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Keywords: biosphere, ecosystems, Forsmark, regolith.

Abstract

This report is part of a project which aims at increasing the understanding of the long-time ontogeny of lake ecosystems in the Forsmark area. This knowledge can be used to assess the future development of the ecosystems and their functioning as traps for possible contaminants from a future deep repository that might be located within the area. The retention of phosphorus, a substance involved in ecosystem production processes, has been studied in deep sediment cores from three lakes within the Province of Uppland. The purpose of this investigation was to elucidate whether all these lakes had passed through an oligotrophic hardwater stage after being isolated from the sea.

Lake Vikasjön, an alkaline brownwater lake which was isolated some 3700 years ago, showed clear signs of an oligotrophic hardwater period in the form of large amounts of calcium-associated phosphorus accumulated in the sediments from this period. The other two lakes investigated, the alkaline brownwater Lake Skälsjön and the deep eutrophic Lake Limmaren, showed no signs of oligotrophic hardwater conditions in the past. The absence of this stage may be explained in different ways for these two lakes. Lake Limmaren is too deep to sustain photosynthetic activity at the bottom and develop the thick “microbial mat”, which is characteristic for the oligotrophic hardwater lakes in the area, and which has an important role in the retention of phosphorus. The other lake, Lake Skälsjön is situated just below the 13 m high water falls at Lövstabruk. Hence, most of the drainage area of this lake had been raised from the sea long before the lake basin became isolated. Upstream lakes had already passed their oligotrophic hardwater stage and developed into brownwater systems. The water entering and flushing through Lake Skälsjön thus mediated a direct transfer of this lake into a brownwater ecosystem.

From the results of this investigation we concluded that the lakes developed today, and also those formed in the future, within the Forsmark area, may be of four types, representing three different lines of ontogeny: Ia) the currently oligotrophic hardwater lakes (not included in this investigation but represented by e.g. Lake Eckarfjärden in the Forsmark area), Ib) the former oligotrophic hardwater but currently alkaline brownwater lakes, e.g. Lake Vikasjön), II) the alkaline brownwater lakes that were formed directly after isolation and never passed through the alkaline hardwater stage, e.g. Lake Skälsjön, and III) the deep eutrophic lakes, e.g. Lake Limmaren (also without any oligotrophic hardwater stage in their ontogeny).

Knowledge of the possible lines of ontogeny, and the conditions favouring one or another of them, is essential for evaluating the consequences and future accumulation of radioactive substances if a leakage from a nuclear waste repository would occur. Especially interesting in terms of carbon turnover and carbon budgets is the oligotrophic hardwater lakes which host unusually thick benthic “microbial mats” of living microorganisms that affect chemical as well a biological processes within the lake ecosystem. The knowledge of sediment formation and dynamics of different elements below and within this microbial mat should be further elucidated.

Sammanfattning

Detta är en delrapport i ett arbete vars syfte är att förbättra förståelsen och kunskapen om långtidsutvecklingen av sjöekosystem i Forsmarksområdet. Denna kunskap är nödvändig för att kunna bedöma riskerna vid eventuella läckage från ett djupförvar av radioaktivt kärnbränsle. Sjöarna i området utvecklas kontinuerligt varvid sjöbäckena fylls ut med sedimenterande material och omvandlas till våtmark. Samtidigt nybildas sjöar när Östersjö-vikar avsnörs på grund av den fortgående landhöjningsprocessen.

Undersökningarna utförs inom ett områden längs Upplandskusten, vars berggrund domineras av sura bergarter såsom granit och gnejs. Berggrunden överlagras av en kalkrik morän som har sitt ursprung i kambrosilurområdet i Bottenhavets södra del, vilket eroderats och transporterats med isälvar till de östra delarna av Uppland. Tidigare arbeten har identifierat tre olika typer av sjöar i området: kalkoligotrofa sjöar, brunvattenssjöar samt djupa eutrofa sjöar. De kalkoligotrofa sjöekosystemen utbildas i grunda och nyligen avsnörda havsvikar och består under ca 1000 år, en geologiskt sett mycket kort tid. Därefter förändras de till andra typer av sjöekosystem, t ex har en utveckling från kalkoligotrofa förhållanden till brunvattenssjö påvisats genom paleo-limnologiska undersökningar. Den ontogenetiska processen är dock inte helt utredd, och det är oklart om alla sjöar genomgår det kalkoligotrofa stadiet efter avsnörning.

I denna första del av undersökningarna har djupa sedimentproppar från tre olika sjöar analyserats kemiskt med avseende på fosforkoncentrationer. I alla tre sjöarna har sedimenten provtagits ner till ett djup som innefattar även marina förhållanden. Sedimentpropparna representerar således sjöarnas historia från marin havsvik och fram till de sötvattensekosystem de är idag. De sjöar som undersökts är två brunvattenssjöar i Forsmarksån, Vikasjön (belägen 28 möh, 3700 år gammal) och Skälsjön (13 möh, 1800 år gammal), samt den djupare och näringsrika Limmaren, belägen nära Norrtälje (3,9 möh, 1100 år gammal). Resultaten av analyserna visar att endast en av de tre sjöarna, Vikasjön, har genomgått ett kalkoligotroft stadium. Detta avspeglas tydligt i form av höga koncentrationer av kalciumbunden fosfor, som fällts ut och bevarats i sedimenten från denna tidsperiod i sjöns historia. Avsaknaden av ett kalkoligotroft stadium i Limmaren kan förklaras av sjöns morfometri (medeldjup 4,7 m jämfört med Vikasjöns 1,2 m), som förhindrar att ljus tränger ner till bottnen. Därmed finns inte förutsättningar för att fotosyntetiserande organismer ska kunna tillväxa och utbilda den tjocka ”mikrobiella matta” som är karakteristisk för kalkoligotrofa sjöar och som troligen spelar en stor roll i fosforns retention i sedimenten. Anledningen till att Skälsjön inte varit kalkoligotrof kan sökas i det faktum att sjön är kraftigt genomflödad av vatten från uppströms belägna brunvattenssjöar (bl a Vikasjön). Eftersom Skälsjön är belägen strax nedströms de 13 m höga vattenfallen vid Lövstabruk, hade den största delen av sjöns avrinningsområde varit landområden under en lång period innan själva sjön avsnördes. Eventuella kalkoligotrofa perioder i uppströms belägna sjöar hade alltså passerats och det vatten som transporterades till och genom Skälsjön bidrog till att den redan från början utvecklades till en brunvattenssjö.

