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Late Quaternary terrigenous plant and coaly fragments found at the Vestnesa Ridge, Fram Strait: implications for postglacial plant colonization at Svalbard

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One of four marine cores of glacial sediments collected from a water depth of about 1200 m at Vestnesa Ridge (west of Svalbard) contained small fragments of coal, charcoal and moss. This material was restricted to a single level, and ^{14}C dating of bivalves both above and below indicates an age of c. 18.0–15.5 kyr BP. Chemical analyses of the coal indicate that the provenance area was from the northern part of Andøya, North Norway. The moss fragment was identified as *Aulacomnium turgidum*, which is a well-known species from the northern part of Andøya, which was an ice-free refugium with tundra vegetation during the Weichselian maximum. One small piece of charcoal with reasonably well-preserved cell structures is derived from burnt *Salix* sp. These findings are important, because they demonstrate the presence of drift ice carrying organic material from the northern part of Andøya towards the west coast of Svalbard during Heinrich event H1, an event of extensive ice-rafting in the Nordic seas. This also implies that some components of the vascular plant communities growing on Svalbard today, might originally have been imported as seeds floating on sea ice, before stranding along the coast of Svalbard. The plant colonization of Svalbard can thus have started already during Heinrich event H1. The finding of charcoal can only be explained by a fire due to lightning and not by campfire, because the first human population arrived in northern Norway at a much later time (probably during Preboreal). The charcoal is thus from the oldest known wild fire in Norway. □ *Plant dispersal, provenance area, Andøya, drift ice, organic matter, Heinrich event H1*

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Knowledge of the variation in sea-ice extent in the subpolar North Atlantic during the lateglacial and deglacial periods is still limited. According to the reconstructions by Müller & Stein (2014) there was a permanent sea-ice cover during the transition between the last glacial maximum and Heinrich event H1 (time interval 18,000–15,500 BP). However, Sarnthein *et al*. (1995, 2003), Weinelt *et al*. (1996), Nørgaard-Pedersen *et al*. (2003) and Zamelczyk *et al*. (2014) have shown that large parts of the Nordic Seas were ice free during the summers of the Last Glacial Maximum. During Heinrich Event H1 in the early deglaciation, the permanent sea-ice layer broke up with an export of sea ice and icebergs to the North Atlantic.

Quaternary marine sediments in the northern part of the Atlantic Ocean, the Barents Sea and the Arctic Ocean all contain erratic rock and mineral fragments. This material originated from adjacent land and shelf areas and was mainly transported by sea ice and/or icebergs and in some instances by turbidity currents downslope from shelf areas or banks. The quantitative composition of the mineral grain assemblages from different marine areas has been used to determine the most likely provenance (see Bischof *et al*. 1997). However, a shortcoming of such quantitative approaches is that they can only narrow down the sources to relative large areas as e.g. western Norway (Bischof 1990) or northern Norway (Vassmyr & Vorren 1990).

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In addition to clastic grains deposited on the sea bottom, the presence of driftwood logs on raised beaches in Svalbard has been used to elucidate long range transport and provenance. As shown by Häggblom (1982) and Hellmann *et al.* (2013, 2017) much of the driftwood originates from northwest Russia, southern Siberia and Arctic North America. Because of the limited period of buoyancy of logs in water (6–17 months depending on species), compared with up to about five years transport time from the Siberian coast to Svalbard, the logs must have been rafted by sea ice. The amount and composition of the driftwood that is delivered to the Arctic Ocean from a certain region is closely related to river discharge rates and the distribution of dominant forest types (Hellmann *et al.* 2017). Most of the trees have been growing along the river banks of large boreal river systems, and enter these by erosion of the banks during floods, storm surges, or ice break-up in the spring. Seeds and fruit as well as other organic material are also often transported together with recent driftwood, giving more information about the provenance areas (e.g. Alsos *et al.* 2016). The finds of ice-rafted coal fragments in sediments from the Fram Strait and the Norwegian Sea also point to a provenance in northern Siberia (Bischof *et al.* 1990).

Scandinavia is less relevant for Arctic driftwood because it lacks large river systems (Hellmann *et al.* 2016), but the Norwegian Atlantic Current is known to carry marine organisms of southern origin to the high north as, for example, tropical radiolarians have been located north of Svalbard (Bjørklund *et al.* 2012). Northward transport of water masses most likely also occurred during the last glacial period (e.g. Sarnthein *et al.* 1995; Weinelt *et al.* 1996; Nørgaard-Pedersen *et al.* 2003; Rasmussen *et al.* 2007). Many examples of ice-rafted material from specific locations exist. Coccoliths of Cretaceous age have been deposited from drifting sea ice and/or icebergs (Rosell-Melé *et al.* 2011) and chalk originating from bedrock and Quaternary tills from the North Sea have been found on the western margin of Svalbard in sediments from the Last Glacial Maximum and early deglaciation (Elverhøi *et al.* 1995). The quantitative composition of the erratic material from the western Svalbard margin indicates shifting sources of ice-rafted material, from local Svalbard-Barents Sea provenances to mainly crystalline quartz derived from surrounding continents of the Nordic seas (e.g. Bischof 1994; Elverhøi *et al.* 1995; Jessen & Rasmussen 2019). In the present investigation, we performed provenance analysis of rare clasts of organic origin in deep sea sediment samples (coal and plant debris) with the purpose of finding the origin of this specific association and thus achieve a better understanding of the transport mechanisms and pathways to the Fram Strait during Heinrich event H1.

