



Unlocking varve details: high-resolution sampling via freeze-melt technique

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Abstract Sediment archives, and especially annually laminated sediments, can provide valuable records of past climate and environmental change. However, the extraction of high-resolution sub-millimetre (seasonal to annual) and uncontaminated discrete subsamples from fresh sediment cores has proven difficult, time-consuming and labour-intensive. Obtaining such samples is essential for determining the relationship between measurable sediment proxies and specific climate variables, as well as for the quantification of paleoproxies. In this technical note we present a freeze-melt technique for a high-resolution subsampling of sediment sequences. This method is based on freezing and melting of fresh sediments to obtain very thin discrete subsamples. We

provide details of the method and application examples using two case studies (^{10}Be , ^{137}Cs) with clastic-biogenic varves from lakes Nautajärvi and Ristijärvi in Finland. We discuss the potential advantages of the method, as well as risks and limitations that need to be considered.

Keywords Sediment · Varves · Subsampling · High-resolution · Finland

Introduction

Lake sediments offer continuous paleorecords of climate and environment change over thousands of years (Sabatier et al. 2017; Lapointe et al. 2020; Martin-Puertas et al. 2023; Zander et al. 2024). Sedimentary archives with varved (annually laminated) sediments are particularly attractive, as they enable studies at the highest possible resolution, with calendar-year chronologies and precise calculations of sediment accumulation rates (Ojala et al. 2012; Zolitschka et al. 2015). However, the study of varved sequences requires meticulous and high-resolution subsampling, which is technically challenging, especially when aiming for annual or even seasonal resolution. Typical varves are 0.5–1.0 mm thick and composed of 2–4 seasonal laminae, although the characteristics and thickness of varved records vary greatly in both marine and lacustrine environments worldwide (Zolitschka

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et al. 2015; Schimmelmann et al. 2016). The typical sub-millimetre thickness of varves sets a critical benchmark for the requirements of high-resolution slicing and sediment subsampling, in order to obtain annually or seasonally resolved discrete subsamples for reconstructions. The same applies to non-laminated undisturbed sedimentary records, even though discernible seasonal deposits are not visually identifiable.

The ability to carry out high-resolution subsampling of lacustrine sedimentary records on sub-annual to annual scales is particularly important for several reasons. First, there is a growing need for seasonally resolved paleoclimate reconstructions of the Holocene and earlier periods. These reconstructions aim not only to capture annual to decadal averages, but also to identify seasonal changes in temperature and precipitation through different time-scales. Such high-resolution records remain relatively rare in paleoclimatology, particularly those that provide information for multiple seasons, such as certain varved sequences (Swierczynski et al. 2012; Zolitschka et al. 2015). Second, the current climate is changing rapidly, and extreme events are occurring more frequently worldwide, significantly impacting lacustrine environments and ecosystems (Hughen et al. 2000; Smol et al. 2005; Lapointe et al. 2012; King et al. 2024). High-resolution paleoproxies are essential for providing natural analogues, revealing modes of climate variability, and understanding the rapidity and magnitude of climate change and extreme events, such as heat waves, storms, floods and droughts, as well as their consequences in the context of ongoing global warming (e.g. Lapointe et al. 2024; Schmitt et al. 2025). Third, the calibration of paleoproxies remains one of the key challenges in current paleoclimate research. Adequate subsampling resolution is necessary to calibrate sedimentary paleoproxy records against instrumental observations, such as temperature, ice cover time, precipitation and run-off (Amann et al. 2014; Van Wyk de Vries et al. 2023).

Considerable efforts have been made in the past to develop and improve sampling and subsampling procedures of sedimentary records for paleoclimate and environmental reconstructions (e.g. Von Gunten et al. 2012). These include the sampling of sediment sequences with aluminium or plastic trays for sediment epoxy embedding with freeze-drying or

