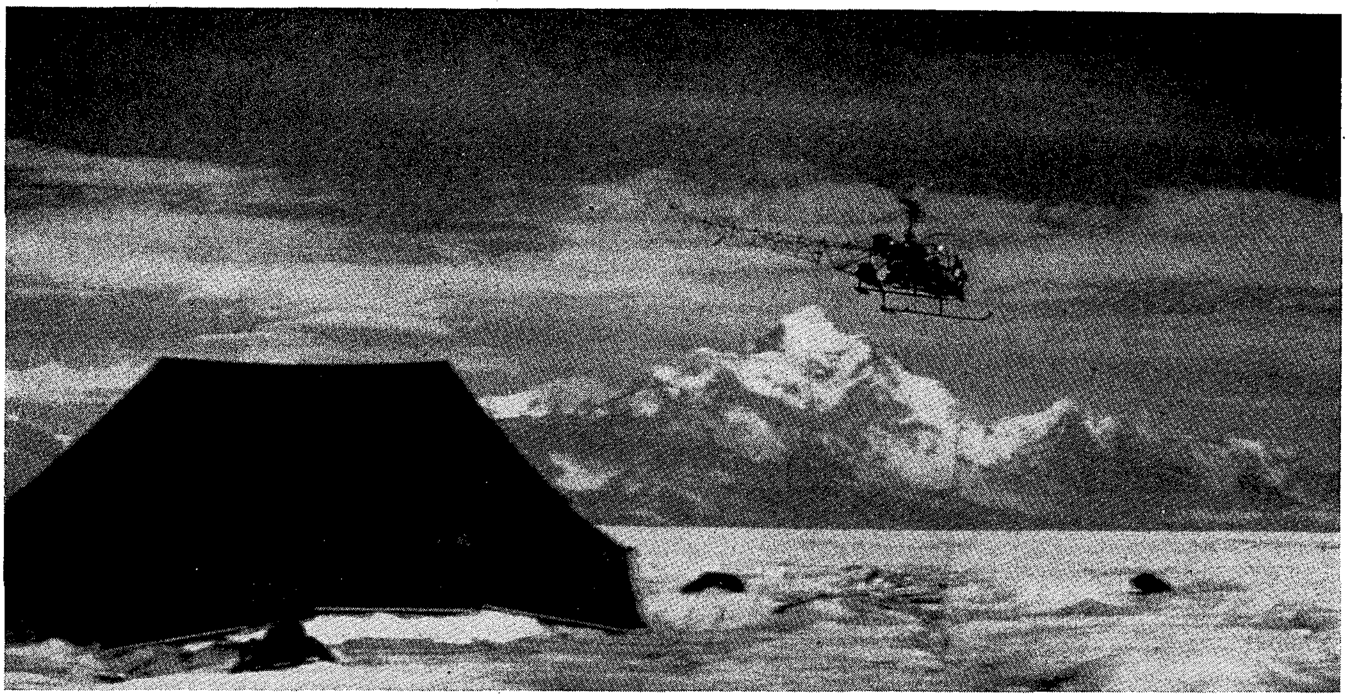


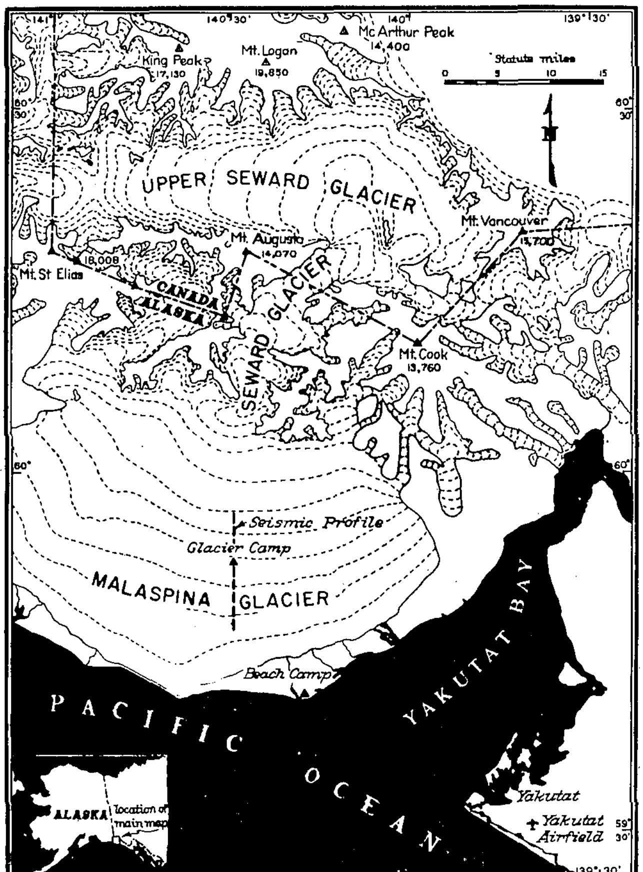
Field camp near the center of Malaspina Glacier was linked to the outside world by means of a helicopter.

ON ICE

A report on Caltech's third season of field studies on Alaskan glaciers

by ROBERT P. SHARP

"HERE COMES THE EGG BEATER" was always a welcome cry at our camp on ice (above) near the center of Malaspina Glacier. It meant that our heliocopter, the last link in a somewhat tenuous chain of communication with the outside world, was coming in from the "Beach Camp" (left) with news, mail, supplies, equipment, and possibly a highly prized box of cereal flown in from Yakutat to brighten up the breakfast menus. Pilot Al Luke and mechanic Bob Luman successfully maintained their link in this chain in spite of difficult operating conditions, but communication between the "Beach Camp" and Yakutat, the main source of supplies, was broken in mid-summer by the tragic disappearance of the expedition's Norseman plane during a routine flight from the upper Seward Glacier. Its fate remains unknown to this day.



Map showing field area for "Project Snow Cornice"

East margin of Malaspina Glacier, covering more than 1000 square miles of the flat coastal plain of southern Alaska.

The summer of 1951 constituted Caltech's third season of field studies on Alaskan glaciers as part of "Project Snow Cornice," an endeavor of the Arctic Institute of North America directed by Walter A. Wood. Initial phases of this activity have been earlier reported in *Engineering and Science* (November, 1948). Field work in 1949 yielded good data on temperature regimen, melt-water behavior, the processes and mechanisms converting snow to glacier ice, and the items of income and expenditure in the glacier's budget. This work will not be treated here except to note that even in an average year the budget of the Seward-Malaspina glacier system shows a deficit in the neighborhood of 850 billion gallons of water, thus overshadowing in size at least, the deficit in our national monetary budget.

