

The NSF/OPP Contribution To Antarctic Glaciology: A Personal Perspective

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I retired from the University of Maine on 15 January 2010 from a joint appointment in the Department of Earth Sciences and the Climate Change Institute, both located in the Bryand Global Sciences Center. This provided the opportunity to produce a personal account of the contribution to Antarctic glaciology made by the Office of Polar Programs (OPP) in the United States National Science Foundation (NSF) over the last half century. For convenience, my account will be made decade-by-decade, beginning in the mid Twentieth Century. The old hands, affectionately called Old Antarctic Explorers (OAEs), are a vanishing breed, so it is important for an account to be made before the Dying of the Light.

1950—1960

The Cold War began at the end of World War II when the victors, primarily the USA and the USSR, battled diplomatically to dominate a new world hegemony. It was an ideological struggle that pitted Capitalism against Communism. The Communist hegemony spread first in Eastern Europe as the Red Army occupied these countries up to what Winston Churchill called an Iron Curtain.

I like to have some fun with this in an age without teleprompters. Winston is at his podium in Missouri, looking out over the crowd: “From Trieste in the Baltic to Stettin in the Adriatic, an Iron Curtain has descended across the continent.” [pause] “I mean from *Stettin* in the Baltic to *Trieste* in the Adriatic!” [grumbles to himself]

Then, in 1949, Mao Tse Tung overthrew the Nationalist Chinese government and China entered the Communist orbit. The Heartland of Asia was in Communist hands. This was the latest round in the Great Game at the end of the Nineteenth Century, when the prevailing geopolitical theory was “Whoever controls the Heartland controls the World Ocean, and whoever controls the World Ocean controls the World.” At that time, Czarist Russia controlled the Heartland and the British Empire controlled the World Ocean. The Great Game was fought along the southern border of Asia, where “spheres of influence” were carved out in Persia and China. The Great Game ended in Afghanistan, in two disastrous campaigns for the British Army. A century later, both the USSR and USA have gotten bogged down in Afghanistan. “The more things change the more they stay the same.”

To counter the Communist hegemony in Eurasia, the USA and its allies in the West began a diplomatic offensive to contain International Communism within Eurasia by establishing the North Atlantic Treaty Organization (NATO) in 1949 with Western Europe and the Southeast Asia Treaty Organization (SEATO) in 1955 with Asian countries from

Thailand to Japan. In between, the Central Treaty Organization (CENTO) in 1955 enlisted Muslim countries from Turkey to Pakistan. These alliances depended mainly on American naval power, notably aircraft carriers, that controlled the World Ocean. Despite this, International Communism remained a threat, in Western Europe, the Middle East, Africa, and Latin America. The only continent not affected was Antarctica, isolated over the South Pole and uninhabited, but close to shipping lanes around South America.

To prevent Antarctica from being drawn into Cold War rivalries, diplomats from the USSR and the USA initiated talks aimed at preserving Antarctica for international cooperative scientific research only. This required drawing together twelve countries, seven claiming “slices” of the Antarctic “pie” dating from the Nineteenth Century when Western Imperialism was gobbling up the World. The first step toward this goal was the International Geophysical Year (IGY) in 1957-1958 in Antarctica, which involved the twelve nations maintaining “research” stations. The IGY nations signed the Antarctic Treaty on 1 December 1959 in Washington, in which signatory nations suspended territorial claims to Antarctica so the scientific cooperation during the IGY could be preserved.

During this decade, glaciology was transformed from being a descriptive branch of geology to being an analytical branch of physics. Mirroring the “Big Four” powers of the Cold War, the USSR, USA, UK, and France, the “Big Four” glaciological theoreticians who brought about this transformation were Petr Shumsky (USSR), Hans Weertman (USA), John Nye (UK), and Louis Lliboutry (France). Their glaciological disputes could be as energetic as those of Cold War diplomats.

Into this cauldron stepped the NSF Office of Polar Programs (NSF/OPP), charged with coordinating and funding American Antarctic research under the guidelines of the Antarctic Treaty. During the IGY, nations with territorial claims in Antarctica located “research” stations in their slices of the Antarctic pie. The USSR and the USA recognized none of these claims.

To cement its claim to “discovering” Antarctica during the Czarist circumnavigation of Antarctica by the 1819-1821 Bellingshausen Expedition, the USSR located stations all around the coast of Antarctica, including slices of the pie claimed by other nations, with a main inland station called Vostok near the central dome of the Antarctic Ice Sheet in East Antarctica. Unknown at the time, it was located above a large subglacial lake 4 km below the ice surface. This was to become the site of the deepest hole drilled through the Antarctic Ice Sheet, providing the longest record of climate recovered from ice cores and preserved in stable isotopes, trace ions, atmospheric gases, windborne dust, and even diatoms, all acting as proxies believed to record changes in the climate over Antarctica.

To counter that, the USA located a station at the South Pole, with a major logistical and scientific station on Ross Island called McMurdo Station. Ships and airplanes could reach McMurdo Station from New Zealand. Ships were escorted by U.S. Coast Guard icebreakers. Lockheed Constellation aircraft landed on wheels at an airstrip bladed by caterpillars on the sea ice of McMurdo Sound. From there, Hercules LC-130 aircraft equipped with both wheels and skis flew people to South Pole Station and Byrd Station, located in the middle of the West Antarctic Ice Sheet. West Antarctica was the only unclaimed part of Antarctica. It

was to become the main focus of American glaciological research. A fourth station, Palmer Station, was located on an island alongside the Antarctic Peninsula, accessible by ship. It was established mainly to conduct biological research, but also to occupy the slice of the Antarctic pie claimed by Argentina, Britain, and Chile. In following decades, many other nations would establish research stations on islands in this slice of the pie.

Much of coastal Antarctica remained undiscovered and therefore unmapped prior to the IGY. The U.S. Navy, in Operation Highjump (1946-1947) and Operation Windmill (1947-1948), sought to photograph and map the coast of West Antarctica using seaplane tenders, ships with a door in the hull that housed seaplanes equipped with a camera bay from which a “tricamera” took three photos, vertically downward and at angles to the right and left, that could be combined to give a stereographic view of the landscape along the flightlines. During and after the IGY, the Navy was given the primary logistical responsibility for supporting American scientific research, a charge it accepted as Operation Deep Freeze.

During this early period, one seaplane tender called the *Pine Island* launched aerial photo missions along the Amundsen Sea coast of West Antarctica. These flights included an ice-free “polynya” in the Amundsen Sea that came to be known as Pine Island Bay. The two largest and fastest ice streams in West Antarctica were photographed at that time, Pine Island Glacier and Thwaites Glacier. These two ice streams were to figure large in Antarctic glaciological research.