Utifrån dessa resultat konstateras att fyra olika typer av sjöar kan identifieras i östra Uppland, representerande tre olika utvecklingslinjer: Ia) kalkoligotrofa sjöar (bl a Eckarfjärden i Forsmarksområdet), Ib) tidigare kalkoligotrofa sjöar som övergått till brunvattenssjöar, t ex Vikasjön, II) brunvattenssjöar som inte varit kalkoligotrofa efter avsnörningen från havet, t ex Skälsjön, och III) djupa eutrofa sjöar, t ex Limmaren.

Dessa skillnader mellan olika sjöar med avseende på ontogeni och sedimentens karaktäristika kommer att användas som en del i underlaget för att kunna bedöma förutsättningarna för retention av olika ämnen i sjöekosystemen. Det långsiktiga målet för projektet är att hitta en koppling mellan recent sedimentdynamik med avseende på näringsämnen (dvs ekosystemfunktion) och den långtidsutveckling av sedimentens sammansättning som avspeglas i djupare sedimentlager.

Contents

1 Introduction

Lakes are found on the continents wherever the geological and morphological prerequisites for formation of lake basins are fulfilled. In Scandinavia, a majority of the lakes present today were formed during the last glaciation, when geomorphologic processes substantially altered the entire landscape. As the big glacier retired, erosion, transport, and deposition of material resulted in the formation of numerous lake basins in the landscape. Still 8000 years later, effects of the former ice cover continue to alter the morphology of the Scandinavian peninsula. The shoreline of the Baltic Sea is gradually modified, as the continent is recovering from the pressure that the ice caused. This results in a substantial shoreline displacement in the central and northern parts of Sweden and Finland. As a consequence, freshwater lake basins are continuously formed along the coast as bays become isolated from the brackish water of the Baltic Sea.

The ecosystems that develop in such lake basins are gradually maturing in an ontogenetic process which includes subsequent sedimentation and deposition of allochtonous (transported from the surrounding catchment area) as well as autochtonous (originating from/produced within the lake) substances. Hence, the long-time ultimate fate for all lakes is an inevitable fill-up and conversion to either a wetland or a more dry land area, the final result depending on local hydrological and climatic conditions. A usual pattern for this lake ontogeny, which is often referred to, is the subsequent development of more and more eutrophic conditions as the lake depth and lake volume are decreasing. In later stages, aquatic macrophytes speed up the process by colonising large areas of the shallow sediments /Wetzel, 2001/. However, varying environmental conditions may alter this general pattern, and there are examples of lake ontogeny that includes transitions also to more oligotrophic conditions /Engstrom et al, 2000/.

The Forsmark area in the province of Uppland belongs to the part of the Baltic coast along which lakes are continuously being formed, as the shoreline displacement succeeding the last glaciation period is still substantial /Ignatius et al, 1981/. The coastal bays in the area are mostly shallow and their isolation from the sea either directly results in formation of wetlands or in the formation of shallow lake basins. A few deeper lake basins are found in the area /Brunberg and Blomqvist, 1998/. The bedrock of the area is dominated by granites and gneisses, while the overlaying soils include a till very rich in calcareous material /e.g. Ingmar and Moreborg, 1976/. Weathering of the calcium-rich till results in that newly formed lakes initially undergo an ephemeral oligotrophic hardwater stage with a duration of about 1000–1500 years. After that the alkalinity of the lake water decreases and the lake ecosystem changes. The development of the ecosystems following the oligotrophic hardwater stage has been unclear, and different lines of ontogeny have been proposed, one including a transformation to more eutrophic conditions /Willén, 1962/ and another colonisation by *Sphagnum* mosses and transfer to dystrophic conditions /Brunberg and Blomqvist, 2000/. /Brunberg et al, 2002a/ recently found indications that not all lakes in the area have passed through the oligotrophic hardwater stage. They suggested that the requirements for an oligotrophic hardwater stage to develop not only includes that the incoming water is rich in calcium ions, but also that the lake basin is shallow enough for a microbial mat of photosynthesising organisms to establish at the bottom. When these conditions are met, photosynthesis at the bottom leads to precipitation of lime and subsequent co-precipitation of phosphorus, which together creates the oligotrophic hardwater stage. In the deeper lake basins of the area, in which light is not enough for photosynthetic organisms to establish over large parts of the bottom area, conditions would instead become naturally highly eutrophic. An interesting question that also arises when examining the shoreline displacement process in the area is: what happens when lakes are formed downstream existing lakes of a given character? Will the presence of a lake/lakes that have already passed through the oligotrophic hardwater stage and turned brownwater systems erase the formation of new oligotrophic hardwater lakes downstream in the river system?

One purpose of the currently ongoing lake studies in the Forsmark area is to elucidate the differences in sediment characteristics between different lake types, as a part of the background data used for assessing the retention of various substances. One approach used in these investigations was to analyse the differences in sediment composition in deep sediment cores from the lakes. The results from these analyses, which are presented in this report, are also used to evaluate the proposed ontogeny /Brunberg and Blomqvist, 2000/ of different lake types in the area.

2 Methods

2.1 Area description

The province of Uppland in the eastern part of central Sweden has a post-glacial geological history that differs from that of most other parts of Sweden. It is located well below the highest shore-line of all but the present stage of the Baltic Sea and close to the large Cambrosilurean limestone deposit currently found at the bottom of the Bothnian Sea. The latter has been eroded and transported southward and has covered the original, acidic, prekambrian bedrock of the province with a till very rich in calcareous matter. The shoreline displacement in the area is substantial at some 50 centimetres per century /Påsse, 1997; Hedenström, 2003/ and, as a result, new calcareous soils are continuously added along the coastline. Due to the large amounts of easily weathered substances, newly formed lakes and rivers in the area are highly alkaline. Long-term weathering of the soils, together with the establishment of terrestrial ecosystems, results in a decrease of the alkalinity of surface waters over time and waters at higher altitudes in the area are only weakly alkaline. Hence, in terms of the alkalinity of the water, the aging process gives rise to a gradient of lake types in the province.

