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PROGRESS IN GLACIAL GEOLOGY DURING THE LAST FIFTY YEARS

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ABSTRACT. The principal objectives of glacial geology over the last 50 years have been to establish and explain the history of ice, and in particular glaciation, on Earth and to understand the origin of the erosional and depositional products of ice. One of its major successes has been to establish the tempo and magnitude of change in the global glacier mass during the late Cenozoic ice age, and to demonstrate Earth orbital forcing of these changes. On the larger time-scale of the whole geological record, there has been steady elucidation of the frequency of ice ages since the first evidence of glaciation in rocks 2700 Ma old.

There has also been considerable progress in identifying the processes of glacial erosion and deposition and systematizing their products. It is now important that glacial geologists and glaciologists attempt to establish ways in which glacier behaviour is related to sedimentary processes, and via the geological product of those processes to relate the dynamics of glaciers in the past to processes in the lithosphere, hydrosphere, and atmosphere.

INTRODUCTION

For the purposes of this review, I define glacial geology as the study of the origin, form, and structure of the erosional and depositional products of glaciation, and the elucidation of the Earth's glacial history. The last 50 years of research in this field comprises two major linked scientific strands. The first has been to establish a history of glacial fluctuation on Earth both during the recent (and present) late Cenozoic ice age and in earlier epochs of Earth history, and to seek for causes. The second has been to identify the erosional and depositional products of glaciation and to explain their origin. These two objectives are linked in that our ability to recognize and explain the products of glaciation help us to determine the history of glaciation on Earth.

THE LATE CENOZOIC ICE AGE AND THE CAUSES OF GLACIAL/INTER-GLACIAL CYCLES

The world of ice, as it is now, is very different from that of 20 000 years ago. One of the considerable achievements of geology in the last 100 years has been to establish the tempo and character of the major changes of global environment in the recent geological past, whose most dramatic index has been the periodic growth and decay of large ice sheets in the mid-latitudes of the Northern Hemisphere. The demonstration of an insistent pulse of environmental change with frequencies of 40 000 and 100 000 years has been one of the two most important geological discoveries of the last 50 years, the other being the plate-tectonic synthesis of Earth's structural evolution.

By 1936, the year in which the Glaciological Society was founded, the "Glacial Theory", the concept that large areas of the globe had once been submerged by great flowing domes of ice, was already a hundred years old. These great ice invasions had been identified from scratched and striated boulders, and bedrock surfaces, and the poorly sorted tills which they had left behind in areas now thousands of miles from the nearest glacier. Although the theory was constructed through the painstaking observations of scientists of many nationalities, the greatest credit should go to the Swiss geologist, Louis Agassiz, who applied it widely and ensured its general application.

By the 1870s, the maximum extent of these Pleistocene ice masses had been established, as three times the area covered by ice today. Their generalized patterns of flow had been recognized from striae and glacier-oriented land forms, indicating that the great Northern Hemisphere ice sheets did not coalesce over the Pole, but flowed both to north and south from mid-latitude ice centres. This pattern of flow was recognized as reflecting the radial flow of great ice domes, whose surface gradients could be reconstructed from the upper limit of the signs of glaciation on hills around which the ice had flowed, whilst the deposits of well-defined "ice streams" were identified near to the peripheries of these ice domes long before modern ice streams were recognized in Antarctica. These conclusions were drawn in the absence of information about modern ice sheets, for the dome-like form of the Greenland ice sheet was not known until the 1850s, and the interior of Antarctica remained unknown until the end of the last century. They enabled geologists such as Whittlesey (1868) from Ohio to calculate a global sea-level fall of 400 ft [130 m] due to mid-latitude ice-sheet growth, whilst Jamieson (1865) from Scotland recognized that, near the ice sheets, the softer material beneath the Earth's crust would flow away from the centre of the ice-sheet load, causing the land to sink on glacier expansion and rise on glacier decay, thus producing the high shorelines and their marine faunas which we see today in "Scandinavia and North North America, as well as in Scotland".

The fact of repeated glaciation with intervening warm periods (glacials and inter-glacials) was first established by Geikie (1863) in Scotland, whilst the first great temporal synthesis of geologically recent glaciation was achieved in the northern foreland of the Alps by Penck and Brückner (1909), who recognized four great glaciations, separated by warm periods. From studies of post-glacial sediments in Swiss lakes in relation to plausible sedimentation rates, they estimated the time since the last glaciation as 20 000 years, and by extrapolation suggested that their four glaciations covered some 600 000 years. Four major expansions of the North American ice sheet had also been identified, which were generally assumed to correlate with the Alpine sequence; and three major expansions of the European ice sheet were assumed to correlate with the last three Alpine events.

Since 1936, a wide range of dating techniques has become available to geologists: ^{14}C, U/Th, K/Ar, palaeomagnetism, thermoluminescence, etc. but, because of the range limitation of about 30 000–40 000 years of ^{14}C dating on carbonaceous remains (the most commonly dated material) and the difficulty of finding sequences to which other dating techniques can be applied, absolute dating by itself has not yet succeeded in firmly establishing a time-scale for the major glacial episodes. However, the decay of the last great mid-latitude ice sheets, which took place in a time-frame readily accessible to ^{14}C dating, has been defined with considerable and growing precision. Establishment of the areal pattern of this last deglaciation has been achieved by a considerable collaborative international effort in mapping moraines, drumlins, striae, erratic fans, etc., but in which the work of the synthesis represents the tip of a very large iceberg (e.g. Leverett, 1929; Prest, 1968; Flint, 1971; Black and others, 1973; Shilts, 1982; Andrews and others, 1983, for the North American ice sheet; and Gripp, 1924; Lundqvist, 1948; Charlesworth, 1957; Woldstedt, 1958; Galon, 1964; Hansen, 1965; Andersen, 1968; Hoppe, 1972; Chebotareva and Makaryceva, 1974; Sollid and Sørbel, 1975; Sissons, 1979; Lagerlund, 1980, for the European ice sheet). The tempo of this last deglaciation, an index of the pattern of climatic amelioration in the transition to the present warm period, is now well established. The most detailed chronology is to be found in Sweden, where de Geer (1940) recognized that pro-glacial sedimentation in a lake dammed up in the Baltic basin showed an annual rhythm which can be used to reconstruct the retreat of the glacier front (Fromm, 1970). It reveals a period of rapid deglaciation between 13.5 and 11 ka and, after a stabilization of the glacier front, another period of rapid retreat after 10 ka. The tempo of decay of the last great mid-latitude ice sheets and of many of the Earth's other glacier masses have been reconstructed in a splendid compilation by Denton and Hughes (1981).

