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Notes

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ABSTRACT

The Malaspina Glacier on the southern coast of Alaska is a partial analog of the late Wisconsinan Laurentide Ice Sheet that occupied New England and adjacent areas. Ice lobes of the Malaspina are similar in size to end moraine lobes in southern New England and Long Island. Estimated ablation rates, surface slopes, and meltwater discharge per unit of surface area for the Laurentide Ice Sheet are comparable to measured ablation rates, surface slopes, and meltwater discharge rates for the Malaspina Glacier.

Meltwater moves from the surface of the Malaspina down-glacier and toward the bed of the glacier along intercrystalline pathways and through a series of tunnels. Regolith beneath the glacier, which is eroded and transported to the margin of the glacier by subglacial and englacial streams, is the source of essentially all fluvial and lacustrine deposits on the Malaspina Foreland. By analogy, a similar hydrologic system existed at the southeastern margin of the Laurentide Ice Sheet. Subglacial regolith, which was eroded from beneath the ice sheet by meltwater, was the source of most stratified sediment deposited in New England and adjacent areas during the late Wisconsinan. Similarly, Wisconsinan ice-contact landforms in New England were built by the same processes that are constructing landforms composed of stratified sediments in contact with the Malaspina Glacier. For the Malaspina Glacier and the Laurentide Ice Sheet, therefore, we reject the concept of the "dirt machine" by which debris near the base of the glacier is carried to the surface of the glacier along shear planes and then washed off the surface to form ice-contact stratified deposits.

INTRODUCTION

Recent glacial depositional and erosional processes have been investigated by many authors to understand how stratified Quaternary glacial sediments were deposited. On the basis of this research and our studies of the Malaspina Foreland, Alaska, southern New England, and Long Island (Gustavson, 1974, 1975a, 1975b, 1976; Gustavson and others, 1975; Boothroyd and Ashley, 1975; Boothroyd and others, 1976; Boothroyd and Nummendal, 1978), we argue that the Malaspina Glacier, a temperate, piedmont glacier covering 2,680 km^2 on the northeastern Gulf of Alaska coast (Fig. 1), is a modern analog, at least in part, of the late Wisconsinan Laurentide Ice Sheet that occupied southern New England and adjacent areas (Fig. 2). Both Hartshorn (1952) and Kaye (1960) have suggested similarities between the Malaspina and the southeastern margin of the Laurentide Ice Sheet, but our work establishes both quantitative and qualitative similarities between the Malaspina Glacier and the Laurentide Ice Sheet. Furthermore, our study documents the processes by which landforms on the Malaspina Foreland are being built.

Sources of stratified sediment deposited on the Malaspina Foreland are largely subglacial. Sediment is supplied by subglacial mass movement and fluvial erosion and carried to the ice margin in systems of tunnels (Gustavson and Boothroyd, 1982). Sequences of fluvial and lacustrine sediments, commonly beginning at the ends of tunnel systems, mark where subglacially derived sediments were deposited, or are being deposited, at the margin of the Malaspina Glacier. Similar late Wisconsinan fluvial and lacustrine deposits in New England suggest that depositional processes at the margin of the Laurentide Ice Sheet were analogous to processes observed on the Malaspina Foreland. We argue, therefore, that the Wisconsinan sediments of the Laurentide Ice Sheet were derived mostly from subglacial regolith by subglacial fluvial erosion and mass movement and transported to the margin of the Laurentide Ice Sheet in a series of tunnels.

An alternative concept, called the "dirt machine," envisions that a continuous supply of basal englacial debris moves to the surface or near surface of a glacier by shearing as active ice overrides stagnant ice near the glacier margin (Kaye, 1960; Koteff, 1974; Koteff and Pessl, 1981). Melting at the surface of the glacier causes some of this material to be deposited as superglacial moraine. Meltwater, derived principally from surface melting of live ice, passes through surface and near-surface concentrations of debris and carries entrained sediment to the margin of the glacier, where it is deposited as ice-contact fluvial or lacustrine sediment. Ice-contact faces on late Wisconsinan stratified deposits in New England may exceed 30 m in height, and these landforms are commonly higher in elevation than surrounding bedrock surfaces. According to Koteff and Pessl (1981), the most likely process for constructing these landforms was the transportation of englacial or superglacial debris from the adjacent stagnant ice.

We argue that the "dirt machine" occurs only on a very minor scale and is not a significant part of the process by which sediment is transported to the margin of glaciers such as the Malaspina or the Laurentide Ice Sheet to form stratified deposits.

Ice-marginal stratified sediments are derived primarily from beneath, within, or from the surface of the ice (outwash) or from areas that are not ice-covered, such as valley walls and nunatacks ("inwash" of Evenson and Stephens, 1984,

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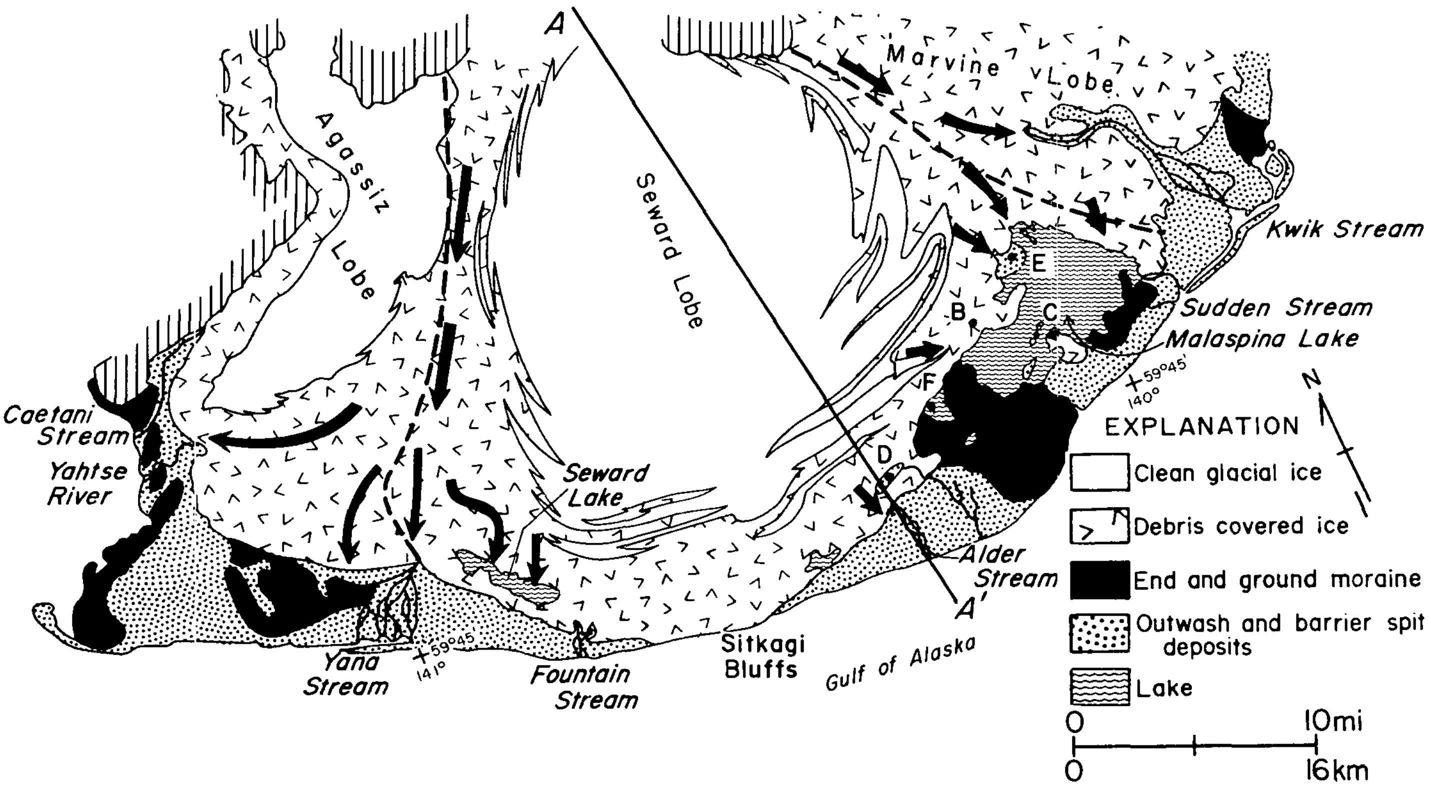


Figure 1. Geologic map of the Malaspina Glacier and surrounding region. A–A′ locates Figure 7. B locates Figure 3. C locates Figure 4. D locates Figure 5. E locates Figure 6. F locates Figure 10. Arrows locate major paths of meltwater movement.

and Evenson and others, 1986). The following discussion of glacial sediment sources and processes of sediment acquisition, however, does not consider the sources of inwash or the processes by which it is acquired, transported, and deposited.

HYDROLOGIC CHARACTERISTICS OF TEMPERATE GLACIERS

Field and laboratory studies completed during the past 35 yr have yielded considerable insight into the movement of meltwater through glaciers that are at, or very near, the pressure-melting point of ice. The hydrologic characteristics of several temperate glaciers are compared with those of the Malaspina Glacier in the following sections.

