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Erosion of the Laurentide Region of North America by Glacial and Glaciofluvial Processes

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Collection of seismic reflection data from continental margins and ocean basins surrounding North America makes it possible to estimate the amount of material eroded from the area formerly covered by Laurentide ice sheets since major glaciation began in North America. A minimum estimate is made of 1.62×10^6 km^3, or an average 120 m of rock physically eroded from the Laurentide region. This figure is an order of magnitude higher than earlier estimates based on the volume of glacial drift, Cenozoic marine sediments, and modern sediment loads of rivers. Most of the sediment produced during Laurentide glaciation has already been transported to the oceans. The importance of continental glaciation as a geomorphic agency in North America may have to be reevaluated. Evidence from sedimentation rates in ocean basins surrounding Greenland and Antarctica suggests that sediment production, sediment transport, and possibly denudation by permanent ice caps may be substantially lower than by periodic ice caps, such as the Laurentide. Low rates of sediment survival from the time of the Permo–Carboniferous and Precambrian glaciations suggest that predominance of marine deposition during some glacial epochs results in shorter lived sediment because of preferential tectonism and cycling of oceanic crust versus continental crust.

INTRODUCTION

The theory of deep erosion due to continental glaciation (White 1972) has not been well received in the literature (Gravenor, 1975; Sugden, 1976, 1978; Higgs, 1978; Rutter, 1980). These authors raise many important issues which suggest that the original concept of shallow erosion (Flint, 1971) is the more correct theory. Some of these issues are (1) the presence of a large Paleozoic sedimentary basin under Hudson Bay and the Foxe Basin; (2) the presence of heavy minerals and rock fragments of Canadian shield rocks in Nebraskan-age tills; (3) evidence of Paleozoic unroofing of the Precambrian shield in sediments from the continental shelf of Labrador.

Central to this debate is the demonstration of the existence or nonexistence of the huge amounts of glacial segments required by the deep-erosion theory. Flint (1971) estimated 25 m of erosion for the Fennoscandian Shield based principally on terrestrial glacial sediments, although he warned that the figure may not be reliable because of unknown amounts of glacial-marine sediment and other complicating factors. The first attempt to estimate the volume of glacial-marine sediments was by Matthews (1975) who used isopach maps to compare volumes of Cenozoic sediment along the continental margin of North America. He concluded that the data did not support the theory of glacial exhumation of the Canadian Shield, although he did state that a final determination awaited a precise estimate of the volume of Pleistocene sediments alone. Ruddiman (1977) suggested

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that glacial-marine sediments are principally ice-rafted detritus and calculated that the volume of ice-rafted detritus in the North Atlantic is equivalent to 16 m of uncompacted material eroded from North America and Greenland.

These estimates, however, do not adequately reflect the large volumes of glacial-age sediments in continental margin deposits and abyssal-plain turbidites. Laine (1980) determined the volume of glacial-age turbidites and margin deposits in the western North Atlantic and estimated which portions of Greenland and North America were the source areas for this sediment. Based on low-frequency seismic profiles and Deep Sea Drilling Project (DSDP) drill holes, he calculated that 55–95 m of rock have been eroded by continental glaciation from eastern North America and southern Greenland.

The greatest uncertainty in Laine's work was his determination of the source area of marine sediments. Although a multidome reconstruction of the Wisconsin-age Laurentide Ice Sheet (Shilts *et al.*, 1979; Andrews, 1982) sheds much light on the problem (Laine and Bell, 1982), it is difficult to calculate the percentage of sediment derived from eastern North America that was deposited in the Gulf of Mexico rather than in the North Atlantic. Such a calculation would be particularly uncertain for the earliest ice sheets, which probably differed in both size and shape from the Wisconsin-age Laurentide Ice Sheet. This difficulty can be overcome by calculating the total glacial sediment derived from the entire Laurentide region since the initiation of major glaciation in the Northern Hemisphere.

METHOD

The volume of sediment derived from the Laurentide region since glaciation began can be calculated by identifying those areas that received sediment, estimating the volume of that sediment which is of glacial age, and subtracting non-Laurentide sediment inputs. Estimation of these sediment volumes has been made possible by the large number of seismic and DSDP studies carried out in the last 15 yr. This paper is based primarily on published reports of these recent investigations.

Definition of Glacial Age

Based on interpretation of oxygen-isotope records and the age of ice-rafted debris in the North Atlantic, major Northern Hemisphere glaciation is considered to have begun 3 my ago (Berggren, 1972; Kennett, 1977; Shackleton and Opdyke, 1977). There is evidence of earlier Northern Hemisphere glaciation, at least as early as the late Miocene, from ice-rafted debris in the Arctic Ocean (Herman, 1974, 1979; Clark *et al.*, 1979). The stability of the $^{18}O/^{16}O$ record between 5 and 3 my in comparison with the large fluctuations of the record from 3 my to the present (Kennett, 1977) indicates that the erosive capability of ice sheets during these early glaciations was small. Therefore, the glacial age for North America will be defined in this paper as the period since 3 my ago.

Contribution by Fluvial and Glaciofluvial Erosion

Some component of Laurentide marine sediments may have been derived from erosion by interglacial streams and by streams draining the Laurentide region while the ice sheets were not at their maximum extents (proglacial streams). Unfortunately, it is not possible to distinguish between fluvially eroded and glacially eroded marine sediments on seismic profiles, making a determination of the relative efficacy of the two processes difficult.

This difficulty may only be a matter of definition. Any weathered regolith capable of being eroded by the low-gradient streams typical of the Laurentide region was probably stripped off by the earliest glaciations. Such regolith is generally absent in glaciated parts of North America (Flint, 1971) and modern streams must work against fresh bedrock surfaces that are harder to erode. Modern stream loads in the Laurentide region are probably principally derived from stratified glacial drift, a material that is easy to erode because of its unconsolidated consistency and high porosity. Thus continental glaciation works in consort with fluvial erosion in the Laurentide region by providing the only sediment which these low-gradient streams can effectively erode.

Gordon (1979) has investigated the Holocene (postglacial) erosion rate of central New England. Based on the volume of recent sediment in the Long Island Sound, he calculated an erosion rate of only 10×10^{-2} $kg/m^2/yr$ or an average regional denudation of 0.4 cm/1000 yr, indicating that the low-gradient streams now draining this glaciated region are unable to erode the land significantly. Gordon also suggested that what little sediment these rivers do carry is almost entirely derived from stratified drift, principally glacial lake sediments, with practically no contribution from compact till. Thus, in central New England, fluvial transport is working in consort with earlier glacial erosion in the interglacial denudation of the region.

Our approach is to estimate the effect of continental glaciation on total denudation rates, either by direct erosion by overriding ice or by preparing sediment for later fluvial erosion and transport. The distinction between fluvial and glacial processes is unimportant in estimating total denudation and, in our analysis of glacial-age sediments, no attempt is made to distinguish between sediments of glaciofluvial or direct glacial origin. Only in the Gulf of Mexico Province, where much sediment was received from areas unaffected by glaciation, is it necessary to correct for a significant contribution from fluvial processes.