Uncertainties about the tempo and global magnitude of glaciation during the last few million years have largely been dispelled by the work of marine geologists during the last 40 years. Marine micro-faunas taken from low-latitude deep-ocean cores showed dramatic changes with depth, which were taken to reflect cooling and warming of ocean water during the major phases of global warming and cooling (e.g. Ericson and others, 1961). Statistical analysis of these faunas in relation to the conditions in which they live today permitted Imbrie and Kipp (1971) to estimate the magnitude of these changes, which involved a 2°C water-temperature change in the Caribbean between cold and warm periods. Earlier attempts by Emiliani (1966) to use the oxygen-isotope composition of calcareous skeletons of marine micro-organisms as a palaeotemperature indicator gave much larger values of temperature change (6°C), until Shackleton (1967) demonstrated that the largest part of the oceanic oxygen-isotope signal reflected the changing storage in glaciers of oxygen isotopes preferentially enriched in ^{16}O compared with ^{18}O. The development of a time-scale for these cores, based on the known frequency of reversal of the Earth's magnetic field, has therefore permitted us to gauge the frequency and amplitude of global changes of glacier ice mass (Shackleton and Oppdyke, 1973). The most recent results show a dramatic and sudden increase in the amplitude of the ^{18}O maximum at about 2.4 Ma ago, which must reflect a considerable enlargement of the global glacial mass during cold periods. The length of the typical climatic cycle at this time appears to have been about 40 000 years. Between 0.9 and 0.6 Ma ago, the amplitude of the ^{18}O maxima increased again, and has been sustained until at least the last glacial cycle, which peaked at 20 000 years ago. At the same time, the cycle length increased to 100 000 years. It is to the six major glacial cycles of the last 600 000 years that the four major identified glaciations of North America and the Alps, and the three identified in North-West Europe belong, although precise ocean/continent correlations are still in some doubt.

These deep-ocean data provided the key to the glacial/inter-glacial cycle which controls the evolution of the Earth's surface environment. Spectral analysis of $\delta^{18}O$ values from bottom-dwelling micro-fossils from deep-ocean cores showed peaks at frequencies of 100 000, 43 000, 24 000, and 19 000 years (Hays and others, 1976). This coincided with the solar insolation peaks derived from Milankovitch's (1941) computation of Earth orbital variation, in which there is a 100 000 year cycle in orbital eccentricity, a 41 000 year cycle in axial tilt, and 23 000 and 19 000 year cycles in precession of the ecliptic. It demonstrated that solar variation has been the driving force behind geologically recent environmental change on Earth and on the tempo of glaciation.

These conclusions also offer a remarkable validation of former speculations on the relationships between solar radiation and environmental change on Earth, exemplified by works such as that of James Croll (1875), who predicted a tempo of climatic change on Earth based on his estimates of the interaction of precession and eccentricity, and of Zeuner (1959), who used Milankovitch's predictions to estimate the age of glacial periods.

It is clear, however, that the temporal pattern of the Earth's net radiation receipt does not explain in a simple way the magnitude of timing of the Earth's glacial response. The change in mean surface temperature between glacial and inter-glacial periods is too large to be explained simply by changes in incoming solar radiation. There are clearly terrestrial factors which amplify the environmental and glacial response, and generate lags within the Earth's environmental system. The internal working of the Earth's atmosphere/ocean/ice-sheet system is highly coupled and determines the response to solar forcing. It is also important in attempting to predict the future of climate and the environmental system, and their response to anthropogenic effects. Elucidation of the interactions in the system are therefore major items on the agenda of geology, geophysics, and environmental science, and should be an important pre-occupation of glaciologists.

PRE-LATE CENOZOIC GLACIAL EPOCHS IN EARTH HISTORY

The rhythmic succession of cold, glacial periods separated by inter-glacials, driven by solar radiation cycles during the recent, late Cenozoic period, constitutes a *glacial epoch*. Pre-Cenozoic glacial beds have long been recognized. A great deal of work during the last 30 years has led to identification of glacially deposited sediments throughout much of Earth's geological record. Since 1969, collation and synthesis of these data has been orchestrated by the International Geological Correlation Programme (IGCP) Project 38 on Pre-Pleistocene Tillites and presented in the volume *Earth's pre-Pleistocene glacial record* by Hambrey and Harland (1981).

The earliest well-documented evidence of glacial activity on Earth comes from rocks in South Africa dated between 2600 and 2720 Ma old. After the Earth's formation at 4700 Ma ago, solidification of surface rocks and volcanic degassing produced water, carbon dioxide, nitrogen, and hydrogen sulphide on the surface. Despite a presumed lower solar flux, there is evidence of a water-covered Earth, taken to imply the presence of enough atmospheric CO_2 to produce an early "greenhouse" warming effect. It is assumed that a subsequent decreasing quantity of atmospheric CO_2 and screening of incoming radiation by ozone build-up and volcanic gases led to sufficient cooling to permit glaciation to develop by 2700 Ma. Subsequent major glacial epochs occurred in the periods 2500–2100 Ma (late Archaean), 1000–600 Ma (late Proterozoic), 470–430 Ma (late Ordovician–early Silurian), and 300–270 Ma (late Carboniferous–early Permian), whilst significant Cenozoic glacial activity began in Antarctica about 25 Ma ago (late Oligocene), spread to Alaska and Iceland between 10 and 5 Ma ago (Miocene), and expanded dramatically at 2.4 Ma and 0.9–0.6 Ma with major mid-latitude glaciations. Many late Proterozoic glacial beds appear to have formed in close proximity to banded iron formations, thought to reflect lateritic weathering in tropical environments. Palaeomagnetic studies suggest they formed in very low latitudes, an enigmatic association which has been explained as a result of a considerably greater orbital obliquity compared with the present day.

Several processes have been suggested as having a major influence on the development of glacial epochs. Flint (1971) suggested that the existence of large land masses in polar positions would tend to initiate glacierization which by its cooling effect on the global environment lead to glacial epochs. Thus, the clustered continents of Permo-Carboniferous time, with Antarctica located in a polar position, might explain the extensive contemporary glaciations, evidence of which survives in Antarctica, South America, Australia, Africa, and Asia.

The role of continental plate positions and motions in determining the timing of glacial epochs is supported by some recent work by Manabe and Broccoli (1984). They have modelled the general circulation of the atmosphere in relation to major topographic features of the Earth's surface. They showed that with significant tectonic uplift in the Himalayan/Tibetan region and the western American Cordilleras, the Earth's atmospheric flow became strongly perturbed, and major Rosby waves developed in the planetary circulation, which increased the meridional component of atmospheric transport and developed much colder winters in their lee. Thus, the dramatic uplift of the Himalayas and the Rockies in the last few million years, with uplift surges in the former at about 15 Ma and 3 Ma may have played an important role in developing and intensifying a glacial epoch.

The coincidence of inter-plate collision leading to mountain-belt uplift, and glacial epochs in the geological record suggests a possible causal link between mountain-building episodes and glacial epochs because of the former's perturbation of the pattern of planetary circulation.

