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Physical and geochemical characteristics of lakes and ponds in Vestfjella, Dronning Maud Land

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Abstract: Shallow Antarctic surface lakes belong to the most extreme aquatic environments on the Earth. In Vestfjella, proglacial surface lakes and ponds are characterized by a 2–5 months long period with liquid water, depth less than 2 m. We give a detailed description of nine seasonal lakes and ponds situating at three nunataqs (Basen, Plogen and Fossilrygen) in western Dronning Maud Land. Their physical and geochemical properties are provided based on observations in four summers. Three main `lake categories´ were found: (i) supraglacial lakes, (ii) epiglacial ponds, and (iii) nunataq ponds. Category (iii) can be divided into two sub-groups whether the melt water source is glacial or just seasonal snow patches. Supraglacial lakes are ultra-oligotrophic (electric conductivity EC < 10 µS cm^{-1}, pH < 7), while in epiglacial ponds the concentrations of dissolved and suspended matter and trophic status vary in a wide range (EC 20–110 µS cm^{-1}, pH 6–9). In nunataq ponds, the maxima were EC = 1042 µS cm^{-1} and pH = 10.1; and water temperature may have wide diurnal and day-to-day fluctuations (max 9.3°C), because snowfall, snow drift and sublimation influence on the net solar irradiance.

Key words: Antarctica, lakes, ponds, supraglacial, epiglacial, seasonal, hydrology, geochemistry, classification

Introduction

The Antarctic continent possesses three types of surface lakes. Epiglacial lakes are found close to the oceanic boundary of the continent and at foot of nunataqs, and supraglacial lakes form in the surface layer of the ice sheet where "blue ice" exists (e.g. Menzies 1995; Vincent et al. 2008; Hodgson 2012). Epiglacial lakes are characterized as lakes in contact with a glacier and with inflow from glacial meltwater. They are an important habitat of life in the polar world (Kaup 1994; Hawes *et al.* 2008). Supraglacial lakes, in turn, are a part of the ice sheet forming a liquid water layer on top. They are extremely low in biota (Keskitalo *et al.* 2013) and represent one type of extreme habitats. They show high sensitivity to atmospheric conditions and thereby assist detection of regional climate change (e.g. Winther *et al.* 1996; Leppäranta *et al.* 2013b; 2016).

The present study region is in Vestfjella, Dronning Maud Land, near the grounding line of Riiser-Larsen Ice Shelf. The Finnish Research Station Aboa acted as the field base. In its neighbourhood, epiglacial and supraglacial seasonal lakes and ponds exist in summer at three nunataqs, Basen, Plogen and Fossilryggen. Altogether, these water bodies have not yet been thoroughly investigated, although they are located in an area with two research stations with 30 years of operation. Geological and geochemical studies have focused on the Jurassic flood basalt succession which forms the exposed bedrock in the area (Luttinen *et al.* 1998, 2015; Heinonen *et al.* 2010, 2018). A reconnaissance-type geochemical study on the surface lakes has been reported in Lehtinen & Luttinen (2005) and Lehtinen (2006). The structure of Vestfjella supraglacial lakes was reported by Leppäranta *et al.* (2013b), and it has been shown that lakes and ponds in the region support habitats for single-cell and multicellular organisms (Keskitalo *et al.* 2013). These habitats have major importance for studies regarding the survival of life in extreme environmental conditions.

In the Dronning Maud Land there are such perennial ice-covered lakes where the accumulated water storage is deep enough, more than a few meters, so that wintertime ice growth does not reach the lake bottom. The largest of them is Lake Untersee, surface area 11.4 km^2 and maximum depth 169 m (e.g., Wand *et al.* 2004). However, these lakes are located far east from the Vestfjella region.

Our field programme on Vestfjella lakes and ponds was initiated in austral summer 2003–2004, and four field seasons were completed by 2014–2015. Altogether we discovered 28 seasonal water bodies in the study region, with nine of them mapped in more detail. They represent three different types of seasonal surface lakes and ponds. The liquid state period relies on meltwater from the ice sheet or, on top of nunataqs the meltwater from local small glaciers or seasonal snow patches. The lifetime of small pools formed from meltwater of seasonal snow can be shorter than the length of the two-month (December–January) summer (see Leppäranta *et al.* 2013a). In contrast, lakes and ponds with inflow from glacial meltwater grow during two summer months and possess liquid water still in autumn months, but the rest of the year they are in solid state.

The thermodynamics of the proglacial surface water bodies is governed by the radiation balance and penetration of solar radiation into the ice (Leppäranta *et al.* 2013b, 2016). Ponds on nunataqs are shallow with rock or soil bottom, which collects radiative heat during the summer. In such environments, water temperature may vary in a wide range (*cf.* Quesada *et al.* 2008), and stratification can be influenced by dissolved substances in addition to temperature. According to Hawes et al. (2011a,b), small ponds, which are very common in ice-free areas, can possess extreme chemical conditions with high level of pH and DO concentration.

Based on the field programme in 2003–2015, this paper gives a classification of Vestfjella seasonal lakes and ponds, examines their annual cycle of freezing and melting, bathymetry and hydrology, and analyses their geochemistry for electric conductivity, dissolved oxygen, pH and nutrients. The study is largely based on the fieldwork in austral summer 2014–2015, but for a broader view also uses our earlier physical and biological results from 2010–2011 (Keskitalo et al. 2013, Leppäranta et al. 2013b) and geochemical and physical results from 2003–2004 and 2004–2005 (Lehtinen & Luttinen 2005, Leppäranta et al. 2013b). These shallow water bodies are so-called cold environment polar lakes and ponds where a thin ice cover exists and the ice surface temperature is below the freezing point. Most of them are small ponds rather than lakes in the strict sense.

Material and methods

Sites

The present field research was carried out in the Finnish Research Station Aboa in the western Dronning Maud Land, located on Basen nunataq at 73° 02.5'S, 13° 24.4'W, altitude 485 m above sea level (a.s.l.). The data was collected mainly from nine proglacial lakes and ponds in Vestfjella at the nunataqs Basen, Plogen and Fossilryggen (Fig. 1; Table 1) during four field seasons: December–January in 2003–2004, 2004–2005, 2010–2011, and 2014–2015. Besides the nine study targets, a few extra lakes were mapped. Especially, in summer 2004–2005 a pond was mapped in the Swedish station Svea to serve as a significantly colder site reference

(74°34.6'S, 11°13.5'W, elevation 1261 m a.s.l.), and in summer 2014–2015 we verified 17 ponds with liquid water around and on top of Basen nunataq.

The water bodies are here called lakes and ponds. There is no generally accepted distinction between them; here the size distinction is taken, as often, at the area of 50,000 m^2 or five hectares. The nine study lakes and ponds are situated as follows: three ponds (Toppond1, Toppond2 and Rockpool) on the top of Basen, three ponds (Velodrome, Penaali and Ringpond) at the foot of Basen, one lake (Lake Suvivesi) next to Basen, one pond on top of Fossilryggen (Fossilryggen pond), and one lake at the foot of Plogen (Plogen lake). The last two targets are, respectively, at 45 and 30 km distance from Basen. All the water bodies are shallow with a maximum depth of ≤ 2 m and only one of them is larger than 1 km^2. Long-term weather statistics by Kärkäs (2004) are used as a reference for the local climate.

Fig. 1a. Map of the study area in the western Dronning Maud Land, Antarctica, **b.** The study lakes around and on the top of Basen, **c.** Plogen lake next to the nunataq, and **d.** Fossilryggen lake on top of the nunataq.

Table 1. Lake type, location, surface area, maximum depth, altitude and site information of the study lakes and ponds. The types are nunataq ponds (nqpo), supraglacial lakes (supra), and epiglacial ponds (epi) (explained in the section Classification of lakes and ponds of Results -chapter).

Data collected

In each field season, the period of observations was December–January. The data collection consisted of manual sampling and sounding sites, and automated stations. Hydrological investigations included formation, horizontal and vertical morphology and dimensions, and mass and heat balance of the lakes and ponds. Chemical investigations, in turn, included ice, snow, and water samples for a wide set of analyses. Hydrological and chemical measurements were carried out in all field seasons. In addition, biological studies were included in 2010–2011 and 2014–15; their outcome concerning the ecosystem is not reported here but is in preparation for a forthcoming publication.

The first field campaign in December 2003–January 2004 (Lehtinen & Luttinen 2005) involved acquisition of water and rock samples, and measurements of pH and electric conductivity of lake water. Altogether seven water bodies were included. For Lake Suvivesi, the changing surface conditions were documented and the thickness of ice-cover and water layer were monitored by drilling at about every second day. Albedo measurements on Lake Suvivesi (five spots), on adjacent snow-covered areas, and on a snow-free slope on Basen were performed using a Middleton EP-16 pyrano-albedometer system (spectral range 0.30–3.0 μm). The positions of five aluminium poles were determined on December 8 and 22, 2003, and January 14, 2004 with Real Time Kinematic GPS measurements using the Aboa permanent GPS station as a reference station in order to monitor ice flow.

In the second field season, December 2004–January 2005, Lake Suvivesi was mapped for the cross-sectional structure and heat balance (Leppäranta *et al.* 2013b). A radiation station was deployed on the ice cover of the lake. Global solar radiation (range 0.3–3 μm) was measured with the Middleton EP-16, and the net radiation (range 0.2–100 μm) was recorded with Kipp & Zonen NR Lite net radiometer. Recording underwater sensors for photosynthetically active radiation (PAR, 400–700 nm band), manufactured by MDS-L Alec Electronics Co. Ltd., Japan, were used at several sites, including recordings inside the lake ice and water body. Ice and water samples were taken for the geochemistry only from Lake Suvivesi. The summer was quite warm and in large areas over the central lake the ice cover was less than 5 cm thick with even open spots in places. The thickness field was patchy and it became more and more difficult to cross the lake with dry feet. The liquid water production was vertically 1–1.5 m in the lake body. Investigations of other lakes were largely limited to visual observations and photography.

The third field season was performed in December 2010–January 2011. Lake Suvivesi was again the main study site with largely similar field programme as in the previous case (Leppäranta *et al.* 2013b). A radiation station was deployed as in the previous case. The sampling programme was expanded to eight lakes and ponds (all except Rockpool in Table 1) with hydrographic soundings. Mass and energy balance of snow patches on Basen nunataq was also examined providing valuable information of the liquid water production from these spots (Leppäranta *et al.* 2013a). *In situ* measurements included water temperature and conductivity by YSI Professional sounding device. Samples for geochemistry were transported in frozen state (–20 °C) to Finland for analyses in the laboratory of Lammi Biological Station (LBS), University of Helsinki. Plankton samples were taken from several sites and transported in liquid phase to LBS for microscopic species analyses (Keskitalo *et al.* 2013).

The most extensive field season was December 2014–January 2015. The field programme was performed from December 4, 2014 to January 28, 2015. The seven sampling sites at

Basen (Table 1) were visited weekly while Plogen lake and Fossilryggen pond were visited three times during the summer. Therefore, the summertime evolution of the water bodies was possible to obtain in detail. In addition, 22 snow samples were collected for basic chemistry analyses from the study sites. This summer was the coldest of all, and liquid water production at the sites was down to almost half of that in the warm summers. The automated radiation station was deployed in Lake Suvivesi as before, and manual PAR soundings were made in Suvivesi, Plogen and Fossilryggen with LiCor sensors for spherical and planar irradiance in the water and planar irradiance just above the surface. Water temperature and dissolved oxygen (DO) concentration (optical sensor) were mapped using an YSI Professional sounding device, while pH was measured after returning to Aboa with Orion pH meter (Model 201). Also, MiniDOT and Optolog data loggers were used in Lake Suvivesi, Toppond1 and Rockpool for temperature and DO. The loggers were covered by aluminium foil to avoid any warming due to sunlight. Plankton samples were analysed in Aboa, and geochemistry samples were transported in frozen state (–20 °C) to the LBS laboratory.

This paper gives a classification of Vestfjella seasonal lakes and ponds, examines their annual cycle of freezing and melting, bathymetry and hydrology, and analyses their geochemistry. In later papers, the light transfer and biology will be treated in detail.

Data analyses

The geochemical analyses of water samples from summer 2003–2004 were performed at the Natural Resources Institute Finland, Rovaniemi. The cations were analysed using Dionex AS40 automated sampler and Dionex ICS-1000 with IonPack CG12A and IonPack CS12A columns. Anions were analysed using Dionex DX-120, with IonPack AG 9-HC and IonPack AS 9-NC columns. The pH and EC measurements were carried out using a Mettler Toledo pH meter at Aboa station within 12 hours after sampling.

In the LBS laboratory, 2010–2011 and 2014–2015 geochemistry samples (meltwater) were analysed for absorption spectrum, electrical conductivity, pH, total nitrogen, total phosphorus and cation concentrations. All chemical determinations were completed within one month since they had been received at LBS in the middle of April. pH was measured with Orion 3 Star pH meter, electrical conductivity with YSI 3200 pH meter, and cation concentrations with Varian SpectrAA 220/FS atomic absorbance spectrophotometer (AAS). Total phosphorus (TP) and total nitrogen (TN) concentrations were determined after wet oxidation with a Gallery Plus Thermo Scientific analyser (Koroleff 1983). Absorption spectra were measured with a Shimadzu Spectrophotometer (UV-2100) across 200–750 nm band with 2 nm spectral resolution.

Most statistical analyses for geochemistry were performed by SigmaPlot12.5 and Real Statistics Soft wares. The normalized chemical variables $\frac{x_i - \bar{x}}{s}$, where $\bar{x}$ is mean and s is standard deviation, were included in the K-Means Cluster analysis. The water variables included were pH, electrical conductivity, colour (beam absorption of filtered sample at 440 nm wavelength), total phosphorus (TP), total nitrogen (TN), potassium, sodium, calcium, magnesium, iron and manganese.

Results

Classification of lakes and ponds

The hydrological classification of Antarctic surface water bodies (Table 1) is made on the basis of the time scale (seasonal/perennial), bottom type (ice/ground) and water source (glacial/seasonal snow). The study lakes and ponds are all seasonal and belong to the following groups:

1) Nunataq group. Ponds on nunataqs, ground bottom of inorganic sediment and/or rock. Sub-classification is based on the source of water: 1a) Glacial meltwater (Toppond 1 and 2, Fossilryggen pond), 1b) Meltwater of seasonal snow patches (Rockpool);
2) Supraglacial group. On top of ice sheet, inflow mainly glacial meltwater (Lake Suvivesi, Plogen lake); and
3) Epiglacial group. At edge of ice sheet, fed by melt-water from ice sheet and drainage from land (nunataq) (Ringpond, Penaali, Velodrome).

