Research paper

Radiocarbon dating of naturally shed reindeer antlers melted out of retreating ice masses in western Norway

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Rising summer temperatures, especially since the start of the 21st century, have caused negative mass balance and retreat of glaciers and ice patches. In western Norway, twenty-two naturally shed reindeer antlers have during the recent decades emerged from underneath the margins of fourteen receding and down-wasting ice masses, which have been radiocarbon-dated in this study. Reindeer antlers from four mountains in Sunnmøre and Nordfjord are located outside the present distribution of wild reindeer in western Norway. The reindeer antlers show no signs of having been sawn or cut off the skull, or any engravings/scrape marks, if the antlers had been handled by humans. Calibrated to calendar years, the oldest reindeer antler in this study dates to 2201 – 2132 years before the Common Era (cal. yr BCE), whereas the two youngest antlers are from 1832 – 1892 years Common Era (cal. yr CE). Grouped in 100-year time ranges, the dated antlers fall within the age ranges c. 2200 – 2000, 1200 – 1000, 900 – 800, 400 – 300, and 100 – 1 cal. yr BCE, as well as c. 700 – 800, 1200 – 1600, and younger than c. 1800 cal. yr CE. The highest number of dates (*n* = 10) are between c. 1200 and 1600 cal. yr CE. Summer temperature decline and increased winter precipitation causing glaciers to advance and non-erosive ice patches to grow during the Late Holocene (from c. 4200 cal. yr BP onwards), including the early phase of the Little Ice Age (LIA) (16th to 19th centuries), provided good preservation conditions for the reindeer antlers during the LIA, with extensive ice and snow cover in the high mountains in western Norway. Glacier melting and recession have led to the emergence of reindeer antlers and other objects previously encased in the ice, reflecting a global pattern of increasing discoveries as ice masses worldwide are receding.

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INTRODUCTION

Due to rising temperatures that can be observed on global, regional as well as local scales, especially since the beginning of the 21st century, the cryosphere is undergoing visible and fundamental changes, as manifested for example in a reduction in both snow cover and depth, retreating glaciers and ice patches, as well as thawing permafrost (e.g. Beniston *et al*. 2016; Solomina *et al*. 2016; IPCC 2019, 2021; Andreassen *et al*. 2022; Nesje & Matthews 2024). In Norway, the total area of glaciers with a size greater than 0.01 km^2 (n = 5260) was 2328 km^2 in the measurement period 2018 – 19 (Andreassen *et al*. 2022). In addition, there are more than 1470 ice bodies less than 0.01 km^2 in size, covering a total area of just over 8 km^2 (Andreassen *et al*. 2022). During the Holocene thermal maximum (c. 8000 – 6000 cal. yr BP), most Norwegian glaciers were melted away (e.g. Nesje & Matthews 2024). During the following Neoglacial period, renewed glacier growth during the Late Holocene took place subsequent to approximately 4200 cal. yr BP. The Norwegian glaciers reached their Little Ice Age (LIA) (16th to 19th century) maximum extent during the mid 18th century (e.g. Grove 2004; Nesje & Matthews, 2024).

The mass balance (volume) of ice patches is influenced by direct snowfall during the accumulation season and summer temperature in the ablation season. In addition, wind-transported snow from the surroundings plays an important role for the mass balance of ice patches. Therefore, numerous ice patches in southern Norway exist well below the regional glaciation threshold and equilibrium-line altitude (ELA). In contrast to glaciers, high-elevation ice patches in southern Norway are typically thin and partly, at least during the winter season, frozen to the ground (Ødegård *et al*. 2017). They are therefore subject to negligible or no (basal) movement, and the mass (snow and ice) is therefore not transferred from an upper accumulation area to a lower ablation area (Ødegård *et al*. 2017). The ice patches have therefore no frontal time lag, as in contrast to glaciers (Nesje *et al*. 2012; Ødegård *et al*. 2017). As an example, high-lying ice patches in central, southern Norway (Jotunheimen) are underlain by frozen ground (permafrost) (e.g. Ødegård *et al*. 2017) and the basal ice is therefore frozen to the substratum. A study of Juvfonne in central Jotunheimen that included radiocarbon dating, demonstrates that the basal ice layers date back to approximately 7700 cal. yr BP (Ødegård *et al*. 2017) (postdating the Holocene summer thermal maximum; e.g. Nesje 2009; Nesje & Matthews 2024) and that the Juvfonne ice patch has existed continuously since that time.

The ongoing and accelerating recession and thinning of glaciers and ice patches around the world (IPCC 2019; Rounce *et al*. 2023), has led to vast numbers of animal remains, archaeological objects and artifacts, as well as macroscopic remnants of ice-entombed plants to be uncovered and exposed (e.g. Farnell *et al*. 2004; Callanan 2012, 2013, 2016; Andrews & MacKay 2012; Meulendyk *et al*. 2012; Nesje *et al*. 2012; Miller *et al*. 2013, 2017; Recklin 2013; Brunswig 2014; Dixon *et al*. 2014; Dance 2015; Ramstad 2015; Ødegård *et al*. 2017; Rosvold 2018a, b; Jarret 2019; Taylor *et al*. 2021; Skar & Rosvold 2022). Archaeological finds resulting from the uncovering due to glacier retreat have been reported from Austria, Canada, Italy, Mongolia, Norway, Switzerland, and USA (e.g. Andrews & MacKay 2012).

In earlier times, wild reindeer (*Rangifer tarandus tarandus*) were more widely spread, however, due to hunting and catching the reindeer were limited to the Langfjella, Dovre, and Rondane regions (Figure 1) in South Norway by the end of the 19th century. Wild reindeer have their present distribution in the northern parts of Europe, Asia,

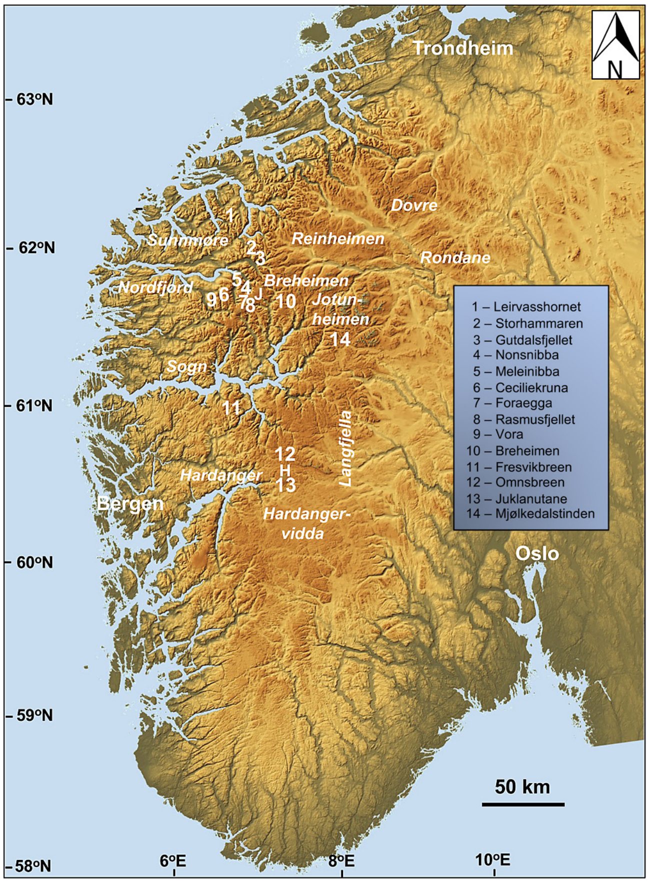

Figure 1. Location map (locality 1-14), southern Norway. J - Jostedalsbreen, H - Hardangerjøkulen. Map source: norgeskart.no.

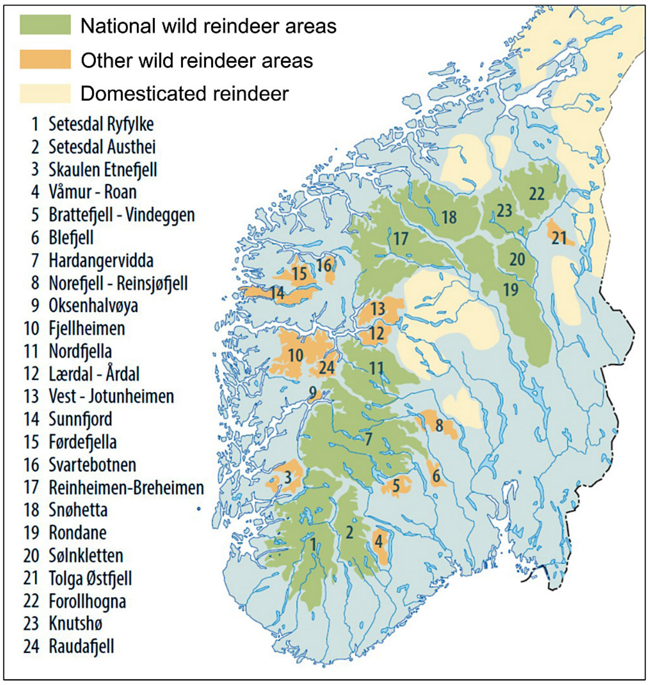

Figure 2. Reindeer areas in southern Norway. Adapted from https://villrein.no.

North America, Svalbard and Greenland. In Norway, wild reindeer can presently only be found in the mountainous areas of southern Norway, where they at present are separated into 24 management units (Reimers 2007, villrein.no) (Figure 2). This distribution is the result of natural factors (e.g. topography), human infrastructure (e.g. paths, roads, railways) and practical management considerations (Gundersen *et al*. 2022). In total, about 25,000 wild reindeer live in wintertime (after the hunting season) in southern Norway, of which approximately 4000 – 5000 reindeer (*Rangifer tarandus tarandus*) live on Hardangervidda during winter, the largest mountain plateau in northern Europe.

In warm, sunny summer days, reindeer commonly gather on high mountain and alpine snow and ice patches to reduce insect plagues (Ion & Kershaw 1989; Anderson & Nilssen 1998; Hagemoen & Reimers 2002; Rosvold 2016) mainly by reindeer warble fly or reindeer botfly (*Hypoderma tarandi*) and the reindeer nose botfly (*Cephenemyia trompe*). Insect harassment may therefore influence grazing and fattening, in addition to group behaviour of reindeer herds.

In contrast to most cervid species, the female reindeer also grow antlers. The size of the antlers varies between the reindeer subspecies, however, the bulls' antlers are commonly larger than those of the females, ranging from ~100 cm in width and ~135 cm in length. The size of the antlers normally reflects the health condition of the animal and the nutrient availability (e.g. Reimers 2007). On males, the antlers start to grow in March – April, whereas the females' antlers start to grow in May – June. Growing antlers are covered by velvet and filled with blood. After the antler is grown to full size, the velvet is rubbed off. During the mating season, the males use their antlers to compete with other males. The males lose their antlers after the mating season in late autumn/early winter. The female reindeer, however, keep the antlers until they have calved in early spring, thus keeping a higher rank in the herd when searching for food (Reimers 2007; Gundersen *et al*. 2022).

This paper presents the results of radiocarbon dating conducted on a significant quantity of reindeer antlers that have emerged from underneath the margins of retreating and down-wasting ice masses in western Norway, with the aim of studying whether the ages can be related to Late Holocene glacier-size variations in western Norway, and whether the mountain areas with reindeer finds overlap with the present distribution of wild reindeer in western Norway. Because temperatures are expected to rise in the coming decades (Klima i Norge 2100, https://klimaservicesenter.no/kss/rapporter/kin2100), the ice masses in southern Norway are expected to be reduced, and more reindeer antlers and other objects are therefore likely to emerge. To obtain a more complete picture of the temporal and geographical pre-historic distribution of wild reindeer in western Norway, more dates of naturally shed reindeer antlers are needed.

