Papers

Anomalies in the physical and chemical structure of the Gdańsk Deep caused by groundwater seepage*

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Abstract

Seepage of freshwater into the near-bottom layer (*ca* 100 m depth) of the Gdańsk Deep was reported during short-term studies on the variations of concentration of chemical compounds and the stratification of this basin. As a result, the salinity fell to below 1 PSU and the temperature rose from 5 to *ca* 7.5°C in this layer; further consequences were changes in the chemical and hydrological stratification throughout the water column. Directly above the area of seepage there was a zone of powerful turbulent convection where the temperature-salinity Rayleigh number was of the order of 10^{16}. Large quantities of suspended matter and poorly oxygenated deep waters were carried by the convection current from below the halocline up to the sea surface. This seepage of groundwaters is probably a continual and not an intermittent phenomenon.

1. Introduction

An integral component of terrestrial hydrography, the seepage of groundwaters onto the sea floor is poorly understood. Seldom measured directly, it is rather more frequently assessed on a global scale (Zekster and Loaiciga, 1993). The few papers on the subject published so far have

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tended to concentrate on coastal areas, where underwater seepage has modified the physical and chemical properties of sediments and near-bottom waters. Changes of this nature were reported from the coastal zone off western Australia (Johannes, 1980; Johannes and Hearn, 1985), where relatively weak seepage controlled the distribution of salts and supplied the near-bottom water with nitrates and silicates in quantities exceeding several times those arriving in surface waters from terrestrial run-off. Bokuniewicz (1980) holds the view that the substantial seepage of groundwaters from the bottom of Great South Bay near New York could be playing a significant part in reducing the salinity of coastal basins.

As far as the Polish coastal zone of the Baltic Sea is concerned, this problem has been investigated in detail only in Puck Bay (Jankowska and Bolałek, 1990; Jankowska *et al.*, 1994), where areas of groundwater seepage were detected wherever an abrupt fall in salinity, a change in chemical content of the sediments or a drop in the salinity of interstitial water were recorded. Nothing has yet been published on such seepage in the deep-water zone of the open Baltic.

That part of the Gdańsk Deep (*ca* 100 m depth) subjected to scrutiny in the present investigation is among the deepest in the Gdańsk Basin. The temperature and salinity stratification varies here during the year. In the spring – the season when the measurements for this study were made – the thermocline has either not yet formed, or else there is an incipient thermocline in the surface layer. In May, winter waters below 3°C are present in the intermediate layer (50–70 m). The near-bottom water layer (below the pycnocline) remains relatively stable throughout the year; here, the salinity can rise to *ca* 12 PSU and the temperature to 5°C. Such distributions of temperature and salinity ensure a fairly stable density distribution in waters where negative temperature gradients are balanced by positive salinity gradients.

This publication supplies the results of an examination of the changes in salinity, temperature and selected chemical parameters due to groundwater seepage in the Gdańsk Deep. Reference is made to the fact that the density distribution in the stratified water column is destabilised by turbulent convection.

2. Materials and methods

The study was carried out on board r/v 'Kopernik' anchored at a permanent sampling station ($\phi = 54°52'$N, $\lambda = 19°10'$E) in the Gdańsk Deep (Fig. 1). Every two hours from 5 to 11 May 1997 the temperature and salinity were measured with an STD probe, additionally equipped with a sensor to measure the light attenuation coefficient in the 660 nm band.