/Brunberg and Blomqvist, 1998/ described the lakes in the County of Uppsala which covers the NW half of the province, including those in the Forsmark area selected by SKB as a potential site for a deep repository for radioactive waste. In an analysis of what types of lakes that may appear in the future due to the shore-line displacement, /Brunberg and Blomqvist, 2000/ used data about these lakes as well as data from lakes in the County of Stockholm, which covers the southern part of the province. They suggested that the lakes of the province of Uppland could be divided into three categories, based on their ecosystem functioning; shallow and oligotrophic hardwater lakes, shallow alkaline brownwater lakes, and deeper highly eutrophic lakes. All these three lake types are represented today, or may be represented in the future, in the area affected by a construction of a deep repository /Brydsten, 1999/.

The area where oligotrophic hardwater lakes are formed and exist today is shown in Figure 2-1. For the investigations of historical records of this lake type, older lakes were chosen, i.e. lakes situated at higher elevation over the sea level. Two representatives of brownwater lakes were selected; Lake Vikasjön in the uppermost part of River Forsmarksån and Lake Skälsjön further downstream in the same river system. Deep eutrophic lakes are not as frequent as the other lake types in this area, but they do occur and the predicted future landrise will create deep lake basins along the coast which might develop into similar lake ecosystems. For this investigation the eutrophic Lake Limmaren was selected.

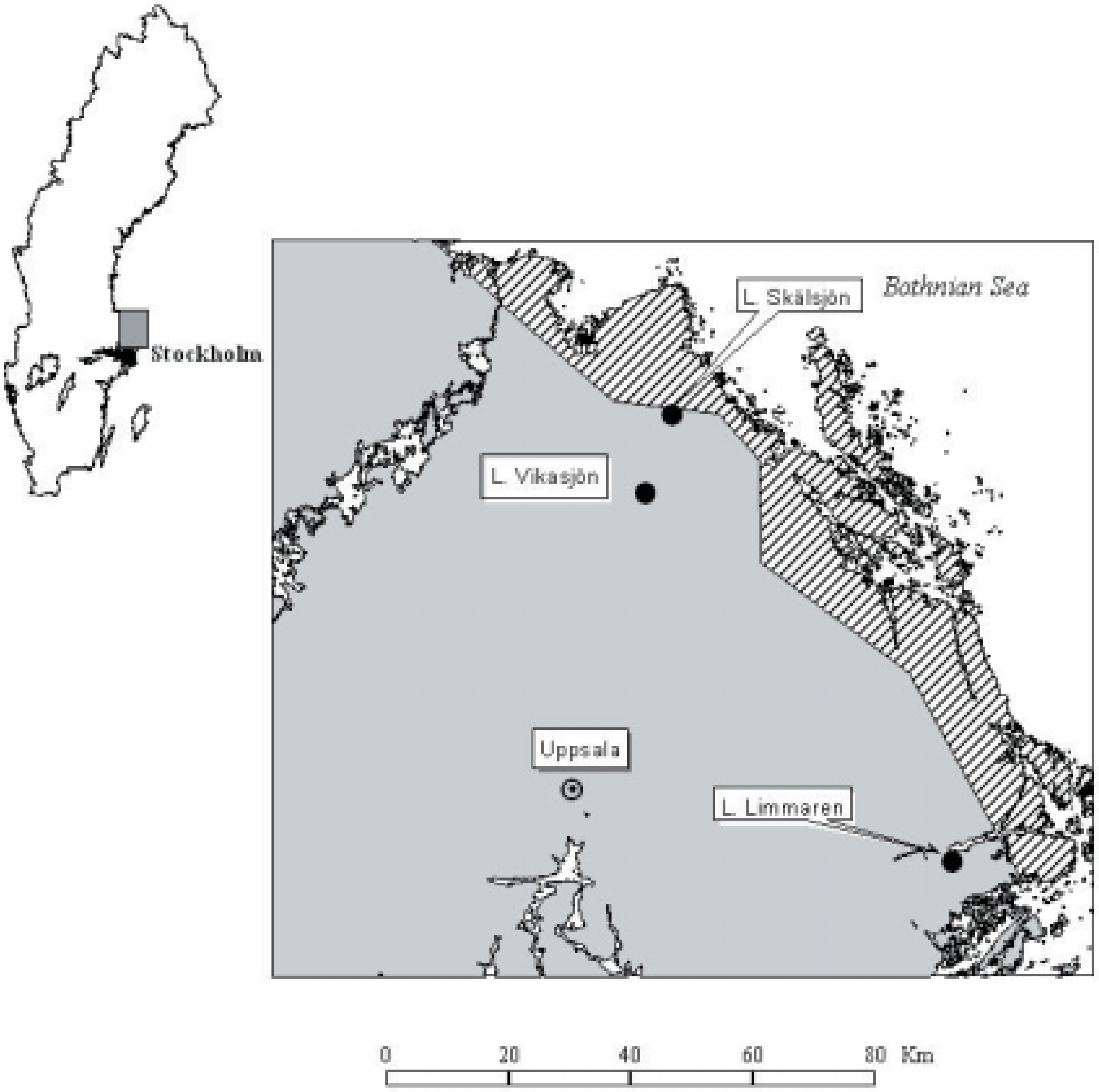

Figure 2-1. *The Forsmark area, Sweden, with Lake Vikasjön, Lake Skälsjön and Lake Limmaren indicated. The stripes show the area along the coast where oligotrophic hardwater lakes are formed and exist today.*

Lake Vikasjön is elevated 28 m over the present mean sea level, which corresponds to an age of 3700 years /Brydsten, 1999/. Situated in the upper parts of River Forsmarksån, it constitutes one part of the former ancient lake that was isolated from the sea and later divided into several lakes as mires successively developed in the area. Today the catchment is dominated by forest and mires, in about equal parts. Regarding water chemistry the lake can be described as an alkaline brownwater system (Table 2-1). Paleo-ecological studies based on diatom analyses of the sediments have shown that this lake passed through an oligotrophic hardwater stage during the first millennium after isolation /Ingmar, 1963/. The sediment layer originating from the lake phase is 150–200 cm deep, and consists in the deeper parts of the characteristic “cyanophycée-gyttja” formed during oligotrophic hardwater conditions, and in the more surficial layer of “dy”; sediments developed mainly from humic compounds entering the lake from the surrounding mires. The estimated sediment accumulation rate corresponds to 1–1.5 mm per year during the oligotrophic hardwater stage, and 1 mm per year during the following brownwater stage /Brunberg et al, 2002a/.

