Annals of Glaciology 36 2003

How much do we really know about glacier surging?

William D. HARRISON,[1] Austin S. POST[2]

[1]*Geophysical Institute, University of Alaska Fairbanks, 903 Koyukuk Drive, Fairbanks, AK 99775-7320, U.S.A.*
E-mail: harrison@gi.alaska.edu
[2]*10275 SW 127th Street, Vashon, WA 98070, U.S.A.*

ABSTRACT. Some of the ideas about glacier surging are considered, mainly but not entirely in the light of observations of temperate glaciers in Alaska, U.S.A., made within the last 15 years. Climate has an influence on surge recurrence interval. Climate and weather also affect surge initiation, termination and magnitude. Regional studies lead to the speculation that subglacial "till" plays a key role in surging, and it has been found under all surge-type glaciers studied so far, including Black Rapids and Variegated Glaciers, Alaska. In most of the glaciers studied, till deformation processes dominate the motion in quiescence. The linked-cavity model of surge triggering and rapid motion is not consistent with these observations, but the limited coverage of the observations does not rule it out under parts of the glaciers studied. The till observations in Alaska raise old questions about the interaction between till and the hydraulic systems of temperate glaciers. The role of stored water, which observations show to be active even in winter on Black Rapids Glacier, is noted.

INTRODUCTION

This is the third of three papers with rather similar titles. The first, by Meier and Post (1969), defined the surging-glacier problem and has been the basis for much of the subsequent research. The second (Raymond, 1987) was a comprehensive review that took into account the progress made in the subsequent 15 years or so. Another 15 years has passed, but because most of the points in the 1987 review still stand, the present paper is not comprehensive. We do concentrate on results since 1987, but we deal mainly with temperate surge-type glaciers in Alaska, U.S.A., while trying to maintain some regional perspective for comparison. We reference older results which merit interpretation or synthesis, or which are needed for comparison with new results. Finally, although there has been a great deal of theoretical and laboratory work involving surge mechanisms and related properties of till and hydraulic systems, we deal almost exclusively with results from field observations, and with regional studies of the distribution of surge-type glaciers.

Some of the data which we consider were obtained during recent surges: Bakaninbreen in Svalbard (Murray and others, 2000), Skeiðarárjökull in Iceland (Björnsson, 1998), West Fork Glacier in the Alaska Range (Harrison and others, 1994), and Bering (see Fatland and Lingle, 1998, for an overview) and Variegated (Eisen, 2001) Glaciers, Alaska, in the coastal Saint Elias Mountains. The last of these surges occurred in 1995, 13 years after the initiation of the previous, well-studied surge. Observations continued on the well-studied but quiescent Trapridge Glacier, Yukon Territory, Canada (e.g. Kavanaugh and Clarke, 2001), and Black Rapids Glacier, Alaska (e.g. Truffer and others, 2000).

Our discussion breaks down into three main categories. The first is the effects of geometry, climate and setting on surging, the second is the critical issue of basal morphology, and the third is water.

GEOMETRY, CLIMATE AND SETTING

Geometry and geologic setting

The non-random geographic distribution of surge-type glaciers throughout the world, if it could be understood, would likely place some constraints on the mechanism of surging. Efforts to do so have been summarized by Hamilton and Dowdeswell (1996) and Jiskoot and others (2000). One of the approaches has been to search for a statistical correlation between various geometric parameters and surging. Long glaciers seem most likely to surge in Svalbard and in the eastern Saint Elias Mountains (Clarke, 1991). Wilbur (1988), on the other hand, found that "bottom-heavy" glaciers, those with relatively large areas at low elevation, were most likely to surge in an ensemble of glaciers more or less representative of all of western North America. Evidently the correlation is difficult because the picture is complicated.

