Paleomagnetic correlations between scandinavian ice-sheet fluctuations and greenland dansgaard–oeschger events, 45,000–25,000 yr B.P.

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Abstract

Two paleomagnetic excursions, the Skjong correlated with the Laschamp (about 41,000 GISP2 yr B.P.) and the Valderhaug correlated with the Mono Lake (about 34,000 GISP2 yr B.P.), have been identified in stratigraphic superposition in laminated clay deposited in ice-dammed lakes in three large caves in western Norway. During both periods the margin of the Scandinavian Ice Sheet advanced and reached the continental shelf beyond the outermost coastline. The mild, 4000-yr-long Ålesund interstade, when the coast and probably much of the hinterland were ice-free, separated the two glacial advances. The two paleomagnetic excursions have also been indirectly identified as increased fluxes of ^{36}Cl and ^{10}Be in the GRIP ice core, Greenland. This article presents a correlation between ice-margin fluctuations of the Scandinavian Ice Sheet and the stratigraphy of GRIP/GISP cores, using the paleomagnetic excursions and the ^{36}Cl and ^{10}Be peaks and thus circumventing the application of different dates or time scales. Some of the fluctuations of the Scandinavian Ice Sheet were of the "Allerød/Younger Dryas type" in the sense that its margin retreated during mild interstades on Greenland and readvanced during cold stades. However, some fluctuations were apparently not in phase with the Greenland climate.

Author Keywords: Scandinavian Ice Sheet fluctuations; Ålesund interstade; Laschamp excursion; Mono Lake excursion; Dansgaard–Oeschger oscillations

Introduction

Signals of rapid and large-amplitude Dansgaard–Oeschger (D-O) climatic events are reproduced in ice cores from different locations in Greenland [16 and 17] and subsequently identified as paleoceanographic changes in the North Atlantic [9] and tropical Atlantic [32], vegetation changes on the Iberian Peninsula [33], and glacial fluctuations monitored by ice-rafted detritus in marine cores [13]. However, how the Scandinavian Ice Sheet reacted to, or interplayed with, the D-O oscillations is hardly documented by field observations, except for the last deglaciation (e.g., the Allerød–Younger Dryas) [8]. There are several reasons for the scarcity of documented older oscillations. The most obvious is that the ice sheet eroded and removed nearly all older deposits during the last glacial maximum (LGM), about 20,000 yr B. P.

Correlations are also problematic because pre-LGM sediments are difficult to date with the accuracy required to correlate them with the short-lived D-O events. For ^{14}C-dated events the calibration to "calendar" years, and even correction for marine reservoir ages, easily introduces uncertainties larger than the duration of a half, and even a full, D-O cycle. The GISP and GRIP time scales now agree better than before [17], but the translation of ice-core years to calibrated or uncalibrated ^{14}C years is still uncertain enough to complicate correlations based only on dates.

In this article we correlate recorded fluctuations of the Scandinavian Ice Sheet in the time interval 43,000–26,000 GISP2 yr B.P. with D-O events in Greenland by using paleomagnetic directional excursions in deposits from western Norway and fluctuations in cosmogenic isotopes found in Greenland ice cores. This can be done because during a magnetic excursion the geomagnetic field is weakened, causing higher production of the cosmogenic isotopes ^{10}Be and ^{36}Cl in the atmosphere and therefore higher content of these isotopes in snow deposited on the Greenland Ice Sheet. Thus we circumvent the problem of converting ^{14}C ages to ice-core years. The paleomagnetic excursions and magnetic-field intensity are also recorded in marine cores from the North Atlantic, which we therefore also use for the correlations.

Paleomagnetic excursions in the ice cores and innorth atlantic marine cores

Two paleomagnetic excursions are described from the period 50,000–25,000 yr B.P. The oldest, Laschamp, is generally accepted as an excursion of the dipole field. [19] assigned an age of about 40,000 GISP2 yr B.P. for Laschamp based on a stack of magnetic paleointensity records in marine cores from the North Atlantic (NAPIS-75).

The younger excursion was first described from Lake Mungo, Australia [4], and Mono Lake, California [22]. It has been discussed whether the different events correlated with these two sites really represent a global excursion. Just before we submitted this article, [18] maintained that the Mono Lake excursion at its type locality in fact should be correlated with Laschamp, whereas later Benson et al. (2002) presented dates that convincingly show it is indeed younger. They concluded that the age of the Mono Lake is about 33,000 GISP2 years, close to that proposed by [19] from the NAPIS-75 stack.

Several places in and around the North Atlantic two paleomagnetic excursions in stratigraphic superposition in the same sections or cores are well documented, including in the three localities described by us [20, 24, 35 and 36]. In these sites (see below) the younger excursion, now named Valderhaug, is separated from the older Skjong (correlated with Laschamp) by the Ålesund interstade, which is dated with 50 AMS ^{14}C dates to 35,000–28,000 ^{14}C yr B.P. (Fig. 1). Two excursions, and/or two geomagnetic intensity lows, are also reported from marine cores with minor bioturbation [38, 19, 29 and 37].

