Journal of Field Archaeology

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/yjfa20

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To cite this article: Erlend Kirkeng Jørgensen, Vibeke Vandrup Martens, Dag-Øyvind Engtrø Solem & Erich Nau (2025) A Novel Protocol for Reconstructing Depositional Histories of Anthropogenic, Sedimentary Records: the Case of the Holocene-Deep Kirkhellaren Cave Deposits in Coastal Arctic Norway, Journal of Field Archaeology, 50:1, 60-80, DOI: 10.1080/00934690.2024.2426958

To link to this article: https://doi.org/10.1080/00934690.2024.2426958

Published online: 20 Jan 2025.

JOURNAL OF FIELD ARCHAEOLOGY
2025, VOL. 50, NO. 1, 60–80
https://doi.org/10.1080/00934690.2024.2426958

A Novel Protocol for Reconstructing Depositional Histories of Anthropogenic, Sedimentary Records: the Case of the Holocene-Deep Kirkhellaren Cave Deposits in Coastal Arctic Norway

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ABSTRACT
This paper presents a novel protocol for reconstructing formation processes of archaeological depositional sequences, applied to Holocene-wide cave deposits located on a remote coastal island in Arctic Norway as a case study. Extensive GPR surveying is correlated with geochemical analysis and in situ environmental deposit monitoring for sedimentary fingerprinting and forecasting of future preservation of organic remains. Subsurface deposit characteristics are integrated with a high-precision, laser-based 3D-reconstruction of the cave, enabling triangulation with historic photos and local informant knowledge that facilitate modeling and quantification of erosional history. The results showcase detrimental depletion of critical organic heritage, accelerated by the removal of protective surface layers after the A.D. 1930s. Critically, subsurface deposits are trending towards overshooting a threshold for accelerated in situ degradation. The results act as a direct validation of the methodology. Measures for future protection of similar archaeological deposits are discussed and an outline of the general applicability of the protocol.

ARTICLE HISTORY
Received 1 December 2023
Revised 9 August 2024
Accepted 12 August 2024

KEYWORDS
Erosion; formation processes; GPR; soil chemistry; cave archaeology; 3D-modeling; in situ environmental monitoring

Introduction

The erosion or depletion of cultural heritage is detrimental to the very objective of the historical sciences, particularly for archaeological deposits containing stratigraphic and contextual information. As anthropogenic soils form the archive for chronologically resolved and (occasionally) well-preserved assemblages of zoological, paleontological, and paleobotanical remains, they are becoming prime data sources for paleoecological research, acting as sedimentary archives of past ecosystem states in addition to their more traditional role in cultural history and archaeological research (Hambrecht et al. 2018; Martens et al. 2016). Any damage to intact anthropogenic strata or sequences therefore poses a threat of multi-disciplinary information loss.

In recognition of the extraordinary scientific information potential contained by archaeological deposits, a range of international heritage management regulations and national guidelines have been implemented to safeguard and preserve such deposits (Climate Change and Cultural Heritage Working Group International 2019). This is becoming increasingly urgent given the rapid and accelerating erosion and loss of deep time anthropogenic deposits due to development-induced pressures from human impacts planet-wide and the growing threat posed by climate change. The latter is most keenly felt in coastal and Arctic regions, where increased precipitation and storminess, relative sea level rise, and acceleration of permafrost thawing produce devastating coastal erosion (Blankholm 2009; Hollesen 2022; Hollesen et al. 2016, 2017, 2018; Nicu et al. 2020; Sesana et al. 2021). This is evident in instances of single storm events eroding large chunks of coastland around the Circumpolar region (Jensen 2017; Nicu et al. 2021; Nicu and Fatorić 2023). Erosion now occurs at a rate far surpassing the ability of the heritage management sector to document the loss of invaluable scientific information at archaeological sites. This is exacerbated by the frequent lack of precise and objective assessment of the state of preservation and stratigraphic intactness of remaining heritage deposits, obscuring the efficient evaluation of management policy development for future preservation action.

While ongoing climate change and its negative impacts on in situ organic preservation at wetland and frozen sites is increasingly brought to attention (Boethius et al. 2020; Hollesen et al. 2018; Matthiesen et al. 2022), the state of anthropogenic deposits in natural shelters is far less studied. This is further exacerbated by the apparent threat to future preservation of anthropogenic cave deposits posed by accelerated landscape erosion and deposit depletion in recent years—with examples and concerns now coming to the fore (Barbieri et al. 2021; Mattes 2016; Patania et al. 2022; Wojenka 2018). As we document in this paper, recent human interventions and economic changes pose the most active threat and erosional agent to such deposits after having been preserved for up to tens of thousands of years—calling for targeted mitigation. Yet the impact of modern landscape use, tourism, and climate changes, we argue, remains an underappreciated problem in archaeology given the knowledge gap of how recent human/climate

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Supplemental data for this article can be accessed online at https://doi.org/10.1080/00934690.2024.2426958.

induced erosional processes degrade anthropogenic deposits, spurred on by the lack of communal response, as well as no systematic and long-running monitoring of carefully selected indicator sites.

Here, we present a novel methodology for the purpose of reconstructing formation processes and erosional histories of anthropogenic, sedimentary records. Ongoing research at the Kirkhellaren ("Cathedral") cave on an oceanic island on the Arctic Circle, northern Norway, serves as a case study. The cave is an invaluable archaeological site, containing Holocene-wide anthropogenic deposits with organic preservation unmatched in the region and hosts a rich archaeological and faunal assemblage. We present the first assessment of the state of preservation, environmental conditions, and the impact of modern erosion at the site based on an analytical suite comprising in situ deposit monitoring and geophysical and geochemical analyses, including a ground-penetrating radar (GPR) survey, high-precision laser scanning, historic surface reconstruction, and local knowledge—supplemented by stratigraphic evidence from excavation. The results demonstrate severe erosion of almost the entire internal floor area, estimated to an astounding 411 m^3 during the last 100–120 years, with loss rates accelerating throughout the post-war period. We map the distribution and scale of the erosion and discuss potential causes, as well as the consequences for in situ preservation of organic remains and stratigraphic information.

In providing an innovative, multi-component protocol as a first attempt to mitigate and quantify deposit degradation, we suggest that the methodology presented here has transferable potential to a wide range of international sites and settings, aiding in more precise mapping, monitoring, and future protection of archaeological deposits. As such, it is our ambition that the results produced from systematic application of this analytical protocol may inform and help cultural heritage management with tools and data for long-term deposit preservation. Beyond presenting the methodology applied to the Kirkhellaren site as a case study, the results are evaluated for upscaling and general application. Identified and potential limitations of the methodology are discussed.

Background

The Kirkhellaren cave is located on Sanna in the archipelago of Træna municipality, one of the most remote islands off the Norwegian coast, exactly intersected by the Arctic Circle (Figure 1). Despite its small size (3 km^2 surface area), Sanna is a rare archaeological hotspot, containing an almost complete Holocene sequence of heritage remains. The island is best known for the Kirkhellaren cave, yet this is only one of 17 caves and rockshelters, of which many contain known archaeological records. In addition, the island contains rich Medieval human osteological material and house remains dating from the middle Mesolithic (9000 CAL B.P.) to the Medieval period, as well as cairns, Medieval farm mounds, and historic boat houses. The Kirkhellaren cave figures as a top-tier national archaeological heritage site in Norway given the spectacular record of well-preserved faunal remains and bone tools from the Mesolithic through to the Bronze Age—possibly the richest Bronze and Iron Age pottery assemblage in northern Norway—and a total of 33 fully preserved Medieval individuals buried in various grave constellations inside the cave. The fact that three mass graves are located on the island, one of which is inside the cave, has contributed to the legendary status of the island. The complete human osteological material comprises 60 individuals, all of whom probably date from the 13th century A.D., with the Black Death pandemic being the suspected cause (Gjessing 1943, 157; Holberg 2015, 216; Johansen, Gulliksen, and Nydal 1986). The cave continues to be of importance to the present day, much in line with the various modern uses of caves (cf. Peša 2013).

Prior archaeological investigations on the island have primarily been limited to the campaign of Gutorm Gjessing´s between A.D. 1937 and 1939, who surveyed and, to a large extent, excavated the abovementioned sites and graves (Gjessing 1943). The Kirkhellaren cave was the primary object of investigation during this campaign, completely excavating 250–300 m^2 of the 674 m^2 internal floor area. Methods and documentation standards of the time do not allow reliable reconstruction of the cave stratigraphy or chronology. However, typological evidence from the original excavation, combined with radiocarbon dates from the ceramic assemblage (Jørgensen et al. 2023; Pääkkönen et al. 2018) and semi-subterranean house remains in the Hellarvikkja Bay just outside the cave (Storvik 2008), showcase what is at least a 9000 year deep sequence of site use. Detailed analyses of the complete lithic inventory of the island demonstrate the lack of Early Mesolithic (11,700–10,000 CAL B.P.) tool types (Eigeland 2023). This corresponds well with shoreline displacement models, setting a maximum habitable age of 10,500 CAL B.P. anywhere on the island. This time constraint is based on currently low-resolution extrapolation in the SeaLev program (https://www.tgo.uit.no/sealev/), given the lack of local isostacy studies. Coring of local bogs and lakes was conducted in October 2023 to improve the shoreline displacement data of the outer coast of the Helgeland region—results are pending.

New investigations are currently being carried out through the Norwegian Institute for Cultural Heritage Research (NIKU) project "ARCAVE: constructing baselines of coastal ecosystem change from Archaeological CAVE deposits," which aims to provide a firm understanding of chronology, stratigraphy, sedimentology, and formation processes, as well as the faunal and archaeological records of the cave. The aim of the project is to showcase the potential role of archaeological cave deposits as an archive for multidisciplinary research into deep-time human/environmental interactions and past ecosystem reconstruction.

The formation processes occurring at natural shelters such as caves and rockshelters consist of a variation of autochthonous (internal) and allochthonous (external) geogenic sedimentation, which may include local collapse and weathering of wall/roof bedrock, as well as aeolian input of weathered material from the cave exterior. Additionally, biogenic deposits form and intermix with geogenic deposits through resident/visiting populations of various species (rodents/birds/bats/domesticates/soil organisms). Varying degrees of anthropogenic inputs follow in the case of human use and occupation of the site. Humans also form a powerful turbation and erosional agent of cave deposits. The dynamic combination of these sedimentary processes through time are critical for evaluating the stratigraphic integrity and developing robust interpretations of human occupation histories (Farrand 2001; Hunt et al. 2015; Inglis et al. 2018; Karkanas et al. 2021). Yet the potential for such multi-disciplinary gains to be had from anthropogenic deposits fundamentally

