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RELATIONS BETWEEN LAKE MORPHOMETRY AND THE PRESENCE OF LAMINATED LAKE SEDIMENTS: A RE-EXAMINATION OF LARSEN AND MACDONALD (1993)

C. P. S. LARSEN[†], R. PIENITZ[‡], J. P. SMOL[§], K. A. MOSER[*], B. F. CUMMING[§], J. M. BLAIS[‡‡], G. M. MACDONALD[§§], R. I. HALL[**]

[†] *Department of Geography, SUNY at Buffalo, Buffalo, NY 14261-0023, USA*
(e-mail: larsen@geog.buffalo.edu)
[‡] *Centre d'etudes Nordiques et Departement de Geographie, Universite Laval, Quebec, PQ G1K 7P4, Canada*
[§] *Paleoecological Environmental Assessment and Research Laboratory (PEARL), Department of Biology, Queen's University, Kingston, ON K7L 3N6, Canada*
[*] *Department of Geology, University of Toronto, Toronto, ON M5S 3B1, Canada*
[‡‡] *Department of Biology, University of Alberta, Edmonton, AB T6G 2E9, Canada*
[§§] *Department of Geography, University of California Los Angeles, Los Angeles, CA 90095-1524, USA*
[**] *Department of Biology, University of Regina, Regina, SK S4S 0A2, Canada*

Abstract—In this paper we conduct an empirical test of a published equation which relates lake surface area and maximum lake depth to the presence or absence of laminated lake sediments. A 297 lake dataset from New York State and six regions in Canada, representing a number of biogeoclimatic zones, is employed. The results suggest that deeper lakes are more likely to contain laminated lake sediments than are shallower lakes. The percentage of lakes incorrectly predicted to contain laminated sediments (false positives) and that incorrectly predicted to contain massive sediments (false negatives), was much higher than that found in the study in which the original equation was developed. Its low predictive ability suggests, therefore, that in addition to lake morphometry, many other factors affect the formation and preservation of laminated sediments. © 1998 Elsevier Science Ltd. All rights reserved.

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INTRODUCTION

Annually laminated lake sediments (ALLS) are ideal for paleolimnological reconstructions, because they allow accurately dated and precisely resolved chronologies of sedimentation to be developed. Applications of ALLS have been reviewed extensively, and lists of lakes with ALLS have been compiled (O'Sullivan, 1983; Anderson *et al.*, 1985; Saarnisto, 1986). The use of ALLS has, however, been limited by the low number of lakes known to contain them and the difficulty of locating bodies that have ALLS. Recognition could be increased if, for such lakes easily, recognizable morphological characteristics could be identified.

Annual laminae are created by seasonal variations in autochthonous or allochthonous sedimentary inputs to a lake basin (O'Sullivan, 1983; Saarnisto, 1986). ALLS created by seasonal changes in autochthonous inputs typically contain an annual couplet of dark, organic-rich fines deposited in winter when the lake waters are calm, and light coloured material deposited in summer. Light layers may be rich in diatoms (biogenic), calcite crystals (calcareous), oxidized iron (ferrogenic) and mineral matter (clastic). Allochthonous laminae typically comprise coarse mineral matter of fluvial origin deposited when stream discharge is high and fine mineral matter is deposited when it is low.

The probability of ALLS being created and preserved is increased if anoxic conditions in the lake bottom waters are persistent, and if annual sediment accumulation is greater than the depth to which sediment mixing occurs. In lakes where laminae are formed by allochthonous inputs, mixing will usually be controlled by fluvially induced lake currents. In lakes where laminae are formed by autochthonous processes, internal water movements that have been related to lake surface area and depth are important (O'Sullivan, 1983; Larsen and MacDonald, 1993). The profundal sediments of lakes which are deep relative to surface area (typically meromictic lakes) should undergo little or no physical or biological mixing. Progressively shallower lakes will be mixed by spring and fall overturn (dimictic lakes), and by currents and waves (typically polymictic lakes). Equations which relate lake surface area, maximum lake depth and most important mixing mechanisms are given in Larsen and MacDonald (1993).

