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Seasonal Mixing and Genesis of Endogenic Meromixis in Small Lakes in Southeast Norway

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The inland region of Southeast Norway contains many lakes with endogenic meromixis. A synoptic study of seasonal mixing was conducted in 27 oligo- and mesotrophic lakes with surface area 0.0013 – 7.4 km^2 and water colour 2-146 Hazen units. The scope was to identify properties of morphometric, optical and chemical nature that lead to development of endogenic meromixis. The summer mixing depths were found to depend on lake area and water colour. Small lakes (<0.3 km^2) were incompletely aerated during the spring circulation and had hypolimnetic temperatures near the temperature of maximum density throughout the summer stagnation. Insubstantial autumn mixing is considered the primary reason lakes in this area develop meromixis. Iron and manganese concentrations in anoxic deep waters depend on concentrations in the sediments and on accumulation of dissolved inorganic carbon in the deep waters. Development of endogenic meromixis is favoured by iron concentration in the sediment more than 5% of dry weight and manganese more than 0.5% of dry weight.

Introduction

The perennially isolated stratum of water in the deeper regions of meromictic lakes, the monimolimnion, persists because of the higher density of the monimolimnetic waters, while the mixolimnion seasonally traverses through its temperature of maximum density. The monimolimnion can be formed from external processes or events, so-called ectogenic and crenogenic meromixis, and from internal biogeochemical processes (Hutchinson 1957). In this paper the term endogenic meromixis is used for the latter type of meromixis. This is in accordance with Walker and Likens (1975) and synonymous with dynamic meromixis (Findenegg 1937) and biogenic meromixis (Hutchinson 1957). In contrast to ectogenic and crenogenic meromixis, which most often have quite obvious reasons, the question what causes and preserves enhanced solute concentrations in the deep waters of endogenic meromictic lakes sometimes remains unsolved. Therefore, there is a need to develop criteria to forecast genesis of endogenic meromixis and to improve interpretation of paleolimnological evidence of endogenic meromixis. It was the aim of this study to see if such criteria can be based on simple morphometric and physicochemical characteristics.

The majority of lakes with endogenic meromixis in the Northern Temperate Zone are found inside geographic regions with special topographic and climatic conditions. These are: small and relatively deep basins, little wind stress and a continental climate with warm summers and cold winters (Strøm 1945; Hutchinson 1957; Walker and Likens 1975). Small surface areas are most important to reduce the impact of wind induced mixing. A persistent ice-cover during winter is favourable too, since it closes off the wind impact when the water masses are most unstable. Under such conditions meromixis can occur in spite of very low salinity gradients in the deep waters.

Solutes liberated by biochemical processes in the sediments provide the stability necessary for the bottom layer to persist throughout the seasonal mixing periods (Hutchinson 1957). Enhanced carbon dioxide concentrations caused by decay of organic matter in the sediment cause dissolution of minerogenic constituents like calcium, iron and manganese. The dissolution of calcium carbonate will usually be most important for the density stratification in lakes with excessive calcium carbonate precipitation in the water column (Strøm 1945), while iron, and sometimes manganese, dominate in soft water lakes, which have waters far from calcium carbonate saturation. (Kjensmo 1967; Hongve 1980; Bowling and Tyler 1990). High concentrations of iron and manganese are results of redox-driven cycling (Hamilton-Taylor and Davison 1995), and data from one lake where this has been studied in detail (Hongve 1997, 1999) is included in the present study. However, for the purpose of this article only the maximum deep water concentrations are taken into account, and no emphasis is given to how high concentration of iron and manganese build up during the stagnation periods.

Regarding the required combination of favourable basin morphometry and climate, the present study deals with variations in morphometry within a restricted geographic area where the climatical conditions for this purpose can be regarded as constant. Studies from various regions within the Northern Temperate Zone show that the thickness of the mixed layer in stratified lakes is connected to lake size (Ragotzkie 1978; Patalas 1984; Gorham and Boyce 1989). The position of the thermocline during the height of summer stagnation relative to the maximum depth of the lake may be important to predict possibilities to develop a perennial stagnant layer. A thin hypolimnion indicates that the thermal gradient will be wiped out relatively early in the autumn, leading to subsequent equilibration of solute gradients. Reduced water clarity may also be of some significance since it causes shallower thermoclines (Mazumder and Taylor 1994; Fee *et al.* 1996).

Hutchinson's (1957) classical treatise says little about sediment conditions in connection with endogenic meromixis. Dissolved salts of iron and manganese are the most prominent components in the deep waters of many lakes with endogenic meromixis or seasonal stratification in Southeast Norway (Kjensmo 1967; Hongve 1980). Kjensmo (1968) assumed iron loading to be the most important factor for rendering lakes meromictic but few quantitative data were given for iron loading or accumulation of sedimentary iron in meromictic and holomictic lakes. If we hypothesise a causal connection between sediment and deep-water concentrations of iron and/or manganese, it may be possible to find correlations between these parameters.

The inland region of Southeast Norway is known for a rich occurrence of lakes with endogenic meromixis (Walker and Likens 1975). In a selection of 28 small kettle lakes in the Upper Romerike area (Ullensaker district) nine were found to be meromictic (Bremmeng and Kloster 1976; Hongve 1980). The criterion for meromixis is, in this connection, that a part of the water column remains anoxic and has a much greater concentration of solutes than the main water body throughout and after the two annual mixing periods. Up to present, it has not been known why some of the lakes are meromictic while others, looking similar with regard to morphometry and general water quality, remain holomictic. The working hypothesis for the present study has been that the following parameters are important: the depth of the mixed layer at the height of summer stagnation, the maximum depth of the lake and the availability of sedimentary components that can be dissolved in the deep water during prolonged periods of stagnation. Since the depth of the mixed layer, according to the studies mentioned above, might be forecasted from lake size and water clarity, these more accessible parameters may substitute determination of thermocline depths.

