Report for 2002MN6B: Paleohydrologic response of the Mississippi Headwaters watershed to Holocene climate change

There are no reported publications resulting from this project.

Report Follows:

Paleohydrologic Response of the Mississippi Headwaters Watershed to Holocene Climate Change

H.D. Mooers and **P.C. Larson**, Department of Geological Sciences, College of Science and Engineering, University of Minnesota, Duluth

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Summary

This study examines the sedimentary record of major changes in the hydrologic budget of three large lakes in the Mississippi Headwaters area (Cass, Leech, and Winnibigoshish) resulting from multiple diversions of the Mississippi River and its tributaries. Sediment cores collected from Cass and Leech Lakes, in combination with a core previously collected from Lake Winnibigoshish provide a record of the effects of regional-scale climate-driven changes on the hydrology of the Mississippi Headwaters watershed. The lakes' hydrologic budgets were affected by a series of diversion events that altered the main course of the Mississippi, and altered the watershed areas and throughflow rates of the three lakes.

One of the diversion events is recorded as a prominent, abrupt change in the nature of carbon sedimentation in Lake Winnibigoshish. However, this and other diversion events are not apparently discernable in Cass and Leech Lake sediments. The cause of the radically different response of Winnibigoshish to a diversion event is as yet enigmatic, however it implies the existence of an as yet unidentified control on the nature of lacustrine carbon sedimentation.

Ongoing geochemical, stable isotope, and diatom-nutrient calibration work will help distinguish the effects of climate-forced hydrologic variability from those of nutrient loading on sedimentation in the large Headwaters lakes.

Introduction

Most previous paleolimnological investigations in Minnesota have focused on interpreting the sedimentary records of relatively small lakes in small watersheds (Bradbury and Dean, 1993; Winter, 1997). While the high-resolution records found in these lakes are of undoubted value in interpreting past climatic and vegetation history, they are to some extent extremely sensitive to local conditions not reflective of the region as a whole (c.f. Schwalb and Dean, 2002). In contrast, the sedimentary records of the largest lakes in a drainage basin might be expected to record a regional-scale signal of climate change. This study examines the sedimentary record of major changes in the hydrologic budget of three large lakes in the Mississippi Headwaters area due to multiple diversions of the Mississippi River and its tributaries.

During the late Holocene, drainage patterns in the Mississippi Headwaters underwent a number of realignments. Prior to ca. 3 ka bp, the main stem of the Mississippi River flowed from Lake Bemidji to Leech Lake, thence down the present-day Leech Lake River. The outlet of Lake Winnibigoshish flowed southward to the Leech Lake River, and Cass Lake's outlet flowed south to Leech Lake. After this time, three stream piracy events led to diversion of major portions of the watershed into a new Mississippi River channel. The Mississippi now flows from Lake Bemidji through Cass and Winnibigoshish, exiting Winnibigoshish by a new eastern outlet. Leech Lake lies in a much diminished watershed, and continues to drain toward the east.

During the mid-Holocene, Cass and Leech Lakes were characterized by large watershed:lake area ratios (W/L), while the corresponding W/L for Winnibigoshish was small. This condition led to evaporation-forced hydrologic closure of Winnibigoshish, lower lake levels, eolian erosion of bottom sediment, and development of a dunefield on the eastern shore of the lake. These geomorphic relationships, and their implications for the paleohydrologic budgets of the lakes, indicates strong linkages exist between climate, hydrology, landforms, and the sedimentary records of the lakes.

Methods

Coring. Cass and Leech Lakes were cored in August 2001 using the University of Minnesota Limnological Research Center's ETH-Kullenberg system, a raft-mounted piston corer designed for use in deep water. Recovered cores are 9-cm in diameter. On both lakes, the coring location was the deepest part of the lake.