Recent Temperate Glaciers

Meltwater, which consists of rain and melted ice and snow, enters the glacial hydrologic system by intergranular flow around ice crystals (Nye and Frank, 1973) or by moulins or other surface openings and moves quickly to the bed of the glacier (Behrens and others, 1975). Meltwater moves primarily through a series of englacial or subglacial tunnels (Rothlisberger, 1972; Shreve, 1972; Krimmel and others, 1973; Nye, 1973). The frictional heat, resulting from movement of water and sediment, and water pressure in fully occupied tunnels are sufficient to maintain or increase the size of these conduits (Rothlisberger, 1972).

Subglacial and englacial tunnels have been observed directly and indirectly in a number of valley and outlet glaciers. Analysis of the bedrock floor of a small cirque glacier showed that a nearly continuous, nonarborescent network of cavities and channels covered ~20% of the floor and acted as the primary conduit for meltwater (Walder and Hallet, 1979). Meltwater drains in a main subglacial channel in the Bondhusbreen Glacier that tends to remain open even during periods of low discharge (Wold and Østrem, 1979). In some valley glaciers, subglacial stream courses change frequently, and these changes probably help to entrain sediment stored at the base of the glacier (Vivian, 1977; Collins, 1979; Hooke and others, 1985).

Water-level variations in boreholes in temperate glaciers correlate with changes in recharge rates at the surface of the glacier resulting from diurnal temperature changes, short-term weather changes, and seasonal climatic changes. Increases in borehole water levels in the South Cascade Glacier, Washington, may occur as much as two days after the increase in surface recharge (Hodge, 1976). This suggests a transit time of two days for recharged waters to move to the glacier's bed, reflecting both the length and tortuosity of a glacier's system of conduits (Shreve, 1972).

Streams emerging from the margins of the glaciers are usually highly charged with suspended sediment and carry large bed loads. Suspended sediment in the Gornera, a meltwater stream draining the Gornergletscher, ranged from 0.09 to 1.92 g/l (Collins, 1979a). Suspended-sediment loads carried by meltwater from the Bondhusbreen Glacier were 7,500 and 6,800 t during the summers of 1972 and 1973, respectively. From 1979 to 1981, suspended-sediment discharge from the Bondhusbreen ranged from 4,100 to 5,100 t annually (Hooke and others, 1985).

Few data are available for comparison of bed loads to suspended-sediment loads of meltwater streams, although bed loads of most meltwater streams may exceed by one-third the suspended-sediment loads (Sugden and John, 1976). Suspended-sediment loads account for between 78% and 90% of the total sediment load of sev-

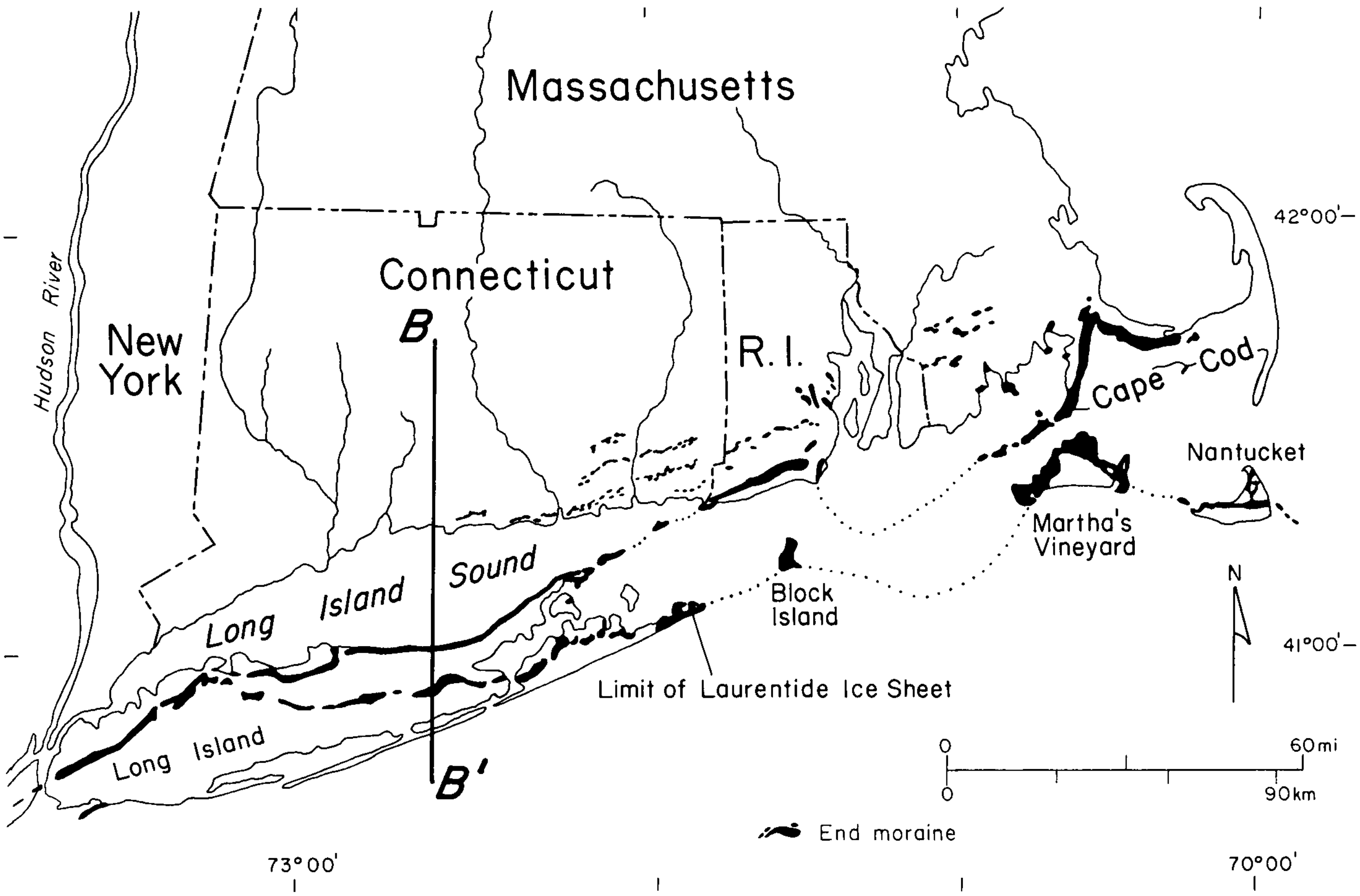


Figure 2. Map showing the distribution of moraines that mark former positions of the Laurentide Ice Sheet as it retreated from southern New England and Long Island during the late Wisconsinan (after Larson, 1982, and Goldsmith, 1982). B–B′ locates Figure 8.

eral proglacial streams draining polar ice on Baffin Island (Church and Gilbert, 1975). In meltwaters draining from the temperate Nigardsbreen Outlet Glacier, Norway, the suspended load amounts to 50% to 70% of the sediment load (Østrem, 1975). Suspended sediment accounts for 44% to 65% of the sediment discharged in meltwater from the Bondhusbreen Glacier between 1972 and 1982 (Hooke and others, 1985).

Malaspina Glacier

Large meltwater streams do not occur on the surface of the Malaspina Glacier and are essentially unknown on the surfaces of other large temperate glaciers in Alaska (for example, Bering Glacier), Iceland (for example, Skeiderajokull), and elsewhere. Recharge enters the hydrologic system of the Malaspina through a variety of pathways. Meltwater was observed entering the near-surface ice through intercrystalline spaces. Large amounts of meltwater also enter deeper into the glacier by more direct routes, including flow into moulins, crevasses, and sinkholes.

Water-volume changes in the Malaspina Glacier, as expressed by changes in meltwater discharge, were measured indirectly by recording changes in the water level of Malaspina Lake, a large ice-contact lake fed primarily by englacial and subglacial discharge (Gustavson and Boothroyd, 1982). Variations in discharge from the Malaspina Glacier are primarily the result of day-to-day and seasonal weather changes. Lake levels rise markedly during the summer melt season in response to precipitation and to periods of warm air temperatures. Lake levels fall during periods of cool dry weather. The time intervals between peak temperature days or rainfall events and peak lake-surface elevations are as long as five days.

Five of the six major streams that drain the Malaspina Glacier arise as fountains at the ice margin, and the sixth drains Malaspina Lake. Smaller fountains, as well as streams discharging from small englacial and subglacial tunnels, also occur along the margin of the glacier. Several large unroofed segments of tunnels containing englacial and subglacial streams were observed as much as 1 km up-glacier from the ice margin. Superglacial eskers, indicating the former presence of englacial tunnels, are exposed as much as 2 km from the ice front and at least 100 m above the floor of the glacier (Fig. 3). Gravel in these eskers and in unroofed streams is evidence that englacial streams carried coarse bed loads and suspended loads high into the glacier. Numerous eskers, showing little evidence of collapse, also occur in recently deglaciated areas near the ice margin and are evidence of a subglacial drainage system (Fig. 4).