A synoptic study was designed to see how the thermal stratification and conditions for deep water mixing varied in accordance with parameters describing surface area, maximum depth and optical conditions. Data on the concentrations of iron and manganese in the deep anoxic waters and sediments of the Romerike lakes are available from a previous study (Hongve 1980) and unpublished material that was collected in connection with this study. These data will be used to test the hypothesis that total concentrations of iron and manganese in sediments can be used to predict deep-water concentrations during periods with anoxic conditions. Finally, the result from the synoptic study and the chemical information will be combined to see if it is possible to establish criteria to forecast endogenic meromixis.

Table 1 – Data extracted from Hongve (1977, 1980) showing morphometric and chemical properties of Romerike lakes with seasonal anoxia or meromixis (m). The deep water concentrations are typical values from the height of the summer stagnation. Water colour was measured in 1998. The sediment data represent dry samples. 3 lakes named in italics were not accessed during the synoptic study.

				Epilimnion				Deep waters			Sediment	
Parameter	No.	A	z_m	Colour	k_{25}	pH	HCO_3^-	Fe	Mn	HCO_3^-	Fe	Mn
Unit		km^2	m	CU	$mS\ m^{-1}$		mM				mmol kg^{-1}	
Majorsetertjern	1	0.001	6.5	63	1.7	5.6	0.01	0.15	0.004	0.30	930	5
Nordkulpen	2	0.001	2.0	90	3.4	6.2	0.02	0.06	0.001	0.33	640	5
V. Bakketjern (m)	3	0.003	8.0	146	2.7	4.1	0.00	0.01	0.001	0.00	50	2
Mjøntjern	4	0.006	8.5	10	23.6	7.6	2.50	0.005	0.037	2.96	1020	55
Vollsnesputten	5	0.008	4.0	10	1.6	5.1	0.01	0.09	0.003	0.13	700	7
Katt-tjern	6	0.01	13.5	14	1.4	5.8	0.01	0.09	0.002	0.25	540	4
Skånetjern	7	0.01	5.5	28	5.3	6.6	0.46	0.01	0.002	0.95	270	4
Skråtjern (m)	8	0.01	12.2	16	10.3	7.6	0.80	0.71	0.032	5.74	550	11
Bakketjern (m)	9	0.02	14.8	35	7.0	6.4	0.50	0.38	0.015	2.00	710	2
Gravtjern (m)	10	0.02	7.0	83	5.8	6.5	0.44	2.18	0.045	5.50	3570	36
Ljøgodttjern (m)	11	0.02	16.3	6	7.4	7.3	0.60	1.41	0.033	5.00	2320	55
Sandtjern	12	0.02	7.0	102	3.7	6.0	0.05	0.33	0.022	0.75	1070	7
Svarttjern	13	0.02	10.5	4	18.0	7.3	0.89	0.14	0.030	1.68	7300	36
Svenskestutjern	14	0.02	18.0	2	1.4	5.1	0.00	0.02	0.001	0.00	160	0.2
Vilbergtjern (m)	15	0.02	17.0	5	1.3	5.9	0.01	0.12	0.001	0.60	250	7
Bonntjern	16	0.05	9.0	8	5.4	7.7	0.53	0.02	0.003	0.92	210	4
Transjøen (m)	17	0.09	22.0	4	26.8	7.9	2.64	0.002	0.177	4.05	520	36
Aurtjern (m)	18	0.12	16.0	7	3.0	6.6	0.20	0.59	0.020	1.70	710	2
Nordbytjern 1997 (m)	19	0.28	23.0	5	27.0	7.3	1.20	0.17	0.213	2.55	2700	120
Nordbytjern 1977 (m)	–	0.28	23.0	5	17.7	7.7	1.05	0.79	1.20	6.02	3200	550
Hersjøen	20	0.64	16.5	5	18.0	7.3	1.70	0.02	0.545	3.70	1130	1800

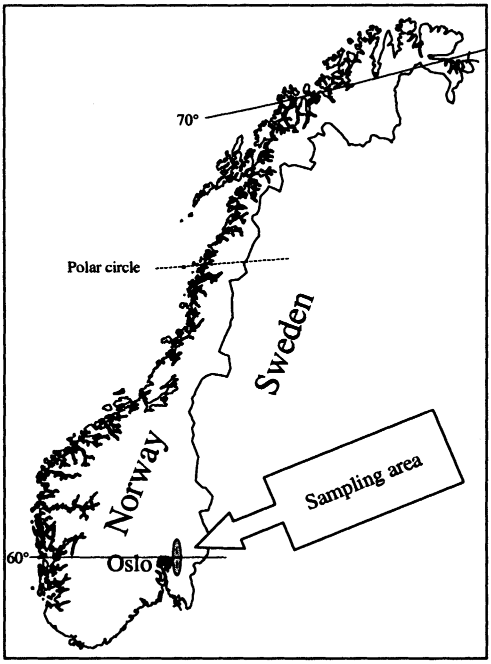

Fig. 1. Location of the sampling area.

Material and Methods

Lakes – This study includes 17 kettle lakes situated in Pleistocene deposits in the Upper Romerike area. The chemical water qualities of these lakes are known from previous studies (Hongve 1977, 1980) and the data used here, except those mentioned further down, are extracted from these studies (Table 1). Data up to 2000 (unpublished) indicate that the water chemistry and mixing conditions, except in Nordbytjernet, have been quite stable and the employed data are representative for the present situation. For Nordbytjernet data from two years, 1977 and 1997, have been used because of major changes in water and sediment chemistry caused by local hydrogeological conditions (Hongve 1999). The sediment data were obtained simultaneously with the previous studies. Eight of the sampled lakes are meromictic and further descriptions of physiography and chemical features have been given earlier (Bremmeng and Kloster 1976; Hongve 1980, 1997). Since all the Romerike lakes are small in surface area (0.0013 – 0.64 km^2, median 0.02 km^2) 11 other lakes in the size range 0.04 – 7.4 km^2 were included in a study of thermal stratification in 1998. These lakes are situated southeast of the city of Oslo, in the districts Oslo, Ski, and Enebakk (Fig. 1). The elevation is 159-193 metres above sea level for the Romerike lakes and 109-205 metres for the other group. According to local environmental authorities (unpublished reports) all the lakes are oligotrophic to mesotrophic with algal biomass normally less than 2 g m^{-3} wet weight during the productive season and the influence of inorganic turbidity is negligible. The influence of turbidity on the light penetration is therefore small in comparison with water colour and is not taken into account in this study. Theoretical water retention times range from around two months to several years. The hydraulic load is lowest during the summer and winter months and direct effects of incoming water on the recorded temperature gradients is assumed to be negligible. It is likely that internal seiches influenced the recorded temperature gradients in the larger lakes in June and August. For the actual purpose this is unimportant and is not given further attention.

