flow (i.e., the lowest range of high-velocity turbulent flow in streams) may be confusing because the same term is used to describe the lowest energy level in glacier mechanics (so-called "streaming" glacier flow). To avoid such confusion, it is suggested that only the term "parabolic" flow be employed for glaciers.

COMPARATIVE ENERGY PHASES IN FLUVIAL AND GLACIAL SYSTEMS

Sketches comparing the various types of flow in fluvial and glacial systems according to the three arbitrary levels of free energy are given in Figure 2. Figure 6 illustrates progressive energy levels in fluvial dynamics and their relationship to the physical concepts of work and power. Here the equation relating velocity and the kinetic energy consumed in river transportation ($v = \frac{1}{e}$) is applied as $e = \frac{1}{v}$. If we view this through a time scale embracing dry season (minimal) and wet season (maximal) flow, we see the transformation of entropy in progressively increasing free energy released for larger amounts of work. As this work is accomplished a corresponding increase in entropy develops over shorter periods of time during which the system passes from laminar to streaming to plunging flow.

The seeming paradox of maximum entropy relating to maximum free energy is resolved by considering these as three distinct rate-characterized sub-systems, each separately obeying the laws of thermodynamics and each representing different levels of power. As power (Work/Time) is a measure of the rate of performing work (i.e., that at which energy can be placed in storage), there are critical points in each sub-system at which untapped potential energy is converted to kinetic energy. In the plunging flow sub-system (left-hand curve), the zone of maximum turbulence reaches the bed of the stream at a velocity of 23.5 m/sec. This is the critical velocity for the conversion of potential to kinetic energy, after which some of the energy of turbulence is applied to erosion. To some extent a similar situation occurs in ice during the progressive release of energy as a glacier passes from *parabolic* to *rectilinear* flow and then to *surging flow.* With respect to glacier regimes, the comparative erosive capabilities of each phase is discussed later.

A further analogy in hydrodynamics illustrates that rivers can become over efficient. When a stream's meanders develop broadly sweeping circular forms away from the tighter sine-generated curves, it cannot reverse its evolutionary steps because of the irreversibility of entropy. Thus, it drastically changes entropy by cutting itself off, leaving dried-up oxbow channels as reminders of a former evolutionary state which went too far. In a geological sense, the stream, in its "frustration", spontaneously reverts to a lower efficiency in which its energy becomes more available for work. Thereafter, by downcutting a new lateral course, it reforms its meanders until it again achieves dynamic equilibrium.

In ice, the geometric constraints are such that a glacier cannot meander horizontally. Rather, in a potentially unstable "trigger" zone, its depth increases, until concentrated energy is directed in a spontaneous manner down-valley. Here the equalizing adjustment takes place both within the system and on its bed. The "cut off" is expressed by increased fracturing, possibly the impounding of sub-glacial water (Robin and Weertman, 1973) and englacial surging. The mechanism involves simply the longitudinal stresses exceeding the ultimate strength of the ice in the glacier's basal