In previous years, most of the work had been devoted to the upper reaches of this glacier system, but in the summer of 1951 attention was focused on the Malaspina Glacier, a great sheet of ice covering more than 1000 square miles of the flat coastal plain of southern Alaska along the foot of the St. Elias Mountains (above). Our principal objectives were to determine the mode of flowage within this sheet of ice and to relate it to the structures developed therein (below). Geologists have

Study of structures like those shown here leads to a better understanding of the mode of flowage within a glacier.

long been interested in glacier movement, because ice is a rock which undergoes solid flowage on the Earth's surface where the process can be observed and not, as in the case of most other rocks, far beneath the surface beyond the view of man.

It is perfectly logical to suppose that an ice stream flowing down a steep mountain canyon moves in part by sliding over its rock floor, especially where its base is well lubricated by meltwater. Nonetheless, studies of glacier flow show that only a small fraction of the total movement occurs in this manner; the rest is by adjustment within the ice body itself. Some of this movement takes place by slippage along discrete shear planes, at least in the brittle and somewhat rigid crust of a glacier, for displacements of this type have actually been measured. However, it seems equally certain that at greater depth within the ice much of the yielding is by a type of solid flowage that obeys some of the laws of fluid mechanics. The laminar character of this solid flow is recorded by the prominent banded or foliated structure in glacier ice. This foliation closely resembles that of metamorphic rocks which are thought to have experienced similar flowage deep within the Earth's crust. The major problem is to determine the mechanism by which this solid flow occurs.

