Limnological characteristics of Northern and Central Yakutian lakes (Siberia) – Physical and chemical properties of surface sediments and water samples

Diplomarbeit
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eingereicht von
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Abstract

Physical and chemical properties of surface sediments and waters of 65 lakes in Northern and Central Yakutia were analysed. The studies included hydrochemical analyses as well as sedimentological, organic and inorganic geochemical analyses, the analysis of stable carbon isotope ratios and the analysis of magnetic susceptibilities.

The objectives of this work were a) to characterise Yakutian lakes by their waters and surface sediments. Additionally, the geographical setting, i.e. the climate, vegetation and the morphology were taken into account. b) To explore parameters attributing for the variation in the measured variables using multivariate statistical methods. c) To characterise the relationships between sediments and waters.

Most of the sampled lakes originated by thermokarst processes and lack in- and outflows. The ionic composition of the waters is strongly influenced by the continentality of the Lakes. Central Yakutian lake waters have considerably higher ion concentrations and electric conductivities than waters sampled in Northern Yakutia. This reflects the negative water balance (evaporation exceeding precipitation) in that region, which results in evaporation of lake waters. C/N ratios of surface sediments sampled in that regions are higher than those in Northern Yakutia as the bioproductivity is generally higher in Central Yakutia. The influence of the vegetation on the watershed is reflected in elevated Na/K ratios of waters sampled in lakes surrounded by taiga forest or pastures. Statistical analyses identified the electric conductivity, ion concentrations and alkalinity of waters as variables controlling the composition of surface sediments.

Sediments rich in nutrients, with high concentrations of elements related to lush vegetation on the watershed and high magnetic susceptibilities were encountered in lakes characterised by a) waters with high ionic concentrations and high electric conductivities and b) their geographical setting, i.e. the vegetation on the watershed and the negative water balance in these regions. These results can be of great value to paleolimnological and paleoenvironmental studies, as analysed sediments are being correlated to recent environments.

Zusammenfassung

Im Rahmen dieser Diplomarbeit wurden Oberflächensedimente und Wässer aus 65 nord- und zentraljakutischen Seen analysiert. Die Untersuchungen umfassten neben hydrochemischen Analysen der Seewässer sedimentologische und geochemische (organisch und anorganisch) Analysen, die Aufstellung von Verhältinssen der stabilen Kohlenstoffisotope ($^{12}C/^{13}C$) und die Erfassung der magnetischen Suszeptibilität. Die Ziele dieser Arbeit waren es a) Jakutische Seen nach ihren Wässern und ihren Oberflächensedimenten zu charakterisieren. Die geographische Lage der Seen, d.h. klimatische Bedingungen, Vegetation, und die Morphologie der Seen wurde dabei berücksichtigt. b) Die Identifikation des Parameters, der für den Großteil der Variationen in den Datensätzen verantwortlich ist. c) Die Beziehungen von Sedimenten zu den Wässern zu erfassen.

Die meisten der untersuchten Seen sind durch Thermokarstprozesse entstanden und haben keine Zu- oder Abflüsse. Die Ionenzusammensetzung der Wässer ist zu einem hohen Grade von der Kontinentalität der Seen beinflusst. Zentraljakutische Seen weisen deutlich höhere Ionenkonzentrationen und damit einhergehende elektrische Leitfähigkeiten auf als Seen, die in Nordjakutien beprobt wurden. Dies resultiert aus der negativen Wasserbilanz (Evaporation größer als Niederschlag) in Zentraljakutien, die zu der Evaporation von Seewässern führt. In dieser Region beprobte Oberflächensedimente weisen größere C/N Verhältnisse auf als solche, die in Nordjakutien beprobt wurden. Dies ist auf die höhere Bioproduktivität in Zentraljakutien zurückzuführen. Der Einfluss der Vegetation der Wasserscheide spiegelt sich in hohen Na/K Verhältnissen in Wässern der Seen wieder, die von Taigawäldern oder Weiden umgeben sind. Die elektrische Leitfähigkeit, Ionenkonzentration und die Alkalinität von Wässern konnten mittels statistischen Analysen als Variablen identifiziert werden, die die Zusammensetzung der Oberflächensedimente massgeblich beeinflussen.

Sedimente mit hohem Nährstoffgehalt und hohen Konzentrationen von Elementen, die mit reichhaltiger Vegetation auf der Waserscheide in Verbindung gebracht werden und hohe magnetische Suszeptibilitäten aufweisen, wurden in Seen angetroffen, die a) durch Wässer mit hohen Ionenkonzentrationen und hohen elektrischen Leitfähigkeiten und b) durch ihre geographische Lage, d.h. durch die hochkontinentale Lage, die Vegetation auf der Wasserscheide und die negative Wasserbilanz charakterisiert sind. Diese Ergebnisse können von großem Wert für paläolimnologische Untersuchungen und Rekonstruktionen von Paläoumwelten sein, da die analysierten Sedimente mit rezenten Umweltbedingungen korreliert werden.

1 Introduction

Small closed-basin lakes are a common feature of the Yakutian landscape. The high number of small lakes in Yakutia is a consequence of thermokarst processes (Nazarova et al., 2005). Information about the limnology of Siberian lakes is sparse. Duff et al. (1999), Laing and Smol (2000), Kumke et al. (2007) and Wetterich et al. (2008) are some of the few studies to date. These works focused primarily on hydrochemical analyses. In this thesis surface sediments were analysed additionally to the analyses of waters. To increase the amount of information about lakes in this region, 65 lakes in Northern and Central Yakutia were sampled during the summers of 2005 and 2007. Global climate changes are expected to affect high latitude sooner and with greater intensity – exceeding the mean global warming by a factor of two (Christensen et al., 2007) – than lower latitudes (Quadfasel et al., 1991; Rouse et al., 1997). Limnological studies in these sensitive regions are not only of interest to paleolimnologists, as aquatic ecosystems are affected by global climate changes in many ways, e.g. increasing water temperatures or changes in subsurface drainage due to decaying permafrost (Schindler et al., 1996; Duff et al., 1999).

The knowledge of physical and chemical properties of lake waters and sediments is important in paleolimnological studies. It is in the nature of paleolimnologic studies that limnological informations are inferred from the analysis of sediments, e.g. sediment cores. Such studies are often based on relationships between aquatic organisms (e.g. diatoms, ostracodes) and abiotic factors (e.g. water chemistry) (e.g. Curry and

Delorme (2003); Wetterich et al. (2005)). Other studies focus on sedimentological and geochemical records, such as magnetic susceptibility (e.g. Peck et al. (1994)), organic geochemistry (e.g. Kaushal and Binford (1999); Melles et al. (2007)), inorganic geochemistry (e.g. Boyle et al. (2004); Minyuk et al. (2007)), carbon isotope ratios (e.g. Brenner et al. (1999); Das et al. (2008)) and grain-size distributions (e.g. Bertrand et al. (2005); Mischke et al. (2005)). The subject of this work is no sediment core, it is surface sediments, i.e. recent sedimentated material. As the studied sediments are recent corresponding lake waters could be sampled and analysed. Furthermore, relationships between sediments and waters could be explored. Hence, the findings of this work contain additional information for the reconstruction of paleoenvironments, as a wide variety of limnological proxies were studied.

The aims of this thesis are as follows:

- Characterisation of lakes
  - by morphological parameters,
  - by the composition of waters,
  - by the composition of surface sediments and
  - by their geographical setting (e.g. climate, vegetation).
- Identification of variables controlling the composition of lake waters and surface sediments.
- Characterisation of the relationship between surface sediments and lake waters.

In addition to sedimentological analyses, organic and inorganic geochemistry, magnetic susceptibility and carbon isotope ratios of the surface sediments were studied. The analyses of lake waters consisted of field measurements (pH, electric conductivity, secchi depth) and hydrochemical analyses to determine their ionic composition and their alkalinity. To assess the effect of continentality on the lakes two study areas were chosen. One in Northern Yakutia, the other in Central Yakutia (see figure 2.1). Statistical methods were used in order to identify controlling variables in the datasets and to explore the relationships between surface sediments and waters.

2 Study area

The Republic Yakutia is located in the eastern part of Siberia (between 57° and 75° N and 110° and 160° E) and is with only 0.3 inhabitants per km^2 a sparsely populated region. The populated areas are mostly in the vicinity of major rivers such as Lena or Vilyuy (Kumke et al., 2007).

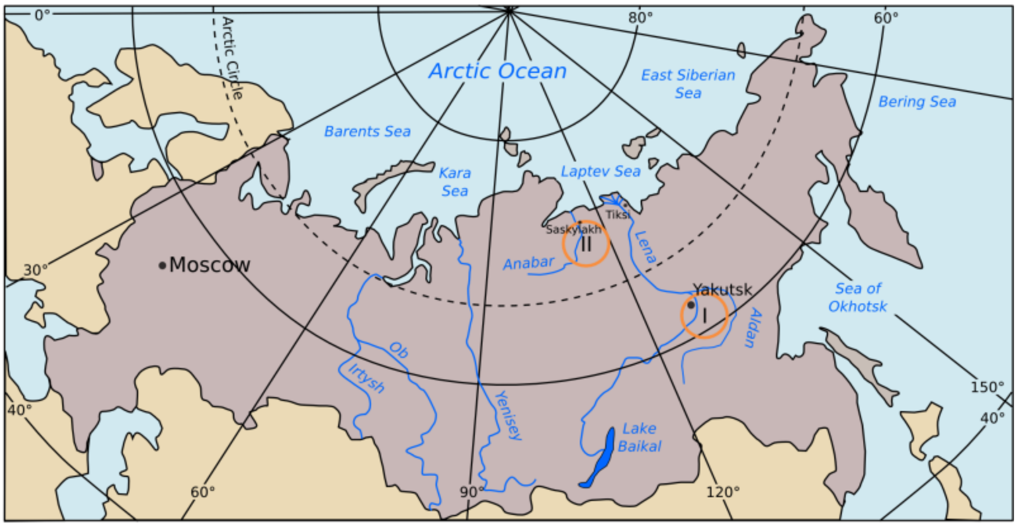

Figure 2.1: Map of Russia with study areas in Central (I) and Northern (II) Yakutia. Map based on The World Factbook, 2008.

With ca. 700.000 lakes in Yakutia (106.000 of those in Central Yakutia), it is safe to say that the majority of the approximately 3 million lakes of Northern Eurasia are Yakutian. Most of those lakes originated by thermokarst processes (see chapter 2.2) and are located in alases. Water depth seldom exceeds 3 m and sizes less than 1 km^2

are characteristic (Koronkevich, 2002; Nazarova et al., 2005).

The central Yakutian study area is located between 62° 07′ N and 132° 14′ E (study area I), the northern Yakutian (study area II) between 73° 23′ N and 115° 45′ E (see figure 2.1). Exact lake locations are listed in table A.1 in the appendix.

2.1 Geology and Geography

Geological setting

Yakutia extends over the Siberian Platform to the west and the Verkhoyansk-Kolyma Orogen to the east (see figure 2.2). The study areas are located on the Siberian Platform, which is made up of two levels: the covering Paleozoic deposits and the basement consisting of various tectonic blocks (Mitrofanov and Taskin, 1994). The single blocks are composed of early Precambrian units and are separated by mobile zones which overlie regional belts of strike-slip faults, thrusts and upthrusts (Mitrofanov and Taskin, 1994). Metamorphic basement rocks are exposed only in the Anabar shield (Rozen, 1995) and the Aldan shield (Koronovsky, 2002). The platform can be divided into several main structures: Aldan shield, Anabar anticline, Tungus syncline, Vilyuy syncline and the Angara-Lena basin.

Quaternary sediments of different genesis cover the Siberian platform. In the northwest glacial sediments are developed, periglacial and lacustrine-alluvial sediments follow to the south (Koronovsky, 2002). Loess-like sediments are widespread in the southern area of the platform (Péwé and Journaux, 1983), they were formed during middle Pleistocene glaciations.

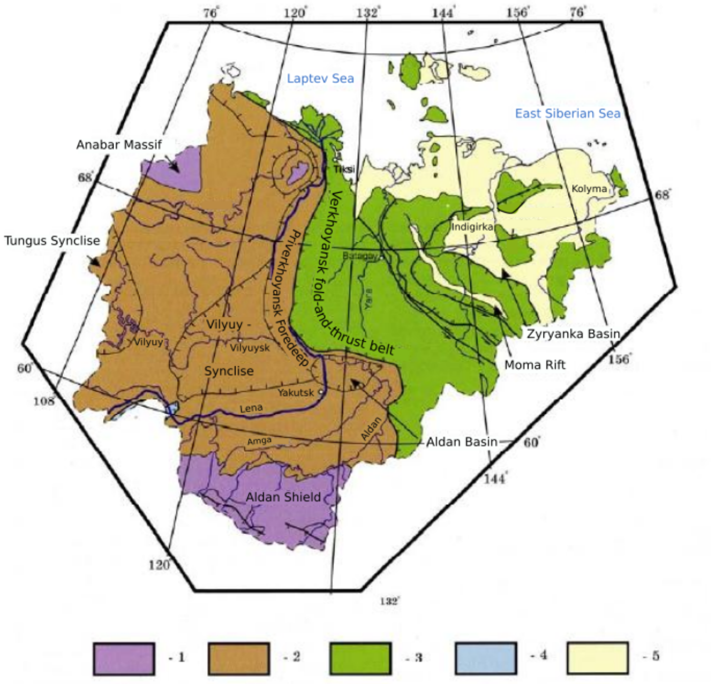

Figure 2.2: Geotectonic map of Yakutia. 1-basement rocks of the Siberian Platform, 2-sedimentary cover of the Siberian Platform, 3-Verkhoyansk-Kolyma orogenic region, 4-fragments of Palaeozoic Baikal-Patom fold-and-thrust belt, 5-main Cenozoic basins. Modified after Popp (2006).

Glaciations during the Last Glacial Maximum (LGM)

The glaciations during the last glacial maximum (LGM, ~20 ka) of eastern and central Siberia were limited to local ice shields in the Verkhoyansk region, the Putorana Mountains and the north-eastern coast of the Taymyr peninsula (Velichko et al., 2002; Galabala, 1997; Svendsen et al., 2004) (see figure 2.3). The Verkhoyansk mountains were extensively glaciated on the western slopes, were ice advanced into the foothills (Shagedanova et al., 2002), whereas the Laptev Sea was never subject to glaciation (Romanovskii and Hubberten, 2001). Velichko and Spasskaya (2002) distinct between two glacial events (alternating with interstadials), the extent of which was restricted by arid conditions.

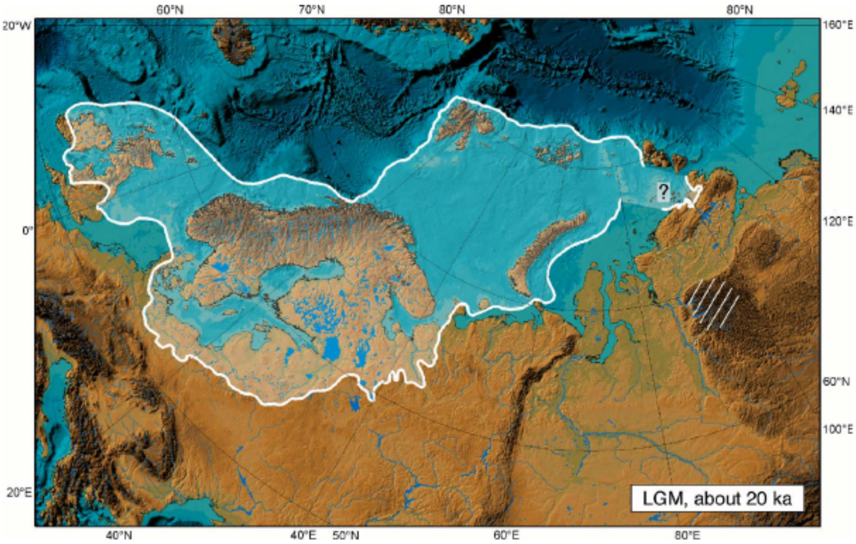

Figure 2.3: Reconstructed extent of northern Eurasian glaciation during the last glacial maximum (~ 20 ka). The glaciation of the north-eastern coast of Taymyr peninsula is thought to be caused by surging from elevated parts of the Barents-Kara Ice Sheet. The local glaciation of the Putorana mountains is indicated by hatched lines (Svendsen et al., 2004).

Soils

Soils of Yakutia are – as they are in the zone of continuous permafrost (see chapter 2.2) – cryosols (Scheffer and Schachtschabel, 1989). The soils of central Yakutia are usually referred to as “dry cryogenic soils” (Ivanova et al., 2006). Main soils of central Yakutia are Pale Calcareous, Pale Solodic and Pale Podzolic soils (Sokolov et al., 2004). Pale Calcareous and Pale Solodic soils develop within alluvial sediments (here the Lena terraces) on loesslike deposits (Péwé and Journaux, 1983). Pale Calcareous soils are predominantly to be found on higher elevation, whereas Pale Solodic soils occupy depressions (e.g. alases). Pale Podzolic Soils develop in sandy or sandy-loamy deposits and are to be found on low plateaus under larch vegeta-

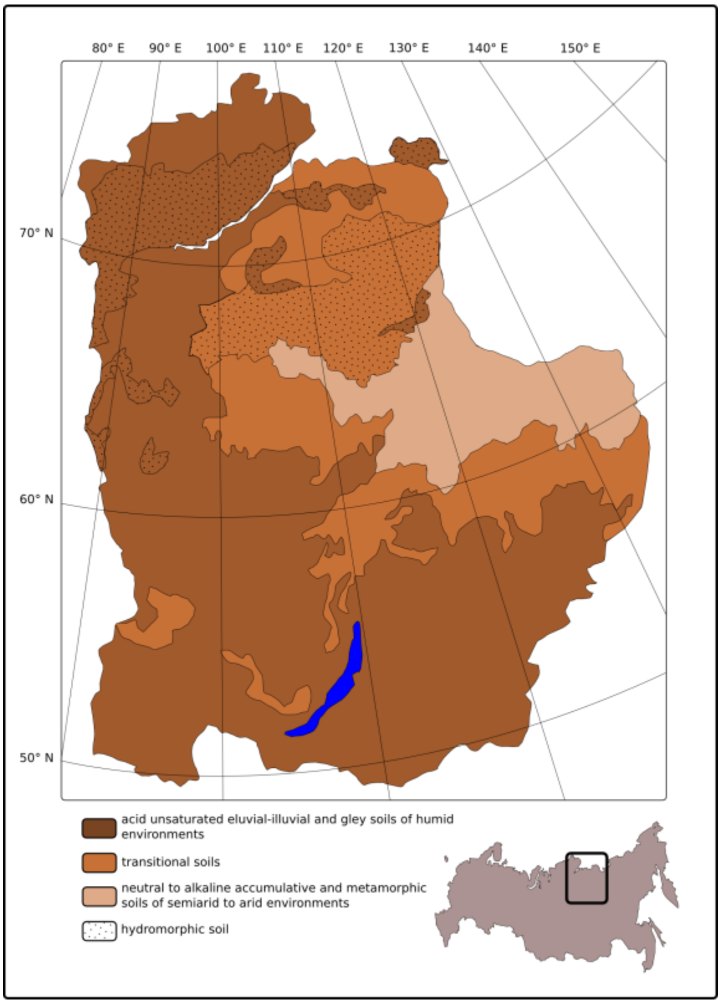

Figure 2.4: Schematic soil map of Central Yakutia, using drainage as classifying attribute. Simplified after Sokolov et al. (2004).

tion in semiarid climates (Sokolov et al., 2004). Peat soils form in northern Yakutia in cryogenic depressions (troughs), and can be divided into Cryic Histosols (thaw depth ~ 20 cm) and Gelic Histosols (thaw depth 1 – 1.5 m).

2.2 Permafrost and thermokarst processes

The majority of Siberia is underlain by continuous permafrost (figure 2.5), which reaches a thickness of 300 m in the southern and 600 m in the northern parts (French, 2007). Large areas (up to 40 % according to Czudek and Demek (1970) and Brouchkov et al. (2004)) of the central Yakutian lowland are affected by thermokarst processes, and alases cover approximately 17 % of the area (Katamura et al., 2006). This attributes to the composition of the Lena terraces, which consist of silty and sandy loam (Péwé and Journaux, 1983) with high ice contents (up to 50 – 80 % according to Brouchkov et al. (2004)). These sediments are known as "ice-complex" (Brouchkov et al., 2004). Due to the relatively dry conditions, only 10 % of the area is currently undergoing thermokarst modifications (French, 2007).