MATERIAL AND METHODS

Immediately after arrival of the reindeer antlers or small samples of reindeer antlers at Department of Earth Science, University of Bergen, the material was inspected for engravings/scrape marks before stored in a cold storage chamber (air temperature 2 – 5^{o}C). Because antlers from nine of the fourteen mountains in thus study are broken/crushed, the size of the antlers have not been measured according to standard protocol. Before submitting a sample for radiocarbon dating to the Poznan Radiocarbon Laboratory in Poland (amu.edu.pl/en/research/research-centres-and-labs/ams-laboratory), the small-size sample (~2 – 5 cm^3) was wrapped in aluminum foil and sealed in a labelled plastic bag. Mass spectrometers are used to detect atoms of specific elements according to their atomic weights. The Accelerator Mass Spectrometry (AMS) radiocarbon dating was performed according to standard procedures at the Poznan AMS laboratory in Poland. The measured radiocarbon (^{14}C) age is reported as an age or date 'before present' (BP) (the 'present' is by convention set to 1950) ± 1 standard deviation (1σ) (68.3 % probability). To calibrate the radiocarbon dates into calendar years, the calibration program Calib, version 8.20, was used (Reimer *et al*. 2020). Calibrated calendar dates are given as median probability ages in years Before the Common Era (cal. yr BCE) or years Common Era (cal. yr CE), with age ranges of 1 standard deviation (1σ) and 2 standard deviations (2σ) (68.3 % and 95.4 % probability, respectively).

RESULTS

In this study, twenty-two naturally shed reindeer antlers found along the margins of fourteen retreating ice patches and ice caps on high-altitude mountains in western Norway have been radiocarbon dated. The reindeer antlers do not show any signs of been sawed or cut off the skull (which may have been the case if the reindeer were hunted) or any engravings/scrape marks (if the antlers had been handled by humans). The oldest reindeer antler in this study dates to 2201 – 2132 cal. yr BCE (1s age range) (Tables 1 and 2). Two dated antlers

Table 1. Sites (*n* = 14) with naturally shed reindeer antlers (*n* = 22) melted out of ice masses in western Norway. For location (no. 1-14), see Figure 1. State of preservation: C = complete/ near complete, F = fractured, Fr = fragment.

No. Locality	Coordinates (EU89 UTM zone 33)	Altitude (m a.s.l.)	Year	State of preservation	Discovered/ provided by
Sunnmøre					
1-Leirvasshornet	73745.77E/6925588.69N	1533	2021	C	Thomas Skogvold
2-Storhammaren	85148.27E/6901969.25N	1585	1970	C	Jarle Hole
Nordfjord					
3-Gutdalsfjellet	90439.68E/6891952.22N	1320	2021	C, F	Mons Rune Guddal
4-Nonsnibba-1	78209.713E/6873668.104N	1780	2014	C	Kay Roger Haugen
4-Nonsnibba-2	78209.713E/6873668.10N	1780	2014	C	Kay Roger Haugen
4-Nonsnibba-3	78209.713E/6873668.104N	1780	2014	Fr	Rune Holen
4-Nonsnibba-4	78218.969E/6873857.188N	1740	2014	C	Rune Holen
5-Meleinibba	71854.904E/6880918.086N	1567	?	C	Oddvar Auflem
6-Ceciliekruna	66842.5E/6876629.14N	1640	2021	C, F	Torstein Opskar
7-Foraegga	70503.19E/6869484.28N	1645	?	C, F	Olav Kvame
8-Rasmusfjellet	72601.98E/6864043.33N	1685	2023	C, F	Rune Aabrekk
9-Vora	55497.156E/6872008.66N	1430	2010	C, F	Rune Holen
Breheimen					
10-Breheimen-1	106596.56E/6851513.12N	1190	?	?	Liv Byrkjeland
10-Breheimen-2	97636.89E6852867.12N	1600	?	?	Liv Byrkjeland
10-Breheimen-3	102402.34E/6848905.61N	1340	?	?	Liv Byrkjeland
10-Breheimen-4	96991.63E/6852930.58N	1550	?	?	Liv Byrkjeland
Sogn					
11-Fresvikbreen	57425.02E/6792832.717N	1370	2002	Fr	Bjørnar Øyri
Hardanger					
12-Omnsbreen-1	89595.742E/6747416.859N	1520	2012	C	Olav Rondestveit
12-Omnsbreen-2	89513.762E/6747853.207N	1550	2014	F, Fr	Atle Nesje
13- Juklanutane	84177.898E/6730749.398N	1640	2011	C, F	Ingeborg Stakseng
Jotunheimen					
14-Mjølkedalstinden-1	140336.363E/6833307.268N	~1780	2014	C, F	Ragnhild Helsing
14-Mjølkedalstinden-2	140336.363E/6833307.268N	~1780	2014	F, Fr	Ragnhild Helsing

Table 2. Radiocarbon dates and calibrated ages of naturally shed reindeer antlers (*n* = 22) melted out of ice patches and ice caps in western Norway. For location (no. 1-14), see Figure 1. Calibrated calendar dates are given as median probability ages in years before the Common Era (cal. yr BCE) or years Common Era (cal. yr CE), with age ranges of 1 standard deviation (1σ) and 2 standard deviations (2σ) (68.3 % and 95.4 % probability, respectively).

No. Locality	Radiocarbon age BP (yr BP ± 1σ)	Lab. no	Calibrated age* (median probability)	Calibrated ages (CE/BCE)* ± 1σ (68.3 %)	± 2σ (95.4 %)
Sunnmøre					
1-Leirvasshornet	2930 ± 20	TRa-16779	BCE 1137	BCE 1200-1169	BCE 1214-1050
2-Storhammaren	625 ± 30	Poz-151571	CE 1348	CE 1301-1326	CE 1296-1398
Nordfjord					
3-Gutdalsfjellet	470 ± 30	Poz-142503	CE 1435	CE 1425-1447	CE 1409-1458
4-Nonsnibba-1	350 ± 30	Poz-65140	CE 1557	CE 1574-1629	CE 1539-1635
4-Nonsnibba-2	365 ± 30	Poz-65141	CE 1527	CE 1467-1520	CE 1454-1528
4-Nonsnibba-3	360 ± 30	Poz-65142	CE 1545	CE 1473-1521	CE 1550-1634
4-Nonsnibba-4	2075 ± 30	Poz-65143	BCE 87	BCE 116-43	BCE 172-25
5-Meleinibba	130 ± 30	Poz-65139	CE 1834	CE 1832-1892	CE 1798-1942
6-Ceciliekruna	3740 ± 35	Poz-144210	BCE 2146	BCE 2201-2132	BCE 2209-2031
7-Foraegga	420 ± 30	Poz-144716	CE 1462	CE 1439-1478	CE 1427-1509
8-Rasmusfjellet	415 ± 30	Poz-167988	CE 1466	CE 1440-1483	CE 1430-1518
9-Vora	2905 ± 30	Poz-72634	BCE 1093	BCE 1126-1045	BCE 1135-1009
Breheimen					
10-Breheimen-1	Modern	Beta-530368			
10-Breheimen-2	330 ± 30	Beta-530369	CE 1561	CE 1549-1598	CE 1480-1640
10-Breheimen-3	1280 ± 30	Beta-530370	CE 726	CE 677-707	CE 662-775
10-Breheimen-4	580 ± 30	Beta-530371	CE 1348	CE 1323-1356	CE 1305-1365
Sogn					
11-Fresvikbreen	2725 ± 30	Poz-64853	BCE 867	BCE 898-863	BCE 923-810
Hardanger					
12-Omnsbreen-1	835 ± 25	Poz-58927	CE 1220	CE 1208-1232	CE 1174-1264
12-Omnsbreen-2	3680 ± 35	Poz-66391	BCE 2073	BCE 2136-2077	BCE 2144-1953
13-Juklanutane	130 ± 30	Poz-68693	CE 1834	CE 1832-1892	CE 1798-1942
Jotunheimen					
14-Mjølkedalstinden-1	2015 ± 30	Poz-67089	BCE 4	BCE 45-CE25	BCE 55-CE 80
14-Mjølkedalstinden-2	2300 ± 30	Poz-67090	BCE 379	BCE 401-362	BCE 407-353

*Radiocarbon calibration program: Calib ver. 8.20 (Reimer *et al.* 2020).

fall within the period c. 2200 – 2000 cal. yr BCE, but then there is a gap until c. 1200 cal. yr BCE. Single dates fall within the time ranges c. 1200 – 1000, 900 – 800, 400 – 300 cal. yr BCE, as well as c. 700 – 800 and c. 1200 – 1300 cal. yr CE. Two dated antlers are within the time range c. 100 – 1 cal. yr BCE, followed by a gap until c. 700 cal. yr CE. Ten dates (45 %) fall within the time range c. 1200 – 1600 cal. yr CE. The specific details of the dating results can be found in Tables 1 and 2. The reindeer antlers from Leirvasshornet, Gutdalsfjellet, Nonsnibba, and Melheimnibba are located outside the present distribution of wild reindeer in western Norway. The antlers from Storhammaren, Fresvikbreen, and Mjøledalstinden are located adjacent to areas with wild reindeer today. Finally, the reindeer antlers from Ceciliekruna, Foraegga, Omnsbreen, and Juklanutane are from areas with wild reindeer today (Figure 2).

Sunnmøre

Along the margin of a vanishing ice patch on the mountain Leirvasshornet (elevation 1533 m a.s.l.), Stranda municipality, a reindeer antler was found (Figure 3) that was radiocarbon dated to 2930 ± 20 yr BP (1200 – 1169 cal. yr BCE).

At the margin of an ice patch on the mountain Storhammaren (1585 m a.s.l.) in Sunnylven, a reindeer antler was found in 1970 (Figure 4). A sample of the antler was radiocarbon dated to 625 ± 30 yr BP (1301 – 1326 cal. yr CE).

Nordfjord

At the margin of a snow/ice patch on the mountain Gutdalsfjellet north of Hjelledalen, a reindeer antler was found at an altitude of 1320 m a.s.l. in the summer of 2021 (Figure 5). The reindeer antler was dated to 470 ± 30 yr BP (1425 – 1447 cal. yr CE).

Along a retreating margin of an ice patch on the mountain Nonsnibba in Lodalen, two complete reindeer antlers (Nonsnibba-1 and 2) were found at an elevation of 1780 m a.s.l. (Figure 6). Samples Nonsnibba-3 (altitude 1780 m a.s.l.) and Nonsnibba 4 (altitude 1740 m a.s.l.) were found a few weeks later than the first two. Sample Nonsnibba-1 was radiocarbon dated to 350 ± 30 yr BP (1574 – 1629 cal. yr CE). Sample Nonsnibba-2 was radiocarbon dated to 365 ± 30 yr BP (1467 – 1520 cal. yr CE). Sample Nonsnibba-3 was radiocarbon dated to 360 ± 30 yr BP (1473 – 1521 cal. yr CE). Finally, sample Nonsnibba-4 was radiocarbon dated to 2075 ± 30 yr BP (116 – 43 cal. yr BCE).

