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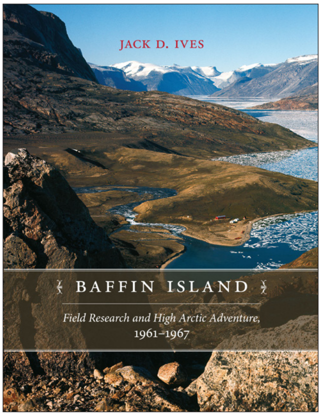

BAFFIN ISLAND: Field Research and High Arctic Adventure, 1961–1967 by Jack D. Ives

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CHAPTER 11

ASSESSMENT OF THE SCIENTIFIC RESULTS

Assessment of the scientific results of the 1961 to 1967 Baffin Island expeditions must be set within the context of the general knowledge and hypotheses that were prevalent during the 1950s and 1960s. Even in the 1960s, additional research was undertaken in neighbouring regions, such as Axel Heiberg and Devon islands, the Canadian Arctic mainland (Lee, 1960; Müller, 1962), and in southern Baffin Island (Blake, 1966). Similarly, the earlier research in Arctic Scandinavia (De Geer, 1912; Frodin, 1925; Gjessing, 1960; Hoppe, 1952, 1957; Mannerfelt, 1945; Schytt, 1949) and my own experience in Iceland (King & Ives, 1956) and with Olav Løken in Labrador-Ungava (Ives, 1960b, 2010; Løken, 1960, 1962) had greatly influenced the evolution of thinking within the Geographical Branch, as previously acknowledged. Much of this work also continued contemporaneously with the Baffin field program and, given the participation of our Scandinavian contingent, cross-fertilization was automatic. In the words of Pat Webber,

> The pursuit of knowledge, that is, science, usually progresses in small steps, each step building on what went before. It is reasonable to say that the Baffin Island expedition members and their students contributed a quantum leap to, and the foundation for, the present level of understanding of the ice age history, the periglacial environment, the Holocene climate, and the biota of the eastern Canadian Arctic. It is also fair to say that the group's early estimates of process rates and interpretations of glacial history have held up remarkably well. Nevertheless, it is extremely satisfying to see the great strides that have been made since the 1960s, especially in recent decades, with the development and application of new technology and methods. (Personal communication, February 20, 2014)

The first task of this chapter, therefore, is to outline what emerged from Geographical Branch efforts in Baffin Island within the stated context. A second task is to address, in retrospect, how the results of later research (1968 to present) have been influenced by the 1961–1967 studies and to what extent the latter have been modified and/or contravened. This is presented only in outline because of the very extensive publication record and the ongoing nature of the research effort. Thirdly, we need to assess the influence of the Baffin project on the careers of a substantial cohort of scholars in geography and related disciplines (see chapter 10).

Concept of Canadian Arctic and Subarctic glaciation prior to 1960

Early publications on the ice age history of the eastern Canadian Arctic and Subarctic were influenced by more detailed work in Fenno-Scandinavia. One of the more relevant hypotheses had been that, during the ice ages, large parts of the Norwegian coastal mountain summit areas had projected above the maximum height of the Fenno-Scandinavian Ice Sheet as *nunataks*; hence the "nunatak hypothesis."[1] The hypothesis was developed to account for the peculiarly restricted distribution of a large group of arctic-alpine plant species that many botanists argued must have survived the ice ages in (or close to) places where they flourish today. The nunatak hypothesis was strenuously contested by most earth scientists of the time, although this interdisciplinary confrontation was by no means absolute.

The Scandinavian dispute about the nunatak hypothesis persisted for almost a century and is still not entirely resolved (Brochmann, Gabrielsen, Nordal, Landvik, & Elven, 2003). The frequently astringent academic exchanges are divided among two distinct groups of researchers: biologists, principally botanists, with a few supporting zoologists, on the one hand, and earth scientists and most physical geographers on the other. The botanists had built an extremely detailed database on the peculiar distribution of the arctic-alpine group of plant species that seemed restricted to specific high mountain areas of Norway and Sweden with no clear means of inmigration following the disappearance of the major ice sheet (Dahl, 1955, 1961; Ives, 1974; Löve & Löve, 1963, 1974). The earth scientists appeared to have scant sympathy for their rivals, although the high mountain areas in question had revealed little, if any, unambiguous field evidence to support the argument that, at its maximum, the Fenno-Scandinavian Ice Sheet had completely overtopped all the high summits. Knowledge of the extent and significance of cold-based ice, however, was not well developed at the time. In contrast, the lower elevations contained widespread and unequivocal evidence of active glacial erosion and deposition (that is, by warm-based ice, as was understood much later). Frequently, this was marked by a distinctly aligned upper limit that sloped down along the main valleys and fiords toward the Norwegian Sea, often paralleled at lower levels by the lateral moraines of former glaciers. The proponents of the nunatak hypothesis took this upper limit as proof of the maximum extent of ice age glaciers (Dahl, 1955, 1961). Nevertheless, it was widely recognized that sections of the high "nunatak areas" had also supported small, thin ice caps and local glaciers. The search for support of the nunatak hypothesis was extended to Greenland, Svalbard, Iceland, and Alaska.

The controversy was also "exported" to northeastern North America, where the same lack of unequivocal mountaintop evidence for glacial erosion became a basis for continued controversy. However, in comparison to Norway and Sweden, the botanical evidence was sparse, simply because the eastern coastal mountains were virtually unexplored. Some botanists employed the nunatak hypothesis to explain what was known about arctic-alpine plant species distribution, principally in New England (e.g., Mount Washington, and Mount Katahdin: see Fernald, 1925). Contrasting sets of earth science data fuelled the argument, focussing on the Torngat Mountains of northern Labrador, northern Newfoundland, and the Shickshock Mountains of Gaspésie, Quebec. Daly (1902) and Coleman (1920, 1921, 1926) argued that the Torngat Mountain summits had remained above the maximum height of the Laurentide Ice Sheet (technically, the Labradorean Ice Sheet at that time). Their reasoning depended heavily on the absence of indications of glacial action on the summits and the assumption that development of the extensive high-level boulder fields (*felsenmeer*, or mountaintop detritus) would take an extremely long time. However, in 1933, Dr. Noel Odell (of Mount Everest fame) reported what he assumed to be definitive evidence of total submergence by ice of all the Torngat Mountains, based on his interpretation of faint glacial striations and his assumption that the mountaintop boulder fields were the product of rapid (i.e., postglacial) frost shattering after the disappearance of the final ice sheet. The time needed for formation of the extensive boulder fields (*felsenmeer*) became central to much subsequent dispute, although a lack of dating techniques at the time meant that much of the argumentation was a matter of personal opinion, if not downright specious.