acetone-epoxy exchange methods (Merkt 1971; Clark 1988; Lamoureux 1994). Numerous techniques have been developed to acquire continuous high-resolution data from embedded sediment blocks or the surfaces of fresh and levelled sediment cores. These techniques include X-ray radiography, digital image analysis, and scanning electron microscopy (SEM), all of which are used to generate quantitative and semi-quantitative paleoproxies (Francus et al. 2002; Ojala and Alenius 2005; Lapointe et al. 2012). Modern techniques also employ visible-spectrum scanning reflectance spectroscopy (VIS-RS) (Von Gunten et al. 2009; Butz et al. 2015), hyperspectral imaging (Schneider et al. 2018; Zander et al. 2021), micro-computed tomography (μ CT) (Martini et al. 2024; Jamba et al. 2025), and micro X-ray fluorescence (μ XRF) (Martin-Puertas et al. 2012; Lapointe et al. 2020; Lapointe et al. 2024; Lincoln et al. 2025), all of which enable the examination of very small sample areas. Nevertheless, many paleoproxies—such as stable isotope ratios, biomarkers (e.g. alkenones), tephra layers, and biological indicators including pollen, diatoms, and chironomids—still require discrete physical subsampling. For multiproxy reconstructions to be effective, it is essential that the sampling resolution for these proxies is closely matched. Coordinated subsampling protocols ensure that proxies can be directly compared within a consistent chronological framework, thereby maximizing the interpretative power of multiproxy datasets and enabling robust reconstructions of seasonal to interannual variability in past climates.

In this short note, we provide details of a high-resolution subsampling procedure, referred to as the *freeze-melt technique*, which we developed for sampling the Nautajärvi and Ristijärvi sequences with seasonal to annual resolution for sediment ^{137}Cs and ^{10}Be contents. These lakes are located in southern boreal zone in central southern Finland and contain clastic-biogenic varves (e.g. Zolitschka et al. 2015; Ojala and Alenius 2005). For Ristijärvi, we focus on the uppermost 20 cm of the sequence, where the varves are typically 1–2 mm thick. As a case study, we use an annually resolved ^{137}Cs concentration record from the Ristijärvi sequence covering the period AD 1980–1992, which includes the AD 1986 Chernobyl nuclear accident, to demonstrate the data quality using the presently described freeze-melt technique. For Nautajärvi our subsampling targets a

section varve-dated to AD 720–820, where the varves are 0.6–0.8 mm thick (Ojala and Alenius 2005). This segment of the Nautajärvi sequence was selected for ^{10}Be analysis to assess the potential of varves as archives of high-energy solar events, such as solar proton events (SPEs) or solar flares. The targeted interval includes the year 774 CE, which is associated with the most intense solar proton event of the last two millennia, as inferred from cosmogenic isotope anomalies in tree rings and polar ice cores (Büntgen et al. 2018). Although the processing and analysis of the ^{10}Be samples are currently underway—given the time-consuming nature of these measurements—this study focuses solely on the sampling and high-resolution subsampling methodology of the Nautajärvi sequence in preparation for future ^{10}Be -based investigations.

The purpose of this note is to describe the freeze-melt technique and share our trial and error experiences and viewpoints of the method. The original idea of this method arises from the ice-core community, where melting of ice-cores for isotopic studies is a standard procedure (Jouzel et al. 1997). Here, we discuss pros and cons of the sediment freeze-melt technique and provide considerations of its strengths and potential shortcomings as a high-resolution subsampling procedure for other paleolimnologists to apply and develop further.

Freeze-melt technique—a new method

The freeze-melt technique consists of four main phases, which are described in the following (Fig. 1). In our case studies, sediment cores from Nautajärvi were collected in spring 2023 using a heavy gravity piston corer (PP-piston corer) developed by the Geological Survey of Finland (Putkinen and Saarelainen 1998), while cores from Ristijärvi were obtained in spring 2025 using a Kajak surface sediment sampler.

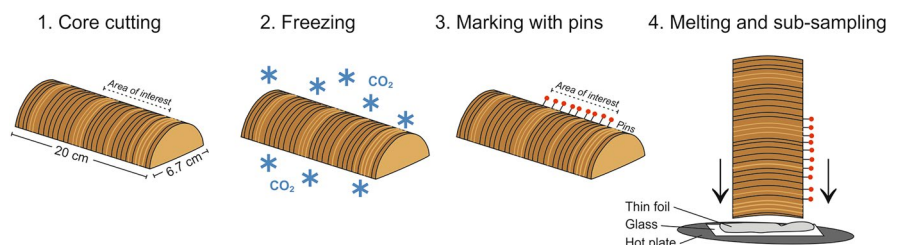
Both coring methods are capable of retrieving undisturbed sequences of fresh sediment in which clastic-biogenic varves remain intact, non-bent and in-situ, lying perpendicular to the core liner (Fig. 1). It is worth noting that the freeze-melt technique can also be applied to freeze-cores (Renberg 1981), in which case the first two phases of the sample treatment procedure can be skipped.