A 640-cm core was recovered from 44-m water depth in Walker Bay of Leech Lake. Sediment in this portion of the lake has a relatively high clastic component and corresponding high density, resulting in incomplete penetration of the coring device. However, the key late Holocene portion of the sediment record was completely sampled.

A 351-cm core was recovered in 34-m water depth in the northern portion of Cass Lake. Although short, this core terminates in glaciofluvial gravel and likely represents a complete postglacial section.

Lake Winnibigoshish was previously cored using a modified Livingston corer. A 575-cm core was recovered in 20-m water depth. Similar to Leech Lake, sediment in the lower portion of the sequence has a relatively high clastic component and corresponding high density, resulting in the inability to recover a complete postglacial section. However, the key late Holocene portion of the sediment record was completely sampled.

Sediment Dry Bulk Density. Sediment dry bulk density was determined by weighing 1-cm^3 samples of water-saturated sediment, freeze-drying, and weighing of the dried sediment. Sediment water content (porosity) corresponds to water loss during drying, and dry bulk density to the mass of dried sediment divided by the original volume.

Magnetic Susceptibility. Whole-core magnetic susceptibility for all three cores was measured at the Limnological Research Center, University of Minnesota. Magnetic susceptibility is a proxy measurement for the relative amount of clastic material in the sediment.

Carbon Analyses. Inorganic carbon and total carbon content of sediment from the recovered core was determined by coulometry at the Large Lakes Observatory, University of Minnesota Duluth. The organic carbon content of sediment is calculated by subtracting the inorganic from the total carbon content.

CNS Analyses. Sediment total carbon, nitrogen, and sulfur contents of Lake Winnibigoshish sediments were analyzed using a LECO at the Large Lakes Observatory, University of Minnesota Duluth. Results of these analyses allow assessment of the origin of organic carbon stored in the Winnibigoshish's sediments.

Carbonate Mineralogy of Lake Winnibigoshish Sediment. The mineralogy of sediments below 265 cm core depth (the interval with an appreciable carbonate content) was determined using a Philips X'Pert-MPD System x-ray diffractometer. The carbonate mineralogy of lacustrine sediments is sensitive to the salinity and Mg:Ca of the lake water in which the minerals formed (Kelts and Hsu, 1978). The Mg-content of calcite and dolomite (determined using the method of Goldsmith and Graf, 1958) and the presence or absence of aragonite will provide evidence of the presence and degree of hydrologic closure and evaporative concentration of lake water during the period of carbonate sedimentation in Winnibigoshish.

Results to Date

Lacustrine Stratigraphy and Sedimentology. The stratigraphy and sedimentology of sediment in each of the three lakes cored is unique, recording the unique history of each lake and its response river diversion events and

Lake Winnibigoshish. The Lake Winnibigoshish core consists of 300-cm of silty marl in the basal (pre-diversion) interval. The diversion event is recorded as the abrupt appearance of fine-grained sand in the sediments, marking the beginning of a 28-cm thick clastic-rich fining-upward sequence. The upper 247-cm of the core are diatom-rich black sapropel. Lake Winnibigoshish sediments have relatively high magnetic susceptibility in the pre-diversion interval, suggesting fluctuating lake levels may have resulted in a small, but steady, influx of silt from the littoral zone to the deep basin. These magnetic susceptibility peaks are absent in the post-diversion interval, suggesting lake level, and therefore the shoreline, was stable through this period.

The magnesium content of endogenic calcite in Lake Winnibigoshish varies between 4.5 and 7.6 mol% in the prediversion interval (Fig. 1). The Mg-content positively correlates with the amount of 'residual' material in the sediment. (The residual is the non-organic carbon and carbonate portion of the sediment, reflecting input of diatom silica clastic sediment eroded from the shoreline during periods of low or unstable lake levels.) This indicates that periods of lake level instability, and potentially hydrological closure, were characterized by a small degree of evaporative concentration and corresponding increase in Mg content of the lake's water.

