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Lake-tilting investigations in southern Sweden

Tore Påsse

Sveriges geologiska undersökning,
Göteborg, Sweden

April 1996

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Keywords: Lake-tilting, glacial-isostasy, land uplift, future uplift, ^{14}C-datings

FOREWORD

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Göteborg in March 1996

Tore Påsse

ABSTRACT

A nonuniform glacio-isostatic uplift results in differential uplift for different parts of a lake. If the lake outlet is situated in the area with the greatest rate of uplift, then the lake will be continuously transgressed. Ancient lake levels can be estimated by dating transgressed peat at different depths in such a lake. Four lakes in southern Sweden have been investigated using this method and **the course of the glacio-isostatic uplift has been determined empirically.**

The investigation shows that the difference in uplift between the outlet and the sampling site can be expressed as

$$\Delta U = 0.6366 \times \Delta A \, (\arctan (T / B) - \arctan ((T - t) / B))$$

where ΔU is the difference in uplift (in m), ΔA is half of the difference of the total uplift between the outlet and the sampling site (in m), T is the time for the maximal uplift (in calendar years), t is the variable time (in calendar years) and B is a declining factor (in calendar years). The values for ΔA, B and T are determined at the four lakes. These determinations are used to predict the future uplift.

SAMMANFATTNING

Genom den glacialisostatiska landhöjningens olikformighet påverkas en sjö med olika belopp på landhöjningen i skilda delar av sin utbredning. Om utloppet ligger i ett område som höjs mer än vad resten av sjön gör innebär detta att sjöns yta transgredierar över tidigare landområden. Sjöstjälpningen kan bestämmas genom att provta transgredierad torv från olika djup och datera dessa. **Sjöstjälpningens förändring med avseende på tiden ger en empiriskt bestämmning av landhöjningens förlopp.** Fyra sjöar i södra Sverige har undersökts med sjöstjälpnings-metoden.

Undersökningen visar att skillnaden i landhöjningen mellan utloppet och provtagningsplatsen kan uttryckas som

$$\Delta U = 0.6366 \times \Delta A \, (\arctan (T / B) - \arctan ((T - t) / B))$$

där ΔU är skillnaden i landhöjning (i m), ΔA är hälften av den totala landhöjningen mellan mellan utloppet och provtagningsplatsen (i m), T betecknar tidpunkten för den maximala landhöjningshastigheten (i kalender år), t är den variabla tiden (i kalender år) och B är en avklingsfaktor (i kalender år). Värdena för ΔA, B och T har bestämts vid fyra sjöar i södra Sverige. Dessa värden har använts för att prognostisera den framtida landhöjningen vid två sjöar.

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SUMMARY

The present knowledge of the glacio-isostatic uplift is mainly derived from marine shore-level displacement curves. The general shape of the uplift has been discernible through this information, but a precise estimation of the course of events has never been done. One reason for this is the duality of the shoreline information, which is composed of two factors: movement of the crust, and the eustatic changes of the sea. Marine shorelines can thus not be used for an exact estimation of the crustal land uplift without a complete knowledge of the eustatic changes.

Lake shorelines are tilted in the same manner as marine shorelines by crustal movements but are not affected by eustasy. Lake shorelines are related to one fixed level, *i.e.* to the level of the outlet. For this reason they are very useful for empirical estimations of crustal changes. The depth of the water in a lake is unaffected by glacio-isostatic uplift in the outlet area. However, in other parts of the lake, where the crustal uplift is faster or slower in reference to the rate at the outlet area, the water level changes in reference to the crust. This mechanism creates a tilting of the lake, in the same way as tipping a vessel. If the outlet is situated in a part of the lake that has the fastest rate of uplift, the rest of the lake will be continuously transgressed. This phenomenon is utilised in the lake-tilting method.

In lakes which have been transgressed, terrestrial and littoral peat today exist at fairly great depths and are in many places covered by gyttja. By dating littoral peat at different depths a record of the ancient levels of the lake surface can be estimated. Graphically the results can be plotted as time-depth curves. These curves show the differences between the amount of the glacio-isostatic uplift at the outlet and at the sampling site. Unfortunately, the lake- tilting information gives no absolute values of the uplift, but by exaggerating the time-depth-function an important tool is achieved for modelling.

Fen or bog peat covered by gyttja show in a convincing manner the course of the transgression. However, these sequences offer poor opportunities for dating ancient shore levels, as such sediments are not formed at the shore. For a close estimation it is necessary to choose sediments formed at close proximity to the ancient shore. *Carex* peat has turn out to be the most suitable sediment for lake- tilting investigations as this peat forms successively at the edges of the lakes during the transgression.

A detailed investigation of the lake-tilting in two lakes in south-western Sweden was presented by Påsse (1990). Since then two more lakes have been investigated. This paper summarises these four investigations. The two lakes previously reported are presented in a new way regarding the ^{14}C-

dates. The dates are calibrated to calendar years in this paper. In Påsse (1990) the course of the uplift was interpreted as declining in an exponential way. This paper gives a new mathematical solution of the problem.

The main aim of the lake-tilting investigations is to determine the course of the glacio-isostatic uplift *i.e.* to find a formula for the uplift. Besides the lake-tilting graphs, knowledge of the recent relative uplift (RAK 1971, 1974) and the gradient of some marine shorelines (Påsse 1983, 1990) are used for solving this problem.

The investigation shows that the difference in uplift between the outlet and the sampling site can be expressed as

$$\Delta U = \mathbf{0.6366} \times \Delta A\ (\arctan\ (T / B) - \arctan\ ((T - t) / B))$$

where ΔU is the difference in uplift (in m), ΔA is half of the difference of the total uplift between the outlet and the sampling site (in m), T is the time for the maximal uplift (in calendar years), t is the variable time (in calendar years) and B is a declining factor (in calendar years).

Curves calculated by the uplift formula with varying values for ΔA, B, T and also for the mean water level have been compared to the empirical lake-tilting data. Statistically this has been done by calculating the standard deviation for the differences between the empirical and the calculated depths. In the iteration procedure ΔA was given a fixed value after which the best fitness was calculated by varying the three other variables. This iteration was continued by giving ΔA a new value and then repeating the procedure.

As there are three variables within the uplift function there will be a lot of "possible" combinations. However, the differences in uplift received by the repeated precision levelling (Δv_o mm/year) can be used as a tool for limiting the number of possible solutions. Δv has been estimated at each lake using the information from the repeated precision levelling (RAK 1971, 1974). This estimation includes a confidence interval. Only those iterations which give values of Δv_o within this interval are possible solutions. Accordingly the number of possible values of ΔA can be reduced. The size of T is dependent on ΔA. This also means that the interval for possible values of T is reduced through this operation. In the same manner the interval for possible values of B are reduced.

T is limited to an interval between 10 700 - 13 500 cal y B.P. This means that the maximal glacio-isostatic uplift in the region must have occurred close to the deglaciation or somewhat later. Whether the maximal uplift occurred as a synchronous event or not can not be concluded by the presented data. There is a significant difference between the values of B at Lake Sommen compared to the other sites. This can also be expressed as the uplift curve is more even at Lake Sommen then at the other sites.

The fact that there are several possible solutions of the time-depth functions are not any serious problem for the continuos work by modelling shore level data with the aim of estimating the absolute uplift-functions. Whether T is 13 000 or 13 500 or 12 500 cal years B.P. influences the conditions for modelling the shore level displacement only to a small degree as long as corresponding values of $(\Delta) A$ and B are used.

The future crustal uplift due to the glacio-isostasy can be predicted at the investigated lakes by applying the parameters for the best solutions at each specific lake.

1 METHODS

1.1 THE LAKE-TILTING METHOD

1.1.1 Introduction

The present knowledge of the glacio-isostatic uplift is mainly derived from marine shore-level displacement curves. The general shape of the uplift has been discernible through this information, but a precise estimation of the course of events has never been done. One reason for this is the duality of the shoreline information, which is composed of two factors: movement of the crust, and the eustatic changes of the sea. Marine shorelines can thus not be used for an exact estimation of the crustal land uplift without a complete knowledge of the eustatic changes.

Lake shorelines are tilted in the same manner as marine shorelines by crustal movements but are not affected by eustasy. Lake shorelines are related to one fixed level, *i.e.* to the level of the outlet. For this reason they are very useful for empirical estimations of crustal changes. The depth of the water in a lake is unaffected by glacio-isostatic uplift in the outlet area. However, in other parts of the lake, where the crustal uplift is faster or slower in reference to the rate at the outlet area, the water level changes in reference to the crust. This mechanism creates a tilting of the lake, in the same way as tipping a vessel. If the outlet is situated in a part of the lake that has the fastest rate of uplift, the rest of the lake will be continuously transgressed. This phenomenon is utilised in the lake-tilting method.

In lakes which have been transgressed, terrestrial and littoral peat today exist at fairly great depths and are in many places covered by gyttja. By dating littoral peat at different depths a record of the ancient levels of the lake surface can be estimated. Graphically the results can be plotted as time-depth curves. These curves show the differences between the amount of the glacio-isostatic uplift at the outlet and at the sampling site. Unfortunately, the lake- tilting information gives no absolute values of the uplift, but by exaggerating the time-depth-function an important tool is achieved for modelling.

1.1.2 Field investigations

Fen or bog peat covered by gyttja show in a convincing manner the course of the transgression. However, these sequences offer poor opportunities for dating ancient shore levels, as such sediments are not formed at the shore. For a close estimation it is necessary to choose sediments formed at close proximity to the ancient shore.

Carex peat has turn out to be the most suitable sediment for lake- tilting investigations as this peat forms successively at the edges of the lakes during the transgression. This fact provides possibilities to date the rise of the water level in just one or few cores. *Carex* -sequences suitable for lake-tilting investigations exist in the inner sheltered parts of shallow bays where the surroundings are flat and recent peat is forming. These conditions often coincide with sites where small inlets reach the lakes.

If more than one sampling site is used and if these are at different distances from the outlet it is necessary to make corrections of the sampling depths. This correction can be made by linear projection. In order to minimise possible errors in these corrections it is advisable to choose a sampling site nearest the outlet as reference point.

The level of the water surface may have altered due to other reasons than tilting e.g., due to man-made regulations. Water-level changes may also have been caused by climatic fluctuations i.e., dry periods may have caused stages of long-lasting low water (cf. Digerfeldt 1988). However, these two processes create water-level changes with the same magnitude over the whole lake, in contrast to changes caused by the tilting, in which the size of change is a function of the distance from the outlet.

It is very hard to make an exact estimation of the natural mean water level of a lake by field observations. Since the transgression during the last 1000 years has been small, the mean water level is probably best estimated applying proper lake-tilting data.

The depth of the *Carex* peat used for datings may have been affected by self compaction to some degree. Corrections for this have not been performed in this study.

1.1.3 Previous investigations with the lake-tilting method

A little more than a hundred years ago, De Geer (1893) discussed the phenomena and effects of lake-tilting. He also predicted the lake-tilting method as being a tool for compiling full knowledge of the course of uplift. The first investigation based on De Geer´s theory was performed by Sandegren (1916). He estimated the elevation of the surface of Lake Hornborgasjön during different periods by pollen analytical datings. Norrman (1964) used the method for numerical analyses of the uplift in an investigation of the Lake Vättern.

