

**Biogeochemistry of benthic microbial mats and laminated sapropelic sediments in
perennially ice-covered Lake Untersee, Queen Maud Land, Antarctica**

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Abstract

Perennially ice-covered Lake Untersee (Queen Maud Land, Antarctica) is an isolated freshwater ecosystem with thick, year-round ice cover preventing direct gas exchange with atmosphere and strongly limits light and external nutrient inputs. It is hypothesized that: (1) Lake Untersee is recharged primarily by subaqueous melting and subglacial meltwater of Anuchin Glacier that releases occluded air bubbles directly to the water column, together with air saturated water and that Lake Untersee receives gases in atmospheric origin and, (2) microbial mat morphology and depth-dependent light availability regulate photosynthetic carbon sequestration, such that flat mats store less organic carbon than conical microbialites and carbon storage decreases with depth. To evaluate these hypotheses, dissolved noble gases (He, Ne and Ar), dissolved O₂/Ar ratios and $\delta^{18}\text{O}$ -O₂ were used to assess gas sources and the contribution of photosynthetic oxygen, while cores from the north and south basins (~10-100 m) were analyzed for stratigraphy, organic carbon abundance, C:N, organic carbon content and radiocarbon of microbial mats and laminated sapropelic sediments. Noble gas isotope ratios ($^3\text{He}/^4\text{He}$, $^{22}\text{Ne}/^{20}\text{Ne}$, $^{40}\text{Ar}/^{36}\text{Ar}$) were near atmospheric values throughout the oxic water column, supporting recharge by mixture of occluded air and air saturated water released during subaqueous melting of Anuchin Glacier and subglacial meltwater. O₂/Ar and $\delta^{18}\text{O}$ -O₂ indicate a measurable photosynthetic oxygen contribution to the oxic water column, although gross photosynthetic rates remain low relative to other perennially ice-covered lakes of Antarctica. In the well mixed and oxygenated north basin, flat microbial mats store ~1-2.5 kg C m⁻² at shallow depths, decreasing to <1 kg C m⁻² near 100 m in parallel with declining photosynthetically available radiation (PAR). In contrast, conical microbialites at comparable depths store substantially more organic carbon and shows differences in $\delta^{13}\text{C}$ values. In the south basin, benthic microbial mats are absent and laminated sapropelic sediments accumulate under persistent anoxic conditions, reaching high organic carbon contents. Radiocarbon and stable carbon isotope measurements indicate that this organic matter is produced near the chemocline within a deep chlorophyll rich layer and subsequently preserved on the lakebed. Overall, the results emphasize the importance of gas sources, microbial mat morphology and basin-specific biogeochemical conditions in regulating carbon cycling and microbial functioning in one of the most extreme aquatic environments on Earth.

Résumé

Le lac Untersee (Terre de la Reine Maud, Antarctique), recouvert de glace de façon permanente, est un écosystème d'eau douce isolé dont la couche de glace épaisse qui le recouvre toute l'année empêche les échanges directs avec l'atmosphère et limite fortement la lumière et les apports externes en nutriments. L'hypothèse est la suivante : (1) le lac Untersee est principalement alimenté par la fonte subaquatique et l'eau de fonte sous-glaciaire du glacier Anuchin, qui libère des bulles d'air occluses directement dans la colonne d'eau, ainsi que de l'eau saturée en air, et que le lac Untersee reçoit des gaz d'origine atmosphérique, et (2) la morphologie du tapis microbien et la disponibilité de la lumière en fonction de la profondeur régulent la séquestration du carbone photosynthétique, de sorte que les tapis plats stockent moins de carbone organique que les microbialites coniques et que le stockage du carbone diminue avec la profondeur. Pour évaluer ces hypothèses, les gaz nobles dissous (He, Ne et Ar), les rapports O_2/Ar dissous et $\delta^{18}O-O_2$ ont été utilisés pour évaluer les sources de gaz et la contribution de l'oxygène photosynthétique, tandis que les carottes provenant des bassins nord et sud (~10-100 m) ont été analysées pour déterminer la stratigraphie, l'abondance du carbone organique, C:N, la teneur en carbone organique et le radiocarbone des tapis microbiens et des sédiments sapropéliques laminés. Les rapports isotopiques des gaz nobles ($^3He/^4He$, $^{22}Ne/^{20}Ne$, $^{40}Ar/^{36}Ar$) étaient proches des valeurs atmosphériques dans toute la colonne d'eau oxygénée, ce qui confirme la recharge par un mélange d'air occlus et d'eau saturée en air libérée lors de la fonte subaquatique du glacier Anuchin et de l'eau de fonte sous-glaciaire. Le ratio O_2/Ar et le $\delta^{18}O-O_2$ indiquent une contribution photosynthétique mesurable de l'oxygène à la colonne d'eau oxygénée, bien que les taux photosynthétiques bruts restent faibles par rapport à d'autres lacs de l'Antarctique recouverts de glace de façon permanente. Dans le bassin nord, bien mélangé et oxygéné, les tapis microbiens plats stockent environ 1 à 2.5 kg C m⁻² à faible profondeur, ce qui diminue à moins de 1 kg C m⁻² à environ 100 mètres, parallèlement à la baisse du rayonnement photosynthétiquement actif (RPA). Aussi, les microbialites coniques à des profondeurs comparables stockent beaucoup plus de carbone organique et présentent des différences dans les valeurs $\delta^{13}C$. Dans le bassin sud, les tapis microbiens benthiques sont absents et des sédiments sapropéliques laminés s'accumulent dans des conditions anoxiques persistantes, atteignant des teneurs élevées en carbone organique. Les mesures du radiocarbone et des isotopes stables du carbone indiquent que cette matière organique est produite près de la chimocline, dans une couche profonde riche en chlorophylle, puis préservée

au fond du lac. Dans l'ensemble, les résultats soulignent l'importance des sources de gaz, de la morphologie des tapis microbiens et des conditions biogéochimiques spécifiques au bassin dans la régulation du cycle du carbone et du fonctionnement microbien dans l'un des environnements aquatiques les plus extrêmes de la planète.

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1 Chapter 1. Introduction

Ice-covered lakes in polar regions provide an opportunity to examine limnological processes under a unique set of environmental conditions (Andersen et al., 1998; Craig et al., 1992; Hawes et al., 2019). The limnology of ice-covered lakes are largely influenced by: 1) the source of water feeding the lakes; and 2) the ice cover, which limits gas exchange with the atmosphere and reduces light penetration (Hawes et al., 2016). Hundreds of ice-covered lakes have been inventoried in Antarctic regions, such as the McMurdo Dry Valleys (MDV), Vestfold Hills, Schirmacher Oasis, and Soya Coast (Bormann & Fritzsche, 1995; Matsumoto et al., 1992; Perriss & Laybourn-Parry, 1997). The lakes can be classified based on their ice-cover regime: coastal lakes typically develop a seasonal ice cover and are typically recharged by a combination of local precipitation, runoff and glacial meltwater (e.g., (Gibson et al., 2002; Lyons et al., 2013)). Inland, where the climate is colder and drier, lakes are perennially ice-covered, but their periphery create moats in the summer. Owing to the perennial ice cover, these lakes do not receive direct precipitation but are recharged by glacial meltwater streams (Andersen et al., 1998; Doran et al., 1994, 2004).

Most of the perennially ice-covered lakes in Antarctica support low trophic level activity such as phototrophic microorganisms that develops organic microbial mats along the lakebed (Hawes et al., 2019; Hawes & Schwarz, 2001; Lawson, Doran, Kenig, Marais, et al., 2004; Love et al., 1983; Moorhead et al., 2005). Microbial mats develop from phototrophic microorganisms that capture the light energy and dissolved inorganic carbon; however, their growth is constrained by the availability of light under the ice cover, carbon, nitrogen and other nutrients (Hawes et al., 2016, 2019). Lakes with a seasonal moat and that are recharged by glacial meltwater streams can replenish CO₂ and other essential nutrients in the water column, which support the metabolic activity of the microbial communities (Kohler et al., 2016; Marsh, 2019; Spigel & Priscu, 1998). Perennially ice-covered lakes are therefore unique environments whereby the biogeochemical cycling is influenced by the perennial ice cover and the indirect interaction between the atmosphere and lake's liquid waters (Andersen et al., 1998; Craig et al., 1992; Wharton et al., 1993).

Lake Untersee is a large perennially ice-covered lake in Dronning Maud Land that is different to most of the lakes in Antarctica (Fig. 1) (Bormann & Fritzsche, 1995; Schwab, 1998). Unlike most ice-covered lakes, the periphery of the ice cover of Lake Untersee does not melt in summer; it remains frozen year-round thus sealing the water column to atmospheric exchange (Fig.

2). As such, the lake is recharged solely by subaqueous glacial melt and subglacial meltwater and/or groundwater (Andersen et al., 2015; W. D. Hermichen et al., 1985; Kaup et al., 1988), and it resembles more the subglacial lakes beneath the Antarctic Ice Sheet (i.e., Lake Vostok) (Wright & Siegert, 2012). The 2008 Tawani International Antarctic Scientific Expedition to Lake Untersee discovered a variety of microbial mats, including large conical stromatolites, flat mats, and pinnacle mats along the lake bed (Andersen et al., 2011). The conical stromatolites up to 70 cm tall are thought to be the only known modern examples of the earliest stromatolites that were present 3.5 billion years ago (Andersen et al., 2011). Metagenomic analysis of 16S rRNA sequencing revealed that the upper layers of the stromatolites consist of photosynthetic cyanobacteria species like *Phormidium* sp., *Leptolyngbya* sp., and *Pseudanabaena* sp, whereas, the deeper layers are dominated by a heterotrophic microbial community, comprising Actinobacteria, Verrucomicrobia, Proteobacteria, and Bacteroidetes (Koo et al., 2017). Hawes et al. (2016) proposed that the conical morphology of the stromatolites have a surface area approximately three times higher than the benthic microbial mats, and suggested they likely have a higher rate of photosynthesis relative to the other forms. Based on $\delta^{13}\text{C}$ and ^{14}C analyses of stromatolites at 10-15 m depth, Marsh et al. (2020) suggested that the growth of the conical mats was limited by the availability of dissolved inorganic carbon (DIC) in the water column. To counteract the limited DIC pool, the stromatolites develop a symbiotic relationship between the photosynthetic and heterotrophic microbial communities whereby the photosynthetic autotrophs would produce organic carbon sourced from the limited DIC pool in the water column as well as from the CO_2 respired by the underlying heterotroph species (Marsh et al., 2020).

Studies have yet to explore if the cyanobacteria that develop the flat mats along the lakebed have growth rates and metabolic process similar to the stromatolites. The conical stromatolites and flat mats along the bottom of Lake Untersee not only have relevance to the strategies microbial communities develop to survive in a nutrient deprived environment and to early life on Earth, but also to life on other icy planetary bodies. Recent astrobiology studies investigated the potential analogy between Enceladus, the icy moon of Saturn, and Lake Untersee (McKay et al., 2017; Wagner et al., 2022). The extreme environmental conditions and unique microbial ecosystems of Lake Untersee may provide valuable insights into the potential extra-terrestrial life on Enceladus, particularly in its ice-covered subsurface ocean where similar cold, low-light, and nutrient-limited conditions might exist (McKay et al., 2014; Peter et al., 2023; Wagner et al., 2022).

1.1 Research Objectives and Hypotheses

Lake Untersee has two large basins: the north basin with oxic waters that reaches a depth of 160 m, and the south basin, with anoxic waters between 50-100 m depth (Fig. 2). Previous studies on Lake Untersee have mostly explored the hydrological mass balance of the lake (Andersen et al., 2015; Faucher et al., 2019), the chemical and biological characteristics of the north and south basins (Bevington et al., 2018; Wand et al., 1997, 2006), and the microbial communities present in the benthic stromatolites and mats in the north basin (Andersen et al., 2011; Faucher et al., 2021; Koo et al., 2017; Marsh et al., 2020). Therefore, the growth rates and metabolic processes of flat mats in the north basin and of the laminated sapropelic sediments in the anoxic waters of the south basin remains poorly understood. In addition, the source of gases into the lake, which provide the CO₂ required for photosynthesis, has yet to be determined. Overall, these are all crucial measurements to further understand the biogeochemical cycling and relationships with microbial communities in a light and nutrient-poor aquatic ecosystem and the relation with their structure.

The objectives of this thesis are to:

1. Determine the sources of gases in the lake from noble gas (He, Ne, Ar), O₂, and $\delta^{18}\text{O}-\text{O}_2$ analyses.
2. Characterize the stratigraphy of the flat mats in the north basin and of the laminated sapropelic sediments in the south basin.
3. Determine the abundance of organic carbon, $\delta^{13}\text{C}$ and ^{14}C of flat mats and laminated sapropelic sediments at different depths in the lake (10-100m) to infer the sources of carbon and their metabolic activity.
4. Assess the role of biogeochemical cycling in the formation and the growth of photosynthetic microbial mats.
5. Evaluate the findings to gain insights into the environmental conditions and ecosystem processes of Early Earth.

Hypotheses:

1. Lake Untersee is recharged by subaqueous melting of glacial ice, subglacial meltwater, and/or groundwater and receives no input from surface meltwater streams (Faucher, 2021; Marsh, 2019). It is hypothesized that the subaqueous melting of glacial ice releases the trapped air bubbles directly into the water-column (i.e., air group) and the lake receives a contribution of air-saturated gases from a subglacial meltwater input to the lake. This hypothesis will be tested by analyzing the noble gases in the water-column, which are conservative and inert in nature, and are considered to be excellent geophysical tracers (Aeschbach-Hertig & Solomon, 2013; Stanley & Jenkins, 2013; Warrier et al., 2015).
2. It is hypothesized that the structure of the photosynthetic microbial mats in Lake Untersee regulates the growth rate and carbon storage. Given that only external inputs of nutrients and dissolved inorganic carbon to the lake occur via Anuchin Glacier related process (i.e. subaqueous melting and subglacial meltwater and/or groundwater) microbial photosynthetic activity rely primarily on these limited resources. Consequently, organic carbon accumulation within the flat mats is anticipated to 1) be lower than in the conical mats because of their smaller surface area, and 2) decrease with depth in response to declining PAR.

Overall, this thesis builds on the study of Marsh et al. (2020) who examined biogeochemical cycling from large conical mats sampled at 10-15m depth (Marsh et al., 2020). This thesis combines organic carbon concentrations, C/N ratios, $\delta^{13}\text{C}$ and ^{14}C of benthic microbial flat mats and sapropelic sediments with isotopic tracers of gases in the water-column attempts to provide a multi-disciplinary understanding of the sources, cycling, and distribution of carbon and nitrogen within the flat mats, as well as their role in the lake's biogeochemical processes and the overall ecosystem dynamics of Lake Untersee.

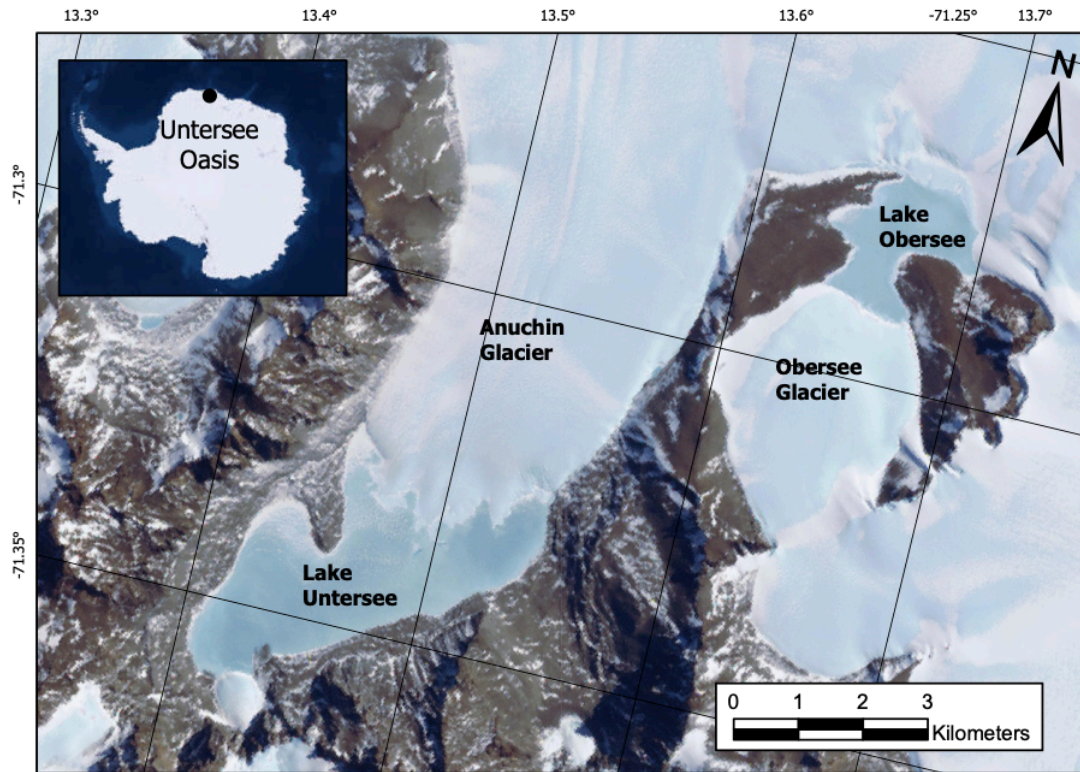
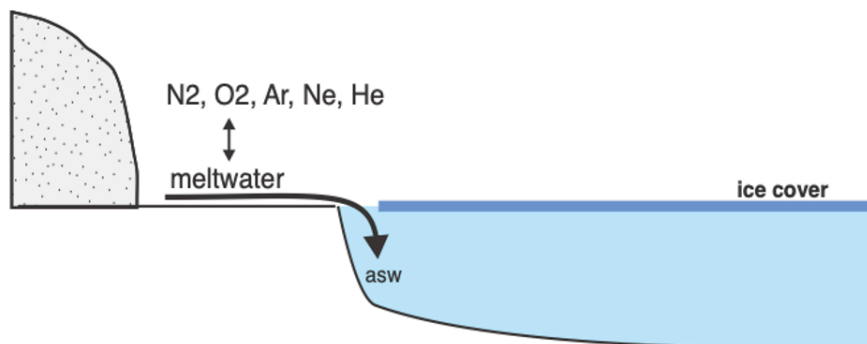


Figure 1. Map showing the location of the Untersee Oasis in East Antarctica with Lake Untersee, the Anuchin Glacier. Background satellite image is retrieved by Esri, Earthstar Geographics, TerraCol.

A) Moating perennially ice-covered lakes



B) Lake Untersee: Well-sealed perennially ice-covered lake

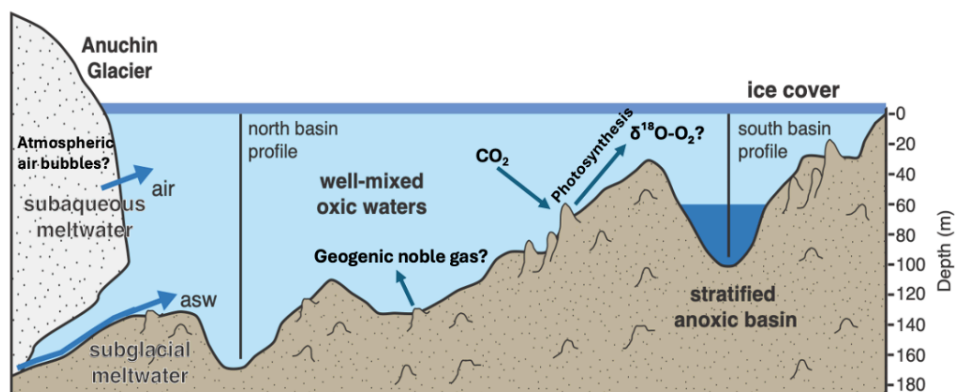


Figure 2. Schematic diagram of recharge mechanism of perennial ice-covered lakes. **A)** lakes that develop moats in summer, receiving air saturated water (ASW), such as those in the McMurdo Dry Valleys. **B)** Well-sealed ice-covered lakes, such as Lake Untersee, Antarctica. Adapted from Marsh et al. (2020).

2 Chapter 2. Study Site

Untersee Oasis (71.40–71.26°S and 13.20–13.80°E) is situated within the Gruber Mountains in the central Queen Maud Land (Dronning Maud Land), East Antarctica and is located approximately 90 km southeast of Schirmacher Oasis (Fig. 1) (Schwab, 1998). Untersee Oasis is characterized by a polar desert climate regime. Ten years of climate data (2008–2017) collected by an automated weather station along the shore of Lake Untersee (71.34°S, 13.45°E, 612 m a.s.l.) shows a mean insolation of $99 \pm 7 \text{ W m}^{-2}$, mean annual air temperature (MAAT) of $-9.5 \pm 0.7^\circ\text{C}$, thawing degree-days ranging from 7 to 51 degree-days, and a mean relative humidity of $42 \pm 5\%$ (Andersen et al., 2015). Despite having a relatively warm MAAT for Antarctica, the region is dominated by intense ablation which limits surface melt features due to cooling associated with latent heat of sublimation (*e.g.*, (Hoffman et al., 2008)).

Lake Untersee is one of the largest freshwater lakes in East Antarctica and is found at 612 m above sea level (W.-D. Hermichen et al., 1985; Schwab, 1998). It is covered all year by a 1.9 to 3.9 m thick ice cover (Faucher et al., 2019). Lake Untersee is about 6.5 km long and 2.5 km wide and has a surface area of about 8.73 km² (Faucher et al., 2019; Marsh, 2019). Measurements of ablation across the ice cover yield an average sublimation rate of $61 \pm 13 \text{ cm yr}^{-1}$, which indicates a loss of approximately $4.90 \pm 1.03 \times 10^6$ of water per year, or $0.94 \pm 0.20\%$ of the total lake volume (Faucher et al., 2019). The water-level of the lake has remained stable since at least 1995, indicating that the lake receives an equivalent inflow of water annually. Based on a hydrological mass balance, it was suggested that the lake is recharged by a nearly equal contribution from subglacial meltwater and subaqueous melting of englacial ice along the interface of the lake the Anuchin Glacier (Faucher et al., 2019).

The lake has two sub-basins, a large one in the northern sector of the lake (north basin) and a smaller one in the southern sector (south basin). The two basins are separated by a sill at 50 m depth, which prevents the mixing of the water between two basins below the sill depth. As a result, the two basins have distinct biogeochemical characteristics (Andersen et al., 2011; Bevington et al., 2018). The north basin reaches 169 m in depth, and it is homo-thermal, well-oxygenated to the bottom, and well-mixed due to buoyancy-driven convection caused by melting of the ice-wall at the glacier-lake interface (Fig. 3) (Steel et al., 2015; Wand et al., 2007). The temperature of the water column remains near 0.5°C, with a pH of 10.6, supersaturated dissolved oxygen levels (150%), specific conductivity of 505 $\mu\text{S/cm}^{-1}$ and chlorophyll levels between 0.1 to 0.5 $\mu\text{g L}^{-1}$

(Andersen et al., 2011; Marsh et al., 2020; Wand et al., 1997). Microbial mats in the form of stromatolitic microbialites, flat mats and pinnacle mats are found along the lakebed of the north basin. The south basin reaches 100 m in depth and the water-column above the sill depth is well-mixed and oxic, just like in the north basin (Fig. 3). However, below the sill level of 50 m depth, the water-column has a chemical stratification and does not mix with the water above. Below 50 m depth, the water temperature increases from 0.5°C to 5°C, the pH decreases to near 7, and the dissolved oxygen (O₂) decreases to near 0% (Fig. 3). The specific conductivity increases to 1100-1300 $\mu\text{S}/\text{cm}^{-1}$, chlorophyll levels increases to 2.5 $\mu\text{g L}^{-1}$ and it is rich in methane (CH₄) (Bevington et al., 2018; Wand et al., 1997, 2006). In the anoxic waters of the south basin, laminated sapropelic sediments occur, which consist of dark-coloured sediments rich in organics.

Light penetration through perennial ice cover is limited to approximately 5% of irradiance transmitted to the water column (Andersen et al., 2011). The intensity of photosynthetically active radiation (PAR) decreases with depth (Fig. 4). In the north basin, near 5 m depth irradiance average around 112 $\mu\text{mol photons m}^{-2} \text{ s}^{-1}$, at 30 m, PAR decreases to approximately 48 $\mu\text{mol photons m}^{-2} \text{ s}^{-1}$, and by 100 m, light availability declines to about 7 $\mu\text{mol photons m}^{-2} \text{ s}^{-1}$. Then at depths near 135 m, the vertical extinction coefficient for PAR is estimated at 0.033 m^{-1} , resulting in only 0.1% of surface irradiance (Andersen et al., 2011; Faucher, 2021; Marsh, 2019).

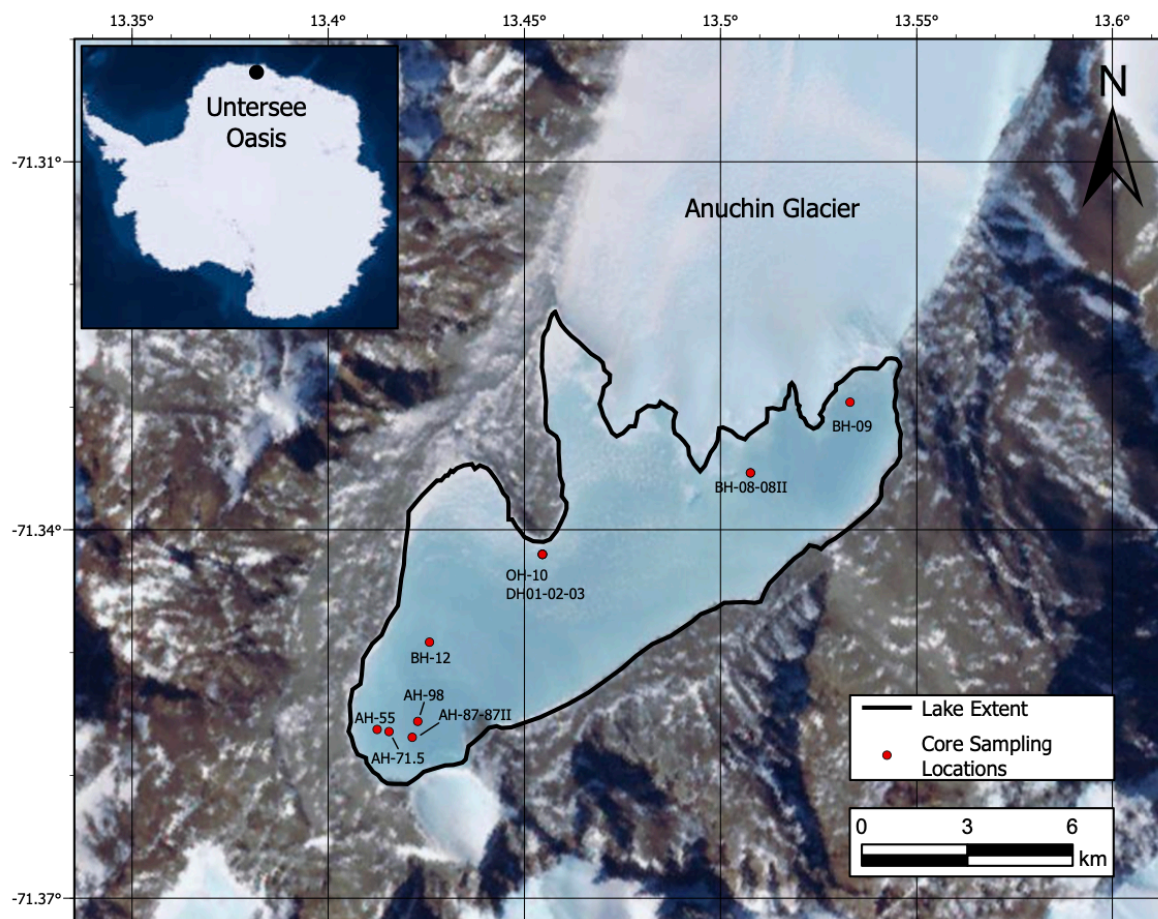


Figure 3 Map showing location of cores taken from Lake Untersee, Antarctica. Background satellite image is retrieved by Esri, Earthstar Geographics, TerraCol.

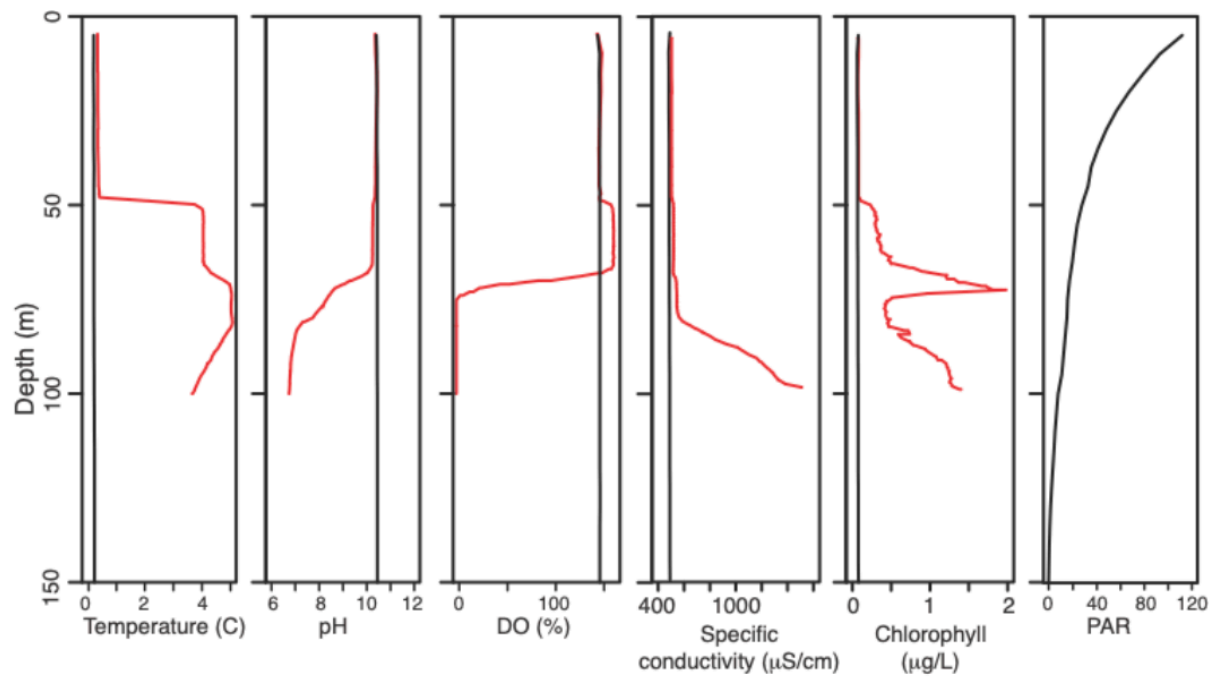


Figure 4. Depth profiles of temperature, pH, dissolved oxygen (DO), specific conductivity, chlorophyll and PAR in the north basin in black and south basin in red of Lake Untersee, Antarctica. Data was measured in 2021 for north basin and in 2015 for south basin, before 2019 glacial lake outburst flood (GLOF).

3 Chapter 3. Methodology

3.1 Gases

3.1.1 Noble gases: sampling, analysis and calculations

Noble gases, like helium (He), neon (Ne) and argon (Ar), are inert gases and their measurements can provide insights into the source of gases in the water column of Lake Untersee: air, dissolved gases and/or other potential non-atmospheric inputs such as crustal ^4He and ^{40}Ar . To evaluate potential source of gases to the lake, dissolved gas concentrations normalized to air saturated water (C_s/C_{ASW}), isotope ratios relative to atmospheric values (R/R_A), and elemental gas ratios ($^4\text{He}/^{40}\text{Ar}$ and $^{20}\text{Ne}/^{40}\text{Ar}$) are reported.