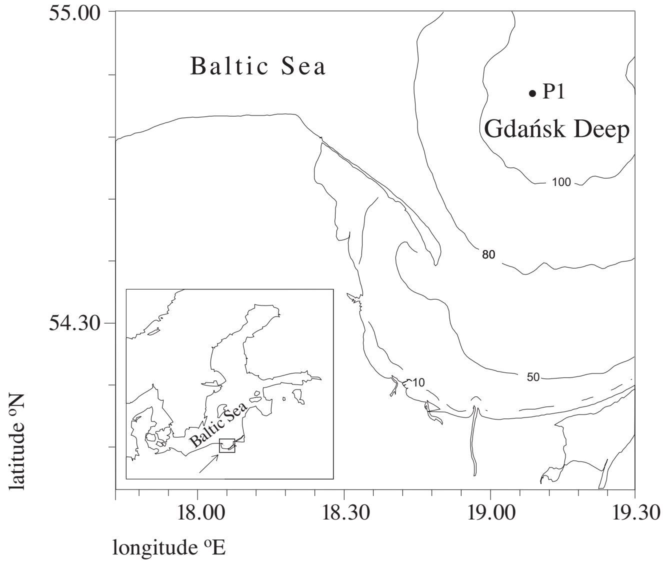

Fig. 1. Location of the sampling station P1 in the Gdańsk Deep

The following parameters were measured in seawater samples taken with a bathometer:

- suspended matter – by filtering 2 dm^3 of water through Whatman GF/F filters;
- oxygen content – by Winkler's method (Grasshoff *et al.*, 1983);
- nutrient content – measured spectrophotometrically by techniques recommended for the chemical analysis of Baltic waters by UNEP/IOC/IAEA (1988).

The times of the probe measurements and the bathometer sampling of the water were staggered by 1 hour.

3. Results and discussion

These investigations, carried on continually over a number of days, demonstrate that there is a constant seepage of groundwater reducing the salinity of the near-bottom seawater (Fig. 2a). Only 13 of 58 profiles showed a constant rise in density from the surface to the bottom, where in the sub-pycnocline layer the salinity varied in the 11–12 PSU range and the temperature from 5 to 5.8°C. In all the other profiles, water of a lower salinity was found to be present in this layer. In a few cases the temperature there was in excess of 7°C (Fig. 2b).

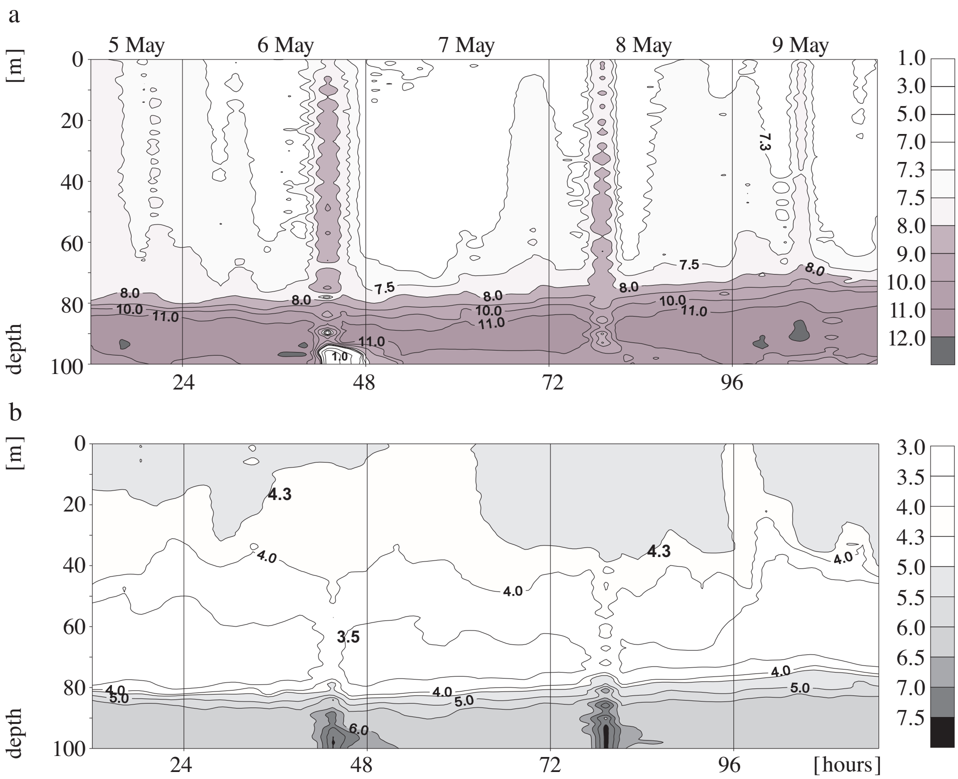

Fig. 2. Temporal variations in salinity [PSU] (a) and temperature [°C] (b) in the Gdańsk Deep (May 1997)

