Maine Geological Survey
Studies in Maine Geology: Volume 5
1989

Timing and Mechanisms for the Deposition of the Glaciomarine Mud in and around the Gulf of Maine: A Discussion of Alternative Models

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ABSTRACT

Glaciomarine mud in the Gulf of Maine, characterized by rhythmic seismic layers that mimic the morphology of the underlying surface, is composed of subequal amounts of silt and clay, variable amounts of sand, and sparse gravel-sized clasts. The mud is Wisconsinan in age and was deposited during the retreat of the last ice sheet. A beginning date of 38 ka, proposed by King and Fader (1986) in their chronology of the last deglaciation, is considered too old. An alternative chronology, more consistent with the continental record to the west, is proposed here. In this interpretation, deposition of glaciomarine mud began about 18 ka when the late Wisconsinan ice retreated from Georges Bank, Great South Channel, and Northeast Channel and ended around 11 ka, when meltwater ceased to enter the Gulf of Maine. Basal-till melt-out from an ice shelf and bergs as the source of the glaciomarine mud, also proposed by King and Fader (1986), is thought to be inconsistent with the volume, widespread rhythmic bedding, and low stone content of the deposit. More likely the source of the glaciomarine mud was rock-flour-laden meltwater that entered the sea along the grounding line of a calving glacier or by way of subaerial meltwater streams. The rock flour was then dispersed by sediment plumes and was deposited when the sediment fell to the sea floor, aided by flocculation and biological agglutination. Rhythmic layers within the glaciomarine mud could represent annual cyclic sedimentation (varves) or cyclic events of lesser duration.

INTRODUCTION

The Pleistocene sedimentary succession in the Gulf of Maine region (Fig. 1) consists, in most places, of stratified glaciomarine mud underlain and locally interbedded with till and coarse stratified submarine drift. The glaciomarine mud in coastal Maine is represented by the Presumpscot Formation (Bloom, 1960, 1963). In the eastern Gulf of Maine, the glaciomarine mud is represented by the Emerald Silt (King and Fader, 1986). The glaciomarine mud in the western Gulf of Maine has no formal name, but is well defined by two long cores in Stellwagen Basin (Tucholke and Hollister, 1973) and by seismic data (Oldale and Bick, 1987). The Pleistocene section is similar throughout the Gulf of Maine and in the emerged region adjacent to the Gulf, suggesting a common origin and geologic history. Despite this, there has been significant disagreement on the origin and history of the glaciomarine mud, for example, Smith (1984) and King and Fader (1986).

Smith, from studies in southwestern coastal Maine (1982, 1984, 1985) and Smith and Hunter (1989) proposed that deglaciation of the Gulf of Maine occurred between 17 and 13 ka, and that the Presumpscot Formation is a distal deposit of a marine-based ice sheet, the mud components of which were transported mostly as low density surface sediment plumes (overflows) and at times as high density turbidity currents (underflows). On the other hand, King and Fader (1986), using seismic data, core data, and radiocarbon dates from the Nova Scotia continental shelf and the eastern Gulf of Maine, proposed that the Gulf was fully

