Nr 95, 2008

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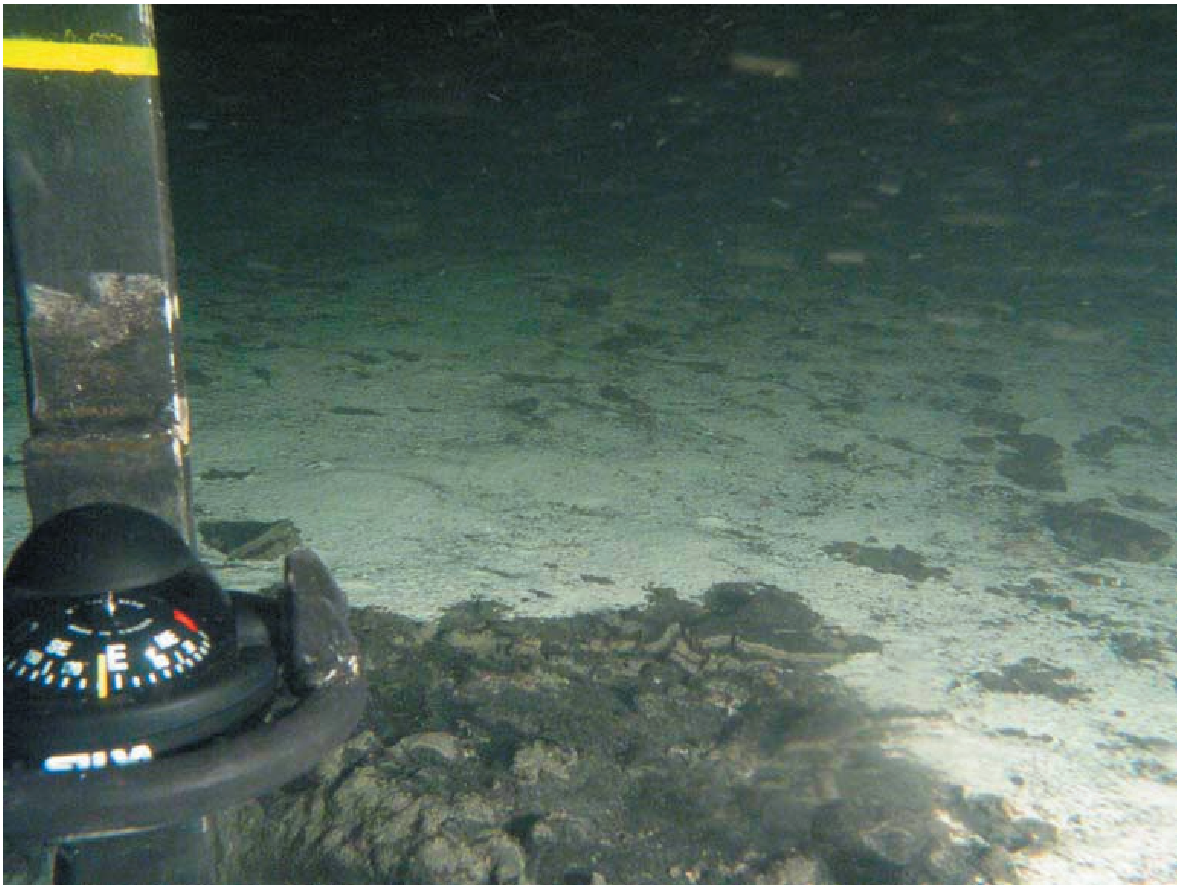

A new approach to state the areas of oxygen deficits in the Baltic Sea

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[1] Geological Survey of Sweden (SGU), Box 670, SE-751 28 Uppsala, Sweden
[2] The Swedish Meteorological and Hydrological Institute (SMHI), SE-601 76 Norrköping

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Ingemar Cato[1], Bertil Håkansson[2], Ola Hallberg[1], Bernt Kjellin[1], Pia Andersson[2], Cecilia Erlandsson[1], Johan Nyberg[1] , Philip Axe[2]

[1] Geological Survey of Sweden (SGU), Box 670, SE-751 28 Uppsala, Sweden
[2] The Swedish Meteorological and Hydrological Institute (SMHI), SE-601 76 Norrköping

Author SGU Box 670 SE-751 28 Uppsala, Sweden SMHI Oceanografiska Enheten Nya Varvet 31 426 71 Västra Frölunda	Project leaders At SGU: Ingemar Cato Ingemar.Cato@sgu.se At SMHI: Bertil Håkansson Bertil.Hakansson@smhi.se
Clients The Swedish National Environmental Protection Agency Vallhallavägen 195 SE-106 48 Stockholm	Contact Sverker Evans Sverker.Evans@naturvardsverket.se
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Frontpage: Anoxic bottom covered with sulphate reducing bacteria (Begiatoa sp.) in the Baltic Sea. Photo: SGU.

Frontpage: Anoxic bottom covered with sulphate reducing bacteria (*Begiatoa sp.*) in the Baltic Sea. Photo: SGU.

Content

Summary

Sediment and near bottom water oxygen data was evaluated to look for correspondence in anoxic conditions. The SGU and SMHI monitoring data showed high correlation, although the actual data tested proved to be few, coincidence in space was promising. The conclusion drawn from the evaluation is that anoxic postglacial sediments were generally overlaid by near bottom anoxic waters. Hence, it is suggested that the spatial distribution of postglacial clays in the sea-bottom surface can be used, together with near bottom waters oxygen data, to improve spatial distribution in mapping oxygen deficits.

Time series of oxygen deficit volume and area was calculated from near bottom data from several sub basins in the southern and central Baltic Proper. In general, hypoxic and anoxic water conditions increased over time but perturbations of improved oxygen conditions linked to major inflow events occurs especially in the Bornholm, Eastern and Western Gotland Basins.

The high spatial variability of the postglacial sediments in the Western Gotland Basin compared to other basins indicates that it is indeed sensitive to the area coverage of anoxic waters. In addition, the relatively weak stratification and high variability over time of oxygen deficit make this basin favourable for oxygen improvement engineering methods.

In coastal waters several bays along the Östergötland and Småland archipelagos should be further evaluated before selected for ecological engineering methods to improve oxygen conditions.

1. Introduction

Areas of oxygen deficiency are widespread in the Baltic Sea causing severely negative effects on the ecosystem, e.g. reduced benthic communities and fish habitats which in turn affect the food chain, fisheries and life around the sea. Oxygen depletion also affects the biogeochemical processes, e.g. mobilization of phosphorous from the sediment to the water column affecting the rate of eut rophication. This situation is not unique in the history of earth. Most of the oil and gas resources in the world were once formed in shallow semi-enclosed seas where the formation of oil and gas started with hypoxic/anoxic conditions and accelerated eutrophication resulting in the formation of organic rich sediments. In this context the oxygen deficiency in the Baltic Sea has to be considered as natural.

The bottom-water concentrations of oxygen in the Baltic Sea are influenced both by physical factors, especially the inflow of dens saltwater from the North Atlantic (e.g. Fonselius 1985), and by biogeochemical factors (e.g. Nehring 1987). These inflows are mainly governed by large-scale meteorological variations, e.g. the distribution and routs of high and low pressure between the Baltic Sea and Skagerrak/Kattegat. Since 1897 about 96 major inflows of saline water (≥17 PSU) have been identified (Schinke *et al.* 1998). Notable is, that only two such major inflows have occurred in the last 25 years (1983 and 1993), which is assumed to have resulted in long-term stagnation of the deepest bottom areas of the Baltic proper with growing areas of hypoxia and anoxia present.