Discharge of meltwater from the Malaspina is primarily from fountains at the contact between glacier ice and outwash or from subglacial or englacial streams into ice-marginal lakes (Figs. 5 and 6). Subglacial and englacial tunnels draining the glacier carry large volumes of meltwater (Table 1), and most of the larger tunnels have

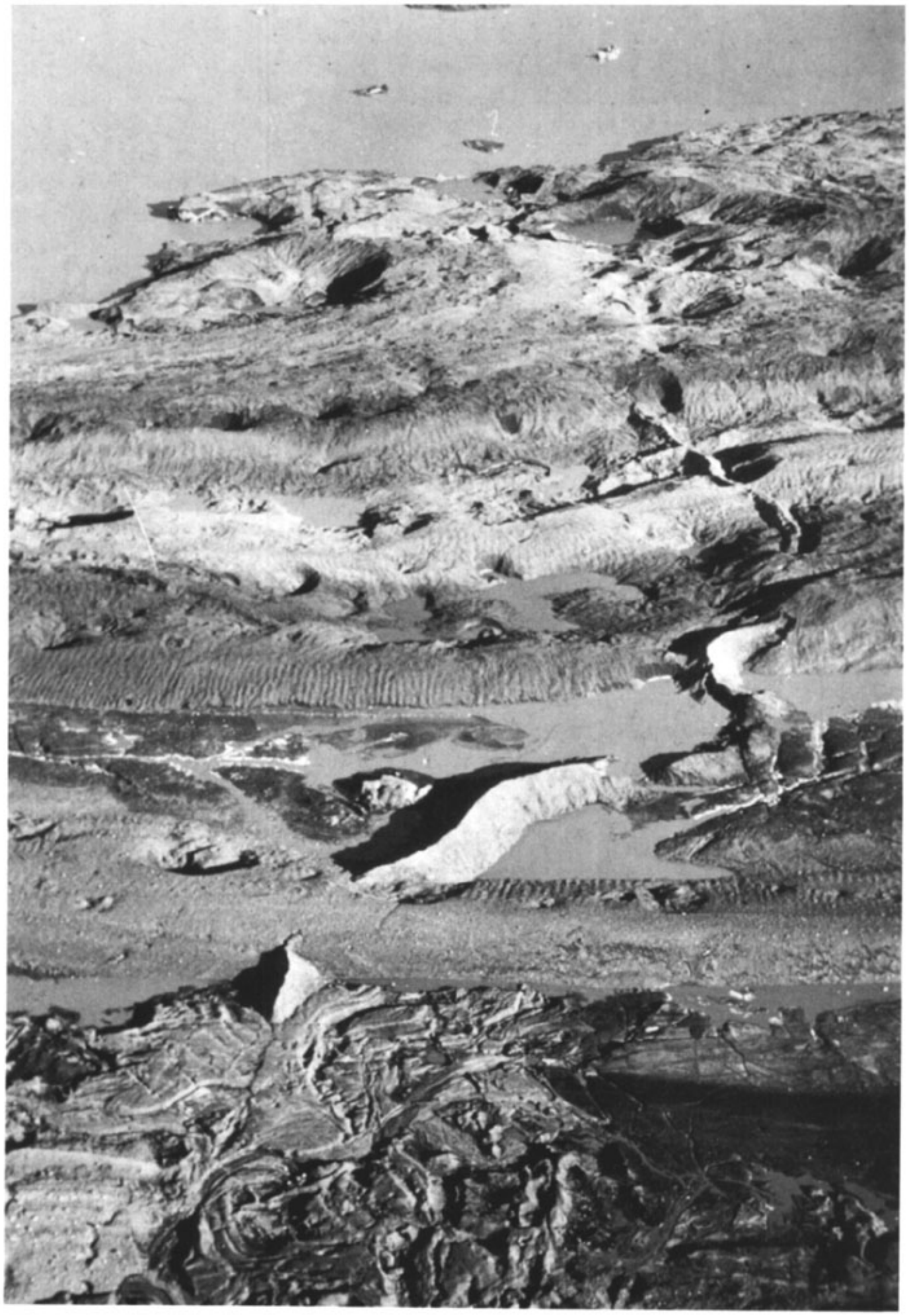


Figure 3. Oblique aerial photograph of the southern margin of Malaspina Glacier at Malaspina Lake. Englacial esker passes into and out of ablation-debris–covered stagnant ice in the middle ground. A superglacial outwash fan has formed in the foreground. Sediment in the outwash fan was supplied by the same tunnel system that was responsible for the esker. Ice thickness is ~100 m beneath the esker. Location of photograph is shown in Figure 1. Esker is ~15 m high. Photograph taken in June 1970.

discharged meltwater from the same outlet for several tens of years. Fountains, which are the present sources of Kwik and Fountain Streams on the Malaspina Foreland, have undergone little change in position since they were first recognized by Tarr and Martin (1914) (Fig. 1). Yana and Alder Streams have also been stable since at least 1970. The fountain source of Yahtse Stream, however, has recently moved 2 km eastward and may have been relocated as much as 10 km since 1891 due to retreat of the Agassiz lobe (Russell, 1893).

Meltwater observed in englacial and subglacial tunnels is highly charged with suspended sediment (Table 2), and the annual suspended-sediment load for meltwater discharged from the Malaspina is ~2,400 ha-m (Gustavson and Boothroyd, 1982). Directly measured bed-load transport data for streams discharging from the glacier are not available, but it is qualitatively clear that transport of bed load is an important process. Estimated annual bed-load discharge of streams draining the Malaspina may be as high as 300 ha-m (Gustavson and Boothroyd, 1982). An ice-contact delta with a surface area of 0.5 km^2 and an estimated volume of 8,000,000 m^3 was deposited by an englacial or subglacial stream in Malaspina Lake in less than 10 yr (Gustavson and others, 1975). Since the last recession of the Malaspina began, between 1700 and 1791, several large fan-deltas consisting of outwash plains and large elongated barrier spits have been built and maintained on the Malaspina Foreland (Plafker and Miller, 1958a, 1958b) (Fig. 1). Numerous chenierlike ridges occur along the coast of the Malaspina Foreland. These features attest to the progradation of the shoreline and indicate that large volumes of bed-load sediment were supplied to the distal margin of the fan-deltas, nourishing the beaches and spits. The proximal ends of these fans are in contact with the margin of the Malaspina, where active fans originate at meltwater fountains. Smaller ice-contact and non–ice-contact fan-deltas have been deposited in ice-marginal lakes.

THE MALASPINA GLACIER: A MODERN ANALOG TO THE SOUTHEASTERN LAURENTIDE ICE SHEET

The Malaspina Glacier is a temperate maritime glacier that is about the size of the state of Rhode Island (~2,680 km^2). Although there are important differences between the Malaspina and the Laurentide glaciers, such as size, many aspects of the Malaspina and its environs are similar to conditions that prevailed during late Wisconsinan time along the southeastern margin of the Laurentide Ice Sheet. These similarities include topography of the bed of the glacier, temperatures of adjacent ocean water, ice temperature, size of ice lobes, ablation rates, surface slopes, meltwater discharge per unit of surface area, and associated ice-disintegration features. Because of these similarities, we believe that the Malaspina is a partial modern analog to at least the southeastern margin of the late Wisconsinan Laurentide Ice Sheet during deglaciation of New England and adjacent areas. In the following sections, these characteristics are compared.

