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A Short and Somewhat Personal History of Yukon Glacier Studies in the Twentieth Century

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ABSTRACT. Glaciological exploration of Yukon for scientific purposes began in 1935, with the National Geographic Society's Yukon Expedition led by Bradford Washburn and the Wood Yukon Expedition led by Walter Wood. However, Project "Snow Cornice," launched by Wood in 1948, was the first expedition to have glacier science as its principal focus. Wood's conception of the "Icefield Ranges Research Project" led the Arctic Institute of North America (AINA) to establish the Kluane Lake Research Station on the south shore of Kluane Lake in 1961. Virtually all subsequent field studies of Yukon glaciers were launched from this base. This short history attempts to document the trajectory of Yukon glacier studies from their beginnings in 1935 to the end of the 20th century. It describes glaciological programs conducted from AINA camps at the divide between Hubbard Glacier and the north arm of Kaskawulsh Glacier and at the confluence of the north and central arms of Kaskawulsh Glacier, as well as the galvanizing influence of the 1965–67 Steele Glacier surge and the inception and completion of the long-term Trapridge Glacier study. Excluded or minimized in this account are scientific studies that were conducted on or near glaciers, but did not have glaciers or glacier processes as their primary focus.

Key words: glacier studies, St. Elias Mountains, Icefield Ranges Research Project, Kluane Lake Research Station, Yukon

RÉSUMÉ. L'exploration glaciologique du Yukon à des fins scientifiques remonte à 1935, à l'occasion de l'expédition du Yukon par la National Geographic Society dirigée par Bradford Washburn et de l'expédition Wood Yukon dirigée par Walter Wood. Cependant, le projet « Snow Cornice » mis en œuvre par Walter Wood en 1948 a été la toute première expédition à être axée principalement sur la science des glaciers. En fait, le projet de recherche sur les chaînons des glaciers mis au point par Walter Wood a incité l'Institut arctique de l'Amérique du Nord (IAAN) à mettre sur pied la station de recherche du lac Kluane sur la rive sud du lac Kluane en 1961. Presque toutes les autres études sur le terrain relativement aux glaciers du Yukon ont eu cette base comme point de départ. Cette brève histoire tente de répertorier la trajectoire des études des glaciers du Yukon depuis leurs débuts en 1935 jusqu'à la fin du XX[e] siècle. On y décrit les programmes glaciologiques réalisés à partir des camps de l'IAAN à la ligne de partage entre le glacier Hubbard et le bras nord du glacier Kaskawulsh ainsi qu'à la confluence des bras nord et centre du glacier Kaskawulsh. On y décrit également l'influence de galvanisation de la crue du glacier Steele de 1965 à 1967 ainsi que la création et l'achèvement de l'étude à long terme du glacier Trapridge. Cette brève histoire aborde à peine, voire pas du tout, les études scientifiques réalisées sur les glaciers ou près de ceux-ci, études pour lesquelles les glaciers ou les processus des glaciers n'étaient pas le point de mire.

Mots clés : études de glaciers, monts St. Elias, projet de recherche sur les chaînons de glaciers, station de recherche du lac Kluane, Yukon

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HISTORICAL CONTEXT

In Europe, the scientific study of glaciers was well established by the 1840s. Early milestones include Louis Agassiz's *Études sur les glaciers* (Agassiz, 1840) and *Système glaciaire* (Agassiz et al., 1847), together with a series of published letters by James D. Forbes (Forbes, 1842a, b, 1843) in which direct measurements of glacier flow were reported. Not surprisingly, glacier science in the United States and Canada lagged far behind. Exploration of the North America Cordillera was underway, but scientific study of glaciers was not a priority. Agassiz's arrival at Harvard in 1847 must have helped to promote interest in glaciers and ice ages, but he himself did not resume glaciological fieldwork. The earliest substantial North American researchers seem to have been G. Frederick Wright of the United States Geological Survey (USGS) and Oberlin Theological Seminary, who worked on Muir Glacier in Glacier Bay and made direct measurements of its flow (e.g., Wright, 1887); Israel C. Russell of the USGS and the

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University of Michigan, who worked on the Alaska coast, including Malaspina Glacier (e.g., Russell, 1893); Thomas C. Chamberlin of the University of Chicago, whose glaciological field sites were in Greenland (e.g., Chamberlin, 1894a, b); and Harold F. Reid of Johns Hopkins University, who measured glacier flow rates in Glacier Bay, Alaska, and encapsulated his insights into remarkably sophisticated contributions on glacier physics (e.g., Reid, 1895, 1896).

Glacier field studies in southwestern Canada began in the late 19th century. Access to the glaciers of the southern Rocky Mountains and the Selkirks had been greatly facilitated by the completion, in 1885, of the Canadian Pacific Railway route through Rogers Pass, British Columbia, and the establishment of Glacier House near the top of the pass (Putnam, 1982). In 1888, William S. Green, using an alidade and a plane table, performed what he correctly described as a "rough survey" to measure the flow of Illecillewaet Glacier, near Glacier House, and found that one marker seemed to have moved 20 feet in 12 days (Green, 1890:218–219). Soon after, members of the Vaux family, well-to-do amateur scientists from Philadelphia, launched a more systematic study of the flow and retreat of Illecillewaet and Asulkan Glaciers in the Selkirks and Victoria, Horseshoe, Wenkchemna, and Yoho Glaciers in the southern Rockies (e.g., Vaux and Vaux, 1899a, b, 1901, 1906). The Smithsonian Institution in Washington organized an expedition in 1904 that focused solely on glaciers of the Canadian Rockies and the Selkirks and resulted in a substantial monograph authored by William H. Sherzer (1907). Sherzer also measured ice flow rate, and his field sites included most of the glaciers studied by the Vaux family, but the ambition of this work is impressive. Somewhat later, combining vocation and avocation, Arthur O. Wheeler, a trained topographic surveyor and eventual president of the Canadian Alpine Club, began to study the flow of Yoho Glacier (Wheeler, 1907, 1910, 1911, 1913). All these studies were driven by curiosity, and by the standards of the time are interesting and worthwhile, but the work was not aimed at testing a scientific hypothesis or answering a clearly framed science question.

YUKON STUDIES

Scientific study of Yukon glaciers was initiated by Bradford Washburn and Walter Wood, dynamic American alpinists with a scientific bent. Washburn was leader of the 1935 National Geographic Yukon Expedition and Wood the leader of the 1935 Wood Yukon Expedition sponsored by the American Geographical Society. The expeditions shared a common focus on exploration and were motivated by the need to test logistics and by the hope of spotting targets and routes for future climbing endeavours. Both expeditions relied heavily on aerial reconnaissance and photography. Washburn traversed the St. Elias Mountains by dog team from a starting point on Lowell Glacier to Nunatak Fiord on the Alaska coast (Washburn, 1936). Aerial photographs were taken and theodolite survey stations established but Washburn was more of an explorer, climber, and cartographer than a scientist (Roberts, 2009). Several years later, he became Director of the Boston Museum of Science. Wood was also an accomplished climber, indeed he was qualified as a Swiss mountain guide, but in addition he had received technical training in photogrammetry from the Eidgenössische Technische Hochschule in Zürich. He launched aerial reconnaissance flights from a base at Burwash Landing to explore the regions of Donjek, Spring, "Wolf Creek" (now Steele), and Klutlan Glaciers and to travel overland from Burwash Landing to the middle reaches of Wolf Creek Glacier near its big bend. Wood and his team took daily meteorological observations and used a Wild theodolite to conduct a topographic survey. The expedition culminated in the first ascent of Mt. Steele, but the scientific legacy was not substantial.

Wood Yukon Expeditions and "Wolf Creek" Glaciers

Wood's 1935 expedition (Wood, 1936) set the stage for subsequent climbing expeditions in 1936, 1939, and 1941, during which first ascents were made of Mt. Walsh and Mt. Wood (named after a former Commissioner of the Yukon Territory, not Walter). Scientifically, the 1941 Fourth Wood Yukon Expedition was by far the most fruitful. Wood had recruited Robert P. Sharp, a young and exceptionally talented geologist who was just starting his academic career at the University of Illinois. Sharp was a remarkable individual (c.f., Sharp, 1981). While a geology undergraduate at Caltech, he quarterbacked the university football team, which, though not always dominant, could boast the Pasadena Rose Bowl as its home field. From there he went to Harvard for a doctorate and then to the University of Illinois. Years later, he became chair of the Division of Geology (subsequently Division of Geological and Planetary Sciences) at Caltech, was elected to the U.S. National Academy of Sciences, and in 1989, was presented the National Medal of Science by President George H.W. Bush.

While at the University of Illinois, Sharp was contacted by Wood, then director of the Department of Field Exploration at the American Geographical Society, and invited to join his 1941 expedition. The focus of Sharp's Yukon fieldwork was the glacial history and glacial geomorphology of the "Wolf Creek" glaciers (Sharp, 1947, 1951a). This work laid the scientific foundation for subsequent studies of Steele Glacier (Fig. 1: site A) and smaller glaciers such as Rusty and Trapridge Glaciers (Fig. 1: site B) located in the "Wolf Creek" drainage basin.