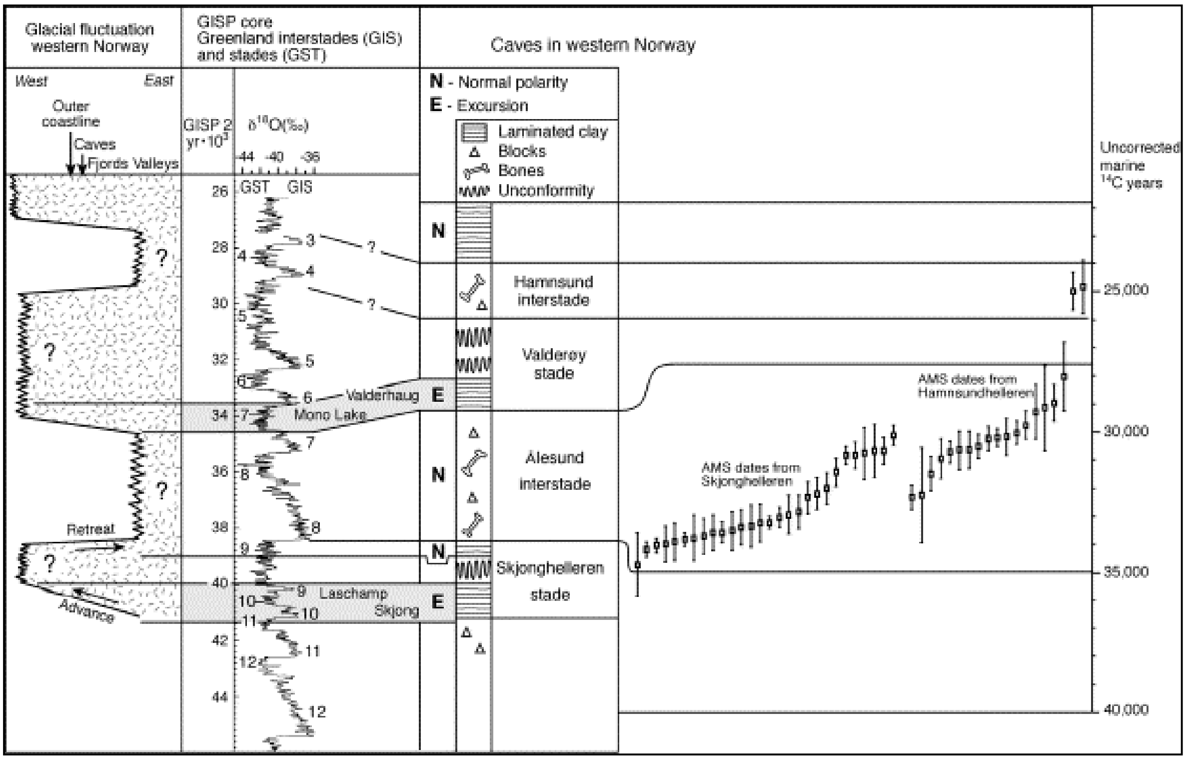

Fig. 1. AMS dates of bones from the Skjonghelleren and Hamnsundhelleren caves are shown in the right panel. Details on the dates from Skjonghelleren will be published in a forthcoming article by S. Gulliksen and his colleagues (personal communication, 2002). The dates from Hamnsundhelleren are cited from [36], with five previously unpublished dates added and corrections for marine reservoir age removed. Note that all dates are performed on sea-feeding animals, and thus should be corrected for reservoir ages of probably 400–800 years, but are plotted here without correction. One single date from Hamnsundhelleren that yielded 37,600 ± 1600 yr B.P. (TUa-1082) is omitted. The next columns to the left show the stratigraphy in the caves; laminated clay beds indicate that a glacier blocked the cave opening and block/bone beds reflect interstades.The Greenland interstades (GIS) and stades (GST) are shown as numbers marked on the GISP2 ^{18}O curve and time scale [34]. The stratigraphic interval of the Mono Lake ^{36}Cl maximum is transferred to the δ^{18}O curve from Figure 2. For the Laschamp only, the interval of maximum ^{36}Cl flux is shaded; this interval corresponds with the Laschamp directional paleomagnetic excursion as identified in marine cores [19 and 38].The main message of this article is the indicated correlations of these events in the ice cores with the paleomagnetic excursions in the caves. In the left-hand column is a time–distance diagram of fluctuations of the margin of the Scandinavian Ice Sheet based on the stratigraphy in the caves. The curve is nearly the same as in [36] and Mangerud (in press), but converted to the GISP2 time scale.

We thus find it demonstrated that there were two paleomagnetic events in the discussed period. We have argued that both were excursions of the dipole field [20, 24, 35 and 36], but that is not crucial for this article and is discussed here. Conservatively we here use the local name (Valderhaug) for the younger excursion and restrict correlations to the Greenland ice cores and North Atlantic cores. However, as all the cited articles use only the name Mono Lake for the younger event in these cores, we have to use that name for correlations. This also seems scientifically justified as Benson et al. (2002) correlate the Mono Lake excursion in the type area with this younger event in the

Greenland and North Atlantic cores.

During a magnetic reversal or excursion the geomagnetic field is weakened. The weakening starts earlier and lasts longer than the directional excursion [12]. Weakening of the magnetic field can be monitored in ice cores as increased concentrations and fluxes of the isotopes ^{10}Be and ^{36}Cl, which are produced in the atmosphere by cosmic rays and deposited with precipitation on the ice sheet.