Phase 1: Core cutting

The first phase of the method involves cutting a sediment section from the core for subsampling the area of interest (Fig. 1). We initially tested the removal of sediment slabs using plastic (and aluminium) trays (1.6×4×15 cm) following the method described in detail by Lamoureux (1994). Removal of trays pushed into the sediment can be done with the ‘cheese cutter’ style tool as described by e.g. Francus and Cosby (2001). While this approach proved convenient, the limited dimensions of the trays restricted the amount of dry sediment recoverable when subsampling at sub-millimetre resolution. To increase dry sediment mass for analysis, we opted to use a split core half (inner diameter 5.6 cm), which was cut into a ca. 20 cm long section around the 5–10 cm long area of interest. After removal, it is essential to carefully clean the surface of the sediment slab or core half prior to freezing (phase 2) to clearly visualize the laminae that will be crucial for phase 3 (marking with pins) and to make sure that laminae (varves) lie horizontally and perpendicular to the slab direction.

We tested this sampling phase in two ways; first, by leaving the sediment slab inside the core liner (half) and second, by carefully removing the half cylinder-shaped sediment slab from the core liner prior to freezing. In our experience, removing the plastic liner before freezing minimizes the formation of significant cracks on the sediment surface, likely because it allows ice crystals to

Fig. 1 Schematic illustration of the four main phases of the freeze-melt technique for high-resolution subsampling of fresh, soft sediment sequences at seasonal to annual resolution



expand more evenly in all directions. For loose and highly water-saturated sediments, which is usually the case with surface sediment samples, we recommend starting the freezing procedure with the plastic liner to prevent any deformation by collapsing, and remove the plastic liner at latest soon after sediment surface is frozen.

The sampled half cylinder-shaped fresh sediment slab was then loosely covered with plastic wrap from below and above before being placed into the freezing container. To ensure that the sample freezes on a flat surface, we also placed it on a rigid and thin cardboard.

Phase 2: Freezing

In the second phase, we used dry ice to snap-freeze the slab of fresh sediment. Dry ice is a solid form of CO₂ that sublimates at −78.5 °C at atmospheric pressure, thus enabling rapid and effective freezing of the sediment while causing minimal structural damage to the laminae (Lotter and Lemcke 1999). The freezing was carried out in an insulated container by covering the sediment slab with dry ice in all directions. In our setup, we found that 30–40 min was sufficient to completely freeze a half-cylinder-shaped sediment slab (length: 20 cm; diameter: 5.6 cm; radius: 2.8 cm) in preparation for the subsequent steps of the method. Some studies have used liquid nitrogen to shock-freeze fresh sediments, which promotes the formation of small cubic ice crystals, but may lead to cracking of sediment structures (Boës and Fagel 2005; Normandeau et al. 2019). It is important to note that complete freezing of the sediment and reaching the desired temperature depend on both sample size and composition as well as on the cooling temperature, as discussed in aforementioned studies.

We also recommend a thorough cleaning of the sediment slab surfaces after freezing to avoid contamination with older or younger sediment. This can be achieved by carefully scraping the frozen sediment surface on all sides of the slab with a scalpel until a clean, undisturbed surface is exposed – this process requires several repetitions. In the case of varved or laminated sediments, the presence of a clearly visible laminae structure

serves as an important verification of the slab's quality for a successful and high-resolution subsampling.