Sampling and Analyses – The lakes were sampled for temperature, Hazen water colour and DOC three times in 1998, 9-14 June, 20-22 August, and 21-26 December. The first sampling was made during the early phase of the summer stagnation while the sampling in August was done around the beginning of the autumn cooling. During the sampling in December all lakes were covered with ice, 15-25 cm thick. The temperature was measured centrally in each lake at one metre intervals, starting just under the surface. A Yellow Springs International Model 57 Oxygen meter equipped with a temperature probe was read to the nearest 0.1 °C by interpolation. The uncertainty in the temperature readings is assumed to be better than 0.3 °C. The Hazen water colour, given as colour units (CU) (Hongve and Åkesson 1996) and dissolved organic carbon (DOC) was measured in water samples from one metre depth. The sediment samples were taken with a gravity corer from the deepest point of each lake. The top 2 cm of each core was dried and digested in an autoclave (120 °C) with nitric acid, 7 mol l^{-1} (ISO 1999). Other physical and chemical methods were as described in Hongve (1980, 1997).

Results and Discussion

Temperature Gradients and Wind Impact

The two largest lakes became ice-free around 20 April 1998, during a warm period for the season. The more persistent ice covers on the smaller lakes melted during the following two weeks (Fig. 2). In lakes where the epilimnion thickness was significantly smaller than the lake depth, hypolimnetic temperatures of some 4 to 6°C persisted throughout the summer. The position of the thermocline (z_t) is read as the inflection point of the temperature graphs (Fig. 3), while epilimnion depth (z_e) is the vertical extension of the upper heated layer with a temperature gradient less than 1 °C m^{-1}. The values of z_t and z_e ranged between 1 m and 13 m. The mean difference, $z_t - z_e$, was 1.3 m in June and 1.4 m in August. The median increase in z_t from June to August was 0.9 m and the maximum increase was 2 m. In December the temperatures, except in the upper metre, were around the temperature of maximum density in lakes with $A<0.3$ km^2. Only lakes with $A>1$ km^2 obtained cooling of the deep waters to temperatures lower than 4 °C during the autumnal circulation.

The allochthonous influence of organic substances varies considerably between

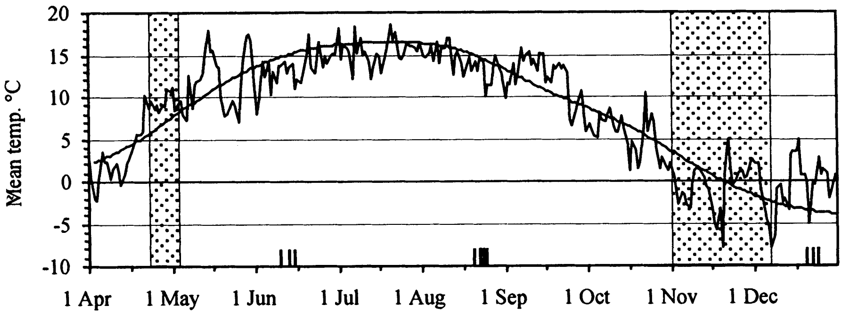

Fig. 2. Daily mean temperatures in Oslo 1998 and mean temperatures for the years 1961-1990. The sampling days are shown by marks on the x-axis. The dates for total ice-cover and ice-off in 1998 were within the shaded intervals.

the lakes, resulting in average water colour from 2 to 150 Hazen units and dissolved organic carbon 2 – 22 mg l^{-1}.

A variation in thermocline depths is observed between lakes with near identical morphometric values. Therefore, multiple regression was used to determine influences from various variables. Dependent variables in the regressions were the values for z_e and z_t in June and August while the independent ones were the lake area (*A*), fetch length, maximum depth (z_m), mean depth and various water quality parameters. The requirements for linear regression could be met better when the variables were expressed in logarithmic units. Stepwise selection of parameters shows that most of the variability in z_e and z_t values is explained by the variability in lake size and water colour (Table 2). Water colour adds around 20% to the degree of explanation (r^2) of the various models as compared with simple regression models with lake area as single independent variable. It is noticed that lake area gives higher correlation coefficients than the different functions of fetch lengths used by Ragotzkie (1978), Patalas (1984) and Gorham and Boyce (1989).

The summer temperatures at 5 m depth (T_5) depended on the same variables as mixing depths (Table 2). In December T_5 showed no dependence on colour and the given correlation coefficient refers to simple regression of temperature versus lake area.

Birgean wind work (*B*), the amount of work per unit area needed to distribute the summer heat income, has been used to compare wind impact on small lakes (Hongve 1980; Bowling 1990; Bowling and Salonen 1990). However, Hongve (1980) assessed that much of the apparent work of the wind resulted from direct absorption of radiant energy in the epilimnion. The direct work, according to Birge (1916), is reduced in proportion with the area of the affected depths and *B* depends therefore strongly on the shape of the basin. For the studied lakes *B* correlates with z_m (r=0.90). Therefore, *B* is not an appropriate parameter for comparing wind impact between lakes with different morphometry.

