Ice Formation in an Alaskan Estuarine Salt Marsh

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ABSTRACT

An extensive ice sheet builds up during the winter in a salt marsh complex (Eagle River Flats) at the mouth of the Eagle River near Anchorage, Alaska. Ice cores were taken along a transect beginning in a 0.5-m-deep pond along the edge of the salt marsh and traversing marsh, shallow pond and subaerial mudflats closer to the river to elucidate how snow accumulation, periodic tidal flooding and freshwater flow contribute to the ice cover formation.

The ice structure and chemistry at Eagle River Flats vary vertically and spatially. Salt and sediment content are correlated, indicating that most of the sediment is deposited by tidal flooding. Generally the ice thickness decreases, and the salt and sediment content increases, with proximity to the river.

Except in the deeper pond at the periphery of the Flats, the ice appears to be grounded. The ice builds from the ground upward and thickens when tidal waters flow over the previously flooded, now frozen, surface. The ice appears to be well bonded to the underlying sediment.

Keywords: Ice formation, salinity, salt marsh, sediments

INTRODUCTION

Eagle River Flats (the Flats) is an 865-ha (2162-acre) estuarine salt marsh located off the Knik Arm of Cook Inlet, Alaska (Fig. 1). About 2.8 km wide near the coast, this salt marsh contains a portion of the Eagle River, its distributaries and levees, and a number of vegetation zones. The zones change from bare or sparsely vegetated mud flats near the river, to sedge and bulrush marshes and shallow ponds, to meter-deep ponds near the periphery of the flats.

The Flats are separated from Knik Arm by a mud-faced shore that slopes toward Knik Arm and is flooded directly by the tide. Except for this shore and for deep distributary channels, the Flats have an average elevation of 4 m above mean sea level (the elevation decreases from levee along the river's edge to the boundary of the Flats) and floods only when water enters and overtops the channel of the Eagle River and its distributaries. In the summer, a high river discharge from glacial meltwater that is dammed by a moderately high tide can cause fresh and salt water to flood various areas of the Flats. In our study pond, Area C, a pressure transducer measured 11 flooding events between 16 August and 21 September 1990 (Racine et al. 1991), corresponding to tides greater than 9.1 m (30 ft). The summer flood waters were observed to drain within a few hours after the high tide. From October to March, an extensive ice sheet builds up in the Flats (Fig. 2). The ice sheet covers areas such as mudflats and levees that have standing water only when flooded by summer high tides.

Most studies of ice formation in northern wetlands have been conducted along the east coast of Canada and the United States. Dionne (1989) studied the effect of ice on marshes and estuaries in Quebec where ice formed on open water and was subjected to large tidal fluctuations. The bottom topography of the estuaries was affected when grounded ice and frozen underlying sediments, were pulled up and deposited elsewhere.

Meese et al. (1987) described estuarine ice from New Hampshire's Great Bay. The water in this estuary is predominantly saline and forms frazil and congelation ice. The ice is generally free floating and subjected to tidal action. Sediments are found between the crystal platelets of the ice and are thought to be incorporated as the ice grows in water containing suspended sediments.

To determine how the ice forms at Eagle River Flats, ice cores and attached frozen sediments were obtained in February 1991 and January 1992. Ice

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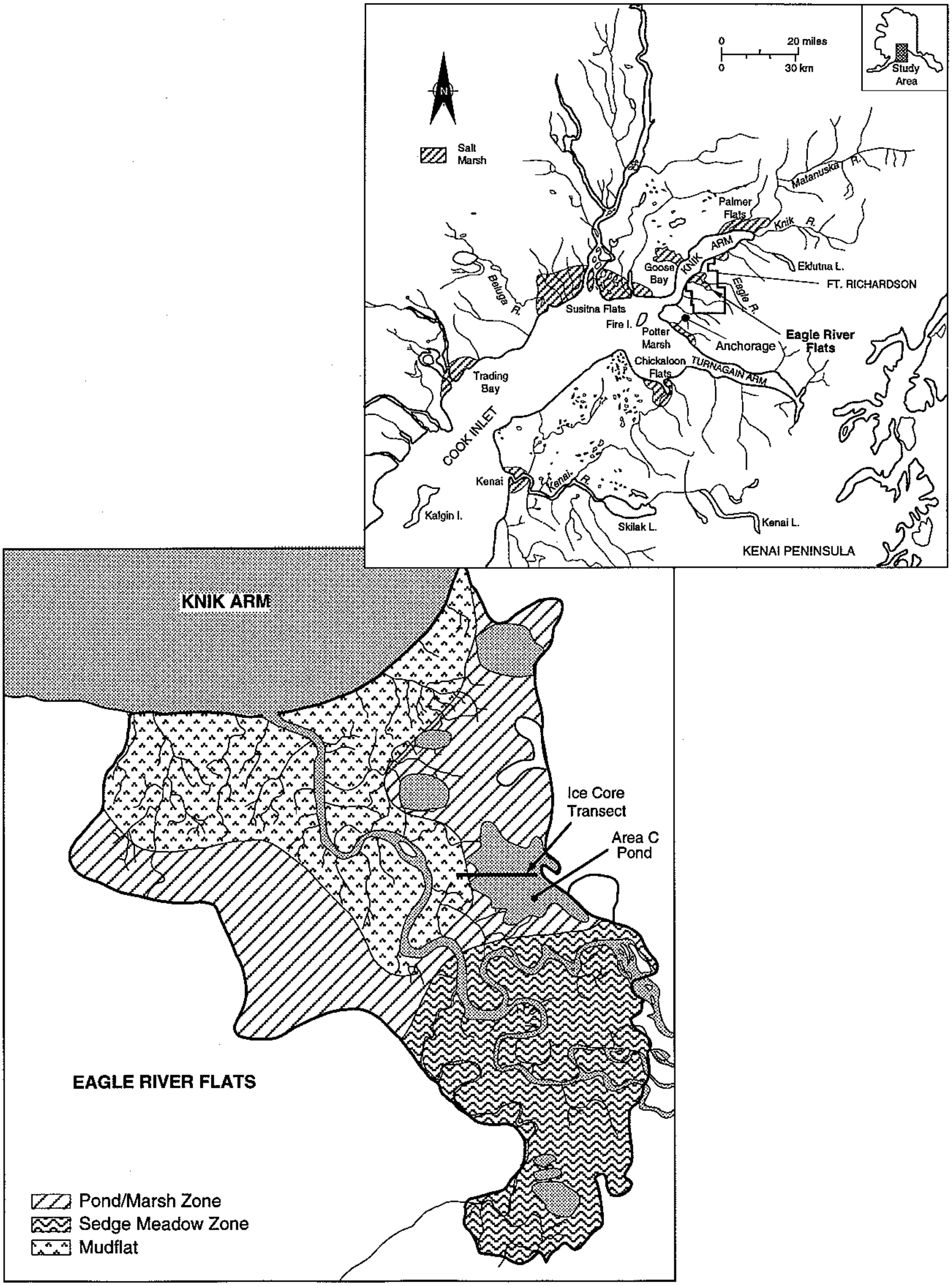


Figure 1. Schematic of Eagle River Flats showing the main vegetation zones and the location of Eagle River Flats in relation to Cook Inlet and Alaska.

