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HYDROGRAPHY OF THE BALTIC  
DEEP BASINS

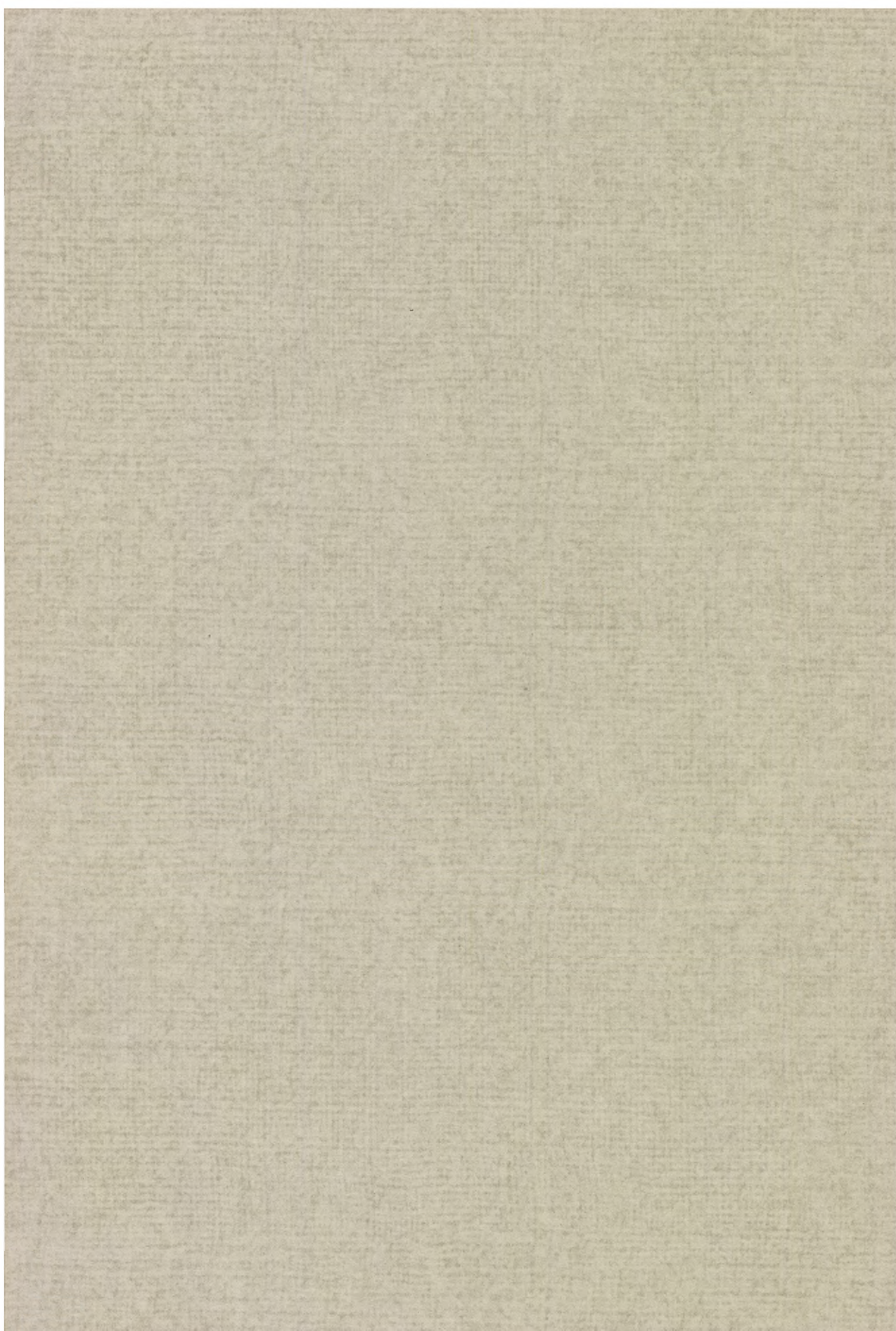
BY

*STIG H. FONSELIUS*

LUND 1962

CARL BLOMS BOKTRYCKERI A.-B.





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## Abstract

The measurements made during the last 50 years and the salinity increase of the Baltic are described. The transport of bottom water between the basins, the salt inflows and the stagnation periods are discussed. The great salt inflow of 1952 and the long stagnation which followed it are described in detail. The conditions during 1960 and the turnover of the water in the Gotland basin in 1961 are discussed and described. The accumulation of nutrient salts in the Gotland basin during the stagnation is described and the conditions are compared to other anoxic basins. The analysis method for hydrogen sulphide is described. The development of the stagnation in the Gotland basin is traced in detail. The speed of the inflow is discussed.



## I. Introduction

Regular hydrographic observations have been carried out on specific deep stations in the main basins of the Baltic from the beginning of the present century. This long record has only been broken during the two world wars and during a short period in the thirties. The work has been made by Danish, Finnish, German, Lettonian, Polish, Russian and Swedish oceanographers. Most of the measurements have been published in *Bulletin Hydrographique*, or in journals from the different institutions taking part in the investigations during different periods. All these journals are listed in the references under Anonymous.

It is a well-established fact that the salinity of the Baltic has increased during this time. This increase has been described and discussed by e.g. GRANQVIST (1952), SEGERSTRÅLE (1953), WYRTKI (1954 a and b) and LINDQUIST (1959).

SEGERSTRÅLE has estimated this increase, measured from Finnish light-ships, at 0.5 ‰ S during the last 50 years. LINDQUIST got the same order of magnitude for the Gulf of Bothnia. WYRTKI (1954 a) has described in detail the unusually great salt inflow in 1951—1952 and calculated the amount of salt brought in through the Belts into the Baltic during this inflow. According to him this salt inflow was great enough to raise the salinity of the whole water mass of the Baltic by 0.1 ‰. Such an inflow every tenth year should be enough to cause the 0.5 ‰ salinity increase of the Baltic estimated by SEGERSTRÅLE.

In a later paper, however, WYRTKI (1954 b) estimated the amounts of salt brought into the Baltic by the bottom current in the Belts, and got results which showed that during one month enough salt was brought in to cause an increase as great as the yearly increase calculated from SEGERSTRÅLE's values. It is obvious that no conclusions concerning the small increase of the salinity in the Baltic can be drawn from these large fluctuations in the salt budget.

Hydrographically the Baltic should be very similar to the Black Sea, but in the Baltic the water exchange with the open ocean is much better than in the Black Sea and therefore it is possible for ocean water to penetrate through the Belts into the Baltic and renew the bottom water in the main deep basins. The relatively small area and shallowness of these basins make



this renewal possible in a short time during favourable weather conditions. This occasional renewal of the bottom water prevents the Baltic from establishing the anoxic conditions typical of the Black Sea. (The word "anoxic" is here used instead of the more common "anaerobic" in agreement with RICHARD's and BENSON's suggestion.) (RICHARD and BENSON 1961 p. 263). Between the above mentioned inflows of oxygen-rich ocean water, there are stagnation periods during which the oxygen content of the deep water in the big basin of the central Baltic under the halocline decreases to values approaching 0 ml/L and during unusually long stagnation periods all oxygen may disappear near the bottom and even hydrogen sulphide may be present in the water.

The purpose of this paper is to describe in greater detail how such salt inflows influence the conditions in the deep basins of the Baltic. MANKOWSKI (1958) has described the conditions in the Bornholm and the Gdansk basins from 1946 to 1956, but since the Bornholm Basin is the most important of the Baltic basins and all inflowing water has to pass through it before reaching the other basins, the Bornholm Basin will be dealt with here again. Unfortunately very few data exist from the deeps in the northern-most part of the Baltic. A lot of data have been published concerning the Gotland Basin and the Landsort Deep and these parts of the Baltic will be discussed below.

## II. The Bottom Topography of The Baltic

Fig. 1 is a chart of the Baltic showing the main hydrographic stations. The Bornholm Basin, the Gotland Basin and the Landsort Deep have maximum depths of 105, 249 and 459 m respectively. The topography of the bottom in the Baltic is such that the heavy high saline bottom water which, through the Belts (sill depth 18 m), flows in, first arrives at the 55-m-deep Arkona Basin (fig. 1 station S12). From there it can only continue over the 50 meter sill (fig. 1 station S11) between Bornholm and the Swedish mainland to the 105-m-deep Bornholm Basin (fig. 1 stations Chr and S24). The Bornholm Basin is surrounded by shallow banks and the only possibility for the heavy bottom water to continue into the rest of the Baltic is to flow over the 60 m sill to the Stolpe Channel (fig. 1 station S23) and through it to the deeps east and north of the Bornholm Basin. The high sill naturally prevents the heaviest water from continuing down into the rest of the Baltic and therefore the salinity at the bottom of the Bornholm Basin is always higher than in the subsequent basins. The Gdansk Deep will not be dealt with here; it is

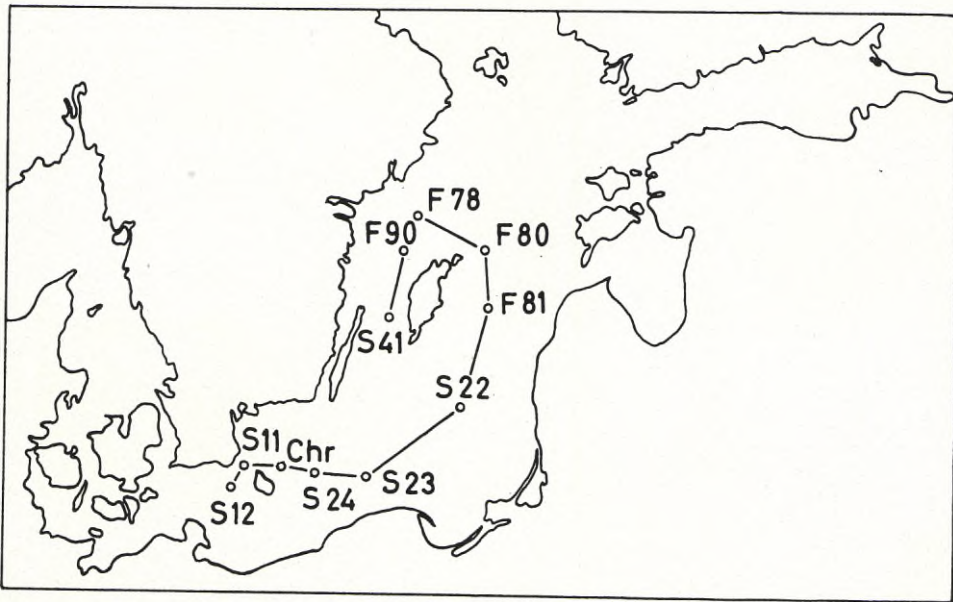


Fig. 1. Chart of the Baltic with the main hydrographic stations mentioned in this paper.



a peripheral area in the bottom topography and therefore not important for the rest of the Baltic. The conditions in the Gdansk Deep have been described by MANKOWSKI (*loc. cit.*).

East of the island of Gotland is the extensive Gotland Basin (fig. 1 station F 81). The 249-m-deep Gotland Basin is isolated from the Fårö Deep (fig. 1 station F 80) by a 140-m-deep sill. The Fårö Deep is 205 m deep at its deepest part and is limited in the north by a sill 115 m deep from a big deep area which continues without sills into the Gulf of Finland and slopes down in the west into the deepest part of the Baltic, the Landsort Deep with a maximum depth of 459 m (fig. 1 station F78). The Gulf of Bothnia is isolated from the Baltic proper by a 70-m-deep sill and will not be dealt with here. The water from the 100 m level in the Landsort Deep can continue to the south over a sill to a deep area including the Norrköping Deep (fig. 1 station F90) and west of Gotland the Karlsö Deep (fig. 1 station S41), 192 and 114 m deep respectively. Shallow banks with a depth of about 20—40 m begin south of this area.



### III. The stagnation periods and the salt inflows in the Baltic

The largest record of measurements is from the Bornholm Basin, where measurements were started around 1902. The work was discontinued in 1914 and started again in 1921. From 1921 we have an almost unbroken series of data. The figures 2, 3 and 4 show diagrams over all published measurements of temperature, salinity and oxygen content at 80 m depth in the Bornholm Basin, as well as unpublished Swedish measurements made during recent years, which will be available in the ICES punchcard system in Copenhagen.

All data are not from the same spot in the basin, but from different stations used by the different research institutes involved in the investigation. Unfortunately, the deepest parts of the Bornholm Basin have been used for dumping war gases and ammunition and are therefore considered dangerous for hydrographic work. However the conditions at different places in the basin do not show any significant hydrographic differences at the same depth.

The most striking changes in the diagrams are found between 1951 and 1952, when the temperature and the salinity suddenly increased to abnormally high values. This is due to the great salt inflow described by WYRTKI (1954 a).

This inflow is followed by a long stagnation period during which the salinity drops regularly from 21 ‰ to 13 ‰. The temperature change is not as continuous as the salinity change, but it shows a clear decreasing trend from 8°C to 5°C.