Oceanographic setting

The North Atlantic Drift, derived from the Gulf Stream, flows north-eastward into the Nordic seas. It continues along western Norway as the warm Norwegian Atlantic Current (e.g. Hansen & Østerhus 2000). In the northern part of Norway it splits into two branches; the North Cape Current flowing eastwards and the West Spitsbergen Current passing western Svalbard (Fig. 1A).

The Fram Strait is dominated by two main current systems; the West Spitsbergen Current in the eastern Fram Strait carries warm saline water of Atlantic origin northwards to the Arctic Ocean (Aagard & Greisman 1975; see also overview by Bauerfeind *et al.* 2009). The East Greenland Current in the western Fram Strait transports sea ice and Polar water from the Transpolar Drift in the Arctic Ocean southwards along the east Greenland margin (Aagaard *et al.* 1987; Besczynska-Möller *et al.* 2012). The Fram Strait thus forms the main pathway between the North Atlantic Ocean and the Arctic Ocean, and was probably just as important during Late Glacial and Holocene time (see e.g. Nørgaard-Pedersen *et al.* 2003; Rasmussen *et al.* 2007; Aagaard-Sørensen *et al.* 2014; Müller & Stein 2014; Rasmussen & Thomsen 2004; El bani Altuna *et al.* 2021; Toucanne *et al.* 2021).

Geological setting

The Vestnesa Ridge is an approximately 50–60 km long NW-SE oriented submarine ridge in the eastern part of the Fram Strait, west of Svalbard (Fig. 1B). The ridge comprises >5 km thick sediments deposited on young (<20 Ma) oceanic crust (e.g. Eiken & Hinz 1993). The upper Pliocene-Pleistocene deposits consist of contourite and glaciomarine sediments. Thick contourites characterise the Late Weichselian and Holocene deposits at 1200–1300 m water depth (Howe *et al.* 2008). The central southeastern part of the Vestnesa Ridge shows a series of pockmarks at about 1200 m water depth with active methane seeps showing up as gas plumes on echosoundings (Vogt *et al.* 1994; Hustoft *et al.* 2009), reflecting most likely biogenic methane production from in-situ organic matter, or even early diagenetic thermogenic gas (Hustoft et al. 2009).