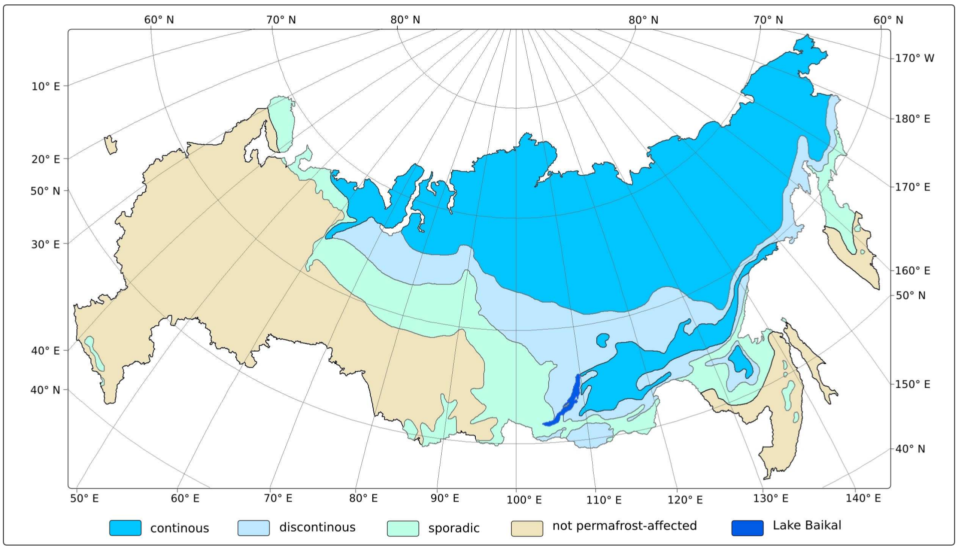

Figure 2.5: Distribution of permafrost in Russia. After Kotlyakov and Khromova (2002).

Central Siberian soils are frozen during most time of the year. The depth to which the soils thaw depends on latitude and soil texture (0.2 m in peat soils to 2.5 m in coarsely textured mineral substrates) (Sokolov et al., 2004). The development of thermokarst can be divided into several stages (Czudek and Demek, 1970; French, 2007):

1. A polygonal system of ice wedges begins to thaw, trough-like depressions above the ice veins form. With further thawing ($> 1-2$ m) the vegetation cover starts to break and the polygon centre form conical mounds, so called "baydjarakhii".
2. As thawing continues baydjarakii collapse and a depression in the centre of the baydjarakh field develops. Connected depressions at this stage are called "dujodas", which are further deepened and widened as soon as they are filled by water, as water has a higher specific heat than the dry ground (fourfold) or ice (twofold) and thereby promotes the development of thermokarst (Washburn, 1979; Weise, 1983).
3. A depression with steep sides and a flat bottom, called an "alas" develops. The term "alas" describes mostly circular depressions, which reach depths between 3 and 40 m and diameters between 0.1 and 15 km (Washburn, 1980). These alases have flat floors which are treeless but overgrown with grass a and in most cases a thaw lake (thermokarst lake).
4. Permafrost aggradates following the disappearance of the lake (by infilling or drainage). Perennial frost mounds or pingos forming in the former alas are called "bulgannyakhii".

Most of the lakes studied during this work are thermokarst lakes.

2.3 Climate

In winter a cold high-pressure system, known as "Siberian High" or "Asian High", builds up over northeast Asia in response to the radiational cooling of the earth surface (Serreze and Barry, 2005; Shagedanova, 2002). Its development is aided by the polar jetstream, which is positioned south of Beringia (Mock et al., 1998). This semipermanent system dominates central Siberia from November to march. As it is thermally induced it is shallow, and is replaced by a trough extending from the Barents Sea south-eastwards at a height of 850 hPa (Weischet and Endlicher, 2000) and (Shagedanova, 2002). It is weakening in late spring (from April onwards) and is more or less dissapeared until May. In June a low-pressure system, with low pressure gradients from north to south develops (Weischet and Endlicher, 2000), which is displaced by the Siberian High in late September.

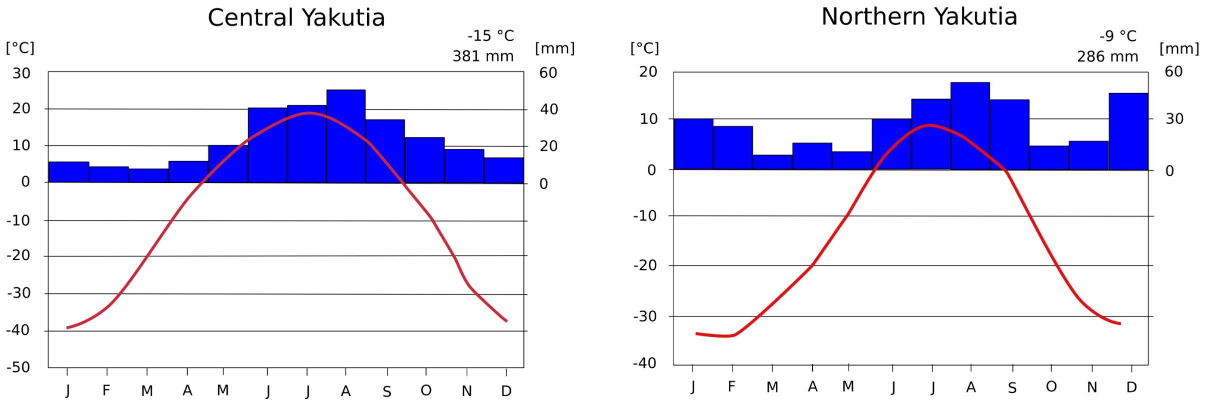

Figure 2.6: Climate of Central and Northern Yakutia. Both graphics are composites of different stations (Yakutsk and Tabaga for Central Yakutia; Saskylakh and Tiksi for Northern Yakutia), due to the sparse Siberian meteorological network, and minor data quality. Data was obtained from the National Climatic Data Center (NCDC).

The climate of the study area is characterised by its high latitude and its continentality: winters are extremely cold (-67.7 °C were recorded Oymyakon on February 1933, -67.8 °C in Verkhoyansk in 1885), summers are hot and dry. Average winter temperatures reach an average of -34 °C in January in Saskylakh and -39 °C in Yakutsk. The difference is due to the continentality of Yaktusk and the proximity of the Laptev Sea to Saskylakh. North of 62° N albedo values are high (up to 80 %) until April (Weischet and Endlicher, 2000), as thaw is just onsetting. Until May temperatures are well below zero north of the polar circle. While summer temperatures in Yaktusk reach an average of 19 °C (1977 – 2008) in July and a maximum of 37 °C, temperatures in Saskylakh reach an average of 12 °C (1977 – 2008) and a maximum of 33 °C in the same time. The temperature amplitude is with ~ 90 K in both places huge.

Because of the high latitudes and the resulting low temperatures, the amount of precipitable water over Yakutia is low (50 mm in January after (Shagedanova, 2002). Wet air masses are blocked by mountain massifs in the south (Altai, Sayan, Pre-Baikalia's and Transbaikalia's) and to the east (Verkhoyansk Range), and the Atlantic Ocean is thousands of kilometers in the west (Antipov et al., 2006). This accounts for the low annual precipitation in central Yakutia (Tabaga: 286 mm p.a.) and northern Yakutia (Tiksi: 381 mm p.a.), approximately 65 % of which falls from May to September (Péwé and Journaux, 1983; NCDC, 2008). The absence of an thick insulating snow cower during winters, due to the distribution of annual precipitation (see figure 2.6), allows the severe cold to penetrate into the ground, promoting permafrost conditions (Popp et al., 2006).

2.4 Vegetation

Northern Yakutia can be divided into three bioms: arctic tundra, typical tundra and southern tundra (Shagedanova, 2002). This classification is based on latitudinal characteristics like continentality, climate and topography. The southern border of the arctic tundra zone is the July 5 °C-isotherm. Mosses and dwarf willows (*Salix polaris* and *S. arctica*) account for the majority of the vegetation of the arctic tundra. However bare ground is abundant (Antipov et al., 2006; Shagedanova and Kuznetov, 2002). Southwards follows the typical tundra with a continuous vegetation cover. It is made up of an increasing number of shrubs (*Salix, Dryas, Cassiope*) and sedges (*Carex ensifolia ssp. arctisibirica*). Further south (beyond the July 10 °C-isotherm), in the southern tundra, single trees (mostly *Larix*) occur, and in the shelter of bushes (*Betula, Salix and Alnus*) a rich grass, shrub (*Betula exiles*) and dwarf-shrub vegetation develops (Shagedanova and Kuznetov, 2002).

The southern study area is characterised by taiga vegetation, which is dominated by coniferous trees. As Larch (*Larix gemlinii*) is very undemanding to climate, it is by far the most frequent tree in central Yakutia (Tishkov, 2002), followed by pine (*Pinus sylvestris*). Common shrubs are birch (*Betula exilis*) and willows (*Salix pyrolifolia*). As forest floors are widespread covered by lingonberry (*Vaccinium vitisidaea*), *Larix-Vaccinium* xerophilous forests account for 75 % of all forested land in central Yakutia (Tishkov, 2002). These forests cover an area of approximately 3.5 x 10^6 km^2 (Tomoaki et al., 2007). As mentioned before the climate is extremely continental, and during dry and hot summers forest fires are common. In the years 1988 – 1994 an average of 3.61 x 10^3 km^2 of forest was burned almost annually in Yakutia (Tomoaki et al., 2007). These forest fires may promote thermokarst processes (French, 2007). Characteristic of Yakutian forests are alases, which floors are mostly grass-covered (*Elytrigia repens* and *Calamagrostis langsdorfii*) (Tishkov, 2002; Tomoaki et al., 2007).

3 Methods

3.1 Field work

During the summers 2005 and 2007 65 lakes were sampled in Northern and Central Yakutia (see figure 2.1). The lakes were accessed with an inflatable boat. While crossing the lake the water depth was measured using an echolot. As soon as the deepest part was reached – usually the centre of the lake –, several limnological parameters were assessed on-site. Conductivity, redox potential, pH and temperature of the surface water were measured using a multi-parameter field meter (WTW Multi 350i). The water transparency was determined using a Secchi disc. The measurements were followed by sampling surface sediment (upper ~ 2 cm) and surface water (~ 30 cm depth).

3.2 Laboratory methods

Laboratory work was performed at the Alfred-Wegener-Institute for Polar and Marine Research in Potsdam, Germany. The sediment samples were prepared for several sedimentological and geochemical analyses. The sample preparation is a vital part for further analysis, as any imprecision propagates and may lead to erroneous results.

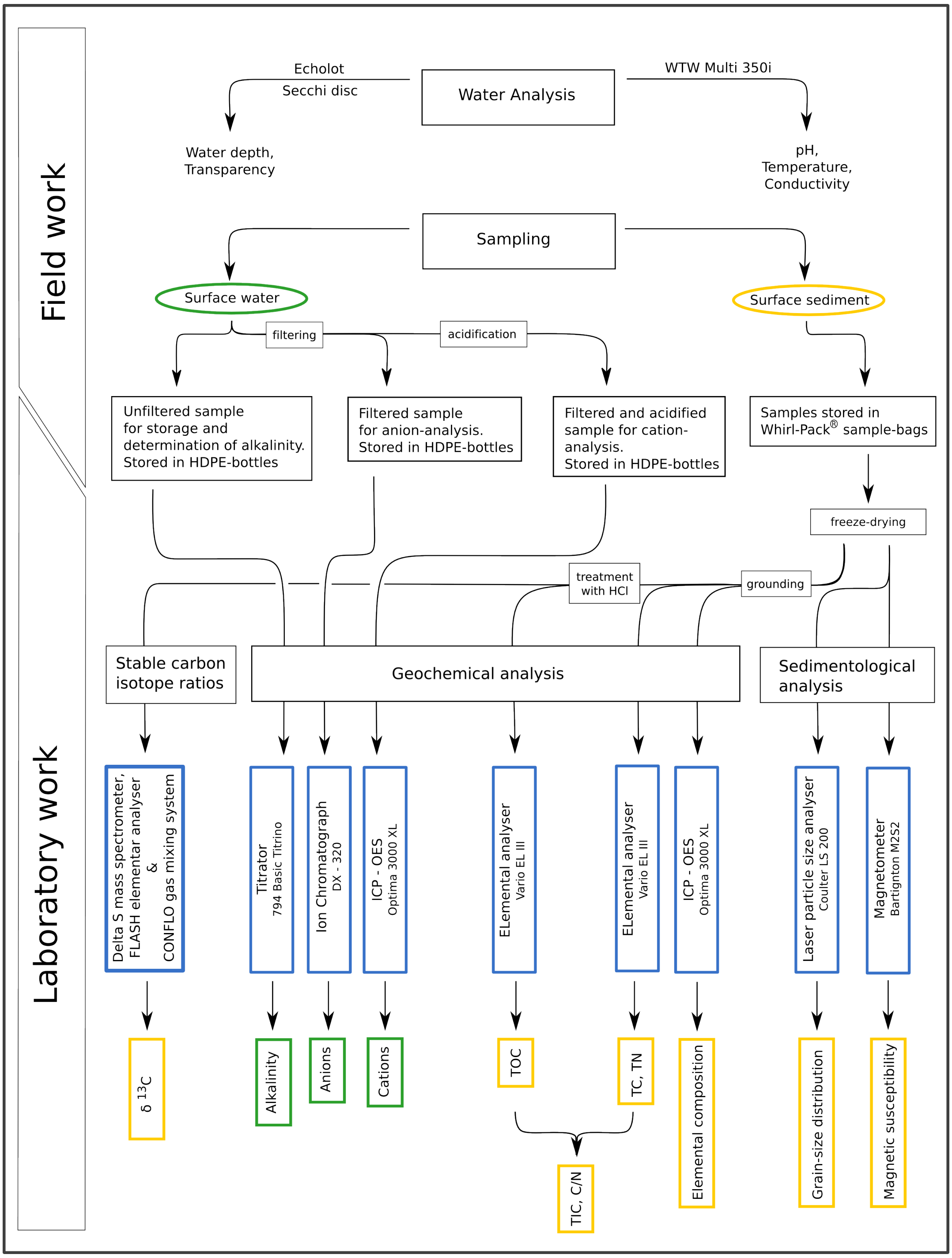

Figure 3.1: Schematic overview on field work, sampling and following laboratory methods.

3.2.1 Hydrochemistry

Water samples were stored in HDPE bottles and kept cool until laboratory analyses could be conducted. Samples for anion and cation analysis were filtered trough cellulose acetate filters (pore size 0.45 μm); the cation sample was furthermore acidified with nitric acid (HNO_3, 65 % sup.). Hydrochemical analyses of Central Yakutian waters were made by Sebastian Wetterich (Wetterich et al., 2008).

Alkalinity

The determination of the alkalinity (or acid neutralising capacity) of a sample is based on it's definition, that is, the amount of an acid that is necessary to bring its reaction to a specified endpoint (here pH = 4.3) (Chester, 1990). The carbonate alkalinity is measured by titrating hydrochloric acid into the sample (0.01 mol), thereby converting HCO_3^- ions to H_2CO_3 until no HCO_3^- is left in the water at a pH of 4.3 (see 3.2). As it is assumed that HCO_3^- is the predominant acid in lake waters, the carbonate alkalinity is treated as equal to total alkalinity (Hütter, 1990; Drever, 1997).

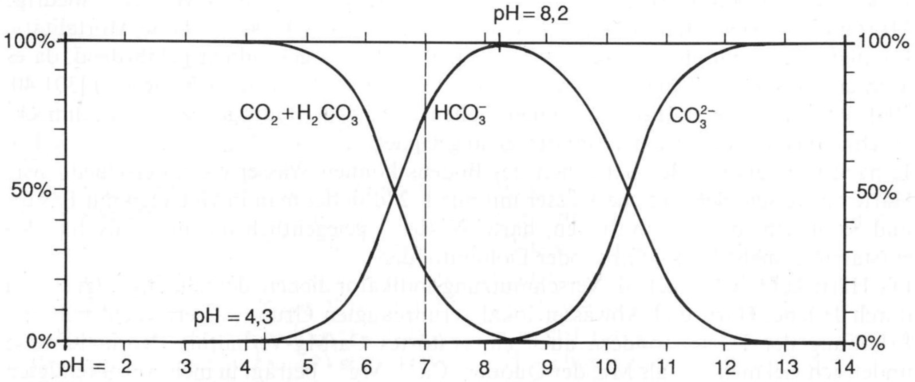

Figure 3.2: The pH dependent equilibrium between bicarbonate and carbonate in fresh waters (Hütter, 1990).

Measurements were carried out with an automated digital titrator (Metrohm, 794 Basic Titrino). This system applies a potentiometric titration and determines the equivalence endpoint where the acid reacted completely with the analyte (pH 4.3). After calibrating the pH-electrode with two buffer pH-solutions two standards with known HCO_3^- concentrations (500 and 1000 μmol/l) are measured to ensure a working set-up. Sample volumes of 2 ml were then titrated with 0.01 mol HCl in μl steps, until the before defined endpoint was reached. The used titre volume can be calculated into concentration of HCO_3^-.

Anions

The concentration of dissolved anions (Br^-, Cl^-, F^-, NO_3^-, PO_4^{3-} and SO_4^{2-}) in the water samples was determined using an ion chromatograph (Dionex DX-320). This system is a High Performance Liquid Chromatography (HPLC) system. Ion chromatography is basically a physical-chemical method to separate ions according to their exchange processes between a mobile and a stationary phase. 25 μl sample is injected into the eluent which is flowing continuously through the system. To prevent clogging of the separation column the eluent is channelled through a guard column beforehand. This and the following separation column make up the stationary phase, consisting of an inert material, which is coated with a film of sulphonic acid, which in turn is coated with aminated latex. Ions contained in the sample are separated according to exchange processes taking place in the stationary phase. These processes can be described after Weiß (2001) as:

$$\mathrm{Latex}^+\mathrm{HCO_3}^- + \mathrm{Anion}^- = \mathrm{Latex}^+\mathrm{Anion}^- + \mathrm{HCO_3}^- \tag{3.1}$$

By moving through the stationary phase at different speeds, it is possible to identify discrete bands or zones (see figure 3.3). To enable ion detection by conductivity

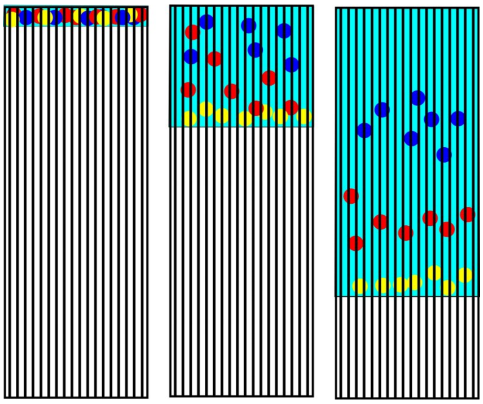

Figure 3.3: Simplified scheme of separation taking place as the eluent passes the stationary phase. Exchange processes are described in equation 3.1.

the eluent is converted into H_2O while analysed ions are converted into their corresponding acids in a suppressor. The resulting differences in conductivity can be detected. Ions are identified by their retention time, which is detected by a conductometric detector analysing the position of the anion peaks on the time axis of the chromatogram. Anion concentrations were derived by calculating the area under the peak using the software PEAKNET (Dionex).

To ensure reproducible results standards of known anion concentration were measured in regular intervals and a blank was inserted to distinguish anion concentrations from background noise.

Cations

The concentration of following dissolved cations were analysed with an ICP-OES: the minor elements Al, Ba, Fe, Mn, Sr (in μg/l) and the major elements Ca, K, Mg, Na, P, Si (mg/l). The methodology of optical emission spectrometry is described in the paragraph "inorganic geochemistry" in chapter 3.2.2.3.

3.2.2 Sedimentological analyses

Subsamples for further analyses were taken from the original sample. This has to be done with care, as the subsample has to be representative for the whole sample. The obtained samples then were freeze-dried (Zirbus Sublimator). Samples for geochemical analyses were finely grounded (Fritsch planetary mill).

3.2.2.1 Grain size distribution

The grain-size distribution was determined using a laser diffraction particle size analyser (Coulter LS 200). In order to remove organic particles from the samples, they were treated with concentrated hydrogen peroxide (H_2O_2) and placed on a platform shaker (innova 2300) for maximal five weeks. The sample then was washed using centrifuges of different sizes (Cryofuge 8500 and Multifuge 3s) and subsequently dried in a cabinet drier. 0.1 to 5.3 g of the dried and organic-free sediment was dispersed in approximately 0.75 l ammonia solution (NH_4 0.0001 %). 0.1 to 2.5 g Petranatriumdiphosphat ($Na_4O_7P_2 \cdot 10\,H_2O$) were added to enhance the dispersion of clay concretions. The suspension then was mixed in an overhead shaker (Gerhardt Laboshake RS 12) for at least 12 hours. Before measuring the sample it was split into eight homogeneous subsamples using a sample splitter (Retsch DR 100) in order to attain a concentration of 8 – 12 %, as the laser unit requires a certain transparency. If the concentration was still to high, 4 of the 8 subsamples were splitted once more. Each sample was measured at least two times, if possible three times or more. The mean of at least two samples was then used to calculate the grain-size distribution using the software Sedivision 2.0 (Beguma). In order to describe grain-size distributions mean, median, kurtosis and skewness in ϕ-grades (Krumbein, 1964) were calculated. The grain-size classes and relating ϕ-grades are displayed in table 3.1.

3.2.2.2 Magnetic susceptibility

The magnetic properties of the samples were measured in polystyrene sample containers (12.5 ml) using a magnetometer (Bartington Instruments Model MS2B). In this

Table 3.1: Grain-size fractions after Wentworth (1922) (as citet in McManus (1988)) and ϕ-grades after Krumbein (1964).