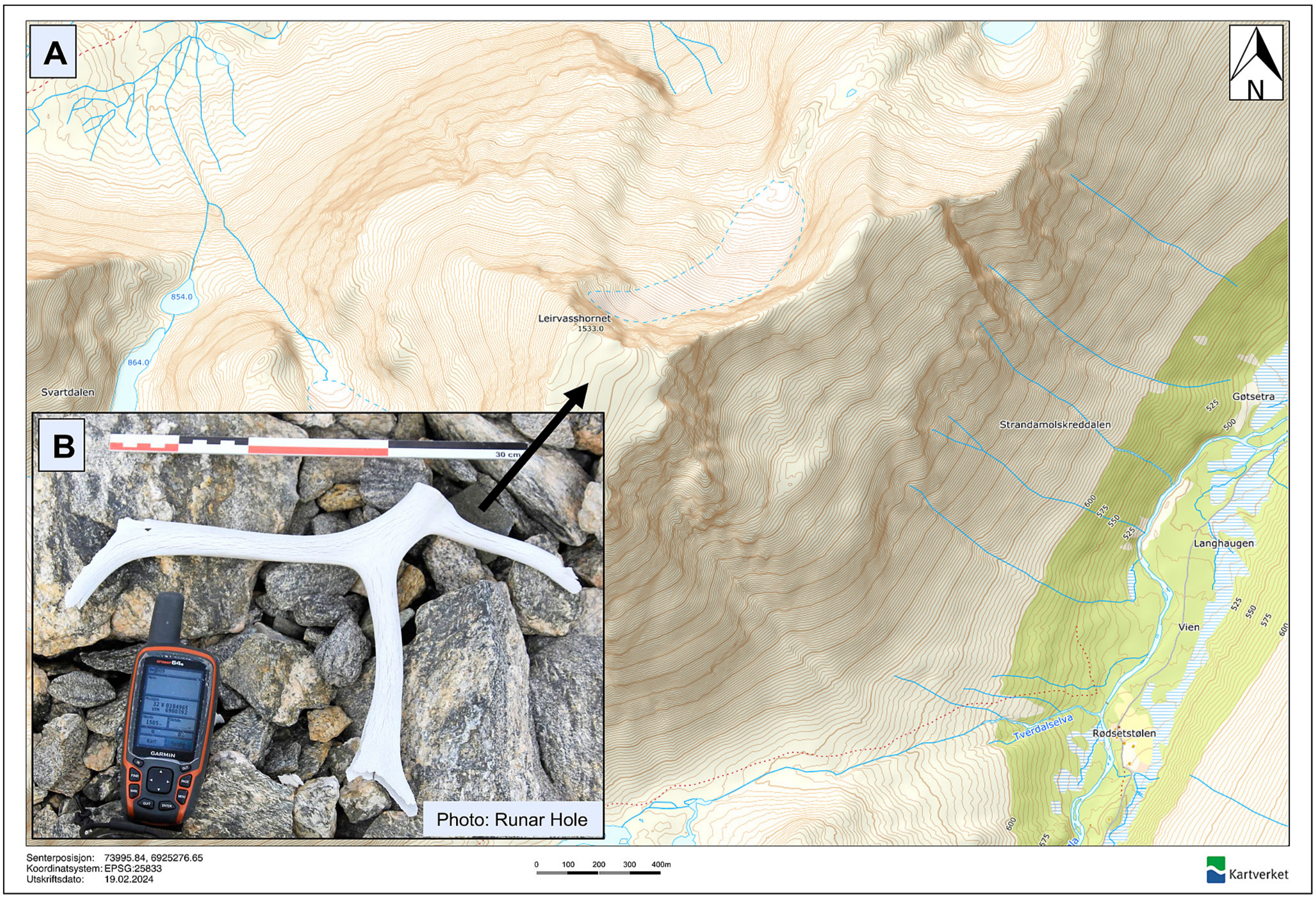

Figure 3. A. Map of the Leirvasshornet area in Sunnmøre. Map source: norgeskart.no. B. Photo of the radiocarbon dated reindeer antler (locality 1-Leirvasshornet). Ruler for scale. Photo: Runar Hole.

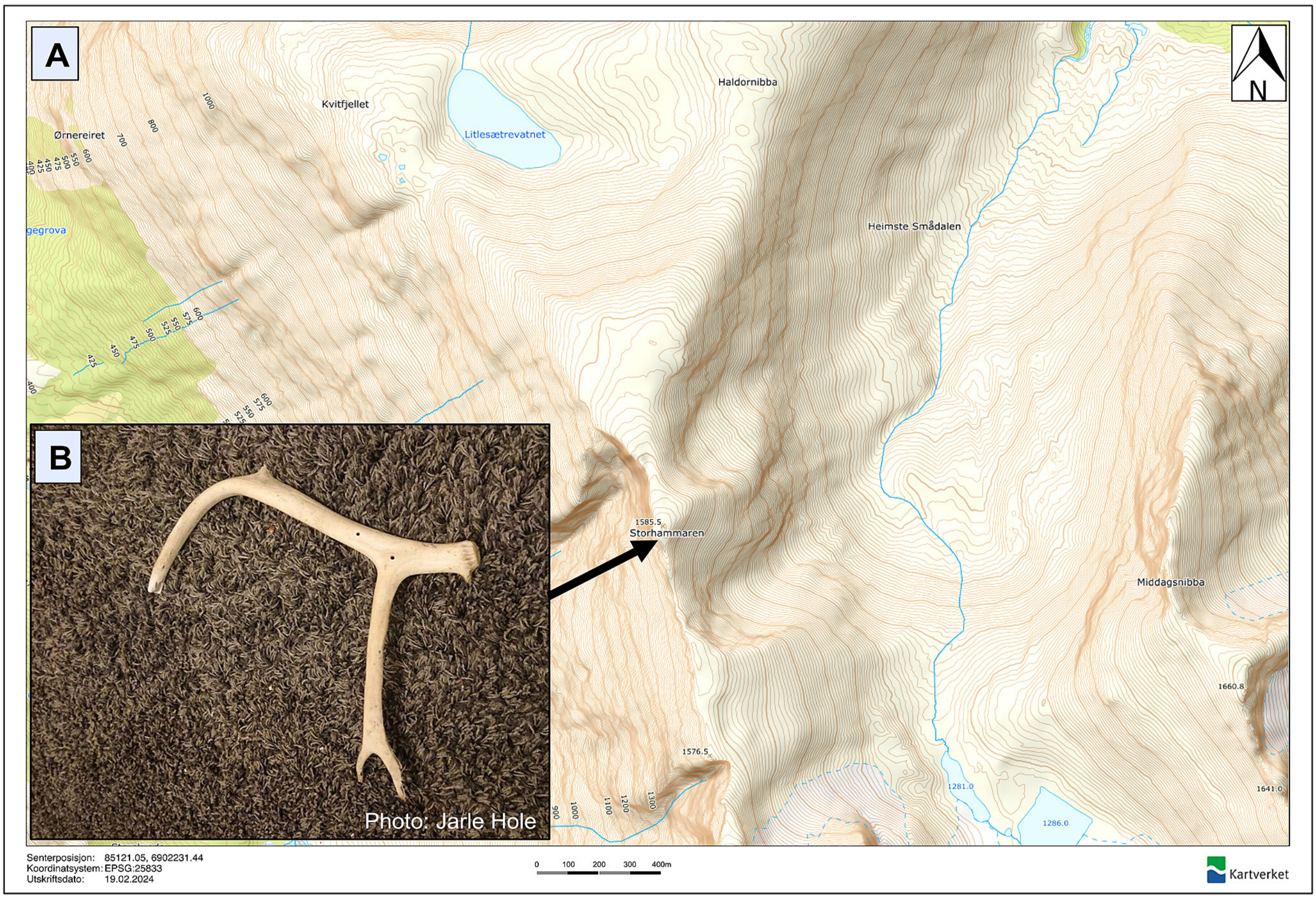

Figure 4. A. Map of the Storhammaren area in Sunnmøre. Map source: norgeskart.no. B. Photo of the radiocarbon dated reindeer antler (locality 2-Storhammaren). Photo: Jarle Hole.

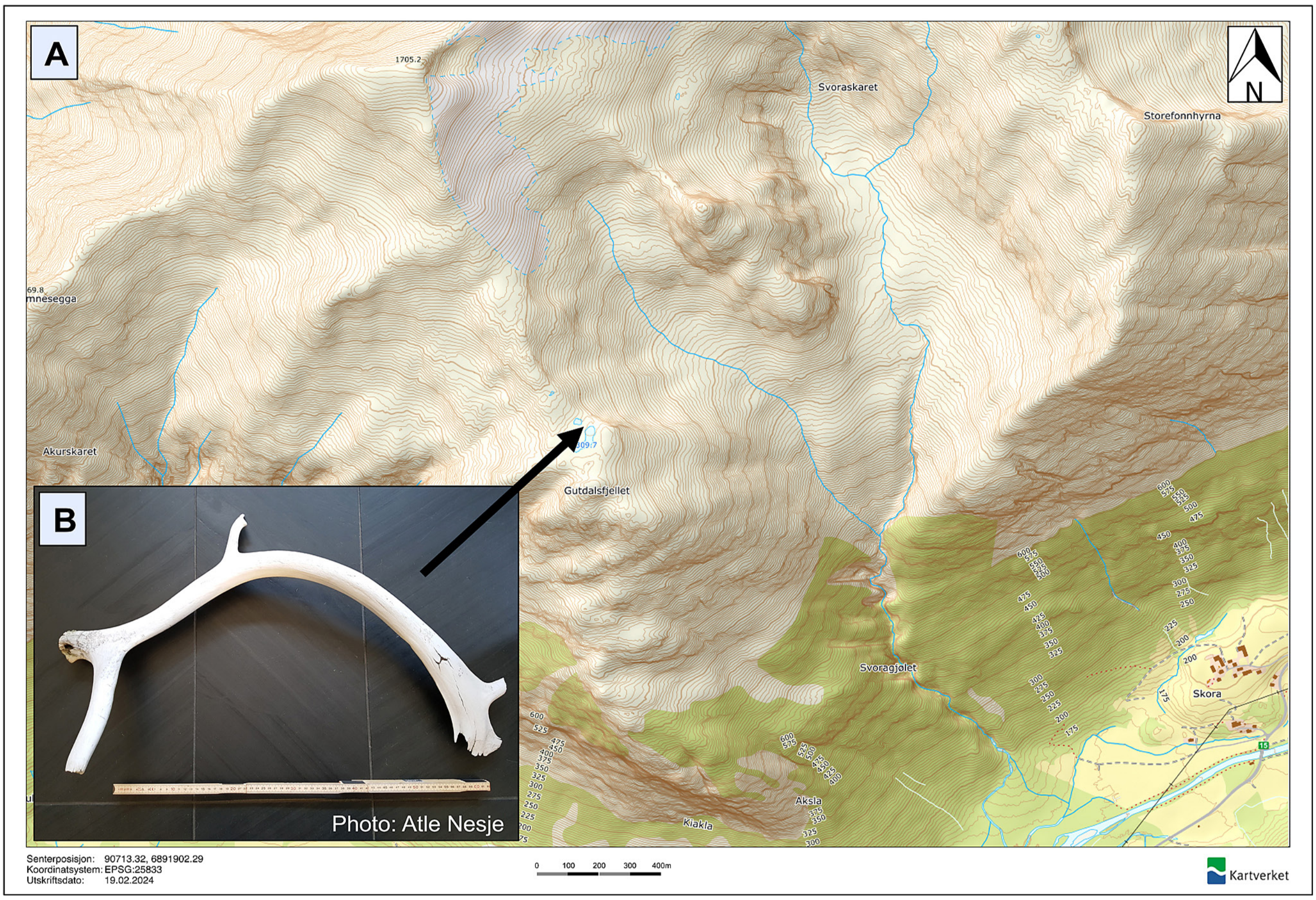

Figure 5. A. Map of the Gutdalsfjellet area in inner Nordfjord. Map source: norgeskart.no. B. Photo of the radiocarbon dated reindeer antler (locality 3-Gutdalsfjellet). Ruler for scale. Photo: Atle Nesje.