O'Sullivan (1983) showed that in lakes containing autochthonous ALLS the relative depth of those with a large surface area is greater than that of lakes with a small surface area. Larsen and MacDonald (1993) compared the surface area and maximum depth of lakes with autochthonous ALLS from around the world, with those of lakes containing massive lake sediments (MLS) from Canada and Alaska (Fig. 2j). They found that the morphometry of lakes with ALLS could be distinguished from those with MLS using the equation:

$$Zm_l = 7.78A_0^{0.294} \qquad (1)$$

where Zm_l is the shallowest maximum depth in meters a lake can be to contain ALLS and A_o is lake surface area in hectares. They suggested that the sediments of lakes deeper than Zm_l contain autochthonous laminae because internal water movements are too weak to mix the bottom most waters and sediments. The application of Eq. (1) to data on lake depth and surface area contained in many databases would allow lakes with ALLS to be identified with minimal costly fieldwork.

In this paper, we test Larsen and MacDonald's relation by further applying it to seven sets of lake data collected from Canada and the United States in different biogeoclimatic zones. We hypothesize that all lakes deeper than Zm_l will contain autochthonous ALLS and that all those shallower than Zm_l will contain only MLS.

STUDY REGIONS

A data set of 297 lakes was compiled from seven regions in Canada and the United States (Fig. 1). The data from each region were not gathered specifically for this study, but are parts of other paleolimnological surveys. All lakes in each study were used. All but two of the lakes contained freshwater. The lakes in the Yukon, Norman Wells and Yellowknife study areas (Fig. 1, regions A–C) are located along transects from boreal forest to tundra (Pienitz and Smol, 1993; Pienitz *et al.*, 1997a,b). The Yukon region area is underlain by metamorphic and sedimentary bedrock (Pienitz *et al.*, 1997a), the Norman Wells area has sedimentary strata and the Yellowknife region has Precambrian granitic gneiss bedrock (Pienitz and Smol, 1993). The lakes in Wood Buffalo National Park (Fig. 1, region D) are in Paleozoic sedimentary and Precambrian igneous bedrock within the boreal forest (Moser *et al.*, in press). Those in the Haliburton region (Fig. 1, region E; Hall and Smol, 1996), in the southern Ontario and Quebec study area (Fig. 1, region F; Blais and Kalff, 1993) and in the Adirondack Park, New York (Fig. 1, region G; Cumming *et al.*, 1992), are all located in Precambrian igneous and metamorphic rocks within mixed deciduous–coniferous