Table 2-1. Characteristics of Lake Vikasjön, Lake Skälsjön and Lake Limmaren.

	Lake Vikasjön	Lake Skälsjön	Lake Limmaren
Catchment:			
Catchment area	45.3 km^2	181 km^2	21.1 km^2
Forest	50 %	65 %	68 %
Wetland	46 %	25 %	0 %
Farmland	1 %	4 %	6 %
Lakes	3 %	6 %	26 %
Lake:			
Coordinates for outlet (RT 90, 2.5 gon W)	668882, 161498	670108, 161862	662767, 166446
Elevation above sea level	28 m	13 m	3.9 m
Approx. age as a lake	3700 years	1800 years	1100 years
Lake area	1.16 km^2	1.83 km^2	5.9 km^2
Maximum depth	3.3 m (3.6 m before drainage/regulation)	1.5 m (2 m before drainage/regulation)	7.8 m (9 m before drainage)
Mean depth	1.2 m	0.8 m	4.7 m
Lake volume	–	1.46 Mm^3	27.3 Mm^3
Water renewal time	–	14 days	2 137 days
Water colour	180 mg Pt/l*	120 mg Pt/l**	20 mg Pt/l***
TOC	25 mg C/l*	19 mg C/l**	9 mg/l***
Tot-P	20 µg/l*	17 µg/l**	54 µg/l***
Alkalinity	0.54 mekv/l*	0.8 mekv/l**	1.4 mekv/l***
Ca^{2+}	0.7 mekv/l*	1,0 mekv/l**	1.5 mekv/l*

* Average from regular Swedish monitoring programs /SLU, 2003/
** Average from two sampling occasions in 1990 and 1995 /SLU, 2003/
*** Average from monthly/biweekly sampling during 1999 /Brunberg and Blomqvist, unpubl./

The other brownwater lake included in the study, Lake Skälsjön, is elevated 13 m over the sea level, and the age of the lake is about 1800 years (Lars Brydsten, pers.comm.). The catchment is dominated by forest and mires (Table 2-1). Although situated in the same river system as Lake Vikasjön and with similar water chemistry (Table 2-1), we expected the ancient lake ontogeny to differ substantially. Lake Skälsjön is a flow-through lake, situated within the main stream of River Forsmarksån. Furthermore, it is downstream of the 13 m high water falls through Lövstabruk. Due to this difference in topography, the lakes downstream the water falls were isolated much later than the upstream lakes. Hence, at the time when Lake Skälsjön was formed the upstream lakes had already passed their oligotrophic hardwater stages. The water entering and flushing through Lake Skälsjön (water renewal time is about 14 days) was thus probably substantially influenced by the mires and brownwater lakes developed in the upstream areas of the catchment. Given these conditions, /Brunberg and Blomqvist, 2000/ suggested that Lake Skälsjön never passed through any oligotrophic hardwater stage, but instead was transferred directly from a brackish bay to a brownwater lake.

Lake Limmaren is situated near the town of Norrtälje. The elevation over the sea level is today 3.9 m. Taking into account a lowering of the lake level of about one meter, which was the result of a drainage project in the 1930's, the age of this lake is approximately 1100 years. The catchment is dominated by forest (70%) and the lake itself (26%). The lake water is highly alkaline with high nutrient concentrations and low water colour (Table 2-1), and yearly cyanobacterial water blooms occur. No external non-natural sources of nutrients have been identified /Pettersson and Lindqvist, 1991/, and the lake thus may be considered as naturally eutrophic.

2.2 Sampling and analyses

Deep sediment cores were taken from ice with a Livingstone sampler from Lake Vikasjön, Lake Skälsjön and Lake Limmaren, respectively. The construction of the Livingstone sampler makes it possible to take several subsequent sediment cores with a length of approximately 1 m of each core. This was used in Lake Limmaren and in Lake Vikasjön, where three subsequent cores were taken in each lake. In Lake Skälsjön, one core of 1.1 m was sufficient to cover the entire layer of lake sediment overlaying the postglacial marine sediments.

The deep sediment cores were transported to the laboratory and sectioned into 5 cm intervals. After freeze-drying, the sediments were chemically analysed for total phosphorus concentration (acid oxidative digestion and a following photometric analysis of molybdate-reactive phosphorus).

Phosphorus fractionation analysis, according to the protocol of /Hieltjes and and Lijklema, 1980/ was performed on wet sediments, using the following extractants: 1) NH_4Cl, which extracts loosely bound or absorbed phosphorus, 2) NaOH, which extracts phosphate adsorbed to metal oxides and other surfaces, exchangeable against OH^-, and phosphorus soluble in bases, 3) HCl, extracting phosphorus bound to carbonates, apatite-P and phosphorus bound in oxides. In addition to these phosphorus fractions, a residual fraction was calculated by subtracting all the extracted phosphorus from the analysed total phosphorus concentration. This residual fraction represents refractory organic and inert phosphorus.

3 Results

The chemical analyses showed large heterogeneity in phosphorus distribution with depth in the sediments of Lake Vikasjön. In the other two lakes, the distribution patterns showed small variations, with the exception of an increase of phosphorus concentrations towards the surface (Figures 3-1 and 3-2).