Barron (e.g. 1983) has demonstrated how the distribution of continents affects ocean currents, which play a major role in heat advection on the Earth's surface. When the geometry of continent distribution permits circum-equatorial currents to develop, meridional temperature gradients are diminished; but when continental clusters in low latitudes block circum-equatorial currents, circum-polar currents develop, with major gyres trapped in mid-latitude oceans, which together enhance the meridional temperature gradient and make glacials in high or mid-latitudes more probable. The continuous oceanic belt in low latitudes during the Mesozoic, which progressively closed during the Tertiary (from 250 Ma to 50–15 Ma), may explain why this long period of geological time left almost no evidence of glaciation but rather of very warm conditions.

It seems likely that the long-term fluctuations of climate (less than the time-scale of planetary evolution), which give rise to glacial epochs, are largely determined by continental plate distributions and movement, whilst the shorter-term fluctuations which produce glacial and inter-glacial periods in glacial epochs reflect variations in incoming solar radiation.

THE DIRECT GEOLOGICAL AND GEOMORPHOLOGICAL PRODUCTS OF GLACIATION

Glacial erosion

The basic processes by which glaciers erode the landscape were well established during the nineteenth century. Forbes (1843) showed that temperate glaciers moved by a combination of internal flow and basal sliding, and that rock debris embedded in the glacier sole scratched and abraded the rock bed beneath it. He also suggested that colder ice would be frozen to bedrock and therefore would not slide over it or erode it. Matthes (1930) inferred the existence of a complementary process, whereby blocks were "plucked" from the glacier bed, thus providing the tools essential for the abrasion process. McCall (1960) observed how, in a small cirque glacier, rocks falling from the headwall could be incorporated into the basal part of the glacier and thus contribute to the tools which abrade the glacier bed.

Carol (1947) made observations beneath Grindelwald glacier from which he suggested that plucking could be produced by regelation of pressure melt water in the low-pressure zone on the lee sides of bedrock knobs, leading to fracturing of rock masses and their adhesion to the glacier sole to produce the typical *roche moutonnée* forms of glaciated bedrock. A "heat-pump" effect was advocated by Robin (1976) as a means of developing "cold patches" at the ice/rock interface and plucking away rock masses by adhesion, whereas Morland and Boulton (1975) suggested that the stress difference set up by glacier flow across a subglacial obstacle could be sufficient to cause fracturing on its lee side, and permitting fractured blocks to be carried away by the glacier.

Quantitative theories of abrasion of bedrock by clasts carried in basal ice have been developed by Boulton (1974) and Hallet (1979) in which they attempted to relate abrasion rate to basal ice velocity and a number of other local variables such as effective pressure at the ice/bed interface, particle concentration and size, although it is currently difficult to apply them either to the development of individual land forms or larger-scale landscapes.

During the last 10 years we have become aware of important chemical processes at the bed of a glacier which strongly influence the chemistry of basal ice and subglacially derived melt water (Souchez and Lorrain, 1978; Collins, 1981), and fractionation processes which produce subglacial precipitates (Hallet, 1976).

The detailed forms of eroded bedrock surfaces have been well catalogued; by Gilbert (1906) and Matthes (1930) prior to 1936, and subsequently by Demorest (1938) and Dahl (1965). The smooth "plastically moulded" nature (Dahl, 1965) of many of these surfaces has led many to suggest that they cannot merely have been produced by plucking and abrasion. Gjessing (1965) suggested that wet mobile till beneath a glacier may play an important scoouring role, a view which may be given some support by the recent inference from seismic data (Alley and others, 1986) of water-saturated sediment overlying a smooth hard acoustic reflector beneath an Antarctic ice stream.

On the much larger scale, there has been a long tradition of speculation about the origin of the characteristic erosional landscapes produced by glaciers. The large-scale components of these landscapes, cirques, over-deepened and U-shaped valleys, and fjords, were recognized as characteristic products of glaciation by Hutton in the eighteenth century and Ramsay in the nineteenth century. Davis (e.g. 1900) systematized the relationships between these landscape elements in an upland region, regarding them as examples of his general view that major landscape elements reflect an orderly evolution in time. Linton (1957) developed this view further, concluding that as a highland landscape became prone to glacierization small cirques first developed, enlarging and extending into over-deepened U-shaped valleys whose distribution initially reflected pre-existing, non-glacial drainage patterns, but which was progressively modified to reflect radial outflow of the ice mass.

The tendency for large ice sheets flowing over lowland terrain to cause over-deepened trenches to develop locally and thus to enhance local relief independently of the pre-glacial landscape was demonstrated by Clayton (1965) in the Finger Lakes region of New York State, U.S.A., produced not by valley-glacier flow but by selective erosion beneath an ice shot. Sugden and John (1976) contrasted such ice-sheet-produced landscapes of "selective linear erosion" with landscapes of "areal scouring" and suggested that the former develop where the ice sheet is thin, and the ice–bed interface frozen, except in pre-existing valleys which are just deep enough to permit basal melting. This would enhance erosion and glacier-flow rates, and by a positive feed-back produce deeply eroded troughs contrasting dramatically with the uneroded plateaux between them. The deeply entrenched fjords which slice through ice-sheet-glaciated uplands at continental margins may reflect an intensification of this process whereby "streaming" of the ice-sheet margin in a zone of very high ice discharge is able to produce troughs of exceptional depth.

An even larger spatial scale of glacial erosional pattern has been suggested by White (1972), who argued that the areas which lay beneath the centres of the Pleistocene ice sheets of North America and northern Europe, Hudson Bay and the Gulf of Bothnia, were lowered by several hundred metres as a result of glacier erosion. He argued that the depth of erosion diminished outwards towards a peripheral zone of little or no glacial erosion but of predominant deposition. The magnitudes of glacial erosion suggested by White have been shown to be far too large. Laine (1980) used the evidence of Atlantic deep-sea sediments derived from north-east North America to conclude that glacier erosion had been no more than a few metres. However, Sugden (1978), using the distribution of bedrock lakes as an index of erosional intensity, concluded that there were continent-wide patterns of glacial erosion in North America, which he believed reflected the repetitive pattern of basal thermal regime beneath the ice sheets at their successive maxima. Peripheral frozen-bed zones would minimize erosion, whilst immediately inside this zone, a zone of freezing-on of subglacial melt water would enhance erosion and give rise to the ring of lakes at the margin of the Canadian Shield. Andrews and others (1985) also pointed out a contrast in Baffin Island, between a zone of areal scouring to the west and selective linear erosion and absence of erosion in the east, which he explained as a reflection of the boundary between basal melting to the west and freezing to the east, beneath the thinning Laurentide ice-sheet periphery.

Glacial deposition

There have long been two schools amongst those attempting to relate glacial processes to sedimentary products: those who have studied processes and products directly in modern glaciated terrains, and those who have studied ancient Pleistocene sediments and, from them alone, attempted to infer processes. All too frequently, hypothetical explanations of sediment genesis have been preferred to those based on processes that are known to occur. In the last 20 years this division has begun to break down, although several earlier classic studies on modern glacial environments failed to have the impact they deserved because of it. They include such work as that of de Geer on sediment emplacement beneath a surging glacier, the significance of which for Pleistocene terrains was clearly indicated by Lamplugh (1911); of Tarr and Martin (1914) in relating sedimentation to glacier activity; and of Gripp (1929) in relating glacier-tectonic structures to sedimentation and glacier activity. Roughly contemporary attempts to infer processes only from their ancient products, such as those of Goodchild (1875) and Carruthers (1947–48), led others into scientific *cul de sacs* and have not stood the test of time.