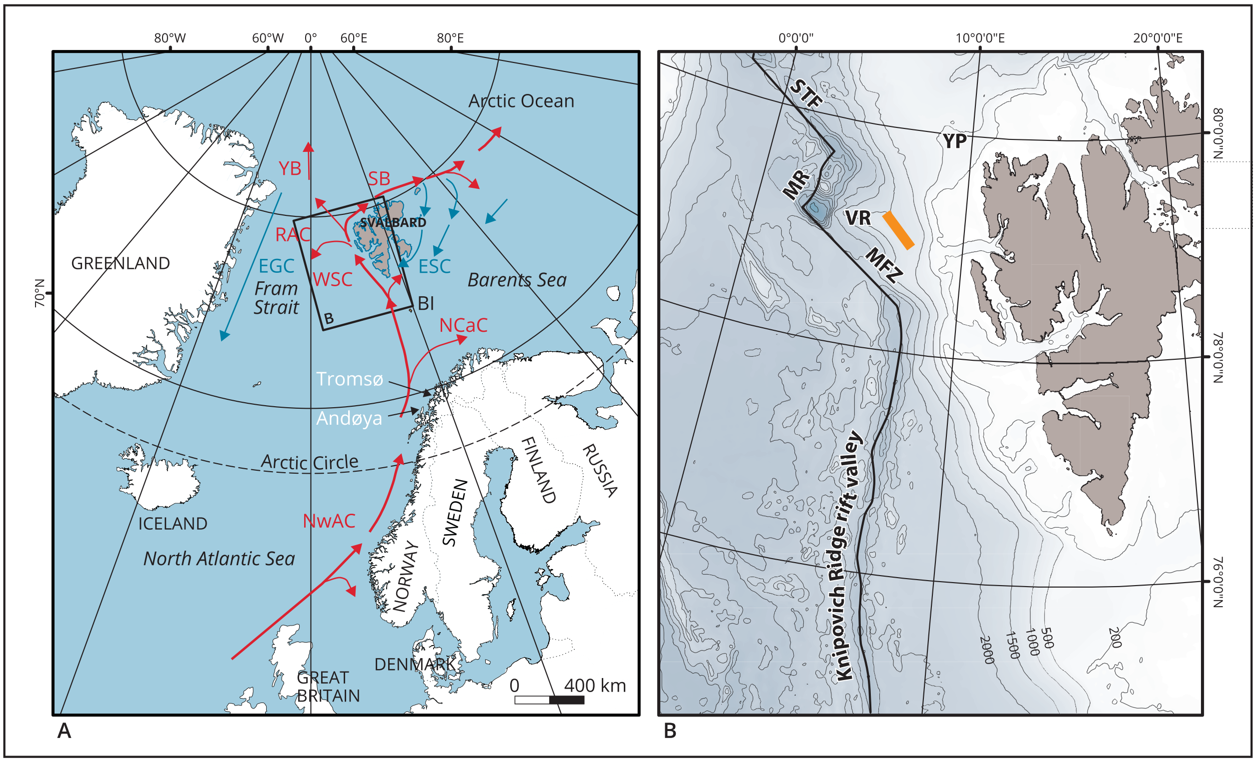


Fig. 1. A, location map. B, the orange shaded rectangle marks the area for sub-sea sampling. Section of the Arctic Ocean and North Atlantic showing the location of Svalbard. The present-day ocean circulation pattern is from Slubowska-Woldengen *et al.* (2008). Red arrows = warm Atlantic water; blue arrows = cold Polar water. EGC = East Greenland Current; NwAC = Norwegian Atlantic Current; NCaC = North Cape Current; WSC = West Spitsbergen Current; RAC = Return Atlantic Current; SB = Svalbard Branch; YB = Yermark Branch; ESC = East Spitsbergen Current; BI = Bear Island. B, bathymetry west of Svalbard. MFZ = Molloy Fracture Zone; MR = Molloy Ridge; STF = Spitsbergen transform fault; VR = Vestnesa Ridge; YP = Yermak Platau. Also see Fig. 11 concerning oceanic circulation patterns during the glaciation i.e. 17 kyr BP.

Material and methods

Core material

Altogether, four cores from the Vestnesa Ridge were investigated for coal fragments and botanical debris. The core material had previously been investigated for ice-rafted debris, macrofossils, trace fossils and benthic and planktonic foraminiferal faunas together with their oxygen and carbon isotopes (Sztybor & Rasmussen 2017a, b; Thomsen *et al.* 2019). Details of the coring locations and descriptions of core sample treatment have been given by Sztybor & Rasmussen (2017a, b), thus only a brief summary is given here. After cutting the cores lengthwise, 1-cm thick slices were taken at 5 cm intervals. The samples were weighed, freeze-dried, weighed again and subsequently wet-sieved through 0.063, 0.1, 0.5 and 1.0 mm sieves. The residue was dried at 40°C. All fossil remains from these fractions were sorted out and studied under a stereo-microscope. Of the four cores investigated, only the interval 120–121 cm below present sea bottom in piston core HH12-928PC revealed the presence of coal fragments (six in total, up to 0.3–0.4 mm in size), one small chip of charcoal (0.95 mm in size) and a moss fragment (2 mm long). Piston core HH12-928PC was taken from a pockmark with aragonite pavement and contained carbonate concretions throughout its length (Sztybor & Rasmussen 2017a), see Figure 2. The carbonate concretions were of variable size (from millimetres to centimetres and probably also decimetre size) embedded in a dark grey matrix consisting of clay/silt (<30%) and sand. The skeletal macrofauna is dominated by molluscs and has been described by Thomsen *et al.* (2019).

Age model

A total of seven ^{14}C datings have been performed of which four were published in Sztybor & Rasmussen (2017a). The three new dates were obtained from bivalves deeper in the core, calibrated to calendar years and published in Thomsen *et al.* (2019), see Fig. 2; Table 1. All ages are calculated as the midpoint of the 1σ probability range.