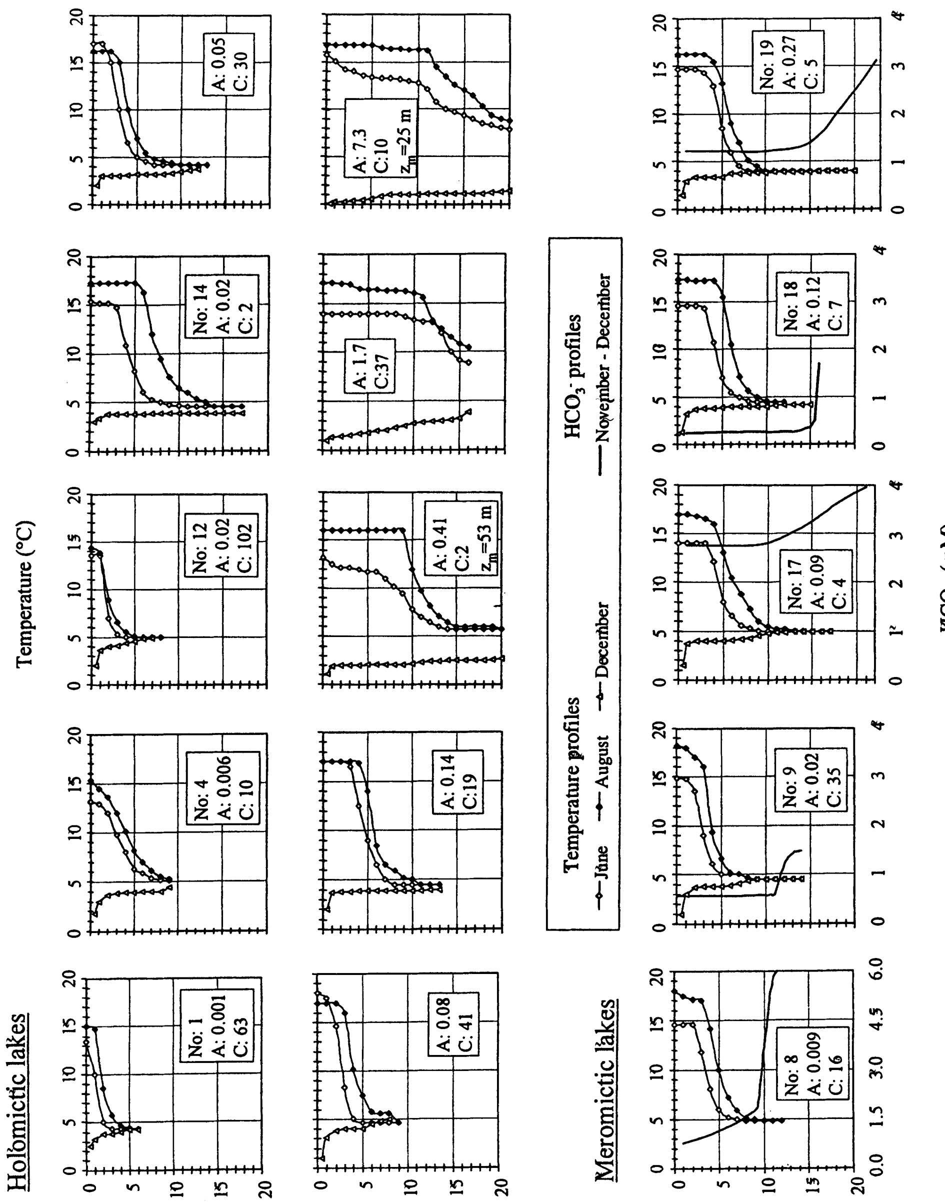

Fig. 3. Depth profiles selected to represent the variation between lakes in size and allochthonous influence. Bicarbonate profiles given for meromictic lakes were measured after the autumn circulation. No: Lake number of Romerike lakes, see Table 1. A: Area, km^2, C: Hazen colour units. z_m: maximum depth (only for holomictic lakes deeper than 20 m).

Table 2 – Results of multiple regression analysis of epilimnion depth (z_e), thermocline depth (z_t), and temperature at 5 m depth (T_5), (dependent variables) versus Hazen water colour (CU) and lake area (independent variables).

Dependent variables	Month	Const.	SD	p	log CU coefficient	SD	p	log area coeff.	SD	p	r^2,%	n
log z_e	Jun	1.29	0.11	<0.0001	-0.46	0.08	<0.0001	0.39	0.05	<0.0001	84.0	28
log z_e	Aug	1.22	0.12	<0.0001	-0.34	0.10	0.0017	0.30	0.06	<0.0001	69.1	27
log z_t	Jun	1.01	0.05	<0.0001	-0.16	0.04	0.0011	0.20	0.03	<0.0001	82.0	28
log z_t	Aug	1.15	0.06	<0.0001	-0.24	0.04	<0.0001	0.18	0.03	<0.0001	81.3	27
T_5	Jun	12.8	0.81	<0.0001	-1.57	0.64	0.0208	2.56	0.37	<0.0001	71.3	27
T_5	Aug	20.65	1.13	<0.0001	-4.87	0.89	<0.0001	2.69	0.52	<0.0001	76.0	27
T_5	Des	2.65	0.33	<0.0001				-0.78	0.16	0.0001	54.1	25

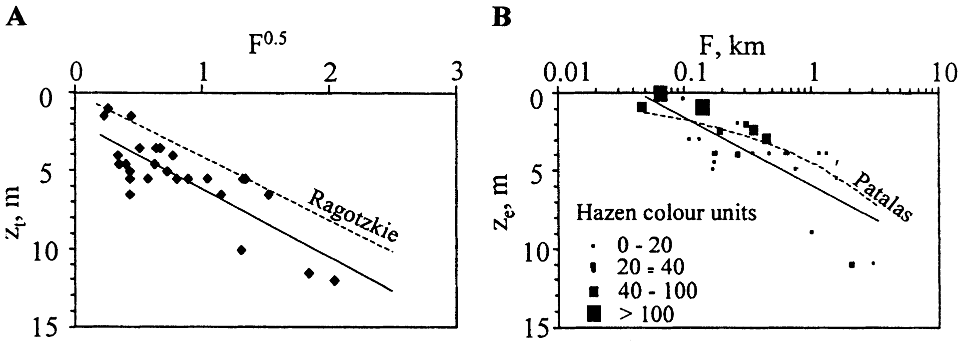

Fig. 4. A: Thermocline depths in August versus fetch lengths compared with the empirical relationship of Ragotzkie (1978). The linear regression line has the equation $z_t \equiv 4.3F_m^{0.5} + 1.9$, $r^2 = 0.66$). B: Epilimnion depths in August versus mean fetch lengths compared with the empirical relationship of Patalas (1984). The continuous line shows the best fitting linear regression line for the present observations ($z_e \equiv 4.5 \log F_a + 6.0$, $r^2 = 0{,}60$) The symbol size indicates the average water colour of each lake.