Contribution of the Dissolved Load

Marine terrigenous sediment results from the oceanic deposition of material carried as the suspended load of rivers. However, a significant fraction of the products of denudation are moved in the dissolved load. Worldwide delivery of dissolved sediment to the oceans is currently about 3.5×10^9 tons/yr (Meybeck, 1979), as compared to 13.5×10^9 tons/yr of suspended matter (Milliman and Meade, 1983). Although these numbers are uncorrected for atmospheric additions to the dissolved load and for anthropogenic influences on both dissolved and suspended sediments, the 1:4 ratio between dissolved and suspended fluxes illustrates the importance of chemical processes in denudation.

A considerable portion of denudation in the Laurentide region since the beginning of continental glaciation possibly is a result of chemical erosion. However, there is not complete agreement on the effect glaciation has on chemical denudation rates. Edmond (1973) and Hurd (1977) showed through cogent argument and experimental evidence that Antarctic glaciation contributes almost nothing to the dissolved silica budget of the Antarctic Ocean. Meybeck (1979) subsequently concluded that glaciers were globally a negligible source of dissolved material, principally on the basis of Edmond's and Hurd's work. Reynolds and Johnson (1972), on the other hand, measured a chemical denudation rate in the alpine watershed of South Cascade Glacier in the North Cascade Range that was more than twice as large as the global average for chemical denudation and several orders of magnitude higher than Edmund's, Hurd's, and Meybeck's estimates for glaciated regions.

The Laurentide region may also be dissimilar to the situation in Antarctica. Transport of sediment from Antarctica to the world's oceans is almost entirely by drifting ice as opposed to flowing water. As the drifting ice melts, the sediment is deposited into polar waters that are cold and already saturated in dissolved silica, effectively preventing dissolution of sediment as it filters down to the ocean floor (Hurd, 1977). Thus, there is little opportunity for the weathering products of Antarctic glaciation to be converted into dissolved ions. In contrast, much or even most of the sediment produced by Laurentide glaciation is carried to the oceans by flowing water in the form of meltwaters or proglacial or interglacial streams. While in river transport, considerable dissolution of glacial sediments, especially fine-grained "glacial flour," is possible. Suspended-load sediments derived from the Laurentide region may also experience substantial dissolution of silica in relatively warm waters of the Gulf of Mexico and North Atlantic and dissolution of carbonate at abyssal depths below the calcium carbonate compensation depth. This suggests that chemical denudation of the Laurentide region since glaciation began has proceeded at a much faster rate than chemical processes in Antarctica. These major differences in style between glacial sediment transport in the Laurentide and Antarctic regions means that Antarctica should not be used as a model for the influence of continental glaciation on chemical erosion in North America.

The most accurate approach would be to measure dissolved contributions directly. Unfortunately, it is very difficult to trace the fate of dissolved ions from a specific source once they reach ocean waters. Any ions from a given source region that remain in solution as a component of ocean salinity are indistinguishable from ions derived from any other region. In addition, the only significant way that dissolved $CaCO_3$ and, to a lesser extent, dissolved SiO_2 are removed from seawater and incorporated into sediments is by the action of foraminifera, radiolaria, and other marine organisms (Broecker, 1974). These organisms extract ions from seawater to construct their shells and, upon death, their skeletal debris sinks to the ocean floor, creating biogenic sediment. This process is controlled by marine environmental conditions such as the location of nutrient-rich upwelling currents, and may occur many thousands of kilometers away from the original sources of SiO_2, and $CaCO_3$. Thus, it is hard to estimate the contributions over time of a specific source to ocean salts and biogenic sediments.

Most of the terrestrially derived marine deposits surrounding North America contain a large percentage of biogenic sediment. For reasons just discussed, many of the ions comprising biogenic sediment may have a non-Laurentide origin. Because of the difficulty in estimating the Laurentide contribution to biogenic sediments, we subtract the biogenic component from all estimated sediment volumes. For similar reasons, no attempt will be made to estimate the Laurentide ions that are still in solution as ocean salts. If chemical erosion rates in the Laurentide region do respond to glaciation in a manner dissimilar to those in Antarctica, our estimate of denudation based on physical erosion rates must then be regarded as a minimum estimate of the total denudation.

VOLUME OF LAURENTIDE GLACIAL-AGE SEDIMENT

Three main ocean areas received glacial-age sediment derived from the area of North American continental glaciation: the Gulf of Mexico, the western North Atlantic, and the Canadian Arctic seas (Fig. 1). The Gulf of Mexico and the western North Atlantic have been well covered by seismic surveys and drilling projects, and reliable estimates of sediment volumes can be made in these areas. In the Canadian Arctic, information on glacial-age sediment volumes is still preliminary and consequently the accuracy of the volume estimates suffers. (A detailed account of how these estimates were calculated is given in the Appendix).

Gulf of Mexico

Approximately 35% of the Mississippi River drainage basin was glaciated by at least one advance of Laurentide ice (Flint, 1948, 1971, Fig. 18–11). However, the Mississippi in the past has carried and today still carries sediment derived from portions

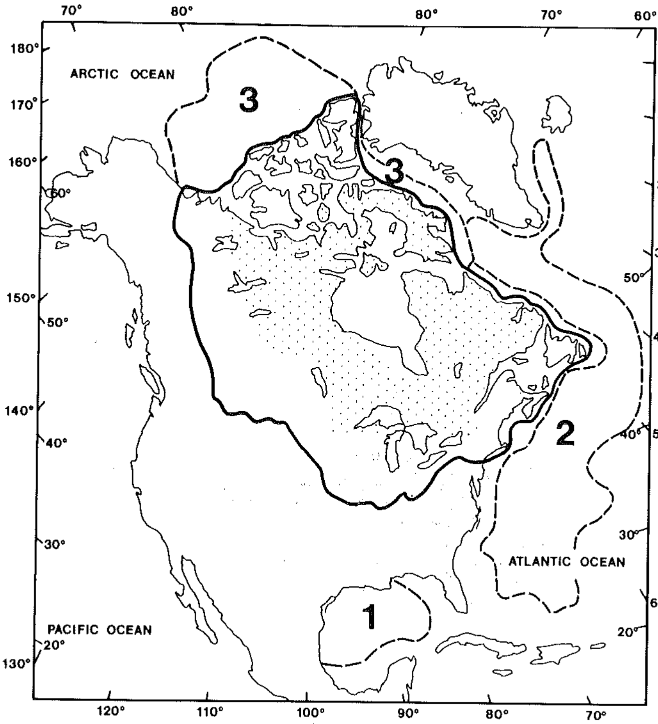

FIG. 1. Areas which received sediment derived from the Laurentide region of North America: (1) Gulf of Mexico, (2) western North Atlantic, and (3) Canadian Arctic. Heavy line circles the Laurentide region.

of the Laurentide region not currently drained by the Mississippi River. During initial stages of retreat, the area drained by the Mississippi River was much increased due to ice damming of the Great Lakes/St. Lawrence River and the Lake Winnipeg/Saskatchewan drainage systems (Kennett and Shackleton, 1975; Bryson *et al.*, 1969, Fig. 2). In addition, as the ice sheets advanced, debris from northern latitudes was transported south (Gravenor, 1975). The location in Ohio and Indiana of the greatest average glacial drift thicknesses (Flint, 1971, Table 7a) suggests that much material derived from more northern areas was in this manner carried to and deposited in the Mississippi drainage basin. Thus, glacial sediment originating from a large portion of the total Laurentide region can be found in the Gulf of Mexico.

