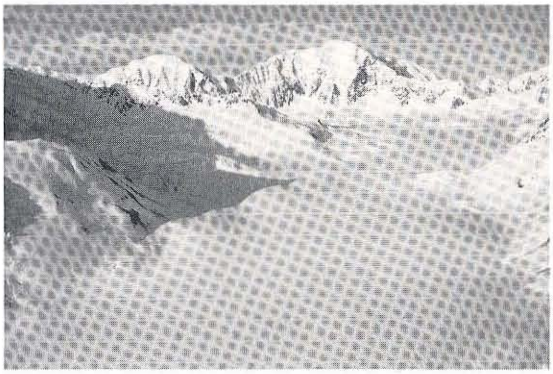
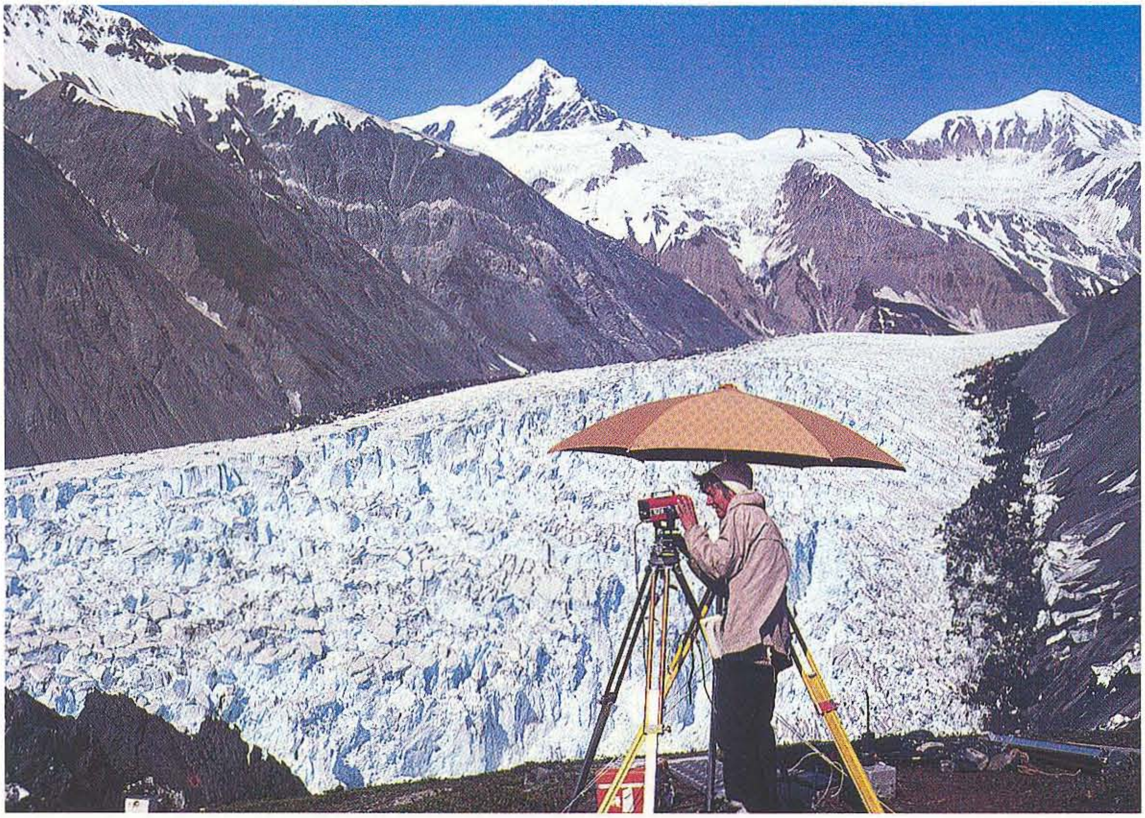


The Surge of an

Variegated Glacier before . . .



. . . and after (or rather during) surge. Almut Iken, who is checking the glacier's forward movement, does not really imagine that she's at the beach; the unbrella protects heat-sensitive surveying equipment from the sun.

GLACIERS DON'T ALWAYS move at a glacial pace. Some of them, after flowing very slowly and steadily for a number of years, suddenly surge forward at up to a hundred times their normal rate, cracking into crevasses as they travel and threatening to overrun an occasional highway, pipeline, Alaskan roadhouse, or scientific camp in their path. Although many glaciers are considered capable of surging, few such "galloping" glaciers have actually been observed since the 1906 discovery of this dramatic phenomenon in the Variegated Glacier in Alaska.