The Laschamp is identified as peaks of ^{36}Cl concentrations and fluxes in the GRIP core [39 and 5]. The concentration peak lasts from Greenland stade (GST) 11 to GST 9, whereas the peak flux is calculated to be located from Greenland interstade (GIS) 10 to 9 (Fig. 2). The peak of the ^{10}Be flux is restricted to GIS 10 [42].

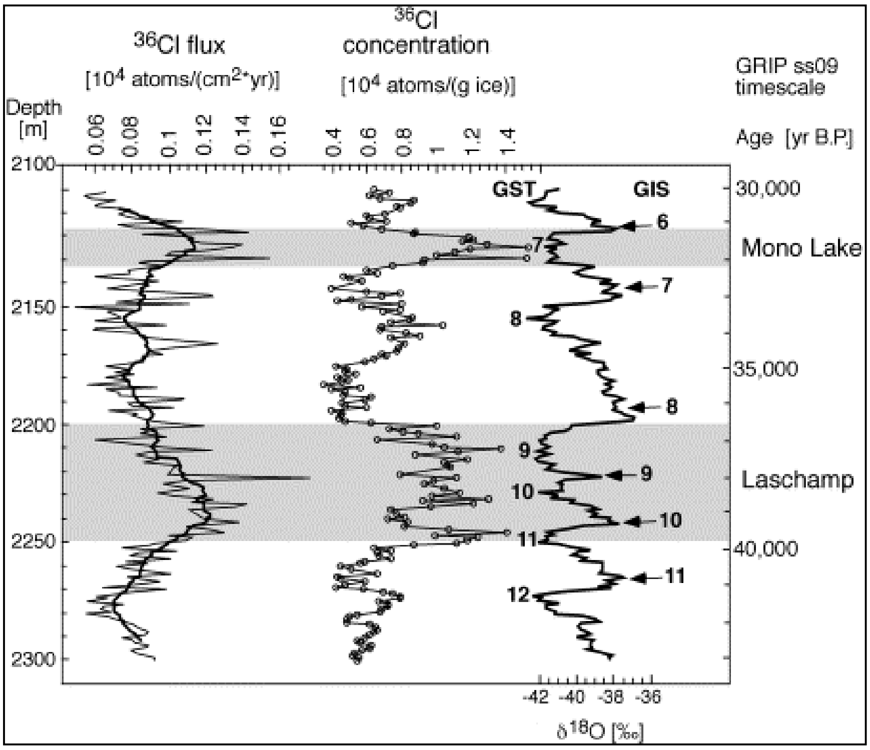

Fig. 2. Concentration and flux of ^{36}Cl in the GRIP core, modified from [39]. Thick line is running mean of 15 data points. The Laschamp and Mono Lake excursions are marked as identified by these curves. Note that for the Laschamp the maximum flux is limited to the interval Greenland interstade (GIS) 10–9. This time interval probably corresponds with the duration of the Laschamp directional paleomagnetic excursion. In Figure 1 the Mono Lake and Laschamp are transferred to the GISP2 time scale by using the oxygen isotope curve.

In the marine cores the directional paleomagnetic excursion is, as expected, restricted to the lowest paleomagnetic intensity values [38, 19 and 37]. Important in this connection is that [19] state that the duration of the Laschamp directional excursion is only about 1000 years in five cores included in their study. The intensity low is up to 2000 years. They correlate the Laschamp directional excursion in these marine cores with the interval GIS 10–9 in the GISP core [38, 19 and 37].

[39] and [5] also found a short-lived ^{36}Cl peak in stade 7 in the GRIP core and related it to the Mono Lake excursion. In the marine core PS2644 collected just east of Greenland (Fig. 3) the Mono Lake was identified as both a directional (inclination) excursion and a weakening of the magnetic field intensity [38 and 37]. An intensity low in the NAPIS-75 stack mentioned above is also correlated with the Mono Lake excursion and GST 7 [19] (Fig. 1).