Steep temperature gradients extending quite to the surface of the smallest lakes evidence that heat distribution in these lakes is determined chiefly by direct absorption of radiant energy. The water colour has a negative influence on the thermocline deepening because it enhances absorption of short waved radiant energy in the superficial layer and increase back radiation to the atmosphere. Steep thermal gradients also suppress turbulence and, therefore, vertical transfer of absorbed heat. The thermocline then acts as a slippery surface permitting relative motions of the surface layer with regard to the hypolimnion (Imboden and Wüest 1995). This causes the major restraint to wind induced distribution of heat in the water column. Direct heat absorption may, on the other hand, contribute to epilimnion deepening in lakes with less water colour.

Ragotzkie (1978) gives an empirical relationship between maximum fetch (F_m) and z_t based on lakes in Wisconsin and central Canada ($z_t = 4\ F_m^{0.5}$, Fig 4A). Most lakes in the present study had deeper summer thermoclines than indicated from this relationship. However, few of Ragotzkie's lakes had fetches shorter than 1 km, and the actual shape of the regression line in this range may be questioned. The mixing depths are better predicted using Patalas' equation (Patalas 1984) for z_e based on average fetches ($z_e = 4.6\ F_a^{0.41}$, Fig 4b). Better predictions of the epilimnion depths are obtained when also the water colour is taken into account (Table 2).

In contrast to incomplete spring circulation, which is frequently mentioned as prerequisite for endogenic meromixis (*e.g.* Hutchinson 1957; Kjensmo 1967; Walker and Likens 1975), variable conditions for isothermal mixing in the autumn seem overlooked or neglected in most studies of endogenic meromixis. However, Strøm (1945) mentions also rapid freezing in the autumn. Most important for deep water

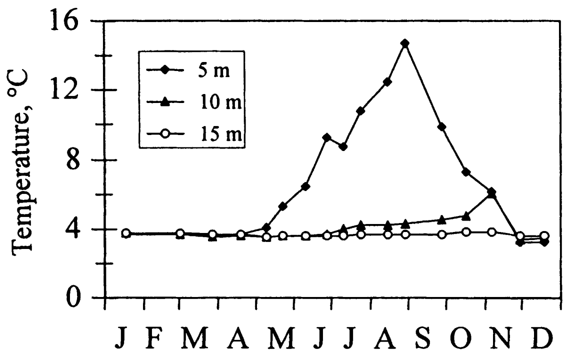

Fig. 5. Temperatures from three depths of the mixolimnion in Nordbytjernet 1977. z_m=23 m.

mixing in this connection is the spell between achievement of isothermal conditions down to the chemocline and the formation of an ice cover (Hongve 1980). Meromictic lakes that do not freeze depend on much larger concentration gradients than the lakes in this study, and the meromixis is seldom of endogenic nature. A close inspection of temperature records from endogenic meromictic lakes in Norway (Kjensmo 1967; 1968; Bremmeng and Kloster 1976; Hongve unpublished data) shows that circulation of the mixolimnion never starts before this layer is cooled down entirely to the temperature of maximum density. Records from the Romerike lakes 1967 – 1998 show that by the end of October the mixed layers use to be 10-12 m in thickness with temperature >5°C. As an example, Fig. 5 shows annual temperature variations at 5, 10 and 15 m depth in one lake. At 10 m depth the onset of isothermal mixing was around the first of November. No temperature increase beyond 4.0°C was seen at 15 m depth. After 12 November the average day temperature in this area is normally below 0 °C and the lakes are soon covered with ice. Therefore, the impact of isothermal mixing on solute gradients in the deep waters is restricted to a few days every autumn, and the persistence of the solute gradient determines whether the lake is holomictic or meromictic. For more shallow lakes, isothermal conditions are achieved earlier in the autumn and at higher temperatures. The longer duration of the autumn circulation reduces the chance that solute gradient may be preserved until the onset of winter stagnation. Lakes that are more wind exposed due to size also have longer periods with full circulation in the autumn because wind-induced currents prevent freezing. The whole water column may then be cooled to temperatures below 4°C (Fig. 3). It is not likely that endogenic meromixis will occur in lakes of this category.

Solute Gradients

Most of the Romerike lakes become depleted in dissolved oxygen in deeper parts of the hypolimnion during the stagnation periods, while the concentrations of inorganic carbon and redox sensitive solutes increase (Hongve 1980). Autumn circulation in the holomictic lakes always reduces iron and manganese concentrations in the deep waters to small values (<0.02 mmol l^{-1}), while bicarbonate attains the same concentration as in the epilimnion. In meromictic lakes the chemical stratification in the deep waters persists through the mixing season although the electrolyte concentrations and the thickness of the anoxic layers are often reduced. Iron and sometimes manganese, together with bicarbonate, give the most significant contribution to the solute gradients in both the meromictic lakes and the ones with seasonal anoxia (Table 1). Epilimnic concentrations of iron and manganese are at trace levels and not relevant for this study. Calcite precipitation in the euphotic zone and dissolution in the deep water is an actual process only in the calcium-rich Transjøen (Bremmeng and Kloster 1976).