Several studies have searched for a connection between surging and geologic setting. In Svalbard (e.g. Hamilton and Dowdeswell, 1996; Jiskoot and others, 2000), the probability of surging is relatively large for glaciers on sedimentary bedrock. The situation is not clear in western North America, but Post (1969) noted that surging glaciers are often associated with fault-shattered valleys (although not all such valleys have surge-type glaciers), and that there were no surge-type glaciers in the granitic Coast Mountains. He speculated that the controlling effect might be permeability of the underlying rock. An alternative speculation, not new (e.g. Clarke and others, 1984; Murray and others, 2000) but more plausible now in the light of our slowly increasing knowledge of glacier beds, is that surge-type glaciers tend to occur over easily eroded materials. Therefore beds of "till" (loosely used here to mean unlithified sediments) could be common beneath them.

Climate

The most obvious effect of climate is on the thermal regime of a glacier, which in turn has a major effect on surging. The surges of the subpolar glaciers of Svalbard seem to be muted relative to those of the temperate glaciers common in most parts of western North America (Dowdeswell and others, 1991); speed in surge is relatively low and the surge duration is relatively long. Thermal control plays a major role in their evolution. Bakaninbreen (Murray and others, 2000) and Trapridge Glacier (Clarke and Blake, 1991) are examples.

Climate effects complicate the problem of understanding the distribution of surge-type glaciers. One manifestation of climate control is the existence of many glaciers that once surged but do not any longer, which makes the distribution of surge-type glaciers a function of time. This has been noticed in Svalbard (Dowdeswell and others, 1995). Another example is Vernagtferner, Ötztal Alps, which underwent strong surges from the 17th to the 19th century, when alpine glaciers were relatively large (Hoinkes, 1969). Several lines of evidence indicate that Black Rapids Glacier is close to surge, but it is doubtful that a surge is possible under present climatic conditions (Heinrichs and others, 1996).

Another aspect of the connection between climate and surging is the effect of climate on surge recurrence interval. The intervals between at least the last four surges of Variegated Glacier correlate with cumulative specific mass balance at a point in the reservoir area (Eisen and others, 2001; W. Tangborn and R. Soemarmo, http://www.hymet.com). Medvizhiy glacier, Russia (Dyurgerov and others, 1985), is similar. These are examples of the long-expected connection between climate and surge triggering (e.g. Hance, 1937). One might expect this connection to be modulated by changes in glacier size due to trends in climate occurring on a time-scale long compared with the typical surge interval. This may depend upon where surges tend to initiate on a particular glacier. If they initiate high on the glacier (as they do on Variegated), the intervals might not be affected much because the shapes of the upper parts of glaciers tend to be relatively insensitive to climate change.

Finally, climate, or perhaps weather, seems to have an effect on surge initiation, termination and magnitude. Surges tend to initiate in winter, or at least when there is little water available from the surface (e.g. Harrison and others, 1994; Roush, 1996). Surge termination often occurs when surface water is abundant, as illustrated by the timing of the termination of both phases of the 1982–83 Variegated Glacier surge, and the single phase of the 1995 surge. Weather may also affect the magnitude of a surge. We have noticed that the relatively strong 1964–65 surge of Variegated Glacier was accompanied by a cool spring in 1965, and the relatively weak one in 1995 by an unusually warm spring. The cool spring, for example, could have delayed the availability of surface water and therefore termination. The fact that surge recurrence time appears to be independent of the magnitude of the previous surge suggests that the upper part of the glacier, where surge initiation occurs, is not much affected either by climate change (discussed above) or by surge magnitude.

BASAL MORPHOLOGY

There is little doubt that the most serious gap in our understanding about surging is basal morphology. On the one extreme, surging could be associated with the disruption of a "soft" (deformable) bed and the hydraulic system there (e.g. Boulton and Jones, 1979; Clarke and others, 1984; Fowler and others, 2001). On the other extreme, the bed could be "hard" (bedrock) and surging could be associated with the disruption of the hydraulic system alone (Kamb, 1987). The physics both of triggering and of rapid motion would be quite different in the two cases, although in either case the disruption of the hydraulic system would lead to high basal pressures and rapid motion. Disturbance of the till would be important in the former, while basal sliding alone would operate in the latter. In what follows, we use the term "basal motion" for the collection of processes acting under the ice. For a soft bed these would include till deformation (part of which could be by faulting) together with sliding at the top and bottom of the till. Faulting or sliding at the till–bedrock interface seems necessary sometime during the surge cycle to supply the clasts found in the till. This picture implies a well-defined boundary at the base of the ice, which may not always exist.

