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SUB–ZONAL SCALE

CHAPTER FOUR

# The Glacier System

Glacier-covered areas comprise one of the three sub-zonal environmental systems within the polar regions (Figure 1.3). The presence or absence of glaciers in any area reflects the interaction of the world-scale systems of plate tectonics and climate. It is important to understand the basic distribution, character and behaviour of glaciers if one is to appreciate the nature of this particular environment. Furthermore it is important to understand the way in which glaciers impinge upon and constrain other systems, in particular the marine and tundra environments and human activities. This chapter aims to discuss both the glacier system *per se* and the ways in which it interacts with other systems. The structure of the chapter is outlined graphically in the flow diagram in Figure 4.1.

## Glaciers in the polar regions

Glaciers cover some 99 per cent of the land area in Antarctica, and this represents by far the greatest amount of glacier-covered land area in the world (Table 4.1). The main exceptions are high mountain peaks which project as nunataks above the ice surface and isolated 'oases' of ice-free ground such as that of the McMurdo dry valley area. In the Arctic glaciers are much more limited in their distribution (Figure 4.2). Apart from the overwhelmingly important Greenland ice sheet, Arctic glaciers are mainly restricted to the eastern uplands of the Canadian Arctic, and the maritime islands and peninsulas off northwestern Eurasia, for example, Svalbard, Franz Josef Land, northern Novaya Zemlya and Severna Zemlya. Outside these areas glaciers occur in isolated uplands such as the Romanzof Mountains of the Brooks Range in northeastern Alaska and some mountains in eastern Siberia, but they are very limited in areal extent. Glaciers in the Arctic are restricted today when compared to their maximum extent which is thought to have been approached on several occasions in the last few million years (Figure 4.2).

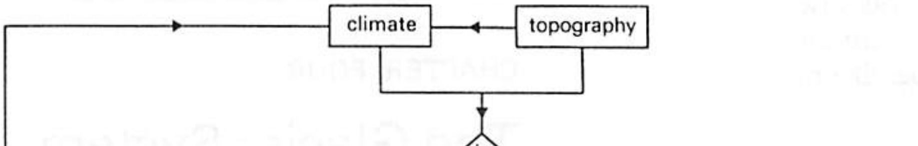

FIGURE 4.1 The glacier system (heavy boxes) and some interrelationships with other natural and human systems.

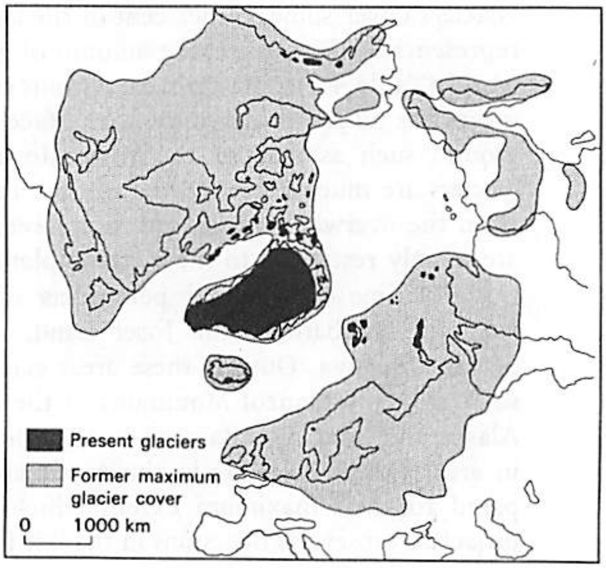

FIGURE 4.2
The current distribution of glaciers in the Arctic and areas formerly covered by glaciers in the Cenozoic.

TABLE 4.1 *Present-day glacier extent in the polar regions (after Flint, 1971)*

| *Region* | *Area* (km²) | *Totals* |
|---|---|---|
| South polar region | | |
| Antarctic ice sheet (excluding shelves) | 12 535 000 | |
| Other antarctic glaciers | 50 000 | |
| Sub-antarctic glaciers | 3 000 | |
| | | 12 588 000 |
| North polar region | | |
| Greenland ice sheet | 1 726 400 | |
| Other Greenland glaciers | 76 200 | |
| Canadian archipelago | 153 169 | |
| Svalbard | 58 016 | |
| Other arctic islands | 55 658 | |
| | | 2 069 443 |
| POLAR TOTAL | | 14 657 443 |
| WORLD TOTAL | | 14 898 320 |

Perspective on the reasons for the distribution of present-day glaciers comes from consideration of the nature of glaciers. In mid and high latitudes a glacier builds up when summer temperature conditions are incapable of removing the previous winter's snowfall. If the snow collects year by year it will accumulate and undergo a change to glacier ice. The term 'firn' is used to describe any snow which has begun this transformation and survived one summer season. Generally it consists of loosely packed ice crystals with interconnecting air passages. When consolidation has proceeded sufficiently to isolate the contained air into separate bubbles the firn becomes *glacier ice*. In cold conditions such as at Plateau Station in Antarctica this transformation does not take place until a depth of 160m is reached and this represents a period of time of around 3 500 years (Gow, 1971). In areas of warmer summers where melting occurs the transformation takes place in a matter of years. In continental arctic climates the winter snowfall may be completely melted but the meltwater freezes on to the underlying cold glacier surface to form what is termed superimposed ice; in these cases the transformation may be completed within a year.

The relationship between winter precipitation and the amount of summer melting suggests reasons for the distribution of glaciers in the polar regions. Conditions favourable for glacier survival are low summer temperatures and/or high winter snowfalls (Figure 4.3).

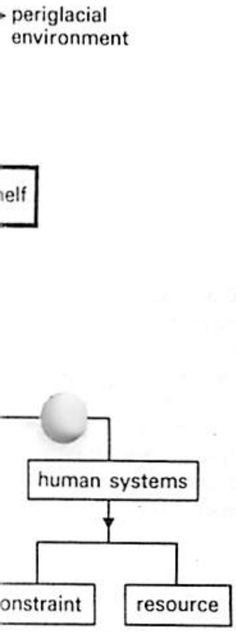

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FIGURE 4.2
The current distribution of glaciers in the Arctic and ar ormerly overe y glaciers in the Cenozoic.

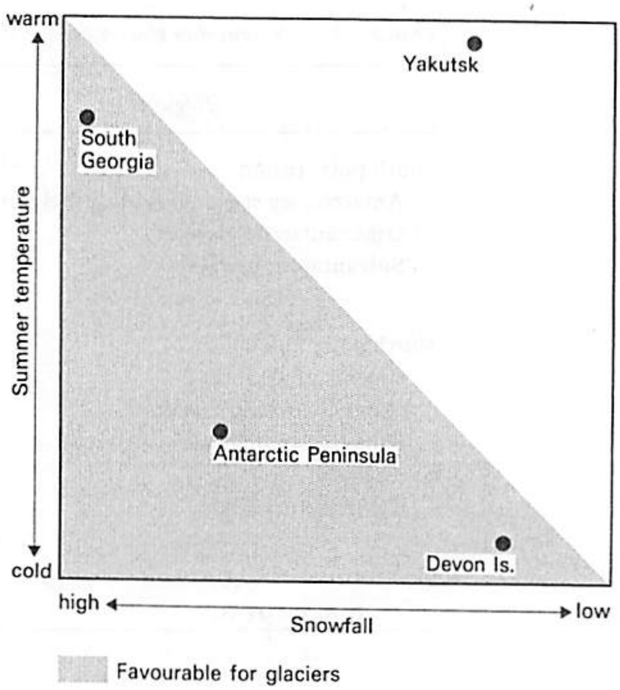

FIGURE 4.3
Diagram to illustrate the suitability of different environments for glaciers in terms the two main variab high winter snowfall and low summer temperatures.