The subterranean waters lying in Upper Cretaceous formations are probably of major importance in the hydrogeology of this region. The ceiling of the aquifer lies on an ordinate *ca* 140 m below sea level at Gdynia and 95 m below sea level at Hel. These Upper Cretaceous waters are under pressure. Their present-day piezometric level has stabilised on the Polish coast somewhat below sea level. They are freshwaters with a constant temperature close to the mean annual air temperature of 6–7°C (Jankowska *et al.*, 1994).

In the two characteristic situations distorting the density structure of the water column, convection circulations were forced by the rising elements of water, whose total buoyancy was greater than the total molecular friction (Fig. 3). The precondition for the formation of laminar convection structures is the first critical Rayleigh number (Druet, 1994):

$$R^I_{a\ \text{crit}} = \frac{27}{4\pi^4}.$$

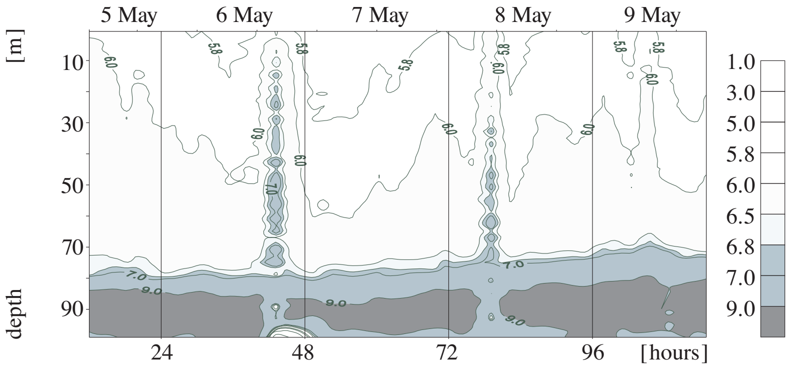

Fig. 3. Temporal variations in density (σ_τ) [g dm^{-3}] in the Gdańsk Deep (5–9 May 1997)

The second critical Rayleigh number defines the transition phase where convection changes from laminar to turbulent:

$$R_a^{II} \approx 50\ 000.$$

In order to recognise the type of the convection, the temperature-salinity Rayleigh number was calculated from the formula

$$R_a^{TS} = g\frac{H_k^3}{\nu}\left(\frac{\beta\Delta S}{k_S} - \frac{\alpha\Delta T}{k_T)}\right),$$

where

g – acceleration due to gravity [9.81 m s^{-2}],
H_k – thickness of the water layer [m] in which differences in salinity ΔS [PSU] and temperature ΔT [°C] occur,
ν – kinematic coefficient of viscosity of water [1.3×10^{-2} cm^2 s^{-1}],
k_T – coefficient of molecular diffusion of heat [1.3×10^{-3} cm^2 s^{-1}],
k_S – coefficient of molecular diffusion of salt [1.3×10^{-5} cm^2 s^{-1}],
α – coefficient of thermal expansion of an element of water [2×10^{-4} °C^{-1}],
β – coefficient of variation in volume of an element of water due to the presence of salt [8×10^{-2} PSU^{-1}].

These coefficients have been taken from Kamenkovich and Monin (1978).