A pre-1960 attempt to break the logjam developed from interpolation of the scattered knowledge of higher sea levels, based on the discovery far above present sea level of marine molluscs (seashells) and terraces similar to modern sea level beaches and deltas. It had long been understood, especially based on earlier work in Fenno-Scandinavia around the shores of the Gulf of Bothnia, that variations in the height of the marine limit was a reflection of regional variations in thickness of the former ice sheets. Here was a substantive argument based on the principal of isostasy—that the weight of the former ice sheets caused a proportionate depression in the earth's crust. After the ice sheet disappeared (indeed, even while it was thinning and retreating), the sea crossed the recently exposed land (which was rebounding to its pre–ice age levels), reaching elevations high above modern sea level and marking the uppermost shoreline (i.e., the marine limit), which often is sixty to eighty metres above modern sea level in the inner fiords of northeastern Baffin Island. But despite the fact that the sea level was rising as the ice sheets melted and retreated, the land eventually rebounded even more extensively, causing the relative position of sea level to lower (or regress) continuously back down to its modern position—this is so-called postglacial rebound.[2] Evidence for the highest former sea levels, at more than three hundred metres above present, is located in the southeastern sector of Hudson Bay; it is thought to mark the former maximum thickness of the Laurentide Ice Sheet and thus the location of greatest unloading of the formerly (glacio-isostatically) depressed land. Prior to the Baffin Island surveys, however, the largely unexplored nature of the eastern Canadian Arctic provided only scattered observations, often limited to sightings from shipboard, of apparently horizontal terraces high above present sea level. When the technique of radiocarbon dating, especially applicable to seashells associated with the raised marine shorelines, became widely available in the 1960s, there was a great leap forward in understanding the interrelations between these raised marine shorelines and the regional history of retreat of the Laurentide Ice Sheet.[3]

Before the 1960s—the decade of the sea level surveys by the Geographical Branch across Baffin Island—the sparsely available evidence was absorbed by Professor Richard Foster Flint, who emerged as the doyen of North American glacial geologists during the period from 1940 to 1972 (Flint, 1943, 1945, 1947, 1957, 1971). He accepted the evidence presented by Odell (1933) from the Torngat Mountains as proof positive that the continental ice sheet had totally overtopped the highest summits. He also interpreted the highly equivocal observations of Wordie (1938) in the fiords of northeastern Baffin Island as ostensibly recording very high former sea levels; this, of course, facilitated Flint's presumption of extremely thick glacial ice sufficient to overtop the highest coastal summits.[4] Thus, he developed a model for the growth and decay of the Laurentide Ice Sheet that became the prevailing paradigm, receiving almost universal endorsement.

Flint referred to his concept of North American glacial history as a "mirror-image model" of the pre-existing Scandinavian theory of growth, climax, and decay of the Fenno-Scandinavian Ice Sheet. This mirror-image depiction, derived from the presumed similarity of the topography on either side of the North Atlantic Ocean, augmented by the much more advanced status of relevant Scandinavian research, could also be directly imported. Flint's vision of east coast Canadian topography was vital to his hypothesis. But while the outlines of the coast had been reasonably well mapped, vast areas of the interior were practically unknown. Nevertheless, he assumed that the eastern coastal areas, from northern Ellesmere Island down the extent of Baffin Island to mid-Labrador, supported high mountains facing Greenland, Baffin Bay, Davis Strait, and the western Atlantic, while their western flanks sloped down steeply to a series of inland plateaus and lowlands leading to Foxe Basin and Hudson Bay.[5] This, in effect, was the mirror image of the high coastal mountains of Norway that sloped eastward across Sweden to the Gulf of Bothnia.

Flint presumed, moreover, that the Gulf of Mexico was the origin of atmospheric low pressure systems that moved northward and northeastward, providing the moisture source for the growth of the Laurentide Ice Sheet once air temperatures began to fall with the onset of an ice age. As Flint's hypothetical snowline lowered with the falling air temperature, it would eventually first intersect the summits of the coastal mountains and so cause the buildup of glaciers and small ice caps. The masses of ice would thicken and spread, forming glaciers that flowed eastward down the fiords and out into the Atlantic Ocean and Baffin Bay, breaking off as icebergs. This would place a check on the increase in accumulation at the higher elevations. In contrast, those glaciers flowing down the "western flank" of the mountains would build up into vast piedmont lobes on the plateau surfaces, a process further augmented by the fact that they were expanding into the source of solid precipitation—the moist air masses flowing from the Gulf of Mexico. This was Flint's so-called model of "highland origin and windward growth." Eventually, the accumulation of ice to the west of the coastal mountains would exceed them in elevation, causing a reversal of flow through the mountains and into the Atlantic, Baffin Bay, and Davis Strait, submerging the highest summits in the process.

Continued westward growth of the ice sheet would eventually engulf Hudson Bay and Foxe Basin and push westward for thousands of kilometres, terminating against the flanks of the Rocky Mountains. This grand model ultimately culminated in a continental-scale Laurentide Ice Sheet, with its centre more than four thousand metres thick. Flint envisaged the reverse of this gigantic process during the receding hemicycle of each successive ice age (the convention of the time was that there were four major ice ages, together with their "interglacials," forming the Pleistocene Period). The last remaining small ice caps and glaciers, therefore, were considered to have been located on the coastal mountains where the process began and where many exist today, as in the Torngat Mountains and Baffin Island. Flint's intriguing and highly persuasive thinking provided the Geographical Branch's Baffin Island project with the major objective of completing the initial challenge to Flint's conclusions that was initiated by the early work of the McGill Sub-Arctic Research Lab in Labrador-Ungava (Ives, 1957, 1960, 2010; Løken, 1960, 1962).