Several attempts during the last five decades have been made to estimate the size of hypoxic bottom areas in the Baltic Proper. Recently this was made by Conley *et al.* (2002) for the period between 1970 and 2000. They used basin-scale integrated approaches on data derived from the Baltic Environment Database (BED) at Stockholm University. From these data they showed, that during these three decades, the areas of bottom underlying water with oxygen concentrations less than 2 ml/l varied between 12 000 km^2 (in 1993) and 67,000 km^2 (in 1971) or between 5 % and 27 % of the total bottom area. Three periods with hypoxic bottom areas covering more than 49,000 km^2 of the Baltic Proper were also identified; 1971-1975, 1978-1982 and 1998-2000. According to the most recent information the latest stagnant period is extended at least up to present time in the Western Gotland Basin, whereas the Eastern Gotland Basin slightly recovered during the inflow event in 2003 followed by a new stagnation period from 2005 up to present time (cf. Figure 7a-d).

However, all these spatial estimates carried out during these years have only been made for the open Baltic Proper and no account has been taken of the size of the hypoxic areas in the coastal zone. Furthermore, very little notice has been taken to the distribution of hypoxia in the Bothnian Sea and the Bothnian Bay, simply since the bottom oxygen content is well above 2 ml/l, while the SGU sediment data indicate that areas are anoxic.

In an approach to include all Swedish marine waters and to make more detailed isopleths of the anoxic/hypoxic bottom-water distribution SGU and SMHI started a joint project where both hydrographical and sedimentological data were used.

2. Data and data processing

2.1 Data sets

In this study two types of data have been used; sediment information from SGU and oxygen measurements from SMHI.

Since the mid-1970s SGU has carried out a regular mapping of the sea-bed within Swedish waters and the Swedish exclusive economic zone (EEZ). The surveys are based on hydroacoustic techniques (shallow seismics, subbottom profiler and side scan sonar), coring and surface sediment sampling. At each sampling site the bottom surface has been inspected and documented with video or digital photo techniques. About 20 % or 32,000 km^2 of the Swedish continental shelf has been mapped in detail. The remaining part has been sparsely surveyed in a regional programme where the mapping has been carried out with full side-scan sonar coverage in mainly east-westerly corridors, 1 km wide, and separated with a distance of about 12 km from each other (Figure 1).

In the mapping programme all sediment samples and cores have been examined, described and subsampled. Since 1990 the information has, directly onboard the vessel, been loaded in a database. Older data were logged on paper and has later been transformed into the database. The information in the paper logs are less detailed than the information collected during the last 18 years, i.e. the data are not fully homogenous.

The oxygen measurements used are data collected by SMHI during monthly monitoring cruises at trend stations and at mapping stations during August to October since 1995 and onwards. Older data from trend stations exists since the early part last century. Measurements are taken at standard depths using bottle data, except the deepest sampling, which is adapted to always take place about one meter above the bottom sediment. The monitoring is quality assured by the SWEDAC (ISO 17025). Since last year bottle data sampling is complemented with a profiling oxygen sensor. In addition, data sampled within the national marine monitoring programme is also used, covering the Gulf of Bothnia and the North Western part of the Baltic Proper. The coastal oxygen data used in this study is collected by regional and local authorities. The data is available at the national data host for oceanographic and biological data (i.e. the SMHI oceanographic data centre).

In this study we used data from the bottom water only. Thus the bottom water samples of oxygen are, if not anoxic, not representative of the oxygen concentrations at the sediment-water interface. However, calculation of oxygen concentrations at the bottom below the diffusive boundary layer suggests that it is likely the oxygen concentrations at the sediment-water interface are anoxic when bottom water oxygen concentrations are <2 ml/l (Rahm 1987, Conley *et al. 2002*), i.e. hypoxic.

2.2 Comparison of oxygen deficits in the water column and in the sediment

By taken this into account the hypothesis in this project is that both anoxia and hypoxia will give rise to characteristic visible signals in the sediment, signals that hopefully have been observed by the sediment examiner and loaded in the database. To find out these characteristics all SMHIs´ oxygen measurement stations from the period May-October were plotted on the seabed sediment map over the Swedish territorial water and Economic Zone of the Baltic Sea, Kattegat and Skagerrak. Prior to the plotting the 77 oxygen measurement stations were classified either as oxic or anoxic. In cases were more than one measurement were made at one and the same station, more than 40 % of the observations have to be found anoxic to allow the station to be classified as anoxic. This value corresponds to the average value (0 ml O_2/l) of the data set from each station. The results of this classification of the 77 oxygen measurement stations are displayed in Figure 3.

The result of the plotting showed, that out of 77 oxygen measurement stations, 29 were located outside the corridors surveyed in the regional mapped areas and 18 of these stations were classified as anoxic. Ten (56 %) of these anoxic stations were located over bottom areas classified as postglacial clay in the marine geological map (Figure 2) and eight (44 %) anoxic stations were located in areas with other types of sediment.

The remaining 44 of the 77 oxygen measurement stations were located in detailed mapped areas and only six of these stations were classified as anoxic. Three (50 %) of these anoxic stations were located in bottom areas classified as postglacial clay in the marine geological map and three (50 %) were located in areas with other types of sediment.

2.3 Formation of search criteria to identify anoxic sediment samples in the database

The next step in the process was to compare the 77 oxygen measurement stations, classified either as anoxic or oxic (Fig. 3), with sediment characteristic from nearby sediment sample sites. Only sediment samples from the same basin and within a radius of three kilometres from the oxygen measurement station were chosen.

With this limits 65 sediment sample sites held in the SGU database were found to match the 77 oxygen measurement stations of SMHI. Out of these 65 sites 19 came from areas with oxygen deficiency. Based on these sediment samples the search criteria of anoxic sediment in the SGU database were identified (Table 1).

Table 1. Set up sediment criteria used in the database search.

Demands	Criteria cod	Criteria description
• The description of structure must not contain:	*Oxyta*	Oxic sediment surface
• Only surficial sediment is allowed:	*Djup_från = 0*	Depth_from = 0
• The sediment deposition period must be:	*Postglacial*	Postglacial
• The main grain-size fraction has to be:	*Ler*	Clay
• One of the following criteria has to be fullfilled:		
• Gas content =	*stort eller måttligt*	large or …..
• Color =	*2.5/N*	2.5/N Muncell Colorchart
• Structure =	*Lamin*	Laminated
• Sulfid =	*Sulf*	Sulphide
• Reduced surface =	*Redyta*	Reduced sediment surface

2.4 Database search

Finally the search criteria in Table 1 were set up in a sql-question aimed to find the anoxic sediment samples in the marine sediment database of SGU. Out of 5,652 samples loaded in the database 528 were by this way found to be anoxic, i.e. 8,8 %.

The sql-question was also run on the data set of 65 sediment samples used to identify the search criteria. By this way 14 out of 19 samples (74 %) could be identified as anoxic and 3 out of 46 as not anoxic (6.5 %). This means that five of the sediment samples where not described in the way that they could be identified as anoxic in the sediment database by the search criteria set up.

2.5 Additional data

As mentioned above, the bottom surface at most of the SGU sediment sampling sites has been documented with video or digital camera. About 1,155 of these records have so far been analysed with respect to the redox-conditions. By this way 223 sampling sites were identified as anoxic due to the occurrence of sulphate reducing bacteria (*Begiatoa sp.*). 112 of these sample sites had been identified in the search in the sediment database, described above, but the remaining 111 sample sites had not been identified. The reason could either be that important redox information had not been observed when the samples were examined and described or rather that the characteristics of anoxia in the sediment surface not yet had been formed, i.e. the oxygen depletion in the bottom water was too young. However, the 111 sample sites identified by the occurrence of *Begiatoa sp.* at the sediment surface were also added to the list of 528 anoxic sample sites found in the database search. Together, this yields in total 639 anoxic sites which are shown in the map, Figure 4.