Another way of expressing the classification is that, in addition to atmosphere, nunataq ponds interact with the ground, supraglacial lakes interact with the ice sheet, and epiglacial ponds interact with both ice sheet and ground. Lakes Suvivesi and Plogen are also close to a nunataq at one side; they are large and predominantly form from the local ice sheet, but close to the nunataq the influence of inflow from the nunataq is significant. Thus, "near-supraglacial" would be a more precise classification of these lakes. In the study area, blue ice spots in the ice sheet were only found at the side of nunataqs created by the dominant wind conditions. It will be shown later that the cluster analysis of the geochemistry of the study lakes supports the chosen classification.

Annual cycle of the proglacial water bodies

Consider heating of the ice sheet prior to the beginning of the ice melting. Using the heat diffusion equation with the solar source term, the temperature distribution can be solved from the quasi-stationary balance between absorption of radiation and heat conduction until the ice starts to melt (see, e.g., Leppäranta 2015). The heat gained inside the ice is partly conducted back to atmosphere and partly used to warm the ice. The maximum temperature is obtained at the depth

$$z_m = \frac{1}{\kappa}\log\left(\frac{Q_{s+}}{Q_0 + Q_{s+}}\right) \qquad (1)$$

where $\kappa \approx 0.6$ m^{-1} is the light attenuation coefficient, Q_0 is the surface heat balance, and Q_{s+} is the net solar radiation penetrating into the ice. For a solution $z_m > 0$, we must have $0 < -Q_0 < Q_{s+}$ for the heat fluxes, *i.e.* there is heat loss at the surface but the total flux is positive. If $Q_0 \geq 0$, the maximum temperature is located at the surface ($z_m = 0$). Ice melting can start when the maximum temperature has reached the melting point.

Our field data from the four summers fit well with the simple theoretical reasoning. According to the observations, $Q_0 < 0$ and melting started at ~ ½ meter depth and then extended from there up and down. This start-up was observed to take place close to December 1st in Basen sites, where the minimum mean monthly air temperature is –21.9°C, in August. The liquid water body formed and grew only during December and January due to the intensive solar radiation. The body of ice changed to liquid state in a continuous manner and more or less monotonously depending on the weather (Fig. 2). The structure is described by the porosity $\nu = \nu(x,y,z;t)$, or the relative amount of liquid water. When the porosity reached the critical 'no strength' level $\nu = \nu_0 \sim \frac{1}{2}$, the ice lost its integrity and remaining ice pieces rose up due to their buoyancy. As a result, a liquid water layer was developed, and the deeper ice was less and less porous with depth.

The amount of liquid water in supraglacial and epiglacial lakes and ponds varied inter-annually by the factor of two. Diurnal variations of liquid water content could be relatively large in small ponds, and ponds where the inflow was from seasonal snow patches could dry up in summer due to lack of water**.** In December, several small pools formed at the top of Basen but later, in January all water had dried up. The water volume was not measured and only a couple of photographs are available in addition to the visual observations at site.

In Lake Suvivesi, in January 2004 and 2005, open water areas formed in places and the water layer was 60–130 cm deep. In the peripheral areas, the ice cover was 5–15 cm thick and the water layer was 40–100 cm thick. The extent of the liquid layer appeared to reach its maximum in mid-January. In January 2011 the situation was almost the same, but in summer 2014–2015 the lake growth ceased at the end of December, water volume was less than in earlier years and surface ice cover was 25–30 cm thick.

Fig. 2. Structural profile of supraglacial lakes and nunataq ponds in Vestfjella.

Refreezing may last for several months. According to the Stefan's formula, a new ice layer grows with accumulated freezing-degree-days (*FFD*, in °C·d) as $a \cdot \sqrt{FFD}$, $a \approx 3$ $\mathrm{cm}(°\mathrm{C} \cdot \mathrm{d})^{-1/2}$ is a coefficient depending on the thermal properties of ice. Thus it requires $FFD \approx 1000$ °C·d or two months with normal autumn temperatures of around –15°C to freeze completely a 1–m water layer. Thus, each year for 4–5 months there is liquid water. The lake bottom is a heat sink, because the glacier or ground beneath the ice is colder than the freezing point of water. It is well known that at 10-m depth the temperature is equal to the annual average air temperature, which is –15°C in the study region. The heat loss to deeper ice sheet can be estimated, assuming a linear temperature profile below the water body, as about 5 W m^{-2}, which corresponds to ice growth rate of 1.4 mm d^{-1}. The heat loss to ground depends on its thermal quality but is not expected to be much different from the heat loss to deeper ice.

Bathymetry

All the studied liquid water bodies were seasonal and shallow regardless of their location, on the top of ice sheet or on the top of a nunataq (Table 1). No perennial lakes or ponds were found in the Vestfjella region. Eq. (1) gives the depth where melting of ice starts in the top layer of an ice sheet. Then the part of the solar radiation, which penetrates through the surface, Q_{s+}, grows the water body vertically up to 1–2 m depth in one summer. The maximum depth can be estimated using the heat balance. The heating power Q_{s+} is distributed vertically as $\kappa e^{-\kappa z}$, and to become part of the water body, melting must bring the porosity to a critical level ν^* during the melt season of length t_m. The scale of the lake depth becomes then

$$H = \frac{1}{\kappa}\log\left(\frac{Q_{s+}}{\rho L} \cdot \frac{\kappa t_m}{\nu^*}\right) \qquad (2)$$

where ρ is ice density and L is the latent heat of freezing. The first factor in the logarithm is the rate of ice melting, and the second factor distributes the melting to an active layer. In our study region, $t_m \approx 60$ days and $\kappa \approx 0.6$ m^{-1}. For $Q_{s+} \approx 50$ W m^{-2} and $\nu^* \approx 0.3$, the melt rate is 1.4 cm d^{-1}, active layer thickness is 2 m and $H \approx 0.9$ m. This corresponds to dominantly clear sky summers at Aboa. If the summer is cold and cloudy weather dominates, the depth may be restricted down to 0.5 m such as in summer 2014–2015. The atmospheric warming rate is about 5°C per month in Vestfjella spring, and therefore in Svea station, at 1 km higher altitude than the foot of Basen, the melt season would be one month shorter with $H \sim 0.3$ m, as observed in January 2005.

In nunataq snow and ice spots, melting may reach the ground (Fig. 3). When the ice sheet thickness is small, $\lesssim \kappa^{-1}$, heating of the ground plays a major role in the formation, growth and freeze-up of the liquid water body. Bottom heating brings the liquid water body to the ground and warms the bottom water. A shallow lake acts like a greenhouse cover above the bottom, and the water temperature becomes notably high. Concentration of dissolved matter may also be high so that it influences the water density and, consequently, the stratification and circulation. Due to the combined influence of solar heating and salinity stratification, temperatures as high as 9°C were observed in the bottom layer of very shallow nunataq ponds (Table 2). In Fossilryggen pond, the warm bottom layer was persistent although the surface ice cover was 20 cm thick in 2014–2015 summer. In our epiglacial and supraglacial lakes the temperature did not get much above 1°C.

Fig. 3. Top pond2 on Basen, January 17, 2015.

Morphology

The state of the lake surface depends on the surface heat balance. When the air temperature is close to the freezing point, both liquid and solid surface states are possible in equilibrium. Continuous surface heat gain from above means open water surface, but otherwise we have an ice cover with surface heat loss compensated by conduction from the liquid water body. Albedo is a stabilizing factor: switching from ice surface to open water adds on absorption of solar radiation and strengthens the stability of the open state and vice versa. In our study lakes, ice surface is the predominant situation. Thus

$$k\frac{dT}{dz} = Q_0 < 0 \qquad (3)$$

where k is thermal conductivity of ice, T is temperature, and z is vertical coordinate. This gives the surface ice layer thickness as $h \sim \frac{k(T_0 - T_f)}{Q_0}$, where T_0 is the surface temperature, T_f is the freezing point temperature; e.g., for $Q_0 \sim -10$ W m^{-2} and $T_0 - T_f \sim -1$ °C we have $h \sim 20$ cm. The surface ice thickness decreases this way approaching the seasonal equilibrium. According to our field results, this equilibrium has been typically 10–30 cm in the study region, with patches down to zero thickness or open water state in warm summers.

The birth and growth of a proglacial surface lake depend strongly on the albedo. According to our measurements, the mean summer albedo is 0.55–0.60 over lake surfaces, with significant spatial variability. Since horizontal transfer of heat is very slow, the result is a patchy appearance of the lake body. There are deep spots with high porosity and more solid spots, depending on the albedo. Due to the positive albedo feedback, the patchy appearance is persistent. The overall structure is comparable to wetland soil. Albedo over snow is much higher than over lakes. Our albedo measurements over snow-covered ice sheet averaged to 0.85 and to 0.70 over nunataq snow patches.

In supraglacial lakes, in the main body $\nu > \nu_0$, and deeper down there is a 1-m soft bottom layer with a sub-structure of hard layers and slush layers with sediment particles. The slush layers form due to absorption maximum by the sediments, which have originated from the nearby nunataq in the past years. Similar stratification was seen also in the Plogen lake and as well in a supraglacial lake at Fossilryggen in summer 2004–2005. Nunataq ponds are as normal ponds with water body possibly covered by an ice layer.

Water balance

Blue ice refers to spots in the accumulation zone where the atmospheric water balance is negative and therefore the surface appears as blue ice in contrast to the normal white snow-covered surface. In blue ice patches snowfall is compensated by sublimation and snow drift, a necessary condition to keep the blue surface. To compensate the mass loss, ice velocity is upward near the surface. Blue ice has much lower albedo and much higher transparency than snow and therefore can absorb several times more solar radiation and let it go deeper. In a warming climate, blue ice spots may grow and locally provide strong positive feedback.

According to the observations, the local production of meltwater in blue ice in December–January corresponds to ½ – 1 m liquid water layer, which is distributed in the top

1–2 meters of the ice sheet. At the foot of nunataqs, also runoff from the mountain adds to the water volume of neighbouring lakes. In Lake Suvivesi, the flow was clearly seen in warm summers. In 2003, minor streams were observed to flow from Basen to Lake Suvivesi already on December 10th. Melting on nunataq was efficient, and the inflow streams were strong. Nevertheless, parts of Lake Suvivesi lacked water layer also during this time, and parts of the lake surface layer dried with large subsurface cavities.

Sublimation accounts on average for 1 mm ice per day and reaches 50–100 mm over the whole summer, but in extreme storm situations sublimation rates of 10–15 mm per day have been observed.

Although some epiglacial ponds around the Basen nunataq are hydraulically inter-connected, large differences in water-tables in many of them indicate that the state is not so for all. The ice sheet is tilting down toward the nunataq and the ponds have been formed in this valley at the nunataq foot (Fig. 4). In summer 2014–2015, Penaali pond received plenty of melt-water from the surrounding ice-sheet while in other ponds no visible hydrological inter-connectivity with the ice-sheet was found. This means that solar radiation was the primary factor causing the sub-surface melting. But, in addition, it was observed that some melt-water drained down from the nunataq, where patches of snow and ice melted in the course of summer. Especially the northern and north-eastern side of Basen, where most of these valley ponds are situated, is exposed to sunlight. Based on site photographs, it was seen that the water level of Ringpond was 2 m higher in 2004–2005 than six years later. Also, old cyanobacterial mats on the cliff in 2014–2015 proved that water table had been at least 2 m higher.

Fig. 4. The valley of ponds on the north side of Basen.

Heat balance.

The heat budget is governed by the solar and terrestrial radiation. The surface radiation balance is close to zero, with turbulent heat losses resulting in a surface ice layer, while solar radiation penetrating beneath the surface takes care of the warm-up and melting of ice (Fig. 5). In Lake Suvivesi, the mean net solar radiation in December–January was 115–148 W m^{-2} in the three last field summers, while the net terrestrial radiation and turbulent losses were 33–78 W m^{-2} and 25–53 W m^{-2}, respectively. The mean December–January heat flux for internal ice melting in the lake was 10–59 W m^{-2} that corresponds to melting by 0.3–1.7 cm d^{-1}.

In supraglacial and epiglacial water bodies, the daytime water temperature may rise a little above the melting point in finite water pockets due to absorption of sunlight and slow molecular diffusion. While conduction is slow, convection may take place daytime driven by solar heating. In short periods, the increased temperature of interior water pockets leads to density-driven convection with sinking warm water. This helps in growing the liquid water layer. Between 29 December 2014 and 13 January 2015, the highest water temperatures at 50 cm depth in Lake Suvivesi were 1.0 °C in the afternoons. After mid-night, the temperature fell back to 0 °C.

The patchy melting brings pressure differences, which force, as observed, horizontal movement of liquid water in the porous, slushy lake body. The velocity depends on the hydraulic conductivity, which is highly sensitive to porosity. According to measurements, the hydraulic conductivity increased from 0.1 to 10 cm s^{-1} when porosity increased from low level to the order of ½ where the solid ice lattice breaks down. In slushy field the conductivity was measured as 6 cm s^{-1}. The conductivity measurements were made by water pumping experiments applying the Dupuit hydraulic well formula and by tube tests.

In shallow nunataq ponds, bottom heating by solar radiation can raise to water temperature much above the melting point in the lower layers. What exactly happens then is also dependent on the water salinity. The density range of fresh water in the temperature interval [0°C, 8°C] is 0.132 kg m^{-3} that corresponds to the range of 0.16 μg L^{-1} in the concentration of dissolved solids. Thus, even a weak salinity stratification can compensate temperature differences for the density in cold water. The thermal stratification in nunataq ponds such as Fossilryggen pond can therefore be influenced by the salinity gradient. When a lake forms from ice, the water temperature keeps near the freezing point until the liquid water level reaches the ground, and bottom heating begins and stratification forms (Table 2). The temperature of the bottom water has been observed to be as high as 9°C in our nunataq ponds. In a case of unstable stratification, turnover would appear but no such event was observed.

Fig. 5 illustrates the heat balance of supraglacial lakes and nunataq ponds. Solar heating of the interior well overcomes the boundary losses and produces liquid water on average by 1.1–1.3 cm per day corresponding to heat gain of 40–45 W m^{-2}. Surface radiation balance is below zero due to terrestrial radiation and turbulent losses, which is seen in the existence of a surface ice layer. The turbulent loss is dominated by sublimation. In three summers, the average net solar radiation was 140 W m^{-2}, of which half was used for the surface balance and half penetrated into the lake. Over thick ice ($\gg \kappa^{-1}$), the loss from the lake body to deeper ice sheet is estimated as around 5 W m^{-2}. In thin ice ($\lesssim \kappa^{-1}$), solar heating is returned back to the water body from bottom.