Based on Pleistocene isopach maps of Stuart and Caughey (1977) and Moore *et al.* (1978) (Figs. 2 and 3) and on Pliocene stratigraphic information from many sources (Fig. 4), the volume of glacial-age sediments delivered by the Mississippi River to the Gulf of Mexico was calculated. Corrections for the biogenic component were derived from DSDP sites in the area. A correction was made, using the Miocene preglacial sedimentation rate of the Gulf of Mexico (derived from Fig. 5) to account for the contribution from nonglaciated portions of the Mississippi drainage. In addition, corrections were made for contributions to the Gulf from rivers other than the Mississippi and from alpine glaciation in the Mississippi drainage basin. These calculations, summarized in the Appendix, yield an estimate of 7.4×10^5 km^3 of terrigenous sediment in the Gulf of Mexico derived from the Laurentide region in the last 3 my.

Western North Atlantic Basin

Laine (1980) calculated that the amount of glacial-age terrigenous sediment in the

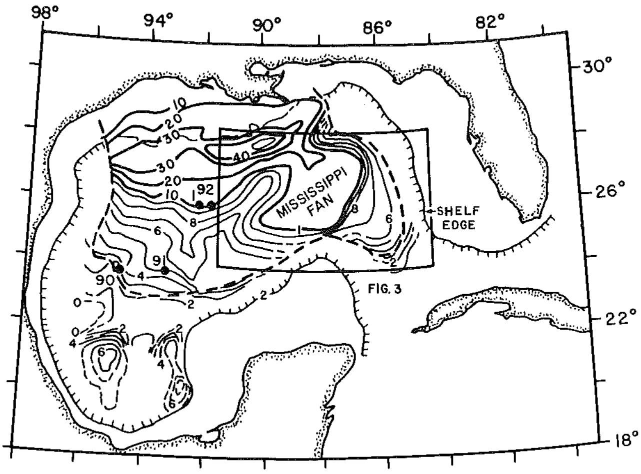

FIG. 2. Isopach map of Pleistocene sediments (10^3 m) in the Gulf of Mexico (after Stuart and Caughey, 1977). Dashed line encloses area of Mississippi-dominated sedimentation, based on DSDP information and heavy-mineral studies of Davies and Moore (1972). Large numbers indicate location of DSDP sites used for making biogenic corrections. Isopach lines are averaged through region of salt intrusion in the Sigsbee Scarp and Rise.

western North Atlantic north of the Blake/Bahama Rise is 1.01 × 10^6 km^3. He estimated that only 2% of this sediment was derived from land that was not glaciated. The bulk of the sediment originated in the Laurentide region, with a much smaller contribution from southern Greenland. Based on the Quaternary history of the Greenland Sea (Eldholm and Windisch, 1974; Johnson *et al.*, 1975; Talwani, *et al.*, 1976; Vogt *et al.*, 1981), a correction can be made for the small Greenland contribution. Also, seismic work on the continental margin of North America (Jansa and Wade, 1974; Uchupi and Austin, 1979; Umpleby, 1979) reveals that the Quaternary section north of George's Bank is thicker than Laine (1980) estimated for this region. Applying corrections for these sources outside the Laurentide region and for this additional sediment on the continental margin, we estimate a volume of 1.2 × 10^6 km^3 of Laurentide terrigenous sediment in the western North Atlantic (Appendix).

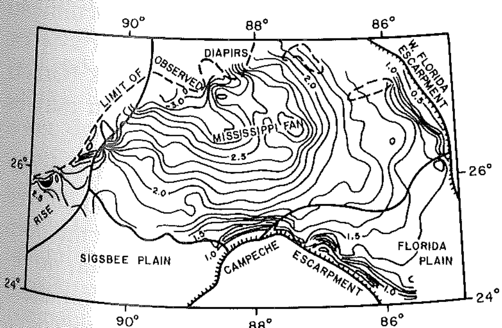

FIG. 3. Isopach map of Pleistocene-age unit A (10^3 m) on the Mississippi Fan (from Moore *et al.*, 1978). Note that these isopachs are considerably larger than the isopachs for the same area of Figure 2.

Canadian Arctic

The Pliocene and Pleistocene history of the Canadian Arctic is still poorly understood; however, preliminary work has shown that the volume of glacial-age terrigenous sediment is probably large. For example, a thick wedge of Pliocene/Pleistocene glacial-age sediment (the Beaufort Formation) is present along the margin of the continental shelf of the Canadian Arctic Islands, with a thickness up to 1800 m off Ellef Ringes Island (Menely *et al.*, 1975; Miall, 1975). Based on these preliminary reports, the volume of Laurentide sediment is estimated to be 2.5 × 10^5 km^3 for the Canadian Arctic Islands continental shelf (Appendix).

A large amount of glacial-age sediment

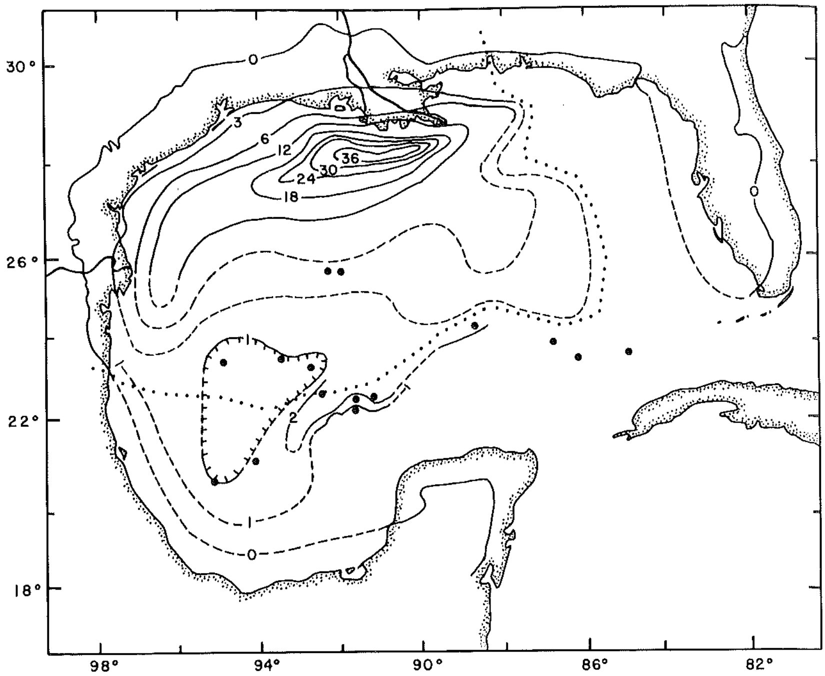

FIG. 4. Isopach map of Pliocene sediments (10^2 m) in the Gulf of Mexico, compiled from many sources. The zero-isopach line is from Cook and Bally (1975), the solid isopachs in the northern half of the Gulf are from Woodbury *et al.* (1973), and the solid isopachs in the southern half of the Gulf are from DSDP core sites (solid dots). Dashed lines indicate isopachs inferred by assuming that Pliocene sedimentation patterns were similar to Pleistocene patterns. Dotted line indicates area of probable Mississippi-dominated sedimentation.

from the Laurentide and Cordilleran regions likely is present in the Mackenzie Delta as well. The Mackenzie drains the most extensive glaciated terrain of any river in North America and currently moves about 100 × 10^6 tons/yr of suspended sediment (Milliman and Meade, 1983). Although the Pliocene/Pleistocene stratigraphy of this region is not yet well established, seismic profiling in the area shows that the Beaufort Formation extends into the Mackenzie Delta as a thick wedge of clastic sediments out to and beyond the shelf edge (Hawkins and Hatelid, 1975).