3. Oxygen deficit

3.1 Oxygen deficit maps

Oxygen deficit maps are provided by SMHI as an indicator for HELCOM annual assessment procedure. The maps are based on monitoring data from several HELCOM partners. Examples are shown in Figure 5. The time series of the oxygen deficit maps goes from 1960 up to date. To improve the map quality model and monitoring data is intended to be used in the future. In this study we try to find out if detailed information on sediment anoxia can improve the information on the horizontal distribution of anoxia on the sub-basin scale. Especially, this can be a problem in the north western and western Gotland Basin where the bottom relief has a larger spatial variability than in the rest of the Baltic Proper. The next step is to include the SGU map on post-glacial sediment distribution as a layer of information for the oxygen deficit maps in areas where the analysis of water sampling and sediment sampling data is positively correlated. However, we are able to include this analysis in the report due to lack of time.

3.2 Definition and methods to calculate oxygen deficit maps, areas and volumes

Vertical profiles of oxygen concentration are extracted from SHARK for all stations during the period of interest. In general, this is autumn (defined as August, September and October) as this is when oxygen concentrations are at their lowest, due to the decay of the summer production. Where hydrogen sulphide is present, these values are converted to “negative oxygen” (the amount of oxygen required to oxidise the hydrogen sulphide) where 1 µmol/l hydrogen sulphide is equivalent to an oxygen concentration of -0.044 ml/l (source: HELCOM 2007).

Along each profile, the depth where the concentration falls below a certain threshold is identified. These threshold values are typically 2 ml/l and 0 ml/l. These depths, combined with information on the station position, are use to define a surface, which represents the depth of the (for example) 2 ml/l oxygen level. Below this surface, the water is hypoxic. Above the surface, the water is reasonably oxygenated.

The depth of the 2 ml/l surface is compared with the water depth at the same points. Where the 2 ml/l surface is shallower than the bottom depth, there is water lying below it. This water is hypoxic. Where the 2 ml/l surface is below the sea floor, the whole water column is considered oxygenated (Figure 5).

In a similar way the Water Frame Work classification scheme is used to calculate volume and area of the 5 different classes within the Anholt (Southern Kattegat), Bornholm, Eastern and Western Gotland Basin. The time series, of areas and volumes from each basin from 1960 to 2007, is presented in Figure 7a-d. In addition, stratification strength time series is given by calculating the maximum stratification (Brunt-Väisälä frequency) and the depth of this maximum (based on CTD-data) is included in the figures.

3.3 Oxygen deficit in coastal waters

As a complement to the open waters oxygen deficits we also present the recent Water Directive assessment on the ecological status of coastal and transitional waters. The results related to oxygen status are summarized in Figure 6. The colours correspond to the classification scheme established by the SEPA. The figure indicates where oxygen is below 2.1 ml/l for the lowest 5% data, covering the period 2003 to 2005. Unfortunately, coastal data from the Stockholm Archipelago has not been available at the national data host and one might also note that data for the Gulf of Bothnia coastal waters are indeed scarce.

3.4 Deep water oxygen deficit results

The Western Gotland Basin (Figure 7a) does have a permanent hypoxia (O_2 < 2.1 ml/l) during the whole period (appr. 40 % of the bottom area) with perturbations of some improvement around and after large inflow events (1976, 1993, 2003). The 1993 inflow event stands out particularly when hypoxia decreased to below 20 % of the bottom area. Anoxia (O_2 < 0 ml/l) is a seasonal event most of the time in this basin, but turns into permanent anoxia around 2001 and onwards. Presently, we have the worst case ever since 1960. According to the maximum stratification parameter the water column stability is increasing since 1995.

The Eastern Gotland Basin does (Figure 7b) also have a permanent hypoxia during the whole period (appr. 45 to 50 % of the bottom area) but with larger perturbations of improvement around and after the major inflow events (1976, 1993, 2003). During the two first events hypoxia disappear for some years where after the hypoxia is introduced again. After the last inflow event the hypoxia remained. Anoxia is permanent in bottom waters between major inflow events, covering 20 to 30 % of the bottoms. This basin also shows another particularity. During 1960:ies and 1970:ies the hypoxic areas cover about 45 to 50 % of the total bottom areas, while during the 1980:ies up to mid 1990:ies the hypoxic areas decreases to about 40 % of the total bottom water areas. This means that bottom water phosphorus can be buried in the surface sediments being oxygenated during this period of time. However, after 1995 these bottom areas are again covered by hypoxic and anoxic bottom water, in which phosphorus once again is released to the water column.

In both the Western and Eastern Gotland Basin anoxic bottom water are less frequent in time and with smaller area extension before 1975 as compared to the period after.

In the Bornholm Basin (Figure 7c) hypoxia covers about 30 % of the bottom waters. The major inflow events clearly show up in the time series as oxygenated waters. We can see that inflows also of less strength influence this basin. In general bottom waters covering at most 30 % of the bottoms are hypoxic. Anoxic water appears annually with some exceptions when covering some years instead. It can also be noticed that anoxic waters is more frequent in the later part of the time series as compared to the first part.

The Arkona Basin (Figure 7d) only holds hypoxia as a reoccurring seasonal event with cases of anoxic bottom waters. Oresund and Kattegat seldom holds anoxia, while hypoxia can occur seasonally.

4. Discussion

All together, the results show that there exist a fairly good correlation between oxygen measurements from bottom waters and sediment data. The sediment mirrors the redox condition over time, i.e. the sediment gives an integrated picture and thus can be used as a complement to oxygen measurement data from the water column. Consequently, by using both types of data a more detailed map of the distribution of anoxia in the Baltic Sea can be constructed.

Volume and area of hypoxia and anoxia has been calculated from monitoring and hypsographic data. Especially, the oxygen situation in deep waters has been presented for the Southern Kattegat, Oresund, Arkona, Bornholm, Eastern Gotland and Western Gotland Basins. The stratification parameter is weakest in the Western Gotland Basin and the anoxia shows large variability over time, covering areas of 0 to 40 % of the total bottom area. The high spatial variability of the postglacial sediments in this basin compared to other basins indicates that it is indeed sensitive to the area coverage of anoxic waters. Therefore, would be more profitable for oxygen improvement engineering methods.

In coastal waters several bays along the Östergötland and Småland archipelagos should be further evaluated before selected for ecological engineering methods to improve oxygen conditions.