Passive diffusion samplers with copper tubes were used to collect dissolved gases at different depth in the water column of the north basin by the equilibrium technique (Fig. 5). The diffusion samplers were left in the water column for at least 14 days, giving sufficient time for the equilibrium of the gases inside the gas-permeable silicone membrane with the gases in the water column (Gardner & Solomon, 2009). Samplers were removed from the water column and immediately crimped (Aeschbach-Hertig & Solomon, 2013). The crimped copper tubes were shipped to the Noble Gas Laboratory of the Advanced Research Complex of the University of Ottawa, ON, Canada.

Noble gases (He, Ne and Ar) were measured on the Thermo Scientific Helix SFT Noble Gas Spectrometer at the Noble Gas Laboratory at the A.E Lalonde Accelerated Mass Spectrometry Laboratory of the University of Ottawa, ON, Canada. During each analysis, internal standards using precise aliquots of clean dry atmospheric air were run to measure instrument drift and sensitivity (ccSTP/fA). Standards and dissolved gas samples in copper tubes were introduced to an ultra-high vacuum preparation system where nitrogen (N_2) and oxygen (O_2) and other trace gases (i.e., carbon dioxide, CO_2) were first removed using liquid nitrogen charcoal traps and two non-evaporable getter pumps (SAES) and a small aliquot was reserved for the analysis of argon (Lott, 2001). Helium was separated from neon by the closed-cycle helium cooled cryostat which cycles down to 5K before the release of helium at 28K and neon at 80K (Lott, 2001; Mabry et al., 2013; Péron et al., 2020). After that, helium and neon were introduced separately into the gas spectrometer under static vacuum. A mass peak centre was applied to each gas, followed by individual integrations performed on each mass peak. With the use of these integrations, a linear

regression was generated to determine peak intensity at time zero (i.e., when the sample was released into the mass spectrometer).

The measured concentrations of ^3He , ^4He , ^{20}Ne , ^{21}Ne , ^{22}Ne , ^{36}Ar , ^{38}Ar and ^{40}Ar , normalized to the volume of their copper tube to account for sampling volume differences, were converted into cubic centimeters of gas per cubic centimeter of water at standard temperature and pressure (ccSTP/ccH₂O). The conversion used the following temperature-solubility equations (Clark, 2015, p. 285):

$$\text{He} \left(\frac{\text{ccSTP}}{\text{ccH}_2\text{O}} \right) = 4.07 \times 10^{-12} T^2 - 2.58 \times 10^{-10} T + 4.98 \times 10^{-8} \quad (1)$$

$$\text{Ne} \left(\frac{\text{ccSTP}}{\text{ccH}_2\text{O}} \right) = 2.50 \times 10^{-11} T^2 - 2.31 \times 10^{-9} T + 2.28 \times 10^{-7} \quad (2)$$

$$\text{Ar} \left(\frac{\text{ccSTP}}{\text{ccH}_2\text{O}} \right) = 1.05 \times 10^{-7} T^2 - 1.06 \times 10^{-5} T + 4.91 \times 10^{-4} \quad (3)$$

where T represents the water temperature (°C) at sampling depth.

The concentrations of each gas were also normalized to their relative concentration in air saturated water (R/R_{asw}) using the temperature at sampling depth. The isotopic ratios for He, Ne and Ar (e.g., $^3\text{He}/^4\text{He}$, $^{22}\text{Ne}/^{20}\text{Ne}$, $^{40}\text{Ar}/^{36}\text{Ar}$) were also calculated with respect to air (R/R_a) to infer an atmospheric source versus geogenic or crustal sources of gases.

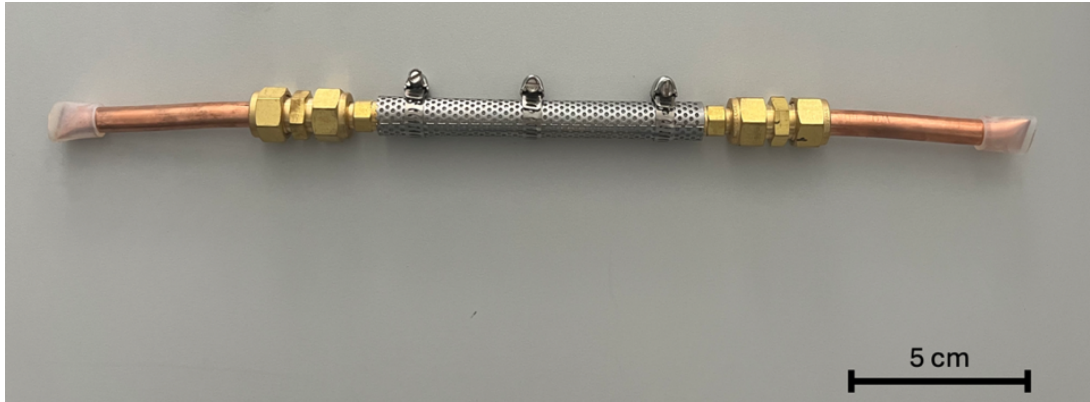


Figure 5. Photo of passive diffusion sampler with protective metal coat used in 2021 sampling in Lake Untersee, Antarctica

3.1.2 Dissolved oxygen, nitrogen and argon (O_2 , Ar and $\delta^{18}O-O_2$): sampling and analyses

Unlike the noble gases, oxygen and nitrogen gases can be affected by biological activity (Burnard, 2013; Emerson et al., 2002). Here, the O_2/Ar and $\delta^{18}O-O_2$ are used to assess potential contribution of O_2 from the photosynthetic activity of the benthic flat microbial mats and conical stromatolites in the lake. In 2021 and 2022, holes were drilled through the ice cover in the north and south basins. Then water samples were collected using a 2.5 L Niskin water sampler at 5-10 m interval. The water samples were immediately transferred into 12 ml exetainers, and care was taken to prevent air bubbles in vial; samples were discarded if air bubbles were present in the exetainer. Finally, samples were kept at 4 °C until the laboratory analysis using two different techniques: isotope ratio mass spectrometry (IRMS), and membrane-inlet mass spectrometry (MIMS).

For the IRMS measurements, 8 mL of water was removed and helium added to the vial using an automated syringe pump to prevent a vacuum. The vials were left in a tray for at least 24 hours at room temperature. The headspace was then analyzed for oxygen (O_2) and argon (Ar) on a Thermo Finnigan Delta XP coupled to a Gas Bench II at the Jan Veizer Laboratory, University of Ottawa, Ottawa, ON (Barth et al., 2004). The O_2/Ar molar ratio in the samples were determined by calibration with distilled air saturated water (ASW). The $\delta^{18}O-O_2$ values were reported against Vienna Standard Mean Ocean Water (VSMOW) and the $\delta^{40}Ar$ values were reported against air (Barth et al., 2004). Analytical precision is calculated ± 0.4 permil.

Another set of samples were analyzed for O_2 and Ar concentrations by the MIMS method at the Institut des Sciences de la Mer (ISMER), Université de Québec à Rimouski (UQAR). Since gas diffusion is highly dependent on temperature, samples were equilibrated in a 4 °C water bath prior to analysis. About 3 mL of the sample was inserted via peristaltic pump through a gas-permeable membrane and flowed through a liquid nitrogen trap before analysis on a mass spectrometer (Bay Instruments). Concentrations of O_2 and Ar in the samples in mg/L were determined by calibration with standards based on distilled air saturated water at 4 °C (Kana et al., 1994). The O_2/Ar molar ratios were then calculated. Analytical precision is typically better than ± 1 % for O_2 and Ar concentrations, and ± 0.5 % for the O_2/Ar ratios.

3.2 Microbial Mats

3.2.1 Sampling of microbial mats in north and south basins

In the 2022 and 2023 field expeditions to Lake Untersee, eight sediment cores from the north basin and five sediment cores from the south basin were collected using a UWITEC corer (Table 1). The sediment cores collected in polycarbonate tubes (with 4.1, 5.2 and 5.9 cm diameters) ranged in depth from 10 to 100 m. To preserve the core and minimize sample disturbance during transport, sodium polyacrylate was added to the water on top of the sediment in the core tube. This method provided a gel seal that does not affect the carbon and nitrogen composition of the material in cores (Tomkins et al., 2008). Then collected cores were shipped to Canada (ISMER-UQAR) and stored at 4°C.

3.2.2 X-ray scanning by a Multi Sensor Core Logger

At the ISMER-UQAR, the sediment cores were first analyzed using non-destructive multi-sensor core loggers and x-ray imaging techniques and also photographed at high-resolution. First, undisturbed whole cores were placed in the MSCL S-XCT for x-ray scanner (radiography) which images the density variations in the core. After, the core tubes were cut along their length using a DREMEL 4000 rotary mini-drill and the cores were split in half using dental floss (Fig. 6). The half cores were analysed with a Multi-Sensor Core Logger S-XD and -XCT (GeotekTM) equipped with imaging and x-ray fluorescence spectroscopy (XRF) (Croudace & Rothwell, 2015; Debret et al., 2011; St-Onge et al., 2007). Measurements were acquired at millimeter resolution.

3.2.3 Carbon and nitrogen concentration, ¹³C and ¹⁵N analyses

After the non-destructive analysis, the cores were subsampled at 1 cm intervals using stainless steel spatulas and tweezers (except core LU-OH-10 which was sub-sampled at millimeter resolution and later removed from analysis due to low quantity of sediment samples). The subsamples were then divided into two equal portions; one was archived at UQAR and the other set used for carbon and nitrogen analyses at the Advanced Research Complex (ARC) laboratories at the University of Ottawa. The subsamples were placed in Thermo Fisher cell culture plates and stored in at 4°C in a walk-in fridge.

For the analysis of organic carbon and $\delta^{13}\text{C}_{\text{org}}$, subsamples were first acidified with 10% HCl for 24 hours in 50 ml falcon tubes and rinsed twice with deionized water to remove the

inorganic carbon. The samples were then dried at 60 °C for 24 hours in an oven and then crushed to a powder with a mortar and pestle.

Since nitrogen can be mobilized during the HCl treatment process, unacidified subsamples were prepared for total carbon and nitrogen concentrations and $\delta^{15}\text{N}$. The unacidified samples were placed in 50 ml falcon tubes and dried at 60 °C for 24 hours. The dried samples were crushed to a powder by a mortar and pestle. The inorganic carbon (C_{inorg}) fraction was then obtained by the difference of total carbon and organic carbon contents:

$$C_{\text{inorg}} = C_{\text{tot}} - C_{\text{org}} \quad (4)$$

After the appropriate pretreatment, all samples were submitted to Jan Veizer Stable Isotope Laboratory of University of Ottawa to measure the concentration of organic carbon, total carbon and nitrogen as well as isotopic ratios ($^{13}\text{C}/^{12}\text{C}$; $^{15}\text{N}/^{14}\text{N}$). All samples and standards were weighed in tin aluminum capsules (10 x 10 mm) and mixed with tungsten oxide (WO_3) to facilitate combustion. The samples were analyzed with an elemental analyser (Vario EL Cube, Elementar) interfaced to an isotope ratio mass spectrometer (IRMS) (Delta Advantage, Thermo). Then samples and standards were flash combusted at about 1800°C. The resulted gas products carried by helium through columns of oxidizing/reducing chemicals optimised for CO_2 and N_2 . The gases were separated by a "purge and trap" adsorption column and sent to IRMS. The $\delta^{15}\text{N}$ values are reported as ‰ vs. air and normalized to internal standards calibrated to international standards IAEA-N1 (+0.4‰), IAEA-N2 (+20.3‰), USGS-40 (-4.52‰) and USGS-41 (47.57‰). The $\delta^{13}\text{C}_{\text{org}}$ values are reported as ‰ vs. VPDB and normalized to internal standards calibrated to international standards IAEA-CH-6 (-10.4‰), NBS-22 (-29.91‰), USGS-40 (-26.24‰) and USGS-41 (37.76‰). The analytical precision of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ is based on an internal standard (C-55), which is not used for calibration and is usually better than 0.2‰. The analytical precision for elemental abundances of carbon and nitrogen is $\pm 0.1\%$.

3.2.4 Organic carbon content

Organic carbon content (OCC) was calculated to quantify the amount of organic carbon stored in the benthic microbial mats and sapropelic sediments. The OCC (kg C m^{-2}) represents the mass of organic carbon per unit surface area and was derived from the bulk density, organic carbon

concentration, and thickness of each subsample. First, the bulk density (BD; g cm⁻³) was determined from the ratio of the dried sample mass (g) to its corresponding volume (cm³):

$$BD = \text{Dry weight (g)} / \text{Volume (cm}^3\text{)} \quad (5)$$

The organic carbon abundances (%C_{org}) was obtained from elemental analysis. For each sample interval of thickness h (cm), OCC (kg C m⁻²) was calculated as described by Tarnocai et al., (2009):

$$OCC = BD \times C_{org} \times h \text{ (cm)} \quad (6)$$

3.2.5 Estimated organic carbon reservoir in Lake Untersee

To estimate the carbon reservoir in Lake Untersee, knowledge on the bathymetry is required since PAR varies with depth. The bathymetry of Lake Untersee was derived from digitizing and georeferencing the bathymetry map of Wand et al. (2006) and interpolating a continuous depth surface using “Topo to Raster Tool” in ArcGIS Pro (3.0.2; ESRI), Depths were converted to a negative value below the surface of the lake and quantified at 1-meter intervals with Surface Volume Tool, constrained by a shoreline polygon. All analyses were performed in an equal-area coordinate system with fixed cell size (WGS1984, UTM Zone 33S). Based on cumulative area outputs, the analysis yielded a surface area of ~8.26 km² and a total water volume of ~4.5 x 10⁸ m³ (which is slightly lower compared to previous bathymetry measurements by Faucher, (2021)). The depth-area relationship shows that approximately 11% of the total surface area lies within 0-10m, and about 28% within 0-30 m depth (Table 2).

Following the determination of OCC for the microbial mats collected at different depths, the measurements were integrated with lake-depth distribution to estimate organic carbon content for different depth intervals: 0-10 m, 0-30 m, 30-100 m, >100 m. For each interval, the mean OCC of all cores located within that depth range was used to interpolate the organic carbon abundance within that depth range. These mean values were then multiplied by the corresponding surface area of the depth range obtained from bathymetric analysis to calculate the total organic-carbon stock of each depth range.

3.2.6 Radiocarbon measurements of microbial mats and sapropelic sediments

Pretreated acidified and dried sub-samples (see the organic carbon content pretreatment section) were submitted to the AMS (Accelerated Mass Spectrometry laboratory) of the University of

Ottawa for ^{14}C analysis. Radiocarbon analyses were performed on an Ionplus AG MICADAS (Mini Carbon Dating System). ^{12}C , ^{13}C and $^{14}\text{C} + 1$ ions were measured after tandem acceleration by a terminal at 185 kV and equipped with He stripping. The data was processed using the BATS data reduction software as described by Wacker et al. (2010). The fraction-modern ($F^{14}\text{C}$) was calculated according to Reimer et al. (2004) as the ratio of the sample $^{14}\text{C}/^{12}\text{C}$ ratio to the standard $^{14}\text{C}/^{12}\text{C}$ ratio (Ox-II), measured quasi-simultaneously. Both $^{14}\text{C}/^{12}\text{C}$ ratios were background-corrected and the result is corrected for spectrometer and preparation fractionation using the AMS measured $^{14}\text{C}/^{12}\text{C}$ ratio normalized to $\delta^{13}\text{C}$ (VPDB). Radiocarbon ages are calculated as $-8033\ln(F^{14}\text{C})$ and reported in ^{14}C yr BP (BP = AD1950) as described by (Stuiver & Polach, 1977).

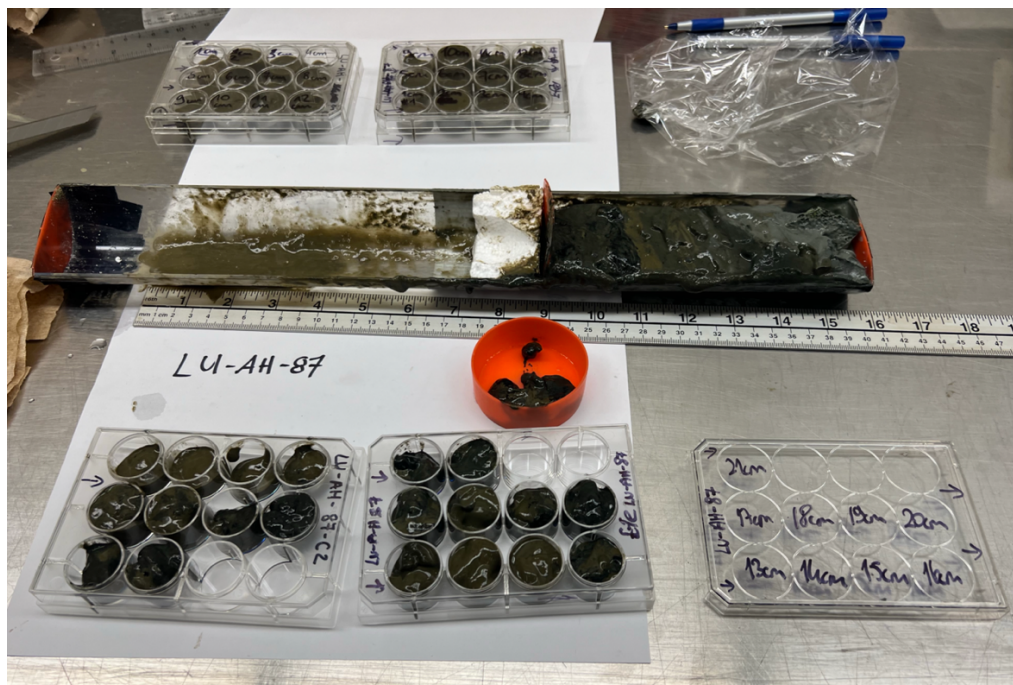


Figure 6. A half of a core from south basin (anoxic waters at 87 m) of Lake Untersee, Antarctica (LU-AH-87) and cell culture plates used in sub-sampling at UQAR-ISMER facilities.

Table 1. Summary of collected sediment cores from both north and south basins of Lake Untersee, Antarctica.

Core ID	Year collected	Sub-basin	Depth (m)	Sub-samples (n)	Lat, Long	Core Diameter (cm)	Total Core Surface Area (cm ²)
LU-OH-10	2023	Oxic	10	58	-71.34200, 13.45460	5.2	21.24
LU-DH-01	2022	Oxic	~15	12	-71.34200, 13.45460	4.1	13.20
LU-DH-02	2022	Oxic	~15	13	-71.34200, 13.45460	4.1	13.20
LU-DH-03	2022	Oxic	~15	12	-71.34200, 13.45460	4.1	13.20
LU-BH-12	2022	Oxic	31	8	-71.34915, 13.42582	4.1	13.20
LU-BH-09	2022	Oxic	98	13	-71.32960, 13.53300	4.1	13.20
LU-BH-08	2022	Oxic	100	5	-71.33536, 13.50762	4.1	13.20
LU-BH-08-II	2022	Oxic	100	14	-71.33536, 13.50762	4.1	13.20
LU-AH-55	2023	Anoxic	55	7	-71.35627, 13.41248	5.9	27.34
LU-AH-71.5	2023	Anoxic	71.5	21	-71.35644, 13.41551	5.9	27.34
LU-AH-87	2023	Anoxic	87	43	-71.35691, 13.42142	5.9	27.34
LU-AH-87-II	2023	Anoxic	87	23	-71.35691, 13.42142	5.9	27.34
LU-AH-98	2023	Anoxic	98	29	-71.35625, 13.42929	5.9	27.34

Table 2. Surface Area, Percentage and Volume for intended depths of Lake Untersee, Antarctica.

Depth Interval (m)	Surface Area (m ²)	Area (%)	Volume (m ³)
0-10	9.17E+05	11.10	4.21E+06
0-30	2.30E+06	27.82	3.27E+07
10-30	1.38E+06	16.76	2.73E+07
30-100	5.20E+06	62.97	3.22E+08
>100	8.24E+05	9.98	9.95E+07
0-160	8.26E+06	100.00	4.52E+08

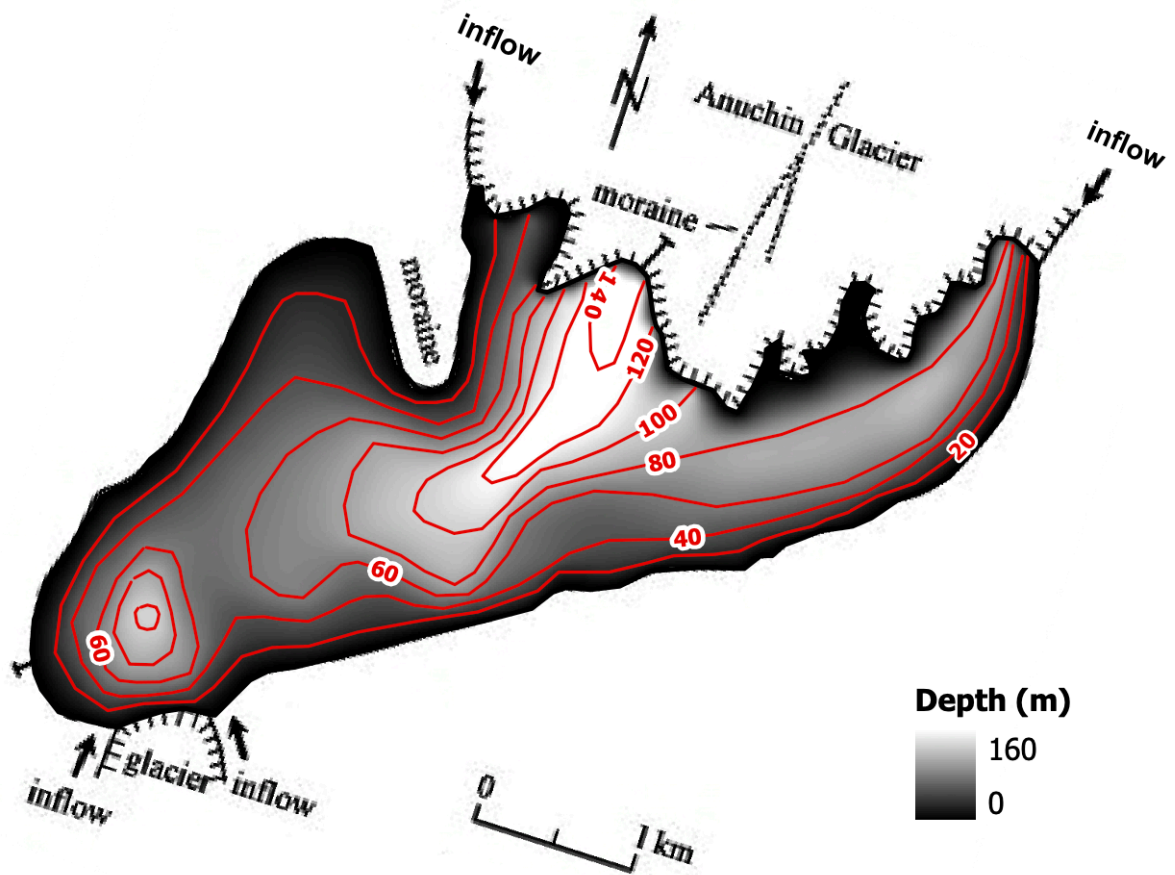


Figure 7. Bathymetry map of Lake Untersee, Antarctica. The bathymetry map of Lake Untersee was derived from digitizing and georeferencing the bathymetry map of Wand et al. (2006) and interpolating a continuous depth surface using “Topo to Raster Tool” in ArcGIS Pro (3.0.2; ESRI). The lake extent and map indicators were adapted from Wand et al. (2006).

4 Chapter 4: Results

4.1 Gases

4.1.1 He, Ne and Ar in the north basin

The dissolved Ar, He and Ne concentrations relative to air saturated water (C_s/C_{ASW}) of samples collected in the north basin are shown in Table 3 and Figure 8. All ratios have values that are supersaturated relative to air-saturated water. Both Ar and Ne have values around 130 to 160%, whereas He fluctuate from 98 to 120%. The hydrostatic pressure under a 2-4 m thick ice cover should result in values near 150%, this is the case for Ar and Ne, but the water column is slightly depleted with respect to He.

The isotope ratios expressed relative to air (R/R_a) can be used to infer sources of gases to the lake (Table 3 and Fig. 8). The $^3\text{He}/^4\text{He}$ ratios range from 0.78 and 1.12, the $^{22}\text{Ne}/^{20}\text{Ne}$ ratios range 0.89-1.03, and the $^{40}\text{Ar}/^{36}\text{Ar}$ ratios range from 0.99-1.00. Overall, all three isotope ratios are close to atmospheric values throughout the water column; a potential contribution of geogenic Ar (decay of K) or geogenic He would cause a deviation from atmospheric ratios. However, ratios close to air doesn't distinguish from air or air saturated water.

A distinction between air and air saturated water can be assessed from the $^4\text{He}/^{40}\text{Ar}$ and $^{20}\text{Ne}/^{40}\text{Ar}$ ratios (Table 3 and Fig. 8). The $^4\text{He}/^{40}\text{Ar}$ ratios range from 2.70×10^{-4} to 3.48×10^{-4} , with the highest value observed at 4 m. The $^{20}\text{Ne}/^{40}\text{Ar}$ ratios vary between 7.18×10^{-4} and 9.92×10^{-4} . These ratios fall in between those expected for air and air-saturated waters, as suggested for the sources of water recharging the lake (Fig. 8).

Table 3. Normalized dissolved gas concentrations to air saturated water (C_s : Concentration for sample, C_{ASW} : Concentration for ASW). Measured noble gas isotope ratio proportions to air ratios (R/R_A). Ratios of ^4He and ^{20}Ne to ^{40}Ar .

Sample ID	Depth (m)	C_s/C_{ASW} He	C_s/C_{ASW} Ne	C_s/C_{ASW} Ar	R/R_A $^3\text{He}/^4\text{He}$	R/R_A $^{22}\text{Ne}/^{20}\text{Ne}$	R/R_A $^{40}\text{Ar}/^{36}\text{Ar}$	$^4\text{He}/^{40}\text{Ar}$	$^{20}\text{Ne}/^{40}\text{Ar}$
LU2018	4	1.19	1.62	1.59	0.78	1.03	1.00	3.48E-04	9.92E-04
LU2021N	40	1.21	1.53	1.73	1.01	1.01	0.99	3.27E-04	8.58E-04
LU2021S	40	1.06	1.55	1.64	1.02	0.89	0.99	3.01E-04	9.21E-04
LU2021S	60	0.98	1.25	1.69	1.12	1.01	0.99	2.70E-04	7.18E-04

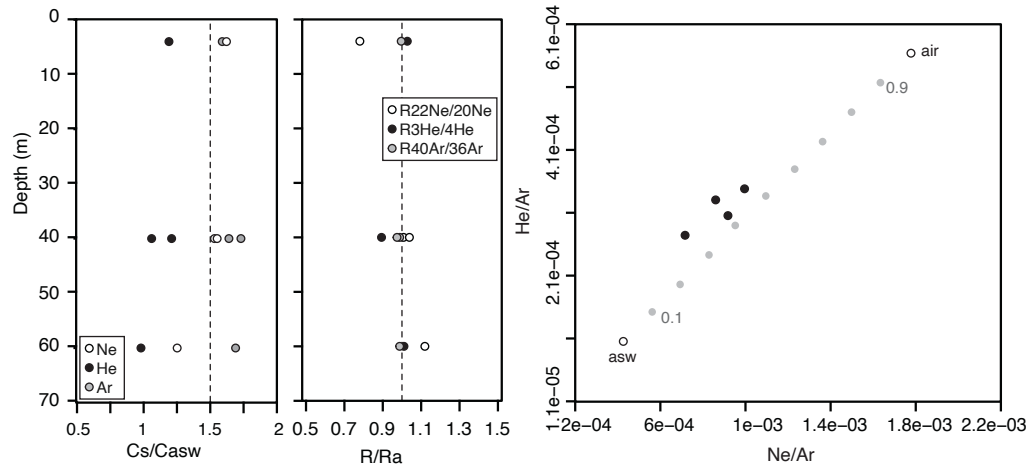


Figure 8. Depth profiles for He, Ne and Ar of C_s/C_{ASW} , measured noble gas proportions to air ratios (R/R_A) and, $^{20}\text{Ne}/^{40}\text{Ar}$ and $^4\text{He}/^{40}\text{Ar}$ ratios compared to air and ASW for Lake Untersee, Antarctica.

4.1.2 Dissolved O_2 , Ar and $\delta^{18}\text{O}-\text{O}_2$ in the north and south basins

In the north basin, measurements of dissolved oxygen (DO) with the YSI instrument shows that the water column is supersaturated with DO being near 150 % throughout the water column (Fig. 9). The measurements of $\text{O}_2/\text{O}_{2ASW}$ from MIMS also have values near 150% and follow closely those from the YSI DO profile (Fig. 9). Similarly, measurements of dissolved Ar from MIMS shows that C_s/C_{ASW} Ar (%) values remain near 150% (144 to 162%) throughout the water column

profile; the measurements from Helix provided values within a similar range (159 to 173%). The O_2/Ar ratios derived from IRMS and MIMS measurements both vary from 19.3 to 19.9 and remain nearly constant with depth. These values are higher than expected for air saturated water ($O_2/Ar_{asw} \cong 16.3$) (Fig. 9). The measured $\delta^{18}O-O_2$ values (ranging from +5.2 to +8.4‰ VSMOW) are lower than the expected value for air (+23‰ VSMOW) (Fig. 9). Both the O_2/Ar and $\delta^{18}O-O_2$ values suggest a contribution of O_2 from a source other than air.

In the south basin, the water column above the sill depth has O_2/O_{2ASW} , O_2/Ar and $\delta^{18}O-O_2$ values similar to the water sampled in the north basin (Fig. 9). However, below the sill depth, DO decreases from 150% to near 0% until the lake bottom is reached (both the DO sensor and MIMS measurements show the same values and trend). The IRMS and MIMS O_2/Ar ratios above the sill depth resembles the oxic column values. However, below 75m, O_2/Ar values decrease to values near 0 for both IRMS and MIMS data because the water column becomes depleted in O_2 . The $\delta^{18}O-O_2$ vary from + 5.3 to + 6.1‰ above the sill depth but decrease in the chlorophyll layer at 60-65 m depth to values of -3.5 to +0.7‰. Below 75 m depth, no measurements of $\delta^{18}O-O_2$ are possible since the water column is anoxic.

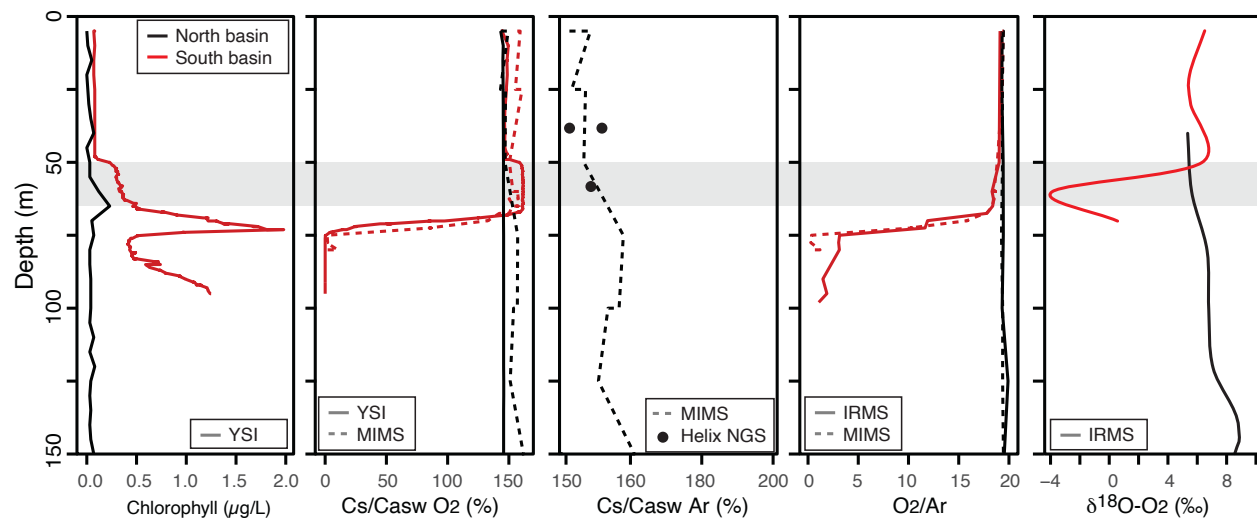


Figure 9. Depth profiles of (from left to right): chlorophyll (μ/L), dissolved oxygen (DO %), Ar/Ar_{ASW} , O_2/Ar and $\delta^{18}O-O_2$ for two basins of Lake Untersee.

