Meromictic Lakes and Varved Lake Sediments in North America

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Meromictic Lakes and Varved Lake Sediments in North America

By Roger Y. Anderson, Walter E. Dean,
J. Platt Bradbury, *and* David Love

Lakes in North America that are meromictic or that contain sediments with annual layers are assessed for their potential for reconstruction of ancient climates

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Meromictic Lakes and Varved Lake Sediments in North America

By Roger Y. Anderson[1], Walter E. Dean, J. Platt Bradbury, *and* David Love[2]

Abstract

Lakes that contain annually laminated (varved) sediments usually are also meromictic, that is, the bottom waters of these lakes are perennially anoxic and therefore no burrowing benthic organisms are present to destroy the laminations. Varves may consist of simple two-component couplets, or complex sequences of several organic or inorganic components which have seasonal pulses. A varved sequence is a powerful interpretive tool for the paleolimnologist, paleoecologist, or paleoclimatologist because it provides a high-resolution time scale for determining rates and timing of lacustrine processes, biological succession, and climate change.

By surveying the literature and many of our limnologist colleagues, we identified about 160 lakes in North America that are meromictic and (or) have laminated sediments. Most of these 160 lakes occur between lat 40° and 55° N., although latitude as such probably is not a critical factor. Lake morphometry, particularly the relation between depth and surface area, appears to be the most important criterion for the development of meromictic lakes, and consequently for the preservation of laminated sediments. Lakes that can accumulate saline water of comparatively high specific gravity also are prone to meromixis. The potential for identifying additional lakes that are likely to contain laminated sediments is excellent, and it is evident that a systematic coring program in many areas of northwestern and northeastern North America would locate a significant number of additional lakes with varved sediments. Our survey of varved and meromictic lakes shows that the geographic distribution of such lakes is adequate to compile high-resolution, varve-calibrated paleoclimatic records of the last 10,000 years from widely spaced areas that were influenced by different air masses and climatic regimes.

INTRODUCTION

Late Pleistocene and Holocene lake sediments often contain continuous depositional records of environmental, vegetational, and climatic changes over time spans of many thousands of years. Such records are the most important tools geologists and biologists have for interpreting climatic changes over the past 10,000–12,000 yr, and for studying the development of lacustrine ecosystems and how they change in response to both human and natural perturbations. A major problem in using a sequence of lake sediments for paleoclimatic and paleoecologic reconstructions is the difficulty of establishing a precise, absolute time scale for the sequence. Radiometric dating techniques, principally ^{14}C and ^{210}Pb, are most often used to provide the chronology for lake-core studies, but both techniques produce only approximate ages that, for a variety of biological and geochemical reasons, may be distressingly inaccurate. In addition, variable sedimentation rates in lakes make extrapolation between radiometric dates suspect, and prevent detailed, year-by-year analysis of changes in environmental conditions.

Occasionally, lake-sediment sequences are found that are varved; that is, the sediment is composed of annual laminations which, like tree rings, can be counted to provide a precise yearly chronology. The paleontological, geochemical, and sedimentological analyses of such sequences provide rare opportunities for precise, high-resolution time calibration of late Pleistocene and Holocene climatic change. Preservation of delicate varve laminations usually occurs in lakes whose bottom waters are perennially anoxic (meromictic lakes). In our discussions that follow, we will use the term "varved lakes" to mean lakes that contain varved sediments. The terms varved lake and meromictic lake are often mutually inclusive, although some lakes with varved sediments are not meromictic, and some meromictic lakes do not contain varved sediments.

The purpose of this study was to compile a list of lakes in North America that are known to contain laminated sediments, or that are meromictic and therefore may contain laminated sediments. To do this, we first surveyed the literature for descriptions of varved and meromictic lakes. We then sent a questionnaire to some of our colleagues asking for information that they might have on the location and character of varved and meromictic lakes. The names and addresses of those colleagues who provided information are included at the end of this report. This survey represents an initial step in assessing the potential of varved lake sediments for reconstruction of

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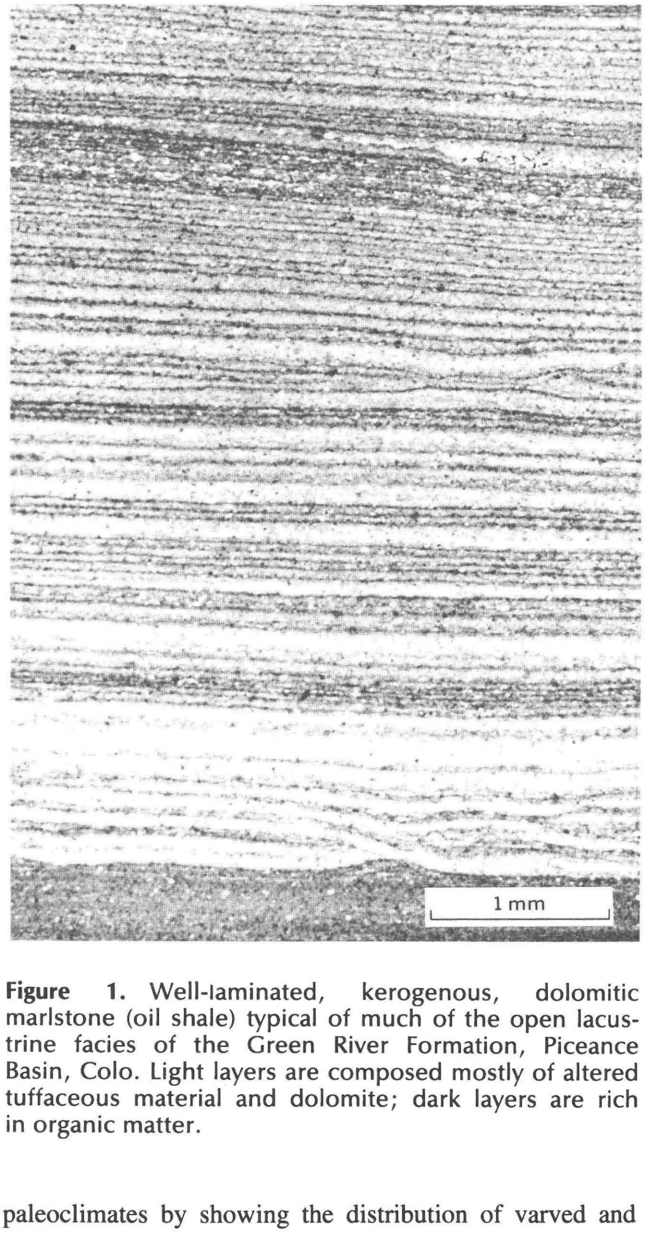

Figure 1. Well-laminated, kerogenous, dolomitic marlstone (oil shale) typical of much of the open lacustrine facies of the Green River Formation, Piceance Basin, Colo. Light layers are composed mostly of altered tuffaceous material and dolomite; dark layers are rich in organic matter.

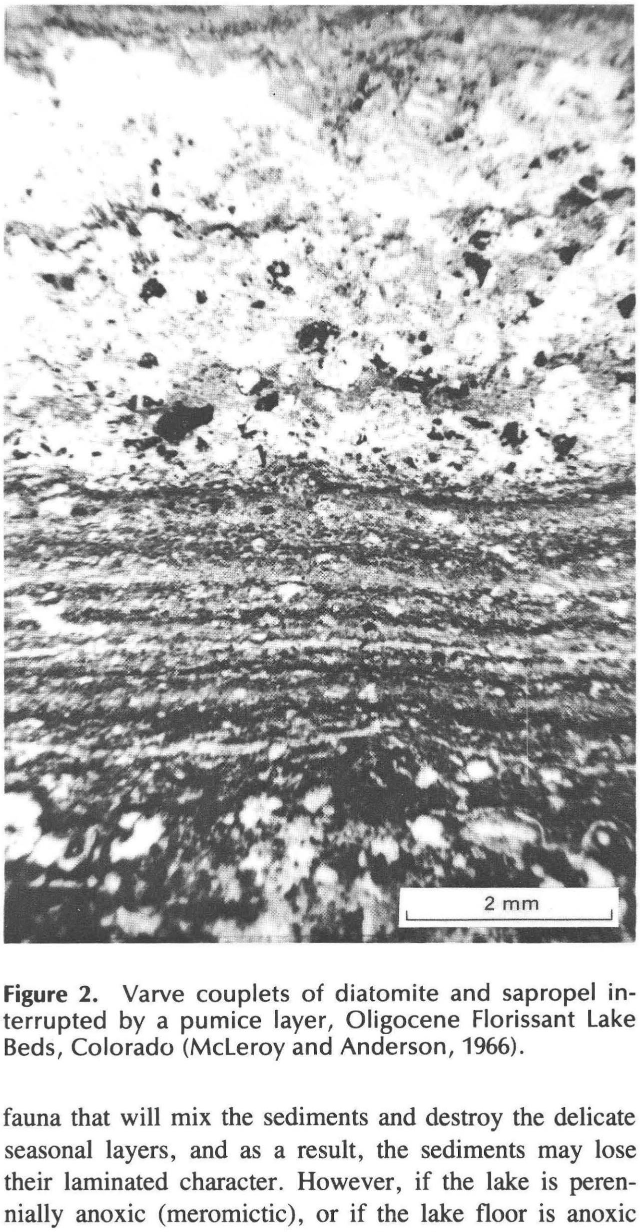

Figure 2. Varve couplets of diatomite and sapropel interrupted by a pumice layer, Oligocene Florissant Lake Beds, Colorado (McLeroy and Anderson, 1966).

paleoclimates by showing the distribution of varved and meromictic lakes.

