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INTERPRETATION OF PRIMARY SEDIMENTARY STRUCTURES

Jon C. Boothroyd[1]

INTRODUCTION

The purpose of this trip is to investigate the nature and origin of stratification and cross-stratification in glacial sediments and in beaches (Fig. 1). The principles and interpretations are not new, indeed most have been well established in the literature for 5-10 years, and reported much earlier than that. What I have observed in 16 years of field work however, is that the patience and care needed to extract information on sedimentary structures from unconsolidated exposures is often lacking. The purpose of the trip is to demonstrate some techniques for preparing exposures and interpreting the results.

The techniques and equipment are absurdly simple: 1) long-handled, pointed shovels for the beach, together with a scraper to smooth the trench walls. I use an aluminum, custom-made trowel (a "magic scraper") first developed by Miles Hayes and myself at the University of Massachusetts. You MUST USE some kind of smoothing device to bring out the details of the stratification. For working in borrow pits in glacial sediments, swap the long-handled shovel for an entrenching tool (foxhole shovel). Use it with the blade locked at a 90° angle to the handle to rough finish pit faces, then fine tune with a scraper. The magic scraper does not work well in fine-grained silt and clay, so a variety of smaller trowels, filet knives, and spoke shaves have been employed. Lastly, use a proper scale for your pictures; one that is clearly graduated and easy to see. Lens caps, pencils and your foot are decidedly second best, and very few Recent and glacial sedimentologists carry a hammer.

REVIEW OF BEDFORMS AND CROSS-STRATIFICATION

This quick review will serve to set the stage for the sedimentary structures you will see on this trip. Please refer to Harms et al. (1975), Walker (1979), or Blatt et al. (1980) for excellent discussions in detail.

Bedform morphology changes with increase in flow strength from straight-crested bedforms, often called 2D, to highly irregular cuspate, or lunate shaped crests (3D) (Fig. 2). As flow strength further increases, the bed is planed to a flatbed configuration. Many different bedform classification schemes have been proposed based on increasing flow strength; Simons and Richardson's (Fig. 3B) is perhaps the best known. Figure 3A lists the scheme in general use by the Coastal Research Division at the University of South Carolina, and by our group at Rhode Island.

The sedimentary structures or stratification produced by the slipface migration

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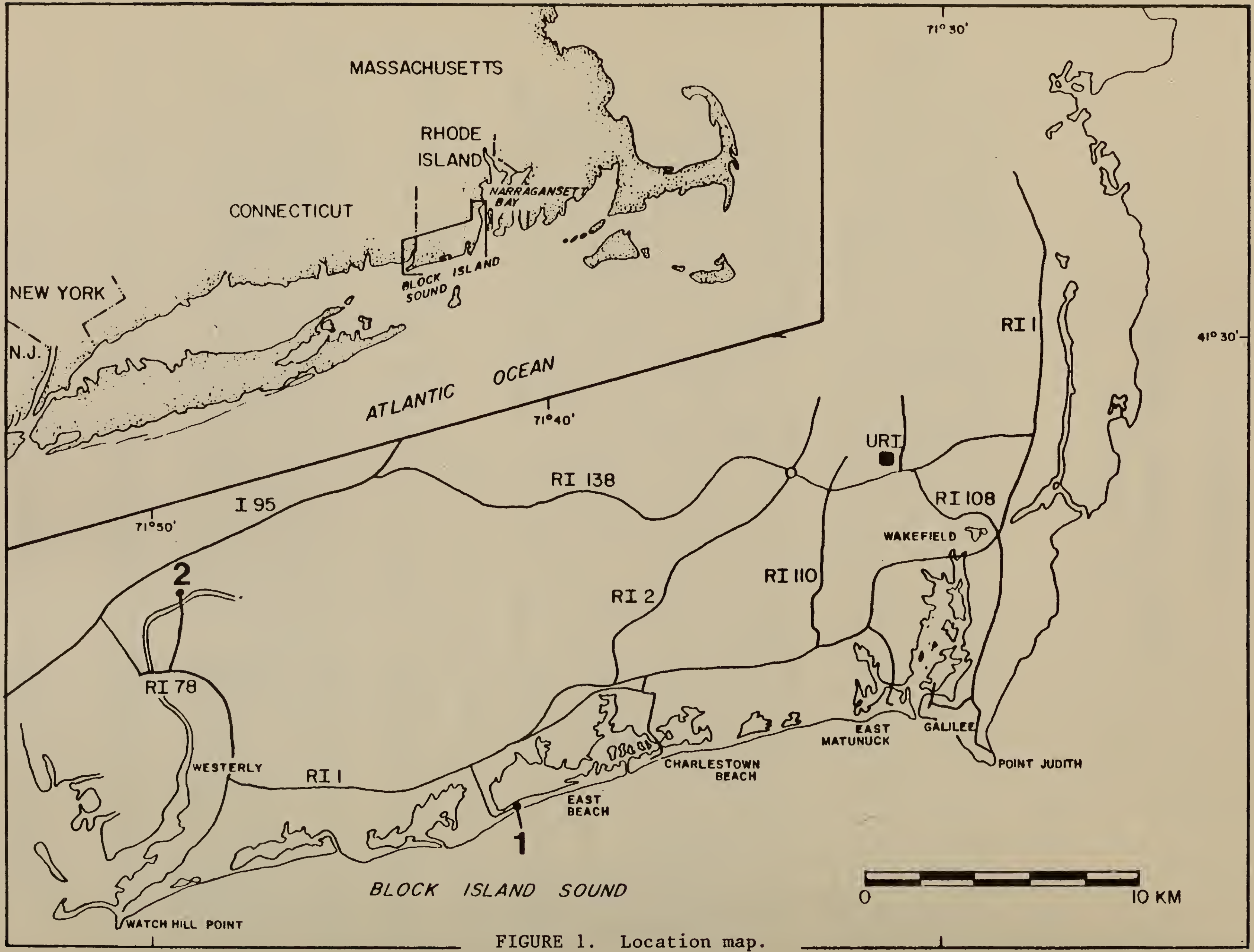


FIGURE 1. Location map.

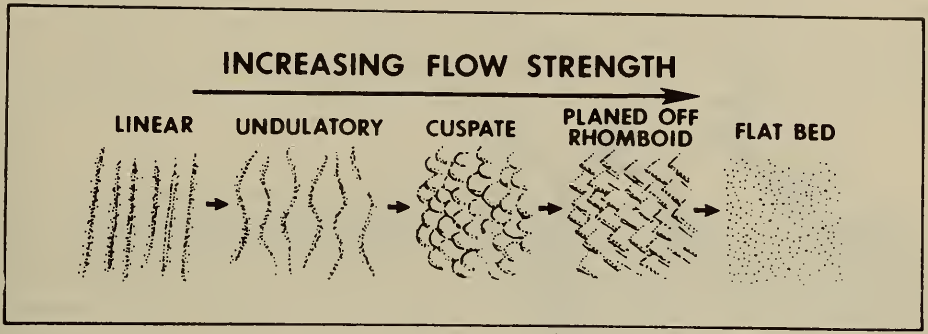


FIGURE 2. Change of bed morphology with increasing flow strength (from Hayes and Kana, 1976).

