The Maximum Extent of the Laurentide Ice Sheet along the East Coast of North America during the Last Glaciation

JACK D. IVES[1]

ABSTRACT. During the last hundred years, two widely opposing views of the maximum extent of the Laurentide Ice Sheet have prevailed at different times. Between 1860 and 1940, it was assumed that ice extent along the eastern seaboard was limited and that ice-free areas persisted during the Maximum of the Last Glaciation. After 1940, this interpretation was replaced by one contending that all high coastal mountains were inundated. This view, proposed by the late R.F. Flint, was widely accepted as fact until the last few years. This paper reviews the opposing interpretations and analyses the frequently equivocal field evidence and the developments of thought responsible for them. On the basis of field work carried out over the last twenty years, it is suggested that the earlier viewpoint was the more accurate. A map is presented of the author's conclusions regarding maximum ice limits.

RÉSUMÉ. *L'étendue maximale de la couche glaciaire des Laurentides le long de la côte orientale de l'Amérique du Nord durant la dernière période glaciaire.* Au cours des cent dernières années, deux opinions nettement opposées ont prévalu, selon les époques, quant à l'étendue maxima de la couche glaciaire des Laurentides. De 1860 à 1940, il fut admis que l'étendue des glaces le long du littoral oriental était limitée et que des régions dépourvues de glaces persistaient au cours du Maximum de la Dernière Période Glaciaire. Après 1940, cette interprétation fut remplacée par une autre, différente, qui soutenait que toutes les hautes montagnes côtières étaient recouvertes de glaces. Cette opinion, proposée par feu R.F. Flint, fut admise par la plupart comme un fait, il y a encore quelques années. L'auteur passe en revue dans cette étude ces interprétations opposées, analyse les constatations, souvent équivoques, effectuées sur place, ainsi que la suite des réflexions qui ont abouti à ces interprétations. En s'appuyant sur les travaux effectués sur place au cours des vingt dernières années, il suggère que c'est la première interprétation qui est la plus exacte. Il offre une carte pour illustrer ses conclusions quant aux limites extrêmes des étendues des glaces.

РЕЗЮМЕ. *Максимальная протяженность Лаврентийского ледникового покрова вдоль восточного побережья Северной Америки в период последнего оледенения.* В последние сто лет преобладала то одна, то другая из двух крайне противоположных точек зрения относительно максимальной протяженности Лаврентийского ледникового покрова. В период с 1860 г. по 1940 г. считалось, что распространение ледникового покрова вдоль восточного иобережья было ограничено и что даже во время максимума последнего оледенения сохранялись участки, свободные от льда. Это представление после 1940 г. сменилось другим, согласно которому все высокие береговые хребты были затоплены. Выдвинутая покойным Р.Ф. Флинтом гипотеза была широко принята еще до недавнего времени. В настоящей работе наряду с обзором противоположных представлений анализируются во многих случаях неоднозначные полевые данные и ход рассуждений, приведших к формированию соответствующих точек зрения. На основе результатов полевых работ, проведенных за последние 20 лет, делается заключение о том, что первоначальная точка зрения была более точной. Заключения автора о предельных границах распространения ледникового покрова представлены на карте.

[1]Institute of Arctic and Alpine Research (INSTAAR) and Department of Geography, University of Colorado, Boulder, Colorado, U.S.A.

INTRODUCTION

For the last thirty-five years it has been widely assumed that during the last (Wisconsin) glaciation the Laurentide Ice Sheet overtopped all the high coastal summits from Maine to northern Baffin Island, and extended seaward as far as the edge of the continental shelf. Further north, ice over Devon and Ellesmere islands has been envisaged as confluent with the Laurentide Ice Sheet, and indeed as an integral part of it, and to have merged with a much expanded Greenland ice sheet. The intervening seas — Baffin Bay and Davis Strait — are assumed to have been covered by a floating ice shelf, if not actually occupied by grounded ice. This "maximum Wisconsin viewpoint" emanates from the epochal work of the late Richard Foster Flint. Yet prior to 1940 a "minimum Wisconsin viewpoint" had prevailed, having been developed through fieldwork by Bell (1884), Chalmers (1896), Daly (1902) and Coleman (1920, 1921, 1922, 1926). These early workers argued that a series of high mountain areas, including the Torngat of northern Labrador, Long Range of Newfoundland, the Shickshock Mountains of Gaspé Peninsula and various highlands of the Canadian Maritime provinces and New England, either remained as nunataks or else had been affected only by local ice caps, cirque glaciers and valley glaciers. Flint (1943) not only proposed an intellectually attractive model for Laurentide Ice Sheet initiation and growth but totally overthrew the "minimum Wisconsin viewpoint" of his predecessors. This stand refuted the conclusions drawn from A.P. Coleman's work in the Shickshock Mountains (Flint *et al.* 1942), and was perpetuated by a series of major publications, including a glacial map of North America (Flint *et al.* 1945) and three text books (Flint 1947, 1957, 1971).

During the past twenty years, there has been a slowly growing opposition to this aspect of Flint's work (Mercer 1956; Ives 1957, 1958a, 1958b, 1960a; Løken 1962a, 1962b, 1966; Andrews 1963; Boyer and Pheasant 1974; Miller and Dyke 1974) which has accelerated in the last few years (Grant 1969, 1976, 1977a, 1977b; Brookes 1970, 1977; England 1976a, 1976b; Dyke 1977). Nevertheless, these studies have dealt only with specific and relatively small areas rather than with the entire eastern seaboard, and the "maximum Wisconsin viewpoint" has remained entrenched in high school and university curricula, and some recent workers continue to support it (Blake 1970, 1975; Hughes *et al.* 1977). Finally, with the need to adapt ice-age boundary conditions as input data for the recently developed global-atmospheric-circulation models (CLIMAP 1976), there has arisen a tendency to rely upon the more easily accessible and widely accepted ice sheet margins, as represented by the "maximum Wisconsin viewpoint."

Much of the critical field data, which have been pivotal for these two extreme viewpoints, relate to conditions on the summits of high coastal mountains. Not only are many of these data equivocal, but adherents to each viewpoint have had to contend with the previous acceptance of false assumptions, such as the efficacy of freeze-thaw processes in Arctic and alpine maritime environments, and the view that striations and glacial erratics on mountain tops must date from Wisconsin time. It is therefore timely to review the evidence and arguments and to propose a new statement on the extent of Laurentide ice along the eastern seaboard during the Last Glaciation. This "new" viewpoint largely reverts to the contentions of Daly (1902) and Coleman. However, neither of these workers fully interpreted local field conditions and, due to limited access, were not able to detect mountain-top glacial erratics that later in the present paper will be shown to exist. It is proposed here that some of these erratics, such as were observed in the Shickshocks by Flint *et al.* (1942) relate to a pre-Wisconsin glaciation of much greater extent, or have been emplaced very early in the Cenozoic period of glaciations before the landscape had taken on its present form. An attempt will be made below to trace the development of thought which led to the total eclipse of the original "minimum" viewpoint in the early nineteen-forties. This review will conclude with a plea for rigorous testing of working hypotheses, and the development of additional hypotheses, in an area of intellectual enquiry that is still handicapped by a shortage of unequivocal data.

The ideas and hypotheses discussed below have evolved over a hundred years. During this time estimates of the duration of the Wisconsin Glaciation have varied considerably, and may still be incorrect. To avoid possible confusion, therefore, this paper will refer to the "Last Glaciation" and will assume that it spanned the period 125,000 — 8,000 BP. Much of the recent work on Baffin Island (Miller *et al.* 1977; Andrews and Barry 1978) has shown that early stades of the Last Glaciation were more extensive than the later stades — the reverse of conditions which existed in mid-continental North America and with regard to which the classical Ice Age terminology evolved. J.T. Andrews (INSTAAR, personal communication, 1978) and Miller *et al.* (1977) prefer the term "Foxe Glaciation" for the Last Glaciation on Baffin Island; in northeastern Labrador-Ungava the term "Saglek Glaciation" (Ives 1976) might be appropriate. But to postulate that "Foxe", "Saglek" and "Wisconsin" are synonymous terms is to risk over-simplifying a complex situation. The term "Last Glaciation" will therefore be used to imply Wisconsin — Würm — Weichselian in a general sense and to refer to a glacial episode characterized by three or four distinct stades. Where the context is clear, local equivalents will be used. Finally, in discussing the dispute between adherents of a "maximum Wisconsin viewpoint" and a "minimum Wisconsin viewpoint", it needs to be pointed out that at issue is how extensive, both vertically and horizontally, was the Laurentide Ice Sheet at the various Last Glaciation *Maxima.* Thus there are two concepts that need to be differentiated: (a) the interpretation of ice conditions at the maximum extent of any, or all, stades of the Last Glaciation, and (b) the hypothetical discussion about a large or small glaciation, as exemplified by the terms "maximum Wisconsin viewpoint" and "minimum Wisconsin viewpoint". The two concepts will be differentiated by use of the upper and lower case "m" respectively.

Results of more recent work (Grant 1977a, 1977b; Dyke 1977) indicate that the most recent weathering zone (Zone A) may relate to the Late Wisconsin. However, the discussion in the present paper cannot be restricted to *Late* Wisconsin conditions until comparable detailed fieldwork has been undertaken along the entire coastal area under consideration.