In contrast to the pre-diversion interval, endogneic calcite deposited in the lake immediately after initiation of diversion of the Mississippi River into the lake is characterized by Mg mol% of 1.7 to 1.9. This suggests that the addition of the Mississippi's flow to the lake's hydrologic budget immediately relaxed the conditions of evaporative concentration and high Mg:Ca prevailing before the diversion.

The C:N ratio of organic material in lacustrine sediments is diagnostic of the organic material source; terrestrial plants are characterized by relatively high and aquatic plants by relatively low, C:N ratios (Meyers and Ishitwatari, 1995). The organic C:N of Lake Winnibigoshish sediments ranged from 8 to 15 (Fig. 1); these low values are consistent with an aquatic plant source with little if any terrestrial input. C:N values rose slightly after the diversion event and have displayed a gradual decline since, however the relatively small magnitude of this change precludes attaching to it any great significance.

Organic carbon mass accumulation rates (MAR) were calculated between 0 and 247 cm depth in the core, based on dates of 1000±32 ^{14}C yr bp at 248 cm core depth and 300±32 ^{14}C yr bp at 32 cm core depth (Fig. 4). Organic carbon MAR ranged from 49 to

105 g·m^{-2}·a^{-1}, averaging 70 g·m^{-2}·a^{-1}, in the post-diversion interval; these values are higher by a factor of 2 to 5 with respect to late-Holocene organic carbon MAR in nearby Elk, Williams, and Shingobee Lakes (OC MAR of 36, 21, and 17 g·m^{-2}·a^{-1}, respectively) (Dean, 1998). Essentially no carbonate was deposited during this interval, so the total carbon MAR is approximately organic carbon MAR.

Leech Lake. The Leech Lake core recovered 640-cm of silty marl occasionally interrupted by minor beds rich in detrital organic material, and thin sand lenses. The organic carbon content of Leech Lake sediments gradually increases from ~2% at the base of the core to ~8% immediately prior to initiation of agriculture and logging in the watershed (Fig. 2). Leech Lake sediments record the overall highest magnetic susceptibility values in the three lakes, reflecting relatively abundant influx of silt to Walker Bay (Fig. 2). Of particular interest are a single magnetic susceptibility peak at 260 cm, and numerous peaks between 434 and 501 cm core depth, corresponding to coarser-grained, clastic-rich intervals. The upper peak likely represents a mass flow event. Peaks in the interval 434-501 represent numerous mass flow events, perhaps recording a relatively long interval of shoreline erosion resulting from lake level instability.

Cass Lake. The Cass Lake core recovered 351-cm of organic-rich marl. The organic carbon content of Cass Lake sediments gradually increases from ~4% at the base of the core to ~8% at 40 cm core depth (Fig. 3). Carbonate shows a corresponding decrease from ~65% to ~45%. Cass Lake sediments have very low magnetic susceptibility, reflecting the very low input of clastic sediment to the northern basin of the lake through the Holocene. This is despite evidence that mid-Holocene lowstands may have resulted in significant sediment redistribution from the littoral zones of the lake.

Sedimentology of the Winnibigoshish dune field. While Grigal and others' (1976) radiocarbon dates have firmly established the presence of eolian activity adjacent to Lake Winniboshish during the mid-Holocene, their conjecture that 580 km^2 of dunefield was active during the mid-Holocene is debatable. The littoral zone exposed to wind erosion during periods of low lake level, and consequently the supply of sand available for export to the dunefield lying southeast of the lake, may have been as little as 10 km^2. It is diffucult to conceive of covering an area of 580 km^2 with sand up to 10 m thick originating from a 10 km^2 source area.