Project "Snow Cornice"

The Arctic Institute of North America (AINA) came into existence during the final stages of World War II, and in 1945, the Institute was chartered by an act of the Parliament of Canada. In 1948, Wood became Director of the New York office of AINA and launched Project Snow

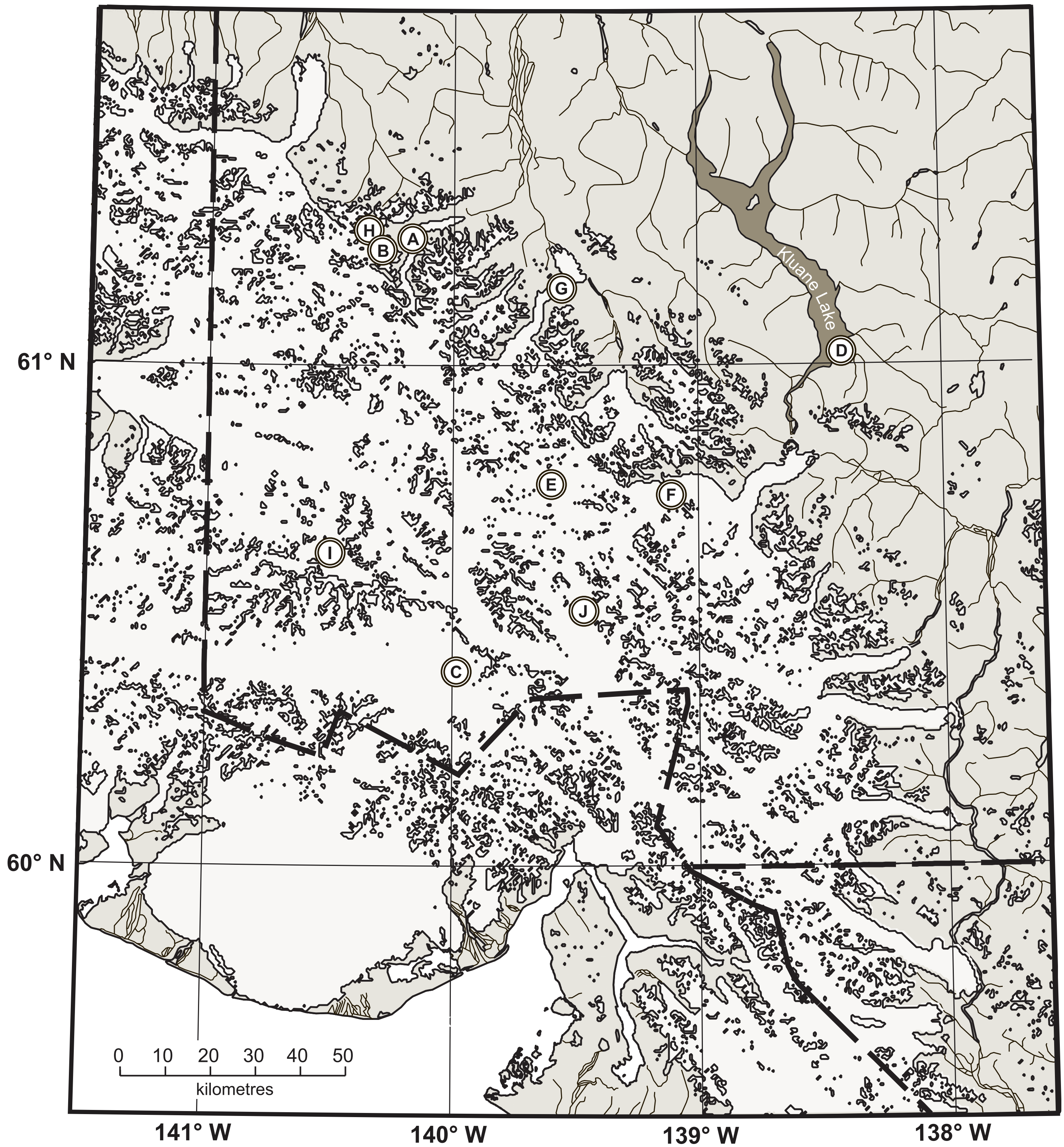

FIG. 1. Map of the main glaciological study sites in Yukon: (A) Steele Glacier, (B) Rusty and Trapridge Glaciers), (C) Upper Seward Glacier, (D) Kluane Lake Research Station, (E) Kaskawulsh–Hubbard Divide Station, (F) Kaskawulsh Glacier confluence, (G) Donjek Glacier, (H) Hazard Glacier, (I) Mount Logan Northwest Col, and (J) Eclipse Icefield.

Cornice, an ambitious glaciological study of the upper Seward Glacier (Wood, 1948). Names can be deceptive, and the upper Seward Glacier (Fig. 1, site C) in Yukon is, in fact, the catchment area of Malaspina Glacier in Alaska; however, it is doubtful that any of those involved thought much about the international border that cut through their object of study. Although the field site was in Yukon, the logistic base for "Snow Cornice" was Yakutat, Alaska, which afforded the nearest and best-supported landing strip for the Institute's Norseman aircraft. Sharp, who by this time had returned to Caltech, was enlisted to run the glaciology and geology programs, and the scientific emphasis of his glaciological research was distinctly geophysical in character. He set out to measure the evolving temperature of the firn layer, using electrothermal hot point probes (then state-of-the-art) to drill and instrument holes as deep as 62 m (Sharp, 1951b). By the standards of the time, this was cutting-edge science.

Fieldwork resumed in summer 1949, 1950, and 1951. The work undertaken in summer 1951 aimed at measuring the vertical distribution of glacier flow velocity at a site on the piedmont lobe of Malaspina Glacier. Sharp was inspired by the success of a British study of Jungfraufirn in the Swiss Alps, led by Max Perutz (Perutz, 1950; later the 1962 Nobel Laureate in Chemistry), which sought to refute the "extrusion flow" hypothesis, a flawed proposal that glaciers flow more rapidly at depth than at the surface. (An engaging account of the history of this theory can be found in Waddington, 2010.) Sharp wished to test the result on piedmont glaciers, which differ in form (and possibly in flow) from Jungfraufirn. To Sharp (1953:182), the piedmont glacier "appears to offer conditions ideally suited for extrusion flow" so this would be a more stringent test than that of Perutz. Accordingly, he used a hot point probe to drill a 305 m deep hole and cased this with aluminum pipe. An inclinometer was then placed in the hole and the variation of tilt angle with depth was measured at intervals of 15 m at two different times. In this manner, Sharp (1953) determined the change in flow rate with depth. Like Perutz on the Jungfraufirn, Sharp found no evidence for extrusion flow. A depth of 305 m was noteworthy for an electrothermally drilled glacier hole: the one on the Jungfraufirn was only 137 m and for that effort a reliable electrical source, the Jungfraujoch Research Station, was close at hand.

Project Snow Cornice ended tragically on 21 July 1951, when the plane carrying Wood's wife, Foresta, daughter, Valerie, and pilot, Maurice King, vanished while flying from the glacier camp to Yakutat (Washburn, 1951).

Icefield Ranges Research Project

Wood's commitment to the Yukon Territory remained strong, and in 1961 he launched the first field season of the Icefield Ranges Research Project (IRRP) and established its base camp on the south shore of Kluane Lake, the present site of AINA's Kluane Lake Research Station (KLRS; Fig. 1: site D). This project was a joint undertaking of AINA and the American Geographical Society, of which Wood was then president. Wood served as project leader and Richard H. Ragle, a trained glaciologist and accomplished pilot, was the field leader. Wood (1969a:xi) had a sweeping vision for the IRRP, one that can still be recognized 50 years after the fact in the collective research efforts of present-day researchers at KLRS:

> [T]his project seeks understanding of the multiple facets that comprise the natural environment of the St. Elias Mountains of Alaska and Yukon Territory. Its approach to the task is truly geographical, within the widely accepted current meaning of geography as an integrator among the scientific disciplines. Not only is the project multidisciplinary in its areas of research, but it is also interdisciplinary in its approach to objectives.

Glacier studies were especially important to Wood's vision, and he saw research on glaciers of the St. Elias Mountains as a counterbalance to the emphasis that polar glaciers and ice sheets had received during the 1957–58 International Geophysical Year (Wood, 1969b).