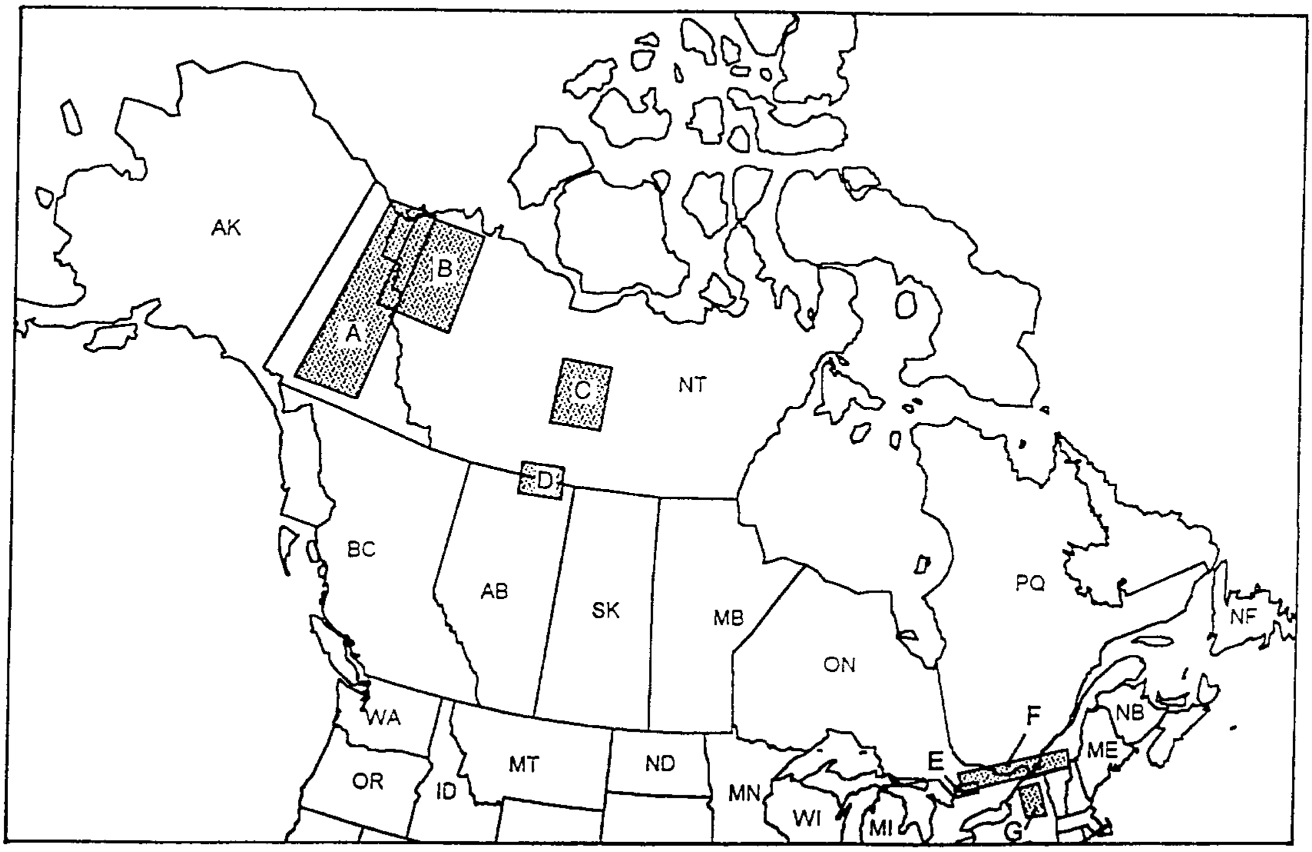

FIG. 1. Location of the seven study regions: (A) Yukon; (B) Norman Wells; (C) Yellowknife; (D) Wood Buffalo National Park; (E) Haliburton; (F) southern Ontario and Quebec; and (G) Adirondack Park, New York.

forest. Further information on each of the 297 lakes, including their latitude and longitude, can be obtained in the appropriate references listed above. The sediments in all of these lakes are believed to be primarily autochthonous in origin.

METHODS

Lake sediments

Sediment characteristics were identified from cores of the top 30–50 cm of the deposit, collected using either a modified Cushing and Wright (1965) piston corer, a modified Kajak–Brinkhurst gravity corer (Glew, 1989) or a mini-Glew gravity corer (Glew, 1991). In most cases, cores were collected at the deepest point. Radiometric dating suggests that most cores contained between 200 and 1000 years' of sediment (see appropriate references for each site). Sediments were classified as laminated, massive (no apparent stratigraphy) or top laminated (laminae in the top of the core and massive sediments below). They were visually examined in the field by eye with no magnification.

It is not known whether in every case laminations are annual, since their structure was not examined in detail. As a result, we refer to these lakes as containing laminated lake sediments (LLS). In this regard, our data are not much different from those used by Larsen and MacDonald (1993), in that many of the studies they cite did not ascertain whether laminae were annual. Indeed, most records of LLS contain some 'missing' laminae and some years with multiple sub-annual laminae. Cross-dating from multiple cores is required to construct an ALLS chronology (e.g. Lamoreux and Bradley, 1996).

The Larsen and MacDonald relation (1993) suggests that, since depth is the critical variable, a lake that has LLS in the top 30–50 cm should contain LLS in its deeper sediments. A lake with MLS in the top 30–50 cm may contain MLS or LLS in its deeper sediments. A shift from LLS at depth to MLS near the surface would occur if the deposits caused the lake to become so shallow that sediments became mixed.

Morphometric relations

The lakes in each study area are plotted by surface area and maximum depth. Symbols denote whether they contain massive or laminated sediments. Also shown is the line which Larsen and MacDonald (1993) used to distinguish lakes with ALLS from those with LLS. The accuracy of Eq. (1) is assessed by determining the number of correct decisions regarding lakes with LLS, the number of false negatives (Type I errors) and of false positives (Type II errors) (Davis, 1986). The number of correct decisions is calculated as the fraction of lakes that Eq. (1) predicted would possess LLS that actually do contain them. False negatives are calculated as the proportion of the lakes with LLS that Eq. (1) predicted would have MLS. False positives are calculated as the fraction of lakes that Eq. (1) predicted would possess LLS that actually contain MLS. In study areas D and E, in which there are some lakes with only top-laminated sediments, graphs and analyses were first conducted with top-laminated sediments classified as MLS, and then as LLS.