5. Acknowledgements

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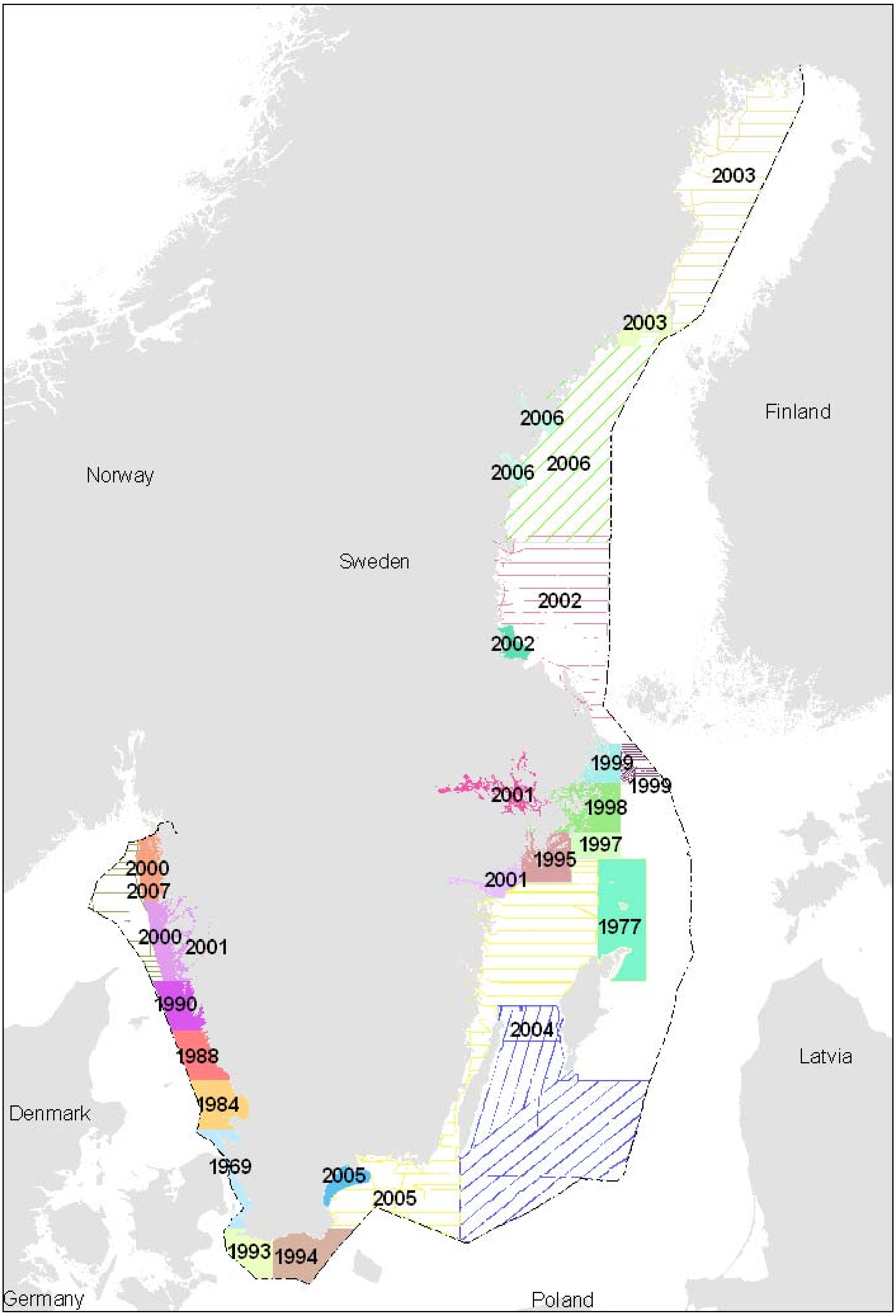

Fig. 1. Areas and corridors, detailed mapped in the Swedish continental shelf by SGU. The figures refer to the start year of the field investigations carried out.

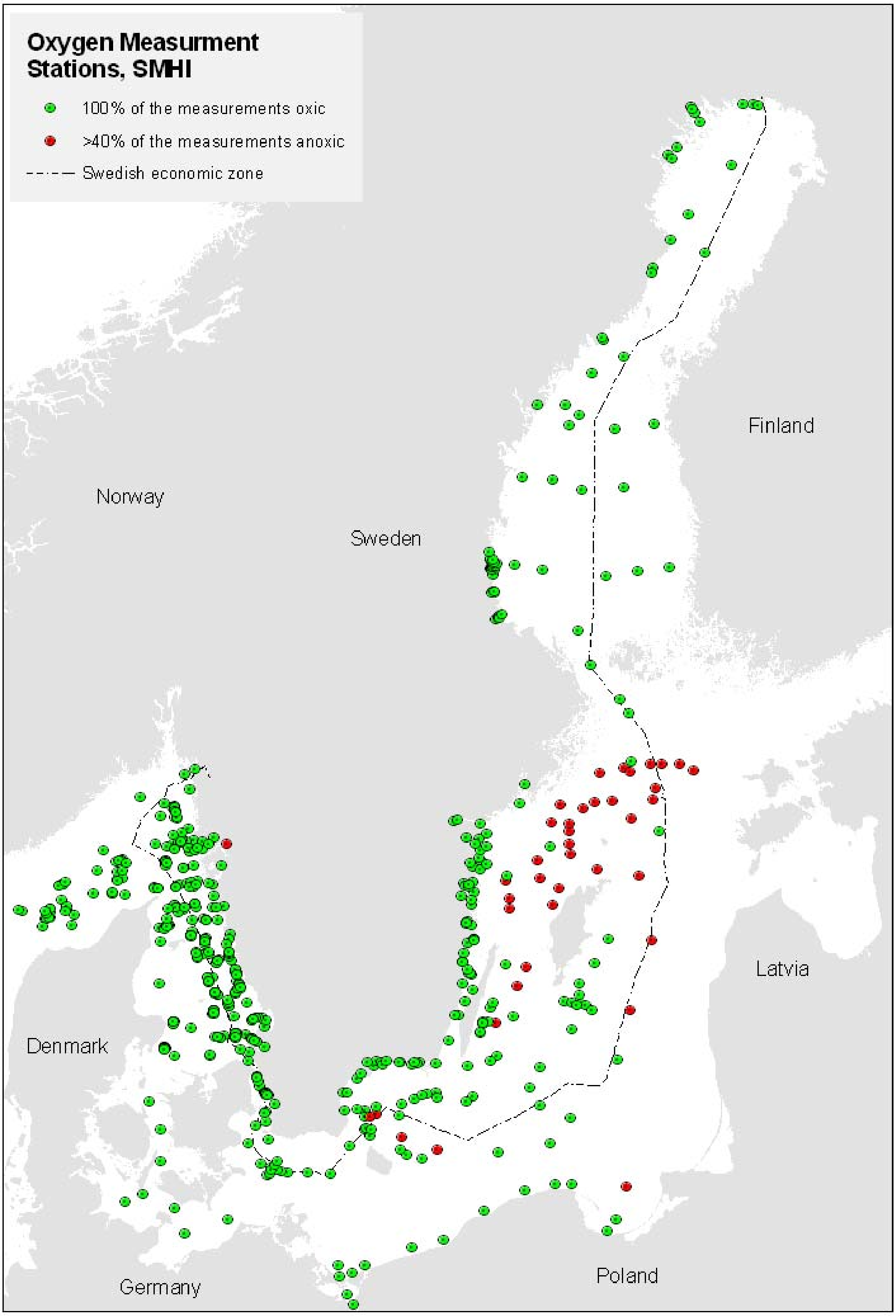

Fig. 2. Oxygen measurement stations (the water column) of SMHI, which has been classified as either oxic (green) or anoxic (red).