Eastern Saint Elias Mountains, Svalbard and Iceland

Information about the basal morphology and motion of Trapridge Glacier, eastern Saint Elias Mountains, has been obtained from borehole measurements in which instruments were inserted into the top of a till layer found there, and from inspection of now exposed till deposited by earlier surges. During the quiescent phase, the surface motion in the area studied is mainly due to basal motion, with over half of this accounted for by sliding at the ice–till interface (Blake and others, 1994). Similar borehole methods during a surge of Bakaninbreen revealed soft sediments near the base of the ice, and basal motion (Porter and Murray, 2001). The nature of sediments (till and marine mud) could be inferred from sampling and from material brought to the surface by faulting near the surge front (Hambrey and others, 1996). Near the terminus of the surge-type Breiðamerkurjökull, Iceland, tunnel observations indicated a layer of basal till roughly 0.5 m thick, the deformation of which accounted for most of the motion during quiescence; sliding at the ice–till interface was small. Extensive layers of subglacially deposited till also exist beyond the margin (Boulton and Hindmarsh, 1987).

Thus, in Svalbard, Iceland and the eastern Saint Elias Mountains of the Yukon Territory, active subglacial till has been found under the few areas of the few surge-type glaciers studied. We next consider some results from Alaska.

Black Rapids Glacier

Black Rapids, located in the central Alaska Range, is a 40 km long glacier which last surged in 1936–37 (Heinrichs and others, 1996). Seismic and drilling studies (Nolan and Echelmeyer, 1999a, b; Truffer and others, 1999) at a site 15 km from the head of the glacier indicated the presence of subglacial till, 7.5 and 4.5 m thick at the two boreholes, where the ice thicknesses were 500 and 620 m. Measurements at the former hole indicated that processes within the till or at the till–bedrock interface accounted for the majority of the surface motion (Truffer and others, 2000, 2001). There was little if any sliding over the top of the till, and little deformation within the top 2 m of it. This information could not have been obtained with the light hammers usually available to place instruments in till, which cannot penetrate more than a few decimeters when clasts are present. We used a large and expensive wireline drill rig.

In our experience, there is usually ambiguity in interpreting borehole data, and, even in the rare cases that the observations are completely successful, only a tiny fraction of the bed is observed. For example, a mixed bed of till with isolated rock protuberances could be difficult to characterize, and of course the bed morphology could change with location. However, on Black Rapids Glacier some inferences about till distribution can be made on the basis of other information. Several years before the till was observed, Heinrichs and others (1996) noticed that the area 14–20 km from the head of the glacier, which included the two drill sites, had several interesting properties. It was the most rapidly moving, and experienced the largest seasonal and secular changes in speed. Moreover, it moved almost as a block. They interpreted the implied large longitudinal coupling length to be due to low basal shear stress. The importance of basal motion was inferred from the small calculated ice-deformation rates, the large seasonal variations in speed, and the high sensitivity of speed to small shear stress variation. The last condition was modeled by Truffer and others (2001) in terms of the effect of subglacial till at failure. High sensitivity to small stress change was also a pre-surge condition observed on Variegated Glacier (Raymond and Harrison, 1988).

These properties of the flow, particularly the characteristically low shear stress, suggest more-or-less uniform basal conditions in this 6 km reach of Black Rapids Glacier, and therefore that the deforming till observed in the boreholes is characteristic of the entire reach. Till is likely important down-glacier as well, since it is being transported in that direction, but interpretation in terms of the surface motion is complicated by the entry of a major tributary from the south. Complications also occur above 14 km, but till probably also extends at least some distance farther up-glacier; Truffer and others (1999) noted that although much of the till was of local origin, some clasts had probably been transported as much as 2 km down-glacier to the drilling site.