To this point, the Laurentide Ice Sheet, at its maximum, was regarded as a single immense dome, centred over Hudson Bay. Its southern perimeter extended deep into the United States; its western limit pushed up against the flanks of the Rocky Mountains, where it came into contact with the Cordilleran Ice Sheet complex; and its northern section engulfed Ellesmere Island and the High Arctic, with the exception of several of the northwestern islands, parts of the Yukon, and northern Alaska that were assumed to have remained ice-free beyond its limits. This would have placed the eastern margin of the Laurentide Ice Sheet along the edge of the North Atlantic/Baffin Bay continental shelf.

In 1960, therefore, the dominance of the "Flintian" hypothesis was beginning to be challenged. Nevertheless, the unknown proportion of the region's glacial history still vastly exceeded that of the known. Bruce Craig and John Fyles (1960) of the GSC had produced an overview of the history of the Laurentide Ice Sheet and argued that its northern limit was much more circumscribed than Flint had assumed.

They postulated an independent, or semi-independent, Ellesmere-Baffin ice complex, although they emphasized the sparseness of field data over a largely inaccessible landmass that was subcontinental in size. This immense region, of course, included Baffin Island and the uncertainty was a major factor in my early fieldwork aspirations.[6]

Arctic glaciology

In the years following the Second World War, Professor J. Tuzo Wilson worked to promote glaciological research in Canada. During the organization of the 1957 meetings of the International Union of Geodesy and Geophysics, which Canada was hosting in Toronto, Wilson urged the addition of glaciology as the one International Geophysical Year (IGY, 1957–1958) science not hitherto included by Canada. He also undertook to ensure a Canadian glaciology contribution to the IGY, which led to a number of initiatives: the first "Glacial Map of Canada"; a multi-year glaciological study of the Salmon Glacier in British Columbia; and many significant spin-offs—in particular, Geoff Hattersley-Smith's organization of Operation Hazen through the Defence Research Board, Ottawa, and his reconnaissance with Bob Christy (of the GSC) of the ice shelves along the northern coast of Ellesmere Island.[7] Separately, the Arctic Institute of North America (AINA) pioneered glaciological research on Baffin Island with the expeditions of 1950 and 1953 led by Pat Baird. Sometime later, Fritz Müller initiated the long series of McGill-Jacobsen expeditions to Axel Heiberg Island (Adams, 2007). Similarly, in the 1970s, Roy (Fritz) Koerner began a long-term glaciological project on the Devon Island ice cap with the Polar Continental Shelf Project.[8] Still, systematic and continuous glaciological investigations were non-existent in 1960—and did not start until the establishment of the Glaciology Section in the Geographical Branch. Significantly, the struggle to establish the Glaciology Section received vital assistance from Tuzo Wilson (see chapter 3).

Some important new glaciological concepts were being proposed during this early period: for example, that all the previous winter's snowfall, even on the highest parts of the Barnes Ice Cap, melted during the following ablation season ("summer"), and nourishment depended on the refreezing of the meltwater (superimposed ice) onto the underlying very cold ice; also, that the Barnes Ice Cap could be a surviving remnant of the last ice age that had been substantially reduced in size during the intervening Climatic Optimum. The so-called end of the last ice age (Wisconsin) had been arbitrarily set worldwide at 10,000 years BP (i.e., at the beginning of the Holocene), leaving Baffin Island and many other glacierized areas as anomalies because of the persistence into the twentieth century of a large number of their glaciers and ice caps.

These were some of the intriguing issues that had prompted Geographical Branch interest—especially the need for verification, so that such major conclusions were not to remain based on a single season's observations or on hypotheses with very limited supporting field evidence. The late 1950s and 1960s were also the period when researchers began to realize that glaciers and ice caps in very cold climates were probably frozen to their beds. While no deep ice drilling had been undertaken at that time, it was hypothesized that actual glacial erosion would be severely restricted except under thick ice—that is, more than three hundred metres—the base of which would remain at the pressure-melting point and so allow the ice to flow over and to erode the bedrock. Similarly, the general understanding of the extent and depth of permafrost and associated landforms was slowly developing (Mackay, 1960, 1965; Brown, 1967). This was also a period when glaciology, as a scientific undertaking, was beginning to attract the attention of physicists, mathematicians, and engineers; thus, contributions to the "physics of ice" were emerging and affecting the hitherto much less rigorous "geographical" study of glaciers (Paterson, 1969). However, these early attempts to establish a systematic glaciological and glacier mapping program in Canada faltered; they were taken up again after 1970.

Botany

Prior to the establishment of the DEW Line, access to Baffin Island was almost entirely confined to visits to the small Inuit coastal settlements, aided by the Hudson's Bay Company annual supply vessels, occasional government icebreakers, and overwintering parties of the late nineteenth and early twentieth centuries such as those led by Bernhard Hantzsch, Franz Boas, Therkel Mathiassen, Dewey Soper, and Tom Manning. Plant collections had been made at many points and incorporated into regional assessments by such leading botanists as Erik Hultén, Erling Porsild, and Nicholas Polunin. The 1950 and 1953 AINA expeditions included botanists Pierre Dansereau and Fritz Schwarzenbach, as well as zoologists V. C. Wynne-Edwards and Adam Watson, so the second phase of more detailed and interdisciplinary investigation had begun in the Clyde and Pangnirtung Pass areas. Nevertheless, in 1960, Baffin Island was 95 percent unknown biologically, except by extrapolation from a few scattered points. This was especially true for our expedition areas, as is patently evident from the famous dot maps in Porsild's masterful 1957 work on the flora of the Arctic, which shows all locations of known vascular plant collections to that point in time. The scientific attraction of this virtual void was augmented by the provisional identification on the new RCAF trimetrogon air photographs of the extensive distribution of light- and dark-toned areas across the Baffin interior north and east of the Barnes Ice Cap. This raised the question that the tonal variation might be a manifestation of vegetation distribution and ground cover. Detailed studies of the vascular plants of northern Labrador and northeastern Baffin Island, comparable with those in Scandinavia, have not yet even been attempted.