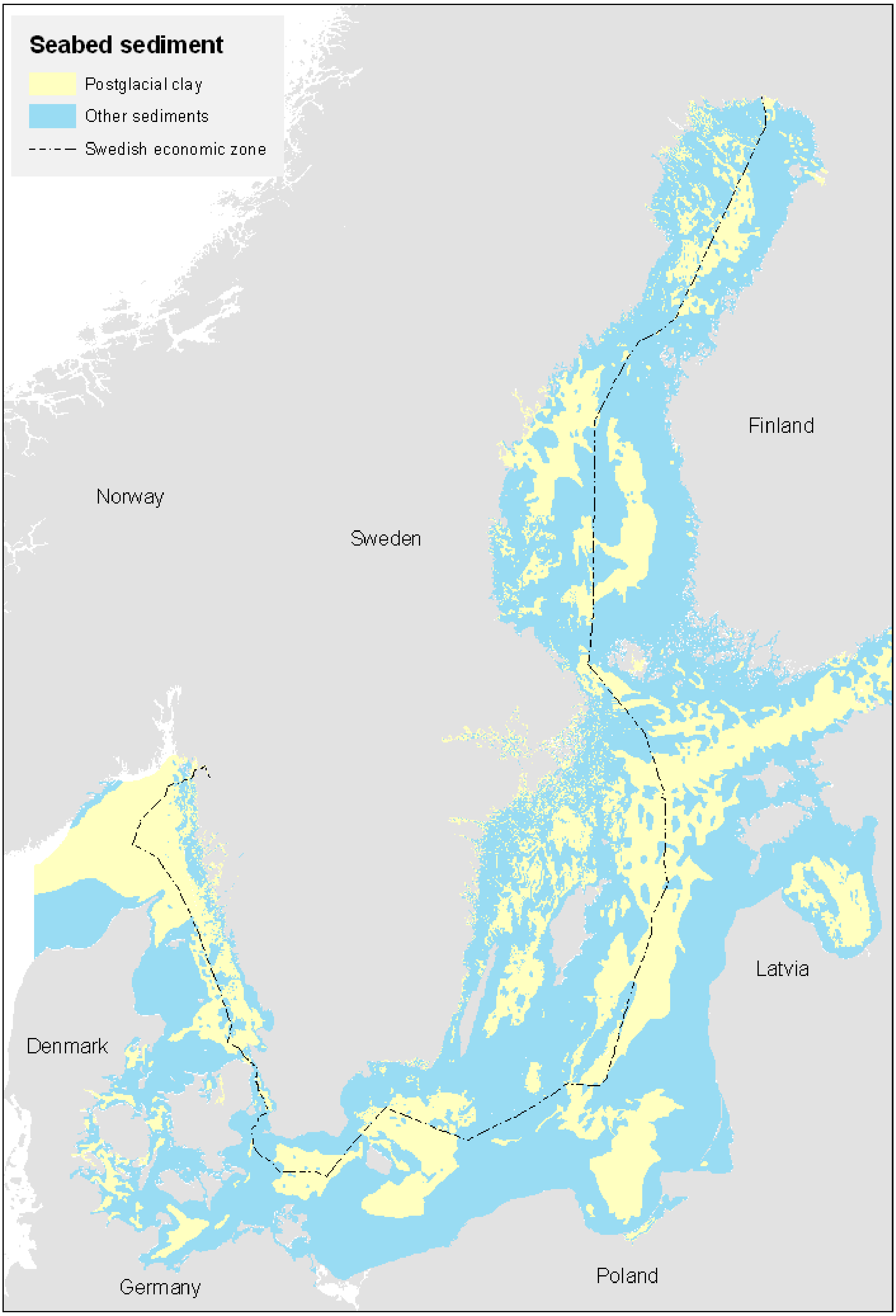

Fig. 3. The distribution of postglacial clay in the bottom surface of the Baltic Sea. The map is compiled by SGU.

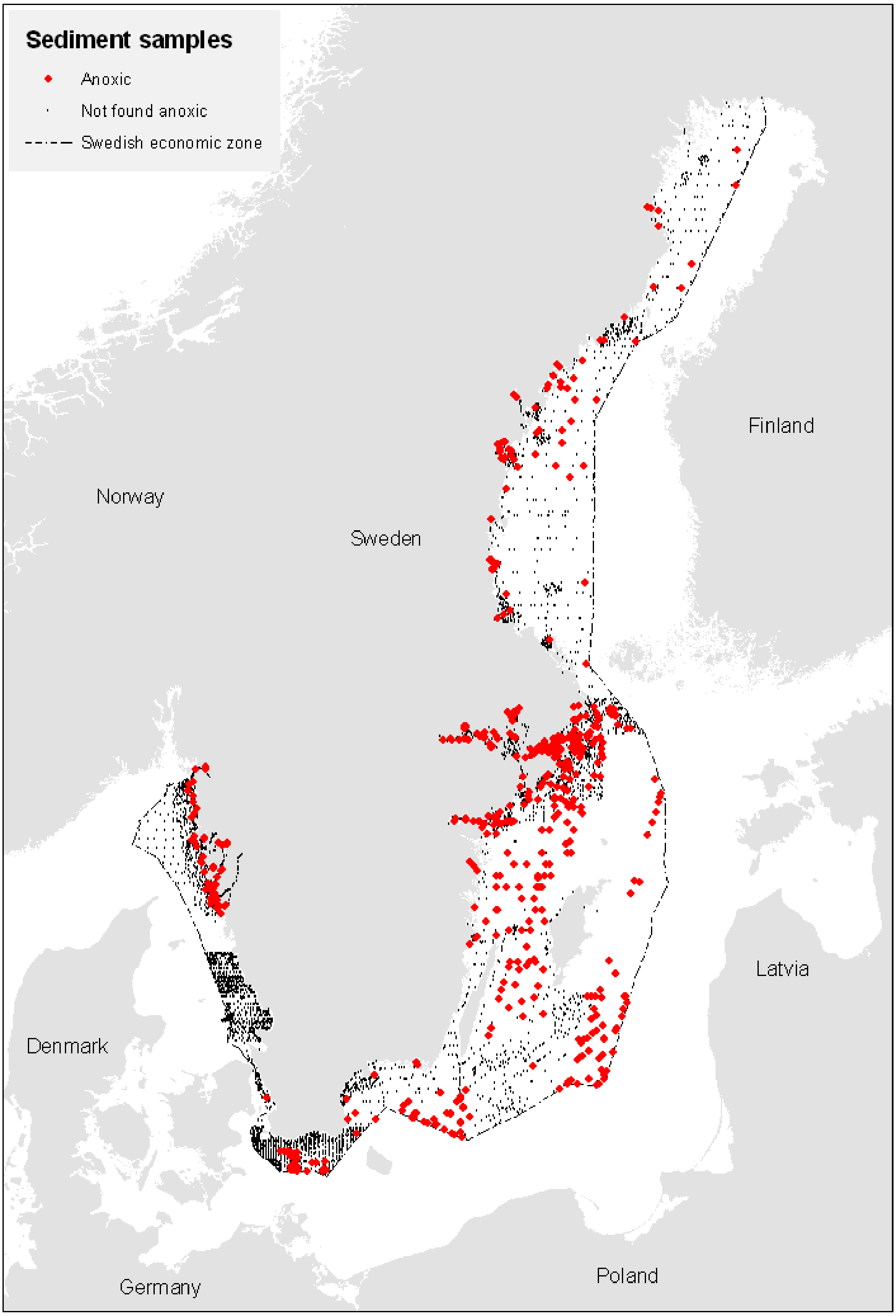

Fig. 4. Sediment sampling sites of SGU, which have been found either anoxic (red) or not anoxic (black) in the search in the SGU database. There is no guarantee that no anoxic sediment can appear in the latter group.