Glaciological research on Ross Ice Shelf in the Ross Sea was conducted by A. P. Crary, E. S. Robinson, H. F. Bennett, and W. Boyd from 1957 to 1960, along a tractor-train circuit of Ross Ice Shelf. Surface meteorology, ice elevations and thicknesses, mass-balance stakes, and snow-pit stratigraphy were all measured along the traverse route. Seismic sounding also recorded depths to the sea floor beneath Ross Ice Shelf. James Zumberge and Charles Swithinbank from the University of Michigan (UM), measured ice velocities and horizontal strain rates on the ice shelf between Ross Island and Roosevelt Island from 1958 to 1963. Tractor-train traverses were also conducted from Ellsworth Station to Filchner Ice Shelf in the Weddell Sea and Dufek Massif, involving John Behrendt, Ed Thiel, and Hugo Neuberger, in 1957-1958, from McMurdo Station to Northern Victoria Land in 1958-1960, led by John Weihaupt from UM, and from McMurdo Station to the South Pole in 1960-1961.

Apart from traverses, glaciological research began in what became known as the Dry Valleys, a part of the Transantarctic Mountains west of McMurdo Station cut through by valleys that had originally been fjords, but which had a headwall too high to allow much East Antarctic ice to spill over into the valleys under present-day conditions. The only glaciers in the Dry Valleys were small local glaciers that came down the valley sides, mostly the shaded southern sides, and ended as calving ice walls before reaching the valley floor. An American geological expedition led by Robert Nichols from Tufts University began mapping the Dry Valleys during the 1957-1958 Antarctic summer. In what Colin Bull named Wright Valley, Nichols named four of these glaciers after his students, Denton, Goodspeed, Hart, Meserve, and Bartley Glaciers. Nichols took George Denton, then 18 years old, to the Dry Valleys the following year, 1958-1959. Denton was to become a giant in unraveling the history of Antarctic glaciation over 30 field seasons spanning three decades.

An equally auspicious event at the end of the decade was a meeting between Richard Goldthwait from The Ohio State University (OSU) and Colin Bull from Victoria University of Wellington (VUW), New Zealand. Bull and his family had moved from the UK to New Zealand in 1956. Two student geologists, Peter Webb and Barrie McKelvey, and biologist Richard Barwick, all from VUW, participated in the Antarctic IGY (which became known as Victoria University of Wellington Antarctic Expedition # 1, VUWAE-1). Bull included them in the first official VUW expedition which he organized and led as VUWAE-2 in 1958-1959 with a VUW expedition to Antarctica every year since then. They did the first glaciological, geophysical, meteorological, geological, and biological research in Wright Valley. At the end of VUWA-2, Bull was at New Zealand's Scott Base on Ross Island when Goldthwait arrived from McMurdo Station. He was interested in establishing a center at OSU to archive glaciological data collected during the IGY and in subsequent years. He invited Bull to help organize what became known as the Institute of Polar Studies (IPS) at OSU, now known as the Byrd Polar Research Center (BPRC). Bull succeeded Goldthwait as Director of IPS from 1965 to 1969, making it the premier American center for Antarctic glaciological research.

1960—1970

Bull returned to the Dry Valleys region several times, beginning in 1959-1960, and joined his OSU/IPS graduate student, Gerald Holdsworth, in the first glaciological study of a cold-based glacier, Meserve Glacier, named by Robert Nichols. The study included instrumenting 100 m of tunnels dug at the base of the glacier, then drilling and instrumenting holes drilled from the surface to the bed, from 1965 to 1970.

From 1960 to 1963, Charles Swithinbank from UM led field parties that measured surface velocities across the floating part of major East Antarctic outlet glaciers passing through fjords in the Transantarctic Mountains and supplying Ross Ice Shelf. This included the first use of aerial photogrammetry on Byrd Glacier, the largest and fastest outlet glacier.

The centerpiece of glaciological research during this decade was tractor-train traverses over the Antarctic Ice Sheet, especially traverses radiating from Byrd Station at the center of West Antarctica, and including a traverse from Byrd Station to South Pole Station in 1960-1961 to deliver two D8 bulldozers. Forest Dowling from the University of Wisconsin (UW) measured surface elevations and ice thicknesses using altimeters and gravimeters, and Henry Brecher from IPS/OSU measured temperatures and snow accumulation rates in 25 snow pits 2 m deep along that traverse, after wintering over at Byrd Station in 1959-1960. In East Antarctica, the Queen Maud Land traverses went from the South Pole to the Pole of Inaccessibility (the farthest point from the sea) and Plateau Station. Charles Bentley from UW led QMLT-1 in 1964-1965. It included Richard Cameron from IPS/OSU. Edgard Piciotto from Belgium led QMIT-2 in 1965-1966, followed by QMLT-3. A 100 m corehole was drilled at Plateau Station to measure variations of temperature and density with depth. Scott Kane, Olav Orheim, and Henry Brecher, all from IPS/OSU, participated.

Glaciological research soon became the main activity along tractor-train traverses. Data included surface meteorology and mass balance studies using flagged stakes and snow pits, ice elevations, ice thicknesses and internal structure determined by seismic sounding, and geophysical gravity and magnetic measurements. Charles Bentley at UW soon took charge

of the West Antarctic traverses. Logistically, these traverses could present serious challenges. A traverse from McMurdo Station to Byrd Station had to navigate a heavy crevasse field known as “fashion lane” on the Shirase Coast of Ross Ice Shelf. D8 bulldozers bladed snow over the crevasses until a snow bridge was created.

It was during these traverses that the West Antarctic Ice Sheet was found to be largely grounded below sea level. Competing theories as to how the West Antarctic Ice Sheet formed were proposed. Bentley and Ned Ostenson, in 1961, favored expansion of ice caps grounded on highlands, mostly islands, into subglacial basins below sea level. In 1960, Harry Wexler had favored thickening and grounding of sea ice over these basins. Perhaps both mechanisms were necessary. Bentley Subglacial Trench was found to be 2500 m below sea level at places.

At this time, John Mercer, an OSU/IPS glacial geologist, was mapping lateral moraines along Reedy Glacier and Beardmore Glacier in the Transantarctic Mountains south of Ross Ice Shelf. He concluded that the West Antarctic Ice Sheet had been both smaller and larger in the past, smaller during the Last Interglacial Maximum (LIM) 125,000 years ago, accounting for Eemian sea levels up to 6 m higher than at present, and larger during the Last Glacial Maximum (LGM) 18,000 years ago when the grounded West Antarctic Ice Sheet had advanced into the Ross Sea, grounding Ross Ice Shelf and thickening East Antarctic outlet glaciers, which then deposited the higher lateral moraines mapped by Mercer. In 1970, Mercer called the West Antarctic Ice Sheet a “marine” ice sheet, and proposed another marine ice sheet on the broad submarine Arctic continental shelf of the Barents Sea between Scandinavia and Spitzbergen. The inherent instability of marine ice sheets first recognized by Mercer has become a major focus of Antarctic glaciological research.