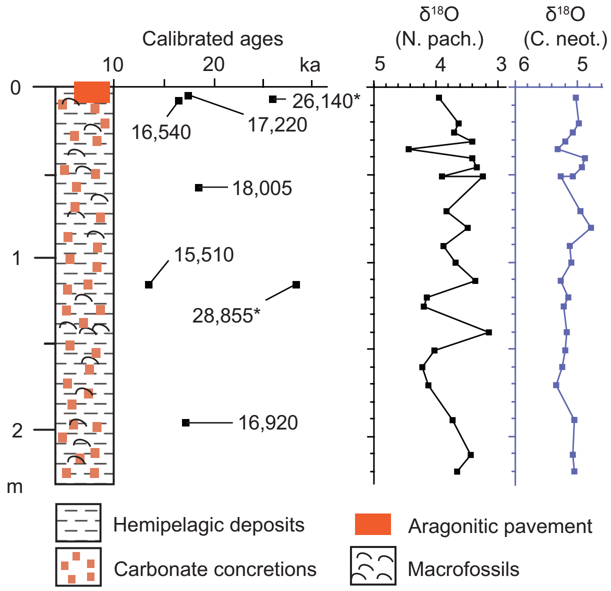


Fig. 2. Lithological log, calibrated AMS ^{14}C dates and planktonic and benthic $\delta^{18}O$ records measured in the planktic foraminiferal species *Neogloboquadrina pachyderma* and benthic foraminiferal species *Cassidulina neoteretis*, respectively, for core HH12-928PC (data from Sztybor & Rasmussen, 2017a). Dates marked by an asterisk were performed on aragonite needles and are regarded as too old; the remaining dates were performed on bivalves (see text for explanation and Table 1).

Table 1. AMS-^{14}C dates and calibrated ages of core HH12-928PC

Depth cm	AMS ^{14}C age*	Cal. Age	Species	Reference
1	14,550 ± 70	17,220 ± 129	Bivalve	1
2	22,345 ± 135	26,140 ± 142	Aragonite needles	1
3	14,120 ± 54	16,540 ± 133	Bivalve	1
53	15,210 ± 66	18,005 ± 97	Bivalve	1
117	25,245 ± 142	28,855 ± 166	Aragonite needles	2
117	13,410 ± 64	15,510 ± 91	Bivalve	2
197	14,350 ± 63	16,920 ± 132	Bivalve	2

*Conventional age, 1) Sztybor & Rasmussen (2017a), 2) Thomsen *et al.* 2019.

Oxygen isotopes were measured in the planktonic foraminiferal species *Neogloboquadrina pachyderma* and the benthic foraminiferal species *Cassidulina neoteretis* (Sztybor & Rasmussen 2017a; see Fig. 2). The planktonic and benthic $\delta^{18}O$ values, given in ‰ VDPB, range from 4.4–3.2 and 5.4–4.8‰, respectively, indicating that the core contains sediments from the glacial period of Marine Isotope Stage 2. The fairly low values of the planktonic record combined with AMS ^{14}C dates suggest it belongs to the deglaciation period although both benthic and planktonic records are very scattered without any clear trend (see Thomsen *et al.* 2019).

In Sztybor & Rasmussen (2017a), the top sediments were tentatively correlated to Heinrich event H1 and the sediments below as belonging to the last glacial maximum (LGM). However, with the addition of the new dates that mostly fall within the H1 interval, it has become clear that all the dated macrofossils are of H1 age (18,000–15,500 years; see Bond *et al.* 1993 and Thomsen *et al.* 2019). The dates performed on aragonite needles are about 10,000 years older than dates on molluscs from the same sample or just above or below (Table 1). These 'outlier dates' are probably affected by the seeping of methane from greater depth which is oxidized to carbonate, causing ages to appear too old (Uchida *et al.* 2008).

Scanning electron microscopy (SEM)

Scanning electron microscopy (SEM) was provided on the wet sieved material of coal, charcoal and moss. This provided detailed high-quality three-dimensional images, which allowed morphological characters and taphonomic processes to be assessed. The SEM investigations of the coal pieces and the charcoal were carried out with a GEOL 6800, while a Hitachi SU500 Field Emission SEM was used for the moss fragment. All material was gold coated.

Chemical pre-treatment of organic material

To estimate the provenance of coal fragments solely on a visual investigation is not very reliable, so it was decided to carry out a chemical characterization of the organic material. An attempt was made to extract a combined sample from all coaly particles using dichloromethane (DCM). Due to the small sample size the crushing was done inside a 0.5 ml glass sample vial using a Pasteur pipette, which easily broke down the particles in line with the assumption that this material could indeed be coal. The result was visible dust size sub-particles which were partly sinking and partly 'hovering' in DCM. With a density of 1.33 g/cm^3 for DCM, both shale and coal will sink while charcoal, which has a lower density, will float in the liquid.

The sample was mixed/extracted actively by the DCM by pumping the crushed grains and DCM up and down into the Pasteur pipette, and left overnight. The extract had no obvious colouration, albeit a slight discolouration was traceable when the sample was concentrated before injection on the GC-FID and the GC-MS instruments.

The sample was concentrated to c. 0.01 ml and 3 microlitres was injected into a GC-FID and also into a GC-MS instrument, see below.