4.2 Microbial mats in north basin

This section presents the results of the physical appearance, internal structures, organic carbon, $\delta^{13}\text{C}$ and ^{14}C of the flat mats collected in the north basin of Lake Untersee.

4.2.1 Stratigraphy, organic carbon, $\delta^{13}\text{C}$ and ^{14}C at 10 m depth

Cores LU-DH-01 (12 cm), LU-DH-02 (13 cm) and LU-DH-03 (12 cm) were taken from flat mats at approximately 10 m depth in the north basin. In the three cores, the upper 5 to 7 cm shows alternating layers of low- and high-density material corresponding the organic-rich and mineral-rich laminae, respectively (Fig. 10). Between 5 and 10 cm, the laminae become less distinctive and likely represents a shift in sediment accumulation. Carbonate spherule inclusions were also identified within this zone of the cores. Additionally, cores LU-DH-02 and 03 contained gravels within the sediments as evidenced from high density inclusions that appear as bright, irregular and angular. The lower 10-12 cm zone of each core consists of sediments with subdued color contrast and higher density on radiographs. These sediments are compact and uniform and likely represent the accumulation of lacustrine and/or glacial flour sediment.

Organic carbon abundances in the mat sections of the three cores ranged between 1.2 and 3.8%, with $\delta^{13}\text{C}_{\text{org}}$ values between -21.5 and -15.9‰ (Fig. 11). The C:N ratios varied between 13.9 and 43.3. In the underlying sediment layers, C_{org} ranges from 0.5 to 3.1%, $\delta^{13}\text{C}_{\text{org}}$ values range from -25.9 to -15.2‰ , and C:N ratios from 18.1 to 90.6. Only core LU-DH-01 was selected for ^{14}C measurements. The mat layer at 1.5 cm depth yielded an apparent ^{14}C age of $17,500 \pm 55$ years BP ($F^{14}\text{C} = 0.1134 \pm 0.0007$). The sediments at 6.5 cm and 11.5 cm depths produced apparent ^{14}C ages of $19,300 \pm 65$ years BP ($F^{14}\text{C} = 0.0908 \pm 0.0007$) and $19,750 \pm 70$ years BP ($F^{14}\text{C} = 0.0857 \pm 0.0007$), respectively (Table 4).

In LU-DH-01, C_{org} in the mat zone (1-5cm) ranges from 2.0 to 3.1% (average = 2.5%) with $\delta^{13}\text{C}_{\text{org}}$ varying from -21.5 to -19.9‰ (average -20.9‰) and C:N ratios from 27.9 to 43.3 (average = 37.9). In the sediment section (6-12 cm), C_{org} ranges from 0.5 to 3.1% (average = 1.5%), $\delta^{13}\text{C}_{\text{org}}$ varies from -25.9 to -16.9‰ (average = -20.6‰), and C:N ratios from 20.9 to 90.7 (average = 43.5),

In LU-DH-02, the mat interval (1-7cm) has C_{org} values between 1.7 and 3.8% (average = 2.6%) and $\delta^{13}\text{C}_{\text{org}}$ from -19.3 to -15.9‰ (average = -17.4‰), and C:N ratios between 15.1 and

30.8 (average = 22.3). The sediment interval (8-13 cm) contains C_{org} between 1.2 and 2.0% (average = 1.5%) and $\delta^{13}C_{org}$ between -19.8 and -15.2‰ (average = -17.8‰), and C:N ratios from 18.1 to 29.5 (average = 23.8).

In LU-DH-03, C_{org} within the mat zone (1–6 cm) ranges from 1.2 to 3.6% (average = 2.2%), with $\delta^{13}C_{org}$ values between -19.8 and -16.8‰ (average = -18.4‰), and C:N ratios ranging from 13.9 to 27.3 (average = 20.5). The underlying sediments (7–12 cm) have C_{org} from 1.1 to 2.8% (average = 1.6%) and $\delta^{13}C_{org}$ from -23.3 to -15.2‰ (average = -19.5‰), and C:N ratios between 23.1 and 41.1 (average = 28.7).

4.2.2 Stratigraphy, organic carbon, $\delta^{13}C$ and ^{14}C at 31 m depth

Core LU-BH-12 was collected from 31 m depth of Lake Untersee. The core material is partially disturbed, and photographs show disrupted and irregular structures rather than laminations (Fig. 10).

In the mat section of the core (1–3 cm), the C_{org} values range from 1.4 to 4.0% (average = 2.3%) $\delta^{13}C_{org}$ values range from -29.5 to -25.2‰ (average = -27.0‰), and C:N ratios range from 18.0 to 67.3 (average = 36.7) (Fig. 11). In the sediment section (4–8 cm), C_{org} values range from 0.5 to 0.7% (average = 0.7%), while $\delta^{13}C_{org}$ values vary between -21.8 and -18. ‰ (average = -20.8‰), and C:N ratios vary from 10.2 to 16.8 (average = 13.9).

A mat sample at 1.5 cm depth yielded an apparent ^{14}C age of $20,200 \pm 75$ years BP ($F^{14}C = 0.0818 \pm 0.0007$). Sediment layers at 4 cm and 7 cm yielded younger apparent ^{14}C ages of $15,800 \pm 50$ years BP ($F^{14}C = 0.1401 \pm 0.0008$) and $15,150 \pm 45$ years BP ($F^{14}C = 0.1525 \pm 0.0008$), respectively (Table 4).

4.2.3 Stratigraphy, organic carbon, $\delta^{13}C$ and ^{14}C at 98-100 m depth

Cores LU-BH-08, LU-BH-08-II and LU-BH-09 were collected from flat mats at depths of 98 to 100 m of the north basin. The cores were dominated by compact fine-grained sediments with little to scarce visible microbial mat layers, representing the deeper, less photosynthetic zone of the lakebed (Fig. 10). The upper and middle sections of LU-BH-08 and LU-BH-08-II appear compressed and fragmented, with unclear layering and irregular density contrast. This disturbance may have resulted from the coring process or post-coring deformation of the unconsolidated fine sediments. On the other hand, LU-BH-09 shows the best-preserved internal structure with clear,

fine sediment layering with alternating high- and low-density zones through most of the core. Relatively small rock fragments are also visible in the so-called transition zone of the core.

Organic carbon content of the flat mats in the three cores ranges from 0.7 to 4.0% (average of 2.0%) with $\delta^{13}\text{C}_{\text{org}}$ ranging between -29.5 and -13.2‰ (Fig. 11). The organic carbon content in the underlying sediments ranges from 0.5 to 3.1% (average 1.2%), and $\delta^{13}\text{C}_{\text{org}}$ values range between -25.9 and -14.9‰ . The apparent radiocarbon ages of the surface mats range from $11,500 \pm 30$ years BP (LU-BH-09) to $13,300$ (BH-8) (Table 4). Sediment samples below the mats yielded ages between $15,100 \pm 45$ years BP and $16,950 \pm 55$ years BP (Table 4).

In LU-BH-09, C_{org} in the mat interval (1–6 cm) ranges from 0.7 to 1.2% (average = 1.0%) and $\delta^{13}\text{C}_{\text{org}}$ values range from -18.1 to -13.2‰ (average = -15.6‰) and C:N ratios from 7.6 to 11.8 (average = 9.6). In the underlying sediments (7–13 cm), C_{org} varies between 0.9% and 1.5% (average = 1.2%) and $\delta^{13}\text{C}_{\text{org}}$ between -23.8 and -15.7‰ (average = -19.9‰) and C:N ratios from 11.5 to 22.3 (average = 16.5). In LU-BH-09, the surface mat (1.5 cm) yielded a radiocarbon age of $11,500 \pm 30$ years BP ($F^{14}\text{C} = 0.2402 \pm 0.0009$). Sediment samples from 6.5 cm and 12.5 cm depths produced ages of $16,950 \pm 55$ years BP ($F^{14}\text{C} = 0.1219 \pm 0.0008$) and $16,300 \pm 50$ years BP ($F^{14}\text{C} = 0.1319 \pm 0.0008$).

In LU-BH-08, C_{org} in the mat section (1–3 cm) ranges from 1.1 to 1.3% (average = 1.2%) with $\delta^{13}\text{C}_{\text{org}}$ between -20.1 and -16.3‰ (average = -18.7‰) and C:N ratios from 12.2 to 15.3 (average = 13.2). The sediment section (4–5 cm) records C_{org} from 1.2 to 1.3% (average = 1.3%) and $\delta^{13}\text{C}_{\text{org}}$ values from -15.9 to -15.8‰ (average = -15.9‰) and C:N ratios between 7.9 and 9.1 (average = 8.7).

In LU-BH-08 II, C_{org} in the mat layer (1–5 cm) ranges between 0.9 and 1.1% (average = 0.9%) and $\delta^{13}\text{C}_{\text{org}}$ between -19.3 and -17.0‰ (average = -17.8‰) and C:N ratios from 10.5 to 13.9 (average = 12.8). In the sediment section (6–14 cm), C_{org} ranges from 0.8 to 1.4% (average = 1.1%) and $\delta^{13}\text{C}_{\text{org}}$ values from -18.9 to -14.9‰ (average = -16.6‰) and C:N ratios between 8.8 and 15.9 (average = 11.7). In LU-BH-08-II, the mat sample from 1.5 cm depth yielded an age of $13,300 \pm 40$ years BP ($F^{14}\text{C} = 0.1912 \pm 0.0008$). Sediment samples at 7.5 cm and 13.5 cm depths produced ages of $15,100 \pm 45$ years BP ($F^{14}\text{C} = 0.1536 \pm 0.0008$) and $16,100 \pm 50$ years BP ($F^{14}\text{C} = 0.1350 \pm 0.0008$).

Table 4. Radiocarbon measurements of cores collected in the north basin of Lake Untersee, Antarctica.

Core ID	Core Depth (m)	Sample Depth (cm)	Material	¹⁴ C yr BP	±	F ¹⁴ C	±	δ ¹⁴ C ‰	±
LU-DH-01	10	1.5	Mat	17500	55	0.1134	0.0007	-886.62	0.75
LU-DH-01	10	6.5	Sediment	19300	65	0.0908	0.0007	-909.25	0.73
LU-DH-01	10	11.5	Sediment	19750	70	0.0857	0.0007	-914.28	0.73
LU-BH-12	31	1.5	Mat	20200	75	0.0818	0.0007	-918.17	0.73
LU-BH-12	31	4	Sediment	15800	50	0.1401	0.0008	-859.88	0.79
LU-BH-12	31	7	Sediment	15150	45	0.1525	0.0008	-847.49	0.81
LU-BH-09	98	1.5	Mat	11500	30	0.2402	0.0009	-759.82	0.87
LU-BH-09	98	6.5	Sediment	16950	55	0.1219	0.0008	-878.07	0.8
LU-BH-09	98	12.5	Sediment	16300	50	0.1319	0.0008	-868.11	0.77
LU-BH-08-II	100	1.5	Mat	13300	40	0.1912	0.0008	-808.8	0.85
LU-BH-08-II	100	7.5	Sediment	15100	45	0.1536	0.0008	-846.43	0.8
LU-BH-08-II	100	13.5	Sediment	16100	50	0.135	0.0008	-864.97	0.77

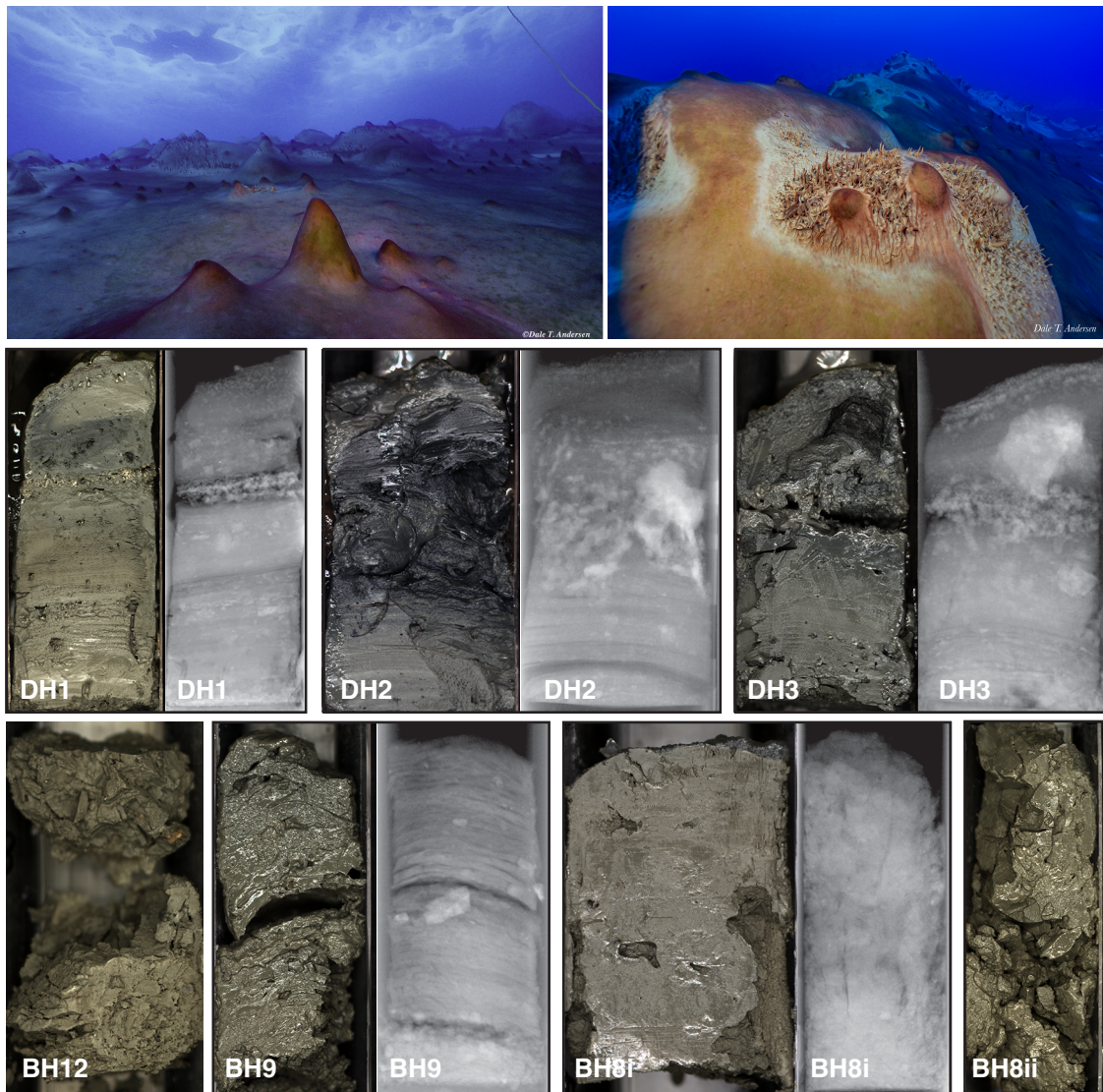


Figure 10. Photographs showing the different types of microbial mats along the lakebed of Lake Untersee, Antarctica. Shown are conical stromatolitic microbialites, flat mats and pinnacle mats. Multi-Sensor Core Logger Scan and X-ray images of north basin cores of flat mats. Photos of lakebed was taken by Dale T. Andersen.

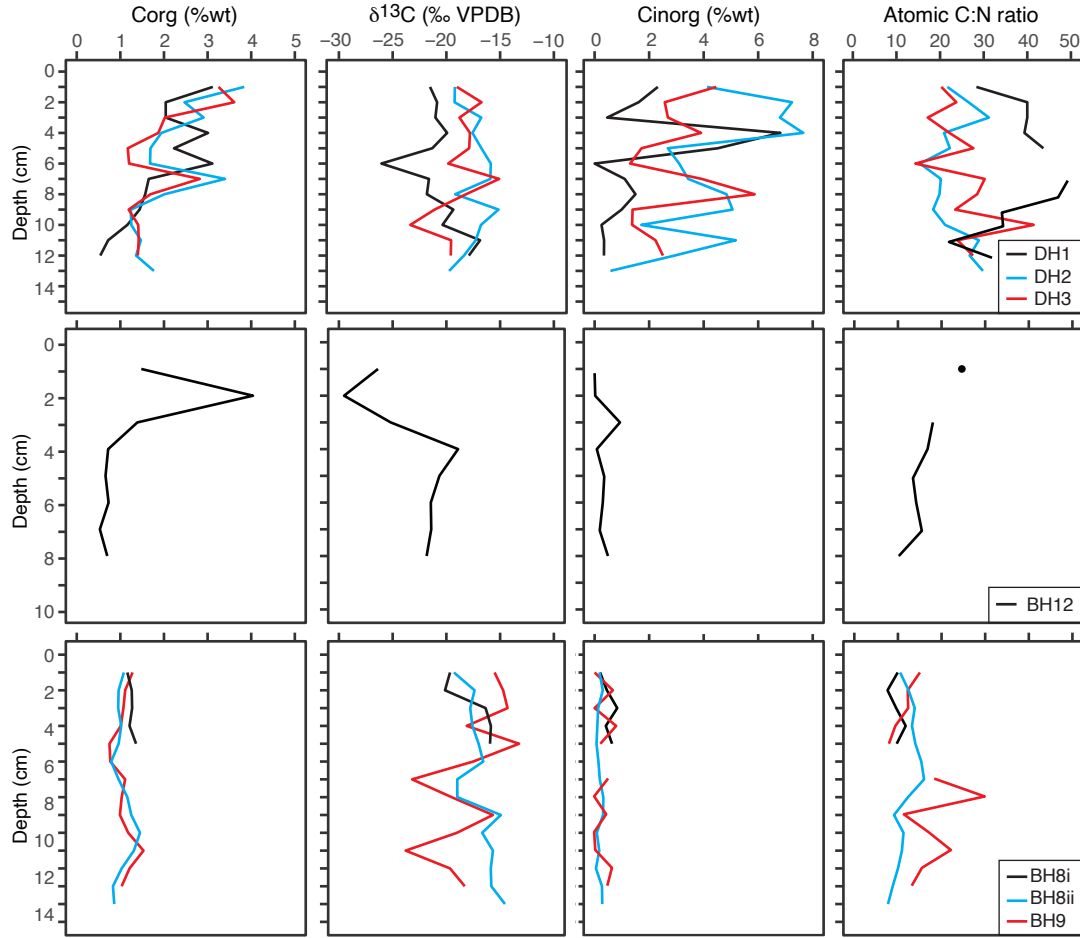


Figure 11. Depth profiles as 3 different categories (~15m, ~30m and ~100m cores) of C_{org} (%wt), $\delta^{13}C_{org}$ (‰ VPDB), C_{inorg} (%wt) and atomic C:N ratio for north basin cores of Lake Untersee, Antarctica.

4.3 Laminated sapropelic sediments in the south basin

This section presents the results of the physical appearance, internal structures, organic carbon, $\delta^{13}C$ and ^{14}C of the cores collected in the south basin of Lake Untersee.

4.3.1 Stratigraphy, organic carbon, $\delta^{13}C$ and ^{14}C

Cores LU-AH-55, LU-AH-71.5, LU-AH-87, LU-AH-87-II and LU-AH-98 were collected from depths of 55 to 98 m of the south basin (Fig. 12). Core LU-AH-55 is slightly above the deep chlorophyll layer, whereas the other three cores are found in the anoxic basin where the lack of oxygen limits the degradation of organic material. LU-AH-55 is a shorter core (7 cm) compared to other ones and showed some disturbance. In LU-AH-71.5, the upper sediments are light

brown and gravels that appear as bright, angular inclusions on radiographs. The sapropelic sediments in core LU-AH-87 is dark and exhibits alternating bands of high- and low- density material and gravels. The material in core LU-AH-98 is also dark and shows layering and several rounded zones interpreted as gas bubbles; these likely formed from methane production in the sediments. In all cores, the sediments at depth show color contrast and uniformly high density typical of compact sediment/glacial flour deposits.

Organic carbon contents in all the cores range from 0.1 to 8.9%, with $\delta^{13}\text{C}_{\text{org}}$ values spanning -22.4 to -5.3 ‰ and C:N ratios varying between 1.5 and 29.8 (Fig. 13). This broad variability likely reflects both differences in depositional depth and the strong influence of anoxia on organic matter preservation and composition. Overall, the south basin sediments lack the microbial mats observed on the north basin and instead represent continuous accumulation of fine organic sediments under long-term anoxic conditions (except LU-AH-55 which is above the anoxic basin).

In LU-AH-55, C_{org} values range from 0.6% to 2.7% (average = 1.3%) with $\delta^{13}\text{C}_{\text{org}}$ values from -18.6 to -10.1 ‰ (average = -13.9 ‰) and C:N ratios ranging from 4.7 to 29.8 (average = 12.9). Radiocarbon measurements show apparent ages of $13,350 \pm 80$ yr BP at 1.5 cm ($\text{F}^{14}\text{C} = 0.1907 \pm 0.0019$), $14,450 \pm 95$ yr BP at 3.5 cm ($\text{F}^{14}\text{C} = 0.1657 \pm 0.0019$), and $13,650 \pm 85$ yr BP at 6.5 cm ($\text{F}^{14}\text{C} = 0.1830 \pm 0.0019$) (Table 5).

In LU-AH-71.5, C_{org} ranges from 0.4 to 4.1% (average = 1.1%) with $\delta^{13}\text{C}_{\text{org}}$ values vary between -19.0 and -5.3 ‰ (average = -14.7 ‰) and C:N ratios between 10.0 and 24.5 (average = 13.9). Radiocarbon ages increase systematically with depth, beginning with $11,000 \pm 65$ yr BP at 1.5 cm ($\text{F}^{14}\text{C} = 0.2549 \pm 0.0019$), followed by $14,150 \pm 90$ yr BP at 11.5 cm ($\text{F}^{14}\text{C} = 0.1726 \pm 0.0019$), and $16,700 \pm 120$ yr BP at 20.5 cm ($\text{F}^{14}\text{C} = 0.1253 \pm 0.0019$) (Table 5).

In LU-AH-87, C_{org} values range from 1.6 to 8.8% (average = 4.2%) with $\delta^{13}\text{C}_{\text{org}}$ values between -21.1 and -14.4 ‰ (average = -17.0 ‰) and C:N ratios range from 2.9 to 10.7 (average = 7.6). The radiocarbon age of the 1.5 cm sample depth is $10,950 \pm 30$ yr BP ($\text{F}^{14}\text{C} = 0.2574 \pm 0.0009$), $11,750 \pm 35$ yr BP at 21.5 cm ($\text{F}^{14}\text{C} = 0.2321 \pm 0.0009$) and $12,250 \pm 35$ yr BP at 42.5 cm sample depth ($\text{F}^{14}\text{C} = 0.2186 \pm 0.0009$) (Table 5).

In LU-AH-87-II, C_{org} values ranges from 2.8 to 8.9% (average = 4.7%) with $\delta^{13}\text{C}_{\text{org}}$ values varying from -21.1 to -14.5 ‰ (average = -17.4 ‰) and C:N ratios between 5.6 and 9.0 (average = 7.0).

In LU-AH-98, C_{org} values range from 0.1% to 7.4% (average = 2.9%) with $\delta^{13}C_{org}$ values range between -22.4 and -14.5‰ (average = -19.4‰) and C:N ratios from 1.5 to 11.1 (average = 6.2). Radiocarbon ages show progressively older sediments with sample depth: $11,450 \pm 30$ yr BP at 2 cm ($F^{14}C = 0.2411 \pm 0.0009$), $14,450 \pm 40$ yr BP at 30 cm ($F^{14}C = 0.1659 \pm 0.0008$), and $15,450 \pm 50$ yr BP at 51.5 cm ($F^{14}C = 0.1465 \pm 0.0009$) (Table 5).

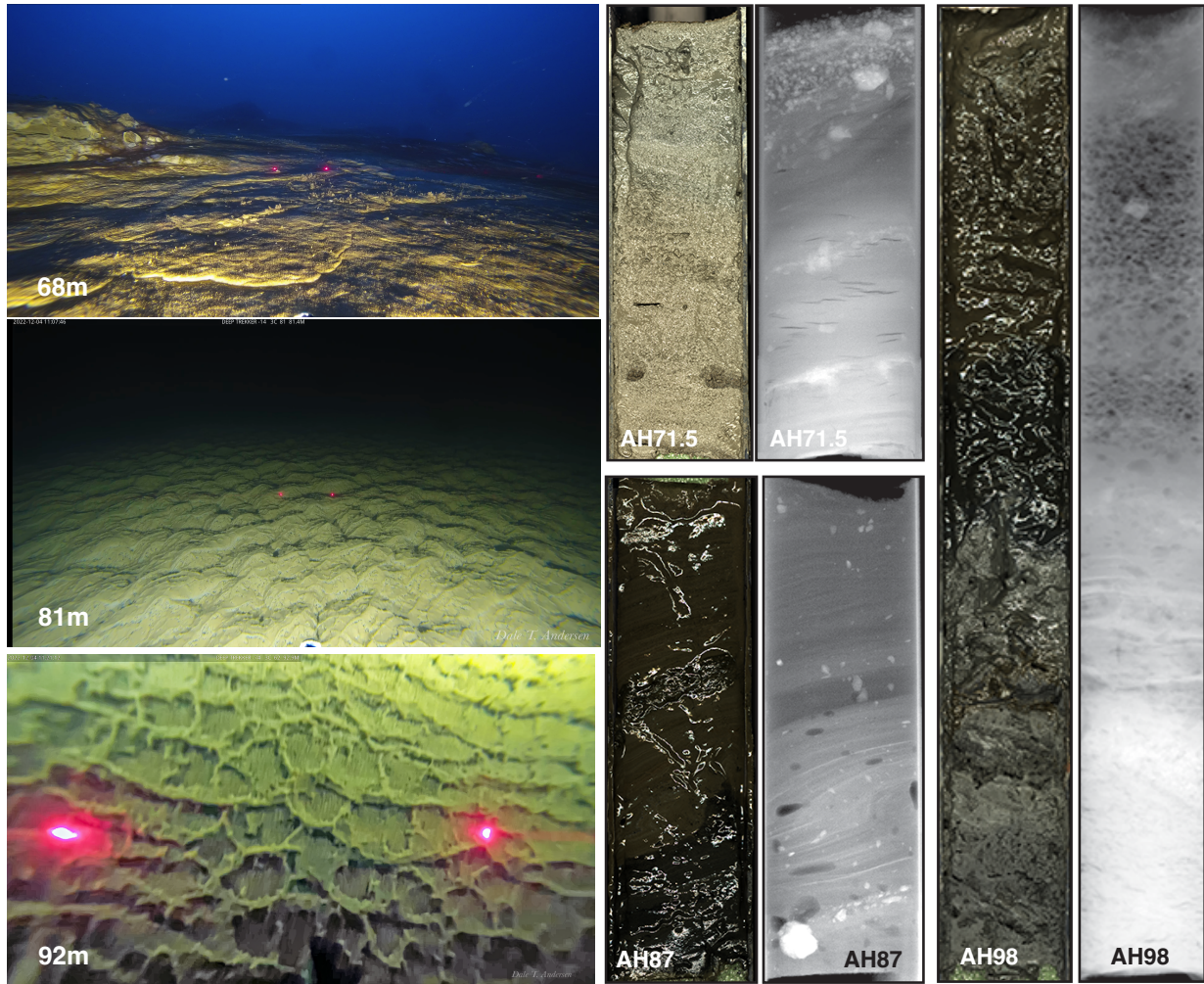


Figure 12. South basin lakebed photos, Multi-Sensor Core Logger Scan and X-ray images of the laminated sapropelic sediments in the south basin of Lake Untersee, Antarctica. Photos of lakebed are taken by Dale T. Andersen (by a Deep Trekker ROV) in December 2022. The laser scaler for 92 m depth image was set to 10 cm.

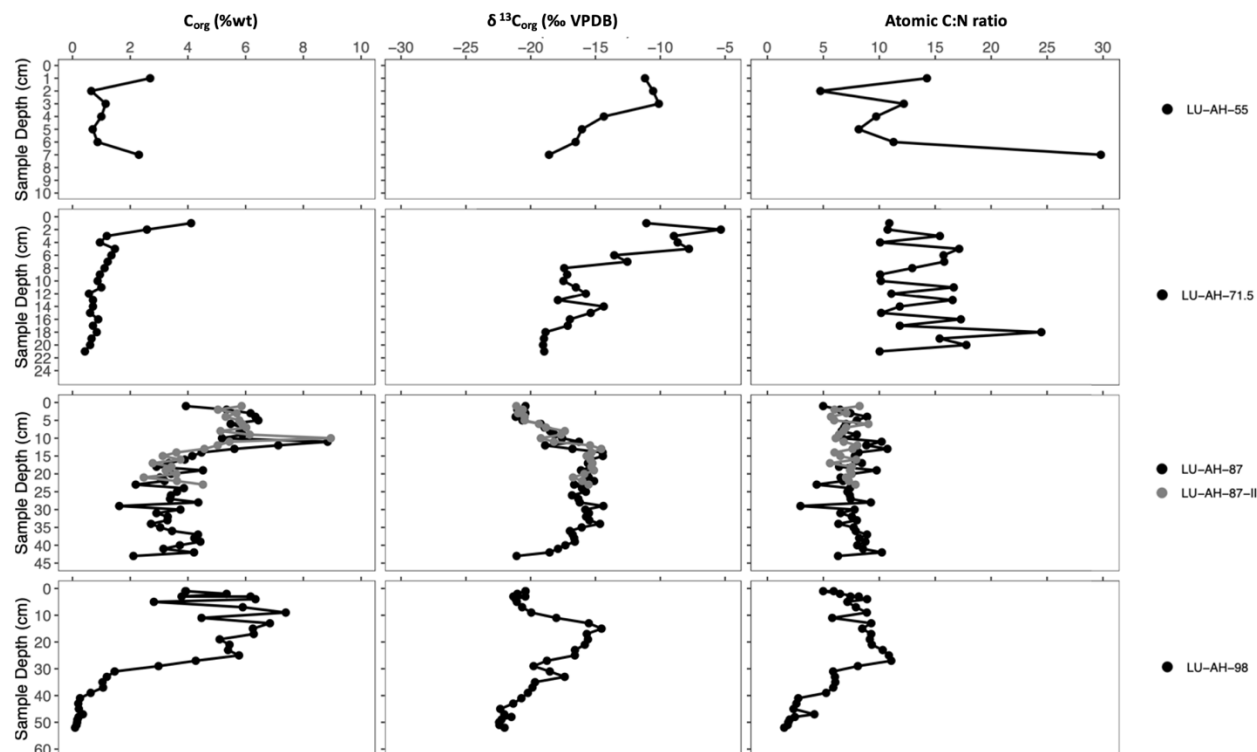


Figure 13. Profiles of C_{org} (%wt), $\delta^{13}C_{org}$ (‰ VPDB) and C:N ratio of laminated sapropelic sediments at 55m, 71.5m, 87m and 98m depth in the south basin of Lake Untersee, Antarctica.