Varved Lacustrine Sediments

Sediment that accumulates on the bottom of any lake is composed of materials that vary in abundance throughout the year in response to seasonal changes in rates of supply. The annual accumulations of sediment may consist of a simple two-component couplet. For example, in summer increased photosynthesis causes precipitation of $CaCO_3$, whereas during the winter, when the lake is ice covered, fine organic material and clay will settle to the bottom. Complex sequences also exist in which several organic and inorganic components have seasonal pulses in rate of supply. Usually the lake bottom is sufficiently oxic to support a benthic epifauna or infauna that will mix the sediments and destroy the delicate seasonal layers, and as a result, the sediments may lose their laminated character. However, if the lake is perennially anoxic (meromictic), or if the lake floor is anoxic for a sufficiently long period during the year to exclude benthic burrowing organisms, the distinctive seasonal components that accumulate on the bottom are preserved as varves (Bradley, 1929; McLeroy and Anderson, 1966; Anderson and Kirkland, 1969; Ludlam, 1969; Kelts and Hsü, 1978; this report, figs. 1–7). A varved sequence is a powerful interpretive tool for the paleolimnologist because it provides a high-resolution time scale for determining rates and timing of lacustrine processes. An example of such a varve-calibrated scale for a Holocene lake-sediment sequence, from Elk Lake in northern Minnesota, is shown on figure 8.

Most lakes that contain varved sediments have perennially anoxic bottom waters. However, some lakes have preserved varves even though mixing and oxygenation of bottom waters do occur, but not frequently enough to allow benthic organisms to establish themselves. In

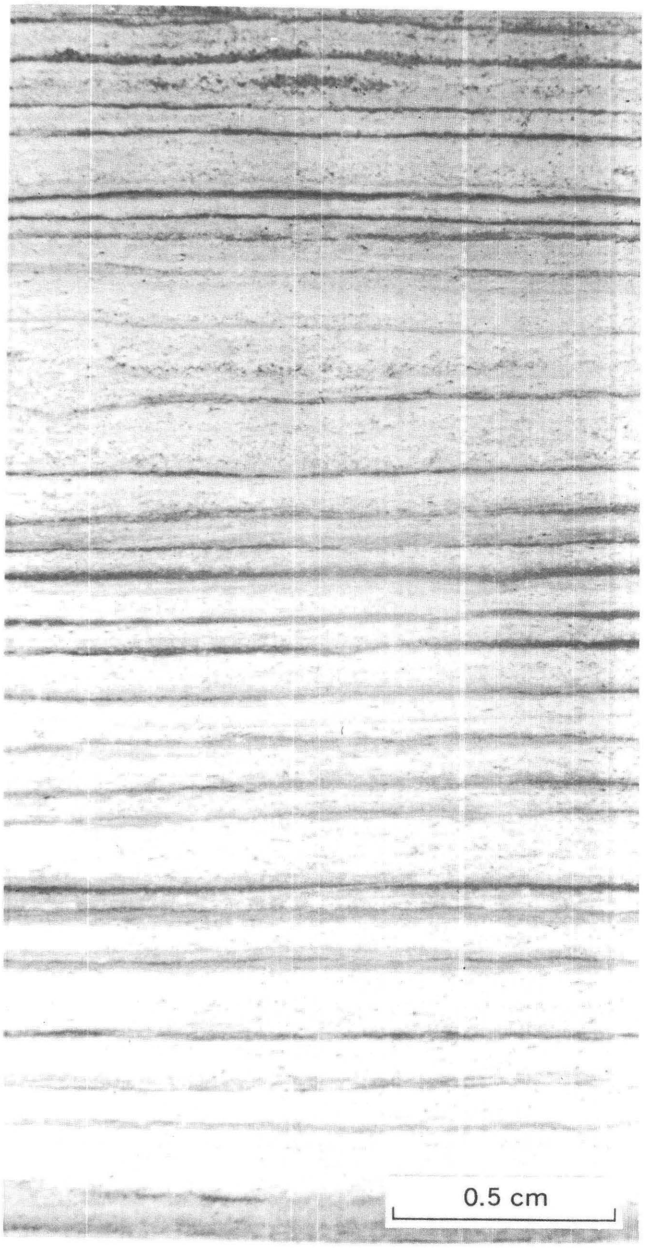

Figure 3. Varve laminae from the Rita Blanca lake beds (early Pleistocene), western panhandle of Texas. Light layers consist mostly of calcite, silt-size quartz grains, clay, and ostracodes; dark layers consist mostly of clay and organic matter (Anderson and Kirkland, 1969). Photograph by Douglas W. Kirkland.

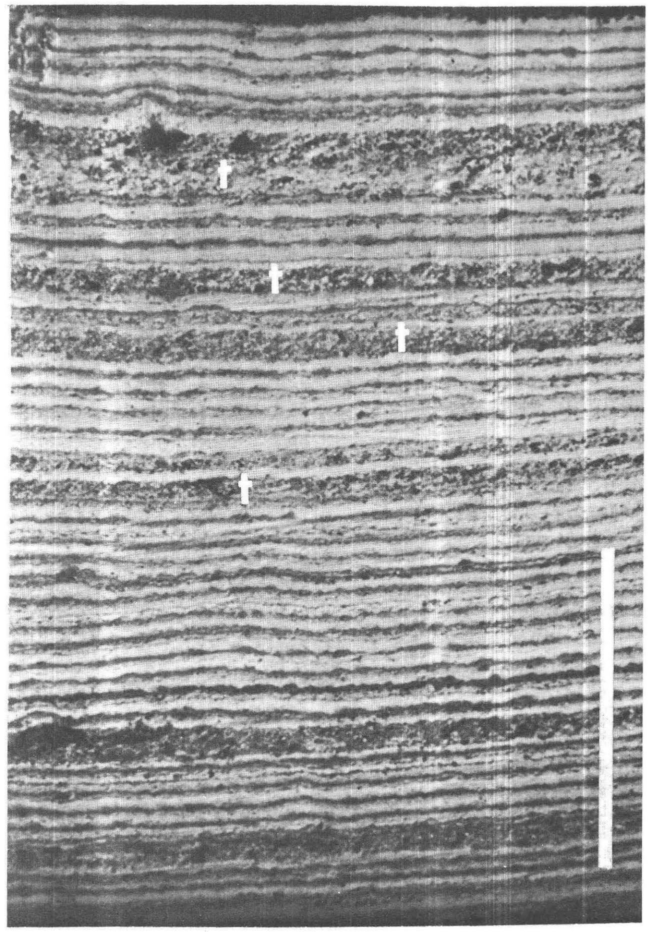

Figure 4. Varve laminae and turbidite layers (t) in sediments from Green Lake, Fayetteville, N.Y. The light lamina in each varve couplet consists mostly of precipitated low-magnesium calcite, and the dark lamina consists mostly of clay and organic matter (Ludlam, 1969). Most of the calcite is precipitated between May and October (Brunskill, 1969). Turbidite layers intercalated with normal varve laminations account for about 50 percent of the sediment that accumulates on the floor of the main basin of the lake (Ludlam, 1974). Bar = 5 cm. Photograph by Stuart D. Ludlam.

fact, Elk Lake, Minn. (figs. 6–8), which contains one of the best and most complete varved-sediment records of the Holocene found thus far, is an example of this type of lake. Other lakes with a strong seasonal influx of clastic material, such as glacier-associated lakes, also have varved sediments without meromixis. Still other lakes have sediments that are laminated, but the laminae are formed by turbidity currents that are episodic but not annual (Lambert and Hsü, 1979). Some nonannual laminae may be varvelike in appearance, but they are generally less regular in thickness because the time between depositional events is variable (nonrhythmic). Nonannual laminae often are less continuous laterally, and this feature may be used to distinguish them from more regular (rhythmic) varves that result from seasonal influx of different organic and inorganic components.