Initially IRRP glaciological research was centred at Divide Camp (Fig. 1: site E), near the divide between Hubbard Glacier and the north arm of Kaskawulsh Glacier. The 1961 field season was devoted to reconnaissance and to logistics, including tests of ski-equipped aircraft and motorized over-snow vehicles (Wood, 1963). As a foundation for future research efforts, Wood established a network of survey reference stations in the Divide area. In summer 1962, an ambitious glaciological program was launched at Divide. Geophysical mapping was initiated by Alex Becker, a McGill-based geophysicist who had previous experience as a member of the McGill University Axel Heiberg Island Expedition (Becker, 1963). Ueli Zysset, a Swiss surveyor who had also served on the Axel Heiberg Expedition, and his assistant Paul Cress, another Axel Heiberg veteran, established a large network of ice flow markers on Kaskawulsh and Hubbard Glaciers. Ralph Lenton, an AINA employee and member of the 1957–58 Commonwealth Trans-Antarctic Expedition, brought a wealth of polar experience and a practical knowledge of glaciology. Zysset's survey set the stage for subsequent surveys in 1963 that would allow surface flow rate to be calculated. The weather that summer was unusually poor, and to my knowledge, excepting expedition reports, no formal scientific publications resulted from that season's field effort.

Exploiting superb summer weather, the 1963 research at Divide finally yielded an abundant scientific return. Having served as Becker's field assistant in 1962, I took over the gravity and seismic survey work as a University of Toronto MA thesis project (Clarke, 1967); Dan Sharni (Ohio State University) resurveyed 60 poles installed by Zysset in 1962; Philip Wagner of the University of Michigan examined changes in the snow cover and facies (Wagner, 1969a, b); and Donald Macpherson of the University of Alberta studied the oxygen isotope ratios in snow and ice samples collected near Divide (Macpherson and Krouse, 1969). That same summer, James Havens (University of London) and David Saarela (Massachusetts Institute of Technology) established the first manned weather station at Divide (Havens and Saarela, 1964).

Glaciological work continued in 1964, with four significant studies organized by the Institute of Polar Studies at Ohio State University. From Divide Camp, Henry Brecher sought evidence for temporal variations in ice flow rate (Brecher, 1966) and concluded that, when measurement error was taken into account, short-time flow rates were indistinguishable from the mean annual rates. In a companion study, Gerald Holdsworth conducted pioneering research on the mechanics of transverse crevasse formation (Holdsworth, 1965, 1969). This work marked a turning point for the IRRP glaciological program because it was the first study to focus on a fundamental problem rather than on the quantitative description of the glacier geometry and flow field. Some 25 km downglacier from the Kaskawulsh – Hubbard Divide and below the equilibrium line altitude, a camp was established near the confluence of the north and central arms of Kaskawulsh Glacier (Fig. 1: site F). The confluence study area is the complementary opposite of the Divide study area: at Divide two glaciers flow apart, whereas at the confluence two tributaries flow together. Both situations are scientifically interesting. At the confluence, Gil Dewart began an ambitious seismic study that included ice thickness mapping, but he added a strong emphasis on measuring physical properties of ice such as the Poisson ratio and acoustic anisotropy (Dewart, 1968). Peter Anderton's (1970) research was mainly concerned with how the stress field near the confluence affected the macroscopic structure of the glacier and the microscopic structure of its ice.

Anderton and Dewart continued their glaciological fieldwork in 1965. They were joined by a student team from the Department of Geography at the University of Michigan led by their professor, the talented and enthusiastic Melvin Marcus, who was to become the IRRP project scientist and field director. Much of Marcus's IRRP research was concerned with alpine climatology and other topics that lie beyond the scope of this history, but one of his students, Karen Ewing, began a two-year study of the surface hydrology of Kaskawulsh Glacier near the confluence camp. Ewing concluded that there were two general categories of supraglacial streams, those that were perennial and those that persisted for a year or less. She found, not surprisingly, that ice flow influenced stream evolution (Ewing, 1972). In the course of this work, she had the opportunity to witness the onset of a short-lived glacial water spout, which attained a height of 4 – 5 m, then terminated, and two days later, reversed its flow and became a moulin (Ewing et al., 1967). At Divide that same summer, Takeo Yoshino from the University of Electro-Communications in Tokyo carried out detailed measurements of the dielectric properties of snow and ice samples (Yoshino, 1972) with the aim of assessing the feasibility of radio echo sounding surveys in that region.

The Icefield Ranges Research Project, so important in reactivating Yukon glaciological research, seems to have faded away rather than died. There was no 1973 IRRP report in *Arctic*. In the absence of a designated scientific leader, Ken de la Barre, Director of AINA's Montreal office, and Andy Williams, the newly hired KLRS camp manager, prepared the 1974 report (de la Barre and Williams, 1975). The final IRRP report to appear in *Arctic* was for 1975 – 76 and was submitted by de la Barre (1977). Wood had conceived the Icefield Ranges Research Project as much more than a research umbrella and had managed to attract financial support for his big-picture vision. When that funding model began to fail, there was a gradual transition to individual projects that came with their own sources of funding.

Steele Glacier Surge and Its Aftermath

The 1965 – 67 surge of Steele Glacier was a turning point for glacier studies in Yukon. *Time Magazine* (Anon., 1966) called Steele the "Galloping Glacier." Coincidentally, the timing of the surge overlapped with the 1967 Yukon Alpine Centennial Expedition (Fisher, 1972), whose climbing parties were camped on the right margin of the actively surging glacier (Fisher, 1968). The surge itself was not noticed until spring 1966, although Austin Post had identified some unusual activity in his August 1965 aerial photographs (Wood, 1972). From the scientific perspective, the timing of the Steele Glacier surge could hardly have been better. Yukon glacier surges had been noted on other occasions, for example, the report of Austin Post (1966) on the surge of Walsh Glacier, but the question of the surge mechanism had received little attention since Alaskan work in the early 1900s by Ralph Tarr and Lawrence Martin (1914). In that study, Tarr and Martin proposed that unusual glacier activity observed in the Gulf of Alaska had been triggered in 1899 by a series of large earthquakes centred near Yakutat Bay, Alaska. An important study by Post (1965) concluded that there was no evidence for an earthquake trigger for surges and that the questions of the surge trigger and mechanism remained unsettled. Post also drew attention to the curious fact that, though rare, North American surging glaciers are highly concentrated in Yukon and Alaska (Post, 1969).

The surge of Steele Glacier thrust the problem of the surge mechanism to centre stage at the very moment when scientific curiosity had been awakened. Several papers describing the progress of the surge were completed (Bayrock, 1967; Stanley, 1969; Thomson, 1972) and the question of mechanism was imaginatively tackled (e.g., Nielsen, 1969). In 1969, shortly after the Steele surge ended, Donjek Glacier (Fig. 1: site G) to the south of Steele began a surge, and Peter Johnson of the University of Ottawa examined its morphological consequences (Johnson, 1972).

A significant and immediate consequence of the Steele Glacier surge was the calling together of an international seminar on the "Cause and Mechanics of Glacier Surges." The meeting, held at St. Hilaire, Quebec, was organized by the National Research Council of Canada Subcommittee on Glaciers and chaired by the McGill glaciologist, Fritz Müller. Many of the most prominent international figures attended, among them William Budd, Colin Bull, William Field, Louis Lliboutry, Mark Meier, John Nye, Gordon Robin, Hans Röthlisberger, Sigurður Þórarinsson, and Johannes Weertman. The proceedings appeared as a special issue of the *Canadian Journal of Earth Sciences* (Ambrose,