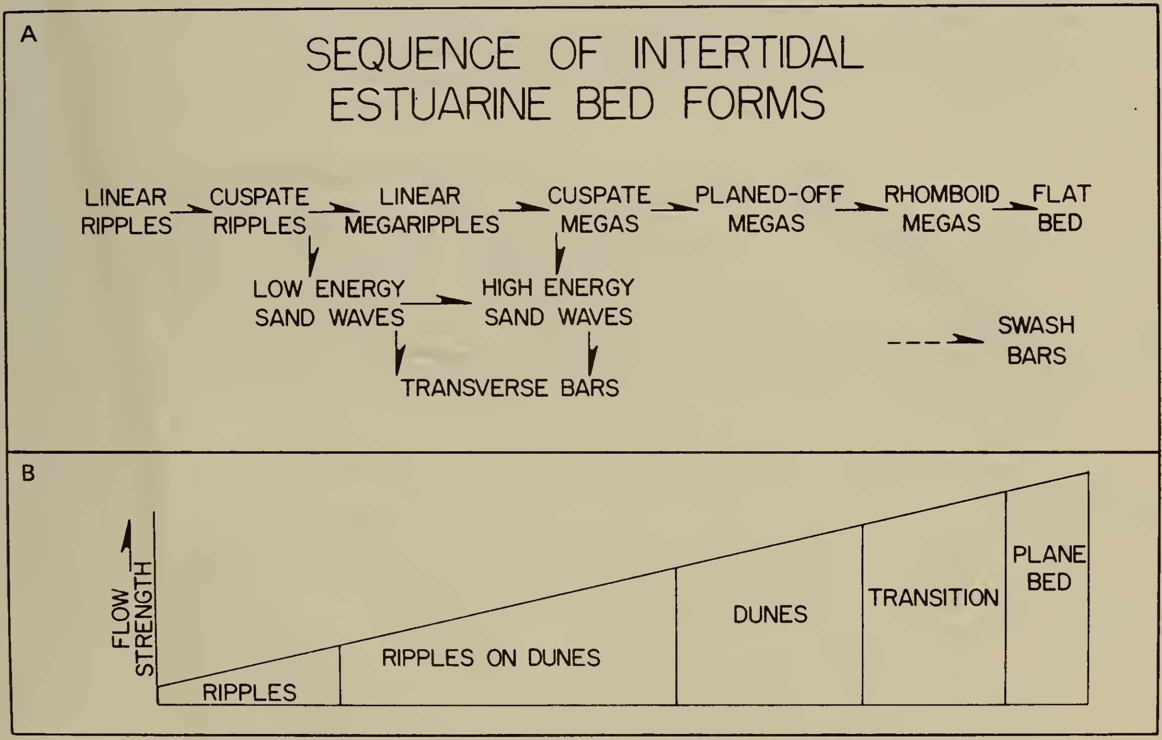
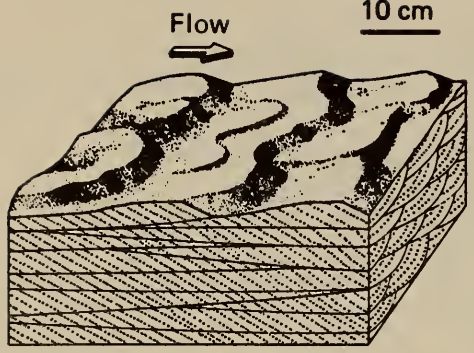
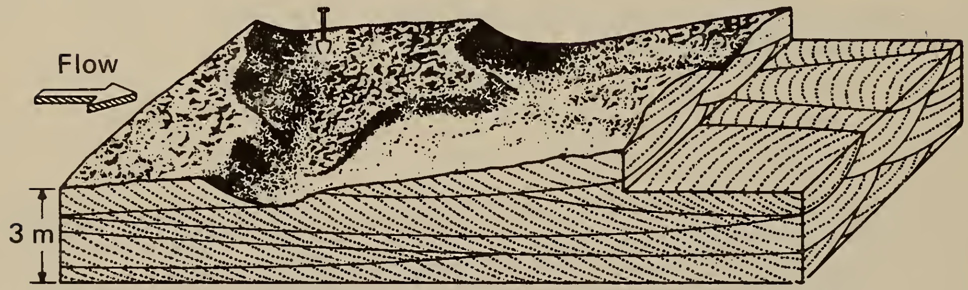


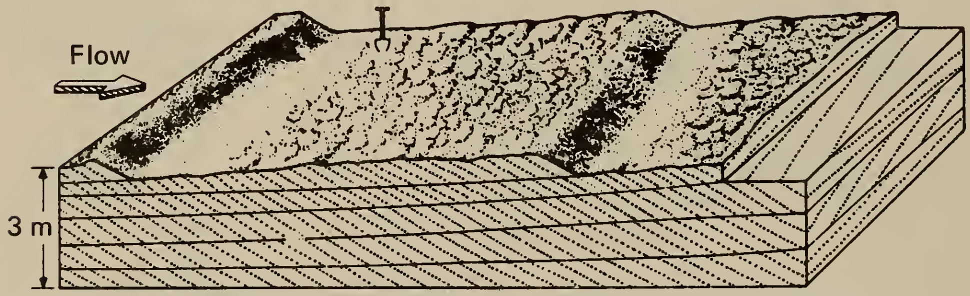
FIGURE 3. Bedform classification schemes (Boothroyd, 1978).
A. System developed for mesotidal estuaries.
B. Simons and Richardson's (1961) classification.



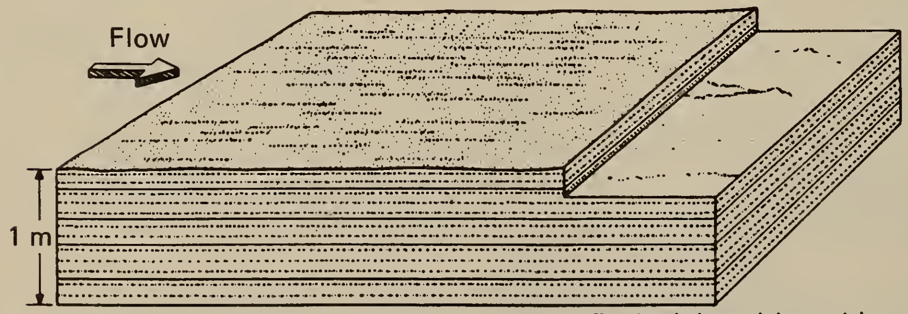
A. Small-scale trough cross-stratification produced by migrating cuspate ripples.



B. Large-scale trough cross-stratification produced by migrating cuspate megaripples.



C. Large-scale tabular cross-stratification produced by migrating linear sand waves.



D. Horizontal stratification produced by upper flat bed deposition with current lineation. Internal surfaces show parting lineation.

FIGURE 4. Stratification types produced by the migration of various bedforms and bed configurations (modified from Harms et al., 1975).

of bedforms (and by flat bed configuration) are illustrated in Figure 4. The morphology of the bedform exerts a strong influence on the form of the internal cross-stratification and the nature of the bounding surfaces. Cross-stratification type can be linked to bedform scale and morphology, and bedforms can be tied to the strength of flow generating the bedform. Thus we can examine sedimentary structures and say something about the energy of the depositing current.

EAST BEACH

East Beach, Stop 1, is a low, narrow, microtidal barrier spit, 5.0 km long, connected to the mainland at Quonochontaug Neck and extending eastward to the Charlestown breachway (Fig. 1,5). The beach exhibits a mature depositional profile consisting of a high flat berm and a steeply dipping beach face (Fig. 6A). The recovery profile after storms is an example of a classic ridge and runnel (Fig. 6B). The ridge, or swash bar, quickly welds to the incipient berm several days after the storm passes. See trip B-9 for more details on the coastal geology of the Rhode Island south shore.