Detail mapping of the dunefield as defined by Grigal and others (1976) and grain size analysis of dune sediment has defined two subareas within their dunefield. A large area (~570 km^2) consists of sand with a wide range of mean grain size and no systematic variation. Dune forms are closely associated with older glacial landforms such as eskers and ice-walled lake plains. The orientation of dune features indicates a generally northwest to southeast sand transport direction. A relatively small area (~8 km^2) immediately adjacent to the lakeshore (including the area of Grigal et al.'s radiocarbon dates) is characterized by dunes consisting of finer-grained sand displaying a systematic fining with distance from the lakeshore. Dune forms within this area are much more distinct than the other subarea. Dune crest orientations indicate a generally southwest to northeast sand transport direction.

These relationships suggest that only a small area of the dunefield was active during the mid-Holocene, and that most of the larger dunefield formed immediately after deglaciation. The close match in area of our mapped younger dunes and their potential source area in the littoral zone further supports this conclusion.

Description of Ongoing Work

Results of the diatom-nutrient calibration and carbonate carbon and oxygen isotope analyses are pending. In addition, some of the radiocarbon dates for the sediment cores are still pending. Final results will complete the geochemical picture of the evolution of these large lakes during the Holocene.

Diatom-nutrient calibration. Diatom analysis of sediment samples from all three lakes is being conducted by J. Kingston at the Natural Resources Research Institute, University of Minnesota Duluth. Diatom population concentration and taxa will be counted, and the resulting data integrated with existing and ongoing diatom-nutrient calibration data for the Minnesota region (Kingston et al. 1992, Ramstack 1999, Kingston, pers. comm. 2002). This diatom-nutrient calibration set references diatom abundance and taxa in modern bottom sediments to a variety of water-quality parameters, including water turbidity, Secchi transparency, color, and dissolved silica, chlorophyll-*a*, phosphorus, and nitrogen contents. The results of these analyses will be used to assess long-term changes in the nutrient status of the three Headwaters lakes. Particular emphasis is being placed on quantifying changes in nutrient status corresponding to transitions in the nature of sedimentation recognized in the cores.

Summary of Important Findings

In Lake Winnibigoshish, diversion of the Mississippi River into the basin and the corresponding increased throughflow rate is accompanied by a radical shift in the nature of carbon sedimentation in the lake, from entirely carbonate to entirely organic carbon. Pre-diversion sediments in the core have very little organic carbon (3-4%) and carbonate contents of 60%. Post-diversion sediments have organic carbon contents of ~20% ranging up to 37%, and carbonate contents generally <12%.

However, a similar diversion and increase in throughflow rate of Cass Lake is not reflected in its carbon sediment record. Similarly, complementary decreases in the throughflow rate of Leech Lake are not reflected in its carbon sediment record. Cass Lake sediments record a gradual increase in organic carbon content from 5-8%, and a complementary decrease in carbonate from 65-50%. In Leech Lake, sediments record a gradual, steady increase in organic carbon from 2-8%, while carbonate varies from 48-78%. This pattern is similar to those reported by Dean (1999) in numerous lakes in Minnesota.

Dean (1999) has suggested that the shift from carbonate to organic carbon preservation in lake sediments is driven by increasing primary productivity. The transition in Lake Winnibigoshish is the most rapid reported in any lake in Minnesota. A 1-cm thick layer of nearly pure organic material in the core immediately following the diversion event suggests diversion was accompanied by increased nutrient loading. However, while the instantaneous increase in watershed area may have delivered increased nutrients to the lake, the presence of Cass Lake serving as a nutrient sink just upstream argues against this hypothesis. Alternately, pre-diversion carbonate sedimentation in Winnibigoshish may have been forced by evaporative concentration of lake water, a condition that was relieved with the initiation of increased throughflow. Results the diatom-nutrient calibration study will help distinguish between these two hypotheses.

Our results suggest that the nature of lacustrine carbon sedimentation is controlled in part by a threshold condition, one which has not been reached in most lakes in Minnesota, including Cass and Leech Lakes. The incremental increase and decreases in throughflow experienced by Cass and Leech during the late Holocene were apparently not of sufficient magnitude to trigger radical change in carbon sedimentation, while the increase experienced by Winnibigoshish was. This suggests that future climate-induced hydrologic changes in the Mississippi Headwaters basin, rather than being gradually manifested, may be characterized by rapid onset of perturbation of lacustrine ecosystems.

