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BOTTOM SEDIMENTS OF THE LAKES OF VARIOUS TROPHIC TYPE

The content of organic matter and calcium in bottom sediments were analysed, and also the calorimetry of sediments and organic matter from these sediments. An attempt was made to estimate the intensity of mineralization processes on the basis of oxygen consumption, treated for that purpose as an indicator.

It was found that the calorific value of sediments is a good indicator of the trophy of lakes. The energy content of organic matter can be an indicator of the intensity of mineralization processes. Sediments from anaerobic environment have a considerably higher oxygen consumption than these from well oxygenated environment. The presence of bottom fauna increases the oxygen consumption of sediments.

Bottom sediments, with the exception of littoral ones, are formed by constant depositing of organic and mineral particles from water. They are formed by modifying first of all organic substances by animals and microorganisms. Part of the material accumulated on the bottom returns to the circulation in the lake. The return intensity of some important elements of this material to the circulation in lake is conditioned by the mineralization rate. Mineralization depends on the composition of accumulated sediments and on many biotic and abiotic factors. It is also connected with the trophic character of water body.

In this paper were characterized bottom sediments of 50 lakes of various trophic type from several lakelands and Tatra Mountains. The contents of organic matter and calcium and calorific value of sediments were used as indicators in order to characterize the sediments. Spatial and time differentiations of the above indicators were analysed in the profundal zone of lakes. An attempt was made to estimate the intensity of mineralization processes in surface layers of sediments of lakes of various trophic types and in different environmental conditions. The role of bottom fauna in these processes was also estimated. The oxygen consumption of bottom sediments was used as an indicator of these processes.

I. INVESTIGATED LAKES

A total of 50 lakes were investigated (Tab. I, Fig. 1). Trophic types of lakes were estimated according to the classification by Naumann-Thienemann (Naumann 1931, Thienemann 1925, 1928).

The papers by Śliwerski (1934), Szaflarski (1936), Stangenberg (1936, 1938), Olszewski (1951, 1953), Kondracki and Mikulski (1958), Szczepański (1958, 1961), Olszewski and Paschalski (1959), Paschalski (1960a, 1960b), Mikulski (1966), Schönborn (1966), The Catalog of Polish Lakes (1954) and the unpublished data of A. Szczepański were the basis of a characteristic of investigated lakes.

Thorough field and experimental investigations were carried out in five lakes: Flosek, Lisunie, Mikołajskie, Śniardwy and Tałtowisko.

II. METHODS

The samples of bottom sediments used for analyses of organic matter, calcium content and calorific value of their surface layer (to the depth of 5 cm) were taken with the help of a tubular bottom sampler (Kajak, Kacprzak and Polkowski 1965). With the help of this sampler three samples were taken from the deepest places of 50 lakes once during the summer. Three samples were taken from five of the thoroughly investigated lakes during whole year in monthly intervals; the deepest place of Mikołajskie Lake was sampled all the year in 2 and 4 week intervals. During the winter 120 samples were taken from the whole surface of Mikołajskie Lake, except for the littoral, to obtain materials on spatial differentiation of investigated indicators. Sediments were analysed to the depth of 5 cm. Changes in vertical section of sediments were also analysed. For this purpose the samples were taken by the same tubular sampler (material was divided to 2 cm layers) 5 times from Mikołajskie Lake and twice from lakes Śniardwy and Tałtowisko. During the spring circulation and summer stagnation, samples were taken from Mikołajskie Lake from near-bottom water layers, in order to analyse the oxygen content and to estimate the degree of losses of oxygen used for mineralization of bottom sediments.

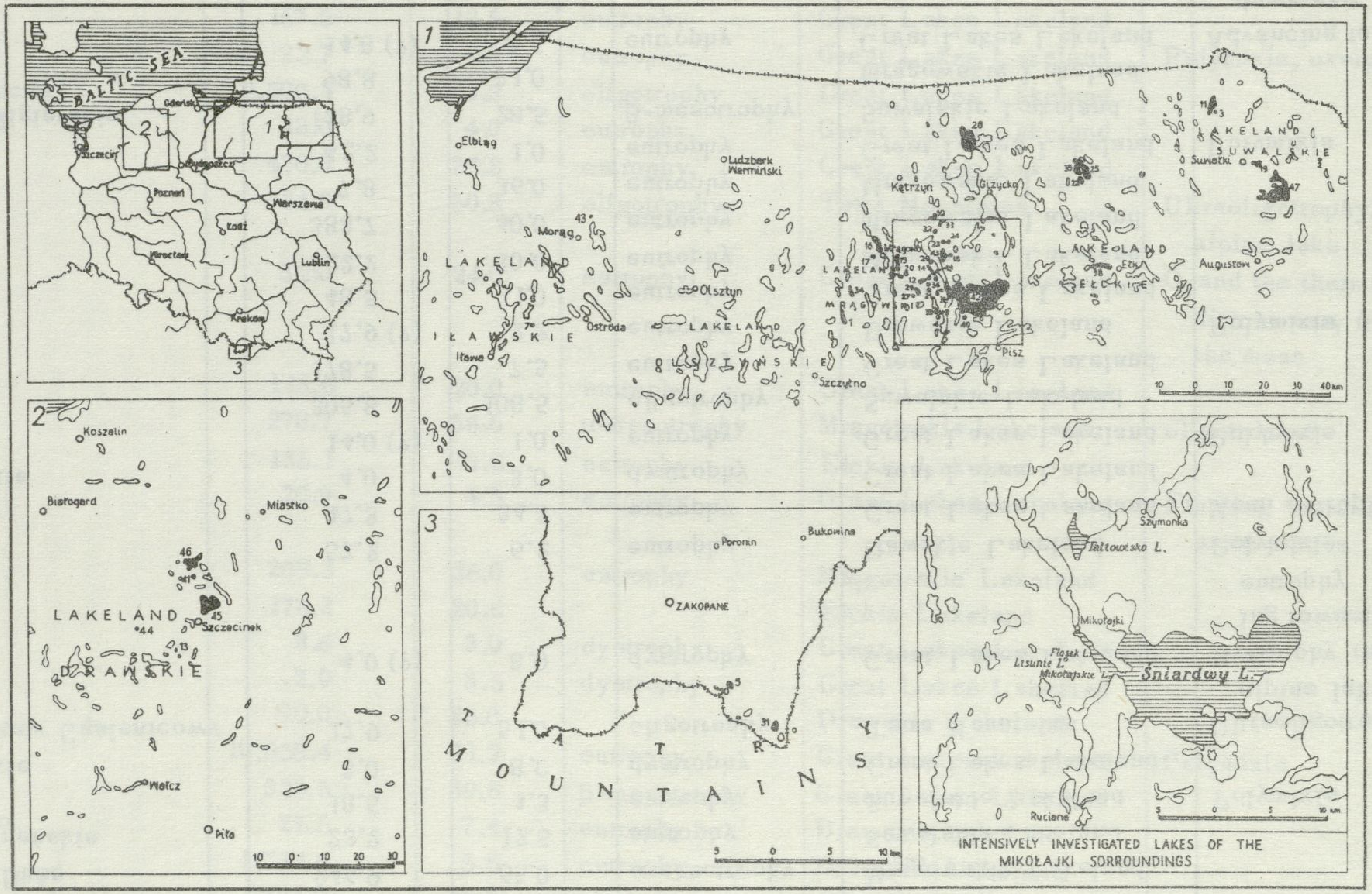

Fig. 1. Localization of investigated lakes

Numbers of lakes are the numbers given in Table I

Tab. I

The characteristic of investigated lakes

Nos.	Name of lake	Area (in ha)	Maximum depth (in m)	Trophic type	Location	Remarks
1	Babięty Duże	246.9	65.0	α-mesotrophy	Mrągowskie Lakeland	
2	Białe Sejneńskie	23.2	12.5	eutrophy	Suwalskie Lakeland	
3	Boczniel	18.5	4.3	eutrophy	Suwalskie Lakeland	Polymixis
4	Borkowskie	3.0	8.0	dystrophy	Great Lakes Lakeland	
5	Czarny Staw Gąsienicowy	17.9	51.0	oligotrophy	Tatra Mountains	Ultraoligotrophy, alpine lake
6	Flosek	4.0 (?)	8.0	dystrophy	Great Lakes Lakeland	Dystrophy regressing toward eutrophy
7	Gil Mały	57.2	6.2	eutrophy	Iławskie Lakeland	Polymixis
8	Głębokie	47.3	34.3	eutrophy	Great Lakes Lakeland	Mean eutrophy
9	Gryżewskie	4.0	3.0	dystrophy	Great Lakes Lakeland	
10	Guber	14.0 (?)	1.0	eutrophy	Great Lakes Lakeland	Polymixis
11	Hańcza	305.8	108.5	oligotrophy	Suwalskie Lakeland	
12	Inulec	178.5	7.5	eutrophy	Great Lakes Lakeland	
13	Jeleń	17.9 (?)	2.2	eutrophy	Drawskie Lakeland	Polymixis
14	Jorżec	48.5	11.0	eutrophy	Great Lakes Lakeland	
15	Juksty	322.2	30.0	eutrophy	Mrągowskie Lakeland	
16	Juno	383.7	40.0	eutrophy	Mrągowskie Lakeland	
17	Kociołek	7.8	36.0	eutrophy	Mrągowskie Lakeland	
18	Kotek	42.2	1.0	eutrophy	Great Lakes Lakeland	Polymixis
19	Krzywe Wigierskie	138.9	28.5	β-mesotrophy	Suwalskie Lakeland	
20	Kuc	98.8	31.0		Mrągowskie Lakeland	
21	Lisunie	14.8 (?)	8.5	eutrophy	Great Lakes Lakeland	Advancing toward dystrophy
22	Litygajno	172.5	17.5	eutrophy	Ełckie Lakeland	
23	Ławki Duże	78.8	17.0	eutrophy	Great Lakes Lakeland	

24	Ławki Małe	37.2	12.0	eutrophy	Great Lakes Lakeland	
25	Łaźno	562.4	18.0		Ełckie Lakeland	
26	Majcz Duży	167.5	13.5	eutrophy	Great Lakes Lakeland	
27	Majcz Mały	22.7	3.0	eutrophy	Great Lakes Lakeland	Polymixis, overgrown
28	Mamry Północne	2,500.4	43.8	oligotrophy	Great Lakes Lakeland	
29	Miałkie	18.0	4.0	eutrophy	Great Lakes Lakeland	
30	Mikołajskie	470.0	27.8	eutrophy	Great Lakes Lakeland	
31	Morskie Oko	34.9	50.8	oligotrophy	Tatra Mountains	Ultraoligotrophy, alpine lake
32	Ołów	52.0	24.0	eutrophy	Great Lakes Lakeland	O_2 and the thermic conditions vary from the mean
33	Orło	113.6	20.0	eutrophy	Great Lakes Lakeland	
34	Piłakno	278.7	56.6	α-mesotrophy	Mrągowskie Lakeland	oligotrophy?
35	Piłwąg	135.1	3.6	eutrophy	Ełckie Lakeland	
36	Płociczno	20.9	4.5	eutrophy	Great Lakes Lakeland	Floating shores in some places
37	Probarskie	209.3	36.0	eutrophy	Mrągowskie Lakeland	
38	Sunowo	176.3	20.6		Ełckie Lakeland	
39	Sęczek	3.6	3.0	dystrophy	Great Lakes Lakeland	
40	Smolaczek	2.0	5.5	dystrophy	Great Lakes Lakeland	
41	Studnica	90.0	23.0		Drawskie Lakeland	
42	Śniardwy	10,558.4	21.2	eutrophy	Great Lakes Lakeland	Polymixis
43	Tałtowisko	323.5	39.5	β-mesotrophy	Great Lakes Lakeland	
44	Trzebiechowo	27.5	7.4	eutrophy	Drawskie Lakeland	
45	Wielimie	1,754.6	5.5	eutrophy	Drawskie Lakeland	
46	Wierzchowo	731.0	26.5	eutrophy	Drawskie Lakeland	
47	Wigry	2,166.2	73.0	α-mesotrophy	Suwalskie Lakeland	
48	Wuksniki	125.0	66.5	oligotrophy	Iławskie Lakeland	
49	Zełwążek	12.1	7.4	eutrophy	Great Lakes Lakeland	
50	Zielony Staw Gąsienicowy	3.8	15.0	oligotrophy	Tatra Mountains	Ultraoligotrophy, alpine lake

The organic matter content in sediments was estimated by ashing in a muffle furnace. In the majority of published papers the percentage content of organic matter in dry weight is based on the annealing of sediments in a furnace. The temperature and time of annealing was optionally treated by various authors. Sediments are ashed most frequently in the temperature 400 to 650°C for one to several hours, and the loss on ignition is treated as a loss of organic matter (per cent of dry weight). Povoledo and Gerletti (1964) suggested ashing in 600°, 650° or 750°C. Such an optional procedure in determining the organic matter content causes that the results obtained by different authors should be carefully compared. Artificially low results can be obtained by ashing in too low temperature or in too short time. Destruction of calcium carbonate in too high temperature can result in an increase of loss on ignition. In such cases calcium carbonate can be regenerated by treating the ashed sample with water saturated with CO_2 and then drying it for the second time in 105°C. Ungemach (1960) analysed in detail the time of ashing of lake sediments. He found that during 1 hour of annealing of a sample in 550°C, 0.3% of $CaCO_3$ will be destructed, in 2 hours – 0.4%, in more than 4 hours – 0.6%. This destruction in temperature above 600°C is 2–3% in 1 hour and 10–20% in four hours. Ashing for 1 hour in about 550°C is known from recent American papers (Frey 1960, De Costa 1964, Mueller 1964). A temperature of 550°C was applied by Goulden (1964), 600°C – by Buscemi (1961). Ungemach (1960), quoted above, recommends ashing in 550°C for 2 hours. This temperature was used also by Stangenberg (1938) and Tadajewski (1956).

The temperature of ashing was established as 550°C and the time as 5 hours, on the basis of the above quoted Ungemach's investigations. In a shorter period of ashing (1–3 hr) a constant weight of samples was not obtained. Carbonates were not regenerated as the temperature applied did not cause considerable losses of these components[1]. Dry weight of samples was determined after drying to the constant weight in oven in 105°C.

The energy content of organic matter can be estimated by use of the calorimetry. This well known and described in handbooks method (Baranowski 1959, Vinberg 1960) is commonly used, e.g. to estimate the calorific value of animals and food components (Ivlev 1939, Richman 1958, Ostapenija and Sergeev 1963), but not much attention was paid to the calorific values of bottom sediments. In this paper energy values of sediments were determined with the help of a KL–3 type of calorimeter with water jacket.

Oxygen dissolved in water was determined by Winkler method. In order to estimate the oxygen consumption by bottom sediments the Warburg apparatus was used. This apparatus is commonly used to estimate the biological oxygen demand in sewage investigations (Kongiel-Chabło 1962, Kańska and Suchecka 1964) and recently also in investigations on the oxygen consumption rate of bottom sediments (Gardner and Lee 1965). A method of

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[1] Experiments with carbonates regeneration were not successful.

"gradient" tubes (Rybak 1966) was also applied, which allows to analyse the oxygen concentration changes in the water layer just above the sediment. Undisturbed samples of sediments, about 10 cm thick (having a natural structure, together with the near-bottom water layer[2], 18 cm thick) obtained with the help of tubular bottom sampler, were incubated in organic glass tubes in constant laboratory conditions. Samples of water for oxygen analyses were taken in 2 cm intervals by injection needless inserted through the walls of the "gradient" tubes, after the exposition period (24, 48 or 72 hr)

III. CHARACTERISTIC OF BOTTOM SEDIMENTS

1. The dependence on the trophic type

Despite the great number of papers dealing with the chemical composition of the bottom lake sediments, only few of them analyse the character of sediments in connection with the trophic type of the body of water. Classification of sediments, based on their chemical composition, allows to distinguish the type of sediment but generally it does not correlate with the trophic type of the lake (Stangenberg 1938). Organic matter content is the only component of all elements of chemical composition of sediments, which is connected with the degree of eutrophication of lakes. It is so, because the quantity of organic matter depends first of all on the production of pelagial, and only in a slight degree on the inflow from the outside of the lake.

Great differences in the quantity of organic matter in bottom sediments of various trophic types were often found (Kuznecov, Speranskaja and Konšin 1939, De Costa 1964). Stangenberg (1949) presents for several lakes of Suwalskie Lakeland, in dependence on their trophy, the following values: 16–25% (oligotrophy), 18–25% (mesotrophy) and 23–69% (eutrophy) of organic matter in dry weight of sediment. For peat-bogs this value was 88%. Deevey (1955) found on the basis of paleolimnological analysis of layers of bottom sediments that the organic matter content increases with an increase of the degree of eutrophication of the lake.

Calcium found in the sediments in the form of carbonate can be percipitated from water, carried down from the drainage basin, or deposited by infows. The occurrence of calcium in the sediments of lakes of various trophy was analysed by many scientists dealing with the chemical composition of bottom sediments. Klust and Mann (1963) tried to find a connection between the rate of cellulose fiber decomposition in lakes with a different degree of eutrophication and the occurrence of calcium. Hansen (1959a, 1959b, 1961) divid-

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[2] In the stagnation period when the near-bottom water was deoxygenated, it was exchanged by water of a greater and known oxygen content.

ed the sediments of investigated lakes, mainly on the basis of calcium occurrence and showed that gyttia type of sediments from oligotrophic lakes contain greater quantities of this component than sediments of eutrophic lakes. The analysis of calcium occurrence made by Stangenberg (1938) for the sediments of Suwalskie Lakeland showed, however, that calcium can occur in great quantities in the sediments of eutrophic and oligotrophic lakes as well. The problem of differences of calcium quantities in sediments of lakes of various trophy is not then sloved.

The content of organic matter and calcium, and the energetic values of sediments from the profundal of lakes were analysed in this paper in connection with the trophic types of lakes. Investigations showed that the organic matter content ranges from 11 to 83% in dry weight (Fig. 2). The majority of investigated lakes (eutrophic) have in their surface layer (5 cm) of bottom

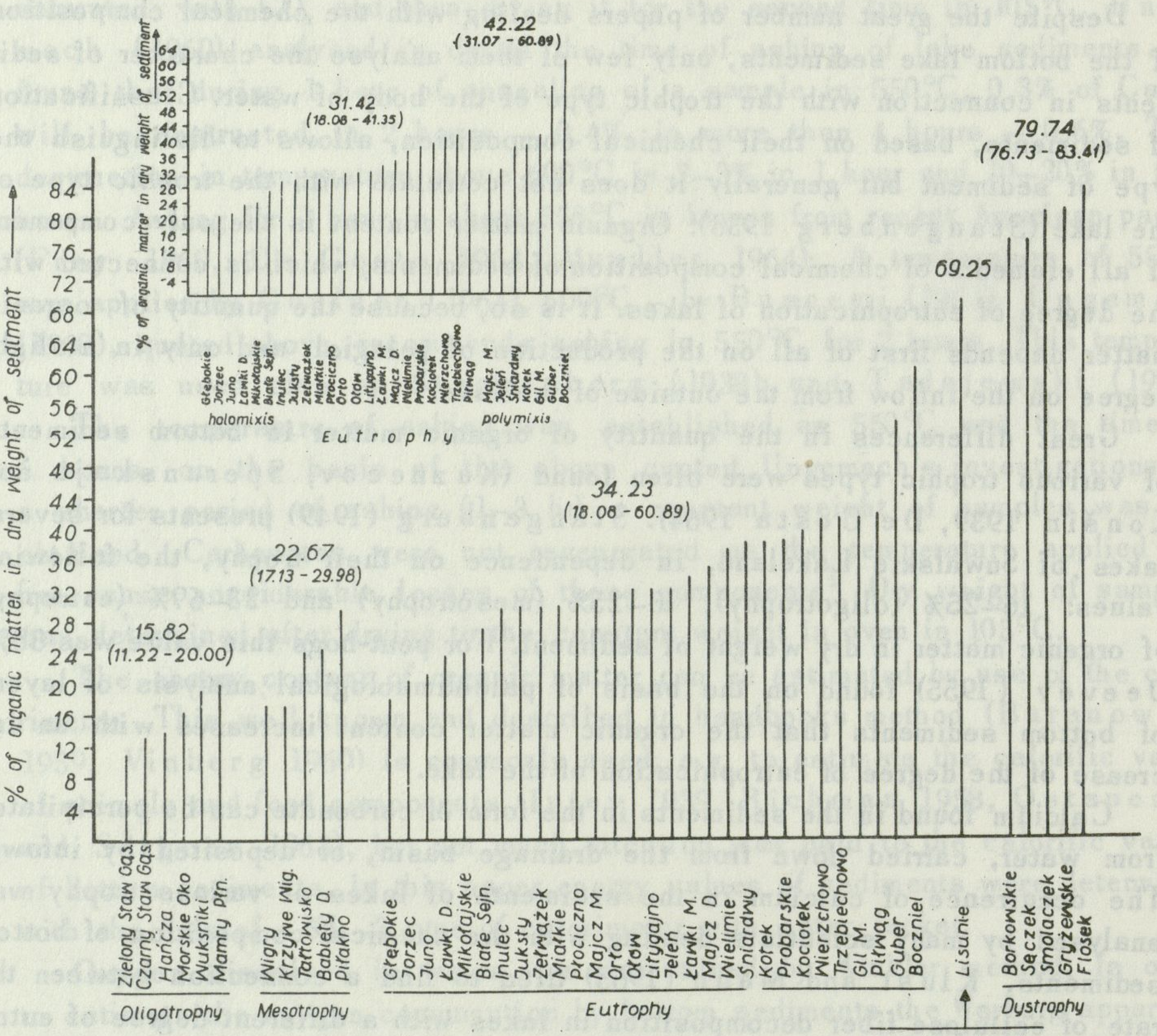

Fig. 2. Organic matter content in bottom sediments of lakes of various trophic types

sediments 18–60% of organic matter. Distinguished trophic types of investigated lakes showed significant differences in the content of organic matter in sediments. Individual lakes within a trophic type showed considerable variations of this value, but the mean value was always higher than the highest value for lakes having lower organic matter content. Average values for all trophic types formed a sequence increasing with the advance of trophic type. The lowest organic matter content was found in sediments of dystrophic lakes.