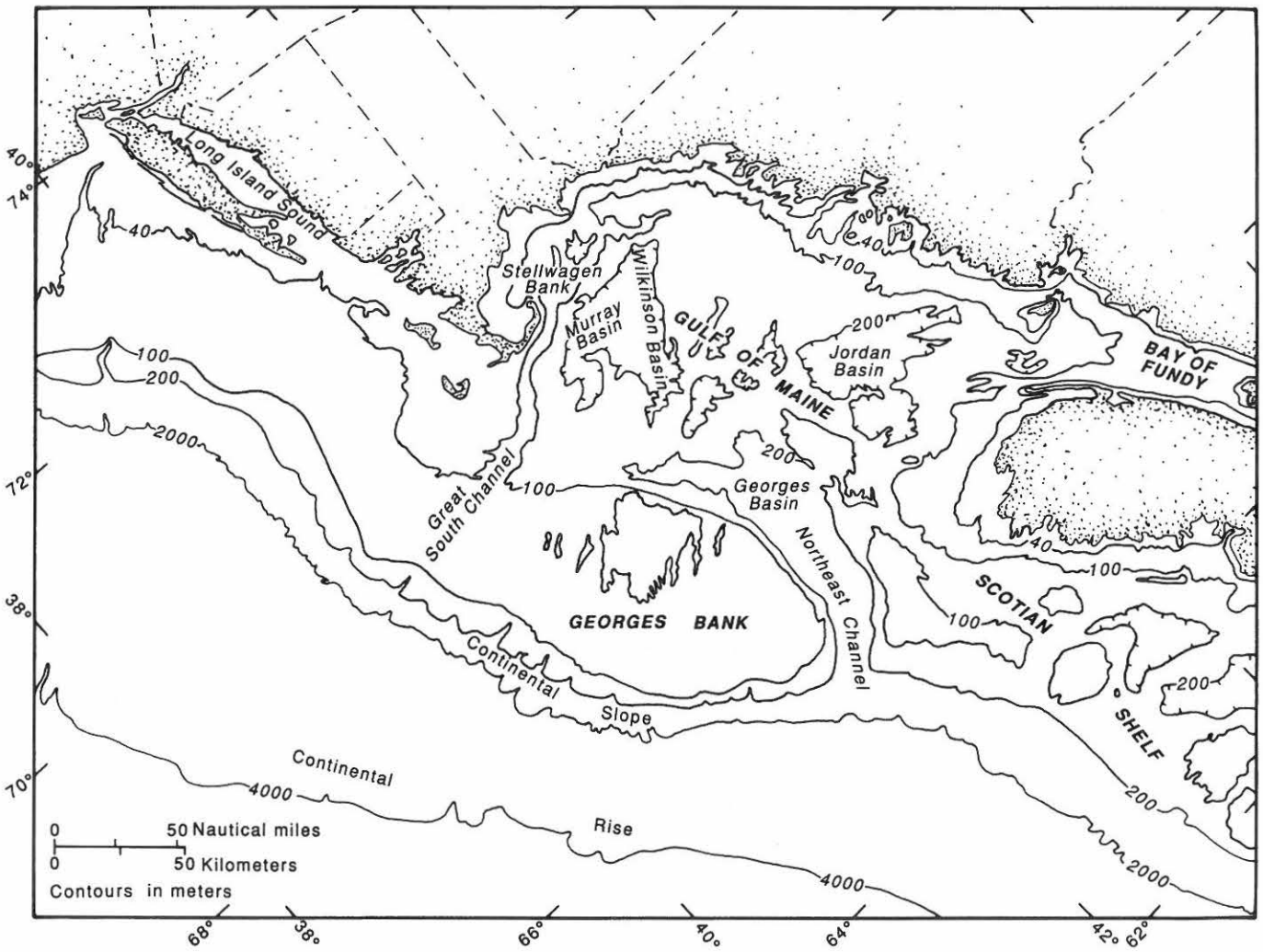

Figure 1. Index map of the Gulf of Maine and adjacent regions showing the major physiographic features.

glaciated throughout most of the Wisconsinan Stage and that deglaciation started about 38 ka. The Emerald Silt was considered by them to be mostly an ice-proximal sediment, deposited when basal till melted out of an ice shelf and sank through the water column to the sea floor. However, the model they proposed for the origin of the glaciomarine mud is inconsistent with some aspects of the deposit. Schnitker (1988) also proposed an ice shelf during deposition of the glaciomarine mud in the western Gulf of Maine, because the sediments lack a microflora. Others who have proposed an ice shelf in the Gulf of Maine include Hughes et al. (1985) and Belknap et al. (this volume).

DESCRIPTION OF THE GLACIOMARINE MUD

High-resolution seismic-reflection surveys have established the occurrence of glaciomarine mud throughout the western Gulf of Maine (Oldale et al., 1973; Oldale and Wommack, 1987; Oldale and Bick, 1987; Birch, 1984; Belknap et al., 1986; Kelley et al., 1986; Schnitker, 1988). Seismic-reflection profiles display the glaciomarine mud as an acoustically laminated unit in which the internal reflectors faithfully mimic the morphology of the underlying surface, generally bedrock or coarse-grained submarine stratified drift and till (Figs. 2 and 3). A generally thin upper part is acoustically less well laminated, having internal reflectors which tend to be more gently undulating than the layers below. Internal reflectors within the marine mud tend to be continuous and can be traced for kilometers; in places, they can be traced completely across a sedimentary basin.

Long piston cores from Stellwagen Basin and seismic profiles across the core sites (Figs. 3 and 4) allow a sedimentological interpretation of the seismic profile features of the glaciomarine mud. Cores (KN-10 and KN-27, Fig. 4) penetrated the Holocene marine mud, the glaciomarine mud, and a gravelly mud that was inferred to be till (Tucholke and Hollister, 1973).

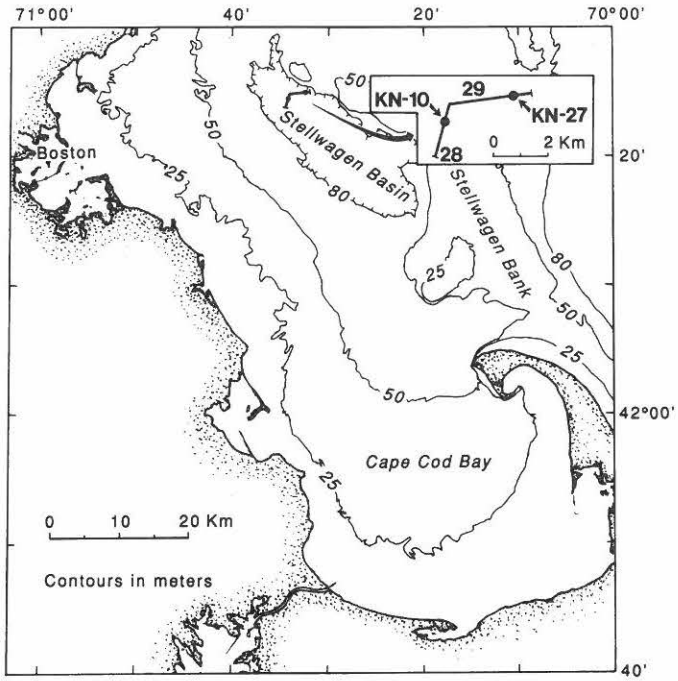

Figure 2. Map of the eastern Massachusetts offshore area showing the location of seismic lines 28 and 29 (Fig. 3) and long piston cores KN-10 and KN-27 (Fig. 4) in Stellwagen Basin.

The following description of the cores and the sedimentology of the glaciomarine mud is based on the Tucholke and Hollister (1973) paper. Glaciomarine mud in Stellwagen Basin consists of black, gray, and olive-green silty clay or clayey silt lacking prominent bedding or laminations. Thin sand pockets and sand laminae occur sparsely in both cores, and in core KN-27, sand is abundant between 16 m and 14 m, and between 6.5 m and 3.5 m. The upper sand interval overlies the glaciomarine mud and is Holocene in age. Except for the gravelly mud at the bottom of both cores, gravel-size clasts are absent. The mixture of silt and clay layers in bulk samples, along with minor amounts of sand, results in poor sorting. The layering and lack of coarse clasts make it unlikely that the deposit is a till. Quartz, mica, and feldspar are the most common minerals in the glaciomarine mud, and shells are sparsely distributed throughout.

Foraminifera occur within the glaciomarine mud and were studied by Schnitker (1975). A benthic foram (*Elphidium clavatum*) appears to be characteristic of the glaciomarine mud, as it is abundant in that deposit and absent in the overlying Holocene marine mud. A similar relationship was noted in the Emerald Silt where *Elphidium excavatum*, probably the same foraminifera as *E. clavatum* (C. W. Poag, pers. commun., 1987), dominates the silt, but it is sparse to absent in the overlying postglacial marine sediments.