Summer temperatures reflect a latitudinal decline in solar radiation towards the poles as well as a decline from continental interiors towards maritime coasts. Superimposed on this any increase in elevation will lead to a lower than normal summer temperature. Thus from a temperature standpoint glaciers are most favoured at high latitudes and in the coastal areas of polar continents, particularly where there are upland areas. High winter snowfalls reflect proximity to both oceans and the storm tracks of mid-latitudes. Thus once again continental margins in cool temperate latitudes are favourable for glacier build-up, especially if they are elevated, while continental interiors which are remote from winter storm tracks are unfavourable. The distribution of glaciers in the Arctic neatly illustrates these generalizations. Most glaciers are on uplands and close to ice-free oceans and winter storm tracks (Hattersley-Smith, 1974). This is most clear in the case of the Atlantic borders and the decline in glacier activity with increasing distance from the open oceans is relatively gradual. This is particularly true of the northern coast of Eurasia which is a favoured track for winter storms. In the case of the Pacific the change is more abrupt. Whereas the cordillera of southern Alaska support many glaciers, litt precipitation penetrates over the mountains into northern Alaska and thus the high Brooks Range is largely free of glaciers. The least favour-

FIGURE 4.3 Diagram to illustrate the suitability of different environments for glaciers in terms of the t[illegible]ain variables: high winter snowfall and low summer temperatures.

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The least favourable place for glaciers is the Yakutsk area of Siberia where winter snowfall is light (because of low temperatures and distance from storm tracks) and summer temperatures are high. In the Antarctic, glacier cover reflects extremely low summer temperatures which are incapable of melting the winter snowfall, however scanty it may be, as well as proximity to an ocean and storm tracks. In this context it is interesting to consider that extensive glaciation of the Antarctic is thought to have occurred only when the split of Australia from Antarctica, and later the breaching of Drake Strait, favoured an intense westerly circulation and associated storm activity (Chapter 7).

Glaciers are dynamic features of the Earth's surface which flow, and it is this characteristic above all else that accounts for their importance as an environmental system. Glaciers flow because ice is a relatively weak solid which deforms under its own weight. If the rock slope is sufficiently steep the glacier will flow down the rock surface by internal deformation and/or sliding. If the rock bed is flattish, then the glacier builds up until its surface slope is sufficiently steep to cause internal deformation and/or basal sliding.

It is useful to conceptualize a glacier as a system. Above a certain altitude, generally conceived of as the equilibrium line altitude, is the glacier accumulation area. Here more snow and ice is accumulated each year than is melted away. Below the equilibrium line is the ablation area where more snow and ice is lost by ablation each year than is received at the surface. If the glacier is to remain in equilibrium and not grow or diminish in size, then the difference must be made up by the transfer of ice from the accumulation area to the ablation area and as a result the glacier flows. Glaciers viewed as systems have been discussed in much more detail elsewhere (Andrews, 1975; Sugden and John, 1976) and interested readers are referred to these sources. However, even the simplified statement given above helps explain several characteristics of glaciers with fundamental implications. The conceptualization emphasizes the link between input and output on a glacier. If the winter precipitation is high, so also must be ablation and the rate of flow if the glacier is to remain in equilibrium. This is the reason why glacier velocities are higher in maritime areas of high precipitation than in continental areas. One can compare, for example, the rate of flow of 3–4 m per year for Meserve glacier in the dry desert environment of Victoria Land, Antarctica (Holdsworth and Bull, 1970) with rates of several hundred metres per year characteristic of glaciers in maritime South Georgia (Figure 4.4) or the extremely high rates of 7–12 km per year in parts of West Greenland (Fristrup, 1966 and Figure 4.5). The need for input to balance output also explains why glaciers with a high accumulation flow into lower, warmer climes in order for ablation to match input; in southern Alaska where snow accumulation rates are very high glaciers may terminate in lush forests. Conversely glaciers with little snow accumulation can end in severe continental climates; in Victoria Land, for example, where there is little melting, there is little snow to melt. If the equilibrium line is at a low altitude or near sea level, there may be insufficient ablation area for the glacier to terminate on land. In these cases the glaciers extend into the sea and the balance of ablation is by calving. This situation occurs round much of the Antarctic continent.

These abstract generalizations become more meaningful if they are linked to specific types of glaciers. Table 4.2 shows a simple morphological classification of glaciers and the functioning of the main types is represented diagramatically in Figure 4.6.

FIGURE 4.4 The snout of Harker Glacier, a fast-moving glacier in South Georgia, Antarctica. Photograph by Gordon Thom.

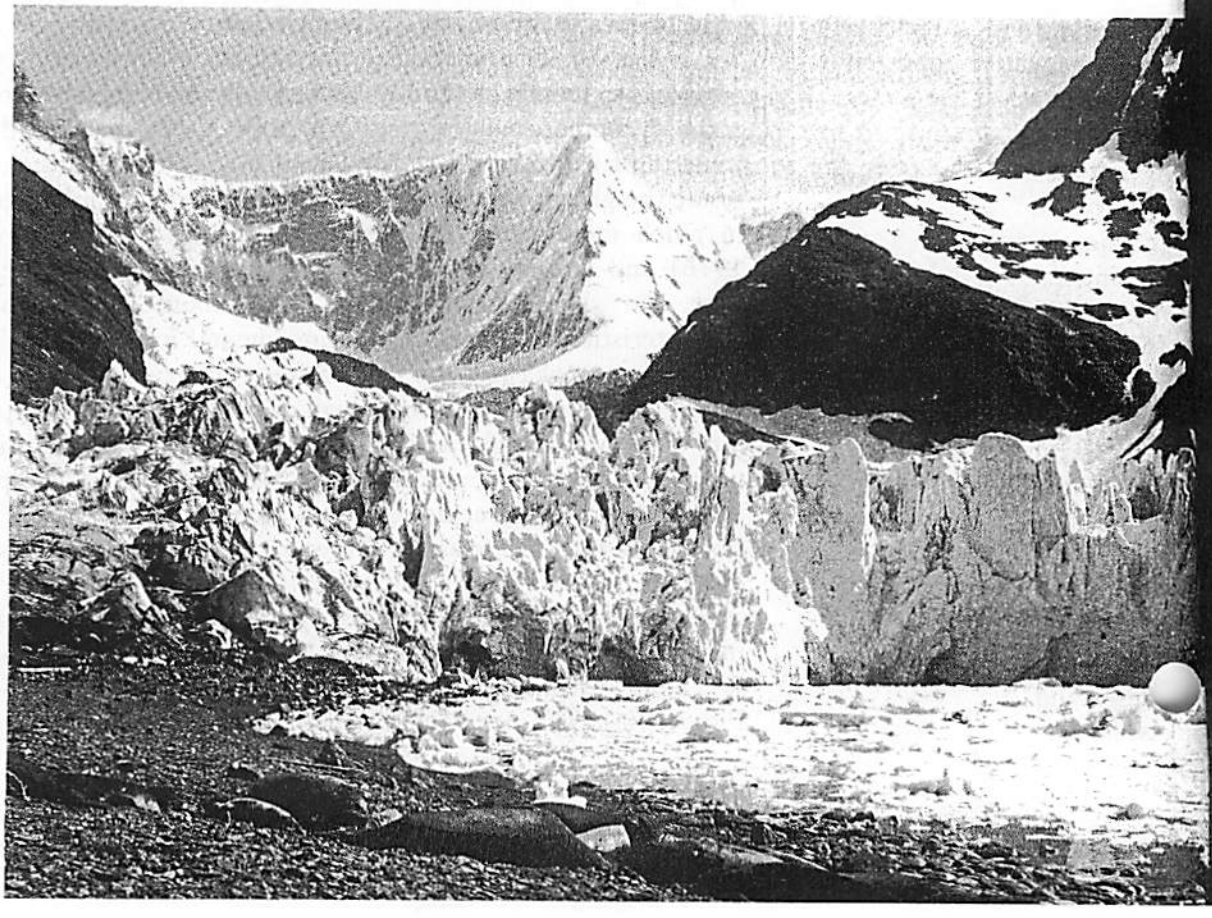

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FIGURE 4.5 The snout of the fast-flowing Rinks Isbrae in West Greenland, calving icebergs and brash ice into the fjord. Reproduced with the permission of the Geodetic Institute, Copenhagen.