Large amounts of glacial-age terrigenous sediments derived from North American and Eurasian sources may also underlie the Canada and Makarov basins of the Arctic Ocean. More than 1100 m of stratified unconsolidated sediments blanket the Marakov Basin directly adjacent to the Lamonosov Ridge (Blasco *et al.*, 1980), implying a high sedimentation rate. In the adjacent Alpha Ridge area, the thin sediment cover is principally late Miocene to recent glacial-marine sediment (Clark *et al.*, 1979), which may imply that the unconsolidated cover in the Marakov Basin is also glacial-marine. In the Canada Basin, sediments have been variously reported as 2–4 km (Mair, 1980) and up to 8 km thick (Grantz *et al.*, 1981); a significant portion may be glacially derived.

Although it seems likely that a substantial quantity of glacial-age sediment derived from North America is present in the deep Arctic Ocean and Mackenzie Delta, no reliable estimates can yet be made for these regions.

Glacial Sediments on Land

The volume of Laurentide glacial sedi-

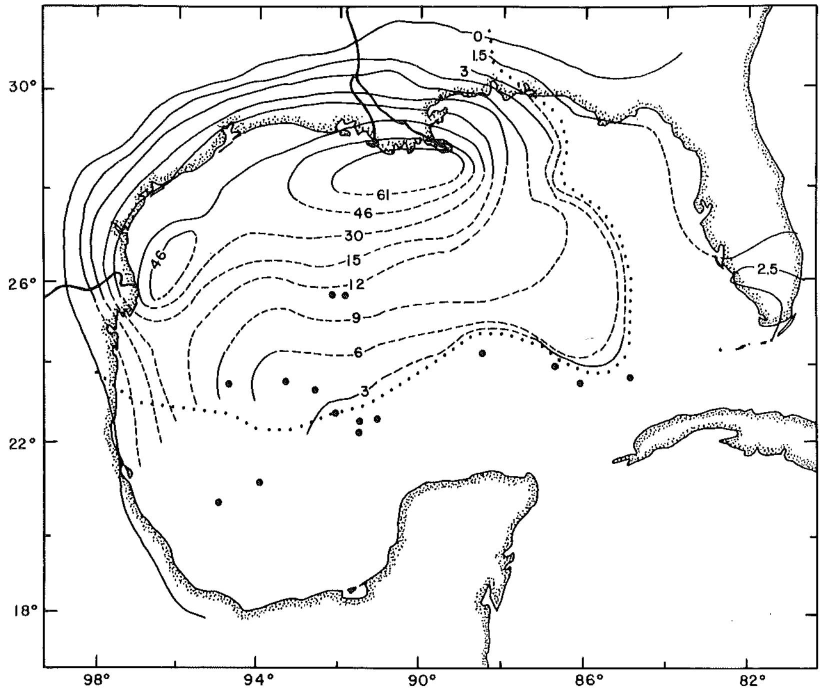

FIG. 5. Isopach map of Miocene sediments (10^2 m) in the Gulf of Mexico, compiled from many sources. The zero-isopach line is from Cook and Bally (1975), the solid isopachs in the nearshore regions are from Rainwater (1964), and the solid isopachs in the deep Gulf are inferred from DSDP core sites (solid dots). Dashed lines indicate isopachs inferred by assuming that Miocene sedimentation patterns were similar to Pleistocene and Pliocene patterns. Dotted line indicates area of sediments included in the calculations of the text.

ment on land in drift, loess, river sands, lake sediments, and fjord sediments is estimated to be about 1.6×10^5 km^3 (Appendix).

AVERAGE DEPTH OF EROSION

Compaction of Sediments

In order to compute the volume of solid rock removed from the Laurentide region (with no distinction between rock and regolith), it is necessary to correct for the lower density of marine terrigenous sediments and glacial sediments on land. Based on the variation in density of terrigenous sediments with depth below the sea floor (Hamilton, 1976) and assuming a crustal density of 2.7 g/cm^3, correction factors for compaction have been calculated for each glacial sediment province (Table 1). Because data are unavailable below 1.3 km depth, in the calculation of the dotted line in Figure 6, the density value at 1.3 km depth was used for all depths greater than 1.3 km. This density, 2.32 g/cm^3, provides a minimum estimate for all densities of deeper terrigenous marine sediment.

Average Contribution of Physical Erosion

The average contribution of glacial-age physical erosion can be calculated by dividing the volume of glacial-age terrigenous sediment by the area of the Laurentide region. That total volume, after applying compaction, source area, and biogenic sediment corrections, is 1.62×10^6 km^3 (Table 1). Several factors included in the calculation require that this figure be regarded as a minimum estimate.

(1) No calculation was made for sediment in the Canada and Marakov basins of the Arctic Ocean and in the Mackenzie Delta.

TABLE 1. VOLUME OF GLACIAL-AGE TERRIGENOUS SEDIMENT DERIVED FROM THE LAURENTIDE REGION

Region	Total glacial-age (km^3)	Total biogenic corrected (km^3)	Total source corrected (km^3)	Compaction correction (%)	Total Laurentide sediment (km^3)
Gulf of Mexico	1.34×10^6	1.04×10^6	7.40×10^5	78.7	5.82×10^5
Western North Atlantic	1.50×10^6	1.34×10^6	1.17×10^6	65.2	7.63×10^5
Arctic Islands	2.5×10^5	2.5×10^5	2.5×10^5	68	1.7×10^5
Glacial sediment on land	1.84×10^5	1.84×10^5	1.84×10^5	57	1.05×10^5
Total					1.62×10^6

(2) No correction was made for SiO_2, $CaCO_3$, and other solids carried as suspended load but lost through solution in warm marine waters or at abyssal depths.

(3) Corrections for compaction of sediments thicker than 1.3 km were calculated low.

(4) The volume of Pleistocene sediment in unit B of the Mississippi fan (Moore *et al.*, 1978) was not included (Appendix).

(5) No calculation was made for Laurentide sediment south of the Blake/Bahama Outer Ridge (Laine, 1980).

(6) No calculation was made for sediment in between the Canadian Arctic Islands, in the Kane Basin, or in the Lincoln Sea (Appendix).

The Laurentide region may be defined as the area reached by any advance of continental ice sheets in eastern North America, including the Ellesmere/Baffin ice complex. Flint (1971) has calculated this area to be 13,386,964 km^2; however, this figure may be too large. England (1976) has argued for only minimal ice cover of the Queen Elizabeth Islands by the late Wisconsin Franklin ice complex. In contrast, Blake (1970) and Mayewski *et al.* (1981) support Flint's view of extensive coverage of the Queen Elizabeth Islands. Flint's figure probably provides a maximum estimate of the size of the Laurentide region. Dividing the volume of sediment (1.62×10^6 km^3) by the source area (13,386,964 km^2) yields a minimum estimate of an average depth of 120 m of rock physically eroded from the Laurentide region in the last 3 my.