A marine ice sheet in the Ross Sea was also recognized by George Denton during his glacial geological studies in the Dry Valleys, beginning in 1967-1968 when Denton was a graduate student at Yale University. The expanded West Antarctic Ice Sheet had diverted East Antarctic outlet glaciers, notably ice from Mulock Glacier, into McMurdo Sound, grounding McMurdo Ice Shelf and sending lobes of ice into the Dry Valleys. Adiabatically warmed katabatic winds rushing down these lobes, and katabatic winds flowing off the East Antarctic Ice Sheet, met in the Dry Valleys and created a warm oasis during the LGM. This increased precipitation and allowed the valley glaciers to advance to the valley floors as warm-based glaciers that produced moraines and meltwater streams that ended in deltas along the shorelines of lakes in the Dry Valleys. Being blocked by ice at both ends, these lakes deepened and algae layers deposited in the lake deltas could be radiocarbon-dated. Former lake levels served as “dipsticks” that recorded the advance and recession of ice lobes from McMurdo Sound into the Dry Valleys.

When the Glacial Theory was first advanced by Louis Agassiz and other Nineteenth Century naturalists, glaciology and glacial geology were viewed as two sides of the same coin, one side showing us the present behavior of glaciers and the other side showing past behavior. That connection was undermined when glaciology fell under the purview of physics and glacial geology remained within geology. This connection was not reestablished until reconstructions of former ice sheets, based on glacial geology and the dynamics of present ice sheets, were undertaken for CLIMAP (Climate: Long-Range

Investigations, Mapping, and Prediction), a project during the 1970-1980 International Decade of Ocean Exploration (IDOE).

Antarctic marine geology began at the end of the 1960s. John Anderson, at Florida State University, did his doctoral research in the eastern part of the Weddell Sea which, like the Ross Sea, has a broad submarine continental shelf once occupied by a marine ice sheet. Crary Trough extends from the edge of the continental shelf, passes under Filchner Ice Shelf, and joins fjords occupied by East Antarctic ice streams from Queen Maud Land in the old Norwegian slice of the Antarctic pie. Over the next four decades, Anderson and his students at Rice University (RU) extended these studies to the broad continental shelves of the Bellingshausen, Amundsen, and Ross Seas, and along the Wilkes Land coast of East Antarctica. Anderson mapped and sampled the sea floor in all these seas, discovering numerous submarine troughs extending from present Antarctic ice streams and under fringing ice shelves to the edge of the continental shelf. All these troughs had the distinctive appearance of being eroded by fast-flowing ice, indicating former extensions of present-day ice streams when the Antarctic Ice Sheet was grounded to or nearly to the edge of the Antarctic continental shelf.

In 1962-1964, UM glaciologists James Zumberge, Charles Swithinbank, and Walther Hoffman conducted the Ross Ice Shelf Survey (RISS). RISS was anchored to Ross Island and extended eastward toward Little America Station. West of Roosevelt Island, an ice rise where Ross Ice Shelf is grounded on the sea floor, RISS turned southward and went halfway to the Transantarctic Mountains. Egon Dorrer, Hoffman, and W. Seufert, repeated the geodetic survey in 1963-1964 to obtain ice velocities, showing that Ross Ice Shelf in this region moved at a largely uniform velocity that increased as ice turned northward toward the calving front. Ice-shelf velocities on the north-south leg of RISS were somewhat slower than ice velocities crossing the Siple Coast of West Antarctica, as calculated from measurements of snow accumulation rates in West Antarctica along the tractor-train traverse routes and elsewhere, published by Colin Bull in 1971. This was the first indication that an ice shelf in a confined embayment and pinned at ice rises is able to buttress, and therefore slow, the ice streams supplying it.

The mass balance of the Ross Ice Shelf ice drainage system was reported by Albert Crary, Ed Robinson, H. F. Bennett, and W. Boyd for Ross Ice Shelf in 1962 and by James Zumberge in 1964, by Mario Giovinetto, Ed Robinson, and Charles Swithinbank in 1966 for the East Antarctic portion, and by Giovinetto and Zumberge for the West Antarctic portion in 1968.

Also in the late 1960s, the first corehole through the Antarctic Ice Sheet was completed at Byrd Station by the U. S. Army Cold Regions Research and Engineering Laboratory (CRREL) located at Hanover, New Hampshire. When the corehole reached the bed, basal water rushed up the corehole and froze onto the cold surrounding ice. The bed was thawed. Earlier in the decade, CRREL had drilled a corehole to a frozen bed through the Greenland Ice Sheet at Camp Century. Lyle Hansen led both CRREL drilling teams and Chester Langway headed the glaciological team studying the ice cores. Studies of cores at both sites included ice densities, temperatures, and fabric development with depth, conducted by Anthony Gow, and measurements of stable oxygen isotopes conducted by a Danish team

led by Sig Johnsen and Willi Dansgaard. The ratio of 18/16 isotopes had a pronounced “spikiness” in ice near the bed that was roughly dated to coincide with the LGM. Was it due to local seasonal storm systems during snow deposition, did it record erratic rapid changes in global climate that caused mass extinctions of large grazing animals and their predators, or did it reflect an unexpected kind of ice dynamics (dyke-sill thermal convection that shuffled the stratigraphic deck was proposed)? The first view eventually prevailed.

Radar sounding of West Antarctic ice streams began near the end of the 1960s. This included identification of five ice streams crossing the Gould, Siple, and Shirase Coasts onto Ross Ice Shelf. These were informally named ice streams A through E in 1970 by British glaciologists at Scott Polar Research Institute (SPRI) in Cambridge: Gordon Robin, Stanley Evans, David Drewry, C. H. Harrison, and D. L. Petrie, published in the NSF/OPP *Antarctic Journal of the United States*. In 1968, Gordon Robin, Charles Swithinbank, and B. M. E. Smith showed that subglacial lakes, possibly interconnected, lay under ice stream C., deduced from strong bed reflections under the nearly flat surface typical of floating ice. These ice streams were later formally named to honor John Mercer, Ian Whillans, Barclay Kamb, Robert Bindshadler, Douglas MacAyeal, and for ice stream F, Keith Echelmeyer.

1970—1980

This decade began with a volcanic eruption featured in *National Geographic Magazine* on Deception Island, a collapsed and flooded volcanic caldera north of the Antarctic Peninsula, on 12 August 1970. It followed eruptions in December of 1967 and January of 1969. The First International Deception Island Volcanological Expedition visited the island in December of 1970, with volcanologists, geologists, and glaciologists from Italy, Britain, Russia, Norway, and the USA, two of them at OSU/IPS. From rifts opened through glaciers, a stratigraphic record of mass balance over 300 years long was obtained by Olav Orheim. Henry Brecher mapped changes in glacier surface elevations photogrammetrically. An ice wall initially 100 m high calved ice slabs into a crater formed during the eruption, making possible the first investigation of calving dynamics. These studies, funded by NSF/OPP, were conducted from 1970 to 1974. During that time, Deception Island was visited by Jacques Costeau on his *Calypso*, by Lars-Eric Lindblad on his *Lindblad Explorer*, by Giovanni Ajmone-Cat on his *San Giuseppe Due*, and by the NSF/OPP *Hero*.