Identification of the sediment layers representing the period of isolation from the sea was made in all the three sediment cores. In Lake Vikasjön, earlier paleo-ecological investigations including diatom analyses /Ingmar, 1963/ have identified the depth of these sediment layers. Thus, by comparing the clearly visible layers in our sediment cores with the earlier detailed descriptions, we could identify the isolation period to 160–190 cm depth of the sampled core. Lake Skälsjön has an age of approximately 1800 years as a lake. In our sampling we covered the entire period after isolation and reached well down into the layer of clay-gyttja, which was found also by /Bergström, 2001/ and which is normally formed before the basin is isolated from the sea (Hedenström, pers. comm.). In Lake Limmaren the differences between the layers were less pronounced and we had to confirm that the sediment core was deep enough to cover the entire freshwater period of the lake. Three samples were picked out from the layers of 95–100 cm, 145–150 cm and 195–200 cm, and scanned for composition of diatoms. Remnants of brackish benthic diatoms were found in the two deepest samples, while the sediment from 95–100 cm only contained freshwater diatoms, mainly of the pelagic genus *Aulacoseira*, indicating sedimentation from pelagic water of a relatively deep freshwater lake. Thus we concluded that the period of isolation of Lake Limmaren from the Baltic Sea was represented by the 100–145 cm depth of the sampled sediment core.

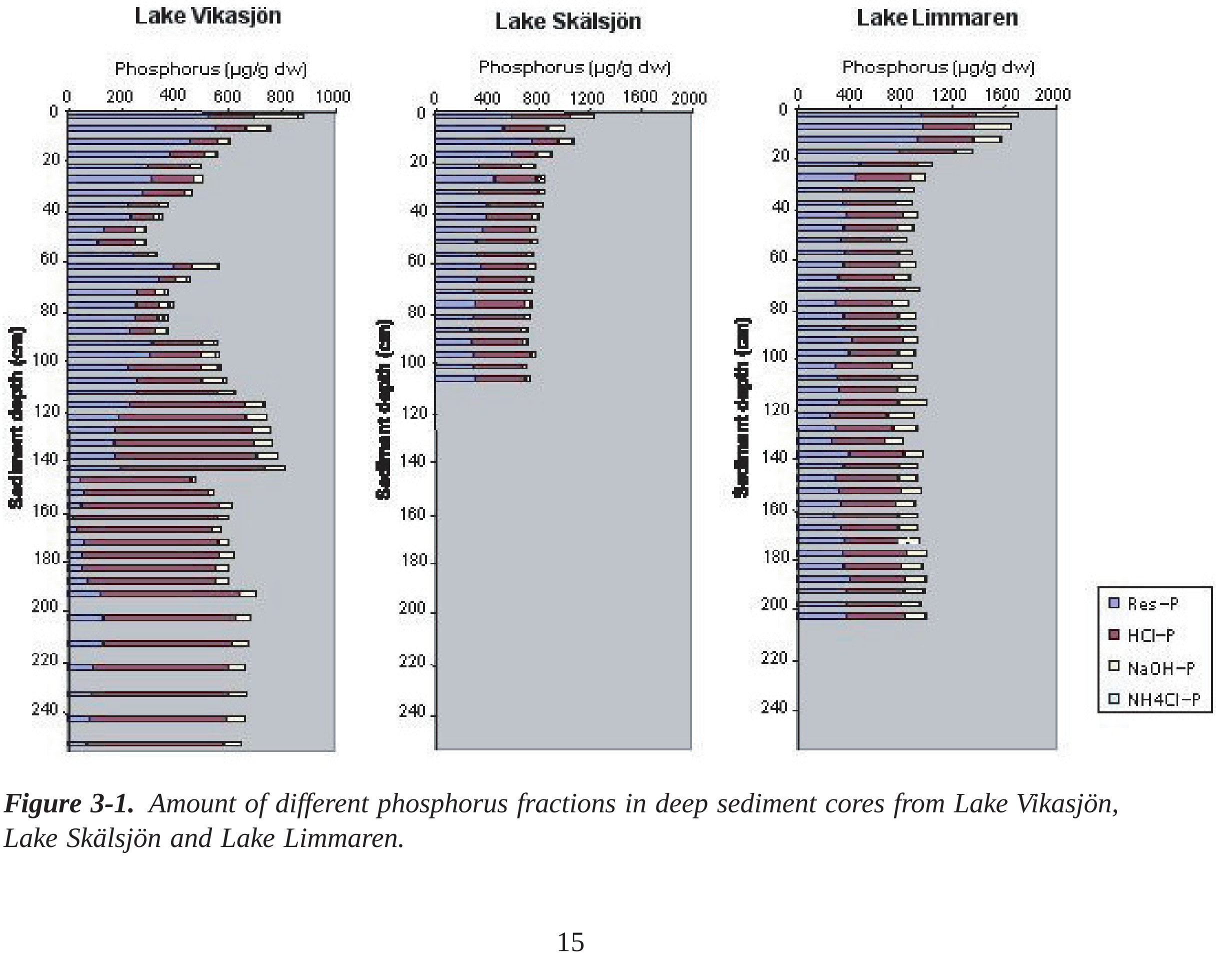

__Figure 3-1.__ Amount of different phosphorus fractions in deep sediment cores from Lake Vikasjön, Lake Skälsjön and Lake Limmaren.