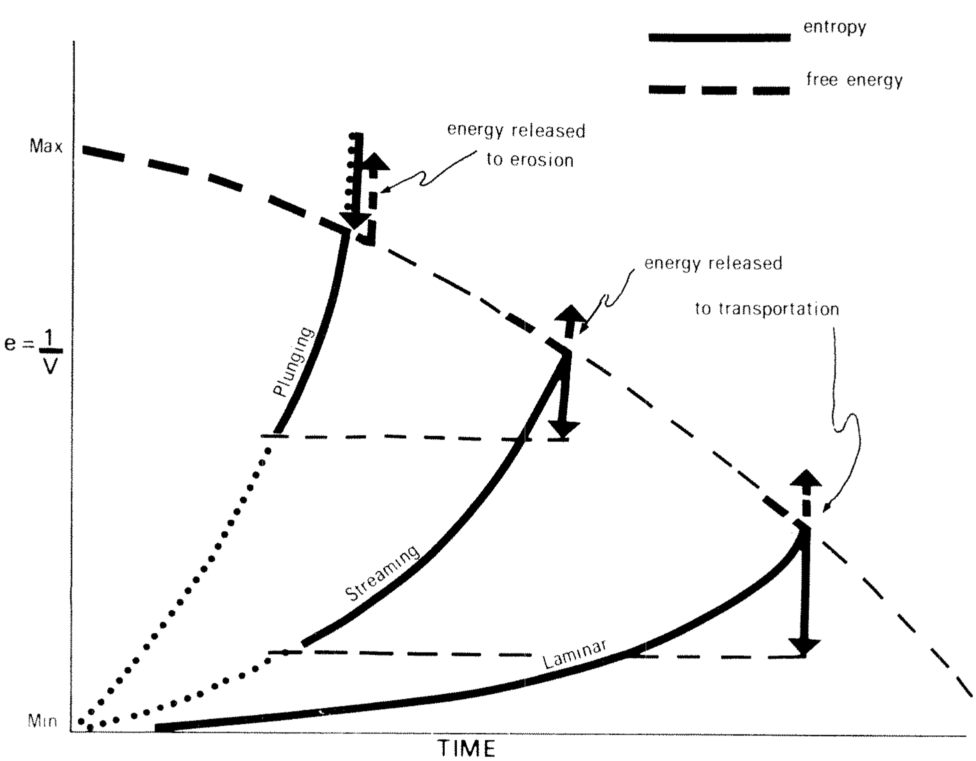


FIGURE 6. Hydro-dynamic analogy illustrating three phases of entropy in successively higher levels of free energy.

zone. Before this takes place and while the glacier is still in a high entropy state, some of the energy in rectilinear flow accomplishes work in the basal zone through the development of accentuated bed foliation and low-angled thrusts (Figure 7). Strong increases in foliation and maximum basal and marginal slippage would appear to be necessary preludes to catastrophic sliding of the sudden slip type. But only if the intensity of inputting energy exceeds the system's boundary conditions will turbulent (surging) flow take place. As in the three-phased fluvial example, this implies a critical upper limit of bed stress at a time of maximum entropy wherein the glacier's storage capacity is fulfilled and with any further stress it becomes too fragile to adjust without large-scale self-regulation. By reference to the table of system characteristics, we can also visualize a lower limit of load stress (in the minimum entropic state) where the glacier's storage capacity is such that it can absorb all inputs without further need for adjustment, at least until its regrowth evolves the sensitivity which the dynamic self-regulation of the intermediate entropic state requires. We have observed this pattern of growth, surge and decay on the Tyeen, Walsh, Dusty, Steele, Turner, Variegated, Haenke and other glaciers studied and photographed in Alaska and the Yukon during recent years (Figures 8 and 9; Miller, 1968, 1971a, 1973).

In this region there are also many examples of rapid increases in accumulation load by climatic change, earthquake avalanching, or both. Often when these load increases occur over a large area in too short a time, or are accentuated by valley-wall constriction, they build the stress to a level above that which permits balance between storage and discharge. Then the available energy, which cannot remain concentrated in one sector, is redistributed throughout the system, often catastrophically. Such stress instabilities are well documented in studies of soil slip and other mass wastage phenomena known in soil mechanics and materials science, so these glaciers are not unique in reflecting dislocation adjustments along the whole channel.

KINEMATIC DISCHARGES

It is also well known that mechanical energy of the kinetic type can be transmitted in wave form. In glaciers, these are referred to as kinematic waves, which presumably relate to a less catastrophic form of spontaneous energy release, although they may actually attend the surging process in glaciers (Paterson, 1969). This may explain why some "surges" do not appear catastrophic, being instead expressions of energy passing kinematically down-valley or through a glacier faster than normal discharge, yet slower than a catastrophic surge or sudden-slip. Whether this represents a transitional or threshold type of self-regulation remains a question. In either case, the energy input appears to exceed the ability of the system to accept and release it by normal flow.