The American Geographical Society published its map of Antarctica in 1970. It showed all the tractor-train traverse routes over Antarctica during and after the IGY, with ice elevations, thicknesses, and bed heights/depths above/below sea level printed at every place where seismic sounding was done. This revealed clearly that large areas of both the East and West Antarctic Ice Sheets were grounded below sea level, making them marine ice sheets. Floating fringes of the ice sheet were identified as ice shelves. Basal pinning points that anchored these ice shelves to the sea floor were shown as surface ice rises. Names of mountains, glaciers, and other geographic features were printed on the map. Most arresting was the contrast between the overall convex surface of the East Antarctic Ice Sheet lying mostly on a Precambrian continental shield in the Eastern Hemisphere, and the overall concave surface of the West Antarctic Ice Sheet lying mostly in a Cenozoic volcanic province in the Western Hemisphere. Steady-state glaciological theory produces convex ice

sheets. Is the concave West Antarctic Ice Sheet a collapsing remnant of a convex steady-state ice sheet? Did Cenozoic volcanism studied by Wesley LeMasurier cause the collapse?

The Glaciology Working Group of the Scientific Committee on Antarctic Research (SCAR), chaired by Charles Swithinbank, recommended in 1974 that NSF/OPP fund a project to fill a glaciological gap, calling it Glaciology of the Antarctic Peninsula (GAP). GAP was too soon to capture the main glaciological events: explosive disintegrations of ice shelves alongside the peninsula, beginning in 1995 and continuing to 2008 and probably into the future. GAP succeeded in one major respect. It coaxed Charles Raymond, University of Washington (UW), to begin his long participation in Antarctic glaciology.

The Dry Valley Drilling Project (DVDP), funded by NSF/DPP, was conducted from 1972 to 1974. Its goal was to recover a climate and tectonic history for this part of Antarctica. Led by Lyle McGinnis at Northern Illinois University, where DVDP Bulletins are archived, scientists from the USA, New Zealand, and Japan participated in studying the geochronology, paleoclimatology, and paleomagnetism obtained from 14 coreholes in the Dry Valleys, McMurdo Sound (a companion study), and Walcott Glacier. Evidence for early Cenozoic glaciations beginning 30 million years ago was found, indicating the Ross Sea Sector of the Antarctic Ice Sheet has been inherently unstable from the beginning.

During this decade and with CLIMAP funding by NSF/OPP, George Denton, now at the University of Maine (UM), found the algae layers in deltas where meltwater streams from local glaciers entered the enlarged lakes on the floor of the Dry Valleys. From radiocarbon dates, he was able to date recession of the ice lobes from McMurdo Sound that caused lake levels to fall, thereby documenting retreat of the marine ice sheet in the Ross Sea Embayment where the Ross Ice Shelf floats today. Toward the end of the decade, he extended his glacial geological studies to moraines deposited by East Antarctic outlet glaciers as far south as Byrd Glacier, notably from Darwin and Hatherton Glaciers. When combined with similar moraines alongside Beardmore and Reedy Glaciers mapped by John Mercer in the 1960s and 1970s, Denton was able to reconstruct the LGM surface of the marine ice sheet all along the Transantarctic Mountains in the Ross Sea Embayment.

Denton arranged for Wiley-Interscience to publish in 1981 the CLIMAP reconstructions of the Antarctic Ice Sheet at the LGM and the LIM in a book, *The Last Great Ice Sheets*. The LIM reconstruction included collapse and disintegration of the West Antarctic Ice Sheet, using an early version of James Fastook's University of Maine Ice Sheet Model (UMISM), to obtain most of an Eemian sea level 6 m higher than at present. This was accomplished primarily by collapsing most of the present West Antarctic Ice Sheet into Pine Island Bay, which has become known as "The weak underbelly of the West Antarctic Ice Sheet."

The "weak underbelly" designation has been a good selling point for planning future Antarctic glaciological research. Is the designation premature? The Ross and Weddell flanks of the West Antarctic Ice Sheet have already largely collapsed, but the Amundsen flank remains. Winston Churchill argued that Hitler's Europe should be invaded from the Mediterranean flank because that was its "soft underbelly." In World War I, British officers ordered Aussie and Kiwi soldiers to their deaths charging Turkish machine guns at

Gallipoli. In World War II the greatest German resistance was at Monte Cassino in Italy. The European “underbelly” wasn’t so “soft.” Will that also prove to be true of Pine Island Bay?

The NSF/OPP helicopter camp in the neve of Darwin Glacier in 1978-1979 was used to support a variety of research. John Splettstoesser coordinated helicopter flights to field camps. The UM glaciological research concentrated on measuring surface ice velocities and elevations along Byrd Glacier. Henry Brecher from OSU/IPS provided the centerpiece of the study with aerial photogrammetric measurements of 601 ice velocities and 1467 surface elevations on photo flights 56 days apart. Summer ablation rates were measured at stakes on the ice surface and the grounding line of the floating portion was determined by measuring changing vertical angles between ice and bedrock surveying stations over a two-day tidal cycle. Charles Swithinbank from the British Antarctic Survey (BAS) participated in these studies. Then Swithinbank convinced David Drewry at SPRI to fly the LC-130 aircraft equipped for radar sounding down Byrd Glacier, a “white knuckle” flight only 100 m above the heavily crevassed surface, in order to obtain a bottom reflection. It succeeded. At places, Byrd Glacier is over 3 km thick.

Drewry was a glaciologist at SPRI in the UK where radar-sounding technology had been developed and first applied to the Antarctic Ice Sheet. This led to a plan to map the West Antarctic Ice Sheet and the Wilkes Land sector of the East Antarctic Ice Sheet using radar sounding along a grid of flightlines flown by LC-130 aircraft equipped with radar antennae. The Technical University of Denmark (TUD) also developed radar technology and joined this enterprise, funded by NSF. It became known as the NSF—SPRI—TUD Radio-Echo Sounding Program. It was curtailed at the end of the 1970s by Richard Cameron, manager of the glaciology program at NSF/OPP, when the SPRI component was slow in sharing data. This program was focused on mapping surface and bed topography over the slow sheet-flow part of the Antarctic Ice Sheet, even though it became clear during the 1970s that most Antarctic ice was discharged by fast ice streams. The heavily crevassed surface of most ice streams scattered too much radar energy to allow a strong bed reflection to be returned.

The centerpiece of glaciological studies during this decade was the Ross Ice Shelf Project (RISP) from 1974 to 1979, conceived by James Zumberge, with a head-office at the University of Nebraska at Lincoln (UNL). The centerpiece of RISP was drilling a corehole through the center of the Ross Ice Shelf. The drilling technology developed for the Byrd Station corehole failed on the Ross Ice Shelf. An engineer from New Hampshire was hired to melt a hole through the ice shelf using what amounted to a blowtorch. No ice core was collected, but arthropods and other marine organisms were found clinging to a chunk of meat lowered to the sea floor. Life existed in perpetual darkness. Russian glaciologist Igor Zotikov brought his driller and drilling rig to the RISP drilling site and succeeded in drilling through Ross Ice Shelf.

The Ross Ice Shelf Geophysical and Glaciological Survey (RIGGS) was connected to RISP. RIGGS established a checkerboard of field camps on Ross Ice Shelf for geophysical measurements by Charles Bentley’s team at UW and glaciological measurements by Robert Thomas at UNL. A grid of radar-sounding flightlines flown by a Twin Otter aircraft over the ice shelf connected the RIGGS stations.