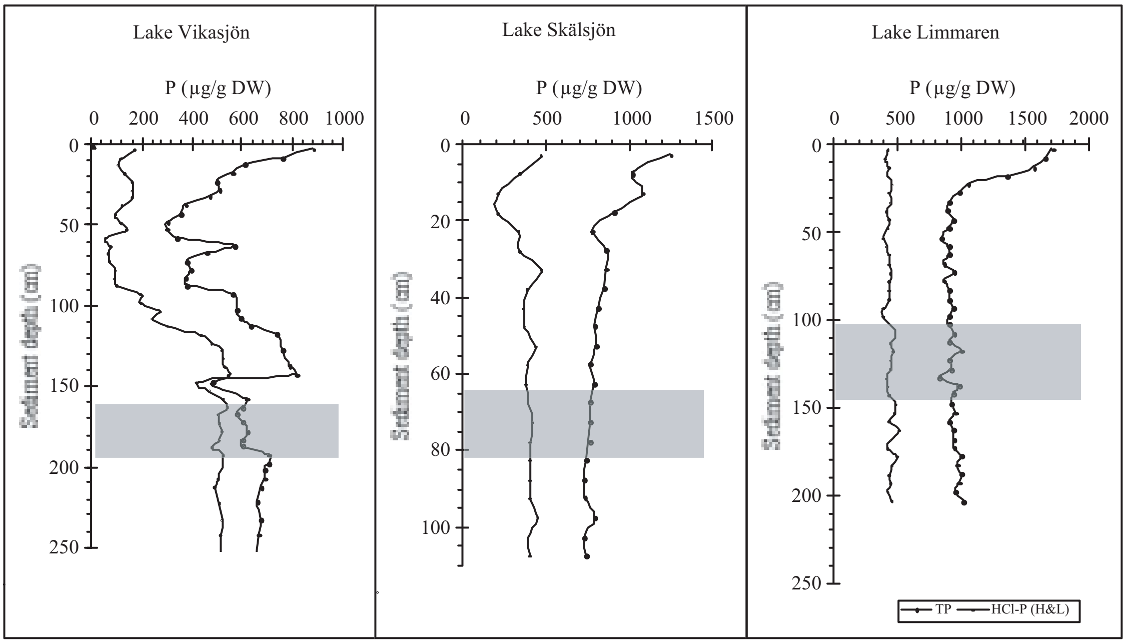

***Figure 3-2.** Total phosphorus concentrations, and the phosphorus fraction related to calcium-bound phosphorus (HCl-P, according to /Hjeltjes and Lijklema, 1980/) in deep sediment cores from Lake Vikasjön, Lake Skälsjön and Lake Limmaren. The shaded areas represent the time period when the lake was isolated from the sea (approximately identified, cf Methods).*

When comparing phosphorus concentrations in the sediments of the three lakes, Lake Vikasjön had the lowest total concentration with a maximum value of 880 µg P/g in the surface layer (Figure 3-1). The concentration decreased down to a minimum of 300 µg P/g dw at a sediment depth of 50 cm, increased again to values around 800 µg P/g dw at a depth of 120–150 cm and then stabilised further down (below/before the isolation period) at a level of about 660 µg P/g dw. The phosphorus in surficial sediments was dominated by the organic-bound fraction (residual-P) varying between 60 and 75% of total phosphorus at 0–45 cm depth. In the deeper sediments, including the layers with high phosphorus concentrations between 120–150 cm, the HCl-extractable phosphorus was strongly dominating the sediment phosphorus. This fraction, which represents phosphorus bound to carbonates and apatite-P, constituted 59–68% (average 65%) during the period of high total phosphorus concentrations in the sediments of 115–145 cm depth, and 79–89% (average 84%) of total phosphorus in the sediments of 145–190 cm depth.

In Lake Skälsjön, the total phosphorus concentration in surface sediments was 1250 µg P/g dw, also here dominated by the organic-bound fraction (residual-P), which constituted approximately 50% of total phosphorus at 0–10 cm depth, and 65–70% at 10–20 cm depth. At about 20 cm depth in the sediment the total concentration of phosphorus decreased to a level of ca 800 µg P/g dw, dominated of approximately equal amounts of organic-bound phosphorus and calcium-bound phosphorus (residual-P and HCl-P, respectively).

Lake Limmaren had maximum values of 1700 µg total P/g dw in the surface sediments. As in the other lakes, the surface sediments were dominated by organic-bound phosphorus. With the exception of HCl-extractable phosphorus, all fractions were present in higher concentrations in the uppermost 20 centimetres than further down in the sediment profile. Further down the concentrations stabilised on a total amount of phosphorus varying between 830 and 1000 µg P/g dw (average 930 µg P/g dw) with calcium-bound phosphorus (HCl-P) dominating (average 47% of total P) together with the organic-bound fraction (average 38% of total P).

The variations in the calcium-bound sediment phosphorus fractions within the lakes (Figure 3-2) shows that for Lake Vikasjön this fraction is closely related to the pronounced variations in the total phosphorus concentrations in the ancient history of the lake. The only exceptions from this are the increases of total phosphorus concentrations in the surface sediments and at a depth of 60–70 cm; they are both caused by an increase in organic-bound phosphorus (Figure 3-2). No variations corresponding to the large fluctuations in Lake Vikasjön are present in the other two lakes, and where variations in total phosphorus concentrations occur, they are only occasionally coincident with the variations in calcium-bound phosphorus.

4 Discussion

Our analysis of sediment cores clearly indicates that only one of the three investigated lakes, Lake Vikasjön, has undergone an oligotrophic hardwater ontogenetic stage. In the deeper and today naturally highly eutrophic Lake Limmaren, no indications of such a stage were found. Neither were there any indications of phosphorus-rich lime precipitates in the today alkaline brownwater lake Skälsjön. /Brunberg and Blomqvist, 2000/ found that there are at least three different lake types present in the Forsmark area today, shallow oligotrophic hardwater lakes, shallow alkaline brownwater lakes, and deeper highly eutrophic lakes. At least one of these lake types, the oligotrophic hardwater lake, which is frequently represented in the Forsmark area today /Brunberg et al, 2002b/, undergoes a major ontogenetic shift before turning into a wetland (mire). However, our results indicates that the oligotrophic hardwater stage is not an obligate part of the lake ontogeny in the Forsmark area, as we could only find remnants of that stage in one of the three selected lakes. Additionally, our findings show that the alkaline brownwater lake type may be divided into two categories; those that have and those that have not undergone an oligotrophic hardwater stage.

Phosphorus fractionation analyses have earlier been used to assess historical nutrient conditions in lakes that have been subject to increasing phosphorus concentrations from anthropogenic eutrophication. However, the eutrophication process itself includes a substantial amount of recycling of phosphorus from the sediments, and the phosphorus fractions involved in these processes (NH_4Cl-P, NaOH-P) are less stable to expected changes in oxygen concentrations and pH in the sediments. In order to confirm indications from the fractionation analyses, stable isotopes and pigment analyses of the sediments have been used /Schelske and Hodell, 1995; Bianchi et al, 2000/. In our case we were looking for a sediment fraction that is considered as more stable and a case where the phosphorus is more or less permanently withdrawn from the lake ecosystem.