A detailed investigation of the lake-tilting in two lakes in south-western Sweden was presented by Påsse (1990). Since then two more lakes have been investigated. This paper summarises these four investigations. The two lakes previously reported are presented in a new way regarding the ^{14}C-dates. The dates are calibrated to calendar years in this paper. In Påsse (1990) the course of the uplift was interpreted as declining in an exponential way. This paper gives a new mathematical solution of the problem.

1.2 CALIBRATING ^{14}C- VALUES TO CALENDAR YEARS

The assumption of an essentially steady concentration of ^{14}C in the atmosphere is fundamental to the radiocarbon method. However, in detail, this assumption is invalid. Accordingly the dates given by the radiocarbon method are not the same as calendar dates. The ^{14}C- chronology is furthermore defective by a systematic error due to the half- live time used. The original half-life established by Libby (1955), with a value of 5568 years, is conventionally used instead of the revised half-live of 5 730 years estimated by Olsson (1968). Converting the date given by the laboratory to the half-live established by Olsson (1968) can be performed by multiplying the given dates by 1.03.

The discrepancy between ^{14}C- and calendar dates are usually neglected when ^{14}C-dates are used to get the ages of for example pollen analytical or deglaciation events. In this manner a special ^{14}C- chronology has been established by Quaternary geologists which is convenient for the purposes mentioned above but hazardous for other purposes. When comparing the ^{14}C- chronology with other absolute dating methods, such as varve chronology or dates performed applying the TL- method, it is necessary to make the comparison in calendar years. This is also necessary for calculations of the glacio- isostatic uplift.

A calibration of the radiocarbon-chronology has been established for the last 8 000 years by ^{14}C-datings of dendrochronological dated tree-rings (e.g. Damon *et al.* 1966, 1978, Suess 1970, Klein *et al.* 1982). The radiocarbon dates in this investigation are calibrated using the computer program from Stuiver & Reimer (1993). However, when dealing with Late Weichselian chronology these calibrations are not applicable. Recently Becker *et al.* (1991) has presented a floating Late Weichselian and Early Holocene chronology of pine (*Pinus sylvestris*) which extend the calibrations backwards to 11 370 calendar years B.P. A tentative calibration curve based on radiocarbon datings of annually laminated lake sediments has been performed by Lotter (1991) comprising the interval 10 600 - 12 700 calendar years B.P. A calibration of the ^{14}C - timescale over the past 30 000 years using mass spectrometric U - Th ages from corals has been performed by Bard *et al.* (1990).

The tree-ring calibration curves comprise detailed information and comprise a large number of small oscillations. However, seen in a more perspicuous perspective these oscillations can be overlooked and a more long-termed trend appears. Figure 1 combines the information presented by Klein *et al.* (1982), Becker *et al.* (1991), Lotter (1991). Some of the younger values reported by Bard *et al.* (1990) are also inserted in Figure 1-1.

Figure 1-1 shows an increasing deviation between the ^{14}C- dates and the dendrochronological dates backwards in time. The most simple way to describe the trend seen in Fig. 1-1 is to express the relationship between the calibrated dates and the ^{14}C- dates by a linear function. A rough calibration of the radiocarbon chronology may thus be received by multiplying the ^{14}C-

dates by 1.095. This relationship is not accurate for young dates where high precision is required. This calibration method is designed to get plausible values for Late Weichselian dates. The dates of Late Weichselian age which are used in this paper are calibrated with this linear calibration.

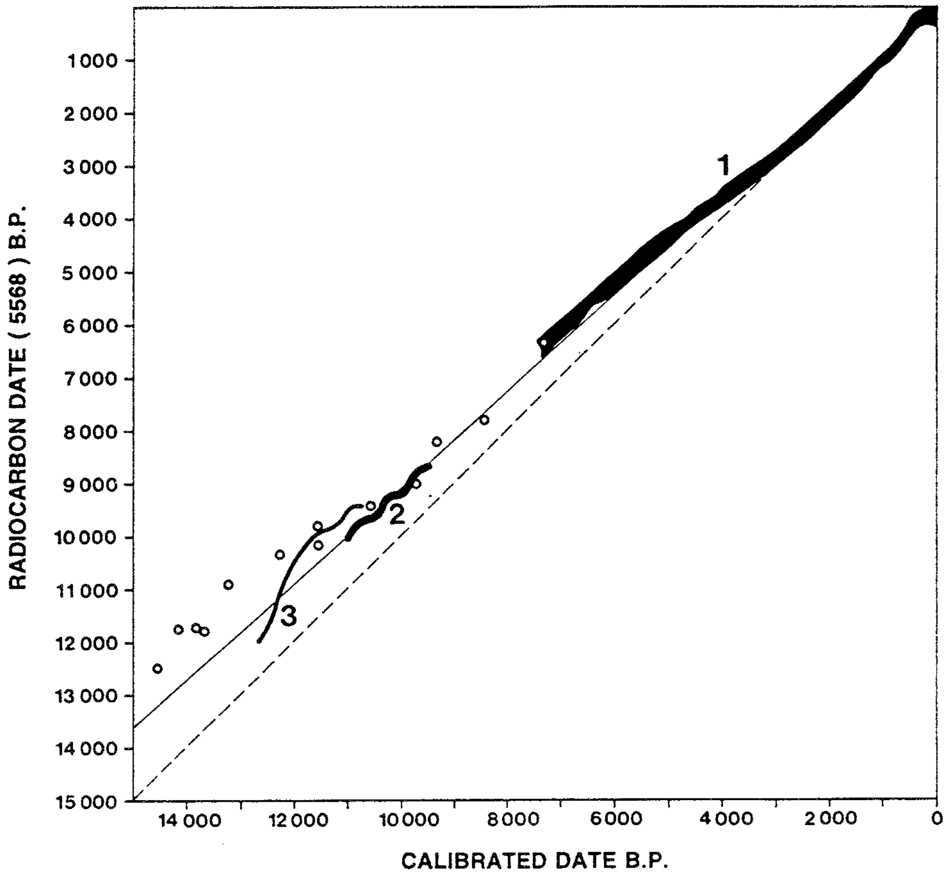

Figure 1-1. Radiocarbon dates (years B.P.) in relation to calibrated dates (calendar dates). Absolute correspondence is represented by the broken line. 1. Tree-ring calibration curve (Klein et al. 1982). 2. Tree-ring calibration curve (Becker et al. 1991). 3. Annually laminated lake sediments (Lotter 1991). 4. Mass spectrometric U - Th dates (Bard et al. 1991). The solid line represents the interpreted trend in the relation between radiocarbon dates and calibrated dates. A rough calibration of the radiocarbon chronology may be obtained by multiplying the ^{14}C- dates by 1.095.

2 FIELD INVESTIGATIONS AND DATINGS

2.1 SITE DESCRIPTIONS

Four lakes are investigated in the southern part of Sweden. The positions of the lakes are shown in figure 2-1. The sampling sites for each lake are shown in figures 2-2 to 2-5.

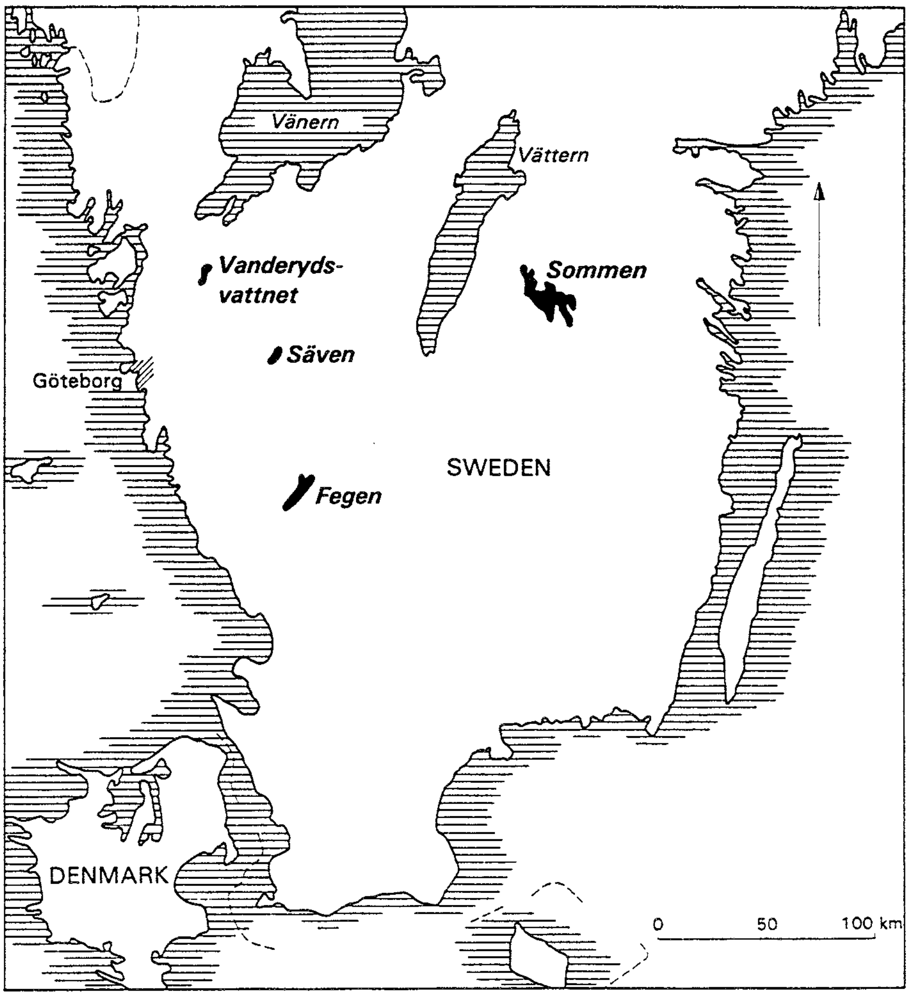

Figure 2-1. Location of the investigated lakes.