Grain-size fraction	Gravel	Sand	Silt	Clay
$[mm]$	> 2 mm	2 – 0.0625	0.0625 – 0.002	< 0.002
ϕ	-5 – 1	-1 – 4	4 – 8	> 8

system a low intensity (~ 80 ampere per meter) alternating magnetic field is generated. The remaining magnetisation of the sample is measured and transformed into values of mass-dependent magnetic susceptibility defined as

$$\chi = \frac{\kappa}{\rho} \tag{3.2}$$

which is expressed in SI units ($10^{-8}\,\mathrm{kg}^{-1}$) (Dearing, 1999b,a). As the system is calibrated to sample weights of 10 g, measured values had to be corrected to the calibration mass by:

$$\chi = \frac{\text{mean of measured value } [SI] \cdot \text{calibration weight}[10g]}{\text{sample weight } [g]} \tag{3.3}$$

Each sample was measured at least twice.

3.2.2.3 Geochemistry

Organic geochemistry

The composition of sedimentary organic matter depends on environmental factors such as temperature, precipitation and sedimentary characteristics. Hence it is possible to draw several conclusions from the analysis of organic matter, e.g. about sources of organic carbon (C/N) or bioproductivity (TOC, TN, TC) (Meyers and Lallier-Verges, 1999; Tyson, 1995).

The concentrations of total inorganic carbon (TIC), total organic carbon (TOC) and total nitrogen (TN) were measured using a Vario EL III (Elementar) elemental analyser. The samples had to be finely grounded and, for the measurement of TOC, made carbonate-free. To dissolve carbonates ~4 % hydrochloric acid (HCl) were added to the sample, which was then heated up to 97 °C for three hours. The carbonate-free sample was then washed with water and dried in a cabinet drier. 5 ± 0.2 mg of finely grounded sample were weighed into tin capsules. Each sample was measured twice, in order to control the measurements by standard deviation. In every measurement cycle samples were appended to various calibration and control standards. Control standards were inserted each twenty samples to assess overall deviation of the system. The tin capsules were inserted in an automatic sampler, which could hold up to 79 samples at once. Additional samples could be inserted in the course of the measurements. The measurement can be divided into three steps: digestion of the sample and removal of foreign gases (e.g. volatile halogens), separation of components to be measured, and detection (*CHNOS Elementaranalysator vario EL III - Bedienungsanleitung*, 2005). The combustion of the sample takes place in an oxygen-rich environment at 1150 °C. After removing foreign gases helium carries the gas mixture through adsorption columns, where the components (here C, N, and S) are separated. The sulphur content was not measured. While the gas mixtures (e.g. He/CO_2) are flowing through a measurement cell, helium is steadily flowing through a reference measuring cell. Differences in electrical properties are equivalent to the elemental concentration.

Detection limits were 0.1 % for carbon and 0.05 % for nitrogen. The carbon to nitrogen ratio (C/N) was calculated by division of TOC by TN, the concentration of total inorganic carbon (TIC) by the difference of TC to TOC.

Inorganic geochemistry

Different elemental ratios can be used to trace changes in the geochemical composition of a lake, triggered for example by human impact. In contrast to pollen that carries a regional signal element ratios reflect the local area (catchment area) through the input of run-off water.

The concentration of major (Al, Na, Fe, Mn, Mg, Ca, K, P, Ti, Ba and Li) and trace elements (Co, Cr, Cu, Ni, Pb, Sr, V, Zn and Zr) was determined using an Inductively Coupled Plasma - Optical Emission Spectrometer (ICP-OES) by Perkin Elmer (Perkin Elmer Optima 3000XL). This method requires samples to be present as stable solutions. As the measurement is only as accurate as the dissolution is reliable (Walsh et al., 1997), a complete digestion was achieved by leaching/treating the samples with nitric, hydrofluoric and perchloric acids in a pressure digestion system (PICO-TRACE Pressure Digestion System DAS). This procedure consists of five steps: pressure digestion, first closed then open fuming off of excess acids and a final digestion. First 3 ml nitric acid (HNO_3, 65 % sup.), 4ml hydrofluoric acid (HF, 40 % sup.) and 3 ml perchloric acid ($HClO_4$, 70 % sup.) were added to 100 mg of finely grounded sample in PTFE-crucibles. After at least 4 hours of cold reaction the crucibles were inserted in a heating block, sealed with PTFE-lids and a pressure plate. This setup was then heated to 170 °C with a rate of 57 °C/h and kept at that temperature for 22 hours. While the system is under pressure solid materials are being decomposed. During the following evaporation phase the sample material is transformed into soluble salts. The system then has to cool down to room-temperature before continuing with closed fuming off excess acids. An PFTE evaporation plate was attached to the crucibles and connected to HDPE-bottles filled with sodium hydroxide solution (NaOH ~ 4 %) which is used as solvent and neutraliser for acid vapours. The system then was heated to 180 °C with a rate of 135 °C/h. To prevent samples to dry up this process was terminated after 4.5 hours. This process was followed by open fuming off at 135 °C. The crucibles were kept on the heating block until the samples reached a gel-like state. In the next step the samples were solubized with 1 ml nitric acid and 5 ml pure water, before placing them in the heating block and starting the final pressure digestion at 150 °C. The soluted samples were then transferred to HDPE-bottles and diluted to 1:500 by adding pure water. In one cycle, consisting of boiling, closed and open fuming off, thirty-two samples (including two standards and two blanks) could be prepared.

An ICP-OES consists basically of a source unit (ICP torch), a spectrometer and a computer. The "Inductively Coupled Plasma" or ICP in the source unit is generated by adding a strong magnetic field using an induction coil (hence inductively coupled) (Boss and Fredeen, 1989; Heinrichs and Herrmann, 1990). The sample is added to the system and excitated in the plasma. While being excitated the atoms and ions emit light, which is measured by a spectrometer. As each element has characteristic spectral attributes, the concentration of each element can be determined by measuring the intensity of the selected spectral lines (Walsh et al., 1997).

The system was calibrated using solutions with known elemental concentrations. Different solution were used for major and trace elements. After calibration the system standards and blanks were measured. The standard showing the least deviation was measured each 10 samples to assess overall deviation throughout the measurement cycle. Major elements were measured in a 1:1000 dilution, trace elements in a 1:500 dilution. If measured element concentrations were out of the calibrated range, the sample was diluted further.

3.2.3 Stable carbon isotope ratios

Natural carbon consists of two stable isotopes, ^{12}C and ^{13}C with abundances of 98.89 % and 1.11 %, respectively. Those isotopes are being fractionated during incorporation (Attendorn and Bowen, 1997; Clark and Fritz, 1997). Carbon isotopes in organic matter can be used to reconstruct productivity rates and the availability of nutrients in surface waters (Meyers and Teranes, 2001), and distinguish between organic matter derived from terrestrial plants (C4 plants) and from open-water sources (C3 algea) (O'Leary, 1981; Hassan et al., 1997).

The carbon isotope composition of the surface sediment samples was determined using a setup consisting of an elementar analyser (Flash EA 1112 Series, Thermo Finnigan), a gas mixing system (CONFLO III) and a MAT Delta-S mass spectrometer (Thermo Finnigan). A calculated net weight – depending on TOC content – of each sample was weighed into tin capsules, which was then released into the system by an autosampler system (AS200). Before measuring the sample a standard gas (CO_2) with known isotopic composition was measured in the mass spectrometer in order to determine the isotopic composition of the sample. Samples are combusted in the elemental analyser at 950 °C in an oxygen-enriched atmosphere, thereby transferring organic matter into CO_2, while other gases (byproducts) are reduced. Upon entering the mass spectrometer, the sample gas is ionised. The ions then are accelerated in an electrostatic field and pass a magnetic analyser. The mass-dependent deviation is recorded and transformed into mass specific peaks, which in turn are recalculated into isotopic contents and their ratio. Standard samples were measured for calibrating purposes. Some samples were measured twice in order to guarantee quality and reproducibility of the data. As only carbonate-free samples were used it is ensured that the measured isotope composition is that of the organic matter. Overall standard deviation was less than 0.15 ‰. The isotope ratios ($\delta^{13}C$) are expressed as ratios of C^{13} to C^{12} (C^{13}/C^{12}) and given delta in per mill (δ, ‰) with reference to the V-PDB international standard (Pee Dee Belemnite Formation in South Carolina, USA as defined by the IAEA in Vienna) (Craig, 1997):

$$\delta^{13}\text{C ‰} = \frac{R_{\text{sample}} - R_{\text{standard}}}{R_{\text{standard}}} \cdot 1000_{\text{V-PDB}} \tag{3.4}$$

3.3 Multivariate statistics

In order to display the dataset in a diagram ordination techniques were used. Patterns in the datasets were revealed by the use of indirect ordination techniques, relationships between surface sediments (treated as species) and waters (treated as environmental data) by the use of direct ordination techniques. In order to achieve a comparable and deskewed dataset all variables (except pH values) had to be log transformed ($x' = log\,(x+1)$) (Leyer and Wesche, 2007).

A detrended correspondence analysis (DCA) was computed so as to verify a linear distribution of the dataset. Detrending was accomplished by dividing the first axis into segments and reducing values by their joint mean, thereby downweighting high values stronger than low ones. Equidistant values along the first axis where achieved by non-linear rescaling. The resulting gradient length was used to decide whether to use linear or unimodal ordination techniques. Gradient lengths, expressed in multiples of standard deviation (SD), shorter than 3.0 SD suggest a linearly distributed dataset (Lepš and Šmilauer, 1999).

As a linear distribution was detected a principal component analysis (PCA) was performed. The goal of this analysis is to explore the variation in the physical and chemical variables of the studied lakes, to identify variables that explain the dataset best and to simplify the dataset by excluding redundant information. This is achieved by calculating the residual sum of squares. The variable featuring the least residual sum of squares is the one explaining the dataset best. Following this, a theoretical variable is built explaining the dataset still better. This variable represents most of the variance and forms the first axis or principal component (principal component I). The fit of that axis is expressed by its eigenvalue. The position of the variables (displayed as vectors) in relation to the principal component indicates how well they are explained by it. The length of the vectors is comparable as the dataset has been log transformed (ter Braak, 1987; Leyer and Wesche, 2007). Physical and chemical properties of surface sediments were used for the first PCA, physical parameters of the studied lakes and hydrochemical data for the second PCA. Each variable was treated as species, so 27 species could be included in the first and 20 species in the second analysis. Both analysis were carried out for 65 study sites. The variables were centred and standardised, resulting in columns with averages equal to zero (centrered) and rows with sums of squares equal to one (standardisation).

In order to explore relationships between surface sediments and waters a redundancy analysis (RDA) was carried out. A RDA is a canonical ordination technique, that combines indirect gradient analysis (here a PCA) with regressions on environmental variables. Thus, relations between species and environmental variables can be explored. To determine which environmental variable explains the species data best, residual sums of squares are calculated. The environmental variable giving the smallest residual sum of squares is the one explaining the species data the best. The theoretical variable built in this analysis is, in contrast to that built in a PCA, dependent on environmental variables (ter Braak, 1987; Leyer and Wesche, 2007). Furthermore a partial RDA was computed. Therefore statistical significant variables were identified by using a Monte-Carlo permutation test. Variables with probabilities $p > 0.05$ were excluded from the analysis.

All ordinations were accomplished using the software CANOCO 4.5 (ter Braak and Šmilauer, 2002), diagrams were plotted using the software CANODRAW 4.0 (Šmilauer, 2002).

4 Results

The results from field and laboratory analyses are summarised in the following chapter. It's structure differs from the preceding in order to ensure readability. Hydrochemical parameters are displayed in the first part, and are followed by sedimentological data. A Principal component analysis (PCA) is applied for each dataset. The results of the Redundancy analyses (RDA) are displayed at the end of the chapter.

4.1 Limnological parameters

The majority of the studied lakes were shallow (< 3 m) and did not exceed water depth greater then 10 m. Water depths range between 0.15 and 5.2 m in Central Yakutia and 0.9 and 8 m in Northern Yakutia. The depth of the presumably deepest Lake (07-SA-08) wasn't measured but estimated, and should therefore not be taken into account for any statistical analysis. Sediment samples were taken at maximum depths. Lake areas range between 2000 x 2000 m and 20 x 30 m. The largest sampled lake is located in the northern study area. When compared to Secchi depths of Northern Yakutian lakes (0.5 – 4.5 m), Central Yakutian lakes have low depths (0.15 – 2 m). The pH ranges between 4.85 and 10.2, with Northern Yakutian lakes being slightly acidic to neutral (pH 4.85 to 7.55) and Central Yakutian lakes being neutral to slightly alkaline (pH 6.6 to 10.2). The electric conductivity of sampled lakes ranges between 0.02 and 5.71 mS/cm. Waters from central Yakutian lakes have considerable higher conductivities (0.1 – 5.71 mS/cm) than those from from Northern Yakutia (0.02 – 0.28 mS cm^{-1}).

Hydrochemistry

Concentrations of cations (Ca^{2+}, K^+, Mg^{2+}, Na^+ and Si^{4+}) and anions (Cl^-, SO_4^{2-}, NO_3^- and HCO_3^-) contained in the water samples were measured in μg/l and mg/l, respectively. Ion concentrations detected by hydrochemical analysis (see chapter 3.2.1) are displayed in ternary diagrams (figure 4.1), and were summarised in table A.2.

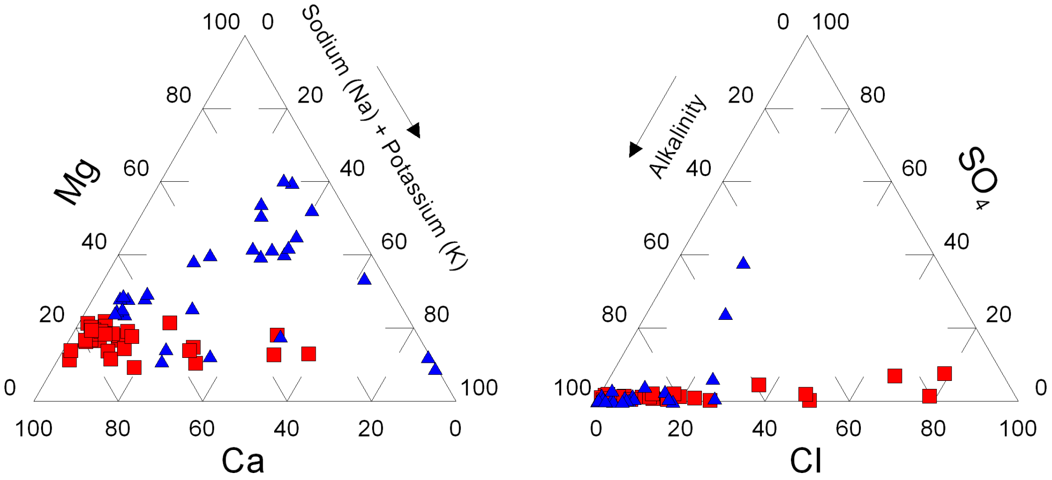

Figure 4.1: Hydrochemistry of sampled waters. Water samples from Central Yakutia are displayed as blue triangles, samples from Northern Yakutia as red squares.

As it is only possible to display three parameters in one diagram, results are divided into two diagrams showing equivalent concentrations of cations (Na^+, K^+, Ca^{2+}, Mg^{2+}) and anions (Cl^-, HCO_3^-, SO_4^{2-}). In these diagrams percental shares of the single ions (or ion groups) in the anion or cation composition of the waters are displayed in one point. Detected mass concentrations were transformed into equivalent concentrations by using the following formula (Hölting and Coldewey, 2005):

$$\text{equivalent concentration } [mol/l] = \frac{\text{mass concentration } [g/l]}{\text{equivalent mass } [g/mol]} \tag{4.1}$$

or

$$c(\frac{1}{z}X) = \frac{\beta(X)}{\frac{1}{z}M(X)} \tag{4.2}$$

In order to asses the data quality an ion balance was calculated by using the following formula (Hölting and Coldewey, 2005):

$$\text{ion balance} = \frac{\sum c(\frac{1}{z}\,\text{cations}) - \sum c(\frac{1}{z}\,\text{anions})}{0,5 \cdot (\sum c(\frac{1}{z}\,\text{anions}) + \sum c(\frac{1}{z}\,\text{cations}))} \tag{4.3}$$

The ion balance should be even, but deviations are common due to various factors, e.g. poor analytical precision, low ion concentrations or long storage of the samples. Deviations are acceptable in certain ranges, but should not exceed 10 % (Hölting and Coldewey, 2005). Errors of ion balances average at 12.4 % for all sampled lakes, at 10.9 % for Northern Yakutian and at 14.2 % for Central Yakutian lakes. Highest deviations coincide ion concentrations that were exceptionally low, sometimes just above detection limit. Detected ion concentrations and ion balances are displayed in table A.2 in the appendix. Ion concentrations show similar cation compositions for lake waters from Northern Yakutia, 88.6 % of which are dominated (>50 %) by Mg^{2+} and Ca^{2+}. Mg^{2+} concentrations range between 17.5 and 44.4 %, Ca^{2+} between 12.4 and 68.7 %. Cation compositions of Central Yakutian lakes have considerably higher concentrations of Na^{+} and characterised by concentrations >85 %. Anion compositions are dominated by HCO_3^- in both study areas, with concentrations varying between 9.17 and 99.4 %. 89.2 % of the studied waters with HCO_3^- concentrations higher than 50 %. According to these high HCO_3^- concentrations the anions Cl^- occurs in low concentrations. Central Yakutian lakes have Cl^- concentrations between 0.3 and 24.3 %.

PCA on limnological parameters

Hydrochemical data, along with lake parameters as size, depth, etc., were treated as environmental variables. The PCA biplot of that data (see figure 4.2) explains ~ 62 % of the variability within the dataset with eigenvalues of $\lambda 1 = 0.499$ and $\lambda 2 = 0.122$, respectively. The first axis accounts for 50 %, the second for 12 %. The third and fourth axes together account for 15 % ($\lambda 3 = 0.079$ and $\lambda 4 = 0.075$). In the following, third and fourth axes are not plotted as their contribution explaining the variance of the dataset is rather small. As above, variables containing values below detection limit were replaced by the value of the detection limit if they occurred below that limit in less than half of the sites, or were below the detection limit in one region (e.g. Northern Yakutia) only. Variables which occurred below their detection limit in more than half of the studied sites were eliminated from the dataset. Three variables (Al, nitrate and phosphate) met that criterion and were removed. Therefore 21 environmental variables and 65 samples were used in this analysis. Variables included in this PCA and their correlation factors are listed in the appendix in table A.6. The eigenvalues and the cumulative variance of the four first axes (or components) are listed in table 4.1.

Table 4.1: Results of PCA performed on 35 water samples and 25 environmental variables.

Axis	Eigenvalue λ	Cumulative variance [%]	Individual axes contribution [%]
1	0.499	49.9	49.9
2	0.122	62.1	12.2
3	0.079	70	7.9
4	0.075	77.5	7.5

The variables pH, conductivity, elevation, Ba, Ca, K, Mg, Na, Sr, fluoride, chloride, sulphate and HCO_3^- are positively correlated to the first axis ($r > 0.5$). These variables are closely related and determine the alkalinity and salinity of the lake waters. The second and third (not shown) axes are associated with water depth, Secchi depth, approximate size and Fe. Furthermore a separation between northern and central Yakutian lakes is clearly visible.

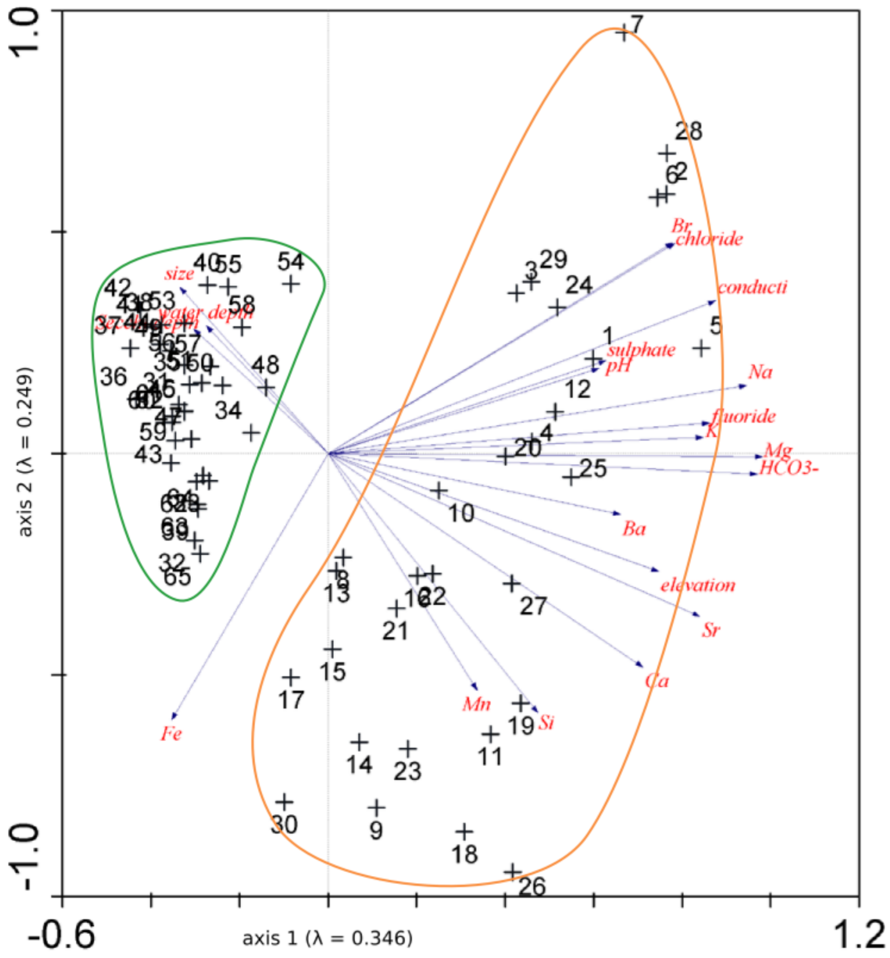

Figure 4.2: PCA of 25 measured environmental variables from 35 sampled lake waters. Northern Yakutian lakes are encompassed by a green envelope, lakes from Central Yakutia by a yellow one.