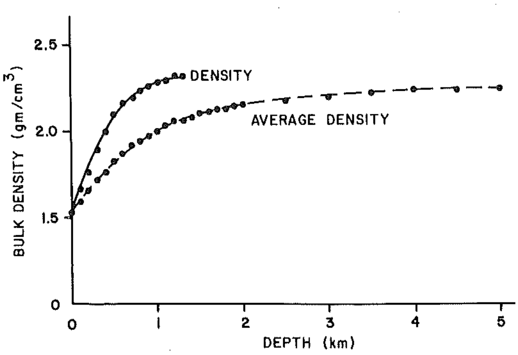

FIG. 6. *In situ* bulk density versus depth of terrigenous marine sediments (solid line; data from Hamilton, 1976) and the average density of terrigenous sediment above a given depth (dashed line). Average densities including sediment from greater than a 1.3-km depth are calculated low (see text for explanation).

Average Depth of Erosion

Milliman and Meade (1983) have calculated modern suspended sediment yields to the oceans (in tons/km^2/yr) for the entire globe, based on fluvial sediment loads. Using Milliman and Meade's figures, we estimate an average yield of about 20 tons/km^2/yr for the Laurentide region. Assuming a bedrock density of 2.7 g/cm^3, this is approximately equivalent to 22 m of physical erosion in 3 my by fluvial processes (Appendix). The near-order-of-magnitude difference with our estimate based on terrigenous sediment volumes indicates that fluvial processes alone can not be responsible for 120 m of physical erosion; this large amount of erosion is a result of continental glaciation. As discussed previously, glaciation works in consort with fluvial erosion by providing the only material which the low-gradient streams on the shield are capable of eroding. Thus, at the broadest level, all 120 m of erosion can be attributed to processes associated with continental glaciation. These processes include (1) the stripping of regolith by early ice sheets, (2) abrasion and plucking of bedrock by ice sheets of all ages, (3) fluvial erosion of residual drift, with limited bedrock erosion, and (4) sediment transport to the oceans by interglacial, proglacial, and meltwater streams, and by calving ice.

The 120 m estimate of physical erosion is much larger than previous estimates by Ambrose (1964), Flint (1971), Gravenor (1975), Sugden (1976), Rutter (1980), and Kaszycki and Shilts (1980). These authors argue that continental glaciation has removed only some few tens of meters of rock and weathered regolith from North America. A rough check of the accuracy of the estimate can be made by recalculating the value using only the well-documented terrigenous sediment volumes in the Gulf of Mexico and the western North Atlantic, leaving out glacial sediment on land and the more speculative estimate for the Canadian Arctic. Using only these two regions, the estimate of the average depth of erosion would be about 100 m.

The 120 m figure represents 15 times as much erosion as was calculated from the volume of glacial sediment on land alone (Table 1). This supports the contention of White (1972) and Laine (1980) that the oceans serve as the main repository of sediment from glaciated areas.

Because of the inclusion of minimizing factors in the calculations, the average depth of erosion is probably substantially more than 120 m. As discussed earlier, chemical erosion, which cannot be measured directly, is likely also to be significant. However, an estimate of the thickness of material removed chemically may be derived by extrapolating the current regional rate of chemical denudation back over the past 3 my. Using data of Meybeck (1979), the present average rate of chemical erosion in the Laurentide region is calculated to be 16.7 tons/km^2/yr (Appendix). This rate may be altered during periods of extensive ice coverage. Although land covered by ice during glacial advances probably experiences little direct chemical erosion, dissolution of the increased amounts of fine-grained suspended sediments carried by streams during glaciation (Reynolds and Johnson, 1972) may have amplified overall chemical contributions from the Laurentide region. Because of this effect, the present rate of chemical erosion probably provides a minimum estimate for the last 3 my. Therefore, if the rate is extrapolated (Appendix), chemical erosion accounts for 18.6 m of rock (average density of 2.7 g/cm^3) removed from the Laurentide region. Therefore, the total average denudation of the Laurentide region over the last 3.0 my, including both chemical and physical processes, is at least 139 m.

A multidome reconstruction of the Laurentide Ice Sheet (Shilts *et al.*, 1979; Andrews, 1982) can be used to estimate the true average depth of denudation in one portion of the Laurentide region. The estimate of sediment volume is most precise for the western North Atlantic. Assuming that Wisconsin-age flow lines are fairly representative of all glacial advances (a debatable assumption; e.g., Denton and Hughes, 1981), the source area for western North Atlantic sediments can be defined (Fig. 7). Laine and Bell (1982) calculated 140 m of physical erosion based on a multidome reconstruction. When the thick Quaternary deposits on the northeast North American continental margin excluded by Laine (1980) and Laine and Bell (1982) are included in the calculations (Appendix), 183 m of physical erosion is estimated. If chemical erosion within the source area is allowed for, over 200 m of total denudation is possible.

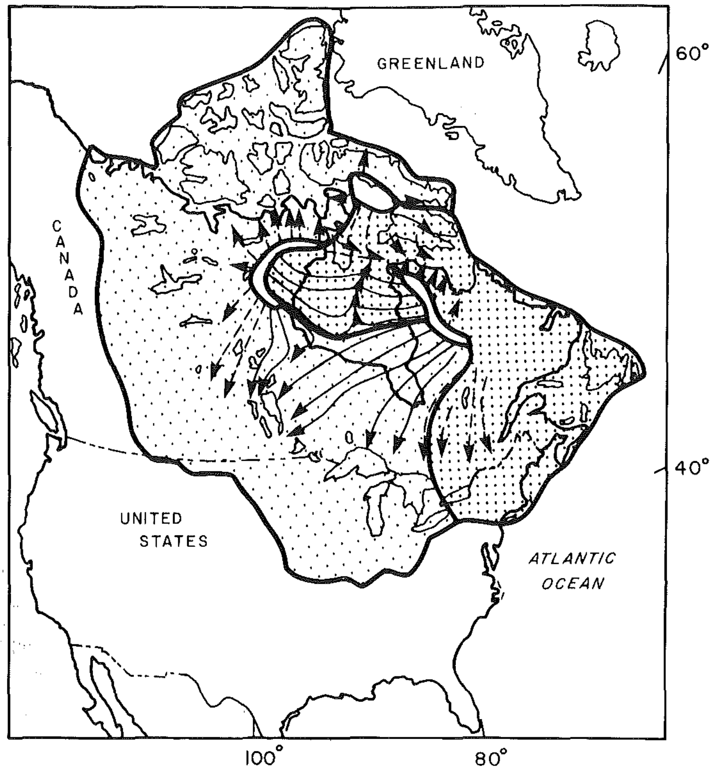

FIG. 7. Area of the Laurentide region that was a sediment source for western North Atlantic (exclusive of the Davis Strait and Baffin Bay). Multidome reconstruction of flow lines after Shilts (1980; Fig. 3) and Andrews and Miller (1979; Fig. 4).

Thus, denudation of a low-relief region by processes associated with continental glaciation appears to be much more effective than by fluvial processes alone. The importance of glaciation in shaping the morphology of the Laurentide region should therefore be reevaluated. However, this higher estimated rate of erosion is still considerably lower than rates in areas of active tectonic uplift. For example, a denudation rate of 70 cm/1000 yr, or 2100 m/3 my, has been calculated for the Himalayas, based on the sediment yield of the Ganges River and on sediment volumes in the Bay of Bengal (Curray and Moore, 1971).