Gas chromatography-mass spectrometry (GC-MS)

The extract was analysed in a Fisons Instruments MD800 gas chromatography-mass spectrometry (GC-MS) system in SIM-mode (selected ion monitoring) equipped with a 50 m long Chromopak CP-SIL 5CB-MS FS 50X.32 (40) WCOT fused silica-type column which had an inner diameter of 0.32 mm and which contained a CP-SIL 5CB low bleed/MS stationary phase. The column had an initial temperature of 80 °C and was heated at 10 °C/min to 180 °C and subsequently at 1.7 °C/min to 310 °C, where it was held for 30 min. Because of the low amount of analyte, the bulk extracts were analysed directly without separation into saturated hydrocarbons, aromatic hydrocarbons and polar compound classes.

Gas chromatography-flame ionization detector (GC-FID)

A Varian capillary gas chromatography-flame ionization detector (GC-FID), model 3800, with a 25 m long Hewlett Packard Ultra II cross-linked methyl silicone gum column which had 0.2 mm inner diameter and a film thickness of 0.33 µm was utilised for GC-FID analyses of the bulk extracts. Initial column temperature was 40 °C with a hold time of 2 min, and a gradient of 4 °C/min until it reached 325 °C, where it was held for 20 min.

Biogenic content

Moss

A 2-mm-long fragment of the outer end of a branch from the bryophyte (moss) *Aulacomnium turgidum* was found in core HH12-928PC, 120–121 cm below the present sea-floor. Species identification is according to Dickson (1986). Although some leaves have been broken off, the material is reasonably well preserved and show little sign of macroscopic posthumous degradation (Fig. 3A). Pyrite, often as spheroidal pyrite, has been precipitated on parts of the outer surface (Fig. 3B).

Charcoal

One 0.95 mm long piece of charcoal was found during wet sieving of the core material from 120–121 cm below present seafloor. It shows some sign of physical abrasion with rounded corners analogue to a subangular grain according to the roundness scale by Powers (1953). Although the Vestnesa material was somewhat distorted during charring, much of the important systematic features have been preserved allowing petrographic examination and identification. SEM examination showed that parts of the original vessels were well preserved without any sign of flattening which would have been anticipated if the material had been derived from Tertiary or older coal beds. Although only one small piece of charcoal was retrieved from the core, the characteristic wood anatomy indicates that the material can be referred to the genus *Salix* (Fig. 4). The size of the vessels fit well with *S. arctica* which is growing on Svalbard today (Rønning 1996). However, it is somewhat uncertain to

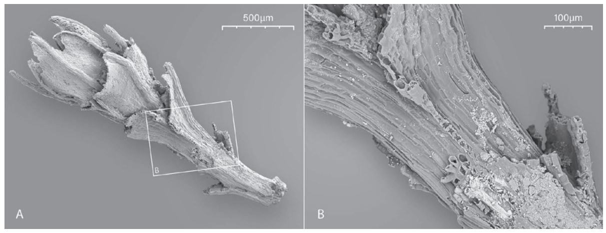


Fig. 3. SEM images of moss fragments in the investigated core HH12-928PC. A, tip of the moss *Aulacomnium turgidum* found in core HH12-928PC, 120-121 cm below the present seafloor. The material is fairly well preserved, although some of the leaves have been broken off at the base. B, pyrite (light spots) has been precipitated on parts of the surface.

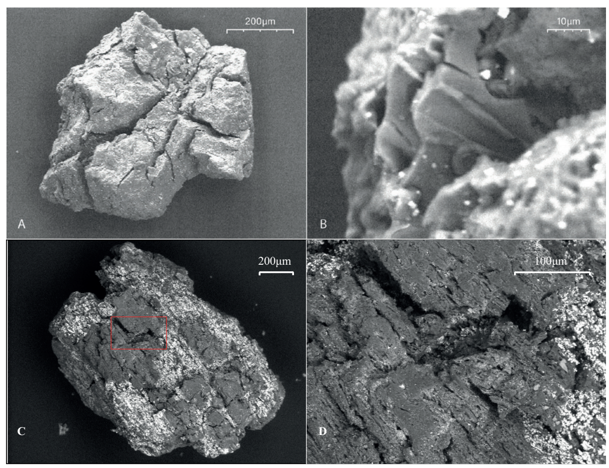


Fig. 4. SEM images of charcoal (A, B) and coal (C, D) fragments in the investigated core HH12-928PC. A, fragment of slightly abraded charcoal showing several cracks due to charring. The original wood structure has been more-or-less destroyed during the charring process, but it is fairly well preserved in a small area close to the lower left area. The scattered light spots are authigenic pyrite precipitated on the surface of the charcoal fragment. B, close up showing length sections of vessels from *Salix* sp. Scattered light spots of authigenic pyrite which have been precipitated on the surface. C, general view of the coal fragment. White spots indicate pyrite. D, enlargement of the box in C showing detail of the coal structure.

identify to species level based on charred wood cells alone. Thus, *Salix herbacea*, *S. polaris* and *S. reticulata*, which are also well known from the recent Svalbard flora, cannot be excluded because their wood anatomy is very much like that of *S. arctica* although they have smaller vessels. We therefore suggest the material to represent *Salix* sp. without further identification.