Several smaller salt inflows can be recognized from the diagram (fig. 3). The first probably occurred just after the measurements started. The single value from 1902 is almost 1 ‰ lower than the two values in 1903 and the difference in temperature is still greater (fig. 2). From 1903 there is a steady decrease of salinity until 1907, when a new salt inflow occurred. The temperature shows a simultaneous increase. The following stagnation was broken in 1909 by a new salt inflow. The new stagnation after this inflow brought the salinity down from 16.8 ‰ to 15 ‰ and in 1912 a new inflow raised it to 16.2 ‰. After the first world war observations were started again in 1921. The salinity was at that time as high as 17.7 ‰ and decreased to 14.1 ‰ in 1924. The single value from 1925 indicates a new salt inflow which reached its maximum in 1926. From 1926 to 1937 there were several smaller inflows. In 1937 a new bigger inflow occurred. The observations during the second

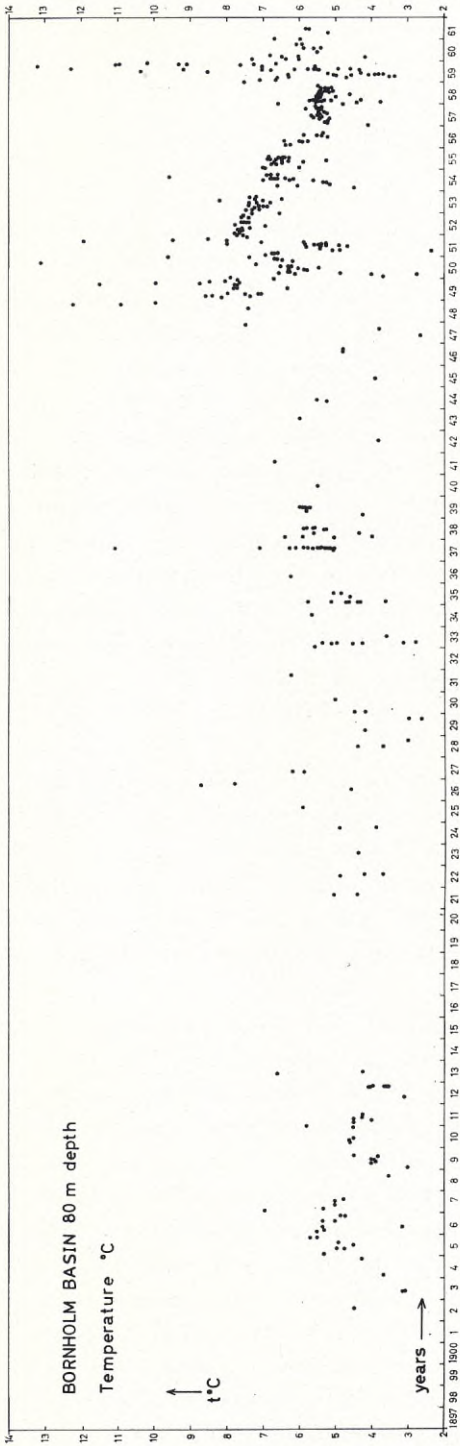


Fig. 2. Temperature values from 1900—1961 in the Bornholm Basin at 80 m.

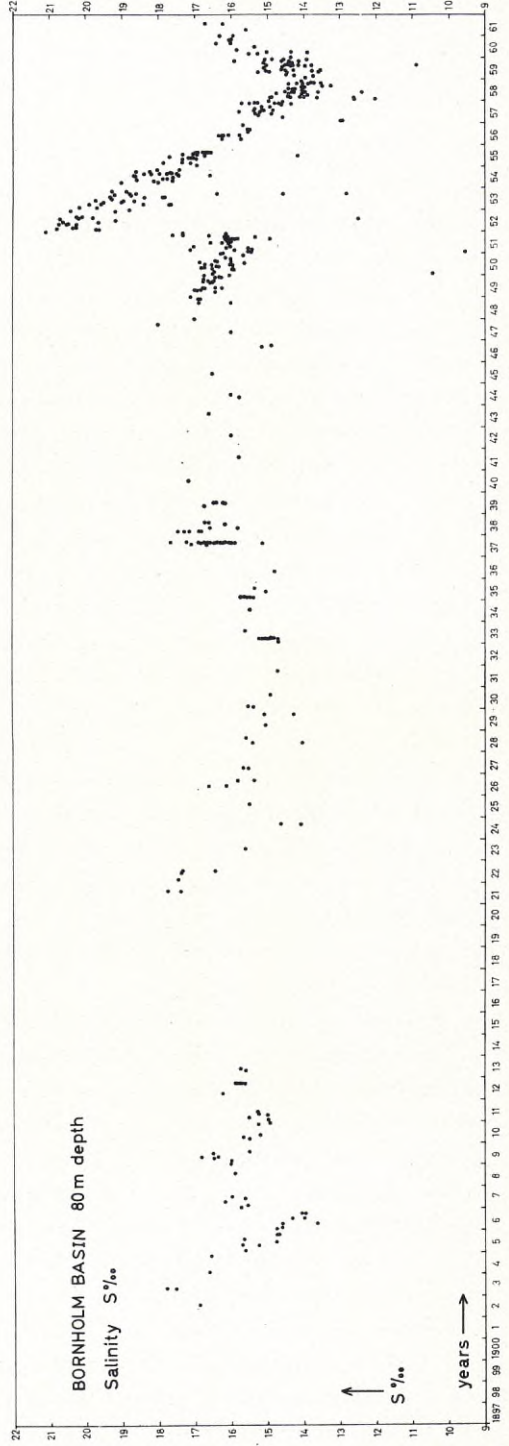


Fig. 3. Salinity values from 1900—1961 in the Bornholm Basin at 80 m.



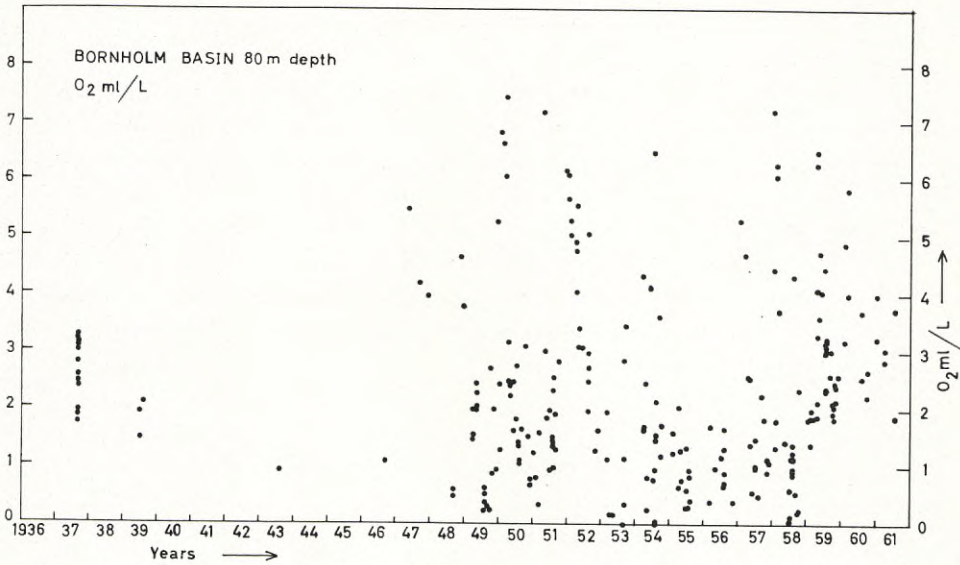


Fig. 4. Dissolved oxygen values from 1937—1961 in the Bornholm Basin at 80 m.

world war are too few to give any details, but they indicate that no great changes occurred during this time. The next great inflow can be found in 1948 followed by a stagnation period until 1951, when the greatest inflow ever observed occurred in November—December, followed by an unusually long stagnation period which was broken first in November 1959. The great salt inflow in 1951 is clearly something extraordinary, which has never been observed before. During the following long stagnation period in the Bornholm Basin, no new oxygen-rich water has flown through the Belts to the rest of the Baltic, and this has caused stagnation and anoxic conditions in the Gotland Basin.

The word stagnation does not mean that no new water is mixed in to the watermass, but that not enough water flows in to modify the stagnant conditions. The oxygen values (fig. 4) vary between saturated values and zero values even during the same month. These great variations indicate that the oxygen is renewed very often, but is used up very rapidly close to the halocline. No low values can be found during the period immediately after the 1951 inflow, and there is a clear decrease of the oxygen until 1957. After 1958, when the new inflow began, no values under 1 ml/l can be found.

The temperature values show great variations (fig. 2) too, but the trend is decreasing until 1959. The rapid and almost linear decrease of the salinity indicates that turbulent mixing or maybe inflow of colder water of low salinity over the surrounding banks cause these rapid changes of temperature and



oxygen content of the deep water. This mixing with colder water might even explain the decreasing temperature of the water mass.

The next figure (fig. 5) shows the temperature, salinity and oxygen values in the Gotland Basin at 200 m (station F81) from 1902 onwards. As can be seen immediately, the variations are not so large as in the Bornholm Basin. It is not always possible to identify the salt inflows described above in the Bornholm Basin, because they may not reach this area. The changes in the Gotland Basin are better compared with the changes at the 60 m level in the Bornholm Basin. The bottom water in the Bornholm Basin is completely isolated from the Gotland Basin as long as stagnation continues in the former basin and small inflows may pass over the heavy bottom water into the latter basin. The salt inflow in 1907 can easily be recognized and also the inflow in 1926. The inflow in 1934 has been described by KALLE (1943) and probably corresponds to the 1933 inflow in the Bornholm Basin. The great inflow in 1937 into the Bornholm Basin seems to correspond to a slowly occurring inflow in the Gotland Basin during 1937 to 1939. This last inflow may have continued after 1939 but the war stopped all measurements in this area for a long time. The measurements started again in 1949 and values obtained then were as high as the last values in 1939. No conclusions can of course be drawn from this, but the few values from the Bornholm Basin during the war did not indicate any abnormal conditions there and there is no reason to believe that any great changes could have taken place in the Gotland Basin without influences from the Bornholm Basin.

The big inflow of 1951 and the subsequent long stagnation are clearly visible, but no traces of the 1959 inflow into the Bornholm Basin can be detected at 200 m until 1961, where the very last value in July shows that the stagnation has now been broken after nine years.

Sometimes temperature is a better indicator of the change of water than salinity. At the beginning of 1955, for example, the temperature in fig. 5 drops suddenly, and a closer investigation of the salinity shows even a small decrease.

Still better than the temperature and the salinity values, the oxygen values show the inflows and the stagnation periods. In 1905 the oxygen value had decreased from about 2.5 ml/l to 1 ml/l and it increased again after the salt inflow in 1908 to 4 ml/l. Stagnation during the 1920's brought the oxygen value down to 0 and the smell of  $H_2S$  was reported 1931 (GRANQVIST 1931). As mentioned above, KALLE has described the great turnover in the Gotland Basin 1934 (KALLE 1943). The long stagnation period after 1952 brought the oxygen down to 0 in 1956 and in 1958 the smell of  $H_2S$  could be detected (personal communication from Mr. S. ENGSTRÖM at our laboratory). The oxygen concentration remained at 0 from 1957 to 1961, when the value in July suddenly rose to 2 ml/l. The  $H_2S$  remained in the Gotland Basin from 1958 to April 1961 and  $H_2S$  could even be detected in the Fårö Deep.

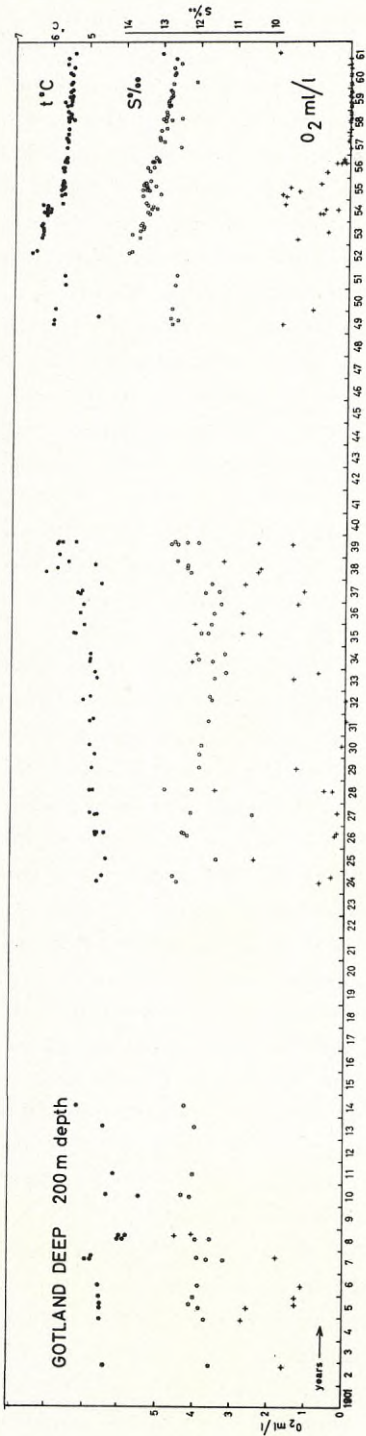


Fig. 5. Temperature, salinity and dissolved oxygen values from 1900—1961 in The Gotland Basin at 200 m.