DEVELOPMENT OF THE "MINIMUM WISCONSIN VIEWPOINT"

Lieber (1861), Bell (1884), Daly (1902) and Coleman (1920, 1921) argued that the coastal mountains of northern Labrador had never been overtopped by the North American continental ice sheet. Bell, Daly and Coleman refer in the above-cited works to a Labradorean ice sheet or glacier; in 1943 Flint made the important contribution of successfully arguing that "Labradorean" was inappropriate usage and proposed the term "Laurentide Ice Sheet", as originally defined by J.W. Dawson and modified by T.C. Chamberlin, and his usage won total acceptance (Prest 1970; Ives *et al.* 1975). Daly (1902 p. 249) reported that glacier ice passing seaward to the Atlantic along major through-troughs in the Torngat Mountains did not exceed in altitude about 650 metres in the vicinity of the fiord heads. This conclusion was based upon recordings of the highest levels at which glacial erosional and depositional features are to be found as well as the all-pervading presence of the felsenmeer (blockfields of frost-shattered bedrock). The only variations in this pattern were the local cirques that were cited as evidence of local glaciation at higher levels. Except for occasional outlet glaciers penetrating through the mountains from the west, Daly regarded the Torngat as "a great dam facing the central névé of Labrador which thus lay on the Kangiva (Ungava Bay) side" (Daly 1902 p. 225). Kangiva was a name given to the supposed flat, low-lying land to the west, above which the western flank of the Torngat Mountains was believed to rise precipitously. This lack of full appreciation by Daly and Coleman, as well as by Flint (see Mercer 1956; Ives 1957; Ives *et al.* 1975) of the actual topographic character of these mountains made it difficult for them to put forward rational interpretations of their glacial history. Coleman (1921), who undertook fieldwork during the summers of 1915 and 1916, generally supported Daly's conclusions, although he argued that no "Labradorean" ice had been able to penetrate the mountains to the Atlantic fiords and that all glacial activity was restricted to local cirque, valley and transection glacier systems. He reinforced Daly's viewpoint that the sharp arêtes of the coastal mountains and deep felsenmeer on the higher surfaces further inland were ample evidence that the higher summits had never been inundated by ice. Coleman's subsequent field studies in Newfoundland, Gaspé and other areas around the Gulf of St. Lawrence led to the maturation of the "minimum Wisconsin viewpoint", and an insistence that felsenmeer indicated non-glaciation, except possibly where local ice caps existed. Coleman even went so far as to suggest that the main continental ice sheet had not reached the southeastern coast of Labrador during the Wisconsin Glaciation (Coleman 1921 pp. 26-27; 1926 pp. 216-7). His work on the island of Newfoundland led to the identification of three landscape types that varied in degree of subaerial weathering (Coleman 1926). While he did not delimit three "weathering zones" at different altitudes — an approach that has recently come into vogue (Pheasant and Andrews 1973;

Boyer and Pheasant 1974; Ives 1975; Brookes 1977; Grant 1977a) — it is quite clear from his descriptions that he had used the presence of felsenmeer as indication of a non-glaciated area (including the higher parts of Long Range, as well as the outer parts of the northeastern peninsulas). He also described an intermediate type bearing obvious indications of glacial erosion and deposition that was noticeably weathered that he ascribed to a glaciation antedating the Wisconsin and an essentially unweathered type which he considered to denote the existence of limited, local ice caps in a late stade of the Wisconsin. Coleman was obviously influenced by the botanical work of Fernald (1925) who applied to northeastern North America the Scandinavian Nunatak Hypothesis as a means of explaining the existence of disjunct and endemic plant species in these mountain areas (Dahl 1955).

ASCENDANCY OF THE "MAXIMUM WISCONSIN VIEWPOINT"

In 1931, Noel Odell, British geologist and Himalayan mountaineer, accompanied the American Geographical Society's Alexander Forbes expedition to northern Labrador. Odell climbed extensively in the Torngat Mountains, and in addition to greatly improving the then existing notion of the topographical characteristics of these mountains, he concluded that, contrary to Coleman and Daly, Laurentide ice had completely overtopped all, or most of, the high mountain summits during the Last Glaciation. He described poorly preserved striations which existed at 1,446 metres and argued strongly that felsenmeer, as a product of vigorous freeze-thaw frost-shattering in Arctic maritime climates, could easily have been formed since the maximum of the Last Glaciation (Odell 1933, 1938). When the present author attempted in 1956 to re-examine Odell's field area he was led to dispute the interpretation of Odell, although the latter's report of high-level erratics in the Komaktorvik Lakes area (59°10′N, 64°00′W) — even though these were not precisely located — would appear reasonable, except for their being ascribed to the Last Glaciation. Tanner and Flint uncritically adopted Odell's conclusions. This acceptance of Odell's refutation of the views of Daly and Coleman was a crucial turning point. It illustrates very well the ease with which the "minimum-maximum Wisconsin" pendulum swung. The whole matter is worth examining in some detail, since this question of maximum ice thickness on coastal mountains has been characterized on both sides of the Atlantic by emotion and strongly defended contentions. In his extensive work on Labrador, Tanner (1944 p. 184) writes:

> On one summit of the central range of the Torngat Mts. there was evidence of ice-polished surfaces at 4,700 feet [approx. 1,400 m], nearly 3,000 feet above what was thought by others to be the maximum extension of the inland-ice. Some of these remains of ice-polished surfaces were to some extent corroded and the present erratic blocks are often superficially weathered. This is however not surprising, if due account be taken of the particular climatic conditions of the region. In the northern part of the mountains, at 2,250 feet [690 m] above sea level, slabs were found with signs of glacial

> polish — evidence that the regional ice had moved across the range towards the north-east. On the south-east slopes of Point 3,620 feet [1,100 m] in the Kaumajet Mts., ODELL also found bare, coarse lava surfaces, showing ice-planation, though with partial decay, and it seems to him probable that this planation was due to the last glaciation. Here no unequivocal erratic material could be found.
>
> The opinion expressed by ODELL, one of the most experienced and far-travelled glaciologists of our time, is conclusive for the writer. During our discussion in his home in Cambridge in 1937, he fully convinced me that COLEMAN's [1921] and FERNALD's [1925] thesis that the higher parts of these mountains formed nunataks during the last ice age can no longer be maintained. The inland-ice of the Wisconsin epoch completely inundated even the highest mountains of the peninsula. Through the great transverse valleys of the Torngat Mts. it sent mighty, relatively swift land-ice currents out over the continental shelf to the Atlantic, whereas the ice on the lofty upland moved but slowly forwards in the same direction. How far on the shelf the land-ice reached is a question on which the writer is not prepared to give an opinion.

Thus Tanner, representing the Fenno-Scandinavian opposition to the Nunatak Hypothesis, accepted Odell's limited and rather vague observations of weathered-bedrock lineations and high-level erratics as adequate, without himself having set foot in the Torngat Mountains.

The next step towards the overthrow of the "minimum Wisconsin viewpoint" was the publication of a paper by Flint, Demorest and Washburn (1942) following their excursion to the Shickshock Mountains. Because of its critical position in the development of Wisconsin glacial concepts the entire abstract of that paper is reproduced here:

> The Shickshock Mountains constitute one of the highland areas that have been considered by Coleman on geologic evidence, and by Fernald on botanical and geologic evidence, to have been nunataks during the maximum of Wisconsin glaciation.
>
> Recent field studies have been made on the two highest parts of the Shickshocks — the broad plateaulike masses known as Mount Albert (summit altitude 3,775 feet [1,150 m]) and Tabletop Mountain (4,230 feet [1,290 m]). Glacial erratics possibly derived from Pre-Cambrian rocks from north of the St. Lawrence were found as high as 3,760 feet [1,145 m] on Mount Albert. On Tabletop Mountain, striated surfaces were found as high as 3,500 feet [1,070 m], and glacial erratics (of local origin) as high as 3,700 to 3,800 feet [1,125-1,152 m]. Detailed search failed to produce any direct evidence of glaciation through the highest 400-500 feet [120-150 m]. Throughout this distance evidences of any possible glaciated surfaces are obscured by mantles of locally derived felsenmeer that presumably originated in postglacial time. In addition, the composition of the bedrock is so heterogeneous that several types of erratic stones might be present without having been recognized. *These circumstances do not demonstrate glaciation of the highest parts of Tabletop Mountain: yet there is no geologic evidence inconsistent with the possibility that the entire Shickshock highland was overtopped by Wisconsin ice* [present writer's italics]. No geologic evidence was found suggesting that any portion of the area existed as a nunatak during the Wisconsin maximum.

> During the waning stages of glaciation, and possibly earlier, Tabletop was the site of radial outflow from a local ice cap.

Flint, Demorest and Washburn (1942) took the view that locally derived felsenmeer "presumably originated in postglacial time" and that what were undoubtedly glacial erratics, 150 metres vertically down from the summit of Mount Jacques Cartier, must date from the Late Wisconsin. The three writers, while expressing some reservations, nevertheless extend their conclusions of total Late Wisconsin submergence of the Shickshocks by Laurentide ice to the Torngat Mountains and Long Range. Having visited Mount Washington, New Hampshire, after their Shickshock fieldwork, they agreed with Goldthwait (1940 pp. 17-19) that, "on the basis of rare though unmistakeable striae, till, and erratic stones", Mount Washington summit was overtopped "by glacier ice within late Pleistocene time" (Flint *et al.* 1942 p. 1225).

The following year, in a paper on the growth of the North American ice sheet during the Wisconsin age, Flint (1943) develops such an excellently reasoned and intellectually stimulating thesis that the "maximum Wisconsin viewpoint" became central to the North American concept of the Last Glaciation.

CURRENT STATUS OF THE "MAXIMUM WISCONSIN VIEWPOINT"

In Fig. 1 is depicted Flint's (1971) portrayal of the maximum extent of the Laurentide Ice Sheet at any time during the Quaternary ice ages. Flint

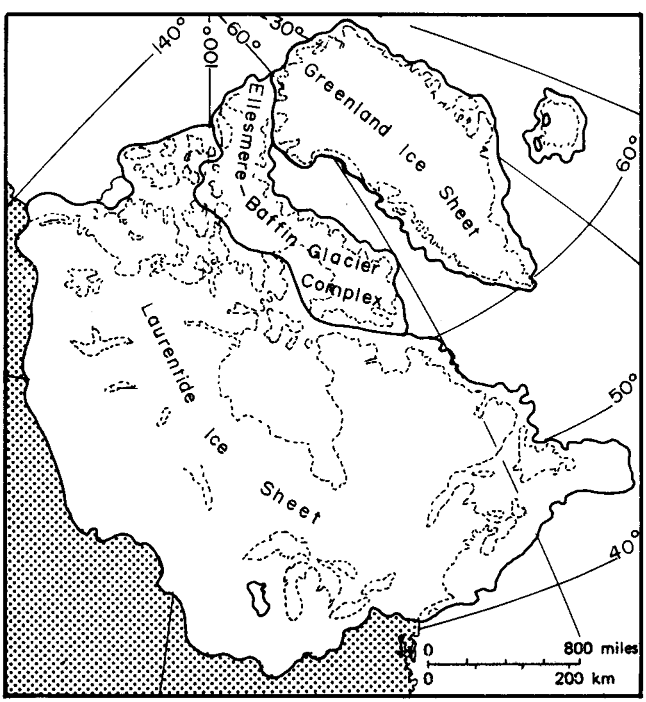


FIG. 1. Outline of major continental ice sheets in North America, regardless of age and east of the Cordillera. Modified from Flint 1971 p. 478.