RESULTS

Lakes with MLS deeper than Zm_l in Eq. (1) occur in five of the study regions (Fig. 2). In three regions lakes with LLS shallower than Zm_l are found (Fig. 2). In the four regions in which LLS occur, the percentage ranged from 1 to 20% (mean = 9.5%, $n = 6$) (Fig. 2; Table 1). Note that regions D and E are included in the calculation twice, once when the lakes with laminations present in the uppermost sediments are considered as LLS (e.g. D_{TLL}), and again when the same sites are treated as MLS (e.g. D_{TLM}).

The fraction of correct decisions regarding whether a lake predicted to contain LLS did possess them ranges from 8 to 50% (mean = 19%, $n = 6$). This value is 18% when all 297 lakes are pooled (Table 1). The proportion of lakes with false negatives varies between 0 and 100% (mean = 34%, $n = 6$), and is 43% when all 297 lakes are considered (Table 1). False positives range from 50 to 100% (mean = 83%, $n = 7$), and is 82% in the pooled data set (Table 1).

The percentage of lakes containing LLS increases with maximum lake depth (Fig. 3). In Eq. (1) the intercept coefficient is 7.78. When this statistic is 3.0 or less, all the lakes possess MLS and none contain LLS. When it is 6.0, then 10% of the basins have LLS. When it is 9.0, 11.8% of the sites possess LLS. When it is 9.0 or greater, LLS are found in 21.4% of the lakes (Fig. 3).

DISCUSSION

The results of this study do not support the hypothesis that all, or even most, lakes deeper than Zm_l, in the equation of Larsen and MacDonald (1993) will contain autochthonous LLS or that all lakes shallower than Zm_l, will possess MLS (Fig. 2). Table 1 shows the proportion of correct decisions was much lower, and the percentage of false negatives and false positives much higher, than those obtained by Larsen and MacDonald (1993). Given that the percentage of false negatives is equivalent to the level of significance of the equation (Davis, 1986), the 43% overall rate of false negatives indicates that predictive accuracy of Eq. (1) is low.

Modification of the intercept coefficient size in Eq. (1) showed that a higher percentage of deep lakes contain LLS than do shallower bodies with the same surface area (Fig. 3). However, this modification did not identify a critical depth at which lakes with LLS become more common. We did find, however, that massive sediments occur in all lakes shallower than