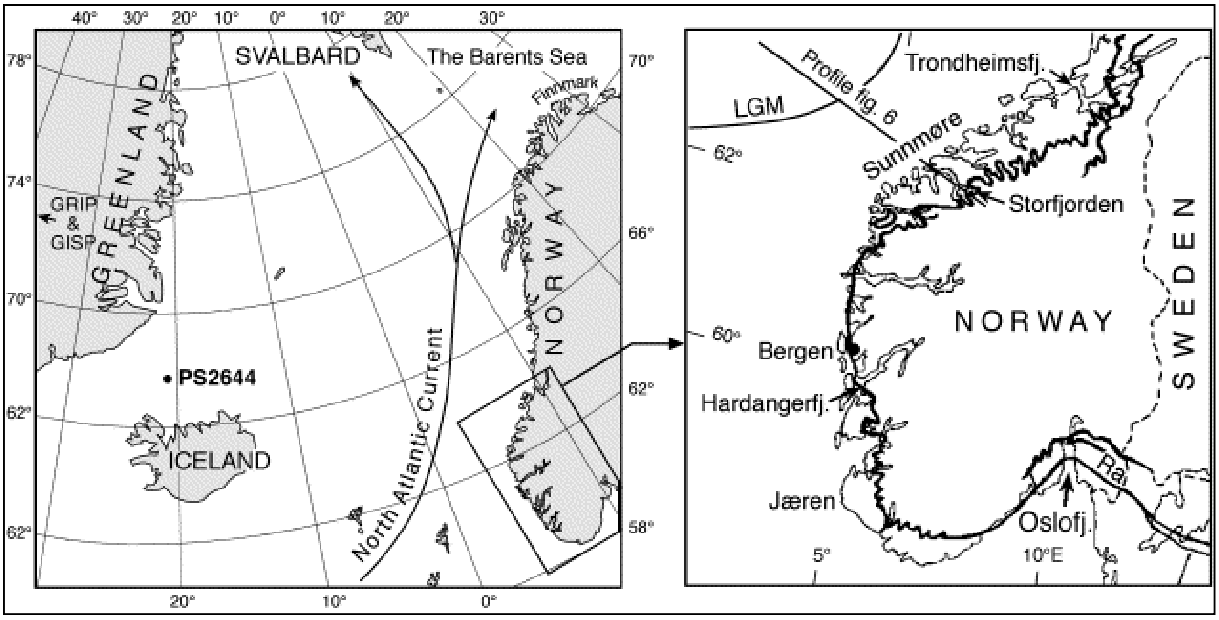

Fig. 3. To the left is a key map of the Nordic Seas area. To the right is a map of southern Norway where the thick line on land is the Younger Dryas ice-sheet margin. The LGM appears in the upper left corner. The profile shown in Fig. 6 is also marked. The three caves discussed in the article are located close to outer coast along this profile.

[39] and [5] used the old GRIP time scale to date the ^{36}Cl and ^{10}Be peaks (Fig. 2). In Figure 1 we have transferred the stratigraphic interval of their Laschamp and Mono Lake ^{36}Cl peaks to the GISP2 time scale [34] using the δ^{18}O curve, which is nearly identical in the two ice cores. The GISP2 time scale is considered to be closer to calendar years in this time interval [17]. According to Figure 1 the Laschamp isotope concentration peak lasted from 41,600–38,600 GISP2 years. However, as discussed above, the paleomagnetic directional excursion was shorter and was probably limited between 41,200 and 40,000 GISP2 yr B.P. The Mono Lake is limited to the GST 7, from 34,600 to 33,600 GISP2 yr B.P.

Paleomagnetic excursions in western norway and correlation with ice cores

Extremely detailed records of parts of two paleomagnetic excursions are found in the Sunnmøre district of western Norway (Fig. 3). Large, old caves, formed by marine abrasion and subsequently uplifted, occur here along the outermost coast. Three caves, Hamnsundhelleren, Skjonghelleren, and Olahola, were investigated. At times when the Scandinavian Ice Sheet expanded and blocked the entrance of a cave, a lake was dammed in the cave (Fig. 4). Thick units of laminated clay were deposited in these lakes. Due to rapid deposition and lack of bioturbation, these clays hold an exceptionally detailed record of paleomagnetic directions. Some of the clay units show normal polarity; here we concentrate on two that exhibit paleomagnetic excursions [20, 24, 35 and 36].

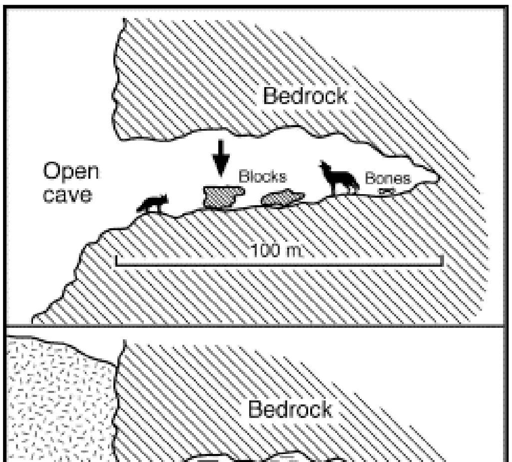

Fig. 4. Conceptional cross sections of uplifted, marine caves in western Norway. The upper sketch shows a cave during an ice-free condition, when blocks fell from the roof and polar foxes brought in bones. The lower sketch shows the opening blocked by a glacier,

causing an ice-dammed lake in the cave and deposition of laminated clay.

During ice-free periods the caves were open, as they are today, and the main depositional process was that blocks were frost-wedged from the roof and fell onto the floor of the caves. However, during some ice-free periods polar foxes brought numerous bones into the caves, notably during the Ålesund interstade, which therefore is well dated by nearly 50 AMS dates on bones (Fig. 1). The ^{14}C analyses yielded ages of 35,000–28,000 ^{14}C yr B.P., not corrected for marine reservoir ages. Presently the reservoir age along this coast is about 400 years [25]; it was about 600 years during the Younger Dryas [10] and was probably of the same order during the Ålesund.