The combination of observations therefore suggests that a long central reach of Black Rapids Glacier is underlain by several meters of till, and that processes within the till or at the till–bedrock interface provide the majority of the surface motion during quiescence.

Variegated Glacier

Direct observations of the basal condition of Variegated Glacier were attempted in 1979 and 1980 in an area about 7 km from the head of the glacier using hot-water and cable-tool drilling with sand-pump bailing and, in some cases, blasting (Harrison and others, 1986). These methods failed to penetrate significantly beyond an ice–sediment interface in six holes. Borehole television (Fig. 1) revealed small or zero sliding at the interface. The interface was reasonably well defined, although some clasts were seen in the ice.

Because cable-tool drilling and sand-pump bailing seemed to produce unlimited amounts of material, it seems likely that the sediment had substantial thickness and perhaps contained no ice. Nevertheless, since we were unable to penetrate significantly beyond the ice–sediment interface, we were unable to provide a direct answer to the key question: Was the interface the top of a relatively thin sediment layer (underlain by ice) that contributed little to the surface motion, or was it the top of a layer of deforming till that contributed significantly? Measurements of borehole deformation and surface motion, taken together, suggest the latter. For the years 1979 and 1980 they indicated that the summer speed of the interface (along which we recall there was negligible sliding) for the two years was 0.22 and 0.35 m d^{-1}. Since in principle the sediment layer could be thin and overlie a thick layer of deforming ice, these are *upper* limits on the basal speeds. However, they are comparable to the increase in speed during the spring speed-up in early June. The speed-up puts a *lower* limit on the basal speed because some basal motion could have been present before speed-up. Since the upper and lower limits are similar, we conclude that we were probably observing the top of a deforming till layer, and that the speed of the ice–till interface was the net basal speed in 1979 and 1980. This contributed about 40% and 50% to the surface motion during the two summer observation periods. This interpretation implies that basal speed before the spring speed-up must have been small. Raymond and Harrison (1988), on the other hand, suggested that basal motion was significant in "winter" after 1978, but their definition of winter was from early September to late June, which must include some basal motion after the spring speed-up.

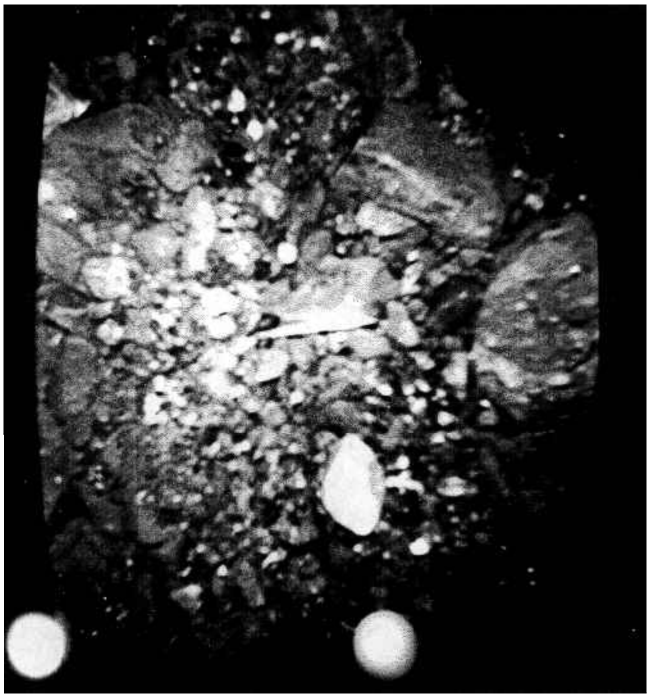

Fig. 1. Bottom of hole VB, 29 July 1980, after drilling, sand pumping and blasting. The ball in the lower center is 18 mm in diameter.