The relative inaccessibility of the subglacial environment has made glaciers particularly difficult to understand compared with other sedimentary agents. The processes by which subglacial debris could be entrained within a polar glacier was suggested theoretically by Weertman (1961) and subsequently demonstrated through direct observation on a temperate glacier by Kamb and LaChapelle (1964). The nature of comminution processes during glacial transport was indicated by Dreimanis and Vagners (1971), who explained the bimodal grain-size distribution of tills in southern Canada as the product of progressive comminution of plucked blocks, which produce a fine-grained silt mode which resists comminution past a "terminal grade" depending on the magnitude of glacier stresses and the mineralogy of the constituents.

The processes of till deposition from englacial debris have received a great deal of attention. The concept of "lodgement" of debris in basal ice because of its frictional interaction with the glacier bed was developed by Chamberlain (1894) and further elucidated by Boulton (1975). The production of "flutings" on subglacial till surfaces, an ubiquitous characteristic of sediment surfaces over which glaciers have moved, was first discussed by Hoppe and Schytt (1953). Boulton (1972) described the production of "melt-out" tills by stagnation of buried debris-rich glacier ice, whilst Hartshorn (1958) inferred from Pleistocene sequences in Massachussetts a process by which dead ice melting led to the production of "flow tills" in environments of ice stagnation. The flow processes in such environments and the characteristics of the resultant sediment have been very thoroughly described by Lawson (1979).

A process which may have very considerable importance in sediment production is that of shear deformation of subglacial sediments producing "deformation till" (Elson, 1961). Alley and others (1986) have shown that a possible reason for the distinctive dynamic behaviour of Ice Stream B in the Ross Sea region of West Antarctica is its uncoupling from the underlying rigid bed by an intervening layer of "weak" sediment with a high interstitial pore-water pressure. This is a particularly important discovery in that it suggests very strong coupling between glacier dynamics and the production and character of subglacial sediments (e.g. Boulton and Jones, 1979), and the possibility that if the products of these processes can be recognized in the mid-latitude regions once occupied by Pleistocene ice sheets they could be a means of reconstructing former ice-sheet dynamics with some fidelity.

The concept of widespread subglacial sediment deformation as a process which might produce drumlins, the ubiquitous subglacially produced streamlined land form, was introduced by Smalley and Unwin (1968). Together with the recent discoveries in Antarctica, it could be taken to imply that the dynamics of many areas of the mid-latitude Pleistocene ice sheets were similar to those of Ice Stream B in Antarctica. However, the cores of many drumlins are composed of coarse-grained fluviatile sediments, and Shaw (1983) and Dardis and others (1984) have suggested that they represent the locations of extraordinarily wide subglacial tunnels. If this explantion were correct for many or most drumlins, their high frequency in many areas, and common evidence for their rapid construction would imply that the ice sheets underwent rapid and catastrophic "dewatering" events which would lead to large-scale instability and have a major impact on our concept of the evolution of glacial cycles. Both hypotheses stress strong coupling between drumlin formation and ice-sheet dynamics and, if we are to understand the latter, it is important that we should understand the former. Drumlin genesis should be a major theme of glacial geological and glaciological research.

A similar argument could be made for an, as yet, enigmatic glacial geological feature, the so-called "tunnel valley". These were first described from Denmark but are best known from glaciated continental shelves where detailed seismic reflection-profiling surveys have been undertaken (e.g. Cameron and others, 1985). They are generally buried valleys with irregular long profiles. They are up to 200–400 m in depth, 2–5 km in width, and generally several tens of kilometres in length. They are radially disposed in many of the soft-sediment areas around the periphery of the European ice sheet and are spaced several kilometres apart. They probably represent subglacial drainage features, and in view of their size and frequency must have played and important role in controlling water discharges beneath the ice sheet. As the state of drainage of the subglacial bed is of prime importance in governing the basal boundary condition, it seems clear that they must have played an important role in glacier dynamics. Like drumlins, we would expect to find them beneath modern ice sheets if our surveying techniques were adequate, and, like drumlins, they illustrate the important role that the glacial geology of the exposed beds of former ice sheets has to play in understanding the behaviour of large ice sheets.

Water-transported sediments are an important part of almost all glacial depositional environments. The development of subglacial channel systems and their role in the glacier-dynamic system has been an important aspect of glaciological research since the papers of Röthlisberger (1972) and Nye (1973), whilst the erosional channels produced by subglacial melt-water flow were analysed in a very perceptive and influential paper by Mannerfelt (1945). Esker sediments, the sedimentary relics of blocked subglacial and englacial tunnels, have been described and analysed in detail (e.g. Banerjee and McDonald, 1975; Saunderson, 1975), whilst McDonald and Vincent (1972) undertook valuable experiments on sedimentation in pipes as a basis for interpretation of esker sediments. Of the many studies of pro-glacial sedimentation on outwash surfaces, the works of Church (1972), and Boothroyd and Nummedal (1978) are particularly noteworthy. Sedimentation in glacial lakes is strongly controlled by the temperature structure of the lake and that of the incoming water and the nature of seasonal fluctuation. Much recent work is concerned to develop concepts which will permit us to infer the characteristics of former lakes from the distinctive characteristics of the fine-grained sediments deposited in them (e.g. Ashley, 1975; Gustavson, 1975; Smith and others, 1982).

Marine environments just beyond glacier margins (proximal glacio-marine environments) are extremely complex, and have been investigated in some detail over recent years. Part of the incentive for this lies in the fact that a large part of the Earth's pre-Pleistocene glacial record is represented by glacio-marine sequences whose correct interpretation needs good process-based sedimentary models. Little is known about sedimentation beneath ice shelves, although the U.S. Ross Ice Shelf Programme did yield some information. Sedimentation near the margins of tide-water glaciers is much better known (e.g. Elverhøi and others, 1980; Powell, 1983; Syvitski and Blakeney, 1983). It is a complex environment in which sediment types and their distribution depend upon the thermal and salinity structure of the water mass and the location of input streams, water depth, ice-calving rate and its distribution, and the circulation regime in the water body.

The history of near-shore glacial environments is also complex in view of the eustatic and isostatic sea-level changes associated with glacier growth and decay. However, the careful dating of such sedimentary sequences which reflect the changing history of sea-levels have enabled us to reconstruct the patterns of crustal flexuring produced by the expansion and contraction of large ice sheets (e.g. Andrews, 1970) and provide a basis by which the rheology of crust and mantle response to loading can be assessed (e.g. Peltier, 1980).