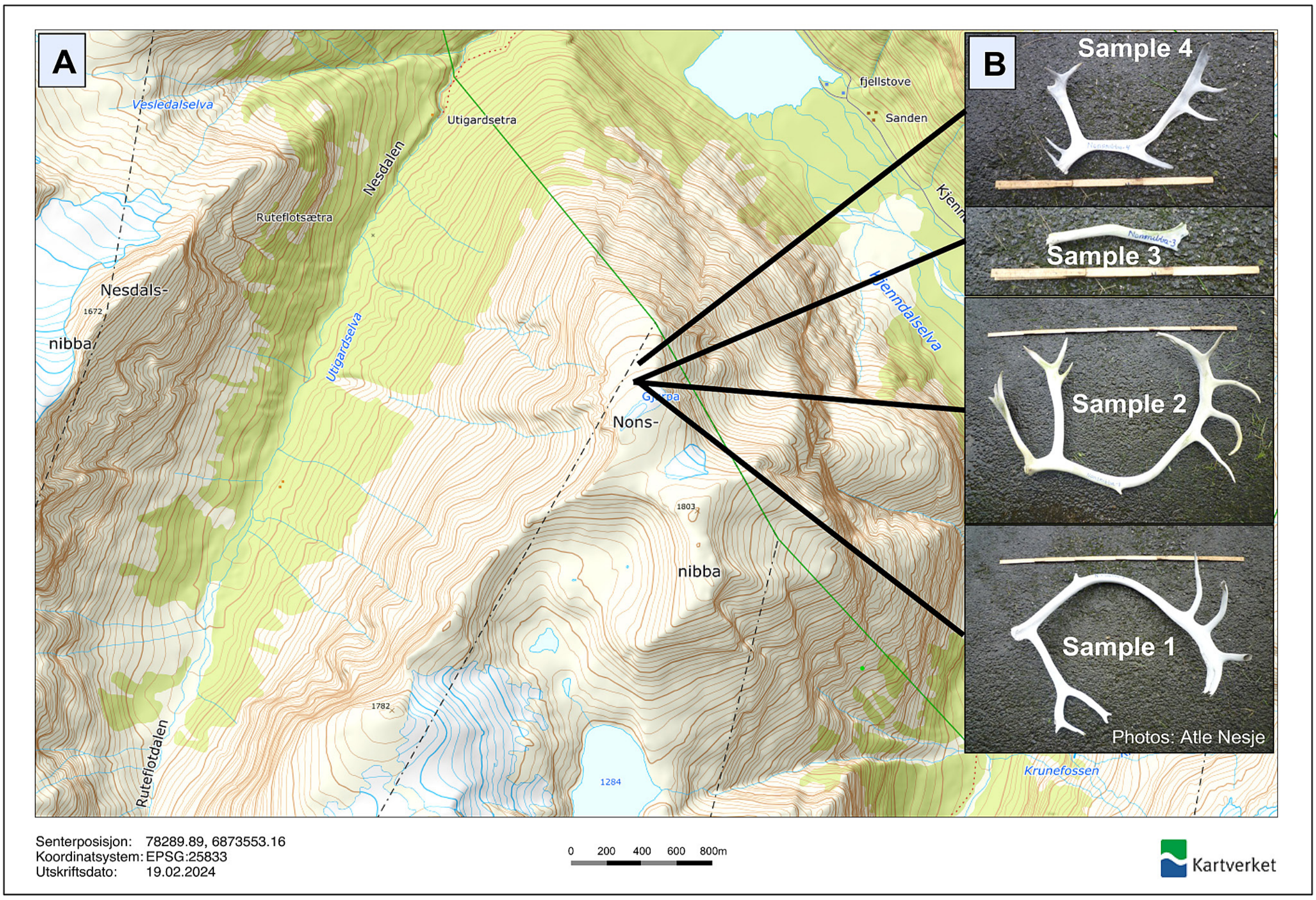

Figure 6. A. Map of the Nonsnibba area in Loen, inner Nordfjord. Map source: norgeskart.no. B. Photos of the radiocarbon dated reindeer antlers (locality 4-Nonsnibba, samples 1-4). Rulers for scale. Photo: Atle Nesje.

At Melheimnibba (1567 m a.s.l.), a reindeer antler was found (Figure 7) and dated to 130 ± 30 yr BP (1832 – 1892 cal. yr CE).

Along a down-melting ice patch on the mountain plateau of Ceciliekruna west of the Oldedalen, at an altitude of 1640 m a.s.l. a reindeer antler was found in the autumn of 2021 (Figure 8). The reindeer antler was radiocarbon dated to 3740 ± 35 yr BP (2201 – 2132 cal. yr BCE). In 1975, 25 domesticated reindeer were introduced to an adjacent area to establish a wild herd of reindeer, and the first hunting on this herd started in 1979.

On the mountain summit of Foraegga, at the margin of the Jostedalsbreen ice cap, a reindeer antler was found at an elevation of 1645 m a.s.l. (Figure 9). A sample of the antler was radiocarbon dated to 420 ± 30 yr BP (1439 – 1478 cal. yr CE).

On the 1680 metre high mountain ridge, locally named “Rasmusfjellet”, that separates Jostedalsbreen’s two western outlet glaciers Briksdalsbreen and Brenndalsbreen, Tore Høgalmen and Gaute Aabrekk found a naturally shed reindeer antler that recently had melted out from underneath the ice cap margin on the plateau summit (Figure 10). A sample of the reindeer antler was dated, yielding a radiocarbon age of 415 ± 30 yr BP (1440 – 1483 cal. yr CE). The date reflects when the antler was shed and incorporated in the ice.

In a topographical depression to the south of the summit of Vora, a reindeer antler was found at an altitude of 1430 m a.s.l. (Figure 11). The antler was radiocarbon dated to 2905 ± 30 yr BP (1126 – 1045 cal. yr BCE).

Breheimen

In the vicinity of the Spørteggbreen glacier in Breheimen, radiocarbon datings of four reindeer antlers (Breheimen-1 to 4) have been reported and radiocarbon dated by Statens naturoppsyn (SNO) Luster (Norwegian Nature Inspectorate) (Figure 12), all of which have been interpreted to have melted out of ice patches. Sample Breheimen-1 yielded a modern age (<1950 yr CE). Breheimen-2 was dated to 330 ± 30 yr BP (1549 – 1598 cal. yr CE), Breheimen-3 was radiocarbon dated to 1280 ± 30 yr BP (677 – 707 cal. yr CE), and finally Breheimen-4 was dated to 580 ± 30 yr BP (1323 – 1356 cal. yr CE).

Sogn

At the SE margin of Fresvikbreen, a fragment of a reindeer antler was found 1370 m a.s.l. in 2002 (Figure 13). A sample of the antler was radiocarbon dated to 2725 ± 30 yr BP (898 – 863 cal. yr BCE).

Hardanger

A complete reindeer antler was found at the margin of Omnsbreen (1520 m a.s.l.) north of Finse (Figure 14A, B). The reindeer antler (sample Omnsbreen-1) was radiocarbon dated to 835 ± 25 yr BP (1208 – 1232 cal. yr CE).

An antler fragment (sample Omnsbreen-2, Figure 14C) was found along the margin of Omnbreen in September 2014. It has a weathered, irregular surface. The antler was radiocarbon dated to 3680 ± 35 yr BP (2136 – 2077 cal. yr BCE).

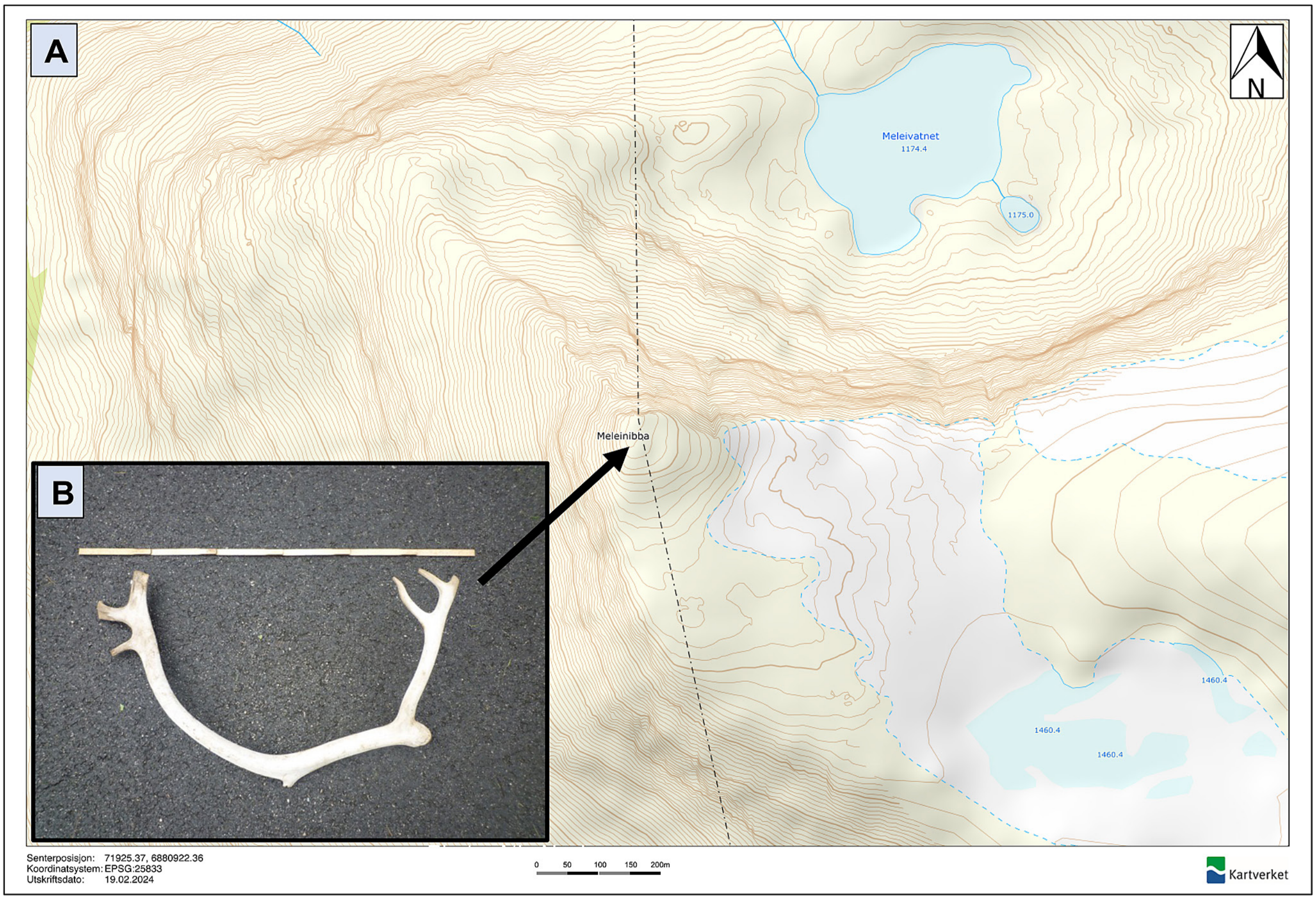

Figure 7. A. Map of the Melheimnibba area in inner Nordfjord. Map source: norgeskart.no. B. Photo of the radiocarbon dated reindeer antler (locality 5-Meleinibba). Ruler for scale. Photo: Atle Nesje.