(1971 p. 677) states that the "area glaciated by the (Laurentide) ice sheet, combining glaciations of more than one ice age, is believed to have totalled nearly 13.4 x 10^6 km^2. However, the Late Wisconsin ice sheet was smaller, having possibly about 90% of the area quoted." Regardless of the problem of Laurentide Ice Sheet extent, the northeastern subdivision, shown as the "Ellesmere-Baffin Glacier Complex" (after Craig and Fyles 1960), is an anomaly, since ice over the Queen Elizabeth Islands has long since been shown to have remained separate from that over Baffin Island. Evidence supporting this interpretation includes ice-flow patterns (Ives and Andrews 1963) and tilt of west-coast, marine-shore features of Baffin Island up toward the southwest (Andrews 1966) indicating that ice over Melville Peninsula — Foxe Basin — Baffin Island formed a great northern dome subsidiary to the main centre over Hudson Bay, while the ice cover of the Queen Elizabeth Islands occurred as a dynamically independent ice cap, or series of ice caps (Andrews 1970; Blake 1970). Flint (1971 p. 484) postulates that "at one time or another during the Wisconsin Age the ice sheet overtopped all the highlands between New York and Labrador". He then provides estimates of minimum ice thicknesses, indicating total submergence of, for instance, the Shickshock Mountains, Long Range and the Torngat Mountains. (Flint 1971 p. 486) also discusses briefly the question of the Nunatak Hypothesis and possible Wisconsin plant refuges on the east-coast mountains in which he recognizes that, while most localities have been shown to have been glaciated on the basis of geologic evidence, in some cases "the higher glaciation antedates the Late Wisconsin".

Close examination of Flint's writings over the years 1942 to 1971 indicates a rather complete commitment on his part to each of two associated theses: (a) that "highland origin and windward growth" of ice masses provide the best explanation of the initiation and development of the Laurentide Ice Sheet; and (b) that such development resulted in ice sufficiently thick for the highest summits of those very highlands to be inundated by easterly flowing ice during Wisconsin, and specifically during Late Wisconsin, time. The first of these theses has been challenged (Ives *et al.* 1975; Andrews and Mahaffy 1976) and it is only necessary here to point out that its refutation does not necessarily invalidate the second thesis, which is central to the present paper. The strong commitment to the second thesis is evident from a glacial map of North America of Flint *et al.* (1945). The following example will serve to illustrate this point. If a large (maximum Wisconsin viewpoint) Laurentide Ice Sheet is to be envisaged, then glacio-isostatic depression and late-glacial/postglacial recovery of the land relative to sea level would be anticipated along the northeastern coast of Baffin Island. The same glacial map indicates the presence of marine-shore features along the Baffin Island fiords raised to considerable elevations. The original source of some of these data is a paper by Wordie (1938). Examination of this paper, however, reveals Wordie's great uncertainty whether terraces 250 metres above sea level, and only identified from shipboard, were of marine origin and comparable to much lower, and definitely marine, features seen along the outer coast. Field reconnaissance in 1962 by the present author revealed that the terraces in question were lateral moraines and kame terraces, and that the Holocene marine limit along the entire length of northeastern Baffin Island varied between zero and about 50 metres above present sea level (Ives 1963a). This conclusion has since been substantiated (Dyke 1974). While subsequent glacial maps of Canada and the United States (e.g., Wilson *et al.* 1958; Flint 1959; Prest *et al.* 1968) do not retain such exaggerated notions of Holocene marine-limit elevations, the example given serves to demonstrate a certain eagerness to interpret ambiguous data in such a way as to accommodate an intellectually attractive hypothesis. An identical criticism can be made of the ready acceptance by Tanner (1944) and Flint (1943, 1957) of Odell's (1933, 1938) observations, and of Flint's interpretation of his own observations on the Shickshock Mountains and Long Range (Flint *et al.* 1942).

As has been indicated above, the fact that two widely contradictory viewpoints developed derives at least in part from the existence of the somewhat ambiguous evidence of the actual mountain-top conditions. Some further ambiguity may be the result of changes over the last thirty years in concepts of the length of Wisconsin (Last Glaciation) time and its character (bi-modal or tri-modal). However, it was already apparent in the early writings of Flint that the Wisconsin could be conceived of as a two-phase glaciation with an intervening interstadial. Whether 25,000 or 14,000 years have elapsed since the Maximum of the final Wisconsin event will have no bearing on the rate of weathering and production of the controversial summit blockfields. Nevertheless, both Shickshock erratics and blockfields were still related to the Late, or "classical," Wisconsin Maximum and postglacial time, respectively. Certainly, much of the divergence of view arises from Odell's (1933, 1938) belief in vigorous freeze-thaw processes in Arctic and alpine maritime climates and from Flint's acceptance of this opinion (Flint *et al.* 1942). A somewhat similar situation relating to the development of ideas concerning glaciation of the Maritime provinces of Canada is discussed in a paper by Grant (1977b) from which it appears that the early work of Goldthwait (1924) refuted the conclusions of Chalmers (1896) and created an effective mental blockage to a more flexible field interpretation until the nineteen-seventies.

COASTAL MOUNTAIN-TOP CONDITIONS AS EVIDENCE

In simplest terms, the ambiguous evidence is the deep rubble of presumably frost-shattered bedrock that covers many of the broad, high mountain tops situated on both sides of the North Atlantic, and the occasional anomalous blocks found within the rubble, which are sometimes assumed to be glacial erratics and at other times are interpreted as weathered-out inclusions, or other locally-derived material. The rubble is variously termed "mountain-top detritus", "felsenmeer" or "blockfield". In more detailed treatment, tors, or tor-like forms (Dahl 1966), weathering pits, tafoni and associated weathering forms, including clay mineral development, are described. The mountain-top detritus can be regarded in two ways: according to the interpretation of Bell, Daly and Coleman, such extensive weathering took far longer than the time available since the Maximum of the Last Glaciation; while according to that of Odell, Tanner and Flint, weathering in these environments is so rapid that full development of mountain-top detritus can be readily assumed to have been possible since the Maximum of the Last Glaciation. Each of these two schools of thought can also be respectively characterized by its acceptance of, or opposition to, the Nunatak Hypothesis — that is, by its standpoint in the controversy over whether plants and animals survived the Last Glaciation in ice-free areas within the mountain groups under consideration. It is also unfortunate that not only is there no directly available information concerning actual weathering rates, but it is not known precisely what processes are operating, or have operated in the past, to produce such forms as detritus, tors and weathering pits. Also, detailed geological maps of bedrock are not available for most of the area under consideration, so that the provenance of the anomalous blocks is frequently a matter of guesswork. Thus again, "opinion" — or rather, preconceived ideas — have frequently influenced interpretation of the admittedly equivocal, and until recently very scanty, field data. The school of thought that insists that mountain-top detritus is the result of rapid breakdown of bedrock often finds itself forced into special pleading to account for the "poorly preserved striations" and high-level glacial erratics upon which depends their hypothesis of total glacial inundation. This notwithstanding, the early supporters of the "minimum Wisconsin viewpoint" failed to find erratics in the summit areas. The present author, from his familiarity with the high mountains along the Baffin Island and Labrador coasts, can easily understand the failure of Bell, Daly and Coleman to discover obvious glacial erratics above about 650 metres, although Flint is justified in criticizing Coleman for accounting for, or explaining away, the Shickshock Mountain erratics (Flint *et al.* 1942).

During early fieldwork in the Torngat Mountains (Ives 1957, 1958a, 1958b, 1960a), the present author was perplexed by the conflicting interpretations of the same field evidence. His personal concern over the chances of misinterpretation of the significance of certain anomalous blocks on high summits and ridges remained with him until an opportunity arose to revisit the area in 1975 (Ives 1976). This concern was heightened by Løken's very appropriate challenge which argued that the anomalous blocks were the product of differential weathering, which itself clearly reflected the difficulties that faced Daly and Coleman (Løken 1962a, 1962b). Yet by the early nineteen-sixties it was quite clear that, regardless of the problem of interpreting the significance of the anomalous summit blocks, three altitudinally-arranged zones of differing degrees of weathering could be identified over wide areas of coastal northern Labrador, rather than the two zones of glaciated lower areas and frost-riven higher areas described by Daly and Coleman (Ives 1958a, 1958b, 1960a, 1963b; Tomlinson 1958, 1963; Løken 1962b; Andrews 1963; Johnson 1969). Furthermore, this identification was soon extended to northeastern Baffin Island (Løken 1966; Ives 1966, 1974; Pheasant and Andrews 1973; Andrews 1974).