Stated another way, "anomalous" glacier advances likely represent nothing more than spontaneous readjustments of the stress-energy distribution in a situation where normal discharge capabilities of a glacier have been temporarily exceeded by threshold changes in some portion of the system. In most cases, this may be the result of climatic perturbations, such as posed by the approximately 90-year cycle we have determined for a number of Alaskan glaciers (Miller 1964, 1971b, 1973). To produce a severe glacier surge, however, there may be other contributory factors, because climatic changes are usually gradual enough to be integrated by the

FIGURE 7. Thrust surfaces developed in terminal zone and basal margins of Narssarsuak Glacier, S.W. Greenland (Photo by M.M. Miller).

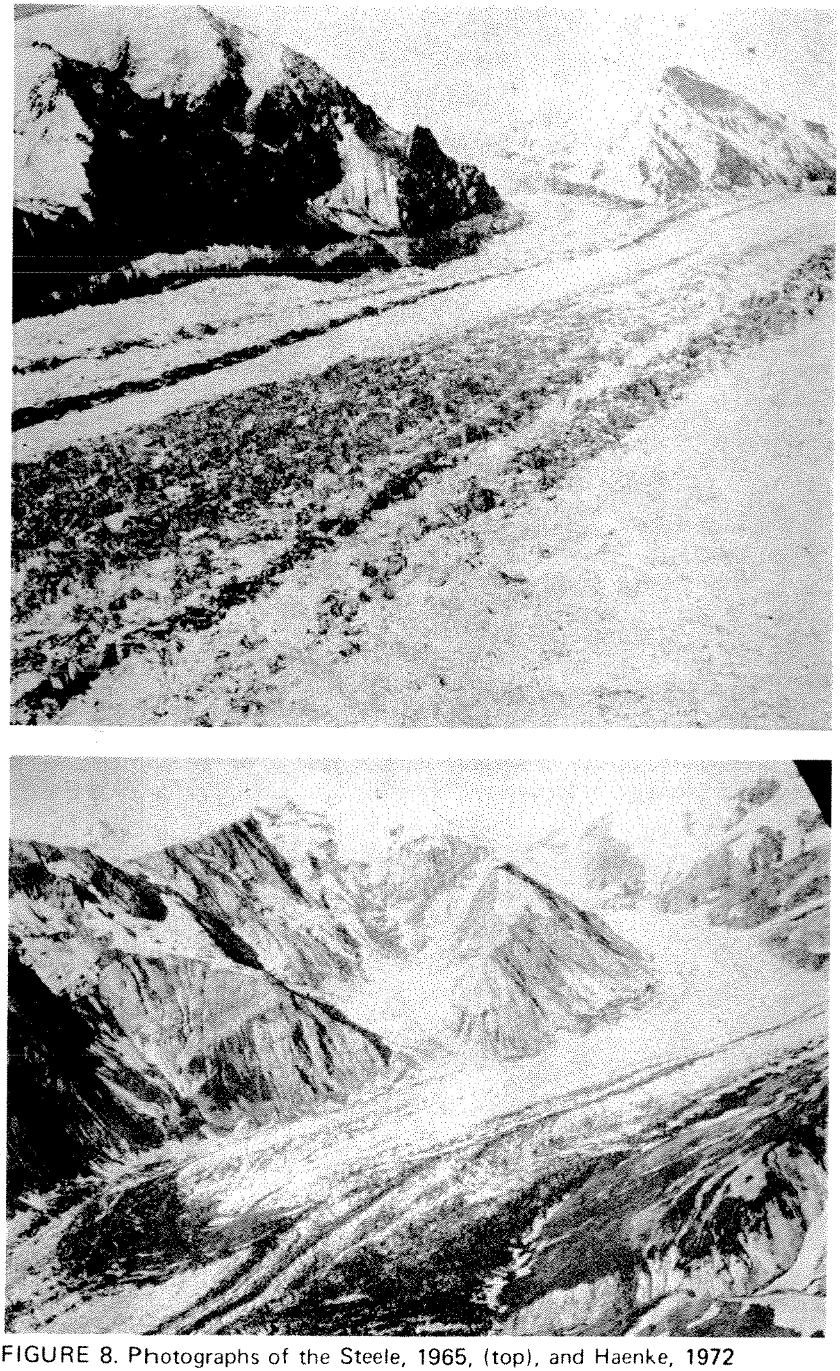


FIGURE 8. Photographs of the Steele, 1965, (top), and Haenke, 1972 (bottom), Glaciers in the St. Elias Mountains, Alaska-Yukon, showing surface characteristics at times of maximum surge. (Photos by M.M. Miller).

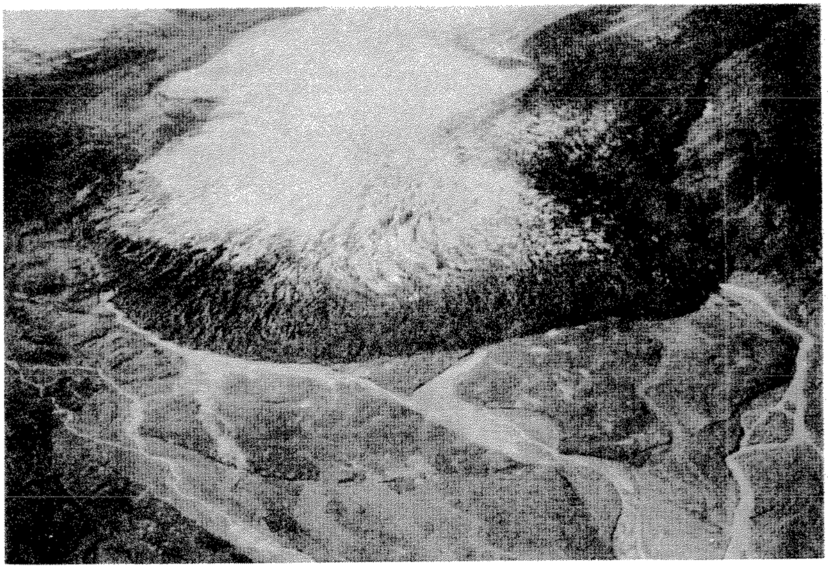


FIGURE 9. Photograph of terminus of Dusty Glacier, 1966, after attenuation of surge. (Photo by M.M. Miller).

self-regulatory capacity of a glacier without recourse to a catastrophic mechanism involving total destruction of entropy and redistribution of free energy.

SURGE BEHAVIOR IN POLAR AND HIGH ALPINE GLACIERS