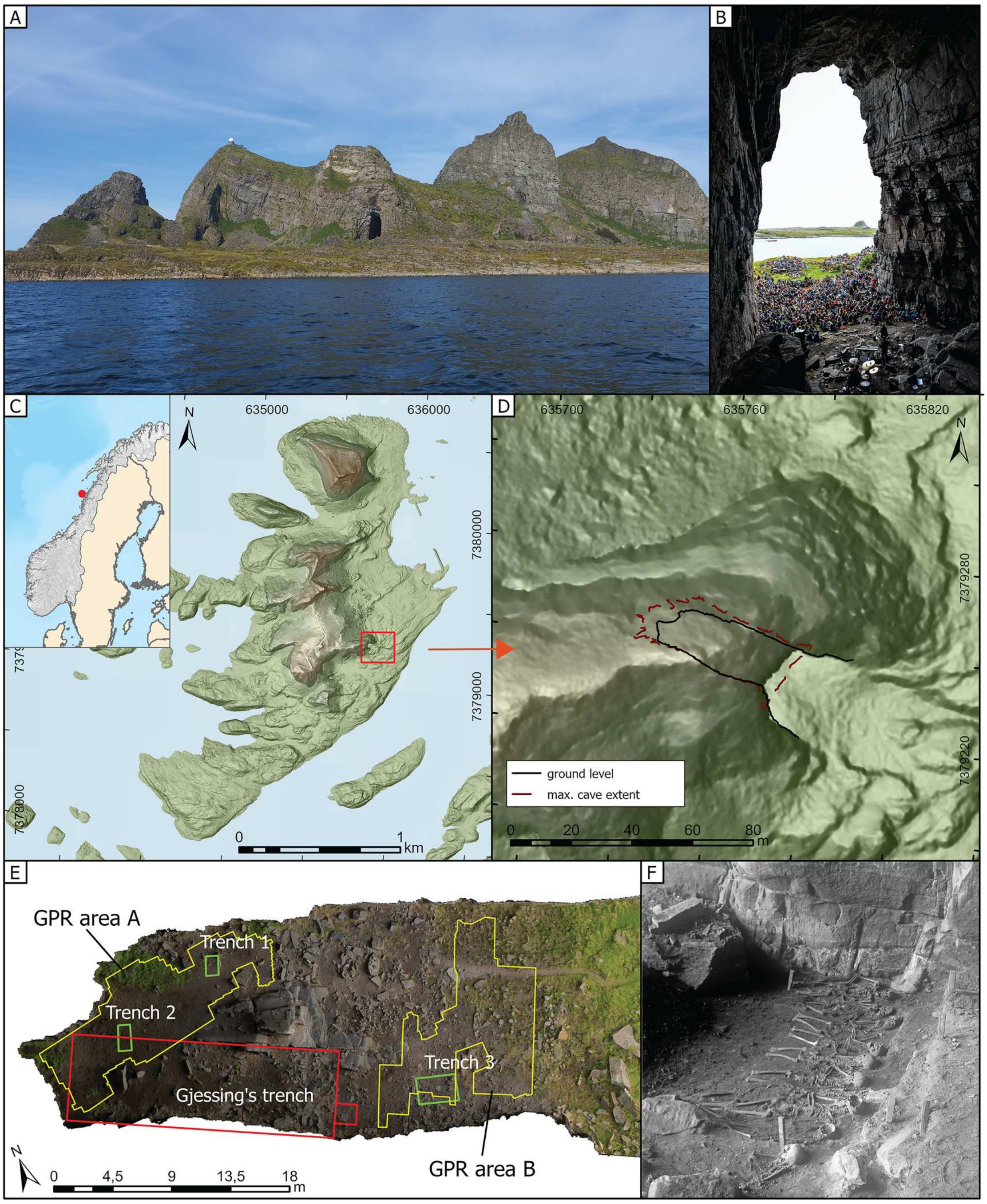

Figure 1. A) The island of Sanna seen from the southeast. The entrance of the Kirkhellaren cave is clearly visible in the center of the photo (photo credit, Erlend Kirkeng Jørgensen). B) Concert in the Kirkhellaren cave during the Træna festival 2022 (photo credit, Tim Patrick). C) DTM of the island of Sanna. D) Detailed DTM with the location and extent of the Kirkhellaren cave. E) Orthoimage of the cave floor and location of Gjessing's excavation trench from A.D. 1937–1939 and the three smaller 2021–2022 excavation trenches of the ARCAVE project, placed within the GPR survey areas. F) Picture of the excavation of one of the mass graves in A.D. 1937.

relies on the intact and continued preservation of stratified, organic archives.

The seldom rivaled quality of anthropogenic deposits contained by caves and rockshelters are of particular interdisciplinary scientific value and have, since the infancy of the archaeological discipline, facilitated fundamental knowledge of non-lithic technologies in deep time. Acting as sediment traps and protected from the elements, caves and rockshelters are unique in the sense of consistently accumulating and preserving debris from occupational events. The accumulation of such debris over time and from events can result in fine-grained stratigraphies representing time-series data whose information value can be unsurpassed to the historical sciences. However, the often nutrient-rich and fine-grained sediments deposited in caves and rockshelters are also widely recognized as excellent fertilizers. While in direct conflict with the heritage and scientific interest in archaeological deposits, the practice of stripping soil from such sites has a long history. This practice is well-documented in central Europe, where it took on an industrial scale in the form of "guano mining" in Poland and Germany throughout the 19th century A.D. (Wojenka 2018), as well as Austria. The latter was instigated by the collapse of artificial fertilizer supply chains during the First World War, with similar attempts reinitiated during the Second World War (Mattes 2016, 293).

Although modern depletion of cave deposits is known from cases such as the above, the global impact is poorly understood. Locally in Norway, depletion of anthropogenic cave and rockshelter deposits has been altogether overlooked, while alarming reports of damage and loss of natural heritage cave ecosystems have been presented (Lauritzen 1991). While possibly being the most renowned cave site in Norway, potential erosion of the Kirkhellaren deposits has never been formally considered or investigated. In fact, the lead excavator of the A.D. 1930s campaign, Gjessing, noted that the archaeological deposits were covered by a thick layer of sheep dung 100 cm thick at the front and gradually decreasing towards the back, where it was reported to be "very thin," although generally about 50 cm thick throughout the floor area (Gjessing 1943, 26).

While Gjessing noted that considerable quantities of manure had been extracted, with "numerous barge loads having been removed and sold as fertilizer," he assumed that this did not significantly reduce the extent of the sheep dung layer, as it was constantly replenished by the continued use of the cave as a sheep pen and shelter (Gjessing 1943, 25). The archaeological deposits were therefore thought to be well protected. More recent test pits were made in the north-central section of the cave in 1973 and uncovered "extensive sheep dung" on the surface (K. Helskog, personal communication 2023).

The potential erosion or depletion of the site has remained unknown to the county heritage management authorities (T. Johnson, personal communication 2023), who issue annual permits to a local festival hosting concerts in the cave (Figure 1B). The site is a popular tourist destination in the region, and during the summer holiday season of 2021, our excavation crew received up to 200 visitors per day. In the spring of 2022, cruise ships began docking at the archipelago and will continue to make regular visits to the site. For evidence-based management of the site and preservation of scientific information, there is a great need to assess the current state of deposits and in situ preservation conditions. If erosion is detected, it is necessary to 1) determine the extent, age, and causes of erosion and 2) determine the implications for the preservation of the soil and its organic components for future conservation.

Methods

To develop and field-test a robust methodology for integrated monitoring and mapping of archaeological deposits, we devised a protocol consisting of the following elements.

Ground penetrating radar

A GPR survey was conducted in Kirkhellaren cave with the main objectives to identify areas suitable for subsequent excavation, looking for deep pockets of fine-grained sediments that could be excavated in smaller trenches and, crucially, to avoid being blocked by large roof spall. Data collection was carried out using a cart-mounted Sensors & Software Noggin 500 GPR system with a center frequency of 500 MHz. The GPR profile data were obtained using a zig-zag acquisition mode along predetermined parallel lines, surveyed using a total station. The profile data were collected with a crossline spacing of 25 cm and an inline trace interval of 2.5 cm. The time window for data collection was set to 70 ns. An extensive GPR survey was conducted of the interior floor area of the cave, measuring a total of approximately 180 m^2 (Figure 1E), encompassing a comprehensive set of 181 transects for the area measurement. In addition, 10 more transects were performed as individual profiles to ensure a robust data collection process. Although large roof spall littered the floor, surface rocks were continuously moved and reinstalled in their original location while the GPR vehicle was running. Only areas of the mid-section were unsuitable for scanning due to bedrock and large boulders on the surface. Additionally, the area previously excavated by Gjessing was not surveyed due to only consisting of disturbed backfill from the original excavation. Subsequent data processing involved the transformation of raw data into a comprehensive 3D data volume using standard GPR processing parameters, which encompassed Hilbert transformation, DC-shift, dewow, band-pass frequency filtering, time-zero corrections, and average trace removal. Due to lack of visible reflection hyperbolas in the single GPR profiles, no velocity analysis was performed, and a constant velocity of 10 cm/ns was applied for the time-depth conversion during data processing. It is important to note that this simplified approach may introduce a potential error margin in the time-depth conversion. Finally, horizontal depth-slices were created. Data processing was executed using the GPR data processing package ApRadar (an in-house GPR data processing package developed by GeosphereAustria). Subsequent data visualization and analysis were carried out in ArcGIS Pro, ReflexW, and using custom Python code.

Environmental deposit monitoring

In situ environmental monitoring equipment was installed in the western section of Trench 2 at the back of the cave (Figure 2). The monitoring method is consistent with the environmental deposit monitoring protocols in the Norwegian Standard (NS9451 2009). A standard is a way to ensure intrasite comparability, using standardized methods and definitions. The equipment consists of three ecoTech pH sensors, four ecoTech redox sensors, three Campbell CS650/655 sensors for soil water content, soil temperature, permittivity, and conductivity, and two Apogee Instruments SO-411 sensors measuring soil oxygen content. These provide running measurements—collected at 6 hour intervals—of soil pH, soil water content, soil temperature, conductivity, permittivity, redox parameters, and oxygen. Combined, these provide valuable data on the current and future state of in situ organic preservation, the environmental conditions, and whether the deposits are stable or subject to degradation. The sensors were manually inserted into the deposits. Some were placed deeper into the section by using a hand auger to extract soil samples for environmental conditions analyses, allowing a deeper placing of large and fragile sensors. The horizontal sensor depth thus varies between 5 and 30 cm. The location of sensors is illustrated in Figure 2. The sensors are attached to a Campbell CR300 datalogger with GSM modem for wireless data transmission. The datalogger is placed in a logger cabinet with batteries charged by solar panels. All data is available at CautusWeb for continuous monitoring.[1] To ensure the safe placing of the sensors and to minimize direct oxygen entry into the deposits, the section was covered in non-marine blue clay before backfilling the trench with excavated material. Through several tests and examples, non-marine blue clay has proven a stabilizing factor to both soil temperature and soil humidity (Halvorsen, Hovd, and Martens 2022, 105), as it slows down both water and air flow without changing the soil chemistry. It is important that it is

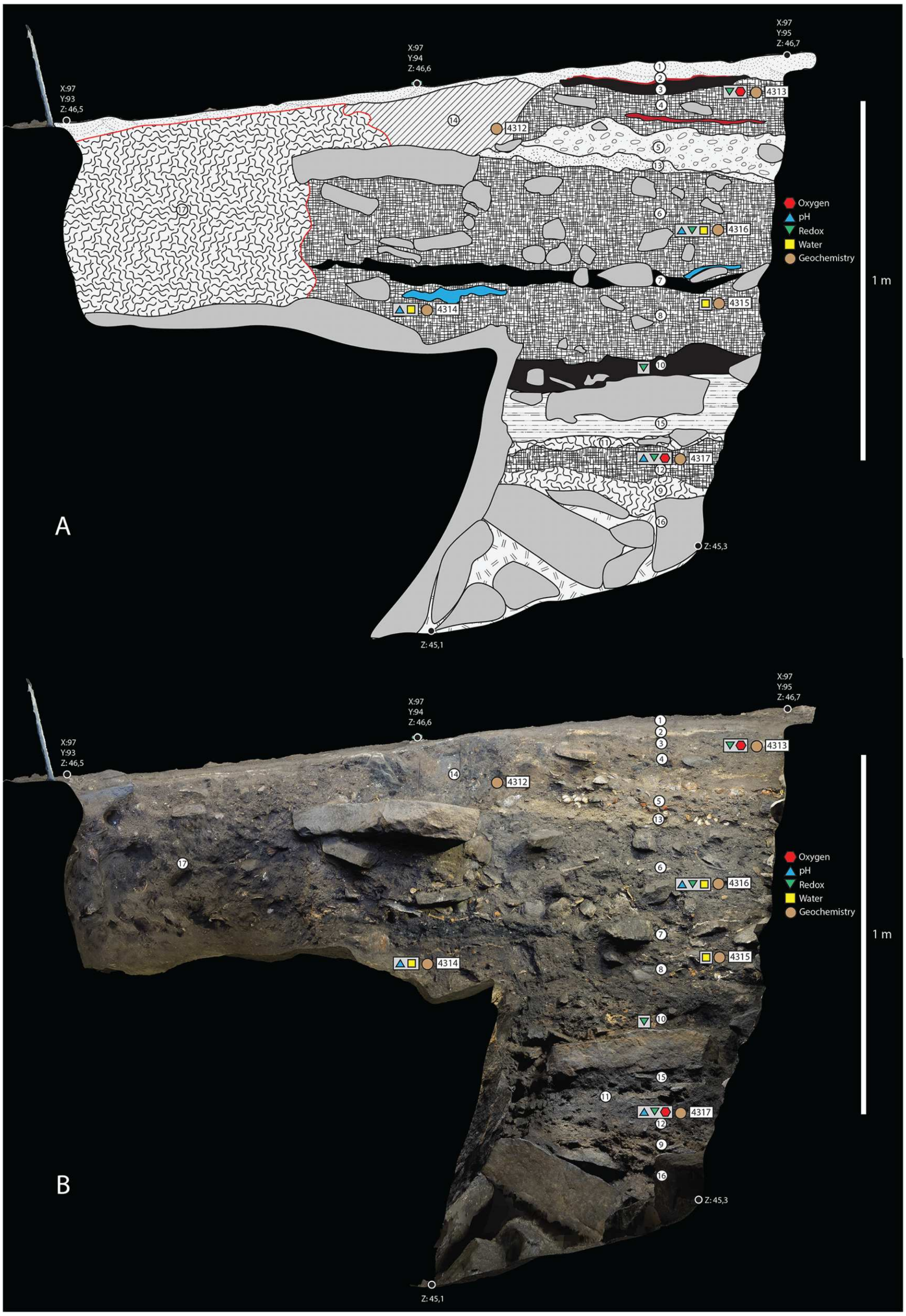

Figure 2. Trench 2, west profile, collage. A) Section drawing of Trench 2, west profile (97x/94y), displaying location of monitoring equipment installed in various strata, as well as sample location for geochemical analyses. ID of geochemistry samples corresponds to ID in Table 3. Drawing based on georeferenced and scaled photogrammetry 3D model. B) Photogrammetry section of A.