The obvious next step was to date one or more of the three weathering zones. The least difficult to date was bound to be the lowest, since its upper (and outer) limit is frequently demarcated by extensive lateral and terminal moraines. In the Torngat Mountains these have been named the Saglek Moraines (Ives 1976); in northeastern and eastern Baffin Island they have been named the Alikdjuak Moraines (Pheasant and Andrews 1973; Andrews and Miller 1972). As a result of the ensuing teamwork, deposits began to be located that, by radiocarbon and uranium-series dating techniques, were proved to be older than the maximum of the Late Wisconsin (Løken 1966; King 1969; Ives and Buckley 1969; Pheasant and Andrews 1973). A good indication was thereby provided that the lowest weathering zone occupied the area covered by ice during the Maximum of the Last Glaciation. Already in 1957, however, it was apparent that the assumption that mature mountain-top detritus could form in late-glacial/post-glacial time was probably invalid. This conclusion was based upon deduction from observations that showed some summits to be covered with mature detritus and others with firm, ice-moulded bedrock along the geological strike, when the only difference between the two types of summit was that the latter were 150-200 metres lower in elevation than the former (Ives 1958b). The only remaining controversy among the team workers referred to above was whether or not the highest zone (Torngat Zone, or Zone I of Boyer and Pheasant 1974) had ever been overtopped by moving ice such as could allow emplacement of glacial erratics. At the moment, this controversy can best be handled by hypothesizing that some mountain tops that are characterized by weathering of the Torngat Zone type were never overtopped by flowing ice bearing erratics (Løken 1962; Ives and Buckley 1969; Ives and Borns 1971; England and Andrews 1973; Boyer and Pheasant 1974), while other summits showing the same weathering characteristics most certainly had been covered (Ives 1966, 1974, 1975, 1976; Ives *et al.* 1976; Sugden and Watts 1977). This anticipates one of the subsequently proposed working hypotheses — that four, rather than three, primary weathering zones may exist. In this sense, the term "Torngat" is reserved for the highest, possibly unglaciated, zone and a new term — "Komaktorvik" — is introduced for the zone characterized by extreme weathering phenomena and glacial erratics (see below). This aspect of the discussion, however, has been further enlivened by the recent work of Sugden (1968, 1974, 1977) who argues that mountain-top detritus, tors and delicate weathering phenomena could have been preserved on high mountain tops due to the hypothesized occurrence of thin, cold-based ice which was still able to emplace glacial erratics, while the less-weathered lower zones were abraded by the thicker, warm-based ice that flowed along the major valleys and through-troughs. However, Sugden certainly does not challenge the conclusion that these mountain-top weathering phenomena could *not* have been developed entirely since the Late Wisconsin maximum.

RECENT EXTENSIONS OF THE WEATHERING ZONE CONCEPT

In recent years Grant (1969, 1976, 1977a, 1977b) and Brookes (1970, 1977) have undertaken detailed field studies in Newfoundland and the Maritime provinces of Canada. These together have resulted in a reappraisal of the early work of Coleman and Flint and the widespread acceptance of the existence of three weathering zones. In consequence, there is need for a return to the "minimum Wisconsin viewpoint" of Daly and Coleman. Similarly, after initial work on this problem in Baffin Island, England (1976a, 1976b) has gathered extensive evidence from Ellesmere Island which would indicate that, contrary to the views of Blake (1970, 1975), the Queen Elizabeth Islands had a relatively limited ice cover during the Last Glaciation and that Blake's hypothesis of a Wisconsin Innuitian Ice Sheet should be replaced by one of a much more restricted ice cover as conceptualized in the term "Franklin Ice Complex". Most recently Dyke, after field studies in Baffin Island (Miller and Dyke 1974; Dyke 1977), has concluded, on the basis of weathering phenomena, that the northern perimeter of the Laurentide Ice Sheet in the vicinity of Somerset Island must be considered to have been much less extensive than is currently assumed (Dyke 1976; Netterville *et al.* 1976). Koerner (1977) has indicated that the hypothesis of greatly restricted Wisconsin ice in the Queen Elizabeth Islands would more readily match interpretations of the stratigraphy of deep ice cores from Devon and Ellesmere islands.

On the basis of the foregoing discussion, a preliminary indication of ice extent at the Maximum of the Last Glaciation of eastern and northeastern North America is presented here in the form of a fold-out map (Fig. 2). Several qualifications need to be made. First, it has become increasingly apparent that raised marine-shore features and marine deposits in northeastern Baffin Island, which antedate the Late Wisconsin Glaciation, and possibly the entire Last Glaciation, are widespread (Løken 1966; Andrews 1978; Miller *et al.* 1977). Such features are frequently to be found between Cape Dyer (66°40′N, 61°10′W) and Sam Ford Fiord (72°00′N, 71°00′W), and in Cumberland Sound at elevations of 20-80 metres (i.e. higher than the Holocene marine limit in the same area). Secondly, a similar conclusion seems valid for raised marine-shore features on Newfoundland (Grant 1977b), which Flint had interpreted as being Holocene in age and whose existence he had also used to strengthen his contention that ice from Labrador had overtopped Newfoundland during the last Wisconsin Maximum. Thirdly, the first radiocarbon dating to before the maximum of the Late Wisconsin Glaciation (30,000 BP or more) has recently been obtained as a result of analysis of marine mollusc shells in northern Labrador (Ives 1977). It would therefore seem advisable to anticipate future discoveries of Wisconsin interstadial and/or pre-Wisconsin raised-marine-shore features in this vast and still little-known area.

The outline of the Laurentide Ice Sheet and associated ice-cap margins in eastern and northeastern North America presented in Fig. 2 is therefore based on the assumption that a minimum of three weathering zones exist and can be correlated. It also implies that the (altitudinally) lowest weathering zone — ~~Saglek (Ives 1976), Zone III (Boyer and Pheasant 1974), and Zone A~~ (Grant 1977a) — represents terrain that was covered by Last Glaciation ice (combined maximum of all stades), while the zones of greater intensity of weathering were either ice-free or covered only by thin, stagnant or cold-based ice for all, or part of, the Last Glaciation.

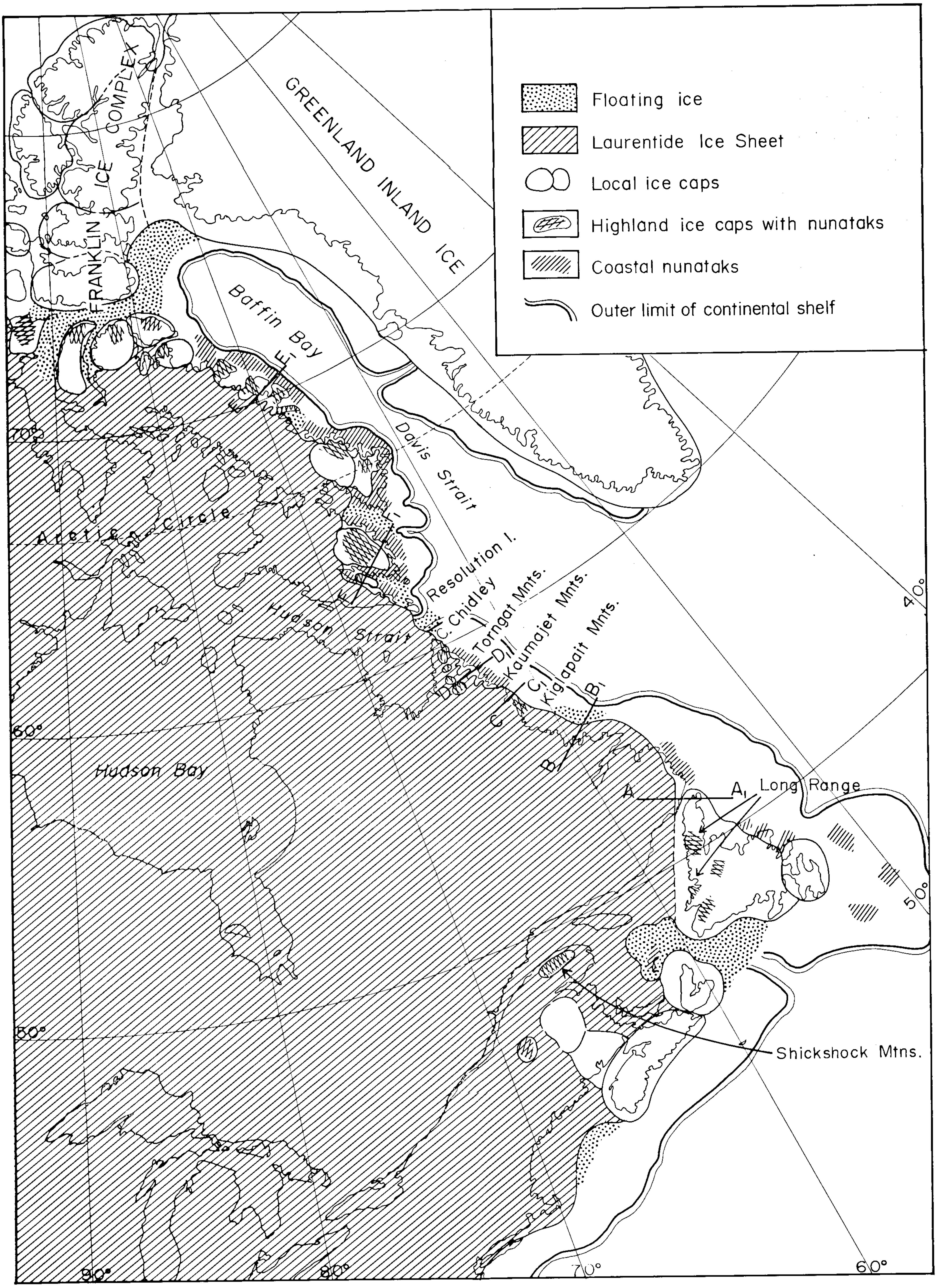
The Baffin Island section of Fig. 2 is to some extent representative of information included in an earlier map (Ives and Andrews 1963 p. 43). It also takes account of a recent map by Miller and Dyke (1974 p. 128). The fact that the relevant section of Fig. 2 displays striking similarities to these other maps is by no means coincidental. Some key items relating to critical areas about which little or nothing has been published serve to augment the map information. The Button Islands, lying immediately north of Cape Chidley (60°31′N, 64°15′W), while bearing widespread evidence of glacial abrasion, have bedrock surfaces sufficiently disrupted by weathering processes for the possibility to arise of their being classified within the intermediate weathering zone (Koroksoak, or Zone II, or Zone B) (J.P. Johnson, Jr., personal communication, November 1977). They are therefore represented on the map as having likely lain beyond the outermost Laurentide Ice Sheet limit of the Last Glaciation, a fact which would justify speculation that Resolution Island, on the north side of Hudson Strait, occupied a similar position. A.S. Dyke (Geological Survey of Canada, personal communication, 1978) is of the opinion that these "older" weathering surfaces may be more correctly considered to have developed since their abrasion by ice during an early, more intensive, stade of the Last (Wisconsin) Glaciation. This interpretation, again, points to the need to differentiate weathering surfaces that may relate to the various stades of the Last Glaciation.