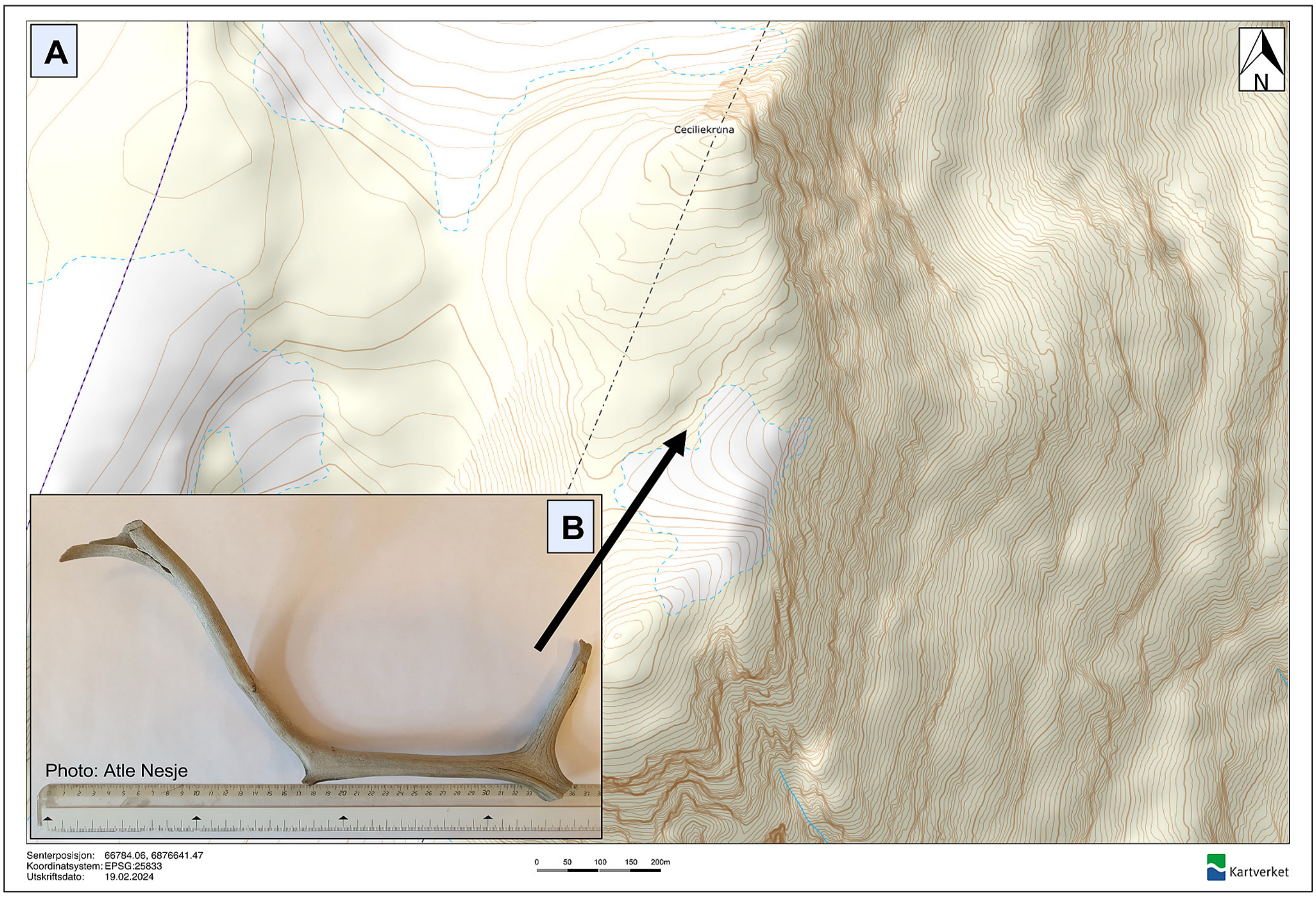

Figure 8. A. Map of the Ceciliekruna area in inner Nordfjord. Map source: norgeskart.no. B. Photo of the radiocarbon dated reindeer antler (locality 6-Cecilikruna). Ruler for scale. Photo: Atle Nesje.

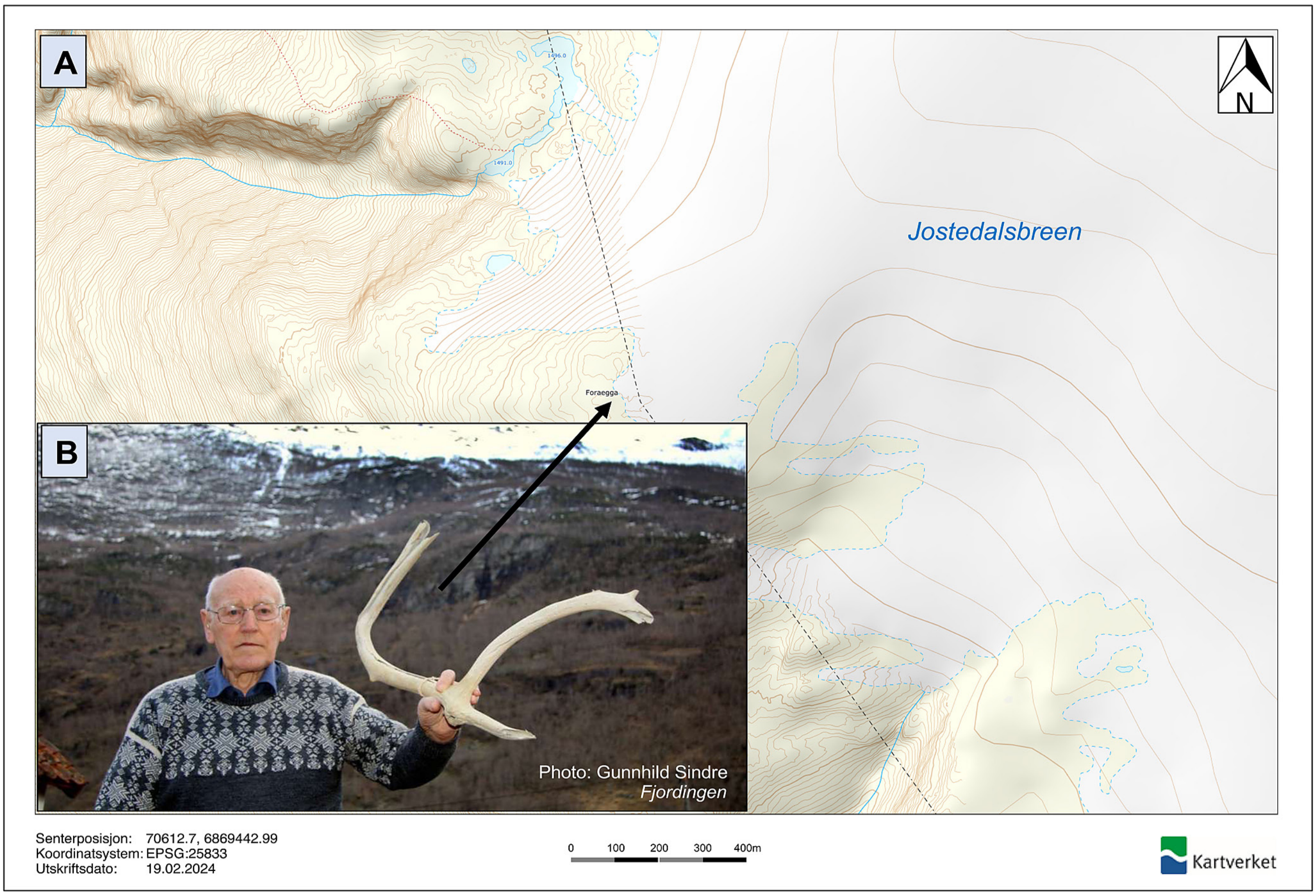

Figure 9. A. Map of the Foraegga area at the margin of the Jostedalsbreen ice cap in inner Nordfjord. Map source: norgeskart.no. B. Photo of the finder, Olav Kvame, with the radiocarbon dated reindeer antler (locality 7-Foraegga). Photo: Gunnhild Sindre, *Fjordingen* newspaper.

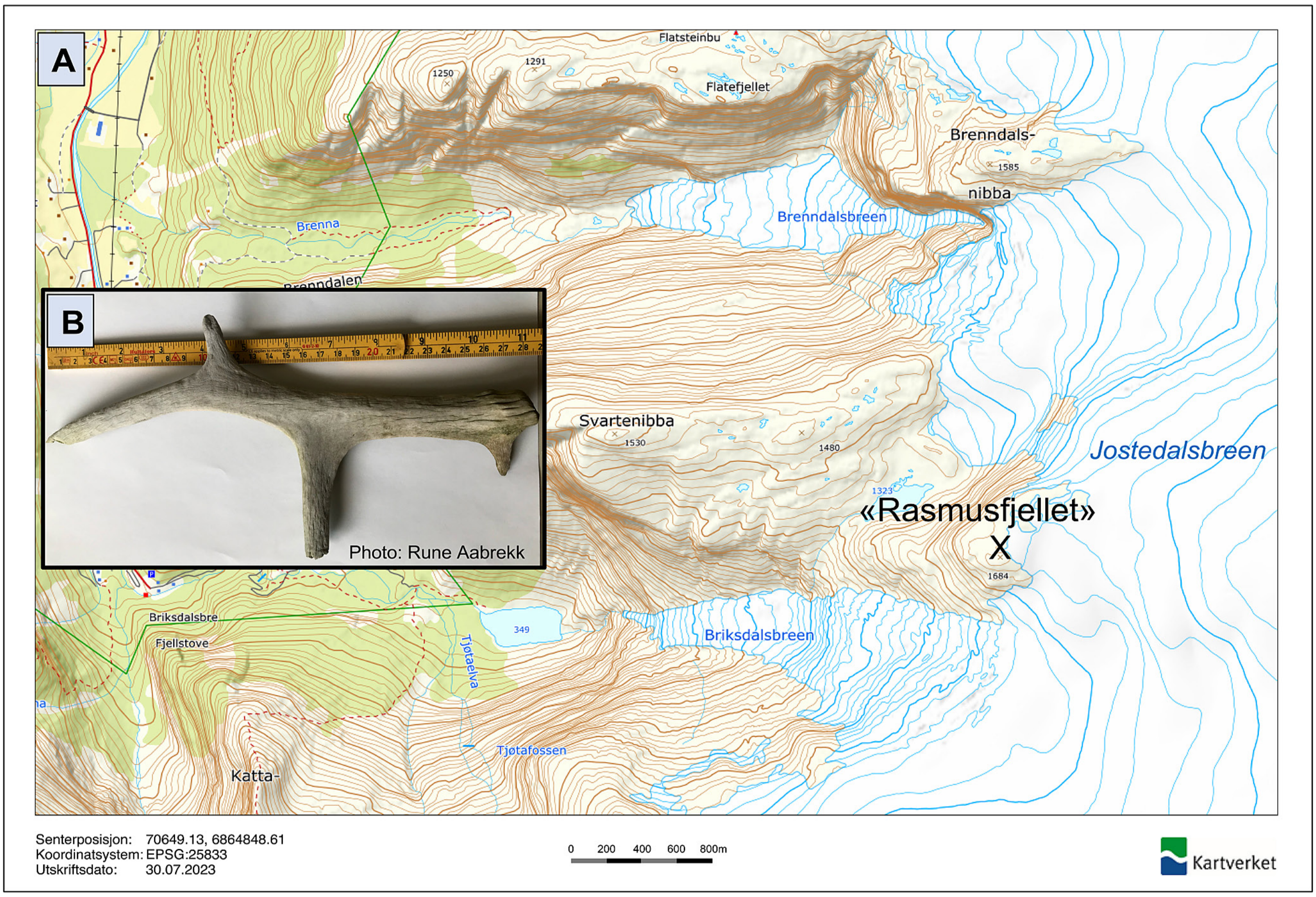

Figure 10. A. Map of the Rasmusfjellet area in in Oldedalen, inner Nordfjord. Map source: norgeskart.no. B. Photo of the radiocarbon dated reindeer antler (locality 8-Rasmusfjellet). Ruler for scale. Photo: Rune Aabrekk.