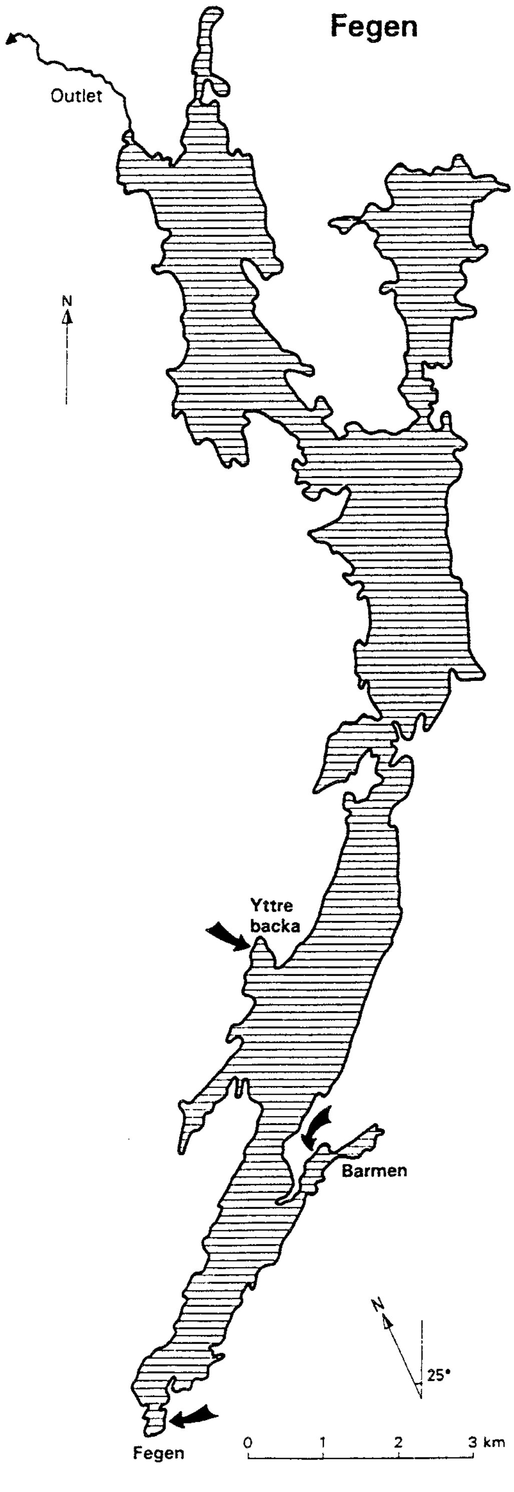

Figure 2-2. Lake Fegen. Arrows indicate the sampling sites.

Figure 2-3. *Lake Säven. Arrow indicates the sampling site.*

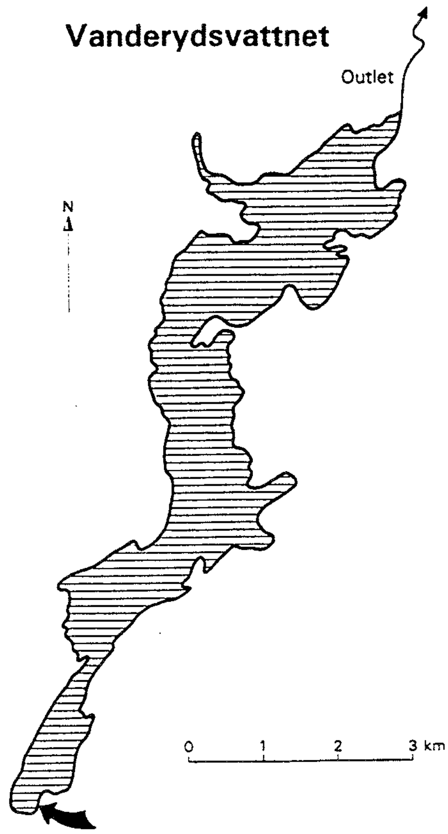

Figure 2-4. *Lake Vanderydsvattnet. Arrow indicates the sampling site.*

Figure 2-5. Lake Sommen. Arrow indicates the sampling site.

2.1.1 Lake Fegen

Lake Fegen is situated above the highest coastline in the western part of the South Swedish Highland. Today the lake is regulated by man through a channel into Lake Svansjön but the original outlet is situated in the northernmost part. The original level of the lake is 132.1 m above sea level and the levels of the dated samples are related to this level. The corings in Fegen have been concentrated in the southernmost part of the lake, and in a bay called Barmen, Figure 2-2. Corings were also made in other parts of the lake. One sample from Yttre Backa is used in the analysis. A generalized picture of the stratigraphy in the southernmost part of Fegen and Barmen, based on 50 corings, is shown in Påsse (1990). Twenty-eight ^{14}C-dates from Lake Fegen are reported in Figure 2-6 and in the appendix, Table 1.

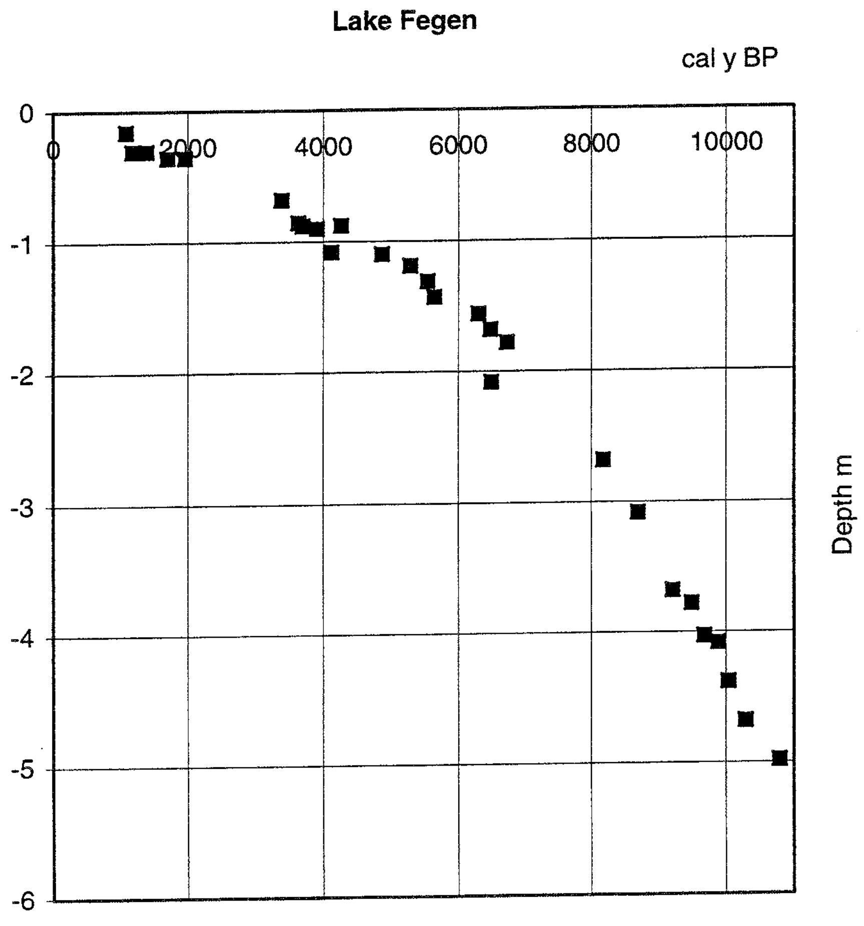

Figure 2-6. Radiocarbon dates for ancient lake levels at Lake Fegen.

2.1.2 Lake Säven

Lake Säven is also situated above the highest coastline and at the western part of the South Swedish Highland, about 85 km north of Lake Fegen. The mean water level at Säven is 155.0 m above sea level. The sampling site is close to the shore of the lake at a small *Carex* fen in the southernmost part, Figure 2-3. The outlet is situated in the northernmost part of the lake. Eighteen ^{14}C- dates from the Lake Säven are reported in the appendix, Table 2, and in Figure 2-7.

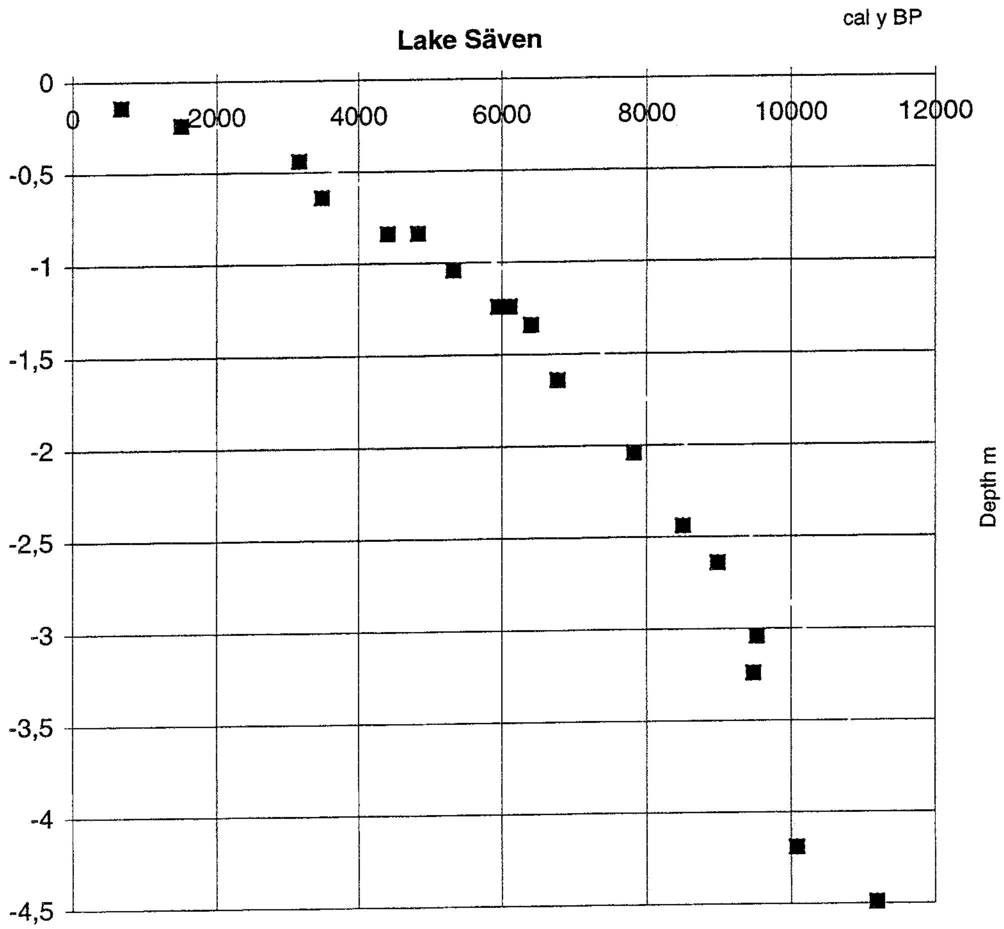

Figure 2-7*. Radiocarbon dates for ancient lake levels at the southernmost part of Lake Säven.*

2.1.3 Lake Vanderydsvattnet

Lake Vanderydsvattnet is situated on the eastern side of the River Göta älv at an altitude of 73.1 m above sea level *i.e.* below the highest coastline. The sampling site is at the southernmost part of the lake, close to the eastern shore, Figure 2-4. At the shore there is a bog which is eroded by a shore cut caused by transgression or by man made regulation which has increased the water level by about 1.5 m. The outlet is situated in the northernmost part of the lake. Twenty-eigth ^{14}C-dates from Lake Vanderydsvattnet are reported in the appendix, Table 3, and in Figure 2-8.