Figure 2. Winter view of the Eagle River. Note the gray areas in the snow cover where selective flooding has saturated the snow.

structure, salinity, thickness and the presence or absence of sediment bands in the ice are described, along with a sequence of events for its formation.

MATERIALS AND METHODS

Three-inch-diameter (7.6-cm) ice–sediment cores were obtained using a SIPRE coring auger. Different land form and vegetative zones were sampled by taking cores along transects running from the deep pond at the periphery of our study area, through a sedge marsh bordering the pond, to a shallow pond (<20 cm) and lastly onto the mudflat (Fig. 1). Deep ponds have permanently standing water; shallow ponds are less than 20 cm deep and they dry out during some years.

The cores were kept frozen and shipped back to CRREL, in Hanover, N.H., for laboratory analysis. Each core was cut in half lengthwise, and one half was bagged and saved. A 1-cm-thick vertical section was cut from the central section of the other half; thick and thin sections of the core were prepared following the methods of Weeks and Gow (1978). The remaining part was then cut crosswise into 1-cm-thick pieces, which were analyzed for salinity and sediment content as a function of distance from the ice surface (Fig. 3).

A Selectro Mark analyzer conductivity meter, calibrated using standards, was used to determine the salinity for all cores except for core 31, where a Dionex ion chromatograph was used. The Selectro Mark was easier to use. After evaporating the water, the weight of the solids, including sediments, salts and vegetation, was obtained with a Mettler balance. The weight of the salt was calculated from the salinity and subtracted to obtain the sediment weight. Except for a few samples there was little or no vegetation, and its contribution to the sediment weight is ignored. A Hitachi 500S scanning electron microscope equipped with a Kevex energy dispersive X-ray analyzer (EDAX) was used to examine selected sediments. To avoid building up a charge on the sample surfaces, they were coated with a layer of gold and palladium using a Hitachi evaporation coater.

Six cores collected in 1991 were studied. Three cores were from a transect running from the deep pond to the adjacent sedge marsh (60, 62 and 178), two were from the deep pond (27 and 31) and one was from a

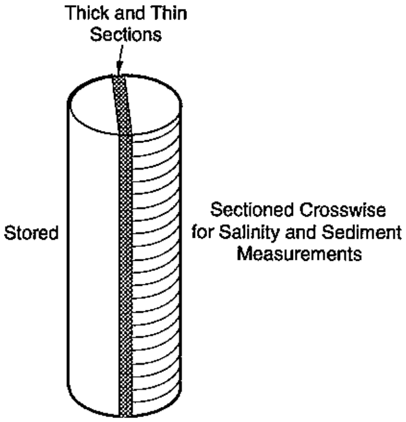


Figure 3. How the ice cores were cut and sampled.