Geophysical measurements at RIGGS stations consisted of gravity and magnetic measurements, and measurements of ice thicknesses and depths to the sea floor under the ice shelf obtained by seismic sounding. The map of gravity anomalies was consistent with a sea floor in isostatic rebound. The topographic map of the sea floor showed that submarine troughs connected ice streams supplying Ross Ice Shelf with troughs mapped by John Anderson from the calving front of the ice shelf to the edge of the Ross Sea continental shelf. These results were consistent with a marine ice sheet drained by fast ice streams occupying the Ross Sea, probably during the LGM. Radar sounding identified bottom crevasses on the ice shelf that may eventually lead to catastrophic ice-shelf disintegration.

Glaciological measurements at RIGGS stations consisted of surface meteorology, temperatures, accumulation rates (from stakes and snow pits), and surveying networks to determine strain rates. These data were used to produce the first finite-element model to simulate deformation and flow of Ross Ice Shelf in the map-plane. This constituted the M.S. research by Douglas MacAyeal, as Thomas' graduate student after Thomas moved to UM in 1976. MacAyeal then got his doctorate at Princeton and went on to an outstanding career in Antarctic glaciology, working from the University of Chicago (UC). Thomas had published a marine-instability mechanism at ice-shelf grounding lines in 1977. He and Bentley applied it to retreat of the grounding line and calving front of Ross Ice Shelf since the LGM.

Retreat of the calving front of Ross Ice Shelf since the LGM was studied by Thomas Kellogg and Davida Kellogg at UM. Using paleomarine micropaleontology to identify fossil micro-organisms in sediments on the continental shelf, they concluded retreat of the calving front of the Ross Ice Shelf began about 8000 years ago.

A key study during this decade was a mass-balance study along the Byrd Station Strain Network (BSSN) established by the U. S. Geological Survey and extending from Byrd Station to the West Antarctic ice divide. In 1971-1972, Ian Whillans measured surface strain rates and Henry Brecher measured surface accumulation rates. Both were at OSU/IPS. Surface velocities were calculated taking zero velocity at the ice divide. The two data sets could be matched only if the ice surface was lowering progressively toward Byrd Station. This was the first direct evidence that collapse of the West Antarctic Ice Sheet that had been underway during the Holocene, based on glacial geological evidence by Mercer and Denton, was continuing at the present time. It shifted attention from Ross Ice Shelf to fast West Antarctic ice streams that were downdrawing the ice sheet and supplying the ice shelf.

1980—1990

Glaciological research during the 1980s shifted from Ross Ice Shelf to ice streams supplying the ice shelf from West Antarctica. Most of these studies focused on two ice streams crossing the Siple Coast, ice streams B and C, the respective fastest and slowest of these ice streams. By the end of the decade, this study had expanded to ice streams A through E crossing the Gould, Siple, and Shirase Coasts of West Antarctica, and was recast by NSF/OPP as the West Antarctic Ice Sheet Initiative (WAIS). WAIS continued into West Antarctica the same kinds of geophysical and glaciological measurements made by RIGGS, with field research concentrated mostly from the West Antarctic Ice Divide to Ross Ice Shelf.

The great addition to WAIS came from the California Institute of Technology (CIT), where the glaciological program was led by Barclay Kamb and his Bavarian driller, Hermann Engelhardt. Hot-point drilling technology had been developed by Kamb and used to drill holes through two Alaskan glaciers, Variegated Glacier during its surge in 1982-1983 and then on Columbia Glacier after its calving front backed off a high moraine sill and entered deeper water in 1987. This introduced an unstable glaciological regime in which both the ice velocity and the ice calving rate increased rapidly as the glacier tried to find a new equilibrium configuration. Technology for drilling the boreholes and then instrumenting the holes were perfected during these two studies. Kamb and Engelhardt applied this technology to West Antarctic ice streams B and C, the fastest and slowest ice streams, drilling and instrumenting many boreholes. They found that glacial till underlying these ice streams offered virtually no resistance to sliding of overlying ice, when the till was subjected to creep experiments. So why was ice stream B so fast and ice stream C so slow?

To further complicate the problem, Kamb found the till deformed near the plastic end of the viscoplastic creep spectrum, whereas a decade later, Sridhar Anandakrishnan and Richard Alley, both at Pennsylvania State University (PSU), used seismic signals generated by tidal forcing to show that the same till also deforms at the viscous end of the spectrum. Apparently the till rheology depends on how forces are applied. Robert Bindshadler, a NASA glaciologist who presided over annual WAIS workshops sponsored by NSF/OPP, recruited E. P. Roberts and Douglas MacAyeal to investigate Crary Ice Rise, a basal pinning point that should buttress flow from ice stream B but not ice stream C. This deepened the mystery.

Drilling was done by using hot water heated in the drilling pipes to melt ice as the weight of the string of pipes drove the melting head down. When the bed was reached, the water level bounced up and down if the bed was wet, before stabilizing at a height that was far above sea level and only about 10 m below the flotation height of ice in water. This behavior allowed deductions about both the subglacial hydrological system and the effect of water on the creep properties of basal till. The link between water-pressure coupling, basal sliding, and till deformation was explored in a series of papers from 1986 to 1989 by R. B. Alley, D. D. Blankenship, S. T. Rooney, and C. R. Bentley, all at the Geophysical and Polar Research Center, University of Wisconsin (GPRC/UW).

The radar-sounding grid over West Antarctica by Sion Shabtaie and Charles Bentley at GPRC/UW located shallow troughs under West Antarctic ice streams, not the deep fore-deepened troughs of fjords through the Transantarctic Mountains occupied by East Antarctic outlet glaciers. Bed topography did not seem to greatly influence the location of ice streams. Low ice ridges between West Antarctic ice streams had generally smooth surfaces, whereas the ice streams had crevassed surfaces. However, ridge AB between ice streams A and B had a rugged surface more typical of ice streams. Was this ridge about to be incorporated into ice streams A and B, making a gigantic ice stream at the southern extremity of Ross Ice Shelf? Could ice streams merge in general when they don't occupy deep troughs? If so, the West Antarctic Ice Sheet may be more vulnerable to further gravitational collapse than had been thought possible.

West Antarctic ice streams are unusually long, extending hundreds of kilometers nearly to the West Antarctic ice divide. Under the ice divide, a Cenozoic volcanic province extended northward from the Transantarctic Mountains almost to the Amundsen Sea. Several mountain nunataks rose above the ice surface. Magnetic mapping by Donald Blankenship revealed features that looked like volcanic calderas. This region was thought to be the source of till that kept the ice streams moving fast because the till offered little resistance to ice motion. Ian Whillans and Kees van der Veen found that side shear against the ice ridges provided much more resistance to ice streams than did basal shear of till. Dynamic boundaries of ice streams were given evocative names (the Unicorn, the Dragon, the Snake, etc.). My favorite is the Duckfoot, named by Robert Jacobel for boundaries where ice stream C switched from the north side to the south side of Siple Ice Dome.