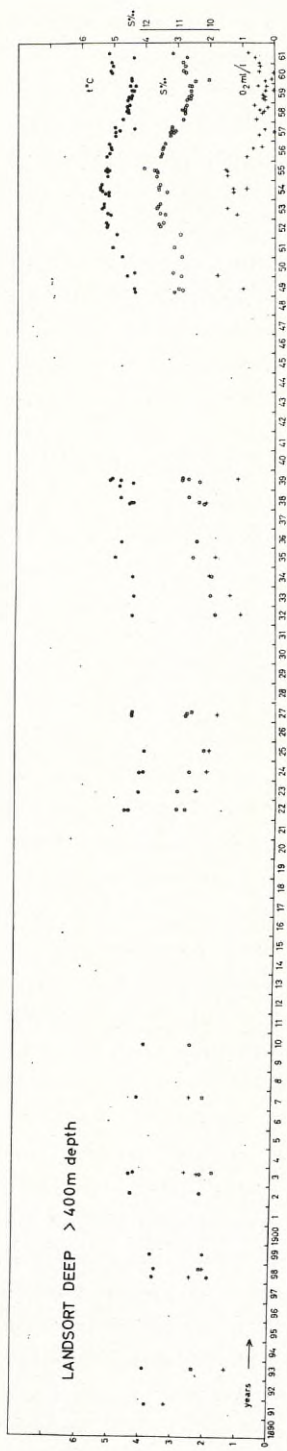


Fig. 6. Temperature, salinity and dissolved oxygen values from 1890—1961 in the Landsort Deep below 400 m.



During the long stagnation there seems however to have been a small inflow of colder water of somewhat lower salinity in the beginning of 1955 as was mentioned above. The oxygen values show a sudden jump from under 1 ml/l up to 2 ml/l. This inflow cannot be found in the Bornholm Basin and it is probably cold oxygen-rich water which has flowed over the high saline deep water in the Bornholm Basin. The values in fig. 6 are from a depth of more than 400 m in the Landsort Deep. The Landsort Deep is the deepest spot in the Baltic and from there some few measurements from the later years of the 19th century exist, but these are too few to allow of any conclusions. Until 1910, when the last measurements before the first world war were made, the values from the Landsort Deep do not indicate any great changes. Even here no work was done during the war and the measurements started first in 1922. The values in 1922 are about 1 ‰ higher in salinity than the prewar values. The salinity decreased from 11 ‰ to 10 ‰ from 1922 to 1925. In 1927 the salinity was again around 11 ‰. No measurements have been found by the author for the period 1927 to 1932. In 1932 the salinity was again 10 ‰ and rose slowly to about 10.5 ‰ in 1935. This may be the inflow described in the Gotland Basin 1934. In 1939, when the work was stopped, the salinity was almost as high as 11 ‰. No measurements were carried out during the war, of course, and the work started again in 1949. Then salinity was again about 11 ‰ and it remained around this value until 1952 when the great salt inflow into the Baltic had penetrated to the bottom of the Landsort Deep and suddenly raised the salinity to 11.6 ‰. Then the salinity remained almost constant to 1955 when the slow decrease began which continued until 1960. Probably the 1959 inflow into the Bornholm Basin arrived at the Landsort Deep in the middle of 1960 and caused this increase of salinity and also of temperature and oxygen content. This water was probably not heavy enough to sink to the bottom of the Gotland Basin, but flowed over the heavy water there to the Landsort Deep. As mentioned above in connection with the Gotland Basin, this inflow could not be detected there at 200 m. As in the Gotland Basin, the oxygen values are good indicators of the water masses. Unfortunately no oxygen analyses were made 1951—1952, but from 1.5 ml/l in 1955 the oxygen dropped to 0.1 ml/l in 1960. The salt inflow in 1960 raised the oxygen concentration to 0.6 ml/l at the beginning of 1961. No traces of  $H_2S$  have been reported from the Landsort Deep, even if some few zero values for oxygen have been found.

From these diagrams it can be seen that the changes in the Bornholm Basin often influence conditions in the Gotland Basin and the Landsort Deep, but that these changes are smaller and slower especially in the Landsort Deep. The long stagnation in the Bornholm Basin seems to have prevented the Gotland Basin from getting any new oxygen-rich bottom water by salt inflows. The great salt inflow raised the salinity in the bottom layers of the Gotland Basin so much that smaller inflows were unable to penetrate to the bottom



of the Basin, but glided over to the Landsort Deep, as happened in 1959—1960. The salinity in the Gotland Basin had to decrease so much that the water in the Bornholm Basin could expel it. The salinity of the water in the Bornholm Basin also decreased during the stagnation period, but in 1959 new water began to flow down and at last the water in the Bornholm Basin had increased its salinity so much that water with a salinity of above 13 ‰ started to flow over the Stolpe Sill and expelled the 12 ‰ water from the Gotland Basin.

The diagrams indicate further that the salinity of the Baltic increased from 1900—1920, decreased to a minimum around 1930 and then begun to increase again.

#### IV. The conditions in the Baltic during 1960 and the salt inflow 1961 into the Gotland Basin

Figs. 7—19 are longitudinal sections of the Baltic from the Arkona Basin through the Bornholm Basin and the Gotland Basin around the island of Gotland to the Landsort Deep and from there to the south, following the track in fig. 1. They show the measurements of salinity, inorganic phosphate and oxygen from RV "Skageraks" cruises in 1960 and 1961. The distances are, as is usual in such figures, suppressed in proportion to the depth and no conclusions regarding the size and the length of the basins and the distance between them should be drawn from the figures.

##### a. Salinity

The first section (fig. 7) shows the salinity in February 1960. At the bottom of the Bornholm Basin (stations Chr and S24) the salinity is over 16 ‰. In the Gotland Basin (F81) the salinity is over 12 ‰ from 150 m down to the bottom. The Fårö Deep (F80) is filled with 11 ‰ water and the Landsort Deep (F78) is from 150 m down to the bottom filled with 10 ‰ water. The Norrköping Deep (F90) is filled with 9 ‰ water.

One month later (fig. 8) low saline water has moved the 12 ‰ isohaline in the Gotland Basin down to 200 m and the isohaline for 10 ‰ in the Landsort Deep down to 425 m. This low saline water has mixed with the water of the Gotland Basin down to the bottom. From fig. 8 can be seen that the salinity at the bottom has decreased to below 12.5 ‰. The amount of new water was not great enough, however, to break the stagnation, as will be shown in connection with fig. 29.

The section from August 1960 (fig. 9) shows that there has been a new inflow of higher saline water and that the isohaline for 12 ‰ in the Gotland Basin is at about 175 m and the 10 ‰ isohaline in the Landsort Deep is at about 150 m, and even in the bottom layers of the Norrköping Deep (F90) there is now water of 10 ‰ salinity. The inflow of ocean water into the Bornholm Basin in 1959 was discussed in Chapter III, and the possibility that during 1960 the water had glided over the deepest parts of the Gotland Basin to the Landsort Deep was suggested. From fig. 9 can be seen that the



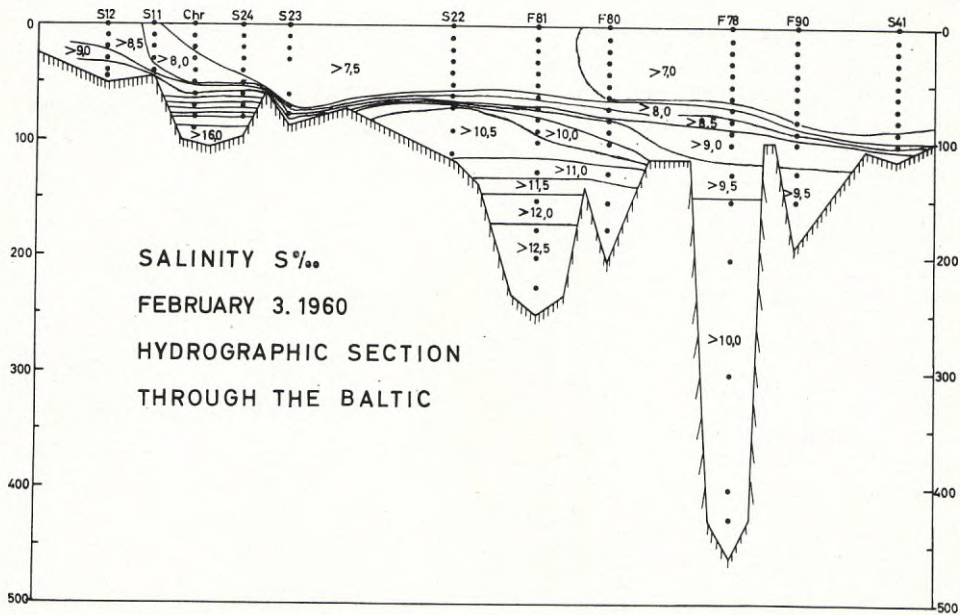


Fig. 7.

Figs. 7—13. Hydrographic longitudinal section through the Baltic from the Arkona Basin—the Bornholm Basin—the Gotland Basin—the Fårö Deep—the Landsort Deep—the Norrköping Deep to the Karlsö Deep. Salinity.

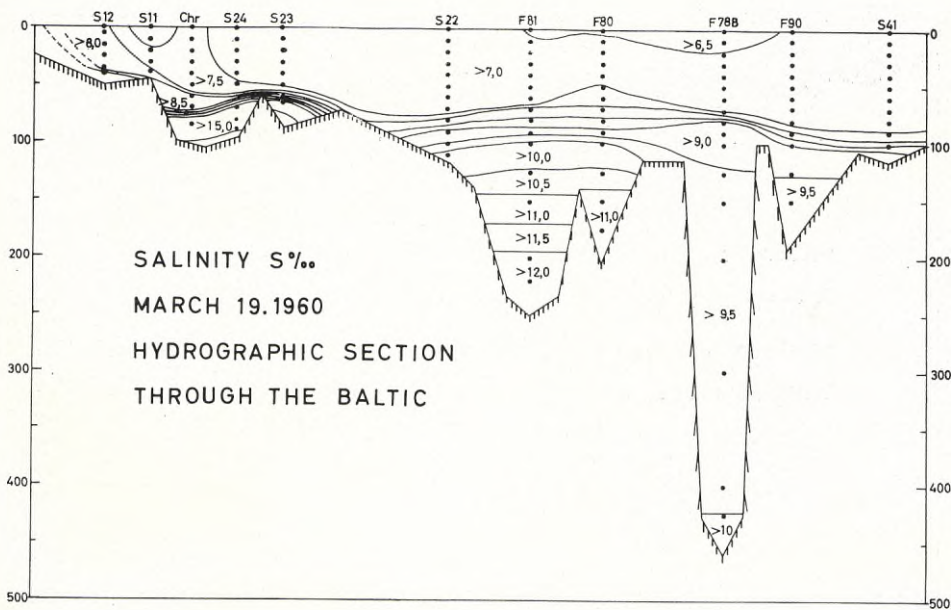


Fig. 8.

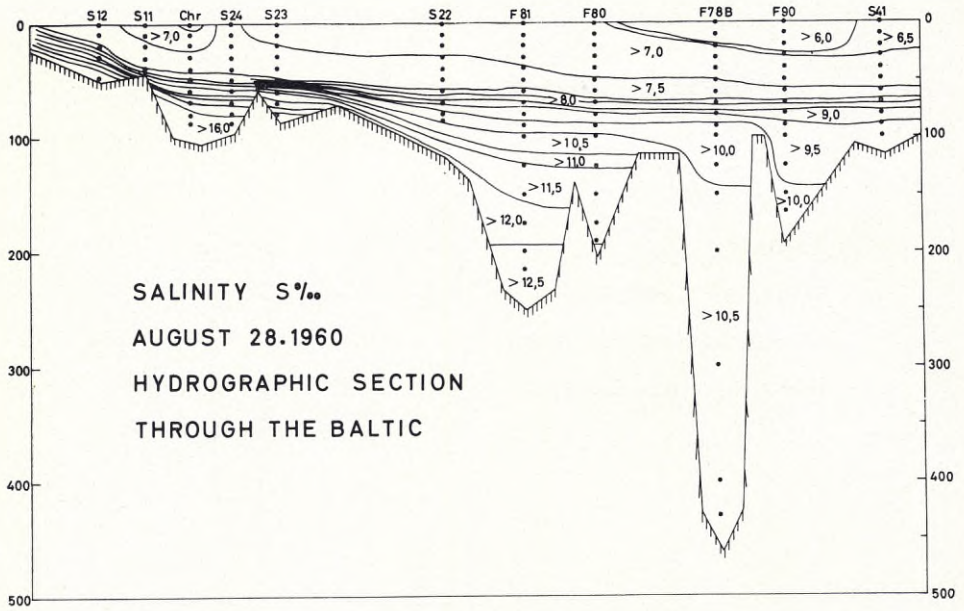


Fig. 9.