Measurements of calorific values of sediments were done paralelly with the estimations of their organic matter content (Fig. 3 and 4). These values

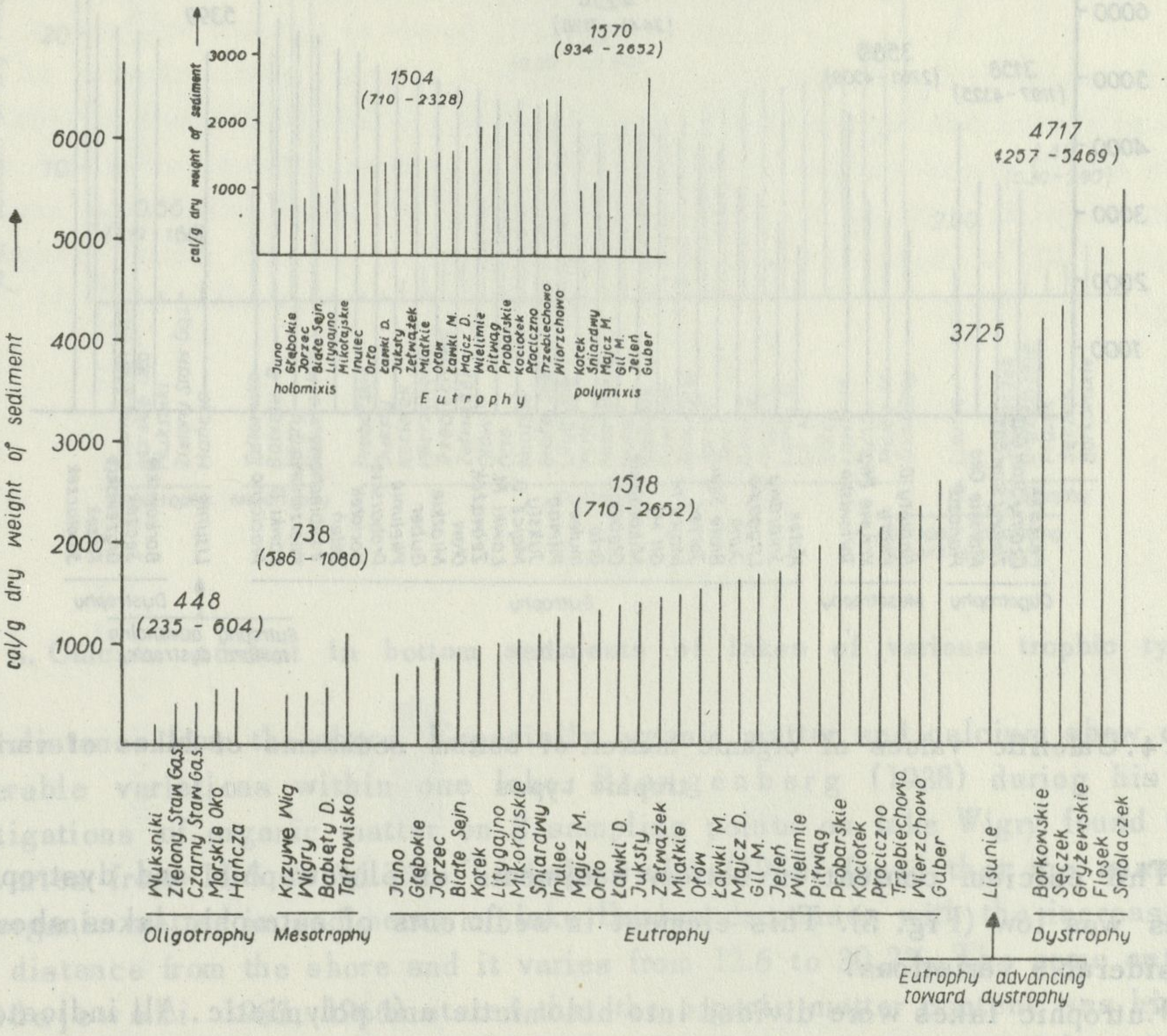

Fig. 3. Calorific values of bottom sediments of lakes of various trophic types

(cal/g dry weight) were within the limits of 700 to 2600 cal for the majority of investigated lakes (eutrophic ones), and their calorific value of organic matter ranged from 2400 to 7200 cal/g. The increase of these both values was observed with an advance of trophy, analogically like for organic matter. Dystrophic lakes were characterized by the highest calorific values (especially expressed per dry weight).

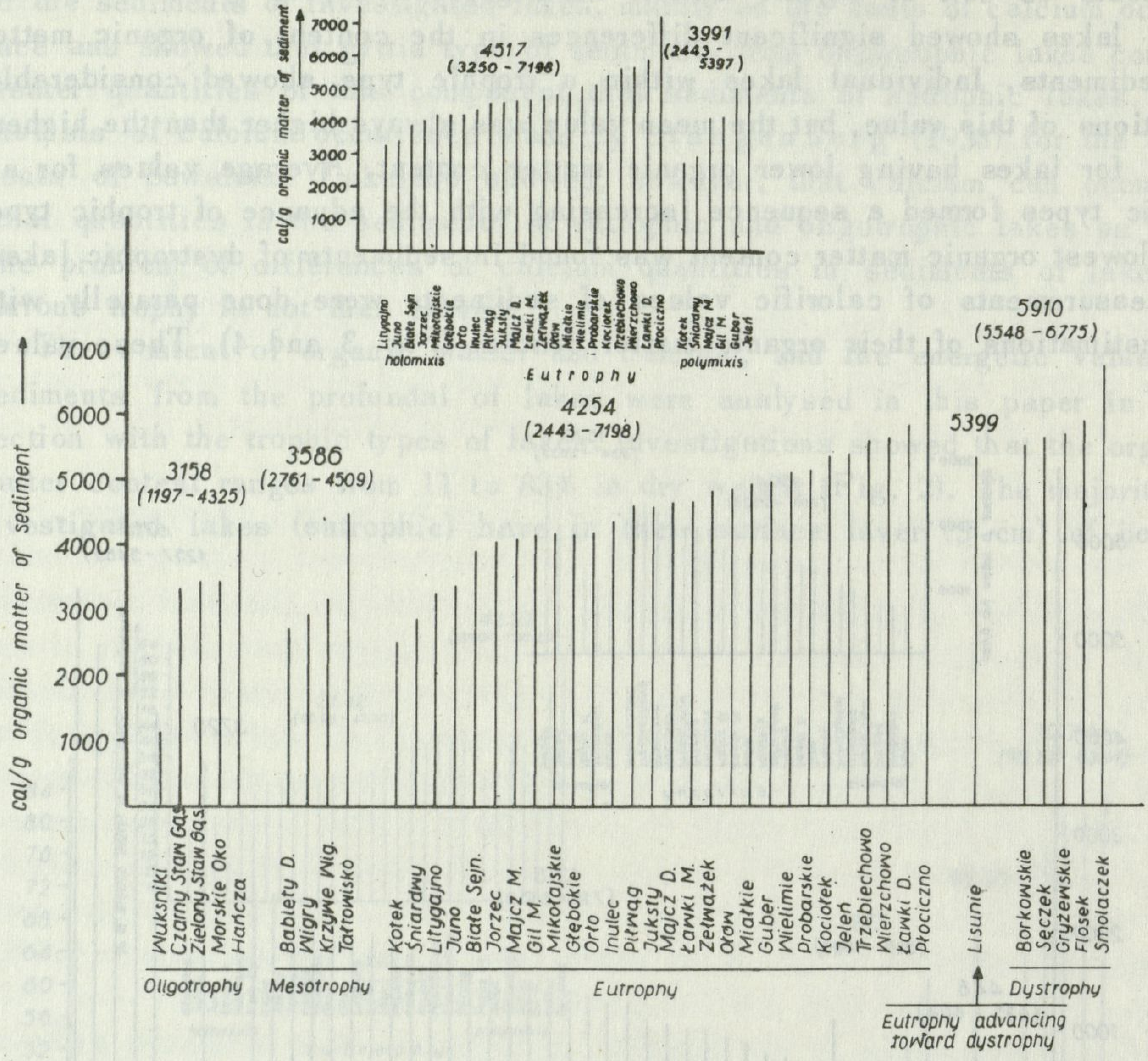

Fig. 4. Calorific values of organic matter of bottom sediments of lakes of various trophic types

The calcium content in bottom sediments of oligotrophic and dystrophic lakes was low (Fig. 5). This element in sediments of eutrophic lakes showed considerable variations.

Eutrophic lakes were divided into holomictic and polymictic. All indicators, except for the calorific value of organic matter, were on average higher in polymictic lakes (Fig. 2–5).

2. Differentiations within a lake

a. Spatial differentiations of bottom sediments

The chemical composition, consistence and colour of sediments are not the same within one lake (Wilson and Opdyke 1941). The differences in content of various substances, among others can be connected with the depth

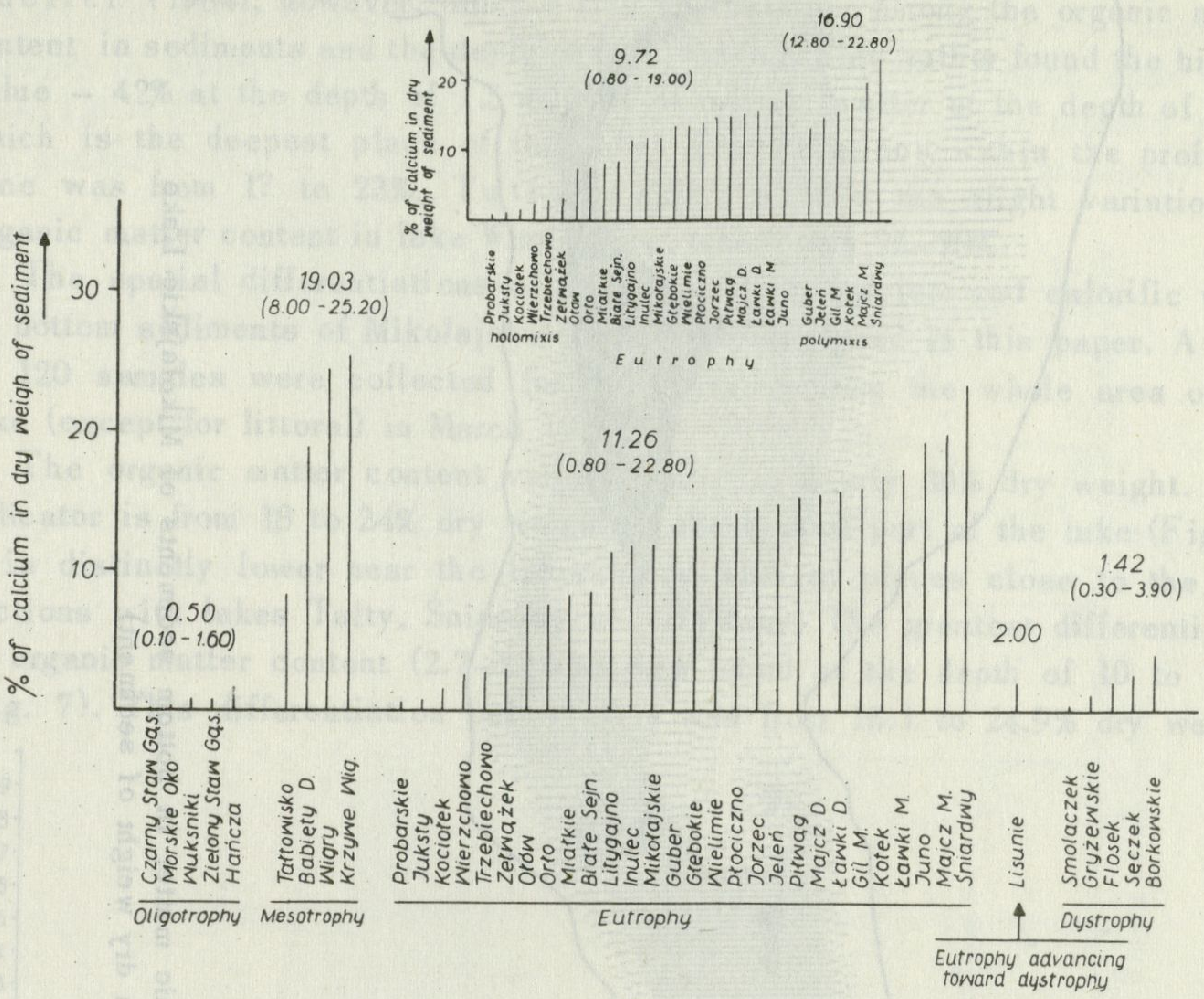

Fig. 5. Calcium content in bottom sediments of lakes of various trophic types

and distance from the shore. Especially organic matter and calcium show considerable variations within one lake. Stangenberg (1938) during his investigations of organic matter on 8 sampling points on lake Wigry found that it varies from 11.5 to 36.7%. Tadajewski (1956) found that the quantity of organic matter in sediments of lake Drużno decreases with the increase of the distance from the shore and it varies from 12.6 to 30.2%. The same author (Tadajewski 1965, 1966) stated that the organic matter content was higher in profundal than in the littoral of Kortowskie Lake, and it varied from 15 to 30% in the open lake area. Investigations of Entz, Ponyi and Tamás (1963) carried out in lake Balaton showed that the organic matter content in dry weight of sediments was 42% on average for the inshore parts (reed stands), and 7% (on average) for the central part of the lake. On the basis of material collected from over 100 sampling stations on Charzykowskie Lake (Stangenberg and Żemoytel 1952) it was found that the content of organic substances varied from 1.3 to 39.8% dry weight, while the most frequent results were 25–30 % on the whole bottom area of this lake. The littoral in this lake (less than 5 m deep) contained smaller quantities of organic compounds than the

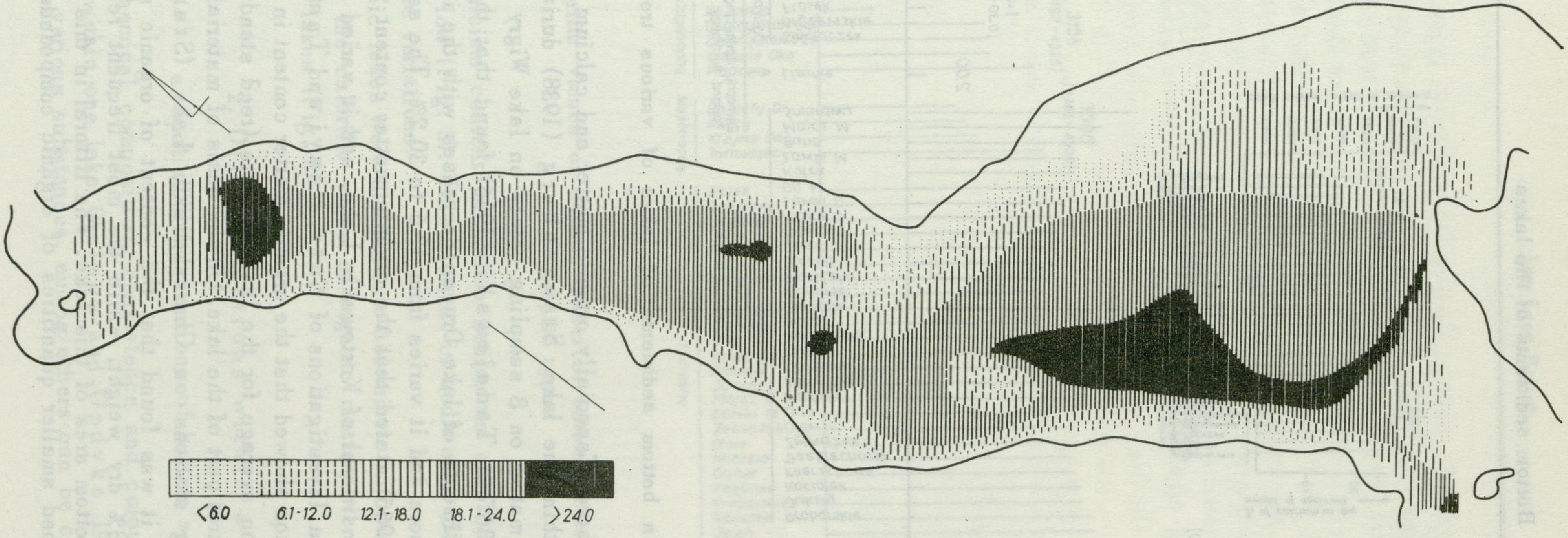

Fig. 6. The distribution of organic matter in bottom sediments of Mikołajskie Lake (% in dry weight of sediment)

central parts of the lake. Similar observations were made by Izjurova (1960). Mueller (1964), however, did not find any relation among the organic matter content in sediments and the depth of lake Winona. This author found the highest value – 42% at the depth of 1.5 m, 17% of organic matter at the depth of 24 m, which is the deepest place of the lake. The variations within the profundal zone was from 17 to 23%. Tutin (1955) described the slight variations of organic matter content in lake Windermere, which was 25–28%.

The spatial differentiations of organic matter, calcium and calorific value of bottom sediments of Mikołajskie Lake were analysed in this paper. A total of 120 samples were collected for this purpose from the whole area of the lake (except for littoral) in March 1965.

The organic matter content varied from 2 to nearly 30% dry weight. This indicator is from 18 to 24% dry weight in the central part of the lake (Fig. 6). It is distinctly lower near the littoral and also in places close to the connections with lakes Tałty, Śniardwy and Bełdany. The greatest differentiation of organic matter content (2.2–29.8%) was found at the depth of 10 to 14 m (Fig. 7). This differentiation below 14 m was from 15.1 to 24.9% dry weight.

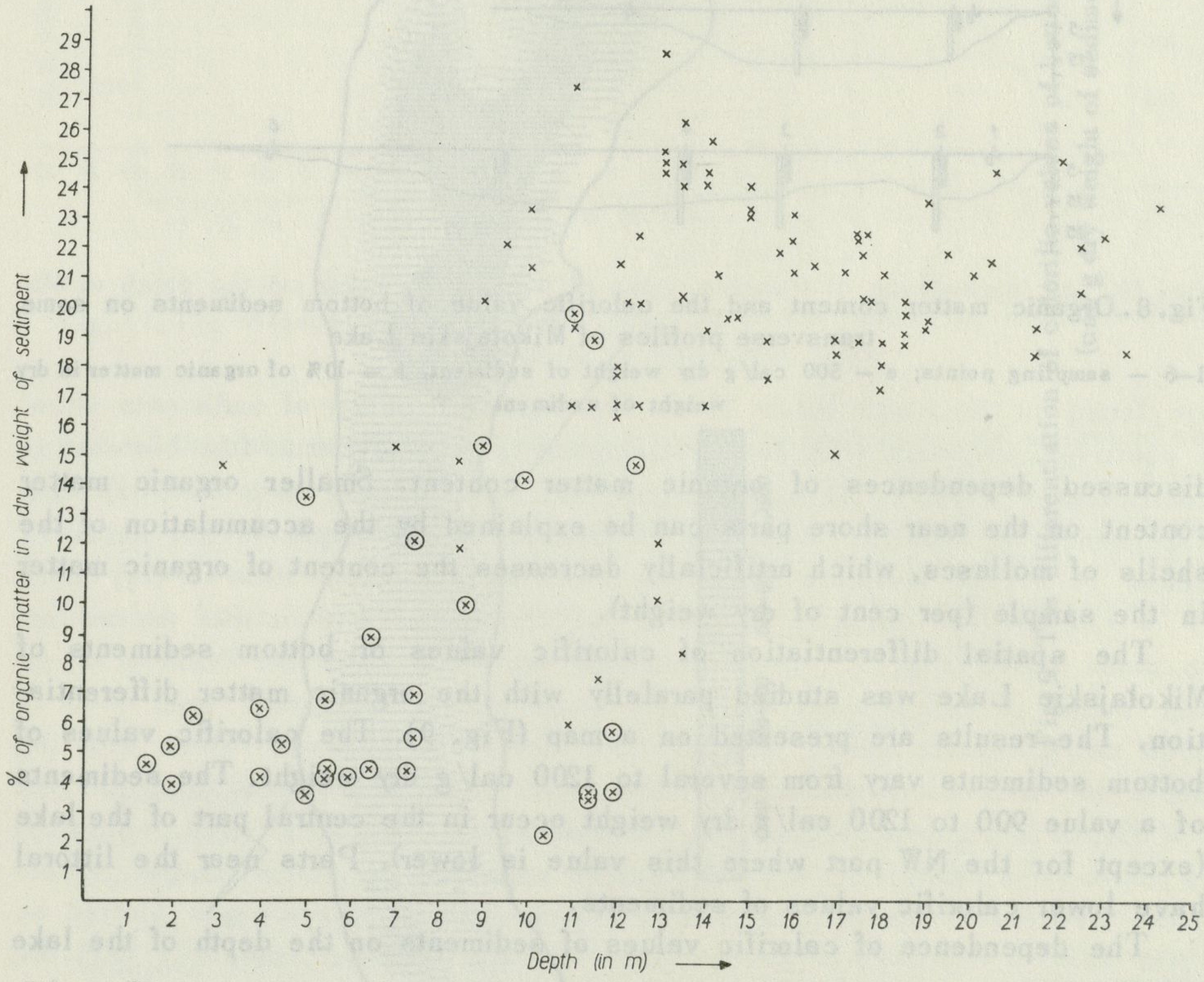

Fig. 7. The dependence of organic matter content in sediments on the depth of Mikołajskie Lake

Shells are indicated by circles

Organic matter content showed a positive correlation with depth (correlation coefficient $r = 0.6265$ is highly significant for the level of $a = 0.001$) in the depth zone down to 14 m. There is only a small differentiation of organic matter content below the depth of 14 m (variation coefficient $V = 0.1150$)[3]. Some transects of the lake shown as an example on Figure 8, illustrate the discussed dependences of organic matter content. Smaller organic matter content on the near shore parts can be explained by the accumulation of the shells of molluscs, which artificially decreases the content of organic matter in the sample (per cent of dry weight).