Variegated Glacier surged again in 1947, in 1964-65 — and probably did so in 1926 also (while no one was watching) — a recurrence period of about 20 years. In order to monitor the glacier during its normal period and follow the buildup to the next anticipated surge, research teams, including that of Barclay Kamb, professor of geology and geophysics, have been watching it closely since 1973. Two former Caltech students, Charles Raymond (PhD '69), of the University of Washington, and William Harrison (PhD '66), now at the University of Alaska, have also been camping on the glacier and studying it over the past decade.

While there are many reasons for studying glaciers, including why they're there in the first place, their role as geological agents in modifying the earth, and what they imply for climatic change, Kamb is particularly interested in the

Alaskan Glacier: A Moving Experience

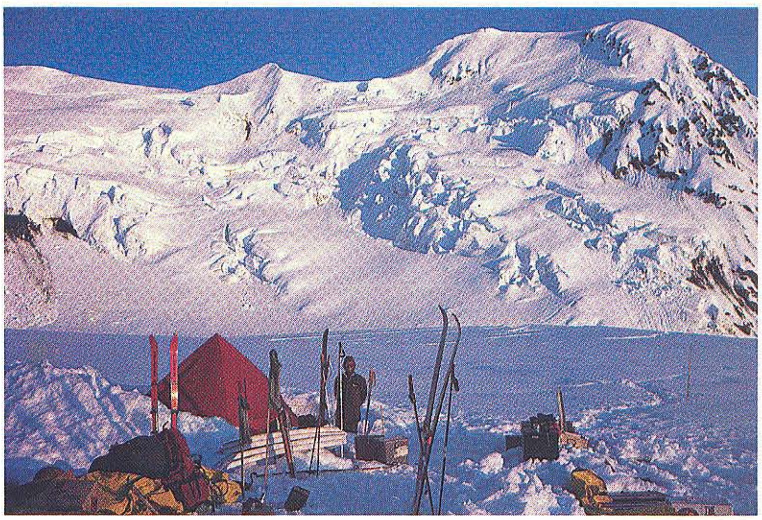
tectonic aspects of glacial flow, the flow phenomenon being in some ways similar to that of mantle convection in the earth's interior. His work has been supported by the National Science Foundation.

Variegated Glacier, which gets its name from the looping bands of different colored rock types in its moraines, is located where the Alaskan panhandle begins, at the head of Yakutat Bay, alongside the much larger Hubbard Glacier, which drains a large part of the St. Elias Range. It's 20 kilometers long and normally flows at a rate of about 0.2 m (meters) per day in the upper part and about 0.1 m per day in the lower glacier. Measurements between 1973 and 1981 showed that during this time the velocity tripled in the upper glacier and doubled in the middle. This slow, steady increase in speed was accompanied by thickening, or increase in elevation, of the ice surface in the upper part of the glacier and thinning downstream.

Normal forward motion of glaciers depends about equally on two different mechanisms — viscous or pseudoviscous creeping of the ice mass internally and basal sliding over its bed. The internal deformation mechanisms are fairly well understood, but what actually goes on at the bottom of the glacier has been more difficult to get at. In 1978 Kamb's group (which has included Hermann Engelhardt of the University of Münster in Germany, formerly a senior research fellow at Caltech, and grad students Melinda Brugman and Keith Echelmeyer, now a postdoc) began a program of drilling boreholes through the ice to study basal sliding, suspected as the prime mover in surging. Drilling the holes required pumping into the ice mass a jet of hot water (under pressure of about 1000 psi), which melted its way to the bottom. Measurements of the tilting of the boreholes provided data on the glacier's movement, which by 1978 was starting to become quite interesting. Short spurts of increased speed were noticeable during the summer.

Kamb called these peaks "mini-surges" because they looked like the beginning of a surge that quite literally didn't get off the ground. In the summers of 1979-1981 his team monitored and documented these mini-surges, four or five of which occurred early each summer. The flow velocity increased rapidly (over an hour or two) to 1 to 3 m per day and then declined back to original speed of 0.4 per day in 10 to 20 hours. This was accompanied by an increase in seismicity (icequakes) and by an abrupt rise in the water level in the boreholes, from normal depths of about 150 m to within 20 to 40 m of the ice surface, strongly implicating basal water pressure in the phenomenon. The hypothesis that the glacier was being temporarily pushed up and "floated" was strengthened by measurements of a simultaneous uplift of a few centimeters in the glacier surface.

The mini-surges propagated down the glacier, and by comparing the spikes in the level of borehole water and the times they occurred at various holes, the researchers determined the



The geologists' campsite on the upper glacier looks idyllic in the relatively calm spring of 1982.

With jets of hot water, boreholes were drilled to the bottom of the glacier to measure its movement and the basal water pressure. Here Barclay Kamb poses amid the pieces of drilling equipment, which occasionally turned temperamental and got stuck in the ice.

speed of the wave as 300-400 m per hour. Minisurges had not been so closely observed before; Kamb thought they were premonitory to a real surge, which, based on his observations of the early summer activity (and the greater availability of water), he presumed would begin in the summer.