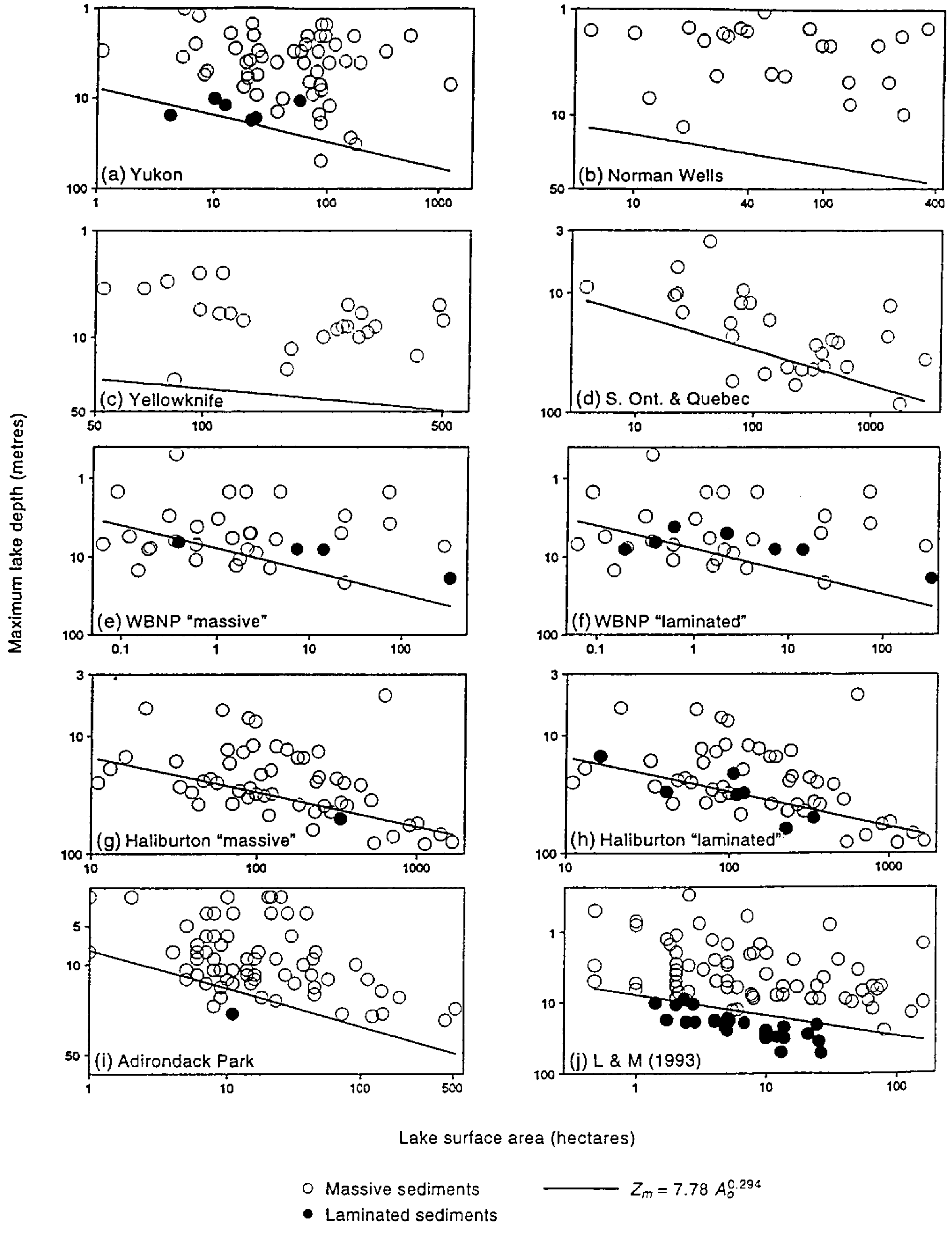

FIG. 2. Relations between lake surface area, maximum lake depth and whether sediments are massive or laminated. (a) Yukon (map region A), (b) Norman Wells (map region B), (c) Yellowknife (region C), (d) southern Ontario and Quebec (map region F), (e) Wood Buffalo National Park (WBNP; top laminated lakes are considered 'massive') (map region D), (f) Wood Buffalo National Park (WBNP; top laminated lakes are considered 'laminated') (map region D), (g) Haliburton (top laminated lakes considered 'massive') (map region E), (h) Haliburton (top laminated lakes considered 'laminated') (map region E), (i) Adirondack Park (map region G), and (j) the published data set (L&M (1993); Larsen and MacDonald, 1993).

a critical depth Zm_m, where:

$$Zm_m = 3.0A_0^{0.294} \qquad (2)$$

Therefore, while we cannot say which lakes are most likely to contain LLS, we can suggest that if the goal is to find them, lakes shallower than Zm_m should be avoided.

Larsen and MacDonald (1993) suggested that, because it would influence the preservation of a seasonal sedimentation signal, morphometry was a critical

TABLE 1 Accuracy of the published equation that relates lake morphometry to the presence of laminated sediments

Map region	No. of lakes	Laminated	Correct decision	False negatives	False positives
A	59	6/59 (10%)	1/2 (50%)	1/6 (17%)	1/2 (50%)
B	24	0/24 (0%)	0/0 (∅)	0/0 (∅)	0/0 (∅)
C	24	0/24 (0%)	0/0 (∅)	0/0 (∅)	0/0 (∅)
D_{TLM}	35	4/35 (11%)	1/13 (8%)	3/4 (75%)	12/13 (92%)
D_{TLL}	35	7/35 (20%)	2/13 (15%)	5/7 (71%)	11/13 (85%)
E_{TLM}	55	1/55 (2%)	1/21 (5%)	0/1 (0%)	20/21 (95%)
E_{TLL}	55	7/55 (13%)	5/21 (24%)	3/7 (43%)	16/21 (76%)
F	30	0/30 (0%)	0/6 (∅)	0/0 (∅)	6/6 (100%)
G	70	1/70 (1%)	1/7 (14%)	0/1 (0%)	6/7 (86%)
Overall	297	21/297 (7%)	9/49 (18%)	9/21 (43%)	40/49 (82%)
Published	96	26/96 (96%)	26/26 (100%)	1/27 (4%)	0/26 (0%)