non-marine, as the sulphide contents of marine clay accelerate degradation of organic matter, which is the opposite of our intention.

Prior to installation, all the deposits were described (Table 1) in accordance with the Norwegian Standard NS9451 (2009). This was done to determine the extent to which the archaeological deposits are exposed to oxygen and other degrading factors. Each deposit was separated into botanical, zoological, and mineral components and artifacts through visual inspection. These four groups constitute 100% of each deposit. The four groups were then specified in detail. As required by the standard, the state of preservation was evaluated by the archaeologist on site, based on the composition of the deposits and in relation to groundwater (A: unsaturated, B: fluctuation zone, and C: saturated) and on a preservation scale of 1–5: very poor, poor, medium,

Table 1. Summary of strata and preservation condition descriptions. Layer numbers refer to those displayed in Figure 2 (section drawing). Each context is defined as 100% split in botanical, zoological, and mineral components and artifacts, as described in text.

Excavation area	Coordinates	Layer nr	Description	Botanic component %	Zoological component %	Mineral component %	Artifacts %	Preservation
Trench 2	97x/94y, west profile	1	Topsoil (cave floor). Dusty, fine-grained loose matter, gray and unconsolidated silt, sitting on top of a 2 mm thin cover of compacted sheep droppings.	30	70	0	0	A1
Trench 2	97x/94y, west profile	2	Carbonate-smear from decomposed shells. White on top, increasingly yellow with depth. Max 1 cm thick lens. Contains some visible traces of disintegrated bones.	10	85	5	0	A1
Trench 2	97x/94y, west profile	3	Charcoal lens immediately below 2. Decomposed charcoal and humus. Gradual transition into the deposit below.	50	15	35	0	A3–4
Trench 2	97x/94y, west profile	4	Mixed deposit. Rich in faunal remains, some shells. Unsorted, fine sandy matrix with fragments of fire-cracked larger rocks and larger chunks of charcoal. Contains minute lenses of sorted, yellowish-gray silty material. Specked with charcoal and bone fragments throughout.	45	14	40	1	A4
Trench 2	97x/94y, west profile	5	Midden consisting of *Patella vulgata* and *Littorina* shells embedded in a light gray, gravel matrix seemingly predominantly originating from heavily disintegrated, fire-cracked rocks, with unsorted ash and charcoal inclusions. Some larger charcoal chunks and fragmented rocks. Shells are clearly burnt and occasionally bifurcated.	35	30	35	0	A3
Trench 2	97x/94y, west profile	6	Mixed archaeological deposit. Loose, dry block. Unsorted matrix of silt, sand, gravel, and fist-sized, fire-cracked rocks, plus shells. Light gray-brown color. High content of well-preserved and articulated faunal remains and large chunks of charcoal.	35	20	44	1	A4
Trench 2	97x/94y, west profile	7	All-black, highly demarcated charcoal layer, consisting of log-sized fragments of burnt wood. Running continuously across the profile, separating the two main blocks of mixed charcoal layers (6 and 8). Extremely well-defined boundary on both top and bottom. Beyond some fist-sized rocks, almost exclusively consisting of charcoal. Thickness of 1–4 cm, narrowing towards the north where it also contains a “sandwich” feature of two charcoal lenses sandwiching a lens of pulverized shell.	80	0	20	0	A4
Trench 2	97x/94y, west profile	8	Mixed archaeological deposit, reminiscent of layer 6. Seems to be a natural continuation of 6, yet separated by the charcoal layer (7). Many of the same characteristics as 6, yet more compacted, and the zoological component is less well-preserved. Very high content of faunal remains, yet less well-preserved. Some disintegrated shell fragments. Speckled throughout with shell and charcoal fragments. Slightly fatty and more brownish color than 6. Mixed matrix predominantly consisting of sand with pebbles and smaller rocks. Gravel seems to be absent. More sorted than 6.	40	10	50	0	A2
Trench 2	97x/94y, west profile	9	Bottom sediment. Minerogenic layer, silt and sandy matrix. Some specks of charcoal and disintegrated bones. Sediment on top and between larger rocks and gravel from roof spall.	2	1	97	0	A1
Trench 2	97x/94y, west profile	10	All-black, charcoal layer consisting of highly disintegrated carbon lacking visibly structured fragments. Mostly a fatty smear of organic, humus-rich carbon, with occasional bones in a powdery state of preservation. Highly	30	0	70	0	A1

(*Continued*)

Table 1. Continued.

Excavation area	Coordinates	Layer nr	Description	Botanic component %	Zoological component %	Mineral component %	Artifacts %	Preservation
			laminated layer consisting of concave and convex, undulating lenses/features of alternating black organic and brighter minerogenic material. Not well-defined in main profile due to presence of large rock, yet undulating and stacked lenses clearly visible as a continuation of the layer in supporting profiles (north and east).					
Trench 2	97x/94y, west profile	11	Minerogenic deposit, carpet of disintegrated roof-spall, mostly small fraction—gravel to fist-sized rocks. Salmon pink coloration, as the parent bedrock of the cave. Badly disintegrated rocks.	0	0	100	0	A0
Trench 2	97x/94y, west profile	12	Decomposed archaeological deposit. Dark gray, homogenous, and finely sorted. Compact block of fatty and compact organic-rich sediment, mostly pulverized charcoal and some disintegrated bone smears. Contains laminated structures of gray, brown, and black. Poor preservation.	27	2	70	1	A2
Trench 2	97x/94y, west profile	13	Minerogenic inclusion directly below midden layer 5. Light, gray-yellow coarse sand and gravel with some pebbles. No visible organic content.	0	0	100	0	A0
Trench 2	97x/94y, west profile	14	Slab-lined pit cutting through the uppermost layers. Clearly dug-down feature with slabs intentionally placed at the bottom and side of feature. Contents are black charcoal and yellow bone powder. Mixed with brown clay inclusions and specked with gravel and pebbles. Very fatty contents. Southern section of feature destroyed and removed by Gjessing's previous excavation.	10	50	40	0	A1
Trench 2	97x/94y, west profile	15	Large rock roof spall (30 + cm) carpeting the entire excavation area. Horizontally aligned rocks with dark, black-brown, humus, and charcoal-rich sediment packed in between. Layer is positioned between charcoal layer (10) and minerogenic layer (11).	10	0	90	0	A1
Trench 2	97x/94y, west profile	16	Bottom rocks. Large roof spall. Gravel and disintegrated rocks between larger rocks. Unconsolidated masses with air pockets. Seemingly sterile. Smells of beach gravel.	0	0	100	0	A0
Trench 2	97x/94y, west profile	17	Backfill from Gjessing's excavation in A.D. 1937–1939. Very loose and unconsolidated mass consisting of brown-gray deposit, mostly sandy matrix with fist-sized rocks and large quantities of shells and faunal material.	10	30	60	0	A2

good, and excellent.[2] The evaluation of the state of preservation was based on the following criteria as defined in the standard: smell, structure/porosity, color change, mechanical strength of e.g. wood, general appearance, and which artifact types were present. All deposits were in the unsaturated zone and ranged in state of preservation from 0 (mineral only) to 4 (good), with the majority defined as very poor or poor but a few defined as good.

Geophysical and geochemical analyses

Soil samples were extracted from the strata that sensors were installed in using a hand auger and trowel. The samples were immediately packed in 500 ml ziplock bags, from which as much air as possible was evacuated, before being placed in further ziplock bags containing a sachet of Anaerocult A (VWR international), which creates an anaerobic vacuum. This ensures the protection and stability of the physical-chemical properties of the soil samples, in accordance with Norwegian Standard (NS9451 2009). Samples were stored and transported in a cooler bag at 4°C at all times until opened in the laboratory in a nitrogen atmosphere within a glove box to keep anaerobic samples free of oxygen.

Samples were analyzed according to NS9451, mapping the following parameters. Extractions of redox sensitive parameters were all conducted in a nitrogen atmosphere. Dry matter content (DM) (heated at 105°C for 24 hours) followed by loss on ignition (LOI) (550°C for 12 hours) was determined on half of each initial sample before analyses on redox sensitive parameters were performed on another sub-sample. Matrix potential (pF) and porosity were also assessed. The pH and conductivity (mS/m) were measured at 23 +/- 2°C. The samples were analyzed for nitrate (NO3-), ammonium (NH_4^+), reduced iron ($Fe2^+$) and oxidized iron (Fe^{3+}), sulphate (SO_4^{2}-), and (acid volatile) sulfide (S2−) (Rickard and Morse 2005), either as % of DM or mg/kg DM. These parameters are evaluated using the following thresholds defined in the Norwegian Standard (Martens and Bergersen 2015, 71; NS9451 2009). Good preservation conditions require high concentrations of e.g. > 50 mg/kg DM (NH_4^+), > 100 mg/kg DM (S2−), > 500 mg/kg DM (SO_4^{2}-), and high percentage reduced iron ($Fe2^+$) > 80%. Poor preservation conditions are characterized by low concentrations, e.g. > 10 mg/kg DM (NO3-), < 500 mg/kg DM (SO_4^{2}-), and low percentage reduced iron ($Fe2^+$) < 20%.

3D documentation and reconstruction of historic cave surface

The entire interior surface of the cave was documented using a high-precision terrestrial 3D laser scanner (Riegl VZ400), capturing 25 individual scan positions, each consisting of 12 million points. The scanner includes a top-mounted Nikon D700 DSLR camera that captured five calibrated images for each scan position. The scan data were registered, colorized, and cleaned using proprietary software (RiScan Pro) and subsequently exported as individual colorized point clouds in .ptx file format.

The large cave entrance posed challenging lighting conditions that resulted in lower quality images. To overcome this issue, a high-resolution camera (Nikon D8000) was used to take approximately 1200 well-lit individual photos of the cave from different angles, using both a standard tripod and a photo-pole. The resulting data from both the colorized point clouds and photos were combined and processed in the RealityCapture photogrammetry software to produce a final high-resolution georeferenced 3D model of the cave (a low-resolution version of this is visible at https://sketchfab.com/3d-models/arcave-kirkehelleren-v02-7549c2e12ccf4b199671f8b3297257d4). The resulting 3D model was then used to create a digital terrain model (DTM) and orthoimages of the cave floor, which were subsequently used in GIS software.