Table 5. Radiocarbon measurements from the laminated sapropelic sediments in the south basin of Lake Untersee, Antarctica

Core ID	Core Depth (m)	Sample Depth (cm)	Material	^{14}C yr BP	±	$F^{14}C$	±	$\delta^{14}C$ ‰	±
LU-AH-55	55	1.5	Sediment	13350	80	0.1907	0.0019	-809.33	1.87
LU-AH-55	55	3.5	Sediment	14450	95	0.1657	0.0019	-834.25	1.91
LU-AH-55	55	6.5	Sediment	13650	85	0.183	0.0019	-817.03	1.91
LU-AH-71.5	71.5	1.5	Sediment	11000	65	0.2549	0.0019	-745.1	1.92
LU-AH-71.5	71.5	11.5	Sediment	14150	90	0.1726	0.0019	-827.38	1.88
LU-AH-71.5	71.5	20.5	Sediment	16700	120	0.1253	0.0019	-874.71	1.86
LU-AH-87	87	1.5	Sediment	10950	30	0.2574	0.0009	-742.59	0.91
LU-AH-87	87	21.5	Sediment	11750	35	0.2321	0.0009	-767.88	0.88
LU-AH-87	87	42.5	Sediment	12250	35	0.2186	0.0009	-781.42	0.88
LU-AH-98	98	2	Sediment	11450	30	0.2411	0.0009	-758.88	0.9
LU-AH-98	98	30	Sediment	14450	40	0.1659	0.0008	-834.08	0.82
LU-AH-98	98	51.5	Sediment	15450	50	0.1465	0.0009	-853.54	0.87

5 Chapter 5: Discussion

Lake Untersee represents one of the most isolated aquatic ecosystems in Antarctica (Andersen et al., 2011; Wand et al., 1997). The permanent ice cover prevents direct atmospheric exchange, while also limiting light and nutrient availability. As a result, the lake's benthic microbial mats rely on internal recycling of carbon to sustain primary productivity under stable, cold, alkaline, and high oxygen conditions (Marsh et al., 2020). Previous studies based on $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ of microbial mats indicates that Lake Untersee differs from other perennially ice-covered lakes. Lawson et al. (2004) examined the $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ composition of four perennially ice-covered lakes in the McMurdo Dry Valleys: Lake Fryxell, Lake Hoare, East Lake Bonney and West Lake Bonney (Lawson, Doran, Kenig, Marais, et al., 2004). These perennially ice-covered lakes retain liquid water year-round and are fed by glacial meltwater and are capped with thick permanent ice (3-6 m). However, in contrast to Lake Untersee, these lakes develop seasonal moats that play a significant role in shaping nutrient cycling and organic matter dynamics. Moats, formed along the periphery of lakes during summer, are zones of biological activity that contribute to distinct carbon isotopic signatures. The organic matter content in summer moat areas of 4 main Taylor Valley lakes is enriched in ^{13}C compared to the benthic organic matter deeper in the lakes. Therefore $\delta^{13}\text{C}$ of moat organic matter was measured as $\sim -20\text{‰}$ and for benthic organic matter as $\sim -26\text{‰}$ (Lawson, Doran, Kenig, Marais, et al., 2004; Moorhead et al., 2005; Warrier et al., 2015). The absence of moat-driven lateral mixing eliminates a major pathway for redistributing nutrients and organic matter between the lake's margins and central water column.

Instead, nutrient cycling in Lake Untersee relies on internal mechanisms, such as microbial activity and the interaction between benthic microbial mats and the overlying water column (Wharton et al., 1993). This results in a relatively stable isotopic and chemical environment compared to MDV lakes, where seasonal moating introduces variability. Also Marsh et al. (2020) highlighted that the photosynthetic mats in Lake Untersee are active, but their gross photosynthesis and organic carbon sequestration rates are significantly lower compared to mats in the McMurdo Dry Valley (MDV) lakes (Hawes et al., 2019; Marsh et al., 2020). The lack of seasonal moats in Lake Untersee limit the spatial extent of nutrient redistribution and concentrate biological activity near benthic microbial mats, highlighting a distinct mode of nutrient cycling compared to the more dynamic MDV lakes.

Previous work by Marsh et al. (2020) provided a quantitative assessment of the organic carbon reservoir in Lake Untersee based on carbon abundances, $\delta^{13}\text{C}$ values and radiocarbon ages from large conical stromatolitic microbialites collected at depth ranging between 13 to 20 m in the north basin. The carbon abundances in the cones are reported as ranging from 1 to 5.8 wt %, with an estimated organic carbon density of approximately $793 \pm 264 \text{ g m}^{-2}$. The $\delta^{13}\text{C}_{\text{org}}$ of the cones averaged $-10.6 \pm 1.9 \text{ ‰}$. Radiocarbon dating of selected layers yielded apparent ages of ~ 9500 and $10,900$ years BP for the uppermost laminae, whereas the deepest layers had apparent ages of $12,000$ to $16,000$ years BP suggesting long-term accretion and preservation of material. The underlying sediments were primarily composed of fine-grained to coarse mineral particles and contained much lower organic carbon content ($\leq 1 \text{ wt}\%$) and older apparent radiocarbon ages (up to $\sim 19,000$ years BP). Additionally, it is underlined that the conical mats use a relation of autotrophic and heterotrophic metabolisms. Organic carbon in the mats are primarily derived from photosynthetic fixation of limited DIC and possibly by recycled CO_2 from heterotrophic respiration below photosynthetic layers of stromatolites (Marsh, 2019; Marsh et al., 2020).

5.1.1 Sources of gases in Lake Untersee

Wand and Perlt (1999) first suggested that Lake Untersee had a permanent ice cover for at least the past 500 years (Wand & Perlt, 1999). Measurements of radionuclides showed no detectable ^3H and ^{129}I in the water-column of Lake Untersee, suggesting that it has been effectively sealed from atmospheric fallout since the mid 20th century nuclear testing period (Marsh, 2019).

Despite this isolation, Lake Untersee receives atmospheric gases through pathways other than direct atmospheric exchange with an open water surface or from surface runoff. Trapped air bubbles in the Anuchin Glacier are released during subaqueous melting at the ice-water interface, delivering old-atmospheric gases to the lake water column. In addition, the subglacial meltwater transport air-saturated water and nutrients in the lake (Faucher et al., 2019, 2021). The $^3\text{He}/^4\text{He}$, $^{22}\text{Ne}/^{20}\text{Ne}$ and $^{40}\text{Ar}/^{36}\text{Ar}$ ratios were all close to atmospheric values, with mean R/R_a ratios of 0.98, 0.99 and 0.99 respectively. This rules out a production of ^{40}Ar from the decay of ^{40}K . It also rules out $^3\text{He}/^4\text{He}$, a geogenic source of He since it would produce a substantially lower ratio due to production of ^4He from the decay of U and Th in rocks (Ballentine & Burnard, 2002; Ozima & Podosek, 2002; Warrier et al., 2015). It also rules out a mantle/magmatic source that would produce a higher $^3\text{He}/^4\text{He}$ ratios (typically 8-50 range; (Graham, 2002; Starkey et al., 2009)), and

there is no tritium in the water column that would produce ^3He from its decay. Therefore, the analysis of noble gas isotopes suggests that the gases entering Lake Untersee are a mixture of atmospheric gases trapped in glacier ice and released into the lake water and from the subglacial meltwater, both with an isotope ratio near R_a . This is different for Lake Vostok where the $^3\text{He}/^4\text{He}$ ratio are near 0.12, which suggests a substantial contribution of geogenic He to the water column (Jean-Baptiste et al., 2018). Further, the surface water of perennially ice-covered Lake Bonney (MDV) has $^3\text{He}/^4\text{He}$ ratio near 0.16 to 0.18, attributed to a brine system with high He flux discharging into the lake (Doran et al., 2014; Hall et al., 2017; Poreda et al., 2004).

The ratios of $^4\text{He}/^{40}\text{Ar}$ and $^{20}\text{Ne}/^{40}\text{Ar}$ were used to determine the contribution of air and air saturated water into the lake (Fig. 8). The values indicate that air bubbles released during the subaqueous melting of the glacier contributes 30-50% of the gases entering the lake. This aligns with the water-mass balance that estimated that 40-45 % of the annual water entering the lake is derived from subaqueous melting of the Anuchin Glacier and the remaining 55-60% from subglacial and groundwater contributions (Faucher, 2021; Faucher et al., 2019). Similar mechanisms have been reported in other Antarctic lakes, including the subglacial Vostok Lake, where meltwater inputs and the release of occluded air during ice melt supply the lake with atmosphere derived gases despite being covered by the Antarctic ice sheet (Jouzel et al., 1999). Overall, results show that the noble gas ratios and abundance values in Lake Untersee indicate air group signature (either as ASW or air). This is due to 1) direct interaction with the atmosphere being prevented by perennial ice cover, 2) absence of non-atmospheric noble gas input via geogenic sources and 3) the release of trapped air bubbles from the Anuchin Glacier are an important air input to Lake Untersee and the remaining part being added as ASW.

5.1.2 Carbon sequestration and metabolic activity of flat mats and conical microbialites in the north basin

The north basin of Lake Untersee hosts photosynthetic microbial mats in the form of conical mats, flat mats, and pinnacles (Andersen et al., 2011; Marsh et al., 2020; McKay et al., 2017). The flat mats have higher C_{org} (between 0.7 and 4.0%, average $\sim 2\%$) than the underlying sediments (0.5 to 1.6%), indicating greater organic matter accumulation and preservation in these layers. The conical mats also have higher C_{org} (typically 1-6%) compared with the underlying sediments ($<1\%$) (Marsh, 2019). To assess the amount of organic carbon stored in the flat mats and conical mats,

the C_{org} were converted to organic carbon content based on equation 6 (Fig. 14). The conical mats at 10-20 m depth have OCC values up to $\sim 10 \text{ kg m}^{-2}$ (Marsh, 2019). The flat mats from the depths of 10-30 m have OCC ($\sim 1\text{-}2.5 \text{ kg m}^{-2}$) about one order of magnitude lower than the conical mats, whereas flat mats that develop at 100 m depth of the north basin have the lowest OCC ($< 1 \text{ kg m}^{-2}$).

There are two observations from the OCC in the microbial mats: 1) at same depth, the conical mats store a higher amount of organic carbon, and 2) the OCC in the flat mats decrease with depth. The decreasing OCC of the photosynthetic flat mats with depth in the north basin is consistent, in part, with the decreasing PAR with depth in the water column (Fig. 15). This trend suggests that organic carbon sequestration by the flat mats in the north basin of Lake Untersee is influenced by the availability of light. However, at same depth, the conical mats have substantially higher organic carbon content compared to the flat mats. These two morphologies also have substantially different $\delta^{13}\text{C}$ values: conical mats in the -12 to -8‰ range and flat mats in the -13 to -30‰ range. This suggests that in addition to the availability of light, that the cones and flat mats have distinct metabolic activity. In typical lacustrine environments where abundant CO_2 is available for carbon fixation by the Rubisco enzyme, photosynthetic activity preferentially utilizes ^{12}C , resulting microbial mats with depleted $\delta^{13}\text{C}$ and leaving the residual DIC enriched in ^{13}C (Hage et al., 2007; Hayes, 1993; Lawson, Doran, Kenig, Des Marais, et al., 2004). Maximum fractionation factor by cyanobacteria ranges from 1.023 to 1.018 (Calder & Parker, 1973; Pardue et al., 1976). However, when DIC is a limiting factor, ^{13}C fractionation is likely negligible since all of the available DIC is used during carbon fixation (Calder & Parker, 1973; Marsh, 2019). The $\delta^{13}\text{C}$ of the DIC in the water column averages -9.1‰ , which reflects the input of CO_2 air released during the englacial melting of the Anuchin Glacier (Marsh et al., 2019). Since the $\delta^{13}\text{C}$ of the conical mats are similar to those of the $\delta^{13}\text{C}_{\text{DIC}}$, Marsh et al. (2019) suggested that the growth of the conical mats was limited by the availability of DIC for photosynthesis. The cones utilize both HCO_3^- and CO_2 sources for phototrophic carbon fixation, and in this carbon-starved ecosystem, they also use heterotrophically respired CO_2 from the decomposition of underlying organics. By contrast, the flat mats with $\delta^{13}\text{C}$ values significantly lower than the $\delta^{13}\text{C}_{\text{DIC}}$ in the water column suggests that they preferentially fix ^{12}C over ^{13}C and are not limited by the available DIC. Therefore, despite being located at a similar depth, the conical mats are primarily DIC-limited, whereas the flat mats are not. This difference can be attributed to their distinct morphology, which

results in the cones to have a much higher surface area to fix the carbon (Fig. 16). Chlorophyll-a measurements from conical mats and flat mats support the influence of morphology on photosynthetic activity and biomass accumulation (Hawes et al., 2019). Chlorophyll-a concentrations measured at 25 m depth show that the top of cones contains substantially higher chlorophyll-a ($24.2 \mu\text{g} \pm 12.1 \mu\text{g cm}^{-2}$) compared to flat mats ($9.5 \mu\text{g} \pm 3.2 \mu\text{g cm}^{-2}$) (Hawes et al., 2019; Hawes & Schwarz, 2001). These pigment distributions demonstrate that large conical mats strongly enhance photosynthetic biomass, consistent with their elevated organic carbon contents and their $\delta^{13}\text{C}$ values approaching those of $\delta^{13}\text{C}_{\text{DIC}}$ in the water column. In fact, the ratios of surface area of cones, their OCC and chlorophyll-a are all 2-3 times higher than those in flat mats (Fig. 14, 15 and 16). As such the cones likely have a higher growth rate and it becomes limited by the limited availability of DIC, whereas the flat mats have a slower photosynthetic uptake allowing Rubisco-related isotope fractionation to take place (Hayes, 1993).

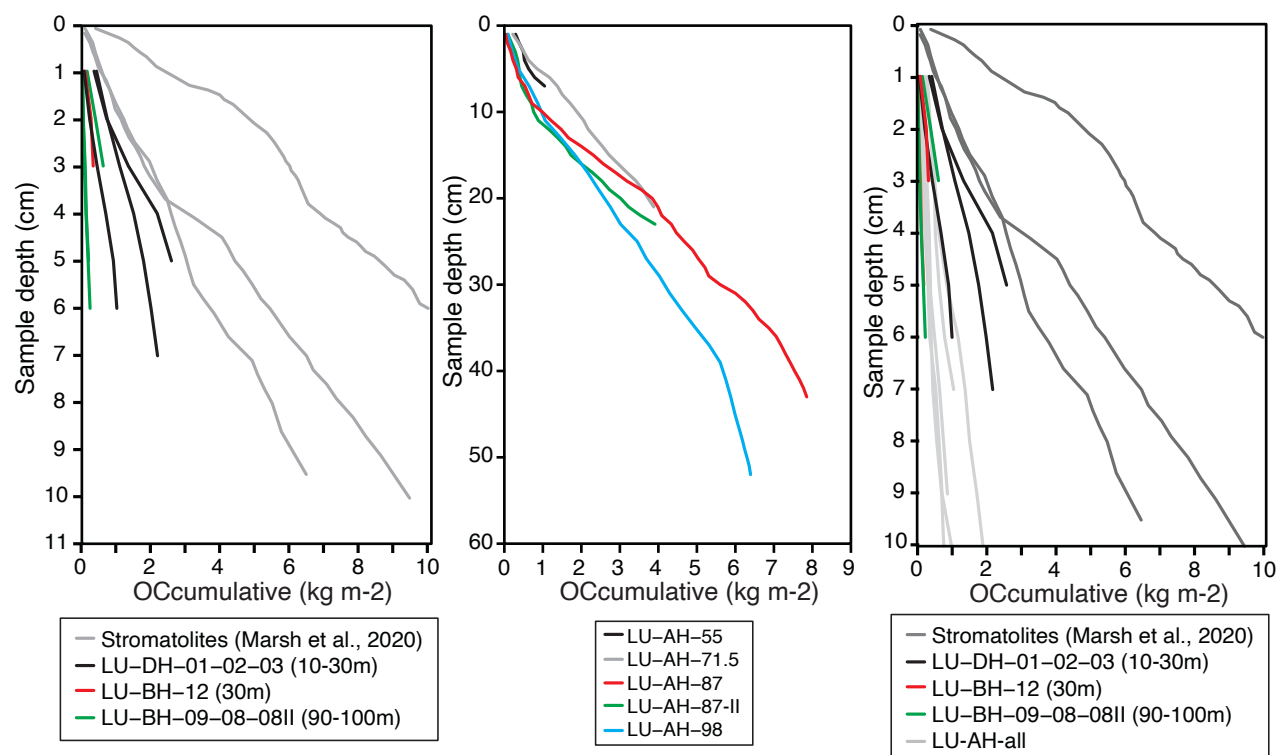


Figure 14. Cumulative organic carbon contents for north basin, south basin and first 10 cm sample depth of all collected cores for Lake Untersee, Antarctica.

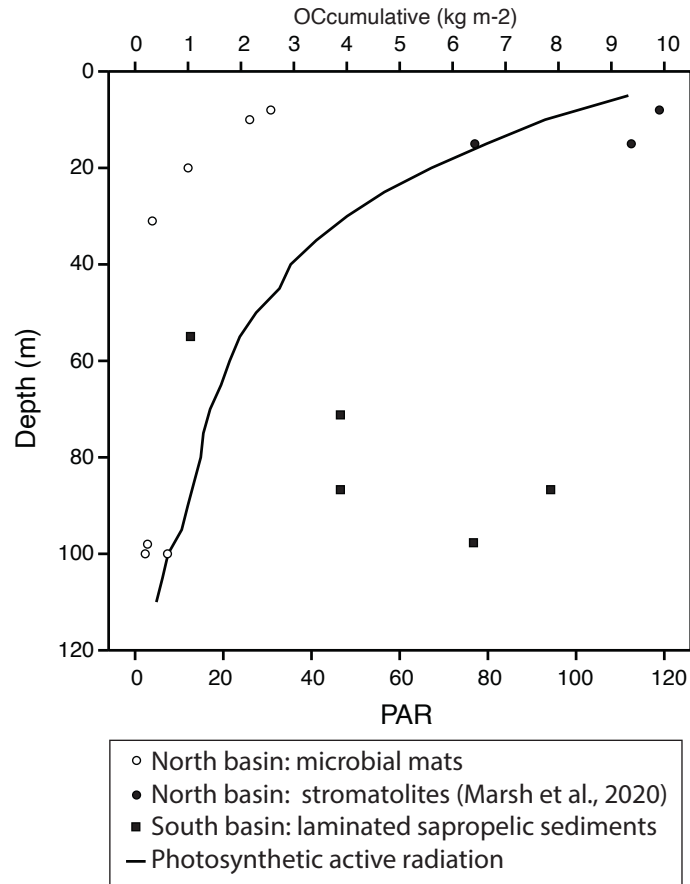


Figure 15. Cumulative organic carbon (OCC) for oxic basin core's microbial mats including previously reported results from stromatolite samples of Marsh et al. (2020) (excluding sediment samples from cores) and photosynthetically available radiation (PAR) of Lake Untersee, Antarctica.

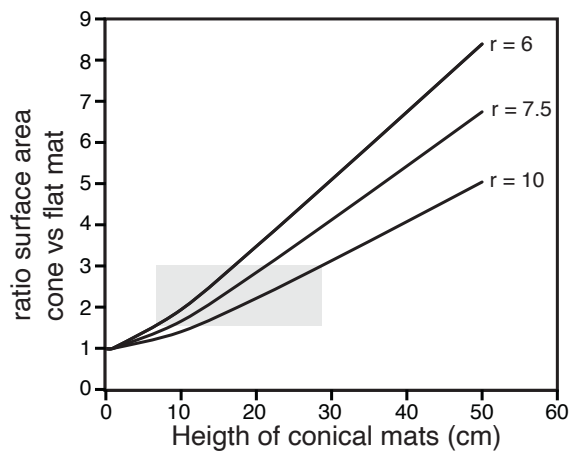


Figure 16. Surface area ratio of conical mats and flat mats based on the height of conical mats for Lake Untersee, Antarctica

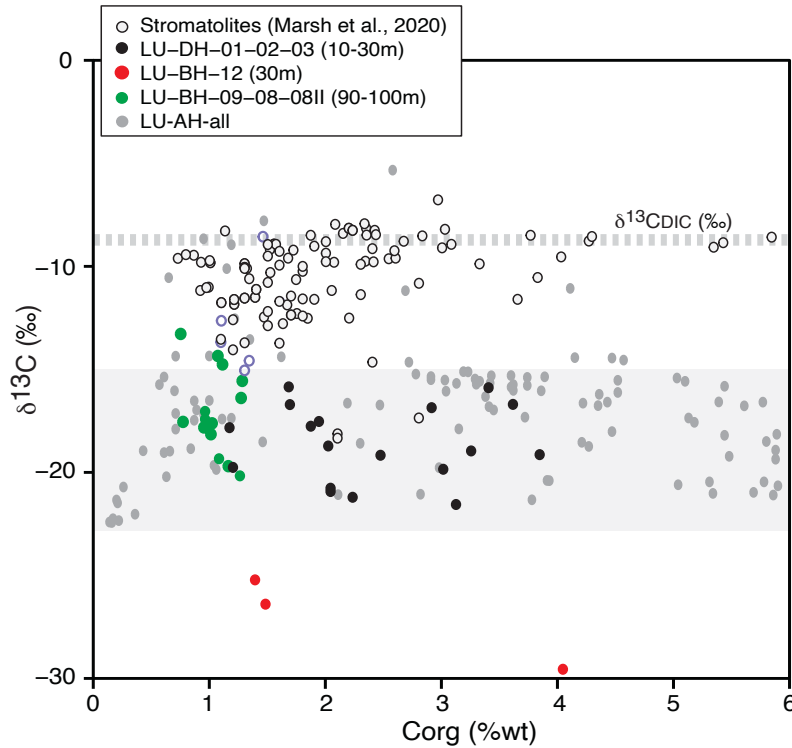


Figure 17. $\delta^{13}\text{C}$ (permil) and organic carbon (C_{org} %wt) for conical mats, flat mats and south basin sapropelic sediments of Lake Untersee, Antarctica.

5.1.3 Contribution of photosynthetically produced O_2 to the water column

The noble gas measurements from the north basin indicate that Lake Untersee receives gases from the air group (Fig. 8). The sources of these gases come from the subaqueous melting of the Anuchin Glacier that releases occluded air directly into the water column and from subglacial meltwater. Their annual contribution to the lake was estimated to be near equal and the annual recharge is equivalent to about 1% of total lake volume (Faucher et al., 2019).

The measurements of O_2/Ar and $\delta^{18}\text{O}-\text{O}_2$ can be used to infer the relative contribution of abiotic and biological O_2 in the water-column derived from photosynthesis ($6\text{CO}_2 + 6\text{H}_2\text{O} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2$). The oxic water in the north basin has DO near 150%, O_2/Ar ratios between 19.3 and 19.9, and $\delta^{18}\text{O}-\text{O}_2$ of +5.2 to +8.4‰ (Fig. 9). When He/Ar is plotted against O_2/Ar , the O_2/Ar measurements deviate from the linear mixing between air and air-saturated water (abiotic source) by a factor of 1.12 (Fig. 18). This suggests an additional source of O_2 to the water column, such as O_2 produced from the photosynthetic activity of the microbial mats (i.e., Craig et al., 1992). The

O₂/Ar data are 11-12% higher than an abiotic source; however, this estimate needs to be corrected for the residence time of the water in the lake (i.e., Jean-Batiste et al., 2018). In Lake Untersee, the residence time of water was calculated to be 100 years (Faucher, 2021; Faucher et al., 2019). If we account for this residence time, the annual contribution of O₂ from photosynthesis would be 0.12-0.13%. The contribution of O₂ from photosynthesis can also be assessed from the $\delta^{18}\text{O}$ -O₂ data. The direct release of atmospheric gases in the water column is a non-fractionating process, and the $\delta^{18}\text{O}$ -O₂ of the DO therefore preserves that of the air (+23‰ VSMOW). In contrast, oxygen produced during aquatic photosynthesis inherits the $\delta^{18}\text{O}$ signature of the source water (Barth et al., 2004; Coplen et al., 2002; Kroopnick & Craig, 1972). In Lake Untersee the water has $\delta^{18}\text{O}$ -H₂O near -40‰ (Faucher, 2021; W. D. Hermichen et al., 1985). The measurements of $\delta^{18}\text{O}$ -O₂ in the water column of Lake Untersee therefore reflect a mixture of these two sources of O₂ (e.g. +5.2 to +8.4‰). Applying a mixing model for $\delta^{18}\text{O}$ -O₂, where $\delta^{18}\text{O}$ -O₂ _{air} VSMOW = +23.5‰; $\delta^{18}\text{O}$ -O₂ _{photosynthesis} = -40‰, and correcting for the residence time of water, suggests that the photosynthesis contributes annually about 0.26% of the O₂ in the lake. It should be noted that $\delta^{18}\text{O}$ -O₂ reflects gross photosynthesis, whereas O₂/Ar reflects net photosynthesis. Consequently, the contribution of photosynthesis estimated from $\delta^{18}\text{O}$ -O₂ is likely expected to be slightly higher than estimates from O₂/Ar. Finally, the amount of O₂ derived from photosynthesis can also be assessed if we assume that all the CO₂ that enters the lake is being consumed by the benthic microbial mats. Assuming an average gas volume of 0.11 cm³ g⁻¹ in ice (Gow & Williamson, 1975; Samyn et al., 2005) and an average CO₂ concentration of 300 ppm for the late Holocene (Monnin et al., 2004), an annual CO₂ input of 1.42 x 10⁻⁶ mole L⁻¹ is estimated for the contribution of subaqueous meltwater. If we assume that the subglacial meltwater transport air saturated water (ASW), the annual CO₂ input would be 2.9 x 10⁻⁵ mole L⁻¹. The subaqueous meltwater and subglacial meltwater contribute near equal volume of water to the lake, giving an annual CO₂ input of 1.52 x 10⁻⁵ mole L⁻¹. The stoichiometry of organic carbon formation by photosynthesis (1 mole CO₂ fixed and 1 mole O₂ released) suggest that the maximum O₂ contribution is 1.5-1.7% per year. This approach leads to a higher estimate from that of O₂/Ar and $\delta^{18}\text{O}$ -O₂, but some of the CO₂ added to the lake is also being consumed during plagioclase weathering which gives the lake its elevated pH (Andersen et al. 2011). These estimates of O₂ derived from photosynthesis in Lake Untersee are about two order of magnitude lower than in the perennially ice-covered lakes in the MDV (Andersen et al., 1998; Craig et al., 1992; Wharton et al., 1986, 1987). This is in line with

the much lower gross photosynthetic rate estimated for Lake Untersee compared to the MDV lakes (Hawes et al., 2019)

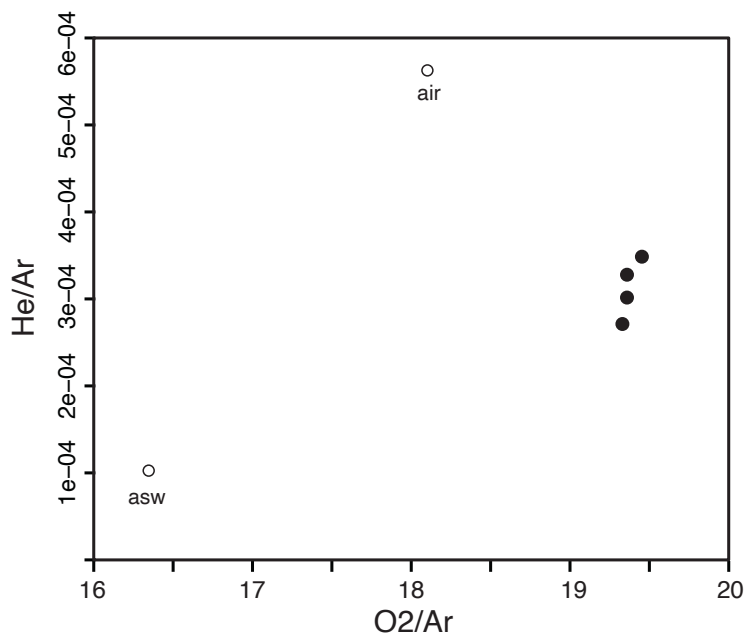


Figure 18. He/Ar and O₂/Ar ratios compared to expected values in air and air saturated water (asw) for Lake Untersee, Antarctica. He/Ar_{asw}: 1.03 × 10⁻⁴, O₂/Ar_{asw}: 16.33, He/Ar_{air}: 5.63 × 10⁻⁴ and O₂/Ar_{air}: 18.09

5.1.4 Metabolic activity and carbon sequestration of organic matter in the south basin

The anoxic waters below the sill depth in the south basin of Lake Untersee hosts the laminated sapropelic sediments and lack the benthic microbial mats observed in the north basin. Cores of the sapropelic sediments sampled at depths of 55 to 98 m have C_{org} up to 8.9%, and OCC values up to 7-8 kg m⁻² (Fig. 13 and 14). If we look at only the uppermost 10 cm of the cores, OCC values range between 1-2 kg m⁻², which is comparable to the flat mat values observed in the north basin (Fig. 14). The δ¹³C_{org} values range mainly between -22.4 and -15‰, with a few outliers with values up to -5.3‰, which are in the range of bulk material measured by Brady et al. (2023) (Fig. 13 and 17). Since the water column below the sill depth has little to no oxygen, it is suggested that the organic material is developed near the chemocline in the deep chlorophyll layer at 70-72 m depth. Given the persistent anoxia below the sill level and the absence of benthic microbial mats in the south basin, in situ benthic production doesn't account for the observed organic carbon inventories. Profiles of chlorophyll-a, conductivity, and δ¹⁸O-O₂ from south basin show that this

signal corresponds to a thin, suspended photosynthetic layers centered at ~70-72 m (Fig. 4 and 9) (Bevington et al., 2018; Wand et al., 2006). Marsh (2019) described this layer as a “cloud” of planktonic phototrophic bacteria. In this layer, the DO shows a slight increase and the $\delta^{18}\text{O}-\text{O}_2$ has lower values (i.e. -3.5 to $+0.7\text{‰}$) than in the well-mixed north basin (i.e. 6 to 8‰). This suggests that photosynthesis is taking place in this deep chlorophyll layer, and the organic matter being produced then sinks in the water column leading to the accumulation of laminated sapropelic sediments. Using the same two component mixing model of $\delta^{18}\text{O}-\text{O}_2$ from the north basin, the lower values in the deep chlorophyll layer suggest an annual O_2 contribution by photosynthesis in this layer of about 0.35 - 0.45% if we also assume a water residence time of 100 years in this layer. However, it is possible that the residence time is higher since Bevington et al. (2018) identified this zone as being poorly mixed. Overall, the laminated sapropelic sediments in the south basin likely represent a continuous accumulation of fine organic sediments produced in the deep chlorophyll layer and their preservation under anoxic conditions along the lakebed (except core LU-AH-55 which is collected from 55m depth above the anoxic basin). This differs to the model proposed by Brady et al. (2023) where it was suggested that the upward diffusion of CH_4 was driving microbial productivity in the anoxic and sub-oxic zone and the subsequent sinking of the detrital organic material (Brady et al., 2023). Here, it is proposed that the deep chlorophyll layer at 70 - 72 m powers the microbial productivity and the accumulation of laminated sapropelic sediments.