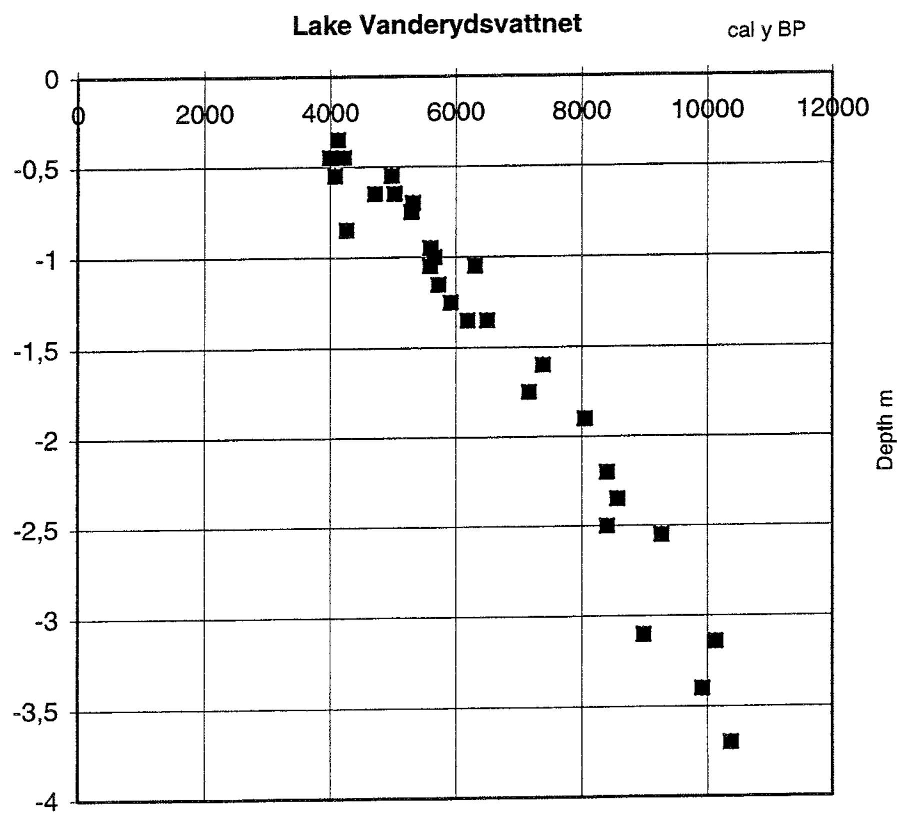

Figure 2-8. Radiocarbon dates for ancient lake levels at the southernmost part of Lake Vanderydsvattnet.

2.1.4 Lake Sommen

Lake Sommen is situated in the eastern part of Sweden at an altitude of 146 m above sea level, which means that the lake is situated somewhat above the highest coastline. The sampling site is at the shore at the bog Rocks mosse, Figure 2-4. The outlet is in the northernmost part of the lake. At Lake Sommen 67 ^{14}C-dates are reported in the appendix, Table 4, and in Figure 2-9.

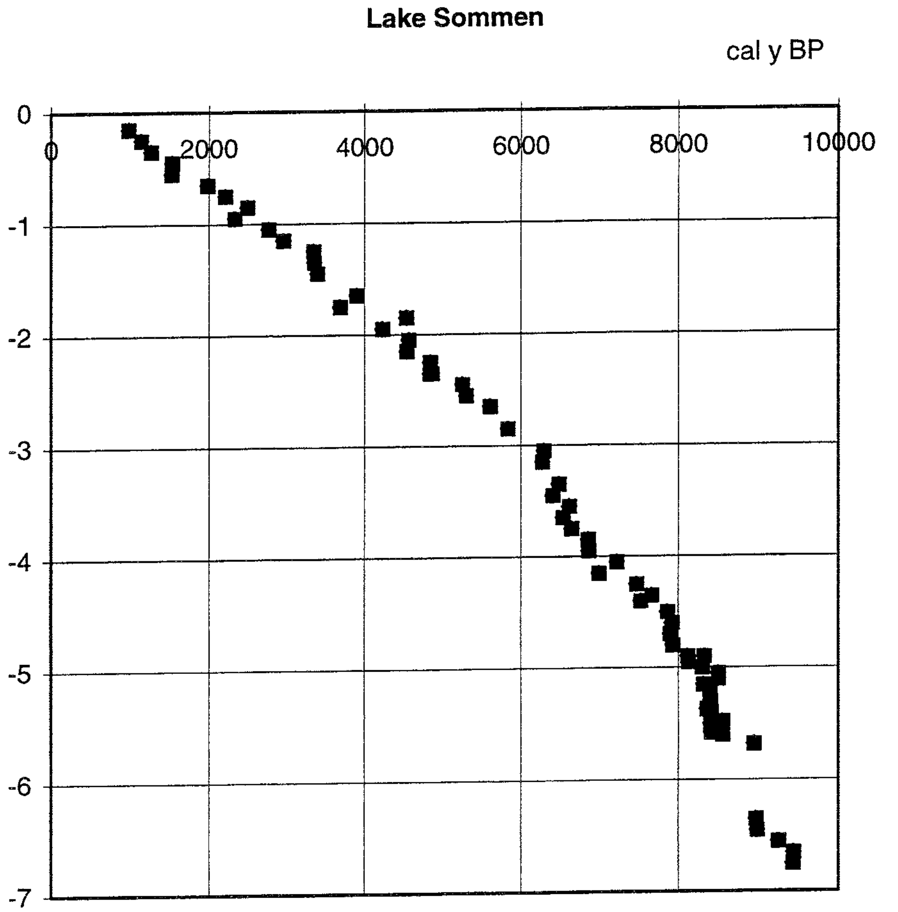

Figure 2-9. Radiocarbon dates for ancient lake levels at the southernmost part of Lake Sommen.

3 MATHEMATICAL TREATMENT OF THE LAKE-TILTING DATA

3.1 GENERAL

The main aim of the lake-tilting investigations is to determine the course of the glacio-isostatic uplift *i.e.* to find a formula for the uplift. Besides the lake-tilting graphs, knowledge of the recent relative uplift (RAK 1971, 1974) and the gradient of some marine shorelines (Påsse 1983, 1990) are used for solving this problem.

The graphs in Figures 2-6 to 2-9 represent the differences of the uplift between the outlets and the sampling sites (Δ *U* m). Most simple mathematical functions, subtracted by a function of the same type, yield a new function of the original type. The absolute uplift functions can thus be assumed to resemble the graphs in Figures 2-6 to 2-9 if these are exaggerated. This assumption will be used as a starting point for a future search of the absolute uplift function.

Most scientists who have tried to calculate shore level displacement have used exponential functions to express the glacio-isostatic crustal upheaval (Bergsten 1954, Norrman 1964, McConnel 1968, Andrews 1970, Cathles 1975, Bergqvist 1977, among others). In a previous report Påsse (1990) interpreted lake-tilting data by an exponential formula with seemingly convincing results for the period investigated. However, calculations carried out according to shore level information revealed that this type of function gave rise to several preposterous conditions inconsistent to the course of the glacio-isostatic uplift in a wider perspective. The most obvious absurdity is that the rate of uplift continuously increases going backwards in time. The function which is looked for must be a function that starts slowly, reaches a maximal rate and after that follows a declining course i.e. an S-shaped function. Some different functions have been tested, for example *tanh*-functions but with negative results. *Arctan*- functions turned out to be the most suitable way of describing the glacio-isostatic uplift.

The *arctan*- functions can be divided into two symmetrical parts. Only the declining part of the function can be tested for its validity of describing the glacio-isostatic uplift. To say that the initial inclining phase of the uplift is symmetrical to the declining phase is an overstatement. Since there is no accessible information from this phase it can be convenient to accept this approximation as guidance. However, in this report only the declining phase is considered.

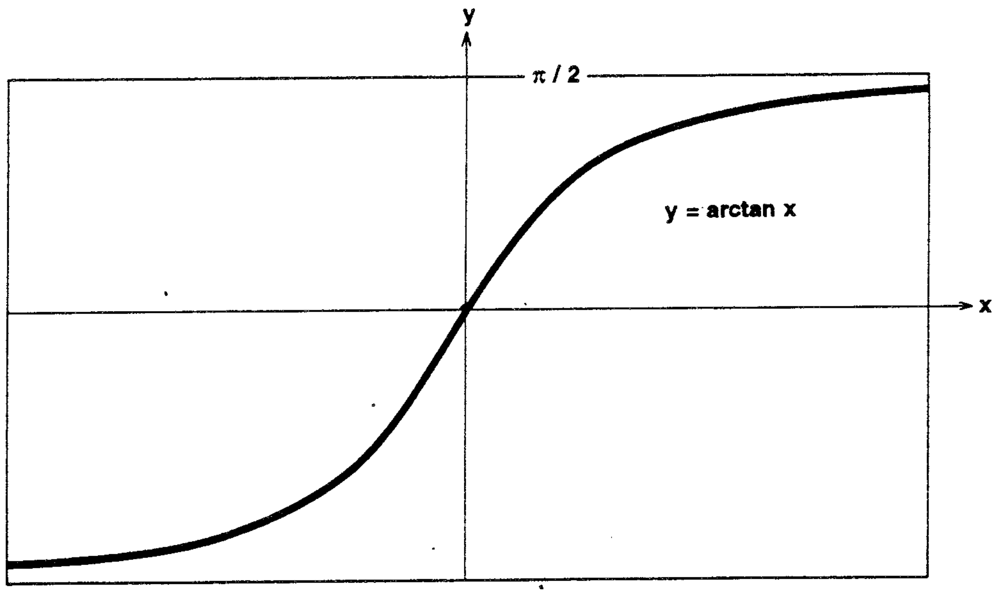

Figure 3-1. *Mathematical definition of the function y = arctan x.*

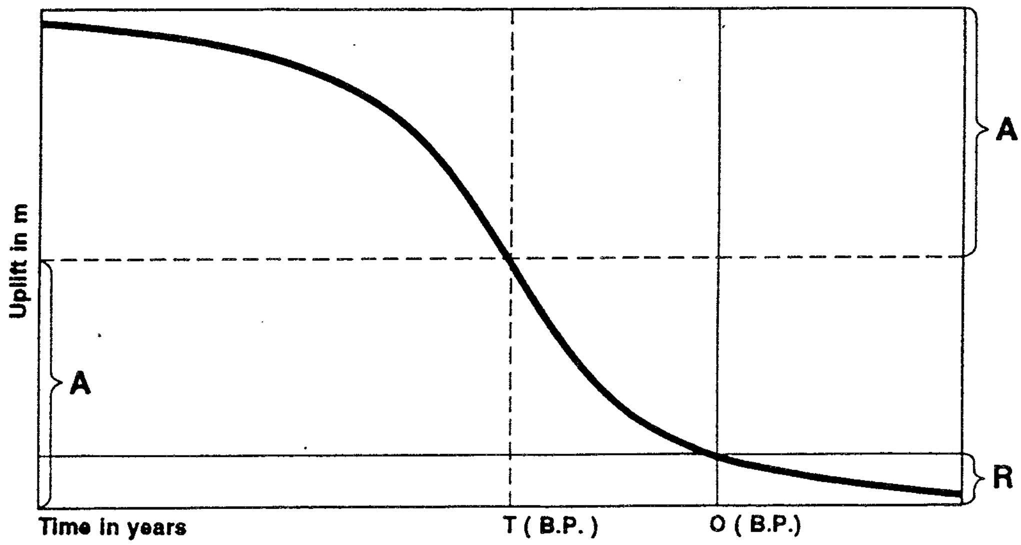

Figure 3-2. *Definition of the general uplift formula*
U= A - R- (2A/π) × arctan((T- t)/B). U (m) is land uplift following the unloading of earth, A (m) is half of the total uplift, R (m) is the remaining uplift, T (year) is the time for the maximal uplift, i.e. the middle of the curve, t (year) is the variable time and B is a declining factor.