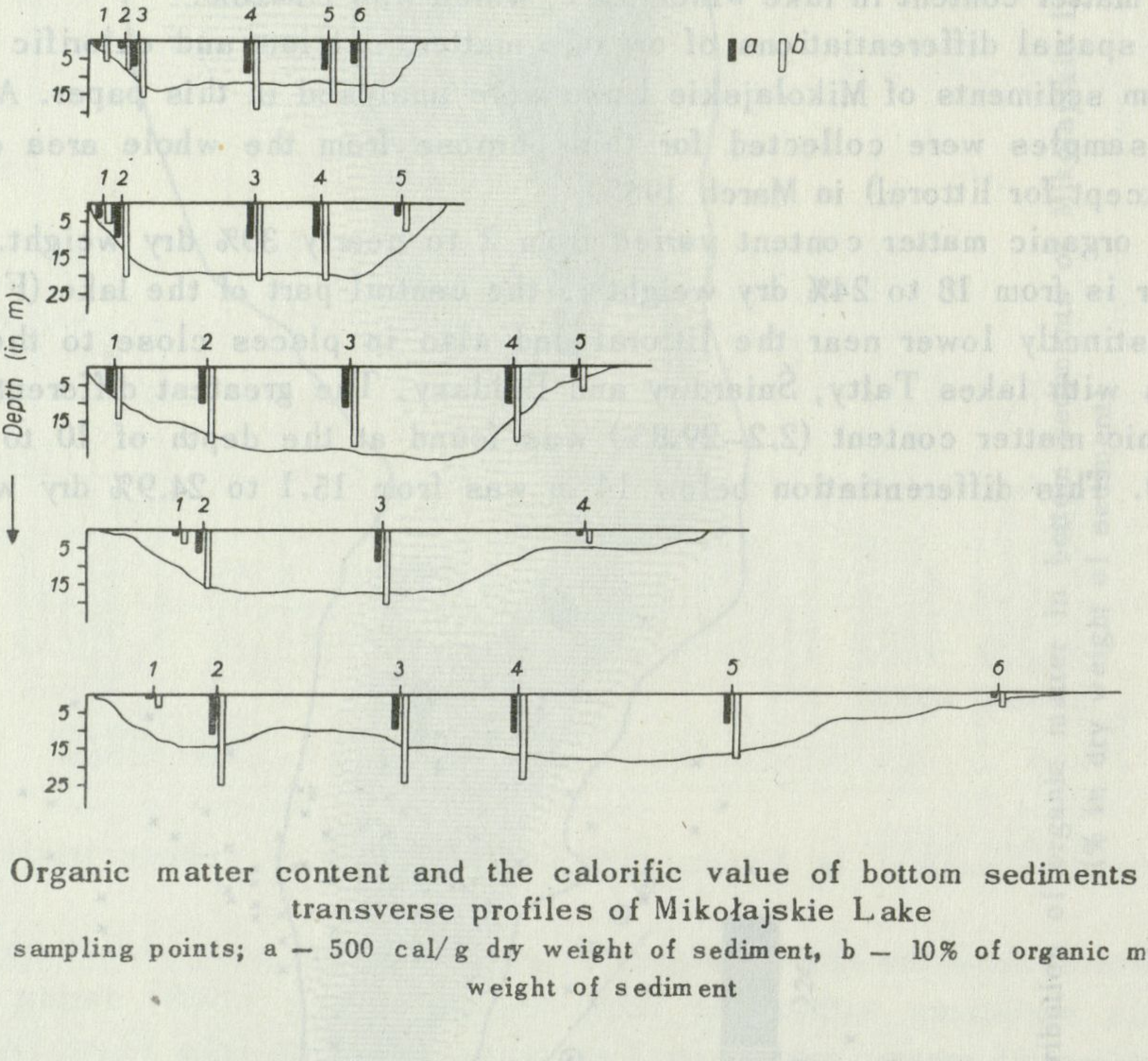

Fig. 8. Organic matter content and the calorific value of bottom sediments on some transverse profiles of Mikołajskie Lake

1–6 – sampling points; a – 500 cal/g dry weight of sediment, b – 10% of organic matter in dry weight of sediment

The spatial differentiation of calorific values of bottom sediments of Mikołajskie Lake was studied paralelly with the organic matter differentiation. The results are presented on a map (Fig. 9). The calorific values of bottom sediments vary from several to 1200 cal/g dry weight. The sediments of a value 900 to 1200 cal/g dry weight occur in the central part of the lake (except for the NW part where this value is lower). Parts near the littoral have lower calorific values of sediments.

The dependence of calorific values of sediments on the depth of the lake

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[3] The variation coefficient was calculated according to the equation: $V = \frac{\sigma}{\bar{x}}$, where σ – standard deviation, $\bar{x}$ – mean.

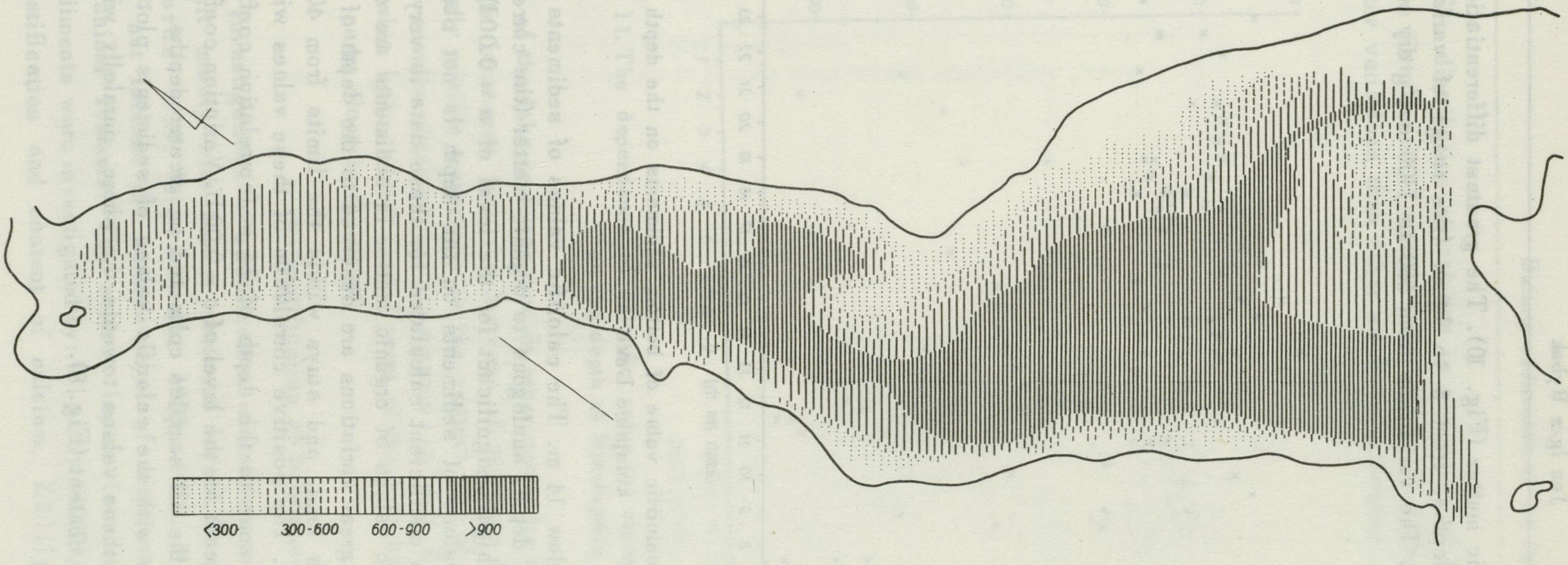

Fig. 9. The differentiation of calorific values of bottom sediments of Mikołajskie Lake (cal/g dry weight of sediment)

is similar to that of organic matter (Fig. 10). The greatest differentiation is observed on the middle depths, from 8 to 14 m (the range of variations 20–1170 cal/g dry weight). The variations from 680 to 1100 cal/g dry weight

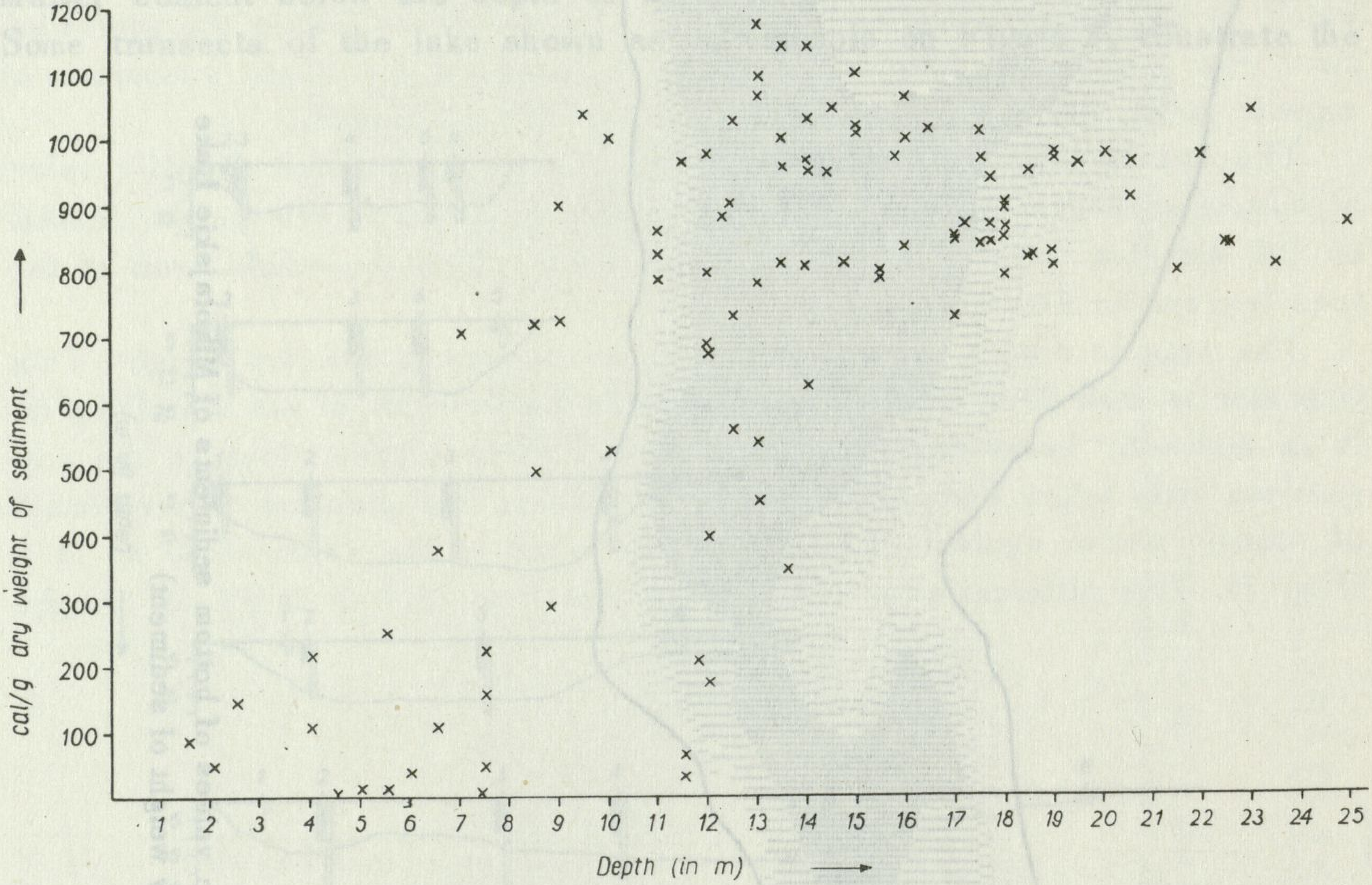

Fig. 10. The dependence of calorific value of bottom sediments on the depth of Mikołajskie Lake

are found on the depth below 14 m. The calorific values of sediments show a positive correlation with depth, analogous to organic matter (the correlation coefficient $r = 0.6825$ is highly significant for the level of $a = 0.001$). The dependence of calorific values of sediments on the depth is not observed below 14 m. The variation coefficient calculated for these data is very little ($V = 0.0815$). The calorific values of organic matter in sediments are similar to these above (Fig. 11); great variations are observed to the depth of 14 m, and below it varies much less, and stays within the limits from 4000 to 5000 cal/g organic matter. The positive correlation of these values with the depth is observed in the zone to the depth of 14 m (correlation coefficient $r = 0.8705$ is highly significant for the level of $a = 0.001$). Variation coefficient is little ($V = 0.0710$) for the all samples collected on greater depths. Transverse profiles of the lake with the calorific values of sediments plotted on them show a decrease of these values towards the shore, paralelly with the decrease of organic matter content (Fig. 8).

The distribution of calcium in sediments of Mikołajskie Lake is similar to the distribution of organic matter (Fig. 12). Calcium content shows, however, greater variations than other analysed indicators. The calcium content in NW part of the lake is lower than in other parts. Its content in dry weight of sediments increases with the increase of distance from the shore. This fact is clearly visible especially in the central part of the lake. It is in reverse to the results obtained by Stangenberg and Żemoytel (1952) in Charzykowskie Lake, where central parts of the lake had lower calcium content than the parts close to the shore.

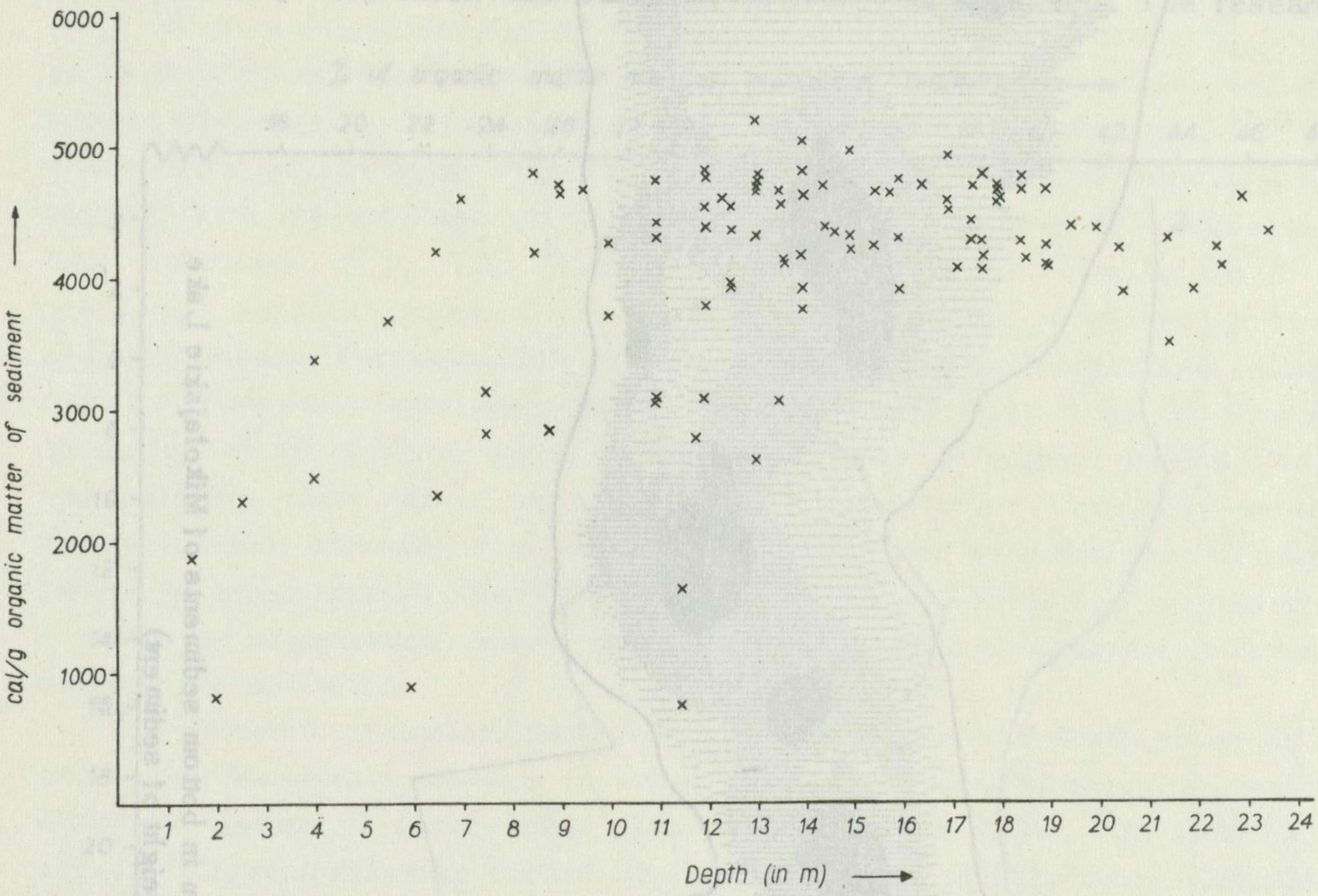

Fig. 11. The dependence of calorific value of organic matter in bottom sediments on the depth of Mikołajskie Lake

b. Stratification of bottom sediments

Investigations of stratification of various substances in bottom sediments dealt mainly with bottom sediment layers from several to over ten meters (Korde 1959, Więckowski 1963, 1966, Mackereth 1965), and often did not include the surface layer of sediments of several centimetres for technical reasons. The surface layers (several scores of centimetres) of sediments were investigated by: Nipkov (1920), who described the appearance, stratification and content of calcium, Züllig (1956), who analysed the

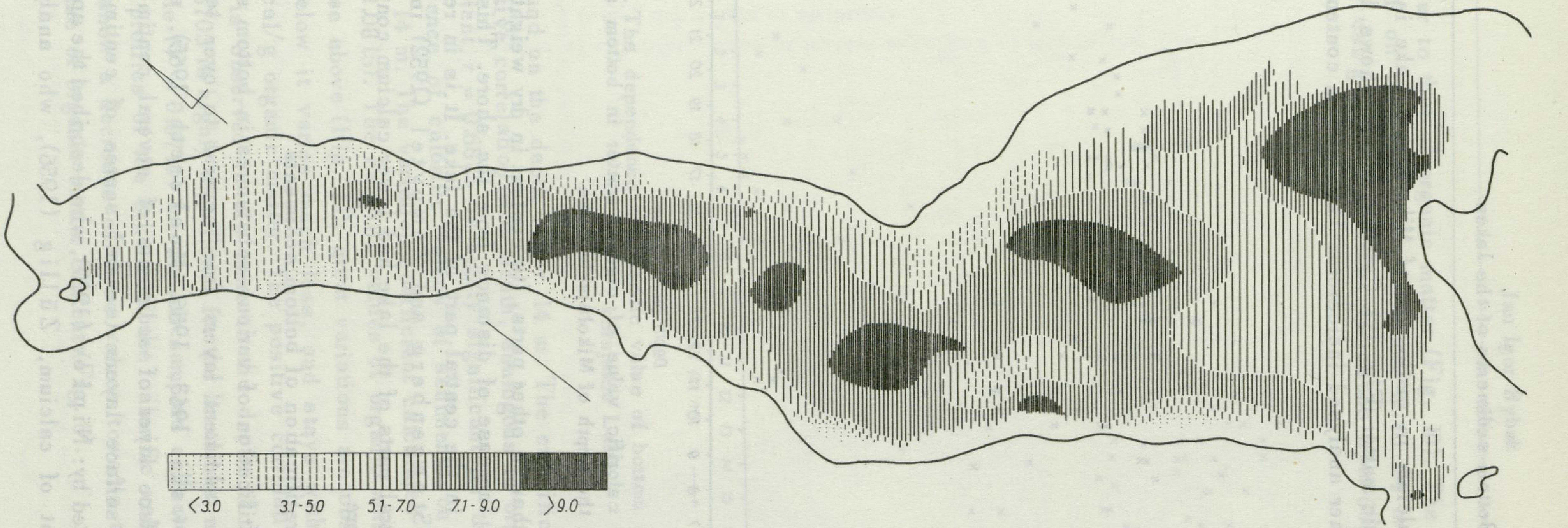

Fig. 12. The distribution of calcium in bottom sediments of Mikołajskie Lake
(% in dry weight of sediment)

occurence of calcium, and **Semenovič** (1966), who described the consistence and colour of successive layers of sediments of lake Ladoga.