In geophysically Polar glaciers of the arctic or high alpine areas, another factor has been suggested by the spectacular surge-like advance of certain glaciers in Ellesmere Land and especially in West Spitsbergen (Liestol, 1969). One of the Spitsbergen ice masses, Brasvellsbreen, was observed in the late 1940's to advance 5 km in 5 months. Such may relate to a condition wherein a formerly "cold" glacier attains englacial temperatures which are nearly isothermal at 0°C. This, in effect, could release a thermal dam via the threshold relationships noted in the table at the beginning of this paper. Thus a so-called "normal" flow could be turned into a surge without significantly large changes in load. In the West Spitsbergen case, this is not unreasonable as a number of glaciers in that region, including some in Northeast Land, have been tempered by ameliorating changes in the Gulf Stream since the early 1900's.

Another factor of significance is the effect of diastrophism, exemplified by observations in Alaska and St. Elias Ranges of Alaska-Yukon (Miller, 1958). It is probably not coincidence that extensive surges have only been reported in regions which lie astride that part of the North American continental margin most severely affected by continuing tectonic activity; vast loads of ice and rock are periodically shaken on to glacier surfaces (e.g., Figure 10). Add to this glaciothermal warming and increased snowfall by climatic change and/or other unique inputs such as a build-up of geothermal heat on the bed, and the effect could lead to maximum surging conditions. In the regional behavior of glaciers in the St. Elias Mountains, avalanching appears to be but a supplemental and generally minor factor in a widespread set of glacial advances initiated by climatological causes.