This general description of the eastern entrance to Hudson Strait would seem to be supported by evidence for a fall in the Holocene marine limit northward along the Labrador coast until it passes below present sea level a few kilometres south of Cape Chidley (Løken 1962a), and a similar fall in marine limit level southward along the Baffin Island northeastern coast to about present sea level at Cape Dyer (Miller 1975; Andrews 1978) and to below present sea level in southernmost Baffin Island (G.H. Miller, INSTAAR, personal communication, October 1977). A partial exception is Løken's (1962a) fifteen-metre horizontal strandline that he correlated with the Tapes transgressions of Fenno-Scandinavia since this is interpreted as resulting from a post-glacial marine submergence which affected the entire area. The notion that the ice cover in the vicinity of eastern Hudson Strait was very limited during the Last Glaciation is at least indirectly supported by Mercer's work on Meta Incongnita Peninsula, although not by his interpretation of terraces of up to 450 metres in height as raised marine-shore features (Mercer 1956). Well-developed detritus is to be found on the summits of mountains on Lady Franklin and Monumental islands. These islands lie 45 kilometres off the eastern coast of Hall Peninsula, Baffin Island (62°50′N, 63°45′W) and the present author assumes that they were situated well beyond the maximum limits of Last Glaciation ice (see Ives 1963b p. 349).

FIG. 2 (fold-out). Reconnaissance map of the eastern perimeter of the Laurentide Ice Sheet at the combined maxima of the last glaciation. Areas of local, dynamically independent ice caps are shown schematically only. Profiles A-A′ to F-F′ have reference to the respective parts of Fig. 4.

While in the vicinity of Hopedale (55°31′N, 60°05′W) and Makkovik (55°05′N, 59°10′W) on the Labrador coast in 1956 and 1957, the present author was able to record that the bedrock of the highest summits (i.e., those of up to 600 metres above sea level) was both minimally weathered and glacially moulded and polished. Thus the outer limit of the Laurentide Ice Sheet during the Last Glaciation is situated well to the east of the present coastline of this part of Labrador. In addition, the high block of the Mealy Mountains seems to have been ice-covered (Gray 1965), but warrants more detailed field investigation (Ives 1960a). There remains the southeastern corner of Labrador facing Newfoundland where, from the descriptions of Coleman (1921, 1926) it would appear that Labradorean (i.e., Laurentide) ice never reached tidewater during the Last Glaciation. Coleman also drew attention to small areas in the vicinity of Cartwright (53°40′N, 57°05′W) which, on the basis of the existence of indurated till, presumably of pre-Wisconsin age, and local summits with intermediate weathering, he concluded remained ice-free during the Last Glaciation (Coleman 1921 pp. 26-27). Nevertheless, although the Laurentide Ice Sheet limit is shown to lie inside the present coastline of southeastern Labrador (see Fig. 2), this conclusion should be regarded as tentative until the results of additional observations become available. For Newfoundland and the Gulf of St. Lawrence in general, reliance is placed upon the work of Prest and Grant (1969), Grant (1976, 1977a, 1977b) and Brookes (1977). It is also assumed that the Shickshock glacial erratics (Flint *et al.* 1942) are pre-Wisconsin. However, the situation in the Presidential Range of New England is more complex, and the careful restatement of Goldthwait (1970) would indicate the need for more work on the high mountains of New England.

There remains a profound problem to be solved before a map of the Laurentide Ice Sheet, such as Fig. 2, can be fully substantiated. The present argument is based upon the assumption that a certain degree of surface weathering in an Arctic stretch of the eastern seaboard is not only the product of subaerial weathering during a particular period of time, but that a similar degree of weathering, 1,000 kilometres further south, developed over approximately the same period of time. In other words, the assumption is made that Zone I, for instance, of Boyer and Pheasant (1974) is the time equivalent of the Torngat Zone of Ives (1958a, 1975), and of Zone C of Grant (1977a). Such a correlation is reasonable as a first approximation, despite a considerable range in climates and microclimates between northern Baffin Island and Newfoundland, and despite the almost certain persistence of such a range through the last 100,000 years or more. This problem, however, needs further consideration, especially in the light of the conclusions of Birkeland (1975) that, on similar rock types, rates of weathering over time in the alpine belt of the Rocky Mountains of the southwest of North America are about one order of magnitude greater than those characteristic of Baffin Island. An independent check could be made by the examination of differing degrees of landscape dissection (D.R. Grant, Geological Survey of Canada, personal communication, 1978). A related problem is the paucity of detailed stratigraphic and palaeo-



Floating ice
Laurentide Ice Sheet
Local ice caps
Highland ice caps with nunataks
Coastal nunataks
Outer limit of continental shelf
GREENLAND INLAND ICE
FRANKLIN ICE COMPLEX
Baffin Bay
Davis Strait
Arctic Circle
Hudson Strait
Hudson Bay
Resolution I.
C. Chidley
Torngat Mnts.
Kaumajet Mnts.
Kiglapait Mnts.
Long Range
Shickshock Mtns.
A
A1
B
B1
C
C1
D
D1
E
E1
70°
60°
50°
40°
90°
80°

geographic information concerning early Wisconsin time, in view of the assumption that the Last Glaciation occurred during the period 125,100 — 8,000 BP (Miller *et al.* 1977). It may be that the zone of intermediate weathering — Zone II of Boyer and Pheasant, Koroksoak Zone of Ives, Zone B of Grant — relates to an early Wisconsin stade, at least in the more southerly areas under consideration. Despite these qualifications, which should provide a motive for future research, the map (Fig. 2) is based upon the assumption that the lowest of the three main weathering zones was formed contemporaneously along the entire eastern seaboard, and relates to the Maximum of the Last Glaciation — even though the "maximum" may have occurred during earlier stades in the north and later stades in the south. The term "contemporaneously", therefore, is used in the broad sense of "Last Glaciation".

ICE CONDITIONS DURING THE LAST GLACIATION: HYPOTHESES

The intriguing question of why the early view of Bell, Daly and Coleman was so easily and suddenly overthrown during the early nineteen-forties remains to be answered. It is of more than passing interest, because it is a classic example of the way in which knowledge in the natural sciences, or knowledge in general, proceeds from one "truth" to another "truth" and, sometimes, back again. It is the more perplexing because similar field evidence from the Yukon, Alaska, the Rocky Mountains and Antarctica, often the subject of similar methods, has been uncontroversially accepted over many decades by all researchers. Thus Bostock (1952) delineates glacial limits in the Yukon on the basis of weathering zones. Flint accepts comparable field evidence from southern Alberta, stating that "measurements at former nunataks give values (of ice thickness) between 300 and 700 m (depending on distance from the ice margin) for Late Wisconsin ice and up to 900 m for Early Wisconsin ice" (Flint 1971 pp. 484-5). More recently, Denton (1974) has applied similar methods in Antarctica and the Yukon-Alaska border as a means of identifying the outer limits of different glacial stages.

Nevertheless, the "maximum Wisconsin viewpoint" has prevailed in regard to the eastern sector of the Laurentide Ice Sheet, despite its dependence upon either unsubstantiated notions concerning the derivation and age of the Shickshock erratics and the form of the Torngat striations and erratics, or else oft-repeated assumptions that felsenmeer could have formed as a result of very rapid frost-riving over the time which had elapsed since the maximum of the Late Wisconsin Glaciation. The question concerning the rejection of the early views of Bell, Daly and Coleman can be at least partially answered by stating that (a) Tanner was a confirmed opponent of the Nunatak Hypothesis as a result of his pre-Labrador experience in Fenno-Scandinavia, as was also Flint; (b) the hypothesis which Flint repeatedly advanced was intellectually attractive; and (c) Bell, Daly and Coleman were dead, and therefore unable to defend themselves.

Nevertheless, despite the fact that a more definitive map of the maximum ice limits for the Last Glaciation along the eastern North American seaboard has been produced (Fig. 2), the problem of mountain-top evolution and glacial history in the area is by no means completely resolved. The warning that is implicit in much of the foregoing discussion should be heeded, and the possibility of stepping *backward* to another "truth" should be resisted. In view of these considerations, some of the remaining ambiguities will now be reconsidered, and a series of working hypotheses propounded for future testing, modification and possible replacement.

Eilif Dahl (1955) made a much needed, but little heeded, plea for earth scientists to accept strict criteria for the identification of glacial erratics, especially if the latter are *thought* to occur in areas identified on separate grounds by botanists as plant refugia. These criteria are as much needed today as they were more than twenty years ago; they are therefore now restated. The principal plea is that, since the existence of large anomalous blocks on mountain tops may be explained in terms of several unrelated processes, a positive identification of a glacial erratic requires demonstration of petrologic, tectonic and geomorphic uniqueness. The different processes include: weathering-out of inclusions, reduction of weathering remnants of higher geological strata by long-term general surface lowering, cold-climate mass movement which causes displacement from source areas, and emplacement and removal of erratics by human action.

Despite the need to identify these problems of glacial erratics, the application of Dahl's criteria, if carried to its logical extreme, could retard progress, rather than assist it, especially with regard to areas of Precambrian rocks that lack detailed bedrock maps. It is partly on this account that the term "perched block" is here proposed for anomalous boulders that cannot be traced to finite source areas and thus shown to be, in the strictest sense, *glacial* erratics. It can also be argued that, under certain circumstances, perched blocks can be regarded as evidence of glaciation.