Map regions are those given in Fig. 1. The 'Overall' region contains all the data in sites A–G, with the top laminated lakes considered as laminated. The 'Published' region refers to the data in Larsen and MacDonald (1993). 'Correct decision' is the fraction or percent of the lakes that Eq. (1) predicted would have laminated sediments that actually do have them. 'False negatives' are the fraction or percent of the lakes with laminated sediments that Eq. (1) predicted would have them. 'False positives' are the fraction or percent of the lakes that Eq. (1) predicted would have laminated sediments that actually have massive sediments. Sites D and E contain some lakes with sediments only laminated in the top 2–10 cm. When the sediments of these top laminated lakes are considered massive the site is subscripted TLM, and when considered laminated it is subscripted TLL.

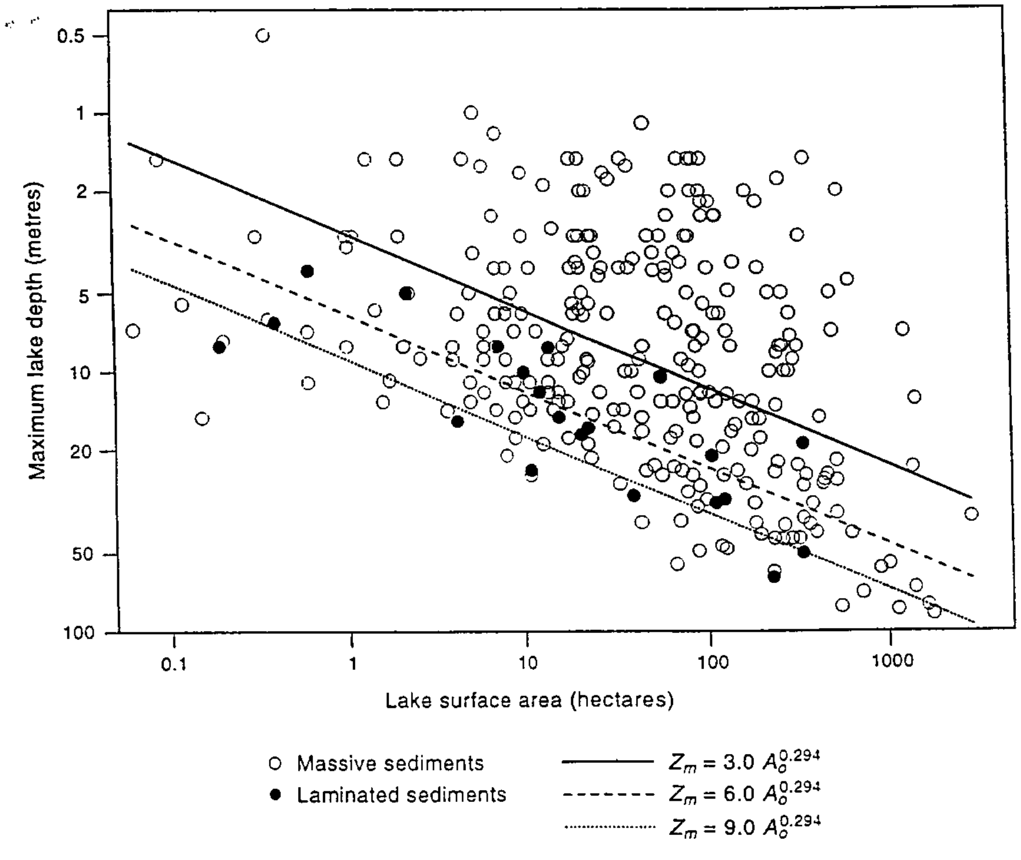

FIG. 3. Relations between lake surface area, maximum lake depth and whether sediments are massive or laminated for the 297 lakes from the seven regions shown in Fig. 1. The top laminated lakes in sites D and E are considered to be laminated. Also shown are three modified versions of the published equation which distinguished between lakes with laminated and massive sediments.