THE IMPLICATION OF PERIODICITIES

In the some 200 key glaciers included in our Alaskan regional inventory (Miller, 1964, 1971a, 1973), normal discharge is the rule, and on most of these there is no evidence of surging. Therefore, in spite of the recognition of surges occurring as a dramatic part of an episodic self-regulating process, their tele-connectional significance appears to be negligible. Even if larger time-scales are considered and the phenomenon is found to be more common, it will probably not be with systematic periodicities. Nevertheless, because many glaciers experience surges, their nature needs to be understood if long sequences of terminal fluctuations are to be effectively assessed and regional records not unduly confused. Efforts should also be made to determine the episodic nature of surges and kinematic waves. If at all possible, it should be determined whether such periodicities are independent of climatic control. Surges are probably aperiodic, and pulsations in the flow of non-surging glaciers are periodic. For these reasons, annual surveys of climatically controlled normal discharge fluctuations in glaciers should be diligently pursued and continuing emphasis placed on systemic long-term programs, which focus on regional studies of glacier regimes and the causal factors involved.

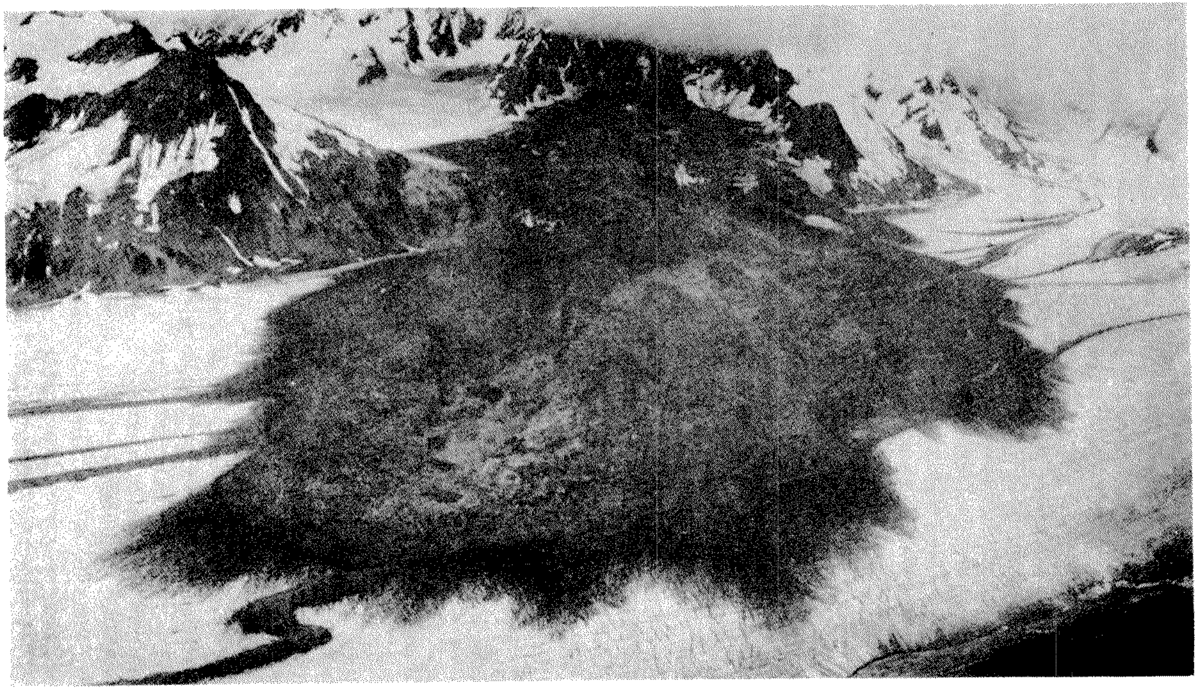


FIGURE 10. Photograph of the Schwaan Glacier in Alaska's Chugach Range, showing effects of gigantic debris slides on glacier surface in consequence of 1964 Alaskan earthquake which involved 8 mi^2 of rock slide material. Note resulting deformation of medial moraine, a few months after the event. (Photo by M.M. Miller, 15 Sept., 1964).