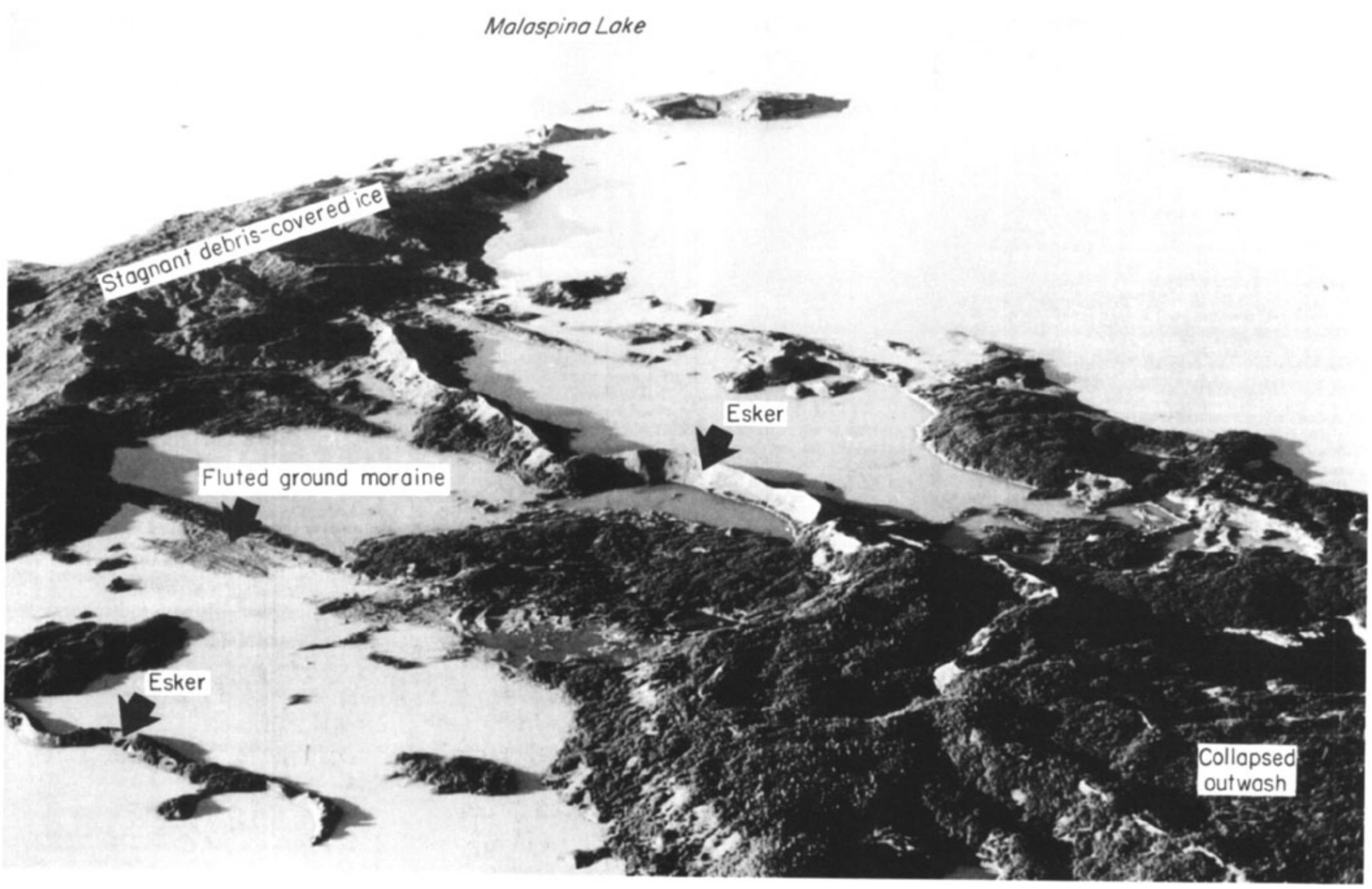


Figure 4. Oblique aerial photograph of a large subglacial esker leading from stagnant ice to collapsed outwash on the southeastern shore of Malaspina Lake. Esker is ~10 m high. Bed load carried by meltwater issuing from a former tunnel, now represented by the esker, fed the outwash plain. Ice-contact faces mark the limits of the collapsed outwash. The presence of fluted ground moraine confirms that both eskers shown in the photograph resulted from sedimentation in tunnels at the base of the glacier. Location of photograph is shown in Figure 1. Photograph taken in June 1970.

Subglacial Topography

The Malaspina Glacier extends locally to the Gulf of Alaska, and the interior of the glacier occupies a topographic basin that is as much as 210 m below present mean sea level (Allen and Smith, 1953). Local subglacial relief along the terminus of the Malaspina exceeds 100 m. In southern New England, the Laurentide Ice Sheet occupied areas of similar local relief as well as a series of topographic basins around the margin of New England, including Long Island Sound, Narragansett Bay, Buzzards Bay, Nantucket Sound, Cape Cod Bay, and Boston Bay.

Ice Temperature

Recent sea-surface temperatures (annual range, 6 to 14 °C) and distribution of zooplankton indicate that subpolar conditions are prevalent in the Gulf of Alaska off the Malaspina

TABLE 1. ESTIMATED ANNUAL MELTWATER AND SUSPENDED SEDIMENT DISCHARGE FROM THE MALASPINA GLACIER, ALASKA

	Area*	×	Mean ablation rate	=	Meltwater volume
Debris-covered ice	0.938×10^{10} m^2		0.394 m/yr*		0.369×10^{10} m^3
Clean ice	1.742×10^{10} m^2		3.937 m/yr*		6.863×10^{10} m^3
Total	2.680×10^{10} m^2				7.232×10^{10} m^3
Internal melting = 0.05 × surface melting*					0.361×10^{10} m^3
Total meltwater					7.593×10^{10} m^3
Total area × (precipitation evaporation†)				=	Available precipitation
2.680×10^{10} m^3 × (3.20 m–0.30 m)				=	7.774×10^{10} m^3
Annual discharge = meltwater + precipitation				=	15.367×10^{10} m^3
Suspended sediment discharge = (annual discharge)				×	(mean suspended sediment concentration)
1.537×10^7 m^3 =	15.367×10^{10} m^3			×	0.001 m^3/m^3§

*Sharp, 1951.
†Department of Commerce, 1969.
§Gustavson, 1973.

Figure 5. Oblique aerial photograph of a series of fountains issuing from the ablation-debris–covered stagnant margin of the Malaspina Glacier north of Alder Stream. Outwash plain is constructed entirely from sediment brought from beneath the glacier by meltwater discharging from the fountains. Note that there are no surface streams on the stagnant ice. Meltwater stream in the foreground is ~15 m wide. Location of photograph is shown in Figure 1. Photograph taken in July 1971.

Foreland (McIntyre and Cline, 1981). There is no evidence of permafrost either in the Malaspina Foreland or beneath the margin of the Malaspina Glacier in areas where we have had access to the glacier bed. A borehole drilled to a depth of 300 m near the middle of the glacier in June 1951 remained open until at least August 1952 (Sharp, 1953). These observations indicate that the Malaspina is a temperate glacier near the pressure–melting point of ice.

Sea-water temperatures (annual range, 0 to 12 °C) during the late Wisconsinan, determined from the distribution of zooplankton, suggest that polar conditions existed off New England (McIntyre and Cline, 1981). The presence of a nearby body of ocean water, even at 0 °C, probably ameliorated winter air temperatures. The few possible ice-wedge casts that have been reported from southern Connecticut and southeastern Massachusetts as of 1983 exhibit none of the structures characteristic of true ice-wedge casts (Black, 1976, 1983). More recently, however, we observed a few additional structures that may represent former ice wedges. Nevertheless, this suggests, at least in low-lying areas along the southeastern margin of the Laurentide Ice Sheet, that climates had warmed enough that permafrost was largely absent during deglaciation. The marine influence and the apparent absence or near absence of permafrost in this area indicate that the southeastern margin of the Laurentide Ice Sheet was a temperate ice mass during deglaciation.

TABLE 2. SUSPENDED SEDIMENT CONTENTS FOR MELTWATER STREAMS, MALASPINA FORELAND, ALASKA

Stream	Range of suspended sediment contents	Number of samples
Alder	1.5–3.5 g/l	5
Fountain	2.5–4.7 g/l	4
Yana	1.1–3.1 g/l	21

Sizes of Glacial Lobes

The Malaspina Glacier consists of three lobes: the Agassiz, Seward, and Marvine. Each of the Agassiz and Marvine lobes is ~20 km wide at its terminus, whereas the Seward lobe is ~54 km wide at its terminus (Fig. 1).

Lobate end moraines, mapped on Long Island, Martha's Vineyard, Nantucket Island, and Cape Cod, indicate that ice lobes in that part of the Laurentide Ice Sheet ranged from 30 to 150 km wide, although most were 30 to 50 km wide (Oldale, 1982; Sirkin, 1982) (Fig. 2). Moraine lobes in eastern Massachusetts and southern Rhode Island range from ~10 to 75 km wide (Stone and Peper, 1982). Morainal segments mapped in Connecticut and Rhode Island suggest that ice sublobes there were typically only 4 to 12 km wide and were probably topographically controlled (Goldsmith, 1982; Oldale, 1986).

Ice-Surface Slopes, Ablation Rates, and Meltwater Discharge

The slope of the ice surface of the Malaspina Glacier is ~14 m/km along A–A′ in Figure 1. Ablation rates for the Malaspina, on the basis of field studies completed between 1945 and 1949, are 3.94 m/yr for clean ice and 0.39 m/yr for areas covered by ablation debris (Sharp, 1951). The amount of water available at the ice surface

Figure 6. Oblique aerial photograph of an englacial stream discharging from the glacier to form a delta at the ice-contact margin of Malaspina Lake near the northeast corner of the lake. The englacial stream that has supplied the sediment that composes the delta issues from a tunnel about 70 m above the floor of the glacier. Crevasse fillings composed of deltaic sediments are preserved in parts of the delta and are forming between blocks of ice in other parts of the delta. Location of photograph is shown in Figure 1. Scale bar is ~1 km. Photograph taken in August 1971.

for discharge from the glacier includes 3.2 m of average annual precipitation in addition to that from ablation. As much as 7.1 m of water per unit area is thus available annually for recharge at the surface of the Malaspina Glacier.

If the slope of the surface and the annual retreat rate of a glacier are known, an estimate of the thickness of ice mass lost annually from the surface can be calculated using simple geometrical relationships. We recognize that profiles of most glaciers approach a parabolic curve, but for the following discussion, we assume a planar surface.

On the basis of the position of end moraines and other features, the estimated slope of the southwestern part of the Laurentide ice surface was probably close to 10 m/km (Matthews, 1972, 1973). Although 10 m/km is less than the slope predicted by the ice-flow theories of Nye (1959) and Hollin (1962), it is a reasonable approximation of the slope of the ice sheet according to Andrews (1973). In the vicinity of the Katahdin esker system in eastern Maine, the slope of the ice surface probably ranged from 4.1 to 11 m/km (Shreve, 1985).

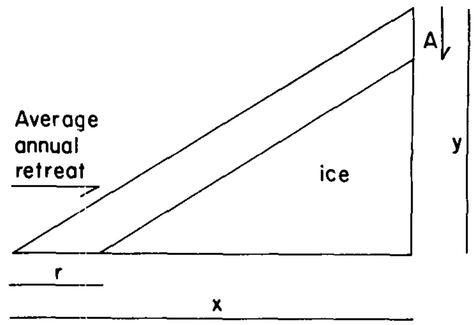
Estimates of the rates of retreat of the southern margin of the Laurentide Ice Sheet are based on a variety of data. A series of ice-sheet profiles illustrating vertical ice-mass losses required for various rates of retreat of the ice sheet were developed by Andrews (1973). He estimated retreat rates of between 100 and 400 m/yr for the southern margin of the ice sheet. Annual retreat rates for the margin of the ice sheet between Martha's Vineyard and Boston, Massachusetts, were estimated as 55 m/yr and as 860 m/yr between Boston and southern Quebec, Canada, using a series of radiocarbon-dated ice-margin positions (Schafer, 1968, 1979). Glacial Lake Hitchcock, which extended 232.5 km along the Connecticut River valley in central New England, existed for no longer than 3,000 yr according to Flint (1956). On the basis of varve counts, however, the lake may have been in existence for 4,100 yr (Antevs, 1922). By using these ages and by recognizing that Lake Hitchcock was in contact with the Laurentide Ice Sheet as it receded (Ashley, 1975), retreat rates can be calculated for the ice sheet in the Connecticut River valley. Based on the estimated ages of Lake Hitchcock, the annual retreat rates of the ice sheet were 58 m/yr or 77 m/yr. Numerical models of Fastook and Hughes (1982) illustrate a retreat rate of ~75 m/yr for much of New England.