TABLE 4.2 *A morphological classification of glaciers (Sugden and John, 1976)*

| | |
|---|---|
| Ice sheet and ice cap (unconstrained by topography) | ice dome<br>outlet glacier |
| Ice shelf | ice shelf |
| Glacier constrained by topography | icefield<br>valley glacier<br>cirque glacier<br>other small glaciers |

### ICE SHEETS AND ICE CAPS

Ice sheets and ice caps build up on a flattish land area and superimpose a roughly radial outflow of ice over the area. The difference between an ice sheet and ice cap is usually accepted as being one of scale. Ice caps are smaller, generally less than 50000km$^2$ in area (Armstrong

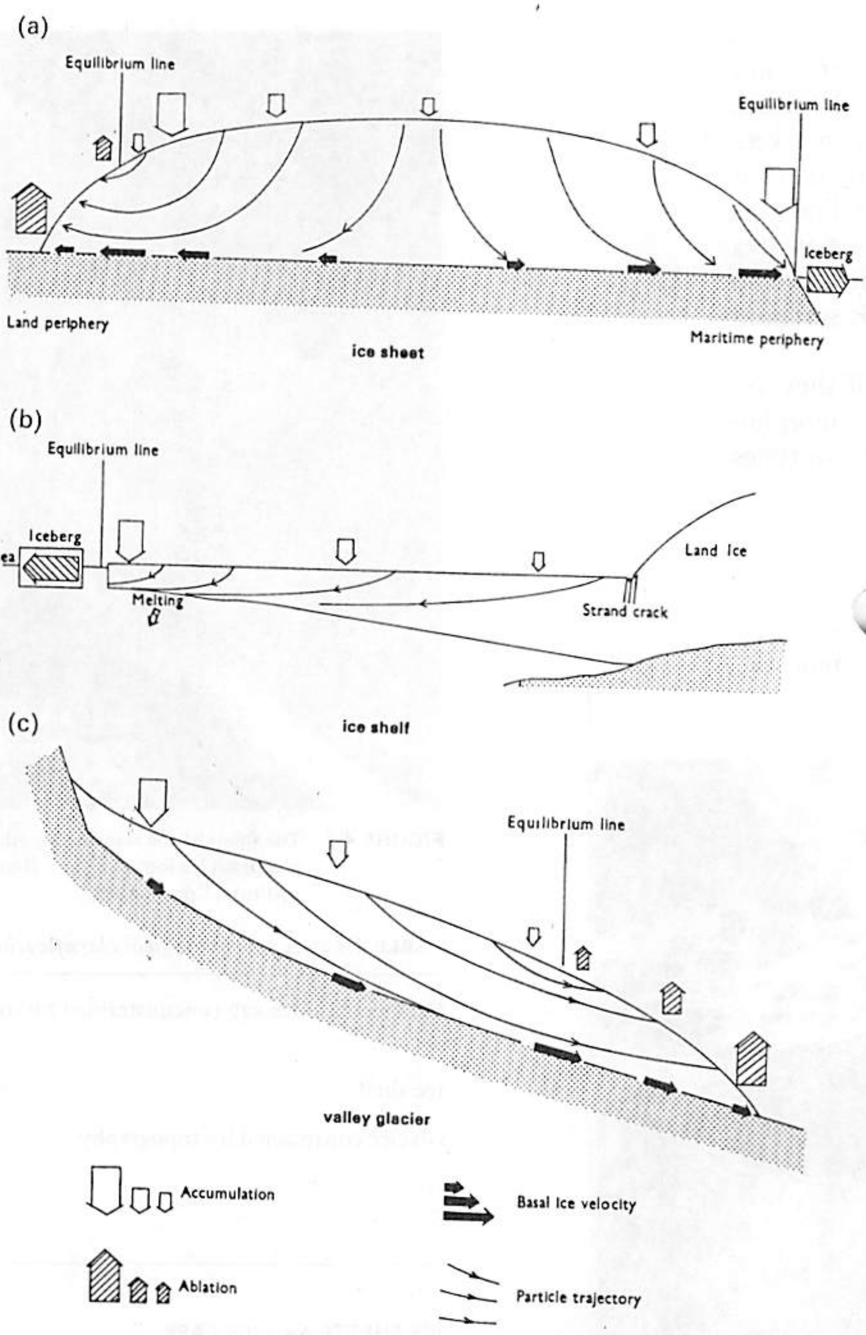
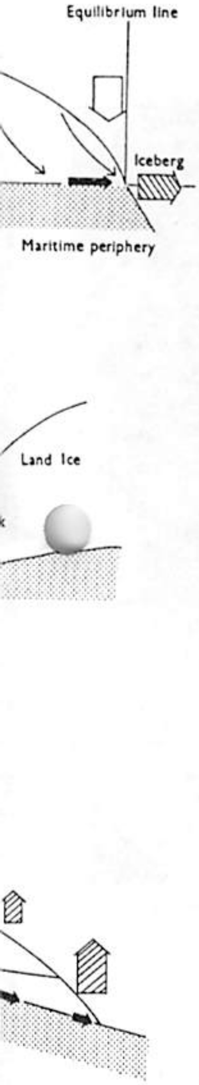


FIGURE 4.6 Models of *(a)* ice sheet *(b)* ice shelf and *(c)* valley glacier, showing the distribution of accumulation and ablation and related flow characteristics. Basal slipping is assumed to occur in models *(a)* and *(c)* and is at a maximum in the vicinity of the equilibrium line. From Sugden and John (1976).

*et al.*, 1973). The main component is an ice dome (Figure 4.7). In East Antarctica the dome reaches an altitude of 4200m (Figure 2.7) while in Greenland it is around 3200m. The domes build up over the underlying relief and may completely submerge mountain ranges and basins with little sign of the achievement on the ice surface. Parts of the Antarctic ice dome are as much as 4300m thick. The overwhelming characteristic of ice domes is the convex-upwards profile with the slope gentlest near the centre and progressively steepening towards the edge. These slopes reflect the underlying flow properties of ice and are consistent from dome to dome at least when the ice is flowing on a rigid rock bed. To give some idea of the slopes involved it is helpful to imagine a continental-sized ice dome beginning at your feet. Ten kilometres distant it would be 450m higher; 50km distant about 960m higher; 100km distant 1400m higher; 500km distant 2700 m higher and 1000km distant 3300m higher. These slopes are characteristic of land-based ice domes (Sugden, 1977). In situations such as West Antarctica where the ice is grounded well below sea level the convex profile is less marked and the ice dome surface is lower.

Figure 4.6a shows the patterns of ablation and accumulation, the trajectory of particles in the ice dome and ice velocities (represented in these models by basal sliding). On domes of continental size precipitation falls off inland with increasing distance from the sea and thus most activity and glacier movement is restricted to the peripheral areas. On smaller ice caps this tendency may not arise. The right-hand side of the ice dome has an equilibrium line at sea level and represents the Antarctic situation. In such a case ice velocities increase towards the coast and calving is the rule. The left-hand side includes an ablation zone which ends on land, as in middle West Greenland. Ice velocities decrease near the margin and the ablation is by melting and creates massive meltwater streams.

Outlet glaciers are a component of the peripheral parts of ice domes and may drain the bulk of ice from the dome. They consists of glaciers constrained by rock walls which may push many kilometres beyond the ice dome margin (Figure 4.8 and also Figure 2.5). Gradients are more gentle than the ice dome (Buckley, 1969) and thus within the dome they form depressions. The best example of this is the 700km long and 50km wide Lambert Glacier which creates a significant depression in East Antarctica (Figure 2.7). An impressive series of outlet glaciers cuts through the Transantarctic Mountains. The Beardmore Glacier, well known from the epic polar journeys of Robert Scott, is one of these and is some 200km long and 23km wide and flows at a velocity of around 1m per day (Swithinbank, 1964). Outlet glaciers



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from the Greenland ice sheet are similar, only they seem to flow at considerably higher velocities. Rinks Isbrae is one of several fast-moving outlet glaciers in West Greenland contributing icebergs to the sea (Figure 4.5).