Meromictic Lakes

Lakes with perennially anoxic bottom water result from meromixis, a term which indicates that only the upper part of the lake's water column is vertically mixed

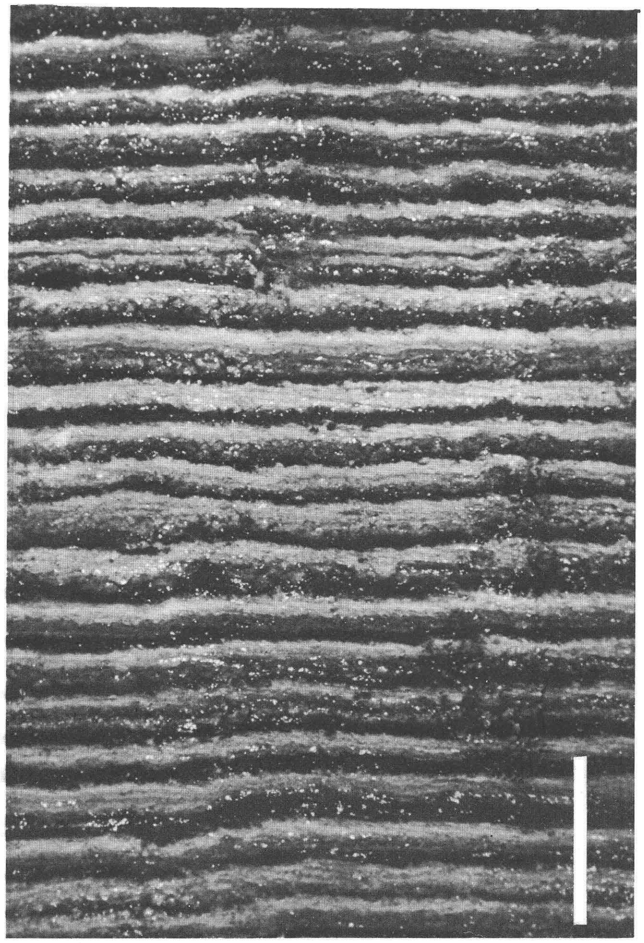

Figure 5. Varve laminae from the central plain of Lake Zurich, Switzerland. Varve couplets generally range between 2 and 5 mm in thickness. A typical varve cycle consists of a dark layer containing organic sludge with algal filaments, iron sulfides, and clay grading upward into a lacy network of diatom frustules and organic matter, overlain by a light layer containing diatom frustules and calcite at the base and almost pure calcite at the top (Kelts and Hsü, 1978). Varve couplets, periodically interrupted by turbidites, have been forming in Lake Zurich since 1885. Bar = 1 cm. Photograph by Kerry Kelts.

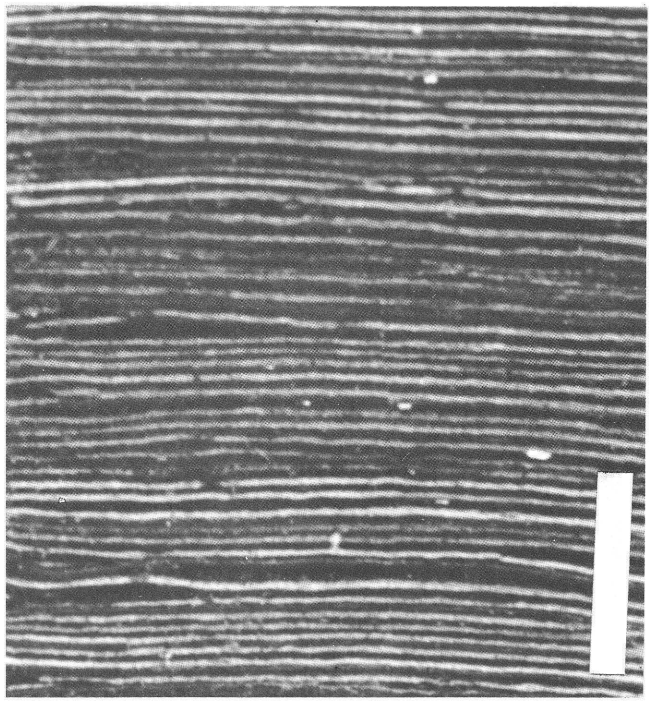

Figure 6. Varve laminations from sediments in Elk Lake, Clearwater County, Minn. Light layers consist mostly of fine-grained low-magnesium calcite and diatoms (shown enlarged in fig. 7); dark layers consist mostly of diatoms and clay. Bar = 1 cm.

and oxygenated during periods of circulation. Partial mixing of the lake water usually occurs when the bottom water is significantly denser than the overlying water because it contains a greater concentration of dissolved solids.

Figure 9 is a diagrammatic cross section of Green Lake, Fayetteville, N.Y., the first meromictic lake to be described in the United States (Eggleton, 1931) and one of the most studied meromictic lakes in the world. The profiles of salinity (specific conductance), temperature, and dissolved oxygen for Green Lake (fig. 9) show characteristics common to most meromictic lakes. These characteristics are (1) a well-mixed, oxygenated, lower salinity, upper water mass (mixolimnion) that usually mixes semiannually like a normal temperate dimictic lake, (2) an intermediate water mass (chemocline) in which salinity increases and dissolved oxygen decreases rapidly with depth, and (3) a lower anoxic water mass (monimolimnion) which has a more or less constant temperature and a higher salinity than the mixolimnion. The higher salinity of the monimolimnion, and therefore the greater density, prevents wind-driven mixing. The cause of meromixis in Green Lake is the inflow of saline ground-water springs below a depth of about 20 m. The springs are rich in dissolved calcium and sulfate as a result of dissolution of gypsum in the bedrock underlying the lake basin.

Another characteristic of meromictic lakes is that the monimolimnion contains high concentrations of hydrogen sulfide and (or) methane as a result of anaerobic bacterial decay and sulfate reduction. In addition, any nutrients utilized by organisms in the mixolimnion and released in the monimolimnion by decay are trapped in the monimolimnion and sediments, and are not returned to the surface by wind-driven mixing as they are in lakes that mix all the way to the bottom (holomictic lakes); any exchange of dissolved materials from the monimolimnion to the mixolimnion is by slow eddy diffusion across the chemocline. Because the monimolimnion is a nutrient sink, meromictic lakes often are unproductive (oligotrophic). Meromictic lakes may range in size from

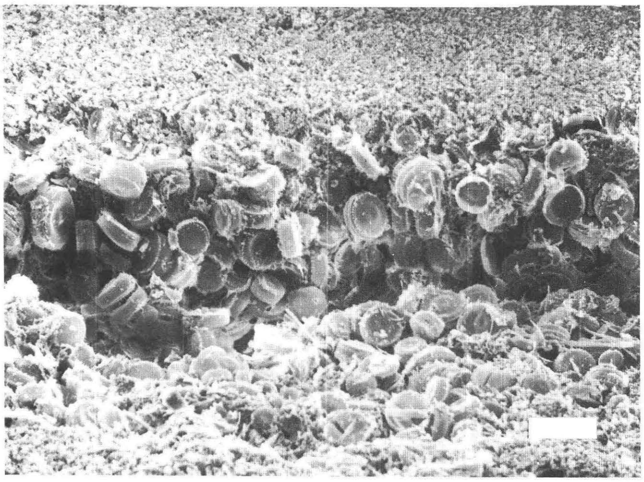

Figure 7. Fine-grained low-magnesium calcite and diatoms (*Stephanodiscus niagarae*) from a varve lamina in sediments from Elk Lake, Minn. (fig. 6). Bar = 0.1 mm.