On the basis of the foregoing published and calculated rates of retreat and on the basis of suggestions that the marginal gradient of the Laurentide Ice Sheet ranged from 4.1 to 11 m/km, estimates of annual ablation rates for the ice sheet can be made (Table 3). Assuming an ice gradient of 10 m/km, estimated retreat rates suggested by Andrews (1972) require ablation rates of 1 to 4 m/yr, retreat rates calculated by Schafer (1968, 1979) require ablation rates of 0.6 to 8.9 m/yr, and retreat rates in the Connecticut River valley require ablation rates of 0.6 to 0.8 m/yr. Ablation rates estimated in this fashion are minimal rates because the effects of ice advances are ignored.

We assume that the average annual precipitation for the southeastern margin of the Laurentide Ice Sheet was 1.3 m, approximately equal to the recent average annual precipitation depth. Combining ablation and precipitation and considering that the volume of advancing ice, as well as basal melting, has been ignored, we find that meltwater discharged from the Laurentide Ice Sheet was equivalent to a minimum depth of between 1.9 and 10.2 m/yr.

TABLE 3. ESTIMATED ICE SURFACE SLOPES AND ABLATION RATES OF THE LAURENTIDE ICE SHEET

Ablation = retreat rate × slope
(A) = (r) × (y/x)



Estimates of the slope (y/x) of the Laurentide Ice Sheet surface.

	(y/x)
Matthews (1972)10 m/km	
Andrews (1973)	10 m/km
Shreve (1985)	4.1-11 m/km

Estimated annual retreat rates (r) for the southeastern margin of the Laurentide Ice Sheet.

	(r)
Antevs (1922)	58 m/yr
Flint (1956)	77 m/yr
Schafer (1968, 1979)	55-860 m/yr
Andrews (1973)	100-400 m/yr
Fastook and Hughes (1982)	75 m/yr

Calculated ablation rates (A) for published retreat rates (r) assuming an ice surface slope of 10 m/km.

(r)	(A)
58 m/yr	0.6 m/yr
77 m/yr	0.8 m/yr
55-869 m/yr	0.6-8.9 m/yr
100-400 m/yr	1.0-4.0 m/yr
75 m/yr	0.8 m/yr

Ice Disintegration Landforms

Ice along the margin of the Malaspina Glacier is passive to stagnant and covered by 1 to 2 m of ablation material. Flowtill and landforms indicative of deposition in contact with ice are common. These features include collapsed lake deposits, crevasse fillings, collapsed eskers, and collapsed fluvial sediment (Figs. 3 and 4). Some of these landforms, including ice-contact lacustrine and fluvial deposits, are still being constructed (Figs. 5 and 6), and the processes of deposition and of collapse due to melting ice are active.

The Charlestown moraine of southern Rhode Island was described as an ablation moraine derived from the melting of stagnant portions of the Laurentide Ice Sheet that were covered with a thick layer of ablation material (Kaye, 1960). Many other writers, including Jahns (1953) and Hartshorn and Koteff (1967), have mapped landforms originally deposited in contact with glacial ice in southern New England. These features include both collapsed stratified sediment and stratified sediment showing little internal evidence of collapse but having preserved ice-contact surfaces. Landforms of the stagnant margin of the Malaspina Glacier have been suggested as possible modern analogs for the Wisconsinan Charlestown Moraine and other

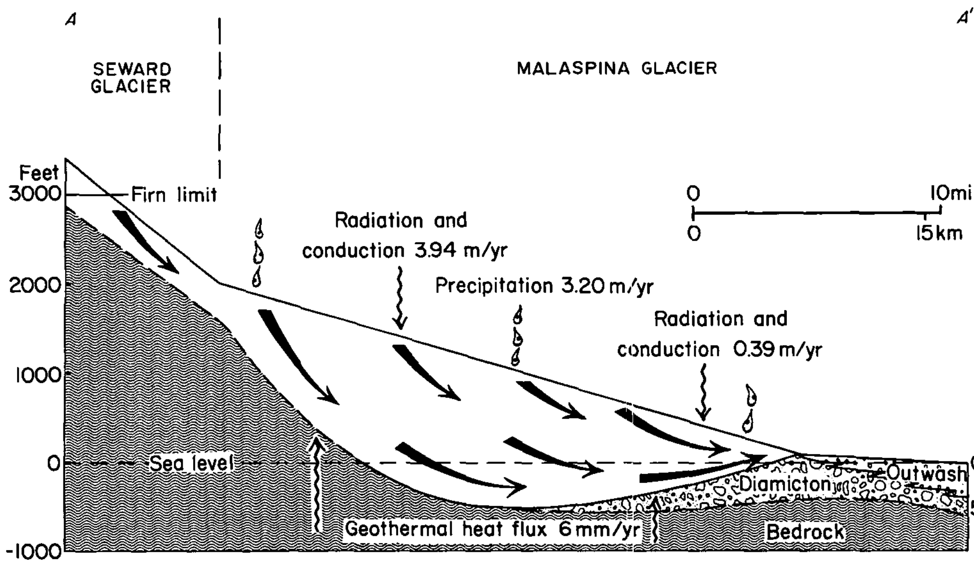


Figure 7. Arrows show generalized path of water movement within the Seward Lobe of the Malaspina Glacier. At the scale of the diagram, the ground-water table is coincident with the glacier surface. Sources of meltwater are precipitation and ablation. Field observations indicate that meltwater moves from the glacier surface downglacier and toward the bed of the glacier through intercrystalline pathways, moulins, crevasses, and sinkholes. Most of the meltwater discharges from the glacier through ice-marginal tunnels and fountains. The cross section represented by the model is located in Figure 1. Ablation rates are from Sharp (1951).

glacial landforms in southern New England (Hartshorn, 1952; Kaye, 1960).

HYDROLOGIC MODELS FOR THE MALASPINA GLACIER AND THE SOUTHEASTERN MARGIN OF THE LAURENTIDE ICE SHEET

A generalized hydrologic model has been proposed for the Malaspina Glacier (Gustavson and Boothroyd, 1982) (Fig. 7). This model is based on hydrologic characteristics of temperate glaciers discussed previously and on the following observations. (1) Ablation combined with precipitation supplies as much as 7.1 m of meltwater per year to the glacier's surface. (2) The Malaspina is a temperate glacier whose internal temperature is at the pressure–melting point of ice. (3) The water table within the glacier lies close to the surface of the glacier and is expressed in ice-marginal lakes and in water-filled sinkholes that are present from near the southern margin of the glacier northward ~32 km to the foot of the Saint Elias Mountains. Elevation of the water table increases from a few metres above sea level near the margin of the glacier to ~600 m above sea level near the mountain front. (4) The hydraulic gradient within the glacier is sufficient to cause large volumes of sediment-laden meltwater to move through a system of internal conduits to ice-marginal fountains at the heads of outwash fans or to positions high within the glacier, as shown by gravel-filled englacial tunnels.

Similarities in topography of ice-marginal areas, temperature conditions, sizes of ice lobes, surface slopes, ablation rates, meltwater-discharge rates, and ice-marginal landforms support the argument that the Malaspina Glacier is at least a partial analog of the southeastern margin of the Laurentide Ice Sheet. Because of these similarities, we argue that the paths of water movement through the margin of the Laurentide Ice Sheet were probably similar to the observed paths of water movement through the Malaspina Glacier. Specifically, a depth of 1.9 to 10.2 m of meltwater and precipitation drained annually from the surface of the Laurentide Ice Sheet, primarily through a system of englacial and subglacial tunnels, discharging from fountains or subglacial streams at the ice margin or discharging from subglacial or englacial streams into ice-contact lakes (Fig. 8).

SOURCES OF STRATIFIED SEDIMENT

Two sources of outwash and two processes for glacial sediment acquisition have been described. Stratified glacial sediment along the margin of the Malaspina Glacier is derived principally from subglacial regolith, entrained by meltwater, and carried to the ice margin in a system of englacial and subglacial tunnels (Gustavson and Boothroyd, 1982). An alternative hypothesis is that stratified sediment along the margin of the Casement Glacier in Alaska and the Laurentide Ice Sheet was derived principally from englacial debris in basal ice that was carried to the surface of the glaciers by ice-marginal shearing. Subsequently, these surface and near-surface concentrations of sediments were transported off the glaciers by meltwater and deposited (the "dirt machine" of Koteff, 1974, and Koteff and Pessl, 1984).