Former high sea levels

Somewhat akin to the sparse knowledge of the distribution of plants was the very scattered information of field evidence for former high sea levels. Some information was certainly available—for areas along the northeast coast of Hudson Strait, the northwestern Foxe Basin, and areas along the northeast coast of Baffin Island. Nevertheless, systematic knowledge was entirely lacking and radiocarbon dating (C_{14}) was still unavailable. This lack of information was rendered more problematic because of the confusion caused by Flint's misinterpretation of Wordie's (1938) account of very high terraces in the inner fiords above 300 metres (see chapter 1) and Mercer's (1956) assumption of former sea levels in Frobisher Bay in excess of 340 metres above present sea level. Sim (1961) had made a reconnaissance of parts of Melville Peninsula for the Geographical Branch; however, with the exception of Løken's work in the Torngat Mountains, there had been no identification of actual strandlines nor their subsequent delevelling (tilting) that would record the direction of maximum postglacial rebound (related to former maximum ice sheet thickness). The scarcity of observations on former raised shorelines and significant misinterpretations attributed to high-level terraces were especially critical because of the widely understood relationship between maximum former sea levels and thickness of the ice age ice sheets.

The scientific objectives

When Dr. Norman Nicholson sought to recruit an experienced physical geographer in 1959–1960, it is understandable that the various topics outlined above ensured that Baffin Island would offer a remarkable field research opportunity. Linked together, they were an essential element of my interest in joining the staff of the Geographical Branch. While by no means unique for Canada's Arctic and Subarctic, Baffin

Island stood out as an obviously attractive place for expansion of the research emanating from the McGill Sub-Arctic Research Laboratory in Labrador-Ungava despite the logistical challenge it posed. These considerations, therefore, provided the basis for the 1961 reconnaissance to Rimrock, Flitaway, and Separation lakes and the trans-island traverse south of the Barnes Ice Cap (chapter 2). And despite the inadequacies of the aircraft charter, the reconnaissance was sufficiently successful that it led to a continually expanding research program. The main results are highlighted in the following sections.

The 1961 reconnaissance

A virtual jigsaw puzzle—that of the light- and dark-toned expanses, the abandoned glacial lake shorelines, and the multiple ridges running perpendicular to the trend of the main valleys north of the Barnes Ice Cap—was provisionally resolved (Figs. 2, 3, and 9). The light-toned areas resulted from the very limited growth and small diameter of rock lichens that left patches of land nearly barren, in contrast with the darker intervening areas whose lichen cover was heavy. It was concluded that this was the result of differential distribution of permanent ice and snow at some time in the past that had either killed off a former mature lichen cover or had inhibited lichen growth in comparison with the areas that remained ice-free. This period of former, more extensive ice cover was originally estimated to have occurred some two to four hundred years ago, based on extrapolation of lichen growth rates. The actual dating estimate needed to be refined and applied more systematically to the area below the pronounced shoreline of a former glacial lake (Glacial Lake Lewis) that similarly marked an upper limit of diminished lichen cover. Nevertheless, it was intuitively compelling to attribute these areas of limited lichen cover to the period of the Little Ice Age (AD 1500–1900), when snowline lowering placed north-central Baffin Island on the brink of instantaneous glacierization. This strengthened the earlier hypothesis of rapid ice age initiation and growth across the Labrador-Ungava plateau (Ives, 1957, 1960b, 1978). And as the main glacial lake shoreline proved to be horizontal (unlike the much older deglacial shorelines, which were tilted), additional support was provided for the assumption that the period of imminent glacierization was recent (Ives, 1962). This assumption was extended by Falconer's subsequent investigation of the Tiger Ice Cap (in northern Baffin Island), the retreat of which was exposing masses of apparently dead plant material (lichens and mosses). Falconer (1966, p. 198) raised the possibility that moss spores may have survived a long period of glacial entombment and that "it cannot be safely assumed that they [the rock lichens and mosses] are dead." At a much later date, these early findings were seen as apparent proof of very-long-term survival (i.e., more than fifty thousand years) of plants beneath thin ice patches presumed to have been frozen to their beds (G. Miller, letter to G. Falconer, November 22, 2013; La Farge et al., 2013; Miller et al., 2013).

The early attempts to interpret the intriguing arrangement of the light- and dark-toned areas quickly went beyond the simple identification of probable partial cover of semi-permanent ice patches that likely existed two to four centuries ago (Beschel, 1957, 1961, Ives, 1962). However, these early assumptions were based on limited evidence and eventually met with strong opposition. Koerner's (1980) paper raised substantial objections to the Baffin project interpretation and caused a significant pause in the scientific exploitation of this aspect of lichenometric application. Much later, more detailed research eliminated Koerner's challenge (Wolken, England, & Dyke, 2005), leaving the original interpretation intact.

The multiple trans-valley ridges were identified as subglacially formed moraines that had been squeezed up into basal crevasses, close behind the calving ice front of earlier extensions of the proto–Barnes Ice Cap that had impounded a series of ice-dammed lakes.

This was initially proposed as a hypothesis in 1961 (Andrews, 1963), although it was later substantiated by additional research (Andrews & Smithson, 1966).

Shell collections by Sim and Ives from former raised marine shorelines along the west coast of Baffin Island were combined to produce the first marine uplift curve for Foxe Basin. There was associated evidence to indicate that an ice divide, centred over Foxe Basin, had been displaced northeastward onto Baffin Island prior to about five thousand years ago, although outlet glaciers from the proto–Barnes Ice Cap were still in contact with the sea (Ives, 1964; Sim, 1964; Andrews, 1966, 1970; Dyke et al., 2002; Miller et al., 2002). A general outline of the glacial history of the northeastern Canadian Arctic, with a semi-independent ice sheet centred over Foxe Basin, was developed (Ives & Andrews, 1963). The proposed "Foxe Dome" was especially significant as it marked the first persistent formal departure from the single-domed Flintian model of the Laurentide Ice Sheet (centred over Hudson Bay), which had been suggested much earlier by Joseph Tyrell of the Geological Survey of Canada (1898) but had been largely abandoned in the literature in favour of Flint's reconstruction. Finally, the overall review paper stemming from the 1961 reconnaissance (Ives & Andrews, 1963) emphasized the importance of the Cockburn Moraines.

The results from the 1961 reconnaissance and the overall discussion of the earlier prevailing status of the several aspects of thinking about ice age history of the Canadian Arctic laid the foundation for progressive enlargement of our research objectives for the following six years and far beyond.