To obtain direct evidence of past floor levels in the cave, a thorough survey of historical photos of the site was undertaken in available archives, reminiscent of the process described by Landeschi and colleagues (2019). As the floor had been significantly modified by the A.D. 1937–1938 excavations, photos had to pre-date this point to provide information on pre-excavation floor levels. Photos taken just prior to the A.D. 1937 excavation demonstrate that the site was used as a sheep pen. Although the floor is not directly visible, the surface at this point was heavily disturbed, as fences and stone walls had been erected to enclose the pen. Thus, older pictures were needed.

Very few photos from the site exist prior to the A.D. 1930s, and of these, few display the floor in sufficient detail to trace the elevation and extent of the deposits against the characteristic features of the walls. Fortunately, a high-resolution photo of the cave interior was made in A.D. 1900–1910, prior to any significant modern alteration of the floor level. Careful efforts were made to accurately reconstruct the original camera position used to capture the photo, which was taken from approximately 50 m from the cave entrance using a 40 mm lens. This was achieved by using the 3D modeling software Blender to overlay the original image onto a high-resolution 3D model of the cave. By reconstructing the exact position of the camera, the surface deposits of the cave floor could be traced against the features of the walls (such as fissures and strata in the bedrock) and large boulders on the cave floor. Finally, the outline of the surface was projected onto the 3D model, resulting in an accurate reconstruction of the floor deposit. The workflow is illustrated in Figure 3.

Once the surface model had been reconstructed, its vertices (or individual points) were treated as a multipoint feature within the GIS (ArcGIS Pro) software and used to generate a digital terrain model (DTM) raster dataset, providing a detailed representation of the historical terrain elevation and slope characteristics of the cave floor in A.D. 1900–1910. Both the documented and reconstructed DTMs were constrained to the same extent of the cave floor and then resampled to a 10 cm grid size, allowing for comparison and analysis of the terrain characteristics. The *Minus* geoprocessing function was used to generate a difference model, with each cell of the resulting raster dataset containing the elevation differences between the two initial DTMs. This difference model was then utilized for visual presentation of the results and for calculating the volume of terrain changes. The mean value of the difference model, obtained through raster statistics, and its surface area were used to calculate the total volume difference.

An earlier photo of Kirkhellaren cave exists, dated to A.D. 1892 (Rolfsen 1916, 267). The photograph does not adequately cover the interior of the cave, and we were unable to obtain the photo at a usable resolution. Whilst it has not been possible to make a formal comparison between this photo and earlier points in time, it does suggest a similar floor level and slope to that of A.D. 1900–1910.

Whilst it is essential to recognize potential error and uncertainty in the reconstruction process, it is challenging to report on specific, statistically determined margins of error. Typical sources of error in such a reconstruction process include data acquisition and processing errors, modeling errors, and human error in manual image matching and interpretation. In this case, data acquisition and processing errors are considered negligible—they have been repeatedly verified by the multiple use of the 3D data in other contexts during the ARCAVE project. The greatest margin of error is expected to be caused by human error in the image matching and reconstruction process. Although the A.D. 1910 image was taken facing directly towards the cave, a significant portion of the cave wall, approximately 40%, is not visible or is only visible from a very acute angle, particularly the southern and eastern cave walls behind the central altarpiece rock formation. Additionally, about 25% of the original cave surface is not visible in the image. This lack of visibility introduces uncertainty in the reconstruction of the cave floor's surface level and slope characteristics.

Furthermore, the resolution and clarity of the original image, particularly in the inner parts of the cave, are somewhat coarse. This factor necessitates an error margin of approximately 10–15 cm to be considered when tracing lines and defining the reconstructed surface. This error margin could potentially impact around 50% of the reconstructed surface area, leading to variations in the accuracy of the digital terrain model (DTM) used for subsequent analyses. Assuming that the errors in surface reconstruction

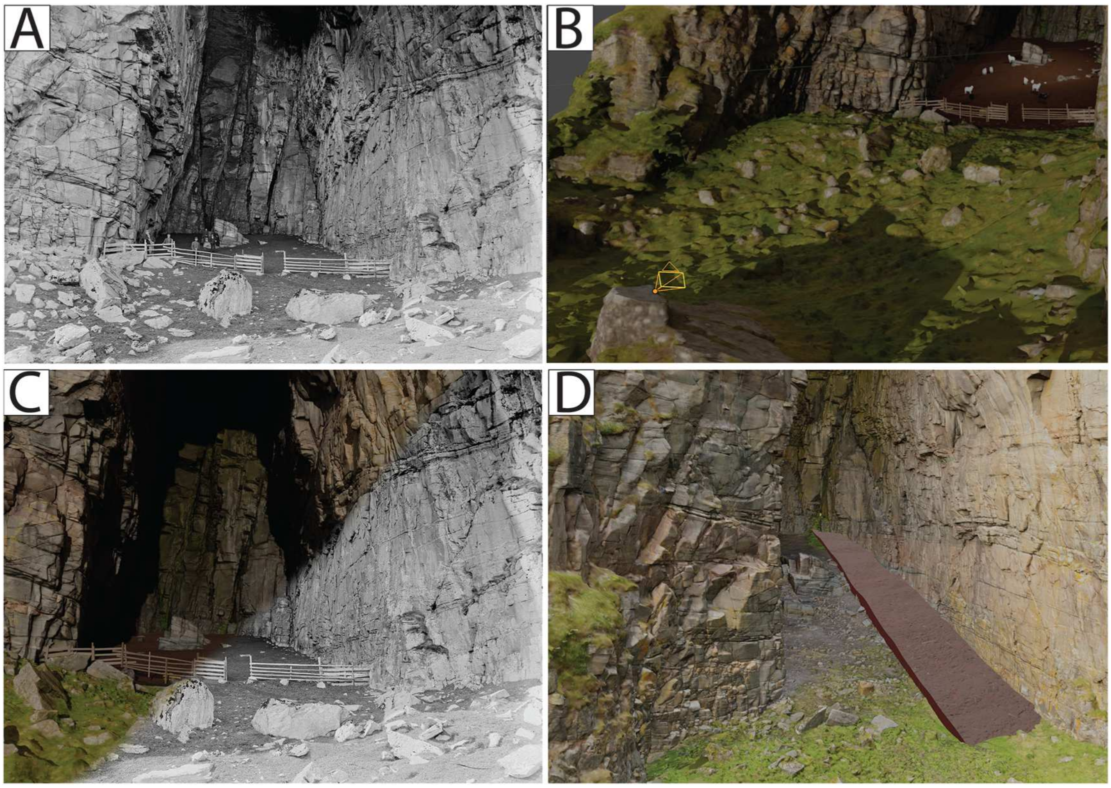

Figure 3. Work process of cave floor reconstruction. A) Original photo sometime between A.D. 1900 and 1910 (photo credit, unknown photographer, open source by Riksarkivet). B) Reconstructed camera position. C) Half-and-half blending of model and original photo. D) Cross-section of missing topsoil within 3D model of current condition.

might lead to both overestimations and underestimations of volume, we estimate that the potential error in the calculated volume change could range from approximately 10–20%. This implies a possible variation of ± 41 m^3 to ± 82 m^3 in the total calculated volume change.

Results

Surface depletion and erosion results

Although the cave is located on a remote island with only two permanent inhabitants and devoid of agricultural activities, excavations during the 2021–2022 campaign revealed evidence of extensive modern soil depletion and surface erosion. The ARCAVE-project recently excavated three areas of the cave, covering the front, central, and inner floors. Sheep dung was only uncovered at the far back of the cave, forming a 0.5 cm thin film of the uppermost layer, below which finely stratified archaeological deposits were preserved. The majority of the current surface level is in fact prehistoric. This is in stark contrast to previous investigations (A.D. 1930s and 1973) reporting up to 100 cm of sheep dung (see Background above) and indicates alarming rates of very recent soil removal and erosion. Regardless of antiquity, the entire site, including topsoil/dung, is protected by the Cultural Heritage Act. Any intervention in the cave is prohibited, including the removal of topsoil.

The rate of erosion became immediately apparent as structurally intact, prehistoric features were uncovered at the modern surface level. Most strikingly, *Patella vulgata* shells were exposed in the surface dust during excavation, subject to direct surface erosion and embedded in situ in subsequent deposits. Upon further excavation, this was identified as an intact cooking pit packed with shells (Figure 4). The recovery of a complete bifacial flint projectile point (type D) from inside the pit, typologically dated to ca. 3500 cal B.P. (Mjærum 2012), combined with the fact that no modern or recent historic artifacts superimposed the feature, suggested significant age of the current floor surface. This was later confirmed by dates from the section, including shells from the same cooking pit, resulting in a marine reservoir corrected date of ca. 3500 cal B.P. using the Marine20 calibration curve. Dating of charcoal embedded in a shell at the site produced perfect overlap with standard marine offset (420 years), corroborating the correct age of the feature containing the bifacial projectile. Partially preserved segments of a stratum (layer 12 in Figure 4) superimposing an area of the cooking pit were dated to 1500 cal B.P., illustrating the erosion of previously preserved, later layers.

Surface deposits throughout the cave have now been dated, and all show prehistoric ages, with the latest dates centered on A.D. 500 (Table 2). The absence of Medieval material anywhere—which was abundant during the A.D. 1930s campaign—suggests that material removal and soil depletion has led to widespread and accelerated wear and erosion.

Mass loss calculation results

Our analysis of mass loss and erosion distribution (Figure 5C) reveals that as much as 1.3 m of soil thickness has been removed, with the most significant mass loss along the northern cave wall. A mean elevation difference of 0.61 m between the reconstructed and documented cave surfaces was determined. As the entire floor area of the cave covers some 674 m^2, an astounding 411 m^3 appears to have been

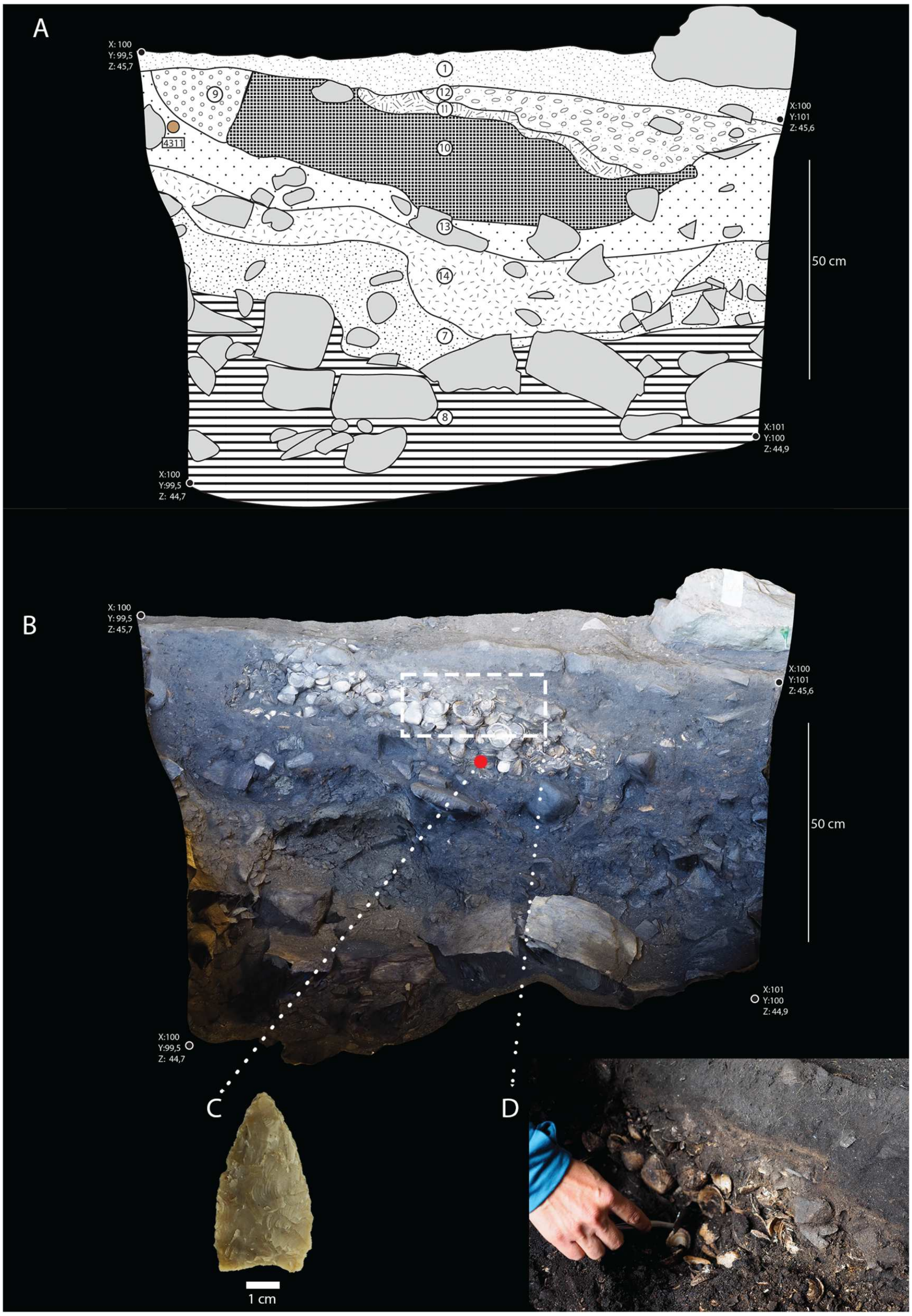

Figure 4. Trench 1, west section, collage. A) Section drawing of Trench 1, west profile (100x/100y). Numbers in center correspond to layer number as discussed in Table 3. B) Photogrammetry section of A. Note the cooking pit packed with shells slanting upwards towards the left and breaching the surface where shells were actively eroded. C) Photo of heart-shaped, bifacial flint point (Ts16074.83). Red dot marks find location. D) Illustration of cooking pit during excavation.