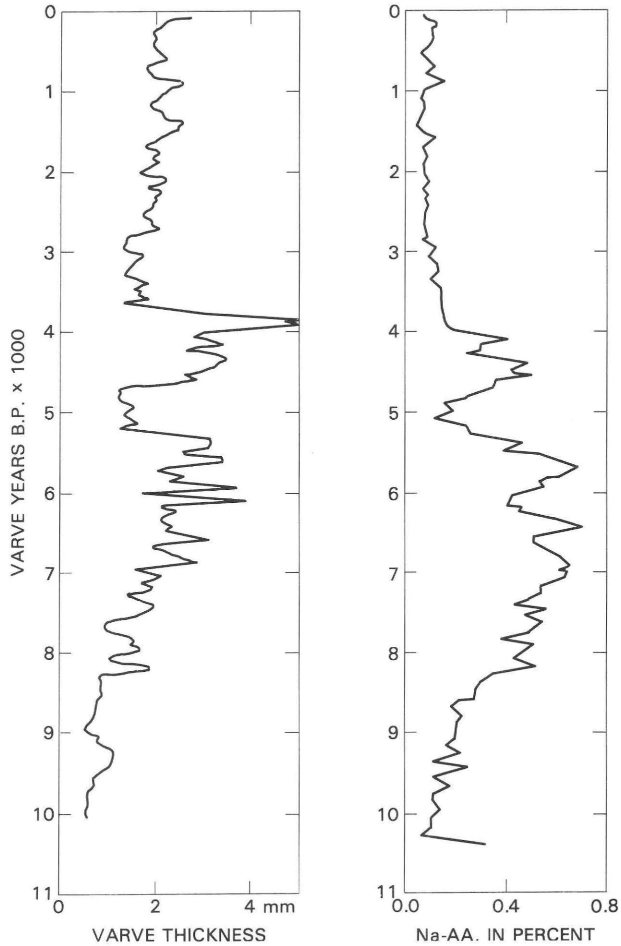

Figure 8. Plots of varve thickness and percent sodium for a 21-m sequence of varved lake sediment from Elk Lake, Minn. The plots show that sedimentation rate has been relatively constant at about 2.0 mm/yr for the last 3,800 yr. The interval between about 3,800 yr and about 8,000 yr B.P. is characterized by conditions that were dryer than at present. In Minnesota, this period of time was marked by maximum postglacial expansion of the prairie into areas now occupied by forest. The varve-thickness plot indicates that the prairie period is recorded in Elk Lake by extreme fluctuations in rate of sedimentation. The sodium curve provides a good index of weathering conditions on soils in the drainage basin of Elk Lake. The higher and more variable fluctuations in sodium concentration during the prairie period (4,000–8,500 yr ago) reflect dryer conditions with less available moisture for chemical weathering so that detrital clastic materials which reached the lake were less altered. During the last 3,000 yr, more available moisture resulted in greater decomposition and therefore lower sodium concentrations.

small ponds less than 100 m in diameter (a cinder-cone pool in New Mexico, Bradbury, 1971; red and green ponds in Arizona, Cole and others, 1967) to the Black Sea (Dickman and Artuz, 1978; Hsü and Kelts, 1978). However, most are small and relatively deep in proportion to surface area. (See table 2.)

Meromictic lakes like Green Lake, Fayetteville, N.Y., are described as completely and permanently meromictic; that is, the monimolimnion is completely anoxic and the density difference between the mixolimnion and the monimolimnion is so great that the energy required to mix these two water masses is not available under existing conditions. Some lakes are only partially or temporarily meromictic. Partial meromixis usually results in lakes that have a sufficient buildup of dissolved solids in the bottom waters to create a density barrier that resists normal wind-driven thermal mixing, but which may mix at times of unusual conditions such as periods of very strong winds. Temporary meromixis sometimes occurs in normally holomictic lakes as a result of some unusual external event such as flooding with seawater. The density stratification created by the external event is often not strong enough to resist the next strong wind-driven thermal mixing, at which time the meromixis is destroyed. Saline-water runoff from street salting into lakes in urban areas (Diment and others, 1974), is producing a type of temporary meromixis that is becoming increasingly common.

CLASSIFICATION OF MEROMICTIC LAKES

The classification of meromictic lakes according to their origin, given in table 1, is adopted from Walker and Likens (1975). The two basic subdivisions of this classification depend upon whether the cause of meromixis is external to the lake (ectogenic meromixis) or internal to the lake (endogenic meromixis). Information for many lakes is insufficient to be certain that the correct cause has been assigned. Even when abundant information is available, it is often difficult to assign a definite cause

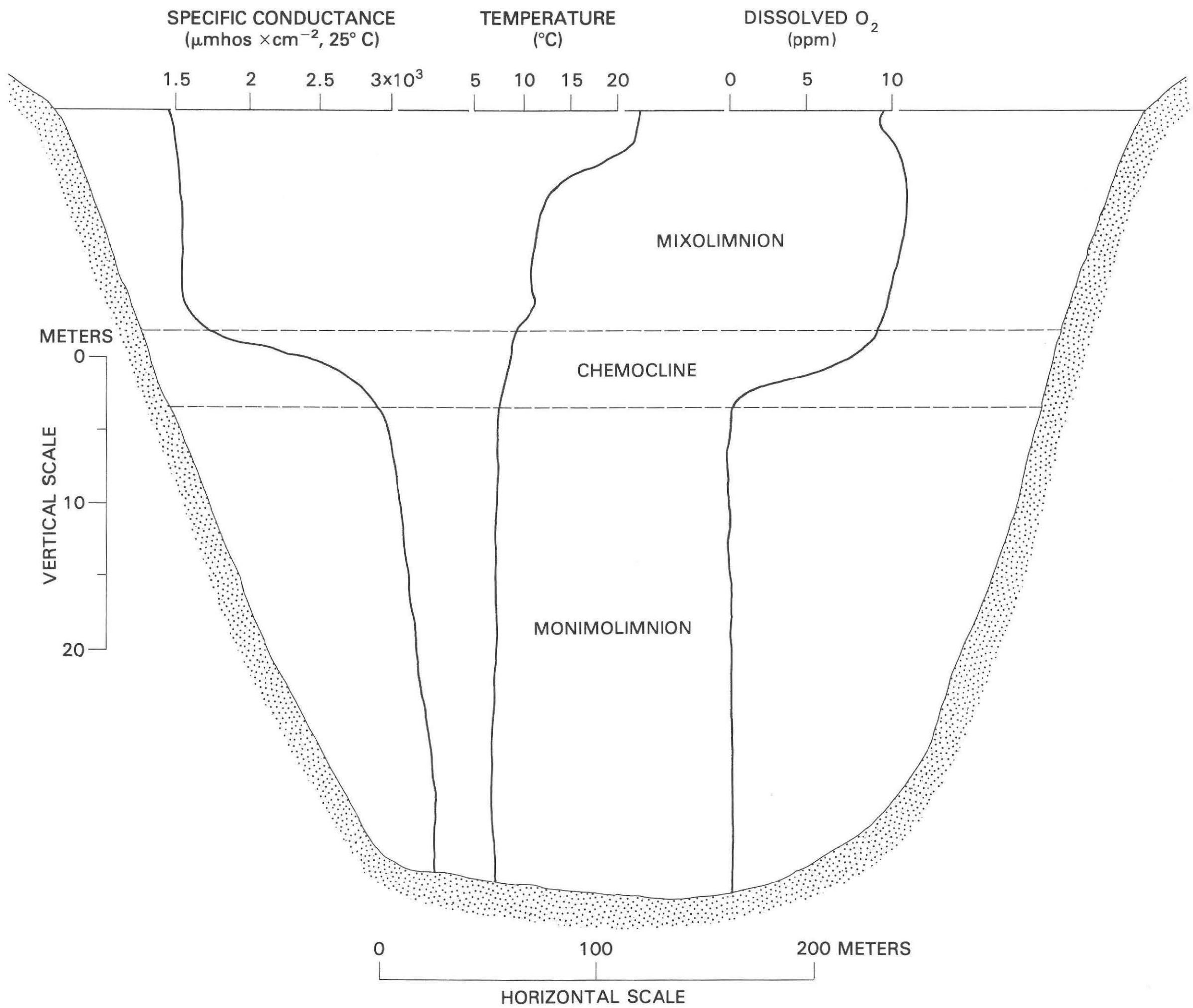

Figure 9. Diagrammatic cross section of Green Lake, Fayetteville,N.Y. showing typical summer profiles of salinity (specific conductance), temperature, and dissolved oxygen. On the basis of salinity and dissolved oxygen, the lake is divided into a lower salinity, oxygenated upper water mass (mixolimnion) that is thermally stratified, and a higher salinity, anoxic bottom-water mass (monimolimnion) that has a relatively constant temperature. The two water masses are separated by a zone (chemocline) of rapid change in salinity and dissolved oxygen.

for meromixis, and some lakes may have more than one factor that leads to meromixis. For example, Green Lake, Fayetteville, N.Y., has been mentioned as one of the most studied meromictic lakes in the world. The lake is in a protected basin, and Walker and Likens (1975) used Green Lake as their type example of Type IV meromixis with a secondary classification of Type III because of subsurface influx of saline ground water. The protected location of Green Lake undoubtedly contributes to the stability of meromixis in the lake, but the primary *cause* of meromixis is the influx of saline ground water, and we would cite Green Lake as a type example of Type III meromixis (along with Round Lake, Fayetteville, N.Y., and Green Lake, Clark Reservation, Jamesville, N.Y., which have identical causes of meromixis as Fayetteville Green Lake).