Highlights of the 1962–1967 research

By the close of the 1962 field season, it had been demonstrated that the highest marine shore features along parts of the northeast coast fronting Baffin Bay did not exceed about eighty metres above present sea level. In addition, after the long outlet glaciers of the last ice age that had flowed down the fiords into Baffin Bay and across the continental shelf had retreated, local mountain ice caps and glaciers had expanded and cut through the older lateral moraines and reached tidewater in the fiords. It could be seen that the extensive fiord outlet glaciers had deposited long lateral moraine systems that were related to the Cockburn Moraines, although the precise relationships and timing still needed to be determined. However, collections of seashells from raised marine terraces that intermingled with the lateral moraines indicated that some of the fiord heads retained calving glaciers until about seven thousand years ago. Even at this early stage of the project, considering also the preceding work in the Torngat Mountains, it could be claimed that Flint's general thesis (especially that ice retreat had occurred much earlier) was no longer tenable.

Thereafter, the field results become so numerous and complex that only the highlights are summarized here:

Mass balance and internal motion of the Barnes Ice Cap

Sagar and Løken determined that the Barnes Ice Cap was experiencing an annual negative mass balance more often than not, although the southwest side was more negative than the northeast side. In effect, the Barnes Ice Cap was still being displaced slowly toward the northeast, as it had been for thousands of years since its centre had been situated over Foxe Basin. Furthermore, extensive traverses across the length and breadth of the ice cap by Housi Weber provided seismic and radio-echo sound data on its thickness and on the nature of the subglacial topography. This confirmed the earlier hypothesis that the Barnes Ice Cap is a relic of the last ice age. Løken also demonstrated that the southwest margin had experienced a significant readvance, possibly a surge, sometime in the recent past (Sagar, 1966; Løken & Sagar, 1968).

Glaciological and hydrological innovations

Østrem introduced new methods for studying the hydrology of turbulent glacier meltwater rivers (Church & Gilbert, 1975; Østrem et al., 1967) and initiated Canada's contribution to the glaciological objectives of the International Hydrological Decade with mass balance studies of the specifically named Decade Glacier (Inugsuin Fiord) and the Lewis Glacier (northwestern Barnes Ice Cap). Equally important was his initiation of a glacier mass balance transect across the Rocky Mountains and British Columbia Coast Ranges (Østrem, 1966); along with Müller's research on Axel Heiberg Island, this was one of the earliest Canadian long-term initiatives, followed later by Koerner's work on the Devon Island ice cap. While long-term study of the five glaciers selected for the transect did not survive the dissolution of the Geographical Branch, work on the Peyto and Place glaciers has continued to the present, rendering that the longest continuous record of mass balance on Canadian glaciers.[9] With Falconer (1962), Østrem also set in motion a series of publications intended as a complete inventory of Canadian glaciers (Falconer, Henoch & Østrem, 1966). Post-1967 work on a glacier inventory for Canada, while extensive, has been intermittent. An early version was produced by the Inland Waters Branch (Henoch & Stanley, 1970). An outstanding and comprehensive account of the history of glacier research in Canada has been provided by Ommanney (2005).

The significance of very old marine molluscs

Løken (1966) collected mollusc shells (seashells) from raised coastal deltas along the northeast coast (Cape Aston and Clyde Foreland) that were radiocarbon-dated at older than 54,000 years BP. This was a first for the Canadian Arctic, initially strengthening support for the nunatak hypothesis—that not only mountaintops but sections of the coastal lowlands remained ice-free for at least the period of the last ice age maximum (Wisconsin). This interpretation would have provided for a variety of ice-free habitats, or refuges, for arctic-alpine plant species. The mountaintop evidence is discussed below. Although this conclusion has since been strongly refuted (Dyke et al., 2002; Miller et al., 2002; Sugden & Watts, 1977), a recent publication by Miller et al. (2013) appears to reverse the refutation. This recent work identifies thin ice patches and glaciers that persisted on the interior highlands north of the Barnes Ice Cap, from the retreating margins of which plant material has been collected and dated possibly as far back as the pre-Wisconsin interglacial (120,000 years ago).[10] My personal interpretation is that such thin ice patches retaining their independence of the Laurentide Ice Sheet at its maximum would place a severe restraint on conclusions concerning its size. While this does not eliminate the possibility that the Clyde and Cape Aston forelands were not themselves mantled with thin inert ice frozen to its bed during the maximum of the last ice age, it appears to reopen the debate. Further to this, recent work from Oslo (Brochmann et al., 2003) has also reintroduced the likelihood that at least a small number of vascular plants of the Amphi-Atlantic group survived the maximum of the last ice age (*Weichselian*, a European term) on *nunataks* in Norway (this controversial hypothesis is elaborated further below). Løken made extensive collections of mollusc shells and examined the sedimentary stratigraphy of the low sea cliffs extending northwest from Cape Christian (Clyde Inlet). This resulted in the invitation to Dr. Rolf Feyling-Hanssen, a marine palaeontologist, to undertake an intensive study of this thirty kilometres of cliff exposure. Rolf's research led to the identification of the area as one of the most important glacial/interglacial (and possibly pre-Pleistocene) stratigraphic sites in the Canadian Arctic (Feyling-Hanssen, 1967, 1976).

Large-scale mapping of crustal (glacio-isostatic) rebound and sea level change

Extensive studies by Andrews of the relation between glacial and raised marine landforms along both the eastern (Home Bay) and western (Foxe Basin) coasts of Baffin Island were extended into Hudson Bay (Andrews & Falconer, 1969). From this research, Andrews produced a leading monograph on late-glacial and postglacial sea level changes, recording the crustal unloading (rebound) induced by the regional retreat of the northeastern sector of the Laurentide Ice Sheet across the eastern Canadian Arctic (Andrews, 1970). As a result of this monograph, Andrews was presented with the prestigious Kirk Bryan Award of the Geological Society of America in 1973. The work also confirmed the initial 1961 proposal (Ives & Andrews, 1963) that Foxe Basin had been a principal centre of ice dispersal for the northeastern sector of the Laurentide Ice Sheet during the maximum of the last ice age, as indicated by the tilt of shoreline features created by former high sea levels. However, Andrews's contention that the marine limit determinations in northern Foxe Basin depicted a contemporaneous surface was later modified. The marine limit there was formed during sequential ice margin retreat, as was the case in most other places (A. Dyke, personal communication, June 26, 2014). Subsequently, ice flow out from the centre of Foxe Basin northeastward across Baffin Island was reversed as the ice divide migrated toward its present position along the crest of the Barnes Ice Cap.