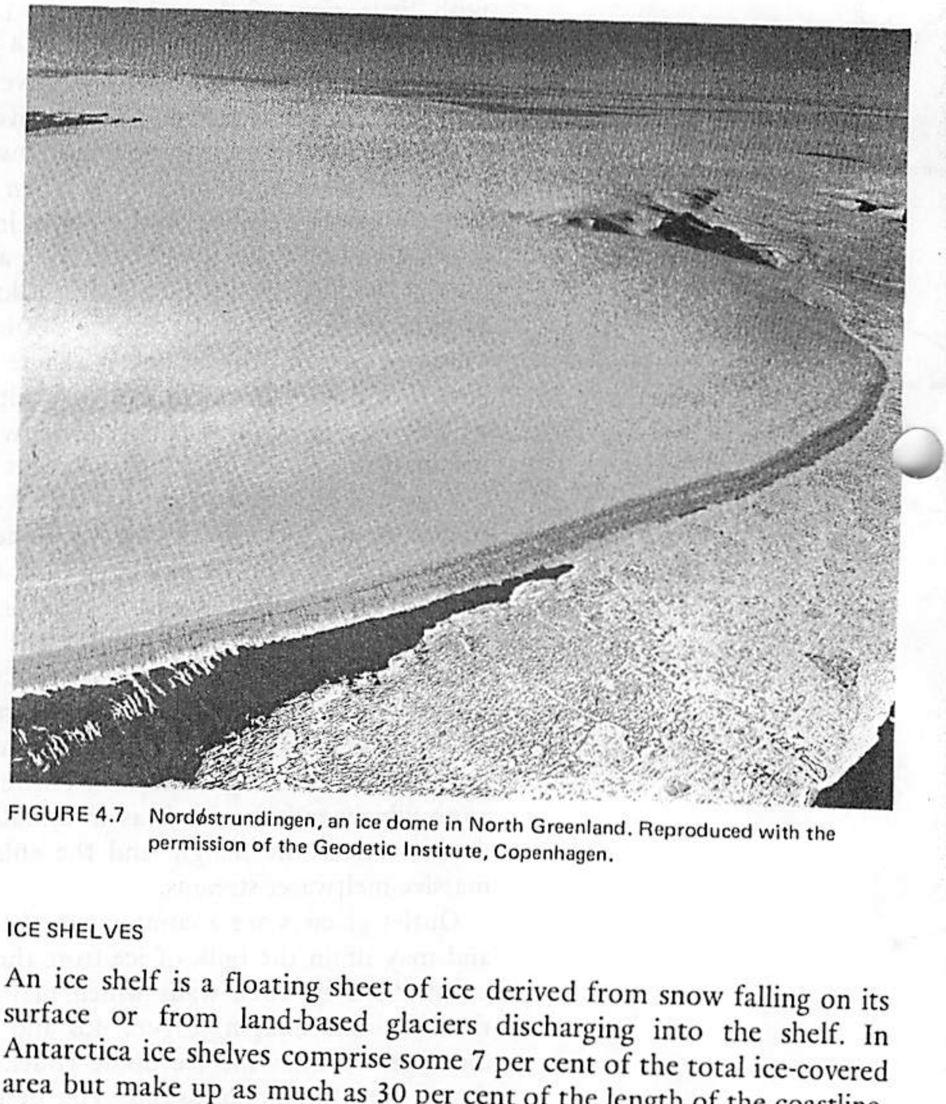

FIGURE 4.7 Nordøstrundingen, an ice dome in North Greenland. Reproduced with the permission of the Geodetic Institute, Copenhagen.

## ICE SHELVES

An ice shelf is a floating sheet of ice derived from snow falling on its surface or from land-based glaciers discharging into the shelf. In Antarctica ice shelves comprise some 7 per cent of the total ice-covered area but make up as much as 30 per cent of the length of the coastline. They occur in embayments in the coastline and the two largest are the Ronne/Filchner Ice Shelf in the Weddell Sea embayment and the Ross Ice Shelf in the Ross Sea embayment. The latter extends some 900 km inland and is some 800 km across. In the Arctic small ice shelves occur along the northern coast of Ellesmere Island (Lyons, Savin and Tamburi, 1971) and in northern Greenland (Figure 4.9).

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FIGURE 4.8 Outlet glaciers draining a small ice dome in the Blosseville Kyst area, East Greenland. Note the medial moraines and surface meltwater streams. Reproduced with the permission of the Geodetic Institute, Copenhagen.

The main characteristics of ice shelves have been clearly described by Swithinbank and Zumberge (1965). The seaward margin forms a sheer cliff which rises some 30 m above sea level. This is the feature that gave the Ross Ice Shelf the name of the Great Barrier. The ice thickness near the cliff is commonly 200 m but may thicken inland to as much as 1000 m. The surface of an ice shelf is virtually flat. The main irregularities are areas of crevassing associated with the hinge line between grounded and floating ice, known as the strandcrack. As tides move the floating ice shelf up and down in relation to the grounded ice there is a great deal of cracking and groaning as ice takes up the stresses.

Some dynamic features of ice shelves are illustrated in Figure 4.6b. Freed of basal friction ice velocities are high and velocities of 0.8–2.8 km per year are common (Swithinbank and Zumberge, 1965). Generally snowfall increases nearer the sea and as a result there is a downward component of movement which is usually accentuated by bottom melting at the ice/sea-water interface (Drewry and Cooper, 1981).

FIGURE 4.9 A floating ice shelf in Osborne Fjord, northern Greenland. The ice shelf ends where the fjord widens and large icebergs have calved off and are surrounded by sea ice. Reproduced with the permission of the Geodetic Institute, Copenhagen.

Periodically, calving removes huge tabular icebergs from the front of the ice shelf (Figure 4.10). The ice islands used as bases by the U.S.A. in the Arctic are derived from the ice shelves of northern Ellesmere Island and Greenland (Figure 4.9), while icebergs up to 144km long have been observed to break away from ice shelves in Antarctica.

## GLACIERS CONSTRAINED BY TOPOGRAPHY

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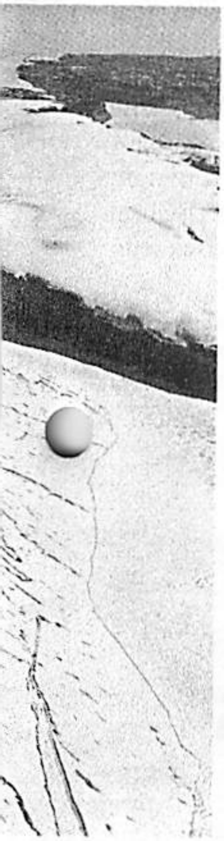

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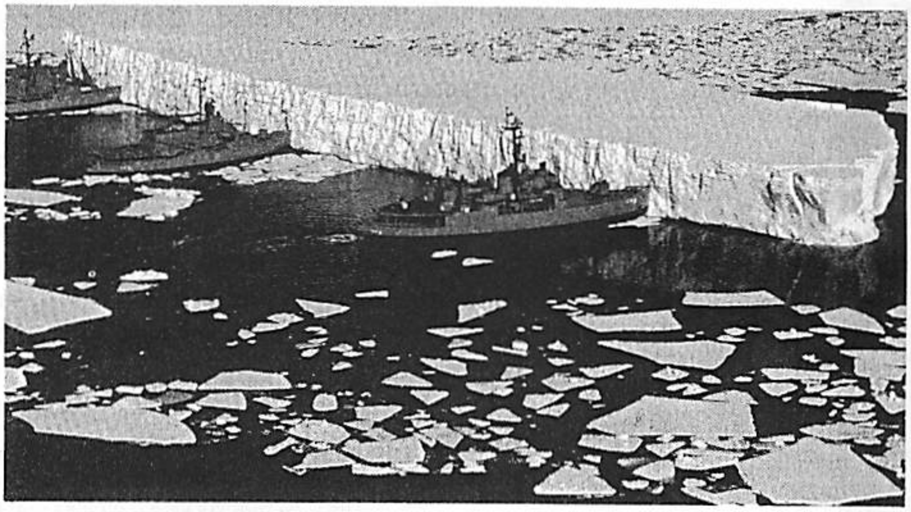

FIGURE 4.10 A tabular iceberg derived from an ice shelf being moved from the approaches to McMurdo Station, Antarctica, by three U.S. ice breakers in 1966. U.S. Navy photograph.

of the underlying ground. They are characteristic of glaciated mountains in the Arctic and those few parts of the Antarctic rising above the ice sheet. In view of their relatively limited extent they do not merit much space here, and readers interested in their more detailed characteristics are recommended to read the illustrated glossary of Armstrong *et al.* (1973), or the detailed inventory of Ommanney (1969).

An icefield is an approximately level area of ice which is distinguished from an ice cap because its surface does not achieve the characteristic domelike shape, and because flow is strongly influenced by the underlying topography. Thin icefields are common on uplands in northern Canada. A valley glacier is characteristic of areas of upland topography where the glacier is overlooked by valley walls. Although such glaciers may approach 100km in length, 10–30km is more common. They extend over a high altitudinal range for their size (Figure 4.6c). This implies a steeply sloping rock bed and a sharp increase in net accumulation with altitude which may be supplemented even further by valley-side snow avalanches. These characteristics, and the fact that flow is confined to a narrow valley, tend to encourage relatively high ice velocities, when compared to the glacier size (Figure 4.4).