Phase 3: Marking with pins

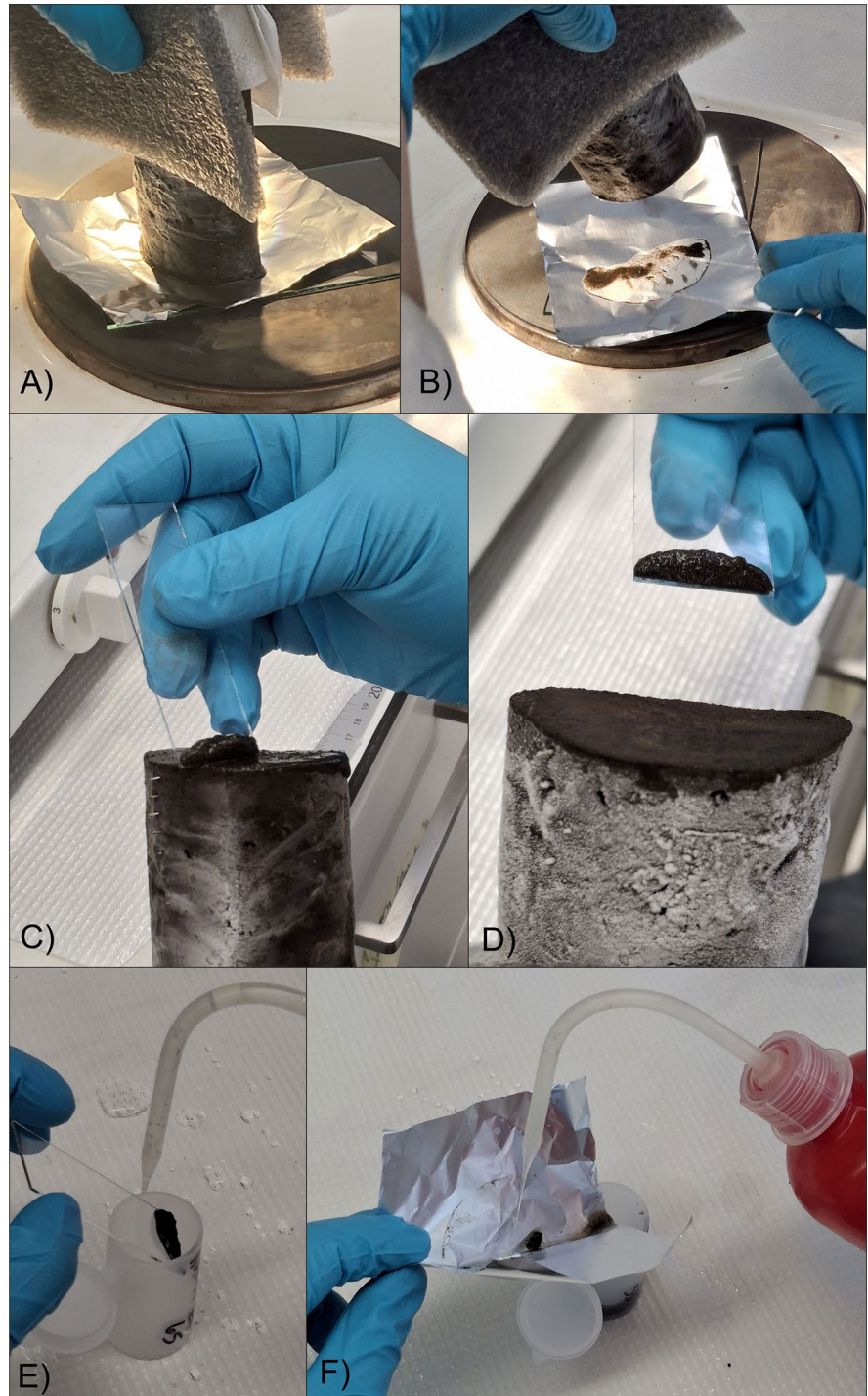
Since the surface of a frozen sample is easily obscured by white frost when removed from freezing temperature (see Fig. 2D), we recommend using marker pins to guide through the melting and subsampling procedure (phase 4). Pins can be placed at regular intervals or aligned according to certain marker horizons within the area of interest. Marker horizons should be anchored to varve chronology and characteristics (Fig. 1). Even in clastic-biogenic varves with clear marker laminae at every 1–3 cm intervals (Tiljander et al. 2002; Ojala and Tiljander 2003; Ojala and Aleenius 2005), we found it challenging to visually detect sediment structures on the frozen slab during freezing and melting cycles. Therefore, marker pins proved especially useful for maintaining orientation and precision throughout the process. In our two case studies, we placed pins at 10-varve intervals (approximately 6 mm) for subsampling the Nautajärvi sequence, and at 3-varve intervals (approximately 3–4 mm) for subsampling the Ristijärvi sequence. In the Nautajärvi case, we aimed at extracting 10 subsamples between each pair of marker pins to achieve annual resolution. For the Ristijärvi sequence, we similarly targeted annual resolution for our ¹³⁷Cs fallout analysis extracting three subsamples between each marker pins.