Manganese is easily reduced and appears in the lower part of the water column as soon as the deep waters become anoxic (Hongve 1980). A significant correlation is obtained between the maximum deep-water concentrations and corresponding sediments (Eq.(1))

$$\log[\mathrm{Mn}]_{\mathrm{Water}} = 0.86 \log[\mathrm{Mn}]_{\mathrm{Sediment}} - 3.2 \quad (n=21,\ r^2=0.70,\ p<0.0001) \qquad (1)$$

The concentrations in Eqs. (1)-(3) are given as mol l^{-1} for water and mol kg^{-1} dry weight for sediments. The relationship above suggests that the aquatic concentrations are chiefly controlled by the available amounts of manganese in the sediments. Both meromictic lakes and holomictic lakes with temporary anoxia fit fairly well with the regression line (Fig. 6a) but the residuals are most often positive for meromictic lakes and negative for those with seasonal anoxia. Higher ratios between aqueous and sediment concentrations in meromictic lakes suggest that these, due to longer equilibration times, are closer to thermodynamic equilibria than holomictic lakes.

The correlation between dissolved and sedimentary iron concentrations is not so good as for manganese, but is also statistically significant (Fig. 6b)

$$\log[\mathrm{Fe}]_{\mathrm{Water}} = 0.94 \log[\mathrm{Fe}]_{\mathrm{Sediment}} - 3.9 \quad (n=21,\ r^2=0.31,\ p=0.009) \qquad (2)$$

The main reason for the poorer correlation may be slower reduction and faster removal rates for dissolved iron (Hongve 1980, 1997; Hamilton-Taylor and Davison 1995). This contributes to a lower ratio between dissolved and sedimentary iron in holomictic than in meromictic lakes, and the correlation between the two parameters becomes poor in holomictic lakes. Bremmeng and Kloster (1976) suggest that ferrous solubility in Transjøen, which has the largest negative residual in the linear regression (Fig. 6b), is restricted by sulphide production. Precipitation of ferrous sulphide in the water column has been observed in Nordbytjernet at the peak of the productive season, but redox coupling with settling manganese oxide was assumed to be more important for control of iron solubility (Hongve 1997).

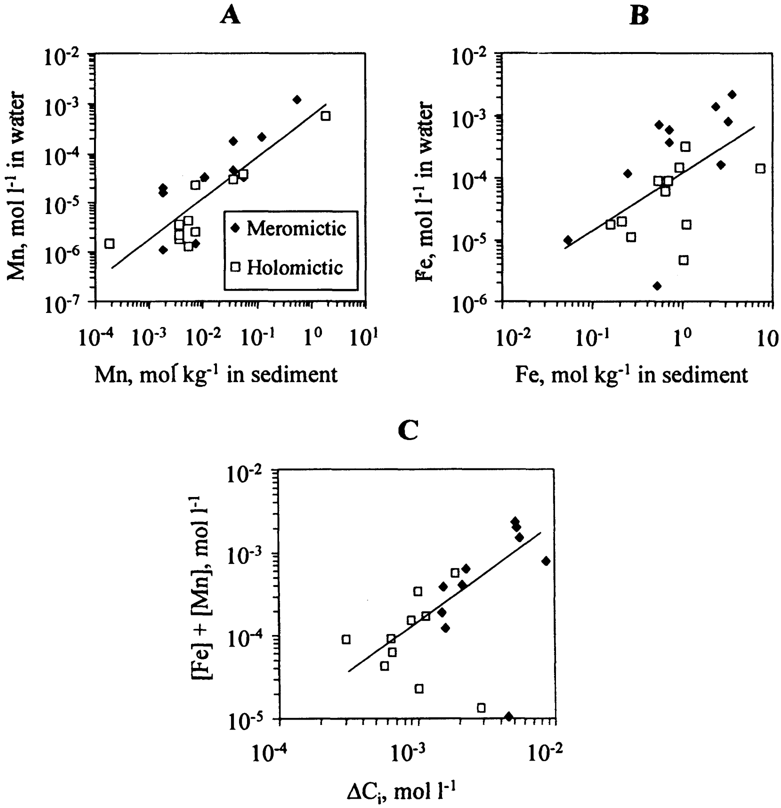

Fig. 6. A and B: Concentrations of manganese and iron in deep waters versus sediment concentrations. C: Dissolved sums of iron and manganese in the deep waters versus accumulation of total inorganic carbon. The equations of the regression lines are given in the text.

The dissolved concentrations of iron and manganese in the anoxic deep waters of lakes depend on adequate supply of carbon dioxide to form soluble bicarbonate salts. Bicarbonate is, therefore, the most prominent component in the stagnant layers of the meromictic lakes. The sum of dissolved iron and manganese concentrations correlate with the vertical increase in total inorganic carbon, ΔC_i, which is the difference between inorganic carbon concentrations at the actual depth and in the mixed layer (Fig. 6c)

$$\log([Fe] + [Mn]) = 1.20 \log[\Delta C_i] - 0.22 \quad (n=18,\ r^2=0.69,\ p<0.0001) \qquad (3)$$

Two lakes, one meromictic (Vesle Bakketjern) and one holomictic (Skånetjern), had much smaller concentrations of iron and manganese compared to inorganic carbon than the others and were excluded in this regression analysis. Both lakes had excess concentrations of dissolved hydrogen sulphide in the deep waters. The variable ratio between the sum of iron and manganese and inorganic carbon can be explained primarily by variable fractions of potentially soluble iron in the sediments. Ferrous sulphide and carbonate (siderite) will not be solubilised by decreasing redox potentials. Fresh amorphous ferric hydroxide (ferrihydrite) can be reduced when dissolved oxygen is depleted, but the stability of the oxide increase with the age of the sediment particles (Langmuir and Whittemore 1971). Fig. 6c shows that the difference between holomictic and meromictic lakes is more pronounced regarding accumulation of inorganic carbon in the deep waters than regarding concentrations of iron and manganese.