The thickness of the convection layer H_k was determined by consecutive measurements of the STD probe (from 0.2 to 5 m, where $\Delta S/\Delta z$ = const). This manner of calculating the temperature-salinity Rayleigh number was adopted following the analysis of the effect particular parameters had on the final result. Of greatest significance here was the difference in salinity between particular measurements; the H_k value exerted a smaller influence, as demonstrated by the following data (Tab. 1):

Table 1. Examples of parameters adopted to calculate the temperature-salinity Rayleigh number

H_k	ΔS	ΔT	order of R_a^{TS}
0.05	0.01	0.01	10^{10}
0.05	0.00	0.01	-10^{4}
0.05	0.00	0.12	-10^{5}
0.63	0.03	0.14	10^{12}
0.84	2.60	0.13	10^{14}
0.89	0.00	0.01	-10^{9}
1.56	0.01	0.01	10^{13}
2.61	6.53	0.02	10^{15}
3.50	0.00	0.12	-10^{10}
4.75	0.01	0.03	10^{11}
4.80	0.09	0.08	10^{14}
6.47	4.65	0.05	10^{17}

On the basis of these computations of the Rayleigh number, one can refer to two distinct situations that occurred during the measurement series:

- one, which occurred twice (6 May, 19:00; 8 May, 07:00) when free convection became turbulent. The temperature and salinity gradients then reached very high values, of the order of ± 3; at *ca* 10^{16}, the Rayleigh number was many times greater than the second critical value (Fig. 4a). Then the more saline water extended beyond the pycnocline right up to the surface layer (Figs. 2 and 3);
- the other, applying to all the other measurement profiles, when turbulent convection was maintained in the sub-pycnocline layer (Fig. 4b), where circulations came into being that tended to remain within that layer.

That salinity term in the equation was responsible for the high values of the Rayleigh number.

Figs. 2 and 3 suggest that seepage in the Gdańsk Deep is intermittent. However, in view of the lack of a plausible scientific explanation for the possible intermittent nature of the seepage, this must be put down to an error in the presentation of the results. This error is fairly easy to explain: despite being at anchor, the vessel changed her orientation depending on the direction and velocity of the wind. The greatest distance from her initial position could have been as much as 300 m (including the length of the anchor chain and the ship herself).