Comparisons of our results with the earlier paleo-limnological investigations performed in Lake Vikasjön /Ingmar, 1963/ showed that the phosphorus fractionation according to /Hjeltjes and Lijklema, 1980/ clearly identified the passed oligotrophic hardwater stage, and thus it is a useful tool for tracking this ontogenic stage in lake sediments (Figures 3-1 and 3-2). This was further verified by /Brunberg et al, 2002a/, who applied two different phosphorus fractionation protocols /Hjeltjes and Lijklema, 1980; Ruttenberg, 1992/ on sediments from Lake Vikasjön. They found that the oligotrophic hardwater period was reflected as a peak in concentrations of total phosphorus and, in all phosphorus fractions related to stable calcium-bound phosphorus, regardless which method was used. This can be explained by the precipitation of carbonates in the lake water, which occurs during this period. Co-precipitation of phosphates occurs frequently, and the precipitates settle to the bottom and are accumulated in the sediments. These precipitates of phosphorus would initially probably be extracted by ammonium chloride, the first step of the Hjeltjes and Lijklema extraction protocol. However, with time this calcium-associated phosphorus may be further transferred by sediment diagenetic processes to the more stable compounds analysed as HCl-exctractable phosphorus in the fractionation analysis. In this way, the phosphorus from an oligotrophic hardwater stage of a lake may be preserved and easily detectable long time after this period of the lake ontogeny has passed.

In Lake Limmaren, no signs of changing nutrient status were found in the sediment phosphorus concentrations. The only dynamics in total phosphorus concentration was the increase towards the sediment surface (Figure 3-1), which was mainly due to increased concentrations of phosphorus bound to organic compounds and Fe/Al-compounds (Res-P and NaOH-P, respectively). These fractions are the ones that usually are involved in phosphorus exchange processes between sediments and lake water. The NaOH-P is known as labile phosphorus sensitive to changes in redox and pH conditions. The Res-P, when consisting of living organic material, has also been found to participate in sediment phosphorus dynamics /Boström et al, 1985; Gächter and Meyer, 1993; Brunberg, 1995/. Lake Limmaren has a large biomass of living cyanobacteria in the surface sediments /Brunberg and Blomqvist, 2002/, which contributes a substantial part of the organic-bound residual phosphorus. The calcium-bound phosphorus (HCl-P) on the other hand, was very stable throughout the entire sediment core. Thus, no signs of an oligotrophic hardwater stage were recorded. A comparison with two similar, but older, lakes in the area strengthens this result. Lake Erken, elevated 11 meters above sea level, and Lake Gavel-Långsjön, at 24 meters above sea level, are both deep eutrophic lakes. They have average total phosphorus concentrations of the lake water of 27 and 22 µg/l, respectively /SLU, 2003; Weyhenmeyer, 1999/, thus not indicating any dramatic shifts in ecosystem functioning with age in this type of lake, apart from a slight decrease in ecosystem productivity over time.

Neither Lake Skälsjön showed any signs of a passed oligotrophic hardwater stage. The relatively thin layer of gyttja accumulated (approximately 30–50 cm thick in our cores, which corresponds well with the findings of /Bergström, 2001/) confirms the general picture of this lake as a flow-through basin situated within the main course of the River Forsmarksån.

There are several possible explanations to the differences in development between the three lakes. First, the differences in characteristics of the catchment areas have to be considered. Lake Vikasjön and Lake Skälsjön are parts of the same river system, and the catchment of Lake Vikasjön is a sub-unit of that of Lake Skälsjön. Their catchments are very similar as regards geology and composition of the soils but differ in age on land and, hence, also in vegetation. The amount of calcium carbonates in the fine material of till in the catchment is high, 1.6–1.9%, despite the fact that millennia of weathering have passed since the land was raised from the sea /Gillberg, 1967/. The catchment of Limmaren is not easily compared to the other two, as it is not as old as the catchments of Lake Vikasjön and Lake Skälsjön. However, although not as high as in the most calcium-rich parts of this region, the levels are sufficiently high to result in a lake water quality that at least theoretically could promote precipitation of calcium carbonate /Brunberg et al, 2002a/. Hence, differences in calcium contents of the surrounding soils do not seem to be a reason for the differences in lake ontogeny.

Hydrological conditions within the catchment may also be of importance when comparing the lakes. There are no large differences between Lake Vikasjön and Lake Limmaren in this aspect. Lake Vikasjön was from the beginning one part of a large bay, which was isolated from the sea. Later this large lake was divided into several different basins, separated by mires and bogs that developed within the catchment. Lake Limmaren as well as the ancient Lake Vikasjön were or are both lacking large tributaries, restricting the water renewal time to intermediate or long for the ancient Lake Vikasjön and long for Lake Limmaren (5.8 years).

/Brunberg et al, 2002a/ instead suggested that the different morphometry of the two lake basins, and the different light conditions coupled to this, is the reason why Lake Limmaren never passed through an oligotrophic hardwater stage after isolation. The differences in light penetration affects the photosynthetic activity along the bottom and thereby the benthic pH values. High pH values along the bottom areas of shallow lakes with substantial benthic primary production promote benthic precipitation of calcium carbonate and co-precipitation of phosphorus. Due to the predominantly high benthic pH, the phosphorus is kept within the sediment and via further diagenetic processes bound in stable calcium compounds. In the deeper lake, dark conditions predominate along the bottom. Pelagic precipitation of calcium carbonates may occur in this type of lake, e.g. when photosynthetic activity enhances the pH. However, these precipitates will to a larger extent be dissolved and recycled to the water column, when settling to the sediments where pH values and oxygen concentrations are low. The 1% level for light penetration, which is considered as the lowest level for sustainable primary production /Rodhe, 1965/, is at about 3 m depth in Lake Limmaren. From this follows that approximately 75% of the bottom areas are too dark for photosynthetic organisms to survive /Brunberg and Blomqvist, 2002/. In Lake Vikasjön today, the corresponding depth for light penetration is 2 meter, which means that only 15% of the lake area is situated below this depth. In addition, the light conditions in the ancient Lake Vikasjön probably were even better, as the lake water was most probably not as coloured by humic substances as it is today. Light-exposed soft bottoms are also characteristic for the lakes that presently are oligotrophic hardwater lakes and situated along the Baltic coast. The sediments in these lakes are covered with a thick “microbial mat”, which holds photosynthesising microorganisms, mainly different species of cyanobacteria /Brunberg et al, 2002b/.