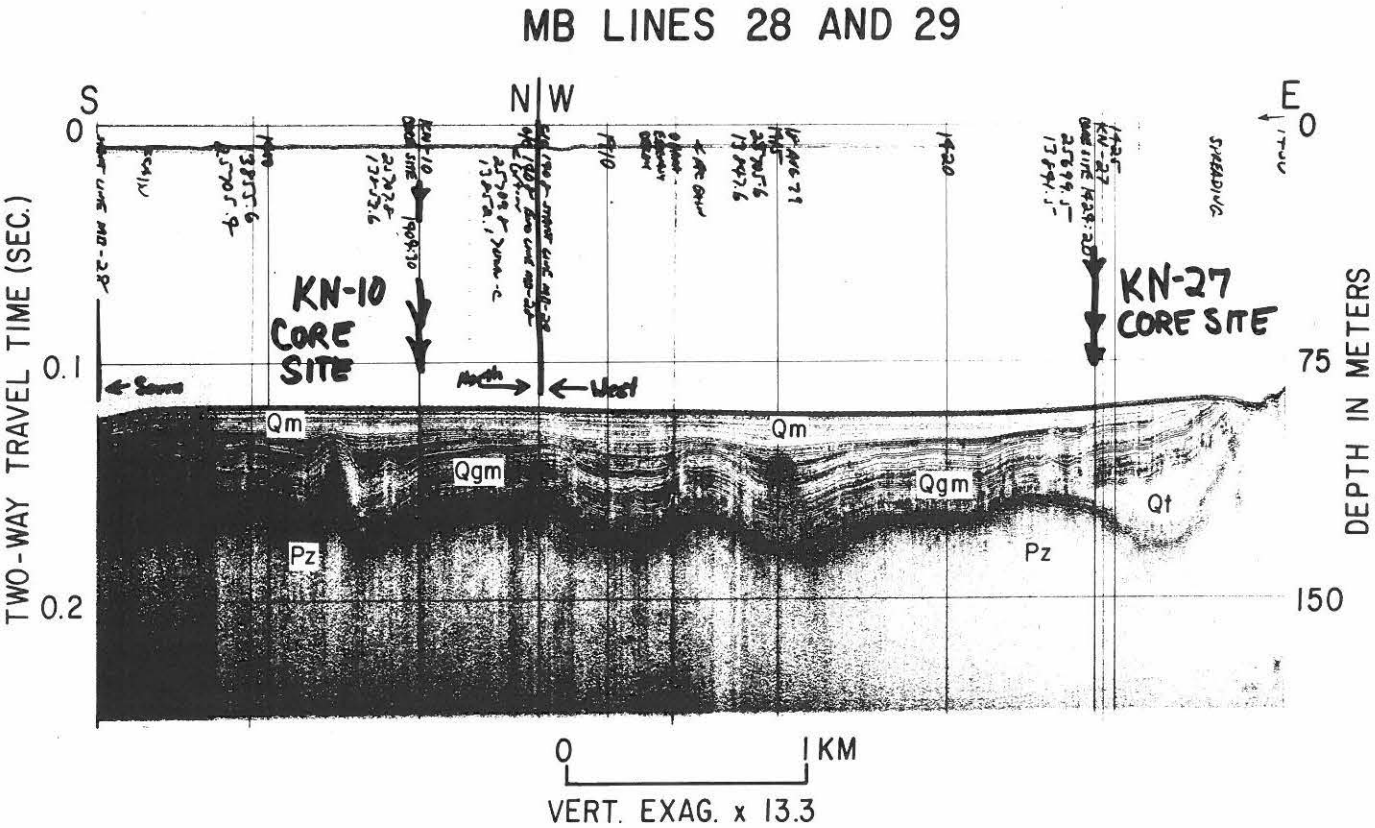

Figure 3. Massachusetts Bay seismic lines from Oldale and Bick (1987), showing the Holocene marine mud (Qm), the late Wisconsinan glaciomarine mud (Qgm), older drift (Qt), and pre-Mesozoic bedrock (Pz).