Vertical stratification of organic matter, calcium and calorific value of bottom sediments were investigated in this paper. The layer of sediments to the depth of 50 cm below the sediment surface was analysed. The research

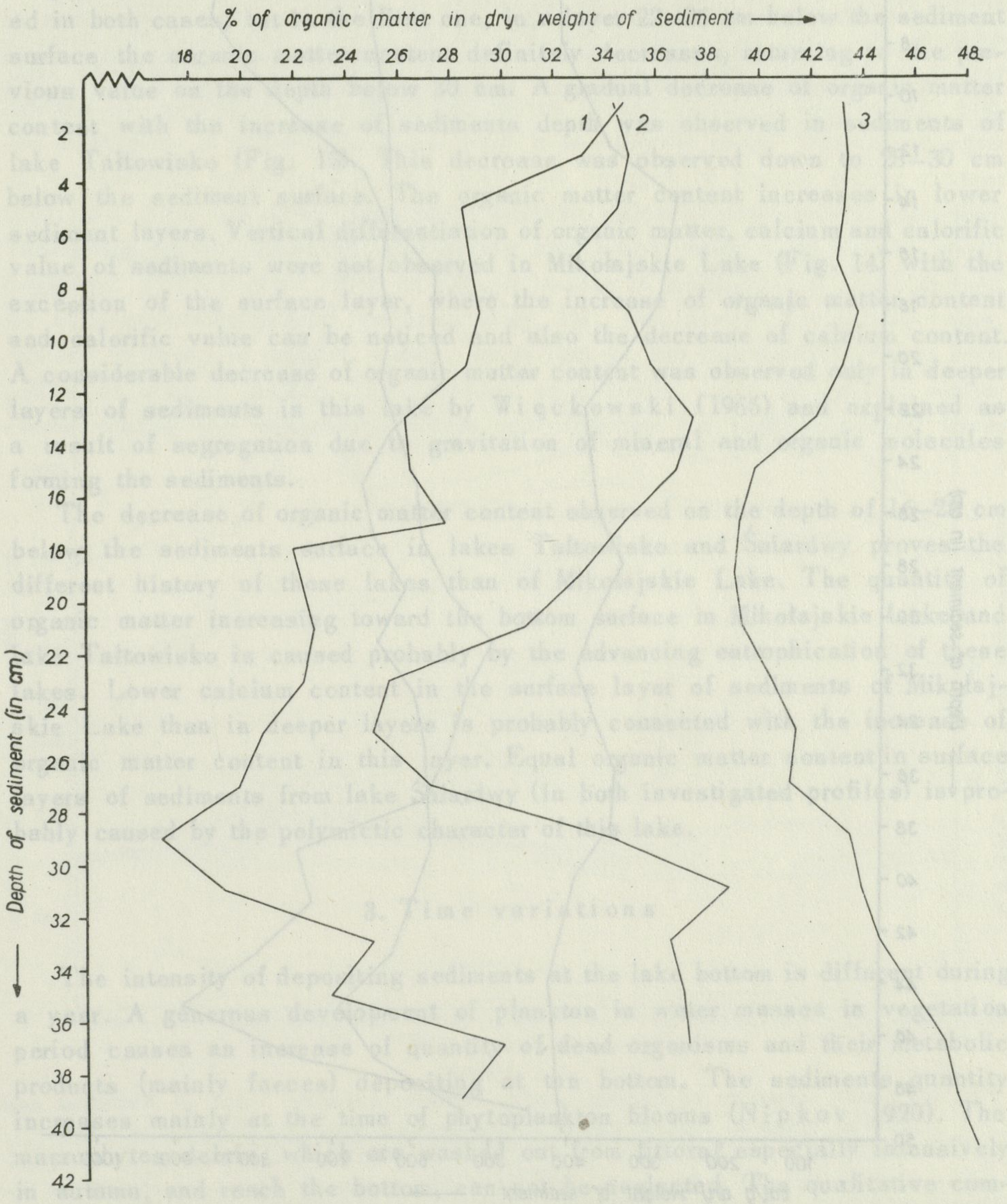

Fig. 13. The vertical differentiation of organic matter content in bottom sediments
1 – lake Tałtowisko (38 m), *2* – lake Śniardwy (17 m), *3* – lake Śniardwy (7 m)

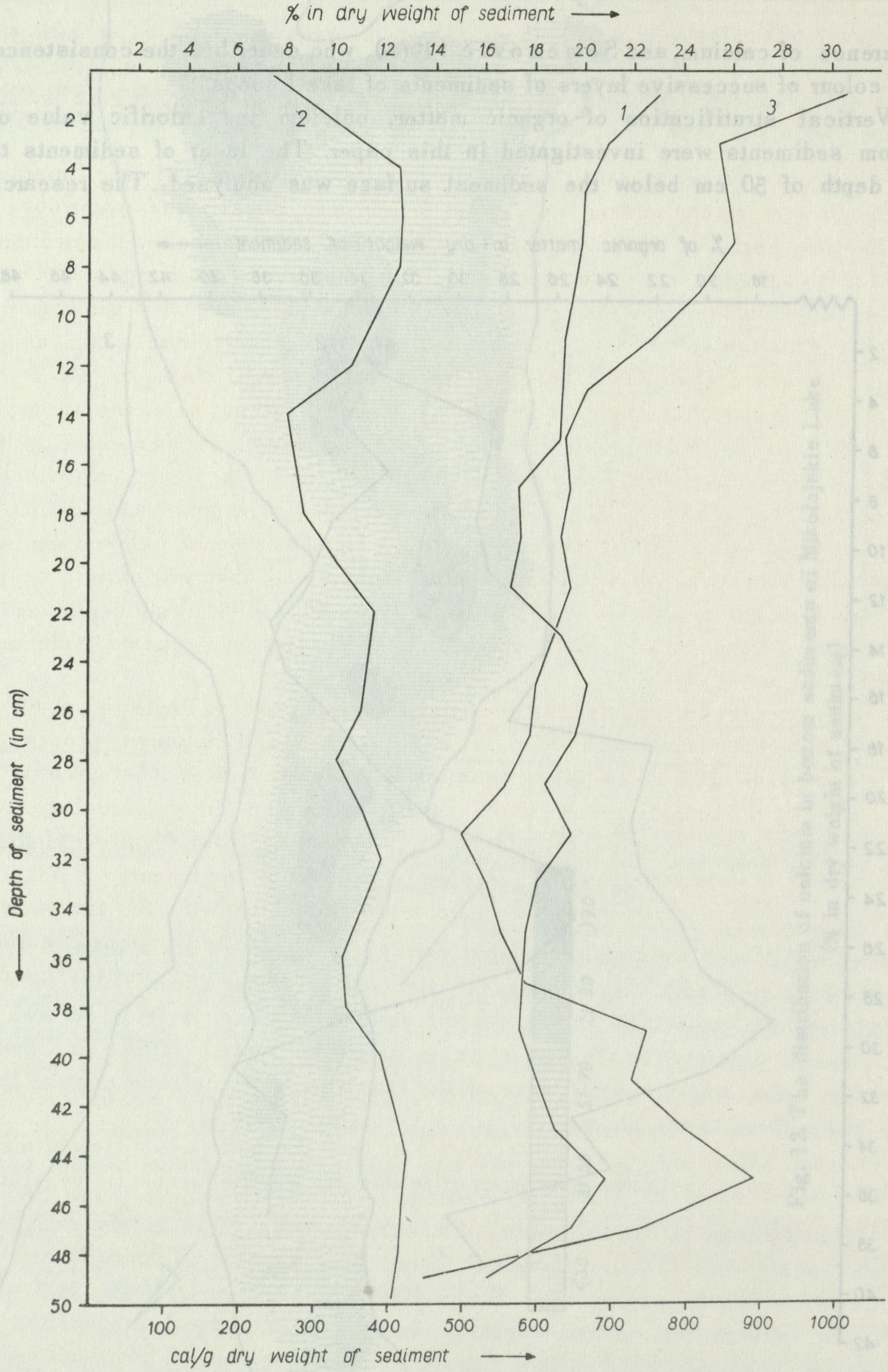

Fig. 14. The vertical differentiation of organic matter content (1), calcium (2) and calorific value of sediment (3) in the deepest place of Mikołajskie Lake

was carried out in Mikołajskie Lake (organic matter, calcium and calorific values) and in lakes Tałtowisko and Śniardwy (organic matter). Samples were collected with the help of a tubular bottom sampler of a surface of 50 cm^2 allowing to analyse the subsequent layers 2 cm thick.

Changes of organic matter content in the vertical profile of lake Śniardwy (Fig. 13) were determined on two depths: 17 and 7 m. Equal values were observed in both cases, but in the first one, in a layer 22–26 cm below the sediment surface the organic matter content definitely decreases, returning to the previous value on the depth below 30 cm. A gradual decrease of organic matter content with the increase of sediments depth was observed in sediments of lake Tałtowisko (Fig. 13). This decrease was observed down to 28–30 cm below the sediment surface. The organic matter content increases in lower sediment layers. Vertical differentiation of organic matter, calcium and calorific value of sediments were not observed in Mikołajskie Lake (Fig. 14) with the exception of the surface layer, where the increase of organic matter content and calorific value can be noticed and also the decrease of calcium content. A considerable decrease of organic matter content was observed only in deeper layers of sediments in this lake by Więckowski (1966) and explained as a result of segregation due to gravitation of mineral and organic molecules forming the sediments.

The decrease of organic matter content observed on the depth of 16–28 cm below the sediments surface in lakes Tałtowisko and Śniardwy proves the different history of these lakes than of Mikołajskie Lake. The quantity of organic matter increasing toward the bottom surface in Mikołajskie Lake and lake Tałtowisko is caused probably by the advancing eutrophication of these lakes. Lower calcium content in the surface layer of sediments of Mikołajskie Lake than in deeper layers is probably connected with the increase of organic matter content in this layer. Equal organic matter content in surface layers of sediments from lake Śniardwy (in both investigated profiles) is probably caused by the polymictic character of this lake.

3. Time variations

The intensity of depositing sediments at the lake bottom is different during a year. A generous development of plankton in water masses in vegetation period causes an increase of quantity of dead organisms and their metabolic products (mainly faeces) depositing at the bottom. The sediments quantity increases mainly at the time of phytoplankton blooms (Nipkov 1920). The macrophytes debris, which are washed out from littoral especially intensively in autumn, and reach the bottom, can not be neglected. The qualitative composition of plankton developing during a year is very important in forming the surface layer of sediments. Different quantities and composition of substances depositing at the bottom should be reflected on the organic matter content of sediments and on their calorific value. Biological decalcification is especially intense during the increased photosynthesis process and has then a considerable influence on the chemical composition of surface sediments layers (Stangenberg and others 1957) formed at that time.

The mineralization processes, that are changeable during a year, have, apart from the above mentioned factors, an influence on the composition of bottom sediments. These processes are strictly dependent on the oxygen content in water and temperature. These both factors are greatly variable within a year in our climate.

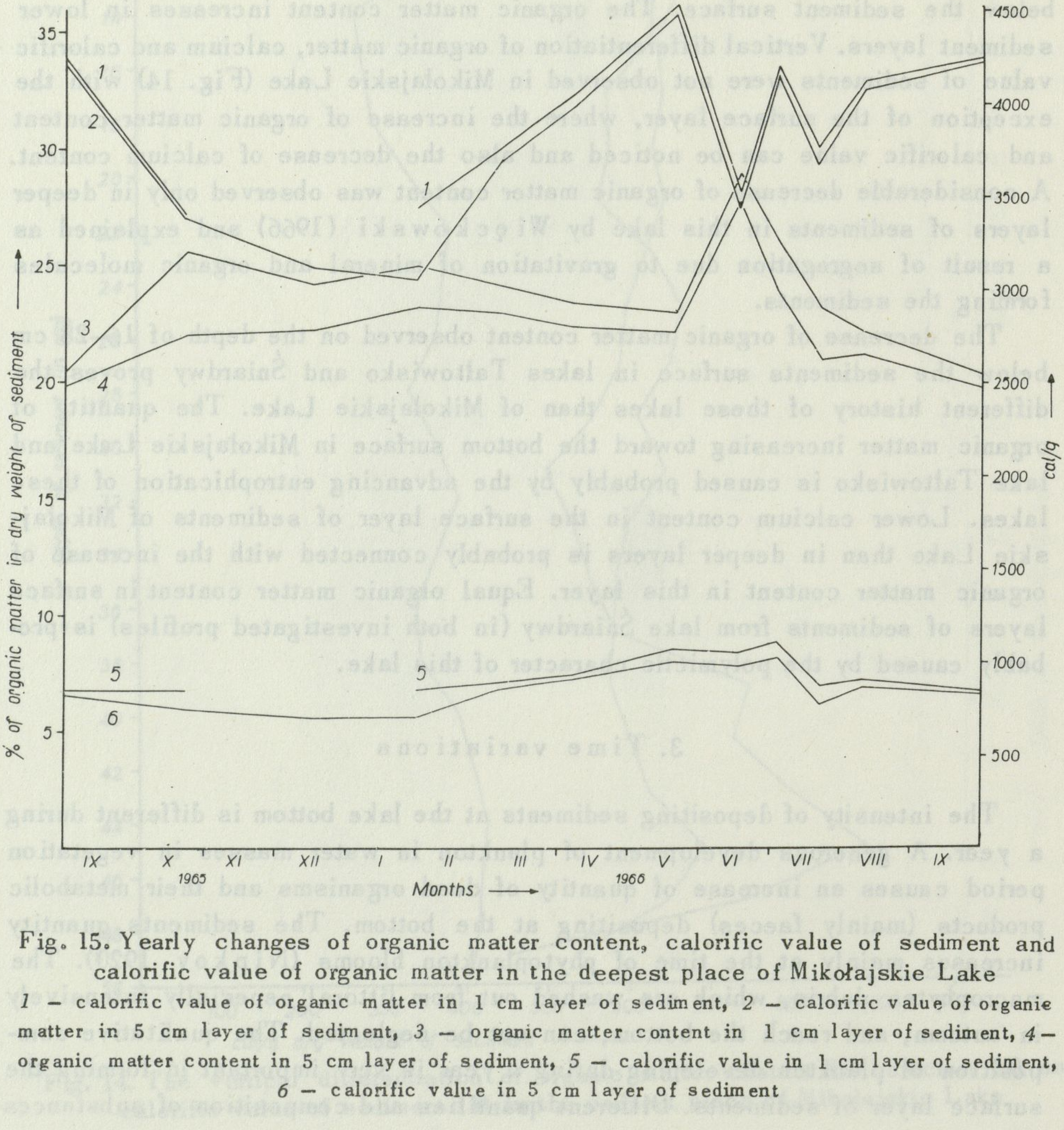

Fig. 15. Yearly changes of organic matter content, calorific value of sediment and calorific value of organic matter in the deepest place of Mikołajskie Lake

1 – calorific value of organic matter in 1 cm layer of sediment, *2* – calorific value of organic matter in 5 cm layer of sediment, *3* – organic matter content in 1 cm layer of sediment, *4* – organic matter content in 5 cm layer of sediment, *5* – calorific value in 1 cm layer of sediment, *6* – calorific value in 5 cm layer of sediment

The time variations of the organic matter content and of calorific value of the surface layer of sediments were analysed in the deepest place of Mikołajskie Lake in the years 1965 and 1966. One and five cm layers of sediments were analysed every 4–6 weeks. An analysis of calcium content in sediments of 5 lakes (with various trophy) from the surroundings of Mikołajki were also made.

The organic matter content in sediments of Mikołajskie Lake shows during a year variations from nearly 20 to 29% dry weight (Fig. 15). Two maxima were observed: first in June and the second one in October. The organic matter content is similar in both analysed layers (1 and 5 cm of sediments), with the exception of autumn (in 5 cm layer it is slightly lower). Annual changes of the calorific value do not correspond with changes of organic matter content (Fig. 15). Slow and even increase of calorific value of sediments is observed during the winter stagnation and spring circulation, later – an equally small decrease. The calorific value of organic matter in sediments is characterized by a considerably greater variation (Fig. 15). Two peaks of calorific value, similar to these of organic matter, occur, but do not correspond in time with peaks of organic matter. The increase of calorific value of organic matter starts during the winter stagnation and reaches its highest values (over

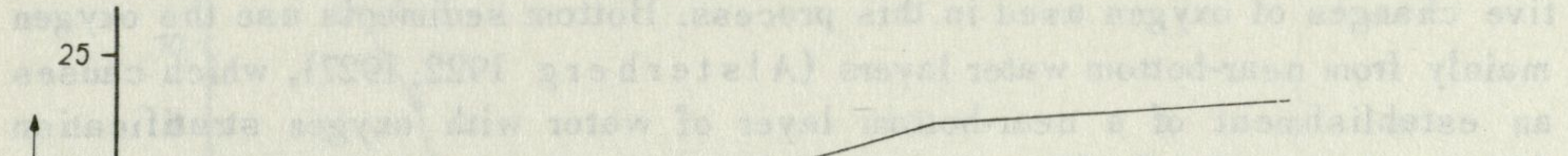

Fig. 16. Yearly changes of calcium content in bottom sediments of lakes of various trophic types

1 – mesotrophy (lake Tałtowisko), *2* – eutrophy (Mikołajskie Lake), *3* – eutrophy-polymixis (lake Śniardwy), *4* – eutrophy advancing toward dystrophy (lake Lisunie), *5* – dystrophy (lake Flosek)

4500 cal/g organic matter) at the end of stagnation. The second increase of calorific value of sediments is observed during the summer stagnation. The increase of calorific value of organic matter in the time of both stagnations is probably due to the intensive reduction processes (oxygen depletion near the bottom), and it can be connected with the different composition of tripton depositing on the lake bottom during the year (Ławacz 1967).

The calcium content in sediments of lakes of various trophic types is almost equal in all seasons (Fig. 16). In mesotrophic, eutrophic and holomictic, and in eutrophic and polymictic lakes a small increase of calcium content was observed at the end of summer stagnation, or even at its beginning (Śniardwy and Tałtowisko), i.e. in the period of intensive photosynthesis processes.

IV. THE PROCESSES IN BOTTOM SEDIMENTS

1. Oxygen consumption as an indicator of mineralization

The mineralization, process with the participation of oxygen dissolved in water, enables the return of many substances from sediments to water masses (Semenovič 1957), and is an important factor influencing the productivity of water bodies. One of the results of mineralization are the quantitative changes of oxygen used in this process. Bottom sediments use the oxygen mainly from near-bottom water layers (Alsterberg 1922, 1927), which causes an establishment of a near-bottom layer of water with oxygen stratification (Alsterberg 1935). The oxygen depletion in the near-bottom water layers was observed several times in many eutrophic lakes having sediments rich in organic matter. It was also observed in oligotrophic lakes (Brundin 1951) and in the sea (Brouardel and Fage 1955).

Measurements of biological oxygen demand, commonly used in investigation of sewage waters, are the most often used method to estimate the oxygen consumption of bottom sediments in laboratory. This method is suggested by Caspers (1962) who recommends BOD–1. The Warburg apparatus can be also applied for this estimation (Kańska and Suchecka 1964). In these both methods the natural structure of sediments is destroyed (sediments are mixed during the incubation period).

A method of analysing the oxygen consumption by bottom sediments in natural conditions was originally presented by Gambarjan (1952). It depends on lowering to the bottom a cylinder for sampling the bottom and near to it water layer. A quantity of oxygen left in water after the period of exposure can be measured. This method does not, however, take into consideration the magnitude of oxygen gradient in the near-bottom water layer. The oxygen depletion thanks to the known negligible diffusion of oxygen in water and a lack of mixing of near-bottom water does not allow oxygen to reach the sediment, and thus artificially lowers the obtained results. Another method is proposed by Edwards and Rolley (1965). These authors after collecting the samples similarly to Gambarjan, mixed the water in cylinders during all experiments to avoid the establishment of oxygen gradient on the water-sediment boundary.

All so far applied methods of investigations of oxygen consumption by bottom sediments in natural and laboratory conditions concerned either mixed sediment samples, i.e. with changed natural structure, and so not answering the natural conditions of the lake profundal, or did not take into account the oxygen depletion formed just over the bottom. The method applied by Mortimer (1941, 1942) to estimate the red-ox potential in the surface layer of sediment and in the water just over it, can not be applied, however it does not demand either the mixing of sediment or water when investigating the oxygen consumption of deposits.