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List of publications and presentations resulting from this project:

Larson, P.C. and H.D. Mooers. 2003. Stream piracy in the Mississippi Headwaters: Implications for mid-Holocene eolian activity in the Midcontinent. Submitted to Geological Society of America Annual Meeting, October 2003, Seattle, Washington.

Description of Student Training provided by the project:

Name: Phillip Larson
Program: Department of Geology and Geophysics, University of Minnesota
Degree being sought: Ph.D.

Name: Kristian Rosendahl
Program: College of Education and Human Service Professions, University of Minnesota Duluth
Degree being sought: B.A.S.
Independent research project.

Name: Ryan Smith
Program: Department of Geosciences, University of Minnesota Duluth
Degree being sought: B.S.
Independent research project.

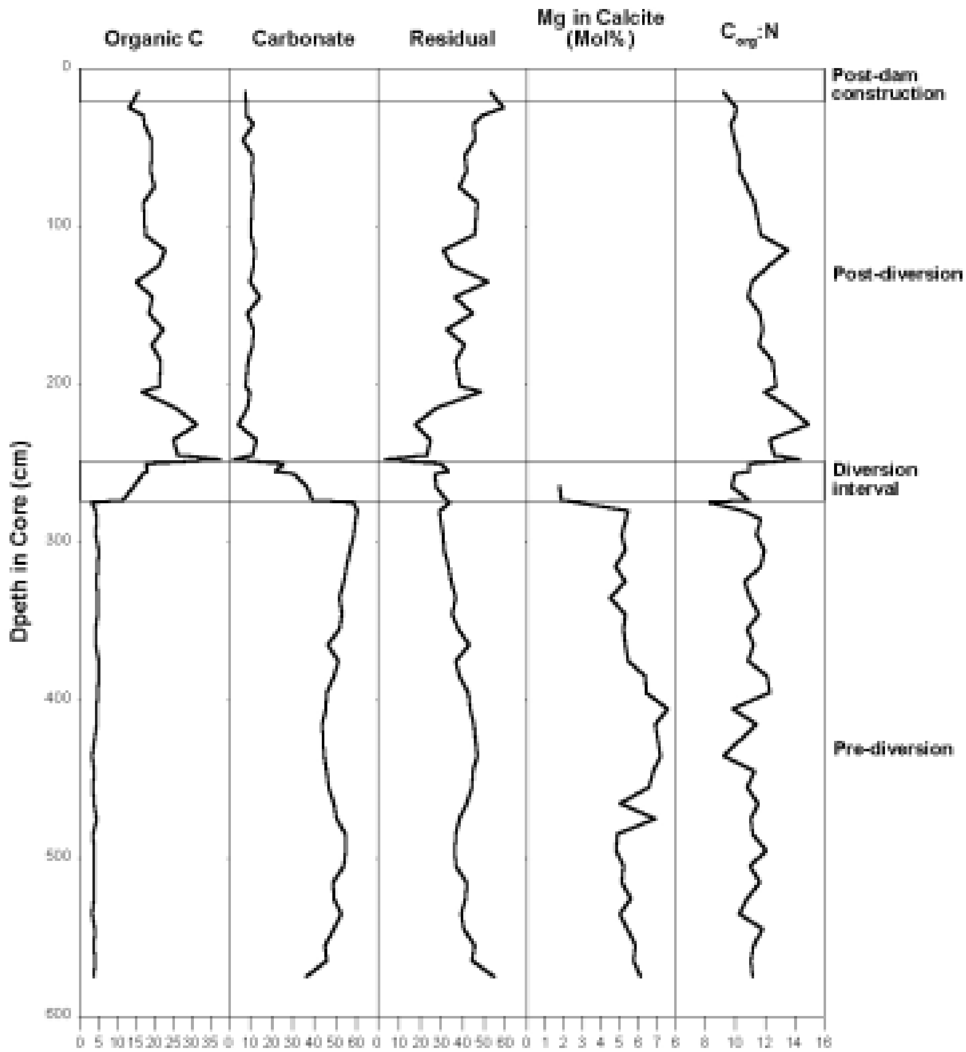

Figure 1.