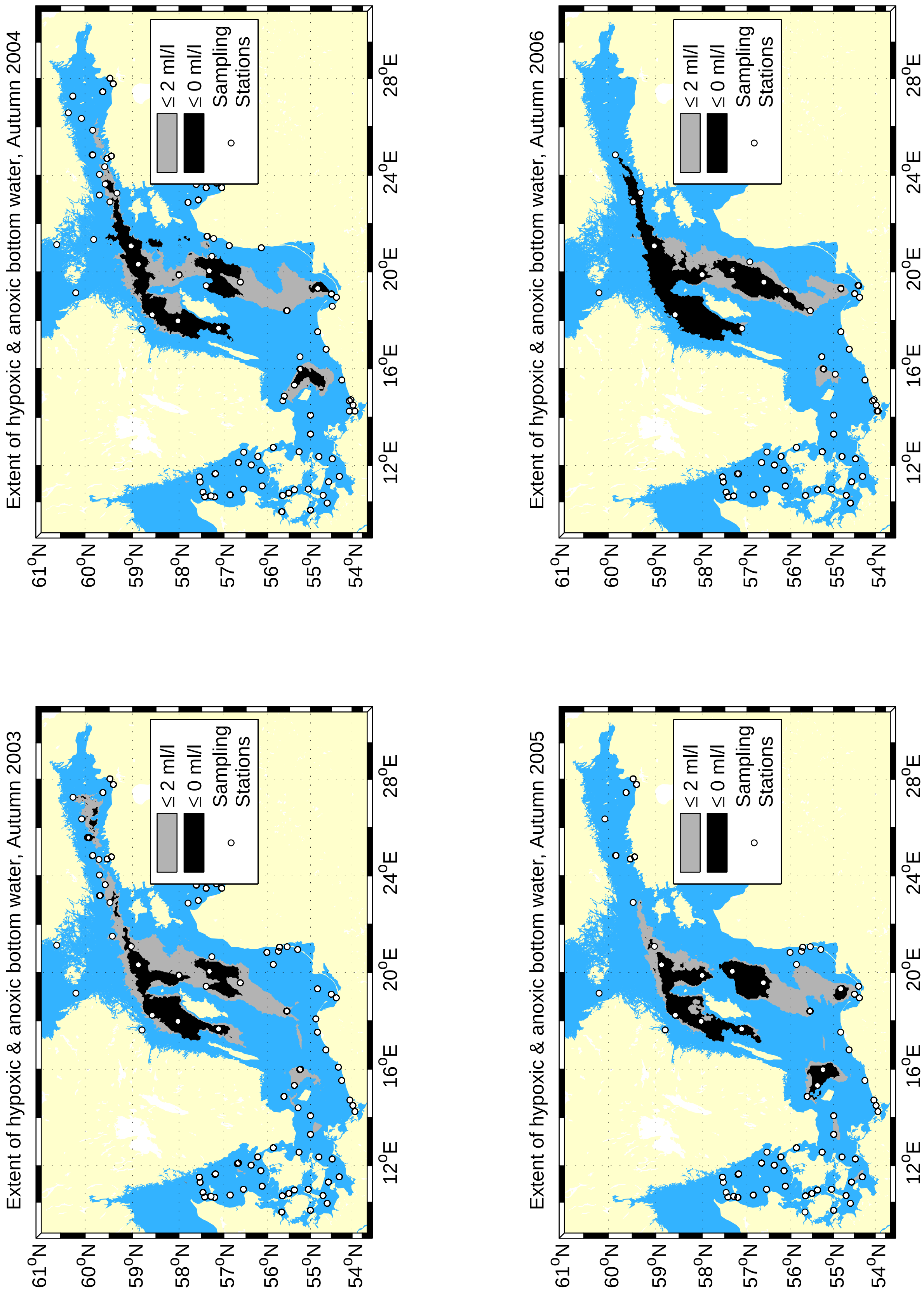

Figure 5: Examples of Oxygen deficits maps for the years 2003 – 2006, based on water sampling data.

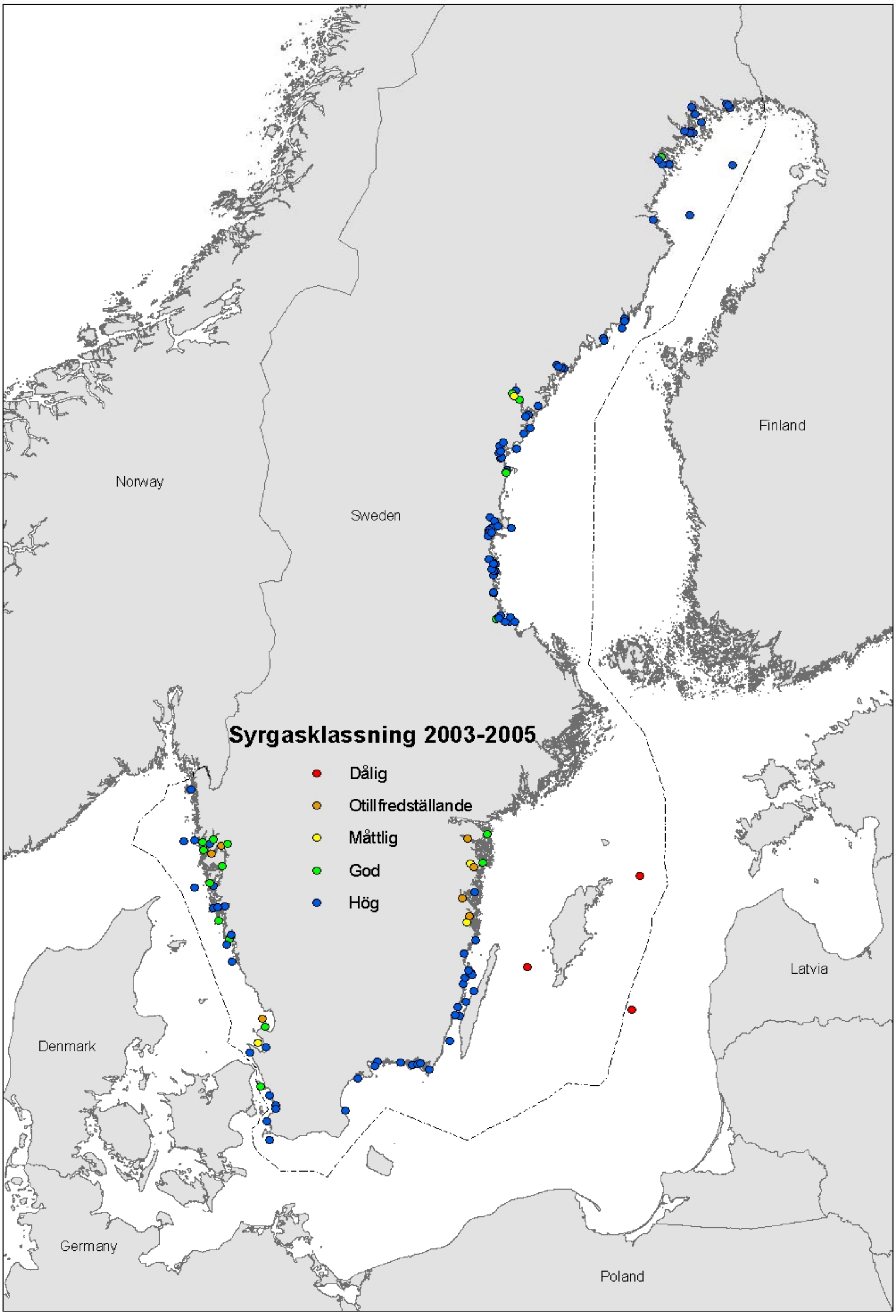

Figure 6: Oxygen classification according the Water Framework Directive.