SOME GEOMORPHOLOGICAL IMPLICATIONS

In coastal regions of the Arctic and Subarctic, large glaciers which terminate in the sea are known to have outflowing streams discharging massive quantities of suspended load. Much of this is in the form of rock flour carried far off shore by tidal currents. In observed surging glaciers, the outflow is usually excessively turbid and includes maximum suspended and bed load detritus, accompanied by greatly increased quantities of water (Bayrock, 1967; Miller, 1971a). The presence of increased water has elicited the special attention of some investigators who conclude that water is critical to the development of a surge (Weertman, 1969, 1972; Clarke and Classen, 1970). A number of questions arise. To what extent does accentuated erosion take place during a surge, and is this related to increased quantities of fluvial bed load and suspended material during the decoupling of ice from its bedrock floor? Is the free energy which is released and made available for work by this sudden reduction in glacial entropy put to work in glacial erosion, or is it mainly used in transportation, in the rolling, tumbling and jamming of chaotic blocks and in the release and outpouring of water? Is it perhaps not more probable that the greatest erosion occurs over longer and more sustained periods of rectilinear flow? (This would be in Block-Schollen or plug-flow which accentuates marginal and basal slippage and allows the glacier as an intact mass to override the ground.)

The answers will come largely from careful field study and measurement, abetted to some degree by further refinement of our theories as to what could happen if the stressing parameters were as simple and neat as those introduced to make modular examples comprehensible.

In spite of the indications that geomorphological interpretations of glacio-hydrological phenomena are complex (especially when taken in association with glacier regimes in the various entropy states) we should not ignore the probability that, if the total mass balance of a glacier is significantly changing, its basal flow (strain) rate characteristics should also be affected. Thus measurements of comparative stress characteristics between glaciers should yield further useful information with respect to their abilities to erode, transport and deposit. Such information can be of value to the arctic and alpine geomorphologist if it does no more than help him to explain the fluvial-sedimentological characteristics of pro-glacial streams, the genetic nature of morainic composition and structures, and the fuller meaning of glacio-fluvial stratigraphy laid down by outflowing streams, which in themselves reflect changes in entropy level of the source glaciers involved.

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REFERENCES

Bayrock, L.A., 1967: Catastrophic advance of the Steele Glacier, Yukon, Canada. Boreal Inst. Univ. Alberta Occas. Publ. No. 3: 20 pp.

Bell, D.A., 1956: *Information Theory.* Sir Isaac Putnam and Sons, London. 174 pp.

Campbell, W.J. and Rasmussen, L.A., 1969: Three-dimensional surges and recoveries in a numerial glacier model. *Can. J. Earth Sci.,* 6: 979–986.

Clarke, G.K.C. and Classen, D.G., 1970: The Fox Glacier project. *Can. Geog. J.,* 81: 27–29.

Glen, J.W., 1955: The creep of polycrystalline ice. *Proc. R. Soc.,* A 228: 519–538.

Kamb, W.B., 1970: Sliding motion of glaciers; theory and observation. *Rev. Geophys. and Space Phys.,* 8: 673–728.

Leopold, L.B. and Langbein, W.B., 1962: The concept of entropy in landscape evolution. U.S. Geol. Surv. Prof. Paper, 500A. 20 pp.

Liestol, O., 1969: Glacier surges in West Spitsbergen. *Can. J. Earth Sci.,* 6: 895–897.

Meier, M.F. and Tangborn, W., 1965: Net budget and flow of South Cascade Glacier, Washington. *J. Glaciol.,* 5: 547–566.

Meier, M.F. and Post, A.S. 1969: What are glacier surges? *Can. J. Earth Sci.,* 6: 807–817.