4.2 Surface sediments

Grain-size analysis

The grain-size distributions of surface sediment samples from 65 lakes were analysed in the course of this work. Gravel was absent in all samples, grain-size classes after Wentworth consist of clay, silt and sand. Clay contents range from 1 to 40 vol.-%, silt contents range from 8 % to 76 vol.-% and sand contents range from 0 to 87 vol.-%. Silt is dominating (>50 vol.-%) 81,5 % of the samples, 12.3 % are dominated by sand. The samples are subdivided into lithological classes using the classification of Shephard (1954). By far the most frequent classes are clayey silt and sandy silt. Other detected classes are silt, silty sand, sand and sand-silt-clay (see figure 4.3). The descriptive parameters mean, skewness and kurtosis were calculated after a method described by McManus (1988), in which each grain-size fraction is taken into account. Results are displayed in table A.3 in the appendix.

Magnetic susceptibility

The Magnetic susceptibility (Xlf) of the surface sediment samples ranges between 3 and 147 Si $10^{-}8$, with an average of 38 Si $10^{-}8$ and a standard deviation of 29 Si $10^{-}8$. The susceptibilities of Central Yakutian surface sediments are generally larger (median = 101 SI) than in Northern Yakutian sediments (median = 81 SI). The results are summarised in table A.3 in the appendix.

Organic geochemistry

The measured concentrations of total carbon (TC), total organic carbon (TOC) and total nitrogen (TN) as well as total inorganic carbon (TIC) and C/N ratios are given in table A.3 in the appendix. TC is present with concentrations of 0.25 to a maximum of 43.8 %. The distribution of TOC follows that of TC and shows a minimum

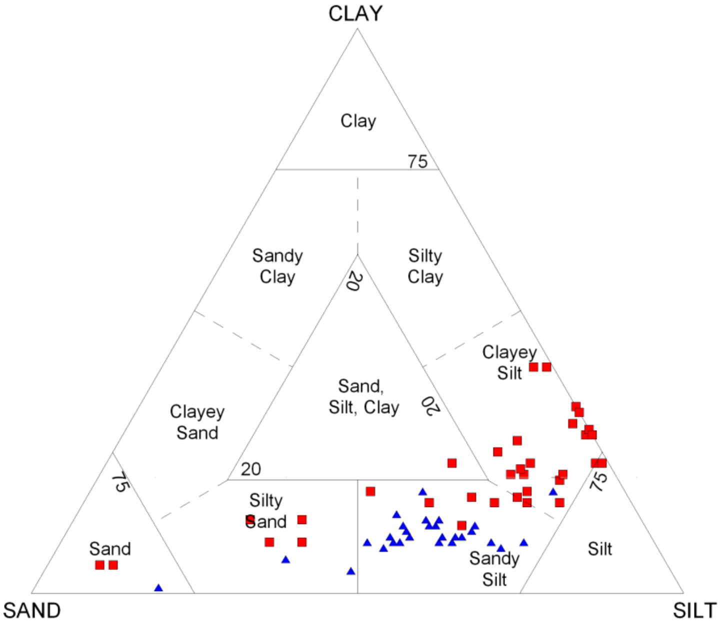

Figure 4.3: Ternary Diagram displaying lithological classes after Shephard (1954). Surface sediments from Central Yakutia are displayed as blue triangles, samples from Northern Yakutia as red squares.

of 0.23 % and a maximum at 47.3 %. The contents of TIC are with 0 to 2.09 % relatively low. TIC of 20 lakes shows negative values. TN is contained at concentrations which range between a minimum of 0.05 % and a maximum of 3.87 %. One sample (07-SA-19) had a TN concentration below detection limit (0.05 %). Calculated coefficients of determination (R^2) show that strong correlations between TOC and TC (0.97) and TOC and TN (0.84) exist. TIC did not correlate with any of the above mentioned parameters. The contents of nitrogen (TN) and organic carbon (TOC) were highest in Central Yakutian sediments. C/N ratios follow that spatial distribution, and range overall between 6.57 and 22.4.

Inorganic geochemistry

The concentration of Lithium (Li) was below detection limit in all sediment samples. Lead (Pb) was only contained in five samples in concentrations high enough for the detection to be reliable. Furthermore concentrations were below detection limit in four samples for chromium (Cr), eight samples for copper (Cu), four for nickel (Ni), two for vanadium (V) and two for zirconium (Zr). Aluminium (Al) concentrations range between a minimum of 0.94 and a maximum of 14.4 %. Concentrations are generally higher in the northern study area, while variations are higher in the central study area. Calcium (Ca) concentrations range from 0.66 to 7.09 %, with highest values in Central Yakutian sediments. Iron (Fe) concentrations range between 0.51 and 15.3 %. Fe is the major element which the highest concentrations in the studied surface sediments, while a trend towards lower values in the Central part is noticeable. Potassium (K) concentration range from 0.14 to 3.28 %. While the minimum occurs in Central Yakutia and the maximum in Northern Yakutia, a spatial pattern could be detected. Concentrations of magnesium (Mg) in the lake sediments range from 0.18 to 12 %. Values are considerably higher in the studied lakes of northern Yakutia. Manganese (Mn) concentrations range from 0.02 to 0.26 %, it is generally contained in similar ranges in the northern and the central part of Yakutia. Sodium (Na) concentrations range from 0.15 to 6.28 %. While the highest values are to be found in a lake located in Central Yakutia, variations between the northern and the southern study area are only small. Phosphorus (P) was contained in concentrations between 0.04 and 0.65 ppm. Lowest concentrations where detected in the northern area. Titanium (Ti) concentrations range between 0.03 and 0.83 ppm, with highest values in the central part of Yakutia. Barium (Ba) concentration range between 115 and 907 ppm. The variability does not follow a north-south trend. Lithium (Li) concentrations were below detection limit in all samples. Concentrations of chromium (Cr) range between 13 and 67.5 ppm, however four samples can not be considered in the further discussion. A spatial pattern is not visible. Copper (Cu) concentrations range between 10 and 35 ppm, but again eight samples contained to little copper for the detection to be reliable. Highest concentrations occur in Central Yakutian lakes. Nickel (Ni) concentrations range between 13.7 and 52.5 ppm. Variations in northern lakes are high, as they feature the full range of Ni concentrations. Lead (Pb) is only in four lakes contained in concentrations above detection limit. All of these lakes are located in Central Yakutia. Strontium (Sr) concentrations range between 98 and 415 ppm, with the maximum in a Central Yakutian lake. Vanadium (V) concentrations range between 13.1 and 124 ppm, with two samples with V concentrations below detection limit. Zinc (Zn) concentrations range between 21.2 and 377 ppm. The highest detected concentration occurs in a Central Yakutian lake and appears to be an outlier, as its concentration is almost 220 ppm higher than the following samples. Zirconium (Zr) concentrations range between 10.4 and 457 ppm. Two samples contained Zr in concentrations below detection limit. The results of the elemental analyses are summarised in table A.4 in the appendix. Characteristics of detected elemental concentrations are displayed in figure 4.4.

Stable carbon isotopes

The δ^{13}C isotope ratios of organic carbon range between 18.7 and 34.6 ‰. The lowest ratio was detected in a Central Yakutian lake (05-YAK-16), the highest in a Lake in Northern Yakutia. Generally, ratios were slightly lower in lakes located in the central part of Yakutia (median = 26.7 ‰), than those from the northern part (median = 29.1 ‰). Due to problems that were encountered during the measurement of δ^{13}C ratios of Northern Yakutian samples two thirds of the results have a systematic error. These are listed in table A.3 in the appendix.

PCA on surface sediments

The relationships between surface sediments and lake locations were explored using a principal component analysis (PCA) based on a correlation matrix. All 65 samples

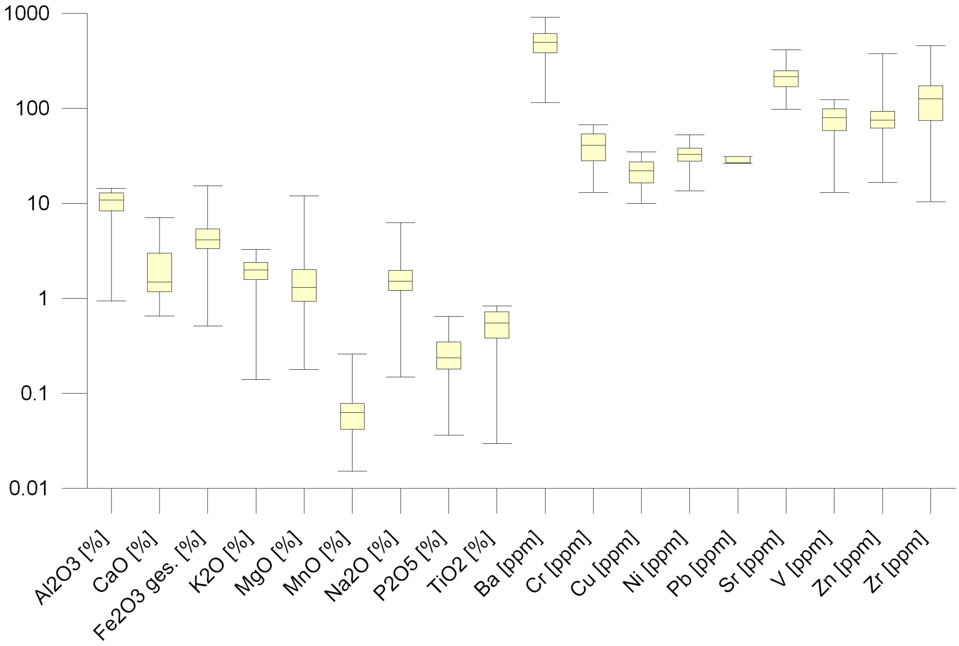

Figure 4.4: Boxplot of detected elemental concentrations in surface sediments. The boxes enclose 50 % of the data with the median concentration of the element displayed as a line. The extending lines mark the minimum and maximum values.

and 27 species – sedimentological variables were treated as species – were used in this analysis. The eigenvalues and the cumulative variance of the four first axes (or components) are listed in table 4.2. A high percentage (79.6 %) of the total variance in the data could be explained by the first four axes. The relevance of the axes decrease rapidly as 71 % of the variance is explained by the first three axes.

The PCA biplot (figure 4.5) explains ~ 60 % of the variability within the dataset with eigenvalues of $\lambda 1 = 0.346$ and $\lambda 2 = 0.249$, respectively. Axis I accounts for 35 % and axis II for 25 % of the variance. Components III & IV are not shown. Small angles between arrows of variables indicate high positive correlations. The longer the arrow (vector) of a variable, the larger its variance and its weight in determining axes. Arrows in the proximity of principal components signify their weight with respect

Table 4.2: Results of PCA performed on 27 measured variables from 35 surface sediment samples.

Axis	Eigenvalue λ	Cumulative variance [%]	Individual axes contribution [%]
1	0.346	34.6	34.6
2	0.249	59.5	24.9
3	0.115	71	11.5
4	0.086	79.6	8.6

to each axis. The ordination of the sampling sites does not show a clear separation between the lakes. The variables lithium (Li) and lead (Pb) were eliminated from the dataset, as their concentrations were below the detection limit in more than 90 % of the study sites. Values below the detection limit were replaced by the value of their detection limit, if they were detectable in the majority of the lakes. Variables included in the PCA are listed in the appendix in table A.5. A strong positive correlation ($r > 0.5$) exists between the first axis and TIC, TOC and TN, while the correlation between that axis and Al_2O_3, Fe_2O_3, K_2O, TiO_2, Ba, Cr, V, and Zr is highly negative ($r < -0.5$). The ordination of sampling sites does not reveal a pattern in the distribution of the lakes. The correlations between the second axis and the variables clay, Na_2O and Sr are positive, whereas $\delta^{13}C$, sand, silt, Cu, Ni and Zn correlate negatively. Nutrient-related variables (i.e. TN, TOC, TC, C/N and P_2O_5) are situated in the lower right quadrant of the ordination, metals and transition metals in the lower left and alkali and alkaline earth metals are located in the upper left quadrant of the ordination.

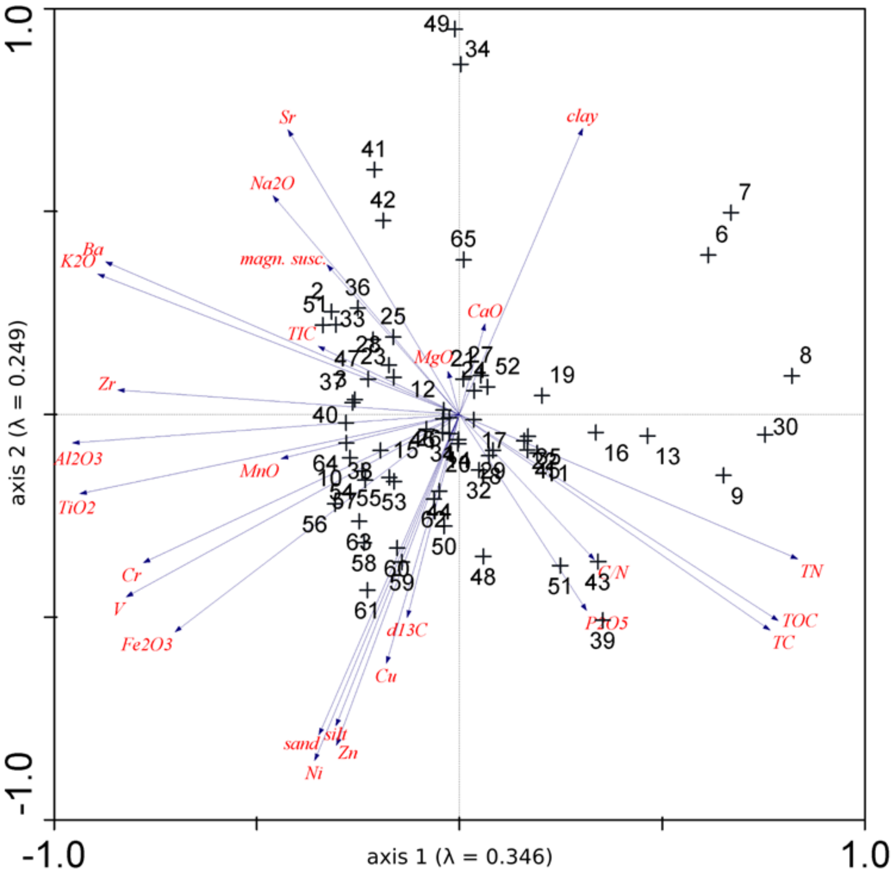

Figure 4.5: PCA of 27 measured variables from 35 sampled lake surface sediments. Study site code key in table A.1 in the appendix.

4.3 Multivariate statistics

Detrended correspondence analysis (DCA)

To determine if the distributions of the datasets are linear or unimodal a detrended correspondence analysis (DCA) for both water and sediment data was computed. As the length of the longest gradient didn't exceed 3.0 SD in both sediment (0.64 SD) and water (0.99 SD) linear distributions were detected. Therefore, linear ordination methods were used to explore the variation in the dataset.

Redundancy analysis (RDA)

The redundancy analysis (RDA) was computed in order to estimate how much variance in the sedimentological data is explained by certain environmental parameters. Variables included in this analysis and their correlation factors are listed in table A.7 in the appendix. Resulting eigenvalues are listed in table 4.3. The first two axes explain 37 % of the species variance, with eigenvalues of $\lambda 1 = 0.251$ and $\lambda 2 = 0.119$, respectively. Species and environmental variables correlate well on the first two axes (axis 1 = 0.865 and axis 2 = 0.763). The sum of canonical eigenvalues was 0.583, the sum of all unconstrained eigenvalues of the RDA being 1.000. Hence, 58 % of the variation of the species (surface sediment samples) is explained by the environmental variables, indicating a close relationship between the two datasets.

Table 4.3: Results of RDA on surface sediments (treated as species) from 65 lakes (treated as samples) and water samples (treated as environmental variables).

Axis	**Eigenvalue** λ	**species/environment correlation**	**Cumulative variance (species)** [%]	**Cumulative variance (environment)** [%]
1	0.251	0.865	25.1	43.1
2	0.119	0.763	37.0	63.4
3	0.092	0.848	46.2	79.3
4	0.056	0.723	51.8	88.9

The RDA triplot (figure 4.6) illustrates the correlations of environmental variables and computed axes. A strong negative correlation exists between the first axis and water depth ($r = -0.61$) and secchi depth ($r = -0.53$), while K correlates positive ($r = 0.56$). The second axis is strongest correlated with conductivity ($r = 0.73$), Br (r = 0.64), chloride (r = 0.59) and Mg (r = 0.53). Variables contributing to water chemistry characteristics are almost exclusively positioned in the upper right quadrant of the ordination. These are closely related to alkalinity and salinity of lake waters. Sample sites are arranged along two gradients: one related to pH, conductivity, HCO_3^- and K, and one related to water depth and secchi depth. Nutrient related variables (i.e. TN, TOC, C/N and P_2O_5) are located in the lower right quadrant, the majority of the metals and transitional metals in the lower left quadrant. Most of the alkaline earth metals such as K, Na and Ca are located in the upper left quadrant of the ordination. The sample sites 6 and 7 are located in the far upper right quadrant of the ordination. This is due to the high alkalinity of the lakes. The results of the RDA are summarised in table 4.3.

Table 4.4: Results of partial RDA on surface sediments (treated as species) from 65 lakes (treated as samples) and water samples (treated as environmental variables).

Axis	**Eigenvalue** λ	**species/environment correlation**	**Cumulative variance (species)** [%]	**Cumulative variance (environment)** [%]
1	0.223	0.829	22.3	53.51
2	0.093	0.810	31.6	76.0
3	0.068	0.816	38.4	92.4
4	0.015	0.313	40.0	96.1

Partial redundancy analysis (RDA)

As to eliminate redundant data from the analysis a Monte-Carlo permutation test (499 unconstrained permutations) was applied. From 20 environmental variables only six where detected as significant ($p < 0.05$) and used in a partial RDA. These were K ($p = 0.002$), Mg ($p = 0.002$), Sr ($p = 0.002$), water depth ($p = 0.004$), conductiv-

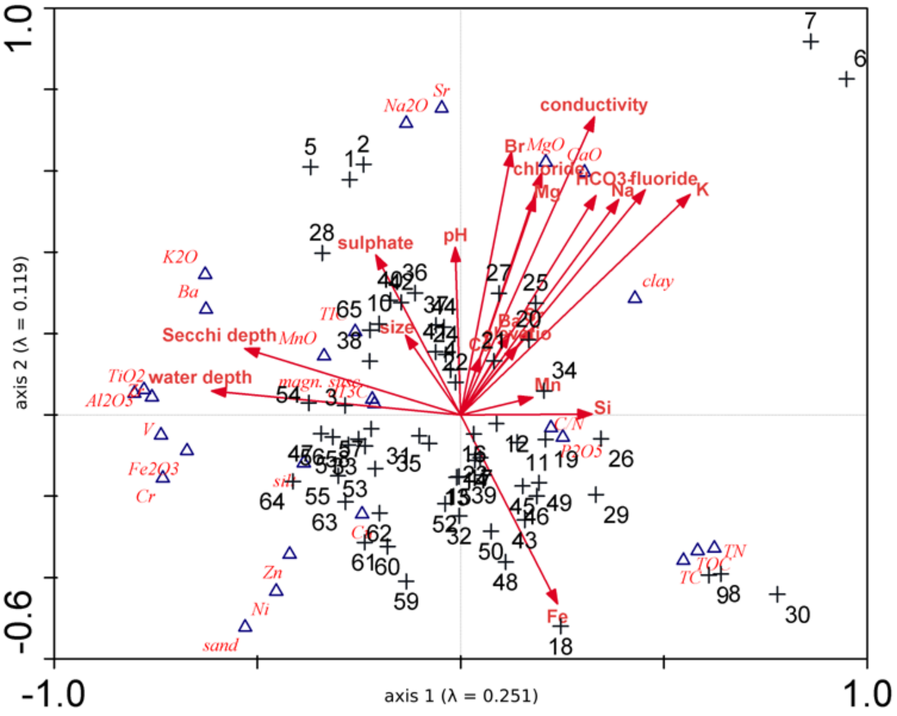

Figure 4.6: Triplot of RDA with 20 environmental variables, 27 species and 65 samples. Environmental variables are displayed as red arrows, species data as blue triangles and samples sites as black crosses.

ity (p = 0.01) and HCO_3^- (p = 0.024). The results of that analysis are summarised in table 4.4, included variables and their correlation factors are listed in table A.8 in the appendix. The first two axes explain 32 % of the species variance, with eigenvalues of $\lambda 1 = 0.223$ and $\lambda 2 = 0.093$, respectively. Species and environmental variables correlate well on the first two axes (axis 1 = 0.829 and axis 2 = 0.810). The sum of canonical eigenvalues was 0.416, the sum of all unconstrained eigenvalues of the partial RDA 1.000. So 42 % of the variation of the species (surface sediment samples) is explained by the environmental variables.