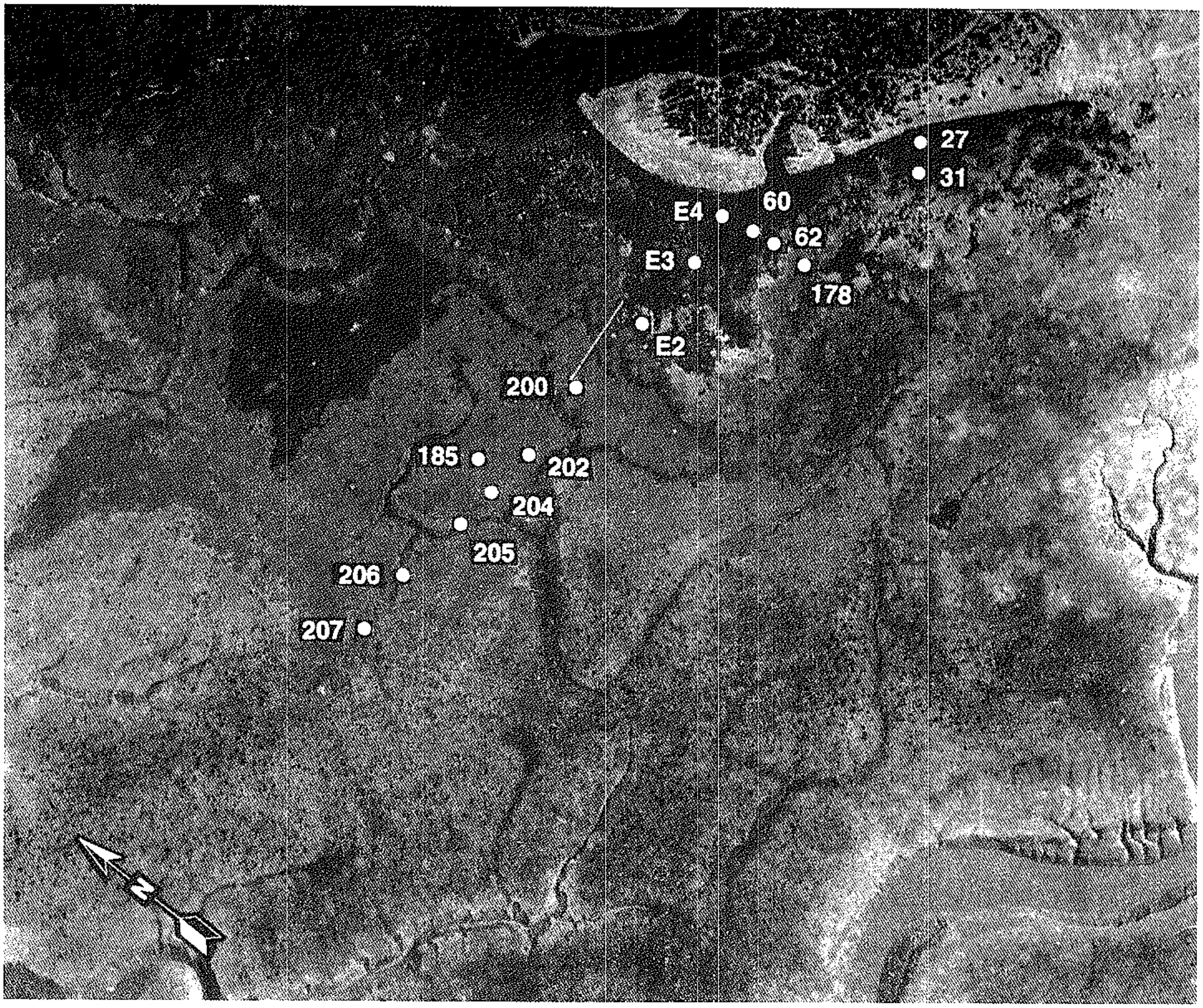


Figure 4. Aerial image showing the locations of the coring sites. Eagle River Flats is an Army artillery impact range, and this is evident from the many craters that pepper the surface.

shallow pond (185) (Fig. 4). The sediment portion of the core taken from the sedge marsh (178) was thick sectioned and X-rayed to clarify the sediment structure and the nature of the ice–sediment boundary. A general description of the processes gleaned from the transect will be discussed followed by a detailed description of a core from a deep pond, sedge marsh and shallow pond.

In 1992, nine cores were taken at 50-m intervals along a single east–west transect running through the deep pond (E4 and E3), marsh (E2), shallow pond (200, 202 and 204), levee (205 and 206) and mudflat (207) (Fig. 4). These, too, were sectioned, and the salinity and sediment content determined. A description of how these cores differ from the 1991 core is given along with a possible explanation for these differences.

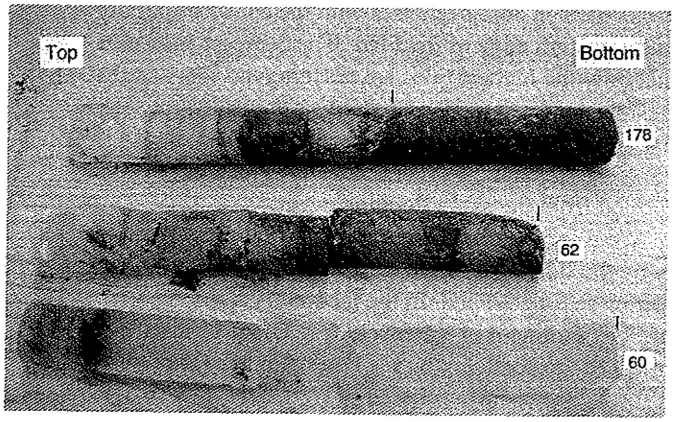


Figure 5. Cores 60, 62 and 178. The lines show the ice–sediment boundary.

RESULTS

1991 Transect

Three cores were analyzed from a February 1991 transect across the pond to the sedge marsh. The ice thickness decreases from the pond at the eastern periphery of the Flats to the marsh (Fig. 5). The salinity and sediment content of the ice versus depth for these cores (60, 62 and 178) are plotted in Figure 6. The top of each ice core is set relative to the ice surface elevation along the transect.

These data show the correlation between salinity and sediment concentration. Also evident is that both the number and the magnitude of salinity and sediment

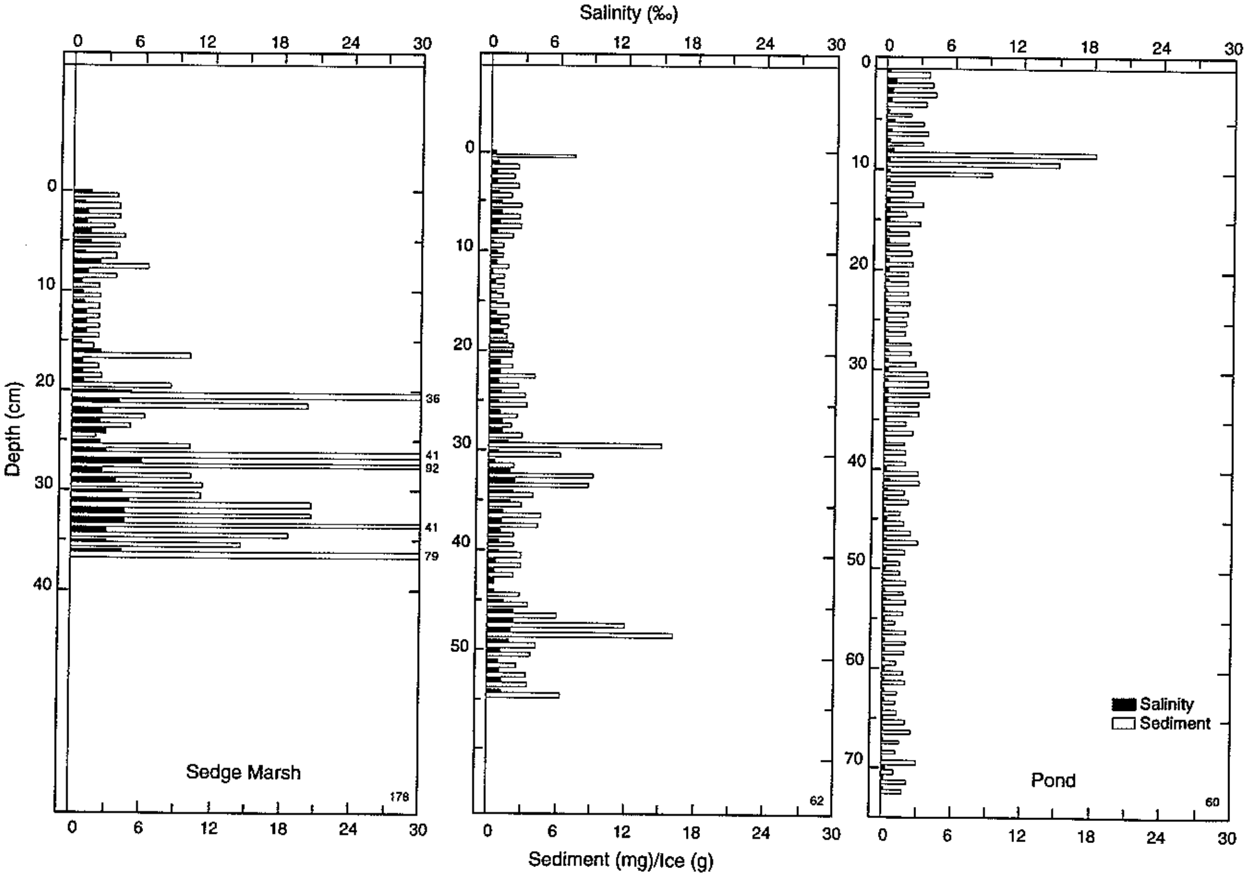


Figure 6. Salinity and sediment profiles for core 60, 62 and 178. The offset among the profiles reflects the difference in the surface elevation among the sites.

peaks of each core decreases with the core's proximity to the eastern edge of the Flats. The decrease indicates that only the highest tides are reaching the shore or that fresh water from the land is diluting the saltwater signature. The salinity–sediment peaks at 30–31 or 34–35 cm (core 62) and 27–28 cm (core 178) may have been formed from the same flooding event.