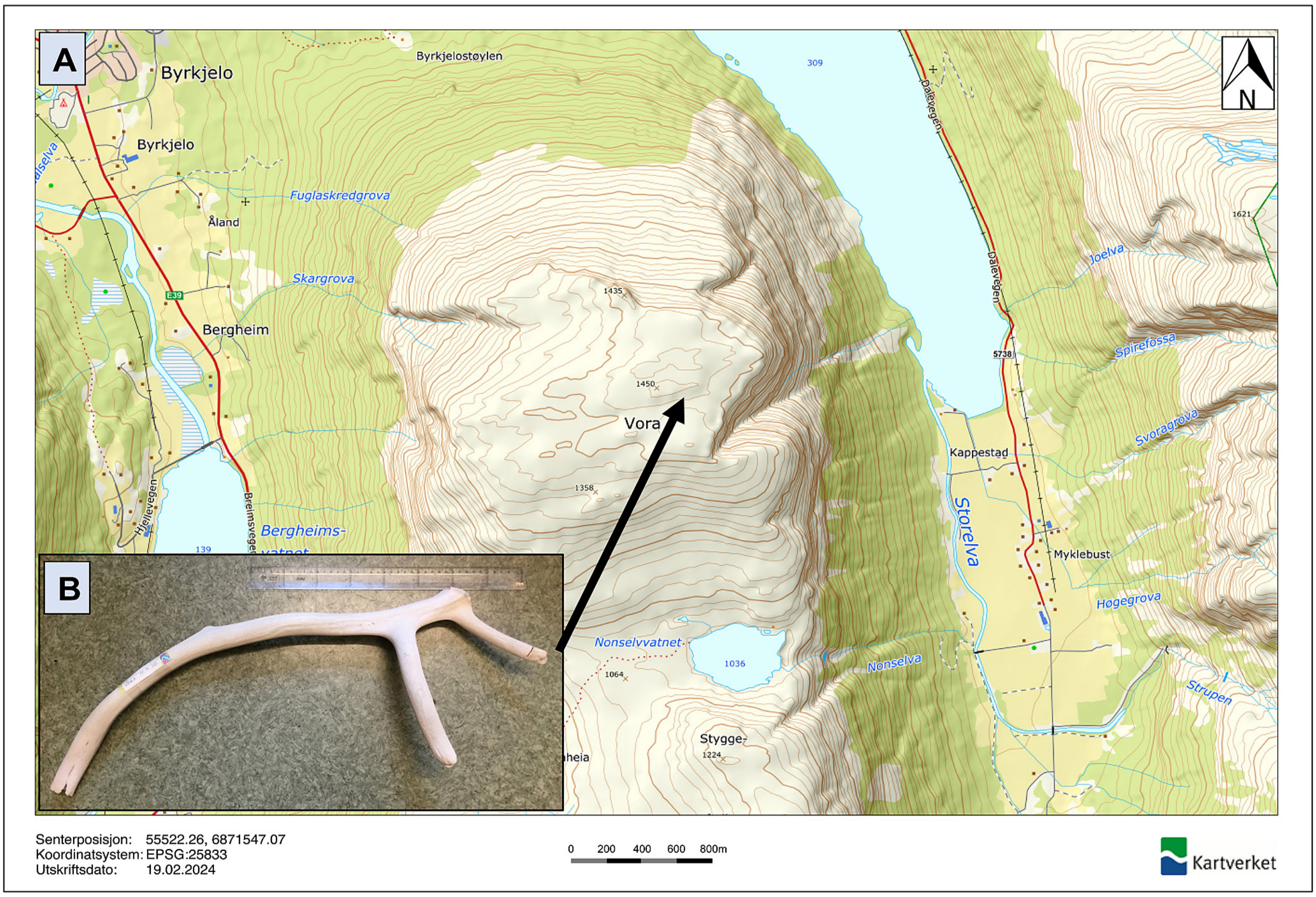

Figure 11. A. Map of the Vora area in Nordfjord. Map source: norgeskart.no. B. Photo of the radiocarbon dated reindeer antler (locality 9-Vora). Ruler for scale. Photo: Atle Nesje.

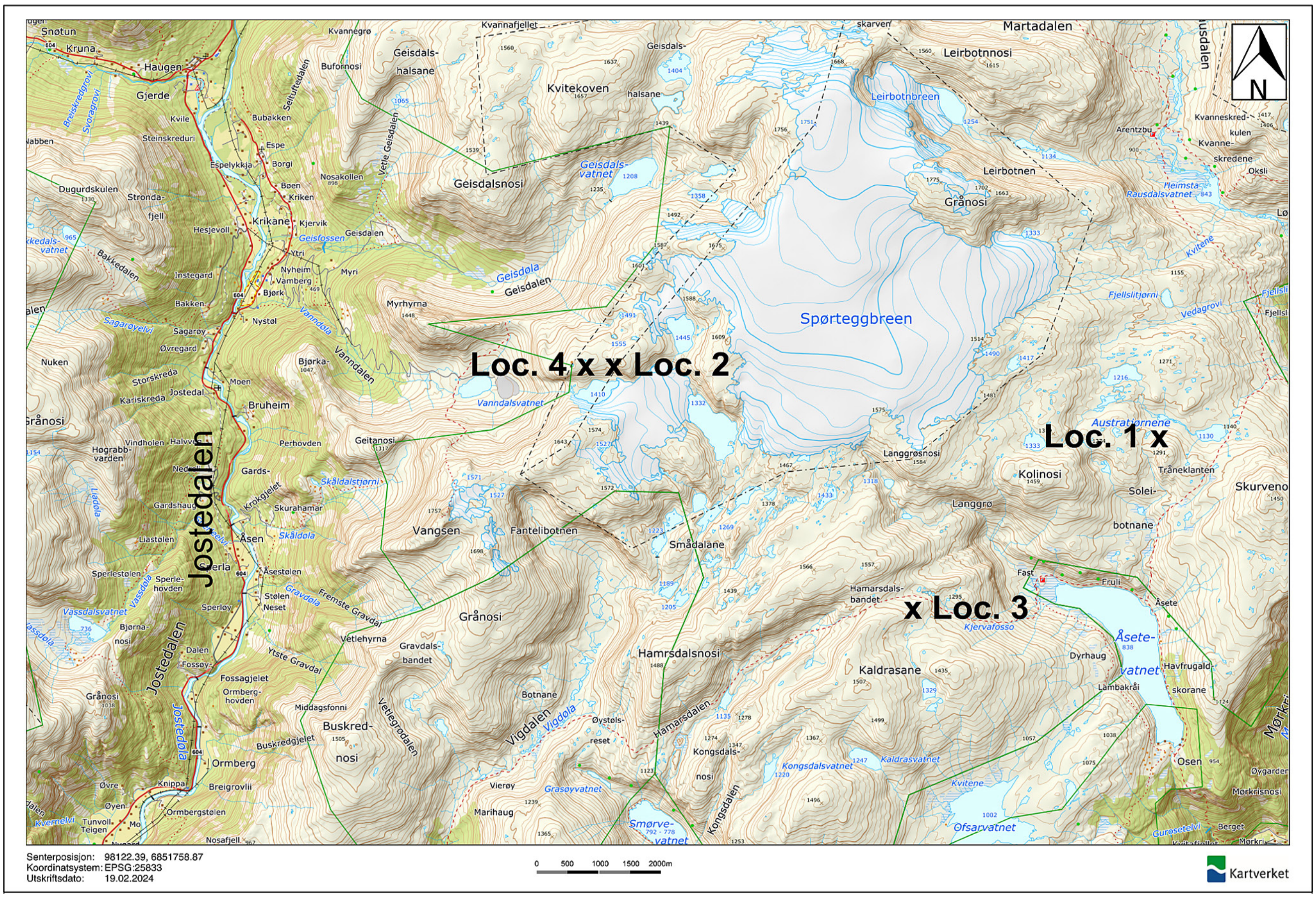

Figure 12. A. Map of the Spørteggbreen area east of Jostedalen in Breheimen. Map source: norgeskart.no. Locations of the dated reindeer antlers 1-4 (locality 10-Breheimen) are indicated.

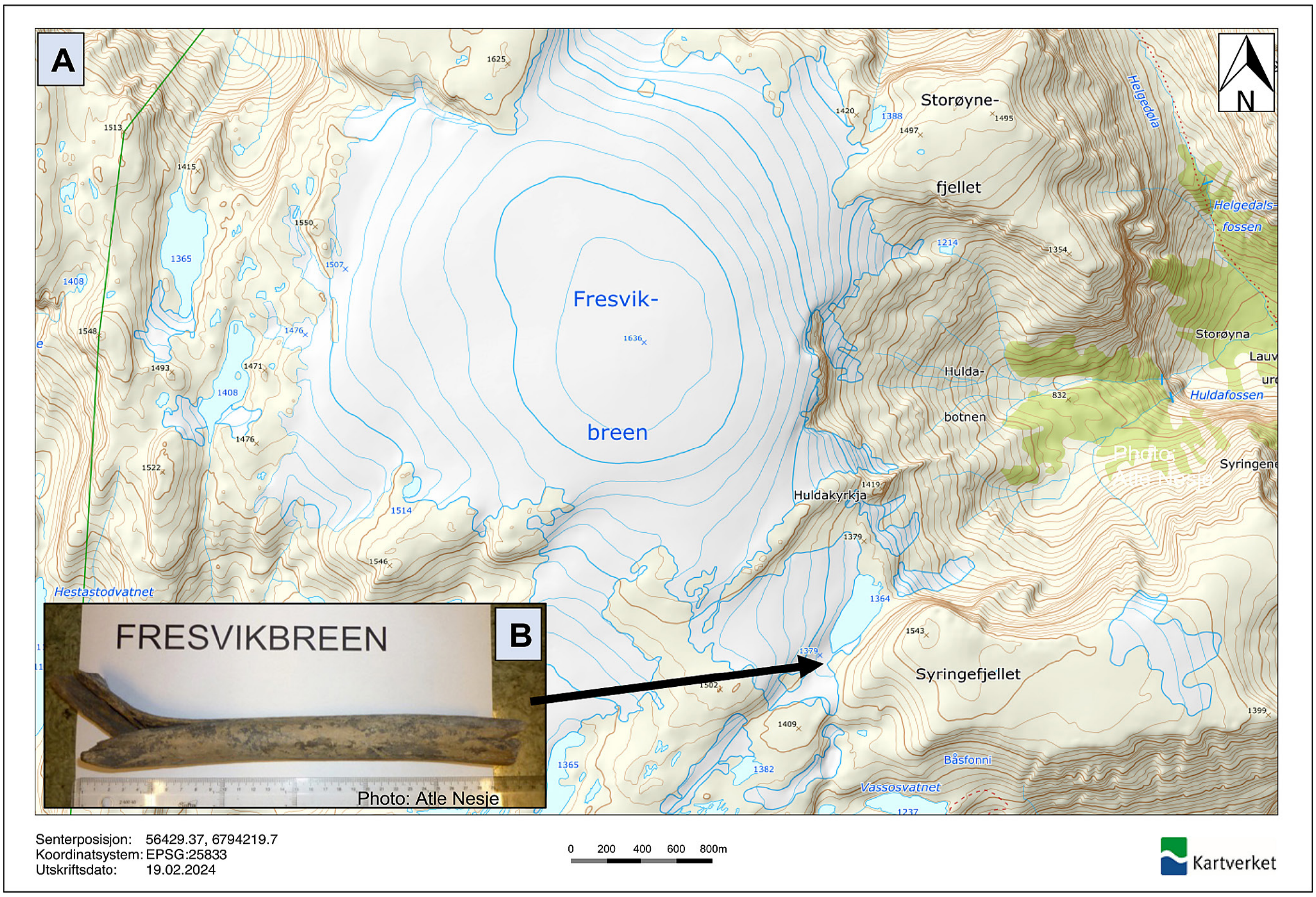

Figure 13. A. Map of the Fresvikbreen area in Sogn. Source: norgeibilder.no. B. Photo of the radiocarbon dated reindeer antler (locality 11-Fresvikbreen). Ruler for scale. Photo: Atle Nesje.

On Juklanutane (1640 m a.s.l.) at the southern margin of Hardangerjøkulen, a reindeer antler was found in August 2011 (Figure 15). A sample of the antler was radiocarbon dated to 130 ± 30 yr BP (1832 – 1892 cal. yr CE).