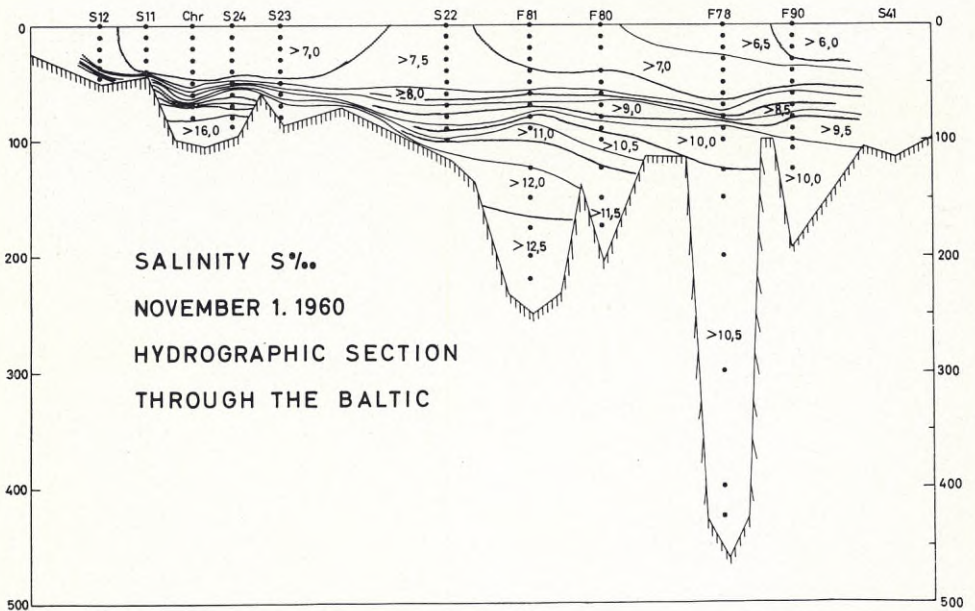


Fig. 10.



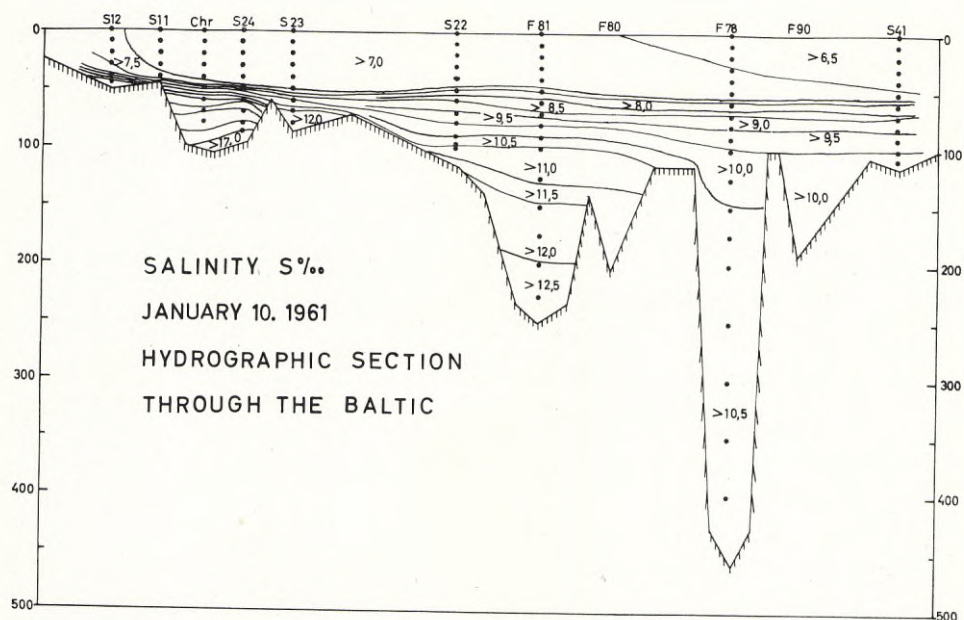


Fig. 11.

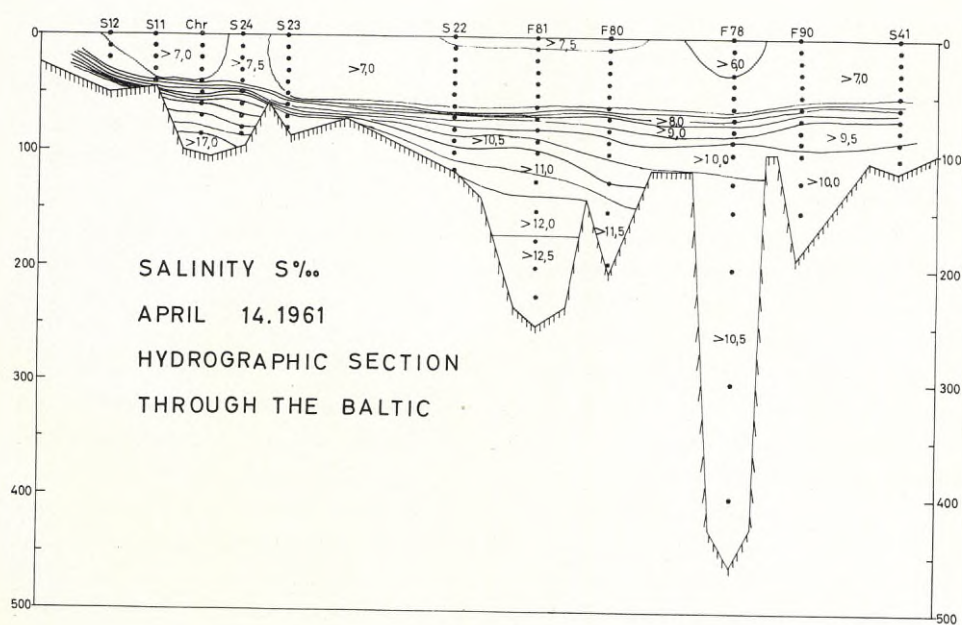


Fig. 12.

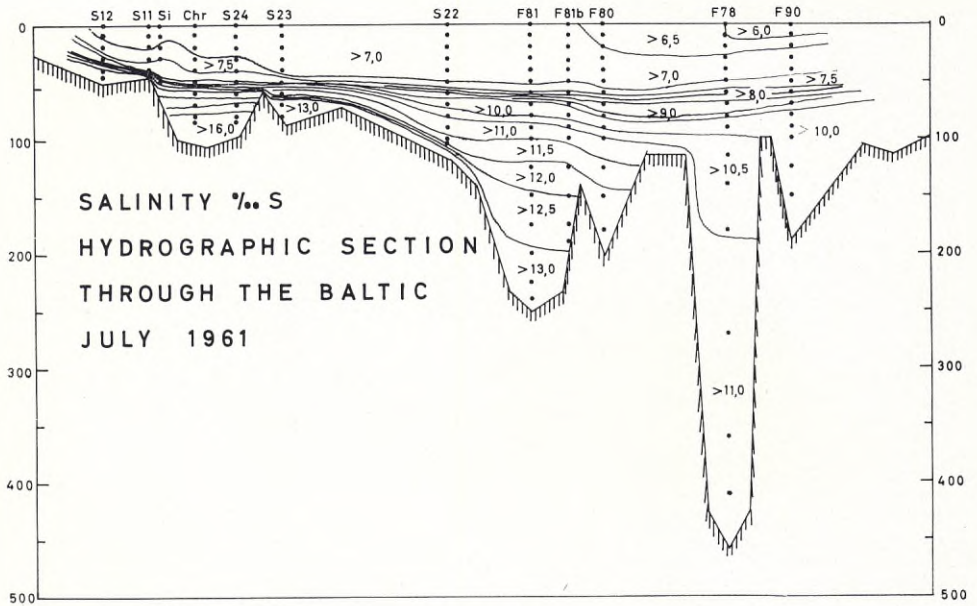


Fig. 13.

isohaline for 12 ‰ has been moved upwards during the inflow, but even if the water mass has flown over the Gotland Basin, some water has mixed with the stagnant water down to the bottom of the Basin. The salinity has again risen in the bottom to over 12.5 ‰, but the stagnation still continues (see fig. 29 for the oxygen content).

In November 1960 (fig. 10) the Landsort Deep had been filled up with 10 ‰ water and the Norrköping Deep was almost filled with the same water. Unfortunately no sampling could be carried out at the Karlsö Deep (S41) due to rough weather.

In January 1961 (fig. 11) the situation was almost unchanged. The salinity had slightly decreased from the halocline down to about 200 m but the deep water was not influenced. The isohaline for 10 ‰ was now at 100 m at station S41. At F90 the rough weather made sampling impossible.

The section from April 1961 (fig. 12), too, showed almost unchanged conditions. Signs of a beginning inflow can be seen in the raising of the isohalines in the Gotland Deep and in the high salinity in the Bornholm Basin (17 ‰ at the bottom at station Chr).

The section from July 1961 (fig. 13) shows that an inflow of high saline water has penetrated from the Bornholm Basin through the Stolpe Channel to the Gotland Basin and the bottom of the Gotland Basin has been filled with 13 ‰ water. The whole basin now contains water with a salinity higher than 12 ‰ and the salinity in the Fårö Deep is also above 12 ‰. The



salinity in the Landsort Deep has risen to above 11 ‰ and the 11 ‰ isohaline is now at about 200 m. The inflow had not then reached the Norrköping Deep.

### b. Inorganic phosphate and dissolved oxygen

Figs. 14—19 show how this inflow has altered the stagnant conditions in the Gotland Basin. If we first look at the inorganic phosphate concentration in the Baltic before the 1961 inflow, we see from figs. 14, 15 and 16 that the inorganic phosphate increased during the whole of 1960. In November 1960 (fig. 16) the phosphate reached values exceeding  $8\mu\text{gAt PO}_4^{3-}\text{-P/l}$  in the Gotland Basin and values exceeding  $2\mu\text{gAt PO}_4^{3-}\text{-P/l}$  in the Landsort Deep. No sections have been drawn for January and April 1961, because no remarkable changes in the P constant have occurred since November 1960.

The result of the inflow of heavy salt water into the bottom of the Gotland Basin during the summer of 1961 is clearly visible in fig. 17 from July 1961. The new water has a low phosphate content and the phosphate values in the bottom of the Gotland Basin are now under  $2\mu\text{gAt PO}_4^{3-}\text{-P/l}$ . The highest concentrations of phosphate are found in the middle layers of the water i.e. at 150 m depth. The water mass has been lifted up by the heavier water and mixed. This mixing process will probably continue during 1961 and all the

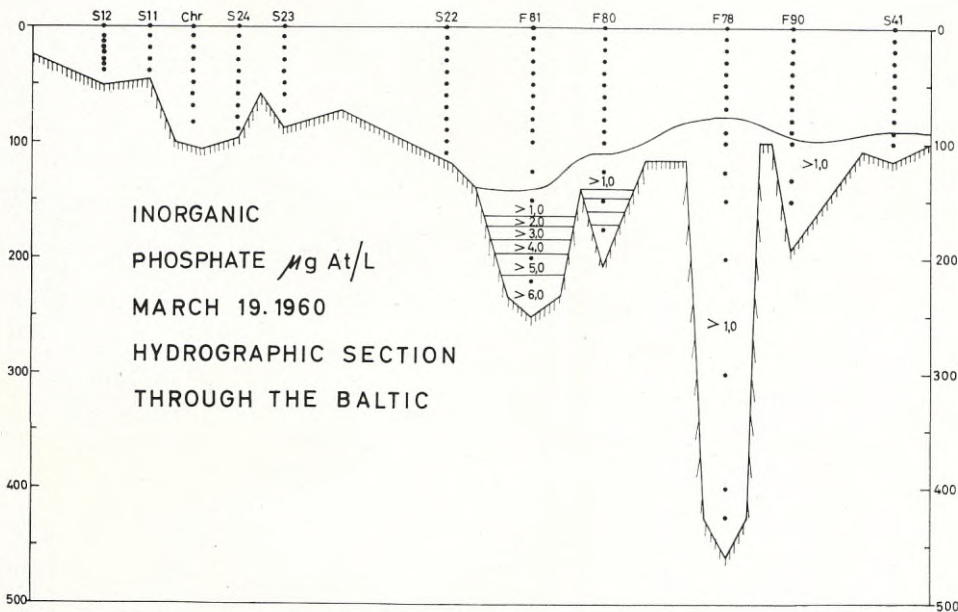


Fig. 14.

Figs. 14—17. Hydrographic longitudinal section. Inorganic phosphate.

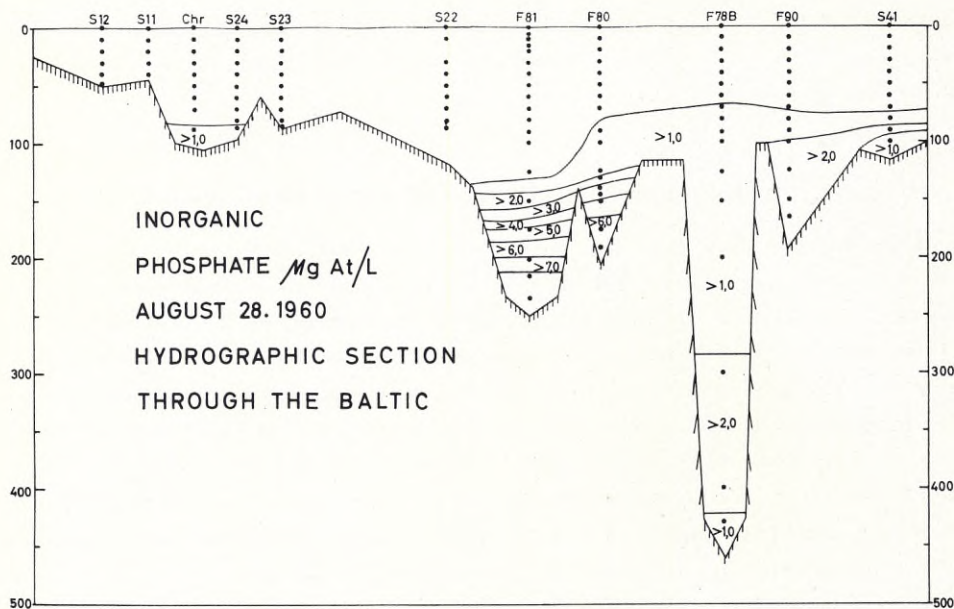


Fig. 15.