removed or eroded compared to the surface level displayed in the A.D. 1910 photo—the equivalent of 10 fully loaded Volvo FMX 460 dump trucks. This equates to an average annual mass loss of 3.7 m^3 throughout the 111 years between the original photo and the current documentation. There is strong evidence that the erosion or mass removal has primarily occurred during the last 30–50 years (due to reasons discussed below) at a rate of 8.22–13.7 m^3 per year. Most likely, the speed of depletion and erosion is exponential, highlighting the need for intervention and mitigation.

GPR results

The primary objective of the GPR survey was to accurately determine the location of excavation trenches, enabling the excavation of a substantial amount of well-preserved

Table 2. Surface layer radiocarbon dates from the three investigated areas.

Cave area/ Trench nr	Date ID	Sample ID	Layer	Age B.P.	Calibrated age	2 Sigma prob. (%)	Dated material	Comment
Entrance/ Trench 3	UBA-48985	6838	L2-bottom. Stratum. First intact culture layer below modern surface.	2128 ± 24	201–89 B.C.	0.801 prob	Branch of short-lived bush, likely Cratageus	
Back/Trench 2	UBA-46496	4070	L14-high = slab lined pit feature.	1936 ± 38	A.D. 7–209	0.985 prob	Picea/Abies	Multiple surface dates range around these two age brackets. Thin layer (sub cm) of sheep dung preserved in this region.
Back/Trench 2	UBA-46494	4068	L3. Stratum. First intact culture layer below modern surface.	2422 ± 30	567–402 B.C.	0.780 prob	Unidentified frags.	
Mid (north of altar)/ Trench 1	UBA-47058	Ts16074.2	L10. Shell-packed cooking pit. West profile.	3696 ± 19	1644–1361 B.C.	Marine corrected	Shell (*Patella vulgata*)	
Mid (north of altar)/ Trench 1	UBA-47067	3569	L4. Stratum. South profile.	3420 ± 32	1775–1622 B.C.	0.884 prob	Salix	
Mid (north of altar)/ Trench 1	UBA-47057	1	L12. Stratum. Partly superimposing L10. West profile.	1624 ± 25	A.D. 407–483	0.612 prob	Ovis tooth	

archaeological deposits. This was unsuccessful. While the direct attainment of this goal encountered difficulties, the survey yielded unexpected yet invaluable insights that significantly contribute to the essence of this study. The initial analysis of the GPR depth-slices uncovered intriguing variations in signal penetration, which initially posed challenges in accurately determining sediment depths. In areas A (inner section of cave) and B (front section), the GPR data revealed significant variations in signal penetration, effectively delineating two distinct zones within the cave (Figure 6A). The eastern and northwestern parts of area A, along with the two northern thirds of area B, displayed a penetration depth of approximately 50 ns/2.5 m, marking the limit of the recorded time-window. In contrast, the central part of area A and the southern third of area B exhibited strong signal attenuation, leading to almost negligible signal penetration. These variations were more pronounced in area A compared to area B. While areas with normal signal penetration displayed reflections that could be attributed to different subsoil strata, it was determined that these patterns are more likely caused by individual boulders within the sediment, rather than solid bedrock, given their relatively modest dimensions.

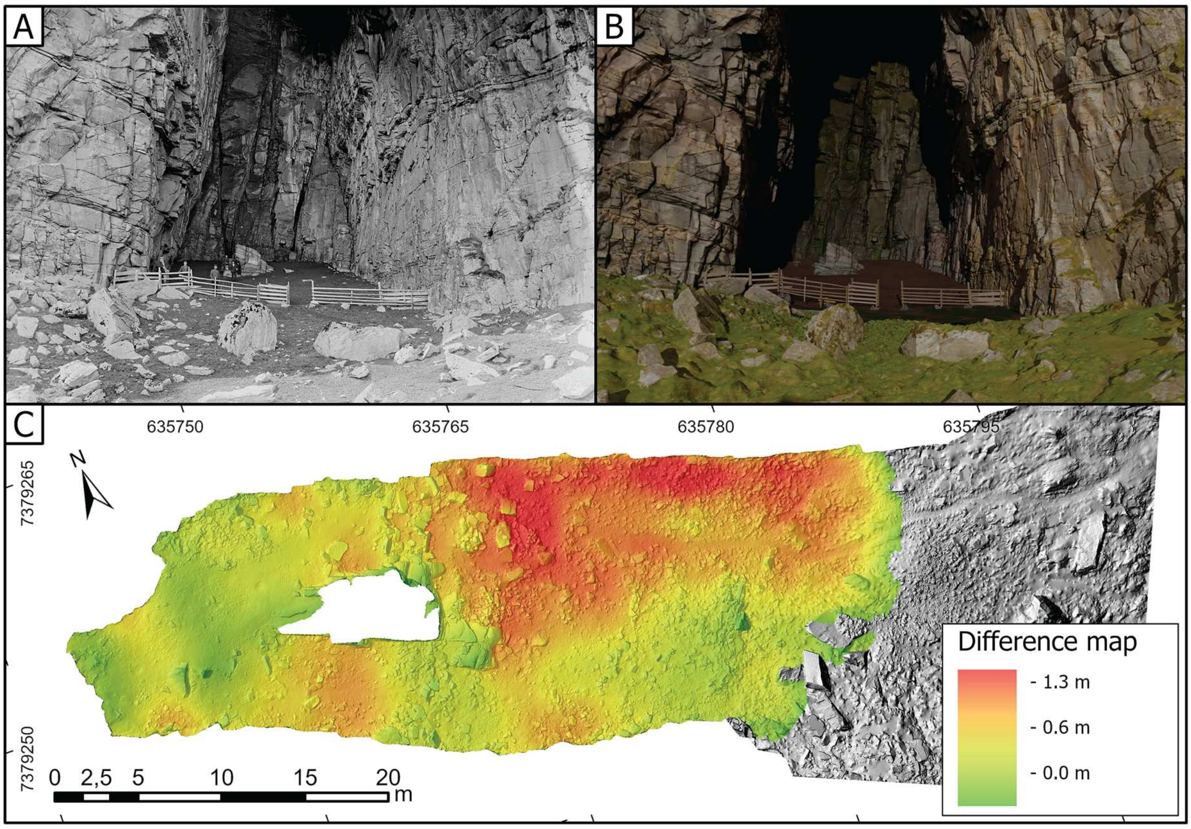

Figure 5. Illustration of mass loss and erosion distribution in Kirkhellaren cave. A) Photo of surface in A.D. 1900–1910. B) Reconstructed surface level set within 3D model of the cave. C) Heatmap of difference model in topview of the cave floor demonstrating the distribution of the erosion.

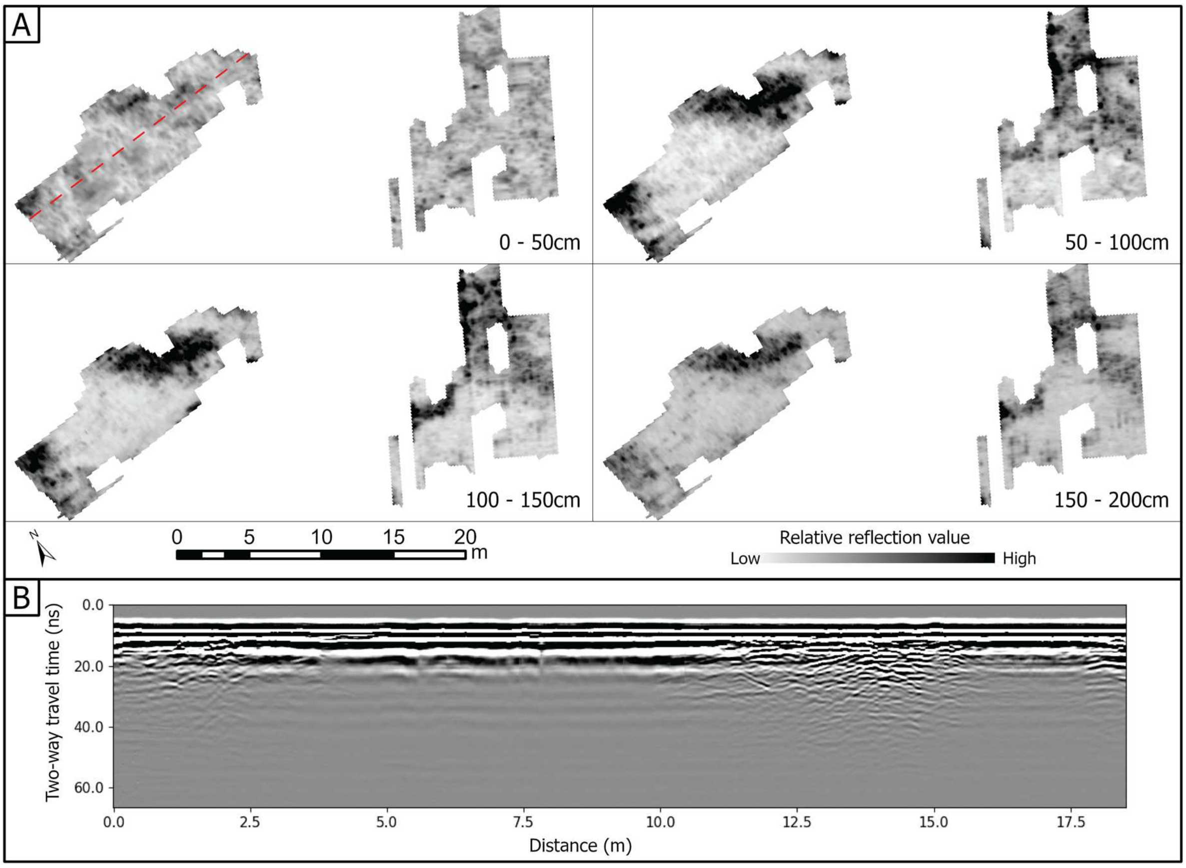

Figure 6. A) GPR results of survey area A—inner section of cave (left part of the depth-slices)—and area B—front section of cave (right part of the depth-slices). The depth-slices reveal clear distinctions within the cave. Bright areas represent GPR data with minimal signal penetration, while dark areas correspond to regions with normal signal penetration. The red line in the upper right depth-slice indicates the position of the GPR profile shown in B. B) Single GPR cross-section (raw data) from area A (see Figure 1E) depicting the absence of signal penetration in the central part of the area. The horizontal pattern evident in the region with low signal penetration is attributed to inherent GPR antenna properties.