At extreme, an open surface is possible in daytime but at night a very thin ice layer has formed. Since the air temperature keeps below the freezing point, in practice it is not possible for open surface to gain heat from the atmosphere. Open surface absorbs more solar radiation but on the other hand terrestrial radiation and turbulent losses are larger more than for just compensation. Thus, in Vestfjella climate, open surface is not a stable situation.

Fig. 5. Heat balance of supraglacial lakes (left) and nunataq ponds (left). The numbers provide the scales (in W m^{-2}) for net solar radiation (SR), net longwave radiation (LW), turbulent fluxes (TF), conductive flux through surface ice (CF), and heat flux to bottom (BF). The circled numbers give the total heat gain by the water body.

Electric conductivity and colour of water

Table 2 shows electrical conductivity (EC) of the lake water samples. In very low salinity as here, the density of water is proportional to EC. When EC $\lesssim$ 10 µS cm^{-1}, the influence of salinity on the density can be ignored here. The supraglacial lakes form a specific group with very low EC, in Lake Suvivesi 1.5–5.3 µS cm^{-1} with average of 3.7 µS cm^{-1}. In summer 2004–2005 only Lake Suvivesi was included for this part, and the result was then 5.0 µS cm^{-1}. This kind of water is of rather high purity level, suitable for car batteries. In the epiglacial ponds at the foot of Basen the EC magnitude was 10–100 µS cm^{-1}, and in nunataq ponds higher values for recorded, up to 1000 µS cm^{-1}, which corresponds to the concentration of dissolved solids of 0.7 g L^{-1}. EC showed decreasing trend through the summer. In summer 2014–2015 the mean EC of snow was 3.2 µS cm^{-1} in the study region, very close to the value in supraglacial lakes.

Table 2. Electrical conductivity at 25°C (EC), maximum (T_{max}) and mean (T_{mean}) temperature, oxygen (O_2) saturation, and CDOM (coloured dissolved organic matter) in beam absorption at 420 nm during the three summer seasons. Temperature and oxygen measurements indicate those made by YSI in daytime. The number of measurements varied from 3 (Plogen and Fossilryggen) up to 11 (Suvivesi).

The transparency of the lakes depends on the concentrations of optically active substances: coloured dissolved organic matter (CDOM), suspended matter, chlorophyll *a*, and iron, as well as the distribution and proportion of ice with its gas bubbles. CDOM is proportional to the limnological colour index of the water. This was more closely examined in the last expedition. In Lake Suvivesi, the light attenuation coefficient ranged in 0.5–2 m^{-1}. In the mixture of ice pieces and water, scattering of light was very strong and was a major factor in the light attenuation in the body of supraglacial and epiglacial water bodies. Especially in supraglacial lakes, the ice and meltwater were very clean with a low absorption coefficient. CDOM values were extremely low in all study lakes and ponds except in the nunataq ponds on Basen nunataq (Table 2). The highest CDOM values were measured in Rockpool and the second highest in Toppond1, both lakes lying above the bedrock and mineral sediment.

Geochemistry

Water pH varied between lakes and between years. But there was a clear distinction in that in supraglacial and epiglacial lakes and ponds pH was mostly within 6.0–7.5, while higher values were found in nunataq ponds (Table 3). In 2014–2015 the highest pH value (10.1) was found in Rockpool, followed by Toppond1 and Fossilryggen, where pH was above nine. The lowest pH, 5.9 was measured in the supraglacial Lake Suvivesi in the same summer. It was only 0.5 units higher than pH of snow. The pH of the frozen samples transported to Finland was generally 0.5–1 units lower than those measured from the fresh samples. It was found that the water pH and EC were strongly correlated ($r > 0.9$, $p < 0.0001$). In summer 2010–2011, very similar chemical results were obtained as in 2014–2015, water pH varied mostly between 6 and 8.5 with a few higher values in Velodrome pond and Fossilryggen.

Table 3. Geochemistry of the study lakes and ponds. Seasonal averages of sodium (Na), potassium (K), magnesium (Mg), calcium (Ca), manganese (Mn), chloride (Cl), iron (Fe), pH, sulphate (SO_4), phosphate (PO_4), total phosphorus (TP), nitrate (NO_3), and total nitrogen (TN). **(a)** In summer 2003–2004 **(b)** In summer 2014–2015, based from three (Plogen and Fossilryggen) up to 11 (Suvivesi) samples. Standard deviations are shown as ±x below the averages,

In summer 2003–2004, different sampling sites showed highly variable ion concentrations, with Rockpool having clearly the highest seasonal average values and Lake Suvivesi the lowest values, with sodium concentrations of, respectively, 72 mg L^{-1} and 0.12 mg L^{-1} (Table 3a). The epiglacial sampling sites all recorded over ten times higher average ion concentrations than in Lake Suvivesi. The water samples collected from Lake Suvivesi indicated an increase of salinity with time. For example, the concentration of sodium (0.04 mg L^{-1} on December 14, 0.10 mg L^{-1} on January 3, and 0.21 mg L^{-1} on January 21), magnesium, chloride and sulphate showed a relatively strong enrichment. These values are averages of three samples from individual drill holes in an about 10^4 m^2 area. Comparison of chemical and EC data obtained from different sites shows pronounced spatial variation, possibly associated with localized inflow from Basen water into Lake Suvivesi. Consequently, the apparent increase in salinity may be an artefact and, instead, it may reveal a minor epiglacial component in Lake Suvivesi. High salinity in nunataq meltwater ponds and streams may at least partly result from the formation of salt deposits in response to repeated evaporation cycles. X-ray diffraction measurements indicated that the light-coloured salt deposits on basaltic bedrock and soil are mainly calcite (aragonite; $CaCO_3$) and thenardite (Na_2SO_4).

In summer 2014–2015, the lowest difference between minimum and maximum element concentration was recorded in total phosphorus. Except iron, potassium and phosphorus the other chemical constituents had their highest concentrations in Rockpool, where also highest pH and colour were measured. In contrast, in Suvivesi the concentrations were generally lowest among the sites. EC correlated strongly with the concentration of sodium, calcium, and magnesium (for each $r > 0.9$, $p < 0.0001$). Also, potassium, manganese and iron concentrations were correlated with EC ($r > 0.58$, $p < 0.05$). Besides, the different cation (K, Na, Ca, Mg, Mn and Fe) concentrations were inter-correlated when the results of the study sites were considered (all combinations had $r > 0.7$ and $p < 0.01$). Among the epiglacial and supraglacial lakes and ponds, the highest EC and cation concentrations were measured in Ringpond and Velodrome (Table 3b). Sodium, magnesium and calcium were the three cations with highest range of variability in concentration among the water bodies.

In line with cations, also nitrogen and phosphorus concentrations varied substantially between the water bodies in summer 2014–2015. The highest concentrations of phosphorus and nitrogen were found in Rockpool. The lowest nitrogen concentrations appeared in Suvivesi, Ringpond and Plogen, while the lowest phosphorus concentrations were found in Toppond1, Toppond2, Fossilryggen and Ringpond (Table 3). Because of low nitrogen and phosphorus concentrations, their inorganic fractions could be reliably measured only in a few water bodies. In Rockpool, ammonium (NH_4-N) and nitrite-nitrate (NO_2+NO_3-N) comprised together 10% of total nitrogen, and phosphate (PO_4-P) comprised 40% of total phosphorus. In summer 2010–2011, total nitrogen and phosphorus concentrations were predominantly low, but once-twice in a small inflowing beck to Suvivesi, in Ringpond and Toppond2 higher concentrations (up to 700 and 30 μg L^{-1}, respectively) were measured.

Hierarchical clustering based on the geochemistry classified the study lakes and ponds into 4–5 groups depending on the variables included in the analysis. When all data were included, Suvivesi, Plogen and Penaali formed one group, Fossilryggen, Toppond1, Velodrome and Ringpond formed the second group, while Toppond2 and Rockpool made their own individual groups (Fig. 6). However, if all measured variables were included Suvivesi and Penaali formed one group, Plogen, Ringpond and Fossilryggen the second one, Toppond1, Toppond2 and Velodrome the third one, and Rockpool its own fourth group. A very similar grouping was given by pH, EC, colour, and TP and TN concentrations.

Fig. 6. Hierarchical cluster three of the study lakes. The lakes are in the following order: 1 – Suvivesi, 2 – Velodrome, 3 – Penaali, 4 – Ringpond, 5 - Toppond1, 6 - Toppond2, 7 - Rockpool, 8 – Plogen, 9 – Fossilryggen. The cluster is based on the data of pH, EC, colour, total phosphorus, total nitrogen, potassium, sodium, calcium, magnesium, manganese and iron concentrations.

In summer 2014–2015, with a few exceptions, dissolved oxygen (DO) concentrations and saturation levels varied within a narrow range in the water bodies (Table 2). The saturation level was mostly below the equilibrium with atmosphere. However, in Rockpool and Fossilryggen the DO concentrations were close to 20 mg L^{-1} with saturation close to 150%. The highest DO concentration was measured in Fossilryggen on January 21, around 30 mg L^{-1} corresponding to 250% saturation. In Rockpool the maximum DO concentration was 21.4 mg L^{-1} or 174% saturation, measured on December 27 and January 3. The highest DO value recorded by the DO/temperature data logger in Rockpool was 17.4 mg DO L^{-1}, 144% saturation, at noon on December 28. In contrast to 2014–2015, in summer 2010–2011 DO supersaturation was measured only twice, both cases in Velodrome pond.

Comparing the geochemistry between the summers 2003–2004 and 2014–2015, it is seen that the element concentrations were alike. The differences can be largely explained by the differences in the weather conditions and in the sampling techniques, and by random variations. For example, the stratification of temperature and chemistry was strong in Fossilryggen pond, and it is therefore understandable that the exact sampling depth has a major role. In the ponds on the top of Basen, biological activity was very high that makes the timing of the sampling important. Our supraglacial lakes were disturbed by inflow from nunataq close to the edge in localized streams, as suggested by observations. In pure supraglacial conditions, the lake water quality would be influenced only by the local ice sheet and atmospheric deposition.

Discussion

Relative to the nunataqs and ice-sheets, the study lakes and ponds can be divided into three major groups. The classification showed follows the lines of Vincent et al. (2008) and Hodgson (2012) but includes only the types of lakes present in Vesfjella region. Supraglacial and epiglacial water bodies, which are situated on the ice-sheet, and nunataq ponds on top of nunataqs (Table 1). The location of a water body relative to the neighbouring nunataq and ice-sheet affects its hydrological and chemical characteristics. The formation of supraglacial and epiglacial water bodies is dependent on the existence of blue ice, which allows light penetration through the topmost layer of the ice-sheet. Plogen and Penaali received meltwater inflow also from the ice-sheet as was also clearly indicated by the chemistry results. The closure of the seasonal lakes is expected to progress by 1–1.5 cm per day or up to 3-4 months for the deepest lakes observed (Hawes et al. 2011a). There are very small water pockets (below 1 m scale) in the ice sheet surface layer, called cryoconite holes, initiated by impurities at the ice sheet surface (Hawes *et al.* 2008) but they have not been considered here.

Nunataq ponds are more strongly influenced by the nunataq water balance, since there is significant meltwater inflow from the surrounding drainage area. Toppond1 was clearly influenced by local melting, while Toppond2 was seemingly influenced by snow and ice melting around. Toppond1 had nearly 1 m thick ice-cap but Toppond2 was very shallow, and the lake was mostly ice-free in daytime if weather was sunny and warm, but frozen if the day was cloudy and cold. Rockpool was very shallow, far from glaciers and gained water from seasonal snow melting. All the snow in its drainage basin melted already early in summer, the water level started to decline, and the pool as well as several other similar water bodies started to dry up. In Rockpool some water remained as long we continued our measurements till the end of January, however. In nunataq snow patches, meltwater runoff was around 1 mm SWE (snow water equivalent) per day (Leppäranta *et al.* 2013a).

Our study lakes in Vestfjella, Dronning Maud Land, are oligotrophic or ultraoligotrophic characterized by low EC and nutrient concentrations, equally with most Antarctic surface lakes (Lyons & Finlay 2008). Their life history depends on the local climate. In much colder environment the summer warming would not reach the melting stage, while in much warmer environment the lakes would become perennial. Our study lakes appear to climatologically quite far from these extreme cold and warm situations.

According to their locations relative to the nunataqs and physical and chemical characteristics, the studied water bodies can be grouped into a few categories. Lake Suvivesi makes its own category because of its large surface area and consequently its weak dependence on the melt water from the nunataq. However, although very little direct impact on the lake also in this case the nunataq has an indirect impact on the lake evolution, because Basen gives a shelter against wind which is a prerequisite for the blue-ice formation. In all lakes liquid water exists only in the uppermost layer of the ice. However, lakes which are situated in close contact with the nunataqs are influenced by the erosion material transported by melt water to the lakes and ponds.

In Lake Suvivesi the element concentrations showed large spatial variability. Comparing with the snow cover in the neighbourhood (Kärkäs *et al.* 2005; Lehtinen 2006), the medians were about the same for sodium, potassium, sulphate and nitrate, while calcium and magnesium were enriched, and chloride concentration was lower in the lake. The differences indicate significant impact from nunataq via inflow.

When transport of inorganic material is strong enough, meltwater discharge affects the pH, EC and other geochemistry variables. The earlier studies have shown that the nunataqs and the surface waters of the present study may have abnormally high cation concentrations, in particular magnesium and calcium, but low levels of nitrogen and phosphorus (Lehtinen & Luttinen 2006; Keskitalo *et al.* 2013).

In those lakes and ponds which are situated on top of Basen nunataq or in close contact with it on the glacier, nitrogen and phosphorus may partially originate from the sea where snow petrels (*Pagodroma nivea*) feed and carry food to their nesting areas in Basen and Plogen. In summer 2014–2015 the populations consisted of 30–50 and 3–5 pairs, respectively in these nunataqs. In addition, in Basen one pair of South Polar Skua (*Stercorarius antarcticus*) was nesting, feeding on the snow petrels and thus releasing nutrients to the environment. Occasionally, also two other petrel species (*Oceanites oceanicus*, *Thalassoica antarctica*) visited in the area, mostly seen above Basen.

In small ponds on top of Basen nunataq cyanobacteria may have supported nitrogen reserves. In small rockpools, in particularly, plankton mat communities have lot of cyanobacteria which can fix atmospheric nitrogen (Bergman *et al.* 1997; Charpy *et al.* 2010). The importance of *in situ* assimilated nitrogen or phosphorus released through erosion relative to those transported from the sea by birds, is unknown, however.