Beach Stratification - Most stratification found in beaches is formed by the dual process of swash uprush and backwash on the beach face and on the berm top. Flow is under upper-flow regime, flat-bed conditions that deposits plane lamination. The pulsating nature of the wave-generated swash gives rise to a series of sets of plane lamination separated by very low-angle truncations as depicted in Figure 7A. Important features to note are: 1) general seaward dip of the lamination; 2) the low-angle truncations between the sets; and 3) the erosional nature of the set contacts. Laminae deposited on the beach face dip seaward at angles of 2-10^{0}, but laminae deposited on the berm top may be horizontal, or dip slightly landward (1-2^{0}). Figure 8A illustrates beach face and berm top stratification; note the prominent truncation indicating an erosional event.

Another type of stratification found in beaches is tabular cross-stratification dipping in a landward direction (Fig. 8B). It is formed by the migration of slipfaces of swash bars (ridges) across the low-tide terrace. This process and type of stratification was first described in detail by Hayes (1969). The swash bars weld rapidly on the Rhode Island south shore and the tabular cross-stratification is usually overlain by over a meter of beach face and berm top plane lamination.

A third type of stratification, hummocky cross-stratification, has not been documented in beaches, but may indeed exist (Fig. 7B). Hummocky cross-stratification (Harms et al., 1975) has been described in various rock sequences (Walker, 1979; Harms et al., 1965; Howard, 1972) but not yet described in Recent sediments. It is thought to form on the shoreface under storm-wave conditions that induce unidirectional surges. However, these conditions are duplicated on erosional low-tide terraces, so "hummocky" or H.C.S. may exist on beaches. Look closely.

BOOM BRIDGE BORROW PIT

The borrow pit is located just over the Pawcatuck River in Connecticut, in the Ashaway 7½ minute quadrangle. Schafer (1968) mapped the area as glacial stream and lake deposits of the Chapman Pond - Green Fall River sequence. Sedimentation occurred during late Wisconsinan deglaciation as a series of small deltas built into ponds and small lakes that were totally filled and then capped by fluvial gravel. The ponds were adjacent to, and partially formed in, stagnant ice that

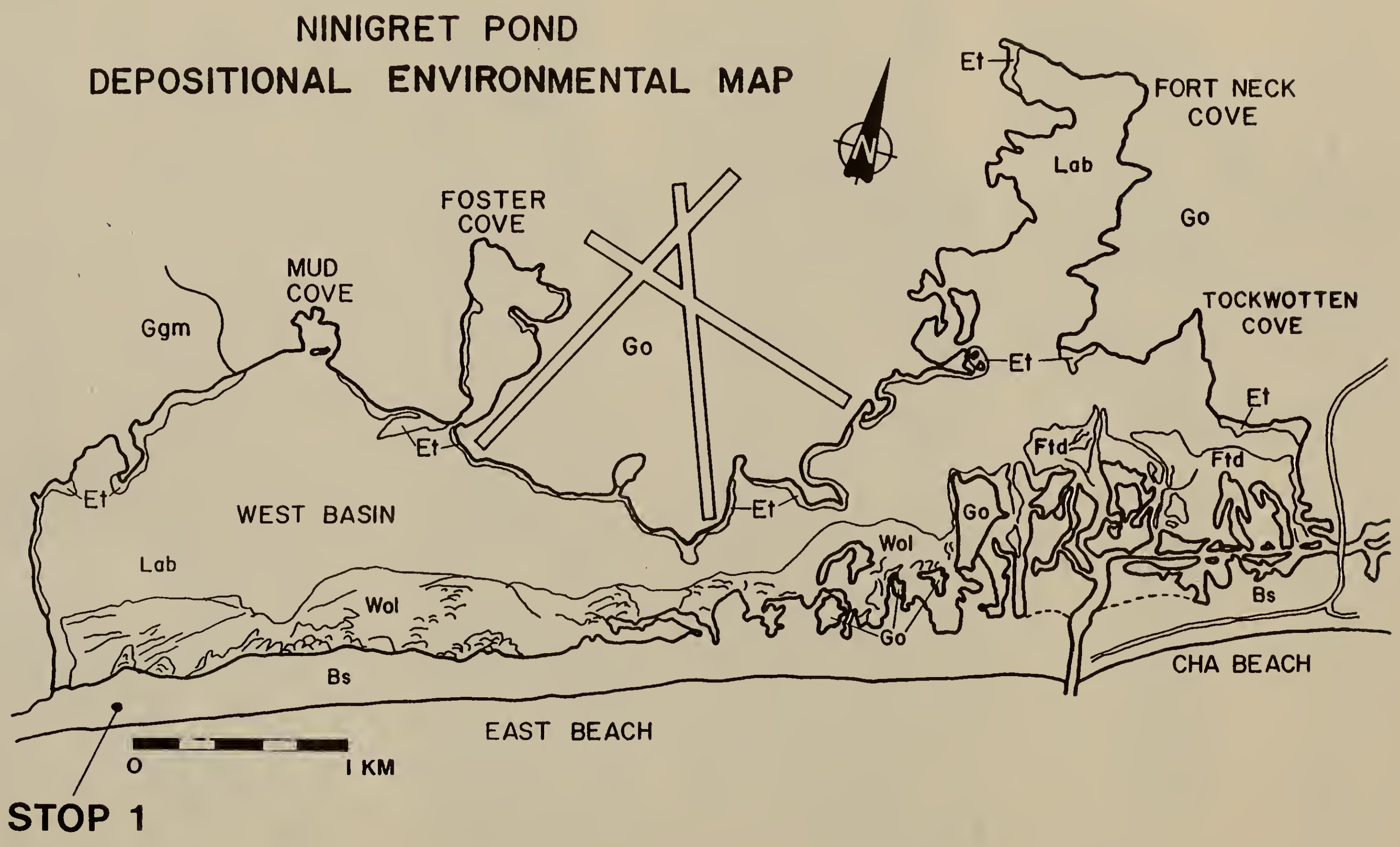


FIGURE 5. Simplified depositional environmental map of the East Beach, Ninigret Pond area. Bs: barrier spit; Wol: washover platform; Ftd: flood-tidal delta; Lab: low-energy lagoon; Et: erosional terrace; Go: glacial outwash; Ggm: ground moraine