Investigations were carried out to find a method to determine the mineralization of organic matter in bottom sediments. In the near-bottom water layer of Mikołajskie Lake[4], similarly to other eutrophic lakes, oxygen depletion was found as a result of oxygen analyses during the time of stagnation. Strong oxygen

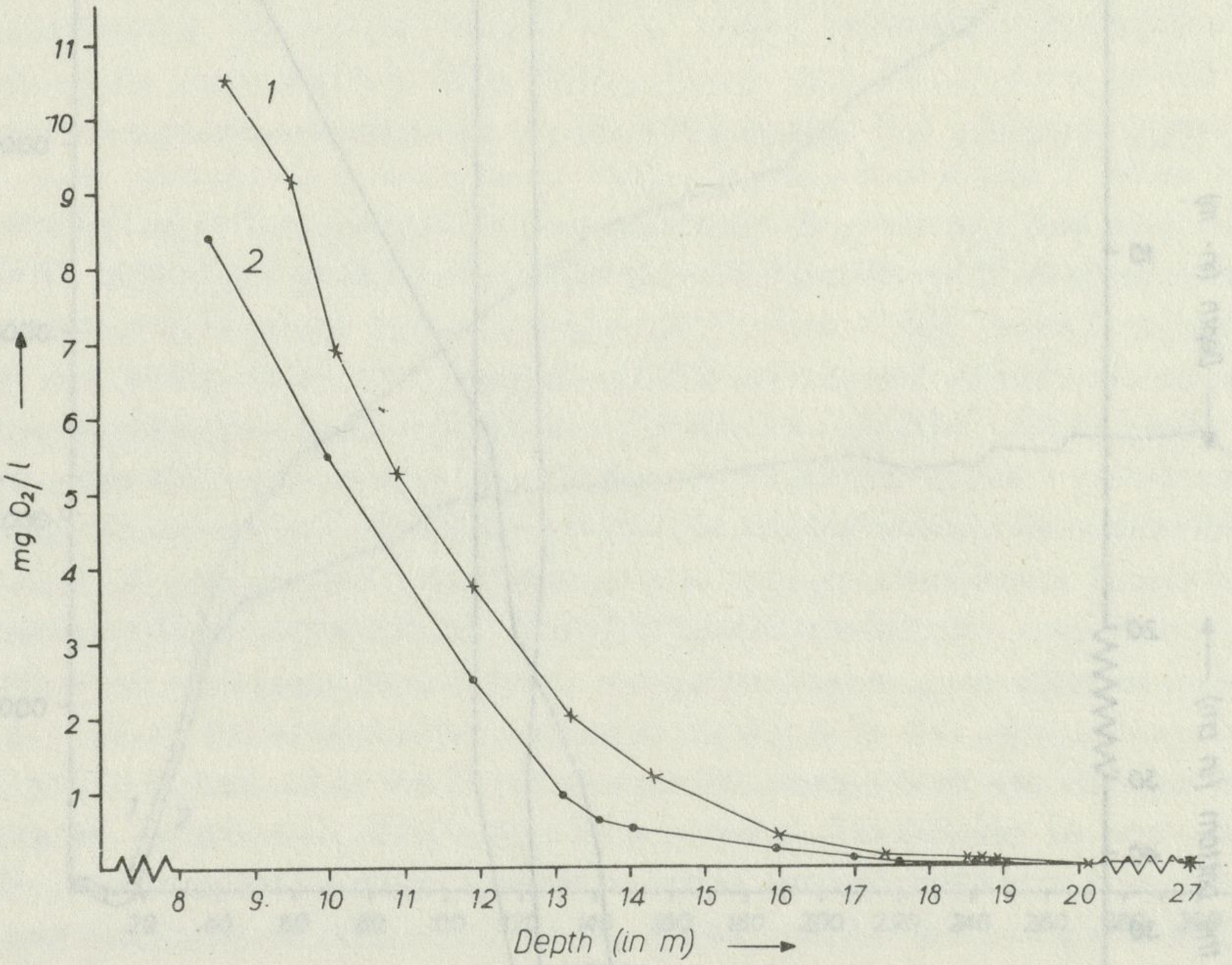

Fig. 17. The dependence of oxygen content in near-bottom water (50 cm above the bottom) on the depth of Mikołajskie Lake
1 – July 14, 1965, *2* – August 3, 1965

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[4] The water samples for oxygen analyses were taken with the help of Ruttner sampler, which was closed 50 cm from the bottom, in various places at the lake.

depletion is observed below the depth of 14 m (Fig. 17), in hypolimnion. A total lack of oxygen was found below 20 m. Oxygen concentration was also analysed in the near-bottom water in the deepest place of Mikołajskie Lake during the autumn circulation. The oxygen should then be equally dispersed in the whole column of water from the surface to the bottom, as the water masses circulate in the whole lake. Samples for analyses of oxygen content were taken from the near-bottom water by the use of a modified tubular bottom sampler (Rybak 1966) allowing to sample a 50 cm long column of near-bottom water (with sediment). Samples were obtained from the apparatus in two centimeter intervals: first one from water directly contiguous to the sediment surface, the second – 2 cm higher, etc. Investigations at the beginning of water circulation in lake (Fig. 18, curves 1 and 2) showed an appearance of oxygen deple-

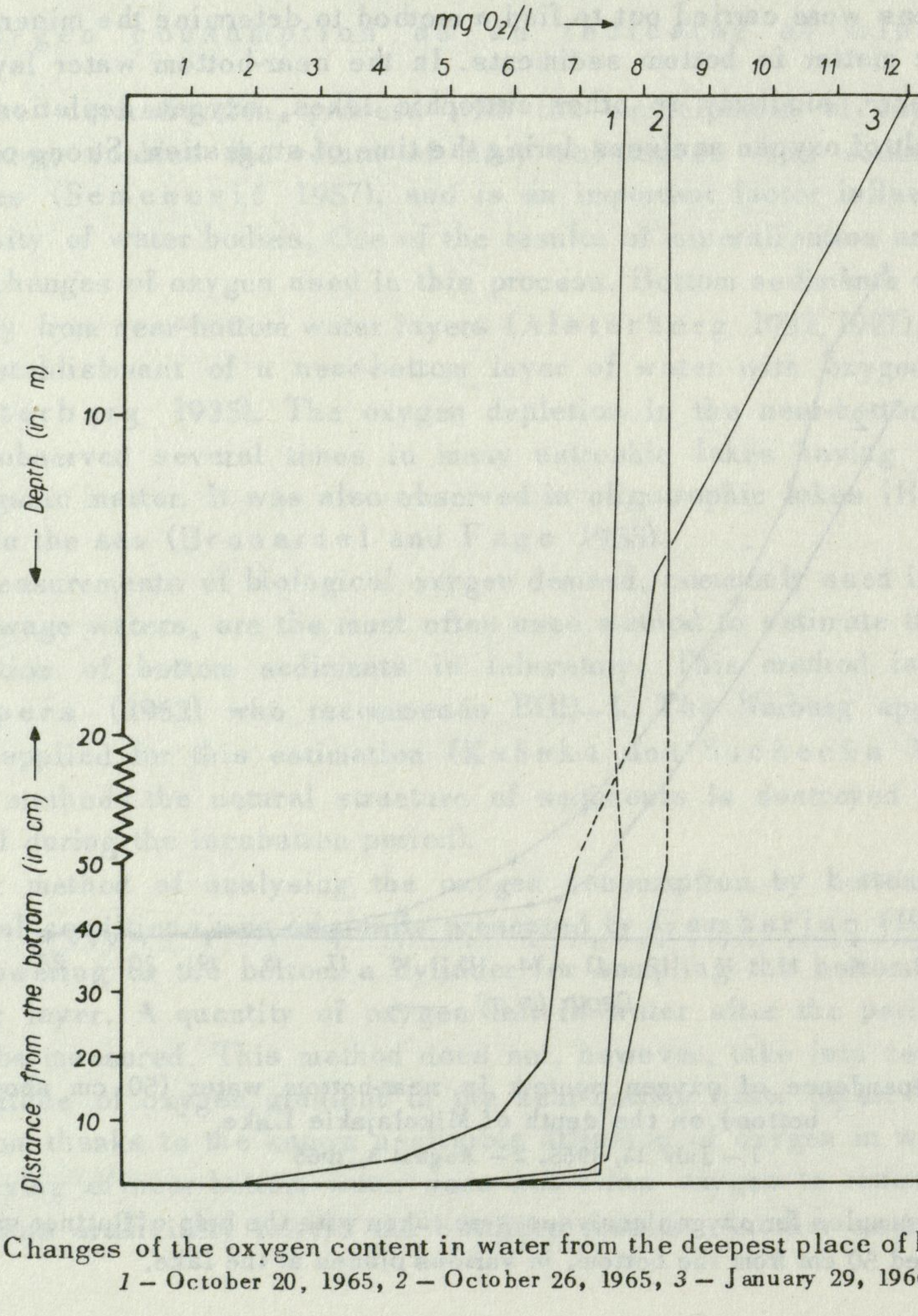

Fig. 18. Changes of the oxygen content in water from the deepest place of Mikołajskie Lake
1 – October 20, 1965, *2* – October 26, 1965, *3* – January 29, 1966

tion progressing in time in the 2 cm near-bottom water layer, and homooxygenation of all other water layers. An analysis made at the beginning of winter stagnation (Fig. 18, curve 3) showed a considerable progress of oxygen depletion reaching 10 cm from the bottom. At the same time an oxygen stratification can be noticed in the upper water layers. These results show an intense oxygen consumption by bottom sediments apart from the constant inflow of well oxygenated water from upper lake layers during circulation.

An experiment for determining the influence of the disturbed structure of sediments on the rate of oxygen consumption was carried out in Warburg apparatus. Quantities of oxygen used by bottom deposits of the same surface contacting the water (1 cm^2) were measured in two series. Samples in one of these series were mixed in order to disturb the natural structure of sediments, the second series contained samples with undisturbed natural structure[5]. The

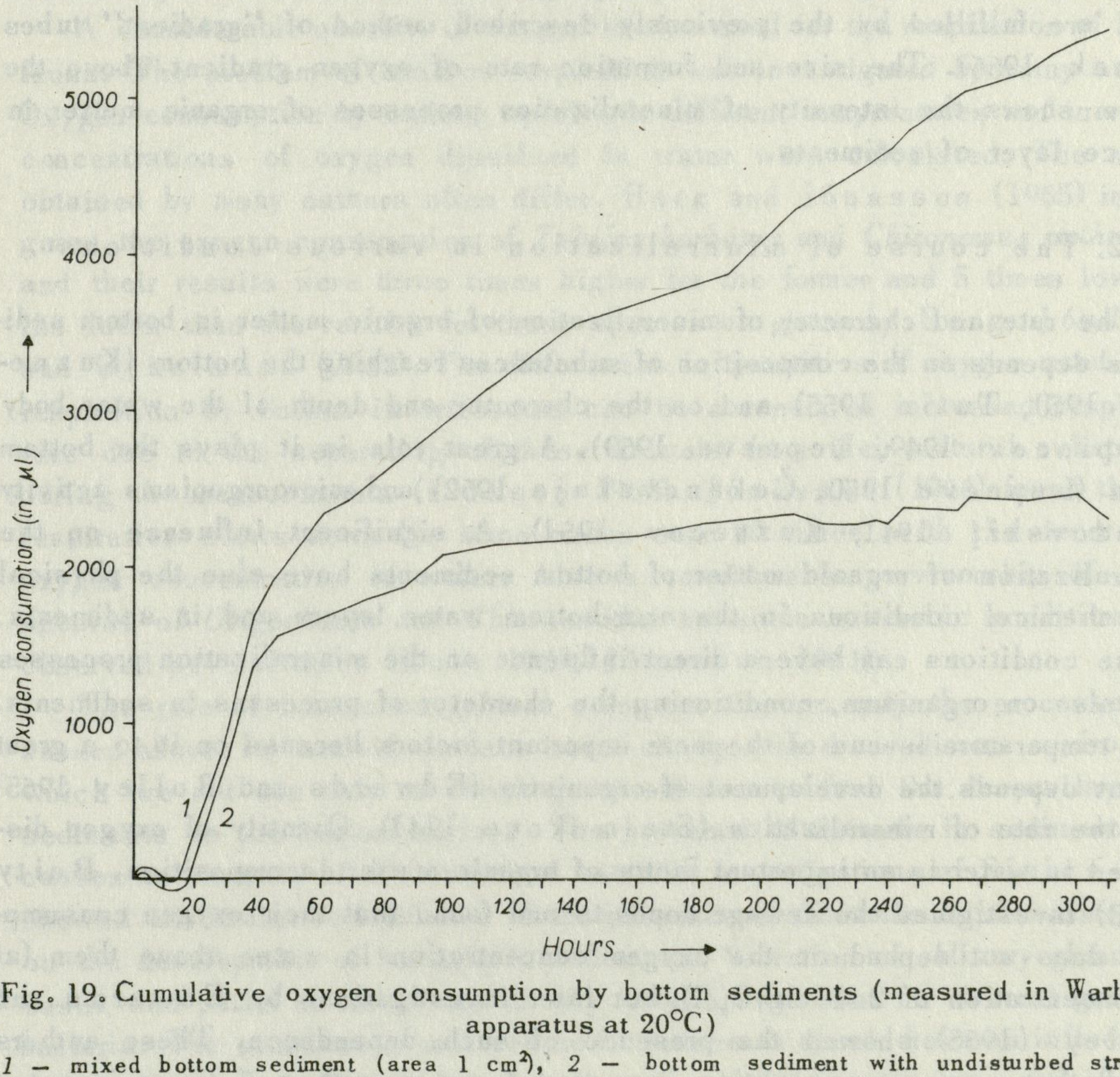

Fig. 19. Cumulative oxygen consumption by bottom sediments (measured in Warburg's apparatus at 20°C)

1 – mixed bottom sediment (area 1 cm^2), *2* – bottom sediment with undisturbed structure (area 1 cm^2)

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[5] In both cases samples were collected from the tubular bottom sampler by the use of glass tubes with an opening surface of 1 cm^2.

oxygen consumption of both series was similar and relatively high in the first 40 hr of experiment (Fig. 19). From then the rate of oxygen consumption of undisturbed samples is decreasing, while this of mixed samples stays on a relatively high level. Close to the end of the experiment the oxygen consumption of samples with mixed structure is more than twice higher than that of the natural structure. This fact proves than an oxygenated layer of sediment is formed just on its surface, which after a short time isolates water from the sediment below it. Sediment mixing causes also its loosening and thus helps the penetration of water to deeper layers of sediments and oxidation of particles below its surface.

The results presented above prove that in the investigations of oxygen changes caused by consumption of bottom sediments a method should be applied allowing to preserve natural structure of sediments and to observe the character of oxygen stratification above the sediment. Both these conditions are fulfilled by the previously described method of "gradient" tubes (Rybak 1966). The size and formation rate of oxygen gradient above the bottom shows the intensity of mineralization processes of organic matter in surface layer of sediments.

2. The course of mineralization in various conditions

The rate and character of mineralization of organic matter in bottom sediments depends on the composition of substances reaching the bottom (Kuznecov 1950, Tutin 1955) and on the character and depth of the water body (Skopincev 1949, Lepneva 1950). A great role in it plays the bottom fauna (Lepneva 1950, Čekanovskaja 1962) and microorganisms activity (Skadovskij 1941, Kuznecov 1951). A significant influence on the mineralization of organic matter of bottom sediments have also the physical and chemical conditions in the near-bottom water layers and in sediments. These conditions can have a direct influence on the mineralization processes and also on organisms, conditioning the character of processes in sediments. The temperature is one of the more important factors because on it to a great extent depends the development of organisms (Edwards and Rolley 1965) and the rate of mineralization (Stalmakova 1941). Quantity of oxygen dissolved in water is an important factor of organic matter decomposition. Baity (1938) investigated the sewage deposits and found that their oxygen consumption does not depend on the oxygen concentration in water above them (at a concentration of 2–5 mg O_2/l), but later investigations by Edwards and Rolley (1965) showed the presence of such dependence. These authors found that oxygen consumption increased 6 times with a 5 times increase of quantity of oxygen dissolved in water (at a concentration 2–10 mg O_2/l). On the basis of these data it can be assumed that the quantity of oxygen dissolved in the near-bottom layer of water should condition the rate of mineralization and the size of oxygen gradient in the water just over the bottom.

Bottom macrofauna due to its size and a possibility to penetrate the deeper layers of sediments has a significance mainly for circulation of substances among sediments and overlying water layers (Rossolimo 1939, Tessenow 1964). Due to their feeding in deeper sediment layers animals (mainly *Oligochaeta*) cause the carrying up of substances to the surface of sediments. By disintegrating many particles and a partial decomposition of substances into more simple compounds (Čekanovskaja 1962) the macrofauna enriches the bacterial flora (Ganapati 1949).

The substances carried out from deeper layers to the sediment surface increase the oxygen demand of sediments. Rossolimo (1939) calculated that *Chironomus plumosus* larvae in lake Beloe (of the density 700 individuals/m^2) carry out to the surface of sediments such a quantity of substances which require for oxidation 11.6 mg O_2/day.

A considerable quantity of oxygen is also used for the respiration of bottom fauna. The problem of benthos respiration was investigated by many authors. Oxygen consumption by various species in different temperatures and in various concentrations of oxygen dissolved in water were calculated. The results obtained by many authors often differ. Berg and Jónasson (1965) investigated the oxygen consumption of *Tubifex barbatus* and *Chironomus anthracinus* and their results were three times higher for the former and 5 times lower for the latter than the results for these species as given by Berg, Jónasson and Ockelmann (1962). The differences in quantities of oxygen used during respiration by bottom invertebrates can be a result of increased respiration rate due to the separating of these animals from their natural substratums during the measurements (Eriksen 1963). Jónasson (1964) found that the respiration slows down (in some cases over 20 times) with the decrease of oxygen concentration in water. Also a considerable survivorship of many species of *Oligochaeta* and *Chironomidae* larvae in anaerobic conditions was observed several times (Cole 1921, Jónasson 1964).

The role of bottom macrofauna does not concern only the processes discussed above. Its activity causes some changes in the sediment environment, which are not due only to carrying out substances from the deeper layers of sediments to the bottom surface. The presence of animals in sediments also causes an increase of the number of bacteria. Investigations of Sinica (1941) showed a stimulative influence of the presence of *Chironomus plumosus* larvae on the development of bacteria in sediments. Secretion of salivary glands, the cases and paths of larvae are a very good nourishment for several groups of bacteria. The presence of macrofauna in sediments should have an influence on the oxygen consumption by these sediments and thus on the intensity of mineralization processes of organic matter.

In this paper were analysed the influence of oxygen concentration in water and the kind of water used in experiments (surface and near-bottom water) on the oxygen consumption by bottom sediments, and also the influence of macrobenthos on this phenomena.

An experiment was carried out to find the size of oxygen gradient over the sediment at a decreasing concentration of oxygen dissolved in water. Bottom sediments of Mikołajskie Lake, with undisturbed structure, were incubated in "gradient" tubes in conditions close to natural ones (darkness and temperature). The water over the sediment contained 9.0 mg O_2/l. Samples were exposed from 24 to 96 hr. An oxygen gradient characterizing the oxygen consumption used for mineralization processes of sediments was established over the sediment (Fig. 20). The rate of oxygen consumption considerably decreases during the time of experiment. During the first 24 hr the difference between the oxygen consumption in the water layer just over the bottom and

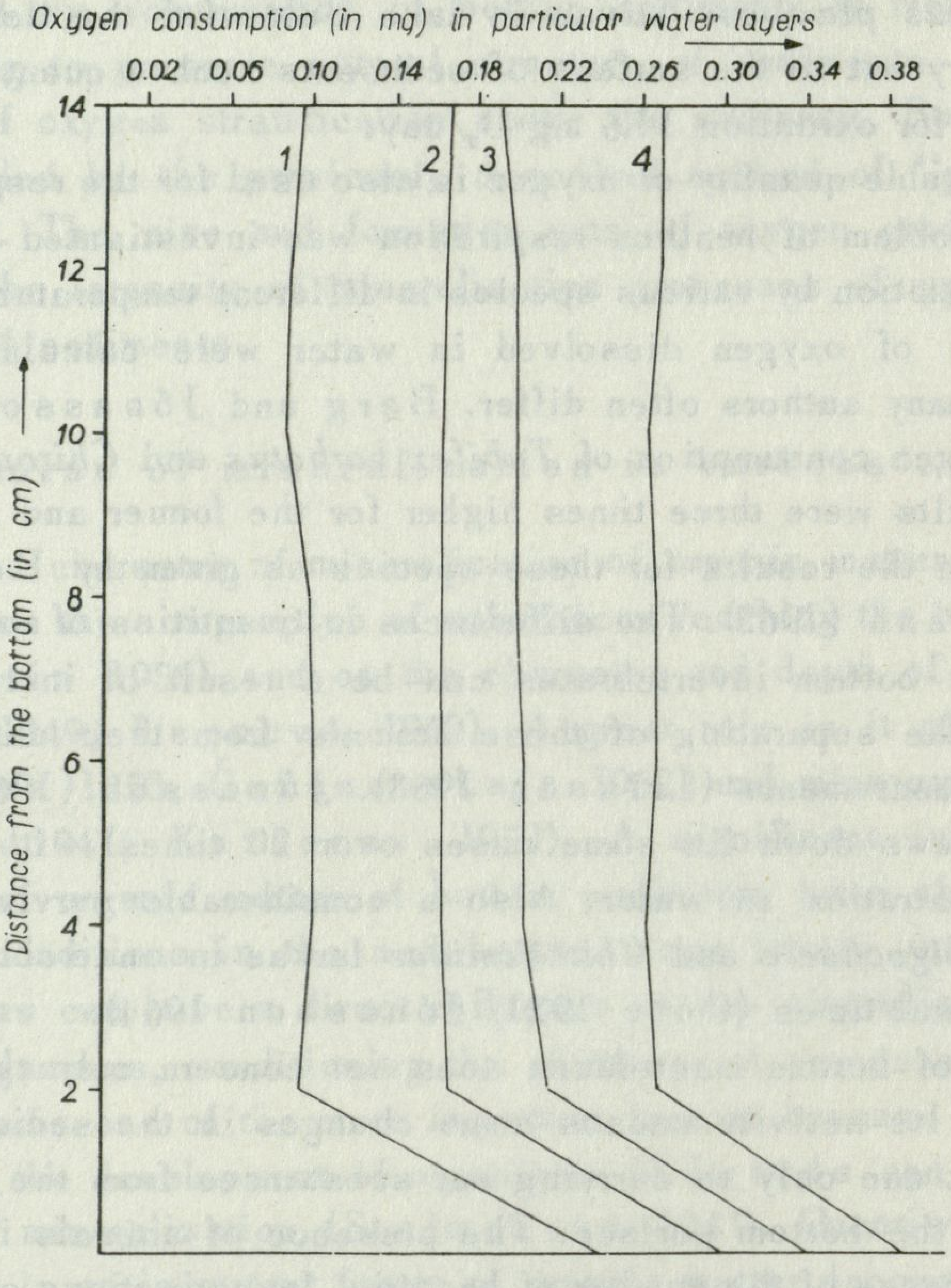

Fig. 20. Oxygen consumption by bottom sediments of Mikołajskie Lake (the method of "gradient" tubes, August 1965)

Exposure time: *1* – 24 hr., *2* – 48 hr., *3* – 72 hr., *4* – 96 hr.