5.1.5 Source of dissolved inorganic carbon (DIC) and sapropelic sediments

Radiocarbon measurements of microbial mats from the north basin and of the laminated sapropelic sediments provide insights into the sources of carbon used during photosynthesis in Lake Untersee. The $^{14}\text{C}_{\text{DIC}}$ in the oxic water column is 6500 - 7000 ^{14}C years BP (Marsh et al., 2020), and one would expect the surface layer of phototrophic microbial mats to exhibit similar apparent radiocarbon ages if carbon fixation was sourced solely from the DIC reservoir. The surface laminae of the flat mats (included in first centimeter of cores) yielded apparent radiocarbon ages ranging from $20,200$ to $11,500$ ^{14}C years BP. These are older than the apparent ages of the surface layer of the conical mats (9500 to $10,050$ ^{14}C yr BP) and of the sapropelic sediments ($10,900$ to $11,450$ ^{14}C yr BP). Since the $\delta^{13}\text{C}$ of the conical mats showed comparable results to the $\delta^{13}\text{C}$ of the DIC, Marsh et al. (2020) suggested that the conical mats used as a source of CO_2 both the DIC in the water-column

and CO₂ produced by heterotrophs during the decomposition of buried organics in the cones. It is also underlined that active conical surfaces in Lake Untersee are radiocarbon dated more than 2500 years older than DIC pool, confirming that stromatolite phototrophs also assimilate recycled carbon from underlying buried layers. Radiocarbon results of an oxic basin core reported by Schwab (1998), further confirm the presence of persistent reservoir effect in photosynthetically fixed carbon. Surface microbial mats yielded apparent radiocarbon ages of 11,290 years BP, which is older in age than the DIC in the water column (Schwab, 1998). Therefore, the conical mats are DIC-limited, and the phototrophs develop a synergy with the underlying heterotrophs that provide them with additional older CO₂.

The ¹⁴C_{DIC} in the sub-oxic and anoxic water is in the range of 10,800 at 70 m and increasing to 11,375 at 98 m (Marsh et al., 2020). The ¹⁴C_{DOC} is also within that range, from 10,975 at 70 m and increasing to 13,635 at 98 m. As such, the ¹⁴C of the surface layer of the laminated sapropelic sediments is within the range of the DIC in the deep chlorophyll layer. Since the δ¹³C of the sapropelic sediments is depleted with respect to the DIC, such depletion likely reflects isotopic fractionation. The phototrophs in the deep chlorophyll layer are therefore not limited by the availability of DIC and they consume the DIC in that layer that has slightly older ¹⁴C age.

The apparent radiocarbon ages of the flat mats are more complex to interpret than those of the conical structures, as they generally exhibit older and age inversion near the transition to sediments zone in the cores. One possible explanation is that flat mats developing on lakebed surfaces are more susceptible to the incorporation of detrital organic material. Alternatively, flat mats may have initiated growth earlier than the conical mats, potentially prior to the establishment of the deep chlorophyll layer. In this case, flat mats would have incorporated inorganic carbon from an earlier lake carbon reservoir, resulting in older apparent ¹⁴C ages.

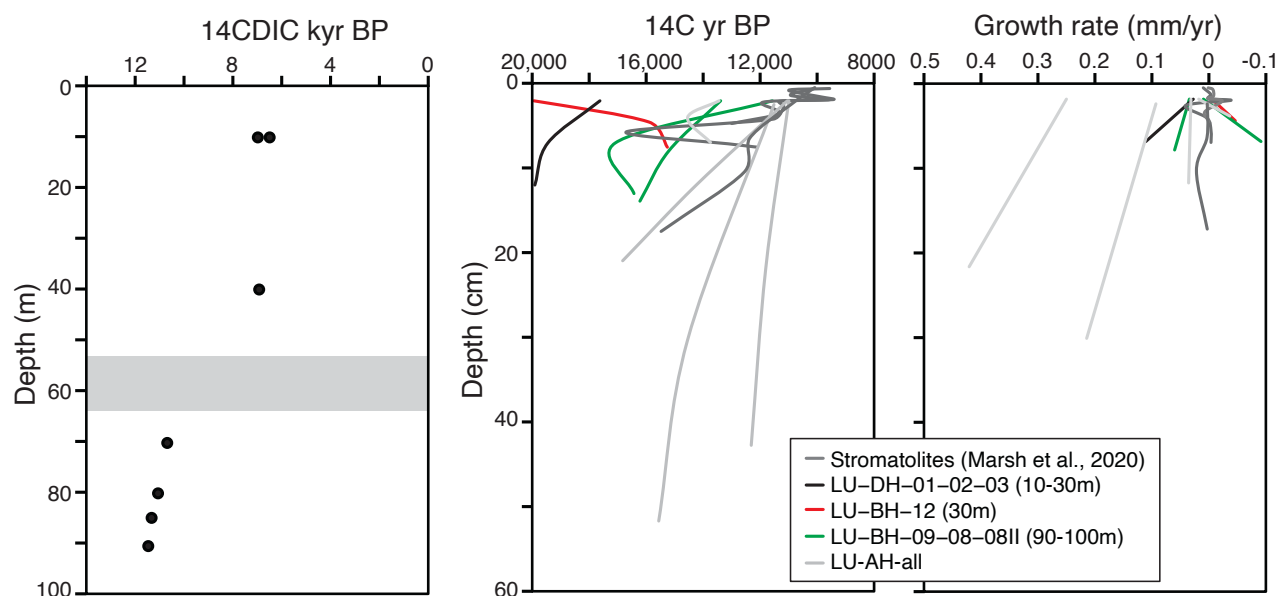


Figure 19. Radiocarbon ages of dissolved inorganic carbon (DIC) of the water column (grey area represents the sub-oxic zone below the sill level). Radiocarbon ages of collected cores from the north and south basins including previously collected conical mats by Marsh (2019). Growth rates of microbial mats and south basin sapropelic sediment layers of Lake Untersee, Antarctica.

5.1.6 Storage of organic carbon in Lake Untersee

Core-scale organic carbon contents show a clear depth-dependent structure in microbial mat carbon storage across the oxic basin of Lake Untersee. Shallow depth flat mats from 10 m group exhibit the highest organic carbon contents, with values ranging from 0.1 to 0.256 kg C m⁻² with an average of 0.191 kg C m⁻². In contrast, flat mats from the 30 m depth show substantially lower organic carbon content (0.032 kg C m⁻²) indicating reduced photosynthetic activity and/or increased degradation with depth. The 100 m depth group shows similarly low values (0.019-0.061 kg C m⁻²) with an average of 0.035 kg C m⁻².

To scale the core measurements to the lake-wide microbial mat carbon reservoir, depth-integrated organic carbon contents were calculated using lakebed surface areas and depth-specific average C_{org} contents. For the 0-10 m interval, the average organic carbon content was derived as the mean of shallow cores from this study (average 0.191 kg C m⁻²) and previously reported shallow-water conical mat cores (Marsh, 2019) from comparable depths (average 0.857 kg C m⁻²), yielding a combined representative value of 0.524 kg C m⁻². For the 10-30 m, cores from 10 (including cores of Marsh, 2019) and 30 m depth and for the 30-100 m, cores from 30 and 100 m depth were used. For example:

$$\text{Average } C_{org} \text{ Content (kg m}^{-2}\text{) for 10 – 30 m depth interval} = \frac{(\text{Average } C_{org} \text{ content of 10 m depth cores} + \text{Average } C_{org} \text{ content of 30 m depth cores})}{2} \quad (7)$$

Lake-organic carbon inventories were estimated by integrating core-scale microbial mat carbon contents with bathymetry-derived surface areas for three depth intervals. Despite the much larger area of the deep basin ($5.20 \times 10^6 \text{ m}^2$ between 30-100 m), the total organic carbon stored in this zone is relatively small ($1.74 \times 10^5 \text{ kg}$). In contrast, the shallow 0-10 m and 10-30 m intervals indicates the largest carbon reservoir ($4.80 \times 10^5 \text{ kg}$ and $4.97 \times 10^5 \text{ kg}$, respectively) even though their surface areas are substantially smaller. These results further underlines that lake scale carbon storage is controlled primarily by biological productivity. Therefore, deepest sections of Lake Untersee represent minor contribution to the total microbial mat carbon reservoir (Table 7.).

Table 6. Core scale carbon contents for microbial flat mats and conical microbailites of Lake Untersee, Antarctica. Cores C1, C2 and C3 were retrieved from Marsh (2019).

Core ID	Total C_{org} (mg)	C content (kg m ⁻²)	Depth Group	Average Total C_{org} (g)	Average C_{org} Content (kg m ⁻²)
LU-DH01	338.51	0.256	10 m	0.252	0.191
LU-DH02	285.86	0.217			
LU-DH03	132.15	0.100			
LU-BH12	42.86	0.032	30 m	0.043	0.032
LU-BH09	64.14	0.023	100 m	0.095	0.035
LU-BH08	167.24	0.061			
LU-BH08II	52.26	0.019			
C3	1537.46	0.248	10 m	1.329	0.857
C2	996.14	0.161			
C1	1454.86	0.235			

Table 7. Bathymetry data integrated, lake-scale total organic carbon contents of microbial mats (including conical mats) for intended depth intervals of Lake Untersee, Antarctica.

Depth Interval	Average C _{org} Content (kg m ⁻²)	Surface Area (m ²)	Total C _{org} (kg)
0-10 m	0.524	9.17E+05	4.80E+05
10-30 m	0.360	1.38E+06	4.97E+05
30-100 m	0.034	5.20E+06	1.74E+05

6 Conclusion

This study investigated gas sources, organic carbon sequestration, and microbial metabolic activity in Lake Untersee using noble gas geochemistry, stable and radiocarbon isotopes and depth-resolved organic carbon measurements. The results confirm that biogeochemical cycling in Lake Untersee is dominated by internal process with limited external inputs due to the presence of permanent thick ice cover.

Noble gas isotope ratios indicate that gases entering the lake are derived from air group, supplied primarily through the release of occluded atmospheric air and air saturated water during subaqueous melting of Anuchin Glacier and through subglacial meltwater. These findings demonstrate that ice-water interactions are dominant mechanism sustaining the lake's gas inventory in the absence of direct atmospheric exchange.

Organic carbon measurements show that carbon sequestration in the oxic basin is strongly controlled by the microbial mat morphology and depth. Conical mats store substantially more organic carbon than flat mats at comparable depths. While organic carbon content in flat mats decreases with depth in parallel with declining photosynthetically available radiation. The $\delta^{13}\text{C}$ values of conical mats closely match those of the dissolved inorganic carbon in the water column, indicating strong DIC limitation during photosynthesis. In contrast, flat mats exhibit more depleted $\delta^{13}\text{C}$ values than those of the water column, consistent with Rubisco-mediated fractionation under non-limiting DIC conditions. These results indicate that conical and flat morphologies of microbial mats operate under distinct metabolic regimes despite occupying similar depth intervals.

Surface microbial mats display apparent radiocarbon ages several thousand years older than the water-column DIC pool. The magnitude of this offset exceeds previously reported values for conical mats and indicates that carbon recycling within the mat-sediment system plays a central role in sustaining a photosynthesis in the oxic basin.

In the south basin, especially in the anoxic waters, organic carbon sequestration is not controlled by benthic photosynthesis. Although a narrow chlorophyll-rich layer exists near the chemocline, it represents a suspended phototrophic population rather than a benthic microbial mat system.

Lake scale carbon inventories show that most of the organic carbon is stored in shallower depth intervals, despite the much larger surface area of the deep basin. This demonstrates that biological productivity, controls organic carbon storage in Lake Untersee. Estimates based on O_2/Ar and $\delta^{18}O-O_2$ further indicate that photosynthetic oxygen production contributes only a small fraction of the total dissolved oxygen inventory, consistent with low gross photosynthetic rates and long water residence times.

Even though $\delta^{15}N$ measurements are reported in this study, further investigation of nitrogen isotopes is required to better constrain nitrogen sources and cycling within the lake ecosystem. Future work should focus on expanded $\delta^{15}N$ analyses across different microbial mat morphologies and associated sedimentary environments. In addition, future studies should focus on gas analyses within blue and refrozen ice of the Anuchin Glacier to better constrain gas sources and pathways into the lake. Targeted sampling of microbial pinnacles, as well as dedicated sampling of Lake Obersee, would further improve our standing of spatial variability in biogeochemical processes across perennially ice-covered lakes.

The internal carbon cycling observed in perennially ice-covered Lake Untersee has direct relevance for astrobiology studies, as it demonstrates that sustained photosynthetic and heterotrophic activity can persist in systems isolated from atmosphere, with limited nutrient supply and minimal external carbon input. The ability of microbial communities to recycle ancient organic carbon and maintain metabolic activity under permanent ice cover provides a terrestrial analogue for potential life in sub-ice aquatic environments on icy planetary bodies such as Enceladus, where surface-atmosphere exchange is absent or very limited and internal recycling may be required to support long-term habitability.

7 References

- Aeschbach-Hertig, W., & Solomon, D. K. (2013). Noble Gas Thermometry in Groundwater Hydrology. In P. Burnard (Ed.), *The Noble Gases as Geochemical Tracers* (pp. 81–122). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-28836-4_5
- Andersen, D. T., McKay, C. P., & Lagun, V. (2015). Climate conditions at perennially ice-covered Lake Untersee, East Antarctica. *Journal of Applied Meteorology and Climatology*, 54(7), 1393–1412. <https://doi.org/10.1175/JAMC-D-14-0251.1>
- Andersen, D. T., McKay, C. P., & Wharton, R. A. (1998). Dissolved gases in perennially ice-covered lakes of the McMurdo Dry Valleys, Antarctica. *Antarctic Science*, 10(2), 124–133. <https://doi.org/10.1017/S0954102098000170>
- Andersen, D. T., Sumner, D. Y., Hawes, I., Webster-Brown, J., & McKay, C. P. (2011). Discovery of large conical stromatolites in Lake Untersee, Antarctica: Large conical stromatolites. *Geobiology*, 9(3), 280–293. <https://doi.org/10.1111/j.1472-4669.2011.00279.x>
- Ballentine, C. J., & Burnard, P. G. (2002). Production, Release and Transport of Noble Gases in the Continental Crust. *Reviews in Mineralogy and Geochemistry*, 47(1), 481–538. <https://doi.org/10.2138/rmg.2002.47.12>
- Barth, J. A. C., Tait, A., & Bolshaw, M. (2004). Automated analyses of $^{18}\text{O}/^{16}\text{O}$ ratios in dissolved oxygen from 12-mL water samples. *Limnology and Oceanography: Methods*, 2(2), 35–41. <https://doi.org/10.4319/lom.2004.2.35>
- Bevington, J., McKay, C. P., Davila, A., Hawes, I., Tanabe, Y., & Andersen, D. T. (2018). The thermal structure of the anoxic trough in Lake Untersee, Antarctica. *Antarctic Science*, 30(6), 333–344. <https://doi.org/10.1017/S0954102018000354>
- Bormann, P., & Fritzsche, D. (Eds.). (1995). *The Schirmacher Oasis, Queen Maud Land, East Antarctica, and its surroundings*. Justus Perthes Verlag.

- Brady, A. L., Andersen, D. T., & Slater, G. F. (2023). Biosignatures of in situ carbon cycling driven by physical isolation and sedimentary methanogenesis within the anoxic basin of perennially ice-covered Lake Untersee, Antarctica. *Biogeochemistry*, 164(3), 555–575. <https://doi.org/10.1007/s10533-023-01053-8>
- Burnard, P. (Ed.). (2013). *The Noble Gases as Geochemical Tracers*. Springer Berlin Heidelberg. <https://doi.org/10.1007/978-3-642-28836-4>
- Calder, J. A., & Parker, P. L. (1973). Geochemical implications of induced changes in C13 fractionation by blue-green algae. *Geochimica et Cosmochimica Acta*, 37(1), 133–140. [https://doi.org/10.1016/0016-7037\(73\)90251-2](https://doi.org/10.1016/0016-7037(73)90251-2)
- Clark, I. (2015). Groundwater Dating. In *Groundwater Geochemistry and Isotopes*. CRC Press.
- Coplen, T. B., Hopple, J. A., Böhlke, J. K., Peiser, H. S., Rieder, S. E., Krouse, H. R., Rosman, K. J. R., Ding, T., Jr, R. D. V., Revesz, K. M., Lamberty, A., Taylor, P., & Bievre, P. D. (2002). Compilation of minimum and maximum isotope ratios of selected elements in naturally occurring terrestrial materials and reagents. In *Water-Resources Investigations Report* (Nos. 2001–4222). U.S. Geological Survey. <https://doi.org/10.3133/wri014222>
- Craig, H., Wharton, R. A., & McKay, C. P. (1992). Oxygen Supersaturation in Ice-Covered Antarctic Lakes: Biological Versus Physical Contributions. *Science*, 255(5042), 318–321. <https://doi.org/10.1126/science.11539819>
- Croudace, I. W., & Rothwell, R. G. (Eds.). (2015). *Micro-XRF Studies of Sediment Cores: Applications of a non-destructive tool for the environmental sciences* (Vol. 17). Springer Netherlands. <https://doi.org/10.1007/978-94-017-9849-5>
- Debret, M., Sebag, D., Desmet, M., Balsam, W., Copard, Y., Mourier, B., Susperrigui, A.-S., Arnaud, F., Bentaleb, I., Chapron, E., Lallier-Vergès, E., & Winiarski, T. (2011).

- Spectrocolorimetric interpretation of sedimentary dynamics: The new “Q7/4 diagram.”
Earth-Science Reviews, 109(1–2), 1–19. <https://doi.org/10.1016/j.earscirev.2011.07.002>
- Doran, P. T., Kenig, F., Knoepfle, J. L., Mikucki, J. A., & Lyons, W. B. (2014). Radiocarbon distribution and the effect of legacy in lakes of the McMurdo Dry Valleys, Antarctica.
Limnology and Oceanography, 59(3), 811–826.
<https://doi.org/10.4319/lo.2014.59.3.0811>
- Doran, P. T., Priscu, J. C., Lyons, W. B., Powell, R. D., Andersen, D. T., & Poreda, R. J. (2004). Paleolimnology of extreme cold terrestrial and extraterrestrial environments. In J. P. Smol, R. Pienitz, & M. S. V. Douglas (Eds.), *Long-term Environmental Change in Arctic and Antarctic Lakes* (Vol. 8, pp. 475–507). Springer Netherlands.
https://doi.org/10.1007/978-1-4020-2126-8_15
- Doran, P. T., Wharton, R. A., & Lyons, W. B. (1994). Paleolimnology of the McMurdo Dry Valleys, Antarctica. *Journal of Paleolimnology*, 10(2), 85–114.
<https://doi.org/10.1007/BF00682507>
- Emerson, S., Stump, C., Johnson, B., & Karl, D. M. (2002). In situ determination of oxygen and nitrogen dynamics in the upper ocean. *Deep Sea Research Part I: Oceanographic Research Papers*, 49(5), 941–952. [https://doi.org/10.1016/S0967-0637\(02\)00004-3](https://doi.org/10.1016/S0967-0637(02)00004-3)
- Faucher, B. (2021). *Hydrochemistry of ice-covered lakes and ponds in the Untersee Oasis (Queen Maud Land, Antarctica)* [Doctoral thesis, University of Ottawa].
<https://ruor.uottawa.ca/items/c49533a2-97d6-4912-a47a-97beaf43b0a2>
- Faucher, B., Lacelle, D., Fisher, D. A., Andersen, D. T., & McKay, C. P. (2019). Energy and water mass balance of Lake Untersee and its perennial ice cover, East Antarctica.
Antarctic Science, 31(05), 271–285. <https://doi.org/10.1017/S0954102019000270>

- Faucher, B., Lacelle, D., Marsh, N. B., Jasperse, L., Clark, I. D., & Andersen, D. T. (2021). Glacial lake outburst floods enhance benthic microbial productivity in perennially ice-covered Lake Untersee (East Antarctica). *Communications Earth & Environment*, 2(1), 211. <https://doi.org/10.1038/s43247-021-00280-x>
- Gardner, P., & Solomon, D. K. (2009). An advanced passive diffusion sampler for the determination of dissolved gas concentrations: PASSIVE DIFFUSION SAMPLER. *Water Resources Research*, 45(6). <https://doi.org/10.1029/2008WR007399>
- Gibson, J. A. E., Vincent, W. F., Van Hove, P., Belzile, C., Wang, X., & Muir, D. (2002). Geochemistry of ice-covered, meromictic Lake A in the Canadian High Arctic. *Aquatic Geochemistry*, 8(2), 97–119. <https://doi.org/10.1023/A:1021317010302>
- Gow, A. J., & Williamson, T. (1975). Gas inclusions in the Antarctic ice sheet and their significance. *US Army Corps Eng Cold Reg Res Eng Lab Res Rep*.
- Graham, D. W. (2002). Noble Gas Isotope Geochemistry of Mid-Ocean Ridge and Ocean Island Basalts: Characterization of Mantle Source Reservoirs. *Reviews in Mineralogy and Geochemistry*, 47(1), 247–317. <https://doi.org/10.2138/rmg.2002.47.8>
- Hage, M. M., Uhle, M. E., & Macko, S. (2007). Biomarker and stable isotope characterization of coastal pond-derived organic matter, McMurdo Dry Valleys, Antarctica. *Astrobiology*, 7(4), 645–661. <https://doi.org/10.1089/ast.2006.0033>
- Hall, C. M., Castro, M. C., Kenig, F., & Doran, P. T. (2017). Constraining the recent history of the perennially ice-covered Lake Bonney, East Antarctica using He, Kr and Xe concentrations. *Geochimica et Cosmochimica Acta*, 209, 233–253. <https://doi.org/10.1016/j.gca.2017.04.023>

- Hawes, I., Jungblut, A. D., Obryk, M. K., & Doran, P. T. (2016). Growth dynamics of a laminated microbial mat in response to variable irradiance in an Antarctic lake. *Freshwater Biology*, 61(4), 396–410. <https://doi.org/10.1111/fwb.12715>
- Hawes, I., & Schwarz, A.-M. J. (2001). Absorption and Utilization of Irradiance by Cyanobacterial Mats in Two Ice-Covered Antarctic Lakes with Contrasting Light Climates. *Journal of Phycology*, 37(1), 5–15. <https://doi.org/10.1046/j.1529-8817.1999.014012005.x>
- Hawes, I., Sumner, D., & Jungblut, A. D. (2019). Complex Structure but Simple Function in Microbial Mats from Antarctic Lakes. In C. J. Hurst (Ed.), *The Structure and Function of Aquatic Microbial Communities* (Vol. 7, pp. 91–120). Springer International Publishing. https://doi.org/10.1007/978-3-030-16775-2_4
- Hayes, J. M. (1993). Factors controlling ^{13}C contents of sedimentary organic compounds: Principles and evidence. *Marine Geology*, 113(1–2), 111–125. [https://doi.org/10.1016/0025-3227\(93\)90153-M](https://doi.org/10.1016/0025-3227(93)90153-M)
- Hermichen, W. D., Kowski, P., & Wand, U. (1985). Lake Untersee, a first isotope study of the largest freshwater lake in the interior of East Antarctica. *Nature*, 315(6015), 131.
- Hermichen, W.-D., Kowski, P., & Wand, U. (1985). Lake Untersee, a first isotope study of the largest freshwater lake in the interior of East Antarctica. *Nature*, 315(6015), 131–133. <https://doi.org/10.1038/315131a0>
- Hoffman, M. J., Fountain, A. G., & Liston, G. E. (2008). Surface energy balance and melt thresholds over 11 years at Taylor Glacier, Antarctica. *Journal of Geophysical Research: Earth Surface*, 113(4), 1–12. <https://doi.org/10.1029/2008JF001029>

- Jean-Baptiste, P., Fourré, E., Petit, J. R., Lipenkov, V., Bulat, S., Chetverikov, Y., & Raynaud, D. (2018). Helium and Neon in the Accreted Ice of the Subglacial Antarctic Lake Vostok. *Geophysical Research Letters*, 45(10), 4927–4932. <https://doi.org/10.1029/2018GL078068>
- Jouzel, J., Petit, J. R., Souchez, R., Barkov, N. I., Lipenkov, V. Y., Raynaud, D., Stievenard, M., Vassiliev, N. I., Verbeke, V., & Vimeux, F. (1999). More than 200 meters of lake ice above subglacial Lake Vostok, Antarctica. *Science (New York, N.Y.)*, 286(5447), 2138–2141. <https://doi.org/10.1126/science.286.5447.2138>
- Kana, T. M., Darkangelo, Christina., Hunt, M. Duane., Oldham, J. B., Bennett, G. E., & Cornwell, J. C. (1994). Membrane Inlet Mass Spectrometer for Rapid High-Precision Determination of N₂, O₂, and Ar in Environmental Water Samples. *Analytical Chemistry*, 66(23), 4166–4170. <https://doi.org/10.1021/ac00095a009>
- Kaup, E., Loopman, A., Klokov, V., Simonov, I., & Haendel, D. (1988). *Limnological investigations in the Untersee Oasis* (pp. 28–42).
- Kohler, T. J., Van Horn, D. J., Darling, J. P., Takacs-Vesbach, C. D., & McKnight, D. M. (2016). Nutrient treatments alter microbial mat colonization in two glacial meltwater streams from the McMurdo Dry Valleys, Antarctica. *FEMS Microbiology Ecology*, 92(4), fiw049. <https://doi.org/10.1093/femsec/fiw049>
- Koo, H., Mojib, N., Hakim, J. A., Hawes, I., Tanabe, Y., Andersen, D. T., & Bej, A. K. (2017). Microbial Communities and Their Predicted Metabolic Functions in Growth Laminae of a Unique Large Conical Mat from Lake Untersee, East Antarctica. *Frontiers in Microbiology*, 8, 1347. <https://doi.org/10.3389/fmicb.2017.01347>

- Kroopnick, P., & Craig, H. (1972). Atmospheric Oxygen: Isotopic Composition and Solubility Fractionation. *Science (American Association for the Advancement of Science)*, 175(4017), 54–55. <https://doi.org/10.1126/science.175.4017.54>
- Lawson, J., Doran, P. T., Kenig, F., Des Marais, D. J., & Priscu, J. C. (2004). Stable carbon and nitrogen isotopic composition of benthic and pelagic organic matter in lakes of the McMurdo Dry Valleys, Antarctica. *Aquatic Geochemistry*, 10(3–4), 269–301. <https://doi.org/10.1007/s10498-004-2262-2>
- Lawson, J., Doran, P. T., Kenig, F., Marais, D. J. D., & Priscu, J. C. (2004). *Stable Carbon and Nitrogen Isotopic Composition of Benthic and Pelagic Organic Matter in Lakes of the McMurdo Dry Valleys, Antarctica*.
- Lott, D. E. (2001). Improvements in noble gas separation methodology: A nude cryogenic trap: IMPROVEMENTS IN NOBLE GAS SEPARATION METHODOLOGY. *Geochemistry, Geophysics, Geosystems*, 2(12), n/a-n/a. <https://doi.org/10.1029/2001GC000202>
- Love, F. G., Simmons, G. M., Parker, B. C., Wharton, R. A., & Seaburg, K. G. (1983). Modern conophyton-like microbial mats discovered in Lake Vanda, Antarctica. *Geomicrobiology Journal*, 3(1), 33–48. <https://doi.org/10.1080/01490458309377782>
- Lyons, W. B., Leslie, D. L., Harmon, R. S., Neumann, K., Welch, K. A., Bisson, K. M., & McKnight, D. M. (2013). The carbon stable isotope biogeochemistry of streams, Taylor Valley, Antarctica. *Applied Geochemistry*, 32, 26–36. <https://doi.org/10.1016/j.apgeochem.2012.08.019>
- Mabry, J., Lan, T., Burnard, P., & Marty, B. (2013). High-precision helium isotope measurements in air. *Journal of Analytical Atomic Spectrometry*, 28(12), 1903. <https://doi.org/10.1039/c3ja50155h>

- Marsh, N. (2019). *Carbon Budget and Cycling in Perennially Ice-Covered Lake Untersee, East Antarctica* [Master's thesis, University of Ottawa].
<https://ruor.uottawa.ca/items/1369c1f8-c3e7-4cc2-a94a-8eb084e4d385>
- Marsh, N., Lacelle, D., Faucher, B., Cotroneo, S., Jasperse, L., Clark, I. D., & Andersen, D. T. (2020). Sources of solutes and carbon cycling in perennially ice-covered Lake Untersee, Antarctica. *Scientific Reports*, 10(12290). <https://doi.org/10.1038/s41598-020-69116-6>
- Matsumoto, G. I., Nakaya, S., Murayama, H., Masuda, N., Kawano, T., Watanuki, K., & Torii, T. (1992). Geochemical characteristics of Antarctic lakes and ponds. *Proc. NIPR Symp. Polar Biol.*, 5, 125–145.
- McKay, C. P., Anbar, A. D., Porco, C., & Tsou, P. (2014). Follow the Plume: The Habitability of Enceladus. *Astrobiology*, 14(4), 352–355. <https://doi.org/10.1089/ast.2014.1158>
- McKay, C. P., Andersen, D., & Davila, A. (2017). Antarctic environments as models of planetary habitats: University Valley as a model for modern Mars and Lake Untersee as a model for Enceladus and ancient Mars. *The Polar Journal*, 7(2), 303–318.
<https://doi.org/10.1080/2154896X.2017.1383705>
- Monnin, E., Steig, E. J., Siegenthaler, U., Kawamura, K., Schwander, J., Stauffer, B., Stocker, T. F., Morse, D. L., Barnola, J. M., Bellier, B., Raynaud, D., & Fischer, H. (2004). Evidence for substantial accumulation rate variability in Antarctica during the Holocene, through synchronization of CO₂ in the Taylor Dome, Dome C and DML ice cores. *Earth and Planetary Science Letters*, 224(1–2), 45–54. <https://doi.org/10.1016/j.epsl.2004.05.007>
- Moorhead, D., Schmeling, J., & Hawes, I. (2005). Modelling the contribution of benthic microbial mats to net primary production in Lake Hoare, McMurdo Dry Valleys. *Antarctic Science*, 17(1), 33–45. <https://doi.org/10.1017/S0954102005002403>

- Ozima, M., & Podosek, F. A. (2002). *Noble Gas Geochemistry*. Cambridge University Press.
- Pardue, J. W., Scalan, R. S., Van Baalen, C., & Parker, P. L. (1976). Maximum carbon isotope fractionation in photosynthesis by blue-green algae and a green alga. *Geochimica et Cosmochimica Acta*, 40(3), 309–312. [https://doi.org/10.1016/0016-7037\(76\)90208-8](https://doi.org/10.1016/0016-7037(76)90208-8)
- Péron, S., Mukhopadhyay, S., & Huh, M. (2020). A new dual stainless steel cryogenic trap for efficient separation of krypton from argon and xenon. *Journal of Analytical Atomic Spectrometry*, 35(11), 2663–2671. <https://doi.org/10.1039/D0JA00052C>
- Perriss, S. J., & Laybourn-Parry, J. (1997). Microbial communities in saline lakes of the Vestfold hills (eastern Antarctica). *Polar Biology*, 18(2), 135–144. <https://doi.org/10.1007/s0030000050168>
- Peter, J. S., Nordheim, T. A., & Hand, K. P. (2023). Detection of HCN and diverse redox chemistry in the plume of Enceladus. *Nature Astronomy*. <https://doi.org/10.1038/s41550-023-02160-0>
- Poreda, R. J., Hunt, A. G., Lyons, W. B., & Welch, K. A. (2004). The Helium Isotopic Chemistry of Lake Bonney, Taylor Valley, Antarctica: Timing of Late Holocene Climate Change in Antarctica. *Aquatic Geochemistry*, 10(3–4), 353–371. <https://doi.org/10.1007/s10498-004-2265-z>
- Reimer, P. J., Brown, T. A., & Reimer, R. W. (2004). ‘Discussion: Reporting and calibration of post-bomb ^{14}C data.’ *Radiocarbon*, 46(3), 1299–1304. <https://doi.org/10.1017/S0033822200033154>
- Samyn, D., Fitzsimons, S. J., & Lorrain, R. D. (2005). Strain-induced phase changes within cold basal ice from Taylor Glacier, Antarctica, indicated by textural and gas analyses. *Journal of Glaciology*, 51(175), 611–619. <https://doi.org/10.3189/172756505781829098>