After inserting the pins into the frozen sediment at the planned intervals, we cut the spherical plastic heads of each pin using pliers before proceeding to heating and subsampling steps (Fig. 2C). This was done to prevent plastic from melting during the heating of the sediment from below and to ensure that the slab remained strictly horizontal throughout the sampling procedure. To ensure the horizontal melting of the desired laminae, the pins can be placed on both sides of the sample to have better control on the sampling procedure.

Phase 4: Melting and subsampling

The final step of the procedure is the most critical phase of the freeze-melt technique, for which all preceding steps are preparatory. A step-by-step visual

Fig. 2 Phase 4 (melting and subsampling) of the freeze-melt technique applied to high-resolution subsampling of varved sediment from Nautajärvi. Different steps of the method include: **A** and **B** melting of the frozen sediment slab, **C** and **D** scraping a thin 0.6 mm layer of sediment from the melted surface, and **E** and **F** rinsing the collected subsample into a container



guide to the phase 4 is provided in Fig. 2. For melting and high-resolution subsampling, we used a setup in which a hot plate was covered with a 3 mm thick glass plate and a layer of thin tin foil (Fig. 2A). During

sampling, the temperature at the surface of the glass plate was maintained at approximately 80 °C (lowest setting of our hot plate), allowing for the controlled melting of a thin layer of frozen sediment. At this

temperature, pressing the frozen sediment against the heated surface for about 2 s was sufficient to melt a layer approximately 0.5–0.7 mm thick (Fig. 2A, B). Based on our experience, we recommend maintaining the plate temperature between 60 and 80 °C to control the rate of melting effectively. Temperatures above 100 °C should be avoided, as they may lead to sublimation, which can disrupt sediment structures and increase the risk of contamination. We strongly advise conducting preliminary tests to determine optimal temperature settings before beginning subsampling of the target interval. The rate and extent of sample thawing are highly sensitive to both the size and the initial temperature of the frozen sediment. Improper temperature control can result in partial melting, distortion of lamination structures, or loss of fine stratigraphic detail—each of which can compromise the integrity of high-resolution subsampling. Therefore, careful optimization of thawing conditions is a critical preparatory step to ensure the preservation of the sediment structure and the reliability of subsequent analyses.

The melted layer of sediment was then scraped from the levelled bottom of the sample slab using either a microscope object glass slide or a scalpel (Fig. 2C, D). We found the object glass particularly convenient, as the scraped sediment tends to adhere to it, making it easier to transfer the subsample into a container using distilled water (Fig. 2E). Additionally, a portion of the melted subsample often accumulates on the tin foil during melting and can also be collected into the same container (Fig. 1F). To minimize the risk of contamination, we strongly recommend using fresh tin foil and a new glass slide for each individual subsample. Furthermore, we found that placing the sample in an insulating support during the subsampling process effectively prevented premature melting of the upper surface, thereby preserving the integrity of the stratigraphy as much as possible (Fig. 2A).

The amount of material that can be easily removed by scraping depends on several factors, including the hot plate temperature, the sample temperature, and the duration for which the sample slab is pressed against the heated glass plate. In our Nautajärvi example, we retrieved 8–10 subsamples between each pair of marker pins across the targeted area of interest in the sequence. This corresponds to sampling resolution of approximately 1–1.25 years or 0.6–0.75

mm per subsample. The variation between 8 and 10 subsamples per 6 mm interval primarily reflects differences in melting time, which proved challenging to control precisely for achieving a consistent 0.6 mm thickness per sample. At room temperature, we found it appropriate and effective to conduct subsampling in cycles, in which the frozen sample slab was returned to a cooling container with dry ice after each 6 mm subsampling interval, i.e. between two marker pins. This approach helps to prevent unwanted melting of the slab's exposed surfaces, which could lead to contamination through dripping or layer distortion. In our setup, each cycle of subsampling and re-freezing took approximately 15 min, 7–8 min for subsampling a 6 mm thick section by scaping and 7 min for re-cooling the sample, once routines were established for a two-person team. Based on this, and assuming parallel processing of 2–3 samples and efficient re-cooling management, we estimate that it is feasible to subsample approximately 6–7 cm of sediment at sub-millimetre resolution within one hour.