During glacial periods, there is an enormous expansion of the zone of distal glacio-marine sedimentary environments which are largely influenced by iceberg-dropped detritus. This is illustrated in a classic paper by Ruddiman (1977) which shows the expansion, fluctuation, and contraction of the zone of distal glacio-marine sedimentation in the North Atlantic during the last glacial cycle.

During the last 20 years, a great deal of effort on the part of many scientists has been directed towards the characterization of sediments produced in different glacial environments and the relationships between lithology and genesis. To a large extent, there have been two schools at work. One, inspired by the INQUA Commission on Lithology and Genesis of Quaternary Deposits (e.g. Dreimanis, 1976), has been concerned primarily to describe Pleistocene glacial sequences and to infer their mode of genesis from general principles, whilst the other, a school of "dirty-ice glaciologists", has been observation of sedimentary processes or relatively directly to infer them, and to relate sedimentary properties to these "known" processes. The work of the latter group has been summarized in recent reviews by Eyles (1983) and Drewry (1986). Progress of the science would benefit from improved dialogue between them and between both groups and "clean-ice glaciologists".

Large-scale glacial depositional patterns

The rhythmic growth and decay of the mid-latitude ice sheets during the last million years or so have shown well-integrated spatial patterns on a continent-wide scale. We would thus expect them to produce areally well-integrated patterns of sediments and depositional land forms, as depositional "landscapes". In comparison with erosional landscapes, they are produced in much shorter time periods. They generally represent the last depositional event rather than an integration of glacial activity over several glacial cycles as erosional landscapes must. Hoppe (1952) was one of the first to recognize such landscapes in attributing large areas of "hummocky moraine" in northern Sweden to stagnation of the last ice sheet, whilst Gravenor and Kupsch (1959) demonstrated some principles of organization of such landscapes and many (e.g. Clayton, 1964; Boulton, 1972; Eyles, 1979) have drawn attention to the supraglacial processes on modern glaciers which generate them.

Lundqvist (1969) illustrated regional patterns in subglacially generated sediment land forms in central Sweden, where he showed how so-called Rogen moraines in the former ice-divide area were progressively replaced by increasingly elongated drumlins in the direction of former glacier movements. Such studies, and the identification of regional patterns in drumlin landscapes, such as those mapped by Hill (1971) in Ireland and Glückert (1973) in Finland, will be important indices of ice-sheet behaviour when the origin of drumlins has been satisfactorily established.

The relationship between these depositional landscapes and the nature and large-scale architecture of the sediments and sedimentary sequences which occur within them are a reflection of glacial history and dynamics, local rock types, and topography. There are a limited number of repetitive patterns of sediment organization and landscape type which reflect several modes of glacial behaviour. It is possible to systematize these into a limited number of model land systems and sediment associations which provide a key to the genesis of sedimentary sequences, even when the origin of individual strata is in doubt, and which reflect glacier behaviour (e.g. Boulton and Paul, 1976; Fookes and Higginbottom, 1978; Eyles, 1983).

Early attempts to map glacial depositional landscapes on an ice-sheet-wide scale, such as those of Bird (1967), Prest (1968), and Flint (1971), showed that very large-scale patterns do exist, and theoretical discussions of their possible significance (e.g. Moran and others, 1980) suggest that they may yield considerable insights into the large-scale behaviour of ice sheets in time and space. The description and analysis on an ice-sheet-wide scale of the complete sediment geometry which results from a single glacial cycle would not only yield important insights about the large-scale behaviour of ice sheets but also provide further powerful tools to interpret the significance of ancient glacial sequences. It should be an important research priority.

A FORWARD LOOK

The mechanisms by which the oceans, atmosphere, and ice sheets interact in response to solar forcing to produce the long-term changes of the Earth's environmental system are a research theme of fundamental importance, involving a wide range of scientists. It requires integration of two complementary components: geological reconstruction of the temporal patterns of change in the physics and chemistry of the environmental system; and theoretical developments which enable us to model and thereby understand these interactions. Their complexities are such that major computational efforts are required.

Not only scientific curiosity, but economic imperatives, require that we look to the future of the environment, particularly since we have become aware of the possible present and future role of anthropogenic effects. Thus, we need to establish the natural background as well as the development of anthropogenic influences.

From integrated glacial geological and glaciological research, we need to know more about the history of the Antarctic and Greenland ice sheets, and to understand the much more dramatic variations of the mid-latitude ice sheets of Europe and North America. To interpret the significance of such information, we need to develop better time-dependent ice-sheet models coupled both to their beds and to the atmosphere and ocean.

The strong probability that ice-sheet dynamics and sedimentary processes on their beds interact strongly suggests that the exposed beds of the last mid-latitude ice sheets contain a wealth of largely unused geological information about the dynamic behaviour of ice sheets through a whole glacial cycle, information largely unavailable from modern ice sheets. Research should therefore pursue the nature of these interactions, and attempt to plot the distribution of significant indicators on an ice-sheet-wide scale.

The Society has sometimes seemed loath to pursue these broader aspects of glaciology in favour of an agenda established earlier in its history. If its second 50 years is to be as successful as its first, it is important that we continue to be prepared to rise to such new scientific challenges.

REFERENCES

Alley, R.B., *and others*. 1986. Deformation of till beneath ice stream B, West Antarctica, by R.B. Alley, D.D. Blankenship, C.P. Bentley, and S. T. Rooney. *Nature*, Vol. 322, No. 6074, p. 57-59.

Andersen, B.G. 1968. Glacial geology of western Troms, north Norway. *Norges Geologiske Undersøkelse*, Nr. 256.

https://doi.org/10.3189/S0022143000215797 Published online by Cambridge University Press

Andrews, J.T. 1970. *A geomorphological study of post-glacial uplift with particular reference to Arctic Canada.* London, Institute of British Geographers. (Special Publication No. 2.)

Andrews, J.T., *and others.* 1983. Multiple deglaciations of the Hudson Bay Lowlands, Canada, since deposition of the Missinaibi (last-interglacial?) Formation, by J.T. Andrews, W.W. Shilts, and G.H. Miller. *Quaternary Research*, Vol. 19, No. 1, p. 18-37.

Andrews, J.T., *and others.* 1985. Patterns of glacial erosion across the eastern Canadian Arctic, by J.T. Andrews, P. Clark, and J.A. Stravers. (*In* Andrews, J.T., *ed. Quaternary environments: eastern Canadian Arctic, Baffin Bay, and western Greenland.* Boston, etc., Allen and Unwin, p. 69-92.)

Ashley, G.M. 1975. Rhythmic sedimentation in glacial Lake Hitchcock, Massachusetts–Connecticut. (*In* Jopling, A.V., and McDonald, B.C., *eds. Glaciofluvial and glaciolacustrine sedimentation.* Tulsa, OK, Society of Economic Paleontologists and Mineralogists, p. 304-20. (Special Publication 23.))