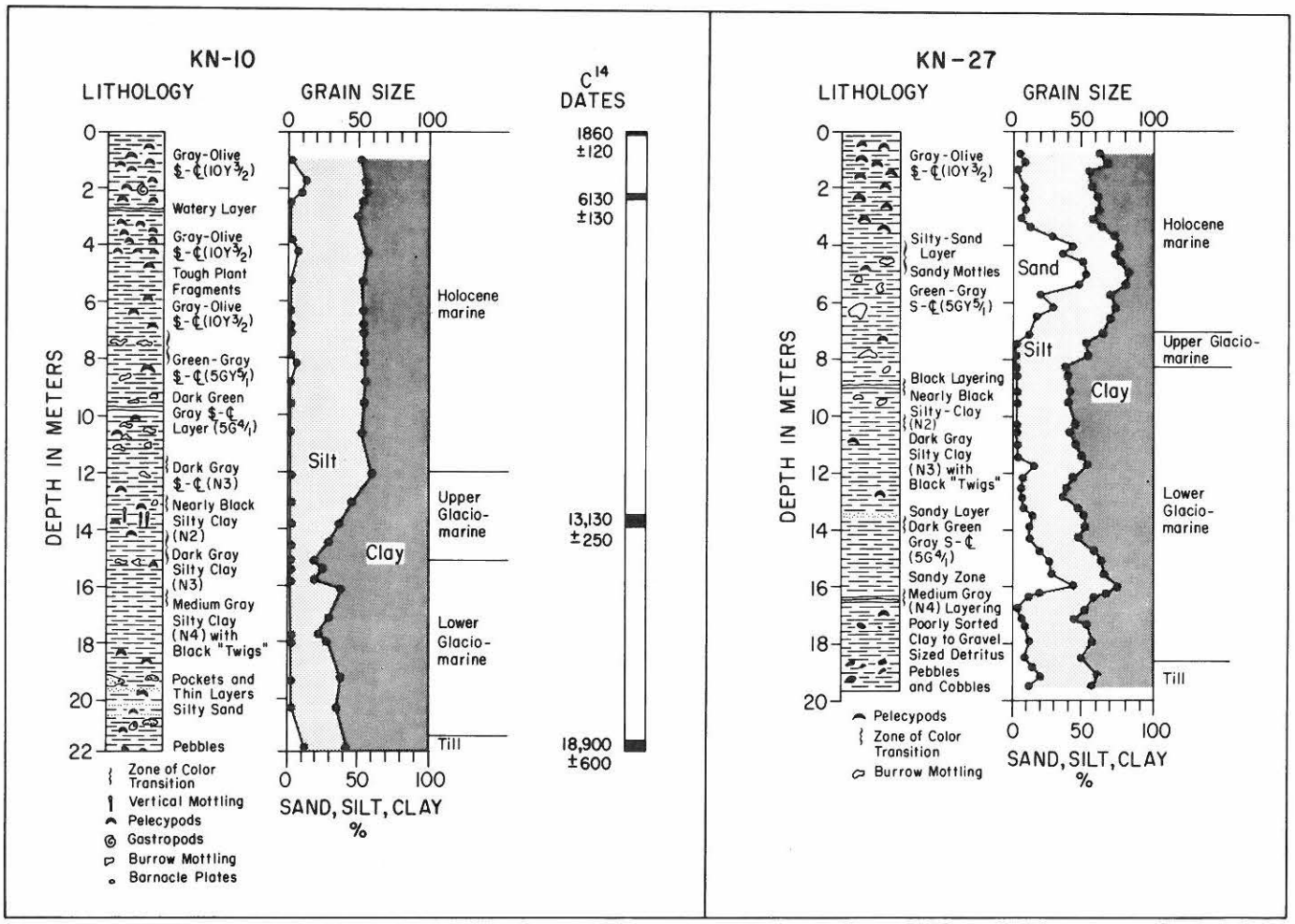

Figure 4. Lithology, grain size, and ^{14}C dates from cores KN-10 and KN-27. From Tucholke and Hollister, Figures 5a and 5b (1973).

Radiocarbon dates obtained on total organic matter (TOM) from both Stellwagen Basin cores were reported by Tucholke and Hollister (1973). A date of 21,950 ± 1,350 yr B.P. (I-6602) from the bottom of core KN-27 (not located on their Fig. 5b) and a date of 18,900 ± 600 yr B.P. (I-5576) from the bottom of core KN-10 (Fig. 4) are suspect because between about 22 ka and 18 ka, the late Wisconsinan ice was at its maximum position (Stone and Borns, 1986) and Stellwagen Basin would have been completely filled by ice. In addition, these dates fall within the range of dates on shell and wood from the outwash deposits on Cape Cod and Nantucket that are considered unreliable because of contamination or recrystallization (Oldale, 1982). A third date, 13,130 ± 250 yr B.P. (Fig. 4) was obtained from between 13.5 m and 13.8 m in core KN-10 in the upper seismic unit of the glaciomarine mud. It is reasonably consistent with dates of 14,250 ± 250 yr B.P. and 13,800 ± 300 yr B.P. obtained nearby from glaciomarine mud in Lynn, Massachusetts (Kaye and Barghoorn, 1964), and establishes a late Wisconsinan age for the deposit.

Correlation between seismic reflectors and contacts in the cores is possible (Fig. 4). The reflector at the top of the lower part of the glaciomarine mud corresponds, in core KN-10, with the beginning of a transitional change in grain size from mostly clay to equal amounts of silt and clay in the Holocene marine mud. The reflector at the top of the upper part of the glaciomarine mud corresponds to the end of this transition in the core. Thus, the less draped upper part of the glaciomarine mud represents the transition from glacial marine to nonglacial marine conditions in Stellwagen Basin. In addition, the last occurrence of the foram *Elphidium clavatum*, characteristic of the glaciomarine mud, occurs at 12 m sub-bottom and corresponds to the seismic reflector at the top of the glaciomarine deposits. A correlation can also be made between the reflector at the top of the glaciomarine mud and a grain size change in core KN-27. At this locality, the upper part of the glaciomarine mud is too thin to resolve in the seismic data or absent. The seismic reflector at the top of the glaciomarine mud corresponds to a change from mostly

clay to muddy sand, characteristic of the lower part of the Holocene deposits.

The gravelly mud at the base of both cores plots within the lower part of the glaciomarine mud in the seismic profiles. It may represent debris that was ice rafted by bergs and dropped into the mud. However, the cores may have sampled till or coarse subaqueous outwash. Deposits of this nature are inferred from seismic data, across the site of core KN-10, at a sub-bottom depth of 29 m, the penetration depth of the core. Similarly, core KN-27 penetrated 24 m sub-bottom, only 3 m above till or coarse outwash inferred from seismic data at that site.

The glaciomarine mud that occurs above sea level along the Gulf of Maine from Boston, Massachusetts, northward has been studied by numerous investigators. Kaye (1982) described the glaciomarine mud exposed near Boston as clay and silt interbedded with sand. He noted that the deposit is well stratified and rhythmically bedded by alternating layers of clay and silt or silt and fine sand. In addition, Kaye (1982) observed that the rhythmic bedding was not noticeable in fresh exposures because of the uniform color of the sediment. The glaciomarine mud, when traced landward, grades into littoral sand and finally into glaciofluvial outwash. The mud in the Boston area is locally fossiliferous; it includes foraminifera, mollusks, and barnacles.

Glaciomarine mud occurs in the coastal region of New Hampshire, but it has been little studied. Goldthwait (1953) mapped its distribution and indicated that the mud consists of clay, silt, and some sand and that the glaciomarine mud becomes more sandy toward the top of the section. In contrast to Kaye's (1982) observations, Goldthwait noted that the mud lacks stratification in most places and, where stratified, does not appear to be rhythmically bedded. However, he noted that physical properties of the glaciomarine and nearby glaciolacustrine sediments were similar.