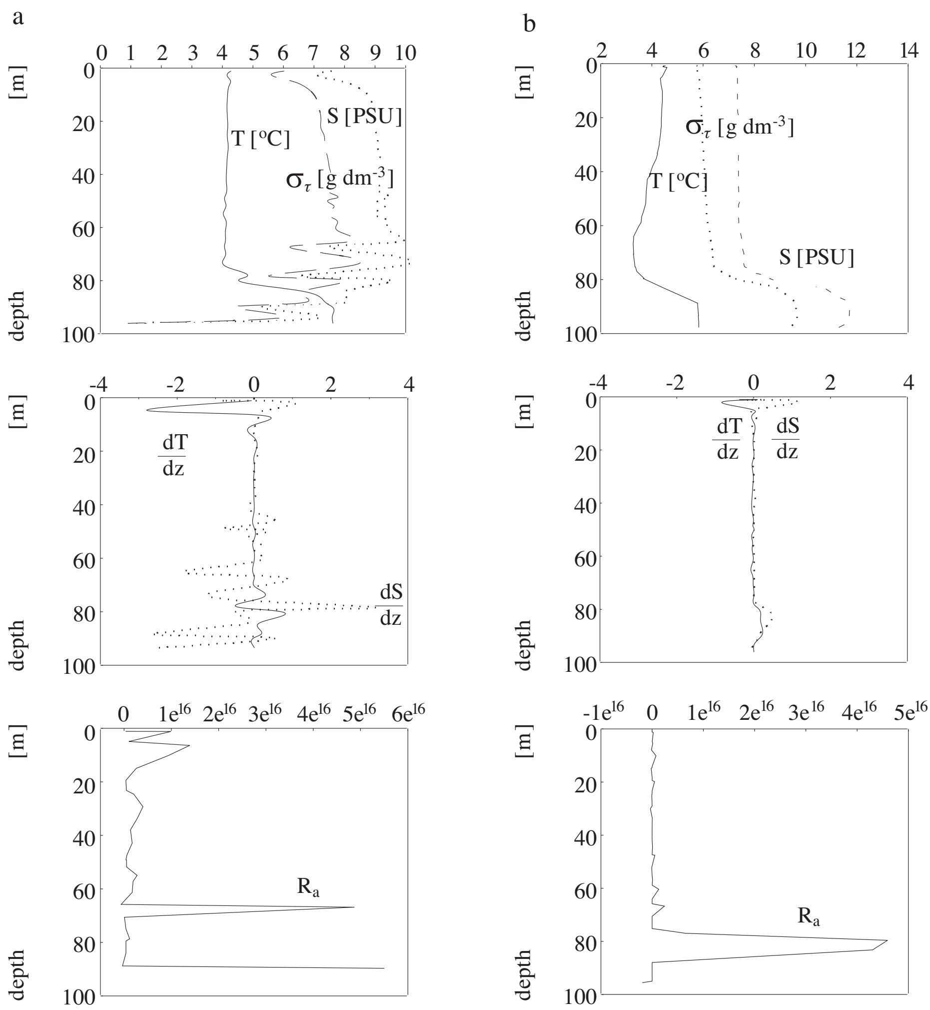

Fig. 4. Vertical distributions of physical parameters in the Gdańsk Deep in the convection zone (6 May 1997, 19:00) (a), beyond the convection zone (6 May 1997, 07:00) (b)

Analysis of wind directions has shown that

- the two characteristic turbulent convection situations were measured when the wind was blowing from the south-easterly sector with roughly the same strength, such that the ship was exactly above the point of seepage, or nearly so;
- in the first case (6 May, 19:00) the wind continued to blow from the south-east for nearly 4 hours;

- in the second case (8 May, 07:00) south-easterly winds blew for less than two hours, while the ship slowly moved around above the seepage area.

It is therefore possible that groundwaters permeate onto a small area of the sea floor, perhaps along a fault line. The likelihood of there being neotectonic dislocations at the bottom of the Gdańsk Deep is discussed by Rosa (1990).

It is the consequences of this submarine seepage of freshwater that would appear to be interesting to the oceanographer. A density distribution in the water column destabilised by powerful convection carries large amounts of the suspended matter accumulating in the near-bottom layer up to the surface (Fig. 5a), considerably elevating the light attenuation coefficient in the 660 nm band (Fig. 5b). A several-fold rise in the suspended matter