Below the Ålesund interstade bed there is a laminated clay (Skjonghelleren stade; Fig. 1) with the Skjong paleomagnetic excursion that we in principle only can demonstrate is older than about 34,000 ^{14}C yr B.P. However, the stratigraphy is similar in all three caves and we have therefore concluded that there is probably no large hiatus below the Ålesund and thus that the excursion is the Laschamp rather than a (much) older excursion [20, 24, 35 and 36]. We could not decide from the sedimentology if the laminated clay was deposited during the entire period that the caves were ice-covered. However, during the excursion the virtual geomagnetic pole (VGP) describes some loops that partly overlap between the three caves (Fig. 5; Skjong excursion). The oldest part of the VGP path is recorded only in Hamnsundhelleren, the cave that would first be blocked during an ice advance (Fig. 6). The younger part of the VGP path in Hamnsundhelleren overlaps with the path in Skjonghelleren, and the youngest part is recorded in Olahola.

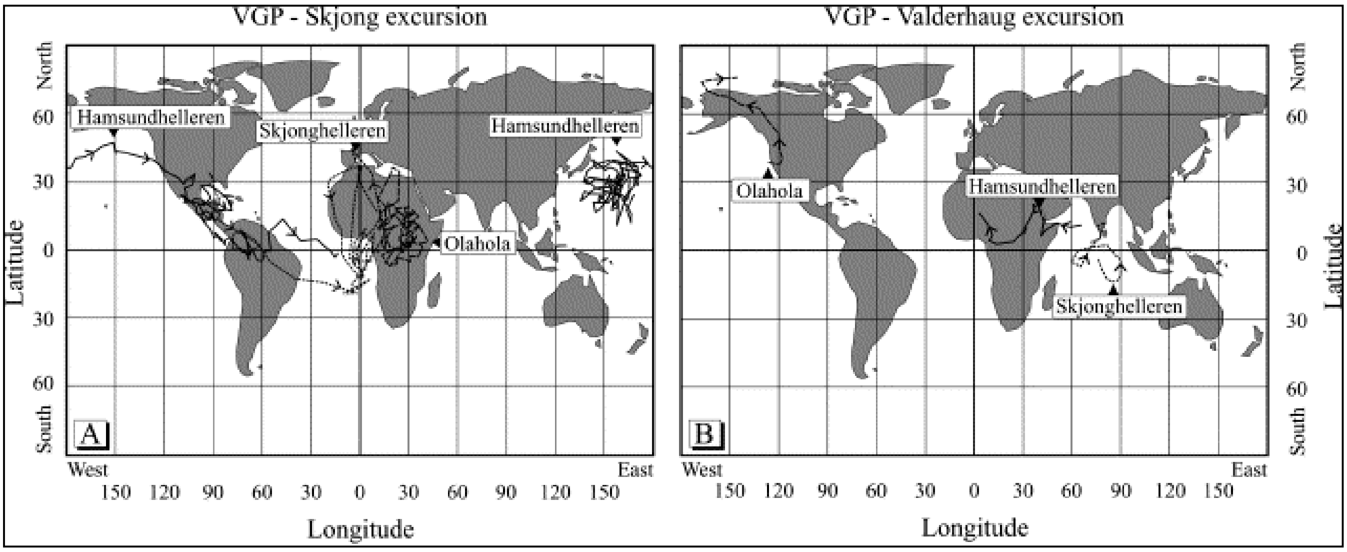

Fig. 5. Virtual geomagnetic pole (VGP) positions for the Skjong (correlated with Laschamp) and the Valderhaug paleomagnetic excursions (correlated with Mono Lake) as measured in the three caves Hamnsundhelleren, Skjonghelleren, and Olahola in western Norway. Arrows on the curves show movement of the VGP. The movements in the clusters are counterclockwise. Simplified from [36].