Antarctic lakes are mostly considered to be phosphorus-limited, although nitrogen and phosphorus concentrations can vary considerably among them (Laybourn-Parry 2003), and in some areas nitrate-rich waters can be found (Vincent & Howard-Williams 1994). In our study lakes nutrient limitation seems to be a major feature as well (Keskitalo et al. 2011), although each water body behaves differently and thus the impact on water chemistry varies from lake to lake. Our results indicate, that among the group of nunataq ponds, 2–3 different sub-groups can be identified based on their hydrological and water chemistry properties. The melt water inflow from the nunataq strongly influences the water chemistry in Penaali and Plogen, and explains that their water chemistry characteristics are close to that of Suvivesi. Shallow rockpools with their rich cyanobacterial mat communities are unique ecosystems due to their food webs and very high photosynthetic potential. In Antarctica, cyanobacterial mat communities can be abundant in many lake and pond ecosystems (e.g. Hawes et al. 1992, Hodgson et al. 2004, Singh & Elster 2007). According to Hawes et al. (2011a), benthic communities usually predominate over planktonic ones in small ponds in ice-free areas of Antarctica.

Regarding the water chemistry and heat balance, inorganic bottom sediment is an important characteristic in small ponds (Toppond1, Toppond2, Rockpool and Fossilryggen) on top of the nunataqs. The presence of sediment differentiates them from the rest of our water bodies, where the liquid water layer was above ice. As a result of the inorganic sediment, small ponds and rockpools on top of the nunataqs had higher water pH and nitrogen and phosphorus concentrations than the other water bodies. Very high pH values (>10) and DO concentrations (up to 100 mg L^{-1}) have been earlier found by Hawes et al. (2011b) in small ponds in McMurdo Ice Shelf close to Bratina Island.

Among our water bodies, Rockpool was a unique environment with overwhelmingly rich cyanobacterial community. Although receiving melt water from the surrounding snow patches, and equally with the two nunataq ponds (Toppond1 and Toppond2) with bottom sediment, we suggest that the rockpools should be considered as specific water formations. The reason is that their life-span is shorter than in other lakes and ponds, and thermal conditions are more variable. In addition, organisms in rockpools are exposed to higher UV radiation than in deeper lakes and ponds with much thicker ice cover.

Conclusions

In Vestfjella, in western Dronning Maud Land, three main `lake categories´ were found: (i) supraglacial lakes, (ii) nunataq ponds, and (iii) epiglacial ponds. Category (ii) can be divided into two sub-groups whether the melt water source is glacial or just seasonal snow patches. Supraglacial waters are ultra-oligotrophic, while in nunataq ponds the concentrations of dissolved and suspended solids vary in a wide range. Each water body behaves as an individual and thus the impact on water chemistry varies from lake to lake. Our results indicate, that among the group of nunataq ponds, 2–3 different sub-groups can be identified based on their hydrological and water chemistry properties.

The heat budget of the Vestfjella lakes is dominated by solar radiation and long-wave radiation losses, with turbulent heat exchange acting strongly only episodically. Sublimation can become a significant part of the mass balance. The limnological quality of the water bodies ranges from ultra-oligotrophic supraglacial lakes to small hypereutrophic nunataq ponds.

Water temperature may also vary widely among the lakes and ponds. Shallow ponds usually freeze over at night-time and during snowstorms and cold weather, while during sunny days they are mostly ice-free. We propose that the three lake types are common in the vicinity of nunataqs in the western and northern Dronning Maud Land.

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Author contribution

Matti Leppäranta has taken part in three field trips in 2004–2015 reported here, Arto Luttinen took care of the lake research in the first one (2003–2004), and Lauri Arvola joined the last one (2014–2015). The analysis and the paper write-up have been made together with equal efforts. Leppäranta is responsible mainly for the physics, Luttinen and Arvola for the geochemistry and biology.

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Table 1. Lake type, location, surface area, maximum depth, altitude and site information of the study lakes and ponds. The types are nunataq ponds (nqpo), supraglacial lakes (supra), and epiglacial ponds (epi) (explained in the section Classification of lakes and ponds of Results - chapter).

Lake or pond	Type	Location from 73°S 13°W	Area (m^2)	Depth max (m)	Altitude (m)	Site information; meltwater source
Lake Suvivesi	Supra	02.84’ 28.66’	$3.61 \cdot 10^6$	2.0	185	Ice sheet surface
Velodrome	Epi	00.91’ 22.00’	710	0.75	215	At rocky Basen base; ice sheet and nunataq ice
Penaali	Epi	01.02’ 24.04’	15,000	0.75	215	
Ringpond	Epi	01.65’ 26.39’	4,700	1.5	205	
Toppond1	Nqpo	01.40’ 24.03’	200	0.5	535	On nunataq soil; nunataq ice, inorganic sediments
Toppond2	Nqpo	01.28’ 23.71’	500	0.2	535	
Rockpool	Nqpo	01.00’ 22.72’	15	0.2	525	On rock; seasonal snow
Plogen lake	Supra	11.90’ 48.51’	135,000	1.0	300	Ice sheet surface
Fossilryggen pond	Nqpo	23.50’ 02.17’	1,100	1.0	700	On nunataq soil, nunataq ice, inorganic sediments

Table 2. Electrical conductivity at 25°C (EC), maximum (T_{max}) and mean (T_{mean}) temperature, oxygen (O_2) saturation, and CDOM (coloured dissolved organic matter) in beam absorption at 420 nm during the three summer seasons. Temperature and oxygen measurements indicate those made by YSI in daytime. The number of measurements varied from 3 (Plogen and Fossilryggen) up to 11 (Suvivesi).

	2003–2004	**2010–2011**	**2014–2015**				
	EC µS cm^{-1}	*EC* µS cm^{-1}	*EC* µS cm^{-1}	T_{max} °C	T_{mean} °C	O_2 *saturation* %	CDOM a_{420nm} in m^{-1}
Suvivesi	1.5	5.3	3.1	1.5	0.5	94	0.010
Velodrome	38	112	59	0.6	0.5	103	0.040
Penaali	48	x	5.4	0.6	0.3	87	0.048
Ringpond		30	19	0.6	0.3	75	0.002
Top pond1		12	59	1.7	0.6	82	0.620
Top pond2	158	25	186	9.3	4.7	91	0.324
Rockpool	1042	x	801	6.9	4.7	147	1.153
Plogen	16	2.0	5.4	0.6	0.4	85	0.066
Fossilryggen	18	64	229	7.6	3.6	159	0.066
Snow	x	x	3.2	0.0	x	x	x

Table 3. Geochemistry of the study lakes and ponds. Seasonal averages of sodium (Na), potassium (K), magnesium (Mg), calcium (Ca), manganese (Mn), chloride (Cl), iron (Fe), pH, sulphate (SO_4), phosphate (PO_4), total phosphorus (TP), nitrate (NO_3), and total nitrogen (TN). **(a)** In summer 2003–2004 **(b)** In summer 2014–2015, based from three (Plogen and Fossilryggen) up to 11 (Suvivesi) samples. Standard deviations are shown as ±x below the averages.

a. **Geochemistry 2003–2004.**

	pH	**Na** mg L^{-1}	**K** mg L^{-1}	**Mg** mg L^{-1}	**Ca** mg L^{-1}	**Cl** mg L^{-1}	**SO4** mg L^{-1}	**NO3** mg L^{-1}	**PO4** mg L^{-1}
Suvivesi	6.3	0.12	0.01	0.05	0.88	0.22	0.15	29.1	117
Velodrome	7.5	2.95	0.04	0.99	8.23	3.81	6.97	297	-
Penaali	6.4	3.22	0.04	1.26	8.11	4.52	6.27	323	-
Top pond2	7.8	10.30	1.02	10.13	28.03	15.67	13.30	-	-
Rockpool	7.4	71.53	1.59	47.99	69.42	175.7	62.50	-	-
Plogen	6.0	0.43	0.02	0.33	2.68	0.48	1.02	72.7	-
Fossilryggen	5.7	1.31	0.16	0.70	1.81	1.57	2.48	305	-

b. Geochemistry 2014–2015

	pH	Na mg L^{-1}	K mg L^{-1}	Mg mg L^{-1}	Ca mg L^{-1}	Mn mg L^{-1}	Fe mg L^{-1}	TP µg L^{-1}	TN µg L^{-1}
Suvivesi	5.8	0.06 ±0.04	0.41 ±0.53	0.02 ±0.01	0.06 ±0.05	<0.01 ±<0.01	0.01 ±0.01	44	98
Velodrome	9.0	1.05	0.06	0.64	6.20	0.01	0.21	163	287
Penaali	6.4	0.35 ±0.16	0.06 ±0.05	0.06 ±0.03	0.35 ±0.07	<0.01 ±<0.01	0.02 ±0.01	52	109
Ringpond	8.7	3.10 ±2.91	0.36 ±0.43	0.91 ±0.92	4.20 ±2.83	0.01 ±<0.01	0.06 ±0.02	8	73
Top pond1	9.3	4.19 ±0.91	0.50 ±0.07	2.50 ±0.08	6.15 ±1.06	0.01 ±<0.01	0.54 ±0.32	9	192
Top pond2	9.0	9.46 ±11.44	1.10 ±1.05	6.39 ±8.70	16.2 ±21.92	0.01 ±<0.01	0.08 ±0.00	6	120
Rockpool	10.1	203 ±124	4.52 ±2.64	21.7 ±31.1	26.8 ±8.34	0.01 ±<0.01	0.08 ±0.08	43	1798
Plogen	6.5	0.11 ±0.11	0.02 ±0.01	0.06 ±0.07	0.40 ±0.42	<0.01 ±<0.01	0.01 ±0.01	9	38
Fossilryggen	9.2	24.6 ±27.40	8.21 ±7.72	8.05 ±9.69	39.5 ±43.13	0.01	0.04 ±0.00	5	283
Snow	5.4	–	–	–	–	–	–	3.8 ±0.8	88 ±37

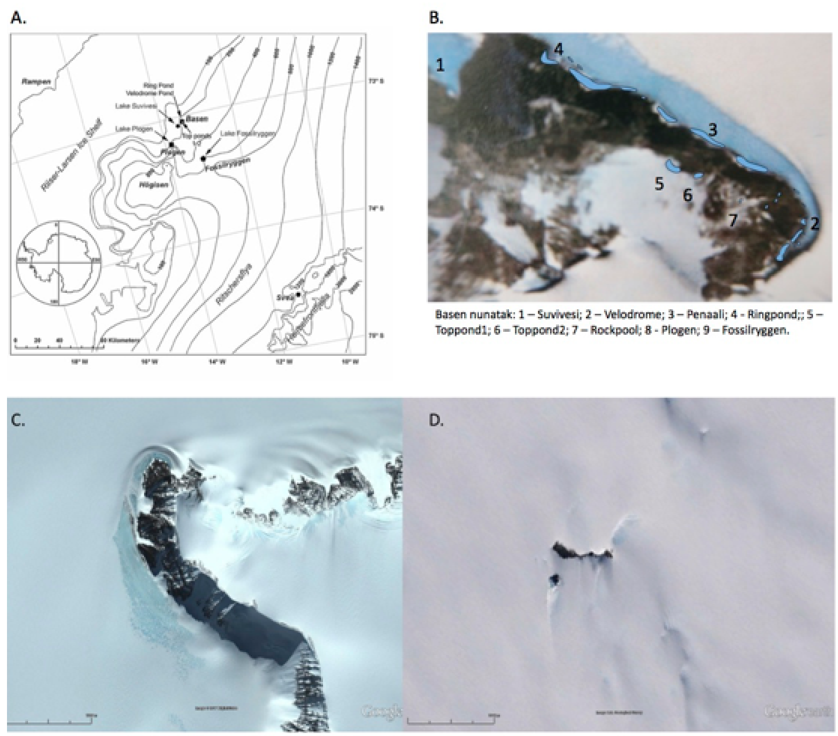

Fig. 1. Map of the study area in western Dronning Maud Land, Antarctica (A). The study lakes around and on the top of Basen (B). Plugen lake next to the nunatak (C). Fossilryggen lake on top of the nunatak (D).

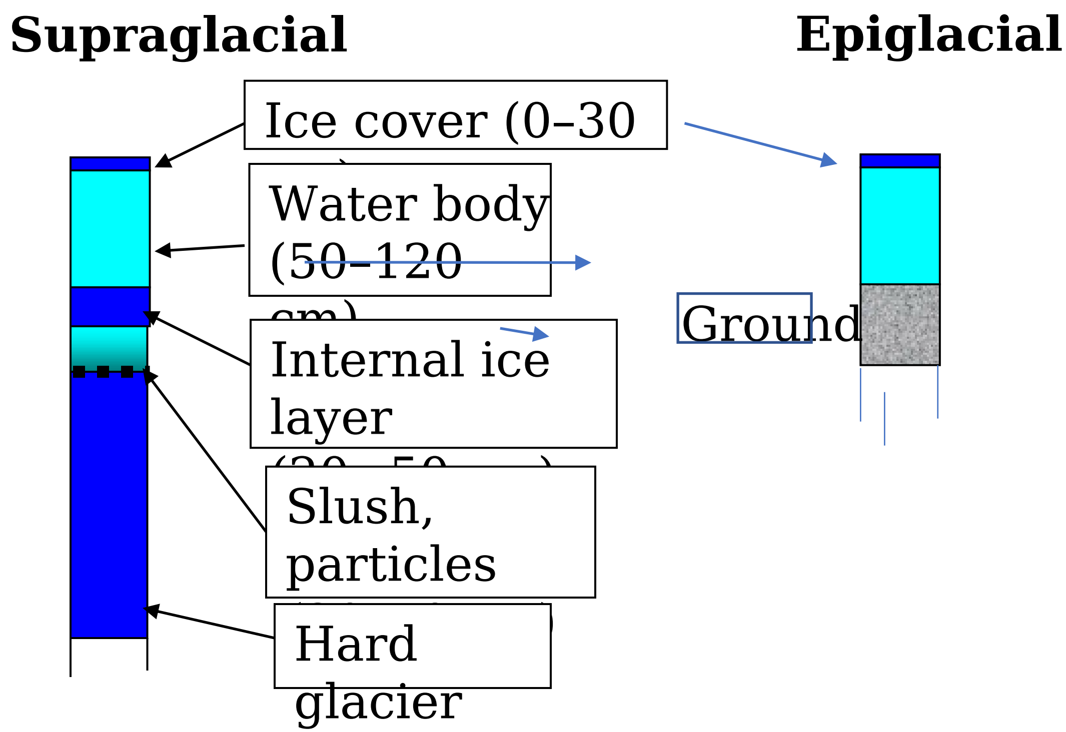

Fig. 2. Structural profile of supraglacial and epiglacial lakes in Vest

Fig. 3. Top pond2 on Basen, January 17, 2015.

Fig. 4. The valley of ponds on the north side of Basen. Note the dark colour of caused by dust and meltwater discharge from the nunatak.