3.2 DEFINITION AND DERIVATION OF A BASIC UPLIFT FORMULA

The graph of the function $y = \arctan x$ is shown in Figure 3-1. In order to use this type of function for calculating the glacio-isostatic uplift it is suitable to choose the origo as present time. It is also necessary to control the slope of the curve. The land uplift following the unloading of earth (U in m) can then be described with the function

$$U = A - R - (2A/\pi) \times \arctan((T - t)/B) \quad \text{3-1}$$

where A is half of the total uplift (m), R is the remaining uplift (m) in present time, T (years) is the time for the maximal uplift, *i.e.* the middle of the curve, t (year) is the variable time and B is a declining factor. Figure 3-2.

When $t = 0$, $U = 0$ yields

$$R = A - (2A/\pi) \times \arctan(T / B) \quad \text{3-2}$$

The basic formula for the land uplift can thus be expressed as

$$U = A - (2A/\pi) \times \arctan((T - t)/B) - (A - (2A/\pi) \times \arctan(T / B)) \quad \text{3-3}$$

simplified as

$$U = 0.6366 \times A\,(\arctan(T / B) - \arctan((T - t) / B)) \quad \text{3-4}$$

When using this formula for lake-tilting calculations it is the difference in uplift between the outlet and the sampling site which should be calculated. In the first approximation the difference in uplift is simply expressed as

$$\Delta U = 0.6366 \times \Delta A\,(\arctan(T / B) - \arctan((T - t) / B)) \quad \text{3-5}$$

provided that T and B can be assumed to be constant at small distances.

3.3 THE RECENT RELATIVE UPLIFT

An essential part for most investigations regarding glacio-isostatic uplift in Sweden is the information received by repeated precision levelling and tide gauges data by the National Land Survey (RAK 1974). The map which is drawn according to this information (RAK 1971) gives a really good picture of the pattern of the glacio-isostatic uplift regarding differences in gradient and direction of the tilt, Figure 3-3.

The record of the recent relative uplift (v_0 mm/year) is equivalent to other shore level data as the figures received are dependent of the eustatic changes. However, the information can be used in another way just by using the differences in uplift (Δv mm/year) received by the repeated precision

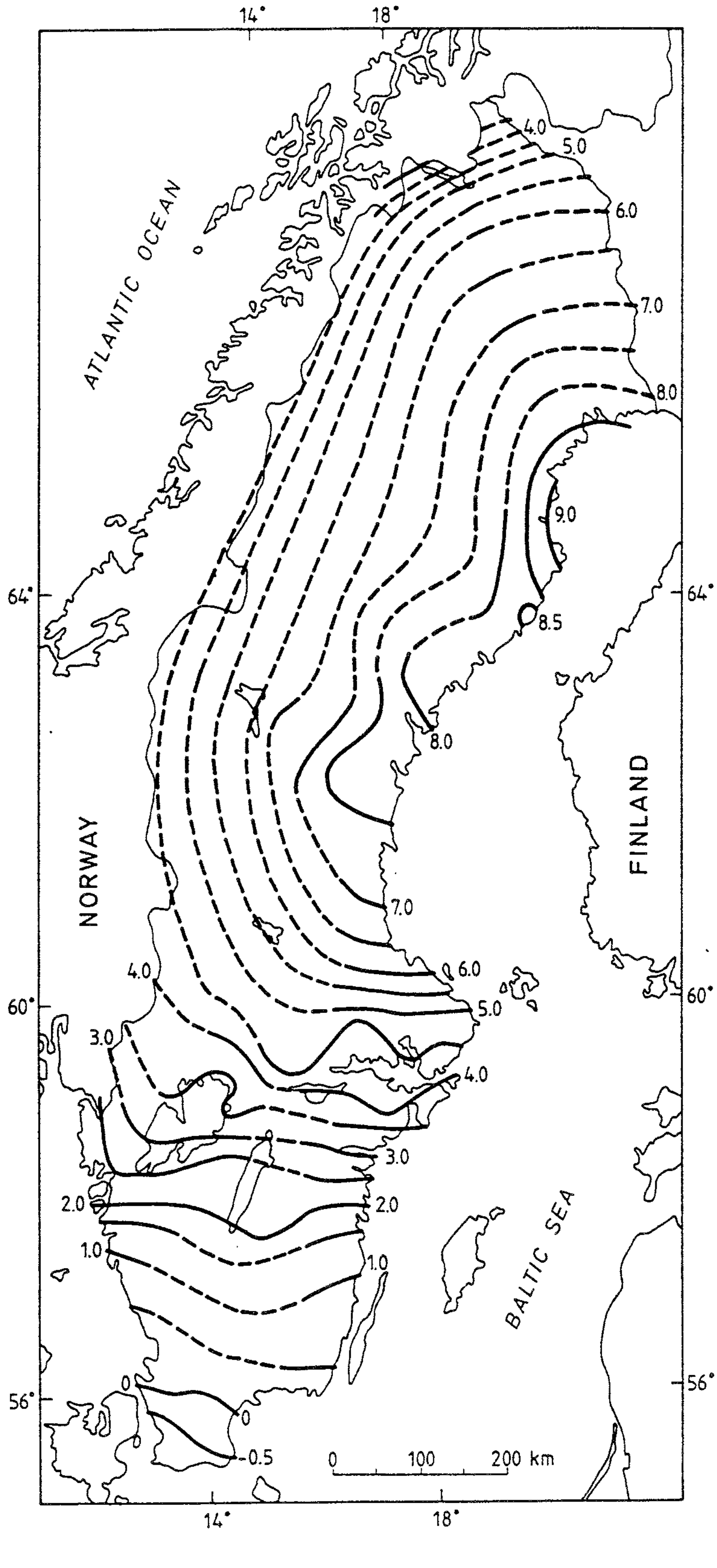

Figure 3-3. Recent relative land uplift in mm/year in Sweden according to repeated precision levelling by the National Land Survey (RAK 1971).

levelling. This type of information is equivalent with the lake-tilting data. The precision levellings represent the tilting during 100 years while the lake tilting gives a record of 10 000 years. record.

In this paper the information of the differences in uplift (Δv_o mm/year) received from precision levelling are used as an answer. The uplift during one year is calculated at each lake by the formula received by the lake-tilting The result should in comparison be similar to the figures received using precision levelling.

Precision levellings are performed in levelling lines as reported in detail in RAK (1974). Some of these are very close to the investigated lakes and can thus be used for very accurate estimations. At Lake Säven and Lake Sommen there is no proximate levelling data and the present relative uplift has been estimated by applying interpolation from the isobase map.

3.3.1 Recent relative uplift at Lake Fegen.

Levelling line 12 runs along the southern shore of Lake Fegen. Line 13 runs perpendicular to the lake 50 km west of the lake. By constructing isolines from the values within these lines, the relative uplift at the southern shore has been estimated at 0.80 mm/y, and at the outlet at 0.98 mm/y. The margin of error in this construction is estimated at ± 0.01 mm/y. These figures give an uplift rate of 0.0104 mm/y/km in the direction of tilting with a confidence interval of ± 0.0005 mm. The sampling site at Barmen is situated 13.8 km from the outlet. The Δv_o factor at Fegen thus ranges between 0.137 and 0.151 mm/y.

3.3.2 Recent relative uplift at Lake Säven.

At Lake Säven, the present uplift is roughly 1.75 mm/y and the uplift rate is estimated at 0.0147± 0,0005 mm/y/km according to the isobase map (RAK 1971). The distance between the sampling site and the outlet is 8.3 km. This means that the difference in the present uplift ranges between 0.118 - 0.126 mm/y at Säven.

3.3.3 Recent relative uplift at Lake Vanderydsvattnet.

The levelling line 29 runs parallel to the western side of the lake. The present relative uplift is c. 2.285 mm/y at the sampling site and c. 2.40 mm/y at the outlet projected in N 25^{o} E. The difference in the present uplift between the sampling site and the outlet can thus accurately be estimated at 0.115± 0.005 mm/ year. The distance between the sampling site and the outlet is 9.5 km projected in N 25^{o} E.

3.3.4 Recent relative uplift at Lake Sommen.

Lake Sommen is situated between the levelling lines 16 and 18. The gradient of the recent uplift differs considerably for those lines. The isobases of the recent relative uplift (RAK 1971) are thus very uncertain in the vicinity of Sommen. The present relative uplift is evaluated to be approximately 2.05 mm/y at the sampling site and 2.36 mm/y at the outlet giving a difference of about 0.31 ± 0.01 mm/y.

3.4 THE GRADIENT OF MARINE SHORELINES

Marine and lake shorelines which are isochronously formed have equivalent values of the gradient. The gradient of marine shorelines can thus be used as a complement to the lake-tilting data. The value of the gradient is defined as the difference in uplift in m/km measured in the direction of the tilt. The value is strongly dependent on the direction of tilt. For the lake-tilting investigations it is not necessary to be exactly sure of the direction of tilt. The principal issue is to use the same direction of tilt for the lake shorelines and for the marine shorelines. That means that when the gradient of marine shorelines is transformed to the lake the distance between the outlet and the sampling site should be estimated by projection in the same direction as the gradient is recorded. For the sites in the western part of Sweden the direction of tilt is approximately N 25^0 E indicated by the isobases of the present uplift.

The gradient has been calculated for three well-dated isochronous marine shorelines along the Swedish west coast by regression analysis (cf. Påsse 1983). The three shorelines are the highest sea levels at the time of formation of the Göteborg Moraine (12 800 B.P.) and the Berghem Moraine (12 250 B.P.) and at the regression maximum at 9 150 B.P. Field data concerning the localities used in the calculations are listed in Påsse (1983). The estimated values of the gradients are 0.80 m/km at 12 800 B.P., 0.70 m/km at 12 250 B.P., and 0.33 m/km at 9 150 B.P. calculated in a direction of N 25^0 E (Påsse 1990).

3.4.1 Gradient values at Lake Fegen

Lake Fegen was deglaciated roughly at the time of the formation of the Göteborg moraine. The lake is situated above the highest sea level. The gradients from the shorelines formed during the formation of the Göteborg moraine and the Berghem moraine can be extrapolated to the area as the gradients are calculated from the same region. The distance between the sampling site and the outlet at Lake Fegen is 13.8 km counted in a direction of N 25^0 E. The gradient at 12 800 y B.P. (14 020 cal y B.P.) is estimated at 0.8 m/km. This means that the tilt at the sampling site in Lake Fegen is $13.8 \times 0.8 = 11.04$ m at this date. The gradient at 12 250 y B.P. (13 410 cal y B.P.) is 0.7 m/km, which gives a tilt of 9.66 m. These figures are inserted in the time-depth curve and presented in Figure 3-5. In a similar way the gradient value for the time 9 150 B.P. can be used in the analyses but as field data is available from this period this gradient value just confirms the field information and gives no new information.