In our Nautajärvi example, using a half cylinder-shaped sediment slab, the following parameters were recorded: the surface area of the melted sediment slab was approximately 9 cm², and the thickness of melted layers 0.06 cm (or 0.075 cm in case of only 8 samples per 10 years). This resulted in a volume of about 0.54–0.67 cm³ for each subsample. For the period AD 720–820, the Nautajärvi sequence is characterised by an average water content of 79.6%, a loss-on-ignition (LOI) of 24.5%, and a wet bulk density of 1.18 g cm⁻³. Given these sediment properties and sampling volumes, we recovered an average of 0.14 g of dry sediment material per subsample.

Example—high-resolution ¹³⁷Cs analysis of the Ristijärvi sequence

We applied the same freeze-melt technique to the Ristijärvi sequence to pinpoint the exact location of the AD 1986 Chernobyl-derived ¹³⁷Cs fallout peak within varves. We targeted subsampling at annual resolution (ca. 1.0 mm) around the varve deposited in AD 1986 (area of interest AD 1980–1992) and compared the results with a 5–10 mm resolution subsampling conducted on fresh core samples spanning AD 1940–2023. All samples were freeze-dried prior

to analysis, and we used a fully digital BrightSpec bMCA-USB pulse height analyzer coupled to a well-type NaI(Tl) detector to analyse ^{137}Cs concentrations, expressed as Bq kg^{-1} of dried sediment (Ojala et al. 2017).

The distribution of ^{137}Cs in the Ristijärvi sequence for lower resolution fresh samples (5–10 mm) and for those obtained using the freeze-melt method (~1 mm) are presented in Fig. 3A and B, respectively. Both analyses show a clear and well-resolved peak value at a depth of approximately 10 cm. Aligned with the varve count, this peak represents the Chernobyl-derived high fallout in AD 1986 (Einola 2025). In the lower-resolution analysis (Fig. 3A), the peak appears in two samples representing the 10.0–10.5 cm and 9.5–10 cm depth intervals, both encompassing 5–6 varves. In the higher-resolution analysis, the

peak is confined to a single varve at 10.2 cm depth, although the samples directly above and below also show elevated values (Fig. 3B). These results demonstrate an accurate method for confirming the chronology of recent varves in the Ristijärvi sequence, especially when combined with the identification of a thicker layer of minerogenic sediments associated with a major ditching event in the inflow system in AD 1970 at 14 cm depth (Fig. 3B). The activity of the maximum fallout peak ranges from $68,000 \text{ Bq kg}^{-1}$ in the lower-resolution samples to $107,000 \text{ Bq kg}^{-1}$ in the higher-resolution samples. However, when calculating the average of the five highest values of high-resolution analysis—spanning the 9.8–10.4 cm interval—the maximum ^{137}Cs activity is very similar between both sampling strategies.