Use of helicopter to test the nunatak hypothesis

Using a helicopter to access many of the high mountaintops between Ekalugad and Gibbs fiords, and several of the outermost forelands between the fiords (e.g., Cape Aston, Cape Christian, Cape Henry Kater, and Remote Lake), led to a much fuller understanding of ice conditions at the maximum of the last ice age. As in the Torngat Mountains of northern Labrador, a distinct upper limit (the glacial trimline) to indisputable glacial erosion and deposition was traced along extensive sections of the fiords from higher than seven hundred metres asl near the fiord heads to below sea level on the outer coast (that is, most of the fiords between Home Bay and North Arm, just south of Pond Inlet). The glacial evidence was principally in the form of long stretches of glacial lateral moraines below which evidence of glacial erosion was profuse. But above them, where mountain summits were gently sloping or plateau-like, the surface was mantled by a deep cover of angular frost-shattered bedrock, from which occasional tors projected. This type of surface, in both Norway and the eastern Canadian Arctic, was widely accepted at the time as evidence that the upper levels had not been overridden by erosive masses of ice at the glacial maximum. Nevertheless, occasional glacial erratics of unknown age were detected on the high summits among the tors and mountaintop detritus (see Fig. 32). This work was followed up by a long series of field investigations much farther south, in the vicinity of Broughton Island and the Penny Highlands, that was organized after 1967 by John Andrews from INSTAAR.

Due to the lack of methods in the 1960s for actual dating of rock surfaces (either tors or erratics), it was concluded that at some time in the past the continental ice sheet had overtopped the highest summits. However, the absence of observable indications of glacial erosion on these surfaces indicated that the ice must have been sufficiently thin and cold to remain frozen to its bed, leaving the boulder and tor surfaces essentially unaltered. In contrast, the ice flowing along the line of the fiords (i.e., outlet glaciers) would have been extremely thick and faster flowing, characteristic of warm-based ice, facilitating the extensive overdeepening of the fiords by glacial erosion. Løken's (1965, 1966) dating of coastal sediments as older than 54,000 years, supplemented by the work of Andrews, Buckley, King, England, and others, together with the dates on the Remote Lake outer moraines, led to the conclusion that any "ice-free" areas delimited by mountaintop detritus and tors predated the Last Glacial Maximum. It was presumed that the scattering of erratics must have been emplaced by a thin cover of ice during an early ice age. This thinking was reinforced by the observation that many of the higher and flatter mountain summits are today mantled by a thin carapace of ice, presumably frozen to the ground surface and from which angular boulder fields are emerging due to the overall northern hemisphere glacier shrinkage of the early twentieth century. However, no work was undertaken on the mountaintop flora; accordingly, the earth science–oriented research moved progressively away from the nunatak hypothesis *per se*. The later introduction of cosmogenic nuclide exposure dating and other techniques has led to significant revision of this rather simplistic interpretation (see below).

Following the Baffin Island expeditions of the 1960s, continuation of this research from INSTAAR, in Boulder, Colorado, appeared to confirm the general hypothesis of a minimum extent and thickness of the Laurentide Ice Sheet during the last ice age, as outlined above. Numerous publications resulted, similar to those of the 1960s. However, they were much more detailed and included a major focus on identification of "weathering zones"; the highest zones, which included the mountain summits and high plateaus, were usually identified as likely to have remained above the maximum limits of the main ice sheet (see also Ives, 1960b). Nevertheless, the occasional enigmatic glacial erratic located on and among tors and weathering pits and within the mountaintop detritus was recorded. Thus, ambivalence persisted until the advent of cosmogenic nuclide exposure dating, as mentioned above, which seemed to provide definitive ages for both the tors and the erratics. A general conclusion was reached: that at the maximum of the last ice age, the Laurentide Ice Sheet was much thicker than previously presumed, had overtopped all the highest summits, and had extended to the edge of the continental shelf.

Regardless, the enigma resurfaced. Art Dyke (pers comm., 15 February 2014) kindly sent me the abstract of a paper to be presented during the 2014 General Assembly of the European Geophysical Union (Margreth et al., 2014). In brief, the research on which the paper is based demonstrates serious inadequacies in the hitherto widely accepted accuracy of the earlier cosmogenic nuclide exposure dating techniques. The authors argue that many of the Baffin Island tors were not covered by ice throughout the last ice age, and some may have been exposed continuously for much longer. It is fascinating that this latest explanation of the enigmatic tors/erratics/mountaintops and maximum thickness of the Laurentide Ice Sheet, while based on many times more research and much more refined methods than were available in the 1960s, remains essentially unchanged (in other words, at least a partial double reversal of thinking has taken place between the 1960s and the present). To my mind, however, there still is no adequate explanation for the presence of glacial erratics on top of tors if the summits were covered only by thin, scarcely moving, or immobile ice patches or ice sheets frozen to their beds.

Final collapse of the Laurentide Ice Sheet

The extensive study of raised marine shorelines and their dating by radiocarbon determinations, together with the systematic mapping of the extent of the Cockburn Moraines, caused us to extend our review of available reseach results and to consider the moraine systems along Melville Peninsula (Sim, 1961) and the Arctic mainland coast. These considerations prompted Falconer to introduce his copy of the draft glacial map manuscript on which he had worked under the direction of Tuzo Wilson. This showed extensive moraine systems that he had sketched but which had not been included on the final printed map (Wilson et al. 1958). In addition, contemporaneous research along the Arctic mainland coast greatly strengthened the early air photo interpretation taken from Falconer's draft manuscript (Lee, 1959; Blake, 1963). From this, it was not excessively conjectural to propose continent-wide projections through Keewatin and northern Ontario/Quebec to produce a theoretical depiction of the final stage of the Laurentide Ice Sheet as it existed approximately eight thousand years ago. And from this, it was concluded that the next phase of late-glacial Laurentide Ice Sheet retreat culminated with the catastrophic collapse of its geographic centre in Hudson Bay as Atlantic waters rushed in to disrupt it. This left remnant ice masses centred on Labrador-Ungava, interior Keewatin, and Baffin Island–Foxe Basin (Falconer, Andrews, & Ives, 1965; Falconer, Ives, Løken, & Andrews, 1965). This concept was revolutionary for the time (i.e., the mid-1960s) and was hotly contested, although the general interpretation has subsequently received convincing support. Viewed from the perspective of the massive discharge of the gigantic Glacial Lake Agassiz, the 1965 papers have received substantial confirmation. According to the much more recent research, Glacial Lake Agassiz broke through its Laurentide Ice Sheet dam to flow into the North Atlantic via Hudson Bay and Hudson Strait. The recent dating of this event at 8,200 years ago (Barber et al., 1999; Clarke, Leverington, Teller, & Dyke, 2004; and many others) coincides remarkably with our earlier prediction of approximately 8,000 years ago, viewed from the opposite side (i.e., the northeast side) of the remnant Laurentide Ice Sheet. As implied above, over the last several decades, knowledge of the deglaciation of North America has advanced prodigiously. One of the most outstanding contributions has been made by Art Dyke (2004), closely matched by John England and Gifford Miller based on decades of fieldwork and numerous earlier publications. These contributions can also be regarded as outgrowths of the 1961–1967 expeditions to Baffin Island.