Glaciomarine mud occurs throughout coastal Maine and in the major valleys in central Maine, as much as 200 km inland and up to altitudes of about 130 m (Thompson, 1982). Bloom (1960, 1963) identified the mud as a silty clay and noted that sand is locally abundant, particularly in the upper part of the section and close to the marine limit. Isolated coarse clasts up to boulder-size occur throughout the deposit. Size analysis of the glaciomarine mud by Lawrence Goldthwait (as reported in Bloom, 1960) indicated that, on average, the deposit consists of 39% clay, 37.9% silt, and 23.5% sand. Caldwell (1959) found a similar grain-size distribution and noted that the glaciomarine mud was well sorted to poorly sorted. According to Bloom (1960), the mud is well bedded and, in places, rhythmically bedded but not varved. Stratification is the result of interbeds of silty clay and fine sand. Thompson (1982) observed that the glaciomarine mud is massive in some places and well stratified in others. Most of the studies of the glaciomarine mud in Maine (Bloom, 1960; Smith, 1982; Thompson, 1982) indicate a general upward and landward increase in sand, interfingering of the mud with submarine ice-contact sand and gravel, and interfingering with subaerial ice-contact deposits and outwash along the marine limit. These studies also indicate that, in many places, the glaciomarine mud contains abundant mollusk and foraminiferal faunas. Radiocarbon dates related to the glaciomarine mud and to the marine incursion of coastal Maine range from 11.4 to 13.8 ka (Smith, 1985) and clearly established the late Wisconsinan age of the deposit.

DISCUSSION

As shown by the previous description, the glaciomarine mud is similar throughout the western Gulf of Maine and adjacent lowlands and appears to be similar to the Emerald Silt, described by King and Fader (1986), in the eastern Gulf of Maine and the Scotian Shelf. Minor differences in grain-size distribution, stone content, texture, stratification, and seismic character can be attributed to such variables as transport (whether the glacier contributed sediments directly to the sea or through a subaerial fluvial system), distance from the sediment source, sedimentation rate, water depth, and distance from the paleoshore. For example, glaciomarine mud in core KN-10 (Fig. 4) is composed mostly of clay with very little sand and may be a deep-water sediment deposited some considerable distance from the sediment source or the paleoshore. On the other hand, the Presumpscot Formation is siltier and contains sand and locally gravel. It is clearly a shallow-water, nearshore glaciomarine mud that was deposited close to its source.

The upward coarsening of the glaciomarine mud was noted in the eastern Gulf of Maine (King and Fader, 1986), in Stellwagen Basin (Tucholke and Hollister (1973) and in the deposits exposed above present sea level (Kaye, 1982; Bloom, 1960). It corresponds to the upper part of the glaciomarine mud portrayed in seismic records (King and Fader, 1986; Oldale and Bick, 1987). In Stellwagen Basin (Core KN-10), it clearly represents a gradual change from a glacial source to a nonglacial source and a gradual reduction in sedimentation rates (Tucholke and Hollister, 1973). These factors may also apply to other basins in the Gulf of Maine. The upward coarsening may be caused by a gradual reduction in the amount of clay being deposited rather than by an increase in the amount of sand and silt deposited. In the shallower parts of the Gulf and up to the late-glacial marine limit, the coarsening may also have been caused, in part, by shoaling as the crust rebounded and relative sea level fell.

Although locally the glaciomarine mud represents different marine environments, overall it represents a single major event: the retreat of the last continental glacier across the Gulf of Maine region from its terminal position against Georges Bank (Fig. 1).

The chronology of the last glaciation proposed by King and Fader (1986) includes these stages: (1) advance to Georges Bank about 70 ka, (2) full glacial conditions between 70 ka and 38 ka; (3) lift off (floating of the ice sheet) and deposition of Emerald Silt facies A beneath an ice shelf, 38.0 to 26.5 ka; (4) readvance of the grounding line of the ice sheet to form the Fundian moraine,

32.0 to 26.5 ka; and (5) ice shelf breakup and retreat to coastal Maine, 26.5 to 13.0 ka. King and Fader (1986) established the chronology of retreat from the Gulf of Maine by arranging cores into a single stratigraphic section controlled by seismic data. When the cores were arranged in this manner, the included radiocarbon dates fell mostly in proper stratigraphic order; the ages increasing with depth. King and Fader (1986) extrapolated from the oldest date, 26.6 ka, to the base of the section to establish that the deposition of the glaciomarine mud began about 38 ka. In spite of their concern about the validity of TOM dates, including reworking and contamination, the stratigraphic continuity of the dates lead King and Fader (1986) to conclude that most of the dates were valid. There is no unequivocal evidence from northern New England or eastern Massachusetts that would preclude this chronology; however, it can be questioned on several grounds. The radiocarbon dates from the Gulf of Maine cores may not be as good as the King and Fader (1986) stratigraphy indicates, and extrapolation back to 38 ka may not be warranted. Dates within individual cores from the Atlantic continental shelf (King and Fader, 1986, Table 3) do not generally fall into proper stratigraphic order. Of 15 cores that include two or more radiocarbon dates in the Emerald Silt, only three had a normal stratigraphic sequence of dates. Eight of the cores had one or more dates stratigraphically reversed. Seven of the cores had dates separated by 75 to 269 cm of sediment that, when the possible error was taken into account, could have been the same age. Thus, reworking and contamination may be factors influencing the validity of the TOM dates from the Emerald Silt and the dates that were later obtained on individual shells using the accelerator mass spectrometer (King and Fader, 1986, p. 37).

A recently obtained radiocarbon date (17.4 ka) on shell near the base of the Emerald Silt from Emerald Basin indicates that deposition of the Emerald Silt may have begun after about 18 ka, and the underlying till may be late Wisconsinan in age (Piper et al., 1988). The Emerald Basin date corresponds closely with a date indicating that glaciomarine deposition was underway in Wilkinson Basin in the Western Gulf of Maine by about 17.6 ka (Schnitker, 1988).