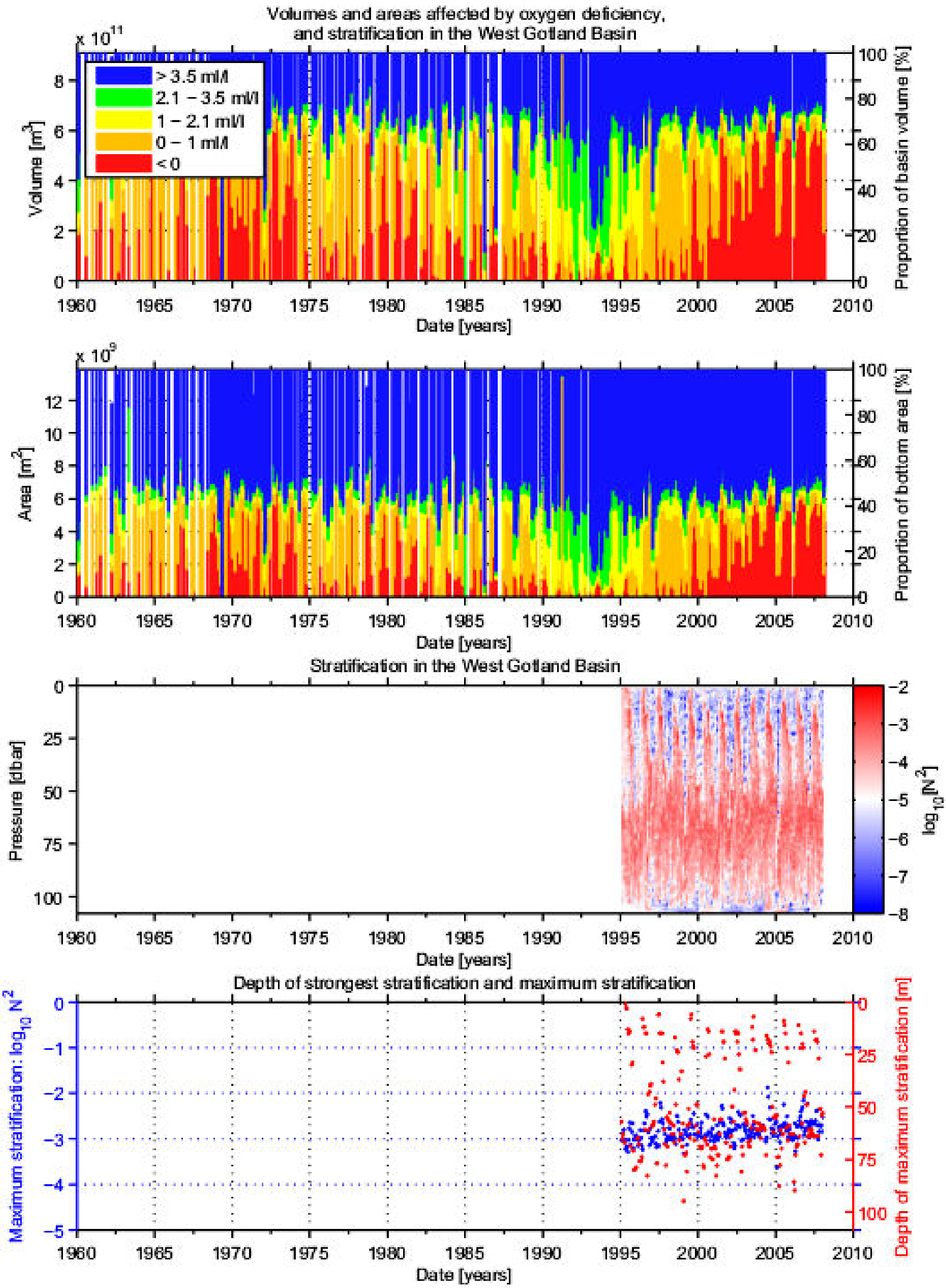

Figure 7a: Time series of volume and area of oxygen deficit, stratification strength and maximum stratification and depth of this maximum.

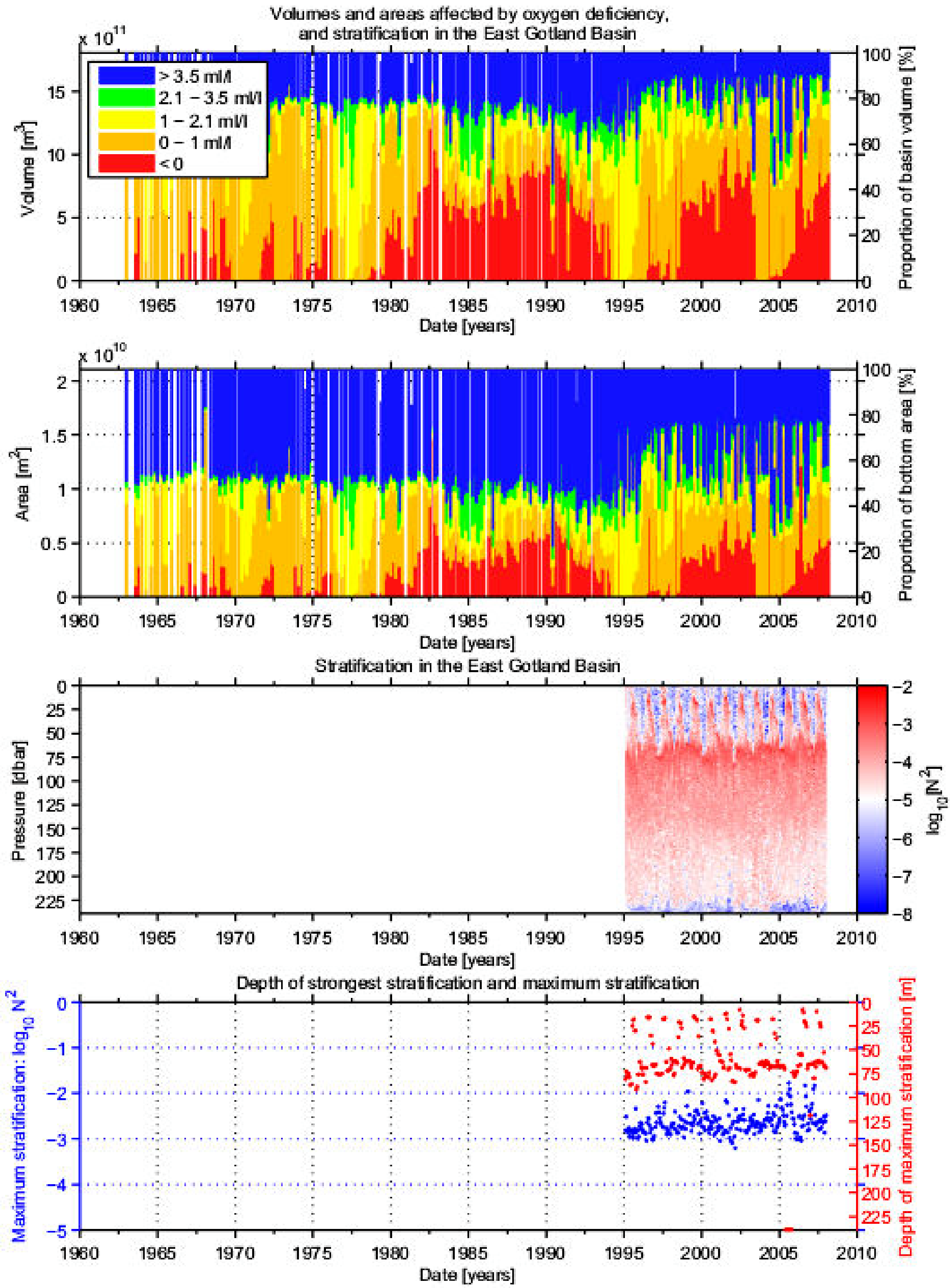

Figure 7b: Time series of volume and area of oxygen deficit, stratification strength and maximum stratification and depth of this maximum.