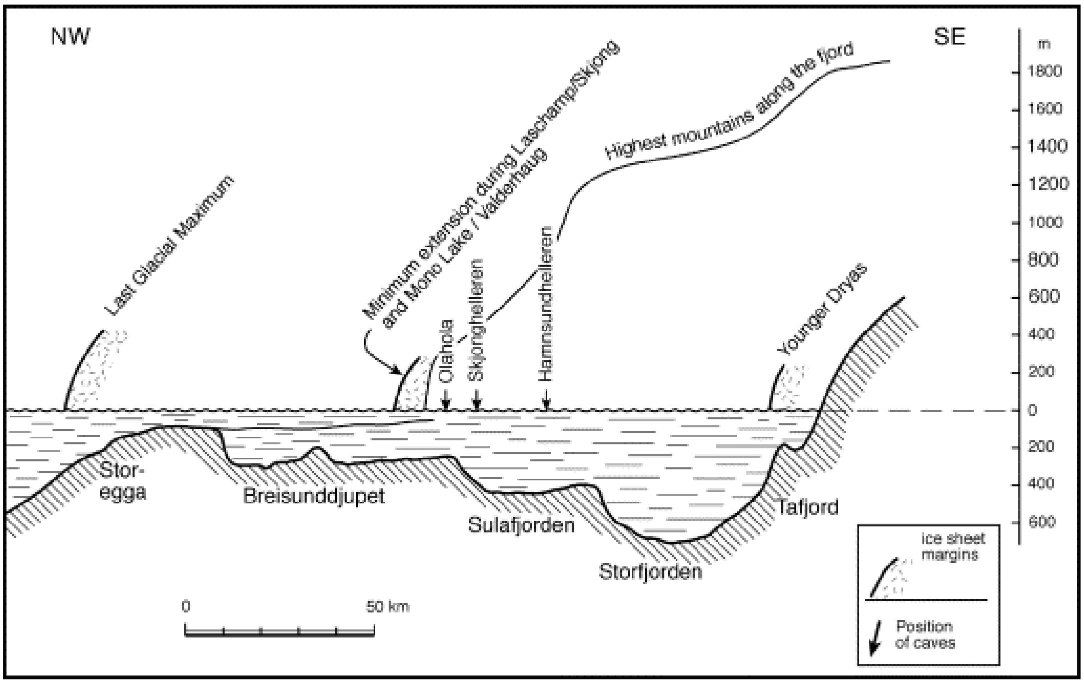

Fig. 6. Profile along the Storfjorden and across the continental shelf at Sunnmøre (location shown in Fig. 3). Note that the profile

follows the deepest trench of the sinuous fjord and therefore is longer than a straight NW–SE line. The depth of the shelf is also shown with a line above Breisunddjupet; the latter is a glacial trough cut into the shelf. The altitudes of the highest mountains along the fjord are shown schematically. The locations of the three caves discussed in this article are projected into the profile. The positions of the ice margin of the Scandinavian Ice Sheet are shown for the LGM (about 20,000 cal yr B.P.) and the Younger Dryas (about 11,500 cal yr B. P.). We have also marked the minimum extension of the ice sheet at the times of the Laschamp/Skjong and Mono Lake/Valderhaug paleomagnetic excursions, at about 41,000 and 34,000 GISP2 yr B.P., respectively.

The glacial-geological implications are (1) the clay was deposited only during an early phase of the ice advance, when the cave was situated along the glacier margin or buried beneath thin ice; and (2) the ice front quickly blocked the caves, one after the other during the paleomagnetic excursion, meaning that the ice front advanced at a rapid rate during the Skjong/Laschamp excursion. The very end of the paleomagnetic excursion is missing in a nonconformity due to erosion or nondeposition of clay in all caves. However, in the Skjonghelleren cave there is another silt bed above the nonconformity. This silt, which has normal magnetic directions, was probably deposited in a new lake that formed during the deglaciation at the end of the Skjonghelleren stade (Fig. 1). This indicates that the VGP had returned to a normal position while the cave still was blocked by the glacier [20 and 24].

The Ålesund interstade beds are dominated by blocks and bones and paleomagnetic directions could not be measured, but some few samples of silt in the Hamnsundhelleren cave show normal directions [36].

Above the Ålesund interstade is another laminated clay that contains the Valderhaug paleomagnetic excursion, which we correlate with the Mono Lake excursion in the North Atlantic cores and the younger ^{36}Cl peak in the GRIP core (Fig. 2). We name this stade the Valderøy stade from the island where Skjonghelleren is situated (Fig. 1). The VGP path does not overlap between the caves as much as during the Skjong excursion, but it is significant that the VGP moved toward the present magnetic pole in Olahola, the cave that was blocked last by the advancing glacier, and thus should record the youngest part of the VGP path (Fig. 5).

The correlations of the Skjong/Laschamp and Valderhaug/Mono Lake paleomagnetic excursions in the caves with the respective ^{36}Cl peaks in the ice cores suggest that the Ålesund interstade should be correlated with Greenland interstades 8–7 or thought to have possibly started in GST 9 (Fig. 1). This correlation can be tested by results from the marine core PS2644 mentioned above. This core is correlated with the GISP (and thus also GRIP) ice core using tephras, Heinrich events, δ^{18}O, and paleomagnetic intensity [38 and 37]. Most AMS dates from the Ålesund interstade are bracketed between 34,000 and 29,000 ^{14}C yr B.P. (Fig. 1), and in core PS2644 the GIS 8–7 are dated to 34,000–31,000 ^{14}C yr B.P. [37 and 2]. Neither set of ^{14}C dates was corrected for marine reservoir ages. Today the marine reservoir age on the Greenland side of the Norwegian Sea is slightly higher than on the Norwegian side, and during the Younger Dryas it was possibly 500 years higher [14 and 10]. Except for this minor difference in marine reservoir age, the dates should be directly correlatable, and we therefore conclude that the results from core PS2644 support the correlation of Ålesund interstade with GIS 8–7. We especially emphasize the close correlation of the start of the Ålesund, as indicated by the immigration of animals, with the onset of GIS 8. The paleomagnetic correlation could allow the deglaciation to start somewhat earlier (Fig. 1), as discussed below.

The given correlations implies that there is an offset of 4000–5000 years between the ^{14}C and GISP2 time scales in this time interval (Fig. 1). It should be noted that [40] also proposed that the onset of the Ålesund and other European interstades occurred at the onset of GIS 8, mainly based on ^{14}C dates. However, they considered that the interstade lasted through GIS 5.