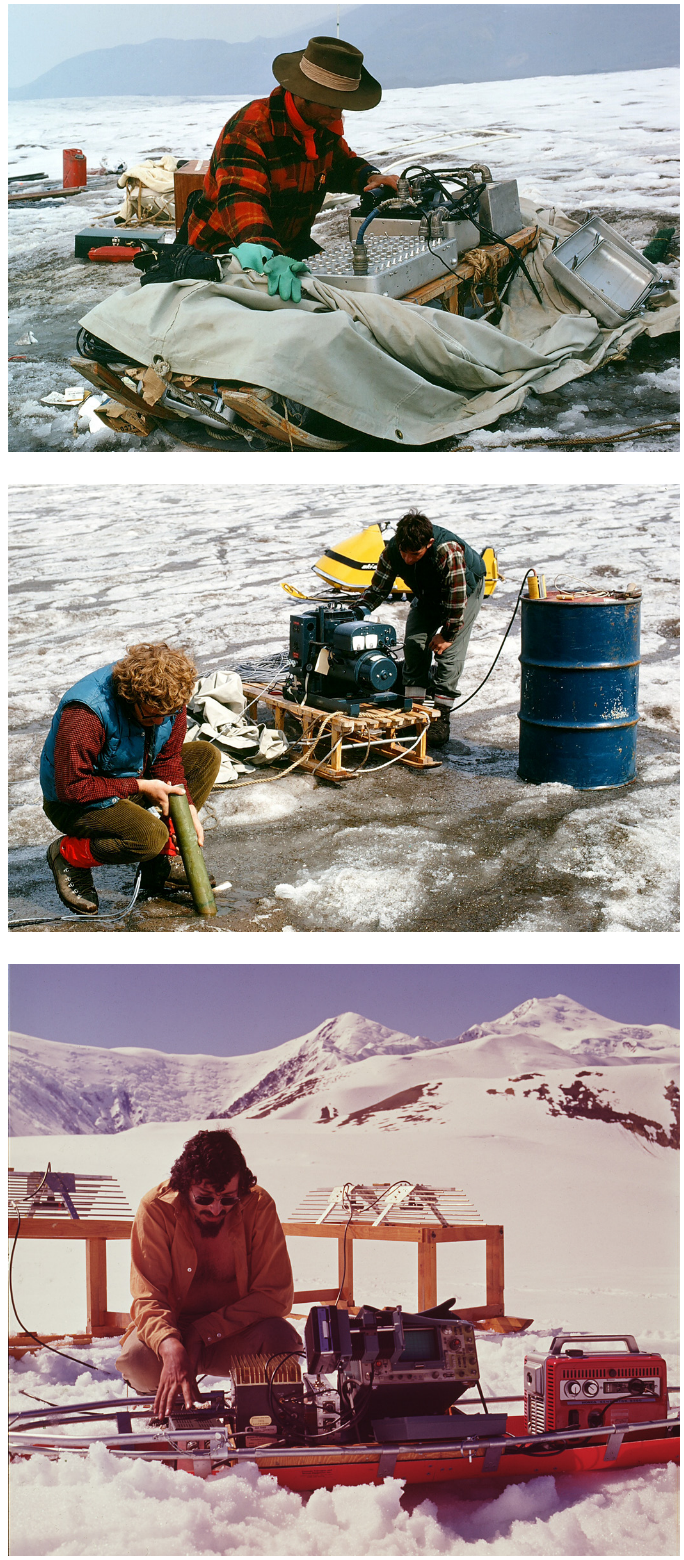

FIG. 2. Top: Seismic reflection survey equipment being operated (unsuccessfully) by the author on Rusty Glacier, 1968. Middle: Electrothermal hot point drilling apparatus in use on Rusty Glacier, 1969. Note the gasoline-fuelled 5 kVA electrical generator (on the sled) and the cylindrical hot point probe (displayed by David Classen). Bottom: Barry Narod testing his UHF radar sounder on Rusty Glacier (1975).

1969). What was then known about surges was summarized clearly in a review paper entitled "What are glacier surges?" (Meier and Post, 1969). The characteristics of surging glaciers include the following: (1) all surging glaciers surge repeatedly; (2) most surges for which we have information on timing are uniformly periodic; (3) surging glaciers occur only in certain restricted regions of western North America, but the reason for this is not evident; (4) the surge trigger is unknown.

The Steele surge brought fresh attention to the problem of surging and helped to reshape the priorities for glaciological fieldwork in Yukon and Alaska. Studying surges after they occur has not proven to be a useful approach to solving the puzzle of surges, and studying large surging glaciers such as the Steele creates the additional problem of scale, at least relative to Canadian levels of research funding. Thus, when the Steele Glacier surge stopped, it spawned new interest in small surge-type glaciers that were currently in their quiescent phase but might be expected to surge. In 1967, Rusty Glacier, a small surge-type glacier in the Steele Creek watershed that Sharp (1947) had previously referred to as "Glacier 12" and Austin Post had dubbed "Fox Glacier," was selected for a multidisciplinary IRRP study of a surge-type glacier. Research on the mass balance (Brewer, 1972), flow (Collins, 1972), hydrology (Faber, 1972), thickness (Fig. 2: top panel; Crossley and Clarke, 1970; Clarke and Goodman, 1975), and thermal structure (Classen and Clarke, 1971, 1972; Clarke and Goodman, 1975) was carried out. The main conclusions relevant to the surge mechanism were that the lower part of the glacier was acting as a dam to flow from the upper part (Collins, 1972), and that despite the cold ice near its surface, parts of the bed of the glacier were at or near the melting temperature. The latter result is consistent with some kind of thermal trigger for surging.

Research on Rusty Glacier continued for several years but it became apparent that the glacier was not recovering from its previous surge. In contrast, neighbouring Trapridge Glacier ("Glacier 13" in Sharp, 1947), also of the surge type, seemed healthy and active. Collins (1972) had established a flow survey network on this glacier as well, and its thickness (Goodman et al., 1975) and thermal structure (Jarvis and Clarke, 1975) were known.

By 1972, the surface of Steele Glacier had become sufficiently smooth that deep drilling could be conducted from its surface. This technique allowed the post-surge thermal structure to be measured at a number of sites (Jarvis and Clarke, 1974; Clarke and Jarvis, 1976) and led to the conclusion that the thermal structure was similar to that of Trapridge and Rusty Glaciers. However, the thermal structure of Steele Glacier was greatly disturbed by the creation of deep and partly water-filled crevasses during the surge. Drilling on Steele Glacier continued in 1975, but with a different emphasis. Thermally drilled holes were "bailed" as the drilling proceeded, a tedious business, and meltwater samples were collected at intervals of 1 or 2 m. These samples were subsequently analyzed in a mass spectrometer, and oxygen isotope ratios ($^{18}O/^{16}O$) were determined. The results were curious and difficult to interpret because the isotopic ratio seemed to vary with depth in a sawtooth pattern, which was attributed to oscillatory surges of Steele Glacier (Ahern, 1980). This conclusion was eventually tested, using a numerical ice dynamics model that included isotopic tracing, and was rejected (Waddington and Clarke, 1988).

The Steele surge raised the surface elevation of the lower half of the glacier and ca. 1967 caused an ice dam to form along the hydrologic left margin of the glacier near the conspicuous "big bend" in the flow channel. The maximum filling level of the ice-dammed reservoir was controlled by a spillway beyond the glacier margin. Because ice is less dense than water, such dams have a tendency to float when the water level rises, which can result in the rapid release of impounded water. The newly formed lake was informally named "Hazard Lake" after Hazard Glacier (Fig. 1: site H) upstream from the dam. In summer 1974, Sam Collins carried out a bathymetric survey of the lake with the aim of estimating its volume and the likely magnitude of an outburst flood or *jökulhlaup*, the Icelandic term for such releases. The lake survey was a complicated business involving a "volunteer," an inflatable kayak, a lead line, and an on-shore surveyor. Calving from the ice face into the lake added to the excitement, but misfortunes were avoided and a bathymetric map of the lake was completed (Collins and Clarke, 1977: Fig. 1). In late July 1975, the lake drained completely through a 13 km subglacial drainage conduit and remained empty through the summer of 1976, belatedly yielding ideal conditions for a bathymetric survey. In 1977, the lake refilled and began an annual cycle of filling and drainage, releasing episodic floods into Steele Creek. Thus, Hazard Lake indeed proved to be a hazard. Though the name is apt it is fortuitous, because the lake bears the surname of Isaac Peace Hazard, who was one of the mountaineers accompanying Wood on his 1935 expedition to climb Mt. Steele (Wood, 1936).

Once again the timing of a natural glaciological event coincided with an important scientific moment. At roughly the same time that the lake was delivering its first flood, John Nye, of Bristol University, was completing work on a seminal paper entitled "Water flow in glaciers: jökulhlaups, tunnels and veins" (Nye, 1976). Nye's theory was based on the example of subglacial lake Grímsvötn beneath the Vatnajökull ice cap in Iceland; annual floods from Hazard Lake presented an opportunity to test this theory. In 1978, we set out to record one of these floods by placing a water-pressure sensor on the lake floor and using it to measure the height of the water column as the lake filled and drained. The timing of outburst floods is not regular or predictable, so we installed the sensor in early July and then departed to a different field site. The flood occurred in early August, and we retrieved the data and pressure sensor in late September. The effort was a complete success and, emboldened by this good fortune, we planned an ambitious follow-up for summer 1979 with improved equipment. When we returned to the lake site on 11 July 1979, we discovered, to our chagrin, that the flood was already in progress, and there was no time to install new equipment. Instead, we simply observed the falling lake level and painted the clock time onto stones as they became exposed by the falling water level. A subsequent survey allowed this information to be converted to a graph of lake level vs. time. Despite our disappointed expectations, it was possible to test and confirm the Nye theory (Clarke, 1982).

Caught flat-footed by the early drainage in 1979, we resolved to arrive much earlier the following year. On 15 June 1980, Hazard Lake had been observed to be nearly full; on 24 June 1980, shortly after we arrived at the KLRS base, we flew over the lake to photograph it and fine-tune our plans. This time, worse than ever, the lake had drained completely. Some might portray the 1980 Hazard Lake study as a fiasco, but it served to turn our attention away from glacier-dammed lakes and back to glaciers. On the same flight that revealed the empty lake, we made an amazing discovery: Trapridge Glacier, which had seemed only mildly active in 1972 and 1974, had undergone a remarkable transformation (Fig. 3: top panel) that set the stage for our long-term field study of that glacier (discussed below in the subsection *Trapridge Glacier Study*).

In summer 1981 and 1982, Michael Maxwell continued the isotopic studies begun by Tim Ahern and collected samples from Trapridge Glacier and Backe Glacier, its neighbor to the south. Samples were collected in solid form by using a hand drill or ice screw to extract ice, and the research aim was to improve understanding of isotopic fractionation associated with subglacial processes. Maxwell (1986) collected samples from the exposed ice surface, subglacial tunnels, and ice cliffs, but the isotopic signals were so complicated that no simple interpretation emerged.