Cirque glaciers occupying armchair-shaped hollows are characteristic of marginally glaciated mountains; for example, northeastern Siberia and the Brooks Range. Cirque glaciers are the best known of an amazingly diverse collection of small glaciers which are restricted to characteristic topographic positions. Any importance is due to their scenic impact on a visitor. They may cling to hollows on steep valley sides, form sheets of ice on rock slopes, nestle in irregular depressions, fringe a coastline or occupy a summit only a few square metres in extent. As a generalization such diverse glaciers are more common in maritime polar environments such as that of the northern Antarctic Peninsula where a combination of low sunshine hours, rime ice (supercooled water which freezes to a surface on impact), and high snowfall favour glacier growth in a wide variety of topographic situations (Figure 4.11). In continental climates, small glaciers are restricted to exceptionally favourable topographic situations such as shady cirques.

FIGURE 4.11 A variety of glacier forms on the east coast of Adelaide Island, Antarctica. The U.K. Rothera base is on the point adjacent to the open water in the background. Photograph copyright of the Directorate of Overseas Surveys.

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### Interrelationships between glaciers and other systems

From Figure 4.1 it can be seen that there are numerous ways in which glaciers affect or otherwise constrain other physical and human systems. The links between glaciers and the higher-order systems of climate and plate tectonics are complex. Whereas the obvious role of climate is in providing conditions suitable for glacier growth, there are important feedback mechanisms by which glaciers may influence climate. Most of these operate to accentuate the conditions suitable for glacier growth, and reflect the role of increased albedo and altitude of the earth surface in further diminishing temperatures. This is most dramatically illustrated in the large-scale case of the Antarctic ice sheet, for it seems that the world cooling associated with its growth was a vital factor in allowing the subsequent glaciation and cooling of the Arctic where trees had been growing in northern Baffin Island (Andrews *et al.*, 1972). Furthermore, it is likely that the Greenland ice sheet is self-maintaining. In other words if it was removed overnight it probably would not reform under present climatic conditions (Weidick, 1975). Glaciers may affect climate in the accentuation of the surface temperature inversion and associated low temperatures and katabatic winds.

Recently it has become accepted that glaciers can change climate in other ways. In its more extreme theory the view is that glaciers can self-destruct by crossing some threshold and surging. Extremely high velocities associated with surging over the whole ice sheet would soon lower the ice sheet surface. The view of ice sheet surging first suggested by Wilson (1964) and Hollin (1965) for the whole Antarctic ice sheet, now seems very pertinent to ice sheets which are based on bedrock floors below sea level. Ice sheets like that in West Antarctica are examples, and there are theoretical grounds for believing they are potentially unstable (Weertman, 1974; Hughes, 1975). In a nutshell the ice sheet is analogous to an iceberg which is sufficiently thick to be grounded below sea level. Any rise in sea level or thinning of the ice sheet (for dynamic or climatic reasons) could cause more of the ice to float. This process would accelerate and the whole ice sheet disappear into the ocean in a matter of centuries (Hughes, 1975). The effects on world climate are difficult to predict. Hughes has argued for an overall cooling caused by the greater expanse of ice in the southern ocean. On the other hand the lower altitude and oceanic circulation over what is now West Antarctica could raise world temperatures overall. Such a scenario might seem in the realms of science fiction. However, a comparable event took place only 8000 years ago when the North American ice sheet over Hudson Bay collapsed within a matter of a few centuries

(Andrews and Peltier, 1976). Such an event must have had major climatic implications. There are fears that the high-latitude warming which may result from the increasing amount of carbon dioxide in the atmosphere produced by burning fossil fuels could be sufficient to cause the West Antarctic ice sheet to collapse in the near future (Mercer, 1978a).

The interrelationships between glaciers and other systems is mainly one in which the glaciers provide a constraint on the operation of the other system. This constraint can be viewed as an independent variable and it can play anything from a fundamental to minor role.

The effect of a glacier on plant growth is overwhelming in that nothing but a red alga grows on ice or permanent snow. A very limited exception is forest growing on ice-cored moraine, for example in southern Alaska. On the other hand a supply of meltwater from a glacier during the summer months in drier parts of the tundra is vital in encouraging a rich flora both in density and the number of species represented (Porsild, 1951). Large tracts of glacier form a barrier t plant diffusion and there is a major field of research among botanists into the problems of plant survival in ice-free refuges throughout the Ice Age in the Arctic (Ives, 1974). However, there is a danger in assuming that glaciers are an absolute barrier to plant movement, for several species of plants are found on nunataks in East Greenland surrounded by ice sheet.

Animals are less restricted than plants and Hattersley-Smith (1974) noted, for example, that arctic fox tracks are common on all ice caps and glaciers in northern Ellesmere Island. However, the Greenland ice sheet is a different matter and caribou and musk-oxen on either side of the Greenland ice sheet are independent groups subject to different histories. Caribou and musk-oxen existed side by side in East Greenland in the early years of this century, but caribou were wiped out by a combination of climatic change and hunting. There is no sign of the West Greenland herds replacing the East Greenland herds. As unbelievable as it may seem, arctic foxes have been seen high on the Greenland ice sheet and, indeed, Vibe (1967) has even suggested that they migrate between northeast and northwest Greenland via the ice sheet.

Where glaciers calve into the sea they provide icebergs and smaller ice fragments known as brash ice. The effects of icebergs on the marine system are examined in a subsequent chapter. Here it is sufficient to note that the input is in restricted places. In the Arctic the majority of icebergs are discharged into the seas of western and northwestern Greenland (Figure 4.12). Subsidiary iceberg sources are in the Eas Greenland fjords. All these icebergs are relatively small in that their size have had major -latitude warming carbon dioxide in uld be sufficient the near future

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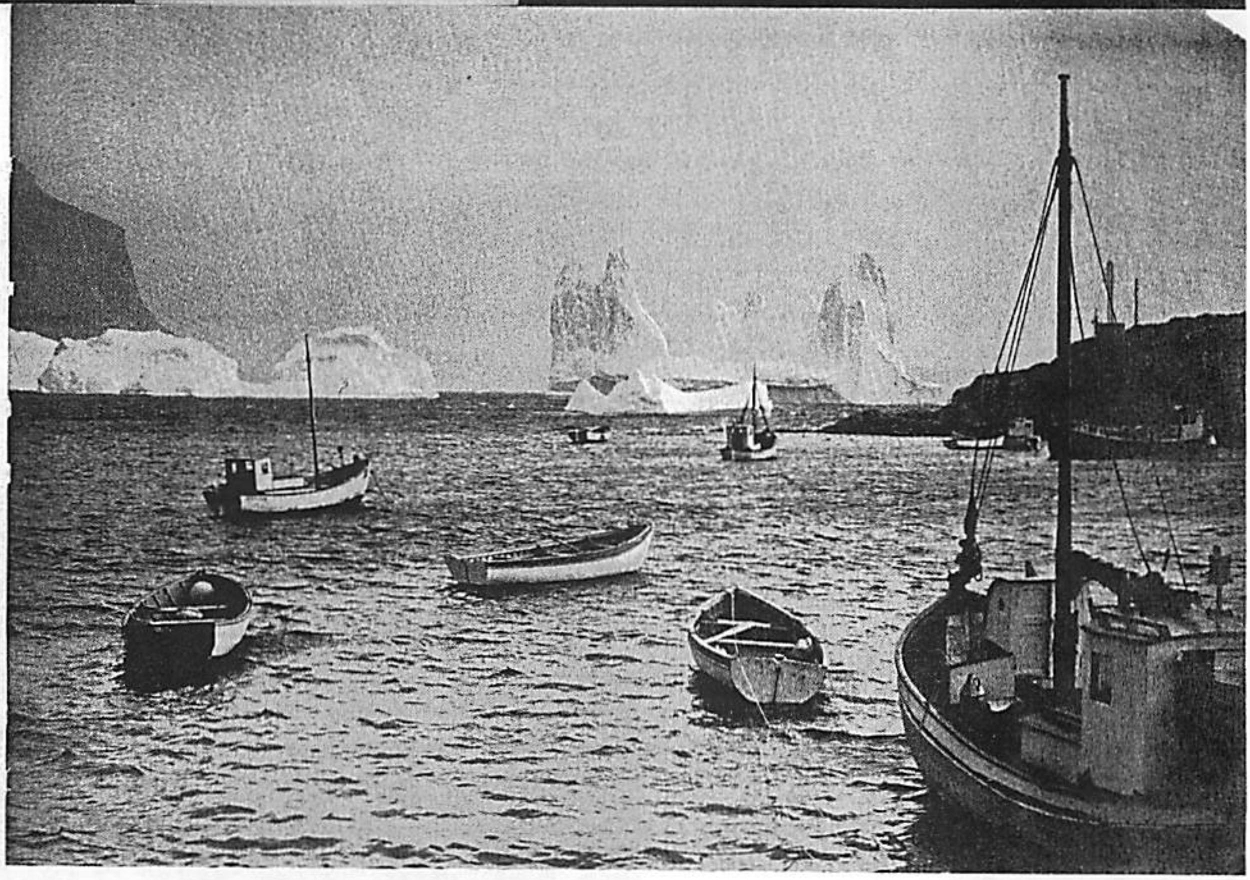