Oxygen consumption in 44 cm^3 of water in the water layers 2 cm from the bottom surface was 0.145 mg O_2, in the following days consequently: 0.140, 0.130 and 0.120 mg O_2. This is probably a result of decreasing oxygen concentration in water, however the decreasing oxygen demand of sediments as a result of progressing mineralization and a lack of sedimentating organic matter can not be neglected.

The size of oxygen gradient in the near-bottom water layers also depends on the kind of water used in experiments (Fig. 21). A different degree of oxygen depletion was found in water overlying sediments if the lake surface or near-bottom water was used in experiments, however both of these kinds of water had the same oxygen content (9 mg/l). The oxygen consumption from the near-bottom water was not only greater than from the surface water, but it also had a wider range and covered a thicker layer, what is shown by the curve of oxygen consumption twisting on the fourth centimetres above the sediment surface (Fig. 21, curve 2).

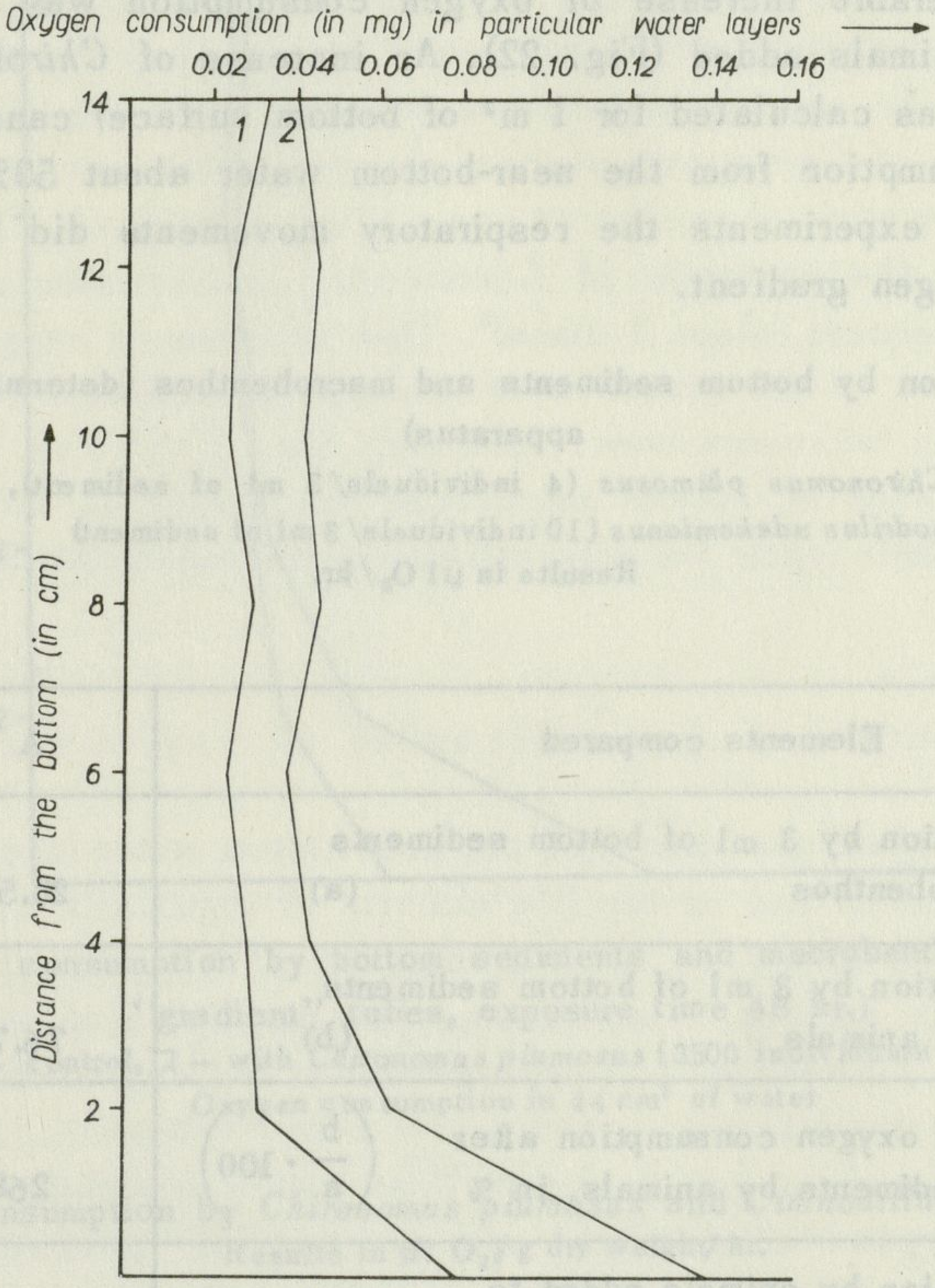

Fig. 21. Oxygen consumption by bottom sediments of Mikołajskie Lake (the method of "gradient" tubes, October 1966)

Exposure time 24 hr.

1 — surface water, *2* — near-bottom water

Oxygen consumption in 44 cm^3 of water

The influence of bottom fauna on the sediments oxygen consumption was measured with the help of Warburg apparatus and "gradient" tubes. The oxygen consumption of sediments deprived of macrofauna and sediments inhabited by *Chironomus plumosus* L. and *Limnodrilus udekemianus* Claparède were analysed.

In the experiment performed with the help of Warburg apparatus it was found that *Ch. plumosus* caused an increase of oxygen consumption greater than 260%, while *L. udekemianus* – 300% (Tab. II). With the help of "gradient" tubes a considerable increase of oxygen consumption was also found for samples with animals added (Fig. 22). An increase of *Chironomus plumosus* larvae to 3500 (as calculated for 1 m² of bottom surface) caused an increase of oxygen consumption from the near-bottom water about 50%. It should be noticed that in experiments the respiratory movements did not disturb the formation of oxygen gradient.

Oxygen consumption by bottom sediments and macrobenthos (determined in Warburg's apparatus)

A – variant with *Chironomus plumosus* (4 individuals/3 ml of sediment), B – variant with *Limnodrilus udekemianus* (10 individuals/3 ml of sediment)

Results in $\mu l\ O_2/hr$.

Tab. II

Elements compared		A	B
Oxygen consumption by 3 ml of bottom sediments deprived of macrobenthos	(a)	28.54	11.20
Oxygen consumption by 3 ml of bottom sediments after addition of animals	(b)	76.77	33.67
The increase of oxygen consumption after inhabiting of sediments by animals, in %	$\left(\frac{b}{a} \cdot 100\right)$	268	300
Oxygen consumption by animals added to sediments	(c)	28.66	10.97
The increase of oxygen consumption through the presence of animals	b – (c + a)	19.57	11.50

In the next experiment oxygen consumption of the two discussed above invertebrate species was measured by two methods: in Warburg apparatus and in glass bottles of the capacity of 250 ml. The experiment was carried out in 20°C. The idea of the experiment was to create different oxygen conditions: great oxygenation in Warburg apparatus and a small one in bottles (successively decreasing during the experiment). The degree of oxygen consumption by investigated organisms was different (Tab. III); higher in Warburg apparatus,

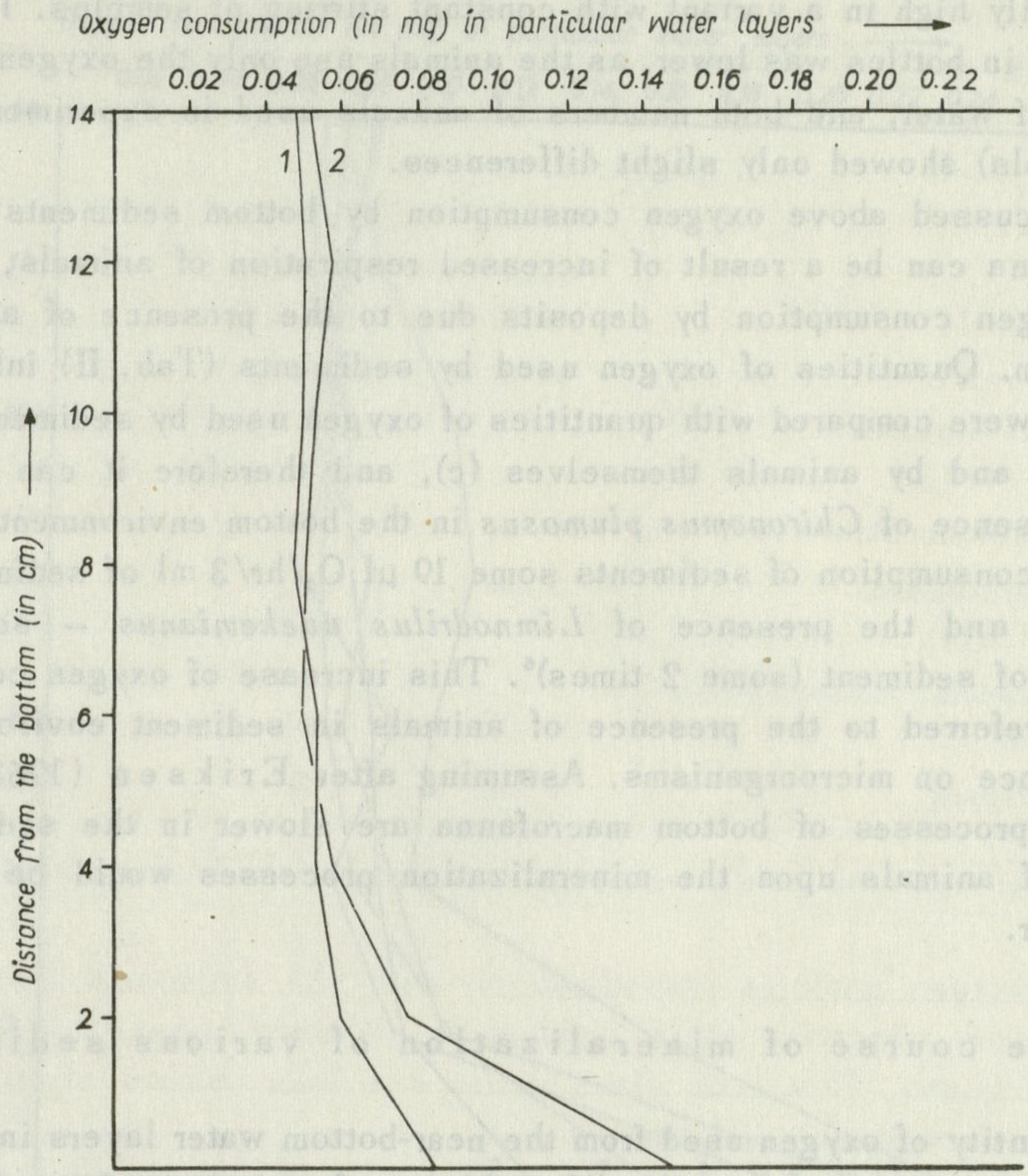

Fig. 22. Oxygen consumption by bottom sediments and macrobenthos (the method of "gradient" tubes, exposure time 48 hr.)
1 – control, *2* – with *Chironomus plumosus* (3500 individuals per 1 m^2).
Oxygen consumption in 44 cm^3 of water

Oxygen consumption by *Chironomus plumosus* and *Limnodrilus udekemianus*
Results in $\mu l\ O_2/g$ dry weight/hr.

Tab. III

Species	Warburg's apparatus*		Bottles 250 ml**	
	Mixed during the experiment	Not mixed	Stock of animals (individuals)	
			20	40
Chironomus plumosus	1,310	1,091	370	405
Limnodrilus udekemianus	1,146	867	493	554

*Time of experiment 10 hr., mixing with the frequency of 60 cycles/min.
**Time of experiment 6 hr.; the initial oxygen content 9 mg O_2/l; bottles were shaken in 30 min. intervals.

and especially high in a variant with constant stirring of samples. The oxygen consumption in bottles was lower, as the animals use only the oxygen dissolved in 250 ml of water, and both numbers of animals used in experiment (20 and 40 individuals) showed only slight differences.

The discussed above oxygen consumption by bottom sediments inhabited by macrofauna can be a result of increased respiration of animals, increased rate of oxygen consumption by deposits due to the presence of animals, or both of them. Quantities of oxygen used by sediments (Tab. II) inhabited by animals (b) were compared with quantities of oxygen used by sediments without animals (a) and by animals themselves (c), and therefore it can be stated that the presence of *Chironomus plumosus* in the bottom environment increases the oxygen consumption of sediments some 19 µl O_2/hr/3 ml of sediment (some 1.5 times); and the presence of *Limnodrilus udekemianus* – some 11 µl O_2/hr/3 ml of sediment (some 2 times)[6]. This increase of oxygen consumption should be referred to the presence of animals in sediment environment and their influence on microorganisms. Assuming after Eriksen (1963) that the respiration processes of bottom macrofauna are slower in the sediment, the influence of animals upon the mineralization processes would be in reality even greater.

3. The course of mineralization of various sediments

The quantity of oxygen used from the near-bottom water layers in the oxidation of organic matter and in the life activity of organisms depends on many factors. These are, among the others, character of a reservoir, its trophy and the depth from its surface to sediments. The magnitude of oxygen depletion, which forms over the sediments is an indicator of the degree of oxygen demand by sediments of the lake.

The magnitude of oxygen depletion over bottom sediments of lakes with various trophic types was measured with the help of "gradient" tubes. Sediments from 5 lakes from the surroundings of Mikołajki were investigated. The experiments were done in darkness and in constant temperature conditions similar to these in the hypolimnion. Different gradients were obtained for near-bottom water of various lakes (Fig. 23). The smallest gradient was formed over the sediments from eutrophic and polymictic lake, i.e. over the sediments, which always obtain oxygen from the upper water layers of the lake. The steepest gradients (the most intensive oxygen consumption) were observed over sediments from dystrophic and eutrophic lakes. The obtained results were partially confirmed by measurements of oxygen consumption of sediments from

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[6] It should be assumed that the quantities of oxygen used for respiration are equal for animals separated from their natural environment and for those in the natural sediment environment. The oxygen conditions were the same in both variants.

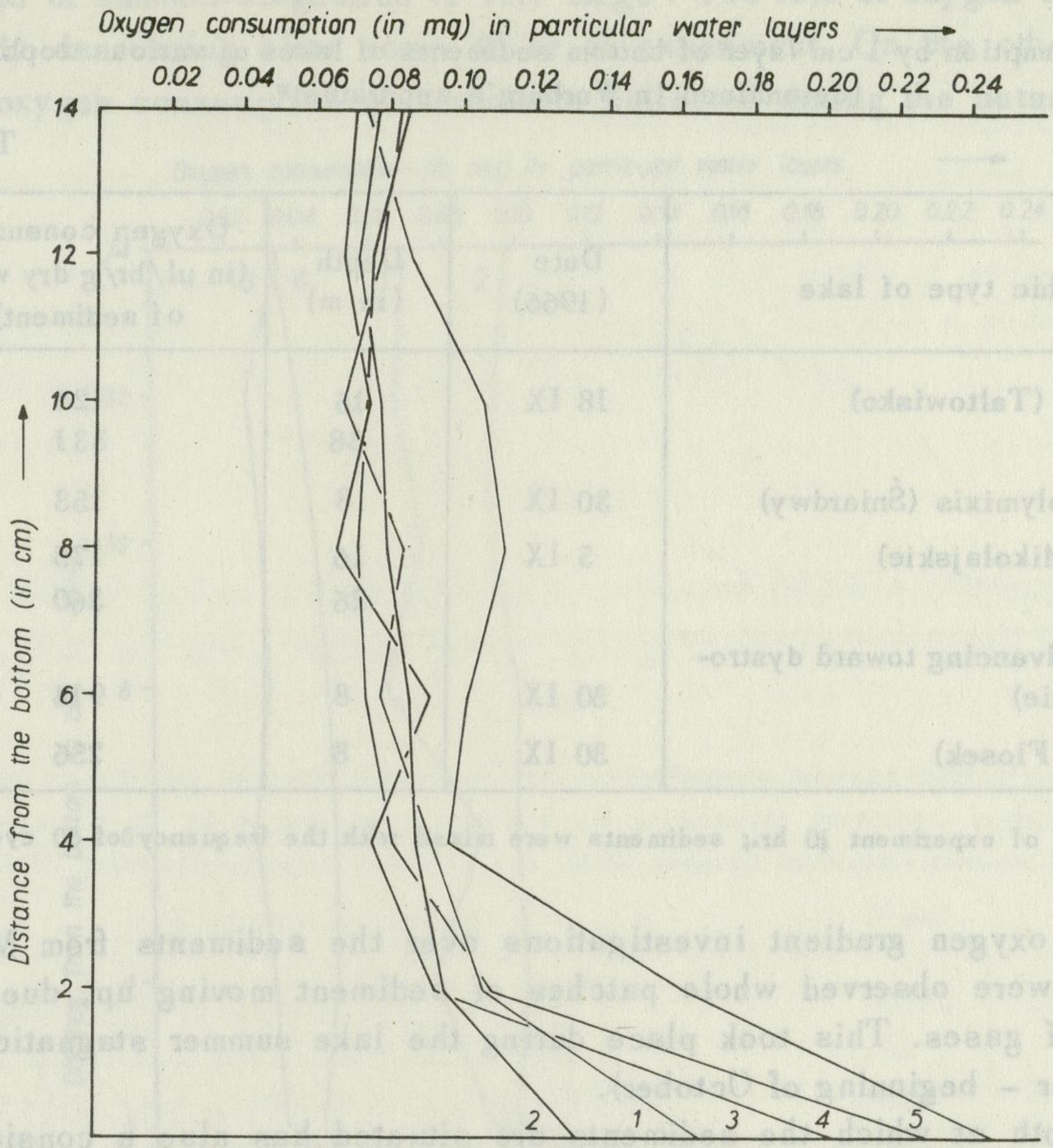

Fig. 23. Oxygen consumption by bottom sediments of lakes of various trophic types (the method of "gradient" tubes, July 1966, exposure time 24 hr.)

1 – mesotrophy (lake Tałtowisko), *2* – eutrophy-polymixis (lake Śniardwy), *3* – eutrophy (Mikołajskie Lake), *4* – eutrophy advancing toward dystrophy (lake Lisunie), 5 – dystrophy (lake Flosek)

Oxygen consumption in 44 cm^3 of water

these lakes obtained in Warburg apparatus (Tab. IV). The measurements in standard conditions with a full access of oxygen to sediments showed that most of oxygen was used by sediments from eutrophic lake advancing toward dystrophic one, least – by sediments from eutrophic-polymictic lake.

Strikingly low (incomparable with the results obtained in "gradient" tubes) oxygen consumption of sediments of dystrophic lake needs a special discussion. It results from the specifity of the applied method. In the Warburg apparatus the changes of gases pressure of the sample are measured in a manometer. In the discussed example the sediment stayed for a long time in anaerobic conditions. It probably caused intense bacterial processes due to great accumulation of organic matter. As a consequence of these processes gases produced by the investigated sediment influenced the manometer reading. Several times

Oxygen consumption by 1 cm layer of bottom sediments of lakes of various trophic types (determined in Warburg's apparatus)*

Tab. IV

Trophic type of lake	Date (1966)	Depth (in m)	Oxygen consumption (in µl/hr/g dry weight of sediment)
Mesotrophy (Tałtowisko)	18 IX	16	124
		38	331
Eutrophy-polymixis (Śniardwy)	30 IX	8	153
Eutrophy (Mikołajskie)	5 IX	16	175
		26	360
Eutrophy advancing toward dystrophy (Lisunie)	30 IX	8	914
Dystrophy (Flosek)	30 IX	8	256

*Duration of experiment 10 hr.; sediments were mixed with the frequency of 60 cycles/min.

during the oxygen gradient investigations over the sediments from Mikołajskie Lake were observed whole patches of sediment moving up, due to an evolution of gases. This took place during the lake summer stagnation (end of September – beginning of October).