It didn't. In January 1982 the surprising onset was detected by a seismometer. At first no one was sure whether to believe this instrument message from the glacier, but Raymond's onsite measurements of average flow velocities of 2.2 m per day in the upper glacier in March and April forced the geologists to take it seriously. Kamb's group (a total of nine) began arriving toward the end of May. Setting up a scientific camp on an isolated glacier is not the most convenient way to do research. It took 8 helicopter flights from Yakutat to the glacier itself and, in addition, 14 airplane flights to a beach near Hubbard Glacier, and from there 15 more helicopter flights to get all the people and equipment to their camp.

The velocity continued to rise gradually to a crest of 8.7 m per day. Then, on the morning of June 26, the flow velocity suddenly dropped in just a few hours to less than half of what it had built up to. Five major pulses of movement occurred after that, superimposed on a generally decreasing trend of velocity. By the end of July the speed had decreased to 1 m per day, which seemed slow, but was still fast compared to the normal, pre-surge speed.

During this time, until mid-August, Kamb's team plumbed Variegated Glacier for all possible clues to the surge movement. They set up a system of seismometers the length of the glacier, drilled boreholes to measure the glacier's movement and the basal water pressure, and attempted to trace the subglacial flow with injected dye and to install survivable pressure transducers at the bed. Besides not being the easiest places to get to, glaciers are not the easiest places to work, either. Icequakes on the surging glacier every few minutes made sleep difficult. ("This was somewhat unnerving," says Kamb, "especially when crevasses were opening up under the tents.") The process of melting snow for the drilling water was time-consuming; drilling equipment got stuck in the ice, forcing cancellation of the transducer experiment; the dye experiment was inconclusive (and trying to pour 60 lbs. of dye down a borehole was "a very messy business"). But the problems brought insights into better ways to do it next time around.

There was indeed a next time. The surge began to build up again in the upper glacier the following October and continued through the winter and spring of 1983. A seismometer and automatic cameras recorded the glacier's movement, and the scientists visited periodically over the winter. The speed gradually increased over the winter, reaching about 5 m per day in the middle of February and about 10 m per day by early May. Kamb and Echelmeyer spent several days on the glacier in February and returned with their team on May 5.

In May and June 1983 the surge front propagated (as a kinematic-type wave, Kamb has concluded) down into the lower glacier; the previous year's surge had been limited to the upper glacier. Ahead of the sharply defined surge front the glacier moved at its normal slow pace; behind it the flow velocity was high — dramatically high, in fact, reaching flow velocities of from 40 to 60 m per day in the lower glacier during June. (The highest recorded was 65 m per day for two hours on June 9.) As the surge front moved through it, the ice in the lower glacier grew up to 100 m thicker, while in the upper glacier it dropped by as much as 50 m from its pre-surge thickness. Large, complex oscillations in flow speed propagated down the glacier at speeds of 600 m per hour.

The strain of the surge now cracked the surface of the glacier into a vast jumble of crevasses, making camping on top of it "very exciting," according to Kamb. In June, as they were forced to abandon one camp that was being sliced apart by crevasses, the rescuing helicopter pilot remarked, "It looks like nature has eaten your camp." Subsequently the researchers located their camp below the surge front, where life was perhaps less fragmented but no less exciting, as the huge wall of ice, the surge front, swept toward them. Much of their work on the surging glacier was carried out from a helicopter, which sometimes could find a flat piece of ice large enough to land on. Other times their ice-movement markers had to be set from the craft as it hovered over the seracs (pinnacles of ice). Many of the markers disappeared into the crevasses as the glacier surface broke up.

Suddenly in the afternoon and evening of July 4, the surge stopped abruptly. In just a few hours, the glacier's speed dropped to a quarter of what it had been; by July 26 it was down to essentially its pre-surge velocity, even less in the upper glacier, where the ice had been thinned by the surge, and somewhat more in the lower glacier where it was thickened.