3.4.2 Gradient values at Lake Vanderydsvattnet

Lake Vanderydvattnet was deglaciated shortly after the formation of the Berghems moraine. The lake is situated below the highest sea level. The gradients from the shorelines formed during the formation of the Berghem moraine are estimated according to data from the Vanderydsvattnet area and can thus be used to calculate the tilt. The gradient value for the time 9 150 year B.P. (10 130 cal y B.P.) can also be used in this calculation. The distance between the sampling site and the outlet at Lake Vanderydvattnet is 9.5 km counted in a direction of N 25^0 E. The gradient at 12 250 y B.P. (13 410 cal y B.P.) is 0.7 m/km, which gives a tilt of 6.65 m. The gradient at 9150 y B.P. is 0.33 m/km and gives a tilt of 3.14 m. These figures are inserted in the time-depth curve and presented in Fig. 3-7.

3.4.3 Gradient values at Lake Säven and at Lake Sommen

Unfortunately the time-depth curves from Lake Säven and Lake Sommen cannot be extended in this way as there are no reliable values of the gradient in these areas.

3.5 ESTIMATION OF THE UPLIFT FUNCTION

3.5.1 The sources of errors

The sources of errors included in the field data can relate to two areas, depth or dating. The sources of errors related to depth are: whether the dated samples really represent the former mean water level; to what degree have the present levels of the sediments been changed by compaction; and has the mean water level been altered. Among the sources of errors regarding dating are: the standard deviation within radiocarbon dating; how much has the thickness of the sample affected the date; the calibration of the dates etc. If all these errors were compiled, the investigation would probably be nonsensical. However, the results by themselves prove that the method can be used for a relatively detailed estimation of the course of uplift.

3.5.2 The uplift calculations

The difference in uplift between the outlet and the sampling site is expressed as

$$\Delta U = 0.6366 \times \Delta A\ (\arctan\ (T\ /\ B) - \arctan\ ((T - t)\ /\ B)) \qquad 3\text{-}5$$

provided that T and B can be assumed to be constant at small distances. Curves calculated by the uplift formula with varying values for ΔA, B, T and also for the mean water level have been compared to the empirical lake-tilting data. Statistically this has been done by calculating the standard deviation for the differences between the empirical and the calculated depths. In the iteration procedure ΔA was given a fixed value after which the best fitness was calculated by varying the three other variables. This iteration was continued by giving ΔA a new value and then repeating the procedure. The results are presented in Tables 3-1 to 3-4 and in Figures 3-5 to 3-8.

Table 3-1. The result of the statistical analysis at Lake Fegen.

A m	T cal y BP	B year	stand. dev.	v_0 mm/y
11	12500	3600	0.158	0.135
12	13500	3875	0.113	0.15
13	13900	3900	0.109	0.155
14	14300	3900	0.106	0.158
15	14600	3900	0.107	0.163
16	14900	3850	0.108	0.166
17	15200	3800	0.109	0.168
18	15450	3800	0.109	0.172
19	15700	3750	0.111	0.174
20	15900	3700	0.111	0.177
21	16100	3650	0.112	0.179

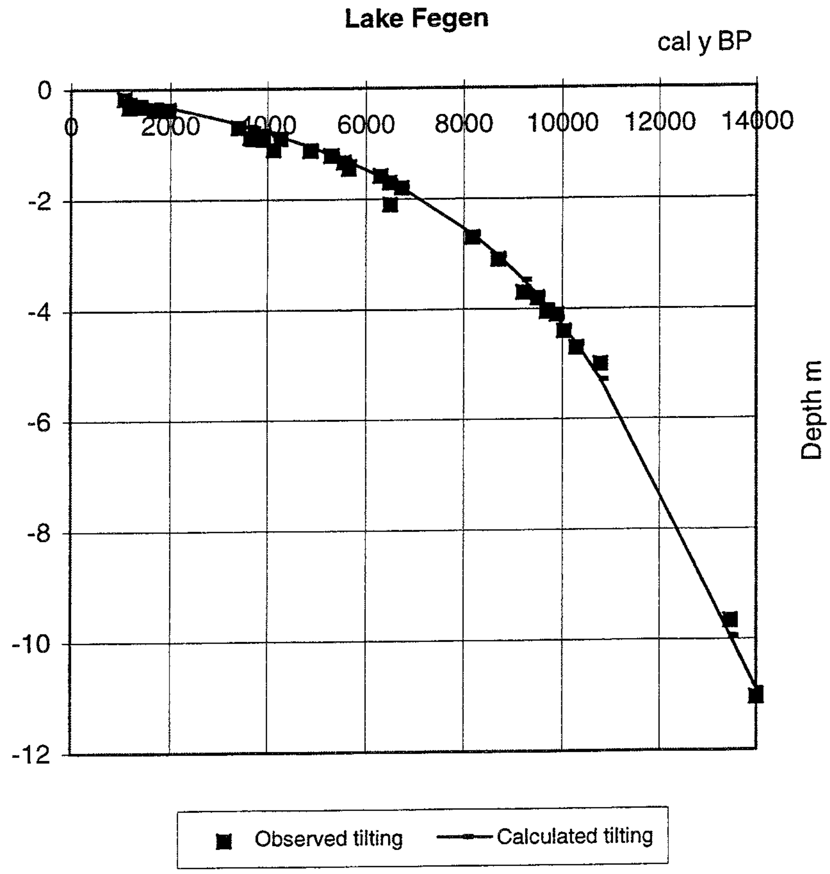

Figure 3-5. A time-depth graph at Lake Fegen. The two lowermost squares are derived from the gradient from the shorelines formed during the formation of the Göteborg moraine and the Berghem moraine. The graph of the calculated tilting is achieved through Δ A=11 m, T= 13 000 cal y B.P. and B= 3 700 cal y B.P.

Table 3-2. The result of the statistical analysis at Lake Säven.

A m	T cal y B.P.	B year	stand. dev.	v_0 mm/y
5	10200	3975	0.151	0.106
6	11100	4250	0.151	0.116
7	11900	4350	0.155	0.122
8	12600	4350	0.159	0.126
8.5	12900	4350	0.160	0.128
9	13150	4200	0.163	0.128
9.5	13400	4200	0.163	0.130
10	13650	4150	0.165	0.130
10.5	13850	4150	0.166	0.134
11	14050	4075	0.167	0.134
12	14350	3850	0.168	0.134
14	14900	3600	0.171	0.137
16	15300	3300	0.173	0.138

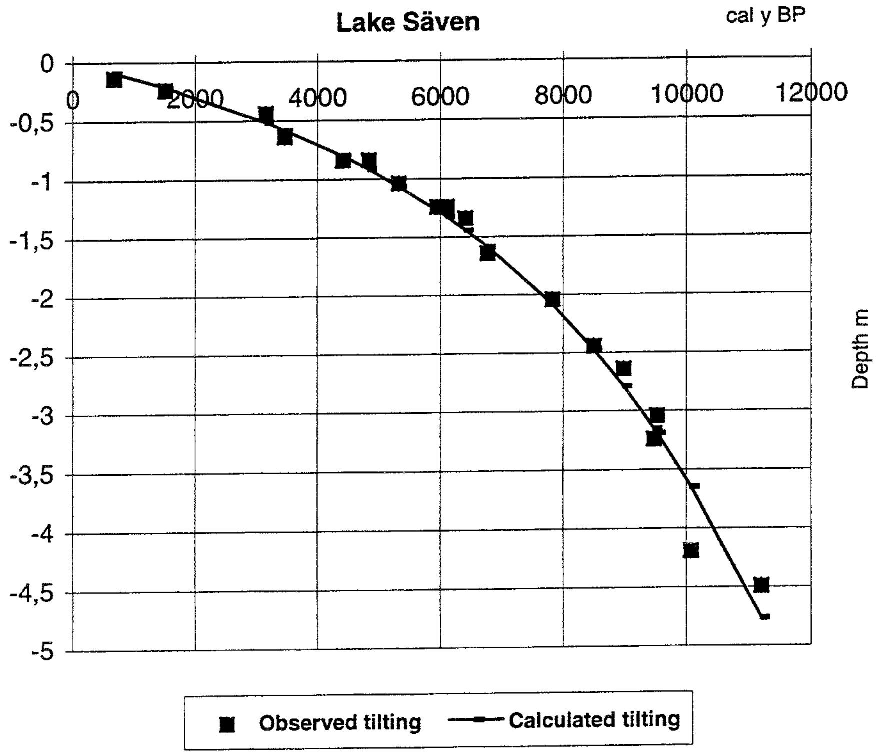

Figure 3-6*. A time-depth graph at Lake Säven. The graph of the calculated tilting is achieved by Δ A= 8.75 m, T= 13 000 cal y B.P. and B= 4 300 cal y B.P.*

Table 3-3. The result of the statistical analysis at Lake Vanderydsvattnet.

A m	**T** cal y BP	**B** year	stand. dev.	v_0 mm/y
6	11400	3750	0.185	0.099
6,5	11850	3950	0.186	0.105
7	12250	4075	0.190	0.109
7.5	12650	4200	0.195	0.113
8	13000	4250	0.200	0.116
8,5	13350	4325	0.205	0.119
9	13650	4350	0.210	0.121
10	14250	4350	0.217	0.125
11	14750	4300	0.223	0.128
12	15150	4150	0.227	0.128
13	15500	4125	0.231	0.132

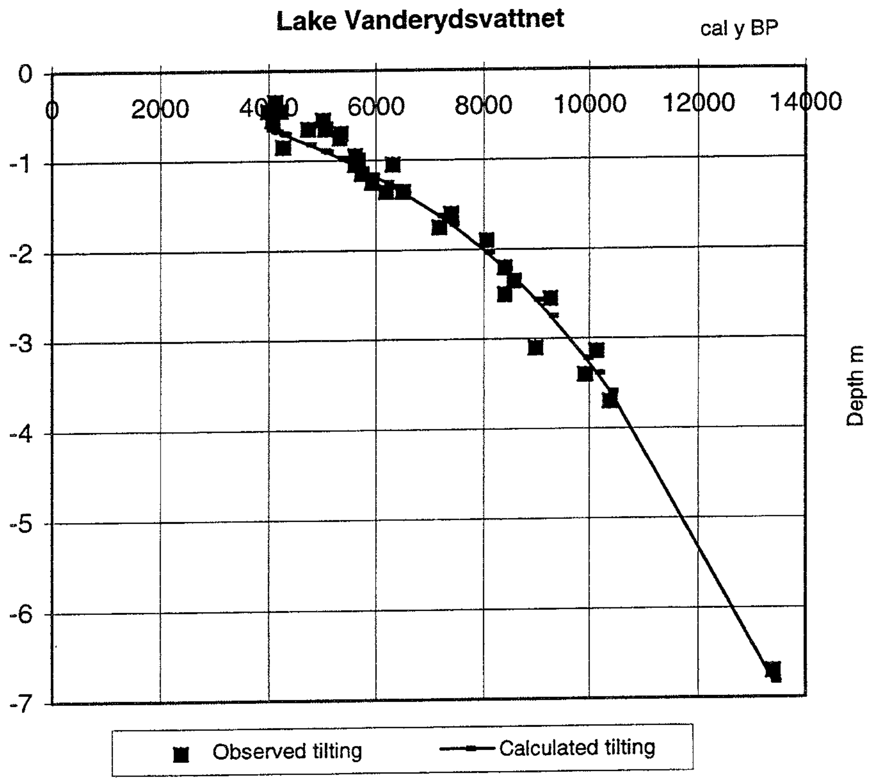

Figure 3-7. A time-depth graph at Lake Vanderydsvattnet. The two lowermost squares are derived from the gradient from the shorelines formed during the formation of the Berghem moraine and at the regression maximum at 9 150 B.P. The graph of the calculated tilting is achieved by ΔA*= 8 m, T= 13 000 cal y B.P. and B= 4 350 cal y B.P.*

Table 3-4. The result of the statistical analysis at Lake Sommen.