The triplot of the partial RDA (see figure 4.7) confirms the results of the RDA as the environmental variables water depth ($\lambda 1 = -0.64$) and K ($\lambda 1 = 0.64$) correlate with the first axis while Mg ($\lambda 1 = 0.86$), Sr ($\lambda 1 = 0.54$), conductivity ($\lambda 1 = 0.84$) and HCO_3^- ($\lambda 1 = 0.84$) correlate with the second axis. The species are positioned in a similar pattern as in the RDA. Nutrient related variables correlate best with the second axis while metals and transitional metals correlate with the first axis. Furthermore Northern Yakutian sample sites are clustered in the lower left quadrant of the ordination. As in the triplot of the RDA the sample sites 6 and 7 are positioned in the far upper right quadrant of the ordination, due to their salinity.

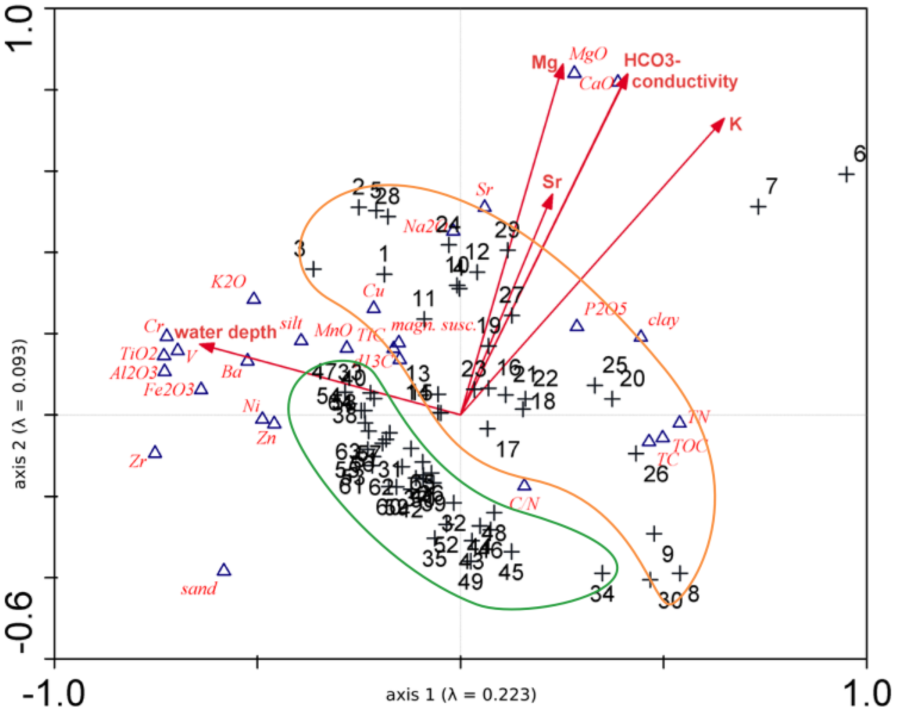

Figure 4.7: Triplot of partial RDA with 5 environmental variables, 27 species and 65 samples. Environmental variables are displayed as red arrows, species data as blue triangles and samples sites as black crosses. Envelopes encompass lakes from Northern (green) and Central Yakutia (yellow).

5 Discussion

Physical and chemical properties of the sampled lakes in Northern and Central Yakutia are similar to those of other lakes in arctic and subarctic regions of Siberia (Duff et al., 1999; Kumke et al., 2007; Laing and Smol, 2000) or Canada (Pienitz et al., 1997; Lim et al., 2001; Michelutti et al., 2002; Lim et al., 2005). The lakes are slightly alkaline to alkaline (mean $pH = 8$) and nutrient-poor. Only 10 Central Yakutian lakes contain phosphorus above detection limit (mean = 0.48 mg/l). These findings are consistent with values recorded in other arctic and subarctic regions.

Limnological parameters

The electric conductivity of the sampled Central Yakutian lakes is considerably higher than that of the sampled Northern Yakutian lakes. As the electric conductivity of waters depends on the amount of dissolved ions, it can be used as a proxy for salinity (Hölting and Coldewey, 2005). The major ions contributing to conductivity are Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, HCO_3^{-}, CO_3^{2-}, SO_4^{-} and Cl^{-} (Wetzel, 2001). These ions originate from weathering of bedrock of the lake basin and the catchment, precipitation (e.g. sea spray) or anthropogenic pollution (e.g. agricultural runoff) (Drever, 1997; Cohen, 2003). Groundwater as ion source can be ruled out as subsurface drainage in arctic regions is often prevented by the sealing effect of permafrost (Pienitz et al., 1997). The higher the concentration of these ions, the higher the conductivity of the waters. Ion concentrations not only depend on the sources, but also (per definition of salinity as mg/l) on the amount of solvent or in this case water. The studied lakes are mainly fed by the low precipitation in these regions (see chapter 2.3) (Wetterich et al., 2008). In spite of the proximity to the Laptev Sea, Northern Yakutian lakes are far more dilute than those located in Central Yakutia. This reflects the negative water balance in Central Yakutia, together with the location in different vegetation zones. Previous studies of Siberian (Duff et al., 1999; Laing and Smol, 2000; Kumke et al., 2007; Wetterich et al., 2008) and Canadian lakes (Lim et al., 2005) revealed a very similar pattern. This demonstrates the influence of the geographical setting (i.e. the continentality) on the hydrochemical composition of lake waters. The difference becomes apparent when comparing electric conductivities of waters from Northern Yakutia (0.02 – 0.28 mS/cm) with waters from Central Yakutia (0.1 – 5.71 mS/cm). As most of the studied lakes lack in- and outflows, any negative hydrological balance is bound to increase the ion concentration by evaporation. The lakes then may become saline (Eugster and Hardie, 1978). Furthermore a connection between increasing thaw depth during summer months and rising ionic contents of thermokarst lakes was pointed out by Lopez et al. (2007) and Wetterich et al. (2008).

The concentration of potassium (K) is caused by leaching from vascular plants, as pointed out by Prentki et al. (1980). As central Yakutian lakes are located exclusively in taiga forests, in contrast to those from Northern Yakutia which are located in the tundra zone (see chapter 2.4), the importance of K as controlling variable is apparent. Another source for solute K may be the lakes‘ sediment. Potassium is assimilated into submerged macrophytes and their epiphytes and utilised by algae (Wetzel, 2001).

Strontium (Sr) is most likely a proxy for ion concentration. Less than one third of sampled northern Yakutian lakes contain Sr above detection limit, albeit in very low concentrations. Detected concentrations should be regarded as unreliable as they were barely detectable, and are thereby prone to errornous results as pointed out by

Nölte (2002).

Chlorophyllous plants require Magnesium (Mg) for various processes. This could make magnesium a limiting factor for bioproductivity. But such conditions are rare compared to limitations by the restricted availability of other nutrients (e.g. P, N or Fe) (Wetzel, 2001). Phosphorus (P) is derived mainly from weathering of bedrock in the lake basin or the catchment. Concentrations were not detectable in Northern Yakutian waters and only one third of the lakes sampled in Central Yakutia contained P in detectable amounts. The generally low concentrations are caused by the absence of phosphate-bearing bedrock, and the season in which the samples were taken, as phosphorus is depleted during the growing season in the epilimnion due to the demand by autotrophs (Cohen, 2003). Silica (Si) is an essential nutrient for diatoms and other siliceous algae. Its distribution in Yakutian waters follows a regional pattern, with concentrations barely detectable in Northern Yakutian waters. Although Si contents are not high in Central Yakutian waters (median = 1 mg/l), they point to higher productivities of those lakes.

Na/Ca ratios, can be used as indicator for the salinity of waters (Kumke et al., 2007). Values confirm the detected electric conductivities, as they are considerably higher (tenfold) for Central Yakutian waters. Two lakes (05-YAK-06 & 05-YAK-06) have extreme high ratios (682 & 657), which is due to their elevated sodium content. Other authors (Eugster and Jones, 1979) use Mg/Ca ratios as proxy for salinity. Central Yakutian lakes have ratios between 0.3 and 57.9 (median = 1.8), while ratios are considerably lower in Northen Yakutian lakes (median = 0.5). Na/K ratios reflect the vegetation sourrounding the sampled lakes (Lim et al., 2005; Kumke et al., 2007). Ratios were expected to be low in Central Yakutian waters and high in Northern Yakutian waters, due to their location in different vegetation zones. This could not be verified, which possibly is caused by the salinity of Central Yakutian waters (Kumke et al., 2007).

Central Yakutian lake waters have generally higher pH values, than waters from

Northern Yakutia. High pH values account to the concentration of hydroxyl ions being released by the dissociation of bicarbonate and carbonate ions (Wetzel, 2001). The pH of waters is regulated by the $CO_2 - HCO_3^- - CO_3^{2-}$ buffering system, as displayed in figure 3.2 (Wetzel, 2001). This reflects the morphology of the lake basins, as the majority has no in- and outflows. These lakes are prone to evaporation resulting in rising ion concentrations. High alkalinities are likely tied to warm and dry conditions, which promote an intense stratification, biomass production and the release of base cations (Psenner, 1988; Battarbee, 2000). Additionally, as carbonate alkalinity is treated as equal to alkalinity (see chapter 3.2.1), elevated alkalinities result from evaporation and weathering of carbonates. Hence, alkalinities of the sampled lake waters reflects the climatic setting of the study areas, a finding that concurs with the findings of Kumke et al. (2007) and Wetterich et al. (2008).

The PCA performed on limnological and hydrochemical data suggests that the waters are arranged along a gradient of variables controlling the salinity of lake waters on the one end, and variables describing the physical and morphological parameters water depth, secchi depth and the approximate size of the lakes on the other end. The sampled lakes appeared in two clearly deliminated clusters in the ordination. These findings corroborate the results presented above, as Central Yakutian waters have higher ion concentration than Northern Yakutian ones.

Surface sediments

Surface sediment samples were obtained from the deepest part of the lakes. Grain sizes should be smallest in this area, the concentration of organic carbon (TOC) can therefore be expected to be high (Thompson and Eglington, 1978; Meyers and Teranes, 2001). The concentration of TOC depends on biomass production prior to deposition and degradation (e.g. microbial reworking) subsequent to deposition (Meyers and Lallier-Verges, 1999), and may vary from place to place in a lake (Meyers and Teranes, 2001). Main contributors to organic matter in lacustrine sediments are the remains of algae, zoo- and phytoplankton, bacteria and aquatic and terrestrial plants (Hassan et al., 1997; Meyers and Teranes, 2001). Allochthonous organic matter may enter the lake via run-off additionally to autochthonous sources. Surface sediments from Central Yakutian lakes contain considerably higher concentrations of nitrogen (TN) and organic carbon. This reflects the higher bioproductivity of lakes located in the taiga forests of Central Yakutia. The sources of organic matter in sediments can be determined by the analysis of δ^{13}C and C/N ratios (Meyers, 1994; Meyers and Teranes, 2001). C/N ratios from organic matter derived from aquatic plants are low and usually between 4 and 10, while land plants have ratios of 20 and higher (Meyers and Ishiwatari, 1993). High ratios are to be expected during phases of high input of allochthonous material (Guilizzoni et al., 1996), e.g. caused by near-lake forest clearances (Kaushal and Binford, 1999; Routh et al., 2007). Central Yakutian lakes are often surrounded by pastures, apart from being located in the taiga, resulting in input of organic matter during mowing. Low ratios on the other hand identify times of high algeal productivity (Kansanen and Jaakkola, 1985). Plants which incorporate carbon using the C3 pathway have relative low δ^{13}C ratios (average -27 ‰) and are thereby distinguishable from plants using the C4 pathway (average -14 ‰) (Smith and Epstein, 1971). If plants (plankton) utilise carbonates (HCO_3^-) instead of CO_2, they become enriched in δ^{13}C, as the δ^{13}C of bicarbonate is 7 to 8 % higher than that of dissolved atmospheric CO_2 (Smith and Epstein, 1971; Hassan et al., 1997; Meyers and Teranes, 2001). Periods in which HCO_3^- becomes an important source of carbon include times of high photosynthetic uptake of DIC when CO_2 becomes depleted, an alkaline pH is keeping the HCO_3^-/CO2 ratio elevated and high temperatures (Bernasconi et al., 1997). HCO_3^- gets conversed to CO_2 slowly at pH values greater than 7 which is leading to low CO_2 concentrations in alkaline lakes (Badger, 1987). The intake of HCO_3^- by algae may result in isotopically heavy organic matter (Bernasconi et al., 1997; Meyers and Lallier-Verges, 1999).

C/N ratios of the sampled surface sediments point to aquatic plants as source of

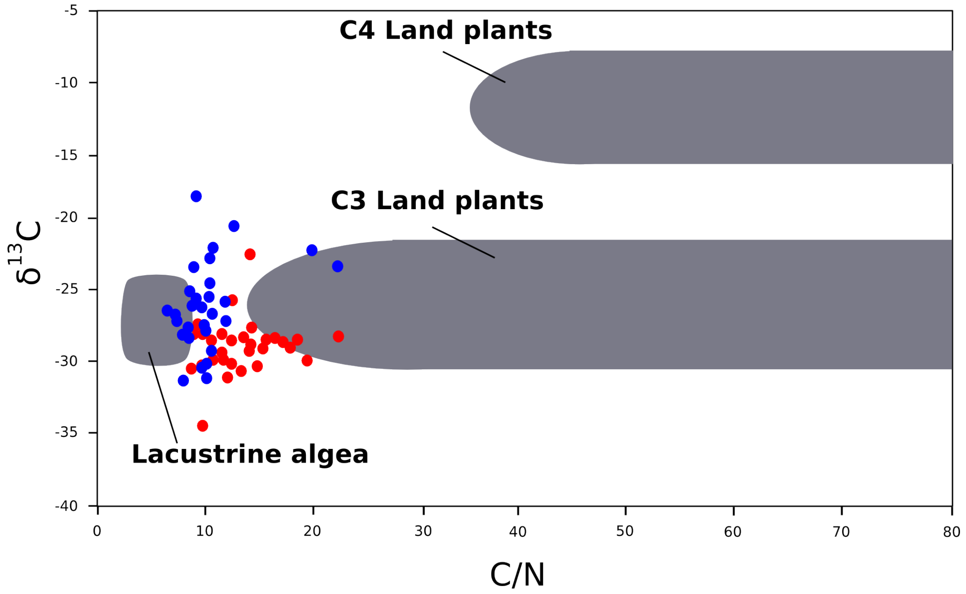

Figure 5.1: Elemental and carbon isotopic composition of sampled surface sediments. Organic matter derives predominantly from lacustrine productivity. Samples from Central Yakutia are displayed as blue dots, samples from Northern Yakutia as red dots. Scheme after Meyers (1994).

organic matter. Ratios of northern samples are slightly higher (median = 12) than those derived from Central Yakutian samples (median = 10). Apart from that, C/N ratios are distributed rather uniformly. δ^{13}C ratios eliminate C4 plants as source of carbon in organic matter. Both parameters combined suggest C3 aquatic vegetation as main source to organic matter in the sampled surface sediments (see figure 5.1). Furthermore, lake sediments can be classified by their C/N ratios after Håkanson and Jansson (1983). Sediments containing organic matter which has not been decomposed yet have high C/N ratios ($> 10 - 15$) are named polyhumic. Sediments with organic matter decomposed to a higher degree should have C/N ratios lower than 10, and are called oligohumic. Following this classification, the majority of the studied lakes are of the polyhumic type. This reflects the climatic restrictions of the study area, as the input of organic matter is limited, and its decomposition is slow. Lakes in the northern study area are affected by these processes to a larger degree, as the input of organic matter is strictly limited by their location in the tundra, which results in higher C/N ratios.

The elemental composition of the sampled sediments holds information not only about the bedrock, but also about climatic conditions of the catchment area. Central Yakutian lakes are characterised by Sodium (Na), potassium (K), magnesium (Mg) and calcium (Ca). Those elements are associated with erosion and weathering activity in the catchment. A closed vegetation cover (as in the Central Yakutian Taiga) supports deep weathering, the dissolved ions are carried subsequently into the lake by runoff waters (Engstrom and Wright, 1984). According to Minyuk et al. (2007) warm periods are characterised by elevated contents of SiO_2, CaO, Na_2O, K_2O and Rb and reduced contents of TiO_2, Fe_2O_3, Al_2O_3 and MgO. Si concentrations were not measured, as Si is removed by the usage of HF during the acid digestion of the samples (see section 3.2.2.3). Biogenic production in the lake and weathering in the catchment, the main sources for these elements, are dependent on climatic conditions. Ca corresponds to organic matter in lake sediments, according to Engstrom and Wright (1984). This relationship could not be verified for the sampled lakes. The results of multivariate statistic analyses on the other hand, suggest a relationship between Ca and variables connected with the bioproductivity in lakes.

Fe/Mn ratios reflect redox conditions in lakes and their catchment (Engstrom and Wright, 1984; Wersin et al., 1991; Koinig et al., 2003). Ratios below 0.04 point to reducing conditions (Wersin et al., 1991), ratios below 0.02 can be interpreted as proxy for anoxic conditions (Koinig et al., 2003). Fe/Mn ratios suggest anoxic conditions for the majority of Northen Yakutian lakes (median = 0.01), while Central Yakutian have slightly higher ratios (median = 0.02). It should be noted that Fe/Mn ratios as proxy for reducing conditions in lakes are difficult to interpret, especially in surface sediments due to processes taking place at the sediment-water interface (Cohen, 2003), and may be best applicable when studying sediment cores.

Magnetic susceptibility can be used to draw conclusions about the paleoenvironment of a lake. This is possible because magnetic susceptibility provides informations about grain-size, mineralogy of sedimentary magnetic assemblages, and variations in the sources of the material (Thompson et al., 1975; Dearing, 1999b), all responding to changes in climate, human activity and limnology (Dearing and Flower, 1982; Sandgren and Snowball, 2001). Ferromagnetic minerals in lake sediments may originate from a) weathering in the catchment, b) air-borne particles and c) authigenic formation in the lake sediment under anaerob conditions (Evans and Heller, 2003). High susceptibilities may be caused by the input of eolian dust (Peck et al., 1994). This dust might contain increased amounts of high coercivity minerals as staining on eolian grains. Peck et al. (1994) described this with regard to eolian input during glacial intervals. Nevertheless, this scheme seems fitting for the studied lakes. High magnetic susceptibility could as well be the result of detritus (pedogenically-enhanced or pedogenically-produced) entering the lake via run-off (Dearing et al., 1998; Chen et al., 1999). Central Yakutian lakes, strongly affected by their continentality, have generally higher magnetic susceptibilities than sediments from Northern Yakutian lakes.

The PCA performed on sedimentological data suggests that the sediments are arranged along a gradient with high TOC, TIC and TN on the one end, and low concentrations of Al_2O_3, Fe_2O_3, K_2O, TiO_2, Ba, Cr, V, and Zr on the other end. Minyuk et al. (2007) related most of these elements to climatic conditions.

Correlation of limnological data and surface sediments

A result of the partial RDA was that lakes from Northern and Central Yakutia appear in two distinct clusters, deliminated by their location (see figure 4.7). This can be explained by the differences in the catchment vegetation and the climatic setting. Surface sediment samples correlating with elevated contents of nutrient related variables, such as TN, TC and P2O5 are located in Central Yakutia. These sediments have higher magnetic susceptibilities than those from Northern Yakutian lakes. Waters of these lakes are characterised by a high alkalinity and electric conductivity. Furthermore, they contain elevated concentrations of potassium (K), magnesium (Mg) and strontium (Sr). Strontium seems to be solely a proxy for the salinity of the lakes water, while K and Mg relate to bioproductivity in the lakes. Elevated Mg/Ca ratios of Central Yakutian waters should indicate the precipitation of low-Mg calcite (Müller et al., 1972). The Concentration of Ca and Mg was considerably higher in these lakes. The results of the partial RDA support these findings, as Mg and Ca were identified as variables correlating with Central Yakutian lakes. Sediments from dilute lakes from Northern Yakutia are coarser than those from Central Yakutia. This may be due to eolian input of dust during the dry and hot summers. The ashes of the frequently occurring forest fires in Central Yakutia (Tomoaki et al., 2007) may be another source for the finer fraction.

Studied morphological parameters of the lakes were the elevation of the water table, water depth and the size of the lakes. The water depth was identified by the partial RDA as controlling variable. Sampled lakes in Northern Yakutia were generally larger than their Central Yakutian counterparts. This may be due to the pronounced evaporation in Central Yakutia, but is more likely an effect of sample lakes not being chosen at random. The depth of the lakes is correlated to Central Yakutian lakes, and may refer to evaporation and the negative water balance in that area, but as well to the size of the lakes.