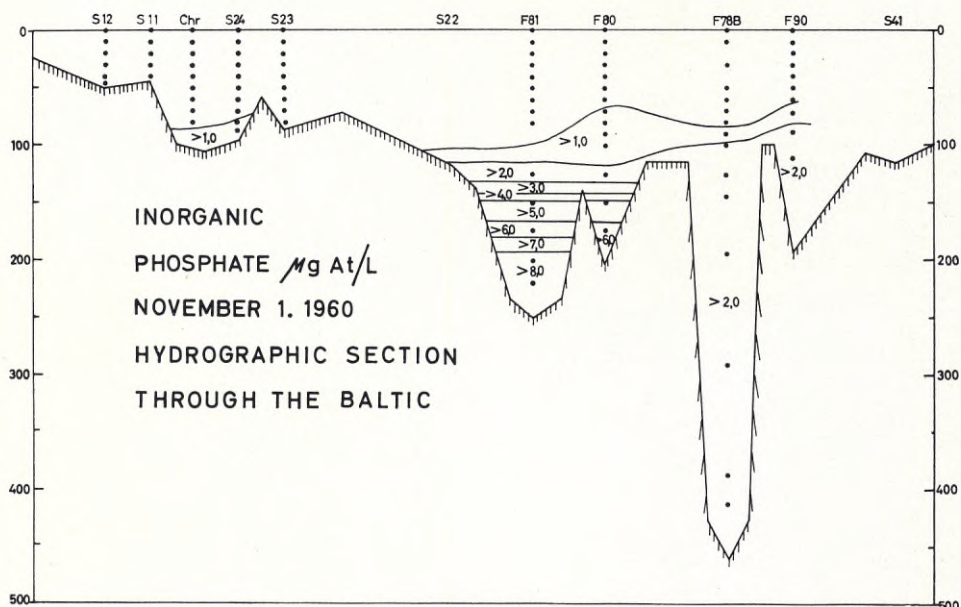


Fig. 16.



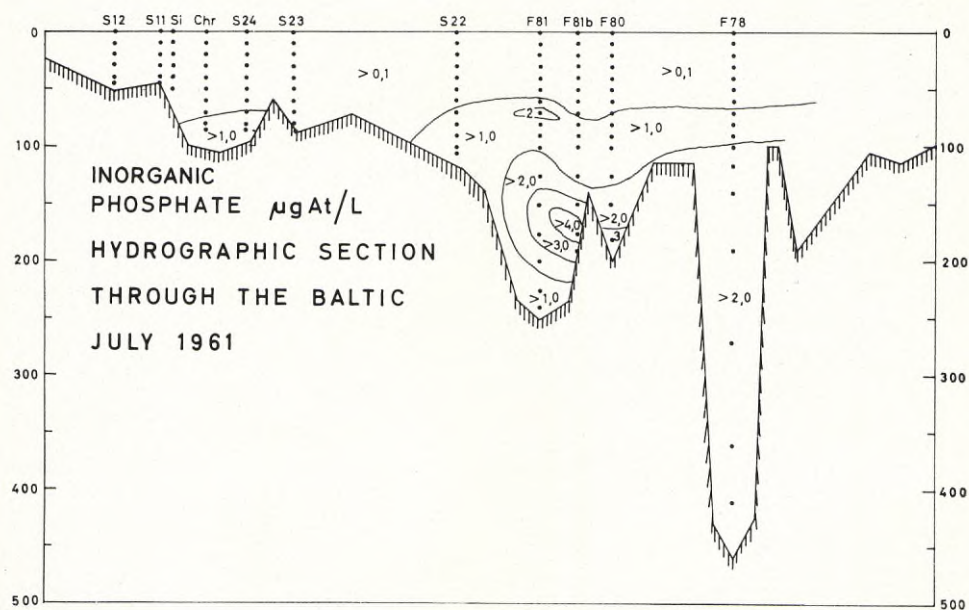


Fig. 17.

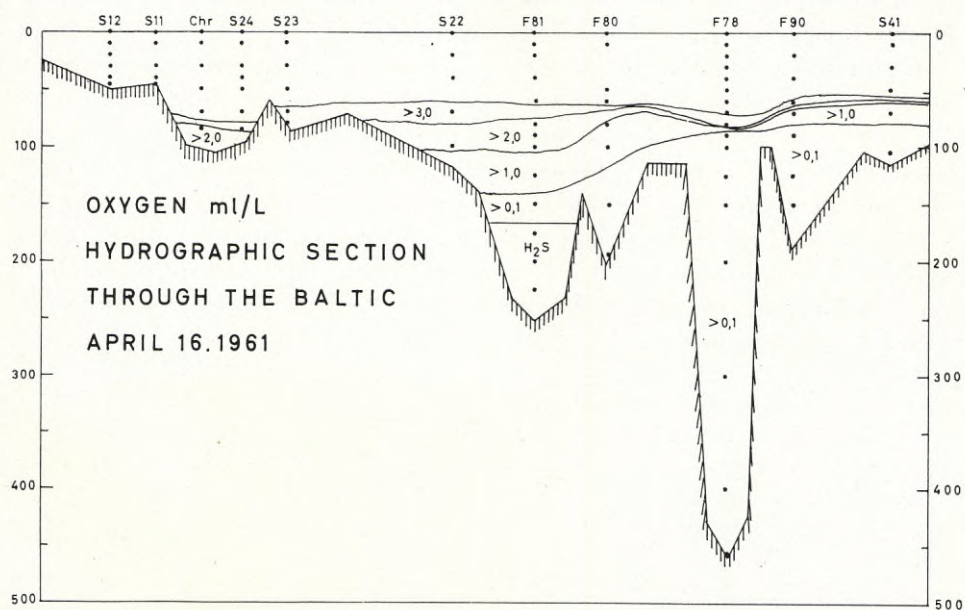


Fig. 18.

Figs. 18—19. Hydrographic longitudinal section. Dissolved oxygen.

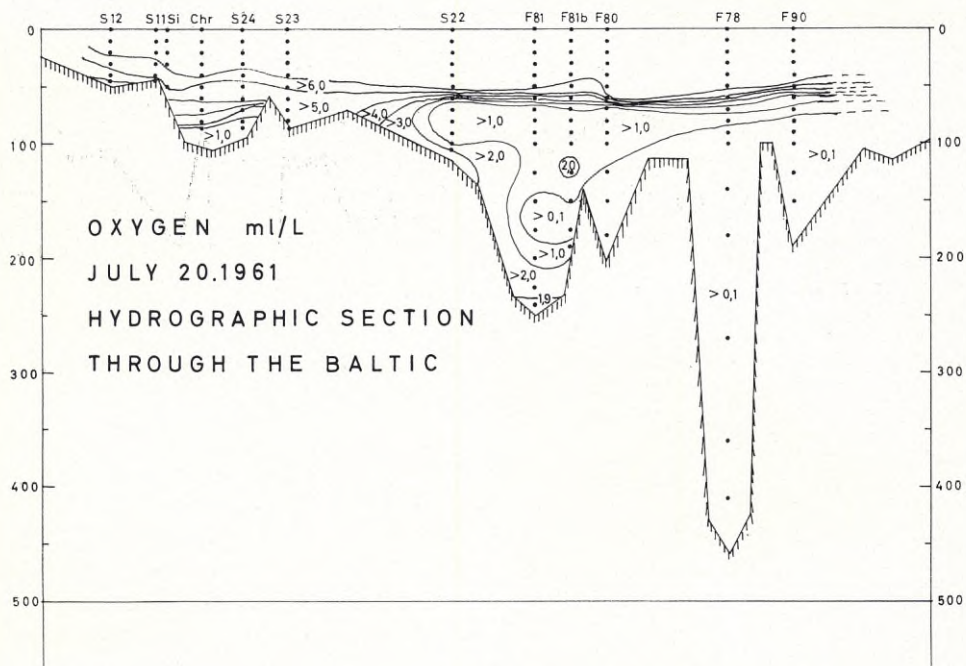


Fig. 19.

accumulated phosphate from the bottom of the Gotland Basin will be spread out over the Baltic.

The following two figures show the same development with the dissolved oxygen in the Gotland Basin. In April 1961 (fig. 18) there was still hydrogen sulphide in the Gotland Basin, but not in the Färö Deep, although it was measured there as late as in January 1961 (table I).

In July the hydrogen sulphide had disappeared completely even from the Gotland Basin and there is now over 2 ml/l oxygen in the bottom water (fig. 19). The lowest concentrations of oxygen (under 1.0 ml/l) are now found around the 150—175 m level indicating the same process in the basin as the phosphate values do.



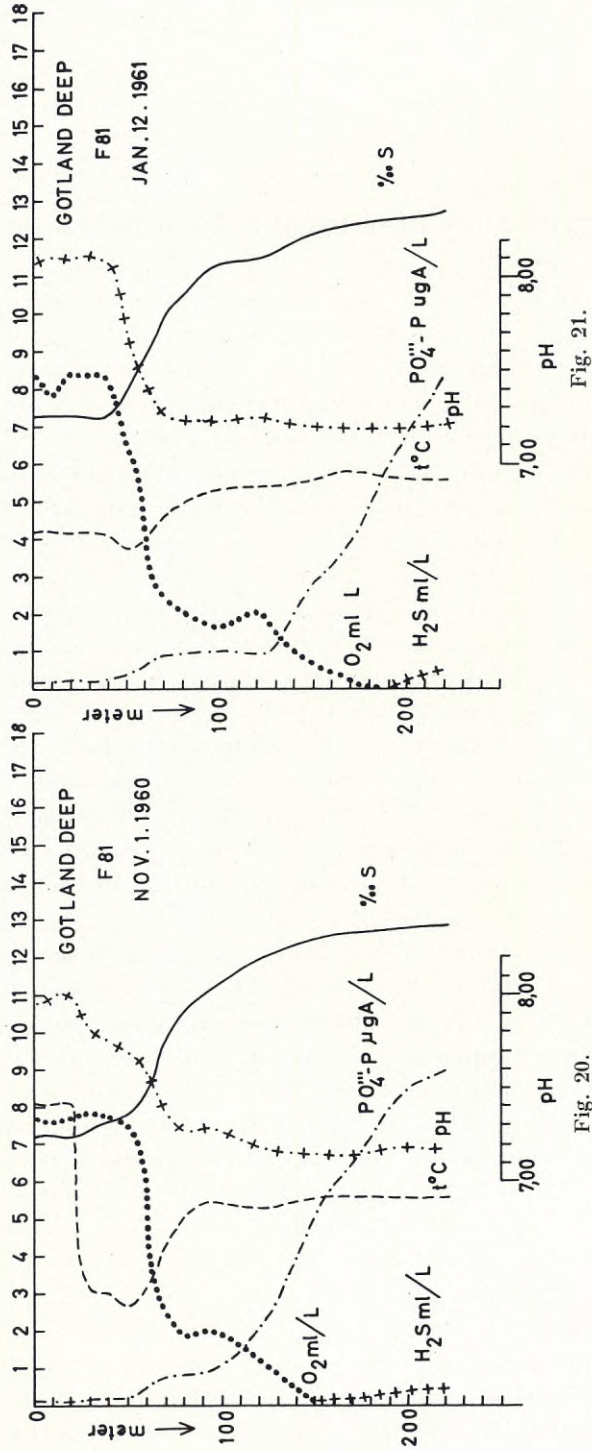
## V. The accumulation of nutrient salts in the Gotland Basin

The following three figures show the vertical distribution of different hydrographic elements in the Gotland Basin at station F81 on three different occasions (figs. 20, 21 and 22). Fig. 23 shows USSR measurements published by the IGY oceanographic data centre at Agricultural and Mechanical College of Texas from the same station in the Gotland Basin.

In the first three figures (20, 21, and 22) the hydrogen sulphide is given as ml/l dissolved  $H_2S$  in order to make the values comparable to the oxygen values. In fig. 23 the silica (Si) is given in  $\mu gAt/l$  but the scale is ten times reduced in proportion to the  $PO_4^{3-}P$  values. Both P and Si increase rapidly under the halocline. The oxygen again decreases sharply under the halocline and disappears completely somewhere below 150 m. As soon as the oxygen concentration reaches zero, the hydrogen sulphide layer begins and the  $H_2S$  concentration increases rapidly downwards. According to the definition for "negative oxygen", the hydrogen sulphide values in ml/l should be multiplied by 2 in order to be equivalent as oxidants to the oxygen values in ml/l. Since hydrogen sulphide is a weak acid, it is to be expected that the pH values would increase a little in the  $H_2S$  layer due to hydrolysis. A small increase of the pH can actually be seen in the figures and in fig. 22 the increase is very pronounced.

Comparison with a similar figure from station F78 in the Landsort Deep (fig. 24) shows immediately the difference between the two basins. In the Landsort Deep the temperature, salinity, oxygen, phosphate and pH remain almost constant from immediately below the halocline down to the bottom. The oxygen sinks to less than 1 ml/l but it never disappears completely, and the phosphate rises to about  $2\mu gAt/l$  phosphate-P and remains at this value through the whole water column. The temperature remains at about  $5^\circ C$ . The salinity differs only 1 ‰ S from 100 m to 459 m. These constant values indicate a very unstable stratification of the water and the deep water is probably mixed and renewed slowly, but fast enough to prevent total anoxic conditions.