We think the sediment in the Flats cores are brought in by the tidal waters and settle out of the water to form a sediment band. In the laboratory a suspension of Flats sediment in water settles in about 10 minutes (most of the sediment on the bottom, murky water on top), with complete separation in less than two hours (clear water over sediment). The sediment at Eagle River Flats is a gray, clay-sized, rock flour; 98% is less than 0.1 mm in diameter.

Deep Pond Core-1991

The pond we sampled had water depths of up to half a meter under ice that was 40–70 cm thick. Core 31 is 66 cm long and from the top down has 15 cm of cloudy ice, 15 cm of orange ice, 6 cm of sediment bands and ice, 8 cm of cloudy ice and 22 cm of clear ice. The bottom 30 cm of core 31 (Fig. 7) is interpreted to be frozen pond water. The central section of the core (30–36 cm) has thin layers of columnar ice that

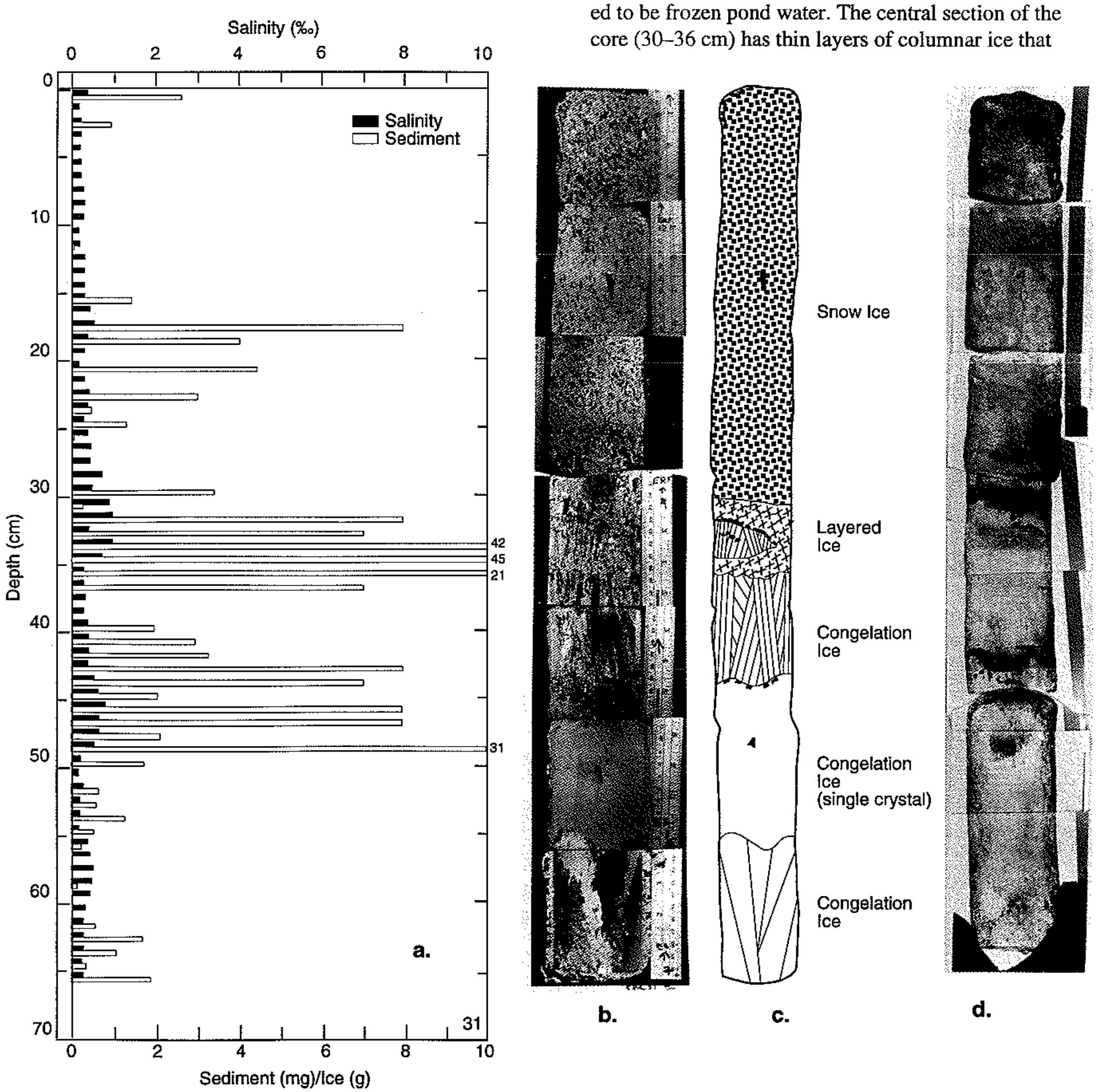


Figure 7. Salinity and sediment content of core 31 and our interpretation of how the ice formed.

have a high sediment content (40–50 mg of sediment/g of ice). These layers are thought to have formed from a series of flooding events over the pond ice surface. Because the salinity of this ice is low, these bands may have a freshwater source (aufeis). Ice elevation surveys indicate that the ice at the edge of the pond is higher in elevation than the ice on the Flats. The top 30 cm of the core consists of ice with grains of various sizes and crystal orientations. We think this section is snow ice, although it does not display the similar-size grains seen in "standard" crystallized, wetted snow.

Bright orange ice is often found in cores near sedge marsh areas. Under the scanning electron microscope, the orange particulates appear as small flakes on much larger precipitated salt crystals; they do not resemble bacteria or fungi. Energy dispersive X-ray analysis indicates they are composed of iron. These flakes could be iron oxides that precipitated in the water column because they became insoluble in the low-pH, anaerobic conditions. Alternatively, oxidation of soluble ferrous iron to the ferric iron precipitate might have occurred around the roots of the sedges, as was found for the species *Phragmites australis* (St. Cyr and Crowder 1989).