factor in determining whether a lake would contain LLS. The low accuracy of predicting and classifying lakes with LLS obtained in this study suggest that factors other than the relationship between surface area and maximum depth expressed in Eq. (1) exert a strong control on formation and preservation of LLS. For example, internal water movements (which may disturb laminations) will also be influenced by variables, such as lake shape, internal morphometry, topography around the lake and whether there are inflowing streams (e.g. Walker and Likens, 1975; Hokanson, 1977; O'Sullivan, 1983; Saarnisto, 1986; Bowling and Tyler, 1990).

Lakes with conditions that allow LLS to be preserved might still not contain them because the water chemistry may not be suitable for the production of seasonal variations in sediment characteristics. For example, Ludlam (1979) discussed how a recent increase in lake productivity in some meromictic lakes in the northeastern United States led to the formation of biogenic laminae in the top parts of the sediment. Increased lake productivity owing to cottage development along the shore has probably led to the formation of top-laminated sediments in some lakes in region E of this study (Hall and Smol, 1996). In contrast, LLS may become obscured towards the top of the sediments by changes in water chemistry. For example, in one lake in region D, laminae were not apparent during field inspection of the top 30 cm. However, a core from this lake previously analyzed microscopically, was found to contain calcareous laminae which increased in visibility with depth (MacDonald et al., 1991). The decreased visibility of the upper most laminae appeared to be due to increased humic acid content (P. R. Leavitt, *pers. comm.*). It is possible, therefore, that fine laminations may be overlooked in the field.

Despite the importance of lake chemistry, our study does not show the existence of any simple trend of lakes in either sedimentary, metamorphic or igneous rocks with higher levels of 'correct decisions' or lower levels of false negatives or false positives. Geological and geochemical conditions and, therefore, water chemistry may play an important role influencing the presence of LLS, but the conditions are not always sufficiently reported or known for their role to be tested.

The importance of these various factors does not explain why in our data set the percentage of correct decisions is lower and the proportions of false negatives and positives is higher than in the lakes studied by Larsen and MacDonald (1993). We suggest that the contrast may be due largely to inter-regional differences in climate. Larsen and MacDonald (1993) included in their data set lakes with ALLS from around the world. Many of those containing MLS came from Canada and Alaska, and so typically from colder, more northerly latitudes. In our study, it is notable that in the two most northerly study regions (A and D), LLS are found in shallower lakes than in the two southern most (E and G; Fig. 2). In addition, it is only in the northerly regions B and C that no lakes with MLS are deeper than the critical level described by Eq. (1). It is therefore possible that lakes of the same or very similar morphometry are not mixed as deeply in cold, northern areas. Further, weather patterns that may be associated with different climates have been noted to influence the time-span and depth of turbulent mixing in meromictic lakes in different years (Salonen et al., 1984; Bradbury, 1988). In addition, it is possible that the more extended period of ice cover in northern regions would promote formation of laminations by providing a longer time over which fine material may settle out of the water column.

Unfortunately, our data are not sufficient to develop a model that would relate climate to depth of lake water mixing. The idea merits further investigation.

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REFERENCES

Anderson, R.Y., Dean, W.E., Bradbury, J.P. and Love, D. (1985) Meromictic lakes and varved lake sediments in North America. U.S. *Geological Survey Bulletin* **1607**, Washington.

Blais, J.M. and Kalff, J. (1993) Atmospheric loading of Zn, Cu, Ni, Cr, and Pb to lake sediments: the role of catchment, lake morphometry, and physico-chemical properties of the elements. *Biogeochemistry* **23**, 1–22.

Bowling, L.C. and Tyler, P.A. (1990) Chemical stratification and partial meromixis in reservoirs in Tasmania. *Hydrobiologia* **194**, 67–83.

Bradbury, J.P. (1988) A climatic–limnologic model of diatom succession for paleolimnological interpretation of varved sediments at Elk Lake, Minnesota. *Journal of Paleolimnology* **1**, 115–131.