Summing these results up, sediments rich in nutrients and with high magnetic susceptibilities are found in lakes with alkaline waters having high ionic concentrations which result in high electric conductivities. These lakes and are located in regions with negative water balances, e.g. in highly continental climates.

6 Conclusion

Physical and chemical properties of surface sediments and waters from 65 Yakutian lakes were studied. Statistical analyses were used to explore differences between the lakes, to identify variables explaining physical and chemical properties and eventually to explore if it is possible to infer information about the composition of waters from the analysis of surface sediments. Two study areas – one in Central Yakutia, the other in Northern Yakutia – were chosen in order to explore the characteristics of lakes located in different climatic settings.

Composition of lake waters and surface sediments

Physical and chemical properties of surface sediments and lake waters vary to a high degree. Central Yakutian lake waters are generally slightly alkaline to alkaline, have high ionic concentrations and high electric conductivities. Northern Yakutian lake waters are slightly acidic to neutral and are generally dilute. The differences in the ionic compositions are immense, as ion concentrations of Northern Yakutian waters were often below detection limit or only slightly above it. Central Yakutian lakes on the other hand contain considerably high ion concentrations, which result in high electric conductivities. A comparison of corresponding surface sediments reveals a pattern much alike. Central Yakutian sediments have higher magnetic susceptibilities and elevated contents of nutrients and generally higher elemental concentrations than surface sediments from Northern Yakutia.

Variables controlling the composition of lake waters and surface sediments

It is evident from the analyses that the continentality has a strong effect on the composition of lake waters and surface sediments. The geographical setting, along with the negative water balance, leads to elevated electric conductivities and ion concentrations in Central Yakutian waters and sediments. The proximity of the Laptev Sea to the Northern Yakutian lakes is not reflected in their ionic composition. Furthermore, additional to the continentality, the vegetation of the watershed has an influence on the ionic composition of lake waters and lake sediments. Lakes located in the taiga are surrounded by forests or pastures. This results in elevated potassium concentrations in lake waters. The location in a zone of higher bioproductivity is reflected by elevated contents of magnesium in the waters and by surface sediments containing considerably higher concentrations of TOC and TN.

Informations about the watershed and the composition of lake waters inferred from the analyses of surface sediments

Statistical analyses were used to explore relationships between surface sediments and waters. Surface sediments enriched in nutrients were found in lakes with high bioproductivities. As the bioproductivity is reflected in the waters (e.g. in high Mg contents) a correlation between sediments and waters of those lakes is possible, and can be shown by analysing the sediments C/N ratios and nutrient concentrations. These highly productive lakes were encountered in a region characterised by its continentality. The negative water balance results in lake waters with elevated electric conductivities, elevated ion concentrations and high alkalinities. Waters of these lakes have high Ca/Mg ratios, and are correlated to sediments with elevated concentrations of the same elements.

The findings can be summarised as follows: a) It is possible to distinct between lakes from Northern Yakutian and Central Yakutia by analysing their waters. Northern lakes are dilute, while Central Yakutian lakes, which are affected by evaporation to a higher degree, are characterised by high ionic concentrations, resulting in high electric conductivities. b) Surface sediments of lakes that are affected by a negative water balance but are still highly productive are characterised by high contents of nutrients and elevated magentic susceptibilities.

The above shows that it is possible to infer informations about the characteristics of a lake (i.e. waters, vegetation, geographical setting) by studying their surface sediments. Recunstructions based on sediment cores should take alteration of the sediments after their deposition into account.

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A Appendix

A.1 Field data

Table A.1: Sampled Central and Northern Yakutian lakes.

Lake-No	**Sample name**	**Latitude** [N]	**Longitude** [E]	**Elevation** [m a.s.l.]	**Approx. size** [m x m]	**Water depth** [m]	**Secchi depth** [m]	**Conductivity** [mS/cm] T_{Ref} 25 °C	**pH**
1	05-YAK-01	61° 45′39,6″	130° 28′15,6″	213	20 x 30	1.8	no data	1.63	8.54
2	05-YAK-02	61° 45′36,0″	130° 28′19,2″	213	60 x 100	3.5	0.9	2.38	9.11
3	05-YAK-03	61° 45′39,9″	130° 28′26,4″	233	80 x 80	4.6	1.5	0.82	8.71
4	05-YAK-04	61° 45′54,0″	130° 27′55,9″	209	40 x 250	1.8	1	0.91	8.08
5	05-YAK-05	61° 46′11,1″	130° 28′07,4″	215	100 x 300	4.6	1.1	1.99	9.05
6	05-YAK-06	62° 06′13,3″	130° 13′21,6″	130	300 x 400	1.3	0.7	5.71	9.96
7	05-YAK-07	62° 01′00,1″	130° 03′57,1″	138	400 x 700	1	0.5	4.14	9.91
8	05-YAK-08	62° 03′60,5″	129° 03′23,4″	228	400 x 800	1.5	0.3	0.1	7.54
9	05-YAK-09	62° 03′28,9″	129° 03′13,9″	228	200 x 300	2.2	0.7	0.12	7.31
10	05-YAK-10	61° 42′11,4″	129° 22′11,1″	160	80 x 150	5.2	0.5	0.42	8.78
11	05-YAK-11	61° 36′50,4″	130° 42′12,6″	182	200 x 350	5.2	0.15	0.5	8.64
12	05-YAK-12	61° 37′06,6″	130° 42′28,1″	172	no data	3	0.35	0.92	8.42

Sampled Central and Northern Yakutian lakes. (...continued)

Lake-No	**Sample name**	**Latitude** [N]	**Longitude** [E]	**Elevation** [m a.s.l.]	**Approx. size** [m x m]	**Water depth** [m]	**Secchi depth** [m]	**Conductivity** [mS/cm] T_{Ref} 25 °C	**pH**
13	05-YAK-13	61° 33′26,0″	130° 32′48,3″	219	200 x 600	3.9	0.25	0.14	8.46
14	05-YAK-14	61° 34′0,60″	130° 33′59,2″	203	100 x 300	1.9	0.3	0.21	6.86
15	05-YAK-15	61° 34′20,7″	130° 36′42,7″	198	80 x 300	1.6	0.4	0.16	7.55
16	05-YAK-16	61° 24′13,4″	130° 33′10,8″	224	150 x 400	1.5	0.4	0.29	10.24
17	05-YAK-17	61° 33′09,3″	130° 51′34,0″	234	40 x 350	1.6	0.6	0.1	6.60
18	05-YAK-18	61° 33′01,5″	130° 53′11,7″	211	no data	1.5	0.15	0.39	8.57
19	05-YAK-19	61° 24′26,0″	131° 07′01,7″	250	50 x 150	1.3	1	0.71	8.02
20	05-YAK-20	61° 32′45,3″	130° 54′18,9″	230	400 x 800	2	0.8	0.81	9.00
21	05-YAK-21	62° 00′11,3″	131° 49′06,1″	208	100 x 200	1.9	0.35	0.33	8.19
22	05-YAK-22	62° 00′23,7″	131° 43′10,0″	207	100 x 200	1.7	0.3	0.36	8.69
23	05-YAK-23	62° 07′54,2″	131° 13′24,9″	169	150 x 350	2.3	0.2	0.26	9.20
24	05-YAK-24	62° 58′05,7″	132° 14′49,7″	182	200 x 300	3.2	0.25	0.79	8.58
25	05-YAK-25	61° 48′05,9″	132° 04′58,8″	198	300 x 500	no data	0.5	0.82	8.75
26	05-YAK-26	61° 54′09,9″	132° 12′22,1″	187	150 x 150	no data	0.45	0.48	8.16
27	05-YAK-27	61° 53′24,2″	132° 09′51,3″	200	200 x 350	2	2	0.65	8.20
28	05-YAK-28	61° 56′23,9″	132° 09′55,8″	171	150 x 200	4.7	0.5	1.95	8.60
29	05-YAK-29	61° 56′46,5″	132° 08′39,2″	207	150 x 200	1.4	0.3	1.04	8.93
30	05-YAK-30	no data	no data	no data	no data	1.2	no data	no data	no data
31	07-SA-01	72° 29′02,5″	114° 06′02,5″	10	2000 x 1000	7.5	0.5	0.03	6.88
32	07-SA-02	72° 28′48,1″	113° 05′48,1″	6	30 x 30	2	0.5	0.03	6.87
33	07-SA-03	72° 35′60,0″	113° 51′60,0″	6	150 x 100	8	0.5	0.06	6.86
34	07-SA-04	72° 15′10,0″	114° 16′10,0″	3	500 x 300	no data	0.5	0.13	6.32
35	07-SA-05	72° 15′16,7″	114° 16′16,7″	3	1000 x 1000	no data	0.5	0.07	4.85
36	07-SA-06	72° 57′20,4″	114° 57′20,4″	0	300 x 200	4.5	2	0.03	5.20
37	07-SA-07	72° 57′20,4″	114° 57′20,4″	0	500 x 500	6.5	1.5	0.02	6.10
38	07-SA-08	72° 53′09,6″	115° 43′09,6″	4	2000 x 2000	10	1.3	0.03	7.47
39	07-SA-09	72° 53′06,0″	115° 45′06,0″	no data	100 x 100	0.9	ground	0.05	7.46

Sampled Central and Northern Yakutian lakes. (...continued)

Lake-No	Sample name	Latitude [N]	Longitude [E]	Elevation [m a.s.l.]	Approx. size [m x m]	Water depth [m]	Secchi depth [m]	Conductivity [mS/cm] T_{Ref} 25 °C	pH
40	07-SA-10	72° 57′23,1″	115° 20′23,1″	11	2000 x 2000	7.8	1.5	0.07	6.92
41	07-SA-11	72° 57′38,4″	115° 19′38,4″	4	4000 x 300	6	1.5	0.02	6.80
42	07-SA-12	73° 04′44,5″	114° 54′44,5″	0	2000 x 2000	5	1.6	0.02	7.14
43	07-SA-13	73° 04′56,3″	114° 55′56,3″	3	500 x 500	1	ground	0.02	6.90
44	07-SA-14	73° 07′32,2″	114° 52′32,2″	1	300 x 300	2.3	2.2	0.02	7.23
45	07-SA-15	73° 07′47,3″	114° 51′47,3″	4	800 x 800	1.3	ground	0.03	7.10
46	07-SA-16	73° 07′45,8″	114° 51′45,8″	4	800 x 800	1.6	ground	0.03	7.20
47	07-SA-17	73° 11′36,1″	114° 57′36,1″	10	500 x 500	7.4	2.3	0.05	7.4
48	07-SA-18	73° 12′56,2″	113° 37′56,2″	8	500 x 300	1.1	ground	0.13	7.42
49	07-SA-19	73° 13′17,6″	113° 37′17,6″	1	600 x 500	1.2	ground	0.02	6.99
50	07-SA-20	73° 22′53,9″	113° 55′53,9″	4	700 x 300	1.2	ground	0.06	7.32
51	07-SA-21	73° 23′13,5″	113° 56′13,5″	4	200 x 80	3.3	2.3	0.05	7.23
52	07-SA-22	72° 49′32,2″	113° 17′32,2″	8	300 x 200	1.8	1.1	0.02	7.22
53	07-SA-23	72° 46′29,7″	112° 58′29,7″	4	600 x 400	6.6	1.8	0.04	7.07
54	07-SA-24	72° 46′35,5″	112° 58′35,5″	1	200 x 200	4.8	1.8	0.28	7.22
55	07-SA-25	72° 46′39,5″	112° 58′39,5″	1	150 x 150	3.1	2	0.11	7.22
56	07-SA-26	72° 19′12,0″	111° 11′12,0″	86	400 x 400	6.8	4.5	0.03	7.32
57	07-SA-27	72° 19′14,4″	111° 11′14,4″	71	500 x 400	3.4	2.4	0.05	7.33
58	07-SA-28	72° 04′16,2″	111° 06′16,2″	41	500 x 300	5.1	1.3	0.08	7.55
59	07-SA-29	72° 04′05,7″	111° 06′05,7″	37	180 x 120	4.7	1.2	0.02	7.37
60	07-SA-30	72° 04′07,0″	111° 06′07,0″	36	200 x 180	5.1	1.3	0.02	7.29
61	07-SA-31	72° 04′15,2″	111° 07′15,2″	38	150 x 150	6.9	1.8	0.02	7.15
62	07-SA-32	71° 44′51,7″	111° 07′51,7″	50	100 x 100	2.7	1.5	0.03	6.97
63	07-SA-33	71° 44′50,9″	111° 07′50,9″	50	600 x 400	5	1.5	0.04	7.20
64	07-SA-34	71° 30′10,8″	110° 49′10,8″	80	400 x 150	7	3.5	0.05	7.18
65	07-SA-35	72° 03′57,5″	113° 54′57,5″	15	300 x 100	2.9	2.9	0.04	6.93

A.2 Laboratory data

A.2.1 Waters

Table A.2: Hydrochemistry of sampled waters from Central and Northern Yakutian lakes. Ions contained in concentration below detection limit are marked by an asterisk (*)

Lake-No	**Al** [mg/l]	**Ba** [mg/l]	**Ca** [mg/l]	**Fe** [mg/l]	**K** [mg/l]	**Mg** [mg/l]	**Mn** [mg/l]	**Na** [mg/l]	**P** [mg/l]	**Si** [mg/l]	**Sr** [mg/l]	**F^-** [mg/l]	**Cl^-** [mg/l]	**SO_4^-** [mg/l]	**Br^-** [mg/l]	**NO_3^-** [mg/l]	**PO_4^-** [mg/l]	**HCO^{3-}** [mg/l]	**ion balance** [mg/l]
05-YAK-01	< 20*	< 20*	33.56	35	3.88	178.72	35.4	147.09	< 0.2*	0.18	292.5	0.18	110	436.80	0.87	< 0.15*	< 0.1*	540.7	8.37
05-YAK-02	< 20*	33.0	24.11	22	4.03	305.26	25.7	267.42	< 0.2*	0.80	290.8	0.14	199	424.20	3.49	< 0.15*	< 0.1*	1210.85	10.4
05-YAK-03	< 20*	34.7	18.64	24.5	1.26	86.23	< 20*	81.08	< 0.2*	0.24	176.8	0.27	33.82	23.98	0.72	< 0.15*	< 0.1*	540.46	11.6
05-YAK-04	< 20*	32.8	17.67	130.5	7.45	65.47	43.7	100.28	< 0.2*	0.61	118.0	0.15	83.13	35.39	0.67	< 0.15*	< 0.1*	454.76	2.66
05-YAK-05	58	47.2	26.5	24	4.47	285.44	62.7	227.81	0.319	2.15	351.2	0.49	147.55	43.53	3.25	< 0.15*	< 0.1*	1509.6	15.5
05-YAK-06	698	< 20*	2.17	1255.0	158.27	96.71	26.0	1481.44	0.467	1.61	< 20*	0.77	408.50	0.52	3.30	< 0.15*	< 0.1*	3791.46	3.80
05-YAK-07	< 20*	< 20*	1.58	< 20*	68.25	91.64	< 20*	1040.92	0.208	0.48	28.6	0.83	350.80	< 0.1*	1.63	< 0.15*	< 0.1*	2578.47	4.62
05-YAK-08	42	28.2	11.61	146	2.74	3.75	< 20*	11.37	< 0.2*	0.62	129.2	0.19	1.32	< 0.1*	< 0.05*	< 0.15*	< 0.1*	56.12	41.1
05-YAK-09	< 20*	< 20*	10.0	428	3.03	4.54	110.2	18.62	< 0.2*	5.30	110.0	0.20	2.59	0.94	< 0.05*	< 0.15*	< 0.1*	75.15	28.3
05-YAK-10	< 20*	< 20*	20.8	208	12.49	41.10	< 20*	24.1	< 0.2*	0.45	152.9	0.40	8.56	0.19	0.10	< 0.15*	< 0.1*	315.74	6.49
05-YAK-11	< 20*	28.9	32.51	265	3.87	54.85	80	41.12	< 0.2*	2.81	260.7	0.30	5.75	0.33	0.20	< 0.15*	< 0.1*	422.73	12.2
05-YAK-12	< 20*	20.1	20.35	< 20*	11.13	86.63	< 20*	124.85	< 0.2*	0.68	195.5	0.36	33.77	10.34	0.79	< 0.15*	< 0.1*	681.52	11.6
05-YAK-13	< 20*	< 20*	14.33	240	2.32	11.90	< 20*	3.46	0.72	1.18	88.6	0.12	0.37	2.48	< 0.05*	< 0.15*	0.48	97.11	14.0
05-YAK-14	< 20*	< 20*	22.17	394	1.30	18.02	39.8	5.46	0.438	2.24	113.2	0.14	< 0.1*	2.87	< 0.05*	< 0.15*	0.40	140.42	19.1
05-YAK-15	22	< 20*	16.74	411	1.53	14.12	27	3.95	0.399	0.97	79.9	0.13	< 0.1*	2.25	< 0.05*	< 0.15*	0.55	107.48	19.8
05-YAK-16	< 20*	< 20*	25.39	69	3.93	22.63	< 20*	12.37	0.321	2.82	110.4	0.16	4.24	< 0.1*	0.07	< 0.15*	0.27	189.83	15.3
05-YAK-17	43	< 20*	10.83	549	2.94	7.32	52	1.80	< 0.2*	0.35	50.1	0.09	0.11	0.13	< 0.05*	< 0.15*	0.18	62.46	22.9
05-YAK-18	< 20*	26.5	36.25	619	3.63	34.62	27	20.26	0.244	2.05	235.7	0.29	1.46	0.30	0.07	< 0.15*	< 0.1*	302.68	11.7
05-YAK-19	45	38.7	21.39	561	4.53	60.50	145	83.24	< 0.2*	0.67	186.0	0.26	19.83	5.18	0.29	< 0.15*	< 0.1*	499.96	9.84
05-YAK-20	23	21.1	37.16	191	5.35	38.23	23	175.36	1.391	0.67	204.3	0.50	33.80	1.49	0.26	< 0.15*	2.79	595.48	17.1
05-YAK-21	< 20*	< 20*	37.71	118	3.81	25.82	< 20*	8.79	< 0.2*	1.09	152.6	0.18	0.96	0.54	< 0.05*	< 0.15*	< 0.1*	242.78	11.0
05-YAK-22	< 20*	29.9	40.31	255	4.73	28.99	< 20*	11.09	< 0.2*	< 0.1*	187.1	0.22	2.98	2.78	< 0.05*	< 0.15*	< 0.1*	262.18	11.8
05-YAK-23	29	22.3	34.50	559	3.01	22.88	47	8.20	0.460	1.99	135.5	0.21	0.58	1.10	< 0.05*	< 0.15*	0.57	208.99	15.2
05-YAK-24	< 20*	25.8	17.18	29	13.05	96.13	< 20*	129.12	< 0.2*	0.63	185.6	0.42	38.37	5.04	1.50	< 0.15*	< 0.1*	737.73	10.2
05-YAK-25	22	36.9	23.50	58	9.22	80.93	< 20*	107.94	< 0.2*	1.45	263.7	0.44	28.36	2.44	0.76	< 0.15*	< 0.1*	637.21	12.2
05-YAK-26	273	33.6	35.89	926	6.61	34.84	104	50.21	< 0.2*	2.99	212.5	0.38	5.95	0.60	0.19	< 0.15*	< 0.1*	346.11	18.0
05-YAK-27	34	33.5	21.66	87	11.81	62.91	< 20*	65.92	0.350	5.94	206.2	0.30	19.19	0.24	0.16	< 0.15*	0.26	480.92	11.1
05-YAK-28	< 20*	47.8	18.10	21	4.09	226.77	< 20*	288.97	< 0.2*	< 0.1*	274.5	0.70	151.35	11.20	3.90	< 0.15*	< 0.1*	1468.27	12.0
05-YAK-29	131	27.8	4.91	171	17.95	64.36	< 20*	180.11	< 0.2*	0.33	71.2	0.19	110.36	6.01	1.82	< 0.15*	< 0.1*	583.77	7.70
05-YAK-30	482	39.1	8.29	716	2.13	3.67	< 20*	8.11	< 0.2*	1.33	130.6	0.16	1.18	2.70	0.05	< 0.15*	< 0.1*	45.26	29.8

Hydrochemistry. (...continued)