Some other principles are worthy of reiteration. Proof that one summit has been covered by moving ice is not proof that all such summits in the general vicinity, and especially in the wider region, have been subject to the same occurrence. Nor does absence of positive evidence of glaciation indicate that a summit has never been glaciated. In this context, it is necessary to distinguish between "glaciated" and "glacierized". The former indicates inundation by moving, or actively eroding, ice; the latter, that a summit has been covered by thin, inert or "cold" ice frozen to the bedrock, either as a separate ice carapace, or in conjunction with, and contiguous with, actively eroding ice that traverses the surrounding valleys and fiords. In the latter case, ultimate disappearance of the ice cover, with the temporary exception of crustose lichen size and percentage cover, may leave no indication of its former presence. Sugden's (1974) hypothesis of "cold-based" ice in areas of selective linear erosion represents something between these two characterizations. Then again, the anomalous block itself, whether glacially emplaced or the product of differential weathering, has no age characteristics, presently recognizable and unequivocal, that will relate it to a particular glacial stage. Unweathered, or little-weathered, glacial erratics in a rubble of mountain-top detritus cannot necessarily be assigned to the Late Wisconsin Glaciation, and the rubble be assumed to have formed since deglaciation (Flint *et al.* 1942); nor can they necessarily be explained as being due to the emplacement by cold-based Late Wisconsin ice, on the assumption that the underlying, earlier-formed rubble had been preserved throughout the period of supposed Late Wisconsin inundation. Certainly, many of the presumed glacial erratics that the present author has discovered in such circumstances have been on ridge crests, actual summits or local eminences which are such that their microclimates will have contrasted with those of their underlying rubble. Therefore, when the different resistances to erosion of the various rock types are also considered, it should be obvious that their "fresh" appearance can be very misleading.

The complexities of the mountain-top conditions of the eastern seaboard can be described in terms of a number of interrelated working hypotheses. These are formulated here to explain differing conditions over time that may have occurred in the same place, and differing conditions at any one time that may have occurred simultaneously along this considerable length of coastline with its contrasting climates and topographic settings. Certain localities may have experienced the entire range of hypothesized conditions, others only one, and still others an intermediate number. In this context, Sugden's mapping of glaciated landscapes is of great value, since it serves to emphasize the existence of landforms of glacial erosion and their relationship to varying temperature conditions at the bedrock/ice interface (Sugden 1977). The individual hypotheses are presented as two series of topographical sections: the first series, with emphasis on changes through time in one locality, appear as valley cross-sections (Fig. 3); the second series, which represents conditions which possibly occurred at the same time along different sections of the coastline, appear as topographical sections drawn perpendicular to the coast (Fig. 4). Type localities are appropriate for the latter set. Taken together, and with other conditions or minor modifications, these topographical sections allow a wide range of possibilities to be portrayed. Careful testing of at least some of these hypotheses in at least a few of the critical areas can provide a basis for important field work in the future.

Fig. 3 UPPER is a graphic representation of the hypothesis that three weathering zones exist, and it can be interpreted in two ways which are discussed below as hypotheses 1A and 1B. The surface characteristics proposed in them are based upon actual field work carried out in the southern Torngat Mountains west of Saglek Fiord (50°30′N, 63°00′W) (Ives 1958a, 1958b). An uppermost weathering zone is a characteristic of much of the broad upland summit area above 800-1,000 metres, which supports a mature, mountain-top detritus, large numbers of deep weathering pits, many tor-like forms and scattered glacial erratics. But, except in the form of erratics, evidence of glaciation is lacking in the area. It is named the Komaktorvik Zone to differentiate it from the Torngat Zone (see below) that has identical weathering characteristics, but which has no known glacial erratics. The intermediate zone, named the Koroksoak Zone, displays abundant evidence of glaciation, both depositional and erosional, but without bounding moraines; "incipient" mountain-top detritus (Ives 1958b p. 27) is widespread, and the general surface weathering is of a type intermediate between that of the Komaktorvik Zone above and the

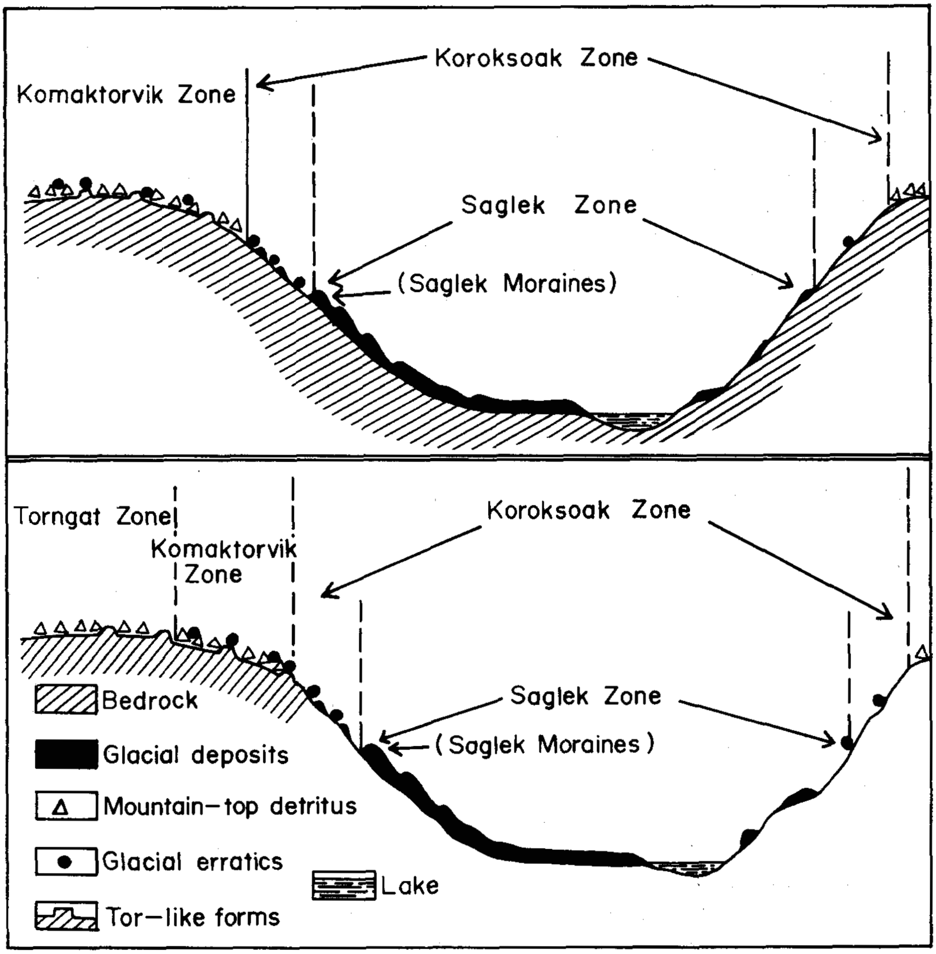


FIG. 3. UPPER: schematic cross-section of a glacial trough in the southern Torngat Mountains, showing surface weathering types and possible weathering zones (for legend see LOWER figure). LOWER: schematic cross-section of a glacial trough in the central Torngat Mountains, showing surface weathering types and possible weathering zones. In this instance, the highest summits are assumed to be unglaciated.

Saglek Zone below. This lowest zone (Saglek) is separated from the Koroksoak Zone by extensive stretches of lateral moraine, kame terrace and glacial-lake shoreline that together comprise the Saglek Moraines (Ives 1976). Surfaces, both bedrock and till, in this zone are "fresh". Striations and polished surfaces are much in evidence on rocks of fine-grained type, and large numbers of glacio-fluvial and glacio-lacustrine features are well preserved.

According to hypothesis 1A, the contrast in surface weathering between the Komaktorvik and Koroksoak zones is the result of a gradual transition and is directly related to a change in basal ice-temperature conditions, from cold-based summit ice to warm-based thicker and faster-moving valley ice (see Sugden 1974, 1977); and, furthermore, both zones were ice-covered during the Last Glaciation (Wisconsin, 125,000-8,000 BP). The assumption in this hypothesis is that the zones relate to an early stade of the Last Glaciation, with the Saglek Moraines representing the maximum of the "classical", or Late Wisconsin, stade. An alternative hypothesis (IB) is that the Saglek Moraines represent the greatest extent of ice at any time during the Last Glaciation, so that the upper weathering zones relate to an earlier glaciation or glaciations. This hypothesis is to be preferred, because of the dates attributed to the lower zone and its boundary moraines on Baffin Island (Løken 1966; Ives and Buckley 1969; Pheasant and Andrews 1973; Miller *et al.* 1977), although the correlation is by no means proven, absolute dating of the Saglek Moraines being required. Hypothesis IB also serves to indicate that the Komaktorvik/Koroksoak break is distinct and separates a pre-Sangamon glaciation (Koroksoak) from a much earlier (Komaktorvik) glaciation that overtopped all, or most, of the highest summits southward of the Komaktorvik Lakes vicinity. A third hypothesis (IC) — that all three weathering zones can be related to Late Wisconsin variations in temperatures and dynamics of basal ice (Sugden 1977) — would appear invalid because of the presence of the Saglek Moraines, which must be assumed to have been formed subaerially. Also, the very distinct boundary between the Koroksoak and Komaktorvik zones, at least in the southern Torngat Mountains, would require an unlikely prolonged stability of the subglacial change from cold-based to warm-based ice (see also Grant 1977a).