A m	T cal y BP	B year	stand. dev.	v_0 mm/y
12	10700	6000	0.161	0.307
13	11200	6000	0.158	0.310
14	11700	6000	0.158	0.309
15	12100	5900	0.156	0.313
16	12500	5900	0.155	0.317
17	12900	5900	0.155	0.319
18	13200	5900	0.155	0.323
19	13600	5900	0.154	0.327
20	13900	5800	0.154	0.328

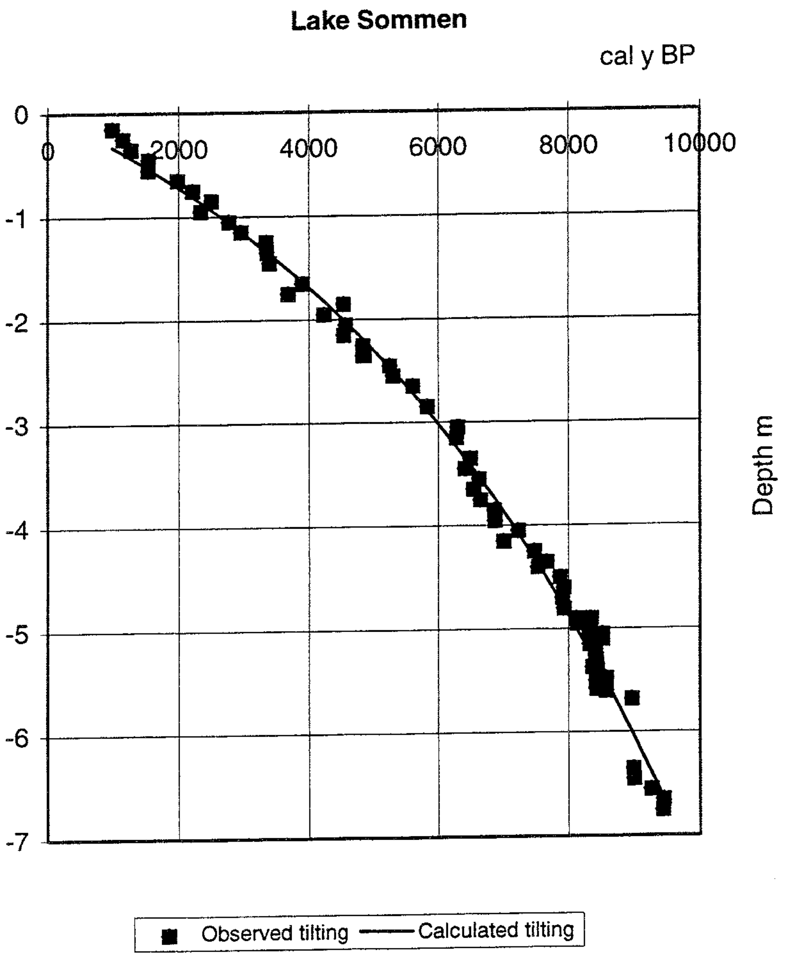

Figure 3-8. A time-depth graph at Lake Sommen. The graph of the calculated tilting is achieved by ΔA= 16 m, T= 12 500 cal y B.P. and B= 5 900 cal y B.P.

3.5.3 Discussion of the calculations

As there are three variables within the uplift function there will be a lot of "possible" combinations. However, the information of $\Delta \nu$ can be used as a tool for limiting the number of possible solutions. As seen from Tables 3-1 to 3-4 the value of $\Delta \nu$ increases when ΔA is enhanced. $\Delta \nu$ has been estimated at each lake using the information from the repeated precision levelling (RAK 1971, 1974). This estimation includes a confidence interval. Only those iterations which give values of $\Delta \nu$ within this interval are possible solutions. Accordingly the number of possible values of ΔA can be reduced. These limitations are reported in Table 3-5. The size of T is dependent on ΔA. This also means that the interval for possible values of T is reduced through this operation. In the same manner the interval for possible values of B are reduced, Table 3-5.

Table 3-5. The most likely values of ΔA, T and B according to the statistical analyses at the four lakes.

	Δ A m	T cal. y B.P.	B year
Lake Fegen	11,2-12	13000-13500	3700-3875
Lake Vanderydsvattnet	7,1-8,7	12300-13500	4105-4325
Lake Säven	6,25-8	11500-12600	4300-4350
Lake Sommen	12-17	10700-12900	5900-6000

According to Table 3-5 T is limited to an interval between 10 700 - 13 500 cal y B.P. This means that the maximal glacio-isostatic uplift in the region must have occurred close to the deglaciation or somewhat later. Whether the maximal uplift occurred as a synchronous event or not can not be concluded by the presented data. Table 3-5 also shows that there is a significant difference between the value of B at Lake Sommen compared to the other sites. This can also be expressed as the uplift curve is more even at Lake Sommen then at the other sites.

As T falls close to the deglaciation gives a new tool for testing the results. During that interval the gradient is known at Lake Fegen and at Lake Vanderydsvattnet. The gradient at Lake Fegen at 13 400 cal y B.P. is c. 0.70 m/km. This figure involves a difference in the uplift between the outlet and the sampling site of approximately 10 m since 13 400 cal y B.P. The remaining uplift between those points is in the order of *c.* 2 m according to Figure 3-9. That means that ΔA ought to be in the order of 12 m at Lake Fegen. This value is equivalent to the value calculated in the statistical analysis. ΔA can be estimated at Lake Vanderydsvattnet in the same manner. At this lake the uplift difference is somewhat more then 6.65 m since 13 400 cal y B.P. A calculation of the remaining uplift gives *c.* 1.75 m at Lake Vanderydsvattnet, Figure 3-10, which means that Δ *A* ought to be in the order of 8.5 m. This value can be compared to 8.75 m which is received by the statistical analysis. These calculations thus show that the interpretations of the lake-tilting investigations are reasonable.

The fact that there are several possible solutions of the time-depth functions are not any serious problem for the continuos work by modelling shore level data with the aim of estimating the absolute uplift-functions. Whether *T* is 13 000 or 13 500 or 12 500 cal years B.P. influences the conditions for modelling the shore level displacement only to a small degree as long as corresponding values of (Δ) *A* and *B* are used.

3.6 THE FUTURE UPLIFT

The future crustal uplift due to the glacio-isostasy can be predicted at the investigated lakes by applying the parameters for the best solutions at each specific lake. Using the uplift formula the future time is counted as negative. The future uplift is here calculated at Lake Fegen and at Lake Vanderydsvattnet. *T* is assumed to be 13 000 cal y B.P. at the both lakes. The results are shown in Figure 3-9 and in Figure 3-10.

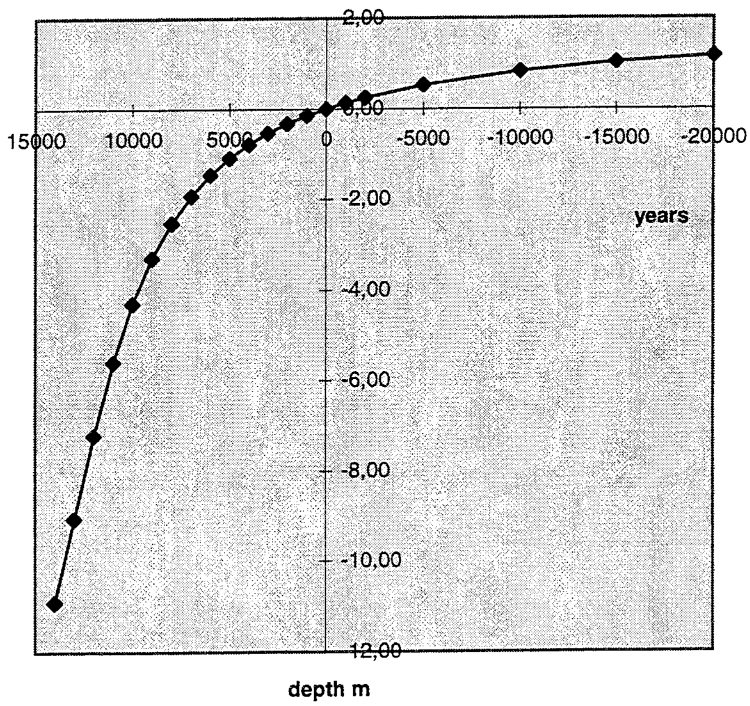

Figure 3-9. *The past and future tilting at Lake Fegen. The future time is counted as negative. T is assumed to be 13 000 cal y B.P.*

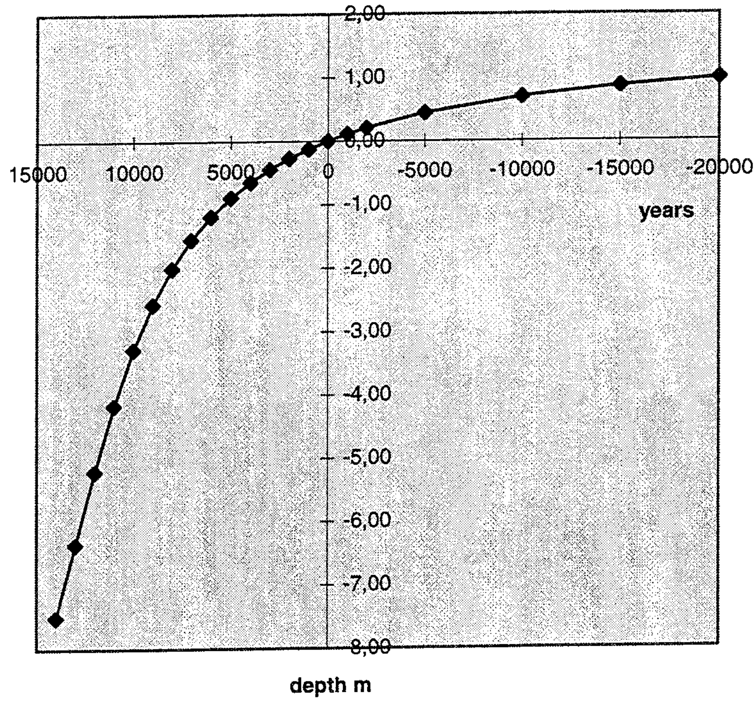

***Figure 3-10**. The past and future tilting at Lake Vanderydsvattnet. The future time is counted as negative. T is assumed to be 13 000 cal y B.P.*

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Appendix 1

Table 1. Datings and depths of the samples from Lake Fegen.