Marsh Core-1991

Core 178, from a sedge marsh, consists from the top down of 19 cm of cloudy ice, 4 cm of clear ice, 17 cm of ice containing vegetation and 30 cm of frozen black silt (Fig. 8). The salinity ranges from 2.5 to 6 parts per thousand (ppt) in the bottom 17 cm of the ice portion of the core, so tidal flooding must have contributed water to this ice. By counting the number of sediment layers present and assuming that the sediment drops out of the water and forms the base of each tidal event, we estimate that four separate flooding events built up the bottom 17 cm of ice.

The first tidal flood provided the water for the first 4 cm of ice. The second deposited the well-defined, horizontal sediment layer 4 cm above the ice–

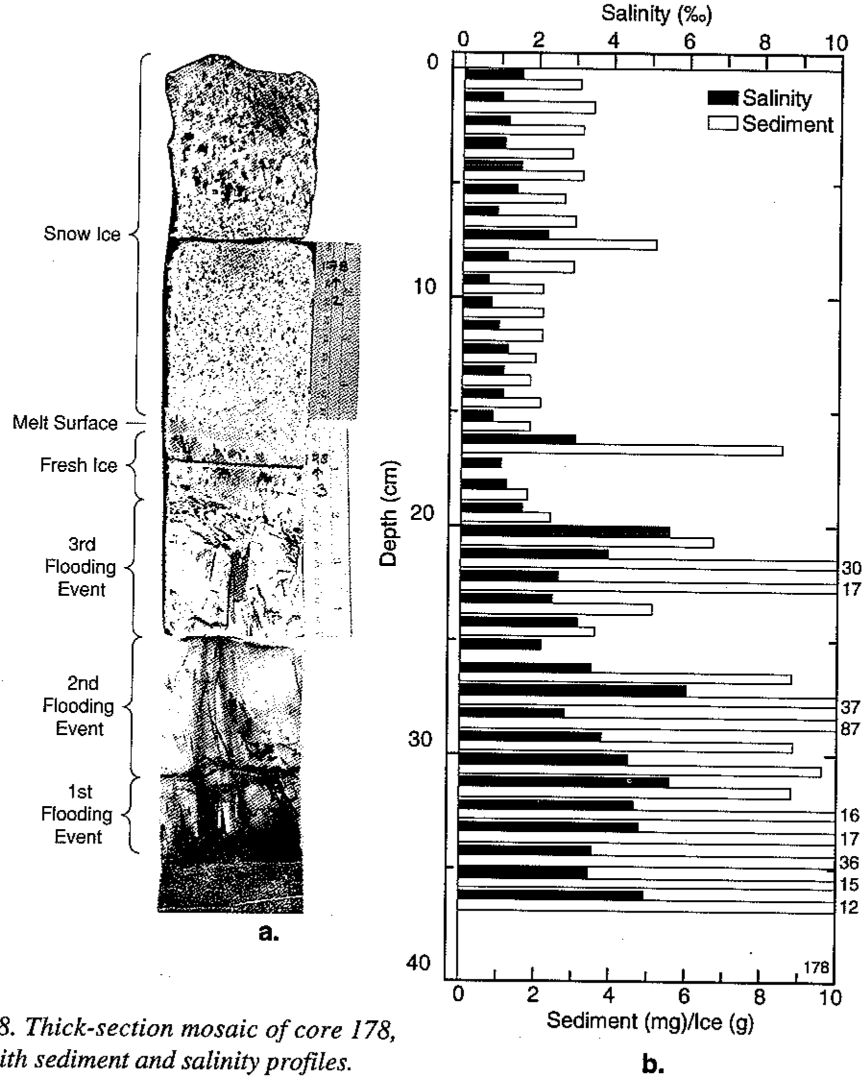


Figure 8. Thick-section mosaic of core 178, along with sediment and salinity profiles.

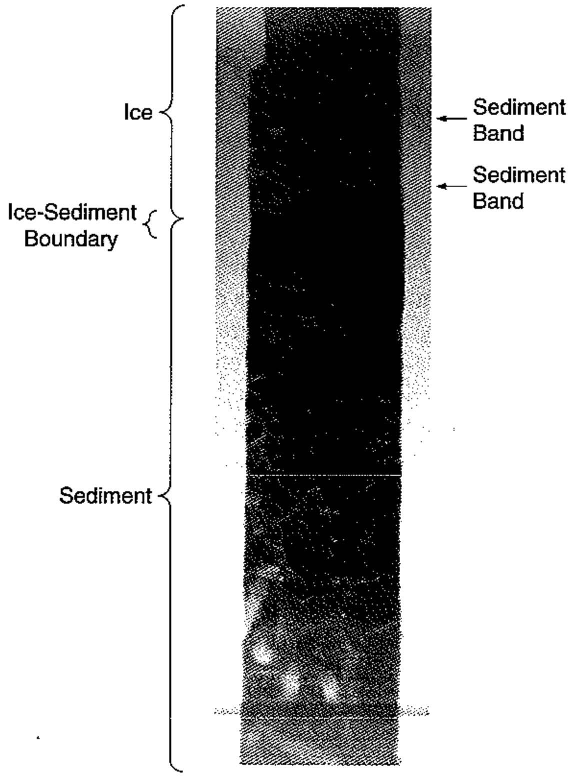


Figure 9. X-ray of a frozen sediment section of core 178, showing the ice–sediment interface. The interface is characterized by ice needles growing into the sediment. A large amount of vegetation, which appears light gray, is incorporated within the sediments.

sediment boundary (Fig. 8). The base of the third is 10 cm from the ice–sediment boundary (where the core broke). The base of the fourth flooding event is at 16 cm from the boundary, where the vegetation, which until then had been upright, becomes incorporated horizontally into the ice. Because sediment bands correlate with peaks in salinity, the sediment is thought to be deposited by tidal flooding.

On top of the 17 cm of saline ice, there are 4 cm of fresh columnar ice capped by a 0.5-cm layer of clear ice. This thin layer is interpreted as a standing surface where the ice was exposed to the elements (sun, rain etc.) before being covered by new snow. On top of the columnar ice, and making up the rest of the core, is snow ice. It has a salinity of less than 1 ppt, except at a sediment layer 21 cm from the ice–sediment boundary and at 30 cm, where the core broke as it was collected. These two horizons may be tidal flooding events. The snow ice has a section of finer-grained crystals under a coarser-grained section.