VARVED AND MEROMICTIC LAKES OF NORTH AMERICA

Table 2 is a compilation of modern lakes in North America that are meromictic and (or) contain laminated sediments. It provides information on the location and distribution of lakes that contain varved sediments which might be used to reconstruct Holocene climatic records with a high degree of time resolution. General locations of these lakes are shown on figure 10.

For this compilation, we attempted to distinguish between lakes known to be meromictic and lakes known to contain laminated sediments. Some sources describe both conditions, others describe only one or the other, and it has been difficult to be certain of both meromixis and the presence of laminated sediments for all lakes in-

Table 1. Classification of meromictic lakes (modified from Walker and Likens, 1975)

Class A: Ectogenic Meromixis

- Type I: Meromixis due to the influx of a layer of fresh water over preexisting layer of saline water or influx of a layer of saline water under a preexisting layer of fresh water.
  - Type Ia: Inland; saline layer is nonmarine
  - Type Ib: Coastal; saline layer is marine
- Type II: Meromixis due to influx of turbidity currents.
- Type III: Meromixis due to subsurface inflow of either fresh or saline water.

Class B: Endogenic Meromixis

- Type IV: Meromixis due to the lake basin being protected from wind mixing. Most examples of this type of meromixis have chemical stratification due to biological processes operating in the deep waters of the lake.
- Type V: Meromixis due to "freezing out" of salts from the surface ice layer and the accumulation of these salts in the deep waters of the lake.

cluded in the compilation. That laminae in lacustrine sediments are indeed varves has been demonstrated for very few lakes. If a lake is meromictic *and* contains laminated sediments, then an annual interpretation for the laminae can be made with some confidence. However, proof of the annual nature of laminae in lake sediments must ultimately come from either a cumulative count of laminations between well-dated horizons or from paleontological evidence. For example, Craig (1972) counted 9,549 laminations in a core from Lake of the Clouds, northern Minnesota. Radiocarbon dating of this core by Stuiver (1971) shows that radiocarbon ages agree closely with the cumulative laminae counts, which demonstrates that laminae probably are annual. Paleontological evidence for the annual nature of some laminations in lake sediments is equally compelling. Tippett (1964) microtomed the laminated sediments of Little Round Lake, Ontario, parallel to the plane of deposition and analyzed the sediment shavings for pollen, chrysophyte cysts, and diatoms. In this way he was able to demonstrate that the alternation of inorganic and organic layers represented summer and winter sedimentation cycles, respectively, because the tree and algal species bloom at known times and the pollen and algal remains become incorporated into the laminae shortly afterwards. A similar study utilizing the microstratigraphic position of leaf fossils, chironomid larval cases, pollen, ostracodes, and carbon and oxygen isotopes proved the annual nature of an early Pleistocene sequence of laminated lacustrine deposits at Rita Blanca, Tex. (Kirkland and Anderson, 1969). That laminae in nonmeromictic lakes are strictly annual, however, is less certain. We have tried to include in table 2 only those nonmeromictic lakes with laminated sediments that we were reasonably confident were varved. However, in order to avoid an interpretation that may not have been intended by the person describing the laminae, we have used the term "laminated" in table 2 if the sediments were only described as laminated. The distinction between using the phrase "varved sediments" in general discussions in the text and "laminated" for specific lakes in table 2 is made so as to avoid presumption, on both our part and the part of the reader.

The information concerning the physical, chemical, and (or) biological characteristics of the sedimentary record is incomplete for the majority of lakes. Observations were made on the completeness of the stratigraphic record whenever possible. The exact location of many lakes is not documented, particularly for lakes that were referred to in personal communications. Figure 10 shows the number and approximate location of lakes for which exact locations are not recorded.

The varved stratigraphic record in lakes that contain varved sediments may not be complete. Some lakes have become meromictic only recently, and the varved record therefore does not include much of the Holocene. Some lakes have sediments that are varved for only part of the Holocene. Lakes are not included in this summary if the processes producing varves stopped some 10,000 yr ago. Figure 10 identifies some lakes in which the Holocene varved sedimentary record is judged to be poor or incomplete because of the late development of meromixis. Table 2 contains remarks regarding data limitations.

No attempt was made to list the type of meromixis for all lakes, except where a previous classification of a lake existed or there was sufficient information for classification. The lake-type classification (table 1) of Walker and Likens (1975) was used whenever possible. Not enough is known about controls on laminae formation and preservation to determine if an association exists between type of meromixis and the quality of the varved record, and no attempt was made to evaluate individual lakes or sediment records for sensitivity to climatic change.

POTENTIAL FOR RECOGNITION OF ADDITIONAL VARVED AND MEROMICTIC LAKES

This investigation has identified about 100 lakes that are known to be, or are likely to be, meromictic, and more than 160 lakes that are meromictic and (or) contain sediments that are laminated and probably varved. The most recent previous compilation (Walker and Likens, 1975) listed 45 meromictic lakes. Additional lakes were found for this study in subsequent references and through the use of a questionnaire circulated to interested limnologists and paleoecologists.

Figure 10 shows that certain areas apparently are

Table 2. Meromictic lakes and lakes containing sediments in North America

[Type refers to classification in table 1. Remarks list information about lakes, sediments, meromictic conditions or age of sediments where available; references generally list only first citations. See list of collaborators for written communication citations. Leaders (---) indicate no data]

State and lake	Location Lat N.	Long W.	Area (km^2)	Maximum depth (meters)	Type	Remarks	References
United States							
Alaska							
Kenai Lake	60°24'	149°37'	---	---	---	Laminated-----	McCullough, 1966.
Long Lake	62°57'	141°52'	0.1	3.2	III,IV	Meromictic----	Likens, 1967.
Malaspina Lake	59°43'	140°38'	---	---	---	Laminated-----	Gustavson, 1972, 1975.
Nuwuk Lake	71°25'	156°28'	---	6	IV,Ib	Meromictic----	Mohr and others, 1961.
Pingo Lake	65°40'	144°20'	.024	8.8	III,Ia	---do---------	Likens and Johnson, 1966.
Redoubt Lake	56°54'	135°15'	16.6	266	Ib	---do---------	McCoy, 1977.
Rosetead Lake	57°29'	152°27'	---	---	---	Meromictic after 1964 earthquake.	McCoy, written commun., 1979.
Skilak Lake	60°25'	150°20'	---	---	---	Laminated-----	Rymer and Sims, 1976.
Summit Lake	---		---	---	---	---do---------	Do.
Upper Trail Lake	60°30'	149°22'	---	---	---	---do---------	Do.
Vee Pond	62°58'	141°56'	.045	1.6	IV,III	Meromictic----	Likens, 1967.
Arizona							
Green Pond	34°51'	109°26'	.0012	2.0	IV	Seasonally meromictic.	Cole and others, 1967.
Red Pond	34°51'	109°20'	.0016	2.6	IV	---do---------	Do.
California							
Castle Lake	Northern		.194	36.5	---	Laminated(?)--	Goldman, written commun., 1979.
Connecticut							
Linsley Pond	41°19'	72°46'	.094	14.8	---	Dimictic; laminated; older than Holocene(?).	Hutchinson and Wollack, 1940.
Florida							
Beville's Pond	29°35'	82°20'	---	>6	IV	Meromictic----	Shannon and Brezonik, 1972.
Deep Lake	26°03'	81°23'	0.007	30	IV	---do---------	Hunt, 1958.
Lake Mize	29°40'	82°11'	.0086	25.3	IV(?)	---do---------	Shannon and Brezonik, 1972.
Lake 27	29°35'	82°20'	---	7.0	IV(?)	---do---------	Do.
Lake Marco Shores	---		---	---	---	Manmade; brackish water.	Courtney, 1979.
Kansas							
Meade salt well	37°10'	100°20'	.001	2.7	Ia	Heliothermic, meromictic(?).	Hollister, 1903.
Kentucky							
Tom Wallace Lake	Near Louisville		.023	9	---	Varved--------	Cole, 1954.
Maine							
Basin Pond	44°27'	70°03'	.136	32	---	Laminated-----	Swain, written commun., 1979.
Conroy Lake	46°17'	67°53'	.100	32	---	---do---------	Do.
Massachusetts							
Goose Pond (lower)	42°15'	73°13'	.91	14	---	---do---------	Ludlam, 1976, 1979.
Goose Pond (upper)	42°15'	73°12'	.17	9	---	---do---------	Do.
Larkum Pond	Berkshire Hills, western Mass.		.08	14	---	---do---------	Do.
Laurel Lake	------do----------		.67	16	---	Laminations (probably varved); iron carbonate.	Do.
Onota Lake	42°26'	73°18'	2.5	20	---	Laminated; iron	Do.
Oyster Pond	41°20'	70°35'	.91	14	---	Occasional overturn.	Walsh in Carter, 1967.
Richmond Pond	42°26'	73°20'	.88	16	---	Laminated; carbonate.	Ludlam, 1976, 1979.