Summary of observations of basal morphology

Although we have seen that methods for determining basal morphology are both difficult and usually limited to small areas of a glacier, it is interesting that all the measurements to date in Alaska and elsewhere have encountered till, often accounting for the majority of the surface motion during quiescence. One possible exception is Tyeen Glacier, Johns Hopkins Inlet, Glacier Bay, Alaska, which seems to overrun bedrock during a surge advance, although the steepness of this area could account for the high speed. Also, it is worth keeping in mind that till is often found under normal glaciers as well (e.g. Boulton and others, 2001).

Implications of the Variegated Glacier observations for the surge process

A prominent aspect of the studies of the 1982–83 surge of

Variegated Glacier (Kamb and others, 1985) was the association of surging with rapid changes in the subglacial hydraulic system, which was observed to switch from a discrete, fast, low-pressure tunnel system to a distributed system with the opposite properties. The distributed system has been interpreted in terms of a system of linked cavities overlying a hard bed (Kamb, 1987). This model of the bed is not consistent with the borehole observations on the glacier, limited though they may be, and with conditions found under other surge-type glaciers. Kamb did point out that a linked-cavity system, or something similar, might exist in the presence of till patches or even a till layer if it had sufficient fixed protuberances to support cavities. This is not inconsistent with the small area sampled. However, the obvious question is whether, during a surge, sliding (at the ice–till interface) would be the dominant process of rapid motion (as is implied by the Kamb approach in order to maintain the cavities), or deformation of the till. The latter situation would be the soft-bed situation invoked by other researchers as described above, in which deformation of the till would contribute both to the destruction of the drainage system and to the rapid motion. We speculate that bed deformation, rather than sliding over a relatively rigid till, seems more consistent with the huge sediment discharge observed during and after the Variegated Glacier surge (Raymond, 1987; Humphrey and Raymond, 1994). Till, if widespread, would impact the discussion of bedrock erosion in the latter paper.

Sliding over till has been observed on Trapridge Glacier (Blake and others, 1994). Engelhardt and Kamb (1998) argued for sliding with minimal or shallow bed deformation beneath Ice Stream B (now Whillans Ice Stream), but for dominant bed deformation in a longer experiment beneath Ice Stream D (Kamb, 2001). However, sliding over till does not seem to be significant for several surge-type glaciers studied in their quiescent phases. The condition of no sliding at the ice–till interface is the one in which most of the dissipation of gravitational potential energy could be available for comminution within the till and for erosion at the till–bedrock interface. In the extreme case in which basal motion is entirely by sliding at a clean ice–bedrock interface, most of the energy would go into melting ice.

Fig. 2. Vertical photograph of Steele Glacier, Yukon Territory, in surge. Distance from top to bottom is about 1.5 km. A lake, or a series of them, follows the margin of the glacier near the top. Three isolated lakes on the surface of the glacier can be seen near the bottom. Photo by A. Post, 17 September 1966.

WATER AND THE INTERNAL HYDRAULIC SYSTEM

As already noted, the 1982–83 surge of Variegated Glacier involved the switch from an efficient discrete basal hydraulic system to an inefficient distributed one. A similar process acted during the 1991 surge of Skeiðarárjökull, Iceland (Björnsson, 1998). The distributed system has no major conduits at the bed, a relatively low down-glacier component of water velocity, a possibly high cross-section but divided into small pieces, and relatively high water pressure. Qualitatively, it has a relatively high impedance to water flow. An extreme case of inefficient drainage occurred during the 1987–88 surge of West Fork Glacier, Alaska, in which the basal system was totally dammed during most of the surge, as indicated by the complete lack of suspended sediment in the stream (Harrison and others, 1994). Distributed systems are thought to exist seasonally under parts of Variegated Glacier during its quiescent phase, and a discrete system to exist below the surge front during surge (Kamb and others, 1985; Raymond, 1987). These patterns could be modified in subpolar glaciers by the complex thermal regimes and the importance of subglacial aquifers; aquifers could play a role in temperate glaciers as well.