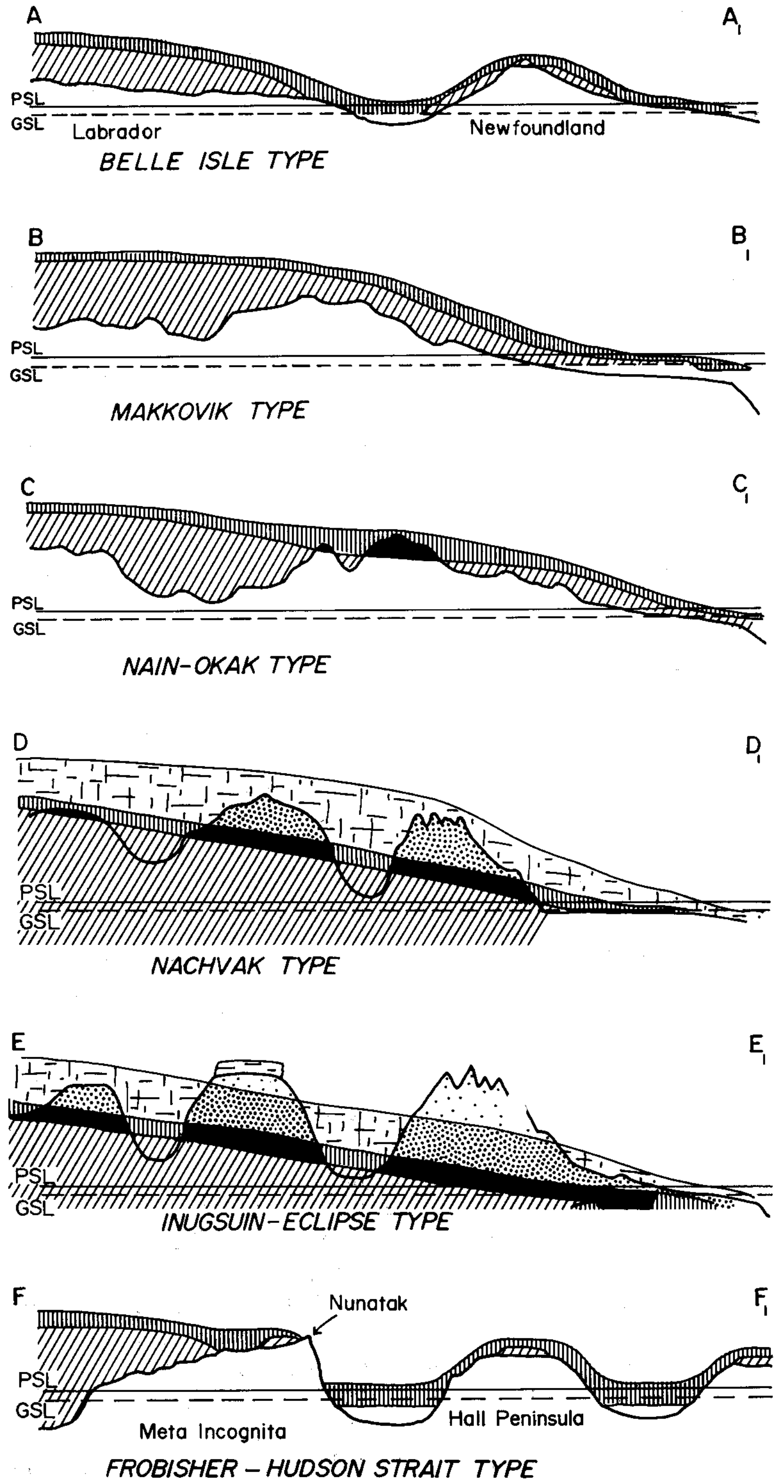
In Fig. 3 LOWER there are depicted the same three weathering zones as appear in Fig. 3 UPPER, but there is a subdivision of the upper zone which is based on an assumed total absence of glacial erratics in the higher unit (Torngat Zone) and the presence of erratics in the lower unit (Komaktorvik Zone). Detailed fieldwork could conceivably lead to these being differentiated on the basis of weathering criteria. Fig. 3 LOWER can be interpreted to infer that the Komaktorvik/Koroksoak transition represents a change from cold-based to warm-based ice; or, alternatively, that the Komaktorvik-Koroksoak boundaries represent the limits of different glacial stages. In either case, and with reference to hypothesis IB, it is assumed that the one or more glaciations antedate the Last Glaciation and that thin, cold-based ice carapaces were present on summits at least during certain periods of the last several glaciations. The term "Komaktorvik Zone" is derived from the Komaktorvik Lakes in the central Torngat Mountains where glacial erratics were first discovered at altitudes of over 1,200 metres (Ives 1957). The postulation of an unglaciated uppermost (Torngat) zone would accommodate the observations of Løken (1962b) in the northern Torngat Mountains and those of the present author in the Clyde — Inugsuin — Sam Ford fiord area of northeastern Baffin Island (Ives 1966, 1974; Ives and Buckley 1969), and also account for the absence of erratics from the Tertiary basalts near Cape Dyer (Clarke and Upton 1971; Ives and Borns 1971; Isherwood 1975).

The various possible interpretations that can be drawn from Fig. 3 serve to emphasize the critical significance of the Koroksoak/Komaktorvik transition. In the Nakvak Lake trough, Saglek Fiord, northern Labrador, this transition can be seen as a sharp line (Ives 1976 p. 406) — possibly too sharp to warrant interpretation as the former glacier basal area where a change occurred from cold-based to warm-based ice. However, in all other localities known to the present author, the transition from the intermediate to the upper weathering zone is much less distinct, and frequently cannot be readily interpreted by eye in the field but only by interpolation between weathering stations after laboratory analysis and data processing. Thus, while it is an unlikely explanation, the possibility must be considered that the Nakvak Lake "upper trimline" (Ives 1958a) is an accident of nature and not indicative of a general condition. The interpretation of field data in the Coronation-Maktak fiord area of eastern Baffin Island (67°15′N, 63°30′W) (Sugden and Watts 1977) serves to emphasize that caution is required in this respect.

A further consideration stems from the foregoing discussion of weathering zone differentiation. So far, for the sake of simplicity, it has been assumed that one glaciation can be equated respectively with each of the major weathering zones. It may be that the threefold weathering-zone division is still not sufficiently refined for subzones to have been detected, though they may actually exist in nature. Certainly, the results of recent, and much more detailed, studies of weathering phenomena on the Cumberland Peninsula area on Baffin Island (Mears 1972; Miller 1973, 1976; Birkeland 1975; Isherwood 1975; Locke 1976; Dyke 1977) have shown that the process of subdivision can be carried much further; in particular, the lowest weathering zone itself has been subdivided into three, indicating correlation with three stades of the Foxe (Last) Glaciation, and a fourth — equivalent to the Neoglaciation — has been substantiated.

Fig. 4 consists of a group of six topographic sections, each roughly perpendicular to the coastline in different localities of the study area selected, because it is believed that they portray glacial conditions that occurred at different phases of the Last Glaciation. The sections are intended to show surface characteristics, such as are represented in Fig. 3, that are indicative of ice maxima during earlier glaciations. Between them the six sections probably represent many, although by no means all, sets of conditions — or glacial styles (Grant 1977b) — that occurred along different lengths of the seaboard at different glacial maxima throughout the Cenozoic Ice Ages. The most notable exception is the possibility of very early glaciation on a topography completely different from that of today.

Fig. 4A is a cross-section through southeastern Labrador and northern Newfoundland, and is classed as the Belle Isle Type. This is a hypothetical composite derived from the work of Coleman (1926), Brookes (1977) and Grant (1977a, 1977b). It portrays a Last Glaciation Maximum, with Laurentide ice not reaching the present-day coastline and an independent ice cap over Newfoundland. An earlier (possibly pre-Sangamon) glaciation is depicted as reaching the Straits of Belle Isle, the ice of Newfoundland and the mainland being contiguous but dynamically independent. At this stage, summits of mountains of Newfoundland, today covered by mature mountain-top detritus, either remained as nunataks or else were covered by thin, stagnant and/or cold-based ice. A somewhat similar pattern of glaciation could apply to the southern Labrador—Gaspé area and to other parts of the region comprising New England and the Atlantic provinces of Canada. Brookes (1977) and Grant (1977a, 1977b) consider Zone B in Newfoundland to be pre-Late Wisconsin


A
A1
PSL
GSL
Labrador
Newfoundland
BELLE ISLE TYPE
B
B1
PSL
GSL
MAKKOVIK TYPE
C
C1
PSL
GSL
NAIN-OKAK TYPE
D
D1
PSL
GSL
NACHVAK TYPE
E
E1
PSL
GSL
INUGSUIN-ECLIPSE TYPE
F
F1
Nunatak
PSL
GSL
Meta Incognita
Hall Peninsula
FROBISHER – HUDSON STRAIT TYPE

but post-Sangamon — i.e., early Wisconsin. This implies that felsenmeer has developed during the Wisconsin or Last Glaciation.

Fig. 4B is named the Makkovik Type after the vicinity of Makkovik briefly studied in 1956 and 1957 (Ives 1958b). In this section of the Labrador coast, mountains rise to heights of 500-600 metres, their summit areas displaying *roches moutonnées,* numerous perched blocks, till, grooves, striations and, in places, delicate polish. Weathering of the Saglek Zone type extends therefore to the highest mountain tops and indicates total glacial inundation by Laurentide ice during one or more stades of the Last Glaciation. It may be assumed that the margin of the ice sheet extended well out onto the continental shelf. The Makkovik Type of continental glaciation probably covered an area extending from a little northward of Belle Isle to the vicinity of Nain (56°35′N, 61°50′W).

Fig. 4C depicts the Nain-Okak Type, characteristic of the area extending from Nain to the vicinity of Cod Island (southernmost Kaumajet Mountains in latitude 57°45′N). This section of the Labrador coast exhibits a much more complex and rugged relief than the more southerly sections; in particular, maximum altitudes approach, and occasionally exceed, 1,000 metres above present sea level. The composite pattern of glacial conditions is derived from the work of Wheeler (1958), Tomlinson (1958, 1963), Andrews (1963) and Johnson (1969). In this area, weathering of the Koroksoak Zone type is widespread on the higher summits both near the coast and for some 40-50 kilometres inland, a fact which may be taken to indicate that many upland areas remained ice-free, or else were covered only by thin, stagnant and dynamically independent ice carapaces, during all stades of the Last Glaciation. The ice-sheet margin extended well out onto the continental shelf. At least one earlier glaciation (Koroksoak) was much more severe and overtopped all the higher land, with the possible exception of a tiny nunatak formed by the uppermost 100 metres of Mount Thoresby (Johnson 1969). In this instance, Mount Thoresby constitutes an anomaly to the Nain-Okak Type. The same is probably true also of nearby Mount Attanekh (height 1,053 m).

Fig. 4D represents the Nachvak Type, named after Nachvak Fiord in the central Torngat Mountains, about midway between Saglek Fiord and Komak-

FIG. 4. Six schematic profiles drawn perpendicular to the general trend of the margin of the Laurentide Ice Sheet. The localities A-A′ to F-F′ are indicated on Fig. 2 (fold-out). The six types are named for specific localities ranging from the Straits of Belle Isle to northeastern Baffin Island.