The difference between Lake Vikasjön and Lake Skälsjön has to be explained in other terms than basin morphometry as both lakes are shallow (Table 2-1). The water level, and thereby the depth, of Lake Skälsjön has been manipulated and regulated in different ways during the past centuries, as the water was used for the local mining and iron industry. However, the depth has probably never been larger than that of Lake Vikasjön. Most characteristics of the drainage areas are also similar between these two lakes, or partly even identical, as the catchment of Lake Vikasjön constitutes 25% of the catchment of Lake Skälsjön. One striking difference, however, is the hydrological conditions. The main river in the water system, River Forsmarksån, enters Lake Skälsjön from northwest and flows through the lake basin to the outlet in the eastern part. This flushing of substantial amounts of water gives a theoretical residence time of the lake of only 14 days, which is much less than the other two lakes.

The ontogeny of the catchment vs lake basin ontogeny also differs substantially from the other two lakes. The reason to this may be found in the varying topography within the area. Lake Skälsjön is situated close to the natural water falls of together 13 m in the municipality of Lövstabruk. Given these conditions, it is obvious that the upstream areas of River Forsmarksån, i.e. a major part of the catchment of Lake Skälsjön, are situated at an elevation that is 13 m higher than the lake level. Hence, most of the catchment was transferred to land area long before the lake itself was isolated, which means that the calcium-rich till in the area had already been subject to weathering processes for thousands of years. In addition, the upstream lakes had already left the oligotrophic hardwater stage and been converted to brownwater lakes. The water entering the lake from the upstream areas was thus affected by the brownwater conditions that probably were prevailing there at the time for isolation of Lake Skälsjön. Substantially coloured and less alkaline water from the upstream areas would not promote any oligotrophic hardwater conditions in the newly formed lake basin of Lake Skälsjön, mainly due to unfavourable light conditions along large parts of the bottom.

From this we conclude that at least three different types of lakes emerge from the land-rise process along the coast of Uppland: I) shallow oligotrophic hardwater lakes, II) alkaline brownwater flow-through lakes, and III) deep eutrophic lakes. The first type of these lakes, the oligotrophic hardwater lakes, shifts to alkaline brownwater conditions approximately 1000 years after isolation from the sea, while the other two lake types seems to last for longer periods without any drastic changes of the aquatic ecosystem. The alkaline brownwater lakes (II) will probably be closed by the surrounding mire growing from the shores. If the inflowing water from upstream areas constitutes large tributaries, as in the case of River Forsmarksån, the main stream of water may be kept open for a longer time period. The deep basin of the deep eutrophic lakes (III) will provide stable conditions for substantial time periods and this lake type will last for much longer time than the other two. As a consequence of the still ongoing shore line displacement, new lake basins are continuously created along the coast of Uppland. Thus, considering the different lines of ontogeny, four different types of lakes can be found in the area today: the currently oligotrophic hardwater lakes (type Ia, not included in this investigation but represented by e.g. Lake Eckarfjärden in the Forsmark area), the former oligotrophic hardwater but currently alkaline brownwater lakes (type Ib, e.g. Lake Vikasjön), the alkaline brownwater lakes that were formed directly after isolation and never passed through the alkaline hardwater stage (type II, e.g. Lake Skälsjön) and, finally, the deep eutrophic lakes (type III, e.g. Lake Limmaren).

5 Conclusions

Substances that are released from the soils by weathering processes and from other processes adding substances to the groundwater may ultimately be transported to the lakes in the water system. The dissolved substances may enter the lake basins in three different ways: a) by surface water entering the lake as a tributary, b) from diffuse sources of surficial groundwater entering the lake via permeable littoral zones, and c) via groundwater penetrating through the accumulated sediments in deeper parts of the lake. The added substances may to a large extent end up in the sediment of the lake, either by direct settling and/or fixation to the sediment or, via uptake in biota and sedimentation as associated with organic material. As lakes in general function as sedimentation basins, the net result will be an accumulation of the settling material. However, a certain part may be recycled to the water column and possibly also be transported further within the catchment. The net result, calculated on an annual basis, is most frequently a retention of different substances in the lake basin. Nevertheless, seasonal variations occur and it is difficult to estimate the proportion of different substances that may be recycled and further transported in the ecosystems in a long-time perspective. The final retention depends on different chemical and biological processes in the sediments, which in turn are governed by environmental conditions, such as temperature, light availability, redox conditions, pH, etc. These environmental conditions may vary substantially between lake basins and lake ecosystems. Large variations in retention may thus be expected and also reflected in the composition of lake sediments.

The three lakes investigated in this study represents three different lines of lake ontogeny, despite being situated within an areally restricted and relatively homogenous land area. They also represent different patterns for retention of phosphorus. Lake Vikasjön is the only lake that has retained phosphorus in deeper sediments in amounts that equals the present concentration in surface sediments. As phosphorus is an important micro-nutrient frequently restricting production of organic material, the differences in phosphorus retention may be expected to affect the production, cycling and retention of organic material within the different lake ecosystems. Hence, the different lake types described in this report may accumulate carbon and other substances (e.g. radionucleids) in different amounts. Knowledge of the possible lines of ontogeny, and the conditions favouring one or another of them, is essential when assessing the future accumulation of radioactive substances that might be released if a leakage from a nuclear waste repository would occur. Especially interesting in terms of carbon turnover and carbon budgets, is the oligotrophic hardwater lakes, which host unusually thick benthic “microbial mats” of living microorganisms that affect chemical as well a biological processes within the lake ecosystem. The knowledge of sediment formation and dynamics of different elements below and within this microbial mat should be further elucidated in order to assess possible future effects of a leakage from a deep repository situated within the Forsmark area.

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