The ice–sediment boundary is obscured by emerging vegetation and sediment bands. Figure 9 is an X-ray of the sediment section, which shows the ice–sediment boundary. Ice needles can be seen growing into the sediment, and the interfingering of ice and mud produces a strong bond. When the cores were drilled, they tended to break along salinity–sediment bands, not at the ice–sediment boundary. A large amount of old vegetation can be seen within the sediment.

Shallow Pond Core-1991

Core 185 was collected from a shallow pond area (Fig. 4) and consisted of 45 cm of ice (sediment bands at 15, 17 and 20 cm) overlying 20 cm of partially frozen silt. Unlike the other cores that were sectioned at 1-cm intervals, this core had such distinct bands and crystal structure that we used them as a guide to sampling (Fig. 10). As this area is dry during the summer, the ice formed from the ground up.

The bottom 20 cm of core is columnar ice, of varying coarseness, and has salinity values between 1 and 3.5 ppt. There are at least four separate flooding events (Fig. 10). The tops of layers 2 and 4 have a thin, clear ice layer, which is interpreted as a rain or melt event that occurred when that ice was at the surface.

This bottom section of ice is covered by a 2-cm layer of freshwater columnar ice and then by 23 cm of relatively fresh snow ice. The snow ice varies from large, equidimensional crystals at the base of the section to smaller grains of random crystal orientation at the top. Because the salinity and sediment content increase at the top of the section, the top of the snow ice appears to have been flooded by tidal water.

1992 transect

In January 1992 a series of cores were collected along a 400-m transect from the pond, across a mixed bulrush–sedge marsh and onto the mudflat (Fig. 4 and 11). The cores are characterized by columnar ice over-

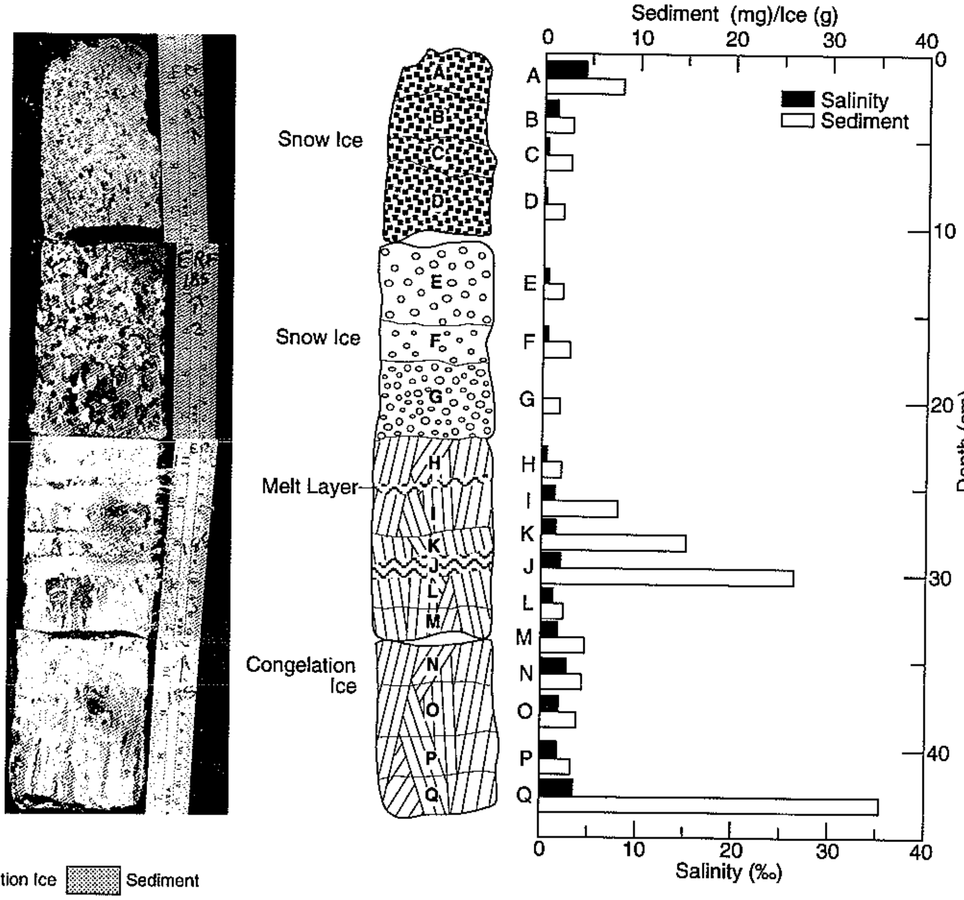


Figure 10. Thin section of core 185, our interpretation of how the ice formed, and the salinity and sediment content.