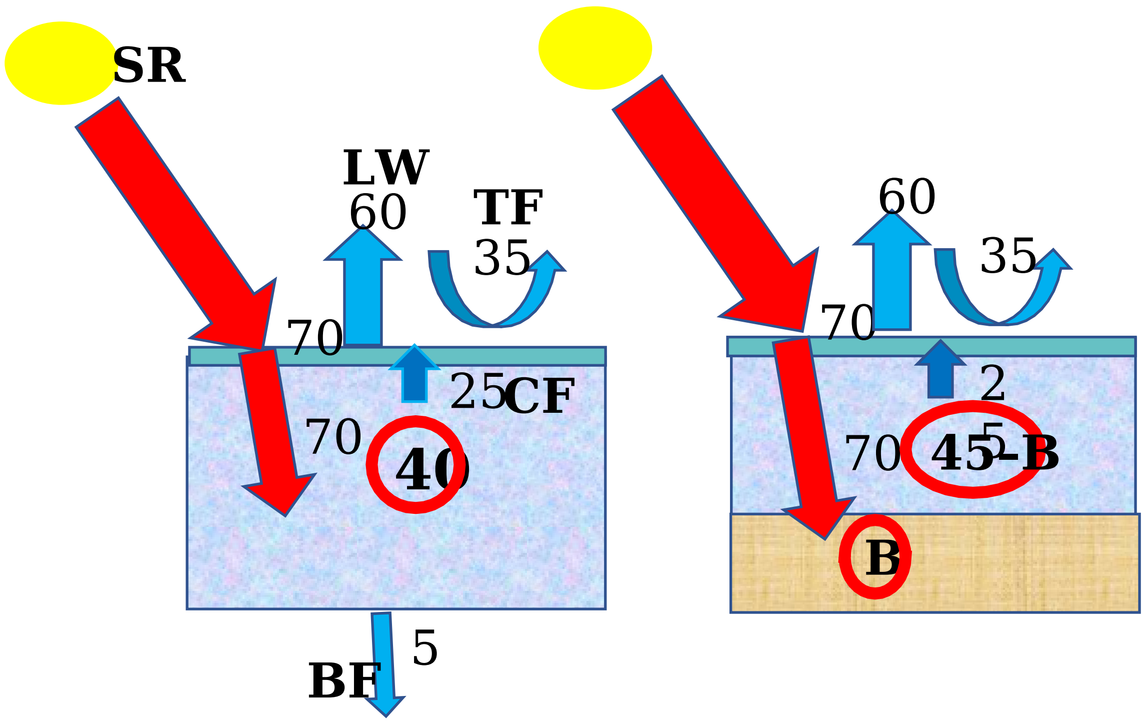

Fig. 5. Heat balance of supraglacial (left) and epiglacial (left) lakes. The numbers provide the scales (in W m^{-2}) for net solar radiation (SR), net longwave radiation (LW), turbulent fluxes (TF), conductive flux through surface ice (CF), and heat flux to bottom (BF). The circled numbers give the total heat gain by the water body.

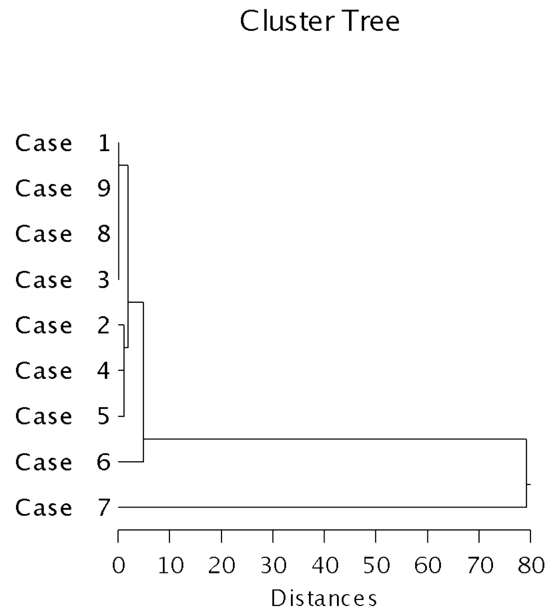

Fig. 6. Hierarchical cluster three of the study lakes. The lakes are in the following order: 1 – Suvivesi, 2 – Velodrome, 3 – Penaali, 4 – Ringpond, 5 - Toppond1, 6 - Toppond2, 7 - Rockpool, 8 – Plogen, 9 – Fossilryggen. The cluster is based on the data of pH, EC, colour, total phosphorus, total nitrogen, potassium, sodium, calcium, magnesium, manganese and iron concentrations.

Running head: Lakes and ponds in Vestfjella, Dronning Maud Land

Physical and geochemical characteristics of lakes and ponds in Vestfjella, Dronning Maud Land

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Abstract: Shallow Antarctic surface lakes belong to the most extreme aquatic environments on the Earth. In the study area, Vestfjella, proglacial surface lakes and ponds are characterized by a 2–5 months long period with liquid water, depth less than 2 m. We give a detailed description of nine seasonal lakes and ponds situating on or at the base of three nunataqs (Basen, Plogen and Fossilrygen) in western Dronning Maud Land. Their physical and geochemical properties are provided based on observations in four summers. Three main `lake categories´ were found: (i) supraglacial lakes, (ii) epiglacial ponds, and (iii) mixed (features from (i) and (ii))nunataq ponds. Category (iii) can be divided into two sub-groups whether the melt water source is glacial or just seasonal snow patches. Supraglacial lakes tend to bare ultra-oligotrophic (electric conductivity EC < 10 µS cm^{-1}, pH < 7), while in epiglacial epiglacial pondsponds the concentrations of dissolved and suspended matter and trophic status vary a lotin a wide range (EC 20–110 µS cm^{-1}, pH 6–9), depending on the location and melt-water source. In epiglacial lakesnunataq ponds, the maxima were EC = 1042 µS cm^{-1} and pH = 10.1; and water temperature may have wide diurnal and day-to-day fluctuations (max 9.3°C), because snow-fall, snow drift and sublimation influence on the net solar irradiance.

Key words: Antarctica, lakes, and ponds, supraglacial, epiglacial, seasonal, hydrology, geochemistry, classification

Introduction

The Antarctic continent possesses three types of surface lakes. Epiglacial lakes are found on the bare ground close to the oceanic boundary of the continent and at foot or on top of nunataqs, and supraglacial lakes form in the surface layer of the ice sheet where "blue ice" exists (e.g. Menzies 1995; Vincent et al. 2008; Hodgson 2012). Epiglacial lakes are characterized as lakes as normal cold region lakes with bottom on rock or soilin contact with a glacier, andbut fed with inflow fromby glacial meltwater inflow. They are an important habitat of life in the polar world (Kaup 1994; Hawes *et al.* 2008). Supraglacial lakes, in turn, are a part of the ice sheet forming a liquid water layer on top. They are extremely low in biota (Keskitalo *et al.* 2013) and represent one type of extreme habitats. They show high sensitivity to atmospheric conditions and thereby assist detection of regional climate change (e.g. Winther *et al.* 1996; Leppäranta *et al.* 2013b; 2016). There are also lakes, which have characteristics of both epiglacial and supraglacial lakes, classified here as the mixed type.

The present study region is in Vestfjella, Dronning Maud Land, near the grounding line of Riiser-Larsen Ice Shelf. The Finnish Research Station Aboa acted as the field base. In its neighbourhood, epiglacial and, supraglacial and mixed type seasonal lakes and ponds exist in summer at three nunataqs, Basen, Plogen and Fossilryggen. Altogether, these water bodies have not yet been thoroughly investigated, although they are located in an area with two research stations with 30 years of operation. Geological and geochemical studies have focused on the Jurassic flood basalt succession which forms the exposed bedrock in the area (Luttinen *et al.* 1998, 2015; Heinonen *et al.* 2010, 2018). A reconnaissance-type geochemical study on the surface lakes has been reported in Lehtinen & Luttinen (2005) and Lehtinen (2006). The structure of Vestfjella supraglacial lakes was reported by Leppäranta *et al.* (2013b), and it has been shown that lakes and ponds in the region support habitats for single-cell and multicellular organisms (Keskitalo *et al.* 2013). These habitats have major importance and interest for studies regarding the survival of life in extreme environmental conditions.

In the Dronning Maud Land there are such perennial ice-covered lakes where the accumulated water storage is deep enough, more than a few meters, so that wintertime ice growth does not reach the lake bottom. The largest of them is Lake Untersee, surface area 11.4 km^2 and maximum depth 169 m (e.g., Wand *et al.* 2004). But However, they these lakes are located far east from the Vestfjella region.

Our field programme on Vestfjella lakes and ponds was initiated in austral summer 2003–2004, and four field seasons were completed by 2014–2015. Altogether we discovered 28 seasonal water bodies in the study region, with nine of them mapped in more detail. They represent ~~the~~ three different types of seasonal surface lakes and ponds. The liquid state period relies on meltwater from the ice sheet or, on top of nunataqs the meltwater from local small glaciers or seasonal snow patches. The lifetime of small pools ~~fed~~ formed from meltwater of~~by~~ seasonal snow can be shorter than the length of the two-month (December–January) summer (see Leppäranta *et al.* 2013a). In contrast, ~~epiglacial~~ lakes and ponds ~~fed by~~with inflow from glacial meltwater ~~usually receive water and~~ grow during two summer months and ~~stay alive in~~possess liquid water still in autumn months, but the rest of the year they are in solid state.

The thermodynamics of the~~se~~ proglacial surface water bodies ~~are~~ is governed by the ~~surface~~ radiation balance and penetration of solar radiation into the ice (Leppäranta *et al.* 2013b, 2016). ~~Epiglacial~~ Ponds on nunataq~~ pond~~s are shallow with rock or soil bottom, which~~and their bottom~~ ~~also~~ collects radiative heat during the summer. In such environments, water temperature may vary in a wide range (*cf.* Quesada *et al.* 2008), and stratification can be influenced by dissolved substances in addition to temperature. According to Hawes et al. (2011a,b), small ponds, which are very common in ice-free areas, can possess extreme chemical conditions with high level of pH and DO concentration.

Based on the field programme in 2003–2015, this paper gives a classification of Vestfjella seasonal lakes and ponds, examines their ~~life~~ annual cycle of freezing and melting, bathymetry and hydrology, and analyses their geochemistry for electric conductivity, dissolved oxygen, pH and nutrients. The study is largely based on the fieldwork in austral summer 2014–2015, but for a broader view also uses our earlier physical and biological results from 2010–2011 (Keskitalo et al. 2013, Leppäranta et al. 2013b) and geochemical and physical results from 2003–2004 and 2004–2005 (Lehtinen & Luttinen 2005, Leppäranta et al. 2013b). These shallow water bodies are so-called cold environment polar lakes and ponds where a thin ice cover exists and the ice surface temperature is below the freezing point. ~~All they are shallow, and m~~Most of them are small ponds rather than lakes in the strict sense. ~~The heat budget is dominated by solar radiation and long-wave radiation losses, with turbulent heat exchange acting strongly only episodically. Sublimation can become a significant part of the mass balance. The limnological quality of the water bodies ranges from ultra-oligotrophic supraglacial lakes to small hypereutrophic epiglacial ponds.~~

Material and methods

Sites

The present field research was based carried out in the Finnish Research Station Aboa in the western Dronning Maud Land, located on Basen nunataq at 73° 02.5'S, 13° 24.4'W, altitude 485 m above sea level (a.s.l.). The data material was collected mainly from nine proglacial lakes and ponds in Vestfjella at the nunataqs Basen, Plogen and Fossilryggen (Fig. 1; Table 1). during fFour field seasons were completed: December–January in 2003–2004, 2004–2005, 2010–2011, and 2014–2015. Besides the nine study targets, a few extra lakes were mapped. Especially, in summer 2004–2005 a pond was mapped in the Swedish station Svea to serve as a significantly colder site reference (74°34.6'S, 11°13.5'W, elevation 1261 m a.s.l.), and in summer 2014–2015 we verified 17 ponds with liquid water around and on top of Basen nunataq.

The water bodies are here called lakes and ponds. There is no generally accepted distinction between them; here the size distinction is taken, as often, at the area of 50,000 m^2 or five hectares. The nine study lakes and ponds are situated as follows: three ponds (Toppond1, Toppond2 and Rockpool) on the top of Basen, three ponds (Velodrome, Penaali and Ringpond) at the foot of Basen, one lake (Lake Suvivesi) next to Basen, one pond on top of Fossilryggen (Fossilryggen pond), and one lake at the foot of Plogen (Plogen lake). The last two targets are, respectively, at 45 and 30 km distance from Basen. All the water bodies are shallow with a maximum depth of $\leq$ 2 m and only one of them is larger than 1 km^2. Long-term weather statistics by Kärkäs (2004) are used as a reference for the local climate.

Fig. 1a. Map of the study area in the western Dronning Maud Land, Antarctica, **b.** The study lakes around and on the top of Basen, **c.** Plogen lake next to the nunataq, and **d.** Fossilryggen lake on top of the nunataq.

Table 1. Lake type, location, surface area, maximum depth, altitude and site information of the study lakes and ponds. The types are nunataq ponds (nqpo), supraglacial lakes (supra), and epiglacial ponds (epi) (explained in the section Classification of lakes and ponds of Results -chapter).

Table 1. Lake type, location, surface area, maximum depth, altitude and site information of the study lakes and ponds. Lake types are explained in the section Hydrology and physics.

Data collected

In each field season, the period of observations was December–January. The data collection consisted of manual sampling and sounding sites, and automated stations. Hydrological investigations included formation, horizontal and vertical morphology and dimensions, and mass and heat balance of the lakes and ponds. Chemical investigations, in turn, included ice, snow, and water samples for a wide set of analyses. Hydrological and chemical measurements were carried out in all field seasons. In addition, biological studies were included in 2010–2011 and 2014–15; , but their outcome concerning the ecosystem is not reported here but is in preparation for a forthcoming publication.

The first field campaign in December 2003–January 2004 (Lehtinen & Luttinen 2005) involved acquisition of water and rock samples, and measurements of pH and electric conductivity of lake water. Altogether seven water bodies were included. For Lake Suvivesi, the changing surface conditions were documented and the thickness of ice-cover and water layer were monitored by drilling at about every second day. Albedo measurements on Lake Suvivesi (five spots), on adjacent snow-covered areas, and on a snow-free slope on Basen were performed using a Middleton EP-16 pyrano-albedometer system (spectral range 0.30–3.0 μm). The positions of five aluminium poles were defined determined on December 8 and 22, 2003, and January 14, 2004 using with Real Time Kinematic GPS measurements using the Aboa permanent GPS station as a reference station in order to monitor ice flow.