A comparison of the oxygen and phosphate curves at stations F81 and F78 shows that on both stations the  $PO_4^{3-}P$  begins to increase when the oxygen reaches values around 1 ml/l, but that in the Landsort Deep, the increase stops at about  $2\mu gAt P/l$  and remains constant around this value down to the



Figs. 20—22. Distribution of  $t^{\circ}\text{C}$ ,  $\text{S } \text{‰}$ ,  $\text{O}_2$ ,  $\text{pH}$ ,  $\text{PO}_4^{3-}\text{P}$  and  $\text{H}_2\text{S}$  at F81.

Fig. 21.

Fig. 20.



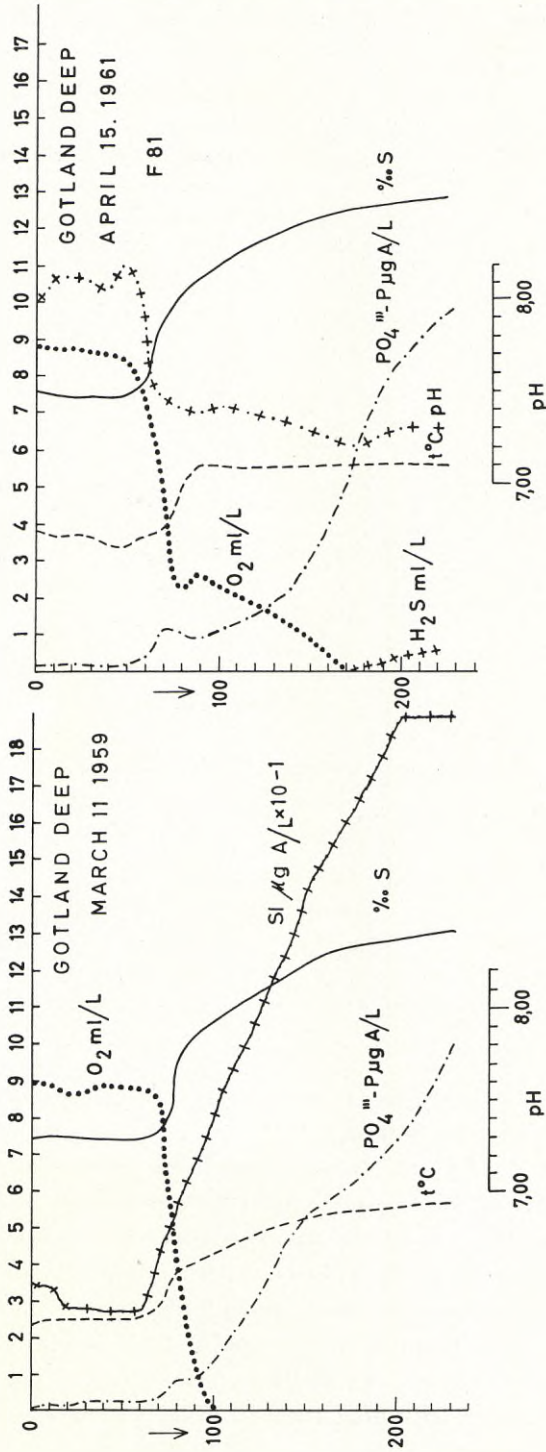


Fig. 23.

Fig. 22. Distribution of  $t^\circ C$ ,  $S$   $\% / \infty$ ,  $O_2$ ,  $PO_4^{3-}$ -P and Si at F81 (USSR IGY-data).

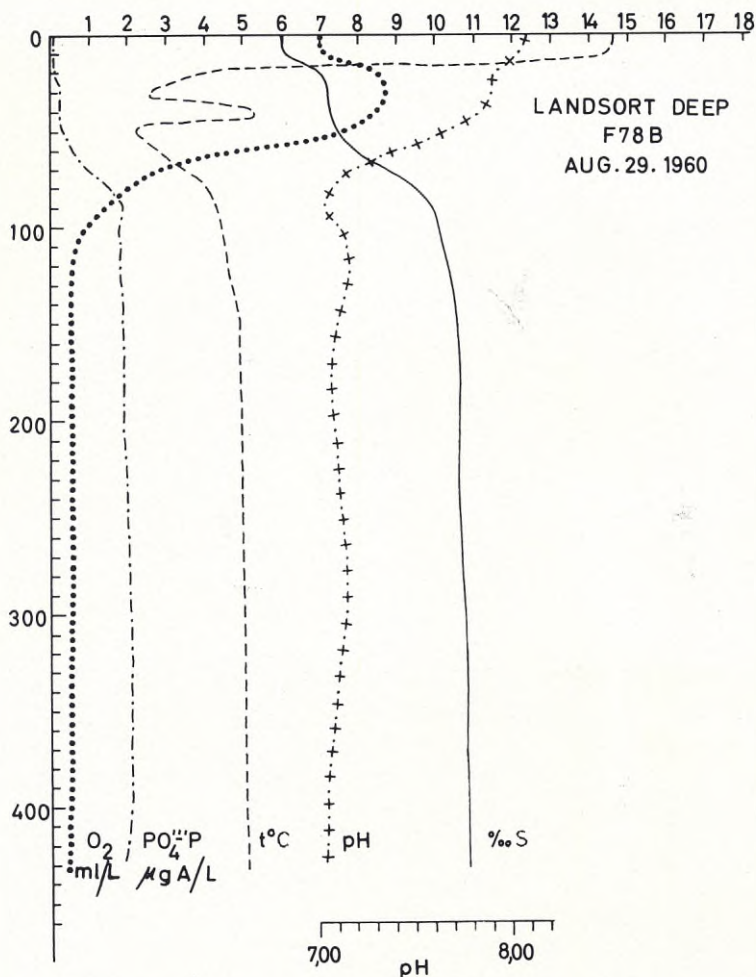


Fig. 24. Distribution of  $t^{\circ}$ , S ‰,  $O_2$ , pH,  $PO_4^{3-}P$  at F78.

bottom. In the Gotland Basin the P increases rapidly and may reach values exceeding  $10\mu gA/l$  near the bottom.

KALLE (DIETRICH-KALLE 1957) has discussed the conditions in the Gotland Basin during the stagnation period around 1932 and he calculated the amount of accumulated inorganic P in the basin at this time to be 30,000 tons P. Nothing was mentioned about the volume of the Gotland Basin, however.

The author has, from Swedish charts, calculated the volume of the Gotland Basin excluding the Fårö Deep, to be  $217\text{ km}^3$  and by weighing the phosphate data from the Swedish station at F81 21 October 1959 he got an amount of 37,300 tons of P accumulated under the 140 m level. Together with the Fårö Deep there should probably have been over 40,000 tons of  $PO_4^{3-}P$  accumu-



lated. Similar calculations of Si from the USSR station on 11 April 1959 in the Gotland Basin (IGYdata) gave an amount of approximately 1,000,000 tons of Si under the 140 m level. However both the P and the Si start increasing rapidly from 80—100 m downwards (figs. 20—23) and the accumulated amounts should accordingly be still somewhat higher than the calculated values, but it is difficult to estimate the limits of the water masses above the 140 m level, since there is a continuous exchange of water with the rest of the Baltic over the sills.

If we assume the above mentioned amounts of P and Si to be spread out over the Baltic proper in the 50 m surface layer, we get an increase of  $0.13\mu\text{gAt/l}$  for the  $\text{PO}_4^{3-}\text{-P}$  and  $3.6\mu\text{gAt/l}$  for the Si. This makes an increase of about 50 % for the phosphorus and about 12 % for the silica, if we assume the normal concentrations of P and Si in this layer to be 0.25 and  $0.0\mu\text{gAt/l}$  respectively and the surface of the Baltic proper to be  $202 \times 10^3 \text{ km}^2$ . This gives the 50 m surface layer a volume of approximately  $10,000 \text{ km}^3$ . KALLE (DIETRICH-KALLE) has discussed the importance of the release of phosphate from the Gotland Basin in 1934, to fishing in the Baltic. According to that, there should now be reason to expect a new period of good fishing in the Baltic.

RICHARDS and VACCARO (1956) have described the anoxic conditions in the Cariaco Trench and have found a relation between inorganic phosphate and total redox reactants. Total redox reactants =  $\text{AOU} + 4\text{S}^{2-}$  where AOU is the Apparent Oxygen Utilization  $\text{O}'_2 - \text{O}_2$  in  $\mu\text{gAt/l}$ .  $4\text{S}^{2-}$  is the amount of  $\text{S}^{2-}$  in  $\mu\text{gAt/l}$  reduced from  $\text{SO}_4^{2-}$  assuming that all  $\text{S}^{2-}$  originates from  $\text{SO}_4^{2-}$  and that  $\text{SO}_4^{2-}$  is equal to four O atoms as an oxidant. RICHARDS and VACCARO found that this relation was also true for oxygen-rich water in the Caribbean Sea, the Atlantic Ocean and the Black Sea. The anoxic water in the Black Sea, however, showed a smaller ratio between inorganic  $\text{PO}_4^{3-}\text{-P}$  and Total Redox Reactants near the bottom. This, according to RICHARDS and VACCARO, is probably due to some oxidation mechanism other than the oxidation of organic material with the concurrent release of inorganic phosphate.

The author has used the above-mentioned  $\text{AOU} + 4\text{S}^{2-}$  for the Gotland Basin, and the values published by RICHARDS and BENSON (1961) for the Dramsfjord in Norway. These values have been plotted against the inorganic phosphate values. The phosphate concentrations in the Baltic surface water are considerably lower than in the oceans, however, and therefore the results from the oxygen-containing Baltic water fall on a line below RICHARDS and VACCARO (fig. 25). The oxygen-rich Dramsfjord values also fall around this line. The anoxic Gotland Basin and the anoxic Dramsfjord show an enormous accumulation of inorganic phosphorus, which gives a much steeper line for these waters. The values from these two anoxic waters fall on the same line. The equation for the oceans and the Cariaco Trench is,

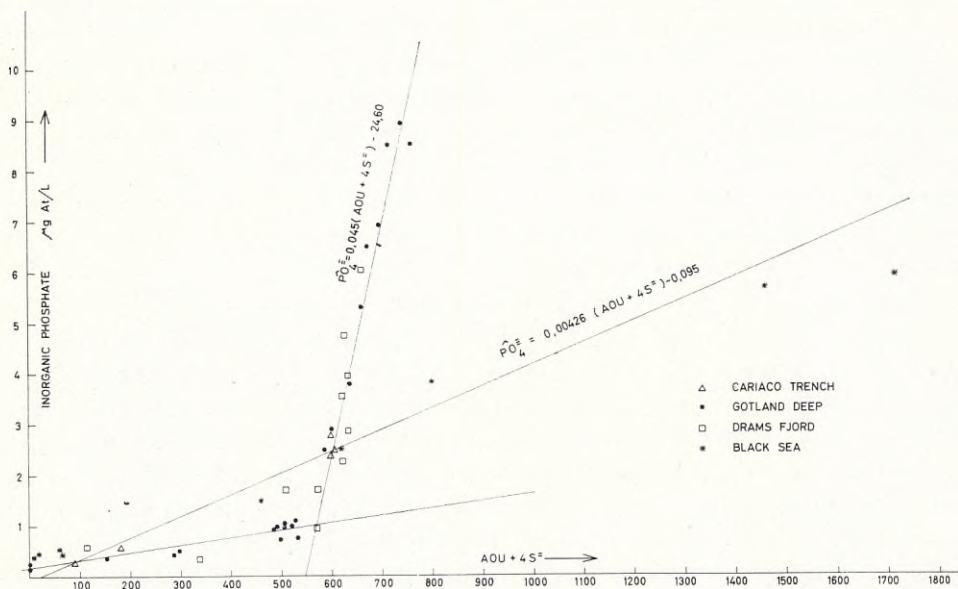


Fig. 25. Total Redox reactants in different stagnant basins.

according to RICHARDS and VACCARO,  $PO_4^{3-} = 0.00426(AOU + 4S^{2-}) - 0.095$ , and for the Gotland Basin and the Dramsfjord we get approximately  $PO_4^{3-} = 0.045(AOU + 4S^{2-}) - 24.6$ . This indicates an oxidation process quite different from the processes suggested by RICHARDS and VACCARO. This accumulation of phosphate is not easy to explain, however. According to Russian measurements (fig. 23), silicate is also accumulated in the same way in the Gotland Basin during stagnation periods. It is to be expected that  $NH_3$  and  $N_2$  would be accumulated in the Gotland Basin, as described by RICHARDS and BENSON (*loc. cit.*), in the Cariaco Trench and Dramsfjord, but unfortunately no measurements could be carried out in the Gotland Basin before stagnation conditions disappeared.



## VI. The H<sub>2</sub>S analysis

The H<sub>2</sub>S-S in the Gotland Basin was estimated quantitatively by the Methylene-Blue method. This method was used by EL WARDANI in the Cariaco Trench (RICHARDS and VACCARO, *loc. cit.*), but the technique has not yet been published. Personal communication with Dr. EL WARDANI showed that the method used by the author was very similar to Dr. EL WARDANI's method.