The depth at which the sediments are situated has also a considerable influence upon their oxygen demand. It can be stated that this demand is more than twice less for sediments from the depth of 16 m than for those at the deepest places of investigated lakes, and that it is similar in both lakes apart from their various trophy (Tab. IV).

The oxygen demand of bottom sediments changes during a year as a result of various conditions in the near-bottom zone during the times of stagnations and circulations. Samples of sediments collected in these two periods, from Mikołajskie Lake, were incubated in "gradient" tubes. The established oxygen gradients over sediments in these two periods differ to a great extent (Fig. 24). A great oxygen demand formed near the bottom due to an oxygen "hunger" causes an increase of oxygen gradient in near-bottom water. This gradient enlarges with the progress of stagnation (Fig. 24). A similar situation was observed during the autumn circulation: at the beginning of this period the gradient formed over sediment is larger than the one formed during the well advanced circulation (Fig. 24). Thus it is visible that the longer is contact of bottom sediments with oxygen, the smaller is the gradient formed over them. A long lasting measurement of oxygen consumption of bottom sediments (200 hr) was made with the help of Warburg apparatus (Fig. 25). It was found that at the beginning of the experiment the oxygen consumption of sediments from the period of summer-stagnation is very large[7]. The rate of oxygen consumption is clearly decreasing after some 40 hr of experiment. On the other side the rate of oxygen consumption of sediments collected during the autumn circulation is more even and the quantity of used oxygen is similar. As in both cases sediments with undisturbed structures were investigated, the results obtained inform about the oxygen demand of the surface layers of sediments. A twist of oxygen consumption curve during the first few hours of experiment with sediments from the stagnation period is probably caused by the evolution of gases from sediments to respirometer.

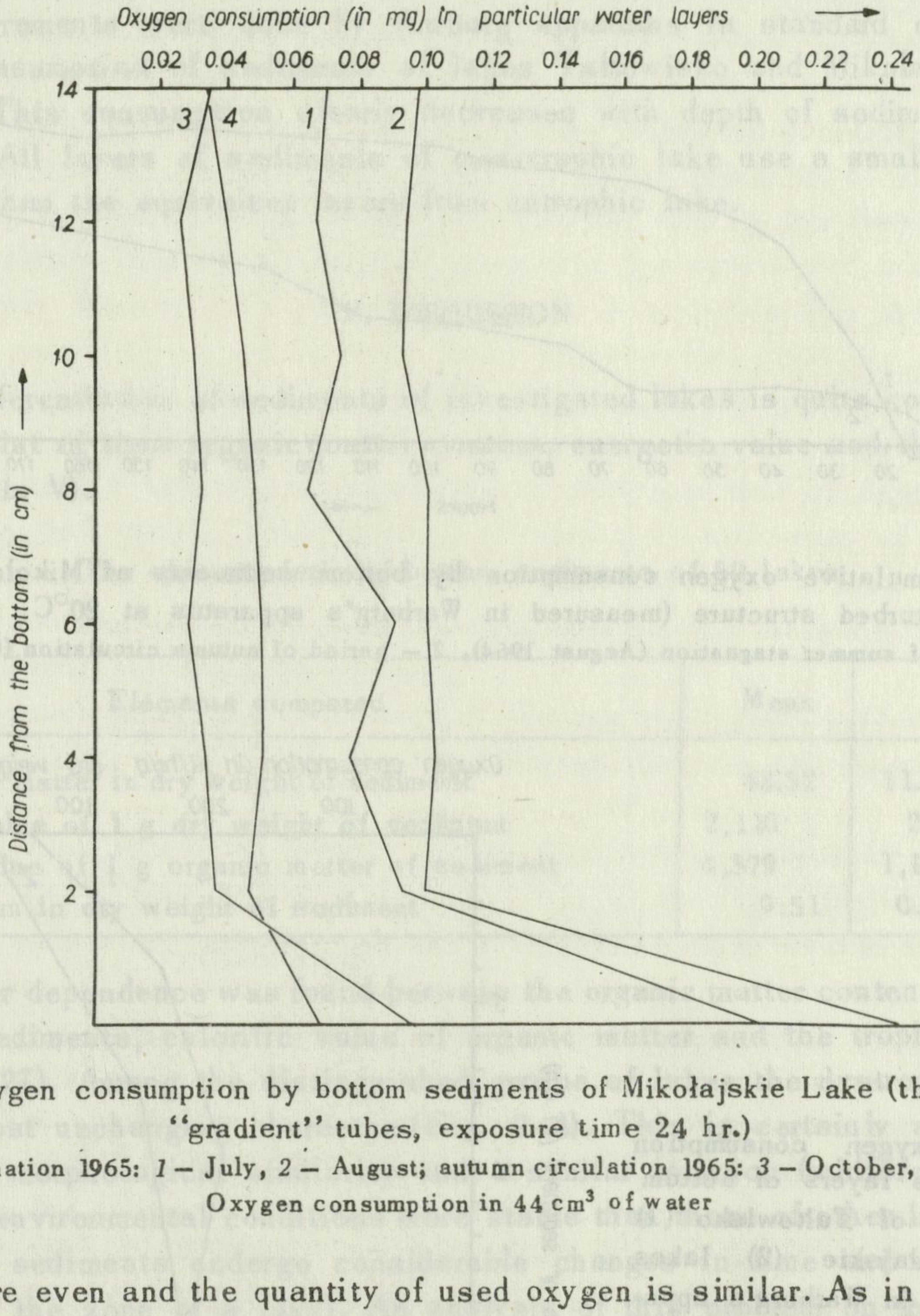

Fig. 24. Oxygen consumption by bottom sediments of Mikołajskie Lake (the method of "gradient" tubes, exposure time 24 hr.)

Summer stagnation 1965: *1* – July, *2* – August; autumn circulation 1965: *3* – October, *4* – November

Oxygen consumption in 44 cm^3 of water

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[7] This is confirmed by findings of Gardner and Lee (1965), who during the investigations of oxidation of lake Mendota sediments found that half of the total quantity of oxygen consumed by these sediments during 45 days experiment was consumed in the first 3 days.

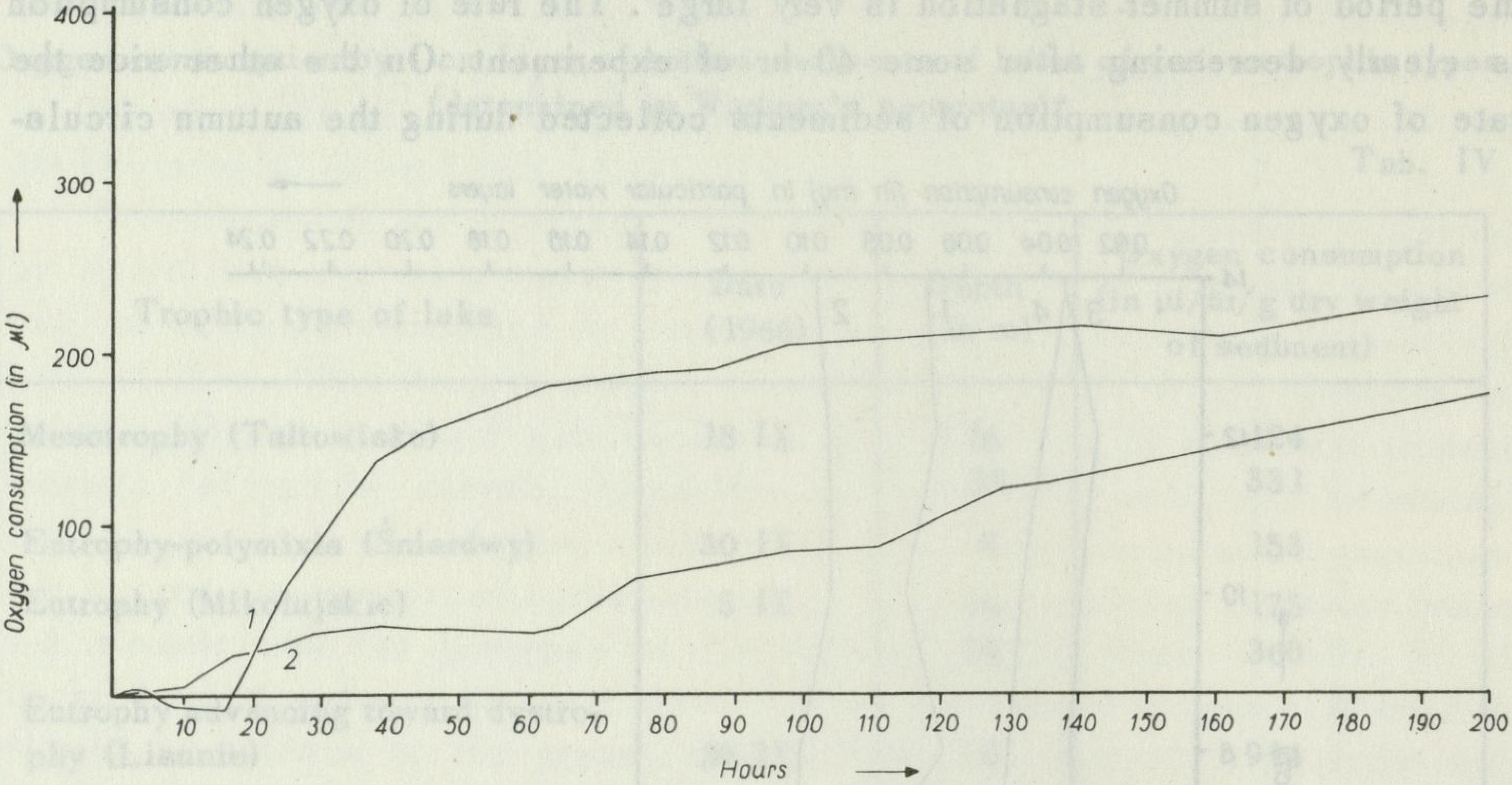

Fig. 25. Cumulative oxygen consumption by bottom sediments of Mikołajskie Lake, with undisturbed structure (measured in Warburg's apparatus at 20°C, area 1 cm²)
1 — period of summer stagnation (August 1964), *2* — period of autumn circulation (October 1964)

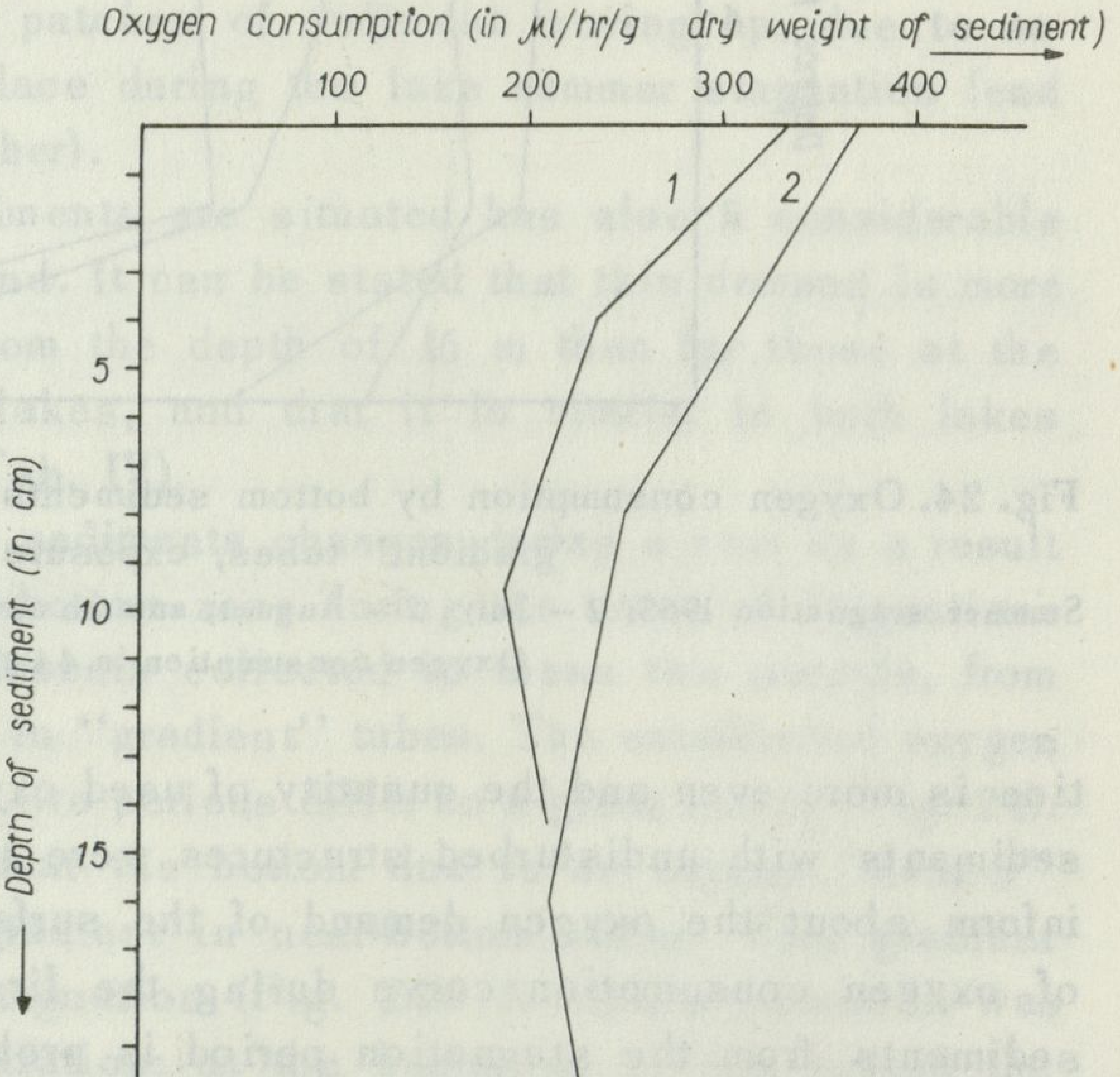

Fig. 26. Oxygen consumption by various layers of bottom sediments of Tałtowisko (1) and Mikołajskie (2) lakes (measured in Warburg's apparatus at 20°C, duration of measurement 10 hr., sediments were mixed with the frequency of 60 cycles/min.)

The oxygen consumption of different layers of sediments was also measured. Samples of sediments were collected with the help of tubular bottom sampler and then divided into separate layers without disturbing the natural structure. The measurements were done by Warburg apparatus in standard conditions. Qxygen consumption of sediments of lakes Tałtowisko and Mikołajskie was analysed. This consumption clearly decreases with depth of sediments layer (Fig. 26). All layers of sediments of mesotrophic lake use a smaller amount of oxygen than the equivalent layers from eutrophic lake.

V. DISCUSSION

The differentiation of sediments of investigated lakes is quite considerable from the point of their organic matter content, energetic value and the calcium content (Tab. V).

The characteristic of bottom sediments of 50 lakes

Tab. V

Elements compared	Mean	Range
% of organic matter in dry weight of sediment	43.52	11.22–83.41
Calorific value of 1 g dry weight of sediment	2,110	235–5,469
Calorific value of 1 g organic matter of sediment	4,379	1,197–7,198
% of calcium in dry weight of sediment	9.51	0.10–25.20

A proper dependence was found between the organic matter content, calorific value of sediments, calorific value of organic matter and the trophic type of lake (Fig. 27). Among the distinguished groups of lakes the dystrophic lakes had the most unchanging character (Fig. 2–4). This is certainly a result of their great morphological similarity and a similar location (midforest), which makes the environmental conditions more stable than those of other lakes.

Bottom sediments undergo considerable changes in time and space (depending on the zone of a lake). An analysis of this problem on the example of Mikołajskie Lake (Fig. 15) showed that the changes of organic matter content in time are within the range 20 to 29%, the calorific value of sediment – 700 to 1090 cal/g dry weight of sediment, and the calorific value of organic matter – 3056 to 4530 cal/g.

The lake zones have sediments of a different character. This is confirmed when analysing all the investigated indicators. The character of sediments from shallower places (to 14 m) is especially variable and depends on the depth. This differentiation in case of organic matter content is 2 to 29%, of calorific value – from some to 1160 cal/g dry weight of sediment, and of the calorific value of organic matter – 760 to 5175 cal/g. The differentiation of sediments from deeper places is not great (as confirmed by statistical analyses). This small differentiation of sediments under the hypolimnion zone (below 14 m in case of Mikołajskie Lake) shows that they can characterize well the given lake.

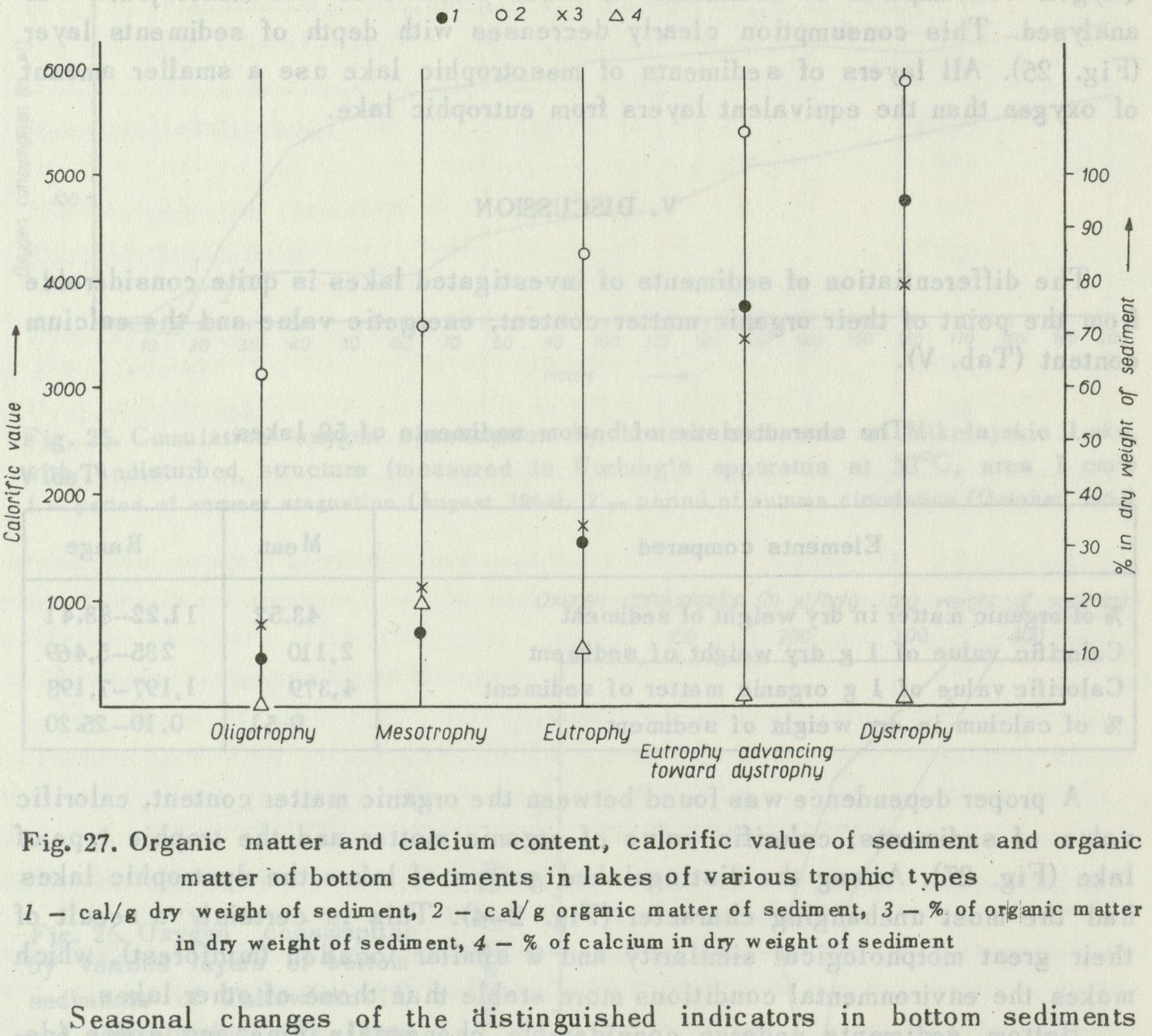

Fig. 27. Organic matter and calcium content, calorific value of sediment and organic matter of bottom sediments in lakes of various trophic types

1 — cal/g dry weight of sediment, *2* — cal/g organic matter of sediment, *3* — % of organic matter in dry weight of sediment, *4* — % of calcium in dry weight of sediment

Seasonal changes of the distinguished indicators in bottom sediments from hypolimnion are considerably smaller than the spatial differentiation within a lake.

An attempt to combine the trophy of lakes with calcium content in their sediments did not result similarly as in the case of indicators discussed above (Fig. 27). A low calcium content was observed in sediments of oligotrophic and dystrophic lakes, and a very differentiated one in sediments of eutrophic lakes. A great differentiation of calcium quantities in sediments of eutrophic lakes is connected with considerable differentiation of these lakes (various character of their drainage basins). Calcium plays an important role in the formation of bottom sediments mainly through its precipitation from water (Ruttner 1965), however large quantities of it can get in there from the drainage basin. The precipitation of calcium, known as biological decalcification (the precipitation of sparingly soluble calcium carbonate), is especially intense in conditions where CO_2 is lacking in water. The decalcification decreases in situations, when respiration and organic matter decomposition processes are not so intense (Stangenberg and others 1957). Assuming that calcium in the sediments is chiefly originating from biological decalcification processes, and that its content depends mainly on the intensity of algal photosynthesis in mid-lake water, it can be expected that in the final period of spring circulation and during summer stagnation the calcium of biogen origin is intensively deposited (Thomas 1956). It is possible that the increase of calcium content observed in three lakes (Mikołajskie, Śniardwy and Tałtowisko) during summer stagnation was due to intense precipitation of calcium in that period (Fig. 16). On the other side the process of calcium precipitation from water is held up by processes of decomposition of organic matter during stagnation period. Small amounts of calcium in sediments of dystrophic lake and eutrophic one advancing toward dystrophy, and a lack of visible changes in time are connected with the midforest locality of these lakes (very small inflow from the drainage basin).