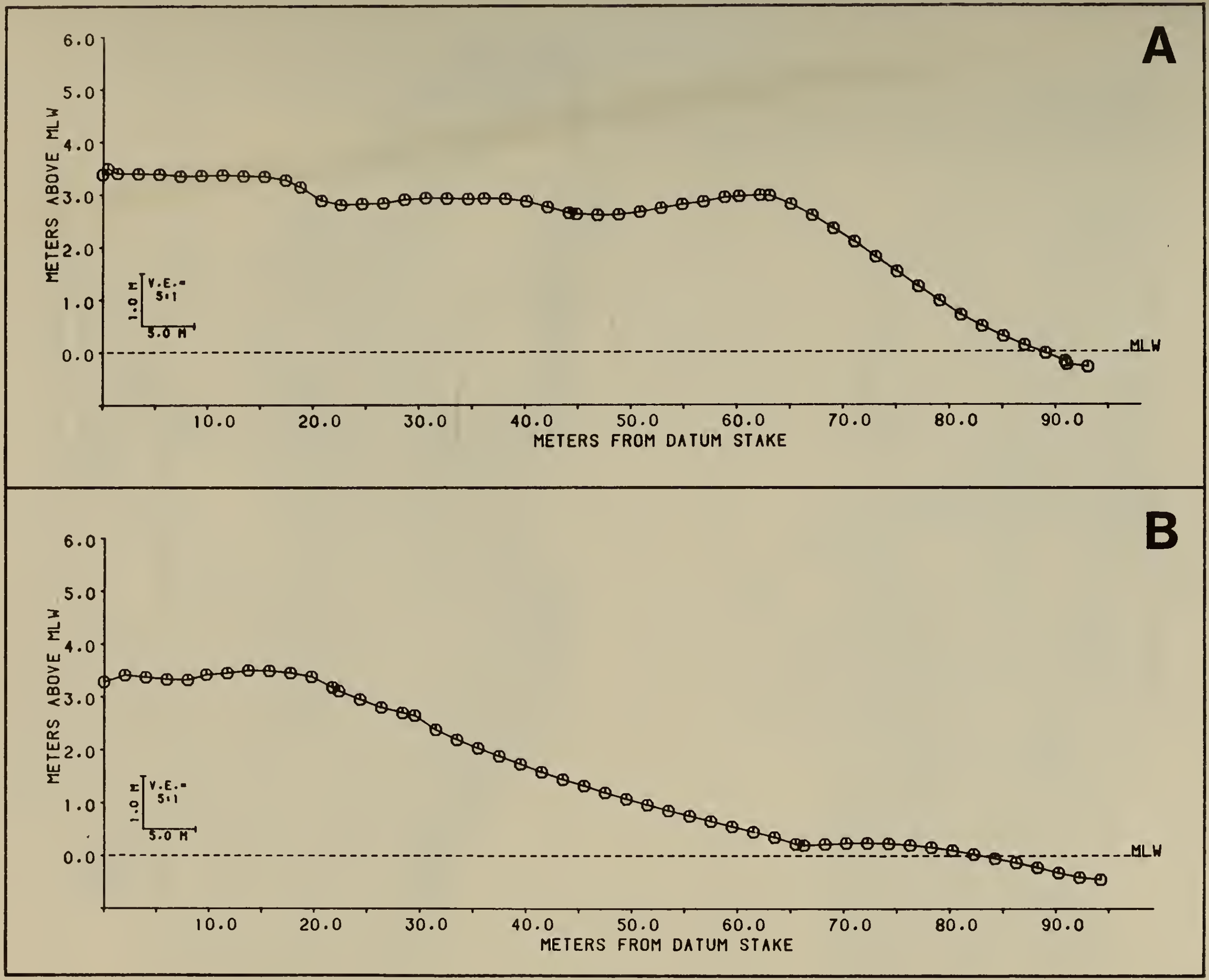


FIGURE 6. Typical profiles of beaches on the Rhode Island south shore.
A. High depositional profile, late summer 1979.
B. Erosional storm profile, October 1980. Note the small swash bar.

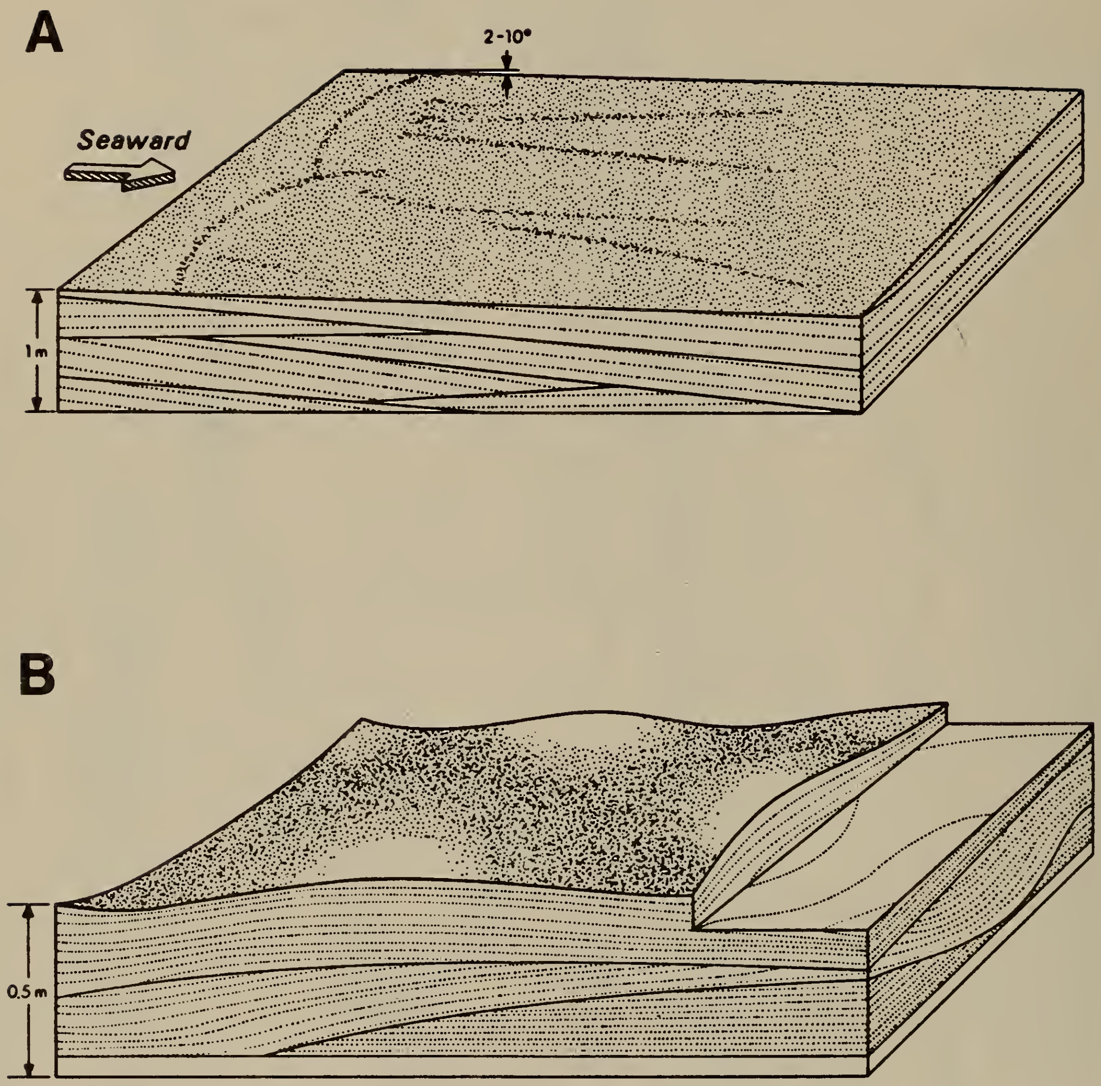


FIGURE 7. Beach and shoreface stratification types (modified from Harms et al., 1975).