Subglacially Derived Stratified Sediment

In the preceding section on the hydrology of temperate glaciers, systems of tunnels in the Malaspina and other glaciers were described that were observed directly at the beds of these glaciers or as much as 100 m above the floor of the glacier. Meltwater in these tunnels carried large bed loads and suspended-sediment loads at locations as much as 2 km from the ice margin. On the Malaspina Glacier, meltwater discharges primarily from fountains at the heads of outwash fans or from englacial or subglacial tunnels into ice-marginal lakes (Figs. 5 and 6). These meltwaters are clearly the only significant sources of sediments contained in ice-marginal alluvial fans and fan-deltas (Gustavson, 1974; Boothroyd and Ashley, 1975) or in ice-marginal lacustrine fans (Gustavson, 1975a, 1975b). Subrounded to subangular gravel clasts make up a significant part of the heads of outwash fans deposited adjacent to fountains, suggesting that gravel-sized material has already been subjected to a significant amount of fluvial transport. Angular superglacial debris, which results from ablation exposure of former lateral moraines (Gustavson and Boothroyd, 1982), covers the glacier adjacent to the heads of outwash and shows no evidence of fluvial transport.

There is significant evidence that stratified sediments from the Laurentide Ice Sheet were deposited directly from englacial or subglacial tunnels. A large lacustrine fan that lies ~35 m below the former surface of glacial Lake Hitchcock (late Wisconsinan) was apparently deposited from a subglacial tunnel (Gustavson and others, 1975). Glaciolacustrine fans and varves were deposited from meltwaters that probably entered glacial Lake Passaic, New Jersey, from englacial and subglacial streams (Reimer, 1984). Subaqueous outwash deposits ("fans" in our terminology) were apparently laid down by meltwater that issued from the base of the Laurentide Ice Sheet nearly 100 m below the surface of the Champlain Sea ~12,000 yr ago (Rust and Romanelli, 1975). Marine fans were probably deposited by subglacial streams along the coast of Maine (Thompson, 1982), and the Katahdin esker system developed at the base of the Laurentide Ice Sheet in northeastern Maine (Shreve, 1985).

The simple excavation of meltwater channels beneath glaciers or the melt out of basal debris into glacial tunnels is probably not sufficient to provide the large amount of stratified sediment that was deposited during Quaternary deglacia-

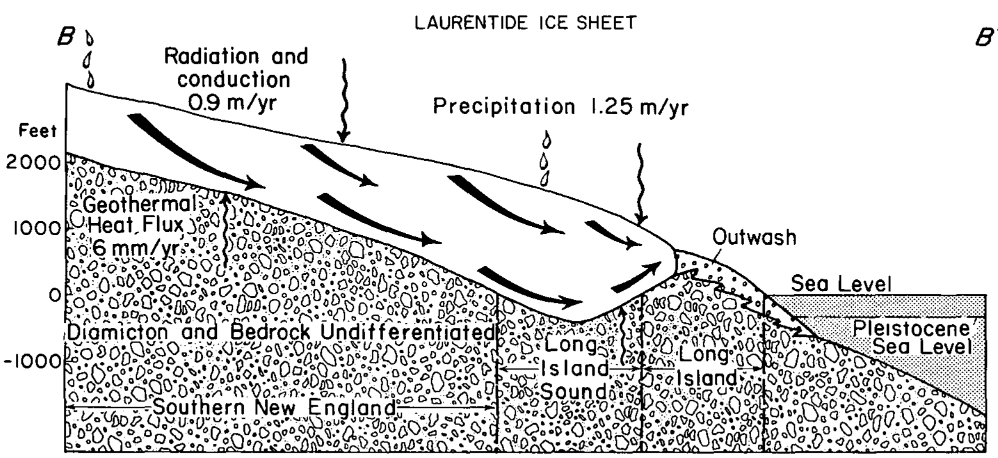
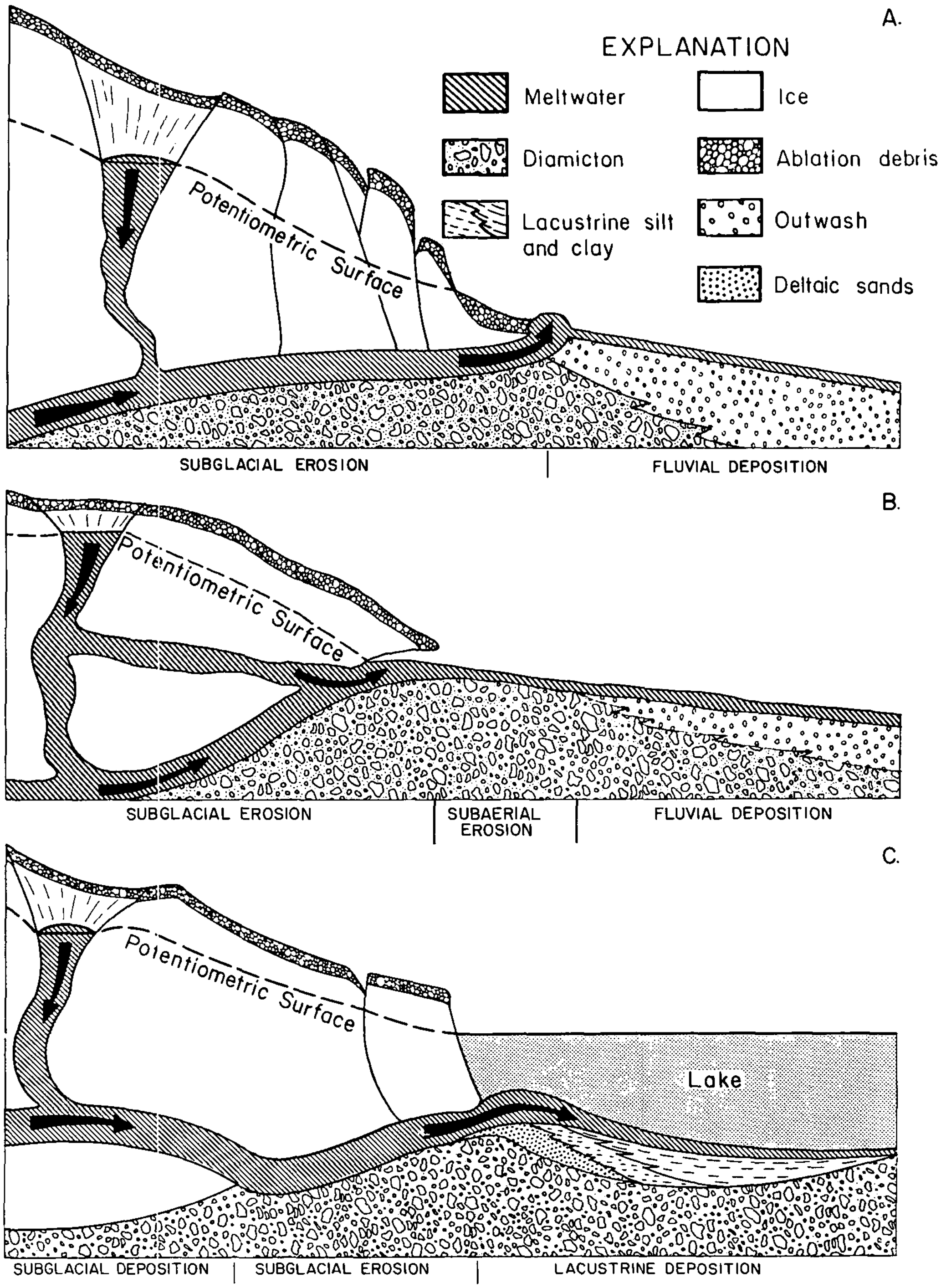


Figure 8. Arrows show the hypothetical paths of meltwater movement through the southeastern margin of the Laurentide Ice Sheet. Sources of meltwater were precipitation and ablation. Meltwater probably moved through the glacier in conduits similar to those observed in the Malaspina Glacier and discharged from the ice sheet through a series of ice-marginal tunnels and fountains. Cross section represented by the model is located in Figure 2.

tion. In addition to bank erosion and lateral migration of subglacial streams, subglacial sediment was probably squeezed into subglacial meltwater conduits. Water at the base of the glacier or water in subglacial sediments may support part of the weight of the overlying glacier. These waters and water-saturated sediment tend to move toward areas of lower hydrostatic pressure, such as subglacial tunnels. Stone fabrics from till ridges at the margins of the Hammesharju esker indicate that the till moved laterally into the ice tunnel in which the esker formed (Embleton and King, 1968). Field evidence supports these interpretations because crevasse fillings, flutes, and drumlins, all of which are formed primarily by deformation of subglacial sediments, occur in several areas on the Malaspina Foreland (Fig. 4) (see Boulton, 1982, and Shaw and Kvill, 1984, for discussions of the development of drumlins; see Hoppe and Schytt, 1953; Paul and Evans, 1974; and Boulton, 1976, for discussions of the formation of flutes; see Hoppe, 1952; and Stalker, 1960, for discussions of the formation of crevasse fillings).

Superglacially Derived Stratified Sediment

Shear planes have been recognized in a number of glaciers, but there is no compelling evidence that they supply large volumes of sed-



Figures 9A–9E. Depositional models for glacial landforms composed of stratified sediment deposited in fluvial and lacustrine environments. Landform models for deposition of (A) an outwash plain or alluvial fan deposited by meltwater issuing from a subglacial tunnel at a fountain. Examples of this style of deposition are seen in Figures 4 and 5. (B) An outwash plain being constructed by a meltwater stream issuing from beneath the glacier. (C) A lacustrine fan being formed on a lake floor by density underflows issuing from a subglacial tunnel.

iment to the ice surface. Shear planes having very thin bands of entrained sediment are present in the Barnes Ice Cap (Goldthwait, 1951), in the Greenland Ice Cap (Bishop, 1957), in the Vestspitsbergen glaciers (Boulton, 1968), and in the Casement Glacier (Koteff and Pessl, 1981). There is no evidence that ice-marginal shearing plays a significant role in moving subglacial material to the surface of the Malaspina Glacier. Most of the superglacial moraine on the Malaspina is derived from melt out of medial and lateral moraines formed in tributary valley glaciers in the Saint Elias Mountains.