Coal analysis and provenance

The small coal fragments were photographed in SEM. Several small, representative areas in each specimen were analysed with an XRF to get information about the geochemical composition. These preliminary investigations were supplemented with a provenance analysis based on the organic content.

The few and small coal samples gave very low concentrations of the analyte and no obviously identifiable peaks were observed on the GC-FID trace, i.e. no obvious n-alkanes, but faint signals corresponding to aromatic hydrocarbon groups in the naphthalene and phenanthrene range were observed which is in general accordance with the aromatic nature of coals (Tissot & Welte 1984).

On the GC-MS, good representative signals of the same compound groups were identified, and some traces are shown below (Figs 5–10). The aromatic hydrocarbon species (Fig. 10) are of major interest due to their use for assessing maturity (Kvalheim *et al.* 1987; Radke 1987, 1988). Good signals were also recorded for steranes and hopanes, plus the aromatic steroids (Figs 5–9).

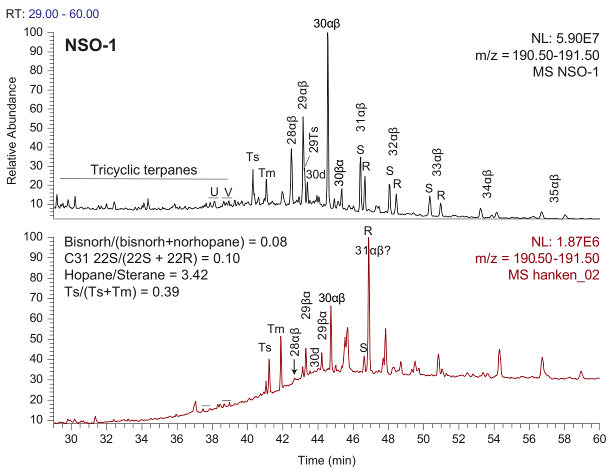


Fig. 5. m/z = 191 GC-MS chromatograms showing terpane biomarkers for the analysed coaly organic particles (bottom). Peak labels indicate terpane biomarkers and identification is in reference to the standard North Sea oil (NSO-1) shown on top (cf. Weiss *et al.* 2000). Ratios of terpane parameters used to assess maturity are shown.

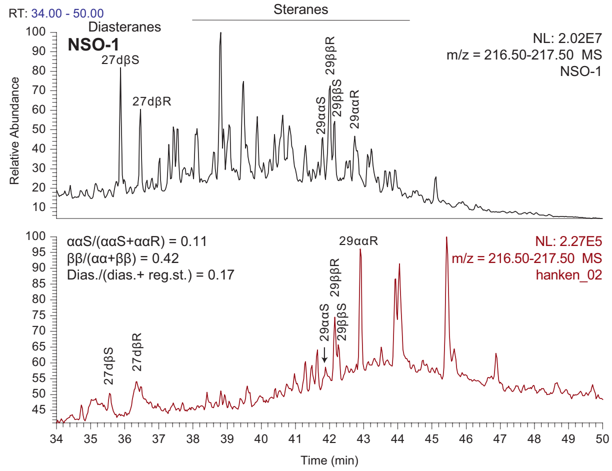


Fig. 6. m/z = 217 GC-MS chromatograms showing diasteranes and steranes for the analysed coaly organic particles (bottom). Peak labels indicate sterane and diasterane biomarkers, and identification is in reference to the standard North Sea oil (NSO-1) shown on top (cf. Weiss *et al.* 2000). Ratios of biomarker parameters used to assess maturity are shown.

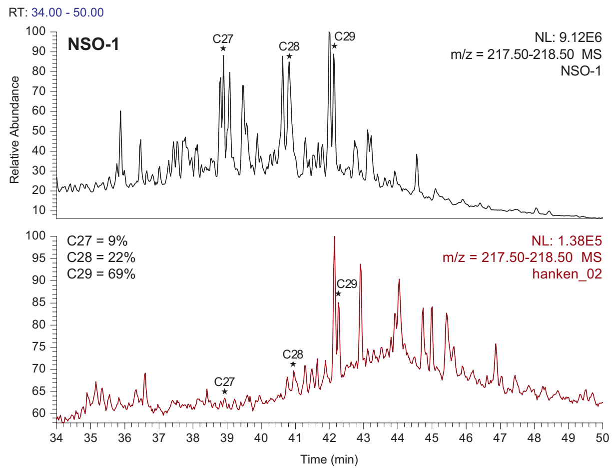


Fig. 7. m/z = 218 GC-MS chromatograms showing C27, C28 and C29 regular sterane for the analysed coaly organic particles (bottom). Peak labels indicate sterane biomarkers, and identification is in reference to the standard North Sea oil (NSO-1) shown on top (cf. Weiss *et al.* 2000). Percentages of steranes used to assess organic source facies are shown.