Carbon content, Mg in calcite, and C:N profiles Lake Winnibigoshish.

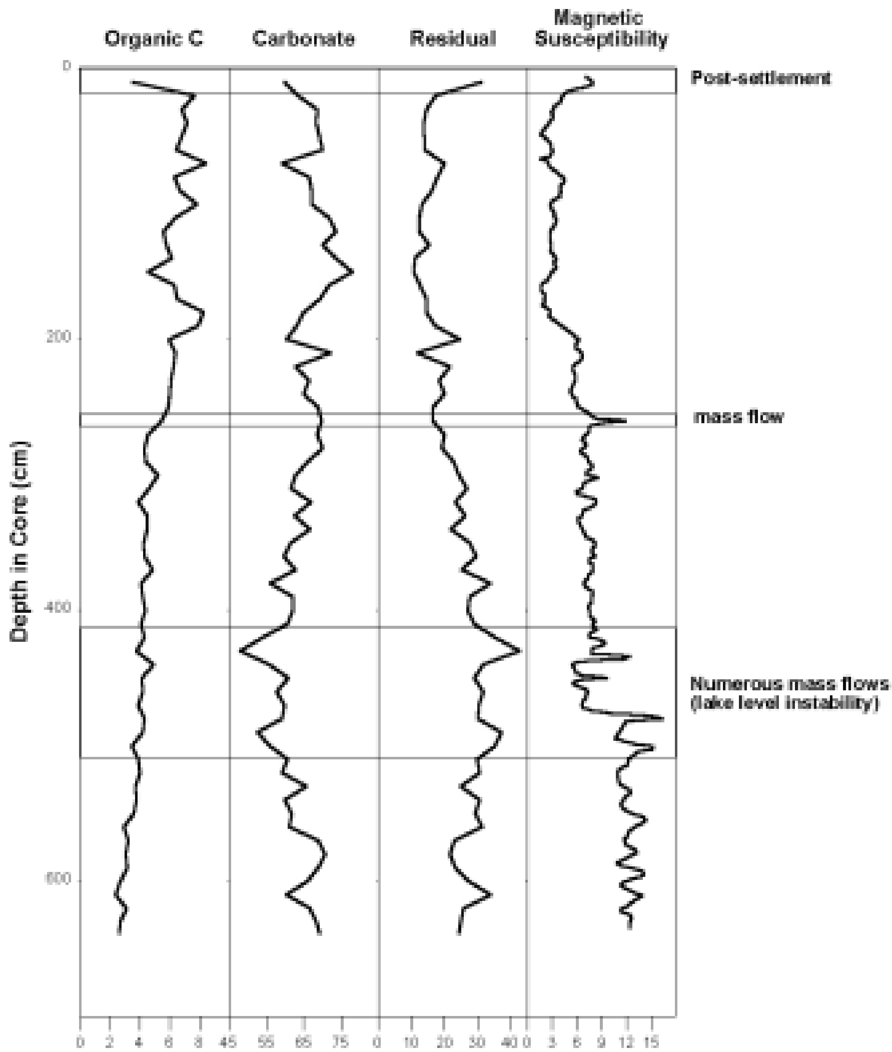

Figure 2.

Carbon content and magnetic susceptibility profiles Leech Lake.