Strong signal attenuation, as observed in parts of the survey area (Figure 6B), is influenced by a range of factors and indicates the presence of material just below the ground surface characterized by specific physical properties: a highly conductive material, leading to an absorption of the electromagnetic signal, or a material with a high dielectric permittivity, causing scattering and reflection of the signal. To determine the origin of the varied signal penetration and its implications for organic preservation and formation history, we excavated two trenches during the 2021 fieldwork. One was established in the area characterized by strong signal attenuation, while another was positioned in an area with normal penetration characteristics. Notably, the areas of normal penetration were identified as rather moist, with moisture and air draining through the lower section of the sediment, ultimately leading to less optimal preservation conditions. In contrast, areas with strong signal attenuation displayed arid conditions and had well-preserved archaeological deposits. Building upon the results of the 2021 excavation, the decision was made to strategically position the trench for the subsequent 2022 excavation in an area showcasing favorable preservation conditions.

Environmental monitoring and preservation results

The samples from Trench 1 are all fine-grained deposits with high dry matter content and low organic content. pH values are slightly alkaline. Conductivity measurements are consistently low in this trench, and total iron content is high with a very small amount of oxidized iron, indicating stable conditions. This data reflects the thin upper section of about 50 cm where archaeological deposits are preserved, above which the deposits are truncated. In addition, the bottom of the section in Trench 1 consists of a 1 m thick boulder deposit of roof spall material, through which air and moisture drains, and where organic material is almost completely decomposed.

Trench 2 samples are also slightly alkaline, consisting of fine-grained material with a high dry matter content. Several deposits had a raised organic matter content. These same deposits also had comparatively high soil water content (Table 3). Most of the deposits in Trench 2 had low conductivity, but the two top deposits had much higher levels. Both these deposits also had a high sulfate content—all indications of better preservation than in Trench 1.

The most notable result is the extreme value of nutrient salts in the surface layer of Trench 2, with 1800 mg/kg of nitrate in layer 2. These are very high nitrate concentrations compared to other monitored archaeological deposits (see Halvorsen, Hovd, and Martens 2022 for a wide selection of Norwegian urban deposit monitoring data). The concentration of nutrient salts varies with depth, with nitrate levels being > twentyfold more abundant in the top layer compared to lower layers. Additionally, sulfate levels are also significantly higher at the surface, leading to high conductivity values in the uppermost layers. This is believed to be responsible for the strong signal attenuation in the GPR survey of the affected area, resulting in limited penetration depth and signal quality issues, as discussed in more detail below.

Table 3. Results from geochemical and geophysical analyses from the two trenches excavated in 2021. Layers are arranged in stratigraphic sequence from top to bottom. Note extreme values for nitrate, sulphate, and conductivity in exposed surface layers, particularly in Trench 2, compared to subsurface layers.

Sample	Trench	Stratum	Organic matter (LOI) (%)	Water content (%)	Sulphide (mg/kg)	pH	Conductivity uScm $^{-1}$	Total Fe (mg/kg)	Iron Fe2+ (µg/kg)	Sulphate (mg/kg)	NO3-N (mg/kg)	NO4-N (mg/kg)	< 5 mm sieving (%)	DM (%)	Preservation			
															Organic material	Inorganic material	Redox conditions*	Archaeological state*
4309	1	Layer 2	8.2	17.9	13	7.9	180	14,000	< 0.1	29	18	< 1	83.7	82.1	poor	poor	reducing	A3 medium
4310	1	Layer 4	7.0	18.2	7.7	8	140	13,000	< 0.1	28	9.2	< 1	79.4	81.8	poor	poor	reducing	A3 medium
4311	1	Layer 13	9.6	22.9	11	8.2	85	13,000	< 0.1	16	4.2	< 1	81.3	77.1	poor	poor	reducing	A4 good
4313	2	Layer 2	12.8	25.5	23	7.1	3200	12,000	< 0.1	580	1800	< 1	85	74.5	poor	poor	reducing	A4 good
4312	2	Layer 14	18	24.8	<5	7.8	1800	8900	< 0.1	580	720	< 1	78.7	75.2	poor	poor	oxidizing	A1 very poor
4316	2	Layer 6	10	24.1	22	9.2	470	10,000	< 0.1	220	92	< 1	85.7	75.9	poor	poor	reducing	A4 good
4314	2	Layer 8S	12.5	29.3	23	7.9	520	11,000	< 0.1	390	200	< 1	68.4	70.7	poor	poor	reducing	A2 poor
4315	2	Layer 8N	15.9	28.6	9.9	8.3	350	12,000	< 0.1	130	89	< 1	73.2	71.4	poor	poor	reducing	A2 poor
4317	2	Layer 12	5.8	21.5	32	8	310	21,000	< 0.1	62	38	< 1	66	78.5	poor	poor	reducing	A2 poor

Surface
Subsurface

Low organic matter 10%
Medium organic matter 10–20%
High organic matter 30–40%
Low water content 10–20%
Medium water content 30–40%
High water content 50–60%

Very poor to poor
Medium
Good–excellent

Oxidizing condition
Reduced condition
* SOPS: NS9451 (2009)

The results vary greatly between the two excavation areas, as the extreme values in the upper deposits are only observed in Trench 2. In fact, the values from all sampled strata in Trench 1 are significantly lower than any strata in Trench 2. This is probably due to active nutrient depletion from moisture draining through Trench 1, as demonstrated by both GPR readings and direct observation of moisture and air cavities in this trench during excavation. This is likely the result of different erosional or soil depleting events, as the current surface layer in Trench 1 is significantly older and more recently exposed through erosion, whereas the surface layers in Trench 2 appear to have been preserved intact and therefore have received significant recent nitrate enrichment from sheep urine.

Active deposit monitoring was initiated after installation of environmental conditions monitoring equipment during the field campaign in 2021. Episodic events of data loss occurred between August and late November 2022 due to a cable disconnection between the probes and the datalogger following a storm. Additionally, the pH sensors could not be activated until the end of November 2022 because of a COVID-19 induced supplier delay in critical components. When the connector was installed (November 30, 2022), the connection between the datalogger and all sensors was also reestablished.

The ongoing monitoring data are displayed in Figure 7 (detailed, individual plots are available in Supplemental Material 1). The results correspond well with the geochemical analyses, with the most crucial results being that 1) in situ environmental conditions display fairly stable trends and 2) that vertical proximity to the exposed surface is the main driver of variance in environmental conditions, indicative of the negative and possibly accelerating impacts of soil depletion at the site. As such, conditions are strongly favorable in the deeper deposits, yet parameters display manyfold increases in values for the uppermost layers (see Figure 2 for location of deposits and probes in the section).

The multiplot clearly demonstrates that temperature, water content, and conductivity of the deposits are strongly related. This is likely due to summer/fall precipitation draining through the mountain and increasing moisture inside the cave deposits. While winter/spring precipitation is even heavier, it is blocked from entering the cave in equal amounts due to ice formation on and inside mountain fissures that act as drainage channels.

The oxygen content of the deposits, as well as the redox potential (which is a function of oxygen availability), is uncorrelated with such seasonal variability in moisture and temperature for the deep deposits. Although the redox probe has only run for a 10 month period, the topmost deposit (layer 4) displays striking trend correspondence with the seasonal cycle of water content and temperature. As there is high amplitude variability in the redox potential of layer 4, this is a troubling result concerning the future preservation of the exposed surface deposits. In more detail, the soil temperature measurements (Figure 7A) show low amplitude variation, typical of a cave interior, with a temperature range of 1–12°C. This is in spite of air temperatures inside the cave having a far wider range (-5–21.4°C). Even though the soil temperatures do vary with the seasons, they are still stable and mostly below 10°C. That is indicative of stable environmental conditions and low risks of ongoing degradation as micro-organismic activity is generally low at temperatures below 10°C (Hollesen and Matthiesen 2015; Hollesen et al. 2015; Martens et al. 2016). It is important to note that temperature measurements from the record heat of the 2023 summer are all above that threshold limit—a potential warning for what is to come.

The soil water content measurements shown in Figure 7C are all consistently low. After an initial low following sensor installment, the humidity increased and stabilized in all three measured deposits, ranging between 11.5 and 20%. There is

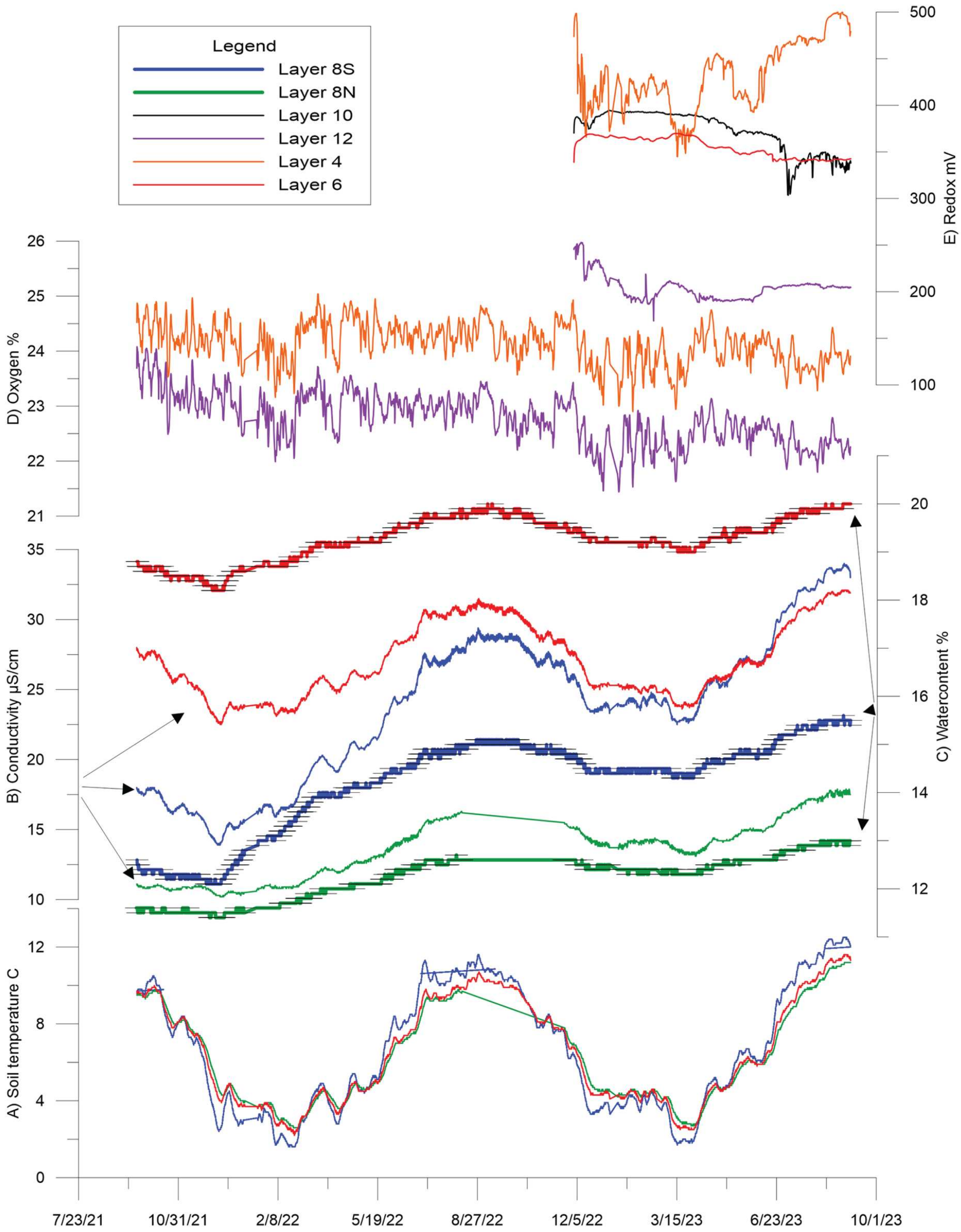

Figure 7. Multiplot of in situ environmental monitoring. Data series from September 2021–August 2023. Note that redox potential data series only runs from December 2021–August 2023.

no direct impact from precipitation, as the probes are located at the back of the cave; water is transported as humidity (e.g. fog) and water dripping from the cave ceiling.