Concerning the type of organic matter present, it is noted from the GC-MS data that the sterane composition of the sample is 69% C_{29} steranes, 22% C_{28} steranes, and only 9% C_{27} steranes (Fig. 7) which is fully corresponding to coal (Peters *et al.* 2005; Tissot &Welte 1984). Marine shales of this composition are unheard of, and the composition is on a par with that reported for Jurassic coaly sediments by Bjorøy *et al.* (1980) from Andøya, but distinctly different from their reported values for Cretaceous sediments. It is for these reasons likely that the samples represent coal.

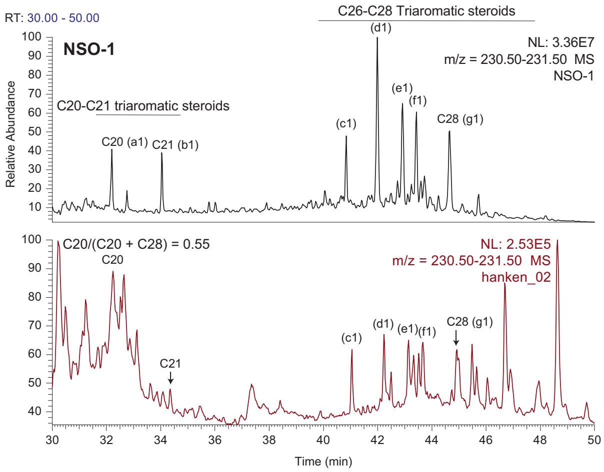


Fig. 8. m/z = 231 GC-MS chromatograms showing C20-C28 triaromatic steroid hydrocarbons for the analysed coaly organic particles (bottom). Peak labels indicate triaromatic steroid hydrocarbons and identification is in reference to the standard North Sea oil (NSO-1) shown on top (cf. Weiss *et al.* 2000).

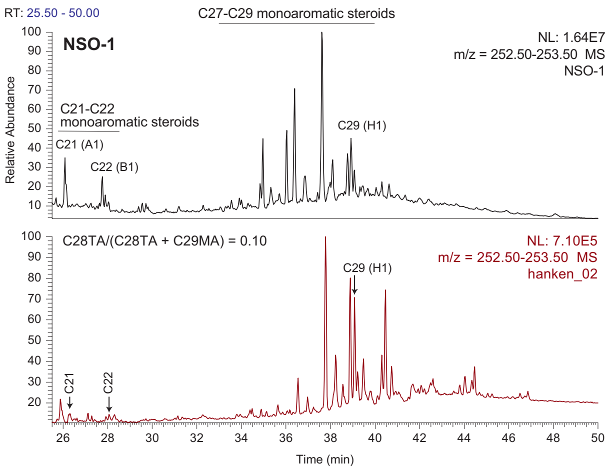
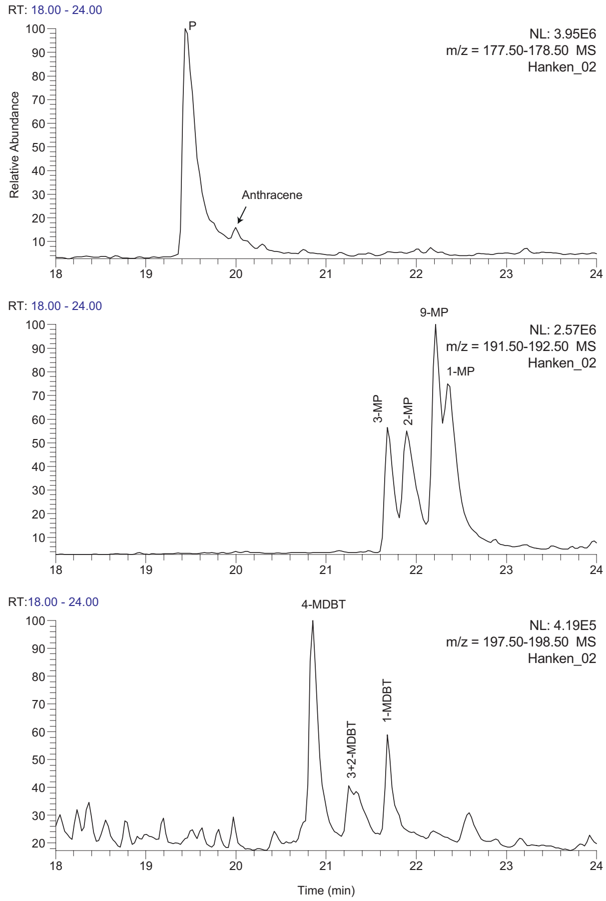


Fig. 9. m/z = 253 GC-MS chromatograms showing C21-C29 monoaromatic steroid hydrocarbons for the analysed coaly organic particles (bottom). Peak labels indicate monoaromatic steroid hydrocarbons, and identification is in reference to the standard North Sea oil (NSO-1) shown on top (cf. Weiss *et al.* 2000).