Jotunheimen

Along the margin of a glacier below the mountain Mjølkedalstinden, at an altitude of 1780 m a.s.l. in Luster municipality in western Jotunheimen, two reindeer antlers were found in the summer of 2014 (Figure 16). Radiocarbon dating of Mjølkedalstind-1 and -2 yielded ages of 2015 ± 30 yr BP (45 cal. yr BCE – 25 cal. yr CE) and 2300 ± 30 yr BP (401 – 362 cal. yr BCE), respectively.

DISCUSSION

Snow fields, ice patches, and minor ice caps attract animals that take advantage of the cool environment in the summer season (e.g. Rosvold 2016). Reindeer, for example, seek to ice patches on warm summer days to escape insects (e.g. Ion & Kershaw 1989; Anderson & Nilssen 1998; Hagemoen & Reimers 2002). As a consequence, various reindeer remains (e.g. hair, bones, antlers, droppings, and archaeological artifacts related to reindeer hunting) are presently melting out of ice patches and ice caps as a consequence of negative mass balance (mainly due to rising summer temperatures) during the recent decades (Andreassen *et al.* 2022), in particular since the turn into the 21st century (Rosvold 2018a, b; Pilø *et al.* 2018, 2021). In Oppland County, more than 900 specimens of faunal remains have been studied from 18 sites, and faunal remains have been recovered from more than 20 mountain ice patches (Rosvold 2018a). As wild and domesticated reindeer still frequent these ice patches, the faunal remains may be of historic or modern age. However, radiocarbon dating of reindeer antlers from Langfonne in Jotunheimen has shown their considerable age, with the oldest naturally shed antler dated to 4840 – 4650 cal. yr BP (2803 – 2769 cal. yr BCE) (Pilø *et al.* 2021). To be preserved for decades, centuries, and millennia, the reindeer antlers were most likely incorporated in the snow/ice during late fall and early winter, and they were subsequently buried in the ice. If the antlers had been exposed on the surface for some time, they would most likely have disintegrated or eaten by scavengers. The shed reindeer antlers dated in this study, along with the naturally shed antlers at Langfonne in Jotunheimen dated by Pilø *et al.* (2021), are evidently not related to hunting.

Some of the antlers studied here (e.g. samples 3-Gutdalsfjellet, 6-Ceciliekruna, 7-Foraegga, 8-Rasmusfjellet, 9-Vora, 11-Fresvikbreen, 12-Omnsbreen-2, 13-Juklanutane, 14-Mjøledalstinden) are fractured or crushed and they may therefore have been subject to downslope movement/displacement due to basal sliding, internal deformation/movement in the ice mass due to the weight of the overlying snow and ice (Jarret 2019), and due to transport by supraglacial meltwater (Pilø *et al.* 2021). The thermal regime of the ice patches where the reindeer antlers were found has not been studied, however, some of the thin and high-lying alpine ice patches may have been cold-based since they are underlain by discontinuous or sporadic permafrost (Ødegård *et al.* 2017). Lower-lying ice patches, on the other hand, may have been on the pressure melting point (warm-based), especially in mild periods (Ødegård *et al.* 2017). Some of the dated reindeer antlers

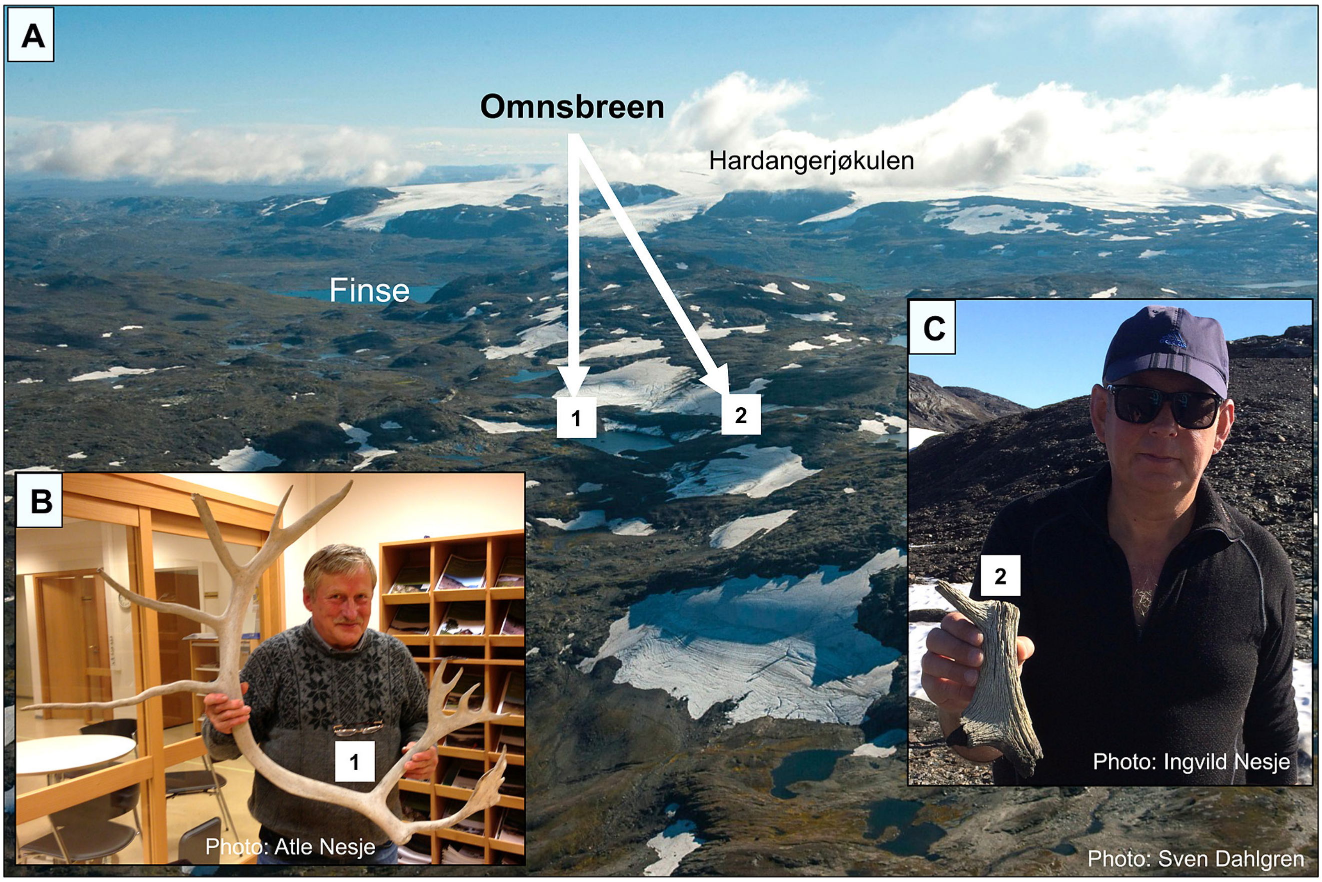

Figure 14. A. Photo of the Omnsbreen area north of Finse and Hardangerjøkulen. View toward south. Photo: Sven Dahlgren. B. Photo of the finder of sample 1, Olav Rondestveit, and the radiocarbon dated reindeer antler (locality 12-Omnsbreen-1). Photo: Atle Nesje. C. Photo of the finder of sample 2, Atle Nesje, and the radiocarbon dated reindeer antler (locality 12-Omnsbreen-2). Photo: Ingvild Nesje.

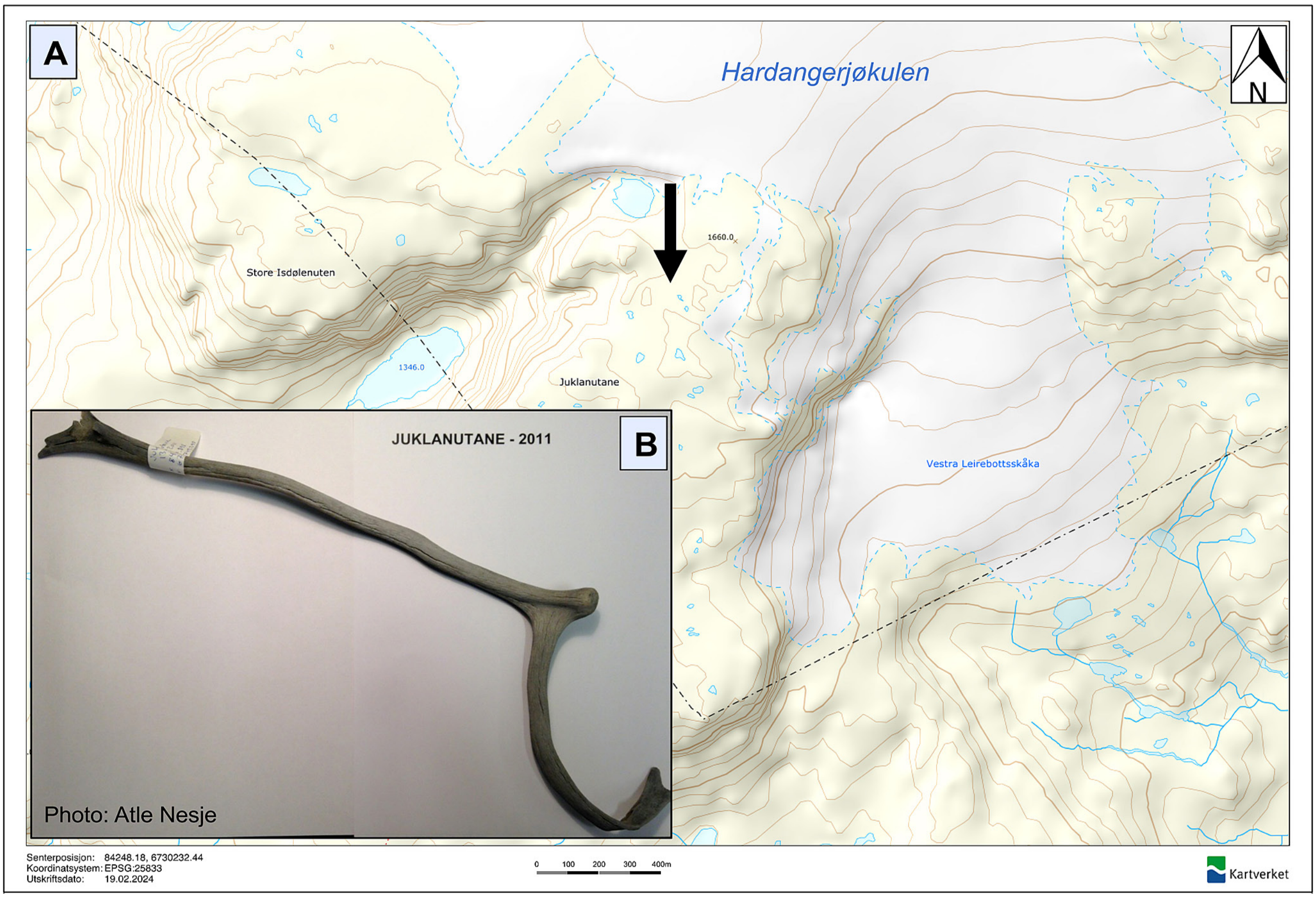

Figure 15. A. Map of the Juklanutane area south of Hardangerjøkulen. Map source: norgeskart.no. B. Photo of the radiocarbon dated reindeer antler (locality 13-Juklanutane). Photo: Atle Nesje.