- Schwab, M. J. (1998). Reconstruction of the Late Quaternary climatic and environmental history of the Schirmacher Oasis and the Wohlthat Massif (East Antarctica). *Reports on Polar Research*, 293, 1–128.
- Spigel, R. H., & Priscu, J. C. (1998). Physical Limnology of the McMurdo Dry Valleys Lakes. In *Ecosystem Dynamics in a Polar Desert: The McMurdo Dry Valleys, Antarctica* (pp. 153–187). American Geophysical Union (AGU). <https://doi.org/10.1029/AR072p0153>
- Stanley, R. H. R., & Jenkins, W. J. (2013). Noble Gases in Seawater as Tracers for Physical and Biogeochemical Ocean Processes. In P. Burnard (Ed.), *The Noble Gases as Geochemical Tracers* (pp. 55–79). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-28836-4_4
- Starkey, N. A., Stuart, F. M., Ellam, R. M., Fitton, J. G., Basu, S., & Larsen, L. M. (2009). Helium isotopes in early Iceland plume picrites: Constraints on the composition of high $^3\text{He}/^4\text{He}$ mantle. *Earth and Planetary Science Letters*, 277(1), 91–100. <https://doi.org/10.1016/j.epsl.2008.10.007>
- Steel, H. C. B., McKay, C. P., & Andersen, D. T. (2015). Modeling circulation and seasonal fluctuations in perennially ice-covered and ice-walled lake untersee, antarctica. *Limnology and Oceanography*, 60(4), 1139–1155. <https://doi.org/10.1002/lno.10086>
- St-Onge, G., Mulder, T., Francus, P., & Long, B. (2007). Chapter Two Continuous Physical Properties of Cored Marine Sediments. In *Developments in Marine Geology* (Vol. 1, pp. 63–98). Elsevier. [https://doi.org/10.1016/S1572-5480\(07\)01007-X](https://doi.org/10.1016/S1572-5480(07)01007-X)
- Stuiver, M., & Polach, H. A. (1977). Discussion Reporting of ^{14}C Data. *Radiocarbon*, 19(3), 355–363. <https://doi.org/10.1017/S0033822200003672>

- Tarnocai, C., Canadell, J. G., Schuur, E. a. G., Kuhry, P., Mazhitova, G., & Zimov, S. (2009). Soil organic carbon pools in the northern circumpolar permafrost region. *Global Biogeochemical Cycles*, 23(2). <https://doi.org/10.1029/2008GB003327>
- Tomkins, J. D., Antoniades, D., Lamoureux, S. F., & Vincent, W. F. (2008). A simple and effective method for preserving the sediment–water interface of sediment cores during transport. *Journal of Paleolimnology*, 40(1), 577–582. <https://doi.org/10.1007/s10933-007-9175-1>
- Wacker, L., Christl, M., & Synal, H.-A. (2010). *Bats: A new tool for AMS data reduction*. 268(7–8), 976–979. <https://doi.org/10.1016/j.nimb.2009.10.078>
- Wagner, N. Y., Andersen, D. T., Hahn, A. S., & Johnson, S. S. (2022). Survival strategies of an anoxic microbial ecosystem in Lake Untersee, a potential analog for Enceladus. *Scientific Reports*, 12(1), 7376. <https://doi.org/10.1038/s41598-022-10876-8>
- Wand, U., & Perlt, J. (1999). Glacial boulders ‘floating’ on the ice cover of Lake Untersee, East Antarctica. *Antarctic Science*, 11(2), 256–260. <https://doi.org/10.1017/S0954102099000310>
- Wand, U., Samarkin, V. A., Nitzsche, H.-M., & Hubberten, H.-W. (2006). Biogeochemistry of methane in the permanently ice-covered Lake Untersee, central Dronning Maud Land, East Antarctica. *Limnology and Oceanography*, 51(2), 1180–1194. <https://doi.org/10.4319/lo.2006.51.2.1180>
- Wand, U., Schwarz, G., Brüggemann, E., & Bräuer, K. (1997). Evidence for physical and chemical stratification in Lake Untersee (central Dronning Maud Land, East Antarctica). *Antarctic Science*, 9(1), 43–45. <https://doi.org/10.1017/S0954102097000060>

- Wand, U., Schwarz, G., Brüggemann, E., & Bräuer, K. (2007). Evidence for physical and chemical stratification in Lake Untersee (central Dronning Maud Land, East Antarctica). *Antarctic Science*, 9(01), 43–45. <https://doi.org/10.1017/s0954102097000060>
- Warrier, R. B., Clara Castro, M., Hall, C. M., Kenig, F., & Doran, P. T. (2015). Reconstructing the evolution of Lake Bonney, Antarctica using dissolved noble gases. *Applied Geochemistry*, 58, 46–61. <https://doi.org/10.1016/j.apgeochem.2015.02.013>
- Wharton, R. A., McKay, C. P., Clow, G. D., & Andersen, D. T. (1993). Perennial ice covers and their influence on Antarctic lake ecosystems. In W. J. Green & E. I. Friedmann (Eds.), *Antarctic Research Series* (Vol. 59, pp. 53–70). American Geophysical Union. <https://doi.org/10.1029/AR059p0053>
- Wharton, R. A., McKay, C. P., Mancinelli, R. L., & Simmons, G. M. (1987). Perennial N₂ supersaturation in an Antarctic lake. *Nature*, 325(6102), 343–345. <https://doi.org/10.1038/325343a0>
- Wharton, R. A., McKay, C. P., Simmons, G. M., & Parker, B. C. (1986). Oxygen budget of a perennially ice-covered Antarctic lake. *Limnology and Oceanography*, 31(2), 437–443. <https://doi.org/10.4319/lo.1986.31.2.0437>
- Wright, A., & Siegert, M. (2012). A fourth inventory of Antarctic subglacial lakes. *Antarctic Science*. <https://doi.org/10.1017/S095410201200048X>

8 Appendix A: Summary tables of north and south basin cores

Table A1. Summary table of organic carbon abundances (%wt), $\delta^{13}\text{C}_{\text{org}}$, nitrogen content and C:N for ~10m depth cores of Lake Untersee.

Core ID	Material	Sample Depth (cm)	Statistics	C _{org} (%wt)	$\delta^{13}\text{C}_{\text{org}}$ vpdb	N (%wt)	Atomic C:N
LU-DH-01	Mats	1-5cm	Min	2.0	-21.5	0.06	27.9
LU-DH-01	Mats	1-5cm	Max	3.1	-19.9	0.13	43.3
LU-DH-01	Mats	1-5cm	Average	2.5	-20.9	0.08	37.9
LU-DH-01	Sediments	6-12cm	Min	0.5	-25.9	0.02	21.0
LU-DH-01	Sediments	6-12cm	Max	3.1	-16.9	0.05	90.7
LU-DH-01	Sediments	6-12cm	Average	1.5	-20.6	0.04	43.5
LU-DH-02	Mats	1-7 cm	Min	1.7	-19.3	0.09	15.1
LU-DH-02	Mats	1-7 cm	Max	3.8	-15.9	0.21	30.9
LU-DH-02	Mats	1-7 cm	Average	2.6	-17.4	0.14	22.2
LU-DH-02	Sediments	8-13 cm	Min	1.2	-19.8	0.06	18.1
LU-DH-02	Sediments	8-13 cm	Max	2.0	-15.2	0.12	29.5
LU-DH-02	Sediments	8-13 cm	Average	1.5	-17.8	0.08	23.8
LU-DH-03	Mats	1-6 cm	Min	1.2	-19.9	0.05	14.0
LU-DH-03	Mats	1-6 cm	Max	3.6	-16.8	0.19	27.3
LU-DH-03	Mats	1-6 cm	Average	2.2	-18.4	0.13	20.5
LU-DH-03	Sediments	7-12 cm	Min	1.2	-23.3	0.04	23.1
LU-DH-03	Sediments	7-12 cm	Max	2.8	-15.2	0.11	41.1
LU-DH-03	Sediments	7-12 cm	Average	1.7	-19.5	0.07	28.9

Table A2. Summary table of organic carbon abundances (%wt), $\delta^{13}\text{C}_{\text{org}}$, nitrogen content and C:N for ~30m depth cores of Lake Untersee.

Core ID	Material	Sample Depth (cm)	Statistics	C _{org} (%wt)	$\delta^{13}\text{C}_{\text{org}}$ vpdb	N (%wt)	Atomic C:N
LU-BH-12	Mats	1-3 cm	Min	1.4	-29.5	0.07	18.0
LU-BH-12	Mats	1-3 cm	Max	4.0	-25.2	0.09	67.3
LU-BH-12	Mats	1-3 cm	Average	2.3	-27.0	0.08	36.7
LU-BH-12	Sediments	4-8 cm	Min	0.5	-21.8	0.04	10.2
LU-BH-12	Sediments	4-8 cm	Max	0.7	-18.9	0.08	16.8
LU-BH-12	Sediments	4-8 cm	Average	0.7	-20.9	0.06	13.9

Table A3. Summary table of organic carbon abundances (%wt), $\delta^{13}\text{C}_{\text{org}}$, nitrogen content and C:N for ~100m depth cores of Lake Untersee.

Core ID	Material	Sample Depth (cm)	Statistics	C _{org} (%wt)	$\delta^{13}\text{C}_{\text{org}}$ vpdb	N (%wt)	Atomic C:N
LU-BH-09	Mats	1-6 cm	Min	0.8	-18.1	0.09	7.6
LU-BH-09	Mats	1-6 cm	Max	1.3	-13.2	0.17	11.8
LU-BH-09	Mats	1-6 cm	Average	1.0	-15.6	0.12	9.6
LU-BH-09	Sediments	7-13 cm	Min	1.0	-23.8	0.07	11.5
LU-BH-09	Sediments	7-13 cm	Max	1.5	-15.7	0.10	22.3
LU-BH-09	Sediments	7-13 cm	Average	1.2	-19.9	0.08	16.5
LU-BH-08	Mats	1-3 cm	Min	1.2	-20.1	0.09	12.2
LU-BH-08	Mats	1-3 cm	Max	1.3	-16.4	0.12	15.0
LU-BH-08	Mats	1-3 cm	Average	1.2	-18.7	0.11	13.2
LU-BH-08	Sediments	4-5 cm	Min	1.2	-15.9	0.15	7.9
LU-BH-08	Sediments	4-5 cm	Max	1.4	-15.9	0.20	9.4
LU-BH-08	Sediments	4-5 cm	Average	1.3	-15.9	0.18	8.7
LU-BH-08-II	Mats	1-5 cm	Min	1.0	-19.3	0.08	10.5
LU-BH-08-II	Mats	1-5 cm	Max	1.1	-17.0	0.12	14.0
LU-BH-08-II	Mats	1-5 cm	Average	1.0	-17.8	0.09	12.8
LU-BH-08-II	Sediments	6-14 cm	Min	0.8	-19.0	0.06	8.8
LU-BH-08-II	Sediments	6-14 cm	Max	1.5	-14.9	0.16	16.0
LU-BH-08-II	Sediments	6-14 cm	Average	1.1	-16.7	0.12	11.7

Table A4. Summary table of organic carbon abundances (%wt), $\delta^{13}\text{C}_{\text{org}}$, nitrogen content and C:N for south basin cores of Lake Untersee.

Core ID	Material	Sample Depth (cm)	Statistics	C _{org} (%wt)	$\delta^{13}\text{C}_{\text{org}}$ vpdb	N (%wt)	Atomic C:N
LU-AH-55	Sediments	1-7cm	Min	0.7	-18.6	0.09	4.7
LU-AH-55	Sediments	1-7cm	Max	2.7	-10.1	0.22	29.8
LU-AH-55	Sediments	1-7cm	Average	1.3	-13.9	0.13	12.9
LU-AH-71.5	Sediments	1-21cm	Min	0.4	-19.0	0.04	10.0
LU-AH-71.5	Sediments	1-21cm	Max	4.1	-5.3	0.44	24.5
LU-AH-71.5	Sediments	1-21cm	Average	1.1	-14.8	0.10	13.9
LU-AH-87	Sediments	1-43cm	Min	1.6	-21.2	0.39	3.0
LU-AH-87	Sediments	1-43cm	Max	8.8	-14.4	1.02	10.7
LU-AH-87	Sediments	1-43cm	Average	4.2	-17.0	0.65	7.6
LU-AH-87-II	Sediments	1-23cm	Min	2.5	-21.1	0.41	5.6
LU-AH-87-II	Sediments	1-23cm	Max	9.0	-14.6	1.71	9.0
LU-AH-87-II	Sediments	1-23cm	Average	4.7	-17.4	0.80	7.0
LU-AH-98	Sediments	1-52cm	Min	0.1	-22.4	0.07	1.5
LU-AH-98	Sediments	1-52cm	Max	7.4	-14.5	0.97	11.1
LU-AH-98	Sediments	1-52cm	Average	2.9	-19.4	0.43	6.2

9 Appendix B: North basin cores data

Table B1. Weights, $\delta^{13}\text{C}_{\text{org}}$, and C_{org} (%wt) of acid-treated (HCl) north basin samples of Lake Untersee.

Sample ID	Sample Depth (cm)	Weight (mg)	$\delta^{13}\text{C}_{\text{org}}$ vpdb	C_{org} (%wt)
LUDH01-1	1	29.8	-21.5	3.1
LUDH01-2	2	32.7	-20.9	2.0
LUDH01-3	3	32.8	-21.0	2.0
LUDH01-4	4	29.4	-20.0	3.0
LUDH01-5	5	30.5	-21.3	2.2
LUDH01-6	6	30.9	-26.0	3.1
LUDH01-7	7	32.8	-21.6	1.7
LUDH01-8	8	29.5	-21.8	1.6
LUDH01-9	9	31.6	-19.4	1.4
LUDH01-10	10	28.3	-20.4	1.2
LUDH01-11	11	33.5	-16.9	0.7
LUDH01-12	12	30.7	-18.0	0.5
LUDH02-1	1	29.4	-19.2	3.8
LUDH02-2	2	32.4	-19.3	2.5
LUDH02-3	3	29.6	-16.8	2.9
LUDH02-4	4	31.5	-17.6	1.9
LUDH02-5	5	33.7	-16.8	1.7
LUDH02-6	6	31.4	-16.0	1.7
LUDH02-7	7	29.2	-16.0	3.4
LUDH02-8	8	30.5	-19.2	2.0
LUDH02-9	9	29.5	-15.2	1.2
LUDH02-10	10	29.3	-16.9	1.3
LUDH02-11	11	31.9	-17.3	1.5
LUDH02-12	12	30.5	-18.4	1.4
LUDH02-13	13	30.8	-19.8	1.8
LUDH03-1	1	29.7	-19.1	3.3
LUDH03-2	2	32.9	-16.8	3.6

LUDH03-3	3	29.6	-18.8	2.0
LUDH03-4	4	31.3	-17.9	1.9
LUDH03-5	5	31.8	-17.9	1.2
LUDH03-6	6	32.1	-19.9	1.2
LUDH03-7	7	29.8	-15.2	2.8
LUDH03-8	8	32.8	-18.2	1.7
LUDH03-9	9	29.0	-21.1	1.2
LUDH03-10	10	29.5	-23.3	1.4
LUDH03-11	11	28.6	-19.6	1.4
LUDH03-12	12	29.4	-19.6	1.4
LUBH012-1	1	30.8	-26.4	1.5
LUBH012-2	2	30.7	-29.5	4.0
LUBH012-3	3	30.5	-25.2	1.4
LUBH012-4	4	32.8	-18.9	0.7
LUBH012-5	5	31.9	-20.7	0.7
LUBH012-6	6	32.4	-21.5	0.7
LUBH012-7	7	32.6	-21.4	0.5
LUBH012-8	8	32.2	-21.8	0.7
LUBH09-1	1	30.1	-15.5	1.3
LUBH09-2	2	31.0	-14.7	1.1
LUBH09-3	3	30.7	-14.3	1.1
LUBH09-4	4	29.8	-18.1	1.0
LUBH09-5	5	30.4	-13.2	0.8
LUBH09-6	6	29.8	-17.5	0.8
LUBH09-7	7	32.1	-23.2	1.1
LUBH09-8	8	32.3	-19.5	1.0
LUBH09-9	9	31.1	-15.7	1.0
LUBH09-10	10	33.2	-19.0	1.2
LUBH09-11	11	30.2	-23.8	1.5
LUBH09-12	12	30.9	-19.7	1.2
LUBH09-13	13	29.8	-18.3	1.0

LUBH008-1	1	31.4	-19.7	1.2
LUBH008-2	2	29.9	-20.1	1.3
LUBH008-3	3	31.2	-16.4	1.3
LUBH008-4	4	31.8	-15.9	1.2
LUBH008-5	5	32.0	-15.9	1.4
LUBH08II-1	1	30.8	-19.3	1.1
LUBH08II-2	2	30.4	-17.4	1.0
LUBH08II-3	3	31.6	-17.8	1.0
LUBH08II-4	4	33.1	-17.6	1.0
LUBH08II-5	5	29.3	-17.0	1.0
LUBH08II-6	6	29.8	-16.6	0.8
LUBH08II-7	7	31.7	-19.0	1.0
LUBH08II-8	8	31.2	-19.0	1.2
LUBH08II-9	9	32.7	-14.9	1.3
LUBH08II-10	10	32.6	-16.7	1.5
LUBH08II-11	11	32.1	-15.7	1.3
LUBH08II-12	12	32.5	-15.9	1.0
LUBH08II-13	13	34.9	-15.8	0.8
LUBH08II-14	14	32.8	-14.6	0.9

Table B2. Weights, $\delta^{13}\text{C}_{\text{total}}$ ‰, C_{total} (%wt), $\delta^{15}\text{N}$ air and N (%wt) of unacidified north basin samples of Lake Untersee.

Sample ID	Sample Depth (cm)	Weight (mg)	$\delta^{13}\text{C}_{\text{total}}$ ‰	C_{total} (%wt)	$\delta^{15}\text{N}$ air	N (%wt)
LUDH01-1	1	24.6	-13.7	5.4	20.2	0.13
LUDH01-2	2	56.6	-17.1	3.7	21.9	0.06
LUDH01-3	3	54.9	-17.1	2.5	21.3	0.06
LUDH01-4	4	40.1	-11.9	9.8	15.5	0.09
LUDH01-5	5	54.8	-14.2	6.8	16.2	0.06
LUDH01-6	6	84.7	-21.4	2.0	19.7	0.04
LUDH01-7	7	85.3	-23.9	2.8	13.5	0.04
LUDH01-8	8	83.2	-16.5	3.1	19.5	0.04
LUDH01-9	9	60.2	-13.9	2.4	16.8	0.05
LUDH01-10	10	84.1	-16.2	1.4	22.0	0.04
LUDH01-11	11	81.5	-14.9	1.1	20.9	0.04
LUDH01-12	12	163.7	-15.8	0.9	22.7	0.02
LUDH02-1	1	16.0	-14.1	8.0	20.0	0.21
LUDH02-2	2	28.8	-13.8	9.7	14.2	0.11
LUDH02-3	3	29.4	-20.0	9.7	19.8	0.11
LUDH02-4	4	31.4	-12.6	9.6	17.0	0.11
LUDH02-5	5	37.6	-14.6	4.4	15.3	0.09
LUDH02-6	6	28.6	-20.8	4.8	19.5	0.13
LUDH02-7	7	18.3	-13.1	6.8	14.3	0.20
LUDH02-8	8	27.4	-13.0	6.8	14.3	0.12
LUDH02-9	9	43.9	-11.2	6.3	15.8	0.08
LUDH02-10	10	45.6	-20.7	3.0	14.5	0.07
LUDH02-11	11	54.6	-13.3	6.6	18.1	0.06
LUDH02-12	12	54.4	-16.8	4.3	17.0	0.06
LUDH02-13	13	49.4	-22.0	2.3	7.7	0.07
LUDH03-1	1	17.7	-13.9	7.7	24.4	0.19

LUDH03-2	2	18.4	-8.2	6.2	15.8	0.18
LUDH03-3	3	13.8	-9.1	4.7	17.0	0.14
LUDH03-4	4	34.3	-11.7	5.8	20.7	0.10
LUDH03-5	5	65.9	-16.6	2.9	20.2	0.05
LUDH03-6	6	34.4	-16.4	2.5	18.8	0.10
LUDH03-7	7	32.4	-10.8	6.7	19.2	0.11
LUDH03-8	8	45.5	-11.2	7.6	17.6	0.07
LUDH03-9	9	55.6	-20.8	2.6	11.5	0.06
LUDH03-10	10	81.6	-22.6	2.8	15.4	0.04
LUDH03-11	11	46.8	-17.4	3.7	15.7	0.07
LUDH03-12	12	54.5	-20.3	3.9	19.7	0.06
LUBH012-1	1	122.0		1.0	8.1	0.07
LUBH012-2	2	119.8		1.8	8.2	0.07
LUBH012-3	3	97.2		2.3	8.9	0.09
LUBH012-4	4	161.3		0.8	6.2	0.05
LUBH012-5	5	189.4		1.0	6.1	0.06
LUBH012-6	6	165.3		1.0	7.6	0.06
LUBH012-7	7	176.2		0.7	8.7	0.04
LUBH012-8	8	99.5		1.2	10.0	0.08
LUBH09-1	1	36.1		1.5	17.5	0.15
LUBH09-2	2	58.4		1.6	14.2	0.17
LUBH09-3	3	63.6		1.9	15.5	0.13
LUBH09-4	4	100.9		1.4	13.1	0.10
LUBH09-5	5	99.3		1.4	12.4	0.09
LUBH09-6	6	170.2		1.4	15.2	0.10
LUBH09-7	7	171.9		1.6	16.5	0.07
LUBH09-8	8	124.1		1.7	15.8	0.07
LUBH09-9	9	102.5		1.4	10.9	0.10
LUBH09-10	10	128.6		0.9	15.0	0.08
LUBH09-11	11	123.7		1.6	14.2	0.08
LUBH09-12	12	82.3		1.9	16.9	0.09
LUBH09-13	13	98.2		1.5	12.9	0.09

LUBH008-1	1	82.6	1.1	15.1	0.09
LUBH008-2	2	82.9	1.9	25.7	0.12
LUBH008-3	3	55.6	1.2	22.2	0.12
LUBH008-4	4	45.0	2.0	25.9	0.15
LUBH008-5	5	56.5	1.6	19.2	0.20
LUBH08II-1	1	83.9	1.3	7.7	0.12
LUBH08II-2	2	82.9	1.3	18.4	0.09
LUBH08II-3	3	97.3	1.1	18.8	0.08
LUBH08II-4	4	85.9	1.1	13.8	0.09
LUBH08II-5	5	100.0	1.0	17.1	0.08
LUBH08II-6	6	70.7	0.9	22.8	0.06
LUBH08II-7	7	125.1	1.2	22.6	0.07
LUBH08II-8	8	84.0	1.5	19.9	0.11
LUBH08II-9	9	41.8	1.6	22.5	0.16
LUBH08II-10	10	58.8	1.5	25.0	0.15
LUBH08II-11	11	54.8	1.5	27.4	0.14
LUBH08II-12	12	55.3	1.1	20.7	0.12
LUBH08II-13	13	72.3	1.1	22.5	0.11
LUBH08II-14	14	70.9	1.1	22.4	0.13

Table B3. Inorganic carbon contents and atomic C:N for north basin cores of Lake Untersee.

Sample ID	Sample Depth (cm)	C_{inorg} (%wt)	Atomic C:N
LUDH01-1	1	2.3	28.0
LUDH01-2	2	1.6	39.7
LUDH01-3	3	0.5	39.7
LUDH01-4	4	6.8	39.0
LUDH01-5	5	4.5	43.3
LUDH01-6	6	-1.1	90.7
LUDH01-7	7	1.1	48.1
LUDH01-8	8	1.5	45.8
LUDH01-9	9	1.0	33.6
LUDH01-10	10	0.3	33.8
LUDH01-11	11	0.3	21.0
LUDH01-12	12	0.3	31.5
LUDH02-1	1	4.1	21.3
LUDH02-2	2	7.2	26.2
LUDH02-3	3	6.8	30.9
LUDH02-4	4	7.7	20.6
LUDH02-5	5	2.7	21.9
LUDH02-6	6	3.1	15.1
LUDH02-7	7	3.4	19.8
LUDH02-8	8	4.8	19.5
LUDH02-9	9	5.1	18.1
LUDH02-10	10	1.7	20.8
LUDH02-11	11	5.2	28.6
LUDH02-12	12	2.9	26.4
LUDH02-13	13	0.6	29.5
LUDH03-1	1	4.5	19.9
LUDH03-2	2	2.6	23.4
LUDH03-3	3	2.7	16.8
LUDH03-4	4	3.9	21.8
LUDH03-5	5	1.7	27.3

LUDH03-6	6	1.3	14.0
LUDH03-7	7	3.9	29.9
LUDH03-8	8	5.9	28.2
LUDH03-9	9	1.4	23.1
LUDH03-10	10	1.4	41.1
LUDH03-11	11	2.2	23.7
LUDH03-12	12	2.5	27.2
LUBH012-1	1	-0.5	24.7
LUBH012-2	2	-2.2	67.3
LUBH012-3	3	0.9	18.0
LUBH012-4	4	0.1	16.8
LUBH012-5	5	0.3	12.8
LUBH012-6	6	0.3	14.2
LUBH012-7	7	0.2	15.5
LUBH012-8	8	0.5	10.2
LUBH09-1	1	0.2	10.0
LUBH09-2	2	0.5	7.6
LUBH09-3	3	0.8	9.6
LUBH09-4	4	0.4	11.8
LUBH09-5	5	0.6	9.7
LUBH09-6	6	0.6	9.0
LUBH09-7	7	0.5	18.5
LUBH09-8	8	0.7	17.2
LUBH09-9	9	0.4	11.5
LUBH09-10	10	-0.3	17.2
LUBH09-11	11	0.0	22.3
LUBH09-12	12	0.7	15.7
LUBH09-13	13	0.5	13.3
LUBH008-1	1	-0.1	15.0
LUBH008-2	2	0.7	12.2
LUBH008-3	3	-0.1	12.3

LUBH008-4	4	0.8	9.4
LUBH008-5	5	0.2	7.9
LUBH08II-1	1	0.2	10.5
LUBH08II-2	2	0.3	12.4
LUBH08II-3	3	0.1	13.8
LUBH08II-4	4	0.1	13.2
LUBH08II-5	5	0.1	14.0
LUBH08II-6	6	0.1	15.4
LUBH08II-7	7	0.2	16.0
LUBH08II-8	8	0.3	12.3
LUBH08II-9	9	0.3	9.1
LUBH08II-10	10	0.1	11.3
LUBH08II-11	11	0.2	10.9
LUBH08II-12	12	0.1	10.0
LUBH08II-13	13	0.3	8.8
LUBH08II-14	14	0.3	7.7

Table B4. Weight and organic carbon content (OCC) measurements for north basin cores of Lake Untersee

Sample ID	Sample Depth (cm)	Split Dry Weight (g)	Total Dry Weight (g)	Carbon Mass (g)	BD (g cm ⁻³)	OCC (kg m ⁻²)	OCC cumulative (kg m ⁻²)
LUDH01-1	1	0.7	1.5	0.05	0.11	0.35	0.35
LUDH01-2	2	1.2	2.3	0.05	0.18	0.36	0.71
LUDH01-3	3	2.0	4.0	0.08	0.30	0.62	1.33
LUDH01-4	4	1.8	3.6	0.11	0.27	0.83	2.16
LUDH01-5	5	1.2	2.4	0.05	0.18	0.41	2.56
LUDH01-6	6	0.7	1.4	0.02	0.11	0.34	2.90
LUDH01-7	7	1.2	2.4	0.02	0.18	0.30	3.20
LUDH01-8	8	0.8	1.7	0.01	0.13	0.20	3.40
LUDH01-9	9	1.5	2.9	0.02	0.22	0.32	3.72
LUDH01-10	10	2.2	4.3	0.03	0.33	0.38	4.10
LUDH01-11	11	1.6	3.3	0.01	0.25	0.18	4.27
LUDH01-12	12	2.6	5.1	0.01	0.39	0.21	4.48
LUDH02-1	1	0.7	1.4	0.06	0.11	0.42	0.42
LUDH02-2	2	0.8	1.6	0.04	0.12	0.30	0.72
LUDH02-3	3	0.8	1.6	0.05	0.12	0.36	1.08
LUDH02-4	4	1.4	2.7	0.05	0.21	0.40	1.48
LUDH02-5	5	1.1	2.2	0.04	0.17	0.28	1.76
LUDH02-6	6	0.8	1.7	0.03	0.13	0.22	1.98
LUDH02-7	7	0.4	0.7	0.02	0.05	0.19	2.17
LUDH02-8	8	1.0	1.9	0.04	0.14	0.29	2.46
LUDH02-9	9	0.8	1.6	0.02	0.12	0.15	2.60
LUDH02-10	10	1.0	2.1	0.03	0.16	0.20	2.80
LUDH02-11	11	1.8	3.6	0.05	0.27	0.40	3.20
LUDH02-12	12	1.9	3.9	0.05	0.29	0.40	3.60
LUDH02-13	13	1.3	2.5	0.04	0.19	0.34	3.93
LUDH03-1	1	0.1	0.3	0.01	0.02	0.06	0.06
LUDH03-2	2	0.3	0.6	0.02	0.04	0.16	0.22
LUDH03-3	3	0.7	1.4	0.03	0.11	0.21	0.44
LUDH03-4	4	0.9	1.8	0.03	0.13	0.25	0.68
LUDH03-5	5	1.2	2.5	0.03	0.19	0.22	0.90
LUDH03-6	6	0.5	1.1	0.01	0.08	0.10	1.00
LUDH03-7	7	0.3	0.6	0.02	0.04	0.12	1.12

LUDH03-8	8	1.4	2.8	0.05	0.21	0.35	1.47
LUDH03-9	9	1.4	2.8	0.03	0.21	0.25	1.72
LUDH03-10	10	1.0	2.0	0.03	0.15	0.22	1.94
LUDH03-11	11	1.6	3.2	0.05	0.24	0.34	2.28
LUDH03-12	12	1.9	3.9	0.05	0.29	0.41	2.70
LUBH012-1	1	0.4	0.8	0.01	0.06	0.09	0.09
LUBH012-2	2	0.3	0.6	0.02	0.04	0.17	0.26
LUBH012-3	3	0.3	0.6	0.01	0.04	0.06	0.32
LUBH012-4	4	0.7	1.4	0.01	0.11	0.08	0.40
LUBH012-5	5	1.0	1.9	0.01	0.15	0.10	0.50
LUBH012-6	6	0.8	1.6	0.01	0.12	0.09	0.59
LUBH012-7	7	0.4	0.8	0.00	0.06	0.03	0.62
LUBH012-8	8	0.8	1.6	0.01	0.12	0.09	0.71
LUBH09-1	1	0.1	0.2	0.00	0.01	0.01	0.01
LUBH09-2	2	0.4	0.8	0.01	0.03	0.03	0.04
LUBH09-3	3	0.4	0.8	0.01	0.03	0.03	0.07
LUBH09-4	4	0.6	1.3	0.01	0.05	0.05	0.12
LUBH09-5	5	1.1	2.2	0.02	0.08	0.06	0.18
LUBH09-6	6	1.0	2.0	0.02	0.07	0.06	0.23
LUBH09-7	7	0.6	1.3	0.01	0.05	0.05	0.29
LUBH09-8	8	1.1	2.1	0.02	0.08	0.08	0.37
LUBH09-9	9	0.8	1.6	0.02	0.06	0.06	0.43
LUBH09-10	10	0.5	1.0	0.01	0.04	0.04	0.47
LUBH09-11	11	1.0	1.9	0.03	0.07	0.11	0.57
LUBH09-12	12	0.9	1.8	0.02	0.07	0.08	0.66
LUBH09-13	13	1.1	2.2	0.02	0.08	0.08	0.74
LUBH008-1	1	1.8	3.5	0.04	0.13	0.15	0.15
LUBH008-2	2	2.6	5.2	0.07	0.19	0.24	0.39
LUBH008-3	3	2.4	4.8	0.06	0.18	0.22	0.61
LUBH008-4	4	1.6	3.2	0.04	0.12	0.14	0.75
LUBH008-5	5	1.2	2.3	0.03	0.09	0.12	0.87
LUBH08II-1	1	0.3	0.5	0.01	0.02	0.02	0.02
LUBH08II-2	2	0.2	0.5	0.00	0.02	0.02	0.04
LUBH08II-3	3	0.8	1.7	0.02	0.06	0.06	0.10
LUBH08II-4	4	0.4	0.8	0.01	0.03	0.03	0.13
LUBH08II-5	5	0.9	1.9	0.02	0.07	0.06	0.19

LUBH08II-6	6	1.1	2.3	0.02	0.08	0.07	0.26
LUBH08II-7	7	2.4	4.7	0.05	0.17	0.17	0.42
LUBH08II-8	8	0.5	1.0	0.01	0.04	0.04	0.47
LUBH08II-9	9	1.0	2.1	0.03	0.08	0.09	0.56
LUBH08II-10	10	1.0	2.1	0.03	0.08	0.11	0.67
LUBH08II-11	11	0.9	1.9	0.02	0.07	0.09	0.76
LUBH08II-12	12	1.6	3.2	0.03	0.12	0.12	0.88
LUBH08II-13	13	2.2	4.5	0.04	0.16	0.14	1.02
LUBH08II-14	14	2.3	4.6	0.04	0.17	0.14	1.16

10 Appendix C: South basin cores data

Table C1. Carbon and nitrogen measurements for south basin cores of Lake Untersee.