In the second field season, December 2004–January 2005, Lake Suvivesi was mapped for the cross-sectional structure and heat balance (Leppäranta *et al.* 2013b). A radiation station was deployed on the ice cover of the lake. Global solar radiation (range 0.3–3 μm) was measured with the Middleton EP-16, and the net radiation (range 0.2–100 μm) was recorded with Kipp & Zonen NR Lite net radiometer. Recording underwater sensors for photosynthetically active radiation (PAR, 400–700 nm band), manufactured by MDS-L Alec Electronics Co. Ltd., Japan, were used at several sites, including recordings inside the lake ice and water body. Ice and water samples were taken for the geochemistry only from Lake Suvivesi. The summer was quite warm and in large areas over the central lake the ice cover was less than 5 cm thick with even open spots in places. The thickness field was patchy and it became more and more difficult to cross the lake with dry feet. The liquid water production was vertically 1–1.5 m in the lake body. Investigations of other lakes were largely limited to visual observations and photography. Plogen lake was mapped for the vertical structure, and also one supraglacial lake in a deep hollow in Fossilryggen (see Leppäranta *et al.* 2013b) not included in the set of the main targets shown in Table 1. The results showed highly similar

~~morphology in all supraglacial lakes.~~

The third field season was performed in December 2010–January 2011. Lake Suvivesi was again the main study site with largely similar field programme as in the previous case (Leppäranta *et al.* 2013b). A radiation station was deployed as in the previous case. The sampling programme was expanded to eight lakes and ponds (all except Rockpool in Table 1) with hydrographic soundings. Mass and energy balance of snow patches on Basen nunataq was also examined providing valuable information of the liquid water production from these spots (Leppäranta *et al.* 2013a). *In situ* measurements included water temperature and conductivity by YSI Professional sounding device. Samples for geochemistry were transported in frozen state (–20 °C) to Finland for analyses in the laboratory of Lammi Biological Station (LBS), University of Helsinki. Plankton samples were taken from several sites and transported in liquid phase to LBS for microscopic species analyses (Keskitalo *et al.* 2013).

The most extensive field season was December 2014–January 2015. The field programme was performed from December 4, 2014 to January 28, 2015. The seven sampling sites at Basen (Table 1) were visited weekly while Plogen lake and Fossilryggen pond were visited three times during the summer. Therefore, the summertime evolution of the water bodies was possible to obtain in detail. In addition, 22 snow samples were collected for basic chemistry analyses from the study sites. This summer was the coldest of all, and liquid water production at the sites was down to almost half of that in the warm summers. The automated radiation station was deployed in Lake Suvivesi as before, and manual PAR soundings were made in Suvivesi, Plogen and Fossilryggen with LiCor sensors for spherical and planar irradiance in the water and planar irradiance just above the surface. Water temperature and dissolved oxygen (DO) concentration (optical sensor) were mapped using an YSI Professional sounding device, while pH was measured after returning to Aboa with Orion pH meter (Model 201). Also, MiniDOT and Optolog data loggers were used in Lake Suvivesi, Toppond1 and Rockpool for temperature and DO ~~recording~~. The loggers were covered by aluminium foil to avoid any warming due to sunlight. Plankton samples were analysed in Aboa, and geochemistry samples were transported in frozen state (–20 °C) to the LBS laboratory.

This paper gives a classification of Vestfjella seasonal lakes and ponds, examines their annual cycle of freezing and melting, bathymetry and hydrology, and analyses their geochemistry. In later papers, the light transfer and biology will be treated in detail.

Data analyses

The geochemical analyses of water samples from summer 2003–2004 were performed at the Natural Resources Institute Finland, Rovaniemi. The cations were analysed using Dionex AS40 automated sampler and Dionex ICS-1000 with IonPack CG12A and IonPack CS12A columns. Anions were analysed using Dionex DX-120, with IonPack AG 9-HC and IonPack AS 9-NC columns. The pH and EC measurements were carried out using a Mettler Toledo pH meter at Aboa station within 12 hours after sampling.

In the LBS laboratory, 2010–2011 and 2014–2015 geochemistry samples (meltwater) were analysed for absorption spectrum, electrical conductivity, pH, total nitrogen, total phosphorus and cation concentrations. All chemical determinations were completed within one month since they had been received at LBS in the middle of April. pH was measured with Orion 3 Star pH meter, electrical conductivity with YSI 3200 pH meter, and cation concentrations with Varian SpectrAA 220/FS atomic absorbance spectrophotometer (AAS). Total phosphorus (TP) and total nitrogen (TN) concentrations were determined after wet oxidation with a Gallery Plus Thermo Scientific analyser (Koroleff 1983). Absorption ~~spectrum~~ spectra ~~was~~ were measured with a Shimadzu Spectrophotometer (UV-2100) across 200–750 nm band with 2 nm spectral resolution.

Most statistical analyses for geochemistry were performed by SigmaPlot12.5 and Real Statistics Soft wares. The normalized chemical variables $\frac{x_i - \bar{x}}{s}$, where $\bar{x}$ is mean and s is standard deviation, were included in the K-Means Cluster analysis. The water variables included were pH, electrical conductivity, colour (beam absorption of filtered sample at 440 nm wavelength), total phosphorus (TP), total nitrogen (TN), potassium, sodium, calcium, magnesium, iron and manganese.

Results~~: hydrology and physics~~

Classification of lakes and ponds

The hydrological classification of Antarctic surface water bodies (Table 1) is made on the basis of the time scale (seasonal/perennial), bottom type (ice/ground) and water source (glacial/seasonal snow). The study lakes and ponds are all seasonal and belong to the following groups:

1) ~~Epiglacial~~ Nunataq group. Ponds on nunataqs, g~~G~~round ~~basin~~bottom of~~,~~ inorganic sediment and/or rock. Sub-classification is based on the source of water: 1a) Glacial meltwater (Toppond 1 and 2, Fossilryggen pond), 1b) Meltwater of seasonal snow patches (Rockpool);

2) Supraglacial group. On top of ice sheet, inflowfed mainly by glacial meltwater (Lake Suvivesi, Plogen lake); and
3) Mixed Epiglacial group. On top ofAt edge of ice sheet and in close contact with nunataq rocky littoral,; fed by melt-water from ice sheet and drainage from land (nunataq) (Ringpond, Penaali, Velodrome).

Another way of expressing the classification is that, in addition to atmosphere, nunataq ponds interact with the ground, supraglacial lakes interact with the ice sheet, and epiglacial ponds interact with both ice sheet and ground. Lakes Suvivesi and Plogen are also close to a nunataq at one side; but they are large and predominantly form from the local ice sheet,. bBut closer to the nunataq the influence of inflow from the nunataq is significant. Thus, "near-supraglacial" would be a more precise classification of these lakesThe limit between supraglacial and mixed is consequently grey. In the study area, blue ice spots in the ice sheet were only found at the side of nunataqs created by the dominant wind conditions. It will be shown later that the cluster analysis of the geochemistry of the study lakes supports the chosen classification.

Life Annual cycle of the proglacial water bodies

Consider heating of the ice sheet prior to the beginning of the ice melting. Using the heat diffusion equation with the solar source term, the temperature distribution can be solved from the quasi-stationary balance between absorption of radiation and heat conduction until it is seen that the ice starts to melt (see, e.g., Leppäranta 2015). in the illuminated surface layer The heat gained inside the ice is partly conducted back to atmosphere and partly used to warm the ice. , under stationary forcing, Tthe maximum temperature is obtained at the depth

$$z_m = \frac{1}{\kappa}\log\left(\frac{Q_{s+}}{Q_0 + Q_{s+}}\right) \qquad (1)$$

where $\kappa \approx 0.6\ \mathrm{m}^{-1}$ is the light attenuation coefficient, Q_0 is the surface heat balance, and Q_{s+} is the net solar radiation penetrating into the ice. This equation comes from the balance between absorption of radiation and conduction of heat. For a solution $z_m > 0$, we must have $0 < -Q_0 < Q_{s+}$ for the heat fluxes, *i.e.* there is heat loss at the surface but the total flux is positive. If $Q_0 \geq 0$, the maximum temperature is located at the surface ($z_m = 0$). Ice melting can start when the maximum temperature has reached the melting point. The heat gained inside the ice is partly conducted back to atmosphere and partly used to warm the ice. Indeed, according to our observations, melting starts at about ½ meter depth and then extends from there up and down, corresponding to the heat balance in the beginning of summer. This start-up was observed to take place close to December 1st in Basen sites, where the minimum mean monthly temperature is –21.9°C, in August.

Our field data from the four summers fit well with the simple theoretical reasoning. According to the observations, $Q_0 \leq 0$ and melting started at ~ ½ meter depth and then extended from there up and down. This start-up was observed to take place close to December 1st in Basen sites, where the minimum mean monthly air temperature is –21.9°C, in August. The liquid water body forms formed and greeows in the study lakes and ponds only during December and January as a result of ice and snow melting due to the intensive solar radiation. The initial condition for Eq. (1) is that the ≈ 1 m surface layer is close to the melting point. The body of ice changes changed to liquid state in a continuous manner and more or less monotonously depending on the weather (Fig. 2). The structure is described by the porosity $\nu = \nu(x,y,z;t)$ ν, or the relative amount of liquid water. When the porosity reachedds the critical 'no strength' level $\nu = \nu_0 \sim \frac{1}{2}$, the ice lostes its integrity and remaining ice pieces roise up due to their buoyancy. As a result, a liquid water layer wais developed, and the deeper ice wais less and less porous with depth.

The amount of liquid water in supraglacial and mixed epiglacial lakes and ponds has varied inter-annually by the factor of two. Diurnal variations of liquid water content can could be relatively large in small ponds, and ponds fed where the inflow was fromby seasonal snow patches may could dry up in summer due to lack of water**.** In December, several small pools formed at the top of Basen but later, in January all water had dried up. The water volume was not measured and only a couple of photographs are available in addition to the visual observations at site.

In Lake Suvivesi, in January 2004 and 2005, open water areas had formed in places and the water layer was 60–130 cm deep. In the peripheral areas, the ice cover was 5–15 cm thick and the water layer was 40–100 cm thick. The extent of the liquid layer appeared to reach its maximum in mid--January. In January 2011 the situation was almost the same, but in summer 2014–2015 the lake growth ceased at the end of December, water volume was less than in earlier years and surface ice cover was 25–30 cm thick.

Fig. 2. Structural profile of supraglacial and epiglacial lakes and nunataq ponds in Vestfjella.

~~In January 2004 and 2005, open water areas had formed in places and the water layer was 60–130 cm deep. In the peripheral areas, the ice cover was 5–15 cm thick and the water layer 40–100 cm thick. The extent of liquid layer appeared to reach its maximum in mid-January. In January 2011 the situation was almost the same, but in summer 2014–2015 the lake growth ceased at the end of December, water volume was less than in earlier years and surface ice cover was 25–30 cm thick.~~

Refreezing may last for several months. ~~A~~According to the Stefan's formula, a new ice layer grows with accumulated freezing-degree-days (*FFD*, in °C·d) as ~~3 cm~~$a \cdot \sqrt{FFD}$, $a \approx 3\ cm(°C \cdot d)^{-1/2}$ is a coefficient depending on the thermal properties of ice. ~~,~~T~~and t~~hus it requires $FFD \approx 1000$ °C·d or two months with normal autumn temperatures of around –15°C to freeze completely a 1–m water layer. Thus, each year ~~up to half a year~~for 4–5 months there is liquid water~~, while in the other half the frozen state prevails~~. The lake bottom is a heat sink, because the glacier or ground beneath the ice is colder than the freezing point of water. ~~At~~ It is well known that at 10-m depth the ~~ice~~ temperature is equal to the annual average air temperature, which is –15°C in the study region. The heat loss to deeper ice sheet can be estimated, assuming a linear temperature profile below the water body, as about ~~4~~ 5 W m^{-2}, which corresponds to ice growth rate of 1.4 mm d^{-1}. The heat loss to ground depends on its thermal quality but is not expected to be much different from the heat loss to deeper ice.

Bathymetry

All the studied liquid water bodies were seasonal and shallow regardless of their location, on the top of ice sheet or on the top of a nunataq (Table 1). No perennial lakes or ponds ~~have been~~were found in the Vestfjella region. Eq. (1) gives the depth where melting of ice starts in the top layer of an ice sheet. Then the part of the solar radiation, which penetrates through the surface, Q_{s+}, grows the water body vertically up to 1–2 m depth in one summer. ~~According to our data~~T~~, t~~he maximum depth can be estimated using the heat balance~~of a water body produced by solar radiation in the top layer of a thick ice sheet can extend down to 1–2 m in one summer~~. The heating power Q_{s+} is distributed vertically as $\kappa e^{-\kappa z}$~~The primary factors behind are the light attenuation coefficient (κ), solar radiation~~, and to become part of the water body, melting must bring the porosity to a critical level ν^*~~,~~ ~~and t~~during~~he length of~~ the melt season of length ~~(~~t_m~~)~~. The scale of the lake depth ~~is~~becomes then

$$H = \frac{1}{\kappa}\log\left(\frac{Q_{s+}}{\rho L} \cdot \frac{\kappa t_m}{\nu^*}\right) \qquad (2)$$

where ρ is ice density and, L is the latent heat of freezing, and ν^* is the sealing porosity at the bottom of the lake. The first factor in the logarithm is the rate of ice melting of ice, and the second factor distributes the melting to an active layer. In our study region, $t_m \approx 60$ days and $\kappa \approx 0.6$ m^{-1}. For $Q_{s+} \approx 50$ W m^{-2} and $\nu^* \approx 0.3$, the melt rate is 1.4 cm d^{-1}, active layer thickness is 2 m and $H \approx 0.9$ m. This corresponds to dominantly clear sky summers at Aboa. If the summer is cold and cloudy weather dominates, the depth may be restricted down to 0.5½ m such as in summer 2014–2015. The atmospheric warming rate is about 5°C per month in Vestfjella spring, and therefore in Svea station, at 1 km higher altitude than the foot of Basen, the melt season would be one month shorter with $H \sim \frac{1}{3}$0.3 m, as observed in January 2005.

In nunataq snow and ice spots, melting may reach the ground (Fig. 3). When the ice sheet thickness is small, $\lesssim \kappa^{-1}$, heating of the ground plays a major role in the evaluation formation, growth and freeze-up of the liquid the water body. Bottom heating bringexpands the liquid water body to the ground and warms the bottom water. A shallow lake acts like a greenhouse cover above the bottom, and the water temperature becomes notably high. Concentration of dissolved matter may also be high so that it influences the water density and, consequently, the stratification and circulation. Due to the combined influence of solar heating and salinity stratification, temperatures as high as 9°C were observed in the bottom layer of very shallow lakes nunataq ponds (Table 2). In Fossilryggen pond, the warm bottom layer was persistent although the surface ice cover was 20 cm thick in 2014–2015 summer. In our epiglacial and supraglacial lakes the temperature did not get much above 1°C.