Numerous raised marine beaches extend along the East Antarctic coast of the western Ross Sea north of Ross Ice Shelf. These features were mapped and dated late in the decade by George Denton and Brenda Hall at UM, and Italian geologists G. Orombelli and C. Baroni. This region was in northern Victoria Land, which was crossed by ice streams from the East Antarctic Ice Sheet that had run into the marine ice sheet in the Ross Sea at the LGM. After the LGM, these raised beaches and higher moraines showed that the marine ice sheet had first lowered and then retreated southward. Stephanie Shipp, Eugene Domack, and John Anderson found geophysical evidence in the Ross Sea supporting this interpretation. Extending their studies to the eastern Ross Sea, they found that the grounding line of Ross Ice Shelf had retreated like a swinging gate anchored on Roosevelt Island.

Further east, in the Amundsen Sea, U. S. Coast Guard Cutter *Glacier*, an icebreaker, had gotten through heavy sea ice into the Pine Island Bay polynya, and its helicopter had landed on Pine Island Glacier in the Antarctic summer of 1985-1986. John Anderson was aboard with graduate students from RU to map the sea-floor topography. Tom and Davida Kellogg from UM were aboard to collect piston cores of sea-floor sediments to determine if a grounded ice sheet at the LGM had become a floating ice shelf before the ice-free polynya formed. Anderson mapped a submarine trough extending from Thwaites and Pine Island Glaciers northward to the edge of the continental shelf. It had all the characteristics of being occupied by a huge ice stream. The Kelloggs found retreat of this ice stream was both rapid and recent, since sea-floor sediments were glacial in origin, and contained few if any marine organisms. This was the first evidence that this flank of the West Antarctic Ice Sheet began rapid gravitational collapse and retreat in historical times.

Ice discharged by Pine Island Glacier begins at a saddle only 1250 m above sea level on the lowest major ice divide in Antarctica. Across the ice divide, ice flows into Rutford Ice Stream, which supplies Ronne Ice Shelf. Ice downdrawn by these ice streams may lower the ice divide nearly to sea level, allowing a calving bay to open a seaway at the base of Antarctic Peninsula. British glaciologists from BAS began a major study of these ice streams during the decade. Snow accumulation rates are maximum on the ice divide, and decrease toward Pine Island Glacier, where katabatic winds have scoured off the snow, exposing firn with a density of around 650 kg per cubic meter. Siple Station had been established near the ice divide by NSF/OPP, and a corehole had been drilled that provided vertical ice densities that should increase downward somewhat like surface density increases from the

ice divide to the calving front of Pine Island Glacier. A lateral moraine along the crest of Evans Knoll, about 100 m above and alongside Pine Island Glacier, contained numerous glacial erratics. Robert Ackert obtained an exposure-age date on one that was over a million years old. Had ice elevations in this region remained stable, while ice lowered both upslope and downslope?

Ice discharged by Thwaites Glacier begins at a much higher saddle on the ice divide, 1800 m above sea level. Across this high saddle, ice flows into ice stream D, which is partly buttressed by Roosevelt Island ice rise on the Ross Ice Shelf and is (therefore?) much slower than Thwaites Glacier. Thwaites Glacier pushed an iceberg tongue 100 km long that seemed to be rotating about a bedrock pinning point. The iceberg tongue is now gone and Thwaites Glacier has accelerated.

Thwaites and Pine Island Glaciers drain about one-third of the remaining grounded West Antarctic Ice Sheet. If they were to merge again, as they did when they occupied the submarine trough extending northward from Pine Island Bay, drawdown of this region would be even faster than at present, causing the ice divide to retreat southward, thereby shrinking the snow accumulation areas supplying ice streams entering Ross Ice Shelf to the west and Ronne Ice Shelf to the east, thereby slowing these ice streams and starving the ice shelves. Pine Island Glacier moves 2 km/a and Thwaites Glacier moves 4 km/a, making them the fastest Antarctic ice streams by far. During Holocene gravitational collapse of the Ross and Weddell sectors of the West Antarctic Ice Sheet, ice entered from the east, west, and south, and left to the north. Today, very little East Antarctic ice enters West Antarctica from the south, and ice leaves from the east, west, and north. This is about a tenfold increase in the rate of ice leaving the West Antarctic Ice Sheet compared to ice supplying the ice sheet. What took 6000 years during the Holocene may now take less than 600 years.

West Antarctic ice draining into Pine Island Bay is flanked by the Ellsworth Mountains in the east and the Executive Committee Range in the west. In 1979-1980, George Denton, James Bockheim, Robert Rutford, Bjorn Andersen, Howard Conway, and John Splettstoesser mapped "trimlines" 400 m to 650 m above the present ice surface in the Ellsworth Mountains. These trimlines can be interpreted as former ice elevations or as a basal thermal boundary that separates a thawed bed below from a frozen bed above. Trimlines exist along ridges flanking the main trend of the Ellsworth Mountains. Weathered "teeth" (tors) of rock follow the crest of these ridges above the trimline, but these teeth are missing and the ridges are much smoother below the trimline. Can slowly moving surface ice remove the teeth? Or were they preserved by nearly stagnant deep ice frozen to them? It makes a difference of perhaps 1500 m in former ice elevations. The trimlines are undated, but now can be, using exposure-age dating. Do the trimlines date from the LGM? In the Executive Committee Range, mountain nunataks are encircled by "bathtub-ring" moraines about 50 m above the present ice surface. These were sampled and mapped on Mount Waesche. Robert Ackert, David Barclay, Harold Borns, Jr., Parker Calkin, Mark Kurz, James Fastook, and Eric Steig reported an exposure-age date of 10,000 years in 1999. Did LGM ice on a frozen bed cover these nunataks, so no higher moraines formed? Pine Island and Thwaites Glaciers have lowered the ice divide, regardless of what interpretation is made for trimlines and bathtub-ring moraines.

1990—2000

New insights regarding the stability of West Antarctic ice streams were made in this decade. In 1994, Richard Alley, Sridhar Anandakrishnan, Charles Bentley, and Neal Lord proposed a “water piracy” mechanism in which ice stream C was slowed virtually to a halt when lubricating basal water was diverted upstream into ice stream B, which then speeded up. Ice stream E has a large bedrock bump that exerts local control on the ice velocity. Using inverse modeling, Douglas MacAyeal, Robert Bindshadler, and Theodore Scambos determined in 1995 that the bump constrained ice discharge, even though it was surrounded by frictionless till similar to that underlying ice streams B and C. Perhaps smaller bedrock bumps not resolved by radar mapping project through the till and into basal ice for these ice streams as well, controlling their velocity. Such pinning points under floating ice shelves certainly slow their velocity, as studies of Cray Ice Rise demonstrated for Ross Ice Shelf.

David Bromwich, a climate modeler at OSU/BPRC, was able to model the atmospheric circulation over the Antarctic Ice Sheet so accurately that flights from McMurdo Station to inland Stations could be planned reliably, based on model output.