Sample ID	Sample Depth (cm)	Weight (g)	C _{org} (%wt)	$\delta^{13}\text{C}$ vpdb	N (%wt)	$\delta^{15}\text{N}$ air	Atomic C:N
LUAH55-1	1	3.0	2.7	-11.2	0.22	21.0	14.3
LUAH55-2	2	3.8	0.7	-10.6	0.16	13.6	4.7
LUAH55-3	3	2.6	1.2	-10.1	0.11	14.7	12.2
LUAH55-4	4	0.8	1.0	-14.4	0.12	11.9	9.7
LUAH55-5	5	4.3	0.7	-16.0	0.10	16.1	8.2
LUAH55-6	6	4.9	0.9	-16.5	0.09	20.6	11.3
LUAH55-7	7	3.1	2.3	-18.6	0.09	17.2	29.8
LUAH71.5-1	1	1.5	4.1	-11.1	0.44	27.3	10.9
LUAH71.5-2	2	1.6	2.6	-5.3	0.28	23.3	10.7
LUAH71.5-3	3	3.0	1.2	-9.0	0.09	20.8	15.4
LUAH71.5-4	4	3.5	1.0	-8.7	0.11	11.4	10.1
LUAH71.5-5	5	4.2	1.5	-7.8	0.10	20.8	17.1
LUAH71.5-6	6	6.5	1.4	-13.6	0.10	23.2	15.7
LUAH71.5-7	7	4.5	1.2	-12.5	0.09	23.4	15.8
LUAH71.5-8	8	3.2	1.1	-17.4	0.10	19.0	12.9
LUAH71.5-9	9	6.0	1.0	-17.2	0.11	17.1	10.1
LUAH71.5-10	10	5.5	0.9	-17.5	0.10	18.0	10.1
LUAH71.5-11	11	4.7	1.0	-16.5	0.07	19.6	16.7
LUAH71.5-12	12	5.5	0.6	-15.7	0.06	14.7	11.1
LUAH71.5-13	13	7.1	0.7	-17.9	0.05	17.4	16.6
LUAH71.5-14	14	7.3	0.7	-14.4	0.07	19.1	11.8
LUAH71.5-15	15	7.8	0.6	-15.4	0.07	23.2	10.2
LUAH71.5-16	16	7.0	0.9	-17.0	0.06	22.5	17.3
LUAH71.5-17	17	8.8	0.7	-17.1	0.07	21.2	11.8
LUAH71.5-18	18	7.8	0.8	-18.9	0.04	24.9	24.5
LUAH71.5-19	19	7.2	0.7	-19.0	0.05	22.7	15.4
LUAH71.5-20	20	6.2	0.6	-19.0	0.04	16.8	17.8
LUAH71.5-21	21	9.3	0.4	-19.0	0.05	14.0	10.0
LUAH87II-1	1	0.4	5.9	-21.1	0.83	17.7	8.2
LUAH87II-2	2	0.5	5.0	-20.6	0.98	14.0	6.0
LUAH87II-3	3	0.5	5.7	-21.0	0.94	15.6	7.1
LUAH87II-4	4	0.3	5.3	-20.5	1.09	11.5	5.7
LUAH87II-5	5	0.2	5.8	-20.5	1.13	12.6	6.0

LUAH87II-6	6	0.1	5.9	-19.4	0.76	16.2	9.0
LUAH87II-7	7	0.2	6.0	-18.8	1.00	16.9	7.0
LUAH87II-8	8	0.6	5.1	-17.4	0.88	16.1	6.8
LUAH87II-9	9	0.6	6.1	-17.7	1.12	21.7	6.4
LUAH87II-10	10	0.2	9.0	-19.2	1.71	23.5	6.1
LUAH87II-11	11	0.6	5.4	-18.2	0.93	20.7	6.8
LUAH87II-12	12	1.4	5.0	-15.4	0.73	19.4	8.0
LUAH87II-13	13	1.4	4.6	-14.6	0.70	20.5	7.6
LUAH87II-14	14	1.6	3.6	-15.3	0.70	21.0	6.0
LUAH87II-15	15	1.2	3.1	-15.7	0.56	20.7	6.5
LUAH87II-16	16	1.9	3.7	-15.4	0.55	19.1	7.9
LUAH87II-17	17	2.8	2.8	-15.2	0.58	21.6	5.6
LUAH87II-18	18	2.0	3.4	-15.3	0.53	21.6	7.5
LUAH87II-19	19	1.6	3.2	-15.1	0.51	22.1	7.4
LUAH87II-20	20	2.2	3.6	-15.9	0.56	22.9	7.5
LUAH87II-21	21	2.3	2.5	-16.7	0.41	21.1	7.0
LUAH87II-22	22	2.4	3.6	-16.0	0.58	21.4	7.3
LUAH87II-23	23	2.3	4.5	-15.5	0.67	20.4	7.9
LUAH98-1	1	0.6	3.9	-20.4	0.77	20.0	5.9
LUAH98-3	3	0.8	3.8	-21.3	0.54	20.5	8.2
LUAH98-5	5	1.5	2.8	-21.1	0.46	20.6	7.1
LUAH98-7	7	1.3	5.9	-20.7	0.87	18.4	7.9
LUAH98-9	9	0.8	7.4	-20.0	0.97	18.8	8.9
LUAH98-11	11	1.2	4.5	-18.0	0.90	21.7	5.8
LUAH98-13	13	1.6	6.8	-15.5	0.86	21.4	9.3
LUAH98-15	15	1.6	6.3	-14.5	0.86	20.1	8.5
LUAH98-17	17	1.4	6.3	-15.7	0.79	21.2	9.3
LUAH98-19	19	1.5	5.1	-15.6	0.65	21.8	9.2
LUAH98-21	21	1.5	5.4	-15.8	0.68	21.3	9.3
LUAH98-23	23	1.4	5.4	-16.6	0.61	23.7	10.3
LUAH98-25	25	2.0	5.8	-16.6	0.62	23.6	10.9
LUAH98-27	27	1.5	4.3	-18.7	0.45	24.7	11.1
LUAH98-29	29	3.1	3.0	-19.8	0.43	23.7	8.1
LUAH98-31	31	5.0	1.5	-18.5	0.29	24.9	5.9
LUAH98-33	33	7.4	1.2	-17.4	0.23	27.0	6.0
LUAH98-35	35	9.0	1.0	-19.7	0.20	26.9	6.1
LUAH98-37	37	9.2	1.1	-19.9	0.21	22.9	5.9
LUAH98-39	39	12.5	0.6	-20.2	0.14	21.6	5.2
LUAH98-41	41	15.3	0.3	-20.7	0.11	18.9	2.8

LUAH98-43	43	17.4	0.2	-21.3	0.09	20.4	2.6
LUAH98-45	45	13.7	0.2	-22.3	0.11	20.4	2.3
LUAH98-47	47	9.8	0.4	-22.0	0.10	24.1	4.2
LUAH98-48	48	8.2	0.2	-21.5	0.10	18.2	2.4
LUAH98-49	49	8.8	0.2	-22.3	0.10	20.7	2.0
LUAH98-50	50	10.9	0.2	-22.4	0.10	19.7	1.9
LUAH98-51	51	11.5	0.1	-22.4	0.09	20.5	1.8
LUAH98-52	52	10.8	0.1	-22.0	0.07	20.5	1.5
LUAH87-1	1	0.2	3.9	-20.4	0.92	13.8	5.0
LUAH87-2	2	0.2	5.3	-21.0	0.96	18.4	6.5
LUAH87-3	3	0.4	6.2	-20.4	0.97	14.4	7.4
LUAH87-4	4	0.2	6.3	-21.2	0.83	18.8	8.9
LUAH87-5	5	0.4	6.4	-20.6	0.94	14.9	8.0
LUAH87-6	6	0.2	5.5	-19.2	0.91	18.9	7.0
LUAH87-7	7	0.8	5.9	-18.9	1.00	17.4	6.9
LUAH87-8	8	0.4	5.8	-18.5	1.02	14.2	6.6
LUAH87-9	9	0.4	5.9	-18.2	0.86	18.8	8.0
LUAH87-10	10	1.4	5.2	-17.6	0.90	20.6	6.7
LUAH87-11	11	0.7	8.8	-16.3	1.01	21.5	10.2
LUAH87-12	12	1.0	7.1	-18.9	0.94	25.1	8.8
LUAH87-13	13	0.9	5.6	-16.8	0.61	22.8	10.7
LUAH87-14	14	2.1	4.5	-14.5	0.64	21.7	8.1
LUAH87-15	15	2.0	4.2	-14.4	0.62	22.6	7.8
LUAH87-16	16	1.8	3.9	-15.4	0.58	22.4	7.8
LUAH87-17	17	2.6	3.3	-15.6	0.46	20.9	8.4
LUAH87-18	18	2.8	2.9	-15.4	0.53	20.6	6.4
LUAH87-19	19	2.3	4.5	-16.1	0.54	20.7	9.8
LUAH87-20	20	2.3	3.4	-15.7	0.53	18.5	7.5
LUAH87-21	21	1.3	3.0	-15.5	0.54	16.5	6.5
LUAH87-22	22	0.9	3.2	-15.1	0.55	20.0	6.8
LUAH87-23	23	3.1	2.2	-16.6	0.58	18.5	4.4
LUAH87-24	24	0.9	3.9	-16.0	0.61	13.5	7.4
LUAH87-25	25	1.5	3.6	-15.7	0.59	16.9	7.2
LUAH87-26	26	1.8	3.4	-16.8	0.54	20.0	7.4
LUAH87-27	27	1.2	3.4	-16.3	0.53	18.8	7.4
LUAH87-28	28	1.1	4.4	-16.2	0.55	14.1	9.2
LUAH87-29	29	1.7	1.6	-14.4	0.64	20.2	3.0
LUAH87-30	30	2.2	3.7	-15.8	0.56	22.1	7.8
LUAH87-31	31	3.7	2.9	-15.5	0.52	20.6	6.5

LUAH87-32	32	2.2	3.3	-15.7	0.51	22.1	7.5
LUAH87-33	33	1.6	3.3	-15.5	0.48	21.9	8.0
LUAH87-34	34	1.6	2.7	-14.7	0.50	22.7	6.3
LUAH87-35	35	2.3	3.0	-16.1	0.46	23.7	7.7
LUAH87-36	36	1.5	3.5	-17.0	0.51	19.0	7.9
LUAH87-37	37	0.8	4.4	-16.8	0.57	16.4	8.9
LUAH87-38	38	0.7	4.2	-16.6	0.60	19.1	8.2
LUAH87-39	39	0.8	4.4	-16.6	0.59	17.6	8.8
LUAH87-40	40	0.9	3.7	-17.3	0.54	16.6	8.0
LUAH87-41	41	1.1	3.2	-17.9	0.43	17.1	8.5
LUAH87-42	42	0.7	4.2	-18.5	0.48	18.8	10.2
LUAH87-43	43	1.1	2.1	-21.1	0.39	19.8	6.3

Table C2. Organic carbon content (OCC) calculations for south basin cores of Lake Untersee

Sample ID	Sample Depth (cm)	BD (g cm⁻³)	OCC (kg m⁻²)	OCC cumulative (kg m⁻²)
LUAH55-1	1	0.11	0.29	0.3
LUAH55-2	2	0.14	0.09	0.4
LUAH55-3	3	0.10	0.11	0.5
LUAH55-4	4	0.03	0.03	0.5
LUAH55-5	5	0.16	0.11	0.6
LUAH55-6	6	0.18	0.16	0.8
LUAH55-7	7	0.11	0.26	1.0
LUAH71.5-1	1	0.05	0.22	0.2
LUAH71.5-2	2	0.06	0.15	0.4
LUAH71.5-3	3	0.11	0.13	0.5
LUAH71.5-4	4	0.13	0.12	0.6
LUAH71.5-5	5	0.15	0.22	0.8
LUAH71.5-6	6	0.24	0.32	1.2
LUAH71.5-7	7	0.17	0.20	1.4
LUAH71.5-8	8	0.12	0.13	1.5
LUAH71.5-9	9	0.22	0.21	1.7
LUAH71.5-10	10	0.20	0.18	1.9
LUAH71.5-11	11	0.17	0.17	2.1
LUAH71.5-12	12	0.20	0.11	2.2
LUAH71.5-13	13	0.26	0.19	2.4
LUAH71.5-14	14	0.27	0.19	2.6
LUAH71.5-15	15	0.28	0.17	2.7
LUAH71.5-16	16	0.26	0.23	3.0
LUAH71.5-17	17	0.32	0.23	3.2
LUAH71.5-18	18	0.29	0.24	3.4
LUAH71.5-19	19	0.26	0.17	3.6
LUAH71.5-20	20	0.23	0.14	3.7

LUAH71.5-21	21	0.34	0.15	3.9
LUAH87II-1	1	0.02	0.09	0.1
LUAH87II-2	2	0.02	0.09	0.2
LUAH87II-3	3	0.02	0.10	0.3
LUAH87II-4	4	0.01	0.06	0.3
LUAH87II-5	5	0.01	0.04	0.4
LUAH87II-6	6	0.00	0.02	0.4
LUAH87II-7	7	0.01	0.05	0.4
LUAH87II-8	8	0.02	0.11	0.6
LUAH87II-9	9	0.02	0.14	0.7
LUAH87II-10	10	0.01	0.06	0.8
LUAH87II-11	11	0.02	0.12	0.9
LUAH87II-12	12	0.05	0.27	1.2
LUAH87II-13	13	0.05	0.24	1.4
LUAH87II-14	14	0.06	0.21	1.6
LUAH87II-15	15	0.04	0.13	1.7
LUAH87II-16	16	0.07	0.26	2.0
LUAH87II-17	17	0.10	0.29	2.3
LUAH87II-18	18	0.07	0.25	2.5
LUAH87II-19	19	0.06	0.19	2.7
LUAH87II-20	20	0.08	0.29	3.0
LUAH87II-21	21	0.08	0.21	3.2
LUAH87II-22	22	0.09	0.31	3.5
LUAH87II-23	23	0.08	0.38	3.9
LUAH98-1	1	0.02	0.09	0.1
LUAH98-3	3	0.03	0.11	0.2
LUAH98-5	5	0.06	0.16	0.4
LUAH98-7	7	0.05	0.28	0.6
LUAH98-9	9	0.03	0.23	0.9

LUAH98-11	11	0.04	0.19	1.1
LUAH98-13	13	0.06	0.40	1.5
LUAH98-15	15	0.06	0.37	1.8
LUAH98-17	17	0.05	0.33	2.2
LUAH98-19	19	0.06	0.29	2.4
LUAH98-21	21	0.06	0.30	2.8
LUAH98-23	23	0.05	0.27	3.0
LUAH98-25	25	0.07	0.43	3.5
LUAH98-27	27	0.06	0.24	3.7
LUAH98-29	29	0.11	0.34	4.0
LUAH98-31	31	0.18	0.27	4.3
LUAH98-33	33	0.27	0.32	4.6
LUAH98-35	35	0.33	0.34	5.0
LUAH98-37	37	0.34	0.36	5.3
LUAH98-39	39	0.46	0.29	5.6
LUAH98-41	41	0.56	0.15	5.8
LUAH98-43	43	0.64	0.13	5.9
LUAH98-45	45	0.50	0.11	6.0
LUAH98-47	47	0.36	0.13	6.1
LUAH98-48	48	0.30	0.06	6.2
LUAH98-49	49	0.32	0.05	6.2
LUAH98-50	50	0.40	0.06	6.3
LUAH98-51	51	0.42	0.06	6.4
LUAH98-52	52	0.39	0.04	6.4
LUAH87-1	1	0.01	0.03	0.0
LUAH87-2	2	0.01	0.04	0.1
LUAH87-3	3	0.01	0.09	0.2
LUAH87-4	4	0.01	0.06	0.2
LUAH87-5	5	0.01	0.09	0.3
LUAH87-6	6	0.01	0.05	0.4

LUAH87-7	7	0.03	0.17	0.5
LUAH87-8	8	0.02	0.09	0.6
LUAH87-9	9	0.01	0.09	0.7
LUAH87-10	10	0.05	0.27	1.0
LUAH87-11	11	0.03	0.23	1.2
LUAH87-12	12	0.04	0.26	1.5
LUAH87-13	13	0.03	0.19	1.7
LUAH87-14	14	0.08	0.34	2.0
LUAH87-15	15	0.07	0.31	2.3
LUAH87-16	16	0.07	0.25	2.6
LUAH87-17	17	0.10	0.32	2.9
LUAH87-18	18	0.10	0.30	3.2
LUAH87-19	19	0.08	0.37	3.6
LUAH87-20	20	0.08	0.28	3.8
LUAH87-21	21	0.05	0.15	4.0
LUAH87-22	22	0.03	0.10	4.1
LUAH87-23	23	0.11	0.25	4.3
LUAH87-24	24	0.03	0.13	4.5
LUAH87-25	25	0.06	0.20	4.7
LUAH87-26	26	0.06	0.22	4.9
LUAH87-27	27	0.04	0.15	5.0
LUAH87-28	28	0.04	0.17	5.2
LUAH87-29	29	0.06	0.10	5.3
LUAH87-30	30	0.08	0.30	5.6
LUAH87-31	31	0.14	0.40	6.0
LUAH87-32	32	0.08	0.26	6.3
LUAH87-33	33	0.06	0.20	6.5
LUAH87-34	34	0.06	0.16	6.6
LUAH87-35	35	0.08	0.25	6.9
LUAH87-36	36	0.06	0.19	7.1
LUAH87-37	37	0.03	0.13	7.2

LUAH87-38	38	0.03	0.11	7.3
LUAH87-39	39	0.03	0.12	7.4
LUAH87-40	40	0.03	0.12	7.5
LUAH87-41	41	0.04	0.13	7.7
LUAH87-42	42	0.03	0.11	7.8
LUAH87-43	43	0.04	0.08	7.9

11 Appendix D: Water column measurements for north basin

Table D1. Data measured by YSI probe in 2021, north basin of Lake Untersee.

Depth (m)	Temperature (°C)	pH	Dissolved Oxygen (DO %)	Specific Conductivity ($\mu\text{S cm}^{-1}$)	Chlorophyll ($\mu\text{g L}^{-1}$)	PAR ($\mu\text{mol photons m}^{-2} \text{s}^{-1}$)
5	0.2	10.4	143.3	512.1	0.00	111.9
10	0.2	10.4	145.4	510.4	0.01	93.0
15	0.2	10.4	145.1	510.8	0.05	79.7
20	0.2	10.4	145.2	510.8	0.00	67.2
25	0.2	10.4	145.3	510.7	0.01	56.5
30	0.2	10.4	145.4	511.0	0.02	48.1
35	0.2	10.4	145.4	511.1	0.04	41.1
40	0.2	10.4	145.5	511.2	0.07	35.3
45	0.2	10.4	145.5	511.2	0.00	32.7
50	0.2	10.4	145.6	511.3	0.03	27.4
55	0.2	10.4	145.6	511.3	0.03	23.7
60	0.2	10.4	145.6	511.3	0.12	21.4
65	0.2	10.4	145.6	511.4	0.23	19.5
70	0.2	10.4	145.6	511.5	0.05	17.0
75	0.2	10.4	145.7	511.5	0.07	15.5
80	0.2	10.4	145.7	511.6	0.03	14.9
85	0.2	10.4	145.7	511.6	0.03	13.4
90	0.2	10.4	145.7	511.7	0.04	12.0
95	0.2	10.4	145.7	511.8	0.04	10.6
100	0.2	10.5	145.7	511.8	0.04	7.5
105	0.2	10.5	145.7	511.8	0.03	6.2
110	0.2	10.5	145.7	511.9	0.07	4.8
115	0.2	10.5	145.7	511.9	0.03	4.1
120	0.2	10.5	145.7	512.0	0.08	3.1
125	0.2	10.5	145.8	512.1	0.04	2.0
130	0.2	10.5	145.8	512.1	0.03	1.1
135	0.2	10.5	145.7	512.1	0.04	0.6
140	0.2	10.5	145.7	512.2	0.03	0.2
145	0.2	10.5	145.7	512.2	0.04	-0.2
150	0.2	10.5	145.7	512.3	0.07	-0.5

Table D2. $\delta^{18}\text{O}$ - O_2 isotope ratio mass spectrometry (IRMS) measurements for north basin of Lake Untersee.

Sample ID	$\delta^{18}\text{O}$ - O_2	Depth (m)
NB 40	5.2	40
NB 60	5.4	60
NB 80	7.3	80
NB 100	6.5	100
NB 104.5	5.7	105
NB 120	6.8	120
NB 140	8.4	140
NB 160	7.2	160
NB 166	5.3	166

Table D3. O_2/Ar , $\text{Ar}/\text{Ar}_{\text{asw}}$ and $\text{O}_2/\text{O}_{2\text{asw}}$ membrane inlet mass spectrometry (MIMS) measurements for north basin of Lake Untersee.

Station	Depth (m)	O_2/Ar	$\text{Ar}/\text{Ar}_{\text{asw}}$	$\text{O}_2/\text{O}_{2\text{asw}}$
NB	5	19.4	143.7	136.5
NB	5	19.4	149.6	142.2
NB	25	19.3	144.4	136.3
NB	25	19.3	148.3	140.2
NB	50	19.4	147.8	139.8
NB	75	19.3	158.9	149.5
NB	100	19.4	157.7	149.3
NB	100	19.4	154.6	146.4
NB	125	19.4	151.9	143.7
NB	150	19.4	162.0	153.9
NB	150	19.4	161.3	152.8

Table D4. O_2/Ar isotope ratio mass spectrometry (IRMS) measurements for north basin of Lake Untersee

ID	Average of O_2/Ar	Depth (m)
5-OH	19.3	5
25-OH	19.3	25
50-OH	19.4	50
75-OH	19.4	75
100-OH	19.3	100
125-OH	19.9	125
150-OH	19.5	150

12 Appendix E: Water column measurements for south basin

Table E1. Data measured by YSI probe in 2015, south basin of Lake Untersee.

Date (M/D/YYYY)	Time (HH:MM:SS)	Depth (m)	Dissolved oxygen (DO%)	Chlorophyll ($\mu\text{g l}^{-1}$)
2015-12-01	11:05:49	5.0	144.4	0.07
2015-12-01	11:05:50	5.0	144.4	0.07
2015-12-01	11:05:51	5.0	144.6	0.07
2015-12-01	11:05:52	5.0	144.6	0.07
2015-12-01	11:05:53	5.0	144.9	0.07
2015-12-01	11:05:54	5.0	144.9	0.07
2015-12-01	11:05:55	5.0	145	0.08
2015-12-01	11:05:56	5.0	145	0.08
2015-12-01	11:05:57	5.0	145.2	0.08
2015-12-01	11:05:58	5.0	145.2	0.08
2015-12-01	11:07:17	10.0	149.5	0.08
2015-12-01	11:07:18	10.0	149.5	0.08
2015-12-01	11:07:19	10.0	149.7	0.08
2015-12-01	11:07:20	10.0	149.7	0.08
2015-12-01	11:07:21	10.0	149.5	0.08
2015-12-01	11:07:22	10.0	149.5	0.08
2015-12-01	11:07:23	10.0	149.5	0.08
2015-12-01	11:07:24	10.0	149.5	0.08
2015-12-01	11:07:25	10.0	149.5	0.08
2015-12-01	11:07:26	10.0	149.5	0.08
2015-12-01	11:08:46	15.0	148.5	0.07
2015-12-01	11:08:47	15.0	148.7	0.07
2015-12-01	11:08:48	15.0	148.5	0.07
2015-12-01	11:08:49	15.0	148.5	0.07
2015-12-01	11:08:50	15.0	148.5	0.07
2015-12-01	11:08:51	15.0	148.5	0.07
2015-12-01	11:08:52	15.0	148.5	0.07
2015-12-01	11:08:56	15.0	148.4	0.07
2015-12-01	11:08:57	15.0	148.4	0.07
2015-12-01	11:08:58	15.0	148.4	0.07
2015-12-01	11:10:03	20.1	148.7	0.07
2015-12-01	11:10:04	20.1	148.7	0.07

2015-12-01	11:10:05	20.0	148.7	0.07
2015-12-01	11:10:06	20.0	148.7	0.07
2015-12-01	11:10:07	20.0	148.7	0.07
2015-12-01	11:10:08	20.0	148.7	0.07
2015-12-01	11:10:09	20.0	148.7	0.07
2015-12-01	11:10:10	20.0	148.7	0.07
2015-12-01	11:10:11	20.0	148.7	0.07
2015-12-01	11:10:12	20.0	148.7	0.07
2015-12-01	11:11:08	25.1	147.9	0.08
2015-12-01	11:11:09	25.1	147.9	0.08
2015-12-01	11:11:10	25.1	148	0.08
2015-12-01	11:11:11	25.1	148	0.08
2015-12-01	11:11:12	25.1	148	0.08
2015-12-01	11:11:13	25.1	148	0.08
2015-12-01	11:11:14	25.1	148	0.08
2015-12-01	11:11:15	25.1	148.1	0.08
2015-12-01	11:11:16	25.1	148.1	0.08
2015-12-01	11:11:17	25.1	147.9	0.08
2015-12-01	11:12:21	30.0	147.1	0.08
2015-12-01	11:12:22	30.0	147.1	0.08
2015-12-01	11:12:23	30.0	147.1	0.08
2015-12-01	11:12:24	30.0	147.1	0.08
2015-12-01	11:12:25	30.1	146.9	0.08
2015-12-01	11:12:26	30.1	146.9	0.08
2015-12-01	11:12:27	30.0	146.9	0.08
2015-12-01	11:12:28	30.0	146.8	0.08
2015-12-01	11:12:29	30.0	146.8	0.08
2015-12-01	11:12:30	30.1	147	0.08
2015-12-01	11:13:07	35.0	146.7	0.08
2015-12-01	11:13:08	35.0	146.7	0.08
2015-12-01	11:13:09	35.0	146.5	0.08
2015-12-01	11:13:10	35.0	146.5	0.08
2015-12-01	11:13:11	35.0	146.5	0.08
2015-12-01	11:13:12	35.0	146.4	0.08
2015-12-01	11:13:13	35.0	146.4	0.08
2015-12-01	11:13:14	35.0	146.3	0.08
2015-12-01	11:13:15	35.0	146.3	0.08
2015-12-01	11:13:16	35.0	146.4	0.08
2015-12-01	11:14:06	40.0	146.7	0.08
2015-12-01	11:14:07	40.0	146.7	0.08

2015-12-01	11:14:08	40.0	146.7	0.08
2015-12-01	11:14:09	40.0	146.7	0.08
2015-12-01	11:14:10	40.0	146.8	0.08
2015-12-01	11:14:11	40.0	146.8	0.08
2015-12-01	11:14:12	40.0	146.8	0.08
2015-12-01	11:14:13	40.0	146.7	0.08
2015-12-01	11:14:14	40.0	146.7	0.08
2015-12-01	11:14:15	40.0	146.7	0.08
2015-12-01	11:14:49	45.0	146.5	0.08
2015-12-01	11:14:50	45.0	146.6	0.08
2015-12-01	11:14:51	45.0	146.6	0.08
2015-12-01	11:14:52	45.0	146.6	0.08
2015-12-01	11:14:53	45.0	146.6	0.08
2015-12-01	11:14:54	45.0	146.7	0.08
2015-12-01	11:14:55	45.0	146.7	0.08
2015-12-01	11:14:56	45.0	146.7	0.08
2015-12-01	11:14:57	45.0	146.6	0.08
2015-12-01	11:14:58	45.0	146.6	0.08
2015-12-01	11:16:05	47.1	148.6	0.08
2015-12-01	11:16:06	47.1	148.6	0.08
2015-12-01	11:16:07	47.1	148.5	0.08
2015-12-01	11:16:08	47.1	148.5	0.08
2015-12-01	11:16:09	47.1	148.7	0.08
2015-12-01	11:16:10	47.1	148.7	0.08
2015-12-01	11:16:11	47.1	148.4	0.08
2015-12-01	11:16:12	47.1	148.3	0.08
2015-12-01	11:16:13	47.1	148.3	0.08
2015-12-01	11:16:14	47.1	148.3	0.08
2015-12-01	11:17:03	48.1	147.1	0.08
2015-12-01	11:17:04	48.1	147.1	0.08
2015-12-01	11:17:05	48.1	147.1	0.09
2015-12-01	11:17:06	48.1	147.1	0.09
2015-12-01	11:17:07	48.1	147.2	0.08
2015-12-01	11:17:08	48.1	147.1	0.09
2015-12-01	11:17:09	48.1	147.1	0.09
2015-12-01	11:17:10	48.1	147.1	0.09
2015-12-01	11:17:11	48.1	147.1	0.09
2015-12-01	11:17:12	48.1	147	0.09
2015-12-01	11:17:28	49.0	147.5	0.11
2015-12-01	11:17:29	49.0	148.3	0.11

2015-12-01	11:17:30	49.0	148.3	0.11
2015-12-01	11:17:31	49.0	149	0.12
2015-12-01	11:17:32	49.0	149	0.12
2015-12-01	11:17:33	49.0	149.7	0.12
2015-12-01	11:17:34	49.0	149.7	0.12
2015-12-01	11:17:35	49.0	150.3	0.12
2015-12-01	11:17:36	49.1	150.8	0.12
2015-12-01	11:17:37	49.1	150.8	0.12
2015-12-01	11:18:05	50.0	158	0.22
2015-12-01	11:18:06	50.0	158.3	0.23
2015-12-01	11:18:07	50.0	158.3	0.23
2015-12-01	11:18:08	50.0	158.4	0.23
2015-12-01	11:18:09	50.0	158.4	0.23
2015-12-01	11:18:10	50.0	158.5	0.23
2015-12-01	11:18:11	50.0	158.6	0.23
2015-12-01	11:18:12	50.0	158.6	0.23
2015-12-01	11:18:13	50.0	158.7	0.23
2015-12-01	11:18:14	50.0	158.7	0.23
2015-12-01	11:18:50	51.1	160.6	0.26
2015-12-01	11:18:51	51.1	160.6	0.26
2015-12-01	11:18:52	51.1	160.6	0.26
2015-12-01	11:18:53	51.1	160.6	0.26
2015-12-01	11:18:54	51.1	160.6	0.26
2015-12-01	11:18:55	51.1	160.5	0.26
2015-12-01	11:18:56	51.1	160.5	0.26
2015-12-01	11:18:57	51.1	160.6	0.27
2015-12-01	11:18:58	51.1	160.6	0.27
2015-12-01	11:18:59	51.1	160.6	0.27
2015-12-01	11:19:23	52.1	160.7	0.29
2015-12-01	11:19:24	52.1	160.7	0.29
2015-12-01	11:19:25	52.1	160.7	0.29
2015-12-01	11:19:26	52.1	160.7	0.29
2015-12-01	11:19:27	52.1	160.8	0.29
2015-12-01	11:19:28	52.1	160.8	0.30
2015-12-01	11:19:29	52.1	160.8	0.30
2015-12-01	11:19:30	52.1	161	0.29
2015-12-01	11:19:31	52.1	161	0.29
2015-12-01	11:19:32	52.1	160.9	0.29
2015-12-01	11:19:47	53.1	161.3	0.29
2015-12-01	11:19:48	53.1	161.4	0.30