Lake-No	**Al** [mg/l]	**Ba** [mg/l]	**Ca** [mg/l]	**Fe** [mg/l]	**K** [mg/l]	**Mg** [mg/l]	**Mn** [mg/l]	**Na** [mg/l]	**P** [mg/l]	**Si** [mg/l]	**Sr** [mg/l]	**F^-** [mg/l]	**Cl^-** [mg/l]	**SO_4^-** [mg/l]	**Br^-** [mg/l]	**NO_3^-** [mg/l]	**PO_4^-** [mg/l]	**HCO^{3-}** [mg/l]	**ion balance** [mg/l]
07-SA-01	39.6	< 20*	4.70	164	0.45	1.16	< 20*	< 0.2*	< 0.1*	0.42	< 20*	< 0.05*	0.27	0.58	< 0.05*	< 0.15*	< 0.1*	16.2	18.1
07-SA-02	123	< 20*	3.88	587	0.53	1.79	< 20*	0.55	< 0.1*	0.18	29.5	< 0.05*	0.53	< 0.1*	< 0.05*	< 0.15*	< 0.1*	13.7	44.8
07-SA-03	29.5	< 20*	8.80	203	0.56	2.72	< 20*	< 0.2*	< 0.1*	0.63	21.1	< 0.05*	0.28	0.67	< 0.05*	< 0.15*	< 0.1*	33.2	17.7
07-SA-04	< 20*	< 20*	9.49	119	0.62	2.30	< 20*	7.46	< 0.1*	< 0.1*	32.8	< 0.05*	14.0	0.19	< 0.05*	< 0.15*	< 0.1*	31.1	9.83
07-SA-05	25.9	< 20*	1.62	206	0.40	1.66	< 20*	7.13	< 0.1*	< 0.1*	< 20*	< 0.05*	15.0	0.45	0.09	< 0.15*	< 0.1*	4.7	5.59
07-SA-06	< 20*	< 20*	2.56	326	0.54	1.07	< 20*	< 0.2*	< 0.1*	0.11	< 20*	< 0.05*	0.56	0.16	< 0.05*	< 0.15*	< 0.1*	12.4	3.47
07-SA-07	< 20*	< 20*	1.62	226	0.45	0.67	< 20*	< 0.2*	< 0.1*	0.11	< 20*	< 0.05*	0.50	0.19	< 0.05*	< 0.15*	< 0.1*	7.9	-0.63
07-SA-08	< 20*	< 20*	3.42	158	0.34	1.32	< 20*	0.21	< 0.1*	0.13	< 20*	< 0.05*	0.51	0.22	< 0.05*	< 0.15*	< 0.1*	15.1	10.8
07-SA-09	21.1	< 20*	4.92	450	0.29	2.80	< 20*	0.98	< 0.1*	0.11	22.5	< 0.05*	0.69	< 0.1*	< 0.05*	0.33	< 0.1*	22.0	31.0
07-SA-10	< 20*	< 20*	6.85	24.7	0.51	3.19	< 20*	1.02	< 0.1*	0.11	26	< 0.05*	0.90	0.25	< 0.05*	< 0.15*	< 0.1*	36.1	5.99
07-SA-11	< 20*	< 20*	2.05	110	0.40	0.83	< 20*	< 0.2*	< 0.1*	0.15	< 20*	< 0.05*	0.48	0.17	< 0.05*	< 0.15*	< 0.1*	10.8	-7.50
07-SA-12	< 20*	< 20*	1.61	201	0.29	0.70	< 20*	0.52	< 0.1*	0.19	< 20*	< 0.05*	1.70	0.18	< 0.05*	< 0.15*	< 0.1*	7.0	0.97
07-SA-13	31	< 20*	1.96	426	< 0.2*	0.93	< 20*	0.99	< 0.1*	< 0.1*	< 20*	< 0.05*	1.15	< 0.1*	< 0.05*	0.18	< 0.1*	8.4	22.8
07-SA-14	< 20*	< 20*	2.07	124	0.40	0.71	< 20*	0.50	< 0.1*	< 0.1*	< 20*	< 0.05*	1.12	0.19	< 0.05*	< 0.15*	< 0.1*	9.0	5.48
07-SA-15	< 20*	< 20*	2.48	193	0.25	0.71	< 20*	1.03	< 0.1*	< 0.1*	< 20*	< 0.05*	2.94	0.18	< 0.05*	< 0.15*	< 0.1*	10.4	-9.62
07-SA-16	< 20*	< 20*	2.39	183	0.38	0.90	< 20*	1.11	< 0.1*	< 0.1*	< 20*	< 0.05*	1.72	0.15	< 0.05*	< 0.15*	< 0.1*	11.3	6.16
07-SA-17	25.4	< 20*	4.91	505	0.46	2.62	< 20*	0.96	< 0.1*	0.79	< 20*	< 0.05*	1.16	0.11	< 0.05*	< 0.15*	< 0.1*	25.5	12.7
07-SA-18	< 20*	< 20*	7.06	99.2	0.52	2.46	< 20*	12.7	< 0.1*	< 0.1*	29.8	< 0.05*	24.8	0.22	0.09	< 0.15*	< 0.1*	21.2	6.27
07-SA-19	< 20*	< 20*	0.94	78.0	< 0.2*	0.48	< 20*	1.67	< 0.1*	< 0.1*	< 20*	< 0.05*	3.29	0.22	< 0.05*	< 0.15*	< 0.1*	4.1	-3.74
07-SA-20	< 20*	< 20*	3.57	87.1	0.24	2.53	< 20*	4.06	< 0.1*	< 0.1*	21.4	< 0.05*	5.84	< 0.1*	< 0.05*	< 0.15*	< 0.1*	20.1	14.0
07-SA-21	< 20*	< 20*	4.45	196	0.31	2.35	< 20*	2.31	< 0.1*	< 0.1*	< 20*	< 0.05*	4.28	0.20	< 0.05*	< 0.15*	< 0.1*	20.7	11.9
07-SA-22	29.6	< 20*	1.72	399	< 0.2*	0.85	< 20*	1.16	< 0.1*	0.14	< 20*	< 0.05*	1.73	0.34	< 0.05*	< 0.15*	< 0.1*	7.3	15.7
07-SA-23	< 20*	< 20*	2.15	158	0.38	1.00	< 20*	3.26	< 0.1*	0.43	< 20*	< 0.05*	5.47	1.13	< 0.05*	< 0.15*	< 0.1*	7.3	13.6
07-SA-24	< 20*	< 20*	5.77	181	1.57	4.96	< 20*	36.4	< 0.1*	0.42	41.5	< 0.05*	63.0	9.94	0.23	< 0.15*	< 0.1*	12.2	6.08
07-SA-25	< 20*	< 20*	3.13	144	0.75	2.04	< 20*	13.0	< 0.1*	0.13	21.8	< 0.05*	22.6	3.89	0.12	< 0.15*	< 0.1*	7.8	7.34
07-SA-26	127	< 20*	2.92	130	< 0.2*	1.38	< 20*	0.53	< 0.1*	0.50	< 20*	< 0.05*	0.70	0.31	< 0.05*	< 0.15*	< 0.1*	16.2	-3.14
07-SA-27	< 20*	< 20*	5.63	53.6	0.21	2.71	< 20*	0.83	< 0.1*	0.15	< 20*	< 0.05*	0.42	0.21	< 0.05*	< 0.15*	< 0.1*	30.2	6.42
07-SA-28	< 20*	< 20*	7.46	< 20*	< 0.2*	3.42	< 20*	2.02	< 0.1*	0.28	24.6	< 0.05*	3.11	0.29	< 0.05*	< 0.15*	< 0.1*	34.9	10.7
07-SA-29	36	< 20*	1.63	393	< 0.2*	0.79	< 20*	0.68	< 0.1*	0.34	< 20*	< 0.05*	1.04	0.28	< 0.05*	< 0.15*	< 0.1*	6.6	20.9
07-SA-30	26.5	< 20*	1.41	409	< 0.2*	0.68	< 20*	0.39	< 0.1*	0.19	< 20*	< 0.05*	0.90	0.14	< 0.05*	< 0.15*	< 0.1*	5.6	16.9
07-SA-31	< 20*	< 20*	1.74	303	< 0.2*	0.82	< 20*	0.58	< 0.1*	0.46	< 20*	< 0.05*	1.14	0.32	< 0.05*	< 0.15*	< 0.1*	7.0	15.3
07-SA-32	< 20*	< 20*	3.49	215	< 0.2*	1.83	< 20*	0.31	< 0.1*	0.54	< 20*	< 0.05*	0.41	0.16	< 0.05*	< 0.15*	< 0.1*	15.9	20.6
07-SA-33	< 20*	< 20*	4.13	477	0.21	2.06	< 20*	0.37	< 0.1*	1.29	< 20*	< 0.05*	0.48	0.25	< 0.05*	< 0.15*	< 0.1*	19.2	17.3
07-SA-34	200	< 20*	5.67	442	0.28	2.25	< 20*	0.59	< 0.1*	1.03	< 20*	< 0.05*	0.51	0.85	< 0.05*	< 0.15*	0.22	24.1	15.9
07-SA-35	< 20*	< 20*	3.97	307	0.4	1.89	106	0.22	< 0.1*	0.18	< 20*	< 0.05*	0.57	0.26	< 0.05*	< 0.15*	0.24	19.1	11.2

A.2.2 Surface sediments

Table A.3: Sedimentological, organic geochemical data and stable carbon isotope ratios from sampled Northern and Central Yakutian surface sediments. δ^{13}C ratios with errornous measurements are marked by a two asterisks (**).

Lake-No	Sand	Silt	Clay	Mean	Skewness	Kurtosis	TC	TIC	TOC	TN	C/N	Magnetic suscpetibility	δ^{13}C
	[vol.-%]	[vol.-%]	[vol.-%]	[ϕ]	[ϕ]							[SI]	[‰]
05-YAK-01	8	68	24	4.09	0.35	3.18	1.29	0.66	0.64	0.05	12.3	81	-27.7
05-YAK-02	9.01	65.99	25	5.32	0.5	3.03	1.79	0.54	1.25	0.13	10.0	100	-27.9
05-YAK-03	12	56	32	5.54	0.1	2.07	5.78	1.05	4.73	0.58	8.14	123	-31.7
05-YAK-04	12	62	26	5.51	-0.2	2.41	14.5	-0.46	15.0	1.45	10.3	97	-30.4
05-YAK-05	9.01	70.99	20	5.54	0.69	3.11	1.58	0.47	1.10	6.57	6.57	152	-26.7
05-YAK-06	3.99	47.01	49	5.54	0.46	2.71	23.3	-13.8	37.1	1.70	22.4	45	-23.7
05-YAK-07	1	19	80	2.45	1.18	4.07	25.2	-11.9	37.0	1.89	20.0	50	-22.4
05-YAK-08	6	36	58	4.09	0.79	2.78	43.8	-3.60	47.3	3.76	12.8	78	-20.7
05-YAK-09	9.99	60.01	30	5.49	0.07	2.39	38.6	-2.22	40.9	3.87	10.7	94	-29.6
05-YAK-10	18	71.01	11	6.57	-0.06	2.56	5.22	0.82	4.40	0.48	9.11	110	-26.3
05-YAK-11	18	51	31	5.8	0.14	1.86	23.2	-1.98	25.3	2.31	10.9	91	-27.0
05-YAK-12	9.99	50	40.01	4.98	0.23	2.14	13.4	0.17	13.2	1.34	9.82	102	-26.6
05-YAK-13	8	50	42	4.81	0.19	2.18	35.0	-2.22	37.2	3.52	10.6	94	-23.1
05-YAK-14	9.99	61.01	28.99	5.4	0.23	2.41	15.8	0.45	15.3	1.52	10.1	99	-28.3
05-YAK-15	12	55	33	5.33	0.21	2.21	12.3	0.60	11.7	1.19	9.85	102	-30.8
05-YAK-16	9.01	46.99	44	4.88	0.4	2.14	31.6	-0.38	32.0	3.47	9.23	108	-18.7
05-YAK-17	11	52.01	37	5.1	0.33	2.28	18.5	0.67	17.9	1.74	10.3	97	-31.5
05-YAK-18	13	53.99	33	5.54	0.17	1.98	17.6	-0.55	18.2	1.83	9.21	109	-23.8
05-YAK-19	9.01	50.99	40.01	4.75	0.24	2.3	24.4	-0.31	24.7	2.31	10.7	94	-25.9
05-YAK-20	14	49	37	5.39	0.26	1.96	12.6	-0.37	13.0	1.24	10.5	95	-25.0
05-YAK-21	11	62	27.01	5.42	0.51	2.56	14.9	1.70	14.3	1.67	8.59	116	-28.2
05-YAK-22	9.99	53.01	37	5.21	0.2	2.08	22.6	0.46	22.1	2.70	8.17	122	-28.5
05-YAK-23	9.01	59.99	31	5.32	0.46	2.69	8.09	0.99	7.10	0.97	7.32	137	-27.5

Sedminentological, organic geochemical data and stable carbon isotope ratios. (...continued)

Lake-No	Sand [vol.-%]	Silt [vol.-%]	Clay [vol.-%]	Mean [ϕ]	Skewness [ϕ]	Kurtosis	TC	TIC	TOC	TN	C/N	Magnetic suscpetibility [SI]	δ^{13}C [‰]
05-YAK-24	9.01	57.99	33	5.36	0.16	2.19	14.6	0.96	13.6	1.57	8.69	115	-25.3
05-YAK-25	9.99	58	32	5.34	0.29	2.25	6.21	0.79	5.42	0.59	9.18	109	-26.2
05-YAK-26	12	51	37	5.22	0.25	2.12	10.8	0.24	10.6	1.20	8.84	113	-28.8
05-YAK-27	9.01	51.99	39	5.03	0.36	2.31	14.3	0.70	13.6	1.52	8.98	111	-26.4
05-YAK-28	13	53.99	33	5.55	0.2	1.97	6.52	1.08	5.44	0.75	7.27	138	-27.1
05-YAK-29	13	56	31	5.81	-0.04	1.89	21.2	-2.01	23.7	1.98	12.0	83	-26.1
05-YAK-30	13	53.99	33	5.57	0.24	2.03	38.0	-1.82	39.7	3.65	10.9	92	-22.4
07-SA-01	17	66.01	17	6.07	0.37	2.25	12.0	0.00	12.0	0.64	18.7	54	-28.7**
07-SA-02	18	67	15.01	6.32	0.12	2.12	17.4	0.74	16.7	1.26	13.3	75	-31.0**
07-SA-03	15.99	53.01	31	5.69	0.63	2.15	2.35	0.28	2.06	0.15	14.1	71	-28.0**
07-SA-04	5	10.01	84.99	2.93	1.97	5.58	0.91	0.35	0.56	0.08	6.9	144	-26.0**
07-SA-05	18	43	39	5.54	0.15	1.67	20.5	-0.93	21.6	0.97	22.3	45	-28.5**
07-SA-06	12	59.99	28.01	5.36	0.91	2.79	1.85	0.36	1.50	0.13	11.6	86	-28.3**
07-SA-07	15.99	73.01	11	6.15	0.51	2.36	63.07	0.18	2.89	0.26	11.0	91	-30.1**
07-SA-08	20	70.99	9.01	6.41	0.42	2.21	6.27	0.25	6.01	0.45	13.5	74	-28.7**
07-SA-09	30	68	2.01	7.42	-0.21	2.39	31.3	-2.47	34.0	2.31	14.7	68	-30.6**
07-SA-10	21.01	63	15.99	6.32	0.35	1.98	3.76	0.36	3.39	0.30	11.5	87	-29.9**
07-SA-11	9.01	37	53.99	4.36	0.85	2.6	0.73	0.11	0.62	0.07	8.56	117	-28.4**
07-SA-12	9.01	31.98	59.01	4.33	1.04	2.96	1.00	0.19	0.81	0.08	9.73	103	-28.4**
07-SA-13	40.01	56.98	3.01	7.75	-0.68	2.95	32.7	-2.58	35.5	1.84	19.3	52	-30.3**
07-SA-14	22.99	75	2.01	6.81	0.28	1.99	13.3	-0.32	13.4	0.76	17.6	57	-29.1**
07-SA-15	22.99	53.01	24	6.3	-0.1	1.77	24.8	2.09	22.7	1.61	14.1	71	-22.8**
07-SA-16	17	59.01	624	5.96	0.18	2.04	12.5	1.05	11.4	0.92	12.4	80	-25.9**
07-SA-17	15.99	63	21.01	5.78	0.69	2.34	3.56	0.33	3.23	0.28	11.5	87	-30.3**
07-SA-18	27.01	61	12	6.86	-0.13	2.07	21.3	-1.39	22.6	1.26	17.9	56	-29.3**
07-SA-19	5	8	87	2.69	1.95	6.03	0.25	0.02	0.23	<0.05	5.72	175	No data

Sedminentological, organic geochemical data and stable carbon isotope ratios. (...continued)

Lake-No	Sand	Silt	Clay	Mean	Skewness	Kurtosis	TC	TIC	TOC	TN	C/N	Magnetic suscpetibility	δ^{13}C
	[vol.-%]	[vol.-%]	[vol.-%]	[ϕ]	[ϕ]							[SI]	[‰]
07-SA-20	25	59.01	15.99	6.54	0.02	1.91	16.4	0.07	16.3	1.07	15.3	65	-29.3**
07-SA-21	40.01	58.99	1	7.68	-0.45	2.22	26.4	-0.93	27.4	1.95	14.0	71	-29.4**
07-SA-22	13	34.99	52.01	4.63	0.62	2.13	11.6	0.67	11.0	0.66	16.7	60	-28.5**
07-SA-23	22.99	65.01	12	6.63	-0.1	2.27	7.88	0.11	7.77	0.50	15.7	64	-28.8**
07-SA-24	21.01	70.99	8	6.66	0.24	2.19	4.62	0.12	4.50	0.36	12.6	79	-28.9
07-SA-25	21.01	64.99	14	6.49	0.15	2.02	7.12	0.13	6.99	0.49	14.2	70	-29.0
07-SA-26	22.99	76	1	6.83	0.35	2.02	4.43	0.29	4.14	0.39	10.5	95	-28.8
07-SA-27	28.01	70.99	1	7.11	0.18	1.91	7.04	0.52	6.53	0.71	9.26	108	-27.7
07-SA-28	33	67	0	7.41	0.01	1.88	6.77	0.11	6.66	0.59	11.3	89	-29.6
07-SA-29	32	68	0	7.48	-0.05	2.06	9.91	0.12	9.79	0.88	11.1	90	-30.5
07-SA-30	28.99	71.01	0	7.34	0.12	2.03	9.31	-0.02	9.34	0.76	12.3	81	-30.5
07-SA-31	32	68	0	7.46	-0.01	2.02	5.95	0.14	5.81	0.48	12.1	83	-31.4
07-SA-32	21.99	64	14	6.45	0.09	2.2	10.5	0.42	10.0	1.04	9.66	104	-34.6
07-SA-33	28.01	71.99	0	7.38	0.27	2.13	5.31	0.23	5.08	0.56	9.05	110	-30.8
07-SA-34	15.99	68.02	15.99	6.1	0.46	2.36	3.28	0.39	2.89	0.29	9.94	101	-30.5
07-SA-35	13	27.01	59.99	4.04	0.68	1.84	3.64	0.85	2.79	0.32	8.61	116	-26.1

Table A.4: Inorganic geochemical data obtained from sampled Northern and Central Yakutian surface sediments. Elements contained below in concentrations below detection limit are marked by an asterisk (*).