Preparing a thin-section of ice for study on an oversized universal stage, which is shown at the left.

Glaciological theories

Glaciers consist of relatively large ice crystals, some many inches in diameter, all in close contact. One theory holds that the ice mass yields by shifting and rotation of these individual crystals, a process presumably facilitated by local and temporary pressure melting. Another concept calls for yielding by slippage along distinct planes within the individual crystals. Neither theory is necessarily exclusive of the other, and just how much of the solid flow in ice is due to intergranular shifting and how much to intragranular slippage remains an open question.

Aspects of this problem were attacked on the Malaspina by George P. Rigsby ('48), assisted by Donald R. Baker ('50), using an oversized universal stage (above), constructed by Rudolph von Huene ('34). Rigsby was able to determine the size, intercrystalline relation, and crystallographic orientation of the grains in thin-sections of ice cut from the glacier. This study showed that the various ice crystals were complexly and intricately intergrown, a relation previously demonstrated by Dr. Henri Bader during the 1949 work. If the same intercrystalline relations exist deep within the glacier as on the surface, significant flowage by intergranular shifting is out of

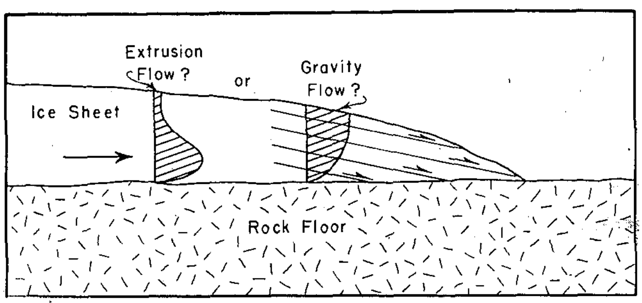
This sensitive micro-altimeter determines elevations accurately for use in gravity survey calculations.

The gravity meter is used for determining the configuration of the rock floor beneath the glacier.

Field workers operate seismic recording equipment for measuring thickness of ice.

the question. It was also found that optical axes of the crystals in the Malaspina ice had strong preferred orientations. According to theory, the orientation should be such that the direction of easiest yielding (a glide plane) in each crystal is parallel to the direction of shear in the ice body. Heretofore, it has been thought that only one direction of easy gliding existed in an ice crystal, but the results obtained here suggest that the picture may be considerably more complicated and that at least two other directions of gliding may be involved. We feel reasonably certain that a considerable amount of the flow experienced by Malaspina ice has occurred by slippage along glide planes in the individual crystals, because the optical orientations of these crystals bear a definite and consistent relation to the banding in the ice created by flowage.

Let us now return briefly to the mental picture of an ice stream flowing down a steep mountain canyon. It is easy to see how a component of gravity parallel to the sloping canyon floor can be the prime motive force for this movement, no matter what the detailed mechanics. But how about a sheet of ice resting on a flat surface?



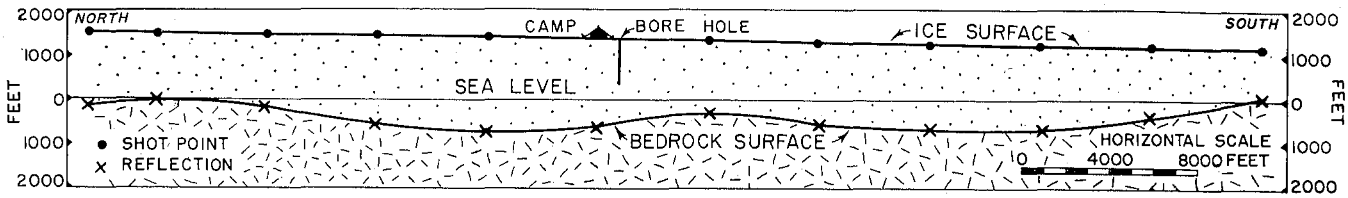
Diagrammatic representation of two possible modes of flow in a sheet of ice resting on a horizontal floor.