2015-12-01	11:19:49	53.1	161.3	0.30
2015-12-01	11:19:50	53.1	161.3	0.30
2015-12-01	11:19:51	53.1	161.3	0.31
2015-12-01	11:19:52	53.1	161.3	0.31
2015-12-01	11:19:53	53.1	161.4	0.31
2015-12-01	11:19:54	53.1	161.4	0.31
2015-12-01	11:19:55	53.1	161.3	0.31
2015-12-01	11:19:56	53.1	161.1	0.31
2015-12-01	11:20:09	54.1	161.2	0.31
2015-12-01	11:20:10	54.1	160.9	0.31
2015-12-01	11:20:11	54.1	160.9	0.31
2015-12-01	11:20:12	54.1	161	0.31
2015-12-01	11:20:13	54.1	161	0.31
2015-12-01	11:20:14	54.1	161.1	0.32
2015-12-01	11:20:15	54.1	161.1	0.32
2015-12-01	11:20:16	54.1	161.2	0.32
2015-12-01	11:20:17	54.1	161.3	0.31
2015-12-01	11:20:18	54.1	161.3	0.31
2015-12-01	11:20:53	55.1	161.4	0.29
2015-12-01	11:20:54	55.1	161.3	0.29
2015-12-01	11:20:55	55.1	161.3	0.29
2015-12-01	11:20:56	55.1	161.4	0.29
2015-12-01	11:20:57	55.1	161.4	0.29
2015-12-01	11:20:58	55.1	161.5	0.30
2015-12-01	11:20:59	55.1	161.5	0.29
2015-12-01	11:21:00	55.1	161.5	0.29
2015-12-01	11:21:01	55.1	161.4	0.29
2015-12-01	11:21:02	55.1	161.4	0.29
2015-12-01	11:21:24	56.0	161.5	0.30
2015-12-01	11:21:25	56.0	161.5	0.30
2015-12-01	11:21:26	56.0	161.5	0.30
2015-12-01	11:21:27	56.0	161.6	0.30
2015-12-01	11:21:28	56.0	161.6	0.30
2015-12-01	11:21:29	56.0	161.4	0.30
2015-12-01	11:21:30	56.0	161.4	0.30
2015-12-01	11:21:31	56.0	161.2	0.30
2015-12-01	11:21:32	56.0	161.2	0.30
2015-12-01	11:21:33	56.0	161.3	0.30
2015-12-01	11:21:49	57.0	161.7	0.32
2015-12-01	11:21:50	57.0	161.6	0.32

2015-12-01	11:21:51	57.0	161.6	0.32
2015-12-01	11:21:52	57.0	161.8	0.32
2015-12-01	11:21:53	57.0	161.8	0.32
2015-12-01	11:21:54	57.0	161.7	0.31
2015-12-01	11:21:55	57.0	161.5	0.31
2015-12-01	11:21:56	57.0	161.5	0.31
2015-12-01	11:21:57	57.0	161.6	0.31
2015-12-01	11:21:58	57.0	161.6	0.31
2015-12-01	11:22:20	58.1	161.5	0.34
2015-12-01	11:22:21	58.1	161.5	0.34
2015-12-01	11:22:22	58.1	161.5	0.34
2015-12-01	11:22:23	58.1	161.6	0.34
2015-12-01	11:22:24	58.1	161.6	0.34
2015-12-01	11:22:25	58.1	161.6	0.34
2015-12-01	11:22:26	58.1	161.6	0.34
2015-12-01	11:22:27	58.1	161.6	0.35
2015-12-01	11:22:28	58.1	161.6	0.35
2015-12-01	11:22:29	58.1	161.6	0.36
2015-12-01	11:22:43	59.0	161.4	0.34
2015-12-01	11:22:44	59.0	161.3	0.34
2015-12-01	11:22:45	59.0	161.3	0.34
2015-12-01	11:22:46	59.0	161.4	0.32
2015-12-01	11:22:47	59.0	161.4	0.32
2015-12-01	11:22:48	59.0	161.5	0.32
2015-12-01	11:22:49	59.0	161.5	0.32
2015-12-01	11:22:50	59.0	161.5	0.32
2015-12-01	11:22:51	59.0	161.5	0.32
2015-12-01	11:22:52	59.0	161.5	0.32
2015-12-01	11:23:12	60.0	161.7	0.33
2015-12-01	11:23:13	60.0	161.7	0.34
2015-12-01	11:23:14	60.0	161.6	0.34
2015-12-01	11:23:15	60.0	161.6	0.34
2015-12-01	11:23:16	60.1	161.5	0.34
2015-12-01	11:23:17	60.1	161.5	0.34
2015-12-01	11:23:18	60.0	161.7	0.35
2015-12-01	11:23:19	60.1	161.5	0.35
2015-12-01	11:23:20	60.1	161.5	0.35
2015-12-01	11:23:21	60.1	161.5	0.35
2015-12-01	11:23:39	61.0	161.7	0.36
2015-12-01	11:23:40	61.0	161.6	0.36

2015-12-01	11:23:41	61.0	161.6	0.36
2015-12-01	11:23:42	61.0	161.5	0.36
2015-12-01	11:23:43	61.0	161.5	0.36
2015-12-01	11:23:44	61.0	161.4	0.37
2015-12-01	11:23:45	61.0	161.4	0.37
2015-12-01	11:23:46	61.0	161.4	0.37
2015-12-01	11:23:47	61.0	161.3	0.37
2015-12-01	11:23:48	61.0	161.3	0.37
2015-12-01	11:24:20	62.0	161.5	0.37
2015-12-01	11:24:21	62.0	161.5	0.37
2015-12-01	11:24:22	62.0	161.6	0.36
2015-12-01	11:24:23	62.0	161.6	0.36
2015-12-01	11:24:24	62.1	161.6	0.36
2015-12-01	11:24:25	62.1	161.6	0.36
2015-12-01	11:24:26	62.1	161.4	0.36
2015-12-01	11:24:27	62.1	161.4	0.36
2015-12-01	11:24:28	62.1	161.3	0.36
2015-12-01	11:24:29	62.1	161.3	0.36
2015-12-01	11:24:42	63.0	160.9	0.38
2015-12-01	11:24:43	63.0	161	0.38
2015-12-01	11:24:44	63.0	161	0.38
2015-12-01	11:24:45	63.0	161.1	0.39
2015-12-01	11:24:46	63.0	161.1	0.39
2015-12-01	11:24:47	63.0	161.2	0.39
2015-12-01	11:24:48	63.0	161.2	0.39
2015-12-01	11:24:49	63.0	161.2	0.39
2015-12-01	11:24:50	63.0	161.4	0.40
2015-12-01	11:24:51	63.0	161.4	0.40
2015-12-01	11:25:13	64.1	161.8	0.47
2015-12-01	11:25:14	64.1	161.8	0.47
2015-12-01	11:25:15	64.1	161.7	0.48
2015-12-01	11:25:16	64.1	161.7	0.48
2015-12-01	11:25:17	64.1	161.9	0.49
2015-12-01	11:25:18	64.1	161.8	0.49
2015-12-01	11:25:19	64.1	161.8	0.49
2015-12-01	11:25:20	64.1	161.6	0.50
2015-12-01	11:25:21	64.1	161.6	0.50
2015-12-01	11:25:22	64.1	161.6	0.48
2015-12-01	11:25:44	65.1	160.7	0.47
2015-12-01	11:25:45	65.1	160.8	0.46

2015-12-01	11:25:46	65.1	161	0.46
2015-12-01	11:25:47	65.1	161	0.46
2015-12-01	11:25:48	65.1	161	0.47
2015-12-01	11:25:49	65.1	161	0.47
2015-12-01	11:25:50	65.1	161.1	0.47
2015-12-01	11:25:51	65.1	161.1	0.47
2015-12-01	11:25:52	65.1	161.2	0.48
2015-12-01	11:25:53	65.1	161.3	0.48
2015-12-01	11:26:07	66.0	161.4	0.50
2015-12-01	11:26:08	66.0	161.4	0.50
2015-12-01	11:26:09	66.0	161.4	0.50
2015-12-01	11:26:10	66.0	161.4	0.50
2015-12-01	11:26:11	66.0	161.3	0.51
2015-12-01	11:26:12	66.0	161.3	0.51
2015-12-01	11:26:13	66.0	161.3	0.53
2015-12-01	11:26:14	66.0	161.3	0.53
2015-12-01	11:26:15	66.0	161.3	0.53
2015-12-01	11:26:16	66.0	161.3	0.53
2015-12-01	11:26:38	67.1	159.4	0.74
2015-12-01	11:26:39	67.1	159	0.75
2015-12-01	11:26:40	67.1	159	0.75
2015-12-01	11:26:41	67.1	158.6	0.76
2015-12-01	11:26:42	67.1	158.1	0.78
2015-12-01	11:26:43	67.1	158.1	0.78
2015-12-01	11:26:44	67.1	157.4	0.78
2015-12-01	11:26:45	67.1	157.4	0.78
2015-12-01	11:26:46	67.1	156.9	0.78
2015-12-01	11:26:47	67.1	156.9	0.78
2015-12-01	11:27:17	68.1	149.4	0.90
2015-12-01	11:27:18	68.1	149.4	0.90
2015-12-01	11:27:19	68.1	148.9	0.91
2015-12-01	11:27:20	68.1	148.9	0.91
2015-12-01	11:27:21	68.1	148.5	0.91
2015-12-01	11:27:22	68.1	148.5	0.91
2015-12-01	11:27:23	68.1	148	0.91
2015-12-01	11:27:24	68.1	147.6	0.92
2015-12-01	11:27:25	68.1	147.6	0.92
2015-12-01	11:27:26	68.1	147	0.92
2015-12-01	11:27:48	69.1	125.3	1.17
2015-12-01	11:27:49	69.1	124.8	1.18

2015-12-01	11:27:50	69.1	124.8	1.18
2015-12-01	11:27:51	69.1	125.1	1.21
2015-12-01	11:27:52	69.1	124.8	1.22
2015-12-01	11:27:53	69.1	124.8	1.22
2015-12-01	11:27:54	69.1	124.5	1.21
2015-12-01	11:27:55	69.1	124.5	1.21
2015-12-01	11:27:56	69.1	124.2	1.20
2015-12-01	11:27:57	69.1	124.2	1.20
2015-12-01	11:28:16	70.1	97.4	1.22
2015-12-01	11:28:17	70.1	88	1.25
2015-12-01	11:28:18	70.1	88	1.25
2015-12-01	11:28:19	70.1	87.1	1.27
2015-12-01	11:28:20	70.1	86.1	1.30
2015-12-01	11:28:21	70.1	86.1	1.30
2015-12-01	11:28:22	70.1	85.2	1.31
2015-12-01	11:28:23	70.1	85.2	1.31
2015-12-01	11:28:24	70.1	84.3	1.31
2015-12-01	11:28:25	70.1	84.3	1.31
2015-12-01	11:28:40	71.1	54.2	1.37
2015-12-01	11:28:41	71.1	52.5	1.38
2015-12-01	11:28:42	71.1	52.5	1.38
2015-12-01	11:28:43	71.1	51.2	1.41
2015-12-01	11:28:44	71.1	51.2	1.41
2015-12-01	11:28:45	71.1	50.1	1.43
2015-12-01	11:28:46	71.1	50.1	1.43
2015-12-01	11:28:47	71.1	45.3	1.44
2015-12-01	11:28:48	71.1	44.7	1.45
2015-12-01	11:28:49	71.1	44.7	1.45
2015-12-01	11:29:50	72.0	25.7	1.67
2015-12-01	11:29:51	72.0	25.5	1.67
2015-12-01	11:29:52	72.0	25.5	1.67
2015-12-01	11:29:53	72.0	25.1	1.68
2015-12-01	11:29:54	72.0	25.1	1.68
2015-12-01	11:29:55	72.0	24.7	1.70
2015-12-01	11:29:56	72.0	24.7	1.70
2015-12-01	11:29:57	72.0	24.3	1.72
2015-12-01	11:29:58	72.0	24	1.72
2015-12-01	11:29:59	72.0	24	1.71
2015-12-01	11:30:24	73.1	17.6	1.81
2015-12-01	11:30:25	73.1	17.3	1.84

2015-12-01	11:30:26	73.1	16.9	1.86
2015-12-01	11:30:27	73.1	16.9	1.86
2015-12-01	11:30:28	73.1	14.3	1.89
2015-12-01	11:30:29	73.1	14.3	1.89
2015-12-01	11:30:30	73.1	14.2	1.91
2015-12-01	11:30:31	73.1	14.2	1.91
2015-12-01	11:30:32	73.1	14	1.95
2015-12-01	11:30:33	73.1	13.8	1.98
2015-12-01	11:30:47	74.0	6.8	0.98
2015-12-01	11:30:48	74.0	6.8	0.98
2015-12-01	11:30:49	74.0	6.5	0.97
2015-12-01	11:30:50	74.0	6.5	0.97
2015-12-01	11:30:51	74.0	6.1	0.97
2015-12-01	11:30:52	74.0	6.1	0.97
2015-12-01	11:30:53	74.0	4.1	0.97
2015-12-01	11:30:54	74.0	3.9	0.96
2015-12-01	11:30:55	74.0	3.9	0.96
2015-12-01	11:30:56	74.1	3.7	0.95
2015-12-01	11:31:29	75.1	0.4	0.52
2015-12-01	11:31:30	75.1	0.4	0.52
2015-12-01	11:31:31	75.1	0.3	0.52
2015-12-01	11:31:32	75.1	0.3	0.52
2015-12-01	11:31:33	75.1	0.3	0.52
2015-12-01	11:31:34	75.1	0.3	0.52
2015-12-01	11:31:35	75.2	0.2	0.51
2015-12-01	11:31:36	75.1	0.2	0.51
2015-12-01	11:31:37	75.1	0.2	0.51
2015-12-01	11:31:38	75.1	0.1	0.52
2015-12-01	11:32:04	76.1	0	0.46
2015-12-01	11:32:05	76.1	0	0.46
2015-12-01	11:32:06	76.1	0	0.45
2015-12-01	11:32:07	76.1	0	0.45
2015-12-01	11:32:08	76.1	0	0.45
2015-12-01	11:32:09	76.1	0	0.45
2015-12-01	11:32:10	76.1	0	0.45
2015-12-01	11:32:11	76.1	0	0.44
2015-12-01	11:32:12	76.1	0	0.44
2015-12-01	11:32:13	76.1	0	0.45
2015-12-01	11:32:39	77.1	0	0.43
2015-12-01	11:32:40	77.1	0	0.43

2015-12-01	11:32:41	77.1	0	0.42
2015-12-01	11:32:42	77.1	0	0.42
2015-12-01	11:32:43	76.9	0	0.42
2015-12-01	11:32:44	76.9	0	0.42
2015-12-01	11:32:45	76.8	0	0.42
2015-12-01	11:32:46	76.8	0	0.43
2015-12-01	11:32:47	76.8	0	0.43
2015-12-01	11:32:48	76.9	0	0.43
2015-12-01	11:34:04	78.0	0	0.42
2015-12-01	11:34:05	78.0	0	0.42
2015-12-01	11:34:06	78.0	0	0.42
2015-12-01	11:34:07	78.1	0	0.42
2015-12-01	11:34:08	78.1	0	0.42
2015-12-01	11:34:09	78.1	0	0.41
2015-12-01	11:34:10	78.0	0	0.41
2015-12-01	11:34:11	78.0	0	0.41
2015-12-01	11:34:12	78.0	0	0.41
2015-12-01	11:34:13	78.0	0	0.41
2015-12-01	11:34:46	79.0	0	0.44
2015-12-01	11:34:47	79.0	0	0.44
2015-12-01	11:34:48	79.0	0	0.44
2015-12-01	11:34:49	79.0	0	0.44
2015-12-01	11:34:50	79.0	0	0.44
2015-12-01	11:34:51	79.0	0	0.44
2015-12-01	11:34:52	79.0	0	0.43
2015-12-01	11:34:53	79.0	0	0.43
2015-12-01	11:34:54	79.0	0	0.43
2015-12-01	11:34:55	79.0	0	0.43
2015-12-01	11:35:22	80.0	0	0.43
2015-12-01	11:35:23	80.0	0	0.43
2015-12-01	11:35:24	80.0	0	0.43
2015-12-01	11:35:25	80.0	0	0.43
2015-12-01	11:35:26	80.0	0	0.43
2015-12-01	11:35:27	80.0	0	0.43
2015-12-01	11:35:28	80.0	0	0.43
2015-12-01	11:35:29	80.0	0	0.43
2015-12-01	11:35:30	80.0	0	0.43
2015-12-01	11:35:31	80.0	0	0.43
2015-12-01	11:37:12	81.0	0	0.45
2015-12-01	11:37:13	81.0	0	0.45

2015-12-01	11:37:14	81.0	0	0.45
2015-12-01	11:37:15	81.0	0	0.45
2015-12-01	11:37:16	81.0	0	0.46
2015-12-01	11:37:17	81.0	0	0.46
2015-12-01	11:37:18	81.0	0	0.46
2015-12-01	11:37:19	81.0	0	0.46
2015-12-01	11:37:20	81.0	0	0.46
2015-12-01	11:37:21	81.0	0	0.45
2015-12-01	11:37:57	81.0	0	0.49
2015-12-01	11:37:58	81.0	0	0.49
2015-12-01	11:37:59	81.0	0	0.49
2015-12-01	11:38:00	81.0	0	0.49
2015-12-01	11:38:01	81.0	0	0.48
2015-12-01	11:38:02	81.0	0	0.48
2015-12-01	11:38:03	81.0	0	0.47
2015-12-01	11:38:04	81.0	0	0.47
2015-12-01	11:38:05	81.0	0	0.46
2015-12-01	11:38:06	81.0	0	0.46
2015-12-01	11:38:14	81.0	0	0.45
2015-12-01	11:38:15	81.0	0	0.45
2015-12-01	11:38:16	81.0	0	0.45
2015-12-01	11:38:17	81.0	0	0.45
2015-12-01	11:38:18	81.0	0	0.45
2015-12-01	11:38:19	81.0	0	0.46
2015-12-01	11:38:20	81.0	0	0.46
2015-12-01	11:38:21	81.0	0	0.46
2015-12-01	11:38:22	81.0	0	0.47
2015-12-01	11:38:23	81.0	0	0.47
2015-12-01	11:39:33	82.1	0	0.46
2015-12-01	11:39:34	82.1	0	0.45
2015-12-01	11:39:35	82.1	0	0.45
2015-12-01	11:39:36	82.1	0	0.45
2015-12-01	11:39:37	82.1	0	0.45
2015-12-01	11:39:38	82.1	0	0.46
2015-12-01	11:39:39	82.1	0	0.46
2015-12-01	11:39:40	82.1	0	0.46
2015-12-01	11:39:41	82.1	0	0.46
2015-12-01	11:39:42	82.1	0	0.46
2015-12-01	11:40:14	83.1	0	0.47
2015-12-01	11:40:15	83.1	0	0.47

2015-12-01	11:40:16	83.1	0	0.48
2015-12-01	11:40:17	83.1	0	0.48
2015-12-01	11:40:18	83.1	0	0.49
2015-12-01	11:40:19	83.1	0	0.49
2015-12-01	11:40:20	83.1	0	0.50
2015-12-01	11:40:21	83.1	0	0.50
2015-12-01	11:40:22	83.1	0	0.50
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2015-12-01	11:40:53	84.1	0	0.67
2015-12-01	11:40:54	84.1	0	0.67
2015-12-01	11:40:55	84.1	0	0.68
2015-12-01	11:40:56	84.1	0	0.70
2015-12-01	11:40:57	84.1	0	0.70
2015-12-01	11:40:58	84.1	0	0.71
2015-12-01	11:40:59	84.1	0	0.71
2015-12-01	11:41:00	84.1	0	0.72
2015-12-01	11:41:01	84.1	0	0.72
2015-12-01	11:41:02	84.1	0	0.72
2015-12-01	11:41:20	85.0	0	0.74
2015-12-01	11:41:21	85.0	0	0.71
2015-12-01	11:41:22	85.0	0	0.71
2015-12-01	11:41:23	85.0	0	0.69
2015-12-01	11:41:24	85.0	0	0.66
2015-12-01	11:41:25	85.0	0	0.66
2015-12-01	11:41:26	85.1	0	0.64
2015-12-01	11:41:27	85.1	0	0.64
2015-12-01	11:41:28	85.1	0	0.61
2015-12-01	11:41:29	85.1	0	0.59
2015-12-01	11:41:58	86.0	0	0.63
2015-12-01	11:41:59	86.0	0	0.63
2015-12-01	11:42:00	86.0	0	0.63
2015-12-01	11:42:01	86.0	0	0.63
2015-12-01	11:42:02	86.0	0	0.63
2015-12-01	11:42:03	86.0	0	0.63
2015-12-01	11:42:06	86.0	0	0.63
2015-12-01	11:42:07	86.0	0	0.63
2015-12-01	11:42:08	86.0	0	0.63
2015-12-01	11:42:09	86.0	0	0.63
2015-12-01	11:42:37	87.0	0	0.73
2015-12-01	11:42:38	87.0	0	0.73

2015-12-01	11:42:39	87.0	0	0.74
2015-12-01	11:42:40	87.0	0	0.74
2015-12-01	11:42:41	87.0	0	0.74
2015-12-01	11:42:42	87.0	0	0.74
2015-12-01	11:42:43	87.0	0	0.74
2015-12-01	11:42:44	87.0	0	0.73
2015-12-01	11:42:45	87.0	0	0.73
2015-12-01	11:42:46	87.0	0	0.73
2015-12-01	11:43:54	88.1	0	0.79
2015-12-01	11:43:55	88.1	0	0.80
2015-12-01	11:43:56	88.1	0	0.80
2015-12-01	11:43:57	88.1	0	0.80
2015-12-01	11:43:58	88.1	0	0.80
2015-12-01	11:43:59	88.1	0	0.80
2015-12-01	11:44:00	88.1	0	0.81
2015-12-01	11:44:01	88.1	0	0.81
2015-12-01	11:44:02	88.1	0	0.81
2015-12-01	11:44:03	88.1	0	0.81
2015-12-01	11:44:38	89.0	0	0.94
2015-12-01	11:44:39	89.0	0	0.94
2015-12-01	11:44:40	89.0	0	0.94
2015-12-01	11:44:41	89.0	0	0.94
2015-12-01	11:44:42	89.0	0	0.93
2015-12-01	11:44:43	89.0	0	0.93
2015-12-01	11:44:44	89.0	0	0.93
2015-12-01	11:44:45	89.0	0	0.93
2015-12-01	11:44:46	89.0	0	0.93
2015-12-01	11:44:47	89.1	0	0.93
2015-12-01	11:46:30	90.0	0	0.99
2015-12-01	11:46:31	90.0	0	0.99
2015-12-01	11:46:32	90.0	0	0.99
2015-12-01	11:46:33	90.0	0	0.99
2015-12-01	11:46:34	90.0	0	0.99
2015-12-01	11:46:35	90.0	0	0.99
2015-12-01	11:46:36	90.0	0	0.99
2015-12-01	11:46:37	90.0	0	0.99
2015-12-01	11:46:38	90.0	0	0.99
2015-12-01	11:46:39	90.0	0	0.99
2015-12-01	11:47:04	91.1	0	1.07
2015-12-01	11:47:05	91.1	0	1.07

2015-12-01	11:47:06	91.1	0	1.07
2015-12-01	11:47:07	91.1	0	1.08
2015-12-01	11:47:08	91.1	0	1.08
2015-12-01	11:47:09	91.1	0	1.08
2015-12-01	11:47:10	91.1	0	1.08
2015-12-01	11:47:11	91.1	0	1.08
2015-12-01	11:47:12	91.1	0	1.08
2015-12-01	11:47:13	91.1	0	1.08
2015-12-01	11:47:29	92.0	0	1.10
2015-12-01	11:47:30	92.0	0	1.11
2015-12-01	11:47:31	92.0	0	1.11
2015-12-01	11:47:32	92.0	0	1.12
2015-12-01	11:47:33	92.1	0	1.13
2015-12-01	11:47:34	92.1	0	1.13
2015-12-01	11:47:35	92.0	0	1.14
2015-12-01	11:47:36	92.0	0	1.14
2015-12-01	11:47:37	92.0	0	1.15
2015-12-01	11:47:38	92.0	0	1.15
2015-12-01	11:48:18	93.0	0	1.21
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2015-12-01	11:48:22	93.0	0	1.21
2015-12-01	11:48:23	93.0	0	1.21
2015-12-01	11:48:24	93.0	0	1.21
2015-12-01	11:48:25	93.0	0	1.21
2015-12-01	11:48:26	93.0	0	1.21
2015-12-01	11:48:27	93.0	0	1.21
2015-12-01	11:48:52	94.1	0	1.22
2015-12-01	11:48:53	94.1	0	1.22
2015-12-01	11:48:54	94.0	0	1.22
2015-12-01	11:48:55	94.1	0	1.22
2015-12-01	11:48:56	94.1	0	1.22
2015-12-01	11:48:57	94.1	0	1.22
2015-12-01	11:48:58	94.1	0	1.22
2015-12-01	11:48:59	94.1	0	1.22
2015-12-01	11:49:00	94.1	0	1.22
2015-12-01	11:49:01	94.1	0	1.23
2015-12-01	11:49:24	95.0	0	1.24
2015-12-01	11:49:25	95.0	0	1.24

2015-12-01	11:49:26	95.1	0	1.25
2015-12-01	11:49:27	95.1	0	1.25
2015-12-01	11:49:28	95.1	0	1.25
2015-12-01	11:49:29	95.1	0	1.25
2015-12-01	11:49:30	95.1	0	1.25
2015-12-01	11:49:31	95.1	0	1.25
2015-12-01	11:49:32	95.1	0	1.25
2015-12-01	11:49:33	95.0	0	1.24
2015-12-01	11:49:55	96.0	0	1.25
2015-12-01	11:49:56	96.0	0	1.25
2015-12-01	11:49:57	96.0	0	1.25
2015-12-01	11:49:58	96.0	0	1.25
2015-12-01	11:49:59	96.0	0	1.25
2015-12-01	11:50:00	96.0	0	1.25
2015-12-01	11:50:01	96.0	0	1.25
2015-12-01	11:50:02	96.0	0	1.25
2015-12-01	11:50:03	96.0	0	1.25
2015-12-01	11:50:04	96.0	0	1.25
2015-12-01	11:50:35	97.0	0	1.27
2015-12-01	11:50:36	97.1	0	1.27
2015-12-01	11:50:37	97.0	0	1.27
2015-12-01	11:50:38	97.0	0	1.27
2015-12-01	11:50:39	97.1	0	1.27
2015-12-01	11:50:40	97.1	0	1.27
2015-12-01	11:50:41	97.1	0	1.28
2015-12-01	11:50:42	97.1	0	1.27
2015-12-01	11:50:43	97.1	0	1.27
2015-12-01	11:50:44	97.1	0	1.27
2015-12-01	11:51:17	98.1	0	1.25
2015-12-01	11:51:18	98.1	0	1.26
2015-12-01	11:51:19	98.1	0	1.26
2015-12-01	11:51:20	98.1	0	1.26
2015-12-01	11:51:21	98.1	0	1.25
2015-12-01	11:51:22	98.1	0	1.25
2015-12-01	11:51:23	98.0	0	1.26
2015-12-01	11:51:24	98.0	0	1.26
2015-12-01	11:51:25	98.0	0	1.26
2015-12-01	11:51:26	98.0	0	1.26
2015-12-01	11:52:02	99.1	0	1.29
2015-12-01	11:52:03	99.1	0	1.29

2015-12-01	11:52:04	99.1	0	1.29
2015-12-01	11:52:05	99.1	0	1.29
2015-12-01	11:52:06	99.1	0	1.29
2015-12-01	11:52:07	99.1	0	1.29
2015-12-01	11:52:08	99.1	0	1.29
2015-12-01	11:52:09	99.1	0	1.29
2015-12-01	11:52:10	99.1	0	1.28
2015-12-01	11:52:11	99.1	0	1.28
2015-12-01	11:52:39	100.0	0	1.38
2015-12-01	11:52:40	100.0	0	1.39
2015-12-01	11:52:41	100.0	0	1.39
2015-12-01	11:52:42	100.0	0	1.39
2015-12-01	11:52:43	100.0	0	1.40
2015-12-01	11:52:44	100.0	0	1.40
2015-12-01	11:52:45	100.0	0	1.40
2015-12-01	11:52:46	100.0	0	1.40
2015-12-01	11:52:47	100.0	0	1.40
2015-12-01	11:52:48	100.0	0	1.40

Table E2. $\delta^{18}\text{O}\text{-O}_2$ isotope ratio mass spectrometry (IRMS) measurements for south basin of Lake Untersee.

Sample ID	$\delta^{18}\text{O}\text{-O}_2$	Depth (m)
SB 5	6.3	5
SB 20	5.3	20
SB 30	5.4	30
SB 40	4.9	40
SB 50	6.1	50
AB 60	-3.5	60
AB 70	0.7	70

Table E3. O₂/Ar, Ar/Ar_{asw} and O₂/O_{2asw} membrane inlet mass spectrometry (MIMS) measurements for south basin of Lake Untersee.

Station	Depth (m)	Replicate	O ₂ /Ar	Ar/Ar _{asw}	O ₂ /O _{2asw}
SB	5	B	19.3	157.9	149.2
SB	5	C	19.4	159.6	151.4
SB	25	A	19.3	156.2	147.7
SB	25	B	19.3	161.8	152.9
SB	50	A	18.8	155.4	143.1
SB	60	A	18.5	161.4	145.9
SB	60	B	18.7	165.7	151.0
SB	60	C	18.6	164.5	149.3
SB	62.5	A	18.5	165.9	150.0
SB	62.5	B	18.5	157.8	142.9
SB	65	A	18.3	163.5	146.3
SB	65	B	18.3	167.3	149.8
SB	65	C	18.4	161.5	145.0
SB	67.5	A	17.8	164.9	143.2
SB	67.5	B	17.6	157.7	135.4
SB	70	A	15.8	163.9	126.6
SB	70	B	15.9	163.5	126.7
SB	72.5	A	10.2	164.3	81.5
SB	72.5	B	10.3	164.3	83.1
SB	72.5	C	10.3	163.8	82.6
SB	75	A	0.3	184.6	3.1
SB	77.5	A	0.4	185.8	3.6
SB	77.5	B	0.3	191.5	2.5
SB	80	A	1.2	193.5	11.3
SB	80	B	0.2	199.2	1.6

Table E4. O₂/Ar isotope ratio mass spectrometry (IRMS) measurements for south basin of Lake Untersee

Sample ID	Average of O₂/Ar	Depth (m)
5-AH	19.1	5.0
50-AH	19.0	50.0
60-AH	18.3	60.0
62.5-AH	18.5	62.5
65-AH	18.4	65.0
67.5-AH	17.8	67.5
70-AH	11.9	70.0
72.5-AH	11.6	72.5
75-AH	3.1	75.0
77.5-AH	3.0	77.5
80-AH	3.1	80.0
90-AH	1.5	90.0
95-AH	1.9	95.0
98-AH	1.1	98.0