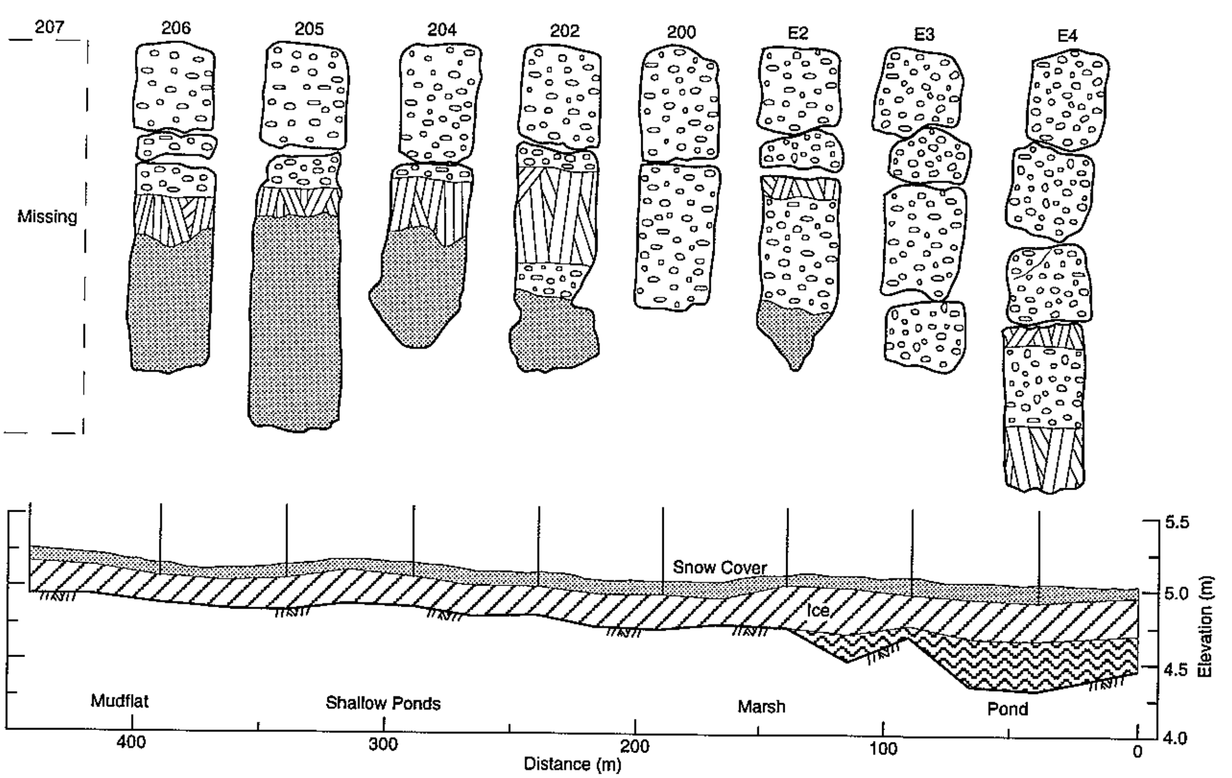


Figure 11. Cross section along the east–west transect in area C, showing the sediment, ice and snow surface elevations. Drawings of the cores, showing length and prominent features such as bubble or sediment bands, are above the cross-section location of each sample site.

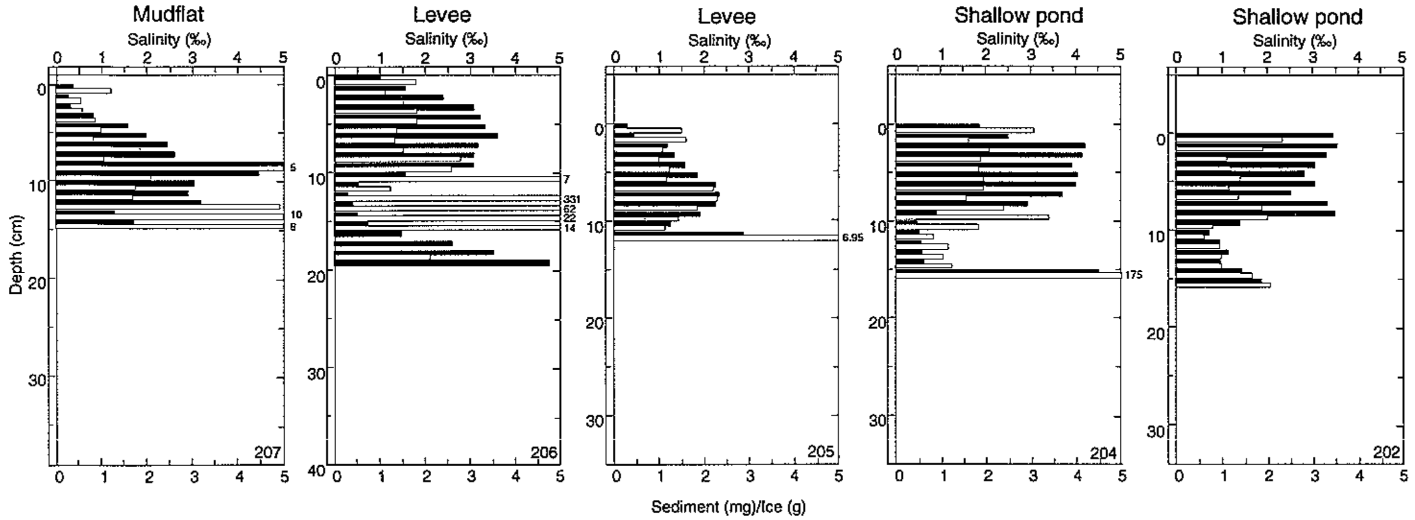


Figure 12. Salinity and sediment content of the 1992 cores. The ice surface elevation of core 207,

lain by very porous snow ice and are about half the length of the 1991 cores. Like the 1991 cores, the 1992 cores of the deep pond and marsh areas are less saline and have less sediment than those from the shallow ponds and mudflat areas (Fig. 12). Also, with the exception of core 206, sediment and salt concentrations are correlated. Unlike the 1991 cores, the columnar ice has lower salt and sediment contents than the overlying snow ice (Fig. 12). The 1992 cores have no distinct ice or sediment layers, and the average amount of sediment in these cores is also lower (2 mg of sediment/g of ice, as compared to 4 mg/g for the same area of the pond in 1991).

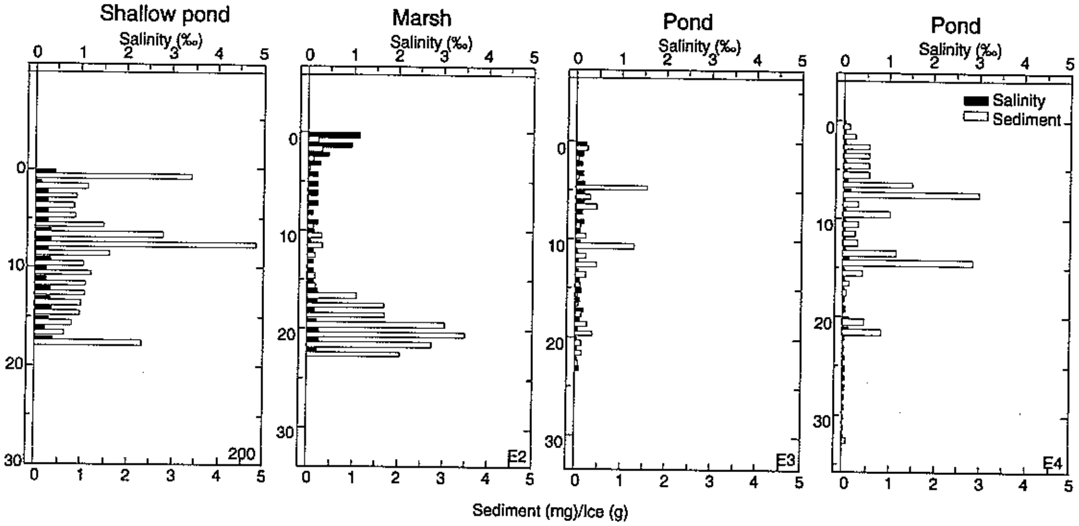
The amount of sediment contained in each core is shown in Table 1. The sediment content of the core varied widely, and there was no clear demarcation among the different salt marsh zones. More noticeable is the difference in sediment content between the two winters; less sediment was present in the 1992 cores.