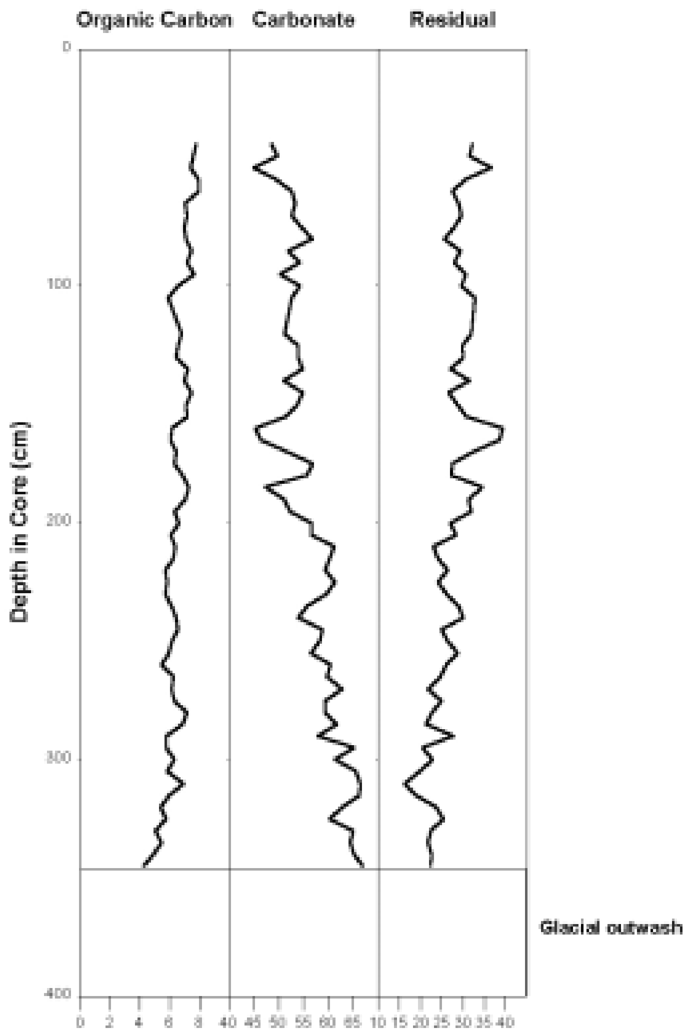

Figure 3.

Carbon content profiles for Cass Lake.

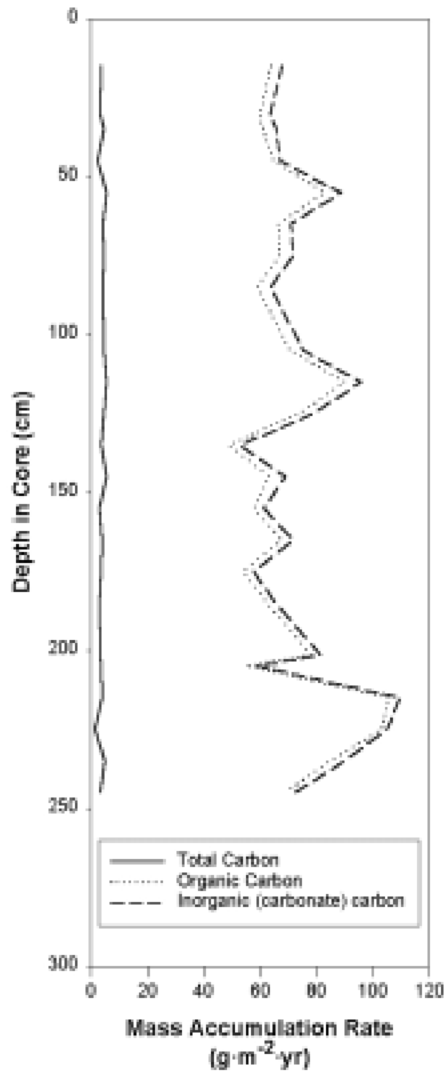

Figure 4.

Carbon mass accumulation rate (MAR) profile for Lake Winnibigoshish.