In many existing glaciers, superglacial moraine is derived mostly from lateral and medial moraines, as well as from sediment carried into the glacier by basal freezing on and shearing. Superglacial moraines on many temperate valley glaciers, however, are commonly less than 1 m thick (Eyles, 1979). Bands of superglacial moraine on the Malaspina Glacier also are commonly less than a few metres thick. These superglacial sediments are the source of gravity flows that result in the deposition of flowtills or remobilized tills (diamictons) at the margin of the glacier (Hartshorn, 1958; Boulton, 1968; Eyles, 1979; Lawson, 1979, 1982) and at least part of the till that makes up landforms resulting from ice disintegration (Kaye, 1960; Schafer, 1965; Clayton, 1962).

Because superglacial moraines are commonly thin and because they are sources of flowtill, a markedly insufficient volume of superglacial material remains as a potential source of stratified glacial sediment. Furthermore, because modern temperate glaciers generally lack significant surface streams, there is no fluvial mechanism to transport and sort large volumes of superglacial material.

If our argument that the Laurentide Ice Sheet was similar to modern temperate glaciers is correct, superglacial moraines on the ice sheet also were thin and poor sources for ice-contact or pro-glacial stratified sediment. In addition, in areas of temperate ice, the ice sheet probably lacked significant surface drainage and therefore did not have a mechanism to transport and sort large volumes of surface sediments.

A DEPOSITIONAL MODEL FOR STRATIFIED GLACIAL SEDIMENTS

Fluvial and lacustrine sediments are being deposited on the Malaspina Foreland as landforms that are similar to the sequences of landforms (morphosequences of Koteff, 1974, and Koteff and Pessl, 1981) composed of stratified glacial sediment that cover much of New England (Jahns, 1941, 1953; and Hartshorn and Koteff, 1967, for example). These sequences commonly begin at the upstream end with landforms that have ice-contact faces, including collapsed outwash, collapsed lake sediments, crevasse fillings, or eskers. Similar sequences of landforms, many in contact with glacial ice, are under construction or are preserved on the Malaspina foreland (Figs. 3 through 6). In each case, major sources of sediment for these landforms are, or were, fountains or englacial or subglacial streams debouching via fountains or open tunnels. Little superglacial sediment has been contributed to these bodies of outwash except as dropstones in lacustrine sediments or as thin lenses of flowtill.

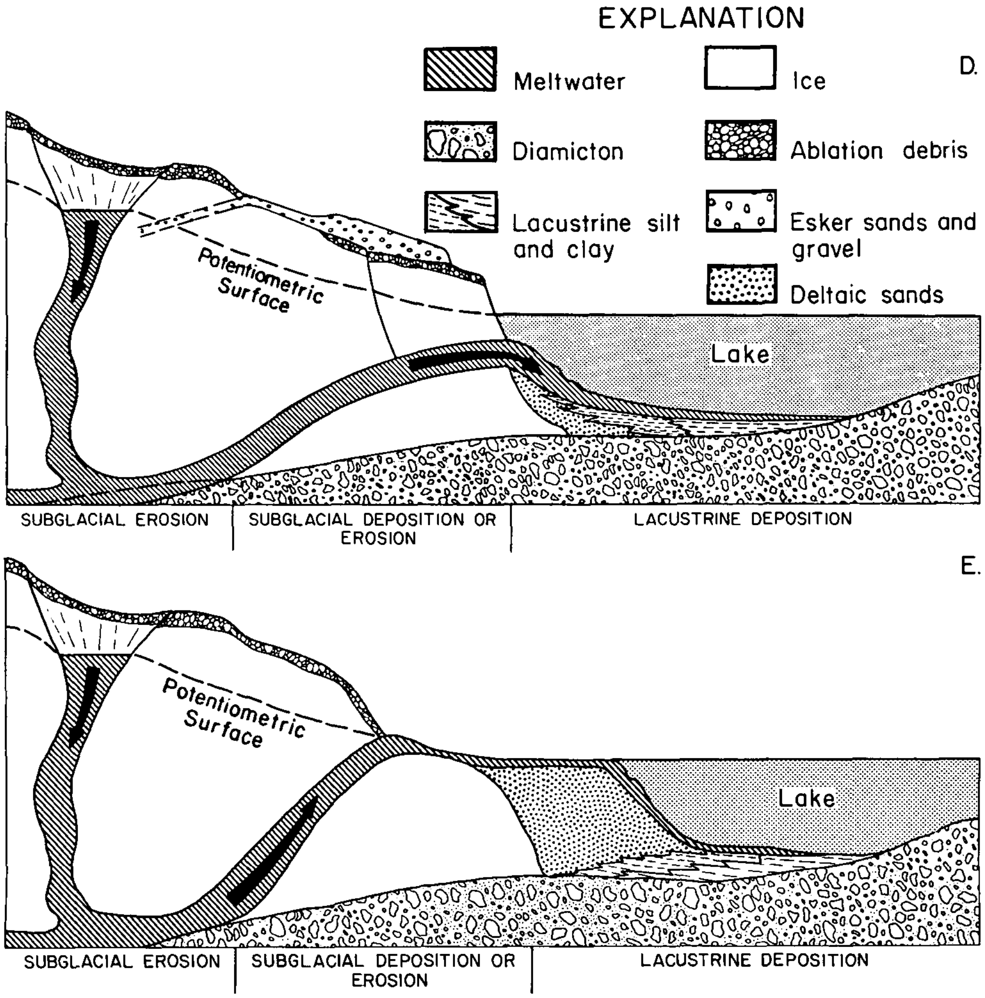


Figure 9. (*Continued*). (D) A lacustrine fan being constructed by density underflows derived from meltwater issuing from an englacial stream. Model also shows the position of an englacial sediment-filled tunnel and its exposure to become a superglacial esker and outwash. An example of the superglacial esker and outwash is given in Figure 3. (E) A lacustrine delta is being deposited by a meltwater stream issuing from an englacial tunnel. An example of deltaic sedimentation is given in Figure 6.

On the basis of the previous discussions of the hydrology of the Malaspina Glacier and observations of fluvial and lacustrine depositional processes on the Malaspina Foreland (Gustavson, 1974, 1975a, 1975b; Boothroyd and Ashley, 1975; Gustavson and others, 1975; Boothroyd and others, 1976; Boothroyd and Nummendal, 1978), we propose a general erosional-depositional model that includes a series of examples that illustrate sediment-source areas and processes of formation for glacial landforms that contain stratified sediments (Fig. 9). Each example begins with the premise that the source of stratified sediments is at the bed of the glacier. Sediment entrained at the base of the glacier is transported to the glacier margin by englacial and subglacial streams. Several of the many possible ice-margin configurations are illustrated to show the development of outwash fans, lacustrine fans and fan-deltas, and other landforms with ice-contact faces.

The sources of sediment and of outwash plains that are being built by Yahtse, Yana, Fountain, Alder, and Kwik Streams on the Malaspina Foreland are shown in Figure 9a. The headwaters of Alder Stream (Fig. 5) illustrate meltwater fountains discharging at the contact between outwash and ice. In this configuration, an ice-contact face will form at the head of the outwash plain as ice melts back from the contact with outwash (Fig. 4).

Meltwater streams also issue from beneath the ice and do not build ice-contact stratified deposits. This configuration is not common on the Malaspina, but it occurs locally. The example (Fig. 9b) illustrates this configuration and shows a meltwater stream depositing outwash away from the ice margin. Non–ice-contact deposition could also occur in a lacustrine or a marine environment.

Depositional examples for subglacial, englacial, and superglacial meltwater streams that discharge into ice-marginal lakes are illustrated in Figures 9c, 9d, and 9e. Sedimentation by englacial or subglacial streams that discharge into Malaspina Lake has resulted in the construction of large lacustrine fans along the southeast margin of the ice (Gustavson, 1975a, 1975b), and these configurations are illustrated in Figures 9c and 9d. The basis for the example illustrated in Figure 9e is a large englacial meltwater stream in an open tunnel that flows subaerially for a short distance before it constructs a large fan-delta in the northern part of Malaspina Lake (Fig. 6). Melting of ice along the ice-contact margin and drainage of lake waters will expose lacustrine and deltaic sediment with ice-contact faces. For example, a lacustrine fan-delta and esker mark where a subglacial stream discharged into a former lacustrine basin (Fig. 10). The examples illustrated in Figure 9 represent only common landforms, and many other variations are possible depending on the character of the ice margin, local topography, glacier hydrology, and previously deposited sediments.

We have established that the Malaspina Glacier is analogous in many respects to the Laurentide Ice Sheet. Therefore, the general erosional-depositional model and the examples that we illustrate in Figure 9 should apply to the origin of stratified sediments deposited at the margin of the retreating Laurentide Ice Sheet.

Figure 11 is a paleogeographic reconstruction of the Narragansett Bay Sublobe of the Laurentide Ice Sheet as it occupied the Narragansett Bay region in Rhode Island during the late Wisconsinan (Pickart and Boothroyd, 1986). This interpretation, based on published maps, evidence from vibracores, studies by Stone and Peper (1982), and analogies with processes that are active on and adjacent to the Malaspina Glacier, shows that ice-contact stratified fluvial and lacustrine sediments were deposited at the margin of the ice sheet by meltwater discharging from englacial or subglacial tunnels.