EROSION DURING A SINGLE GLACIATION

Kaszycki and Shilts (1980, unpublished data) calculated an average depth of physical erosion of 2–10 m on the Keewatin Peninsula and southeast Ontario for the last major glacial–interglacial cycle. These figures are consistent with an average depth of physical erosion of 120–183 m for the last 3 my. Evidence from oxygen-isotope records suggests that the duration of the average glacial cycle is about 100,000 yr (Hays *et al.*, 1976). Thus, perhaps at least 25 ice sheets have advanced since the beginning of major continental glaciation in North America about 3 my ago. Assuming 6 m of physical erosion for the whole Laurentide region during each glaciation, we arrive at an average of 150 m of physical erosion.

Multiple tills in the Hudson Bay/James Bay region deposited since the last interglaciation suggest that the oxygen-isotope record, which represents a global average, is a simplification of the history of the fluctuating Laurentide Ice Sheet (Andrews *et* *al.*, 1983). A more complicated history of pulses and advances might increase the amount of glacial erosion in the Laurentide region. Also, Andrews (1982) has suggested that rates of erosion may have been greatest for the earliest ice sheets. Sedimentation rates of 35 cm/1000 yr for the Pliocene and 10 cm/1000 yr for the Pleistocene at DSDP Site 113 in the Labrador Basin support this contention (Laine and Bell, 1982). Site 113 received sediment primarily from turbidites, as opposed to bottom currents or floating ice, and therefore the sedimentation rates may directly reflect rates of erosion. If these early glacial advances eroded more than the 6 m used in the previous calculation and if ice sheets do fluctuate more than the oxygen-isotope record indicates, a 183-m total depth of physical erosion seems conceivable. Thus, the 2 to 10-m figure of Kaszycki and Shilts is well within the range necessary to reach a 120- to 183-m average depth of physical erosion.

SEDIMENT PRODUCTION BY PERMANENT ICE SHEETS

Sediment production by permanent ice sheets, such as the Antarctic Ice Sheet, may differ from that by periodic ice sheets, such as the Laurentide, either due to differences in processes of erosion or transportation of sediment to the oceans. Although calculation of glacial-age sediment volumes in ocean basins surrounding Greenland and Antarctica is not now possible based on the published literature, some insight into the relative rates of sediment production may be inferred from modern sedimentation rates. It should be noted, however, that relative sedimentation rates do not necessarily reflect relative sediment production rates because of differences in size, shape, and location of ocean basins receiving sediment from permanent and periodic ice sheets.

Seismic reflection work off the southeast margin of Greenland (Johnson *et al.*, 1975) suggests that the amount of Quaternary sediment there is small compared with that along the northeast margin of North America (Jansa and Wade, 1974). The sedimentation rate in the Greenland Sea, which receives sediment only from Greenland and Iceland, has been only 3–4 cm/10^3 yr for the last 300,000 yr (Eldholm and Windisch, 1974). If this rate is extended back 3 my, it is equivalent to only 100 m of sediment. This figure is consistent with results from DSDP holes drilled at Sites 346, 347, 348, and 351 (Talwani, *et al.*, 1976). A further check may be found in the work of Vogt *et al.* (1981), who have calculated a rate for the entire Greenland–Norwegian Sea area of only 2 cm/1000 yr over the last 3 my.

A similar situation exists off Antarctica. In 9 of 10 DSDP holes drilled near Antarctica (DSDP Legs 28 and 35), the depth to late Miocene sediments is less than 300 m (the other is 490 m). The sedimentation rates over the last 7 my at these 9 drill sites are all less than 3.9 cm/10^3 yr. Much of this sediment contains a high percentage of biogenic material making the rate of terrigenous sediment deposition even smaller.

In comparison, Pleistocene sedimentation rates are much higher in the western North Atlantic north of the Blake-Bahama Outer Ridge. Sedimentation rates of 4.5–27.4 cm/1000 yr are reported from DSDP Sites 111, 112, 113, 382, and 383 on the abyssal plains. Sites 6–8, 102–108, and 384–388, located on the Bermuda Rise, the Continental Rise and the Blake/Bahama Outer Ridge, showed more variable rates, of 0–20 cm/1000 yr (Ewing *et al.*, 1969; Peterson *et al.*, 1970; Hollister, *et al.*, 1972; Laughton *et al.*, 1972; Benson *et al.*, 1978; Tucholke *et al.*, 1979). Laine (1980) has estimated a minimum average sedimentation rate of 7 cm/1000 yr over the last 2.8 my in the western North Atlantic. Evidently, the effect of a permanent ice sheet, as opposed to a periodic ice sheet, is to *lower* the sedimentation rates.

SEDIMENT PRODUCTION DURING ANCIENT ICE AGES

The presence of at least 1.62×10^6 km^3 of terrigenous sediment derived from the Laurentide region in the past 3 my (Table 1) indicates that periodic ice sheets can result in high rates of sediment production. It might be expected that ancient glacial epochs would also have followed this pattern and left us with large volumes of sedimentary rock. However, the geologic record shows that the Permo–Carboniferous and late Precambrian glacial epochs are associated with the lowest sediment survival rates of the past 700 my (Fig. 8).

These low rates of sediment survival may be a consequence of predominantly marine deposition of sediments during glacial epochs. The evidence presented in this paper agrees with the conclusion of Laine (1980) that 90–95% of sediment from glaciated areas is being deposited in the ocean. In addition, due to low stands of sea level, most sediment from non glaciated areas is also being deposited in ocean basins. Similar conditions may have affected patterns of sediment deposition during ancient glacial epochs. Since ocean basins are subject to more subduction than continental land masses, a disproportionally small amount of sediment from ancient glacial epochs would have survived the constant cycling of plates. Thus, the late Precambrian and Permo–Carboniferous ultimately appear on the record as times of low sediment survival.

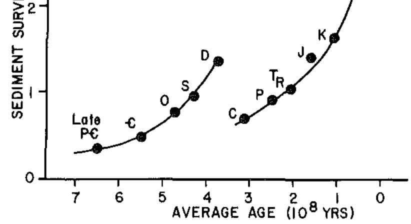

FIG. 8. Sediment survival (in km^3/yr) through time (after Gregor, 1970). Note how the major discontinuity in the graph corresponds to the time of the Permo–Carboniferous glaciations.

Due to its recency, the Pleistocene has the highest sediment survival rate of all geologic epochs. As a result of glaciation, most of this sediment lies on the deep ocean floors and continental margins. With future subduction of the sea floor, most Pleistocene sediments ultimately will be recycled or tectonized, and the Pleistocene may appear on the record as a period of low, as opposed to high, sediment survival—if not a major unconformity.

CONCLUSIONS

(1) A minimum average of 120 m of rock has been physically eroded in the last 3 my from the area covered by Laurentide ice sheets. This estimate suggests that substantial denudation of the Canadian Shield has occurred as a result of glacial and glaciofluvial processes.

(2) Because of the many minimizing factors included in the estimate of 120 m of erosion, the true figure may be as high as 175–200 m.

(3) The ocean basins are the main repositories of glacial-age sediment.

(4) The effect of permanent ice sheets in comparison with periodic ice sheets may be to lower sedimentation rates in adjacent ocean basins.

(5) The predominance of marine sedimentation during glacial epochs may result in their ultimate appearance on the geologic record as the times with the lowest rates of sediment survival.