Development and Field Testing of Improved Drilling Equipment and Ice-Sounding Radars

Most of the glacier drilling carried out in the 1960s and 1970s relied on electrothermal hot point probes (Fig. 2: middle panel) similar to those used by Sharp (1951b, 1953). Drilling rates were excruciatingly slow—a rate of several meters per hour was typical—and for cold glaciers such as Rusty, Steele, and Trapridge the risk of freeze-trapping the probe was inescapable. Drilling proceeded round-the-clock, usually en plein air, with the warmly dressed driller cocooned incongruously on a folding lawn chair watching the tedious slithering of electrical cable as it followed the probe downward toward the glacier bed. News from Switzerland (Iken et al., 1977) that a hot water jet drill, based on an earlier design by Kasser (1960), was capable of drilling rates that exceeded 100 m h^{-1} was received with enthusiasm. In summer 1976, a prototype was developed and tested on Hazard Glacier, and a 220 m deep hole was drilled in four hours with a maximum drilling rate of 120 m h^{-1} (Napoléoni and Clarke, 1978).

During the 1976 field season, three holes were drilled to the bed of Hazard Glacier (Fig. 1: site H) using the new jet drill, and these were instrumented with thermistor cables

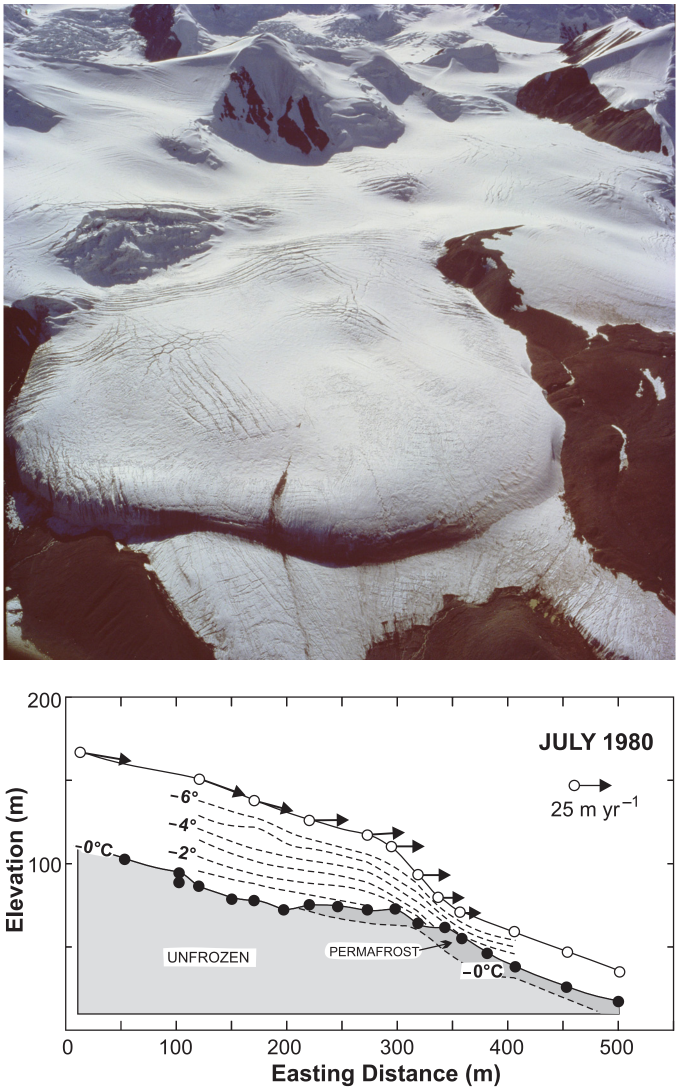

FIG. 3. Top: Oblique aerial photograph of Trapridge Glacier on 24 June 1980, showing the formation of a conspicuous bulge. Bottom: Profile across the bulge feature showing the July 1980 surface elevation profile (open circles), surface flow rate (arrows), bed profile (solid circles) and thermal structure (isothermal contours). Note that the lower part of the glacier (Easting 200–500 m) is frozen to its bed, which results in emergent ice flow (arrows directed outward from the ice surface). The figure is redrawn from Clarke et al. (1984).

to reveal the vertical distribution of ice temperature. This information proved useful when the glacier surged in 1981–82 (Clarke and Collins, 1984). Like other glaciers in the Steele Creek drainage basin, Hazard is cold at its surface, but temperature rises to the ice melting temperature as the bed is approached. As for Steele Glacier, the temperature profiles were complicated, and water-filled crevasses formed during past surges are the likely cause of this complexity.

Radar soundings on Trapridge and Rusty Glaciers had been carried out in the 1970s using an ultra-high frequency (UHF) radar designed by Ron Goodman, then of Environment Canada. The equipment worked brilliantly, but it had been tailored for installation in a Nodwell tracked vehicle rather than on man-hauled sleds. Something more compact, preferably airborne, was desirable, and as a doctoral project, Barry Narod (1979) tackled the problems of design and fabrication of a more portable system (Fig. 2: bottom panel). In the course of this work, helicopter-borne aerial surveys were successfully completed on Rusty, Trapridge, and Hazard Glaciers (Narod and Clarke, 1980, 1983).

Although Narod's UHF radar solved the problem of making airborne radars compact enough to operate from a small helicopter, it was incapable of sounding "temperate" glaciers (ones that are at the ice melting temperature), and it had insufficient power to penetrate more than several hundred metres of ice. This was not a problem for glaciers such as Rusty, Trapridge, and Hazard, which were cold and not thick, but large, cold glaciers such as Steele Glacier or temperate glaciers such as Kaskawulsh were beyond reach. The challenge of sounding temperate glaciers had recently been solved in principle (Watts and England, 1976) and was demonstrated several years later (Watts and Wright, 1981). The new radars were entirely unlike the UHF radar that had worked so well for Narod and Clarke (1980); they involved long wire dipoles that were most conveniently used on the glacier surface rather than trailed from an aircraft. Furthermore, they were light enough to be back-portable, and the transmitters were cheap to build (Narod and Clarke, 1994). With the development of low-power microprocessors, it became attractive to design compact radars as if they were computing equipment (Jones et al., 1989).

Trapridge Glacier Study

When Sharp visited the "Wolf Creek" glaciers, he found "Glacier 13" (now Trapridge) to be "advancing rapidly" (Sharp, 1947:29). We now recognize that the glacier was surging, and that a remarkable number of the glaciers in the Steele Creek basin are also surge-type glaciers (Clarke, 1976, Fig. 1). When Sam Collins (Fig. 4: top panel) began his survey of Trapridge Glacier, he found the glacier to be more active than Rusty Glacier and speculated that "its greater present activity makes it seem at least as likely to enter an active phase soon" (Collins, 1972:248). As in Rusty Glacier, there was some kind of obstruction to the downslope flow that resulted in a zone of flow compression in the lower part of the glacier and an upward component of ice flow. If this situation persisted, it would result in a thickening of ice upflow from the obstruction and a thinning of downflow that would result in the growth of a bulge in the zone of flow compression. There was no surface expression of this bulge in 1972, when the ice thickness (Goodman et al., 1975) and thermal structure (Jarvis and Clarke, 1975) were first measured. The conspicuous bulge that caught our attention in June 1980 (Fig. 3: top panel) had formed rapidly and was interpreted as a precursor of the next surge of Trapridge Glacier. Our disappointment with the Hazard Lake study was therefore short-lived, and we immediately redirected our efforts to Trapridge Glacier, setting in motion an annual field program that continued until 2007.

FIG. 4. Top: Sam Collins performing an ice motion survey of Trapridge Glacier (1984). Bottom: Erik Blake operating a hot water jet drill on Trapridge Glacier (1986).

Although the formation of the Trapridge bulge was a direct consequence of the zone of compressive flow (Collins, 1972), the cause of the flow obstruction was uncertain. Using a hot water drill and improved survey equipment, it was a simple matter to extend the hard-won efforts of Gary Jarvis (Jarvis and Clarke, 1975) and focus attention on the glacier thermal structure in the vicinity of the bulge. It was discovered that the bulge marked the transition between a region of the glacier that was warm-bedded (i.e., the bottom ice was at the melting temperature) and a region downslope, where the bottom ice was frozen to the subglacial bed (Fig. 3: lower panel; Clarke et al., 1984). Thus the bulge was formed by interaction between the flow and thermal structure of the glacier. It was hypothesized that if the thermal obstruction were breached, a surge might be released.