Banerjee, I., *and* McDonald, B.C. 1975. Nature of esker sedimentation. (*In* Jopling, A.V., and McDonald, B.C., *eds. Glaciofluvial and glaciolacustrine sedimentation.* Tulsa, OK, Society of Economic Paleontologists and Mineralogists, p. 132-54. (Special Publication 23.))

Barron, E.J. 1983. A warm, equable Cretaceous: the nature of the problem. *Earth Science Reviews*, p. 1-27.

Bird, J.B. 1967. *The physiography of Arctic Canada, with special reference to the area south of Parry Channel.* Baltimore, MD, Johns Hopkins Press.

Black, R.F., *and others, eds.* 1973. The Wisconsinan stage, edited by R.F. Black, R.P. Goldthwait, and H.B. Willman. *Geological Society of America. Memoir*, No. 136.

Boothroyd, J.C., *and* Nummedal, D. 1978. Proglacial braided outwash: a model for humid alluvial-fan deposits. (*In* Miall, A.D., *ed. Fluvial sedimentology.* Calgary, Canadian Society of Petroleum Geologists, p. 641-68. (Memoir 5.))

Boulton, G.S. 1972., Modern Arctic glaciers as depositional models for former ice sheets. *Journal of the Geological Society* (London), Vol. 128, Pt. 4, p. 361-93.

Boulton, G.S. 1974. Processes and patterns of glacial erosion. (*In* Coates, D.R., *ed. Glacial geomorphology.* New York, State University of New York, p. 41-87.)

Boulton, G.S. 1975. Processes and patterns of subglacial sedimentation: a theoretical approach. (*In* Wright, A.E., *and* Moseley, F., *eds. Ice ages: ancient and modern.* Liverpool, Seel House Press, p. 7-42.)

Boulton, G.S., *and* Jones, A.S. 1979. Stability of temperate ice caps and ice sheets resting on beds of deformable sediment. *Journal of Glaciology*, Vol. 24, No. 90, p. 29-43.

Boulton, G.S., *and* Paul, M.A. 1976. The influence of genetic processes on some geotechnical properties of glacial tills. *Quarterly Journal of Engineering Geology*, Vol. 9, p. 159-94.

Cameron, T.D.J., *and others.* 1985. *Indefatigable sheet, 53°N–0°E. 1/250,000 Series Quaternary Geology.* Southampton, Ordnance Survey.

Carol, H. 1947. The formation of *roches moutonnées. Journal of Glaciology*, Vol. 1, No. 2, p. 57-59.

Carruthers, R.G. 1947–48. The secret of the glacial drifts. *Proceedings of the Yorkshire Geological Society*, Vol. 27, p. 43-57 and 129-72.

Chamberlain, T.C. 1894. Proposed genetic classification of Pleistocene glacial formations. *Journal of Geology*, Vol. 2, p. 517-38.

Charlesworth, J.K. 1957. *The Quaternary era with special reference to its glaciation. Vols. 1 and 2.* London, Edward Arnold.

Chebotareva, N.S., *and* Makarucheva, I.A. 1974. *Poslednеye oledeneniye Yevropi i ego geokhronologiya* [*The most recent glaciation in Europe and its geochronology*]. Moscow, Izdatel'stvo "Nauka".

Church, M. 1972. Baffin Island sandurs: a study of Arctic fluvial processes. *Geological Survey of Canada. Bulletin*, No. 216.

Clayton, K.M. 1965. Glacier erosion in the Finger Lakes region, New York State, U.S.A. *Zeitschrift für Geomorphologie*, Bd. 9, p. 50-62.

Clayton, L. 1964. Karst topography on stagnant glaciers. *Journal of Glaciology*, Vol. 5, No. 37, p. 107-12.

Collins, D.N. 1981. Seasonal variation of solute concentration in melt waters draining from an Alpine glacier. *Annals of Glaciology*, Vol. 2, p. 11-16.

Croll, J. 1875. *Climate and time.* New York, Appleton and Co.

Dahl, R. 1965. Plastically sculptured detail forms on rock surfaces in northern Nordland, Norway. *Geografiska Annaler*, Vol. 47A, No. 2, p. 83-140.

Dardis, G.F., *and others.* 1984. Characteristics and origins of lee-side stratification sequences in late-Pleistocene drumlins, Northern Ireland, by G.F. Dardis, A.M. McCabe, and W.J. Mitchell. *Earth Surface Processes and Landforms*, Vol. 9, p. 409-24.

Davis, W.M. 1900. Glacial erosion in France, Switzerland, and Norway. *Proceedings of the Boston Society of Natural History*, Vol. 29, p. 273-321.

De Geer, G. 1940. Geochronologica suecica; principles. *Kungliga Svenska Vetenskapsakademiens Handlingar*, Bd. 18, Nr.6.

Demorest, M. 1938. Ice flowage as revealed by glacial striae. *Journal of Geology*, Vol. 46, p. 700-25.

Denton, G.H., *and* Hughes, T.J. 1981. *The last great ice sheets.* New York, John Wiley and Sons.

Dreimanis, A. 1976. Tills: their origin and properties. (*In* Leggett, R.F., *ed. Glacial till.* Ottawa, Royal Society of Canada, p. 11-49. (Special Publication No. 12.))

Dreimanis, A., *and* Vagners, U.J. 1971. Bimodal distribution of rock and mineral fragments in basal tills. (*In* Goldthwait, R.P., *ed. Till – a symposium.* Columbus, OH, Ohio State University Press, p. 237-50.)

Drewry, D. 1986. *Glacial geologic processes.* London, Edward Arnold.

Elson, J.A. 1961. *The geology of tills. Proceedings of the 14th Canadian Soil Mechanics Conference, le Oct. 13–14, 1960.* Ottawa, National Research Council, p. 5-35.

Elverhøi, A., *and others.* 1980. Glacial erosion, sedimentation and microfauna in the inner part of Kongsfjorden, Spitsbergen, by A. Elverhøi, O. Liestøl, and J. Nagy. *Norsk Polarinstitutt. Skrifter*, Nr. 172, p. 33-61.

Emiliani, C. 1966. Palaeotemperature analysis of Caribbean cores P6304–8 and P6304–9 and a generalised temperature curve for the past 425,000 years. *Journal of Geology*, Vol. 74, p. 109-26.

Ericson, D.B., *and others.* 1961. Atlantic deep sea sediment cores, by D.B. Ericson, D.M. Ewing, G. Wollin, and B.C. Heezen. *Geological Society of America. Bulletin*, Vol. 72, p. 193-286.

Eyles, N. 1979. Facies of supraglacial sedimentation on Icelandic and Alpine temperate glaciers. *Canadian Journal of Earth Sciences*, Vol. 16, No. 7, p. 1341-61.

Eyles, N., *ed.* 1983. *Glacial geology; an introduction for engineers and earth scientists.* Oxford, etc., Pergamon Press.

Flint, R.F. 1971. *Glacial and Quaternary geology.* New York, etc., John Wiley and Sons.