Stored water, at least some of it englacial, must play a role in the switching between hydraulic regimes. For example, a distributed system probably requires more water, which must be available rapidly from storage to account for the rapid changes (on the order of 1 day or less) observed. A hypothesis for the winter initiation of surges (Raymond, 1987) requires the presence of englacial water trapped late in the melt season when a combination of seasonally declining flow and secularly evolving surface geometry allows early collapse of the discrete hydraulic system. This could trap an unusual amount of water which would have drained under normal conditions. The trapped water could redistribute itself in a distributed system and trigger a surge. Stored water in Variegated Glacier is indicated by floods in the stream during surge slow-downs and at termination, and by an excess of water discharge after termination (Humphrey and Raymond, 1994). Typical amounts of water measured in these floods seem to be on the order of a decimeter or two averaged over the area of the glacier, and on the order of a meter after termination. The observation of water-release events after the surge of Bering Glacier inferred from synthetic aperture radar (SAR) interferometric methods (Fatland, 1998) is an example of water release of the same magnitude.

These observations are representative of the amounts of released water, but not necessarily the total amount stored. One gets the impression from the abundance of water in lakes and crevasses (some of it turbid), that there may be a great deal of water involved in surges (Fig. 2). Some of it could have a surface origin in summer, but near-surface water occurs in winter as well (Kamb and others, 1985). There is also evidence in quiescent times for water and its activity in winter. This is illustrated by Black Rapids Glacier, where lakes apparently can fill in winter (Sturm and Cosgrove, 1990), and SAR interferometry shows features (Fatland and Lingle, 1998; Lingle and Fatland, 2003) which can be interpreted in terms of moving water pockets. Also, in our experience, seemingly unlimited amounts of water can be pumped from some boreholes in winter without significant drawdown of the water level (see Fatland, 1998, p. 89). Water storage and redistribution in winter must account for changes in the surface speed, which tends to go through a broad minimum in late fall or early winter. We do not understand these processes.

It is clear that some of the problems of hydraulics and water storage are similar for surge and normal glaciers. For example, there is a reasonably clear relation between variations in basal motion and storage on Columbia Glacier, Alaska (Kamb and others, 1994). Columbia is a fast tidewater glacier whose dynamics may be more characteristic of surging than of normal flow. However, seasonal water-storage changes, on the order of decimeters as in the examples above, have long been known to occur on normal glaciers (e.g. Stenborg, 1970; Tangborn and others, 1975; Iken and others, 1983).

Another interesting connection between surge-type and normal glaciers is the character of their stream discharges. A study of the stream discharges from the quiescent Black Rapids Glacier from 1986 to 1989 (Raymond and others, 1995) concluded that both the hydraulic system and the surface motion were not significantly different from those of the nearby, normal Fels Glacier, and probably not from other normal glaciers. Any difference in the bed morphology that could be responsible for the surging of Black Rapids Glacier did not affect the hydraulics during the measurement years. Perhaps till is as prominent under Fels Glacier as it is under Black Rapids. Alternatively, the bed morphologies could be different but the hydraulic systems similar before the till under Black Rapids Glacier is seriously disrupted by a surge.

A discussion of the connection between water storage and surges is given by Lingle and Fatland (2003).

CONCLUSIONS

It is becoming increasingly clear that the key issue about surging, and perhaps even about the flow of normal glaciers, is subglacial till and its relationship with the internal hydraulic system. We need to find better ways of detecting and mapping till, and to determine its origin, properties, mass balance, effective pressure and deformation rate as functions of time. The internal hydraulic system and its interaction with the till are equally important. On the one hand, water and the hydraulic system can control effective pressures within the till and therefore till strength. On the other hand, till could control the morphology of the hydraulic system (see, e.g., Fountain and Walder, 1998). The role and amount of stored water remain uncertain, but important.

ACKNOWLEDGEMENTS

Support was from the U.S. National Science Foundation grant OPP-9977796. We are grateful for the comments of M. Truffer, C. F. Raymond, K. A. Echelmeyer, two anonymous referees and the Scientific Editor, C. J. van der Veen.

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