The advent of the hot water drill had a great influence on how mountain glaciers were studied. Much of the previous work had been aimed at a geometric characterization of glaciers. At first, this was limited to mapping their extent and surface topography, usually in combination with measurements of the surface ice flow field. With electrical hot point drills, a limited number of holes could be drilled to the bed in a single field season, and for mainly cold glaciers, such as Steele, Rusty, Trapridge, and Hazard, the installation of thermistors made it possible to measure ice temperature profiles and infer thermal structure. Until the late 1970s, time series data such as air temperature measurements were typically obtained by repeated hand-noted measurements or automatically recorded onto a chart recorder. Transistorized field-capable data loggers had only recently come into existence; for example, Campbell Scientific, Inc., one of the leading manufacturers of low-power electronic data loggers, was founded in 1974. It was another decade before these started to become standard equipment for field glaciologists.

Thus, in Yukon, the first scientific consequence of hot water jet drilling was to allow the usual measurements to be done less painfully. On Trapridge Glacier, this meant that the first applications of hot water drills were to facilitate the drilling of more holes, which were then instrumented with thermistors to allow a close study of glacier thermal structure (Clarke et al., 1984), and to encourage the use of hot water drilling to enable sampling of subglacial water and sediment. At the same time, the international glaciological community was abandoning the idea that glacier surges were thermally triggered and shifting toward the possibility that subglacial hydrology and subglacial sediment deformation might play important roles (e.g., Robin and Weertman, 1973; Boulton and Jones, 1979). In summer 1983, a single subglacial water pressure sensor was installed in Trapridge Glacier, the first for any Yukon glacier, and connected to an early electronic data logger. More than 11 kg of fluorescent Rhodamine WT dye (a standard water tracer) was injected into the same hole. The data logger managed to run unattended for several months, but nothing of great scientific interest came from this first effort; the injected dye seemed to disappear without a trace.

Subglacial Processes and Subglacial Instruments: Perhaps the main benefit of these first experiments was to highlight the fact that we could not make good use of our new ability to drill glacier holes without a greatly improved ability to take and record year-round measurements and without thinking hard about the kinds of measurements and devices that might be put to good use. Developing novel devices we could use to observe internal processes of glaciers year-round became a major theme of the Trapridge Glacier fieldwork—and these innovations are perhaps its greatest legacy. Thinking about the glacier surge mechanism was also developing fast, and as mentioned, the focus had shifted from thermal processes to subglacial processes such as subglacial water flow, subglacial sediment deformation, and the physical interactions of ice, water, and sediment. Hot water drills greatly simplified the challenge of accessing the bed of a glacier and robust low-power data loggers were becoming widely available. Now the priority was to invent sensors and techniques to exploit these new capabilities.

The arrival in summer 1986 of Erik Blake (Fig. 4: bottom panel), a doctoral student with a gift for technical innovation, opened a new phase in the field study of Trapridge Glacier. Blake conceived novel devices to sample subglacial water and sediment (Blake and Clarke, 1991) and imaginative approaches to measuring subglacial sediment deformation (Blake et al., 1992) and glacier sliding (Blake et al., 1994). In the course of this work, Blake pioneered a technique for inserting sensors into subglacial sediment: he used a percussion hammer that was suspended from the glacier surface by wires, from which the hammer dangled some 60 m below (Blake et al., 1992). Knowing where in space a subglacial sensor was placed involves detailed knowledge of the tilt and orientation of the hole through which the sensor was inserted. Blake solved this problem by designing a new kind of borehole inclinometer (Blake and Clarke, 1992), akin to that used by Sharp (1953), but fully electronic.

One of the most robust and useful instruments for probing subglacial sediment properties was the so-called "ploughmeter," devised by doctoral student Urs Fischer (Fischer and Clarke, 1994, 1997a, b, 2001). This device is a javelin-like steel spear onto which strain gauges are bonded. The spear tip is hammered into subglacial sediment, typically to a depth of 15 – 30 cm, while the main body of the spear lies within a glacier borehole. Motion of the glacier relative to its bed gives rise to a clawing action as the spear tip is raked through subglacial sediment. Resistance to motion causes the spear to bend slightly, deforming the strain gauges and producing a signal that is recorded at the glacier surface.

A separate but closely related initiative was to develop approaches for in situ observation of the subglacial water system. These approaches require drilling holes to the glacier bed and instrumenting them with sensors that can measure the pressure, turbidity, and chemical load of subglacial water. Here there were precedents to follow. Subglacial water pressure had been measured by other groups (e.g., Mathews, 1964; Iken, 1972; Hodge, 1976; Kamb et al., 1985), and it was known that subglacial water pressure varies spatially and temporally beneath glaciers. Devices for measuring the turbidity and electrical conductivity of subaerial water in oceans, lakes, rivers, and streams were already in use, but it was necessary to rethink these for subglacial application. Unlike subaerial sensors, which can usually be recovered after deployment, subglacial sensors are commonly installed and used until they fail. The constant attrition of subglacial sensors, combined with tight research budgets, discourages expensive, high-tech approaches. Doctoral student Dan Stone took up these challenges and developed a suite of subglacial hydrological sensors for use beneath Trapridge Glacier (Stone et al., 1993). On a similar path, but years later, doctoral student Jeffrey Kavanaugh puzzled over seemingly inexplicable water pressure records and reached the conclusion that extreme pulses of high water pressure were propagating through the subglacial water system, causing damage to some sensors (Kavanaugh and Clarke, 2000). He pursued that idea and designed special sensors to detect and confirm the existence of this surprising behaviour (Kavanaugh, 2009).

Correlations and Interactions: Without a larger context, individual measurements beneath glaciers have limited usefulness. When measurements of different properties are taken at different spatial locations and over a long period of time, one can gain an understanding of the system behaviour of glaciers. Once Trapridge Glacier had been instrumented with an arsenal of new kinds of sensors, it became possible to examine the interactions among the mechanical, hydrological, and soil-mechanical processes that control glacier motion.

The carefully observed surge of Variegated Glacier in Alaska (Kamb et al., 1985) yielded persuasive evidence that the on – off switch for surges was related to morphological switching of the subglacial drainage system (Kamb, 1987). For the Trapridge Glacier study, using new sensors and new approaches to observing changes in subglacial drainage morphology became a priority. Ice is known to be a poor electrical conductor, and mineralized subglacial water, a good one. We reasoned that morphological changes in the subglacial water system would cause changes in the apparent electrical resistivity of the glacier bed, so Erik Blake designed electrodes and a measurement system in order to observe this effect (Blake and Clarke, 1999). The expected changes were observed and the hypothesis was confirmed, but serendipity brought to light something unexpected and interesting: when the electrical current was turned off, the measured voltages changed nonetheless. For reasons involving complex electrochemistry, these changes correlated beautifully with measurements of subglacial water pressure (Blake and Clarke, 1999).

A glacier borehole that is connected to the subglacial water system is an example of a coupled system that links artificial and natural components. It is easy to manipulate the pressure in a borehole and use this to probe the properties of the natural water system. This is the basis of the standard "slug test" and "pump test" used by groundwater hydrologists to study the properties of aquifers (e.g., Domenico and Schwartz, 1990). Dan Stone applied this approach to characterize the transmissivity of the subglacial water system beneath Trapridge Glacier (Stone and Clarke, 1993; Stone et al., 1997). Not every hole drilled to the glacier bed manages to connect to a transmissive drainage system, and some holes reach the bed without establishing an evident hydraulic connection. For these, it was reasoned, the borehole is coupled to low-permeability subglacial sediment, in many cases comprising subglacial till. The in situ permeability of subglacial till is itself interesting owing to its effect on glacier mechanics. Exploiting this scientific opportunity and fortified by an extreme level of mathematical complexity, MSc student Brian Waddington managed to extract an estimate of the permeability of Trapridge till (Waddington and Clarke, 1995).

More informative than the interaction of an artificial system with a natural one are interactions among various components of a natural system, for example, interactions between the subglacial hydrologic system and glacier flow. However systems are only "natural" when they are not being manipulated. For a natural experiment, one must wait for Nature to deliver experimental moments, occasions when it seems possible to disentangle a natural forcing from a natural response and thus to think in terms of cause and effect, as one does when conducting a true laboratory experiment. Because these opportunities tend to be infrequent and unpredictable, it is important to maintain many sensors operating continuously for long periods of time—a challenge when operating in hostile environments—and then to sieve through the recorded data to isolate experimental moments.

Several of these moments and their interpretations are now sketched. (1) A subglacial hydraulic event occurring in July 1990 revealed the rapid transformation of the subglacial water system from one that operated at high pressure and resisted the through-flow of water to one that was transmissive and fast flowing (Stone and Clarke, 1996). (2) Post-doctoral fellow Tavi Murray noted curious relationships among July 1992 subglacial water pressure signals from five sensors at the bed of Trapridge Glacier. She found that pressure increases in some sensors were mirrored by pressure decreases in others, suggesting the operation of a subglacial "see-saw" and casting light on how the subglacial water system helps to support the weight of the overlying glacier (Murray and Clarke, 1995). (3) That same year, Urs Fischer found clear evidence from his ploughmeter records that the frictional contact between the glacier and its underlying bed varied spatially and temporally in a systematic manner, which led him to conclude that the glacier was underlain by time-varying "sticky spots" (Fischer et al., 1999). (4) Undergraduate student Greg Oldenborger examined the time variation in electrical conductivity in sealed water-filled boreholes during winter 1993–94 and winter 1994–95 and identified these variations as a hydrochemical signal associated with internal deformation of the glacier (Oldenborger et al., 2002). (5) Drawing together an analysis of signals from a wide range of devices that included water pressure sensors, turbidity sensors, water conductivity sensors, englacial strains sensors, englacial geophones, ploughmeters, and specially constructed "load-bolt" sensors, Jeffrey Kavanaugh conducted a detailed hydro-mechanical analysis of a glacier-wide event that occurred in June 1995. He concluded that an abrupt change in basal motion was accompanied by a profound reorganization of the basal shear stress and the switchover from a hydraulically unconnected subglacial water system to a connected one (Kavanaugh and Clarke, 2001).