DISCUSSION

We think that tidal flooding builds the ice sheet by flowing over frozen ground or ice and freezing to form saline ice layers. Occasionally, a high tide may

Table 1. Sediment, salt and ice weights for each core. Also shown are the sediment weight in mg/g of ice and the sediment available for deposition (mg/cm^2).

ERF core no.	*Environment*	*Salt weight (mg)*	*Sediment weight (mg)*	*Ice weight (g)*	*Sediment (mg/g ice)*	*Cross sectional area analyzed (cm^2)*	*Sediment/ cross sectional area of core (mg/cm^2)*
1991 cores							
27	Deep pond	134	203	442	0.46	16	13.53
31	Deep pond	31	236	65	3.63	1	236.0
60	Deep pond	84	1028	378	2.72	15	68.53
62	Pond marsh	987	1337	293	4.56	15	89.13
178	Marsh	482	2248	202	11.13	15	149.87
185	Shallow pond	219	967	185	5.23	15	64.47
1992 cores							
E4	Deep pond	24	185	450	0.41	15	12.33
E3	Deep pond	33	98	303	0.32	15	6.53
E2	Marsh	81	243	349	0.70	15	16.20
200	Shallow pond	134	659	412	1.60	15	43.93
202	Shallow pond	653	405	292	1.39	15	32.40
204	Shallow pond	668	486	275	1.77	15	32.40
205	Levee	454	552	255	2.16	15	36.80
206	Levee	679	6562	294	22.32	15	437.47
207	Mudflat	627	885	304	2.91	15	59.00



E2 and E3 were not recorded the day the cores were collected.

flood all or most of the Flats, but usually flooding spreads out from the distributary channels as lobes or splays of water that build up an ice layer over a limited area. The thickness of these layers will depend on the height of the tide, the local terrain features and the presence or absence of snow. When snow is present, the tidal water either partially or totally saturates the snow (Fig. 2) and freezes to form snow ice, which is bubbly, white and less dense than the clear columnar ice.

We attribute the difference in the 1991 and 1992 cores to the interplay between snowfall amounts and the timing of high tides at the Flats. Tidal records from 1990-91 show three tides over 10 m in October and early November (Fig. 13). The winter had below-average snowfall in October, January and February and 50% more snow in November and December, compared to an average derived from the 1962–1992 snow record. In 1991-92, the tides over 10 m occurred in January and February (Fig. 13), and there was 50–100% more snow throughout the winter than the 30-year average. The absence of ice and sediment layers in 1992 cores could be due to the large amount of snow that fell at Eagle River Flats from October through March and the fact that the highest tides occurred later in the winter after a lot of snow had accumulated. The flood waters are slowed and wicked up by the snow.

CONCLUSIONS

Eagle River Flats is a complex estuarine salt marsh, only a small portion of which was studied. The ice covering the marshes and mudflats formed from the bottom upward as a result of a series of flooding events. This is in sharp contrast to the formation of ice on water bodies. Except in the deep pond at the periphery of

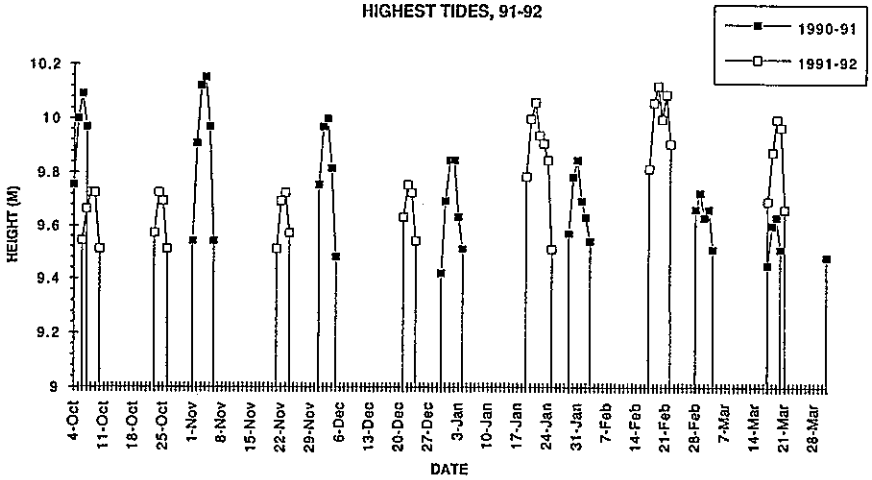


Figure 13. Tides over 9.5 m for the winter months of 1990–91 and 1991–92.

the Flats, we think that the ice is grounded and that tidal flooding occurs over the ice surface. The ice is well bonded to the underlying sediment. Although the ice–sediment boundary is difficult to define and characterize visually, X-rays of the core show the location and nature of the boundary.

The ice cover at Eagle River Flats varies vertically and spatially with regard to salt and sediment contents. The two impurities are correlated, indicating that most of the sediment is deposited by tidal flooding. The sediment in the ice portion of the cores occurs as discontinuous millimeter to centimeter horizontal bands. The ice does not grow through the sediment bands, as it does at Great Bay, N.H. (Meese et al. 1989). Generally the length of the core decreases, and the salt and sediment contents increase, with proximity to the river. The presence of salt and sediment lowers the ice's strength, and when the cores are drilled they tend to break along salt and sediment bands.

Cores from the 1991 and 1992 winter seasons differed significantly. The 1991 cores indicate that several tidal flooding events occurred before snow began to accumulate. Even within the overlying snow ice, layers high in salinity and sediments can be discerned. In contrast, it appears that heavy snowfall early in the 1992 season had the effect of absorbing and limiting tidal flooding. Sediment bands are not seen in the latter cores, probably because the sediment was removed from the floodwater as it was slowed by the snowpack.

Future work should include frequent winter field measurements of snow and ice thickness, along with additional cores. Dye could be used to mark the position of the snow surface at various times so that distinctive features found in the cores can be related to specific events (high tides, heavy rain, snowstorms). How sediments suspended in the flood waters settle out to form bands and how this process is altered by the presence of snow could also be investigated. The effect of different types of wetting (from rain, wicked-up tidal flood water, horizontal flow, brackish water) on the crystal morphology of snow ice is now being studied at CRREL.

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