Fig. 3. Top pond2 on Basen, January 17, 2015.

Morphology

The state of the lake surface depends on the surface heat balance. When the air temperature is close to the freezing point, both liquid and solid surface states are possible in equilibrium. Continuous surface heat gain from above means open water surface, but otherwise we have an ice cover with surface heat loss compensated by conduction from the liquid water body. Albedo is a stabilizing factor: switching from ice surface to open water adds on absorption of solar radiation and strengthens the stability of the open state and vice versa. In our study lakes, ice surface is the predominant situation. Thus

$$k\frac{dT}{dz} = Q_0 < 0 \qquad (3)$$

where *k* is thermal conductivity of ice, *T* is temperature, and *z* is vertical coordinate. This gives the surface ice layer thickness as $h \sim \frac{k(T_0 - T_f)\cancel{T_0}}{Q_0}$, where T_0~~T_0~~ is the surface temperature~~,~~ T_f is the freezing point temperature~~(°C)~~; e.g., for $Q_0 \sim -10$ W m^{-2} and $T_0 - T_f$~~T_0~~ ~ –1 °C we have *h* ~ 20 cm. The surface ice thickness decreases this way approaching the seasonal equilibrium. According to our field results, this equilibrium has been typically 10–30 cm in the study region, with patches down to zero thickness or open water state in warm summers.

The birth and growth of a proglacial surface lake depend strongly on the albedo. According to our measurements, the mean summer albedo is 0.55–0.60 over lake surfaces, with significant spatial variability. Since horizontal transfer of heat is very slow, the result is a patchy appearance of the lake body. There are deep spots with high porosity and more solid spots~~, with~~ depending on the~~high~~ albedo. Due to the positive albedo feedback, the patchy appearance is persistent. The overall structure is comparable to wetland soil. Albedo over snow is much higher than over lakes. Our albedo measurements over snow-covered ice sheet averaged to 0.85 and to 0.70 over nunataq snow patches.

In supraglacial lakes, in the main body $\nu > \nu_0$, and deeper down there is a 1-m soft bottom layer with a sub-structure of hard layers and slush layers with sediment particles. The slush layers form due to absorption maximum by the sediments, which have originated from the nearby nunataq in the past years. Similar stratification was seen also in the Plogen lake and as well in a supraglacial lake at Fossilryggen in summer 2004–2005. ~~Epiglacial lakes~~Nunataq ponds are as normal ~~lakes~~ ponds with water body possibly covered by an ice layer.

Water balance

Blue ice refers to spots in the accumulation zone where the atmospheric water balance is negative and therefore the surface appears as blue ice in contrast to the normal white snow-covered surface. In ~~the~~ blue ice patches ~~precipitation~~ snowfall is compensated by sublimation and snow drift, a necessary condition to keep the blue surface. To compensate the mass loss, ice velocity is upward near the surface. Blue ice has much lower albedo and much higher transparency than snow and therefore can absorb several times more solar radiation and let it go deeper. In a warming climate, blue ice spots may grow and locally provide strong positive feedback.

According to the observations, the local production of meltwater in blue ice in December–January corresponds to ½ – 1 m liquid water layer, which is distributed in the top 1–2 meters of the ice sheet. At the foot of nunataqs, also runoff from the mountain adds to the water volume of neighbouring lakes. In Lake Suvivesi, the flow was clearly seen in warm summers. In 2003, minor streams were observed to flow from Basen to Lake Suvivesi already on December 10th. Melting on nunataq was efficient, and the inflow streams were strong. Nevertheless, parts of Lake Suvivesi lacked water layer also during this time, and parts of the lake surface layer dried with large subsurface cavities.

Sublimation accounts on average for 1 mm ice per day and reaches 50–100 m~~e~~m over the whole summer, but in extreme storm situations sublimation rates of 10–15 mm per day have been observed.

Although some ~~mixed~~ epiglacial ~~type~~ ponds around the Basen nunataq are hydraulically inter-connected, large differences in water-tables in many of them indicate that the state is not so for all. The ice sheet is tilting down toward the nunataq and the ponds have been formed in this valley at the nunataq foot (Fig. 4). In summer 2014–2015, Penaali pond received plenty of melt-water from the surrounding ice-sheet while in other ponds no visible hydrological inter-connectivity with the ice-sheet was found. This means that solar radiation was the primary factor causing the sub-surface melting. But, in addition, it was observed that some melt-water drained down from the nunataq, where patches of snow and ice melted in the course of summer. Especially the northern and north-eastern side of Basen, where most of these valley ponds are situated, is exposed to sunlight. Based on site photographs, it was seen that the water level of Ringpond was 2 m higher in 2004–2005 than six years later. Also, old cyanobacterial mats on the cliff in 2014–2015 proved that water table had been at least 2 m higher.

Fig. 4. The valley of ponds on the north side of Basen. ~~Note the dark colour of caused by dust and meltwater discharge from the nunataq.~~

Heat balance.

The heat budget is governed by the solar and terrestrial radiation. The surface radiation balance is close to zero, with turbulent heat losses ~~negative~~ resulting in a surface ice layer, while solar radiation penetrating beneath the surface takes care of the warm-up and melting of ice (Fig. 5). In Lake Suvivesi, the mean net solar radiation in December–January was 115–148 W m^{-2} in the three last field summers, while the net terrestrial radiation and turbulent losses were 33–78 W m^{-2} and 25–53 W m^{-2}, respectively. The mean December–January heat flux for internal ice melting in the lake was 10–59 W m^{-2} that corresponds to melting by 0.3–1.7 cm d^{-1}.

~~Supraglacial~~ In supraglacial and ~~mixed type~~epiglacial water bodies, the ~~are characterized by the presence of ice. In~~ daytime water temperature may rise a little above the melting point in finite water pockets due to absorption of sunlight and slow molecular diffusion. ~~Between 29 December 2014 and 13 January 2015, the highest water temperatures at 50 cm depth in Lake Suvivesi were 1.0 °C in the afternoons. After mid-night, the temperature had fallen back to 0 °C.~~ While conduction is slow, convection may take~~s~~ place daytime driven by solar heating.~~,~~ In short periods, the increased temperature of interior water pockets leads to density-driven convection with sinking warm water. This helps in growing the liquid water layer. Between 29 December 2014 and 13 January 2015, the highest water temperatures at 50 cm depth in Lake Suvivesi were 1.0 °C in the afternoons. After mid-night, the temperature ~~had~~ feall~~en~~ back to 0 °C.

~~and~~ The patchy melting brings pressure differences, which force, as observed, horizontal movement of liquid water in the porous, slushy lake body. The velocity depends on the hydraulic conductivity, which is highly sensitive to porosity. According to measurements, the hydraulic conductivity increased from 0.1 to 10 cm s^{-1} when porosity increased from low level to the order of ½ where the solid ice lattice breaks down. In slushy field the conductivity was measured as 6 cm s^{-1}. The conductivity measurements were made by water pumping experiments applying the Dupuit hydraulic well formula and by tube tests.

In shallow~~,~~ ~~epiglacial~~ nunataq ponds, bottom heating by solar radiation can raise to water temperature much above the melting point in the lower layers. What exactly happens then is also dependent on the water salinity. The density range of fresh water ~~between~~ in the temperature interval [0°C,~~ and~~ 8°C] ~~temperatures~~ is 0.132 kg m^{-3} that corresponds to the ~~salinity difference~~ range of 0.16 ~~πππ.~~ μg L^{-1} in the concentration of dissolved solids. Thus, even a weak salinity stratification can compensate temperature differences for the density in cold water. The thermal stratification in ~~epiglacial lakes~~nunataq ponds such as Fossilryggen pond can therefore be influenced by the salinity gradient. When a lake forms from ice, the water temperature keeps near the freezing point until the liquid water level reaches the ground, and bottom heating begins and stratification forms (Table 2). The temperature of the bottom water has been observed to be as high as 9°C in our nunataq ponds. In a case of unstable stratification, turnover would appear but no such event was observed.

Fig. 5 illustrates the heat balance of supraglacial lakes and nunataq ponds~~ver summer blue ice~~. Solar heating of the interior well overcomes the boundary losses and produces liquid water on average by 1.1–1.3 cm per day corresponding to heat gain of 40–45 W m^{-2}. Surface radiation balance is below zero due to terrestrial radiation and turbulent losses, which is seen in the existence of a surface ice layer. The turbulent loss is dominated by sublimation. In three summers, the average net solar radiation was 140 W m^{-2}, of which half was used for the surface balance and half penetrated into the lake. Over thick ice ($\gg \kappa^{-1}$), the loss from the lake body to deeper ice sheet is estimated as around 5 W m^{-2}. In thin ice ($\lesssim \kappa^{-1}$), solar heating is returned back to the water body from bottom.

At extreme, an open surface is possible in daytime but at night a very thin ice layer has formed. Since the air temperature keeps below the freezing point, in practice it is not possible for open surface to gain heat from the atmosphere. Open surface absorbs more solar radiation but on the other hand terrestrial radiation and turbulent losses are larger more than for just compensation. Thus, in Vestfjella climate, open surface is not a stable situation.

Fig. 5. Heat balance of supraglacial lakes (left) and nunataq ponds~~epiglacial~~ (left)~~ lakes~~. The numbers provide the scales (in W m^{-2}) for net solar radiation (SR), net longwave radiation (LW), turbulent fluxes (TF), conductive flux through surface ice (CF), and heat flux to bottom (BF). The circled numbers give the total heat gain by the water body.

~~Physical properties~~Electric conductivity and colour of water

Table 2 shows electrical conductivity (EC) ~~and pH~~ of the lake water samples. In very low salinity as here, the density of water is proportional to EC. When $EC \lesssim 10\ \mu S\ cm^{-1}$, the influence of salinity on the density can be ignored here. ~~In summer 2004–2005 only Lake Suvivesi was included for this part.~~ The supraglacial lakes form a specific group with very low EC, in Lake Suvivesi 1.5–5.3 µS cm^{-1} with average of 3.7 µS cm^{-1}. In summer 2004–2005 only Lake Suvivesi was included for this part, and the result was then 5.0 µS cm^{-1}. This kind of water is of ~~classified as~~ rather ~~'~~high purity ~~quality~~ level, suitable for car batteries~~deionized water'~~. In the ~~mixed-type lakes~~epiglacial ponds at the foot of Basen the EC magnitude was 10–100 µS cm^{-1}, and in ~~epiglacial lakes~~nunataq ponds ~~still~~ higher values for re~~ach~~corded, up to 1000 µS cm^{-1}, which corresponds to the ~~salinity~~ concentration of dissolved solids of 0.7 -g L^{-1}ppt. EC showed decreasing trend through the summer. In summer 2014–2015 the mean EC of snow was 3.2 µS cm^{-1} in the study region, very close to the value in supraglacial lakes.

Table 2. Electrical conductivity at 25°C (EC), maximum (T_{max}) and mean (T_{mean}) temperature, oxygen (O_2) saturation, and CDOM (coloured dissolved organic matter) in beam absorption at 420 nm during the three summer seasons. Temperature and oxygen measurements indicate those made by YSI in daytime. The number of measurements varied from 3 (Plogen and Fossilryggen) up to 11 (Suvivesi).Physical properties of lakes and ponds: water layer depth, maximum temperature (T_{max}), electrical conductivity (EC), and coloured dissolved organic matter (CDOM).

The transparency of the lakes depends on the concentrations of optically active substances: coloured dissolved organic matter (CDOM) (coloured dissolved organic matter), suspended matter, chlorophyll *a*, and iron, as well as the distribution and proportion of ice with its gas bubbles. CDOM is proportional to the limnological colour index of the water. This was more closely examined in the last expedition. In Lake Suvivesi, the light attenuation coefficient ranged in 0.5–2 m^{-1}. In the mixture of ice pieces and water, scattering of light was very strong and was a major factor in the light attenuation in the body of supraglacial and mixed typeepiglacial water bodies. Especially in supraglacial lakes, the ice and meltwater were very clean with a low absorption coefficient. CDOM values were extremely low in all study lakes and ponds except in the epiglacial lakesnunataq ponds on Basen nunataq (Table 2). The highest CDOM values were measured in Rockpool and the second highest in Toppond1, both lakes lying above the bedrock and mineral sediment.

Results: Geochemistry

Water pH varied between lakes and between years. But there was a clear distinction in that in supraglacial and mixed typeepiglacial lakes and ponds pH was mostly within 6.0–7.5, while higher values were found in nunataq ponds (Table 3). In 2014–2015 the highest pH value (10.1) was found in Rockpool, followed by Toppond1 and Fossilryggen, where pH was above nine. The lowest pH, 5.9 was measured in the supraglacial Lake Suvivesi in the same summer. It was only 0.5 units higher than pH of snow. The pH of the frozen samples transported to Finland was generally 0.5–1 units lower than those measured from the fresh samples. It was found that the water pH and EC were strongly correlated ($r > 0.9$, $p < 0.0001$). In summer 2010–2011, very similar chemical results were obtained as in 2014–2015, water pH varied mostly between 6 and 8.5 with a few higher values in Velodrome pond and Fossilryggen.

Table 3. Geochemistry of the study lakes and ponds. Seasonal averages of sodium (Na), potassium (K), magnesium (Mg), calcium (Ca), manganese (Mn), chloride (Cl), iron (Fe), pH, sulphate (SO_4), phosphate (PO_4), total phosphorus (TP), nitrate (NO_3), and total nitrogen (TN). **(a)** In summer 2003–2004 **(b)** In summer 2014–2015, based from three (Plogen and Fossilryggen) up to 11 (Suvivesi) samples. Standard deviations are shown as ±x below the averages,

In summer 2003–2004, different sampling sites showed ~~markedly~~ highly variable ion concentrations, with Rockpool having clearly the highest seasonal average values and Lake Suvivesi the lowest values, with ~~e.g., respectively,~~ sodium concentrations of~~-~~, respectively, 72 ~~ppm~~ mg L^{-1} and 0.12 mg L^{-1}~~ppm~~ (Table 3a). The ~~mixed type~~epiglacial sampling sites all recorded over ten times higher average ion concentrations than in Lake Suvivesi. The water samples collected from Lake Suvivesi indicated ~~pointed to~~ an increase of salinity with time. For example, the concentration of sodium (0.04 mg L^{-1} ~~ppm~~ on December 14, 0.10 mg L^{-1} ~~ppm~~ on January 3, and 0.21 mg L^{-1} ~~ppm~~ on January 21), magnesium, chloride and sulphate showed a relatively strong enrichment. These values are averages of three samples from individual drill holes in an about 10^4 m^2 area. Comparison of chemical and EC data obtained from different sites shows pronounced spatial variation, possibly associated with localized inflow from Basen water into Lake Suvivesi. Consequently, the apparent increase in salinity may be an artefact and, instead, it may reveal a minor epiglacial component in Lake Suvivesi. High salinity in ~~epiglacial~~ nunataq meltwater ponds and streams may at least partly result from the formation of salt deposits in response to repeated evaporation cycles. X-ray diffraction measurements indicated that the light-coloured salt deposits on basaltic bedrock and soil are mainly calcite (aragonite; $CaCO_3$) and thenardite (Na_2SO_4).