Theory and Computational Modelling: Field research is fraught with many challenges, including bad weather, equipment failure, unavailability of aircraft, and the unpredictability of natural events such as floods and surges. One way of making the best of adverse situations is to shift effort from the field to the office, where theory and computational models can be developed. Computational models can be classified as either prognostic or diagnostic. Prognostic models (for example, numerical weather forecast models) aim to predict the future state of a system, whereas diagnostic models yield insight by demonstrating how various components of a system interact. Most glaciological models and all of those for Trapridge Glacier are diagnostic models.

The first simulation model for Trapridge Glacier was a flow-line model developed by Clarke (1976) to examine how the thermal structure of a glacier like Trapridge was affected by cyclic changes in flow rate. The model did not attempt to answer the question of how surges occurred, but was intended to illustrate how surges might influence measured ice temperature profiles. The modelled surges were thermally regulated rather than thermally triggered, an idea that was later taken up by Fowler et al. (2001).

By 1995, when Gwenn Flowers began her doctoral research, the possible importance of thermal effects on surging had been displaced by interest in how the subglacial water systems of normal and surge-type glaciers operate. Flowers tackled the challenging problem of characterizing how surface meltwater interacts with the various components of the subglacial and englacial water system. She began with an ambitious field effort to map the bed topography and hydraulic geometry of Trapridge Glacier (Flowers and Clarke, 1999) and then proceeded to develop a diagnostic model to examine subglacial release events (Flowers and Clarke, 2000) such as the July 1990 event described and interpreted in Stone and Clarke (1996). By the time she completed this monumental task she had developed a multicomponent-coupled model of Trapridge Glacier hydrology (Flowers and Clarke, 2002a, b) that is both realistic and widely applicable.

On an entirely different path, Jeffrey Kavanaugh developed a diagnostic model to examine how various sensors installed beneath Trapridge Glacier (measuring subglacial water pressure, subglacial sediment pore pressure, sliding rate, subglacial sediment deformation rate, and forces on an idealized ploughmeter) would respond to various forcings (Kavanaugh and Clarke, 2006). For this analysis, one requires both a model of the subglacial bed behaviour and models of the behaviour of each kind of sensor. Such models can prove invaluable aids to interpreting how time series records for different devices should relate to each other. Armed with the model and a large suite of time series records, Kavanaugh reached strong and convincing conclusions concerning the deformation properties of subglacial sediment. The only possibility consistent with the Trapridge Glacier observations was that subglacial sediment behaves as a Coulomb plastic material (Kavanaugh and Clarke, 2006), a conclusion consistent with measurements on subglacial samples from Whillans ice stream in West Antarctica (Kamb, 1991) and on till samples collected near Storglaciären in northern Sweden and in Michigan (Iverson et al., 1998).

The Surge: But what of the surge? The growth of a pronounced bulge (Fig. 3: top panel) was what turned attention back to Trapridge Glacier. Like Rusty Glacier, Trapridge was known to be surge-type, but it was more active, and its bulge was interpreted as a premonitory sign of a forthcoming surge. It was therefore expected that, at some future time, the glacier would switch to very fast flow, and this would signal the onset of the surge phase. For typical surge-type glaciers, there is a 10- to 100-fold increase in flow rate during the active phase of a surge. During the next decade (Clarke and Blake, 1991), the wave-like bulge continued to steepen and propagated downslope at roughly 30 m yr^{-1}. However, the expected switch to fast flow did not occur, and the average velocity in the central area of the glacier dropped from a maximum value of 42 m yr^{-1} in 1984 to less than 9 m yr^{-1} in 2005 (Frappé and Clarke (2007). The contrast between the Steele Glacier surge and the behaviour of Trapridge Glacier was startling and lent credence to the proposal that Trapridge Glacier had experienced a "slow surge." The idea of slow surges was not contemplated in Meier and Post's (1969) list of defining features of a glacier surge, but Trapridge Glacier was not the only example. It was proposed that slow surges such as those of Trapridge and Bakaninbreen in Svalbard were a consequence of the thermal structure of these glaciers (Murray et al., 2000; Fowler et al., 2001), in effect reinstating a role for ice temperature.

Coda: In art and literature, the "pathetic fallacy" encompasses the idea that Nature can express emotions in response to human actions. On 22 July 2007, the final day of the Trapridge Glacier field study, the glacier that shrouded the north face of Mt. Steele broke free and released a huge slide that disfigured the ice face and registered on seismographs in northwestern Canada and Alaska (Lipovsky et al., 2008). We had never seen the like of it. Exactly what emotion Nature was expressing at that moment remains unclear, but I like to think it was relief: Good riddance to all glaciologists, ice drillers, and their ilk.

Other Glacier Studies

In addition to his work on crevassing, Gerald Holdsworth conducted a major glaciological research program on the northwest col of Mount Logan (Fig. 1: site I) with the aim of extracting and analyzing ice-core records of climate and atmospheric changes (e.g., Holdsworth et al., 1989, 1996; Monaghan and Holdsworth, 1990; Moore et al., 2001, 2002, 2003). For the most part, his study focused on the atmospheric processes and the environmental record of change, rather than on the glaciers themselves; however, high-quality glacier maps were produced, and the glacier geometry, mass balance, and flow in the vicinity of the ice core site were studied and the results summarized (e.g., Holdsworth, 1977; Holdsworth and Jones, 1979). In a separate effort, satellite images showing surges of Tweedsmuir Glacier (in British Columbia) and Lowell Glacier were quantitatively analyzed (Holdsworth et al., 2002).

For many years, Peter Johnson of the University of Ottawa led a summer field school at KLRS that catered to physical geography undergraduates, while at the same time conducting his own research and supervising that of his graduate students. Johnson's research spanned a broad range of topics and much of it had a proglacial focus. Important glaciological contributions include the previously mentioned study of the morphological changes that accompanied the 1961 surge of Donjek Glacier; a survey and description of ice-cored moraines at Klutlan, Steele, Donjek, Kluane, Kaskawulsh, Lowell, and several other glacier sites in Yukon (Johnson, 1992: Fig. 1); and field studies of the hydrology and paleohydrology of ice-dammed lakes in the Kaskawulsh and Dusty Glacier basins (Kasper and Johnson, 1991; Johnson and Kasper, 1992; Johnson, 1995, 1997).

Holdsworth's ice-core drilling began in 1980 and the first core to be extracted was 103 m long. Other ice-core drilling efforts were to follow. In 1996, Cameron Wake from University of New Hampshire and Erik Blake retrieved a 160 m core from Eclipse Icefield (Fig. 1: site J; Yalcin and Wake, 2001; Wake et al., 2002) in the vicinity of the IRRP Divide Camp during a test of the portable ECLIPSE ice-core drill (Blake et al., 1998). In 2002, scientists from the Geological Survey of Canada and University of Maine retrieved a 187 m core from the Prospector – Russell Col drilling site on the Mt. Logan plateau (Fisher et al., 2004), a team from the Japanese National Institute for Polar Research retrieved a 220 m core from King Col on Mt. Logan plateau (Goto-Azuma et al., 2003), and a team from the University of New Hampshire and the University of Maine recovered a 345 m core (Yalcin et al., 2006, 2007). For a more detailed history of ice core drilling in the St. Elias Mountains, see Zdanowicz et al. (2014).

Glacier Inventory

The Canadian Glacier Inventory (CGI) was launched (Ommanney, 1980) as part of an international initiative arising from the International Hydrological Decade (1965 – 74). An important and challenging component of this effort was to obtain an inventory of Yukon glaciers (Ommanney, 1993). AINA co-investigators Richard Ragle and Sam Collins were initially responsible for compiling the Yukon inventory under the direction of Simon Ommanney of the Glaciology Division of Environment Canada (Ragle, 1973; de la Barre, 1977). Today the Yukon data form part of the World Glacier Inventory and can be accessed on-line through the National Snow and Ice Data Center in Boulder, Colorado. As well as quantitative glacier attributes such as length, elevation, and area, the architects of the CGI had the foresight to include information on whether each glacier was or seemed to be surge-type. These data provided a fine opportunity to examine whether certain glacier properties were associated with surging (Clarke et al., 1986; Clarke, 1991). It was determined that, in Yukon at least, long glaciers have a very high probability of being surge-type and that, if length is taken into account, glacier slope has no statistically significant influence.