Cumming, B.F., Smol, J.P. and Birks, H.J.B. (1992) Scaled chrysophytes (Chrysophyceae and Synurophyceae) from Adirondack drainage lakes and their relationship to environmental variables. *Journal of Phycology* **28**, 162–178.

Cushing, E.J. and Wright, H.E. Jr. (1965) Hand operated piston corers for lake sediments. *Ecology* **46**, 380–384.

Davis, J.C. (1986) *Statistics and Data Analysis in Geology*. John Wiley and Sons, Inc., New York.

Glew, J.R. (1989) A new trigger mechanism for sediment samplers. *Journal of Paleolimnology* **1**, 235–239.

Glew, J.R. (1991) Minitiature gravity corer for recovering short sediment cores. *Journal of Paleolimnology* **5**, 285–287.

Hall, R.I. and Smol, J.P. (1996) Paleolimnological assessment of long-term water-quality changes in south-central Ontario lakes affected by cottage development and acidification. *Canadian Journal of Fisheries and Aquatic Science* **53**, 1–17.

Hokanson, L. (1977) The influence of wind, fetch, and water depth on the distribution of sediments in Lake Vanern. *Canadian Journal of Earth Sciences* **14**, 397–412.

Lamoreux, S.F. and Bradley, R.S. (1996) A late Holocene varved sediment record of environmental change from northern Ellesmere Island, Canada. *Journal of Paleolimnology* **16**, 239–255.

Larsen, C.P.S. and MacDonald, G.M. (1993) Lake morphometry, sediment mixing and the selection of sites for fine resolution palaeoecological studies. *Quaternary Science Reviews* **12**, 781–791.

Ludlam, S.D. (1979) Rhythmite deposition in lakes of the northeastern United States. In: Schluchter, C. (ed.), *Moraines and Varves*, pp. 295–302. A.A. Balkema.

MacDonald, G.M., Larsen, C.P.S., Szeicz, J.M. and Moser, K.A. (1991) The reconstruction of boreal forest fire history from lake sediments: a comparison of charcoal, pollen, sedimentological, and geochemical indices. *Quaternary Science Reviews* **10**, 53–71.

Moser, K.A., Smol, J.P., Lean, D.R.S. and MacDonald, G.M. (in press). Physical and chemical limnology of northern boreal lakes, Wood Buffalo National Park, northern Alberta and Northwest Territories, Canada. *Hydrobiologia*.

O'Sullivan, R.E. (1983) Annually-laminated lake sediments and the study of Quaternary environmental changes—a review. *Quaternary Science Reviews* **1**, 245–313.

Pienitz, R. and Smol, J.P. (1993) Diatom assemblages and their relationships to environmental variables in lakes from the boreal forest–tundra ecotone near Yellowknife, Northwest Territories, Canada. *Hydrobiologia* **269 (270)**, 391–404.

Pienitz, R. Smol, J.P. and Lean, D.R.S. (1997a) Physical and chemical limnology of 59 lakes located between the southern Yukon and the Tuktoyaktuk Peninsula, Northwest Territories (Canada). *Canadian Journal of Fisheries and Aquatic Sciences* 54, 330–346.

Pienitz, R., Smol, J.P. and Lean, D.R.S. (1997b) Physical and chemical limnology of 24 lakes located between Yellowknife and Contwoyto Lake, Northwest Territories (Canada). *Canadian Journal of Fisheries and Aquatic Sciences* 54, 347–358.

Saarnisto, M. (1986) Annually laminated lake sediments. *In*: Berglund, B.E. (ed.). *Handbook of Holocene Palaeoecology and Palaeohydrology*, pp. 343–370. John Wiley and Sons, Chichester.

Salonen, K., Arveola, L. and Rask, M. (1984) Autumnal and vernal circulation of small forest lakes in Southern Finland. *Verhandlungen der Internationalen Vereinigung fur Theoretische und Angewandte Limnologie* 22, 103–107.

Walker, K. F. and Likens, G. E. (1975) Meromixis and a reconsidered typology of lake circulation patterns. *Verhandlungen der Internationalen Vereinigung fur Theoretische und Angewandte Limnologie* 19, 442–458.