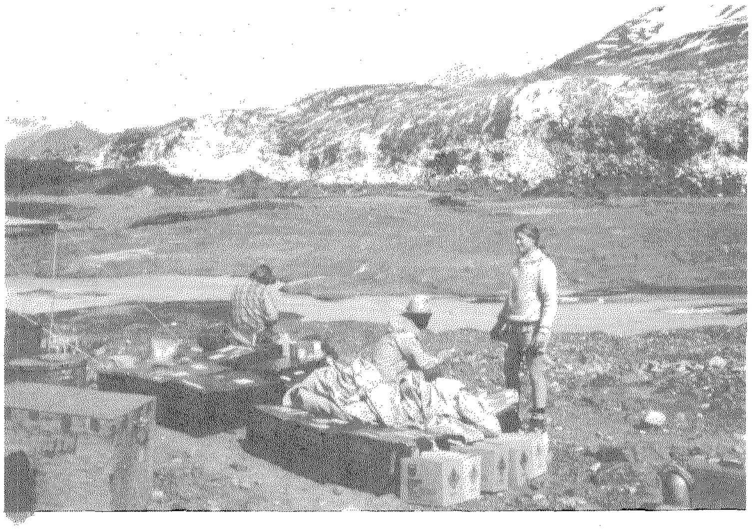
What was, then, actually happening at the glacier bed that had precipitated the surge motion and was now terminating it? Kamb's team once again set about trying to find out. Measuring the shape of boreholes (how far they inclined over several days) demonstrated what had previously been assumed but never actually observed — that essentially all of the surge movement is due to basal sliding, while the internal motion was roughly the same as normal. Boreholes also provided measurements of the water level and thereby the water pressure at the bottom of the glacier. Kamb and his group found that during the surge the basal water pressure was consistently within 3 to 5 bars of the pressure of the overlying ice at the bed. (Pressures are normally 8 and sometimes as low as 16 bars below the overburden pressure.) The surge's sudden stop coincided with lowering of the water pressure. This was very reminiscent of what had been observed earlier in the mini-surges, where peaks of movement coincided with peaks in water pressure.

The emergence of a lake at the edge of the lower glacier implicated basal water pressure still further. Its water welled up from the basal water system through a large crevasse 100 m in from the glacier's edge and then flowed outward to the margin. The lake emptied literally overnight on July 4-5, coinciding with the abrupt end of the surge.

One of the most striking observations was a correlation between marked slowdowns in the surge speed and large floods in the subglacial river emerging from the glacier at its terminus. When the surge ended, a particularly spectacular flood of water emerged. Turbid water gushed and spurted out of cracks and crevasses along the leading edge of the surge front. Kamb thinks this represents the release of stored water from under the glacier, the same stored water

A crevasse advances ominously on the camp before the campsite was moved.

Everyone practices crevasse rescue — just in case.



(Above) With the camp safely relocated on the lower glacier, these members of the research team appear oblivious to the surge front, which looks like a dirty wave in the background, bearing down on them at a speed of up to 60 meters per day.
(Right) When a crevasse interrupted his surveying, Kamb improvised a bridge and continued his work.

that was "levitating" the glacier off its bed during the surge.

To track the subglacial water flow, Kamb's group again injected tracer dye through a borehole to the glacier bed and determined how long it took to reach the main outflow stream down at the glacier terminus. They injected the dye once in June during the surge and again in July after it ended. Results clearly demonstrated a dramatically slower water flow during surge. In the first instance the dye took a mean transit time of 100 hours, corresponding to an average speed of 0.02 m per second; after the surge, it went through in 4 hours at an average speed of 0.7 m per second. *Something* was happening during the surge to retain water under the glacier.

On the basis of their discoveries of the behavior of subglacial water and measurements of uplifts and drops in the surface of the glacier during speedup and slowdown of the surge, Kamb thinks the surge mechanism involves the opening and closing of cavities under the glacier — cavities that fill and retain water during surge and that close and release water when the surge ends. These cavities are created, he believes, as increased basal water pressure causes the glacier to slide over its bed with increasing speed. He sees the cavities as forming an interconnected system of small conduits in a complex network that extends far and wide at the bed of the glacier and is kept open by the high water pressure. In contrast to this, in the glacier under non-surging conditions, as in "normal" glaciers, melt water flows at the bed of the glacier through a single large tunnel, or at most a few large tunnels.

In relating the behavior of the basal water pressure to the mechanism of the surge, Kamb theorizes that a surge is caused when water pressure at the bed approaches within 3 to 5 bars the pressure of the overlying ice, causing it to begin sliding rapidly and causing many cavities to open. If the water pressure exceeded that of the ice, which sometimes does occur in mini-surges, the glacier would literally float off its bed and slide at an increasing rate without stopping. Mini-surges are of such short duration, however, that the high water pressure doesn't have a chance to spread over the whole bed and precipitate an unstoppable slide.

Variegated Glacier's 1983 surge provided a unique opportunity to investigate the mechanisms of glacial flow. But there are still unsolved mysteries. For example, what causes the change in the basal water system that sets the glacier into surge in the first place? What is the switchover process that terminates the surge in summer? Where does the water come from, and how does it become available first in midwinter, when there is no melting to furnish it? And how does the surge mechanism control the propagation of the surge front and of the still unexplained, complex oscillations that accompanied the surge?

The glacier did not surge again in the winter of 1984. But the unanswered questions will continue to draw Kamb and other geologists back to Variegated Glacier even in less "exciting" times. □ — *JD*