A. Swash-generated stratification, the most common type found in berms. Note the low-angle truncations.

B. Hummocky cross-stratification, thought to be formed on the shoreface by storm waves.

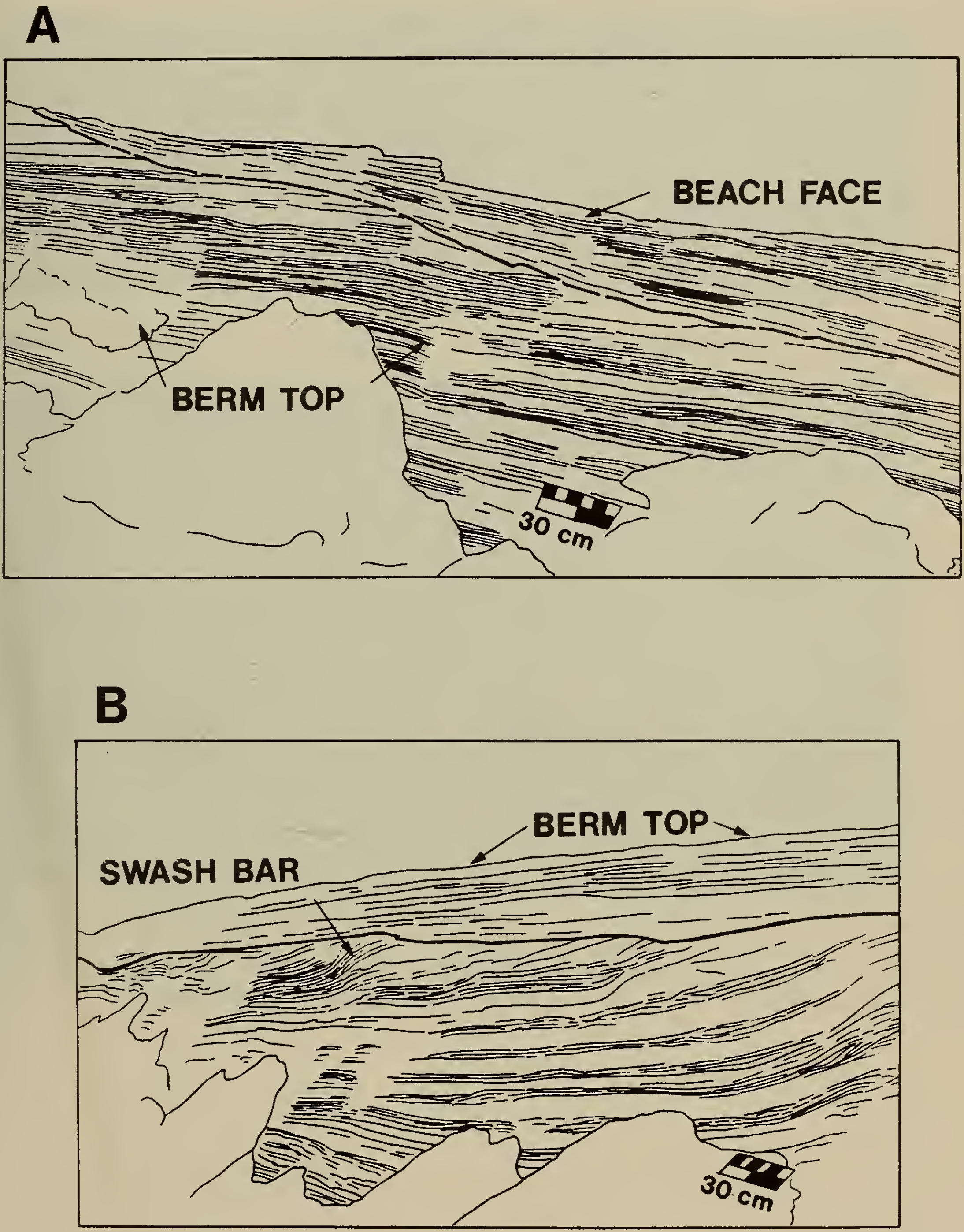


FIGURE 8. Sketches of trench faces illustrating stratification types (modified from Hine and Boothroyd, 1978).

A. Beachface and berm top stratification.

B. Tabular cross-stratification produced by a migrating swash bar, overlain by berm top strata.

melted and led to sediment collapse and formation of deformational structures. These sedimentary units are ice-contact lacustrine-fluvial morphosequences in the terminology of Koteff (1974) and Koteff and Pessl (1981).

Ripple-drift cross-stratification (climbing ripples) - The migration of cuspate ripples, utilizing the sediment supply of the bed alone, gives rise to the stratification seen in longitudinal section in Figure 4, i.e., sets of uneven thickness with erosional, and more or less horizontal top and bottom bounding surfaces. With the addition of sediment supplied from suspension, the ripples accrete upward as well as migrating forward. The preserved ripple form "drifts" or climbs at an angle to the horizontal. Jopling and Walker (1968) have classified the cross-stratification resulting from this type of ripple migration as follows:

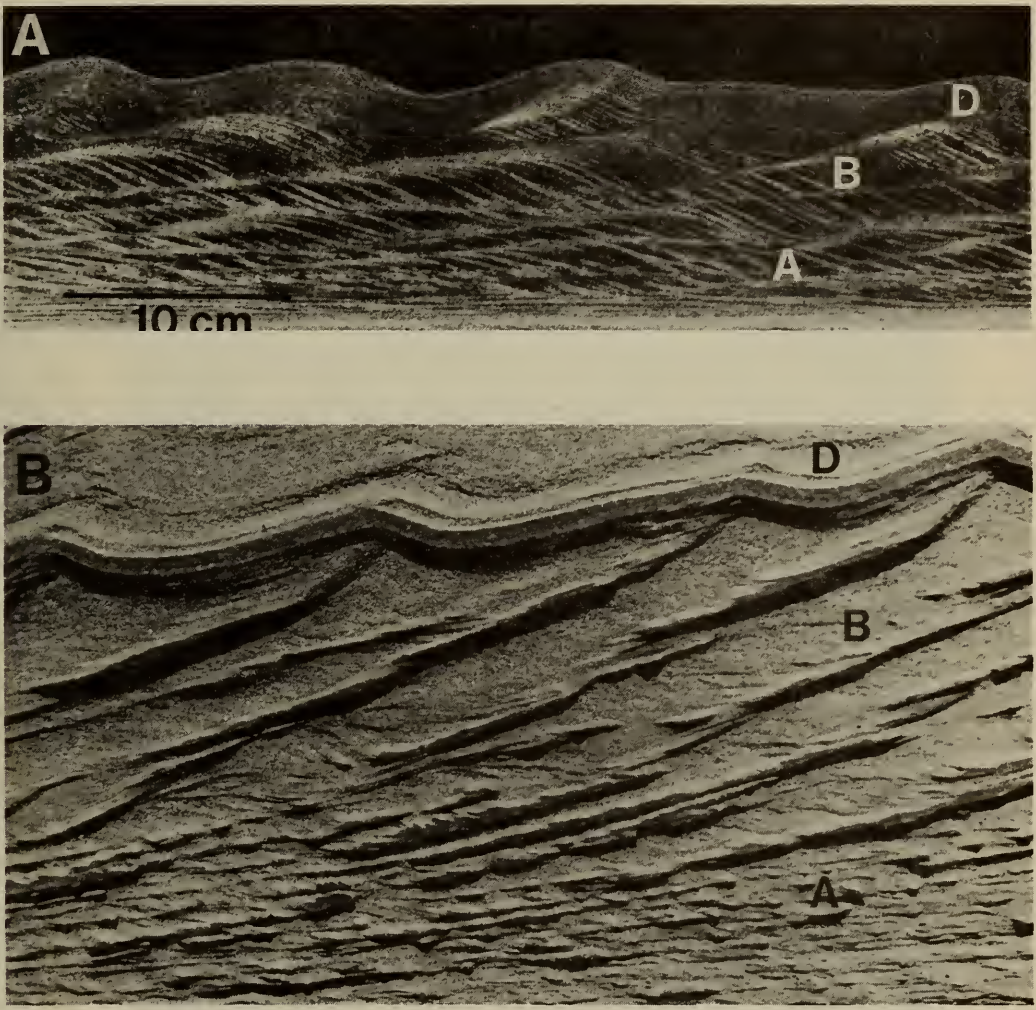
1) Type A - high energy, low angle of climb, no stoss-side preservation;

2) Type B - low energy, high angle of climb, stoss and lee side preservation.