Lichenometry

Under the direction of Roland Beschel, the initiator of lichenometry, Andrews and Webber (1964, 1969) built on the method Beschel had developed in Austria and West Greenland (Beschel, 1957, 1961). They focused only on epipetric lichens. During the 1963 field season, Webber and Andrews, assisted by a virtual army of students, painstakingly produced thousands of measurements on lichen diameters and percentage of lichen cover at varying distances from the Barnes Ice Cap margins, especially in the area stretching from Flitaway Lake southwestward to the confluence of the Isortoq, Striding, and Lewis rivers. Measurements were made on a number of different species so that multiple growth curves could be constructed and cross-checked for their value in determining the age of various periglacial and glacial features comprising boulder and rock surfaces. A number of lichen stations were established where individual lichens were photographed and their outlines traced on mylar sheets. The establishment of these stations was a response to Beschel's prescient urging. Rates of lichen colonization and growth were estimated using reference points of age-since-deglaciation. This was made possible by the combination of excellent air photographs from 1948 and 1961, counts of growth rings of willow taproots, and parsimony about the likely time required for stabilization of the reference points. The two most useful lichens were those of the very slow-growing crustose, yellow-green *Rhizocarpon geographicum* group and the faster-growing foliose-fruticose black *Pseudephebe (Alectoria) miniscula*. From both the data sets and Beschel's experience in West Greenland, Andrews and Webber (1964) reasoned that both lichens grew at a more or less constant rate across the study area and that each had straight-line growth curves. They estimated the diameter expansion for *Rh. geographicum* to be 0.064 millimetres per year and for *Ps. miniscula* to be 0.4 millimetres per year. The largest *Rh. geographicum* thalli were about 50 millimetres and the largest *Ps. miniscula* were about 130 millimetres. The former clearly would be on the order of one thousand years in age. The latter would be getting quite senescent by 130 millimetres and thus provided only a limited age range, but they were particularly useful for Little Ice Age features up to about three hundred years in age. From these rates and from the distribution of maximum diameters across the study area, maps were drawn and published giving the outlines of former glaciers and ice-dammed lakes.

Later research around the southern margins of the Barnes Ice Cap and, farther south, on Cumberland Peninsula has shown that the earlier work stands up extremely well (Andrews & Barnett, 1979; Barnett, 1977; Miller 1973a, 1973b). This work included a revisit, after forty-six years, that provided individual growth rates for ninety-five lichen thalli, thus reaffirming the importance of Beschel's urging. A new reference growth curve with 95 percent confidence limits became available. One specific result of this later work is that, at the northwestern end of the Barnes Ice Cap, the extended and combined small Lewis and Pintail glaciers damming the last remnant of Glacial Lake Lewis at its 268-metres-asl shoreline began to retreat in AD 1788 (give or take thirty years). This caused total drainage of the lake. Developing out of the burst of Baffin Island lichen studies from 1963 to 1979, *A Manual on Lichenometry* (Locke, Andrews, & Webber, 1979) was published and has since expanded worldwide to become the prime reference on the subject.

Still, recent work on the challenges of perfecting lichometry over the last two decades has revealed extensive complications. The assumptions about the feasibility of the simple transfer of lichen growth rates from one region to another and between different rock types have been seriously disputed. Regardless, the comparability of sites within the area of north-central Baffin Island seems basically defensible.

[Author's note: The foregoing section was generously revised and expanded by Pat Webber (personal communication, February 20, 2014).]

Plant ecology and plant collections

Webber's 1963 and 1964 work investigated the nature of the structure and organization of plant communities in the greater Lewis River area; it was founded on extensive collections of vascular plants, mosses, and lichens and the establishment of eighty-nine one-by-ten-metre quadrats. While the flora as a whole are not especially rich (only 84 vascular species around the Lewis Glacier, with 142 on the warmer, older west coast around Eqe Bay), Webber collected and identified more than 1,300 specimens, which were later generously verified by experts at the National Museum of Natural Sciences (today, the Canadian Museum of Nature): A. E. Porsild, I. M. Brodo, and H. A. Crum. The moss collections were re-examined by Guy Brassard and Allan Fife (Brassard, Fife, & Webber, 1979). These thorough collections filled the void mentioned earlier. Most specimens were collected in at least triplicate, meticulously documented by place of collection, labelled by Webber, and placed in world-class herbaria. The first set also went to the Canadian Museum of Nature, where it is now integrated into the main collection and is kept current with regard to nomenclatural changes; Pat has reported (personal communication, March 10, 2013) that the specimens have frequently been annotated by visiting specialists. Replicate sets of the vascular plants can be found in the Fowler Herbarium at Queen's University and the William A. Weber Collection at the University of Colorado Herbarium. The quadrat data and plot photos are also well archived and digitized; the plot data will be held in the Arctic Vegetation Archive (see Villarreal et al., 2014; Walker, 2014; Webber, 2014).