Fookes, P.G., *and* others. 1978. Glacial landforms, their deposits and engineering characteristics, by P.G. Fookes, D.L. Gordon, and I.E. Higginbottom. (*In The Engineering Behaviour of Glacial Materials. Proceedings of the Symposium held at the University of Birmingham ... 1975.* Norwich, Geo Abstracts, p. 18-51.)

Forbes, E. 1843. On the connection between the distribution of the existing fauna and flora of the British Isles, and the geological changes which have affected their area, especially during the epoch of the northern drift. *Geological Survey of Great Britain. Memoir*, No. 1, p. 336-432.

Fromm, E. 1970. An estimation of errors in the Swedish varve chronology. (*In* Olsson, I.U., *ed. Radiocarbon Variations and Absolute Chronology. Proceedings of the Twelfth Nobel Symposium ... at Uppsala University.* Stockholm, Almqvist and Wiksell; New York, John Wiley and Sons, p. 163-72.)

Galon, R. 1964. On the geomorphology of northern Poland. *Geographia Polonica*, Vol. 1, p. 23-39.

Geikie, A. 1863. On the phenomena of the glacial drifts of Scotland. *Geological Society of Glasgow. Transactions*, Vol. 1.

Gilbert, G.K. 1906. Crescentic gouges on glaciated surfaces. *Bulletin of the Geological Society of America*, Vol. 17, p. 303-16.

Gjessing, J. 1965. On "plastic scouring" and "subglacial erosion". *Norsk Geografisk Tidsskrift*, Bd. 20, Ht. 1–2, p. 1-37.

Glückert, G. 1973. Two large drumlin fields in central Finland. *Fennia* 120.

Goodchild, J.G. 1875. The glacial phenomena of the Eden Valley and the western part of the Yorkshire Dales district. *Quarterly Journal of the Geological Society of London*, Vol. 31, p. 55-99.

Grosvenor, C.P., *and* Kupsch, W.O. 1959. Ice disintegration features in western Canada. *Journal of Geology*, Vol. 67, p. 48-64.

Gripp, K. 1924. Über die äusserste Grenze der letzten Vereisung in Nordwest–Deutschland. *Mitteilungen der Geographischen Geschichte*, Bd. 36, p. 159-245.

Gripp, K. 1929. Glaziologische und geologische Ergebnisse der Hamburgischen Spitzbergen Expedition 1927. *Naturwissenschaftlicher Verein in Hamburg. Abhandlungen der Gebiet von Naturwissenschaften*, Bd. 22, Nos. 2–4, p. 146-249.

Gustavson, T.C. 1975. Sedimentation and physical limnology in proglacial Malaspina Lake, southeastern Alaska. (*In* Jopling, A.V., *and* McDonald, B.C., *eds. Glaciofluvial and glaciolacustrine sedimentation*. Tulsa, OK, Society of Economic Paleontologists and Mineralogists, p. 249-63. (Special Publication No. 23.))

Hallet, B. 1976. Deposits formed by subglacial precipitation of $CaCO_3$. *Geological Society of America. Bulletin*, Vol. 87, No. 7, p. 1003-15.

Hallet, B. 1979. A theoretical model of glacial abrasion. *Journal of Glaciology*, Vol. 23, No. 89, p. 39-50.

Hambrey, M.J., *and* Harland, W.B., *eds*. 1981. *Earth's pre-Pleistocene glacial record*. Cambridge, Cambridge University Press.

Hansen, S. 1965. The Quaternary of Denmark. (*In* Rankama, K., *ed. The Quaternary. Vol. 1*. New York, Interscience, p. 1-90.)

Hartshorn, J.H. 1958. Flowtill in southeastern Massachusetts. *Geological Society of America. Bulletin*, Vol. 69, p. 477-82.

Hays, J.D., *and others*. 1976. Variations in the Earth's orbit: pacemaker of the ice ages, by J.D. Hays, J. Imbrie, and N.J. Shackleton. *Science*, Vol. 194, No. 4270, p. 1121-32.

Hill, A.R. 1971. The internal composition and structure of drumlins in north Down and south Antrim, Northern Ireland. *Geografiska Annaler*, Vol. 53A, No. 1, p. 14-31.

Hoppe, G. 1952. Hummocky moraine regions, with special reference to the interior of Norrbotten. *Geografiska Annaler*, Bd. 34, Ht. 1–2, p. 1-72.

Hoppe, G. 1972. Ice sheets around the Norwegian Sea during the Würm glaciation. *Ambio*, Special Report, No. 2, p. 25-29.

Hoppe, G., *and* Schytt, V. 1953. Some observations on fluted moraine surfaces. *Geografiska Annaler*, Bd. 35, Ht. 2, p. 105-15.

Imbrie, J., *and* Kipp, N.G. 1971. A new micro-paleontological method for quantitative paleoclimatology: application to a Late Pleistocene Caribbean core. (*In* Turekian, K.K., *ed. The Late Cenozoic glacial ages*. New Haven and London, Yale University Press, p. 71-181.)

Jamieson, T.F. 1865. On the history of the last geological changes in Scotland. *Quarterly Journal of the Geological Society of London*, Vol. 21, p. 161-95.

Kamb, B., *and* LaChapelle, E. 1964. Direct observation of the mechanism of glacier sliding over bedrock. *Journal of Glaciology*, Vol. 5, No. 38, p. 159-72.

Lagerlund, E. 1980. *Litostratigrafisk indelning av Västskånes Pleistocen och en ny glaciationsmodell för Weichsel*. Lund, Lund University. Department of Quaternary Geology. (Lundqua Report No. 21.)

Laine, E.P. 1980. New evidence from beneath the western North Atlantic for the depth of glacial erosion in Greenland and North America. *Quaternary Research*, Vol. 14, No. 2, p. 188-98.

Lamplugh, G.W. 1911. On the shelly moraines of the Sefström Glacier. *Proceedings of the Yorkshire Geological Society*, Vol. 17, p. 215-41.

Lawson, D.E. 1979. Sedimentological analysis of the western terminus region of the Matanuska Glacier, Alaska. *CRREL Report* 79-9.

Leverett, F. 1929. Moraines and shore lines of the Lake Superior basin. *U.S. Geological Survey. Professional Paper* No. 154, p. 1-72.

Linton, D.L. 1957. Radiating valleys in glaciated lands. *Tijdschrift van net Koninklijke Nederlandsch Aardrijkskundig Genootschap*, Vol. 74, p. 297-312.

Lundqvist, G. 1958. Beskrivning till jordartskarta över Sverige. *Sveriges Geologiska Undersökning*, Ser. Ba, No. 17.

Lundqvist, J. 1969. Problems of the so-called Rogen moraine. *Sveriges Geologiska Undersökning*, Ser. C, Nr. 648.

McCall, J.G. 1960. The flow characteristics of a cirque glacier and their effect on glacial structure and cirque formation. (*In* Lewis, W.V., *ed. Investigations on Norwegian cirque glaciers*. London, Royal Geographical Society, p. 39-62. (Research Series No. 4.))