The environment during the ålesund interstade

The fauna during Ålesund interstade, above correlated with GIS 8–7, has been reconstructed on the basis of more than 30,000 bones found in Skjonghelleren [20]; Hufthammer, unpublished observations) and 15,000 bones in Hamnsundhelleren [36]; Hufthammer, unpublished observations). A total of four fish, 15 bird, and six mammalian species have been identified. The majority of bones are from birds, in particular auks and other sea birds, but ptarmigan is also common. Among the mammals the arctic fox is by far the most abundant, while seals, reindeer, and polar bear are rare. It seams clear that the steep rock walls around the caves were nesting sites during the Ålesund interstade and that the bones were brought into the caves by arctic foxes. Most of the species identified are presently common on western Svalbard (Spitsbergen) or in the adjacent seas. Therefore the fauna may indicate that the climate on Sunnmøre during the Ålesund interstade was similar to the climate of Spitsbergen today, that is, with a July temperature of about 5°C. Currently the mean July temperature on the coast of Sunnmøre is about 13°C [3]. Ptarmigan, willow grouse, and reindeer feed on terrestrial vegetation and their occurrence suggests that a wide zone along the coast was ice-free. Reindeer probably immigrated from the south and their existence therefore indicates that there was a continuous ice-free coast southward, although no site of this age has been found between Sunnmøre and Jæren (Fig. 3).

However, some faunal elements indicate that the climate during the warmest part of the interstade was not much colder than the northern coast of Norway today. Common scoter (*Melanitta nigra*), velvet scoter (*M. fusca*), and razorbill (*Alca torda*) are common breeders on mainland Norway, but rare on Svalbard. The harp seal (*Phoca groenlandica*) has a low arctic distribution and migrates regularly to the coast of Finnmark. The pollock (*Pollachius virens*) has its northernmost extent in the southern waters of Svalbard, but are much more abundant further south in the Barents Sea and along the coast of Finnmark. The Finnmark coast today has a mean July temperature only 3°C colder than the Sunnmøre coast. This also means that the Atlantic Current reached the coast of western Norway during at least the warmest part the Ålesund interstade, as already inferred from the findings of *Arctica islandica* at two of the mollusk-bearing till localities originally used to define the Ålesund interstade [28]. However, the ages of these latter localities cannot be constrained by the paleomagnetic excursions and are mainly based on ^{14}C dates. Both the fauna from the caves and the mentioned mollusc indicate that summer temperatures during the warmest part of the Ålesund interstade were almost as warm as the Bølling–Allerød along the west coast of Norway [26, 23 and 15].

It is striking that many AMS dates from the Ålesund interstade in Skjonghelleren exceeded the oldest ones from the same interstade in Hamnsundhelleren (Fig. 1). The explanation is probably that Skjonghelleren is situated further west and thus was ice-free and inhabited first. More surprising is that the youngest bones were found only in Hamnsundhelleren. One possible explanation is that Skjonghelleren is located on a small island, and the foxes were dependent on sea ice to get across. Possibly they retreated to the mainland (Hamnsundhelleren) during later phases of the interstade when more ice-free land was available.

How far inland the ice front retreated during the Ålesund interstade cannot be decided from the observations in these caves, only that it was inland of Hamnsundhelleren (Fig. 6) and that the finding of reindeer bones indicates a wider ice-free zone. A large new set of AMS dates from different sites would seem to indicate that almost the whole of Norway was ice-free during the Ålesund interstade [31 and 30]. However, most of these dates are from samples with extremely low carbon contents. Generally we are skeptical to such dates, and although we accept that some of them are correct, it is at present difficult to judge which are correct and which are contaminated. [7] reported four TL dates in the range 37,400–40,700 yr B.P. from aeolian sand from a locality in central southern Norway. We leave the question open how far inland the ice margin retreated during the Ålesund, but postulate that it was far inland from the caves described in this article.

In the Ålesund beds in the caves there is a nearly continuous row of ^{14}C dates between 34,000 and 30,000 ^{14}C yr B.P., although there are few dates of 32,000–31,000 ^{14}C yr B.P. (Fig. 1). We correlate Ålesund with the GIS 7–8, including the stade 8 between the interstades. We have no paleoclimatic data that show a cold interval within the Ålesund, but the mentioned gap in obtained of ^{14}C ages corresponds to the age of GST 8 and may indicate that there were fewer animals due to a colder climate. There could of course also have been an ice advance further inland that would not be registered in the coastal caves.

Glacial fluctuations in western norway correlated with the greenland dansgaard–oeschger oscillations

As seen from the descriptions above, the stratigraphy in the caves represents an on–off signal for glacial fluctuations just outside the cave opening: laminated clays show that the cave opening was blocked by glacial ice, whereas block and bone beds show an ice-free opening (Fig. 4) [21].

When we first discovered the Ålesund interstade, such findings were extremely rare inside the limit of the Scandinavian Ice Sheet during the LGM, and we therefore emphasized the conclusion that a considerable part of the coast was ice-free this late before the LGM [28 and 20]. This of course, still holds true. However, recently it has been proposed that most of the ice sheet was gone during parts of marine isotope stage 3 [2, 31, 30 and 41]. Therefore we now emphasize the opposite, namely that the ice front indeed was located beyond the coastline in this part of Norway during both during Skjong (about 40,000–41,000 GISP2 yr B.P.) and Valderhaug (34,000 GISP2 yr B.P.) excursions (Fig. 1). During both these periods the ice margin was considerably closer to the LGM position than to the Younger Dryas position in this particular area (Fig. 6). The observations indeed allow the ice margin to be as far west as the LGM position. A main conclusion is that the amplitudes of fluctuations of the Scandinavian Ice Sheet during isotope stage 3 were much larger than thought previously.