Draped lamination as defined by Gustavson et al. (1975), is a third type that is found when sediment fallout from suspension is deposited on the bed below the threshold of ripple migration. The three types are shown in Figures 9 and 10.

Turbidity Currents and Depositional Sequences - Studies by Ashley (1975), Gustavson (1975), Gustavson et al. (1975), Shaw (1975), and many other workers have shown that the stratification of glacial-lake deltas was formed by density underflow or turbidity-current flow. Sediment-laden meltwater plunged beneath the lake surface, down the delta front and prodelta slope, and out across the lake floor. Coarser sand was deposited nearer the source of the flow, fine sand and silt on the prodelta, and fine silt and clay on the lake floor to give a proximal to distal turbidite sequence. As the flow strength decreased in any one turbidity-current event, a sequence of Type A ripple-drift cross-stratification, followed by Type B, and then draped lamination would be deposited. This sequence ranging in thickness from 10 - 50 cm, is deposited in a matter of a few hours according to Ashley et al. (in press). Figure 10 illustrates a typical sequence.

Varves - Varves, defined as silt/clay couplets deposited in one year, were shown by Ashley (1975) to be deposited by the distal portion of turbidity currents. Prodelta ripple-drift sequences are sometimes bounded on the top and bottom by clay layers, and may be considered proximal varves. Both distal and proximal varves may be seen in this pit, but can be difficult to decipher.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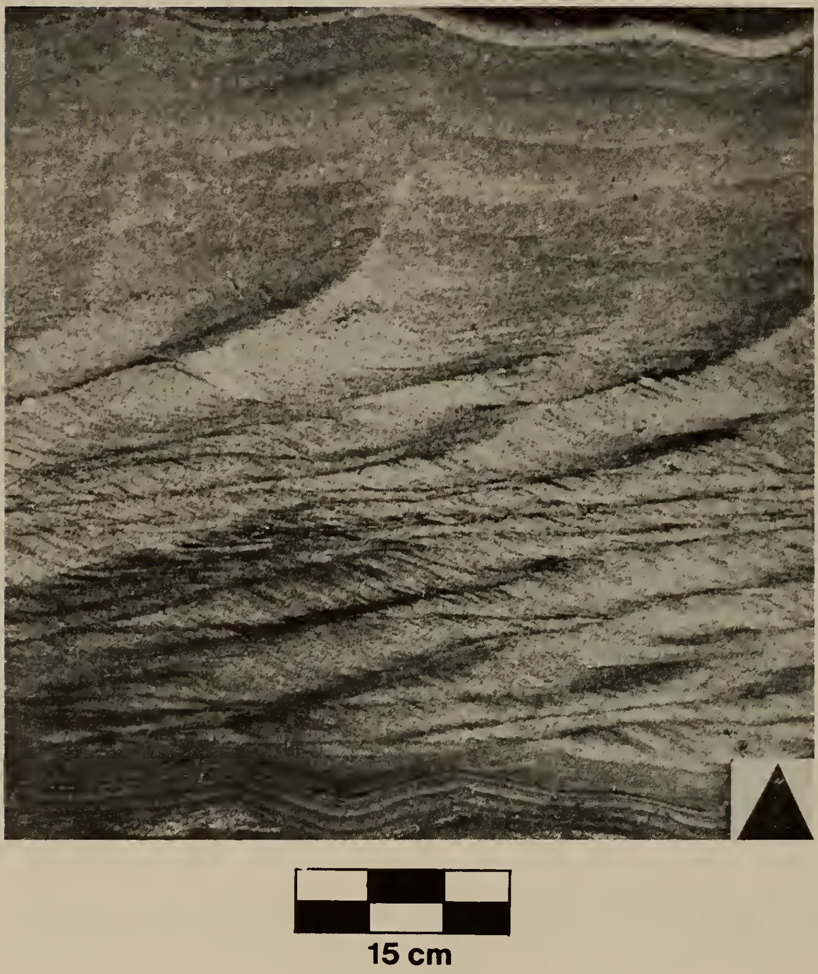

FIGURE 10. A depositional sequence deposited by one turbidity-current event (from Gustavson et al., 1975).

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Itinerary

The trip will leave from the Keaney parking lot by the athletic fields, University of Rhode Island. The return to the University is by a different, and shorter route, than the trip out. Long-handled shovels, entrenching tools, and scrapers are mandatory to uncover and prepare the trenches and pit faces for proper viewing.

Distance (In Miles)		Route and Stops
Pt. to Pt.	Total	
0	0	Leave Keaney parking lot, turn right (west) on RI 138.
0.6	0.6	Intersection of RI 110 at lights. Turn left (south) on RI 110. This route also called Ministerial Road.
3.8	4.4	Tuckertown Four Corners, intersection of Wordens Pond Road on the right (west), and Tuckertown Road on the left (east). On ice-contact deposit is just north of the Charlestown end moriane. Proceed south through the intersection and up onto the moraine.
0.7	5.1	Backside (ice-contact slope) of Charlestown moraine.
1.3	6.4	Intersection with old Post Road, and beginning of proximal outwash plain. Proceed south to US 1.
0.2	6.6	US 1, go west past exits to Moonstone, Green Hill, and Charlestown Beaches.
4.3	10.9	RI 2 exit (north).
2.0	12.9	Exit to former Charlestown Naval Air Station and to Burlingame State Camping Area. The Air Station (now closed)was the proposed site for a nuclear generating station.
0.9	13.8	View of Ninigret Pond, a coastal lagoon, to the left (south). East Beach barrier spit is visible south of the lagoon.
1.2	15.0	Exit left, across median strip at East Beach sign; also at Dunn's Corners Fire District, Station #2, Quonochontaug; and Quonochontaug Grange Hall. Go east on US 1, 0.1 mile to East Beach Road, turn right and proceed south.

1.2	16.2	East Beach barrier spit; turn left (east) and go to State parking lot.
0.2	16.4	STOP 1. East Beach barrier spit, a microtidal barrier dominated by overwash processes. The depositional beach profile exhibits a high, wide berm top and steep beach face. The post-storm recovery profile is a classic ridge and runnel, often with multiple "piggyback" swash bars. Salt marsh peat is well-exposed on the low-tide terrace after severe storm events. Deep trenches dug in the berm will expose stratification deposted during the storm and recovery cycles. Return to US 1.
1.3	17.7	US 1, turn right (east) go 0.2 miles to first U-turn in median, head west on US 1. Pass Quonochontaug, West Beach, RI 216, and Weekapaug Beach exits. Cross over the Charlestown moraine.
3.8	21.5	Dunn's Corner; go west through lights at intersection; pass the Westerly airport that is located on a kame plain north of the moraine.
2.0	23.5	Intersection (lights) with RI 78, Westerly Bypass. Turn right (north).
2.5	26.0	Exit 4, RI 3. Exit and turn left (south on RI 3.
0.7	26.7	T-intersection, turn right (north) on Potter Hill Road; pass under RI 78 to intersection with Boom Bridge Road.
0.6	27.3	Stop sign, Boom Bridge Road. Proceed straight through intersection (north).
1.3	28.6	Boom Bridge over Pawcatuck River; enter Stonington, Ct. Turn left just over bridge onto borrow pit access road. Note: secure permission from pit owner at the house nearest the pit entrance.
		STOP 2. Boom Bridge borrow pit. This pit is in Chapman Pond-Green Fall River glacial stream and lake depostis (Qgc4) of Schafer (1968). Depositional environment was a kame plain with numerous small kettlehole ponds that were filled by lake floor, and delta front and slope deposits, capped by fuvial gravel. Numerous active and inactive faces display proximal varves, and

abundant ripple-drift cross-stratification deposited on complexly interbedded delta lobes. Faulting, deformational structures, and rotated beds are locally abundant due to melting of buried ice. Flow till also is present. Extensive walking about is advised because the pit is 1/2 mile long with active workings that change often.