Arguments to refute the early Wisconsinan to middle Wisconsinan glaciation of the Gulf of Maine proposed by King and Fader (1986) mostly lack conclusive evidence. Many of these arguments are based on numerous radiocarbon dates on material inferred to indicate ice-free conditions, such as shell, wood, peat, bones, and horn (Johnson, 1986; Fullerton, 1986; Stone and Borns, 1986). Many of these dates from the terresterial record are suspect, and the infinite dates within this group do nothing to further the arguments. Indeed, in some places, middle Wisconsinan glaciations are proposed from the continental Wisconsinan section (for example, Bloom and McAndrews, 1972). However, when taken in total, the continental evidence suggests a period of weak and limited glaciation during middle Wisconsinan time followed by a much more extensive glaciation starting around 23 ka. Dredge and Thorleifson (1987) provide three alternative scenarios for the extent of middle Wisconsinan ice. In all three, the Gulf of Maine is shown as being ice free. The King and Fader (1986) chronology appears to be somewhat out of phase with marine oxygen-isotope and sea-level data that indicate less than full glacial conditions worldwide between 60 and 28 ka and an advance to full glacial conditions after 25 ka (Ruddiman and McIntyre, 1981; Chappell and Shackleton, 1986).

Finally, a post-marine, oxygen-isotope stage 5, pre-late Wisconsinan glaciation of the Gulf of Maine is incidental to the discussion on the glaciomarine mud, if the deposit is no older than about 18 ka.

The depositional model proposed by King and Fader (1986), melt-out of basal till from an ice shelf, is not compatible with the most obvious characteristics of the glaciomarine mud. These characteristics include (1) internal seismic layers that can be traced for kilometers and, in some places, basin wide; (2) extensive thin rhythmic beds and laminae, best seen in subaerial outcrops; (3) the large volume of glaciomarine mud; and (4) a grain-size distribution of mostly clay and silt without, or with a very low percentage of, gravel-sized clasts.

Extensive or basin-wide seismic or sedimentary layers of nearly uniform thickness would require simultaneous melt-out of a consistent volume of basal till over broad areas of an ice shelf, an unlikely event. Rhythmic layering in the glaciomarine mud requires that the basal load be renewed after each melt-out event. Since basal melt-out occurs shortly after lift off (Drewry and Cooper, 1981), there seems no way to renew the basal load over broad areas of the ice shelf. Repeated grounding and degrounding of an ice shelf might renew the basal load, as is suggested by King and Fader (1986). However, as they indicate, this process is essentially vertical, the result of changes in sea level or ice thickness, with little or no forward motion of the ice shelf (King and Fader, 1986). Under these conditions, melt-out of the new basal load, following lift off, would be restricted to the vicinity of the grounding line and would not produce extensive rhythmic beds. Even if melt-out events could occur repeatedly, there remains a question as to whether the basal load of an ice shelf is sufficient source for glaciomarine mud whose total thickness is more than 75 meters in many places. Basal sediment loads in existing ice sheets are very low (Drewry and Cooper, 1981) and even lower in ice shelves formed when the ice sheet spreads out seaward of the grounding line. To obtain the volume of glaciomarine mud present in the Gulf of Maine from debris at the base of an ice shelf would require considerable time. If the estimate for the retreat of the ice from the Gulf of Maine favored here, 18 ka to 12 ka, is approximately correct, then low sedimentation rates produced by melt-out from an ice shelf cannot be accepted.

Basal till contains abundant gravel-sized clasts as well as all other grain sizes. As melt-out till sinks through the water column, it is sorted to produce a graded bed with gravel-sized clasts at the bottom and silt and clay at the top, a deposit unlike the stone-poor glaciomarine mud. Repeated melt-out and sorting would produce a deposit consisting of a series of beds similar to the one described above. The resulting deposit would not resemble the

Emerald Silt, the Presumpscot Formation, or the glaciomarine mud in Stellwagen Basin.

Several investigators have inferred an ice shelf in the Gulf of Maine during the retreat of the last ice (Hughes et al., 1985; King and Fader, 1986; Dyke and Prest, 1987; and Schnitker, 1988). Hughes et al. (1985) proposed the ice shelf as part of their scheme for the deglaciation of the Laurentide ice sheet by way of major ice streams, a model based largely on their studies of Antarctica. King and Fader (1986) called upon an ice shelf as the major source for the glaciomarine mud, basing their depositional model on a model for Antarctic ice shelves by Carey and Ahmad (1961). Dyke and Prest (1987) followed the lead of King and Fader (1986) and showed an ice shelf in the Gulf of Maine on their recent map. Schnitker (1988) proposed an ice shelf to explain an absence of microflora in the glaciomarine mud in Wilkinson Basin. An ice shelf in the Gulf of Maine is proposed in a paper included in this volume (Belknap et al., this volume). Draping of the glaciomarine mud has also been used to argue for an ice shelf because it would seem to require the absence of wind-driven currents.

There is little if any evidence for an ice shelf in the Gulf of Maine during the retreat of the last ice. However, there is evidence that the late Wisconsinan ice was temperate and wet-based, thereby precluding the formation of an ice shelf. Ice shelves require a climate cold enough to keep the shelf ice below the pressure melting point (Sugden and John, 1976). Where this condition is not met, a marine-based ice sheet will not have sufficient strength to form an ice shelf (Richard Alley, pers. commun., 1988) and will calve and maintain an ice front close to the grounding line. The evidence for a temperate and wet-based ice sheet in the Gulf of Maine consists of abundant meltwater deposits on the continental shelf beyond the glacial maximum and outwash and ice-contact stratified drift along the margins of the Gulf. In addition, paleontological evidence indicates that relatively warm (above freezing) continental slope water entered the Gulf of Maine to interact with the retreating ice (Schnitker, 1988).