In summer 2014–2015, the lowest difference between minimum and maximum element concentration was recorded in total phosphorus. Except iron, potassium and phosphorus the other chemical constituents had their highest concentrations in Rockpool, where also highest pH and colour were measured. In contrast, in Suvivesi the concentrations were generally lowest among the sites. EC correlated strongly with the concentration of sodium, calcium, and magnesium (for each $r > 0.9$, $p < 0.0001$). Also, potassium, manganese and iron concentrations were correlated with EC ($r > 0.58$, $p < 0.05$). Besides, the different cation (K, Na, Ca, Mg, Mn and Fe) concentrations were inter-correlated when the results of the study sites were considered (all combinations had $r > 0.7$ and $p < 0.01$). Among the ~~mixed~~ epiglacial and supraglacial lakes and ponds, the highest EC and cation concentrations were measured in Ringpond and Velodrome (Table 3b). Sodium, magnesium and calcium were the three cations with highest range of variability in concentration among the water bodies.

In line with cations, also nitrogen and phosphorus concentrations varied substantially between the water bodies in summer 2014–2015. The highest concentrations of phosphorus and nitrogen were found in Rockpool. The lowest nitrogen concentrations appeared in Suvivesi, Ringpond and Plogen, while the lowest phosphorus concentrations were found in Toppond1, Toppond2, Fossilryggen and Ringpond (Table 3). Because of low nitrogen and phosphorus concentrations, their inorganic fractions could be ~~reliable~~ reliably measured only in a few water bodies. In Rockpool, ammonium (NH_4-N) and nitrite-nitrate (NO_2+NO_3-N) comprised together 10% of total nitrogen, and phosphate (PO_4-P) comprised 40% of total phosphorus. In summer 2010–2011, total nitrogen and phosphorus concentrations were predominantly low, but once-twice in a small inflowing beck to Suvivesi, in Ringpond and Toppond2 higher concentrations (up to 700 and 30 µg L^{-1}, respectively) were measured.

Hierarchical clustering based on the geochemistry classified the study lakes and ponds into 4–5 groups depending on the variables included in the analysis. When all data were included, Suvivesi, Plogen and Penaali formed one group, Fossilryggen, Toppond1, Velodrome and Ringpond formed the second group, while Toppond2 and Rockpool made their own individual groups (Fig. 6). However, if all measured variables were included Suvivesi and Penaali formed one group, Plogen, Ringpond and Fossilryggen the second one, Toppond1, Toppond2 and Velodrome the third one, and Rockpool its own fourth group. A very similar grouping was given by pH, EC, colour, and TP and TN concentrations.

Fig. 6. Hierarchical cluster three of the study lakes. The lakes are in the following order: 1 – Suvivesi, 2 – Velodrome, 3 – Penaali, 4 – Ringpond, 5 - Toppond1, 6 - Toppond2, 7 - Rockpool, 8 – Plogen, 9 – Fossilryggen. The cluster is based on the data of pH, EC, colour, total phosphorus, total nitrogen, potassium, sodium, calcium, magnesium, manganese and iron concentrations.

In summer 2014–2015, with a few exceptions, dissolved oxygen (DO) concentrations and saturation levels varied within a narrow range in the water bodies (Table 24). The saturation level was mostly below the equilibrium with atmosphere. However, in Rockpool and

Fossilryggen the DO concentrations were close to 20 mg L^{-1} with saturation close to 150%. The highest DO concentration was measured in Fossilryggen on January 21, around 30 mg L^{-1} corresponding to 250% saturation. In Rockpool the maximum DO concentration was 21.4 mg L^{-1} or 174% saturation, measured on December 27 and January 3. The highest DO value recorded by the DO/temperature data logger in Rockpool was 17.4 mg DO L^{-1}, 144% saturation, at noon on December 28. In contrast to 2014–2015, in summer 2010–2011 DO supersaturation was measured only twice, both cases in Velodrome pond.

Comparing the geochemistry between the summers 2003–2004 and 2014–2015, it is seen that the element concentrations are were alike. The differences can be largely explained by the differences in the weather of the summersconditions, and in the sampling techniques, and by random variations. For example, the stratification of temperature and chemistry was strong in Fossilryggen pond, and it is therefore understandable that the exact sampling depth has a major role. In the ponds on the top of Basen, biological activity was very high that makes the timing of the sampling important. Our supraglacial lakes are were near-supraglacial, disturbed by inflow from nunataq close to the edge and in localized streams,. as suggested by observations. In pure supraglacial conditions, the lake water quality would be influenced only by the local ice sheet and atmospheric deposition.

Discussion

Relative to the nunataqs and ice-sheets, the study lakes and ponds can be divided into three major groups. The classification showed follows the lines of Vincent et al. (2008) and Hodgson (2012) but includes only the types of lakes present in Vesfjella region. Supraglacial and mixed typeepiglacial water bodies, which are situated on the ice-sheet, and epiglacial nunataq ponds on top of nunataqs (Table 1). The location of a water body relative to the neighbouring nunataq and ice-sheet affects its hydrological and chemical characteristics. The formation of supraglacial and epiglacial mixed type water bodies is dependent on the existence of blue ice, which allows light penetration through the topmost layer of the ice-sheet. Plogen and Penaali received meltwater inflow also from the ice-sheet as was also clearly indicated by the chemistry results. The closure of the seasonal lakes is expected to progress by 1–1.5 cm per day or up to 3-4 months for the deepest lakes observed (Hawes et al. 2011a). There are very small water pocketsAt extreme small size (below 1 m scale), in the ice sheet surface layer, called there are small cryoconite holes, initiated by impurities at the ice sheet surface (Hawes *et al.* 2008) but they have not been considered here.

Epiglacial lakes andNunataq ponds are more strongly influenced by the nunataq water balance, since there is significant meltwater inflow from the surrounding drainage area. Toppond1 was clearly influenced by local melting, while Toppond2 was seemingly influenced by snow and ice melting around. Toppond1 had nearly 1 m thick ice-cap but Toppond2 was very shallow, and the lake was mostly ice-free in daytime, if weather was sunny and warm, but frozen, if the day was cloudy and cold. Rockpool was very shallow, far from glaciers and gained water from seasonal snow melting. All the snow in its drainage basin melted already early in summer, the water level started to decline, and the pool as well as several other similar water bodies started to dry up. In Rockpool some water remained as long we continued our measurements till the end of January, however. In nunataq snow patches, meltwater runoff was around 1 mm SWE (snow water equivalent) per day (Leppäranta *et al.* 2013a).

Our study lakes in Vestfjella, Dronning Maud Land, are oligotrophic or ultraoligotrophic characterized by low EC and nutrient concentrations, equally with most Antarctic surface lakes (Lyons & Finlay 2008). Their life history depends on the local climate. In much colder environment the summer warming would not reach the melting stage, while in much warmer environment the lakes would become perennial. Our study lakes appear to climatologically quite far from these extreme cold and warm situations.Further south from Aboa is the Swedish Svea station (74°34.6'S, 11°13.5'W, elevation 1261 m), which is occasionally visited by snow mobiles from Aboa. There is a small supraglacial pond at the station, which was 20–30 cm deep in January 2005. The north-south distance from there to Aboa is 170 km, and the elevation difference with Lake Suvivesi is about 1075 m.

According to their locations relative to the nunataqs and physical and chemical characteristics, the studied water bodies can be grouped into a few categories. Lake Suvivesi makes its own category because of its large surface area and consequently its weaksmall dependence on the melt water from the nunataq. However, although very little direct impact on the lake also in this case the nunataq has an strong indirect impact on the lake evolution, because Basen nunataq gives a shelter against wind which is a prerequisite for the blue-ice formation. In all lakes liquid water exists only in the uppermost layer of the ice. However, lakes which are situated in close contact with the nunataqs are influenced by the erosion material transported by melt water to the lakes and ponds.

In Lake Suvivesi the element concentrations showed large spatial variability. Comparing with the snow cover in the neighbourhood (Kärkäs *et al.* 2005; Lehtinen 2006), the medians were about the same for sodium, potassium, sulphate and nitrate, while while calcium and magnesium were enriched, but and chloride concentration was poorer lower in the lake. The differences indicate significant impact from nunataq via inflow.

When transport of inorganic material is strong enough, meltwater discharge affects the pH, EC and other geochemistry variables. The earlier studies have shown that the nunataqs and the surface waters of the present study may have abnormally high cation concentrations, in particular magnesium and calcium, but low levels of nitrogen and phosphorus (Lehtinen & Luttinen 2006; Keskitalo *et al.* 2013).

In those lakes and ponds which are situated on top of Basen nunataq or in close contact with it on the glacier, nitrogen and phosphorus may partially originate from the sea where snow petrels (*Pagodroma nivea*) feed and carry food to their nesting areas in Basen and Plogen. In summer 2014–2015 the populations consisted of 30–50 and 3–5 pairs, respectively in these nunataqs. In addition, in Basen one pair of South Polar Skua (*Stercorarius antarcticus*) was nesting, feeding on the snow petrels and thus releasing nutrients to the environment. Occasionally, also two other petrel species (*Oceanites oceanicus*, *Thalassoica antarctica*) visited in the area, mostly seen above Basen.

In small ponds on top of Basen nunataq cyanobacteria may have supported nitrogen reserves. In small rockpools, in particularly, plankton mat communities have lot of cyanobacteria which can synthesize fix atmospheric nitrogen (Bergman *et al.* 1997; Charpy *et al.* 2010). The importance of *in situ* assimilated nitrogen or phosphorus released through erosion relative to those transported from the sea by birds, is unknown, however.

Antarctic lakes are mostly considered to be phosphorus-limited, although nitrogen and phosphorus concentrations can vary considerably among them (Laybourn-Parry 2003), and in some areas nitrate-rich waters can be found (Vincent & Howard-Williams 1994). In our study lakes nutrient limitation seems to be a major feature as well (Keskitalo et al. 2011), although each water body behaves differently and thus the impact on water chemistry varies from lake to lake. Our results indicate, that among the group of epiglacial lakesnunataq ponds, 2–3 different sub-groups can be identified based on their hydrological and water chemistry properties. The melt water inflow from the nunataq strongly influences the water chemistry in Penaali and Plogen, and explains that their water chemistry characteristics are close to that of Suvivesi. Shallow rockpools with their rich cyanobacterial mat communities are unique ecosystems due to their food webs and very high photosynthetic potential (Arvola & Leppäranta, unpubl.). In Antarctica, cyanobacterial mat communities can be abundant in many lake and pond ecosystems (e.g. Hawes et al. 1992, Hodgson et al. 2004, Singh & Elster 2007). According to Hawes et al. (2011a), benthic communities usually predominate over planktonic ones in small ponds in ice-free areas of Antarctica.

Regarding the water chemistry and heat balance, inorganic bottom sediment is an important characteristic in small ponds (Toppond1, Toppond2, Rockpool and Fossilryggen) on top of the nunataqs. The presence of sediment differentiates them ~~water bodies~~ from the rest of our water bodies~~the lakes and ponds~~, where ~~melt~~ the liquid water layer ~~existed~~ was above ~~the~~ ice. As a result of the inorganic sediment, small ponds and rockpools on top of the nunataqs had higher water pH and nitrogen and phosphorus concentrations than ~~in~~ the other water bodies. Very high pH values (>10) and DO concentrations (up to 100 mg L^{-1}) have been earlier found by Hawes et al. (2011b) in small ponds in McMurdo Ice Shelf close to Bratina Island.

Among ~~the~~ our water bodies, Rockpool was a unique environment with overwhelmingly rich cyanobacterial community ~~(Arvola & Leppäranta, unpubl.)~~. Although receiving melt water from the surrounding snow patches, and equally with the two ~~epiglacial~~ nunataq ponds (Toppond1 and Toppond2) with bottom sediment, we suggest that the rockpools should be considered as specific water formations. The reason is that their life-span is shorter than in other lakes and ponds, and thermal conditions are ~~varying~~ more variable. In addition, organisms in rockpools are exposed to higher UV radiation than in deeper lakes and ponds with much thicker ice cover.

Conclusions

In Vestfjella, in western Dronning Maud Land, three main `lake categories´ were found: (i) supraglacial lakes, (ii) ~~epiglacial~~nunataq ponds, and (iii) epiglacial ponds~~mixed (features from (i) and (ii))~~. Category (ii) can be divided into two sub-groups whether the melt water source is glacial or just seasonal snow patches. Supraglacial waters ~~tend to be~~are ultra-oligotrophic, while in ~~epiglacial waters~~nunataq ponds the concentrations of dissolved and suspended ~~matter~~ solids vary ~~a lot~~in a wide range. Each water body behaves as an individual and thus the impact on water chemistry varies from lake to lake. Our results indicate, that among the group of ~~epiglacial lakes~~nunataq ponds, 2–3 different sub-groups can be identified based on their hydrological and water chemistry properties.

The heat budget of the Vestfjella lakes is dominated by solar radiation and long-wave radiation losses, with turbulent heat exchange acting strongly only episodically. Sublimation can become a significant part of the mass balance. The limnological quality of the water bodies ranges from ultra-oligotrophic supraglacial lakes to small hypereutrophic nunataq ponds.

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~~Each water body behaves as an individual and thus the impact on water chemistry varies from lake to lake. Our results indicate, that among the group of epiglacial lakes, 2–3 different sub-groups can be identified based on their hydrological and water chemistry properties.~~

Water temperature may also vary widely among the lakes and ponds. Shallow ponds usually freeze over at night-time and during snowstorms and cold weather, while during sunny days they are mostly ice-free. We propose that the three lake types are common in the vicinity of nunataqs in the western and northern Dronning Maud Land.

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Author contribution

Matti Leppäranta has taken part in three field trips in 2004–2015 reported here, Arto Luttinen took care of the lake research in the first one (2003–2004), and Lauri Arvola joined the last one (2014–2015). The analysis and the paper write-up have been made together with equal efforts. Leppäranta is responsible mainly for the physics, Luttinen and Arvola for the geochemistry and biology.

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