APPENDIX

Calculation of Laurentide Glacial-Age Sediment Volumes

Gulf of Mexico

Data for the region of the Gulf of Mexico that is dominated by Mississippi sedimentation (the dashed line in Fig. 2 and the dotted lines in Figs. 4 and 5) were derived from DSDP Legs 1 and 10 site reports (Ewing 1969; Worzel *et al.*, 1973) and from heavy mineral provenance studies of Davies and Moore (1970). The volume of Pleistocene sediment within this region was calculated from the generalized isopach map of Stuart and Caughey (1976) (Fig. 2) and, in the Mississippi Fan, from the more detailed study of Pleistocene seismic unit A by Moore *et al.* (1978) (fig. 3). Throughout the area of their survey, Moore *et al.* found considerably greater thicknesses of Pleistocene sediment, possibly indicating that Stuart and Caughey underestimated sediment thickness in other regions. Some Pleistocene sediment is also present in unit B (Moore *et al.*, 1978) but was not included in our calculations. Assuming a similar region of Mississippi dominance during the Pliocene in the Gulf of Mexico, a Pliocene volume of 5.75×10^6 km^3 was calculated from Figure 4. Northern Hemisphere glaciation was active for only the last 1.2 my of Pliocene time (1.8 to 3.0 my), about 40% of the total span of the Pliocene (1.8 to 4.8–5.0 my) (Benson, 1978; Sheridan, *et al.*, 1983). The extension of turbidite sedimentation into the late Pliocene of the Gulf of Mexico (Worzel and Bryant, 1973) indicates that sedimentation rates were overall higher during the glacial portion of the Pliocene. Therefore, the glacial-age Pliocene sediment is probably at least 50% of the total Pliocene sediment.

The total volume of glacial-age sediments in the Mississippi-dominated portion of the Gulf of Mexico was calculated to be 13.4×10^5 km^3. This volume was corrected for biogenic sediments based on the Pliocene and Pleistocene record of undisturbed DSDP Sites 90 and 91 in the deep Gulf and the Pleistocene record of Sites 1 and 92 for all nearshore sediments shoreward of the 800 m Pleistocene isopach (Pliocene sediment was not recovered in near shore sites because of the extreme thickness of the Pleistocene section). Siliceous microfossils are generally absent in Gulf sediments younger than early or middle Miocene (Sanfillippo and Riedel, 1972) so a correction is necessary only for biogenic carbonate. Two carbonate corrections were used, 32.3% for the deep Gulf and 18.3% for all sediments shoreward of the 800-m Pleistocene isopach. After correcting for biogenic contributions, the volume of terrigenous sediment in the Mississippi-dominated region is 10.42×10^5 km^3.

Almost all of this sediment was likely deposited by the Mississippi as its depositional center migrated along the Gulf Coast shelf edge (Woodbury *et al.*, 1973), with a small amount derived from other rivers. Information on modern fluvial sediment fluxes into the Gulf of Mexico indicates that the Mississippi is by far the biggest contributor of sediment to the Gulf of Mexico. Milliman and Meade (1983) estimate that the Mississippi River moved an average 210×10^6 tons/yr of suspended sediment (38% through the Atchafalaya branch) from 1963 to 1979; Holeman (1968) estimated 344×10^6 tons/yr (35% through the Atchafalaya branch) from 1949 to 1966; and Dole and Stabler (1909) estimated 385×10^6 tons/yr (419×10^6 short tons/yr, with no estimate of additional sediment moved down the Atchafalaya branch). In the years before 1949, discharges of around 500×10^6 tons/yr were often recorded (Holeman, 1968; Curtis *et al.*, 1973). The smaller numbers in recent years are an artifact of reservoir construction and other human activities (Milliman and Meade, 1983; Holeman, 1968) and suggest that the early stream load estimates of Dole and Stabler may provide the most accurate information regarding the relative importance of the Mississippi through time. Assuming a load for the Atchafalaya branch similar to the relative loads measured by Holeman (1968) and Milliman and Meade (1983) (36.5%), the Mississippi River drainage basin in 1909 averaged 525.5×10^6 tons/yr (571.9×10^6 short tons/yr) or 93% of all sediment discharged from the United States Gulf Coast

(Dole and Stabler, 1909, Table 1). Much of the other 7% of non-Mississippi sediment from the United States and additional sediment from Mexican rivers has been deposited in regions not covered by the region of Mississippi-dominated sedimentation, suggesting that at least 93% of the sediment enclosed by the Mississippi-dominated region originated from the Mississippi.

The contribution of erosion in the non-Laurentide drainage of the Mississippi was estimated from the preglacial Miocene sediment isopachs in the Gulf of Mexico (Fig. 5). The area of the preglacial Mississippi drainage was 77% as large as that of today (Flint, 1971, Fig. 9-3) and roughly approximated the size and coverage of the 65% of total Mississippi drainage which has not been covered by Laurentide ice. The region of Mississippi dominated sedimentation in the Gulf was also smaller, partly due to the decreased size of the drainage basin and partly because the Miocene Rio Grande was a major carrier of sediment and built large deltas north of its present mouth (Rainwater, 1964). We chose to overestimate the importance of erosion in the non-Laurentide Mississippi drainage by assuming the same Miocene region of Mississippi-dominated sedimentation as in the Pliocene and thus including much sediment that actually originated in the Rio Grande drainage. The total volume of Miocene sediment in this region of the Gulf is 1.6×10^6 km^3 or 2.7×10^6 km^3 per 3 my. Assuming similar compaction and content of biogenics in the Miocene section, this volume of sediment represents a sedimentation rate that is about 20% of the glacial-age sedimentation rate. Since compaction of the Miocene section is undoubtedly greater than that for the Pliocene/Pleistocene section, the assumption of similar compaction may offset the inclusion of sediment derived from the Miocene Rio Grande.

A small portion of the non-Laurentide drainage of the Mississippi may have experienced accelerated erosion over the last 3 my because of alpine glaciation. Approximately 50,750 km^2 of glaciated alpine terrain in the Rocky Mountains is drained by the Mississippi, representing just 1.5% of the total modern Mississippi drainage and about 4.5% of the Laurentide area currently drained by the Mississippi (Flint, 1948, 1971; Fig. 18-11; Montagne, 1972). Since the Mississippi has carried sediment from a much larger portion of the Laurentide region than it presently drains as a result of damming of the St. Lawrence, Mackenzie, and Hudson Bay drainage systems during glacial retreat, the contribution of alpine glaciation is probably less than 4.5% of the total volume of sediment.

Using the 4.5% figure for an alpine glaciation correction and applying the 7% correction for non-Mississippi inputs to the Gulf of Mexico and the 20% correction for erosion in the non-Laurentide region, the total volume of glacial-age terrigenous sediment in the Gulf of Mexico derived from the Laurentide region is estimated to be 7.40×10^6 km^3 (Table 2).

Western North Atlantic

The volume of glacial-age terrigenous sediment in areas of the western North Atlantic dominated by Laurentide sedimentation was calculated by Laine (1980) to be

TABLE 2. VOLUME OF GLACIAL-AGE TERRIGENOUS SEDIMENT IN THE GULF OF MEXICO DERIVED FROM THE LAURENTIDE REGION

Age	Volume of glacial-age sediments (10^5 km^3)	Volume corrected for biogenics (10^5 km^3)
Pleistocene	10.5	8.2
Pliocene[a]	2.88	2.22
Total	13.4	10.42
Volume corrected for sources other than Mississippi (7%)		9.69
Volume corrected for nonglacial contribution (20%)[b]		7.75
Volume corrected for contribution of alpine glaciation (4.5%)		7.40

[a] Only includes Pliocene sediments younger than 3 my.
[b] Based on the Miocene preglacial sedimentation rate.