0.0	0.0	Easy route to U.R.I. Leave pit and proceed straight ahead (north) on Boom Bridge Road; do not turn back over the bridge. Go up hill onto a large kame plain; bear left at Anthony Road (0.8 miles) to stay on Boom Bridge Road.
1.1	1.1	Pass over I 95
0.5	1.6	Intersection with CT 184, New London Turnpike. Turn right (east).
0.6	2.2	Intersection with CT 216 and I 95. Turn right, go under I 95, turn left up the northbound on-ramp of I 95. Proceed north on I 95.
7.4	9.6	Exit 3A, to RI 138 east. Exit and turn right (east) on RI 138.
2.0	11.6	RI 112 intersection.
5.2	17.8	RI 2 rotary.
1.4	19.2	RI 110 intersection.
0.6	19.8	Keaney parking lot, URI

END OF TRIP

Advances, retreats, readvances, and surges in the glacial story of southern New England

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University of Massachusetts

To my colleagues who do not know much about the glacial geology of southeastern New England and for whom a modern summary article would have been useful, I apologize for not writing it. Such an article could only be written by J. P. Schafer, whose lifetime of work in this area is unmatched by any, but who was not available. Instead I have chosen to write briefly about a few of the problems of the Pleistocene in southern New England that we may encounter. If you feel the need for an overview, read Schafer and Hartshorn (1965), which is still the only general summary on the Quaternary of New England available.

More than 140 years ago E. H. Hitchcock gave the earliest real endorsement to the glacial theory in New England. Today, after innumerable field conferences and 72 (?) previous meetings of the NEIGC, the glacial geology of southern New England and the Quaternary history it reveals are still largely unresolved. The field trips we glacial (or Quaternary) geologists will undertake here at this 1981 meeting of the NEIGC will show us several aspects of glacial process and stratigraphy. Skepticism is invited. After all, geology is still growing and adding new hypotheses. Publication of maps or articles do not render truth, but they are tangible platforms on which to build. Progress in glacial geology is fitful; it acts like the glacier itself--in advances, retreats, readvances, and, to make the most far-out comparison, surges.

In 1976, I listed what seemed to me to be the major unsolved problems in the New England Quaternary (Hartshorn, 1976). Those problems, in brief, are the number and extent of the glacial advances, the ages of the tills, the origin of the upper and lower tills, the details of deglaciation, the paucity of meaningful radiocarbon dates, the origin and meaning of glaciofluvial sequences (for which I would now substitute morphosequences, see Koteff and Pessl, 1981, p. 6), the late-glacial and postglacial isostatic readjustment. At that time I was somewhat pessimistic about resolving these problems and suggested that old-fashioned detailed quadrangle mapping seemed to be the solution. Today I am more optimistic. It is true that quadrangle mapping has provided the basic data for larger scale interpretations, and it also is clear that those geologists with this kind of experience have lately been able to expand their data base as they compile maps of larger areas, so that we are experiencing a readvance in knowledge once more.

From the earliest studies in New England, the ideas on how the glaciers accomplished the results we see in today's landscapes have waxed and waned as fitfully as the glaciers themselves. Some of the ideas on glacial history or processes have gone essentially in one direction (an advance). For instance, after the early statements about the advance of the ice sheet to the two great outer moraines (Chamberlin, 1883), the first maps of the "terminal" moraines on Cape Cod showed the moraines extending continuously from the Elizabeth Islands (or Woods Hole if we insist on remaining on the mainland of the Cape) all the way around the western, northern, and eastern sides of the Cape, and as far north as the modern beach and dune area of Provincetown. The myth of the "interlobate moraine" extending up the forearm of the Cape lingered for many years (Mather, 1952), despite Grabau's (1897) recognition of the great westward-sloping outwash-delta plains fed from the easternmost lobe of the ice. Since those early ideas, the moraines have shrunk to the Sandwich and Barnstable Moraines (Woodworth and Wigglesworth, 1934) and most lately to the present interpretation, in which the moraine ends to the east in Yarmouth (Oldale, 1974). In these interpretations, we have seen a steady retreat in the extent of the moraine, a result of detailed mapping on the increasingly better maps as the U.S.G.S. went from 1:62,500 to 1:24,000 and from 20-foot to 10-foot contour intervals.

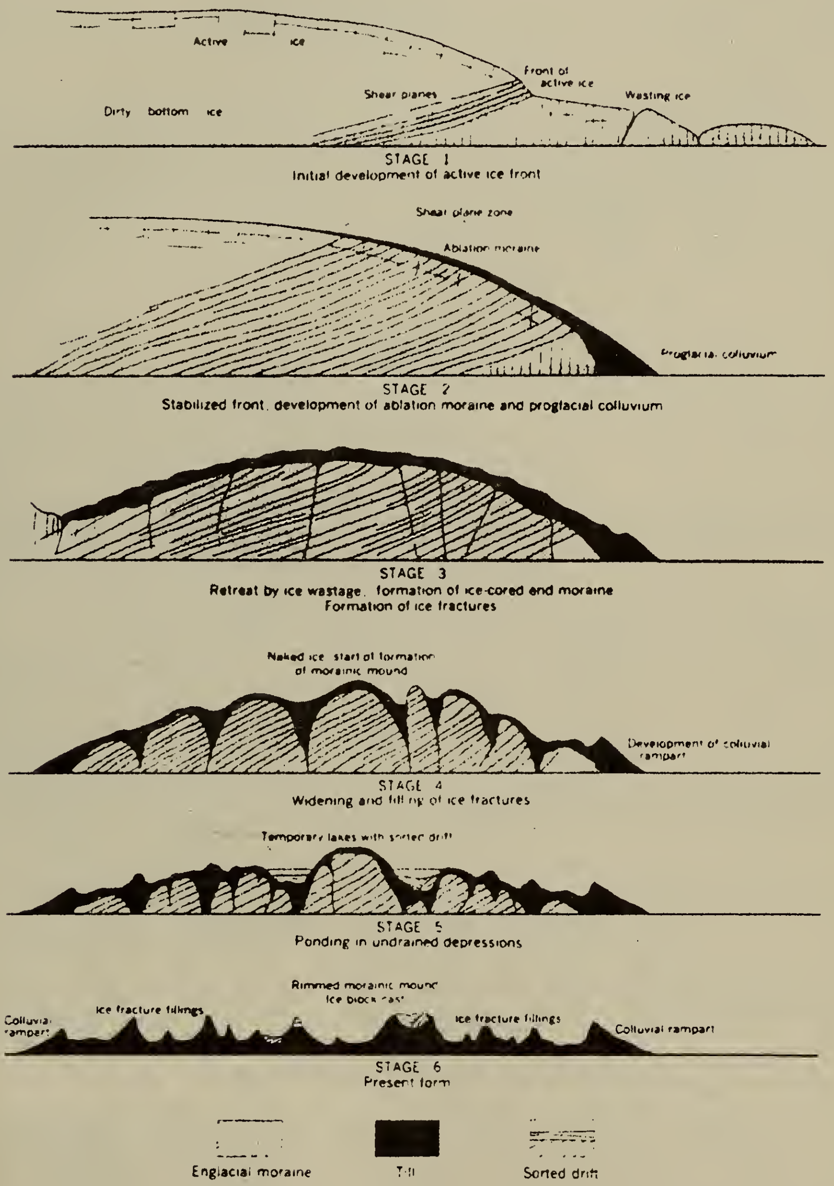
With the better maps, ideas about the nature of the end moraine have changed. The Charlestown Moraine, which we will visit, was long thought of as an ordinary pile of debris pushed up at the terminus of a normally retreating glacier. Tectonism on a small scale is usually implied in the term moraine; the ice pushes up a ridge of generally unstratified debris in front of it. Kaye (1960), however, using air photos and modern maps, took a closer look at the internal textures and structures and external forms of the Charlestown Moraine and gave us different ideas about the great load of debris deposited at the stagnant margin of the receding ice and the subsequent development of an array of stagnation phenomena: ice-block casts, deformed lake deposits with flowtill, marginal ridges or colluvial ramparts, and variously oriented till ridges or ice-fracture fillings within the borders of the moraine. Schafer's later work (1965) at Watch Hill, R.I., extended the work of Kaye to the west; his map explanation implies the same origin given by Kaye. Although no retreats from Kaye's ideas have been documented, still a residue of doubt exists. Can that huge moraine--2 miles wide at its east end, mostly about a mile wide, although narrowing to about a third of a mile; about 20 miles long; with ridges of from a few feet to 80 feet high and (in the Kingston quadrangle) 1 to 2 miles long; and numerous roughly circular mounds tens of feet high--have formed from the debris brought to the glacier terminus during the limited number of years available to build that moraine? And could that much debris be incorporated in a stagnant ice zone with no replenishment (Figure 1)?