### Reagents:

a) N,N-Dimethyl-p-Phenylene-Diamine-Dihydrochloride (RIEDEL-DE HAEN A. G. SEELZE, Hannover). 1 gr was dissolved in 500 ml 6-n HCl. (According to EL WARDANI the sulfate salt gives a faster reaction).

b) Ferrichloride p.a. 4 gr was dissolved in 250 ml 6-n HCl.

c) Standard solution of Na<sub>2</sub>S. Na<sub>2</sub>S×9H<sub>2</sub>O p.a. Merck. and O<sub>2</sub>-free aq.dest.

The O<sub>2</sub>-free water was made by boiling and cooling ordinary dist. water; it was used immediately. Na<sub>2</sub>S-crystals were quickly washed with distilled water, dried with filterpaper, and about 750 mg were weighed and dissolved in the O<sub>2</sub>-free water and diluted to 1 liter. 5 ml was pipetted into a 100 ml bottle and again diluted with O<sub>2</sub>-free water to 100 ml. This standard contains 0.005 mg S per ml.

Procedure: The water samples were taken from the ordinary Knudsen-samplers, coated with plastic on the inside. Ordinary Winkler bottles, about 100 ml, were used. The Winkler bottle was filled with sample and 1 cc of each reagent was introduced using byrettes with long tips as in the oxygen determination. The bottle was immediately closed and shaken. Standards with suitable concentration were immediately made by pipetting standard solution into Winkler bottles and by filling with O<sub>2</sub>-free water. The bottles were treated with reagents exactly as the samples. After one hour the blue colour was measured with a Beckmann B spectrophotometer at 670 m $\mu$  using 5 cm cells. No salt correction was necessary. If the prepared samples and standards are stored under the same conditions, the colour may be measured on land after the cruise. The standard stock solution has to be prepared as late as possible before the cruise or preferably on board immediately before the sampling. Storing in a dark bottle and in a dark room will of course be of some help, but the solution should not be older than two or three days.

The  $H_2S$ -S was determined in the Gotland Basin at F81 in October 1960, in January, 1961 and in April 1961. In July 1961 the  $H_2S$  had disappeared and no traces of it could be found. Table I shows the results:

Table I.  $H_2S$ -S in the Gotland Basin and the Fårö Deep in  $\mu gA/l$

The Gotland Deep St F81		The Fårö Deep St F80	
Depth in meters	$H_2S$ -S $\mu gA/l$	Depth in meters	$H_2S$ -S $\mu gA/l$
November 1 1960		November 1 1960	
125 .....	0.0	125 .....	0.0
150 .....	0.7	150 .....	1.5
175 .....	8.5	175 .....	9.0
200 .....	17.0		
220 .....	21.0		
January 12 1961		January 12 1961	
150 .....	0.0	The rough weather made all sampling impossible	
175 .....	0.0		
193 .....	4.0		
199 .....	12.0		
211 .....	19.0		
221 .....	25.0		
April 15 1961		April 15 1961	
150 .....	0.0	150 .....	0.0
175 .....	3.0	195 .....	0.0
200 .....	18.0		
225 .....	23.0		
July 20 1961		July 20 1961	
No traces of $H_2S$ could be detected and oxygen was present at all depths.			



## VII. A detailed study of the hydrography of the Gotland Basin during the stagnation period

Fig. 26 shows a time section of the changes in salinity in the Gotland Basin at station F81 from the beginning of 1955 to the middle of 1961. In March 1955 there seems to have been inflow of water with lower salinity, but this water was immediately replaced by water of higher salinity. The salinity of the bottom water decreased until April 1957, when no 13 ‰ water was present in the basin. A new inflow of higher saline water in July 1957 brought the isohaline for 13 ‰ up to 175 m. Then followed a new decrease of the salinity and after May 1959 all 13 ‰ water had disappeared. In March 1960 an inflow of low saline water occurred. The salinity decreased through the whole water column and this decrease could be observed at all stations north and east of the Bornholm Basin, as described earlier in connection with fig. 8. A detailed study of the salinity development at stations S24, S23 and S22 (fig. 27) shows that this low saline water cannot be observed at S24 but that it arrived at S23 in February 1960 and at S22 in March, and in the same month also at F81. In August the salinity had again risen and, as described in connection with fig. 9, there seems to have been a new inflow of higher saline water into all the basins investigated. The new inflow of high saline water in the summer of 1961 can clearly be seen from fig. 26. The isohaline for 13 ‰ appears again and reaches to about 200 m.

A similar temperature diagram (fig. 28) does not show exactly the same conditions. The inflow of low saline water in March 1955, however, corresponds to a lowering of the temperature. A lowering of the temperature occurs in July 1958, but no corresponding change in the salinity can be found. A surprising feature is the layer of water over 6°C which appears in February 1960 between 100 and 200 m. Traces of it or another watermass can still be found in January 1961. This warm, low saline water shows an instability in the deep water which may indicate a coming turnover of the water column. The thermocline was at about 75 m in 1955 and sank slowly to nearly 100 m in 1959. From June 1959 the thermocline started to rise and was at about 65 m in June 1961. In the summer of 1961 the temperature was almost constant between 5.50 and 5.75°C from 90 m down to the bottom. A similar diagram showing the oxygen concentration (fig. 29) from 1953 to 1961 shows that the 2ml/l oxygen line (the limit for higher biological life)



was at about 160 m at the beginning of 1953 and rose to 90 m by the end of 1954. The inflow of colder water richer in oxygen but of lower salinity described in Chapter III and at the beginning of this one in connection with the salinity and temperature charts, brought the 2 ml/L oxygen limit down to 170 m and in the bottom layers the oxygen concentration changed from 0.18 ml/l to 1.76 ml/l. The anoxic conditions were restored rapidly and in the summer of 1955 the limit for 2 ml/l oxygen again extended up to 90 m. Early in 1957 the oxygen had totally disappeared from the bottom water and the zero oxygen line reached up to 150 m in April 1957. In the autumn of 1957 an inflow of high saline water richer in oxygen followed, but the concentration of oxygen under the 100 m level was still extremely low, below 1.0 ml/l. In 1958 the oxygen again disappeared totally from the deep water and at the beginning of 1959 the zero line was at 140 m. Then the unstable conditions during 1960, mentioned earlier, caused an oscillation of the oxygen limit, but there was always an oxygen-free water mass in the deeper parts of the Basin.

The inflow of low saline water in March 1960 corresponded to a small increase of the oxygen content in the middle layers, but the conditions in the deep water were unchanged. The inflow of higher saline water during the summer did not bring in any detectable amounts of oxygen. Probably the reducing conditions were so strong that the oxygen in the small amount of water mixed down in the deep water, was used up completely in a short time.

This oxygen-free water contained, as has been mentioned earlier, hydrogen sulphide but no measurements of the  $H_2S$ -S concentration were carried out before November 1960. The smell of hydrogen sulphide was observed at the beginning of 1958 (personal comm. from Mr. S. ENGSTRÖM). In the summer of 1961 the hydrogen sulphide disappeared, however, as has been described earlier in this paper, and in July no traces of it could be found. As can be seen from fig. 29, oxygen-rich water has penetrated down to the bottom of the basin and the lowest concentrations of oxygen are now found in the middle water layers as was described in Chapter IV.

Unfortunately very few  $PO_4^{3-}P$  measurements were carried out before 1957. There is no commonly accepted standard method for inorganic phosphorus. The analyses made by Finnish, Russian and Swedish oceanographers since 1957 may differ slightly in methods and accuracy, because no comparisons of reproducibility have been tried. The results may therefore be difficult to compare in a figure, and detailed conclusions can hardly be drawn. Fig. 30 is an attempt to combine all these measurements and it can be seen that the phosphate had already begun to accumulate in the bottom layers when the measurements were started in 1957. During the second part of 1957 the phosphate-P concentration at 200 m rose from  $2\mu gAt/l$  to  $5\mu gAt/l$ . In June 1958 the concentration at the bottom was over  $8\mu gAt/l$ , but the minimum in August the same year seems to be doubtful and is



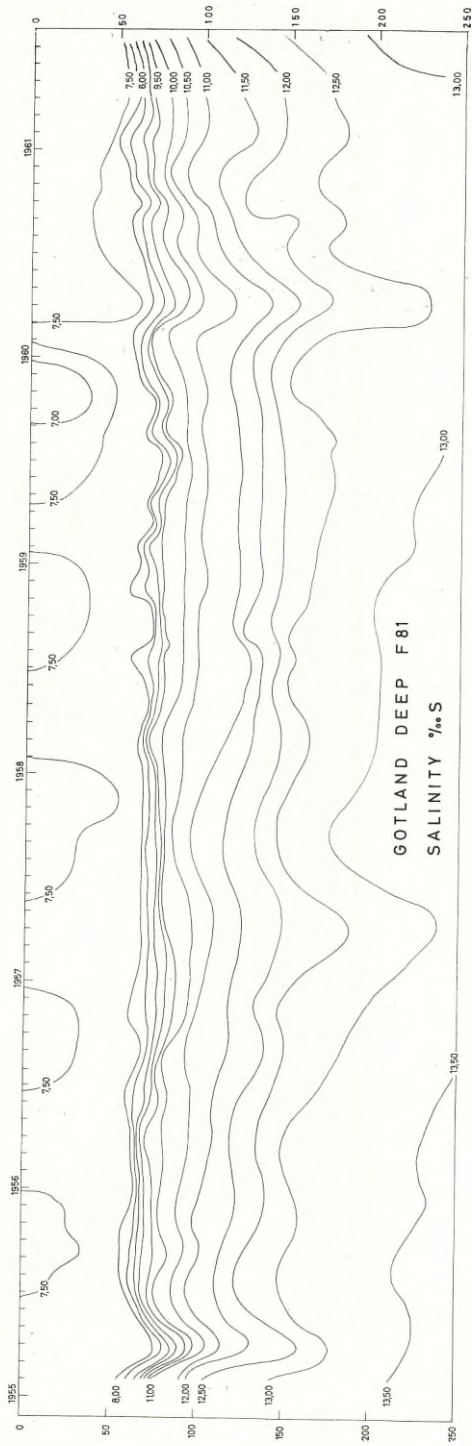


Fig. 26. Time section of the salinity from 1955—1961 in the Gotland Basin.

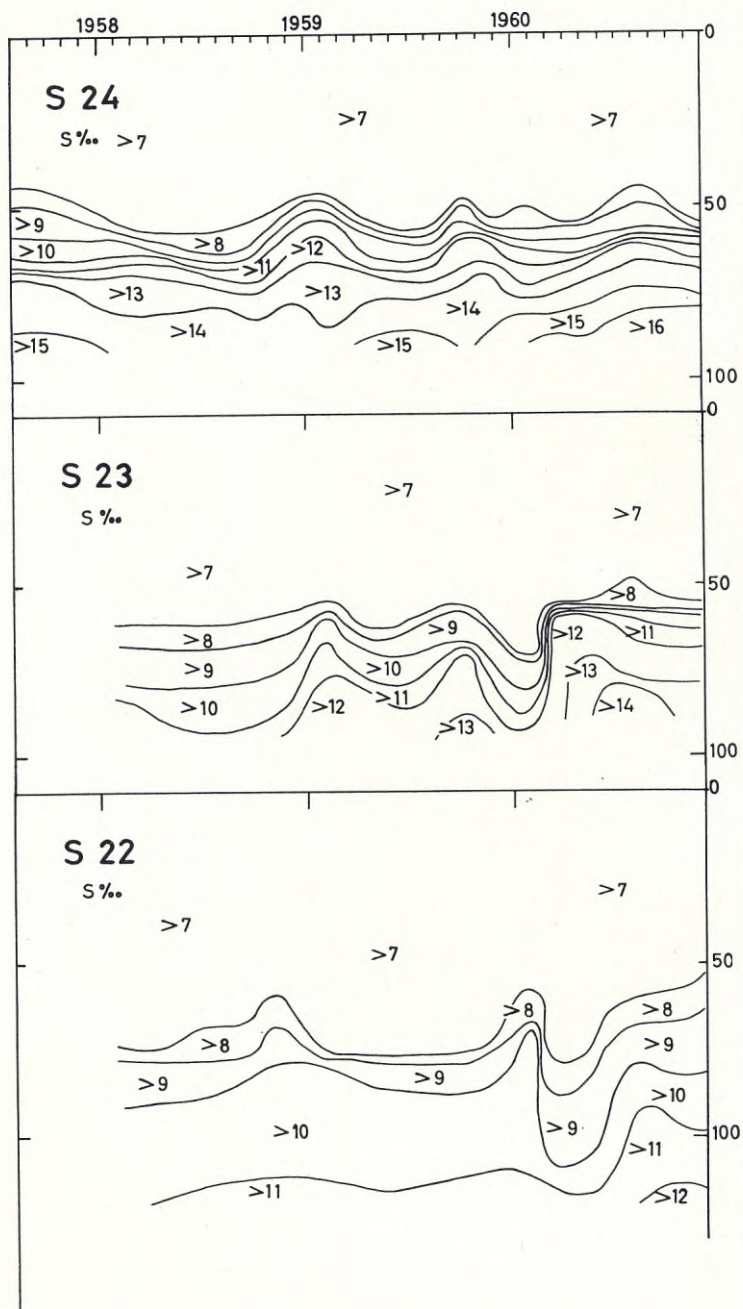


Fig. 27. Time section of the salinity from 1958—1960 at the stations S24, S23 and S22.