FIGURE 4.12 Icebergs at the entrance of Umanak harbour, West Greenland. Photograph by Valerie Haynes.

is limited by characteristic crevasse patterns on outlet glaciers. Much ice is provided as small fragments. Occasionally an iceberg may measure 1 km across. Ice shelves provide big tabular icebergs. The only sources in the Arctic are in northern Ellesmere Island and Greenland and these have calved the ice islands which may be 32 km long and used by the U.S.A. as Arctic research stations (Koenig *et al.*, 1952). The largest tabular icebergs and the largest supply is in the Antarctic where ice shelves are common (Swithinbank, 1969).

The glacier system has an important effect on several earthbound systems. Where glaciers have extended beyond their present limits in peripheral Antarctica and in much of the Arctic the landscape of today bears many signs of glacial modification. Much of my research in recent years has been devoted to an examination of the characteristics of landscapes of glacial erosion in the Arctic and fuller details can be found elsewhere, for example in Greenland (Sugden, 1974), in Arctic Canada (Sugden, 1977, 1978a) and in Antarctica (Sugden and John, 1976). The crux of this work is that the main landscape features of the formerly glaciated areas of the polar regions can be interpreted

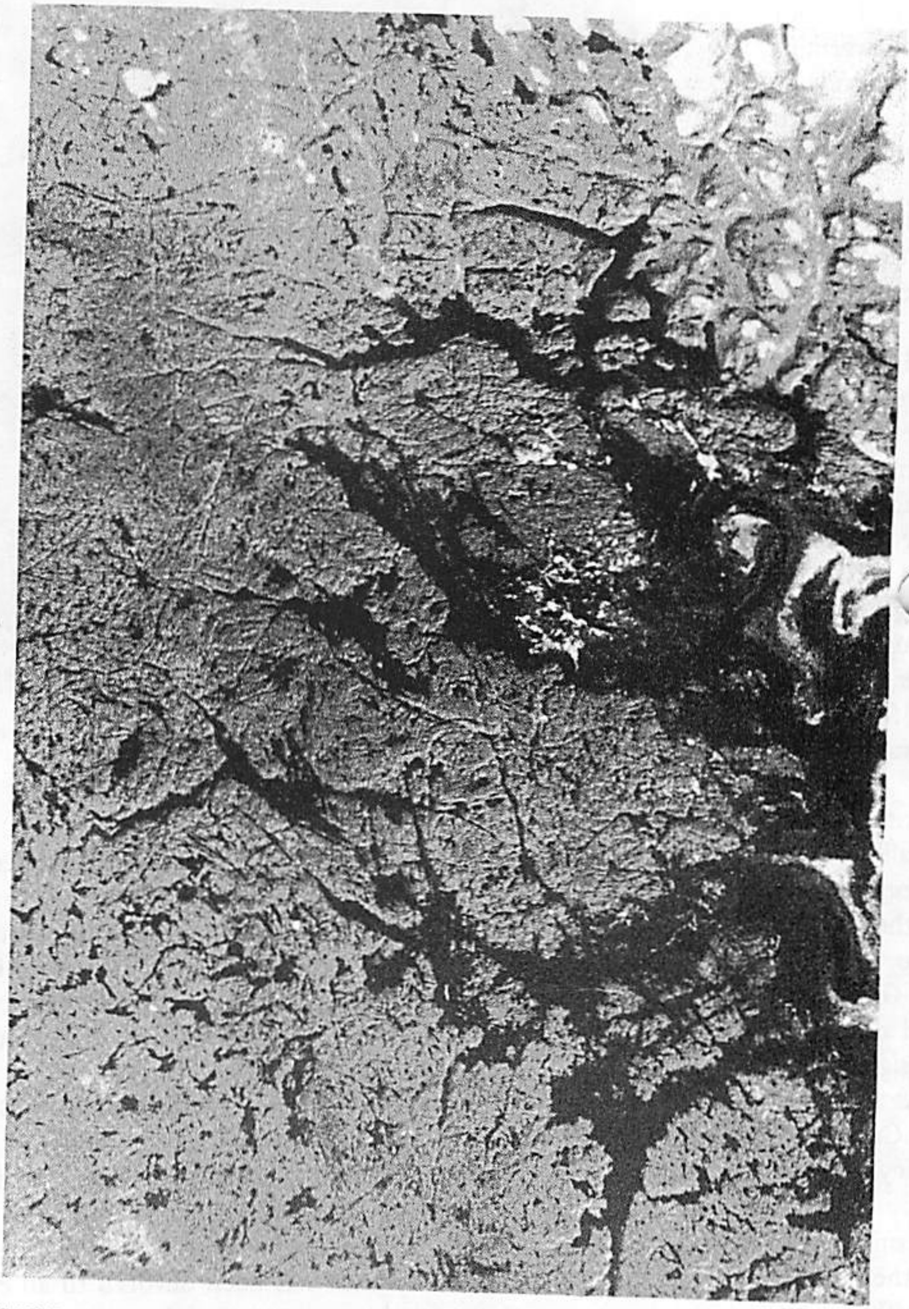

**FIGURE 4.13** Satellite image of ice-scoured shield at the head of Cumberland Sound, Baffin Island, which is typical of a landscape of areal scouring. The lake pattern picks out the structural etching by ice. The area measures 165 km from north (top) to south (bottom). LANDSAT-1, N.A.S.A.

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km from north (top)

in terms of whether there has been modification by glaciers and, if so, what type of modification.

The landscapes may be classified into several types on morphological grounds. Although there is bound to be overlap between the various categories, their recognition does allow some progress to be made in understanding the main processes involved. *Landscapes with little or no sign of glacial erosion* include those areas known to have been covered by ice but which bear no obvious sign of the event; gentle, regolith-covered slopes, river valleys and features such as hill-top tors are characteristic. *Landscapes of areal scouring* everywhere bear signs of glacial erosion (Figure 4.13). Joints, faults and dykes are the master features which are generally eroded to form depressions. In between are upstanding bosses of rocks which are often shaped like roches moutonnées with blocky, craggy, downstream facets and smoothly convex, polished upstream slopes. *Landscapes of selective linear erosion* describe situations where glacial erosion has been confined to the excavation of troughs and where intervening uplands are undisturbed and may support thick regolith and tors (Figure 4.14). Finally, *Alpine landscapes* consist of jagged mountain peaks separated by a network of glacial troughs (Figure 4.15).

The various landscape types may be related to the processes operating at the base of the ice. Landscapes with little or no erosion represent areas where the ice is colder than its melting point and frozen to the bed. Under these circumstances, and provided the ice is free of debris, there is no erosion and the glacier moves solely by internal deformation. Areal scouring is thought to represent glacier sliding, a process which occurs when the basal ice is at the melting point and a film of water may be present. Selective linear erosion represents an intermediate situation where the basal ice over the troughs is at the melting point but where the ice over the intervening uplands is frozen to the bed. Alpine scenery occurs when a mountain massif protrudes above the ice sheet surface and is sculpted by valley glaciers, the common situation in current nunatak areas such as the Ellsworth Mountains in West Antarctica.