The conductivity probes measure salinity and electric conductivity in the deposits, as shown in Figure 7B. The pH measurements all indicate a slightly alkaline environment with measurements just above 7, in line with the geochemical analyses. Deposit 8N has consistently low measurements, whereas deposits 6 and 8S have higher salt contents but also more variation. The conductivity is clearly connected to the soil water content measurements.

An important indicator of environmental conditions is the oxygen content (Figure 7D), which shows consistent presence of oxygen in the deposits, varying from 21.5–25%, with a few peaks up to 27%. As all deposits are loose and dry, oxygen was expected to be present. This does allow for active degradation processes, but if soil temperatures stay low, this may be only very slow degradation. That degradation is ongoing is corroborated by the redox potential measurements, which are all above 200 mV from bottom to top in the section, yet with significantly higher values closer to the surface (Figure 7E).

Combined, the monitoring results demonstrate that the Kirkhellaren deposits are mostly just below a critical threshold, and thus the site is sensitive to environmental change. Any additional increase in temperature, oxygen, and moisture within the deposits will accelerate bacterial/fungal activity and drive loss of organic remains.

Discussion

Rate and cause of erosion

Our results clearly demonstrate that mechanical erosion or removal of contextual information have severely impacted the state of preservation at Kirkhellaren cave. Most critically, the erosion of the upper layer of sheep dung likely also has negative consequences for the continued in situ preservation of the remaining archaeological deposits given their now highly exposed state. The compacted sheep dung that used to cover the entire floor area acted as a sealing agent for oxygen and moisture penetration, with environmental conditions throughout likely to have been reductive prior to intrusion and subsequent removal. The sheep dung layer itself is of limited age, with current evidence suggesting that domesticates (sheep) were introduced to central and northern Norway approximately 4000–3500 years ago (Hultgreen, Johansen, and Lie 1985; Jensen 2020). The exact timing for the arrival of Bovidae at the island and cave site is currently under review by the project, but a comparable age is expected based on preliminary stratigraphic and faunal data. Although the main bulk of preserved deposits in the cave corresponds to and postdates this event, the presence of significantly older and equally well-preserved strata suggests a different factor than sheep dung is responsible for the continued preservation through time.

Dates from the uppermost stratum suggest the cessation of longer-term habitation/activity at the site during the early Iron Age, when soil accumulation was discontinued. While the rich Medieval grave materials identified at the site clearly demonstrate that the site did not go out of use, it likely reflects a shift in the function of the site —tentatively, away from profane activities towards funerary practices, in line with the general trend observed across cave and rock-shelter sites in western Norway during the Early/Late Iron Age transition (Bergsvik 2017). Following the Medieval burial events, the only material evidence from the site points to a functional shift towards a seasonal sheep pen. The discontinued habitation and feasting activities during the Iron Age appear to have made the mass balance shift to a negative loss, which would likely have degraded the hitherto preserved layers were it not for the later accumulation of sheep dung, both acting as a sealing agent and preventing more active soil depletion through mechanical and chemical erosion.

It is worth noting that, on a grander scale, cave sites all over Norway have thick sheep dung surface deposits which are demonstrably deteriorating and increasingly exposing the valuable subsurface archaeological deposits. This has been witnessed firsthand by the first author and appears to be a widespread phenomenon across Norway. Given comparable urbanization and discontinuation of grazing on rural coastland elsewhere, similar erosion and depletion of sheep dung surface deposits is likely to be an international trend. This paints a bleak picture for the continued preservation of similar socioecological environmental records. As such, we fear that the current state of preservation at Kirkhellaren is rapidly deteriorating. Whilst all but one of the geochemical samples demonstrated reductive soil properties, this appears mostly to result from extensive compaction of the layers. Continued exposure to weathering and erosion is likely to facilitate oxygen intrusion into the subsurface strata, which in turn will accelerate organic decay—threatening the unique ecological and archaeological record stored in this Holocene-deep stratigraphy. This begs the question of what caused the erosion and to what extent it is possible to reconstruct the erosional history and narrow down the time frame to calculate the erosional rate.

After realizing the extent of the erosion, we approached elders of the island community for local knowledge. Their feedback, when presented with evidence of erosion, provided valuable and previously overlooked insights. Several locals over the age of 70 recalled the "common practice since childhood of local wives going to the site to collect fertile soil, mainly for flower beds, but also for potato fields," and that this practice likely continued even after the site had been established as a protected heritage site and embedded in the local identity as containing unique archaeology. There are even stories of large-scale soil removal in the 1960s–1970s by someone filling a small barge, needing soil to level a plot on a nearby island. These factors suggest severe modern soil depletion since the original excavation was conducted in the late A.D. 1930s. The very recent origin of the soil depletion was further corroborated by unpublished information from the archaeological community. As recently as 1973, test pits were made in the north-central section of the cave during prospecting of the site for an unpublished research project (Ericka Engelstad and Knut Helskog). They uncovered "extensive sheep dung" covering the surface to such an extent that they left the site without penetrating the dung layer and reaching the rich archaeological deposits below (K. Helskog, personal communication 2023).

These lines of evidence have major implications for estimating the rate of erosion and soil depletion at the site, suggesting that the majority of the erosion and soil removal occurred after 1973. While the rate of erosion would count as spectacular had it all occurred since the A.D. 1939 excavations, it is all increasingly alarming when happening during the last 50 years. If this is indicative of general trends, it paints a bleak picture for the preservation of similar socioecological records elsewhere—which does not seem unlikely given the strong acceleration of human impacts on Earth systems in the post-war era.

Although intentional soil stripping has evidently played a role in the erosion of this and other sites globally, unintended consequences of other factors may in fact have been more decisive in this case. If sheep dung acted as a protective sealing agent for the archaeological deposits, the discontinuation of sheep farming on the island, and in particular of sheep penning inside the cave, appears to be the critical factor. The faunal record shows that sheep have been present continuously since the early Bronze Age, while finally becoming discontinued in 1982. The discontinuation of sheep may have hindered the maintenance and mass balance of the dung protective layer, which instead was subject to decomposition, deterioration, and net loss. Wind and mechanical erosion may also contribute, accelerating the breakdown and dissolving of the protective dung layer. Although not the dominant wind direction, whenever there is a southeasterly wind, gusts frequently enter the cave and kick up large clouds of dust from the now very loose and unconsolidated surface layer, visibly removing sediment from the cave.

A second factor to consider is the increasing impact of tourism. As one of the most iconic tourist attractions in the region, national and international tourists are increasingly visiting the cave. No official count of visitors to the cave or the island exists, so we collected and calculated proxy statistics (see Supplemental Material 1). Combined with counts made during the excavation campaign, we estimate 10,000–15,000 visitors (in 2021), with almost 80% of traffic occurring during the June–August holiday season. In absence of the protective layer of sheep dung, this is likely to amount to severe mechanical erosion of the surface layers, as the topography of the cave (including larger roof debris) channels visitors into a small set of tracks subject to the most pressing degradation. The timing of both the termination of sheep farming and the increased number of tourists fits well with the proposed erosion mainly occurring over the last 50 years. Although it seems likely that increasing traffic will further accelerate erosion and degrade preservation conditions, it is difficult to accurately assess the impact of tourism on the preservation/erosion of the site given the lack of sufficiently deep time-series data.

It is noteworthy that the distribution of the floor erosional impact in Kirkhellaren is heavily concentrated in the front (northeastern section). This corresponds to the area most intuitively subject to fertilizer extraction during the last century, as people would have started extracting soil at the cave entrance to reduce the workload. It remains unclear why the southeastern section of the front should be significantly less affected, as appears to be the case. Photos from the original excavation demonstrate that the backfill was stored in large heaps across the floor and at the entrance. Considering the lack of evidence of similar erosion in Trench 3 (see Figure 1E)—which lies in front of the area excavated in the late A.D. 1930s—it is possible that the area was concealed by backfill sediments which helped to preserve and protect this section of the cave entrance.

The impacts of increased tourism and downscaling of outfield livestock grazing is reflected in international land use developments of the post-war period, with globalization being the driver in the former and urbanization and an aging demographic profile of rural populations in the latter (Kerckhof et al. 2016). Furthermore, the increased precipitation, temperatures, sea-level rise, and extreme weather events that follow climate change drive soil and landscape erosion at a global scale (Eekhout and de Vente 2022), with downstream impacts on both the structural integrity and in situ preservation of heritage sites (Nicu and Fatorić 2023).

These combined factors pose the most active threat and erosional agent to anthropogenic cave deposits, after having been preserved for up to tens of thousands of years. This necessitates targeted mitigation. Yet the impact of modern landscape use, tourism, and climate changes remains an underappreciated problem in archaeology given the knowledge gap of how recent human/climate induced erosional processes degrade anthropogenic deposits. While mitigation response has been suggested at the site or regional level (Patania et al. 2022), archaeology is short of a communal response, as well as a program for systematic and long-running monitoring of carefully selected indicator sites (cf. Hambrecht et al. 2018). As such, we hope the protocol presented here may be a step in that direction.

Consequences and added value of the protocol

Beyond documenting serious erosion of protected heritage, the project also develops a protocol of combined monitoring, geochemistry, and GPR surveys for holistic monitoring and risk assessment of archaeological deposits, useful for the reconstruction of formation processes. Our field testing of this protocol could provide important learning points for future applicability and up-scaling beyond the case presented here. Being able to use non-invasive prospective methods in the early stages of otherwise destructive investigations (e.g. excavation) can greatly improve project efficiency in selecting suitable areas for excavation, while simultaneously reducing the impact on non-renewable resources (archaeological sites and anthropogenic deposits). The initial use of non-invasive prospecting also helps reduce both costs and risks of project designs compared to more traditional, destructive, and "blind" prospecting methods (extensive testing/coring), which can accelerate organic decay through oxygenating previously anaerobic deposits. The penetration depth of coring/probing is frequently cut short in anthropogenic deposits with strong organic preservation by mixed and coarse-grained matrixes rich in clasts of heated rocks and faunal remains. Such probing thus provides unreliable test measures of depth for area selection, which was the direct experience at Kirkhellaren, and may therefore be effectively assisted by GPR.

The protocol demonstrated here is therefore superior in a number of ways. Although developed to meet the project needs in a cave, trying to minimize the impact of excavation and maximize information output in the most sensitive way, the protocol should have great potential for any complex site where priorities need to be set in terms of area selection, project risk, and cost reduction. It can be applied not only to archaeological contexts but to any fine-grained sedimentological sequence, thus playing to the needs of a wide range of paleoecological, pedological, and geological researchers. The protocol is well suited to most fine-grained sedimentary deposits. The more fine-grained, the better, although it may be limited by clay deposits due to low signal penetration of clay beds. Marine transgression and submerged sites may therefore pose an issue.

The effectiveness of our proposed analytical suite began on the premise that GPR would function as planned in cave environments. In our experience, there are several factors that may thwart this effort. The effectiveness of GPR in mapping subsurface structures largely depends on the magnetic and electrical properties of subsurface materials, particularly the relative dielectric permittivity (RDP). The RDP is in turn influenced by various material properties, with water content being the most critical factor but also including mineral composition and porosity. Besides RDP, the electrical conductivity of a subsurface material can have a major impact on the quality of GPR data. Highly conductive materials can significantly reduce the strength of the radar signal, making it difficult to detect objects or features below the surface (Conyers 2023).

The process of acquiring interpretable and dependable GPR scans of cave deposits, as we encountered in Kirkhellaren cave, may carry profound implications for analogous studies encompassing cave environments and intensively utilized living floor deposits. The variability of GPR readings within Kirkhellaren cave was striking: a substantial portion of the inner section yielded predominantly unusable data due to the presence of an exceptionally reflective topsoil. This phenomenon was substantiated by soil chemistry analyses from the inner section (Trench 2), which revealed nitrate concentrations rarely encountered on open-air sites, in fact corresponding to heavily fertilized modern agricultural land. Based on a literature review, the only comparable results of guano/dung layers interfering with GPR surveys in caves, to our knowledge, is presented by Arthur and colleagues (2019), where radar penetration was blocked by a subsurface layer of bat guano.