Development of Meromixis

Temperatures close to the temperature for maximum density preserved in the deep waters of the smaller lakes after the circulation periods and limited aeration of the water column evidence inefficient mixing of the deep waters. However, in contrast to the view of Hutchinson (1957), often cited in subsequent limnological literature, no evidence in this study supports that a missing spring circulation is most important for development of meromixis. Incomplete or missing spring circulation is a very common feature of small inland lakes. A more unusual feature is that the duration of the autumn circulation is very short due to the climatic and morphometric conditions. Circumstances that yield additional restraint to full circulation may therefore be decisive for initiation of meromixis. A solute gradient that persists after the temperature equilibration is completed may provide sufficient stability to retard full circulation for a limited period until new-formed ice closes off the wind impact. Fig. 3 shows the profiles of bicarbonate in the meromictic lakes after completion of the autumn circulation. The increases with depth are balanced by increases in iron and manganese. The holomictic lakes had, in contrast, no depth gradients after the autumn circulation.

Based on sedimentary records, many authors have inferred endogenic meromixis to be triggered by events that have increased the external loading and lake productivity in historic time (*e.g.* Frey 1955; Julia *et al.* 1998). Cultural eutrophication by agricultural and domestic drainage is also mentioned (Hasler 1947). However, inferring the starting point of meromixis from a single historical event may be wrong, as shown by Schmidt *et al.* (1998) in a recent paleolimnological study. Many pristine small lakes in the Northern Temperate Zone have gone through a natural development after the last deglaciation due to accumulation of organic matter in the catchment and in the sediments. When favoured by the climate, catchment development and morphometric conditions, the natural development may lead from anoxic deep waters during the stagnation periods to perpetual meromixis. The Schmidt stability may, however, remain low for morphometric reasons or if the inventory of components that dissolve in the stagnant layer is limited. In such cases mixing events may influence the deep water stratification from time to time. A phenomenon of intermittent meromixis is probably quite common (Wetzel 1983). Making absolute distinctions between holomictic lakes with poor mixing of the deep waters, and meromictic lakes with low stability seem difficult and may be of little practical interest. These conditions may change from year to year due to changing external influences without noticeable consequences for the water and sediment quality (Hongve 1999). Changing levels of oxygen saturation of the deep waters with respect to climate change emphasise the dynamic type of meromixis (Schmidt *et al.* 1998).

The solute gradients in endogenic meromictic lakes are mainly due to bicarbonates since microbial decomposition is the main reason for accumulation in the depths. Kjensmo (1968) assumed that supply of iron from the catchment and accumulation of ferrous bicarbonate in the anoxic deep waters during prolonged stagnation periods was the primary factor rendering lakes meromictic. The present study confirms a role of iron in the genesis of endogenic meromixis since lakes with much soluble iron in the sediments develop higher deep-water concentrations of iron under anoxic conditions and these lakes are most liable to be meromictic. The causal relationship between iron concentrations and meromixis are, however, not so clear. Hongve (1980) assessed that dissolved iron had only minor influence on the Schmidt stability in the meromictic Romerike lakes. An effect of iron, which may be more important than its direct influence on the density of the deep waters, may be that conversion of carbon dioxide to bicarbonate reduce the vertical flux and preserve high concentrations of inorganic carbon species in the deep waters.

Manganese occurs in lower concentrations than iron in most lakes, but lakes with a high load of manganese seem to become meromictic more easily than iron-rich lakes. This is because manganese is more readily reduced to manganous ions, and dissolved manganous bicarbonate is more stable in the water column than ferrous bicarbonate (Hamilton-Taylor and Davis 1995; Hongve 1997).

Conclusions

The present study confirms that the depth of the mixed layer at the height of summer stagnation and the impact of the autumn circulation on the deep water stratification can be predicted from lake area and water colour. Lakes with surface area ranging from 0.0013 to 7.4 km^2 were investigated and meromixis was seen only in lakes smaller than 0.3 km^2 (Table 1). Lakes larger than 1 km^2 obtained significant hypolimnetic heating in spring and were cooled beyond 4 °C in the deep waters during the autumn circulation in 1998. Lakes ranging from 0.4 to 1 km^2 were well mixed during the spring circulation and obtained deep water temperatures up to 6°C. The autumnal cooling below 4°C was, however, more variable. The efficient mixing of the deep waters at least once a year evidence that lakes with A>0.4 km^2 will not develop endogenic meromixis unless the ratio between maximum depth and surface area is significantly larger than for the lakes in this study.

Lakes with A<0.3 km^2 and z_m>10 m had well-developed hypolimnia with temperatures <5°C after the spring circulation in 1998. It has been demonstrated (Hongve 1980, 1997) that lakes of this size and depth obtain poor aeration of the water column during the spring circulation. Accordingly, these lakes are either spring meromictic or truly meromictic. The hypolimnetic temperatures remained low throughout the summer stagnation. The persistence of the chemical deep-water gradients during the autumn circulation determines whether these lakes develop true meromixis.

Shallower lakes (z_m = 9-10 m) with surface area <0.3 km^2 and without visible water colour (≤10 CU) were mixed and heated to 5-6°C in their deepest parts during the spring circulation 1998 and the water column consisted after that of two layers, corresponding to epilimnion and metalimnion. Lakes with similar size and depth (z_m = 6-9 m) containing coloured water (63-146 CU), were spring meromictic and obtained summer stratification with a shallow epilimnion and a well-developed hypolimnion.

In accordance with these findings, poor spring circulation looks to be prerequisite, but not the decisive factor for development of meromixis. Only lakes with poor impact of autumnal mixing develop this feature. In lakes with small surface area (<0.3 km^2) and relatively deep basins (z_m>12-15 m) the impact of isothermal mixing on the deep waters is of short duration and may not be sufficient to erode solute gradients. Seven of the meromictic lakes in this study had maximum depths between 12 m and 23 m. Two meromictic locations with maximum depths 7-8 m seem to owe their meromixis to great organic loading and dark water colour in combination with a very small surface area (V. Bakketjern) or a very high iron load (Gravtjern). If the criteria for surface area and maximum depths are fulfilled, meromixis occur most likely if the deep water sediments contain more than 1 mol Fe kg^{-1} (~5% of dry mass) or more than 0.1 mol Mn kg^{-1} (~0.5% of dry mass).

Finally, it should be emphasised that the result of this study will be valid only for areas with a similar climate, *i.e.* the lakes are frozen 5-6 months during the winter and the summers are relatively warm. Lakes in areas with milder winters need larger concentration gradients or larger depths to withstand the mixing forces during longer periods with isothermal conditions.