NASA Earth-orbiting satellites made major contributions to Antarctic glaciology during this decade. By selecting appropriate electromagnetic wavelengths from satellite transmitters, surface elevations, temperatures, accumulation and ablation rates, and velocities could be measured with varying but ever-improving reliability and accuracy. Particularly useful was synthetic aperture radar interferometry that detected migrations of ice-shelf grounding lines and subtle changes in surface ice velocities, and laser altimetry that detected changes in ice surface elevations to 0.01 m of accuracy. Ice-shelf grounding lines and ice streams crossing them in West Antarctica proved to be very sensitive to small changes in boundary conditions. Eric Rignot at the Jet Propulsion Laboratory of CIT has been especially diligent in reporting these instabilities. Major ice streams were shown to be supplied by many smaller tributary ice streams, much as in river drainage systems. Kenneth Jezek at BPRC/OSU collaborated with NASA and the Canadian Space Agency to produce the RADARSAT-1 Antarctic Mapping Project that showed in high resolution all the sheet to stream to shelf flow transitions in BPRC Report No 22, circulated in 2008. A major glaciological conflict developed during the 1990s. Peter Webb and David Harwood at OSU, with Barry McKelvie, Howard Brady, and M. C. G. Mabin in a series of papers, concluded that marine diatoms and fragments of Antarctic Beech trees (*Nothofagus* species) found in tillites of the Sirius Group high in the Transantarctic Mountains had been deposited after the marine Wilkes Land sector of the East Antarctic Ice Sheet had collapsed to sea level during the Pliocene and disintegrated into icebergs, so that marine diatoms entered the resulting ice-free marine embayment and contributed to the sea-floor sediments. Then this sector re-formed, the diatoms were scraped from the sea floor along with other sediments and deposited along the Transantarctic Mountains as tills that lithified to become the Sirius Group tillites. This view was presented in *National Geographic Magazine* as a revolutionary idea that became known as the dynamicist theory.

Countering this view was the stabilist theory presented by George Denton, David Sugden, David Marchant, Brenda Hall, and Thomas Wilch in 1993. Using concepts of

landscape evolution developed by South African geologist Lester King, they showed that landscapes all along the Transantarctic Mountains are very old, especially in the Dry Valleys, and precluded the much warmer Pliocene temperatures and tectonic uplift rates required by the dynamicist theory. Overriding of the Transantarctic Mountains by the East Antarctic Ice Sheet, as required to deposit the Sirius tillites, had to have been much older, at a time when climatic and tectonic conditions were much different from Pliocene conditions. In 1975, Paul Mayewski showed, by mapping high glacially striated bedrock pavements along some 1000 km of the Transantarctic Mountains, that a glacial overriding event had occurred in the Cenozoic Era (it can now be exposure-age dated). He called this the Queen Maud Glaciation. Thomas and Davida Kellogg from UM, and Lloyd Burckle at Columbia, showed that both marine and lacustrine diatoms were present in Sirius tillites, they were windborne, and appeared in snow and ice all over Antarctica. Burckle and E. M. Pokras gave evidence for Pliocene stands of *Nothofagus* within 500 km of the South Pole.

In 1999, John Anderson at RU published his landmark book, *Antarctic Marine Geology*, that linked former ice streams that occupied glacial troughs on the continental shelf of West Antarctica to present-day ice streams. The swinging-gate retreat of the Ross Ice Shelf grounding line, past and future, was reported in 1999 by Howard Conway, Brenda Hall, George Denton, A. M. Gades, and Edwin Waddington. In 2001, the American Geophysical Union published *The West Antarctic Ice Sheet: Behavior and Environment*, edited by Richard Alley and Robert Bindschadler. It reported the main glaciological findings in West Antarctica during the 1990s.

At the end of the 1990s, the research ship *Nathaniel Palmer* sailed from McMurdo Station eastward along the calving fronts of Ross Ice Shelf and Getz Ice Shelf into Pine Island Bay. Aboard were John Anderson studying marine geology using chirp sonar mapping, Thomas and Davida Kellogg doing seismic profiling and collecting sea-floor sediments in piston cores, and Stanley Jacobs conducting temperature-salinity-depth oceanographic measurements. They found a series of deep sea-floor channels extending from under Getz Ice Shelf to the edge of the continental shelf in the Amundsen Sea, as had been found in the Ross Sea north of Ross Ice Shelf. Oceanographic data showed that warm Antarctic water was spilling over the continental shelf and following the deep troughs that passed under the ice shelf. This warm water would cause high basal melting rates along the ice-shelf grounding line where ice streams become afloat. This is a powerful destabilizing mechanism for the marine West Antarctic Ice Sheet in the Amundsen Sea. Surface air temperatures do not have to reach the melting point in order to destabilize this critical boundary condition. Marine currents need to warm only slightly to accomplish the same thing. Satellite radar showed Getz Ice Shelf is deeply fragmented under its snow cover.

2000—2010

A new project of the decade was drilling through Siple Ice Dome between ice streams C and D in West Antarctica. Radar horizons and oxygen-isotope stratigraphy down the corehole led to the conclusion by Edward Waddington and colleagues in 2005 that the flanking ice streams were probably less than 1000 m high and active at the LGM, making them an astounding 1000 km long. This view was challenged in 2010 by Gordon Bromley and colleagues who mapped and exposure-age dated lateral moraines above nearby Reedy

Glacier that were originally mapped by John Mercer in the 1960s. The LGM moraine is up to 1400 m above the present Ross Ice Shelf grounding line where Reedy Glacier joins ice stream A. This team has now mapped similar high lateral moraines 1200 m high alongside nearby Scott Glacier, also a cold-based East Antarctic outlet glacier at the LGM. Are these former ice elevations dating from the LGM compatible with much lower ice elevations of wet-based ice streams C and D alongside Siple Ice Dome at the LGM?

The most dramatic event of this decade was rapid disintegration of Larsen Ice Shelf on the eastern side of the Antarctic Peninsula, first the northern sector in 1995 and then the central sector in 2002. This explosion of icebergs into the Weddell Sea was modeled by Douglas MacAyeal, Theodore Scambos, Christine Hulbe, and Mark Fahnestock in 2003. It was accompanied by a simultaneous surface lowering and velocity increase of glaciers in the mountains of the Antarctic Peninsula that were supplying ice to Larsen Ice Shelf, as reported by Hernan De Angelis and Pedro Skvarca, also in 2003. This settled the old dispute, dating from 1972, whether confined and pinned ice shelves are able to buttress ice streams that supply them.

Removing a buttressing ice shelf is not the only way to accelerate an ice stream. The glacial surge mechanism studied on Variegated Glacier in Alaska in 1982-1983 by glaciologists from UW led by Charles Raymond and by Barclay Kamb from CIT will as well. The surge began at the head of the glacier and propagated to its foot. With ice streams, a surge also propagates downstream from their head. Robert Bindshadler reported in 1997 that West Antarctic ice stream B, and probably ice streams D and E, show this behavior.