more favorable for the development of such lakes than others. Although the greatest abundance of endogenic meromictic lakes occurs between lat 40° and 55° N., latitude as such is not a critical factor. Many regions in Alaska and northern Canada have received very little limnological attention, and apparently the climatic regime of

Table 2. Meromictic lakes and lakes containing sediments in North America—Continued

State and lake	Location Lat N.	Long W.	Area (km^2)	Maximum depth (meters)	Type	Remarks	References
			United States--Continued				
Massachusetts--Continued							
Stockbridge Bowl	Berkshire Hills, western Mass.		1.5	15	---	Laminated (probably varved); diatoms, carbonate; Holocene.	Ludlam, 1976, 1979.
Michigan							
Canyon Lake	---		---	---	IV	Meromictic, not laminated.	Smith, 1941; Davis, written commun., 1980.
Douglas Lake	---		15	27	---	Laminated-----	Ludlam, 1979.
Heart Lake	Ostego County		.25	36	---	Varved--------	Bernabo, 1977.
Hemlock Lake	---		---	---	---	Meromictic, not laminated.	Fast, 1973.
Hull Lake	43°07'	85°28'	0.048	22	---	Laminated-----	Swain, written commun., 1980.
Peter Lake	Gogebic County		.024	19	---	Varved--------	Swain, written commun., 1979.
Sodon Lake	42°18'	83°17'	.023	17.7	IV	Meromictic, not laminated.	Newcombe and Slater, 1948, 1950; Davis, 1980.
Third Sister Lake	---		---	---	---	Laminated, Holocene(?).	Eggleton, 1931; Potzger and Wilson, 1941.
Minnesota							
Arco Lake	47°11'	95°11'	.0139	10.2	IV	Occasional mixing.	Baker and Brook, 1971; Gorham, written commun., 1979.
Budd Lake, Itasca Park.	47°10'	95°15'	.02	10.8	IV	Meromictic----	Baker and Brook, 1971.
Deming Lake	47°11'	95°11'	.05	17	IV	Occasional overturn.	Baker and Brook, 1971; Gorham, written commun., 1979.
Elk Lake	47°13'	95°12'	.10	30	---	Laminated; 10,500 varves.	R. Y. Anderson, J. P. Bradbury, and W. E. Dean, unpub. data, 1983.
Josephine Lake	47°11'	95°11'	.03	10.3	IV	Occasional overturning.	Baker and Brook, 1971; Gorham, written commun., 1979.
Lake of the Clouds	48°8.5'	91°6.7'	.12	31	IV(?)	Meromictic and varved.	Craig, 1972; Swain, 1973; Anthony, 1977.
Rivalry Lake	48°09'	91°06'	.017	17.5	---	Laminated, age not determined.	Anthony, 1977.
Squaw Lake	47°14'	95°17'	.61	24	IV	Meromictic----	Baker and Brook, 1971.
Swain's Pond	48°08'	91°07'	.004	4.5	---	Laminated, age not determined.	Anthony, 1977.
Tin Cup Lake	West of Itasca Park		---	---	---	Meromictic(?)-	Gorham, written commun., 1979.
Montana							
Leon Lake	48°05'	115°11'	.088	26	---	Laminations intermittent.	Swain, written commun., 1979.
Nevada							
Big Soda Lake	39°31'	118°52'	1.6	64.5	Ia	Recent changes in meromixis.	Hutchinson, 1937; Kimmel and others, 1978; Axler and others, 1978.
Pyramid Lake	40°01'	119°35'	46.7	>91	---	Laminated, in part.	R. Y. Anderson, unpub. data, 1979.
New Hampshire							
Barbadoes Pond	---		---	---	---	Laminated-----	Baker, written commun., 1979.
Lake Winninsquam	43°35'	71°30'	17.45	47	---	---do---------	Do.
New Mexico							
Cinder Cone Pool	34°15'	76°05'	.002	7	Ia	Seasonal meromixis.	Bradbury, 1971.

the subtropics and tropics can favor meromixis in lakes that have the proper morphometry. Arid regions, such as the Dakotas, south-central Canada, Southwestern United States, and the north half of Mexico are less likely to contain appropriate bodies of water for the development of meromixis.

Lake morphometry, specifically the relation between lake depth and surface area, appears to be the most

Table 2. Meromictic lakes and lakes containing sediments in North America—Continued

State and lake	Location Lat N.	Location Long W.	Area (km^2)	Maximum depth (meters)	Type	Remarks	References
				United States--Continued			
New York							
Cayuga Lake	Central Finger Lakes region.		172	132	---	Meromictic; varved.	Ludlam, 1967 and 1979.
Clark Reservation Green Lake.	42°55'	76°05'	.03	16	III	Meromictic not laminated.	Brunskill and others, 1969; W. E. Dean, unpub. data, 1974.
Clear Pond	43°45'	74°02'	.10	28	---	Laminated-----	Swain, written commun., 1979.
Devils Bathtub	43°00'	77°34'	.007	14.7	IV	Meromictic----	Brunskill and others, 1969.
Fayetteville Green Lake.	43°03'	75°58'	.26	52.5	III,IV	Meromictic; varved.	Eggleton, 1931; Brunskill and Ludlam, 1969; Diment, 1969; Ludlam, 1969, 1974, 1981.
Fayetteville Round Lake.	43°01'	76°01'	.13	51	III,IV	---do---------	Brunskill and Ludlam, 1969.
Grossman's Pond	43°02'	77°28'	.027	14	---	Meromictic----	Diment in Walker and Likens, 1975.
Junius Pond	42°57'	76°57'	.065	17	---	---do---------	Do.
Lake Ontario	Western		19,552	244	---	Rhythmically bedded.	D. R. Hutchinson, written commun., 1979.
Seneca Lake	Central Finger Lakes Region.		175	188	---	Meromictic; varved.	Woodrow and others, 1969; Ludlam, 1979.
Ohio							
Brown's Lake	40°41'	82°04'	0.026	6	IV(?)	Formerly meromictic; senescent.	Sanger and Crowl, 1979.
Silver Lake	41°09'	81°28'	---	---	---	Laminated; age undetermined.	Ogden, 1966.
Pennsylvania							
Ely Lake	41°46'	75°50'	.136	22.5	---	Laminated-----	Swain, written commun., 1979.
Rose Lake	41°50'	77°55'	---	6	---	---do---------	Crowl, written commun., 1980.
Rhode Island							
Coastal Lagoon	---		---	---	Ib(?)	Meromictic(?)-	Brooks and Deevey, 1966.
South Dakota							
Medicine Lake	---		---	---	---	Meromictic----	Hayden, 1972; Beaver, 1973.
Washington							
Blue Lake	48°39'	119°46'	.44	34	Ia	---do---------	Walker, 1974.
Lake Chelan	47°51'	120°01'	---	450	---	Meromictic(?)-	Edmondson, 1963.
Cottage Lake	47°45'	122°05'	---	7.5	---	---do---------	Edmondson, written commun., 1979.
Dog Lake	46°40'	121°22'	.240	21	---	Laminated-----	Swain, written commun., 1979.
Gillette Lake	48°37'	117°32'	.192	26	---	Varved--------	Do.
Hall Lake	47°48'	122°19'	.028	16	IV	Intermittently meromictic.	Culver, 1977.
Hot Lake	48°58'	119°29'	.013	3.25	Ia,III	Meromictic----	Anderson, 1958; Walker, 1974.
Langlois Lake	47°38'	121°53'	---	29	---	Meromictic; laminated.	Edmondson, written commun., 1979; Swain, written commun., 1979.
Lower Goose Lake	46°57'	119°17'	.218	28	Ia	Meromictic----	Walker, 1974; Edmondson and Anderson, 1965.
Reflection Lake	46°46'	121°44'	.052	18	---	Laminated-----	Swain, written commun., 1979.
Swan Lake	48°31'	118°50'	.206	28.5	---	Varved--------	Do.
Soap Lake (Grant County).	47°23'	119°30'	3.39	27	Ia	Meromictic; laminated.	Walker, 1974.
Soap Lake (Okanogun County).	48°14'	119°39'	.63	17.5	Ia	Meromictic----	Do.

important criterion for the development of meromictic lakes, and consequently for the preservation of laminated sediments. It is obvious that the deeper a lake is relative to its area the more likely meromixis becomes, but any circumstance that effectively reduces the wind stress on the lake surface, which mixes and circulates the water mass, will promote meromixis. Lakes in treeless prairies are therefore less likely to become meromictic than lakes of identical morphometry in dense forests.