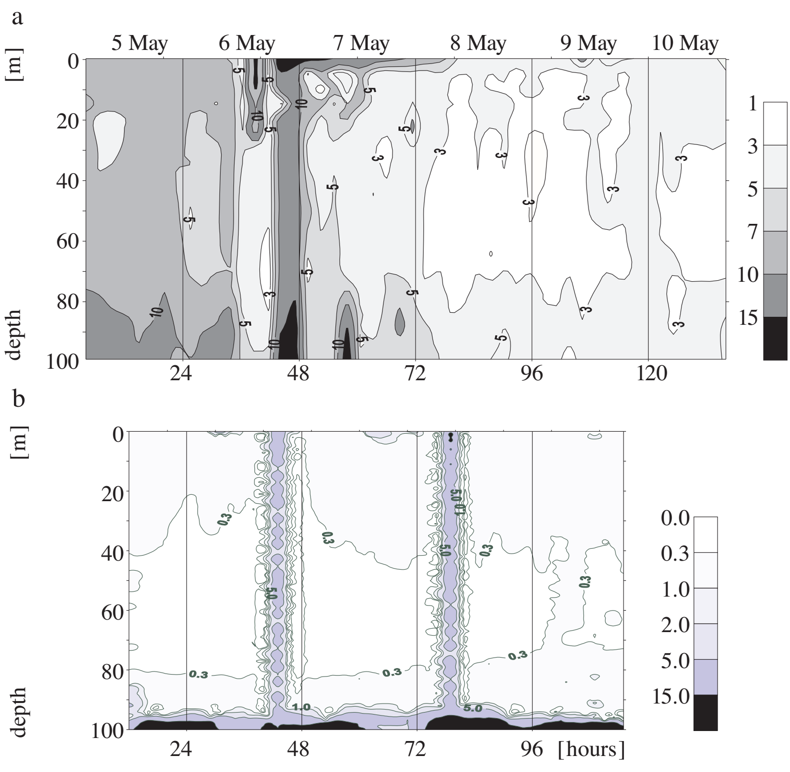

Fig. 5. Temporal variations in suspended matter concentration [mg dm^{-3}] (a) and the light attenuation coefficient [m^{-1}] (b) in the Gdańsk Deep (May 1997)

concentration in the water column was detected only during the first powerful convection. In the second case, there was no such elevation of the suspended matter concentration. This may well have been due to the fact that there was an hour's lapse between the STD probe reading and the bathometer water sampling. The ship's orientation with respect to the seepage source must have changed during that hour. Whereas the probe took readings within the convection current itself, the bathometer will have sampled the water beyond it. This suggests that the seepage area is quite small, or else that the ship moved perpendicularly to the fault line from where the groundwater was escaping.

The presence of gases in the turbulent convection of water elements is also likely. A temperature rise of a few degrees reduces not only the solubility of gases, but also the probability of chemical compounds changing from the ionic form into a gas. Moreover, oxygen has frequently been recorded as being absent from the sediments and interstitial waters of the Gdańsk Deep (Trzosińska, 1990). Under reducing conditions, denitrification can produce molecular nitrogen, which as a non-reactive gas permeates the water column and escapes into the atmosphere. Nevertheless, unequivocal confirmation of the participation of gaseous molecules requires direct measurements to be made.

Analysis of the oxygen content showed that weakly oxygenated near-bottom waters (*ca* 2 cm^3 dm^{-3}) were being raised towards the surface (Fig. 6). Equally, high concentrations of phosphates and nitrates, usual

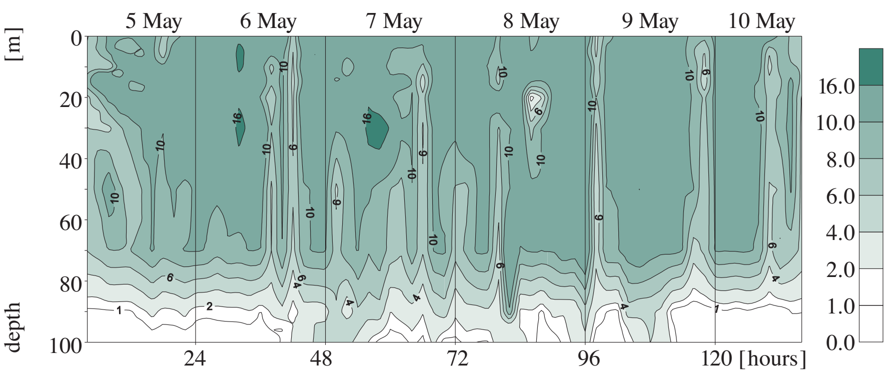

Fig. 6. Temporal variations in oxygen content [cm^3 dm^{-3}] in the Gdańsk Deep (May 1997)

in deep waters below the pycnocline (Trzosińska, 1990; Trzosińska and Łysiak-Pastuszak, 1996), were being raised above it (Figs. 7a and 7b). The convection cells, clearly marked, for example, by the short-term variations in nitrate concentration in the near-bottom layer, testify to the importance of this process. Apart from convection, the internal waves occurring at the density boundary may be playing an important part in raising chemical compounds stored below the halocline. Stimulated by groundwater seepage, the steep temperature and salinity gradients may intensify both the amplitudes of internal waves and the flow of nutrients up to the surface layers.