Lake-No	Al_2O_3	CaO	Fe_2O_2 (gesamt)	K_2O	MgO	MnO	Na_2O	P_2O_5	TiO_2	Ba	Li	Cr	Cu	Ni	Pb	Sr	V	Zn	Zr
	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[ppm]	[ppm]	[ppm]	[ppm]	[ppm]	[ppm]	[ppm]	[ppm]	[ppm]	
05-YAK-01	13.77	3.54	4.36	2.88	2.44	0.07	2.43	0.17	0.69	698	< 0.5**	51	17.6	28.75	26.45	324	84.5	64.5	263.5
05-YAK-02	13.64	2.85	4.05	2.9	2.02	0.1	2.62	0.13	0.68	725	< 0.5*	48.9	13.1	30.85	26.65	333.5	80	59.5	318
05-YAK-03	13.4	4.09	5.4	2.59	2.92	0.11	1.75	0.26	0.69	612	< 0.5*	64	27.2	39.65	29.3	249	85.5	91.5	147.5
05-YAK-04	10.35	2.98	3.92	2.07	2.6	0.08	1.52	0.21	0.5	472	< 0.5*	54	28.9	36.95	< 25*	223	77	67.5	111.5

Inorganic geochemical data. (...continued)

Lake-No	**Al$_2$O$_3$**	**CaO**	**Fe$_2$O$_2$**	**K$_2$O**	**MgO**	**MnO**	**Na$_2$O**	**P$_2$O$_5$**	**TiO$_2$**	**Ba**	**Li**	**Cr**	**Cu**	**Ni**	**Pb**	**Sr**	**V**	**Zn**	**Zr**
			(gesamt)																
	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[ppm]	[ppm]	[ppm]	[ppm]	[ppm]	[ppm]	[ppm]	[ppm]	[ppm]	
05-YAK-05	13.6	2.84	4.98	2.78	2.42	0.08	2.29	0.16	0.65	665	< 0.5*	58	18.55	32.95	26.75	302	83	68.5	278
05-YAK-06	1.36	7.09	1.25	0.95	12.02	0.04	6.28	0.48	0.07	166	< 0.5*	< 10*	< 10*	< 10*	< 25*	365.5	19.35	21.15	10.4
05-YAK-07	1.18	5.67	1.32	0.52	11.94	0.04	4.87	0.45	0.06	180	< 0.5*	< 10*	< 10*	< 10*	< 25*	415	17.35	35.2	< 10*
05-YAK-08	0.95	1.34	0.51	0.18	0.25	0.03	0.18	0.27	0.03	159	< 0.5*	< 10*	10	22.9	< 25*	129.5	< 10*	35.45	< 10*
05-YAK-09	1.43	1.09	2.17	0.27	0.23	0.05	0.24	0.53	0.05	215	< 0.5*	13.45	13.15	26.55	< 25*	111.5	13.05	69	18.85
05-YAK-10	14.13	4	6.26	2.82	2.9	0.1	1.34	0.42	0.69	620	< 0.5*	67.5	32.45	44.7	31.1	237.5	109.5	102.5	113
05-YAK-11	7.24	3.75	3.8	1.36	1.99	0.06	0.96	0.38	0.35	372	< 0.5*	39	26.85	28.7	< 25*	220.5	58.5	69	41.5
05-YAK-12	10.88	3.53	4.29	2.23	2.74	0.08	1.39	0.26	0.54	523	< 0.5*	56	27.6	35.45	< 25*	249.5	81.5	72.5	74.5
05-YAK-13	4.38	1.37	1.69	0.81	0.81	0.02	0.61	0.32	0.2	244	< 0.5*	27.2	21.65	23.1	< 25*	121	34.05	55	22.9
05-YAK-14	10.37	1.76	4.4	1.94	1.71	0.03	1.44	0.29	0.47	505	< 0.5*	49.95	31.3	32.75	< 25*	201.5	71.5	88	116.5
05-YAK-15	12.04	1.64	3.97	2.35	1.84	0.03	1.6	0.25	0.58	550	< 0.5*	50.5	29.8	37.1	< 25*	218.5	75.5	94	154.5
05-YAK-16	5.73	1.48	2.52	1.11	1.21	0.03	0.75	0.37	0.28	287	< 0.5*	29.55	24.3	25	< 25*	131.5	46.5	52.5	74
05-YAK-17	9.94	1.4	2.57	1.95	1.19	0.03	1.37	0.23	0.49	496	< 0.5*	41.45	28.7	27.8	< 25*	201	66	93	164.5
05-YAK-18	9.26	3.4	4.23	1.69	1.82	0.07	1.14	0.34	0.45	456	< 0.5*	40.4	35	37.95	< 25*	219.5	70	98.5	36.8
05-YAK-19	7.12	2.6	3.12	1.47	1.74	0.06	1.08	0.2	0.35	387	< 0.5*	24.7	21.35	25.6	< 25*	216.5	52.5	51.5	70
05-YAK-20	10.88	4.16	6.49	2.05	2.01	0.09	1.44	0.58	0.54	546	< 0.5*	27.85	28.85	35.2	< 25*	236.5	85	79	64.5
05-YAK-21	9.84	2.31	3.06	2.07	1.45	0.04	1.56	0.28	0.51	504	< 0.5*	21.95	20.8	26.6	< 25*	231.5	58.5	65	151
05-YAK-22	8.37	2.28	3.09	1.67	1.57	0.03	1.01	0.38	0.4	390	< 0.5*	35.8	30.25	33.8	< 25*	169 63	5	73	47.75
05-YAK-23	12.7	2.25	4.42	2.58	92	0.05	1.78	0.25	0.63	610	< 0.5*	51	22.95	32.4	< 25*	236.5	81	75	150.5
05-YAK-24	10.03	4.07	3.8	2.11	2.45	0.07	1.5	0.36	0.51	489	< 0.5*	40.4	22.6	29.3	< 25*	244.5	68	67	18.95
05-YAK-25	12.26	3.58	4.03	2.65	2.34	0.07	2	0.2	0.61	638	< 0.5*	41.65	16.45	27.6	< 25*	313	73.5	63.5	127
05-YAK-26	11.64	4.1	4.82	2.28	2.17	0.08	1.34	0.31	0.55	534	< 0.5*	40.8	32.5	34.85	< 25*	238	82	82	22
05-YAK-27	9.81	4.39	3.7	2.13	2.52	0.06	1.4	0.28	0.5	501	< 0.5*	27	22.1	28.4	< 25*	255	67.5	65	24.6
05-YAK-28	12.94	3.29	4.66	2.6	2.77	0.09	1.97	0.24	0.64	619	< 0.5*	23.65	23.85	36.8	< 25*	265.5	83	77.5	87.5
05-YAK-29	8.77	3.08	3.92	1.89	3.55	0.08	1.43	0.31	0.49	385	< 0.5*	43.9	25.7	32.25	< 25*	202.5	71	77.5	92
05-YAK-30	0.94	1.14	0.75	0.14	0.26	0.04	0.15	0.22	0.03	115	< 0.5*	< 10*	11.95	36.3	< 25*	131	< 10*	41.1	12.7
07-SA-01	10.9	1.53	3.65	1.9	0.88	0.05	1.86	0.14	0.67	499	< 0.5*	53	16.35	27.6	< 25*	213.5	85.5	48.85	192.5
07-SA-02	8.31	1.3	2.8	1.42	0.94	0.04	1.21	0.17	0.5	370	< 0.5*	49.65	14.85	31.55	< 25*	165	66.5	115.5	138
07-SA-03	12.32	1.64	3.52	2.7	1.1	0.05	2.47	0.14	0.66	680	< 0.5*	53	10.75	25.45	< 25*	271.5	76	65.5	253
07-SA-04	9.79	0.97	1.13	3.28	0.18	0.08	2.79	0.05	0.19	907	< 0.5*	13	< 10*	< 10*	< 25*	346.5	17.5	17.85	103
07-SA-05	8.67	0.91	3.88	1.57	0.82	0.08	1.19	0.22	0.35	363	< 0.5*	38.1	16.2	19.15	< 25*	182 60	47.85	101.5	
07-SA-06	13.7	1.87	3.73	2.7	1.14	0.06	2.8	0.16	0.78	706	< 0.5*	28.25	< 10*	24.9	< 25*	343.5	81	65.5	292
07-SA-07	14.42	1.54	5.89	2.49	1.36	0.08	2.51	0.29	0.8	626	< 0.5*	35.15	13.6	32.6	< 25*	292.5	98.5	92	202
07-SA-08	13.3	1.51	5.88	2.26	1.36	0.07	2.04	0.23	0.79	552	< 0.5*	37.05	20	36.6	< 25*	228	110.5	78.5	180
07-SA-09	3.36	1.29	4.62	0.52	0.56	0.08	0.31	0.44	0.17	220	< 0.5*	13.95	21.65	45.75	< 25*	131	30.95	376.5	65
07-SA-10	12.94	1.55	8.29	2.36	1.24	0.18	2.21	0.28	0.72	621	< 0.5*	44.25	18.65	32.3	< 25*	247	97.5	67	187.5
07-SA-11	11.81	1.34	2.39	3.02	0.64	0.05	2.48	0.1	0.79	855	< 0.5*	25.75	< 10*	13.65	< 25*	338	54.5	36.95	456.5

Inorganic geochemical data. (...continued)

Lake-No	Al_2O_3 [%]	CaO [%]	Fe_2O_2 (gesamt) [%]	K_2O [%]	MgO [%]	MnO [%]	Na_2O [%]	P_2O_5 [%]	TiO_2 [%]	Ba [ppm]	Li [ppm]	Cr [ppm]	Cu [ppm]	Ni [ppm]	Pb [ppm]	Sr [ppm]	V [ppm]	Zn [ppm]	Zr
07-SA-12	12.21	1.44	3.33	2.88	0.75	0.08	2.83	0.12	0.5	821	< 0.5*	26.65	< 10*	16	< 25*	355	50.5	43.55	201
07-SA-13	5.27	0.85	5.22	0.62	0.47	0.03	0.53	0.28	0.27	235	< 0.5*	20	12.5	31.05	< 25*	98	63.5	62	65
07-SA-14	12	1.23	4.39	1.82	1.08	0.07	1.74	0.18	0.61	487	< 0.5*	29	18.6	33.15	< 25*	211.5	96.5	92.5	123.5
07-SA-15	6.86	1.14	4.12	1.04	0.64	0.07	1.04	0.18	0.36	332	< 0.5*	19.05	11	31	< 25*	147.5	58	74.5	91.5
07-SA-16	10.71	1.22	4.03	1.88	0.97	0.04	1.79	0.22	0.53	521	< 0.5*	30.2	15	33.2	< 25*	228.5	80	87.5	123.5
07-SA-17	13.47	1.72	4.15	2.4	1.28	0.08	2.44	0.14	0.75	608	< 0.5*	38.8	15.95	30.75	< 25*	273.5	96	79.5	179.5
07-SA-18	10.47	1.39	5.88	1.22	1.23	0.06	0.94	0.22	0.57	328	< 0.5*	41.05	23.1	44.3	< 25*	134.5	121.5	98.5	87.5
07-SA-19	8.09	0.92	1.69	2.39	0.4	0.04	1.78	0.04	0.38	693	< 0.5*	26.35	< 10*	< 10*	< 25*	246.5	27.8	16.6	266
07-SA-20	10.92	1.38	5.05	1.6	1.43	0.06	1.18	0.17	0.64	362	< 0.5*	65.5	23.15	42.8	< 25*	150.5	106	120.5	117.5
07-SA-21	5.57	1.61	3.26	0.93	0.85	0.03	0.79	0.35	0.34	234	< 0.5*	29.05	21.9	37.5	< 25*	124	51	110	75.5
07-SA-22	7.97	0.93	4.13	1.67	0.55	0.05	1.36	0.13	0.39	494	< 0.5*	36.2	11.75	27.45	< 25*	180.5	61 58	105	
07-SA-23	13.79	1.12	5.3	2	1.35	0.05	1.7	0.17	0.81	472	< 0.5*	58.5	20.2	36.65	< 25*	199.5	124	99	146.5
07-SA-24	14.28	1.2	4.92	2.41	1.64	0.05	1.93	0.18	0.83	457	< 0.5*	60.5	25.9	42.75	< 25*	230.5	122	119	173.5
07-SA-25	12.85	1.13	4.79	2.2	1.4	0.04	1.85	0.19	0.75	448	< 0.5*	67.5	24.25	41	< 25*	215	113.5	110	167
07-SA-26	11.96	1.34	9.59	1.93	1.18	0.26	1.75	0.37	0.75	500	< 0.5*	60.5	21.85	38.15	< 25*	198	109	85.5	186
07-SA-27	12.77	1.41	5.36	1.99	1.31	0.07	1.71	0.2	0.78	518	< 0.5*	53.5	25.45	40.6	< 25*	197	112	80.5	201.5
07-SA-28	11.54	1.18	13.5	1.75	1.17	0.15	1.52	0.37	0.72	458	< 0.5*	61	24.65	40.75	< 25*	177.5	109.5	76	160
07-SA-29	12.07	0.96	5.88	1.65	1.15	0.05	1.27	0.24	0.69	410	< 0.5*	53.5	28.65	51	< 25*	146	117	136	139.5
07-SA-30	13	0.99	5.83	1.77	1.26	0.05	1.37	0.2	0.74	440	< 0.5*	59.5	23.95	43.6	< 25*	154.5	116	132	140
07-SA-31	12.19	0.97	15.3	1.73	1.17	0.1	1.46	0.65	0.73	438	< 0.5*	60.5	27.4	52.5	< 25*	162	122	116.5	151
07-SA-32	10.2	1.07	6.21	1.58	1.07	0.04	1.36	0.48	0.6	429	< 0.5*	52.5	23.65	38.2	< 25*	156	91.5	82	126.5
07-SA-33	13.6	1.12	6.93	2.02	1.44	0.07	1.63	0.37	0.8	493	< 0.5*	58	29.45	44.7	< 25*	177.5	124	94.5	149.5
07-SA-34	12.91	1.31	6.1	2.07	1.31	0.17	1.79	0.25	0.78	510	< 0.5*	55	21.8	38.65	< 25*	201	106.5	91.5	173.5
07-SA-35	7.69	0.66	6.06	2.12	0.34	0.08	1.34	0.11	0.22	634	< 0.5*	25.3	< 10*	13.75	< 25*	193.5	25.2	30.25	104

A.3 Multivariate statistics

Table A.5: Correlation of species data and principal components I – IV. PCA of species data.

Variable	Axis I	Axis II	Axis III	Axis IV	**Variable**	Axis I	Axis II	Axis III	Axis IV
	$\lambda1 = 0.3461$	$\lambda2 = 0.2490$	$\lambda3 = 0.1148$	$\lambda4 = 0,0858$		$\lambda1 = 0.3461$	$\lambda2 = 0.2490$	$\lambda3 = 0.1148$	$\lambda4 = 0,0858$
TC	0.7666	-0.5324	0.1840	-0.0758	**MgO**	-0.0279	0.1071	0.9277	0.1894
TOC	0.7866	-0.5088	0.2032	-0.0259	**MnO**	-0.4402	-0.1091	0.1346	0.0252
TIC	-0.3494	0.1682	0.1361	-0.3380	**Na_2O**	-0.4601	0.5393	0.4169	0.4814
TN	0.8348	-0.3563	0.1721	6 -0.3003	**P_2O_5**	0.3142	-0.4841	0.4719	-0.1402
C/N	0.3337	-0.3590	-0.0040	0.8349	**TiO_2**	-0.9368	-0.1957	0.0597	0.0788
$\delta^{13}C$	-0.1284	-0.5006	0.2715	0.2277	**Ba**	-0.8735	0.3766	-0.0245	-0.1229
sand	-0.3466	-0.7906	-0.3771	0.1023	**Cr**	-0.7804	-0.3658	0.0892	-0.0782
silt	-0.3042	-0.7681	0.2403	0.0673	**Cu**	-0.1801	-0.6143	0.3959	-0.4106
clay	0.3046	0.7054	0.1925	-0.1650	**Ni**	-0.3572	-0.8539	0.0597	-0.2171
magnetic susceptibility	-0.3272	0.3698	0.0022	-0.8316	**Sr**	-0.4232	0.7020	0.4673	0.2133
Al_2O_3	-0.9550	-0.0708	0.0007	-0.0637	**V**	-0.8223	-0.4499	0.1473	0.0914
CaO	0.0637	0.2239	0.9100	-0.0885	**Zn**	-0.3031	-0.8158	0.0891	-0.0709
Fe_2O_3	-0.7023	-0.5362	0.0517	0.0384	**Zr**	-0.8433	0.0604	-0.3490	0.1274
K_2O	-0.8928	0.3465	0.1347	-0.0612					

Table A.6: Correlation of environmental data and principal components I – IV. PCA of environmental data.

Variable	Axis I	Axis II	Axis III	Axis IV	**Variable**	Axis I	Axis II	Axis III	Axis IV
	$\lambda1 = 0.4992$	$\lambda2 = 0.1219$	$\lambda3 = 0.0788$	$\lambda4 = 0.0755$		$\lambda1 = 0.4992$	$\lambda2 = 0.1219$	$\lambda3 = 0.0788$	$\lambda4 = 0.0755$
pH	0.6131	0.1925	-0.2634	0.4521	**Mg**	0.9826	-0.0076	-0.0706	-0.0605
conductivity	0.8760	0.3453	0.0934	0.1584	**Mn**	0.3375	-0.5344	-0.1824	0.0875
elevation	0.7478	-0.2665	-0.3355	0.1999	**Na**	0.9465	0.1538	0.1572	0.0403

Correlation of environmental data and principal components I – IV. (...continued)

Variable	Axis I	Axis II	Axis III	Axis IV	**Variable**	Axis I	Axis II	Axis III	Axis IV
	$\lambda 1 = 0.4992$	$\lambda 2 = 0.1219$	$\lambda 3 = 0.0788$	$\lambda 4 = 0.0755$		$\lambda 1 = 0.4992$	$\lambda 2 = 0.1219$	$\lambda 3 = 0.0788$	$\lambda 4 = 0.0755$
water depth	-0.2751	0.2889	-0.7668	-0.0782	**Si**	0.4746	-0.5860	-0.2400	0.2683
Secchi depth	-0.3040	0.2808	-0.6747	0.0746	**Sr**	0.8407	-0.3679	-0.1005	-0.2578
approximate size	-0.3351	0.3759	-0.1482	0.5183	**fluoride**	0.8629	0.0687	0.1098	0.2860
Ba	0.6612	-0.1381	-0.0589	-0.3700	**chloride**	0.7792	0.4766	0.1968	-0.0414
Ca	0.7121	-0.4824	-0.2082	-0.1894	**sulphate**	0.6287	0.2099	-0.1516	-0.5798
Fe	-0.3539	-0.6020	0.1791	0.2966	**Br**	0.7843	0.4745	0.0354	-0.0629
K	0.8485	0.0371	0.1839	0.3414	**HCO_3^-**	0.9704	-0.0466	-0.0419	0.0874

Table A.7: Correlation of species data and axes I – IV in RDA

Variable	Axis I	Axis II	Axis III	Axis IV	**Variable**	Axis I	Axis II	Axis III	Axis IV
	$\lambda 1 = 0.251$	$\lambda 2 = 0.119$	$\lambda 3 = 0.092$	$\lambda 4 = 0.056$		$\lambda 1 = 0.251$	$\lambda 2 = 0.119$	$\lambda 3 = 0.092$	$\lambda 4 = 0.056$
TC	0.5480	-0.3578	0.3051	0.0591	**MgO**	0.2098	0.6214	0.5675	0.3788
TOC	0.5833	-0.3340	0.2937	0.1208	**MnO**	-0.3357	0.1443	0.0594	0.0366
TIC	-0.2594	0.2046	0.1044	-0.3568	**Na_2O**	-0.1340	0.7169	-0.0939	0.3764
TN	0.6243	-0.3279	0.3582	-0.1227	**P_2O_5**	0.2514	-0.0547	0.4725	0.1843
C/N	0.2225	-0.0323	-0.2980	0.6026	**TiO_2**	-0.7788	0.0619	0.0762	0.1105
δ^{13}C	-0.2120	0.0267	0.1829	0.0302	**Ba**	-0.6262	0.2599	-0.0426	-0.249
sand	-0.5299	-0.5222	-0.1247	0.1717	**Cr**	-0.7326	-0.1554	0.3061	0.1160
silt	-0.3858	-0.1183	0.2907	0.0523	**Cu**	-0.2420	-0.2444	0.6500	0.0256
clay	0.4290	0.2862	0.0853	-0.2922	**Ni**	-0.4533	-0.4340	0.3438	0.0024
magnetic susceptibility	-0.2171	0.0389	0.2929	-0.6033	**Sr**	-0.0466	0.7542	0.0293	0.0206
Al_2O_3	-0.8025	0.0527	0.0741	-0.0621	**V**	-0.7371	-0.0496	0.2069	0.1971
CaO	0.3047	0.5965	0.6563	-0.0160	**Zn**	-0.4204	-0.3429	0.2681	0.1221
Fe_2O_3	-0.6733	-0.0885	0.1162	0.1499	**Zr**	-0.7594	0.0442	-0.3056	-0.0010

Correlation of species data and axes I – IV in RDA(...continued)

Variable	Axis I $\lambda 1 = 0.251$	Axis II $\lambda 2 = 0.119$	Axis III $\lambda 3 = 0.092$	Axis IV $\lambda 4 = 0.056$	**Variable**	Axis I $\lambda 1 = 0.251$	Axis II $\lambda 2 = 0.119$	Axis III $\lambda 3 = 0.092$	Axis IV $\lambda 4 = 0.056$
K_2O	-0.6285	0.3456	0.0718	-0.1127					

Table A.8: Correlation of species data and axes I – IV in partial RDA

Variable	Axis I $\lambda 1 = 0.251$	Axis II $\lambda 2 = 0.119$	Axis III $\lambda 3 = 0.092$	Axis IV $\lambda 4 = 0.056$	**Variable**	Axis I $\lambda 1 = 0.251$	Axis II $\lambda 2 = 0.119$	Axis III $\lambda 3 = 0.092$	Axis IV $\lambda 4 = 0.056$
TC	0.4638	-0.0658	-0.2623	-0.2130	**MgO**	0.2804	0.8405	0.2153	-0.1407
TOC	0.4977	-0.0561	-0.2048	-0.2354	**MnO**	-0.2800	0.1641	0.0787	0.0831
TIC	-0.1650	0.1628	-0.2130	0.0671	**Na_2O**	-0.0180	0.4520	0.5839	-0.0356
TN	0.5393	-0.0201	-0.4115	-0.1286	**P_2O_5**	0.2865	0.2168	-0.1259	-0.1524
C/N	0.1570	-0.1749	0.5419	-0.2142	**TiO_2**	-0.7302	0.1454	0.0550	-0.0307
$\delta^{13}C$	-0.1499	0.1364	-0.0786	-0.0575	**Ba**	-0.5246	0.1328	-0.0774	0.0847
sand	-0.5827	-0.3838	0.0083	-0.1316	**Cr**	-0.7235	0.1929	-0.1332	-0.1594
silt	-0.3924	0.1820	-0.1488	-0.0336	**Cu**	-0.2140	0.2620	-0.4268	-0.1636
clay	0.4437	0.1906	-0.2129	0.0844	**Ni**	-0.4881	-0.0108	-0.3120	0.0135
magnetic susceptibility	-0.1521	0.1773	-0.5342	0.2234	**Sr**	0.0594	0.5108	0.2377	0.0985
Al_2O_3	-0.7289	0.1067	-0.0839	-0.0411	**V**	-0.6962	0.1578	0.0099	-0.1411
CaO	0.3876	0.8188	-0.1517	0.0418	**Zn**	-0.4587	-0.0217	-0.1708	-0.1330
Fe_2O_3	-0.6388	0.0622	0.0430	-0.0678	**Zr**	-0.7522	-0.0943	0.1717	0.0582
K_2O	-0.5092	0.2840	-0.0192	-0.0025					

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