Lakes that can accumulate saline water of compara-

Table 2. Meromictic lakes and lakes containing sediments in North America—Continued

State and lake	Location Lat N.	Long W.	Area (km^2)	Maximum depth (meters)	Type	Remarks	References
United States--Continued							
Washington--Continued							
Wannacut Lake	48°52'	119°34'	1.67	48.8	Ia	Meromictic----	Walker, 1974.
Lake Washington	47°38'	122°16'	---	760	---	Indistinctly laminated.	Edmondson, 1975.
Wisconsin							
Dark Lake	45°16'	91°29'	.052	18.5	---	Laminated-----	Swain, written commun., 1979.
Dudley Lake	45°25'	89°29'	.040	18.5	---	---do---------	Do.
Hells Kitchen Lake	46°11'	89°42'	.028	19	---	Varved--------	Swain, 1978.
Knaack Lake	---		.011	22	IV	Meromictic----	Winfrey and Zeikus, 1979.
Lake Mary	46°04'	90°09'	.012	25.2	IV	---do---------	Likens, 1967; Weimer and Lee, 1973.
Little Pine Lake	45°17'	91°29'	.04	18	---	Laminated-----	Swain, written commun., 1979.
Max 2	---		---	5.5	IV	Meromictic----	Stewart and others, 1966.
Max 3	---		---	4.0	IV	---do---------	Do.
Perch Lake	46°32'	91°23'	.10	25	---	Laminated-----	Swain, written commun., 1979.
Ruby Lake	45°16'	91°28'	.068	19.5	---	---do---------	Do.
Scaffold Lake	---		---	---	---	Meromictic----	Manning and Juday, 1941.
Stewarts Dark Lake	45°18'	91°27'	.007	8.8	IV	---do---------	Likens, 1967; Gorham and Sanger, 1972.
Wausau Granite Quarry.	---		.01	20.6	IV	---do---------	Stewart and others, 1966.
Outside United States							
Canada							
Alberta							
Bow Lake	51°40'	116°27'	---	50	---	Laminated; periglacial.	Kennedy and Smith, 1974.
Hector Lake	51°35'	116°22'	5	87	---	---do---------	Smith, 1978.
Lake Cavell	52°42'	118°04'	---	11.3	---	---do---------	Kindle, 1930.
Lake Louise	51°25'	116°14'	.84	70.1	---	---dp---------	Johnston, 1922; Smith, written commun., 1979.
Peyto Lake	51°43'	116°31'	---	---	---	---do---------	Vendl and Smith, 1977.
Upper Waterfowl Lake.	51°50'	116°40'	5	5.0	---	Laminated only near delta.	Smith, 1975.
Lake Wabumun	52°32'	114°35'	---	---	---	Laminated-----	Smith, written commun., 1979.
British Columbia							
Corbett Lake	50°00'	120°40'	242	19	---	Laminated(?)--	Teraguchi and Northcote, 1966.
Emerald Lake	Southeastern B.C.; Rockies.		---	---	---	Laminated; periglacial.	Smith, written commun., 1979.
Gardom Lake	---					Meromictic, not definite.	Northcote, written commun., 1979.
Garibaldi Lake	49°57'	123°00'	10.3	259	---	Meromictic; questioned by Northcote, written commun., 1979.	Mathews, 1956.
Lyons Lake	50°57'	120°07'	.36	12	IV	Meromictic----	Northcote and Halsey, 1969.
Mahoney Lake	49°17'	119°32'	.02	18.9	IV	---do---------	Do.
Nitinat Lake	48°42'	124°50'	27.6	205	Ib	Actually an estuary.	Northcote and others, 1964.
Powell Lake	49°53'	124°32'	117	358	Ib	Meromictic----	Williams and others, 1961; Barnes and others, 1974.
Sakinaw Lake	49°38'	124°02'	---	140	Ib	---do---------	Northcote and Johnson, 1964.
White Lake	51°22'	121°53'	.99	15	IV,III	---do---------	Northcote and Halsey, 1969.
Yellow Lake	49°10'	119°45'	.32	40	IV	---do---------	Do.

tively high specific gravity are prone to meromixis, and examples of coastal lakes, particularly isolated fjords, are common. The few occurrences of meromictic lakes in arid regions appear to reflect the stratification of lighter fresh water overlying saline water produced by evaporation or dissolution of evaporites.

The potential for identifying additional sites where varved sediments are likely to exist is excellent. Several

Table 2. Meromictic lakes and lakes containing sediments in North America—Continued

State and lake	Location Lat N.	Long W.	Area (km^2)	Maximum depth (meters)	Type	Remarks	References
			Outside United States--Continued				
Canada--Continued							
British Columbia--Continued							
Lillooet Lake	50°30'	123°	15	137	---	Glacial; turbidity flows.	Gilbert, 1975.
Pitt Lake	49°25'	122°30'	55	---	---	Tidal---------	Ashley, 1977, 1979.
Labrador							
Tessiarsuk	56°30'	61°57'	5.5	>50	Ib	---	Carter, 1963.
Northwest Territories							
Baker Lake	About 65°, 95°		---	---	---	Meromictic----	Johnson, 1964.
Campbell Lake	Dolomite Uplands		---	---	---	---do---------	Richie and others, 1976.
Garrow Lake	Little Cornwallis Island.		4.2	50	Ib	---do---------	Dickman and others, 1971.
Lake A	Ellesmere Island		4.9	57	Ib	---do---------	Hattersley-Smith and others, 1970.
Lake B	Ellesmere Island		.9	40	Ib	---do---------	Do.
Lake C	Ellesmere Island		.8	57	Ib	---do---------	Do.
Ogac Lake	62°52'	67°21'	1.5	60.5	---	---do---------	McLaren, 1963.
Sophia Lake	East shore, Cornwallis Island.		---	---	---	---do---------	Ouellet, written commun., 1983.
Sunday Lake	72°43'	94°11.5'	---	---	---	---do---------	Johnson, 1964.
Tuberg Lake	Ellesmere Island		60	130	Ib	Meromictic; glacial.	Hattersley-Smith and Serson, 1964.
Winton Bay Lake	80°50'	79°00'	---	---	---	Meromictic----	Carter, 1961.
Ontario							
Atkins Lake	44°45'	75°51'	---	3.3	---	Laminated-----	Ouellet, written commun., 1983.
Big Ohlman Lake	70 mi southwest of Ottawa.		---	39	---	Meromictic(?)-	Carter, written commun., 1979; MacKay, 1979.
Crawford Lake	43°28'	80°57'	.05	25	IV	Meromictic; varved.	Boyko-Diakonow, 1979.
ELA 120	49°39'	93°50'	.09	19	IV	Meromictic----	Schindler and Holmgren, 1971; Brunskill and Schindler, 1971.
ELA 241	49°40'	93°33'	.02	12.5	IV	---do---------	Do.
Found Lake	Algonquin Park		---	---	---	Laminated in part; possibly meromictic.	Smol, 1979; Dickman, written commun., 1979; MacKay, written commun., 1980.
Greenleaf Lake	46°00'	78°00'	.57	76	---	Presumed varved	Cwynar, 1978.
Jake Lake	Algonquin Park		---	---	---	Meromictic; laminated.	Smol, 1979.
Lake of the Hills	---		---	---	---	Meromictic; varved.	McNeely, written commun., 1979.
Lake on the Mtn.	Near Picton		---	---	---	Meromictic----	Dickman, written commun., 1979; Terasmae and Miryech, 1964.
Little Round Lake	44°45'	76°43'	.074	17	---	Laminated in part	Tippett, 1964; McNeely, 1973.
Loon Lake	46°08'	81°40'	.065	33	---	Meromictic; laminated, 6500 from surface.	Davis, written commun., 1979.
McGinnis Lake	Near Peterborough		---	---	---	Meromictic----	Cheek, 1979; Dickman, written commun., 1979.
McKay Lake	45°27'	75°40'	---	10.5	---	Laminated in part	Tippett, 1964.
Simeon Lake	Near Aurora		---	---	---	Possibly meromictic.	Dickman, written commun., 1979; MacKay, written commun., 1979, 1980.
Sunfish Lake	---		.08	20	IV	Laminated; oligomictic.	Duthie and Carter, 1970; Adams and Duthie, 1976.

lakes with laminated sediments have been identified in the State of Washington (fig. 10) where many lakes have been surveyed, and it is evident that a systematic coring program in many areas of northwestern and northeastern North America would produce a significant number of additional lakes with varved sediments. Information about area, depth, and salinity of lakes, on a regional basis, would facilitate such a program.