The main purpose of this article is to point out the correlations based on the paleomagnetic excursions (Fig. 1). However, here we also discuss some climatic and glaciologic aspects of the correlations. In western Norway major glacial oscillations have for decades been known for the Allerød/Younger Dryas/Preboreal [1], and references therein). Similar "mild/cold/warm" oscillations were subsequently found in the Greenland ice cores for this time interval. With the present accuracy of dating and correlation, these oscillations in western Norway and Greenland appear synchronous. Therefore, a natural question to ask is if all Dansgaard–Oeschger oscillations on Greenland are mirrored by glacial fluctuations in western Norway.

The paleomagnetic correlation indicates that the readvance in western Norway during the Valderhaug/Mono Lake excursion took place just at the transition from GIS 7 to GST 7 in the Greenland cores (Fig. 1). Thus, when compared with Greenland, this readvance can be considered as a similar type of response as the Younger Dryas readvance.

We have described above that the ^{14}C AMS dates of bones from the caves, as correlated with the marine core PS2644, indicate that the beginning of the Ålesund interstade is concurrent with the beginning of GIS 8. So, again the Scandinavian Ice Sheet margin in western Norway seemingly reacted in concert with a temperature change on Greenland. However, we point out that the paleomagnetic correlation allows that the ice retreat started late in GST 9 (Fig. 1), before the immigration of animals. This is significant because Heinrich event 4 occurred late in GST 9 [9]. This event represents a major down-draw of the Laurentide Ice Sheet and thus a sea level rise that probably triggered breakup of the tidewater-based front of the Scandinavian Ice Sheet and other ice sheets, and this positive feedback mechanism led to the total sea level rise of 10 m [11]. At the onset of the warm GIS 8/Ålesund interstade the Scandinavian Ice Sheet continued to shrink by melting and calving.

The advance during the Skjong/Laschamp excursion cannot be tied to a major Greenland stade. According to the discussion above it occurred during the period GIS 10–9 (Fig. 1). Certainly, one may discuss the accuracy of this correlation. The VGP pattern in the caves is so consistent that we feel confident that the ice front advanced and passed the opening of the caves after the onset of the Skjong excursion (Fig. 1). The reason for correlating Skjong with GIS 10–9 is that the Laschamp directional excursion is correlated with that interval in the marine cores discussed above, and the ^{10}Be peak in the GRIP core is also restricted to GIS 10. However, the ^{36}Cl concentration peak covers the entire period from GIS 10 to GST 9 (Fig. 1 and Fig. 2), but the directional magnetic excursion cannot be determined in the Greenland cores. So possibly the ice margin passed the caves during GST 10 or GST 9 (Fig. 1).

Interestingly, an advance of the Scandinavian Ice Sheet is produced for the period 43,000–38,000 GISP2 yr B.P., that is, from GST 12 to the end of GST 9, in a glaciological model driven by temperatures derived from the GISP2 record [2]. This is consistent with our observations and interpretations. Note that when we discuss the timing of the advances, we discuss when the ice margin passed the cave openings. The advances may have started earlier further up-fjord. Also, the advances probably continued further onto the continental shelf, after the ice margin had passed the caves.

Two AMS dates on bones indicate that Hamnsundhelleren was ice-free again about 25,000 uncorrected ^{14}C yr B.P. (Fig. 1) [36]. This would be about 4000 years after the end of the Ålesund interstade. If this Hamnsund interstade can be correlated with any Greenland interstades, we consider 3 and 4 to be the best candidates (Fig. 1). However, this correlation is so uncertain that we do not include it in the present discussion of glacial fluctuations.

The conclusion is that some of the ice-front fluctuations in western Norway 42,000–30,000 GISP2 yr B.P., notably the start and end of the Ålesund interstade, have been synchronous with climate fluctuations on Greenland. This correlation is easy to understand and can be considered as an Allerød/Younger Dryas analog; the cold climate caused glacial advances, and milder climates caused ice margin retreat. Possibility there is a one-to-one correlation between Dansgaard–Oeschger oscillations and glacial fluctuations in western Norway, but with varying amplitudes. The major difficulty in testing this hypothesis is the limited amount of well-dated observations in Scandinavia.

However, all correlations are not that straightforward. This is especially the case for the advance during the time of the Skjong–Laschamp paleomagnetic excursion. The explanation is probably some "trade-off" between temperature and precipitation and even duration. During the coldest stades there was certainly little melting, but also considerably less precipitation. During interstades the precipitation increased, and if the interstades were not warm and long enough, perhaps the increased precipitation was more important than increased melting, giving balance or even advance of the ice margin. Another example of "non-Younger-Dryas-analog" is that stade 8 in Greenland apparently was as long and cold as stade 7 (Fig. 1), whereas in the Sunnmøre area the glacial advance must have been considerably less than during stade 7, if there was any advance at all. [6 and 27]

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