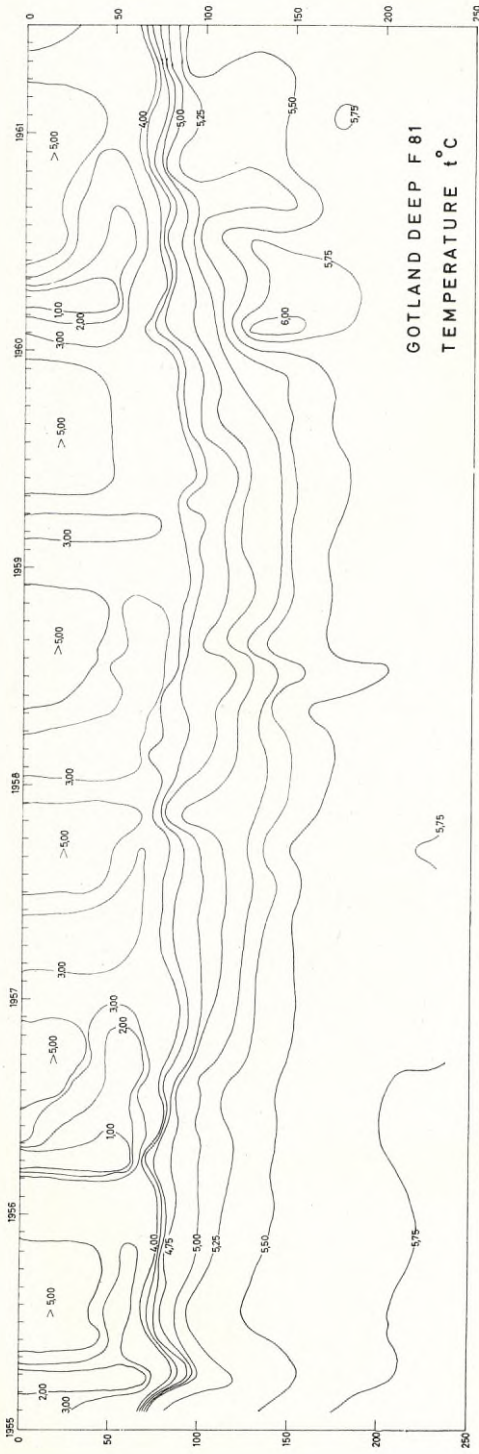


Fig. 28. Time section of the temperature from 1955—1961 in the Gotland Basin.

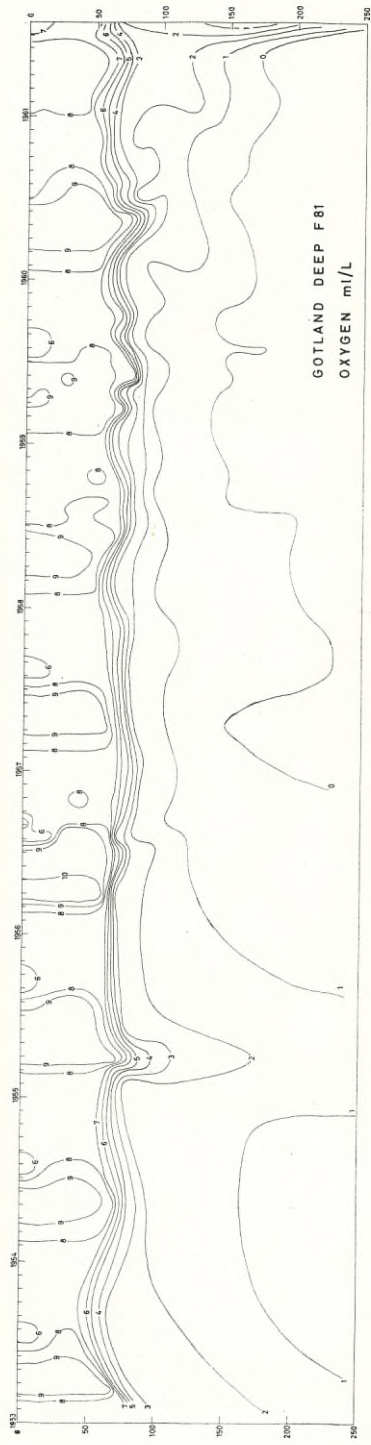


Fig. 29. Time section of the dissolved oxygen from 1953—1961 in the Gotland Basin.

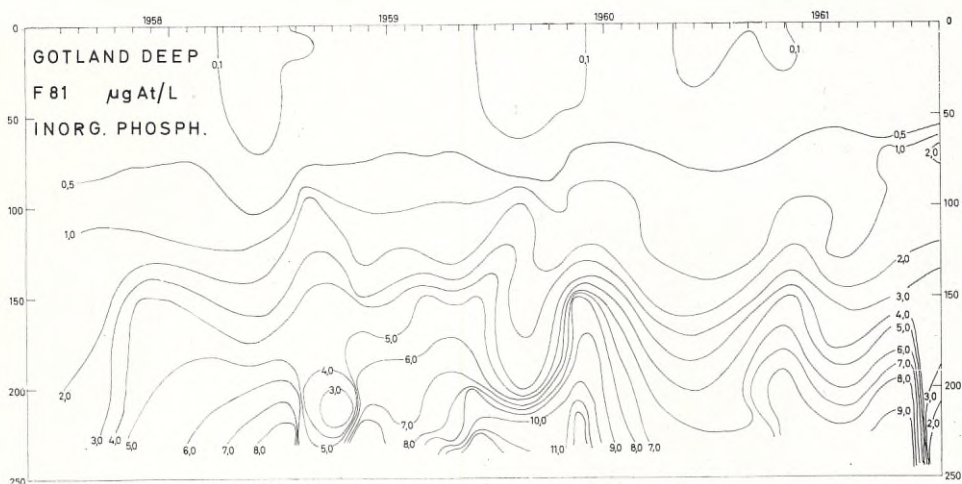


Fig. 30. Time section of the inorganic P from 1957—1961 in the Gotland Basin.

probably due to different methods of analysis. The highest P-values, exceeding  $12\mu\text{gAt/l}$ , were measured in December 1959.

The inflow of low saline water in March 1960, mentioned in this chapter in connection with the salinity, can also be observed in the phosphate concentration. The phosphate values decreased through the whole water column and increased again after this to over  $8\mu\text{gAt/l}$ .

Here too, the inflow of oceanic water in the summer of 1961 can be recognized. Suddenly the phosphate-P decreases at the bottom to below  $2\mu\text{gAt/l}$  and the highest values exceeding  $3\mu\text{gAt/l}$ , are found at the 150 m level as described in fig. 17.



## VIII. Conclusions and discussion

Salinity has increased in the Baltic during this century. Even in the bottom of the deep basins this increase is visible. If a mean line is drawn for the salinity in figs. 5 and 6, we get an increase of about 0.5—1.0 ‰ S for the Gotland Basin and the Landsort Deep. The salinity variations in the Bornholm Basin are too large to allow of any conclusions. The mechanism of the salinity increase has not yet been explained. The deep water is occasionally renewed by inflows of heavy ocean water, which, under suitable meteorological conditions, flows through the Belts into the Baltic. These inflows prevent the Baltic from establishing the stagnant conditions typical for the Black Sea. The sills between the different basins distribute water of different salinity to the basins. The inflows have most effect on the conditions in the Southern Baltic.

The Gotland Basin is the only big basin which really stagnates so that totally anoxic conditions are built up. The Bornholm Basin gets small supplies of oxygen-rich water through the Belts and from the Baltic without influencing the Gotland Basin. The Landsort Deep never stagnates completely. The water in the Landsort Deep has a very unstable stratification and probably the water under the halocline is slowly renewed from the Northern Baltic independent of the conditions in the Gotland Basin. Greater changes in the Gotland Basin or the Bornholm Basin, however, influence the conditions in the Landsort Deep.

The study of the inflow in the Bornholm Basin 1959 gives an idea of the speed of the water transport in the bottom of the Baltic. The inflow began in February-March 1959 in the Bornholm Basin, where the isohaline for 14 ‰ water (fig. 27, station S24) started to rise at this time. In November 1959 12 ‰ water began to flow over the 60 m sill to the Stolpe Channel, where a sharp increase of salinity was observed in February 1960, (fig. 27 station S23). This increase was not observed until August at S22 (fig. 27); because unfortunately no values from June exist from that station, but at F81 the increase was observed as early as in June (fig. 26) and in the Landsort Deep too, the increase was observed in August (fig. 6). The bottom water in the Gotland Basin was, however, not influenced by this inflow before the summer of 1961 (figs. 5, 13 and 26). According to fig. 3, the inflow into the Bornholm Basin at this time shows signs of decreasing. The whole inflow

process seems to have taken two years and some months. The first signs of the inflow could, however, be observed in the Landsort Deep in August 1960, which gives a water front speed of about 1 1/2 years from the Bornholm Basin to the Landsort Deep.

These values should not, of course, be regarded as normal speeds for the water in the bottom of the Baltic. The speed is obviously regulated by the speed and amount of inflowing water through the Belts and these factors depend upon the meteorological conditions in Northern and Western Europe. The 1951 inflow e.g. took, from its beginning in the Bornholm Basin in December 1951, about 6 months before it arrived to the Landsort Deep in the summer of 1952.

The reducing process during stagnation seems to be related to the reduction in the Norwegian fjords, but differs from the process in the Cariaco Trench and the Black Sea.

The increased interest in the measurements in the Baltic, during recent years, manifested in the greater amount of data, especially on oxygen and phosphate, now available, will probably contribute towards a better understanding of the behaviour of the Baltic.

### Acknowledgements

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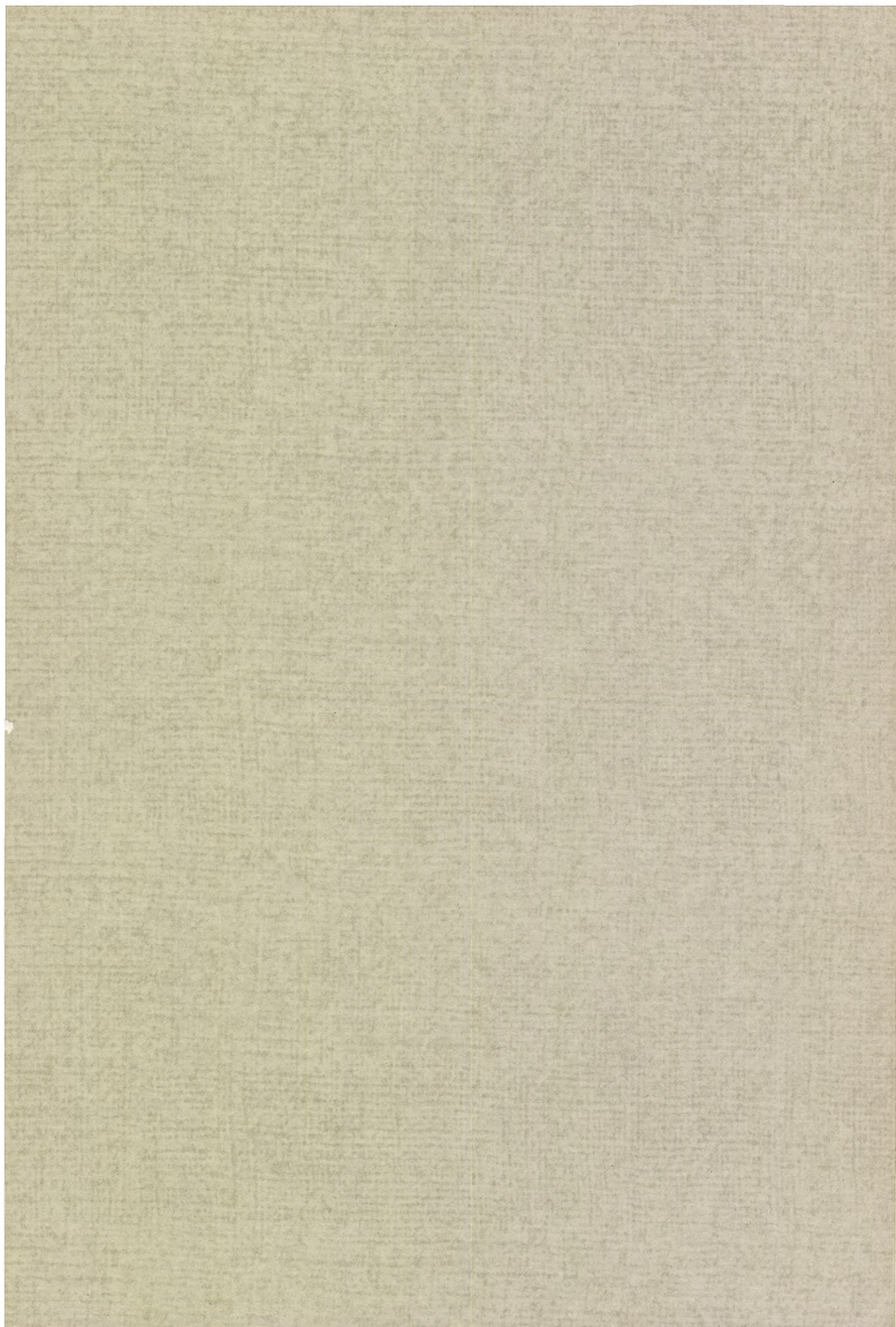














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