Although the above explanation of particular landscape types is merely a hypothesis it does seem to help explain the distribution of the various landscape types, for example in Arctic Canada and coastal Greenland (Figure 4.16). Although there are many variables affecting basal ice temperatures, there are certain generalizations which can be made. Cold-based ice sheets tend to be found in continental climates, especially where the ice is less than around 2 500 m thick. Thus northern Greenland and the northern Canadian archipelago appear to have escaped pronounced modification by ice and pre-glacial fluvial landscapes prevail. Warm-based ice occurs beneath the centre of thick ice sheets and on the maritime peripheries of ice sheets. This accounts for the areal scouring around Hudson Bay and in maritime Labrador as well as for the tendency for areal scouring to be dominant in maritime western Greenland rather than in eastern Greenland. Basal ice temperatures tend to be lower over uplands where ice diverges and higher over depressions where ice converges. This helps to explain the landscapes of selective linear erosion associated with all except the most maritime uplands of Greenland and Arctic Canada. In these areas the ice was cold-based except where it was channelled into fjords. Good Alpine relief in Greenland and Arctic Canada is restricted to uplands which are calculated to have been sufficiently high and sufficiently close to

FIGURE 4.14 Well-preserved plateau remnants immediately adjacent to Nordvest Fjord, East Greenland, which are typical of a landscape of selective linear erosion. An outlet glacier from the Greenland ice sheet calves into the fjord. Reproduced with the permission of the Geodetic Institute, Copenhagen.

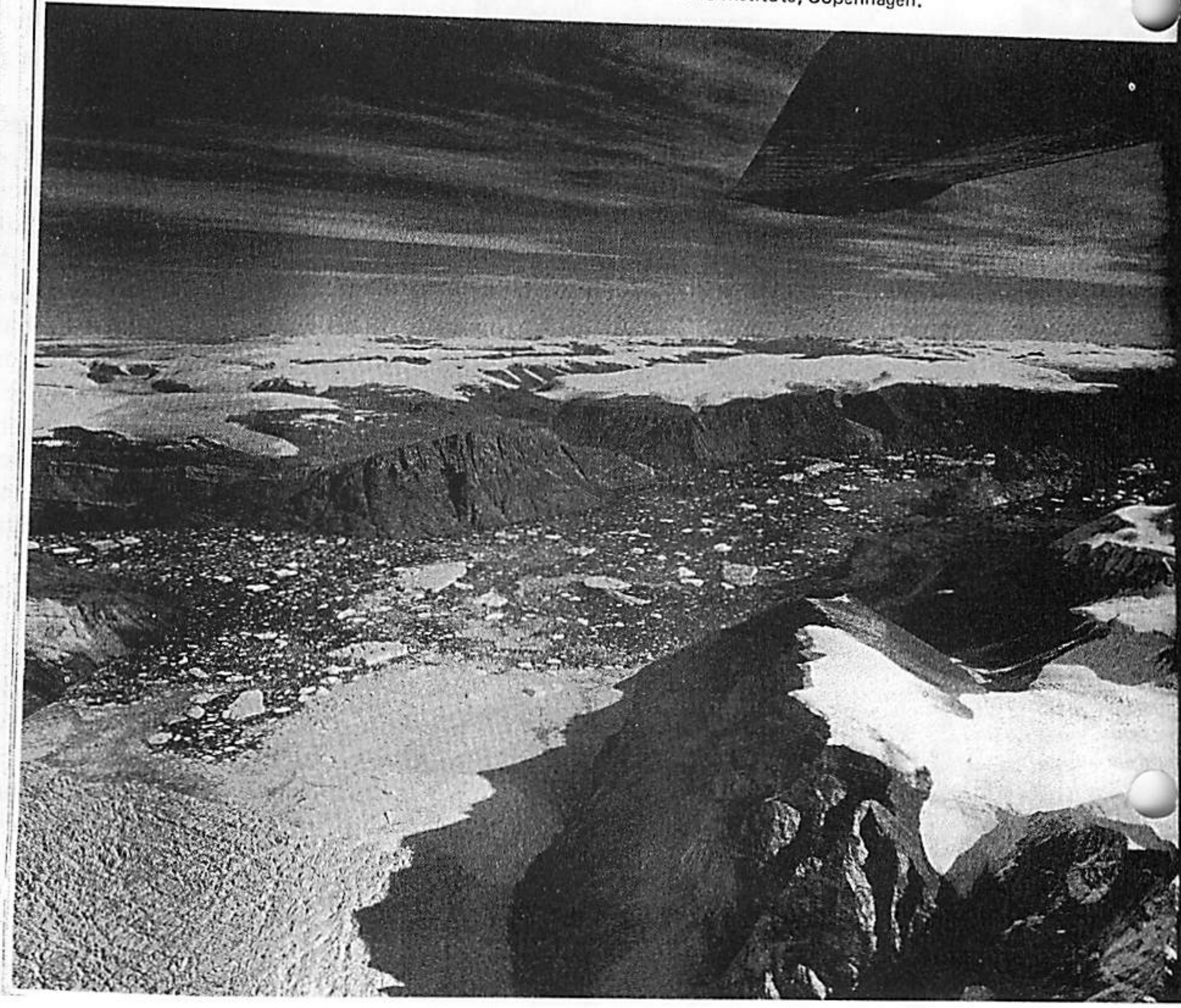

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FIGURE 4.15 An alpine landscape being sculpted by glaciers, Sorte Brae, Blosseville Kyst area, East Greenland. Reproduced with the permission of the Geodetic Institute, Copenhagen.

the ice sheet margin to have risen above the ice sheet profile at its maximum.

In the absence of analysis of the landscapes of glacial erosion in Eurasia, little can be said about their distribution. Superficially one notes the areal scouring characteristic of the shield areas around the Baltic Sea lie beneath the former Scandinavian ice sheet centre. Selective linear landscapes occur in the Sarek uplands of northern Sweden. Areal scouring occurs in the maritime west. One could predict that landscape modification by the ice sheets of continental eastern Siberia would have modified the landscape to a relatively small extent and large areas of little glacial erosion might exist. In Antarctica the coastal margins where ice free are characteristic of areal scouring. This would be expected along a maritime periphery. Selective linear erosion is characteristic of uplands such as the Prince Charles Mountains. Alpine relief occurs on most existing nunataks that rise high above the ice sheet surface.

Landforms of glacial deposition also characterize the Arctic and Antarctic. As one might expect, moraines, zones of drumlin formation, spreads of till and eskers can be common. However, one major characteristic of the Arctic is the sparseness of drift when compared

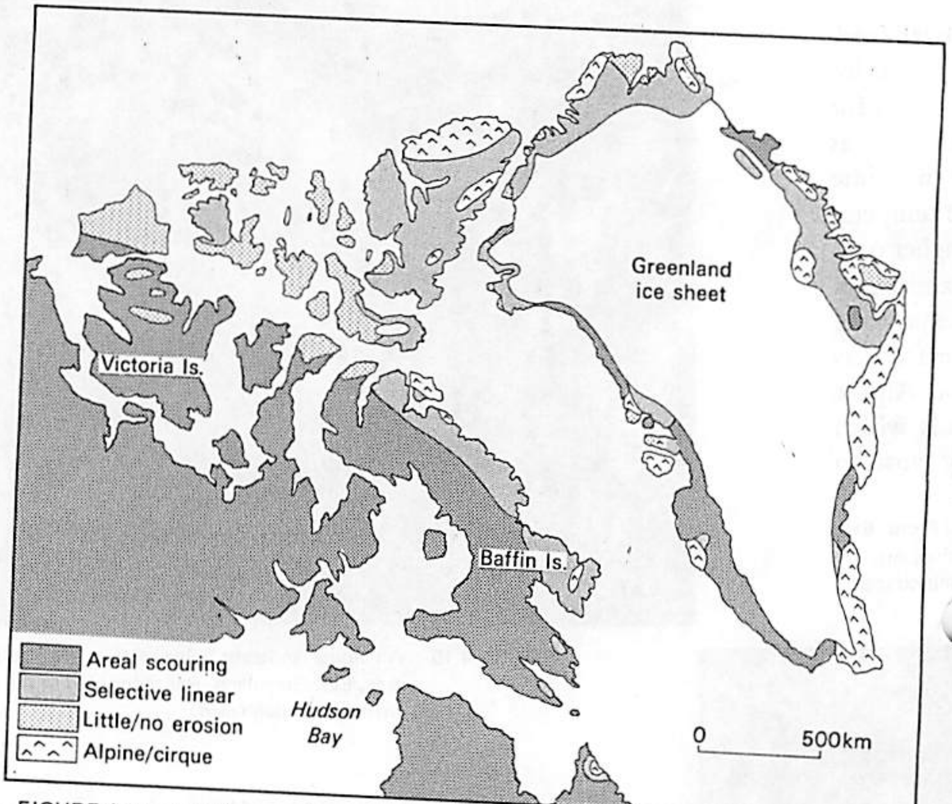
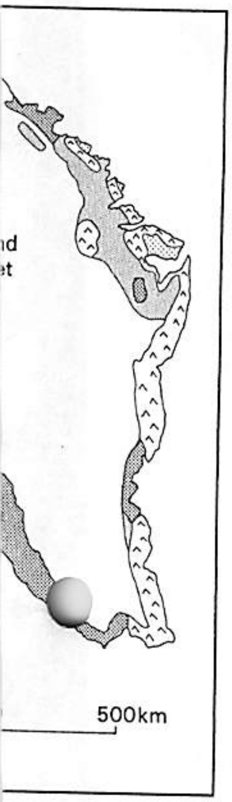