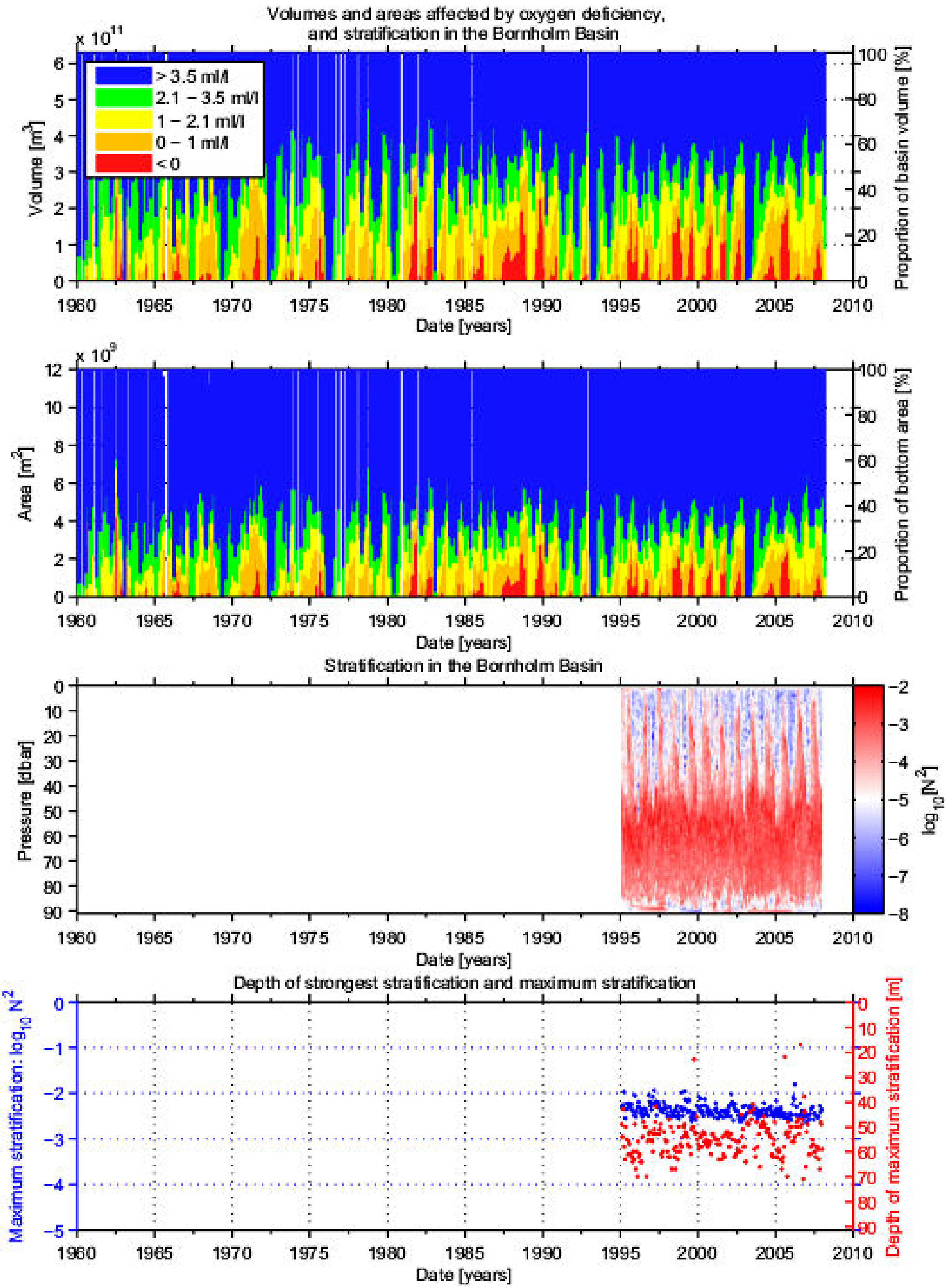

Figure 7c: Time series of volume and area of oxygen deficit, stratification strength and maximum stratification and depth of this maximum.

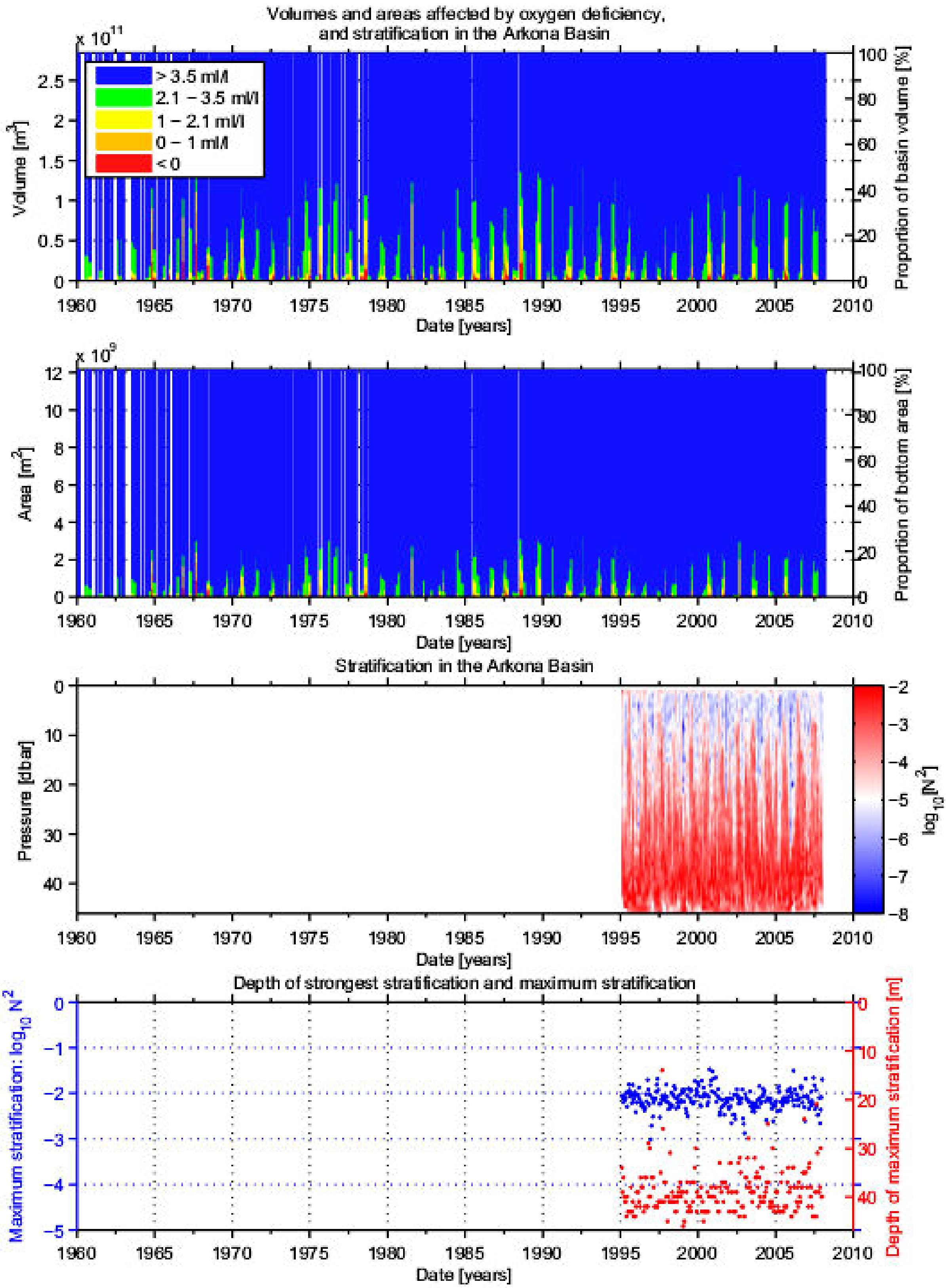

Figure 7d: Time series of volume and area of oxygen deficit, stratification strength and maximum stratification and depth of this maximum.

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601 76 Norrköping
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