Ice shelves are not necessary to the formation of glaciomarine mud. Deposits on the Labrador Shelf display draped, acoustically laminated, rhythmic reflectors characteristic of glaciomarine mud elsewhere. The sediments contain abundant erratic limestone clasts that were transported to the Labrador Shelf by current-driven bergs, a process that requires open-ocean conditions (Josenhans et al., 1986). Iceberg scours, also requiring an open ocean, have been recently identified within glaciomarine mud in Emerald Basin on the Scotian Shelf (Gipp, 1988), indicating that the Emerald Silt in its "type locality" was, at least in part, deposited in the absence of an ice shelf.

For the reasons just presented, the chronology of the Wisconsinan glaciation of the Gulf of Maine and the depositional model for the glaciomarine mud proposed by King and Fader (1986) and by other investigators (Hughes et al., 1985; Schnitker, 1988; Belknap et al., this volume) are believed to be incompatible with the available evidence. In their stead, a revised Wisconsinan chronology for the Gulf of Maine and a depositional model involving meltwater discharge of suspended sediment from a retreating grounded ice front are proposed.

The chronology is based on the inference that dated material older than 20 ka in part represents nonglacial marine conditions in the Gulf and subaerial conditions in southern New England, and on the assumption that the Wisconsinan history of the Gulf of Maine is compatible with the continental record to the west. The older dated material was picked up and incorporated into the drift during the late Wisconsinan ice advance. The youngest of this material, generally dated around 21 ka, is inferred to represent the advance of the ice to its terminal position at Northeast Channel, Georges Bank, Great South Channel, and the terminal moraines in southern New England that are represented by the offshore islands (Fig. 1). Shell, seaweed, and TOM from the glaciomarine mud that date younger than about 18 ka are thought to represent the deglaciation of the Gulf of Maine. This chronology for the Gulf of Maine (ice-free before about 23 ka, full glacial conditions between about 21 and 18 ka, and retreat from the glacial maximum to the marine limit between 18 and 13 ka) is compatible with the continental record to the west (Richmond and Fullerton, 1986, their Chart 1), to the east on the Labrador Shelf (de Vernal and Hillaire-Marcel, 1987), and with the worldwide Wisconsinan, marine oxygen-isotope ice-volume, and sea-level records (Ruddiman and McIntyre, 1981; Chappell and Shackleton, 1986).

King and Fader, by applying the Carey and Ahmad (1961) model, and Hughes et al. (1985) have used present-day glacial conditions in Antarctica as a modern analogue for the deglaciation of the Gulf of Maine. This analogue may be inappropriate for a retreat from full glacial conditions between roughly 41° and 43° North latitude and a retreat characterized by copious meltwater and abundant outwash. An abundant supply of silt and clay (rock flour) was available over several thousand years to produce the large volume and great thickness of glaciomarine mud, even with the high sedimentation rates that likely occurred in the glacial environment. The glaciomarine mud is as much as 65 m thick in Stellwagen Basin and as much as 100 m thick in the eastern Gulf of Maine (King and Fader, 1986). In addition, meltwater, and thus the sediment supply, was periodic (seasonal) and may have produced the rhythmic bedding in the mud. Meltwater laden with glacial rock flour provided abundant sediment to the sea throughout the retreat of the ice from the Gulf of Maine and coastal northern New England. Most likely, the fluvial rock-flour supply diminished with time as glacial lakes trapped the sediment and as the ice volume decreased, events represented by the upper part of the glaciomarine mud. Finally, the rock-flour supply ceased when meltwater flow was diverted into other drainage systems or when the ice in northern New England melted completely, around 11 ka (Stone and Borns, 1986). Evidence for abundant meltwater entering the marine environment along the grounding line of a retreating glacier has been demonstrated for the Champlain Sea in the Ottawa region of Canada (Rust and Romanelli, 1975) and by Smith (1984) and

Smith and Hunter (1989) for coastal Maine. Interfingering of ice-contact delta deposits and glaciomarine mud at the marine limit in Maine indicates that subaerial glaciofluvial meltwater provided another source of sediment to the marine environment (Thompson, 1982). The association of submarine outwash and glaciomarine mud led Smith (1984) and Smith and Hunter (1989) to propose a depositional model for the glaciomarine mud. This model includes a warm-based glacier that terminated in the sea. Subglacial meltwater entered the sea at the grounding line where coarse debris was immediately deposited. Fine sand, silt, and clay were carried to sea as low-density overflows. There the sediment fell to the sea floor, probably aided by flocculation and biologic agglutination. Although this model proposed a marine-based glacier, such may not have been the case for the entire interval represented by the glaciomarine mud. Sediment was carried to the sea by subaerial meltwater streams, as is indicated by the interbedding of glaciomarine mud and glaciofluvial delta deposits. A glaciofluvial source was proposed by Fillon and Harmes (1982) for the glaciomarine mud on the shelf off Labrador, where they inferred that the glaciomarine mud was derived from rock flour carried to the sea by meltwater streams draining outlet-valley glaciers.

Deposition of glaciomarine mud has been observed in fjords (Syvitski and Murray, 1981; Hoskins and Burnell, 1972; Mackiewicz et al., 1984; and Elverhoi et al., 1983). Depositional processes described in these studies include overflow plumes of sediment-laden fresh meltwater, flocculation and biological agglutination of fine sediment, and consequent settlement of the suspended sediment to the sea floor. Interflows, underflows, turbidity currents, and debris flows appear to be less important or minor processes in the formation of glaciomarine mud in fjord environments. Although the sedimentary processes observed in fjords may be applicable to glaciomarine sedimentation in the Gulf of Maine, the glaciers themselves are constrained by the walls and rock threshold of the fjords. Thus, they are not fully satisfactory as a model for the deglaciation of the Gulf of Maine.

Studies of Holocene glaciomarine sedimentation in the Gulf of Alaska and off the Nordaustlandt Glacier in the Svalbard archipelago, in open-shelf environments, may be more useful in understanding the origin of the glaciomarine mud and may prove to be more reasonable than Antarctic analogues for the retreat of the ice in the Gulf of Maine.