Table 2. Meromictic lakes and lakes containing sediments in North America—Continued

State and lake	Location Lat N.	Long W.	Area (km^2)	Maximum depth (meters)	Type	Remarks	References
Outside United States--Continued							
Canada--Continued							
Ontario--Continued							
Van Nostrand Lake	44°	79°	---	---	---	Laminated; oligomictic.	Dickman, 1979.
Québec							
Bédard Lake	47°16'	71°07'	.04	10	---	Laminated; meromictic.	Bernard and Lagueux, 1970.
Chubb Lake	61°17' (Ungavba Crater).	73°41'	---	---	---	Oligotrophic; possibly meromictic.	Martin, 1955; Dickman, written commun., 1979.
Green Lake	46°11'	76°19'	.20	25	IV	Meromictic----	Dickman and others, 1971.
Lake 22	50°21'	65°53'	---	---	IV,Ib	Laminated-----	Ouellet, written commun., 1983.
Matamek Lake	50°22'	65°54'	---	---	---	---do---------	Do.
Pink Lake	45°30'	76°00'	.12	20	Ib,IV	Meromictic----	Dickman and others, 1975.
Cuba							
Lake Valle-De-San Juan.	---		.001	25	Ib	---do---------	Romanenko and others, 1976.
Bahamas							
Devils Kettle	---		---	---	---	---do---------	Kohout and others, 1968.
Greenland							
Saelso Lake	77°03'	20°35'	120	112	Ib	---do---------	Trolle, 1913.
Guatemala							
Encantada	Near El Salto		.083	14	IV	---do---------	Brezonic and Fox, 1974.
Eckixil	16°56' (Peten).	89°55'	1.97	21	IV	---do---------	Do.
Juleque	16°56' (Peten).	89°55'	.03	25.5	IV	---do---------	Do.
Lago de Peten	16°56' (Peten).	89°55'	567	32	IV	---do---------	Covich, 1976; Brezonic and Fox, 1974.
Mecanche	16°56' (Peten).	89°55'	---	>40	IV	---do---------	Brezonic and Fox, 1974.
Paxcamen	16°55' (Peten).	89°55'	---	30	IV	---do---------	Do.
Panama							
Miraflores Third Lock.	09°01'	79°36'	.002	26	Ib	Meromictic, postcanal.	Bozniak and others, 1969.

POTENTIAL FOR PALEOCLIMATIC RECORDS

The geographic distribution of varved lakes is adequate to compile high-resolution, varve-calibrated, paleoclimatic records from widely spaced areas that were influenced by different air masses and climatic regimes. The largest unknown factor in evaluating varved-sediment and meromictic lakes for their potential in establishing paleoclimatic records is the quality and completeness of their sedimentary records.

The sites in Washington and British Columbia will be particularly useful in compiling comparative records outside the well-studied north-central and northeastern United States. Sedimentary paleoclimatic records from the remote sites in northern Canada and Alaska would help determine the rate of climatic change in relation to deglaciation as suggested by Andrews and others (1979).

The sites in Guatemala are especially interesting. Little is known of the character of the sediments and whether they are varved. The geographic location of the lakes, however, would allow an examination of the relationship of tropical moisture and temperature to short-period climatic response.

The records available from the lakes listed in table 2 hold promise for looking at climatic variables in terms of lacustrine processes. These include the little-known processes taking place in coastal fjords, lagoons, and marginal lakes in British Columbia; under-ice algal productivity in northern Ellesmere Island; glacier meltwater events; biogenic activity in tropical lakes; and a variety of biological and chemical processes in temperate, inland, endogenic meromictic lakes. Little is known about the specific relationship of these processes, as recorded in lake sediments, to climatic variables. However, lacustrine sys-

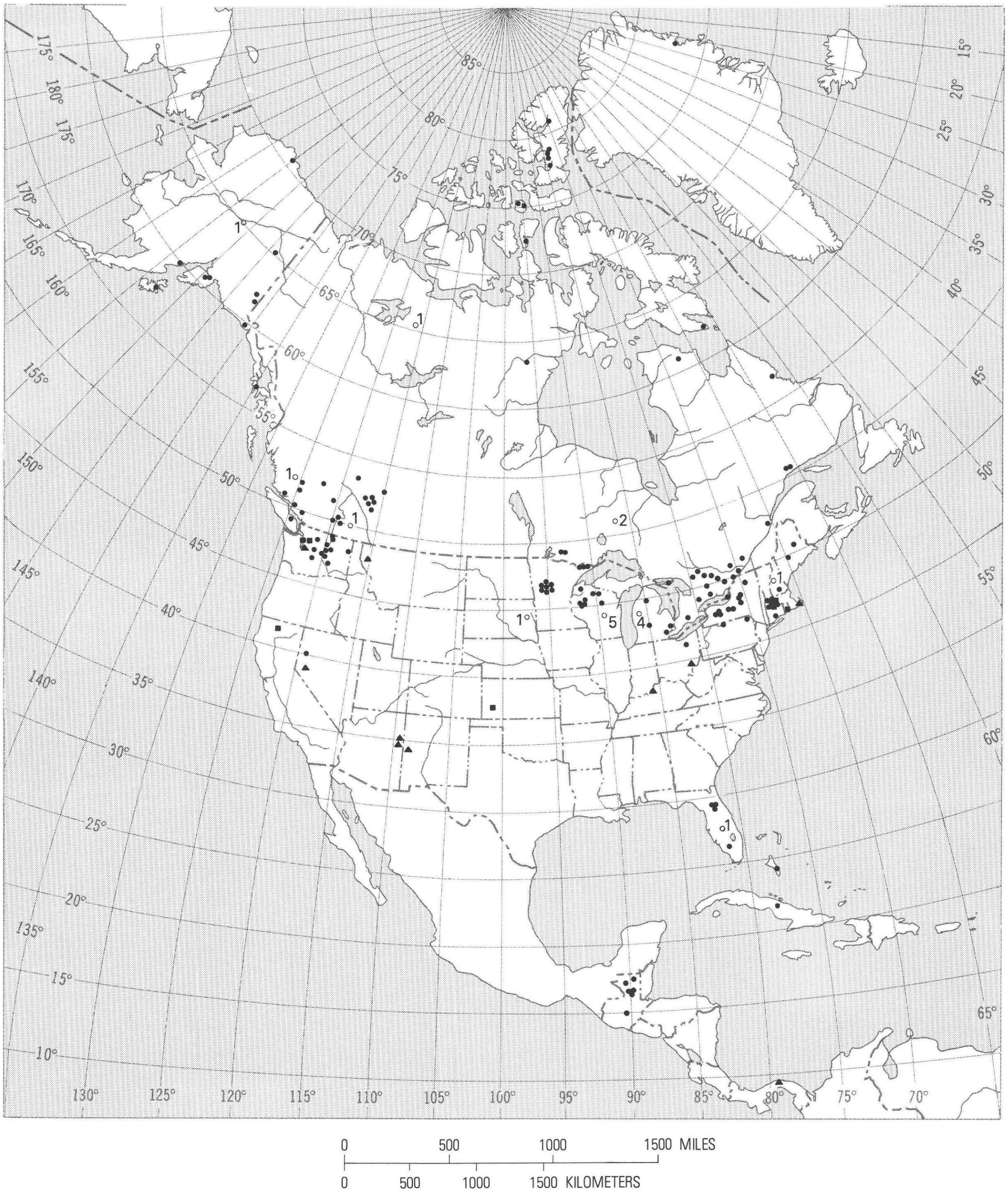

Figure 10. Map of North America showing locations of meromictic lakes and lakes that contain laminated sediments. Solid circle, location of meromictic lake or laminated lake sediments. Square, lake that probably or possibly is meromictic or contains laminated sediments. Triangle, length or quality of Holocene record is poor. Numbered circle, number and approximate location of meromictic lakes or lakes that contain laminated sediments for which specific locations are not available.

tems, and the records they contain, are known to be closely linked to climatic factors. It is likely that varved lake sediments have the geographic distribution, the quality of information, and the high-resolution time control needed to precisely document the climatic changes of the last 10,000 yr.

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