It is known that such masses flow, but the motive force cannot be a component of gravity parallel to the flat rock floor. In the early stages of World War II, Max Demorest, an American glaciologist who later perished during a rescue mission on the Greenland Ice Sheet, expressed more clearly than before the idea that flowage in such a sheet is caused primarily by pressure differences within the ice mass arising from unequal thicknesses. According to this concept, plastic ice deep within the glacier is squeezed or extruded from regions of high pressure toward regions of lower pressure, usually the margins of the sheet (below).

This deductive idea has been attacked on theoretical grounds by British glaciologists and physicists, with the counter suggestion that a sheet of ice flows across a flat land surface by movement along planes within the glacier which slope downward toward the margin. It was obviously time for a return to the field to gather further data and to test these opposed concepts. This was another objective of the Malaspina work.

Field testing

First, we had to know something about the configuration and slope of the rock floor beneath Malaspina Glacier. This problem was attacked by C. R. Allen (M.S., '51) and G. I. Smith (M.S., '51) with seismic equipment (above) and a gravity meter, the latter generously loaned by Atlas Exploration Co. of Houston. The gravity work was greatly aided by a sensitive micro-altimeter loaned by United Geophysical Co., Pasadena. Allen and Smith, briefed and trained by Dr. C. H. Dix of the Institute staff, obtained observations along a 10-mile north-south radial profile on the Malaspina. These showed that the floor beneath the center of the glacier slopes back



A ten-mile radial profile on Malaspina Glacier obtained from seismic reflections. Vertical exaggeration is 2x.

toward the mountains and that the ice thickness ranges between 1130 and 2075 feet (above). It was also discovered that the floor beneath the center of this glacier is at least 685 feet below sea level.

Thus, the sheet of ice constituting Malaspina Glacier moves uphill on much of its journey outward from the base of the mountains. This it cannot do by gravity, at least in so far as movement over its floor is concerned. Nor can the thrust of the Seward Glacier pouring out of the St. Elias Mountains provide the motive force, for this would be a little like trying to shove a sheet of tissue paper up a slope by pushing on one edge with a toothpick.

To solve the problem of mode of flow within the Malaspina sheet the vertical velocity profile within the glacier must be known. To obtain this information, we proposed to sink a vertical hole as deep into the glacier as possible, leave the drill pipe in the hole, and to measure the subsequent deformation as the pipe was bent by the flowing ice. No very satisfactory mechanical drilling methods simple enough for our use and suitable for penetrating to any great depth in ice have been developed. Our hole was bored with an electrically heated hot point (below), a gigantic soldering iron, so to speak. This was designed and fabricated in the Caltech Electrical and Mechanical shops on the campus—largely through the good efforts of Tex Mangum.

Space does not permit a recounting of the trials and tribulations experienced by Don Baker and the rest of us in boring this hole. It is sufficient to say that a depth of 1000 feet was finally attained. The orientation of the pipe was successfully determined by means of an inclinometer generously loaned by the Parsons Company of South Gate, California, before the glacier camp was evacuated at the end of August. A resurvey of the pipe is planned for 1952 which should yield data bearing on the opposing theories of flowage in a sheet of ice like Malaspina Glacier. Ultimately, the pipe will probably be sheared through or crushed, and measurements of its deformation will no longer be possible. However, a similar experiment in a Swiss glacier suggests that this is not likely to happen for several years.

If the theory of pressure-controlled extrusion flow is correct, the pipe should show a deformation or flowage curve in which the lower part moves outward more rapidly than the top. If the reverse occurs, then support will be given to some other concept, perhaps that of the British in which movement is by gravity flow along planes sloping outward toward the margin. Study of surface structures in the Malaspina Glacier makes us doubt that flow occurs along such outward sloping planes.

Boring a thousand-foot hole into ice by means of an electrically heated hot point.