A dependence among the occurrence of calcium and organic matter described by Tadajewski (1956) from the lake Drużno was not confirmed by these materials.

The calorific values of organic matter from bottom sediments are within some broad limits: from 760 to 7100 cal/g (Fig. 4 and 11). Large differences of calorific values are observed among the investigated lakes and also among different zones of the same lake (Mikołajskie Lake).

An analysis of the dependence of organic matter content in sediments and its calorific value is linear for sediments of lakes with various trophy (Fig. 28)[8]. The correlation coefficient calculated for all samples is $r = 0.5789$ and is highly significant for the level of $a = 0.05$. The above correlation in connection with the phenomenon that the calorific value of sediments depends mainly on their organic matter content causes that a linear dependence between organic matter content and calorific value of investigated lakes can be observed. Both these indicators increase with an advance of trophy of lakes (Fig. 29). Data from dystrophic lakes are also situated according to this linear dependence. Thus the discussed dependence is a good indicator of lake trophy.

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[8] This dependence is not true for some samples. These samples had a considerably high (as compared with rest of samples) amount of calcium. It is possible that calcium influenced the calorific value of sediments and at the same moment their organic matter. Investigations of Paine (1966) shown that calorific value (as determined in calorimetric bomb) depends on the quantity of $CaCO_3$, as some part of heat produced by combustion is used for endothermic reaction of calcium carbonatae destruction.

Lower calorific values of organic matter from sediments of oligotrophic and mesotrophic lakes and of eutrophic-polymictic lakes (Fig. 4) and also from shallow parts of eutrophic lake (Fig. 11) can be explained on the basis of data obtained by Kononova (1958) by:

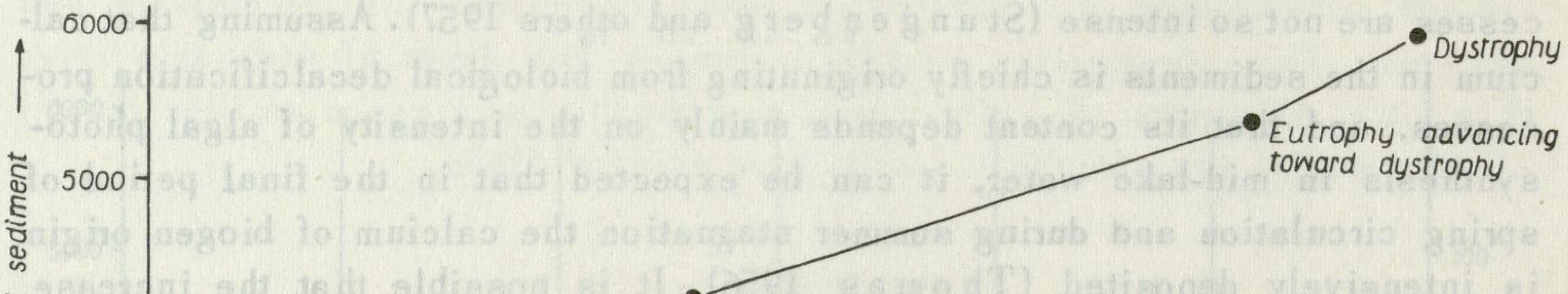

Fig. 28. The dependence of organic matter content on calorific value of organic matter of bottom sediments in lakes of various trophic types

1) A high degree of oxidation of organic substances in such type of environment (large quantities of oxygen have an access to sediments for more than half of a year). Oxidation of organic matter decreases the amount of carbon thus causing the decrease of calorific value of this substance;

2) The non-saturated character of compounds of the soil and bottom sediments type;

3) High organic nitrogen content in these substances.

On the other hand a high calorific value of organic matter was found in sediments of dystrophic lakes. A degree of oxidation of these sediments is very small due to long periods when there is a lack of oxygen in near-bottom water in connection with big organic matter content in sediments of these lakes. These sediments are characterized by a high organic carbon content and a low content of nitrogen. Process of humification causes a constant increase of the amount of carbon in relation to other elements. C/N ratio in sediments of this type of lakes is 10:1 (ZoBell 1963). In deep parts of many eutrophic lakes with great amounts of organic matter there are similar long periods of oxygen depletion in near-bottom water. The oxidation processes of organic matter are in such conditions very weak, and the calorific value of this matter is high.

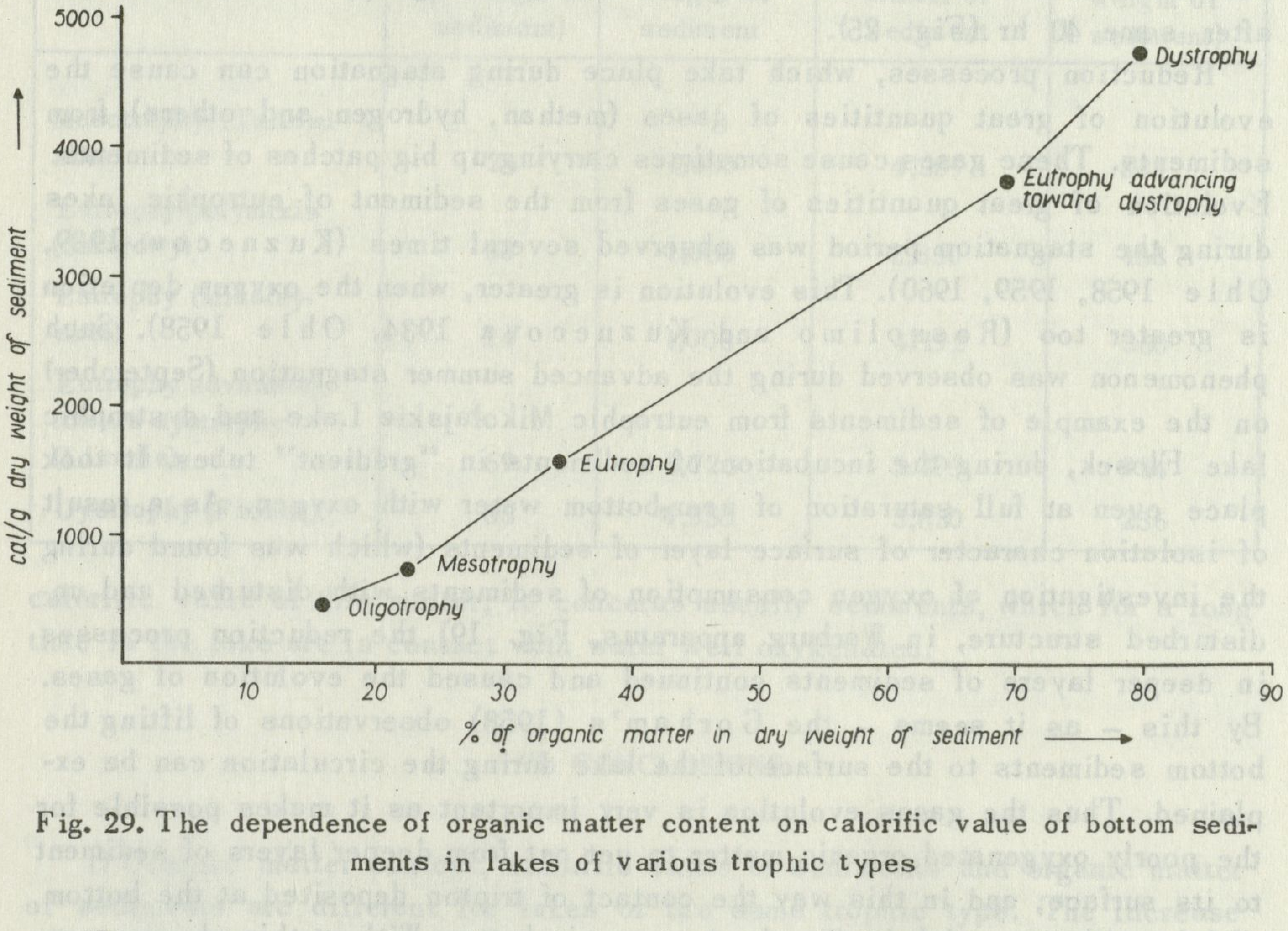

Fig. 29. The dependence of organic matter content on calorific value of bottom sediments in lakes of various trophic types

Thus a low calorific value of organic matter is found in well oxygenated environments and those poor in organic matter, while the high value occurs in environments with common lack of oxygen and high organic matter content. This allows to draw a conclusion that the calorific value of organic matter in bottom sediments can be a good indicator of the intensity of mineralization processes.

Bottom sediments undergo constant changes which can result in the amount and the rate of oxygen consumption. During the periods of circulation bottom sediments of deep parts of holomictic lakes are in a contact with water well saturated with dissolved oxygen. However, the oxygen conditions in near-bottom water are worse than these in upper water layers, as shown by observations during the circulation periods (Fig. 18). It results from the intense oxygen consumption at that time. The comparison of oxygen consumption by deposits during periods of circulation and periods of stagnation (Fig. 24 and 25) showed that this consumption was higher when sediments did not contact the well oxygenated water for a long time. Thus during the stagnation, when organic matter does not contact oxygen, the oxygen demand is greater. It can be said that the oxygen "hunger" increases at that time. Satisfying this "hunger" causes an establishment of oxygen gradient in near-bottom water at the beginning of circulation period (Fig. 18). Satisfaction of oxygen "hunger" of sediments in the conditions of experiment in Warburg apparatus takes place after some 40 hr (Fig. 25).

Reduction processes, which take place during stagnation can cause the evolution of great quantities of gases (methan, hydrogen and others) from sediments. These gases cause sometimes carrying up big patches of sediments. Evolution of great quantities of gases from the sediment of eutrophic lakes during the stagnation period was observed several times (Kuznecov 1939, Ohle 1958, 1959, 1960). This evolution is greater, when the oxygen depletion is greater too (Rossolimo and Kuznecova 1934, Ohle 1958). Such phenomenon was observed during the advanced summer stagnation (September) on the example of sediments from eutrophic Mikołajskie Lake and dystrophic lake Flosek, during the incubation of sediments in "gradient" tubes. It took place even at full saturation of near-bottom water with oxygen. As a result of isolation character of surface layer of sediments (which was found during the investigation of oxygen consumption of sediments with disturbed and undisturbed structure, in Warburg apparatus, Fig. 19) the reduction processes in deeper layers of sediments continued and caused the evolution of gases. By this – as it seems – the Gorham's (1958) observations of lifting the bottom sediments to the surface of the lake during the circulation can be explained. Thus the gases evolution is very important as it makes possible for the poorly oxygenated organic matter to get out from deeper layers of sediment to its surface, and in this way the contact of tripton deposited at the bottom of lake with water rich in dissolved oxygen is better. Without this phenomenon, the isolating layer formed at the sediment surface, which keeps oxygen from lower sediment layers, would make the mineralization of organic matter in these lower layers of sediments impossible.

The magnitude of oxygen consumption of bottom sediments of lakes with various trophy (Fig. 23, Tab. IV) and sediments from different depths (Tab. IV) shows similar changes as the organic matter content and calorific value of sediments (Tab. VI). Sediments, which consume less oxygen are poorer in organic matter (with the exception of polymictic lake) and have in general a lower calorific value. Calorific value of organic matter is also lower in sediments, which are characterized by smaller oxygen consumption. This last regularity is probably connected with the degree of oxidation of organic matter. Generally it can be stated, that the lower is the oxygen consumption of deposits (per unit of time), the lower is their organic matter content and

Organic matter content, calorific value of sediment and of organic matter and oxygen consumption by bottom sediments of lakes of various trophic types

Tab. VI

Trophic type of lake	Organic matter content (% in dry weight of sediment)	Calorific value of 1 g dry weight of sediment	Calorific value of 1 g organic matter of sediment	Oxygen consumption (µl O_2/hr/g dry weight of sediment)
Mesotrophy (Tałtowisko)	24	1,080	4,509	331
Eutrophy-polymixis (Śniardwy)	38	1,050	2,850	153
Eutrophy (Mikołajskie)	24	1,006	4,192	360
Eutrophy advancing toward dystrophy (Lisunie)	69	3,726	5.399	914
Dystrophy (Flosek)	83	4,850	5,830	256

calorific value of this matter; it concerns usually sediments, which for a long time in the lake are in contact with water well oxygenated.

VI. CONCLUSIONS

1) Organic matter content, calorific value of sediments and organic matter of sediments are different for lakes of the same trophic type. The increase of the mentioned indicators from oligotrophy to eutrophy is, however, visible. Dystrophic lakes are characterized by the greatest values of these indicators. The smallest quantities of calcium were found in sediments of oligotrophic and dystrophic lakes.

2) Changes in time of organic matter content and its calorific value in bottom sediments are smaller than changes observed in particular lake zones.

3) The calorific value of sediments in connection with organic matter content is a good indicator of the lake trophy.

4) Calorific value of organic matter is low in sediments poor in organic matter but found in well oxygenated zones of lake. And vice versa – high calorific value of organic matter is characteristic of sediments rich in this matter situated in poorly oxygenated zones.

5) Calorific value of organic matter which is a result of oxydation processes of different intensity can be an indicator of the intensity of mineralization processes.

6) Oxygen consumption of bottom sediments from anaerobic environment is considerably higher than that of sediments from well oxygenated environments. The rate of oxygen consumption of bottom sediments depends on oxygen conditions in the near-bottom water layers. During the oxygen depletion the oxygen "hunger" of sediments is increasing. Satisfaction of this "hunger" at the beginning of circulation causes the establishment of oxygen gradient in the near-bottom water layer, which confirms the intense mineralization processes of organic matter.

7) The bottom fauna by its oxygen consumption in respiration processes increases considerably the total oxygen consumption. Apart from that, the presence of animals in the bottom environment increases the oxygen consumption of sediments (1.5 to 2 times), probably by stimulating the development of bacteria and by carrying up to the sediments surface particles from the lower, less oxygenated layers.

8) Processes, which take place in sediments during stagnation (when there is a lack of oxygen near the bottom) cause the evolution of great quantities of gases, which cause that the big patches of sediments are carried up. It considerably increases the mineralization process of organic matter.

9) The quantity of oxygen consumed by bottom sediments increases with the advance of trophy. The sediments consume less oxygen if they are poorer in organic matter and their calorific value is lower. This concerns most often sediments which for a long time contact with well oxygenated water in the lake.

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OSADY DENNE JEZIOR RÓŻNYCH TYPÓW TROFICZNYCH

Streszczenie

W ramach pracy scharakteryzowano osady denne 50 jezior różnych typów troficznych (fig. 1, tab. I), leżących na terenie kilku pojezierzy i w Tatrach, oraz analizowano procesy mineralizacji materii organicznej osadów. Do charakterystyki użyto jako wskaźników: zawartość materii organicznej i wapnia oraz wartość kaloryczną osadów (fig. 2–5). Przeprowadzono analizę przestrzennego zróżnicowania wymienionych wskaźników w profundalu jeziora (fig. 6–14) oraz ich zmienności w czasie (fig. 15–16). Intensywność procesów mineralizacji materii organicznej określano na podstawie ilości zużywanego przez osady denne tlenu.

Zróżnicowanie osadów badanych jezior pod względem zawartości materii organicznej, kaloryczności i zawartości wapnia jest znaczne (tab. V). Stwierdzono prawidłową zależność między zawartością materii organicznej, kalorycznością osadów i kalorycznością materii organicznej a typem troficznym zbiornika (fig. 27). Obserwuje się mianowicie wyraźny wzrost wartości wymienionych wskaźników wraz ze wzrostem trofii jezior. Jeziora dystroficzne charakteryzują się największymi wartościami powyższych parametrów (fig. 2–4). Zmiany zawartości wapnia tej prawidłowości nie wykazują (fig. 27). Najmniejsze ilości tego składnika znaleziono w osadach jezior oligotroficznych i dystroficznych. W jeziorach typu eutroficznego zawartość wapnia w osadach jest bardzo zróżnicowana (fig. 5).

Zawartość materii organicznej w osadach dennych jeziora oraz jej kaloryczność zmienia się wyraźnie zarówno w czasie, jak i w przestrzeni (w poszczególnych strefach Jeziora Mikołajskiego). Szczególnie wyraźny wzrost obserwowano w okresie stagnacji (fig. 15). Zmiany w czasie są jednak mniejsze niż zmiany obserwowane w poszczególnych strefach zbiornika.

Szczegółowej analizie poddano kaloryczność materii organicznej osadów dennych. Waha się ona w dość szerokich granicach: od 710 do przeszło 7100 cal/g (fig. 4 i 11), tak między poszczególnymi jeziorami, jak i w różnych strefach jednego zbiornika (Jezioro Mikołajskie). Analiza korelacji pomiędzy zawartością materii organicznej w osadach a jej kalorycznością, przeprowadzona dla osadów jezior różnych typów troficznych wykazała, że istnieje zależność liniowa (fig. 28). Ta zależność w powiązaniu z faktem, że o kaloryczności osadów decyduje prawie wyłącznie materia organiczna w nich zawarta sprawia, że obserwujemy w badanych jeziorach prostą zależność pomiędzy zawartością materii organicznej a kalorycznością osadów (fig. 29).

Jeśli przyjąć, że większość substancji organicznych dopływających do dna pochodzi z organizmów wodnych, to materia organiczna osadów powinna mieć we wszystkich wypadkach zbliżoną kaloryczność. Tak więc jej zmienność jest spowodowana różną intensywnością procesów mineralizacji. Tempo utleniania materii organicznej jest zależne od jej ilości w osadach i od warunków środowiskowych. Niższą kaloryczność materii organicznej stwierdzono w osadach dennych, które przez większą część roku kontaktują się z wodą dobrze natlenioną: w osadach jezior oligotroficznych i mezotroficznych oraz jezior eutroficznych polimiktycznych (fig. 4), jak również w płytszych partiach jeziora eutroficznego holomiktycznego (Jezioro Mikołajskie) (fig. 11). Osady tych środowisk są zarazem ubogie w materię organiczną (fig. 1 i 7). Z drugiej strony, wysoką kaloryczność materii organicznej stwierdzono w osadach, które przez długie okresy nie kontaktują się z wodą natlenioną: w osadach jezior dystroficznych i w osadach pochodzących z głębinowych partii wielu jezior eutroficznych (fig. 4). Procesy utleniania materii organicznej w tych warunkach są nieznaczne i kaloryczność jej duża. W osadach tych spotyka się znaczne ilości materii organicznej (fig. 2). Tak więc niską kaloryczność materii organicznej stwierdza się w środowiskach dobrze natlenionych i ubogich w materię organiczną, podczas gdy wysoką — w środowiskach, w których często brak jest tlenu, a zawartość materii organicznej jest wysoka. Możemy zatem wysnuć wniosek, że kaloryczność materii organicznej osadów dennych stanowi dobry wskaźnik intensywności procesów mineralizacji.

Miarą procesów mineralizacji osadów dennych może być ilość i tempo zużycia przez nie tlenu. Przeprowadzone eksperymenty wykazały, że wielkość zużycia tlenu przez osady jezior różnej trofii (fig. 23, tab. IV) oraz przez osady pochodzące z różnych głębokości (tab. IV) zmienia się wraz ze zmianą zawartości materii organicznej i kaloryczności osadów (tab. VI). Osady zużywające mniej tlenu są uboższe w materię organiczną oraz wykazują na ogół mniejszą kaloryczność. Kaloryczność materii organicznej jest niższa w osadach, które charakteryzują się mniejszym zużyciem tlenu. Ta ostatnia prawidłowość jest zapewne związana ze stopniem utlenienia materii organicznej.

Doświadczalnie stwierdzono, że zużycie tlenu przez osady denne pochodzące z okresu stagnacji jest znacznie większe niż przez osady pochodzące z okresu cyrkulacji (fig. 24–25). Wiąże się to z większym zapotrzebowaniem na tlen mułu, który w okresie stagnacji pozbawiony był dostępu tlenu. Można powiedzieć, że w okresie tym rośnie „głód tlenowy" osadów. Obserwowane tworzenie się gradientu tlenowego w warstwie wody przylegającej do dna w początkowym okresie cyrkulacji (fig. 18) jest spowodowane zaspokajaniem tego „głodu".

Fauna denna, dzięki zużywaniu tlenu na procesy oddechowe, zwiększa w wydatny sposób ogólne zużycie tlenu. Ponadto sama jej obecność w środowisku mułowym powoduje zwiększenie zużycia tlenu przez osady (tab. II), przypuszczalnie na drodze stymulowania rozwoju bakterii oraz przez wynoszenie na powierzchnię osadu cząstek położonych niżej, w warstwach mniej utlenionych.

Przy zmniejszeniu zawartości rozpuszczonego w wodzie tlenu maleje tempo mineralizacji osadów dennych (fig. 20).

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