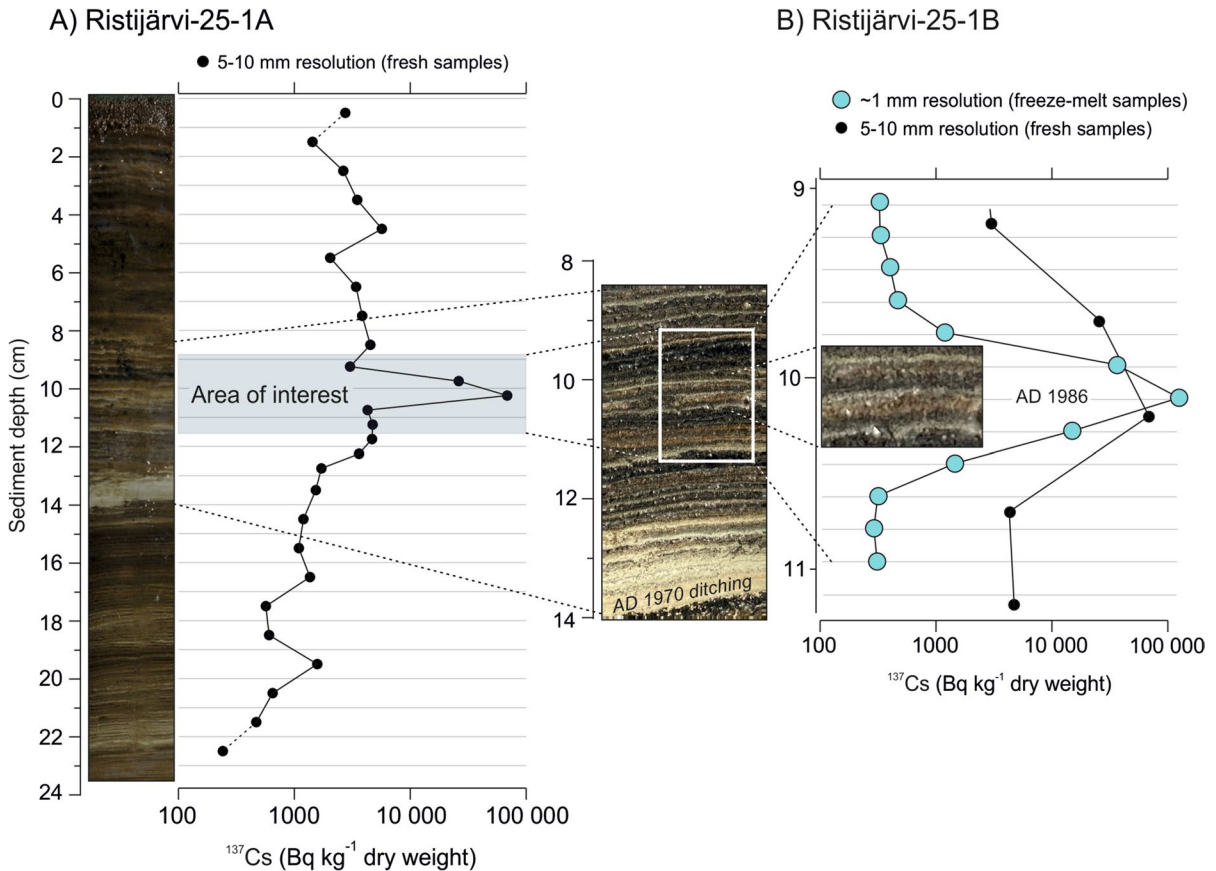


Fig. 3 Cesium-137 (^{137}Cs) concentrations (dry weight) in clastic-biogenic varved sediments of Ristijärvi. **A** Mass-normalized values from freeze-dried subsamples taken directly from a fresh sediment core and analysed at 5–10 mm reso-

lution. **B** Higher-resolution subsamples obtained using the freeze-melt technique around the AD 1986 peak (AD 1980–1992), analysed at approximately annual (~1 mm) resolution. Note that ^{137}Cs values are given with logarithmic scales

These results indicate that the freeze-melt technique enables ultra-high-resolution sampling at the annual scale in clastic-biogenic varves. We also note that such fine-resolution facilitates detailed studies of sedimentary processes affecting ^{137}Cs activity, such as post-Chernobyl catchment mobilization and redeposition, downward chemical diffusion, potential pore-water transfer mechanisms, and the tendency of cesium to bind to fine-grained mineral particles. These processes are frequently discussed when using radioactive ^{137}Cs as a tracer for dating sediments and investigating sedimentation dynamics, especially in high fallout regions (Klaminder et al. 2012; Ojala et al. 2017; Mouri 2020). Indeed, it remains uncertain whether the three samples with values exceeding $30,000 \text{ Bq kg}^{-1}$ in the high-resolution study of the Ristijärvi sequence (Fig. 3B) reflect these sedimentation processes involving ^{137}Cs within the basin or are the result of minor inaccuracies in the sampling procedure. The Ristijärvi lake basin is situated in the highest Chernobyl-derived ^{137}Cs fallout area in central southern Finland, and any mixing of the highest concentration varve of AD 1986 in upper or lower subsamples during the sampling procedure would influence their values.

Discussion and conclusions

Carefully conducted sampling and freezing phases are essential prerequisites for clean and high-resolution subsampling of sediment sequences. Disturbance structures formed during sampling, as well as cracking of sediment during freezing, are common sources of error and can significantly compromise the accuracy of subsampling. These issues often depend on sediment composition and water content, but can also result from abrupt and significant temperature changes during the freezing of fresh sediment. Such disturbances are relatively easy to detect in thinly laminated or varved sediments, where structural integrity is visually apparent. We recommend testing various sample sizes and freezing conditions to determine the most effective parameters for preserving the sediment structure and to achieve satisfactory results. For instance, in our trials, we left a 15 cm long half-cylinder of sediment overnight inside a plastic core liner (half) and at dry ice temperature. This resulted in substantial cracking

and disturbances through the sediments likely due to the prolonged exposure to low temperatures and/or the confinement within the core liner. Based on our experience, removing the sediment slab from the plastic liner before freezing yields significantly better results for high-resolution subsampling using the freeze-melt technique.