Lab. no	^{14}C date y B.P.	Standard dev. ±	Calibrated date y B.P.	Original depth cm	Mean water cal cm	Sediment
Samples from Barmen						
St 11255	1200	70	1078	15-20		Carex peat
St 11256	1245	70	1169	30-35		Carex peat
St 10873	1510	70	1387	30-35		Carex peat
St 10870	1760	70	1694	35-40		Carex peat
St 11254	2030	70	1958	35-40		Carex peat
St 10933	3190	70	3385	60-80		Carex peat
St 10874	3400	70	3632	135-140	85-90	Coarse etritus gyttja
St 11742	3860	135	4264	80-100		Carex peat
St 10872	3620	70	3906	140-145	90-95	Coarse detritus gyttja
St 10934	3755	70	4121	100-120		Carex peat
St 10936	5725	80	6492	200-220		Carex peat
St 10928	7455	90	8178	260-280		Carex peat
St 10929	7920	95	8700	300-320		Carex peat
St 10930	8235	95	9212	360-380		Carex peat
St 10931	8855	260	9887	400-420		Carex peat
St 10932	9285	190	10290	460-480		Carex peat
Samples from the most southernmost part						
St 10875	3400	70	3694	110-115		Carex peat
St 11743	4355	70	4869	135-145		Carex peat
St 11738	4560	70	5292	145-160		Carex peat
St 11741	4670	75	5545	160-175		Carex peat
St 11740	4915	75	5646	175-190		Carex peat
St 11737	5520	80	6300	190-205		Carex peat
St 11744	5705	80	6482	205-220		Carex peat
St 11739	5890	80	6728	220-235		Carex peat
St 10867	8550	95	9497	545-560	470-485	Coarse detritus gyttja
St 10186	8705	190	9682	495-515		Carex peat
St 10869	9060	100	10038	620-635	545-560	Phragmites peat
Sample from Yttre Backa						
St 10877	9530	260	10789	460-490	385-415	Carex peat

Table 2. Datings and depths of the samples from Lake Säven.

Lab. no St-	^{14}C date y B.P.	Standard dev. ±	Calibrated date y B.P.	Depth cm	Sediment	$\delta\ ^{13}C$
11553	750	70	668	10-20	Carex peat	-29,5
11554	1595	70	1508	20-30	Carex peat	-29,2
11555	2990	70	3162	40-50	Carex peat	-28,6
11556	3295	70	3475	60-70	Carex peat	-28,8
11557	3935	70	4407	80-90	Carex peat	-29,1
10991	4250	70	4833	80-90	Carex peat	-28,0
11558	4680	75	5328	100-110	Carex peat	-29,1
10992	5245	75	5953	120-130	Carex peat	-27,2
11559	5340	80	6110	120-130	Carex peat	-28,9
11560	5630	185	6411	130-140	Carex peat	-29,3
10993	5945	80	6772	160-170	Carex peat	-27,1
10994	7050	80	7825	200-210	Carex peat	-27,1
10995	7785	95	8507	240-250	Carex peat	-27,7
11320	8090	315	8986	260-270	Carex peat	-26,3
10996	8640	80	9532	300-310	Carex peat	-27,5
11321	8500	95	9480	320-330	Carex peat	-27,6
10998	9180	100	10078	415-425	Carex peat	-27,8
10999	9990	110	11200	445-455	Carex peat	-29,2

Table 3. Datings and depths of the samples from Lake Vanderydsvattnet.

Lab.no St-	^{14}C date y B.P.	Stand. dev. ±	Calibrated date y B.P.	Depth cm	Sediment	$\delta\ ^{13}C$
12371	3695	120	3989	180-190	Carex peat	-29,8
12368	3705	70	4073	190-200	Carex peat	-28,9
12366	3755	85	4121	170-180	Carex peat	-29
12367	3810	90	4221	180-190	Carex peat	-29,4
12378	3860	75	4264	220-230	Carex peat	-30,7
12370	4180	90	4719	200-210	Carex peat	-29,3
12372	4440	90	4992	190-200	Carex peat	-29,3
12379	4440	75	5034	200-210	Carex peat	-29,2
12375	4590	125	5302	210-220	Carex peat	-30,4
11762	4680	75	5328	205-215	Carex peat	-28,2
12380	4865	110	5597	240-250	Carex peat	-30,2
12377	4875	75	5601	230-240	Carex peat	-30,4
11766	4955	70	5660	235-245	Carex peat	-27,8
12373	4990	70	5726	250-260	Carex peat	-29,8
12376	5170	80	5922	260-270	Carex peat	-30,1
12374	5385	80	6189	270-280	Carex peat	-30,3
11760	5565	150	6314	240-250	Carex peat	-27,5
11763	5740	105	6506	270-280	Carex peat	
11750	6260	85	7175	310-320	Carex peat	-28,6
11754	6555	80	7393	295-305	Carex peat	-28,7
11755	7255	85	8054	325-335	Carex peat	-29,5
11758	7640	90	8402	355-365	Carex peat	-29,2
11759	7640	90	8402	385-395	Carex peat	
11757	7870	90	8572	370-380	Carex peat	-28,9
11753	8100	90	8988	445-450	Carex peat	-29,1
11756	8315	165	9271	390-400	Carex peat	-27,5
11751	8915	95	9920	475-485	Carex peat	-28,1
11768	9405	100	10374	505-515	Carex peat	-28,5

Table 4. Datings and depths at Lake Sommen.

Lab.no St-	^{14}C date y B.P.	Stand. dev ±	Calibrated date y B.P.	Depth cm	Sediment	δ ^{13}C
13252	1100	70	977	60-70	Carex peat	-27,90
13253	1215	70	1136	70-80	Carex peat	-28,10
13254	1310	70	1265	80-90	Carex peat	-27,90
13255	1630	70	1527	100-110	Carex peat	-28,40
13521	1640	45	1531	90-100	Carex peat	-27,90
13517	2035	40	1983	110-120	Carex peat	-27,70
13256	2245	70	2210	120-130	Carex peat	-28,20
13257	2295	70	2332	140-150	Carex peat	-28,30
13524	2490	45	2496	130-140	Carex peat	-27,60
13520	2685	35	2769	150-160	Carex peat	-27,70
13258	2865	70	2956	160-170	Carex peat	-28,20
13504	3110	50	3345	170-180	Carex peat	-27,90
13259	3130	70	3354	180-190	Carex peat	-28,20
13522	3200	70	3392	190-200	Carex peat	-28,40
13261	3425	70	3684	220-230	Carex peat	-28,40
13505	3615	55	3897	210-220	Carex peat	-28,30
13262	3825	70	4228	240-250	Carex peat	-29,00
13506	4075	55	4533	230-240	Carex peat	-27,70
13263	4085	75	4538	260-270	Carex peat	-28,70
13503	4105	70	4565	250-260	Carex peat	-28,60
13525	4245	50	4835	270-280	Carex peat	-27,30
13264	4250	70	4833	280-290	Carex peat	-28,40
13519	4310	65	4860	280-290	Carex peat	-27,10
13516	4505	50	5249	290-300	Carex peat	-27,30
13265	4585	70	5300	300-310	Carex peat	-28,10
13515	4880	45	5605	310-320	Carex peat	-27,50
13513	5050	65	5829	330-340	Carex peat	-27,30
13268	5445	80	6278	360-370	Carex peat	-27,20
13512	5520	65	6300	350-360	Carex peat	-27,30
13536	5635	55	6412	390-400	Carex peat	-27,00
13269	5720	70	6489	380-390	Carex peat	-27,60
13533	5760	65	6544	410-420	Carex peat	-27,70
13270	5775	80	6621	400-410	Carex peat	
13271	5810	105	6647	420-430	Carex peat	-27,60
13530	6000	55	6854	430-440	Carex peat	-26,90
13272	6020	80	6865	440-450	Carex peat	
13273	6115	80	6995	460-470	Carex peat	-25,30
13534	6345	50	7221	450-460	Carex peat	-27,70
13532	6635	65	7473	520-530	Carex peat	-28,30
13274	6670	80	7524	535-545	Carex peat	-26,90
13518	6900	70	7666	530-540	Carex peat	-27,70
13529	7030	75	7865	545-555	Carex peat	-27,70
13527	7100	65	7905	565-575	Carex peat	-26,80
13276	7145	85	7923	555-565	Carex peat	-27,20
13275	7165	85	7932	575-585	Carex peat	-25,70

13537	7330	65	8118	610-620	Carex peat	-28,10
13277	7375	90	8130	590-600	Carex peat	-26,60
13281	7480	85	8304	620-630	Carex peat	-27,50
13278	7520	90	8321	610-620	Carex peat	-27,40
13511	7540	55	8329	585-595	Carex peat	-27,50
13535	7595	65	8366	633-643	Carex peat	-27,30
13282	7625	85	8399	640-650	Carex peat	-27,50
13507	7655	50	8406	650-660	Carex peat	-28,80
13509	7675	75	8411	670-680	Carex peat	-27,60
13279	7680	90	8412	630-640	Carex peat	-27,90
13280	7715	90	8421	653-663	Carex peat	-28,20
13283	7715	90	8421	660-670	Carex peat	-28,30
13508	7780	50	8503	630-640	Carex peat	-27,60
13531	7780	55	8503	600-610	Carex peat	-27,30
13284	7850	90	8560	680-690	Carex peat	-27,90
13523	7850	50	8560	643-653	Carex peat	-28,10
13539	8040	70	8957	663-673	Carex peat	-29,30
13510	8060	75	8981	680-690	Carex peat	-28,10
13528	8120	60	8991	690-700	Carex peat	-27,60
13285	8290	90	9256	700-710	Carex peat	-28,80
13287	8425	95	9435	720-730	Carex peat	-28,50
13286	8450	95	9442	710-720	Carex peat	-28,80

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Karsten Pedersen (editor)

Department of General and Marine Microbiology, The Lundberg Institute, Göteborg University, Göteborg, Sweden

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S Stroes-Gascoyne[1], K Pedersen[2], S Daumas[3], C J Hamon[1], S A Haveman[1], T L Delaney[1], S Ekendahl[2], N Jahromi[2], J Arlinger[2], L Hallbeck[2], K Dekeyser[3]

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[2] University of Göteborg, Department of General and Marine Microbiology, Göteborg, Sweden

[3] Guigues Recherche Appliquée en Microbiologie (GRAM), Aix-en-Provence, France

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Daqing Cui, Trygve E Eriksen

Department of Chemistry, Nuclear Chemistry, Royal Institute of Technology, Stockholm, Sweden

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Jordi Bruno, Lara Duro, Salvador Jordana, Esther Cera

QuantiSci, Barcelona, Spain

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Virginia M Oversby

VMO Konsult

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John Smellie[1], Fred Karlsson[2]

[1] Conterra AB

[2] SKB

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