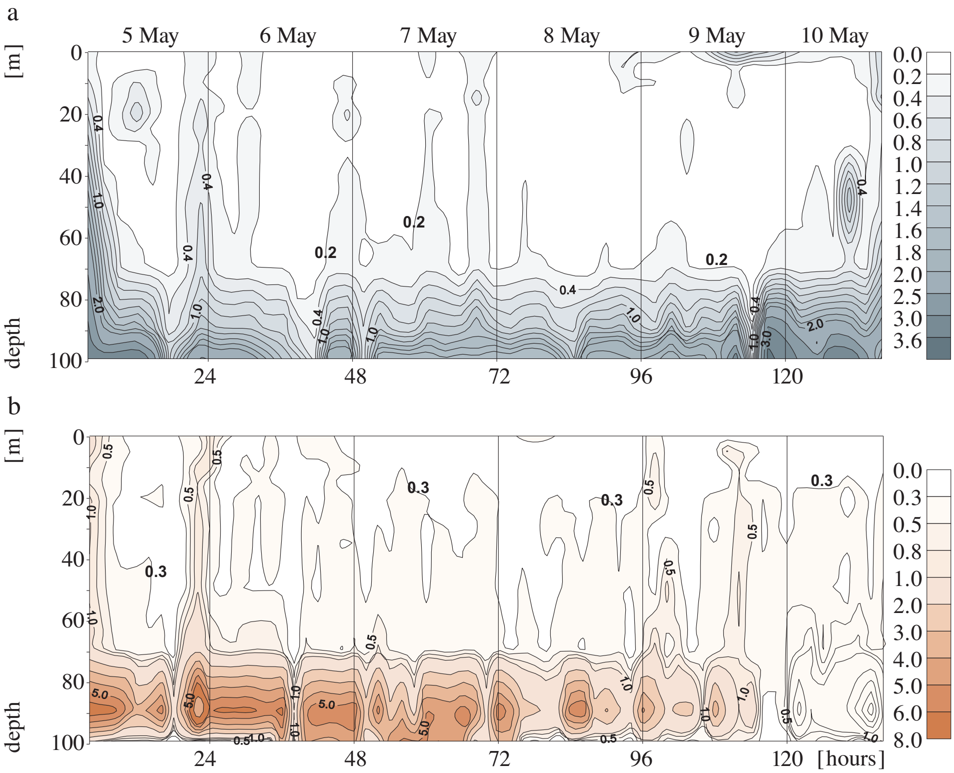

Fig. 7. Temporal variations in the concentrations of phosphates (a) and nitrates (b) [mmol m^{-3}] in the Gdańsk Deep (May 1997)

4. Conclusions

1. The strongly depressed salinity to below 1 PSU and the elevated temperature (5–7.5°C) of the near-bottom water layer is probably due to the presence of groundwaters.
2. The layered density structure of the basin is disturbed by turbulent convection. The temperature-salinity Rayleigh number exceeded by far the second critical value and in extreme cases was equal to $\pm 10^{16}$. Such high values were due largely to the great differences in salinity in the near-bottom water, and to a lesser extent to temperature differences.

3. Large quantities of suspended matter were raised from the bottom by the powerful convection current, bringing about a considerable increase in the light attenuation coefficient.
4. The elevation above the halocline of inorganic phosphorus compounds and nitrates in clearly marked circulation cells and of poorly oxygenated water was due to turbulent convection.
5. The observed seepage of groundwater probably occurs continually.
6. Further research should attempt to answer the following questions:
   - What area is affected by seepage? What is its intensity? What are the hydrogeological conditions obtaining in the seepage zone?
   - What is the nature of the movement of water masses and the magnitude of sea currents within the convection area and beyond it?
   - What changes in the chemical composition of near-bottom waters are caused by this seepage?
   - Do gases participate in the convection process?
   - What effect do anomalies of this kind have on the environmental conditions of the basin?

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