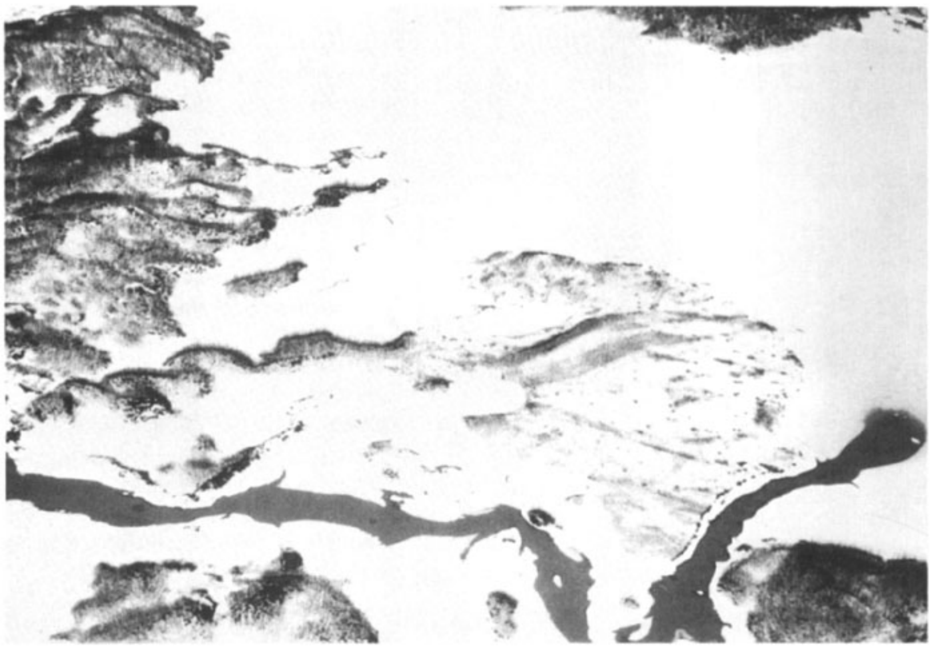


Figure 10. Oblique aerial photograph of a snow-covered esker leading into the apex of a lacustrine kame delta. The esker and delta occur at the northern shore of a small snow-covered glacial lake west of Malaspina Lake. The stagnant margin of the Malaspina Glacier appears along the left side of the photograph. Sediment eroded from beneath the Malaspina Glacier apparently was transported to the delta in a subglacial tunnel. Sediments deposited in that tunnel are now expressed as the esker. The esker is ~7 m high. Photograph taken in April 1969.

SUMMARY AND CONCLUSIONS

Meltwater enters the Malaspina Glacier via intercrystalline spaces, moulins, crevasses, or sinkholes and moves down-glacier through a system of englacial and subglacial tunnels. Stratified sediment preserved in these tunnels indicates that meltwater erodes the bed of the glacier. Meltwater exits the glacier as fountains or from open tunnels to form outwash plains or from englacial or subglacial tunnels that discharge into ice-marginal lakes. Meltwater discharge varies with surface recharge as a result of day-to-day and seasonal weather changes. These characteristics of the Malaspina are shared by many temperate glaciers. Collectively, they constitute a preliminary descriptive model for the hydrology of the Malaspina and possibly other temperate glaciers.

The temperate, maritime Malaspina Glacier is at least a partial modern analog to the late Wisconsinan Laurentide Ice Sheet that occupied southern New England. Proximity to the Atlantic Ocean and the lack of confirmed permafrost features suggest that the Laurentide Ice Sheet was a temperate ice mass during deglaciation. Ice lobes on the Malaspina Glacier range from 20 to 54 km wide. In southern New England, end-moraine lobes, comparable to ice lobes of the Laurentide Ice Sheet in width, range from 4

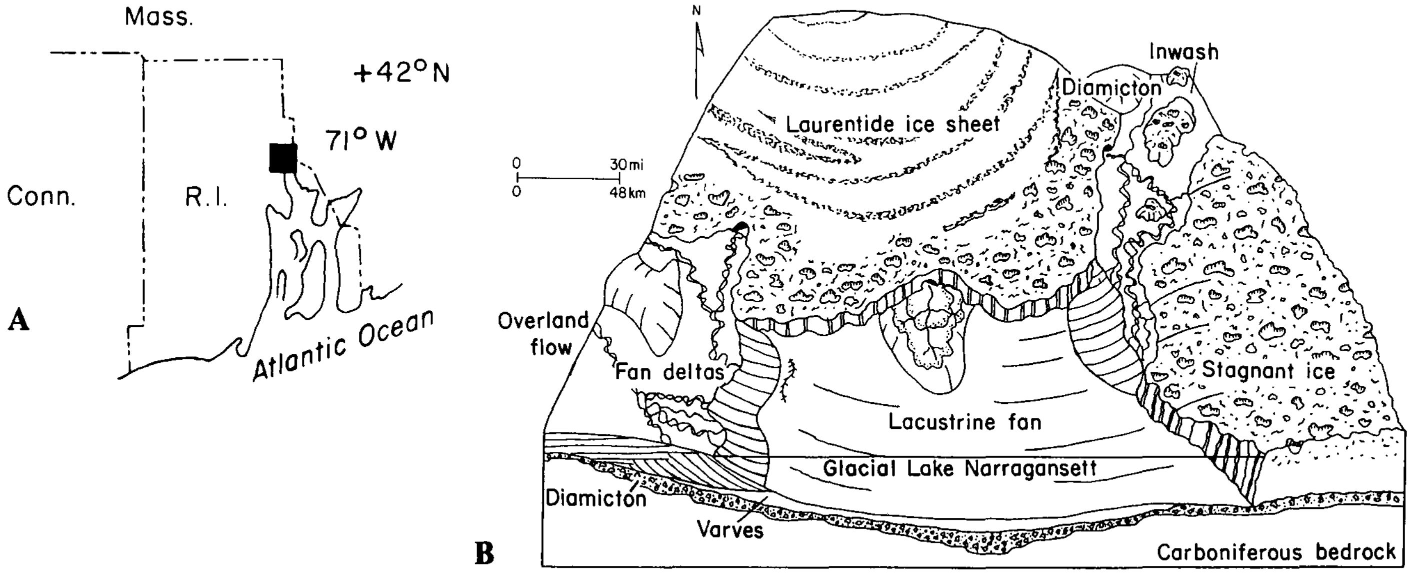


Figure 11. Paleogeographic reconstruction of upper Narragansett Bay, Rhode Island, at about 15,500 B.P. A. Location map shows area of block diagram. B. Lobate margin of the active to passive Laurentide Ice Sheet sits over the present site of Providence, Rhode Island (P), with a large stagnant ice mass to the southeast. Meltwater discharging from tunnels and fountains is building fan deltas and a lacustrine fan into Glacial Lake Narragansett. Some ice marginal (inwash) and overland flow is also apparent. This interpretation is based on published maps, evidence from vibracores, and by analogy with present processes on, and adjacent to, the Malaspina Glacier (modified from Pickard and Boothroyd, 1986).

to 150 km wide, although most end-moraine lobes range from 30 to 50 km wide. The depth of meltwater available for recharge at the surface of the Malaspina Glacier is as much as 7.1 m/yr, and estimated depths of meltwater available from the Laurentide Ice Sheet ranged between 1.9 and 10.2 m/yr.

Because the Laurentide Ice Sheet was a temperate ice mass as it receded, the hydrologic model that was developed from studies of the Malaspina Glacier and other temperate glaciers can be used to infer hydrologic conditions at the margin of the ice sheet. Specifically, meltwater and water from precipitation drained from the surface of the Laurentide Ice Sheet through a system of englacial and subglacial conduits to discharge from fountains or open tunnels at the ice margin or from subglacial or englacial tunnels into ice-contact lakes.

Landforms composed of stratified sediment and retaining ice-contact faces were deposited throughout New England as the Laurentide Ice Sheet receded. Koteff (1974) and Koteff and Pessl (1981) wrote that these landforms probably formed when debris at or near the ice surface was transported off the ice sheet. A continuous supply of debris-laden basal ice was thought to have been supplied to the ice surface by shearing of active ice over a marginal zone of stagnant ice. This conveyor-beltlike process was called the "dirt machine."

Landforms composed of stratified sediments, which are analogous to the Wisconsinan glacial landforms of New England, are being constructed on the Malaspina Foreland. These features are commonly in contact with the margin of the Malaspina Glacier and are formed from sediment carried to the margin of the glacier in subglacial or englacial tunnels. There is little evidence that shearing within the margin of the glacier has added any appreciable sediment to the surface of the glacier or that the superglacial sediment contributes substantially to the formation of stratified sediment at the margin of the glacier. For these reasons and because the hydrologic system that operated in the Laurentide Ice Sheet is thought to have been similar to the hydrologic system of the Malaspina, sediment that composes outwash and related deposits in New England probably was derived largely from the regolith underlying the ice sheet and carried to the margin of the glacier in a series of englacial and subglacial tunnels. A continuous supply of sediment was provided by mass movement of water-saturated till or by lateral migration of subglacial channels.

The observations and interpretations presented here suggest that the "dirt machine" hypothesis should be abandoned as an explanation for the processes by which stratified sediment originated along the southeastern margin of the Laurentide Ice Sheet.

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