In 1962, John Andrews and Bruce Smithson discovered extensive plant-bearing beds on the east bank of the Isortoq River some ten kilometres below its confluence with the Lewis River. The deposits were sampled extensively in 1963 along with a similar, probably contemporary, isolated mound of deposits at Flitaway Lake discovered by graduate student Dave Harrison. The palynology and plant macrofossils were described by Terasmae et al. (1966). The macrofossils dated beyond the realm of radiocarbon technology and were assigned to the Sangamon Interglacial. The deposits contained a number of well-preserved remains of plants no longer present in today's local flora, for example, *Ledum groenlandicum* (Labrador tea) and *Betula nana* (Dwarf birch). Modern pollen rain was collected for two years at the Flitaway climate station and used as reference. The modern flora and the careful analysis of the fossil material provided a clear picture of the ancient climate that would have been wetter by some thirteen centimetres per year and warmer in July by one to four degrees Celsius. The growing season was twenty to twenty-five days longer than the present ninety days. Re-examination of these deposits with the newest dating techniques, and their use as a yardstick given the present warming climate, should provide worthwhile scientific rewards. The work also pointed to the value of *Betula nana* as a phytogeographic and climate zonal indicator. For example, Jacobs, Herm, and Luther (1993), in follow-up pollen analysis in southern Baffin, referenced the presence of *Betula nana*—a short but erect shrub presently restricted to southern Baffin and a good indicator of the Low Arctic. It is an amphi-Atlantic plant that figures prominently in the recent, and best, whole Arctic vegetation map (CAVM team, 2003).

In his doctoral dissertation, Webber (1971) established the paradigm that, while High Arctic vegetation was best viewed as a continuum classification into reasonably discrete entities, it could go hand in hand with ordination. Ordination analysis was the best way to correlate plant distribution with environmental controls, and classification was the best basis for communication, mapping, and experimentation where replication was needed. Such notions will be seen today as "old hat," but there was much controversy in the 1960s about the levels of organization within the Arctic plant community.

As Pat noted, it was somewhat serendipitous that the plant collections, Quaternary paleobotanical studies, and quadrat data now form a benchmark and a useful basis for assessing the consequences of a warming Arctic.

The 2009 Back to the Future project (Callaghan, Tweedie, & Webber, 2011) under the auspices of the Fourth IPY was able to resample and precisely geo-reference eighty-seven of the Webber quadrats. Two student participants, Mark Lara and Sandra Villarreal, who represent the latest generation of Arctic botanists, included in their doctoral dissertations (Lara, 2011; Villarreal, 2012; Villarreal et al., 2014) the new lichenometry picture and the recorded vegetation changes. They were able to take advantage of John Jacobs's newly assembled sixty-year climate record for Central Baffin Island and the Lewis and Flitaway areas, which shows a sustained increase in July temperatures and summer warming index (SWI) since the mid-1960s. Lara and Villarreal demonstrated that the Lewis Valley is greening (Bhatt et al., 2010) and that while the communities are changing, their trajectories and explanation of these changes are complicated because of the interaction of warming and ageing of the surfaces (that is, retreat of the glacier and ice cap margins). Lara focused on community functional changes such as light reflectivity and productivity of the vegetation over a decadal timeframe using gas exchange, soil moisture, and spectral reflection methods. Such methods had been only a pipe dream in the 1960s. Villarreal showed, using an updated classification and ordination, that the number of plant species, primary productivity rates, and extent of ground cover have significantly increased since the 1960s. The greatest change was noted in plant communities with high soil moisture. For example, two pond margin communities, *Campylium-Aulacomnium*-moss meadows and *Eriophorum-Pleuropogon* wetlands, had increased in biomass by 178 percent and 46 percent, respectively, while greenness had increased 35 percent and 16 percent, respectively. Soil moisture was found to have decreased in *Carex* stand wet meadows and *Campylium-Aulacomnium*-moss meadows by 30 percent and 24 percent, respectively. Overall, Villarreal and Lara found evidence of a general drying of the landscape and of dramatic changes close to the ice cap, suggesting that plant community succession (vegetation cover and species richness) has accelerated over the past half century—especially on surfaces that have been exposed from the ice for less than two hundred years.

The 2009 IPY crew noted the increased frequency of *Astragalus alpina* (Milk vetch), *Vaccinium uliginosum* (Blueberry), and *Salix Richardsonii* (Erect willow), which had previously been rare to the area. Only one solitary blueberry plant was seen by Webber during all his perambulations around the Lewis Glacier in 1963 and 1964; yet the species was common enough near the Isortoq plant fossil beds in 2009, where Gifford Miller reported that he was able to add handfuls of blueberries to his breakfast cereal. This certainly could not have been done by John Andrews and Pat Webber in the 1960s! The increased stature of *Salix Richardsonii* is commensurate with the general Arctic-wide increase of erect shrubs reported by Tape, Sturm, & Racine (2006).

These findings demonstrate the importance of careful records and a need to continue to monitor tundra landscapes over decadal time scales in our changing world.

[Author's note: The foregoing section was generously contributed by Pat Webber (personal communication, February 28, 2014).]

Submarine topography

Løken's shipboard submarine surveys provided extensive information on the topography of the continental shelf off the eastern Baffin Island coast and along many of the fiords (Løken & Hodgson, 1971). This information was vital in its own right for improving navigation safety. It also inaugurated what has become a central issue concerning the marine geology not only of the Canadian Arctic but also of other glaciated continental shelves in both the Arctic and Antarctic. Further, Løken's marine research provided an essential complement to the longstanding emphasis of the time spent on the terrestrial record on adjacent islands, such as Baffin Island and Greenland.

General influence on subsequent research

As inferred earlier, for many years following 1967, Baffin Island constituted the primary target of the developing Arctic element of the research activities of INSTAAR under the leadership of John Andrews. In fact, I was able to initiate and host an annual "Baffin workshop" for inter-institutional meetings in Boulder, Colorado; the workshop subsequently became the International Arctic Workshop under the guidance of John Andrews. It is held in alternate years in Boulder and at other leading research centres in the United States, Canada, Norway, Iceland, Sweden, and Denmark. It has continued without interruption to the present and, whereas it began informally with only a handful of faculty and graduate students, it is now attended by hundreds.

The total amount of research on Baffin Island has multiplied to many times that carried out in the 1960s. It is far too extensive to detail here; also it would go far beyond the scope of this book and the competence of the author. However, it is reasonable to claim that the Geographical Branch endeavour provided a critical stimulus and seeded many internationally acclaimed careers in Arctic environmental science, many still active in numerous university and governmental agencies around the globe. Indeed, many of these careers are now at least three "academic generations" removed from the Canadian Geographical Branch and its initial beneficiary, INSTAAR. The prospect of compiling the many hundreds of available research papers and publishing a major book (or books) from them would be a formidable task. Yet until that is done, we will not realize the full value and impact of the now more than a half century of Arctic field research.