TABLE 3. VOLUME OF GLACIAL-AGE TERRIGENOUS SEDIMENT IN THE WESTERN NORTH ATLANTIC DERIVED FROM THE LAURENTIDE REGION

	Area (10^4 km^2)	Thickness (m)	Total volume (10^4 km^3)	Biogenic, corrected (10^4 km^3)
Sohm abyssal plain[a]	110	320	35	34
Hatteras abyssal plain[a]	30	200	6.0	5.1
Nares abyssal plain[a]	10	150	1.5	1.3
Continental rise[a]	8	285	2.3	2.0
Labrador and Newfoundland basins[a]	130	390	51	46
Continental margin[a]	130	96	12	10
Bermuda rise[a]	67	47	3.2	2.9
Total			111.0	101.3
Correction for sources outside glaciated regions (2%)[a]			108.8	99.3
Correction for	130[b]	100[b]	−13.0	−12.0
contribution of southern Greenland	33[c]	96[c]	−3.2	−2.7
Additional continental margin	96.8	(500–96)	+39.1	+32.5
Total			134.9	117.1

[a] Data from Laine (1980).
[b] Labrador and Newfoundland basins correction.
[c] Continental margin correction.

1.01×10^5 km^3. This figure includes sediment derived from southern Greenland and a small amount (2%) of sediment from nonglaciated areas (Laine, 1980). Greenland likely only contributed terrigenous sediment to the Labrador and Newfoundland basins and continental margin provinces of Laine (1980). The contribution to the Labrador and Newfoundland basins province may be estimated by comparison with the Greenland Sea which receives sediment only from Greenland and Iceland and contains an average of just 100 m of glacial-age sediment (Eldholm and Windisch, 1974; Talwani *et al.*, 1976; Vogt *et al.*, 1981). Assuming no complications due to differences in basin morphology and transport, 100 m can be removed from the Labrador and Newfoundland basins province of Laine as an estimate of the Greenland contribution to this province. Laine's estimate for the continental margin of Greenland was extrapolated from thicknesses found off eastern North America south of George's Bank (Laine, 1980). Greenland's contribution to the continental margin province may be removed by simply subtracting the relative percentage coverage of Greenland's continental margin (25%).

The Quaternary section of the continental margin north of George's Bank was reestimated and added to the continental margin province of Laine based on new reports of seismic investigations (Jansa and Wade, 1974; Uchupi and Austin, 1979; Umpleby, 1979). The section has a doubly lensoid cross section with thicknesses up to 2000 m along the shelf edge, generally thin sediments on the middle slope (100–500 m), and thick deposits, often greater than 1800 m, along the rise. Overall, it may average about 500 m. For the same region, Laine (1980) provided a minimum estimate of the average thickness of 96 m. Thus, an additional 404 m (500–96 m) may be added to the portion of the continental margin province north of George's Bank.

When these corrections for nonglacial

sources, southern Greenland, and additional continental margin sediment are made, the volume of glacial-age terrigenous sediment in the western North Atlantic derived from the Laurentide region is estimated to be 1.17×10^6 km^3 (Table 3).

Canadian Arctic Islands

Thick sequences of Pliocene/Pleistocene clastic sediments (the Beaufort Formation) are present along the margin of the Canadian Arctic Islands with thicknesses up to 1800 m (Menely *et al.*, 1975; Miall, 1975). In both the Davis Strait and western Baffin Bay, there are over 6100 m of late Eocene and younger fluvial and deltaic sediments (Beh, 1975). Because Baffin Island was a major ice dispersal center, probably much of the 6100 m is of glacial age. The thickness of the glacial-age section along the whole margin of the Arctic Islands may be similar to the continental margin of northeastern North America and average about 500 m. Multiplying by the area of margin considered (5.25×10^5 km^2) yields an estimate of at least 2.5×10^5 km^3 of sediment. Due to the general nature of this calculation, no correction for biogenic sediments was made.

Laurentide Glacial Sediment on Land

The average thickness of glacial drift in North America ranges from about 2 to 60 m (Flint, 1971) with an overall average of about 7–8 m. Thus, the total volume of drift on the 13,386,964 km^2 Laurentide region is about 1×10^5 km^3.

Additional Laurentide sediment is present in river sands with a major portion in the Mississippi embayment. From the frontispiece of Fisk's work on the Mississippi (Fisk, 1944), the embayment is estimated to contain 1×10^4 km^3 of sediment. Assuming that about 20% of this sediment has a non-Laurentide origin (Appendix: Gulf of Mexico), the Laurentide contribution is 8×10^3 km^3. Laurentide sediment in other river sands may triple this number.

An additional 1.8×10^4 km^3 of glacial sediment can be found in the Great Lakes (Thomas *et al.*, 1973; Dell, 1974; Wickham *et al.*, 1978; Lineback *et al.*, 1979; Johnson, 1980). There may be as much as 4×10^4 km^3 of sediment on the bottom of Baffin Island fjords (J. T. Andrews, 1983, personal communication). Also, at least 1.6×10^6

TABLE 4. LAURENTIDE GLACIAL SEDIMENT ON LAND

Sediment type	Volume (10^5 km^3)
Glacial drift	1.0
River sands (including Mississippi embayment)	0.24
Lake sediment in the Great Lakes	0.18
Sediment in Baffin Island fjords	0.4
Loess	0.016
Total	1.84

TABLE 5. CHEMICAL EROSION OF LAURENTIDE REGION

Morphoclimatic region	% Total area	Chemical erosion rate[a] (tons/km^2/yr)
Temperate humid	7	35
Temperate	8	28
Taiga humid	23	15.5
Tundra and taiga	60	14
Arid	2	3
Average		16.7

[a] Data from Meybeck (1979).

TABLE 6. MODERN SUSPENDED SEDIMENT YIELD IN THE LAURENTIDE REGION

Region	% Total area	Suspended sediment yield[a] (tons/km^2/yr)*
Canadian Shield	48	8
Mackenzie drainage basin	15	55
St. Lawrence drainage basin	11	4
Canadian Arctic Islands	11	1
Mississippi drainage basin	10	59
Atlantic coast	5	17
Average		19.4

[a] Data from Milliman and Meade (1983).

km^2 of central North America is underlain by loess ranging from a few centimeters to 35 m thick (Flint, 1971), and perhaps averaging 1 m. The total volume of all glacial sediment on land is estimated to be 1.84×10^5 km^3 (Table 4).

Chemical Erosion of Laurentide Region

Rates of chemical erosion in the Laurentide region were derived from Meybeck (1979) and are corrected for the contribution of oceanic cyclic salts and atmospheric CO_2 (Table 5). If average chemical erosion e is 16.7 tons/km²/yr, then total chemical erosion equals

$$e/g \times t = 18.6 \text{ m}$$

where t is 3×10^6 yr and g is an average specific gravity of 2.7 g/cm³.

Modern Suspended Sediment Yield in the Laurentide Region

Rates of modern suspended sediment yield in the Laurentide region are available from the recent global compendium of this kind of information by Milliman and Meade (1983) (Table 6). Using an average figure for the entire region and applying it to the equation above,

$$e/g \times t = 21.6 \text{ m}$$

where e is 19.4 tons/km²/yr.

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