NASA glaciologist Robert Thomas, in collaboration with the Chilean Navy, conducted laser-altimetry and radar-sounding flights to the Amundsen Sea sector of the West Antarctic Ice Sheet in 2002 to map submarine troughs occupied by Pine Island Glacier and Thwaites Glacier, and the ice surface downdrawn by these fast ice streams. This spurred NSF/OPP to conduct similar research, but employing a tighter grid of flightlines. These studies showed that the whole ice drainage basin of Pine Island and Thwaites Glaciers is lowering, and these ice streams are accelerating. Thomas produced a model of this behavior in which longitudinal stresses that resist gravitational spreading of ice shelves allow these ice streams to pull out interior ice. Bottom melting at ice-shelf grounding lines was critical in driving grounding-line retreat and downdraw of interior ice as ice-shelf buttressing weakens. Eric Rignot, CIT Jet Propulsion Laboratory, and Stanley Jacobs, Columbia University, showed in 2002 that grounding-line basal melting in the 4 to 40 m/a range is widespread today all around Antarctica, peaking in Pine Island Bay, with 1 m/a of bottom melting per 0.1 C increase in ocean temperature.

In 2004, Kathy Licht, Jason Lederer, and Jeffrey Swope mapped the provenance of the sand fraction in glacial till all over the Ross Sea continental shelf north of the Ross Ice Shelf calving front. This linked present-day ice streams from both East and West Antarctica to ice streams that occupied glacial troughs in this region at the LGM.

The U. S. component of the International Trans-Antarctic Scientific Traverses (ITASE) led by Paul Mayewski at UM occupied much of this decade. These were tractor-train traverses along which surface meteorology was conducted and high-resolution shallow ice

cores were taken to recover historical climate records from stable isotopes, air bubbles, trace ions, dust, and diatoms, all of which serve as proxies for changes in weather and climate. Individual storm systems could be detected. Stratigraphy from snow pits and the cores were tied together by shallow radar sounding that recorded continuous reflecting surfaces produced seasonally. These data were used in mass-balance studies by Gordon Hamilton at UM. Deep radar sounding was conducted by Robert Jacobel at St. Olav College in Minnesota to determine ice thickness and bed conditions. The traverse routes were just below the ice divides of the Amundsen Sea ice drainage system and the Ross Sea ice drainage system in West Antarctica, with one route passing through a gap in the Transantarctic Mountains informally called the “bottleneck” to finish at South Pole Station. An East Antarctic traverse began at Taylor Dome near McMurdo Station, and passed south of the Transantarctic Mountains to South Pole Station.

Douglas MacAyeal at UC undertook studies of giant icebergs released by Ross Ice Shelf in 2002. He became aware of ocean swells that begin from volcanism, earthquakes, and even storms as far away as the North Pacific and then move southward in attenuated form to pass under Antarctic ice shelves. This induces resonant frequencies in the ice shelf that may release the giant icebergs along pre-existing crevasses, so tectonic and meteorological disturbances, if sufficiently strong, can lead to major calving events from Antarctic ice shelves. MacAyeal and colleagues updated these observations in 2009, adding local calving events and iceberg collisions that generate ocean waves possibly linked to sudden disintegration of Antarctic ice shelves. In 2009, Ted Scambos and colleagues updated work on the ongoing explosive disintegration of ice shelves alongside the Antarctic Peninsula.

Robert Bindshadler, Matt King, Richard Alley, Sridhar Anandakrishnan, and Laurence Padman showed in 2003 that tides induce stick-slip discharge of West Antarctic ice stream D, with slip propagating at 88 m/s. Leigh Stearns, Ben Smith, and Gordon Hamilton showed in 2008 that Byrd Glacier, the largest and fastest ice stream supplying Ross Ice Shelf, had a ten percent increase in velocity when two large subglacial lakes beyond the head of Byrd Glacier drained suddenly. These results emphasize the role of rapid, sudden events on the dynamics of ice streams. If sustained, such events could have a major impact on the stability of ice streams, and hence of the ice sheet.

In 2005, NSF/OPP with NASA support established a science and technology center at the University of Kansas (KU) called the Center for Remote Sensing of Ice Sheets (CReSIS), under the leadership of S. Prasad Gogineni. The main technological goals are to develop radar sounding capable of reaching the bed of heavily crevassed ice streams, which was impossible during the NSF-SPRI-TUD Radio-Echo Sounding Program in Antarctica during the 1970s, and to develop unmanned remote-controlled surface and air vehicles that collect and transmit basic glaciological data on ice streams and other sites where crevassing makes a human presence problematic. The scientific goals are to use Earth-orbiting satellites to gain a continuous record of dynamic changes in the Antarctic and Greenland Ice Sheets, and collect data on surface temperatures, accumulation and ablation rates, elevations, and velocities, and then to make detailed field studies at sites showing unusual dynamic activity, notably along ice streams and at the grounding lines and calving fronts of ice shelves. By 2010 these projects and goals were on schedule or reached.

At the end of the decade, glaciologists Jack Holt at the University of Texas (UT) and Gordon Hamilton at UM headed teams that began a long-awaited precision study of Byrd Glacier, beginning with radar sounding of the bed and placing GPS receivers on the surface.

The showpiece of the decade for WAIS has been drilling a corehole to the bed of the West Antarctic Ice Sheet near the ice divide separating the ice drainage systems for Thwaites Glacier in the Amundsen Sea sector and Bindschadler Ice Stream (formerly ice stream D) in the Ross Sea Sector. Ice from the drilling site flows toward Thwaites Glacier, so the vertical record down the corehole can be correlated with downstream flow of ice to the fastest ice stream in Antarctica. The site is above a subglacial basin which probably contains subglacial lakes. These lakes are widespread in Antarctica, as reported in 2009 by Ben Smith, Helen Fricker, Ian Joughin, and Slawek Tulaczyk. The lakes often become interconnected beneath ice streams, as reported by Robin, Swithinbank, and Smith in 1968 for Kamb Ice Stream (formerly ice stream C) and by Fricker and Ted Scambos in 2009 for Mercer and Whillans Ice Streams (formerly ice streams A and B).

The Vostok corehole, 4 km deep, is near the high central dome of East Antarctica and is now just above subglacial Lake Vostok, which is the size of Lake Michigan. Penetration into the lake awaits technology that will prevent contamination of the lake water and perhaps an uncontrolled rise of high-pressure lake water in the corehole. The core contains the longest climate record in Antarctica. Many papers have presented interpretations of this record. Gordon Robin was a co-author of one paper. Charles Swithinbank informed me that Gordon (now deceased) would have preferred being listed higher among the authors. I replied that, at least for authors listed alphabetically, Gordon could become lead author merely by changing his name to Horst S. Aas. Science should not be taken too seriously.

I wish to acknowledge NSF/OPP program managers for glaciology over the past half century. With the kind assistance of Guy Guthridge, they and their tenures are:

Mort Turner, 1960—1972.

H. Jay Zwally, 1972—1974.

Richard Cameron, 1975—1985.

Craig Lingle, 1986.

Harold Borns, Jr., 1987—1989.

Julie Palais, 1990—present.

This was produced on Halloween so some goblins crept in. Did you notice? Many glaciologists contributed to the themes in this account and aren't mentioned. To them I apologize. In compensation I don't mention me either. Subsequent revisions were made

after input from Henry Brecher, Olav Orheim, John Splettstoesser, Charles Swithinbank, and Jay Zwally. Their input extended the original 16 pages on Halloween to 18 pages.