**FIGURE 4.16** Distribution of main types of landscape of glacial erosion in Greenland and Arctic Canada.

to mid-latitude landscapes of glacial deposition. In the Arctic and Antarctic a thin veneer of erratic boulders is characteristic. Depositional landforms are relatively rare, although this is not to deny their often outstanding importance for their size; for example eskers as a source of fill.

Finally, it is worth mentioning the relationship between glaciers and adjacent geomorphological systems. Where glaciers end on land most ablation is by melting and the meltwater is discharged by means of streams. Meltwater streams are highly seasonal. They reach their peak discharge in middle to late summer when meltwater is free to flow off the glacier rather than freeze when it comes into contact with snow or ice below 0°C (as is common in spring and early summer until the glacier surface warms to 0°C). Superimposed on this overall seasonal rhythm there are flood periods with durations of several days, diurnal variations and those lasting only a matter of hours or minutes (Paterson, 1981; Østrem *et al.*, 1967; Ziegler, 1972). There



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are important regional variations in meltwater activity in the polar regions. Meltwater streams are unimportant in the Antarctic, even in Victoria Land, but important in the Arctic where most glaciers end on land. The world's biggest meltwater streams flow from the western edge of the Greenland ice sheet to the sea and are capable of prodigious feats of sediment transport.

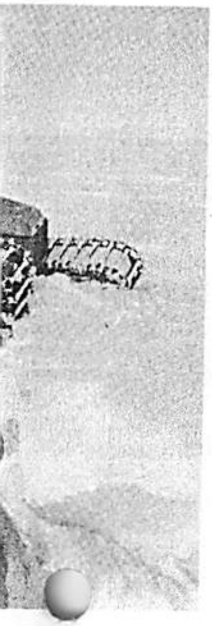
The relationship between glaciers and human systems is apparently so obvious that it hardly bears further consideration. Yet it is helpful to examine how glaciers provide both a constraint and a resource. The dynamic nature of glaciers as surface landforms has a curious two-fold effect. Whereas the existence of uniform surfaces provides one of the easiest land surfaces for travel in the world, it is at the same time one of the most difficult in which to maintain more permanent features such as settlements and physical communications. Given an aeroplane with skis, most of the Antarctic and Greenland ice sheets become accessible for landings. On the other hand a building soon becomes buried by accumulating snow and sinks to uneconomic depths and pressures. The higher the accumulation, the quicker the tendency to sink. Thus a base like Halley near the Antarctic periphery has a potentially shorter life than one near the ice sheet centre, for example the Amundsen-Scott base at the South Pole. Also any permanent base is subjected to horizontal movement as the ice deforms. On ice shelves where annual movement can be of the order of a kilometre or so each year, the lack of a fixed site can become important for various scientific experiments which depend on comparable data from year to year. Furthermore, future projects to drill for oil through ice sheets will find this horizontal displacement a major problem.

Ice surface conditions present special problems for ground travel. Crevasses form when the ice accelerates too quickly for the tension to be taken up by deformation within the ice. Zones of differential flow in steep topography or near ice sheet margins present problems well documented in many expedition accounts. A particularly common problem is the crevassing associated with the acceleration of ice as a glacier floats, for example the strandcrack at the landward edge of an ice shelf. Crevasses in this zone of the Filchner Ice Shelf provided a major obstacle for the Commonwealth Trans-Antarctic Expedition 1956–58 (Figure 4.17), whereas tractor trains passing from the Ross Ice Shelf to Byrd Station relied on a specially prepared, bulldozed track across the strandcrack zone. The morphology and strength of the surface snow is an important constraint on surface movement. Sastrugi, or snow dunes, are hard-packed and play havoc with tractor tracks. Such dunes are most common in windy, peripheral areas of ice sheets

FIGURE 4.17 A sno-cat experiencing crevasse trouble during the course of the Commonwealth Trans-Antarctic Expedition, 1956–58. Reproduced by permission of the British Antarctic Survey.

where katabatic winds prevail. On the other hand, the absence of wind, for example in central East Antarctica, means that the snow pack is soft. Problems of travel in soft snow is one of the reasons why it took the Russians longer than expected to establish Vostók base in central East Antarctica in 1956/57. Other areas to avoid where possible are zones of melting snowpacks such as are common on arctic glaciers in summer. It is a common experience for an expedition to walk up a glacier in summer, starting on bare ice near the snout, and to wade through thigh-deep slush before reaching firmer, unmelted snow in the upper reaches of the glacier.

Ice edges are dynamic environments with their own particular problems. In Antarctica several bases are sited on ice shelves. Periodic collapse of the ice front may present problems for offloading ships' stores, whereas more serious is the problem of the base finding itself on a detached iceberg. One such abandoned base from the Ross Ice Shelf, Camp Michigan, was seen in the side of an iceberg in 1972 (Zumberge, 1974). On land, ice edges present problems if disturbed. One potentially interesting example is the Isua iron ore deposit in southwest Greenland which lies partially beneath the ice edge (Colbeck, 1974). A plan for open-cast mining by removing the ice overburden has been proposed and will involve the removal of around 172 × $10^6$ $m^3$ of



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ice in order to expose the ore. The resultant steepening of the ice edge will accelerate ice flow and a further 7.9 × $10^6$ $m^3$ of ice will need to be removed each year to keep the ice from advancing into the pit. Even if undisturbed an ice edge may advance over the years. Thus an ice-free environment close to a glacier snout is a potentially unreliable site for occupation, although mass balance studies will give some forewarning of a re-advance.

Glaciers in the Arctic and Antarctic provide one very real world resource – fresh water. Nearly 75 per cent of the world's fresh water resources are contained in glacier form in the polar regions (Nace, 1969). The resource is potentially important in two situations. In the Arctic an adequate supply of untainted water is difficult to obtain in liquid form – at least for large centres. Glaciers are compact reservoirs of fresh water conveniently stored in solid form which have yet to be utilized (Hattersley-Smith, 1974). In the Antarctic icebergs derived from ice shelves provide mobile, stable sources of water. The feasibility of transporting these icebergs to desert areas of the southern hemisphere has been the subject of several symposia (Weeks, 1980), and it seems likely that trials may take place in the future.

Glaciers may yet prove to be important resources in other ways other than for their intrinsic scientific interest. The idea of using glaciers for long-term cold storage for food has been mooted (Potter, 1969). Also, and less welcome, was the proposal in the mid-1970s to use the Antarctic ice sheet as a dump for nuclear waste (Zeller, Saunders and Angino, 1973, 1976). The idea is elegant at first sight. The waste is deposited in the middle on the ice surface. By the time it reaches the periphery, *c.* 100000 years later, the waste is no longer radioactive. However, problems could arise if the container is fractured against the rocky bed, because radioactivity could then contaminate basal meltwater which has a much more rapid transit time and could reach the ice sheet edge in a matter of decades.

## Further reading

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