When sediment sampling and freezing (Phases 1 and 2) are successfully implemented, the maximum subsampling resolution that can be achieved depends largely on the thickness and quality of varves. In fact, the horizontal orientation of the varves and the sediment sample size and shape determine how accurately the sediment can be subsampled down to seasonal laminae or laminae couplets/triplets using the freeze-melt technique. In the case of varved sediments, especially when supported by marker pins (phase 3), it is relatively straightforward to visually confirm that the laminae remain perpendicular to the direction of the sediment slab throughout the subsampling procedure. However, for homogenous sediments lacking discernible marker layers, it may be impossible to ensure correct orientation of a sample slab, which can compromise the sampling resolution and accuracy. Typical inaccuracies in high-resolution subsampling of varved sediments with freeze-melt technique or any other method may arise under the following conditions: (i) varves have undulating or wavy surfaces, which can occur in complex or organic-rich varves (Zolitschka et al. 2015), (ii) the upper part of the sediment sequence contains a high water content and has undergone minimal compaction, (iii) the varve structure has become deformed or tilted toward the sides of the core liner during the coring process.

If varves and laminae within are significantly wavy or distinctly banded, we recommend subsampling using a (ceramic) scalpel, following the method described by Silvester (2024). This approach involves visually tracking and gently scraping down one seasonal lamina or varve at a time. While this method is considerably more time-consuming than the freeze-melt subsampling technique described in the present study, it allows to precisely follow varve and lamina boundaries throughout the procedure—provided that the seasonal laminae exhibit clear visual differences (e.g., in color or composition).

Our freezing and melting experiments with the 0.6–0.7 mm thick varves from the Nautajärvi

sequence highlight some of the challenges with high-resolution subsampling of finely laminated sediments. Even with careful marking of every tenth varve using pins, it remains difficult to consistently melt and scrape an evenly thick (0.6 mm) sediment layer across ten consecutive cycles. In the Nautajärvi interval of interest (AD 720–820), we ultimately obtained 8–10 subsamples representing one decade of sedimentation—approaching an annual subsampling resolution. Although these varves appeared visually very horizontal and perpendicular to frozen sediment slab, it must be acknowledged that each sample likely includes minor portions of both underlying and overlying varves. Even with ten subsamples per decade, complete separation of individual varves is difficult, and the mixing likely increase with increasing sample size. Based on our results, we estimate that following our setup each subsample is primarily composed of one varve. However, it is safe to assume that our sampling resolution is close to annual (1–1.25 years) and that each subsample contains parts of sediment from 2–3 consecutive years.

In the case Ristijärvi varves, we were able to subsample at a temporal resolution where each subsample was confined to a single varve. This enabled us to analyse sediment ^{137}Cs activity at an annual resolution, which can be used to confirm the annual nature of clastic-biogenic laminae couplets and to anchor the varve chronology of the upper sediment sequence (Zolitschka et al. 2015). In this case study, however, we felt that even extraction of seasonal laminae would have been possible using the freeze-melt method, as demonstrated by Silvester (2024) through scraping of frozen sediment.

This technique offers significant potential for extracting a wide range of parameters from varved sediments. It enables the analysis of grain-size, trace element concentrations, and, with ongoing improvements in analytical sensitivity, may even allow for the detection of extremely small amounts of organic material, such as DNA, potentially at annual resolution. Moreover, annual to sub-decadal subsampling facilitates proxy-to-proxy calibration, which can further enhance temporal resolution when combined with advanced analytical methods such as hyper-spectral imaging, $\mu\text{-CT}$ - and μXRF -scanning. These developments open the door to increasingly detailed

multiparameter reconstructions of past environmental and climatic conditions.

Finally, we strongly recommend testing and practicing each phases of this freeze-melt technique by sampling areas outside of the main zone of interest. The rate of freezing and melting can vary significantly, which likely depends on factors such as sediment composition, water content, sample size and temperature, as well as hot plate and freezing temperatures.

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Author contribution AO conceptualized the study and wrote the original draft. FL, EK and AO collected and analysed the data, prepared figures, interpreted the results and reviewed the manuscript.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

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