The amount of debris that must be carried to the end and to have accumulated supraglacially on that ephemeral stagnant ice margin in order to produce such large features is staggering. Still, if we wish to retreat from Kaye's ideas prior to a readvance or surge in knowledge, what better solutions have been offered? The "dirt machine" of Koteff and Pessl (1981) would be sufficient to bring debris, perhaps, but where is the evidence of meltwater runoff?

A waxing, waning, and waxing of ideas in glacial history has occurred in the mapping of minor moraines. Although Black (1981) denies the presence of several lines of moraines along the southern coast of Connecticut, it is clear that in general our ideas have turned from one of no moraines (save Fishers Island as part of the Charlestown-Harbor Hill morainic complex) to one where Goldsmith (1981) sees segments of moraine comprising five separate named moraines, several of which are double.

Some early maps of Massachusetts (Antevs, 1922) depicted linear end moraines, which were later ignored in part (Hartshorn, 1967) in favor of the idea that they were a series of high kames emplaced, for whatever reason, in a

Figure 1. Schematic north-south cross section of the Charlestown Moraine (Fig. 56 from Kaye, 1960, p. 367). U.S. Geological Survey.



number of areas and parallel to the ice front. Thus the Middleborough Kame Moraine of Mather (1952) retreated from the scene only to readvance again in Larson (1981). Certainly the geologist recognizes notable morainic segments (Koteff, 1964) and has mapped them. Now the question here, as in the Connecticut Valley (Hartshorn and Koteff, 1967; Larsen and Hartshorn, 1981), is how to align high kames along the margin of a retreating ice mass. They then are perhaps not moraines in the classic sense, but must somehow be related to the terminus of the ice sheet (Stone and Peper, 1981).

The large surficial maps at 1:125,000 in Connecticut and 1:250,000 in Massachusetts, now being compiled by the U.S.G.S., may signal a surge, or at least a readvance, in the mapping and interpretation of moraines in southern New England. The field trips led by Les Sirkin and J. P. Schafer at this 73rd (1981) meeting of the NEIGC should leave us with as many questions as answers.

Another area of glacial interpretation that has undergone changes of direction is the mode of deglaciation. We generally subscribe to a general retreat to the northward, with thinning of the ice and the appearance of nunataks near the margin. Some have viewed the ice as active to the outermost parts (Lougee, 1951); others, however, use the doctrine of stagnation-zone retreat (e.g., Jahns, 1941; Koteff, 1964; Koteff and Pessl, 1981). For a short period, R. F. Flint of Yale, as a young man, misled by bad topographic maps and his own misinterpretation of field evidence, advocated a north-to-south retreat, which he quickly disavowed. A major geological opponent (thoroughly ignored by Flint), R. J. Lougee of Clark, never ceased to point out his lapse from grace. This controversy of the 1930's may now be renewed in a modified form in the 1980's as Black (1981) minimizes the concept of stagnation-zone retreat, except in local areas. He envisions regional thinning and basin-by-basin stagnation, with marginal retreat of inactive ice. May the arguments be long, detailed, furious, yet restrained and Friendly. Lougee, whose emphasis on "hinge lines" led him to devise a unique chronology for the late-glacial history of New England (Lougee and Lougee, 1976) that stands entirely alone, used as his most valued mapping (and process) criterion the contact between the topset and foreset beds of deltas or deltaic kame terraces (altitudes sometimes inappropriately measured to the hundredths of a foot; Lougee, 1971). New England geologists have always recognized the deltaic contact, never giving it the interpretation or the importance Lougee did in the many glaciofluvical-appearing stream valleys of southern New England. Lately, U.S.G.S. surficial quadrangle maps have been published that extend some of Lougee's ideas on that contact, as well as using much other substantial geologic data, to show the ubiquity of glacial lakes and ponds, for instance in southeastern Massachusetts (Volckmann, 1975; Stone and Peper, 1981). But where Lougee saw only marine water bodies with uptilted marine terraces, present-day workers see topographically controlled extensive river-valley lakes, held in by bedrock, till, or ice spillways or outlets, whose bottom deposits are commonly covered by glaciofluvial sands and gravels of topset beds or graded deposits on the lake beds.

Lately the vexing problem of the tills of New England underwent a long series of advances, retreats, and readvances. After a lengthy history of debate, traceable at least back to Upham, the problem of whether we have a general blanket that includes a lodgement till/superglacial till section (the lower till below the upper till) or two tills from different ice advances and different times (old till below the new till) is still with us. We have had continuous controversy until the present time. The multiple-advance-till faction (e.g., Pessl and Schafer, 1968; Newton, 1978) seems to be leading the way. As usual, part of the recent controversies centered around misunderstandings. The idea that one of the till sheets in the controversy (the Bakersville Till studied by Pessl and formally named by Newton) commonly turned out to have a less sandy lower and a more sandy, commonly stratified upper facies helped to confuse things throughout the whole of New England. If, then, we cannot even separate or identify the lithologic unit to which a till belongs, how can we map in detail the till deposits of the area? So far, we have not.

It is obvious that we have not solved all, or even most, of the problems in New England. A field trip can only be a progress report. Of the three trips that specialize in glacial geology, Block Island and Glacial Geology in Southern Rhode Island will touch on many of the controversial areas. The trip on Interpretation of Primary Sedimentary Structures will concentrate on process, but within features whose place in the late-glacial history is perhaps not fully known. Together they should leave us with an appreciation of the problems found in the glacial geology of southern New England.

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