Present Status and Future Directions

The study of rare, episodic phenomena is high-risk science. We were right to stop work on Rusty Glacier, which has done nothing but shrink since it was first surveyed by Collins (1972), but it was disappointing that Trapridge Glacier did not deliver an intense surge. Yet the "slow surge" of Trapridge has opened new lines of investigation (Flowers et al., 2011), and our efforts to unmask subglacial processes were highly successful. By taking full advantage of greatly improved drilling methods and the advent of robust low-power digital data loggers, we changed our strategy from one based on remote sensing of the glacier bed to one based on in situ measurements. By doing so, we gained a wealth of new knowledge concerning the subglacial environment and its processes. There is growing evidence that glaciers can slow their surge cycle or completely lose their surge tendency when subjected to unfavorable changes in mass balance (Dowdeswell et al., 1995). Rusty Glacier, for example, seems to have become a non-surging glacier, and Trapridge Glacier could be following the same path. Such uncertainties underscore the virtues of a diverse research agenda rather than one focused on narrow objectives.

With the conclusion of our field program and those of Gerald Holdsworth and Peter Johnson, the generational torch has passed to a talented cadre of young glaciologists who are actively creating the history of 21st century glacier studies (see Flowers et al., 2014). Gwenn Flowers (Canada Research Chair, Simon Fraser University) started her field research program in summer 2006 on two small glaciers that are accessible by helicopter from KLRS: "South Glacier," near Kaskawulsh Glacier, and "North Glacier," near Kluane Glacier. Her diverse program includes the design and application of a new ice-penetrating radar system (Mingo and Flowers, 2010), evaluation of energy balance melt models (MacDougall and Flowers, 2011; MacDougall et al., 2011; Wheler and Flowers, 2011), and the development of thermomechanical and hydrologic glacier models (Flowers, 2008; Flowers et al., 2011; De Paoli and Flowers, 2009; Pimental et al., 2010; Pimental and Flowers, 2011; Wilson and Flowers, 2013). In 2008, in collaboration with Flowers, Christian Schoof (Canada Research Chair, University of British Columbia) launched a complementary field program on "South Glacier." Schoof's research emphasizes subglacial physics, while for Flowers the emphasis is on hydrology and near-surface processes. The two efforts are closely linked because surface-derived meltwater is a key agent for activating subglacial changes. Schoof is using the insights gained from his Yukon field studies to propose generalized models that characterize the subglacial hydrology of Earth's great ice sheets (Creyts and Schoof, 2009; Schoof, 2010). It is satisfying to note that Flowers and Schoof both contributed to the Trapridge Glacier study. The glaciological program of Luke Copland (Associate Professor, University of Ottawa) has a strong focus on global change (Foy et al., 2011) coupled with a deep commitment to undergraduate training. Taking over from Peter Johnson, Copland now leads the University of Ottawa summer field school and has intensified its focus on glaciers. Farther afield, Jeffrey Kavanaugh (Associate Professor, University of Alberta), another Trapridge Glacier alumnus (Kavanaugh, 2009; Kavanaugh and Moore, 2010; Kavanaugh et al., 2010), has become director of the Juneau Icefield Research Program (JIRP). Launched by Maynard Miller in 1948 with a logistic base in Atlin, British Columbia, JIRP continues to make singular contributions to the education of young geoscientists.

Looking to the future, it is safe to predict that Yukon glacier research will continue to deliver surprises. When the Trapridge study was launched, I never imagined that instrumenting the ice-bed contact would become possible, let alone play a central role in our research program. I failed to anticipate advances in glacier drilling technology and the advent of robust digital data loggers and portable computers and how these would transform the science of subglacial processes (Clarke, 2005). One of the major themes for present and future Yukon glaciologists will be the rate and consequences of the disappearance of Earth's mountain glaciers. Climate-forced numerical glacier dynamics models will play an important role in forecasting changes, but we need improved understanding of how glaciers function so they can be better represented in such models. Thus continued research on subglacial hydrological and mechanical processes will remain a research priority. Additionally, serious mismatches between the output of global climate models and the inputs to mountain glaciation models, both in terms of spatial and temporal scales and in their detailed physics, must be addressed.

The almost complete lack of measurements of subglacial topography constitutes a major knowledge gap. Such information is necessary to estimate the contribution of glacier melt to sea level rise and as input to simulation models of ice dynamics that can be used to project the effects of climate-forced deglaciation on the water cycle. It is a remarkable fact that the subglacial topography of Martian ice caps is better known (Picardi et al., 2005; Plaut et al., 2007) than that of glaciers and icefields of the St. Elias Mountains. Helicopter-borne ice penetrating radars need to be developed for application to Earth's mountain glaciers, and this would be a worthy undertaking for Canadian glaciologists. Developing suitable radar systems is only one part of the problem: it is essential to secure sufficient funding to enable a comprehensive survey effort.

All discussion of future glacier research in Yukon is contingent on the existence of the Kluane Lake Research Station. Without the establishment of KLRS under the inspired leadership of Walter Wood, the scientific study of Yukon glacier studies might never have taken root. Throughout the field sciences, there is increasing pressure to assume that our understanding of processes is adequate and thus to replace direct field measurement by remotely sensed measurements. With no wish to belittle the value of remote sensing, the two modes of research must operate in tandem. Fieldwork is costly and not always enjoyable so there are seductive pressures to substitute a virtual world, represented by complex computer programs, for the real one. It is essential to ensure that such computer models are not running on hot air but are based on sound understanding of glacier physics. Without field stations and field research we could well return to a medieval style of science that explains everything but gets nothing right.

CONCLUDING REMARKS AND AFTERWORD

Viewed in retrospect, the 20th century effort could be faulted for dwelling on details while ignoring the larger drama that was unfolding. Wood's erudite foreword and introduction to the Icefield Ranges Research Project volumes (Wood, 1969a, b) make no reference to "climate change" or "ice wastage," and few, if any, of the glaciologists who contributed to the 20th century study of Yukon glaciers could imagine that they might be bearing witness to a catastrophe in slow motion. Using airborne laser altimetry to measure recent glacier surface elevations and comparing these to maps dating back to the 1950s – early 1970s, Arendt et al. (2002: Fig. 3) measured the elevation changes for 67 glaciers in northwestern North America, including Kaskawulsh Glacier, which they found to be thinning at a glacier-wide average rate of ~1.5 m yr^{-1} water equivalent (w.e.). The average thinning rate for all 67 glaciers in their study was 0.52 m yr^{-1} w.e. Using a different method, Berthier et al. (2010) found an area-averaged thinning rate for glaciers in the St. Elias and Wrangell Mountains of Alaska – Yukon of 0.47 m yr^{-1} w.e. over the interval 1962 – 2006. A recent inventory of Yukon glaciers (Barrand and Sharp, 2010) concludes that the area-averaged thinning rate from 1957 – 58 to 2007 – 09 was 0.78 m yr^{-1} w.e., with an associated area loss of 22%. These observations are consistent with unpublished computer modelling projections indicating that by the end of the 21st century, anthropogenically forced climate change is expected to cause the disappearance of most glaciers in Alberta and British Columbia and a substantial depletion of those in the Alaska – Yukon glacier refugium (Clarke et al., 2012).

Knowing that glaciers will shrink or disappear without having any deep understanding of their fundamental processes makes for poor science. Our ability to predict glacier responses to a range of climate forcings relies on an understanding of how glaciers function. Building this foundation has been the great triumph of 20th century glaciology, and without this basis, any claims to understanding the future would be weak.

Intentionally, I have excluded most references to unpublished work such as theses and unrefereed reports, though much of this work is substantial and rewarding. Where possible, I have cited related publications in accessible research journals that in many cases provide traceable citations to this unpublished body of work. The *Scientific Results of the Icefield Ranges Research Project*, which appear as a four-volume set, contain a mix of original and reprinted or slightly modified material. The IRRP volumes are no longer readily accessible and are not ISI-listed, but volumes 1 – 3 are available from the Yukon Archives digital library (http://yukondigitallibrary.ca); where possible, I have cited original publications rather than the reprinted versions. I have attempted to make a distinction between studies of glaciers and studies that happen to be conducted on or near glaciers. Thus I have largely excluded accounts of romantic travel, exploration, topographic and geological mapping, glacial geology, meteorology, climatology, snow studies, and those ice-core drilling efforts that are mainly aimed at extracting records of climate and volcanism. I recognize that some of these distinctions are subjective. Readers interested in the history of glacier studies in Canada, not simply those conducted in Yukon, are encouraged to read Simon Ommanney's (1996, 2002) excellent accounts. Other useful resources include William Field's (1975) monumental compendium *Glaciers of the Northern Hemisphere*, the chapter on "Glaciers of the St. Elias Mountains" in the USGS *Satellite Image Atlas of Glaciers of the World* (Clarke and Holdsworth, 2002), and John Theberge's (1980) *Kluane: Pinnacle of the Yukon*.

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