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References

Birge, E. A. (1916) The work of the wind in warming a lake, *Trans. Vis. Acad. Sci. Arts Lett. Vol 18*, pp. 341-391.

Bowling, L. C. (1990) Heat contents, thermal stabilities and Birgean wind work in dystrophic Tasmanian lakes and reservoirs, *Aust. J. Mar. Freshwater Res., Vol 41*, pp. 429-441.

Bowling, L. C., and Salonen, K. (1990) Heat uptake and resistance to mixing in small humic forest lakes in Southern Finland, *Aust. J. Mar. Freshwater Res., Vol. 41,* pp. 747-759.

Bowling, L. C., and Tyler, P. A. (1990) Chemical stratification and partial meromixis in reservoirs in Tasmania, *Hydrobiol., Vol. 194*, pp. 67-83.

Bremmeng, G. S., and Kloster, A.E. (1976) Transjøen, a groundwater influenced lake with special redox and sulphate conditions, *Nord. Hydrol., Vol. 7*, pp. 307-320.

Fee, E. J., Hecky, R. E., Kasian, S. E. M., and Cruikshank, D. R. (1996) Effects of lake size, water clarity, and climatic variability on mixing depths in Canadian shield lakes, *Limnol. Oceanogr., Vol. 41*, pp. 912-920.

Findenegg, I. (1937) Holomiktische und meromiktische Seen, *Int. Rev. gesamt. Hydrobiol. Hydrogr., Vol. 35,* pp. 586-610.

Frey, D. G. (1955) Längsee: a history of meromixis, *Mem. Ist. Ital. Idrobiol., Suppl. 8*, pp. 141-164.

Gorham, E., and Boyce, F. M. (1989) Influence of lake surface area and depth upon thermal stratification and the depth of the summer thermocline, *J. Great Lakes Res., Vol. 15,* pp. 233-245.

Hamilton-Taylor, J., and Davison, W. (1995) Redox-driven cycling of trace elements in lakes, In: Lerman, A., Imboden, D. M. and Gat , J. R. (eds.), *Physics and chemistry of lakes.* Springer. pp. 217-263.

Hasler, A. D. (1947) Eutrophication of lakes by domestic drainage, *Ecology, Vol. 28,* pp. 383-395.

Hongve, D. (1977) The ionic composition of lakes fed by ground water and precipitation in the upper Romerike district, *Nord. Hydrol., Vol. 8,* pp.141-162.

Hongve, D. (1980) Chemical stratification and stability of meromictic lakes in the Upper Romerike district, *Schweiz. Z. Hydrol,. Vol. 42,* pp. 171-195.

Hongve, D. (1997) Cycling of iron, manganese, and phosphate in a meromictic lake, *Limnol. Oceanogr., Vol. 42*, pp. 635-647.

Hongve, D. (1999) Long-term variation in the stability of the meromictic lake Nordbytjernet caused by groundwater fluctuations, *Nord. Hydrol., Vol. 30,* pp: 21-38.

Hongve, D., and Åkesson, G. (1996) Spectrophotometric determination of water colour in Hazen units, *Water Research, Vol. 30*, pp. 2771-2775

Hutchinson, G. E. (1957) *A treatise on limnology,* I. J. Wiley & Sons.

Imboden, D. M., and Wüest, A.(1995) Mixing mechanisms in lakes, In: Lerman, A., Imboden, D. M. and Gat , J. R. (eds.), *Physics and chemistry of lakes,* Springer. pp. 83-138.

ISO (1999) *ISO/DIS 15587-2. Water quality – Digestion methods for the determination of elements – Part 2: Nitric acid digestion method.* International Organization for Standardization. Geneva.

Julia, R., Burjachs, F., Dasi, M. J., Mezquita, F., Miracle, M. R., Roca, J. R., Seret, G., and Vicente, E. (1998) Meromixis origin and recent trophic evolution in the Spanish mountain lake La Cruz, *Aquatic Sci., Vol. 60*, pp. 279-299.

Kjensmo, J. (1967) The development and some main features of "iron-meromictic" soft water lakes, *Arch. Hydrobiol./Suppl. 32*, pp. 137-312.
Kjensmo, J. (1968) Iron as the primary factor rendering lakes meromictic, and related problems, *Mitt. Internat. Verein. Limnol., Vol. 14*, pp. 83-93.
Langmuir, D. L., and Whittemore, D. (1971) Variation in the stability of precipitated ferric oxyhydroxides, *Am. Chem. Soc. Adv. Chem. Ser., Vol. 106*, pp. 209-234.
Mazumder, A., and Taylor, W. D. (1994) Thermal structure of lakes varying in size and water clarity, *Limnol. Oceanogr. Vol. 39*, pp. 968-976.
Patalas, K. (1984) Mid-summer mixing depths of lakes of different latitudes, *Verh. Internat. Verein. Limnol., Vol. 22*, pp. 97-102.
Ragotzkie, R. A. (1978) Heat budgets of lakes, In: Lerman, A. (ed.), *Lakes, chemistry, geology, physics,* Springer. pp. 1-19.
Schmidt, R., Wunsam, S., Brosch, U., Fott, J., Lami, A., Löffler, H., Marchetto, A., Müller, H. W., Prazakova, M., and Schwaighofer. B. (1998) Late and post-glacial history of meromictic Längssee (Austria), in respect to climate change and anthropogenic impact, *Aquatic Sciences, Vol. 60*, pp. 56-88.
Strøm, K. M. (1945) Lakes with stagnant depths, *Skr. norske Videnskabs-Akademi. Mat.-Nat. Kl. No. 7*, pp. 1-16.
Walker, K. F., and Likens, G. E. (1975) Meromixis and a reconsidered typology of lake circulation patterns, *Verh. Internat. Verein. Limnol., Vol. 19*, pp. 442-458.
Wetzel, R. G. (1983) *Limnology*, 2nd. ed. Saunders.

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