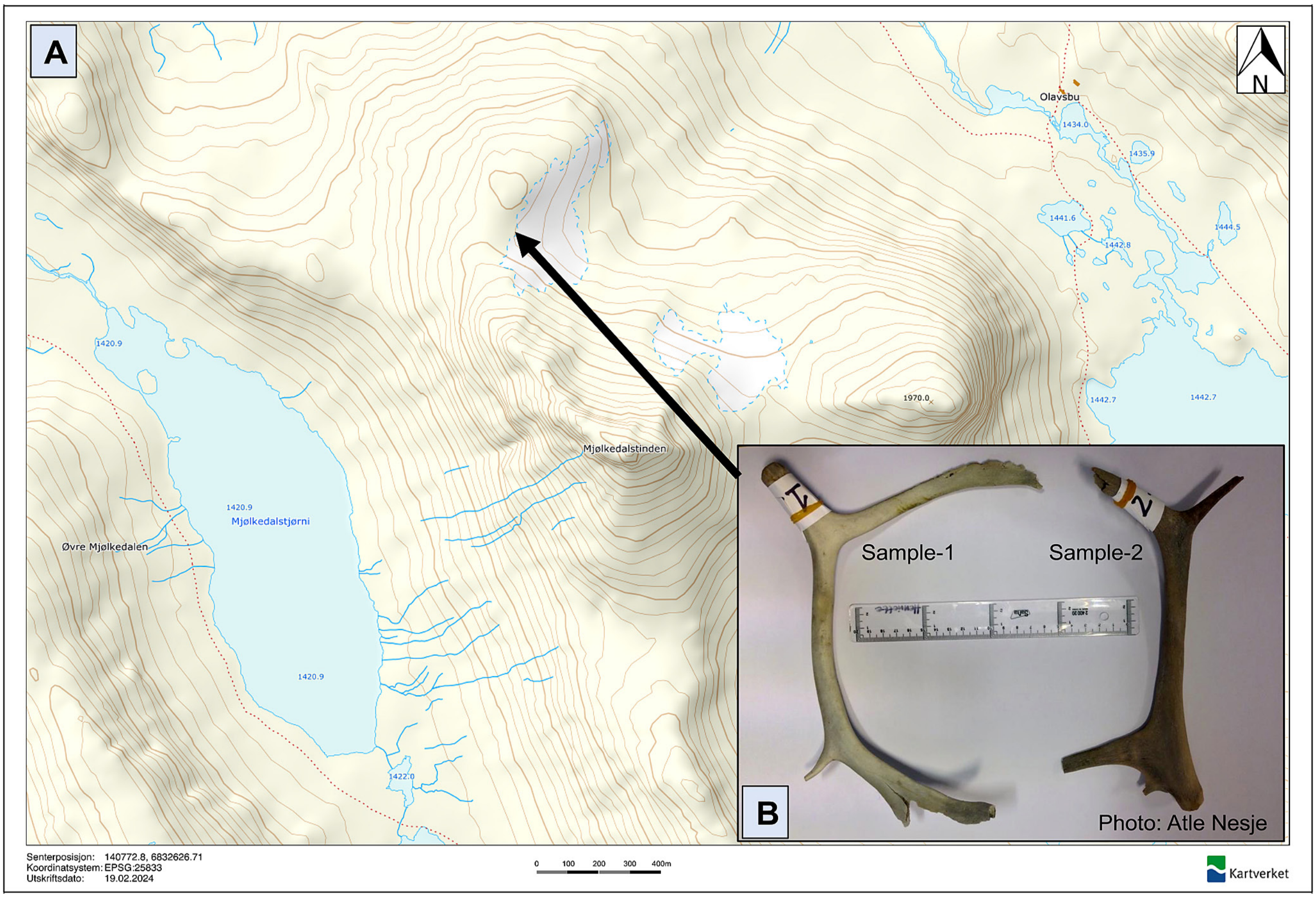

Figure 16. A. Map of the Mjølkedalstinden area in western Jotunheimen. Map source: norgeskart.no. B. Photo of the radiocarbon dated reindeer antlers (locality 14-Mjølkedalstinden). Ruler for scale. Photo: Atle Nesje

(e.g. samples 1-Leirvasshornet, 2-Storhammaren, 4-Nonsnibba, 5-Meleinibba, 12-Omnsbreen-1) are, however, fairly well preserved, and this suggests that they have not been subject to basal sliding and crushing. Layering seen as alternating light and dark bands observed in some of the ice patches may indicate the cumulative growth of the ice patches. Discordant ice layers, on the other hand, most likely indicate shorter periods of surface melting (Ødegård *et al*. 2017).

Studies of the Holocene development of modern Norwegian mountain glaciers indicate that most glaciers were melted completely during the early to mid-Holocene, and that the glaciers started to regrow from c. 6000 – 4000 cal. yr BP. Most Norwegian glaciers reached their maximum LIA extent during the mid 18th century (Nesje 2009; Nesje & Matthews 2024). The ages of the reindeer antlers most likely reflect the time when the antlers were shed and subsequently buried in the ice patches.

More than half of the twenty-two dated reindeer antlers in this study predate the LIA, indicating that the antlers were incorporated and buried when the ice masses grew due to the Northern Hemisphere climate deterioration during the Late Holocene (Neoglacial) period, including the early phase of the LIA (e.g. Grove 2004). Good preservation conditions prevailed during the LIA, with extensive ice and snow cover in the high mountains in southern Norway (Pilø *et al*. 2018, 2021), as exemplified in Figure 17 by the mean ELA variations at Jostedalsbreen [adapted from Nesje & Matthews (2024)]. A mean low ELA reflects periods of extensive/advanced ice masses, whereas a mean high ELA reflects periods of smaller, less extensive glaciers and ice patches. The first group of finds between c. 2200 and 2000 cal. yr BCE is apparently associated with a significant contemporaneous lowering of the ELA at Jostedalsbreen (and elsewhere in western Norway). Similarly, the later groups of finds are also apparently related to periods when the ELA at Jostedalsbreen was lower than at present.

During its mid-18th century maximum LIA position, the Jostedalsbreen ice cap was 20% larger than at present (2019 CE) (Carrivick *et al*. 2022; Andreassen *et al*. 2023). During the LIA maximum, Hardangerjøkulen covered an area of 110 km^2 (Weber *et al*. 2019), and in 2019 the ice cap had an area extent of c. 64 km^2 (Andreassen 2022). Thus, the ice cap was 72% larger during the LIA than in 2019. The preservation conditions were most likely best if the reindeer antlers were shed and incorporated in the ice in the central, thickest part of a growing ice patch, and less favourable if the reindeer antlers were incorporated close to the margins of retreating perennial snowfields and ice patches. In the latter case, the antlers would most like have soon melted out and been exposed, thus reducing the possibility for long-term preservation in the ice. Because the winter accumulation/mass balance on most ice patches is strongly influenced by wind transport of dry snow, artifacts that were incorporated in leeward terrain depressions of prevailing wind direction(s), in north-facing slopes receiving less short-wave radiation, or among big boulders have the highest preservation potential.

Over the last decades, a great number of mammal remains and archaeological objects/artifacts have emerged from underneath receding ice patches around the world (e.g. Farnell *et al*. 2004; Callanan 2012, 2013, 2016; Andrews & MacKay 2012; Meulendyk *et al*. 2012; Nesje *et al*. 2012; Recklin 2013; Brunswig 2014; Dixon *et al*. 2014; Dance 2015; Ramstad 2015; Rosvold 2018a, b; Pilø *et al*. 2018; Jarret 2019; Taylor *et al*. 2021; Skar & Rosvold 2022). Older reindeer antlers that have emerged from melting ice masses have previously been dated from Jotunheimen, central southern Norway (Pilø *et al*. 2018). The melt-out of Late Holocene reindeer antlers in western Norway therefore follows both a Scandinavian and a global pattern.

Due to global warming, melting of ice patches in Scandinavia and other glaciated areas on Earth is expected to continue in the coming decades, and therefore older ice is expected to be exposed. In areas where wild reindeer live at present, or have been distributed in prehistoric times, older antlers from ice patches than have emerged and dated up to now are therefore expected to melt out of ice patches in the coming years.

CONCLUSIONS

In this study, twenty-two naturally shed reindeer antlers found along retreating and down-wasting ice patches and ice caps at fourteen mountains in western Norway are reported and radiocarbon dated. The oldest reindeer antler dates to 2201–2132 cal. yr BCE. Distributed in 100-year time ranges, two dated antlers fall within the age range c. 2200 to 2000 cal. yr BCE. No antlers date to the period between c. 2000 to 1200 cal. yr BCE. Four single dates fall within the time range c. 1200 – 1000, 900 – 800, and 400 – 300 cal. yr BCE. Two dates are within the time range c. 100 – 1 cal. yr BCE, followed by a gap until c. 700 cal. yr CE. One date falls within the time-period c. 700 to 800 cal. yr CE, followed by a gap until c. 1200 cal. yr CE. Ten dates fall within the time range c. 1200–1800 cal. yr CE, the highest number (*n*

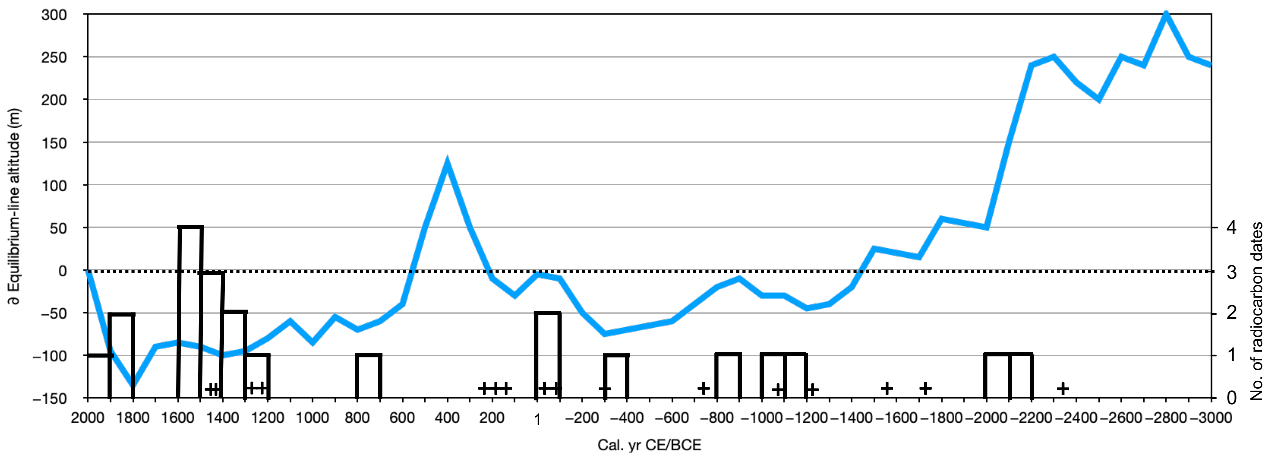

Figure 17. Histogram (100-yr intervals) of the calibrated ages of the reindeer antlers (*n* = 22) in this study plotted together with equilibrium-line altitude (ELA) variations at the Jostedalsbreen ice cap (adapted from Nesje & Matthews 2024). The mean modern ELA is indicated by the punctuated line. + Calibrated ages of dated, naturally shed reindeer antlers at the Langfonne ice patch in eastern Jotunheimen (Pilø *et al*. 2021).

= 4) between c. 1500 and 1600 cal. yr CE, i.e. during the early phase of the LIA. Finally, two antlers were dated to c. 1800–1900 cal. yr CE.

The climate deterioration during the Neoglacial period, including the early phase of the LIA, provided good preservation conditions for the reindeer antlers, with extensive ice and snow cover in the high mountains in western Norway. A significant glacier retreat in southern Norway, starting around 1930 CE, is considered to mark the termination of the LIA (e.g. Nesje & Matthews 2024). A rise in summer temperatures in western Norway during the last decades, in particular since the beginning of the 21st century, has caused a significant reduction in the volume and areal extent of ice patches, ice caps, and perennial snow fields in southern Norway. This has caused that reindeer antlers buried in ice and snow for up to c. 4200 years, have melted out. The emergence of reindeer antlers from melting ice masses in western Norway follows a Norwegian/Scandinavian (Swedish), as well as a global pattern, with numerous finds from melting ice masses.

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