P.S.L.- Present Sea Level G.S.L.- Glacial Sea Level

Ice at maximum of the Last Glaciation

Ice at maximum of Penultimate Glaciation

Koroksoak Weathering Zone

Komaktorvik Weathering Zone

Ice at maximum of Komaktorvik Glaciation

Torngat Weathering Zone

torvik Lakes, where the existence of three weathering zones and mountain-top glacial erratics was first demonstrated (Ives 1957, 1958a, 1958b). This, therefore, is the representative region of the Saglek, Koroksoak and Komaktorvik weathering zones and their associated glaciations. Saglek Zone weathering surfaces are limited to glacial troughs and occasional areas of lower land on the Atlantic side of the Labrador - Nouveau Québec watershed. It is doubtful whether, in the area between Saglek and Nachvak fiords, ice reached the outer coast in any quantity during the maximum of any stade of the Last Glaciation. Local cirque glaciers, valley glaciers and ice caps existed. South of Saglek Fiord, the upland gradually loses altitude, and between Hebron Fiord (58°15′N, 63°00′W) and the Kaumajet Mountains (southern limit of the Nachvak Type area) mainland ice almost certainly extended well out onto the continental shelf. Similarly toward the northern limit of this area, and located in the vicinity of Kangalaksiorvik Fiord (59°25′N, 64°00′W), outlet glaciers undoubtedly extended beyond the fiord mouths (Løken 1962a, 1962b). The cross-section (Fig. 4D) also indicates the occurrence of two earlier glaciations (Koroksoak and Komaktorvik); the latter overtopped the highest summits, as indicated by the identification of numerous erratics (Ives *et al.* 1976). It may be noted, however, that the highest mountains in the Nachvak Type area (Cirque Mountain and Mont d'Iberville), just south of Nachvak Fiord, exceed 1,600 metres and are appreciably higher than any that have been studied so far. It is therefore by no means certain that evidence of glaciation will be found when these summits are eventually examined closely.

The double name Inugsuin-Eclipse (Fig. 4E) concerns the northern Torngat Mountains and the Inugsuin Fiord area (70°00′N, 68°00′W) of northeastern Baffin Island, which both exhibit well-developed characteristics of the same type of glacial conditions and have also been studied in some detail (Løken 1962a, 1962b, 1966; Ives and Buckley 1969; Miller *et al.* 1977). This type is comparable to the Nachvak type in that the areas concerned contain three major weathering zones. It is, however, distinguished from the Nachvak Type because of the existence of large numbers of higher summits, especially ones closer to the coast that lack any indication of glacial erratics. Thus this glaciation type is characterized by an uppermost surface pattern described in northern Labrador as the Torngat Weathering Zone. Ice carapaces probably formed on many of these high "unglaciated" tops at various times, as is the case today in the northeastern Baffin Island subtype.

The Frobisher Bay - Hudson Strait Type (Fig. 4F) is the final one now described, although several others could be identified in the area between Bylot Island and northern Ellesmere Island. This sixth type is somewhat different from the other five, because it is to be found in the vicinity of the former massive Hudson Strait outlet glacier, whereas the others are related to more or less straight expanses of mainland coast. This also means that the profile shown in Fig. 4F does not trend down the local main ice-flow lines, but obliquely to them. It is, moreover, the least clear-cut of the six types (Fig. 4) because of the complexity of former land-water-ice distributions and because of the great limitation of available field data. Nevertheless, representing a working hypothesis, the profile indicates limited Last Glaciation Maxima ice on the higher parts of Meta Incognita Peninsula (Mercer 1956); dynamically independent ice on Hall and southern Cumberland peninsulas; possibly, floating outlet glaciers at the entrances to Hudson Strait, Frobisher Bay and Cumberland Sound; and a considerable number of both highland and lowland nunataks.

CONCLUSIONS

While the proposed delimitation of the eastern perimeter of the Laurentide Ice Sheet at the Maximum of the Last Glaciation would be very similar to one drawn by R.A. Daly or A.P. Coleman fifty years ago, it is based upon a much more extensive body of field data than was available to them, and upon a much fuller appreciation of the relationships amongst actual topography, climate and past climate, glacial chronology and weathering processes. Fig. 2 also depicts an ice-sheet perimeter somewhat more restricted than that envisaged by Prest (1969, 1970), although it cannot be compared closely with the maps of Bryson *et al.* (1969) because their concern had been to draw isochrones based upon available radiocarbon dates, and these were absent for Last Glaciation Maximum conditions. While the new map does not represent a major reduction in actual area when compared on a continental scale with the "maximum Wisconsin viewpoint" (Fig. 1), it does, however, have several important implications. First, the proposed changes in ice *thickness* along the coast, here defined as the area between the mid-section of the continental shelf and the heads of the fiords, are considerable, varying between about 200 metres and 2,500 metres according to the particular latitude and distance from the hypothetical "maximum" ice-sheet margin. From this it follows that, at least on a local scale, large areas above present sea level along most of the ice-sheet perimeter remained ice-free, or had only local ice caps, cirque glaciers and valley glaciers, with intervening ice-free areas. The map also presupposes that significant areas *below* present sea level, on the continental shelf, also remained ice-free. Thus ample land, with a range of altitudes and ecological niches, would have been available for the survival of plant and animal life throughout the Last Glaciation. Their present, disjunct occurrence could then be assumed to be identical with, or proximate to, their refuges during the various glacial maxima. Nevertheless, it is emphasized that knowledge of actual plant-species distributions in eastern North America, despite the work of Fernald (1925), is minimal compared with that in Scandinavia. Herein lies an opportunity for biological research of great potential now that a reasonable geologic basis is developing.

The map (Fig. 2) also implies that current efforts to model global atmospheric circulation during various phases of the Last Glaciation should be to reassess boundary conditions used as computer input (Williams *et al.* 1974; CLIMAP 1976). In particular, a recent paper by Hughes *et al.* (1977) should be regarded as largely speculative in this respect, since it has not taken into account a large amount of readily available field data that conflict with the conclusions it reaches. Despite this, Fig. 2 itself represents only a working hypothesis which will probably be modified as a result of detailed fieldwork. Also, the present study throws little light on the problem of whether there was a floating ice shelf or thick pack ice off shore. This problem is particularly relevant both to the location of possible ice-free areas and to the determination of ice-sheet boundary conditions as a basis for computer modelling.

The hypothesis can be tested in certain critical areas. Perhaps the most important is the eastern entrance to Hudson Strait, including Frobisher Bay, Cumberland Sound and Ungava Bay. There, a major outlet glacier, deriving much of its supply from the Hudson Bay area itself, obviously terminated somewhere between Cape Chidley, Resolution Island and Loks Land (62°30′N, 64°40′W) and discharged enormous quantities of ice into the Labrador Sea. But, under the present hypothesis, this giant outlet glacier would be much less extensive and less powerful than would be the case with a larger Laurentide Ice Sheet. This in turn invites consideration that the ice sheet itself may not have been the simple, monolithic dome with maximum thickness over Hudson Bay, as presumed under the "maximum Wisconsin" model. Part of Hudson Bay, and especially the northern part, may have remained an ice-topographic low during one or more of the Wisconsin Maxima. This tendency would have increased progressively after about 13,000 BP. This topic has been discussed from the point of view of analysis of glacio-isostatic conditions by Andrews and Peltier (1976). They conclude that the Laurentide Ice Sheet, as a simple dome, must have collapsed shortly after 12,000 BP, a problem originally discussed by Falconer *et al.* (1965) upon realization that the Cockburn Substage did indeed terminate about 8,000 BP with a catastrophic evacuation of glacier ice from Hudson Bay. The earlier lowering of the ice-sheet surface would have served to reduce the amount of energy necessary for ablation required to account for such a catastrophic collapse (Andrews 1973; Hare 1976). In this context, the radiocarbon date, 10,450 ± 250 BP (laboratory number I-488), on shells from near the marine limit in the vicinity of Sugluk (62°15′N, 75°45′W), recorded by Ives (1963b) and Matthews (1967), deserves further review. This also bears upon the timing of ice disappearance from Ungava Bay, which in turn would cause the drainage of the Naskaupi Glacial Lakes (Ives 1960b).

Other areas of critical importance include the Straits of Belle Isle, the Shickshock Mountains, Bylot Island, Lancaster Sound, Jones Sound, Judge Daly Promontory and the coastlands of northwestern Greenland.

Indications that glacial erratics do exist on certain high coastal summits well above the upper limits of ice of the Last Glaciation, from the Shickshocks to northeastern Baffin Island, and probably further north, would seem to imply the occurrence of an early glaciation (or glaciations) of much greater magnitude than that of the Last Glaciation, or else very early, and probably Tertiary, glaciation(s) that developed when the general landscape relations were very different from those of today. Thus, absolute altitudes may have been much smaller and possibly fiord formation had barely begun. It is also necessary to test the hypothesis that through a combination of more refined methods and more detailed field study the existence will be revealed of more weathering zones than the three or four that have been described so far. Alternatively, as a result of future advances in glacier mechanics, some of the "zones" that are currently distinguished may no longer be supportable. Inevitably, the most critical test of the viability of the general weathering-zone hypothesis will be the dating of sediments directly related to weathering-zone boundaries. (Dating of the Saglek Moraines has a high priority.) Another would be the identification of long stratigraphic sequences with uninterrupted pollen deposition. And, in a broader context, development in understanding of glacio-isostatic conditions constitutes a complementary approach to the overall problem of the size and shape of the Laurentide Ice Sheet, a topic which is beyond the scope of the present discussion.

Finally, it must be emphasized again that rigidity of interpretation can become a serious deterrent to progress. Hypotheses are put forward to be tested and, if necessary, replaced, not to be defended beyond their usefulness. Only a small fraction of the total available field data are currently assembled, so that this one view of the "truth" is seen, at best, through a glass darkly. The area is vast and comparatively little studied. Many of the field areas are known only from reports of the person who originally investigated them and have not been checked since. Even where some degree of independent check has been accomplished, usually based upon degree of comparability of different areas studied by different workers, the map and general conclusions have evolved largely from the work of a single "school" or team. Thus the scheme proposed here is to be regarded emphatically as a series of interrelated working hypotheses.

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