Miller, M.M., 1948: Observations on the regimen of the glaciers of Icy Bay and Yakutat Bay, Alaska. Unpublished Master's thesis, Columbia Univ. New York. 71 pp.

————, 1955: Observations on the regimen of the glaciers in Icy Bay and Yakutat Bay, Alaska. Special Report, Foundation for Glacier Research, Seattle, Washington.

————, 1957: Phenomena associated with the deformation of a glacier borehole. Extrait des Comptes Rendus et Rapports, Internat. Un. Geod. Geophys. Internat. Assoc. Sci. Hydrol. *Assemblee Generale de Toronto,* Tome IV: 437–452.

————, 1958: The Role of diastrophism in the regimen of glaciers in the St. Elias District, Alaska. *J. Glaciol.,* 3: 292–297.

————, 1964: Inventory of terminal position changes in Alaskan Coastal Glaciers since the 1750's. *Proc. Amer. Phil. Soc.,* 108: 257–273.

————————, 1968: 1965–1968 studies of surge activity and moraine patterns on the Dusty Glacier, St. Elias Mountains, Yukon Territory. Proc. 19th Alaska Sci. Conf. Amer. Assoc. Adv. Sci.

————————, 1971a: Glaciological and geological investigations on the 1965 Mount Kennedy Yukon Expedition. Nat. Geog. Soc. Res. Rep., 1965 Project, 161–179.

————————, 1971b: The Alaskan Glacier commemorative project, phase II. Nat. Geog. Soc. Res. Rep., 1965 Project, 181–194.

————————, 1973: A total systems study of climate-glacier relationships and the stress instability of ice. Nat. Geog. Soc. Res. Rep., 1966 Projects. Alaskan Glacier Commemorative Project, 157–196.

Nye, J.F., 1963: The response of a glacier to changes in the rate of nourishment and wastage. *Proc. Roy. Soc.,* A 275: 87–112.

————————, 1965: The flow of a glacier in a channel of rectangular, elliptic, or parabolic cross section. *J. Glaciol.,* 5: 661–690.

————————, 1969: A calculation of the sliding of ice over a wavy surface using a Newtonian viscous approximation. *Proc. Roy. Soc.,* A 311: 445–467.

————————, 1971: Glacier sliding without cavitation in a linear viscous approximation. *Proc. Roy. Soc.,* A 315: 381–403.

Paterson, W.S.B., 1969: *The Physics of Glaciers.* Pergamon Press. 241 pp.

Post, A.S., 1960: The exceptional advances of the Muldrow, Black Rapids and Susitna Glaciers. *J. Geophys. Res.,* 65: 3705–3712.

Robin, G. de Q. and Barnes, P., 1969: Propagation of glacier surges. *Can. J. Earth Sci.,* 6: 969–977.

Robin, G. de Q. and Weertman, J., 1973: Cyclic surging of glaciers. *J. Glaciol.,* 12: 3–18.

Scheidegger, A.E. 1970: *Theoretical Geomorphology.* Springer-Verlag, Berlin-New York.

Tarr, R.S. and Martin, L., 1914: *Alaskan Glacier Studies.* Nat. Geog. Soc. Washington. 500 pp. (for review see Miller, M.M., 1957: Alaskan Glacier Studies. *J. Glaciol.,* 3: 79).

Weertman, J., 1951: Travelling waves on glaciers. Internat. Un. Geod. Geophys. Internat. Assoc. Sci. Hydrol. Chamonix Symp., 162–168.

———————— 1957: On the sliding of glaciers. *J. Glaciol.,* 3: 33–38.

————————, 1962: Catastrophic glacier advances. Internat. Un. Geod. Geophys. Internat. Assoc. Sci. Hydrol. Obergurgl Symp., 31.

————————, 1969: Water lubrication mechanism of glacier surges. *Can. J. Earth Sci.,* 6: 929–942.

————————, 1972: General theory of water flow at the base of a glacier or ice sheet. *Rev. Geophys. and Space Phys.,* 10: 287–333.