McDonald, B.C., *and* Vincent, J.S. 1972. Fluvial sedimentary structures formed experimentally in a pipe, and their implications for interpretation of subglacial sedimentary environments. *Geological Survey of Canada. Report* 72-27.

Manabe, S., *and* Broccoli, A.J. 1984. Ice-age climate and continental ice sheets: some experiments with a general circulation model. *Annals of Glaciology*, Vol. 5, p. 100-05.

Mannerfelt, C.M. 1945. Några glacialmorfologiska formelement. *Geografiska Annaler*, Bd. 27, Ht. 1–2, p. 1-239.

Matthes, F.E. 1930. Geologic history of the Yosemite Valley. *U.S. Geological Survey. Professional Paper* No. 160.

Milankovitch, M. 1941. Kanon der Erdbestrahlung und seine Anwendung auf das Eiszeitenproblem. Belgrade, Royal Serbian Academy. (Special Publication No. 133.)

Moran, S.R., *and others*. 1980. Glacier-bed landforms of the prairie region of North America, by S.R. Moran, L. Clayton, R.L. Hooke, M.M. Fenton, and L.D. Andriashek. *Journal of Glaciology*, Vol. 25, No. 93, p. 457-76.

Morland, L.W., *and* Boulton, G.S. 1975. Stress in an elastic hump: the effects of glacier flow over elastic bedrock. *Proceedings of the Royal Society of London*, Ser. A, Vol. 344, No. 1637, p. 157-73.

Nye, J.F. 1973. Water at the bed of a glacier. *Union Géodésique et Géophysique Internationale. Association Internationale d'Hydrologie Scientifique. Commission de Neiges et Glaces. Symposium on the Hydrology of Glaciers, Cambridge, 7–13 September 1969*, p. 189-94. (Publication No. 95 de l'Association Internationale d'Hydrologie Scientifique.)

Peltier, W.R. 1980. Models of glacial isostasy and relative sea level. (*In* Walcott, R.I., *ed. Dynamics of plate interiors*. Washington, DC, American Geophysical Union, p. 111-28.)

Penck, A., *and* Brückner, E. 1909. *Die Alpen im Eiszeitalter*. Leipzig, Chr. Herm. Tauchnitz.

Powell, R.D. 1983. Glacial-marine sedimentation processes and lithofacies of temperate tidewater glaciers, Glacier Bay, Alaska. (*In* Molnia, B.F., *ed. Glacial-marine sedimentation*. New York, Plenum Press, p. 185-232.)

Prest, V.K. 1968. *Glacial map of Canada. Map 1253A*. Ottawa, Geological Survey of Canada.

Robin, G. de Q. 1976. Is the basal ice of a temperate glacier at the pressure melting point? *Journal of Glaciology*, Vol. 16, No. 74, p. 183-96.

Röthlisberger, H. 1972. Water pressure in intra- and subglacial channels. *Journal of Glaciology*, Vol. 11, No. 62, p. 177-203.

Ruddiman, W.F. 1977. Late Quaternary deposition of ice-rafted sand in the subpolar North Atlantic (lat. 40° to 65°N). *Geological Society of America. Bulletin*, Vol. 88, No. 12, p. 1813-27.

Saunderson, H.C. 1975. Sedimentology of the Brampton esker and its associated deposits: an empirical test of theory. (*In* Jopling, A.V., *and* McDonald, B.C., *eds. Glaciofluvial and glaciolacustrine sedimentation*. Tulsa, OK, Society of Economic Paleontologists and Mineralogists, p.

155-76. (Special Publication No. 23.))
Shackleton, N.J. 1967. Oxygen isotope analyses and Pleistocene temperatures re-assessed. *Nature*, Vol. 215, No. 5096, p. 15-17.
Shackleton, N.J., *and* Opdyke, N.D. 1973. Oxygen isotope and palaeomagnetic stratigraphy of equatorial Pacific core V28–238: oxygen isotope temperatures and ice volumes on a 10^5 and 10^6 year scale. *Quaternary Research*, Vol. 3, No. 1, p. 39-55.
Shaw, J. 1983. Drumlin formation related to inverted melt-water erosional marks. *Journal of Glaciology*, Vol. 29, No. 103, p. 461-79.
Shilts, W.W. 1982. Quaternary evolution of the Hudson-James Bay region. *Naturaliste Canadien*, Vol. 109, No. 3, p. 309-32.
Sissons, J.B. 1979. *Scotland*. London, Methuen.
Smalley, I.J., *and* Unwin, D.J. 1968. The formation and shape of drumlins and their distribution and orientation in drumlin fields. *Journal of Glaciology*, Vol. 7, No. 51, p. 377-90.
Smith, N.D., *and others*. 1982. Comparison of sedimentation regimes in four glacier-fed lakes in western Alberta, by N.D. Smith, M.A. Venol, and S.K. Kennedy. (*In* Davidson-Arnott, R., *and others, eds. Research in glacial, glacio-fluvial and glacio-lacustrine systems. Proceedings of the Sixth Guelph Symposium on Geomorphology, 1980. Edited by R. Davidson-Arnott, W. Nickling, and B.D. Fahey*. Norwich, Geo Books, p. 203-38.)
Sollid, J.L., *and* Sørbel, L. 1975. Younger Dryas ice-marginal deposits in Trøndelag, central Norway. *Norsk Geografisk Tidsskrift*, Bd. 29, Ht. 1, p. 1-9.
Souchez, R.A., *and* Lorrain, R.D. 1978. Origin of the basal ice layer from Alpine glaciers indicated by its chemistry. *Journal of Glaciology*, Vol. 20, No. 83, p. 319-28.
Sugden, D.E. 1978. Glacial erosion by the Laurentide ice sheet. *Journal of Glaciology*, Vol. 20, No. 83, p. 367-91.
Sugden, D.E., *and* John, B.S. 1976. *Glaciers and landscape; a geomorphological approach*. London, Edward Arnold.
Syvitski, J.P.M., *and* Blakeney, C.P. 1983. Sedimentology of Arctic Fiords Experiment: HU82–031 data report. *Canadian Data Report of Hydrography and Ocean Sciences*, No. 12.
Tarr, R.S., *and* Martin, L. 1914. *Alaskan glacier studies*. Washington, DC, National Geographical Society.
Weertman, J. 1961. Mechanism for the formation of inner moraines found near the edge of cold ice caps and ice sheets. *Journal of Glaciology*, Vol. 3, No. 30, p. 965-78.
White, W.A. 1972. Deep erosion by continental ice sheet. *Geological Society of America. Bulletin*, Vol. 83, No. 4, p. 1037-56.
Whittlesey, C. 1868. Depression of the ocean during the ice period. *Proceedings of the American Association for the Advancement of Science*, Vol. 16, p. 92-97.
Woldstedt, P. 1958. *Das Eiszeitalter. Bd. 2.* Stuttgart, Ferdinand Enke.
Zeuner, F.E. 1959. *The Pleistocene period; its climate, chronology and faunal successions*. London, Hutchinson.