However, GPR readings were significantly more amenable when approaching the cave entrance (GPR area B). Experimental GPR research performing extensive re-scanning of the same field throughout the year demonstrated that the quality of GPR data and thus the clarity of the results was largely determined by local weather patterns, with sufficient soil moisture helping to accentuate the results (Schneidhofer et al. 2022, 29). Considering that airborne moisture (rain and fog) frequently settles on the outer section of the cave (perfectly mapped by the distribution of moisture-dependent vegetation [*Stellaria media*, chickweed, and *Anthriscus sylvestris*, cow parsley]), topsoil moisture content thus seems to play a crucial role in the applicability of GPR (Figure 8). Intuitively, seasonal input of moisture to the topsoil in the cave front appears to dissolve the high nitrate concentrations and consequently reduce the high electrical conductivity that is detrimental to radio signal penetration.

However, one issue remains to be resolved for the protocol to be fully scalable and applicable regardless of archaeological/sedimentary context. It remains unclear why the nitrate levels blocked signal penetration at Kirkhellaren, when GPR readings work well in modern fields subject to heavy nitrogen fertilization and, consequently, whether the poor conductivity is caused directly by the concentration of nutrient salts or is in fact linked to specific soil properties. The extreme aridity and nutrient salt values of the deposits make for an untypical combination. Salt pan formations in arid environments, characterized by high salinity and unique soil properties, may offer insights into the factors affecting signal penetration in Kirkhellaren Cave. These conditions might lead to increased signal attenuation, especially when combined with the truncation of surface deposits, which is not commonly addressed in existing GPR literature. This requires future follow-up; however, we would tentatively suggest that the combination of extreme nitrate concentration with low soil permeability (high compaction) and very low water content seems likely to be confounding factors. This would be consistent with GPR working successfully on fertilized fields because tillage increases soil porosity and water content and open-air sites are directly exposed to precipitation. This is also consistent with the patterns observed in the cave, where areas exposed to surface or drainage moisture were more amenable to GPR readings. Regardless, we believe that the full analytical protocol presented here, including GPR surveying, has significant transfer value to other cave/rockshelter deposits.

The origin of the spectacular concentrations of nutrient salts in Kirkhellaren is likely related to the historic use of the cave as a sheep pen. The accumulation of the now largely eroded layer of sheep dung was made possible by prolonged occupation of sheep during the summer shearing period. While sheep roamed the island freely the rest of the year, an enclosure kept them stationary within the cave during shearing season. This practice appears to be of considerable age, as suggested by local knowledge, historical photos (Figure 9), and the multiple generations of stone wall foundations observable at the cave entrance. The accumulation of sheep dung is likely to have enriched superimposed layers through compaction/trampling, dung degradation, and vertical mixing by surface/subsurface disturbance from animal and human activities, yet greatly amplified by sheep urine seeping through and transporting salts into underlying strata.

Despite the challenges encountered in the GPR survey, its significance as a tool for identifying areas of robust preservation within the cave cannot be overstated. GPR, when effectively applied, aids in differentiating zones of potential archaeological interest from those with diminished preservation potential. This critical insight enabled the strategic

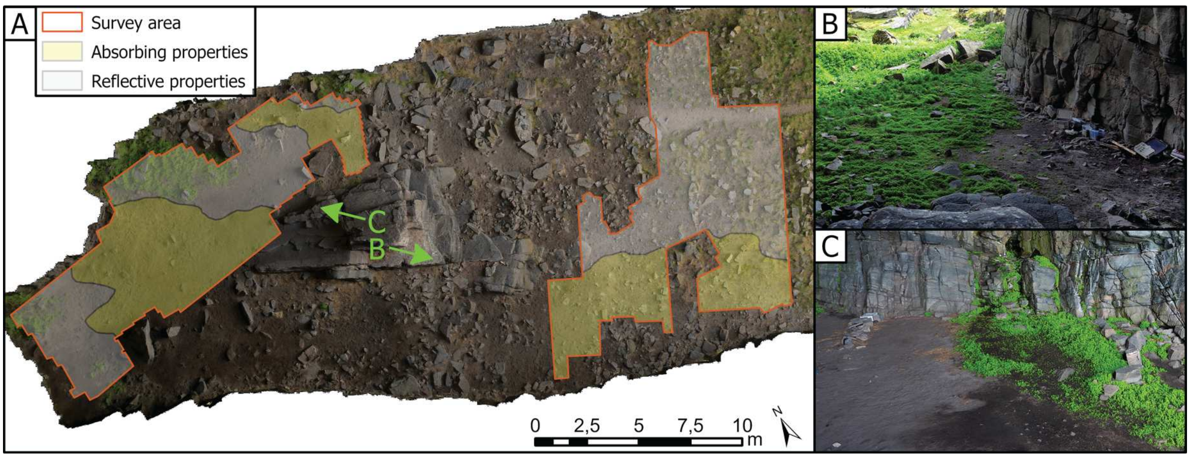

Figure 8. A) Orthoimage of the cave floor from September 2021 showing outlines of areas with different physical properties identified by GPR. Despite the sparse vegetation during the image capture, there is a noticeable correlation between areas lacking vegetation and highly attenuating areas in the GPR. Additionally, B–C) photos taken during spring 2022 provide a clearer representation of the vegetation cover.

Figure 9. Illustration of vegetation cover resulting from a particularly wet spring (June 2022). A) Demonstrating the influx of moisture into the cave entrance, as fog and rain frequently enter the front half of the cave, facilitating plant growth in the northeastern section that receives the most sunlight and airborne moisture. B) Detail of the floral community during a year of strong growth, dominated by *Stellaria media*, chickweed, and *Anthriscus sylvestris*, cow parsley. C) Historic photo from A.D. 1937 of sheep pen in the cave, prior to original excavations. Note sheep on the "altar" bedrock protrusion in the center, as well as several fence structures. Photo credit: G. Gjessing; digitized scan provided by Tromsø Museum.

positioning of excavation trenches, ensuring a focused investigation of areas primed for yielding well-preserved archaeological deposits. To circumvent the problems identified here, future applications of the proposed analytical protocol presented here may benefit from initially doing some phosphate/nitrate analysis of the topsoil to test for potential suitability of GPR. As demonstrated, very high concentrations of nutrient salts can cancel out the radar penetration. Carrying out some minor soil chemistry prior to GPR is a simple and cost-effective solution to this issue.

Conclusion

This paper presented an innovative analytical protocol for monitoring and reconstructing the erosional history of sedimentary deposits. The protocol consisted of combining GPR survey of archaeological cave deposits, correlated with geochemical analysis and a high-precision 3D-reconstruction of the erosional history of the cave floor throughout the last 100 years, based on a combined laser-based 3D reconstruction of the cave mapped onto a historical photo of the cave from A.D. 1900.

The results of the applied methods showcase critical new knowledge that would otherwise be unobtainable. Most telling is the identification of severe erosion of almost the entire internal floor area, estimated to be 411 m^3 during the last 100–120 years, primarily within the past 50 years (post-1973). Furthermore, the monitoring results demonstrate that the Kirkhellaren deposits are just below a critical threshold, and thus the site is sensitive to environmental change. Any additional increase in temperature, oxygen, and moisture within the deposits will accelerate bacterial/fungal activity and drive loss of organic remains. The outputs highlight the value of the protocol to heritage management authorities, as the archaeological deposits were thought to be well-preserved and intact, despite being a highly acclaimed tourist attraction, attracting thousands of visitors every year. The cultural heritage authorities were immediately informed of the soil depletion observed during fieldwork and updated along with the progression of our investigations. Effective countermeasures to protect and preserve the site can now be made due to the protocol developed in this paper. The most appropriate protective measures will be determined by the responsible authorities, with the ARCAVE project providing data and advice on how to potentially cover the cave floor with a new sealant to ensure favorable preservation of the site and its sedimentary record into the future.

The environmental monitoring data also demonstrate how sensitive initially well-preserved anthropogenic deposits may be to modern climate change. Degradation is ongoing but at a very slow pace due to low soil temperatures. Much of the observed degradation probably already occurred at the depositional stage or the centuries just after considering the age of the deposits; however, degradation stabilized once soft tissues and low-calcine materials had degraded and deposits were superimposed. Regardless, the protective layers of sheep dung that were observed at least until 1973 have reduced oxygen entry and penetration and thus helped stall microbial degradative activity, as well as given physical protection against wear and erosion. Now that those protective layers are gone, the site is sensitive to all environmental changes, as well as the physical wear exacerbated by an increasing number of site visitors. With increasing air temperatures, the soil temperatures may rise to a mean level above 10°C, which will accelerate all degradation processes and damage the remaining artifacts and ecofacts, potentially to the point where further analyses may no longer be viable, thus reducing the possibilities of further exploration of past activities at the site.

The reconstruction of erosional history at Kirkhellaren cave strongly suggests that severe and irreversible erosion coincided with the termination of sheep herding at the island. Despite the large-scale fertilizer depletion known at Kirkhellaren its impact seems to have been largely counterbalanced by the continuous input of sheep dung. If this is the case, it begs the question of whether reintroducing grazing animals (sheep/goats) may in fact be the most cost-efficient, sustainable, realistic, and mutually beneficial solution to the problem, with sheep/goats being preferrable over cattle, due to the much stronger trampling and surface alteration caused by cattle. Other options would include introducing a mostly minerogenic sediment that is fine-grained enough to settle into a compact, sealing strata yet coarse enough to withstand mechanical erosion from wind and rain. An unsorted sediment would be preferable, particularly when including sufficient nutrients to foster plant colonization that can help stabilize the sediment. However, there are significant logistical and financial downsides to this option, given the volume of sediment needed to sufficiently cover the 700 m^2 floor area in a remote location. Regardless of preventive action, sealing mats separating the archaeological deposits and introduced materials should be installed to prevent bioturbation and mechanical mixing between strata.

Limiting the impact of visitors can be achieved through installing fenced, plank walkways and/or fencing off the interior. Any limitation to the number of visitors should be supplemented with providing access through guided tours, which is already a successful practice at the Solsem cave painting site in Leka Municipality. Finally, digital tourism is made possible through our freely available 3D model of the site, where anyone can experience the site from the comfort of their home (https://shorturl.at/pDEIR). A more immersive model could be developed to help reduce the need to physically visit the site.

Future work should evaluate various protective measures suitable for similar anthropogenic deposits and balance this against the financial and logistic ability of most Cultural Resource Management authorities on the global stage. While relevant conservation literature abounds for protected buildings, artifacts, and monuments, this is insufficiently established for anthropogenic cave deposits. A first step in developing a systematic response to this lack in archaeology could be to draw on the comparatively rich knowledge base of "cave conservation," encompassing both speleology and biodiversity (Donato, Ribeiro, and Souto 2014; Rabelo, Souza-Silva, and Ferreira 2018; Silva, Martins, and Ferreira 2015). This could assist in developing robust selection criteria for which sites to prioritize and which protection strategies work efficiently.

Endnotes

1. Contact the authors for access to monitoring data at https://accounts.cautusweb.com/.
2. The Norwegian Standard on cultural heritage monitoring (NS9451 2009, English translation from 2012) has a state of preservation scale which includes the term "lousy," meaning "very poor." However, an updated European Standard EN17652 2022, uses "very poor." This term will therefore be used in this paper.

Acknowledgements

The project is greatly indebted to everyone who so generously took part and helped facilitate fieldwork during the 2021 campaign, of which there are too many to name. We particularly extend our gratitude to Anders Budde, Albane Mazet, Isabell Schmidt, Götz Ossendorf, Marit Bertheussen, Terese Berge, Hege Antonsen, and the Steineger family, as well as all locals who have shared important historical information on the use of the cave. Thanks to Lise Loktu and Rebecca J. S. Cannell for doing a thorough read of drafts.

Funding

The ARCAVE project is funded by the Norwegian Institute for Cultural Heritage Research by the program for "strategic institute funding," ID:1022021.

Statement of Interests

The authors have no competing interests to declare that are relevant to the content of this article.

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