In the Gulf of Alaska, meltwater-generated sediment plumes have been traced more than 50 km offshore during the summer and early fall (P. R. Carlson, pers. commun., 1975). Molnia (1983) made the following observations in the Gulf of Alaska: Glaciomarine mud is characterized by minor amounts of gravel-sized clasts (generally less than 1%). Glaciomarine mud is deposited from large suspended sediment plumes that originate when sediment-laden meltwater enters the sea directly, from floating or tide-water glaciers, or indirectly, from subaerial glaciofluvial systems. Suspended-sediment plumes travel great distances and glaciomarine mud is deposited as far offshore as the middle and outer shelf.

Molnia and Carlson (1978) described the seismic character of the Holocene glaciomarine mud in the Gulf of Alaska as consisting of numerous, continuous internal reflectors that extend for many kilometers. The internal seismic reflectors resemble those in the glaciomarine mud in the Gulf of Maine; however, the substrate in the Gulf of Alaska is flat, so that mimicking of the underlying morphology is not obvious.

Observations along the ice front of Nordaustlandt Glacier have been made by Pfirman (1985). The glacier front, more than 200 km long and as much as 130 m thick, is grounded along its entire length in up to 100-m water depth. Sedimentation in the region seaward of the glacier front is dominated by deposition from meltwater sediment plumes. Turbid meltwater enters the sea through subglacial tunnels associated with subglacial and sea-floor valleys. Meltwater plumes rise to the sea surface as the suspended sediment loads are insufficient to overcome the heavier sea water and form underflows. At the sea surface the suspended sediment plumes are driven by currents and possibly by katabatic winds. The plumes can be identified, by suspended sediment loads above background, up to 18 km from the discharge point. Although at the present time major melt-water discharge occurs at only two places, Solheim and Pfirman (1985) speculate that during a historic surge, meltwater discharge and sediment plumes occurred along the entire front. Meltwater discharge from the present tunnels occurs from July to September, leading Pfirman (1985) to conclude that most of the meltwater was derived from melting of the glacier surface. She also observed that extensive sea ice cover occurred from November to May, a feature that may reduce the frequency and power of wind-driven bottom currents.

SUMMARY AND CONCLUSION

Glaciomarine mud in the Gulf of Maine region is characterized by extensive internal seismic reflectors that mimic the underlying surface morphology. In cores and outcrop, the deposits have rhythmic bedding, variable amounts of sand, and sparse gravel-sized clasts. The glaciomarine mud was deposited as the last glacier retreated from the north flank of Georges Bank across the Gulf of Maine and coastal northern New England. This retreat occurred between about 18 and 12 ka. Radiocarbon dates from the glaciomarine mud that suggest ice retreat prior to 18 ka probably resulted from dating older detrital material, mostly from interglacial or interstadial marine deposits. The youngest of these dates, therefore, provide the timing for the advance of the Wisconsinan ice into the Gulf of Maine, sometime between 25 and 21 ka.

Glaciomarine mud similar to that in the Gulf of Maine occurs on continental shelves off eastern Canada and Alaska, and in fjords in Alaska and Scandinavia. Glaciers along the Gulf of Alaska, the Nordaustlandt Glacier in the Svalbard archipelago, and fjord glaciers provide reasonable modern analogues for a glaciomarine sedimentation model in the Gulf of Maine region.

They indicate that sedimentation from rock-flour-laden surface plumes of meltwater is the chief source of the glaciomarine mud. The plumes entered the sea in various ways. In the deeper parts of the Gulf of Maine, meltwater discharge probably occurred subglacially along the grounding line of a calving glacier. Sediment plumes of low-density fresh meltwater, generated during the warmer months, rose to the sea surface and extended seaward many kilometers beyond the ice front. An ice shelf probably did not occur in the Gulf of Maine, and one is not necessary to deposit glaciomarine mud or to preserve the draped layers characteristic of the mud. Sea ice during many months of the year could have reduced the frequency and power of wind-driven bottom currents. As the retreating ice front approached the marine limit, meltwater may have reached the sea along a tidewater glacier front. In this case and in the case of a calving front, iceberg rafting would be a constant but minor source of coarse clasts. Once the ice sheet retreated from the marine limit, sediment-laden meltwater reached the Gulf of Maine by way of subaerial meltwater streams, and the contribution of coarse clasts by berg rafting ceased. However, fast ice may have drifted free to eventually provide a minor coarse clast component to the mud. The glaciofluvial contribution of rock flour continued until the ice within the Gulf of Maine drainage area melted away or meltwater flow was diverted into other drainage systems. The amount of rock flour delivered to the Gulf of Maine diminished gradually as glacial lakes trapped the sediment and as the ice volume became less. The absence of ice-rafted stones and the transitional change in grain size in the upper part of the glaciomarine mud in Stellwagen Basin and elsewhere probably represent these changes.

Rhythmic layers in the Gulf of Maine glaciomarine mud may represent annual beds, related to summer melt and winter freeze, equivalent to varves in the glaciolacustrine environment. Other cyclic bedding may represent shorter repetitive events, for example, a tidal cycle (Hoskins and Burnell, 1972).

The chronology of late Wisconsinan glaciation and the sedimentation model presented here differs significantly from those proposed by King and Fader (1986). The model also differs from other models that propose the development of an ice shelf in the Gulf of Maine during the late Wisconsinan ice retreat (Hughes et al., 1986; Schnitker, 1988; Belknap et al., this volume). None of the interpretations is fully supported by unequivocal data, and much more work must be done before a unified story, acceptable to most investigators working on the glaciated shelf, is established. The solution may be in additional careful analyses of radiocarbon dates and in studies of present-day glaciomarine sedimentation (outside polar environments) that may serve as reasonable analogues for the Wisconsinan glaciation of the mid-latitude northeastern North American continental shelf.

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