Calculated vitrinite reflectances

%Rc1 = 1.1 x $\log_{10}$MPR + 0.95 = 0.80

%Rc2 = 0.60 x MPI1 + 0.40 = 0.70

%Rc3 = 2.242 x F1 - 0.166 = 0.7

%Rc4 = 0.073 x MDR + 0.51 = 0.67

Fig. 10. GC-MS chromatograms showing phenanthrene and anthracene (m/z = 178), methylphenanthrenes (m/z = 192) and methyldibenzothiophene (m/z = 198) for the analysed coaly organic particles. Vitrinite reflectances (%Rc), calculated based on four different methods (Kvalheim *et al.* 1987; Radke 1987, 1988), are shown.

It is evident from the distribution of the methylphenanthrene isomers that the maturity of the sample is in the range of about 0.7%Rc, while the methyldibenzothiophene isomers indicate a maturity of about 0.6–0.7%Rc (Fig. 10). The existence of monoaromatic steroids (Fig. 9) in the sample reflects that the maturity is less than 0.8–0.9%Rc (cf. Karlsen *et al.* 1995), which corresponds reasonably well with the estimates based on the isomers of the geomarkers methylphenathrene and methyldibenzothiophene.

Aromatic compounds are normally abundant in coals due to the highly aromatic nature of the coal matrix (Tissot & Welte 1984), and the methylphenanthrene ratios normally show very good correlation with optically determined vitrinite reflectivity. For these reasons is it likely that the true maturity for the bulk of these samples lies within the range of c. 0.6–0.7%Rc.

Contrastingly, lower maturities than this was observed for the hopane isomerization S/(S + R) at C22 and also for the sterane isomerizations at C20, see Fig. 5 and Fig. 6, respectively. Isomerization of the hopanes is normally reaching the equilibrium ratio of c. 0.6–0.62 at a maturity of about 0.6%Rc (Seifert & Moldowan 1986). In these samples, the ratio is only 0.1, and similarly the ratio for sterane isomerization S/(S + R) at C20 is only 0.11, i.e. indicating absolute immature samples – i.e. the actual maturity may be up to about 0.3–0.4%Rc, but not higher given a normal slow burial rate (Mackenzie 1984, Mackenzie *et al.* 1980). Surprisingly, the isomerization ratio of the ββ/(ββ + αα) steranes is 0.42, which would correspond roughly to a maturity of about 0.6–0.7%Rc corresponding better to the Ts/(Ts + Tm) ratio of 0.39, which can be observed in mature source rocks and coals plus oils.

It can be concluded that there is contrasting maturity information among the hopanoid and sterane biomarker parameters internally, as well as with respect to the methylphenanthrenes and the methyldibenzothiophenes. The reasons for this are not obvious, but most likely related to the analysed bitumen extract representing particle samples, which represents several individual particles with potentially different origin and preservation potential.

The contrasting maturity information when comparing the more abundant methyldibenzothiophenes and the methylphenanthrenes, to the much less abundant biomarkers, i.e. the steranes and hopanes, suggests that the samples are not completely homogenous in origin i.e. some of the particles could represent coal of much lower maturity while others may be presumed to be reworked from older beds.

The known maturity of samples from Andøya (Bjorøy *et al.* 1980), which represent Cretaceous and less mature Jurassic sediments, including coaly sediments (the Mid Jurassic Hestberget Mb.), show maturities in the range of 0.32 to 0.45%Rc, but also maturities indicated towards 0.6%Rc (with reported Tmax values mostly around 415–430 °C).

Compared to this, the maturity of the Tertiary coals in Svalbard range mostly higher i.e. from c. 0.65–0.78%Rc (Marshall *et al.* 2015a, b), and even higher for the older coals (Van Koeverden *et al.* 2011). Coals from Bjørnøya (Bear Island) sedimentary system are highly mature to over mature. Reported values range mostly around 1.4–1.5%Rc (Bjorøy *et al.* 1981; Van Koeverden *et al.* 2011), which is significantly higher than the maturity of migrated oils in Svalbard that are clearly derived from Triassic, and in some rare cases, even older source rocks (Abay *et al.* 2017, 2022.

Based on this, the low maturities indicated from the hopanoid and sterane parameters, and the higher maturity indicated from the methyldibenzothiophenes and the methylphenanthrenes represented by much higher concentrations in these few and spurious samples, a first approximation is that a sedimentary system belonging to the general Andøya, or associated offshore regions is more likely as source for this material. Further work on similar materials should involve age-specific biomarkers; this was prohibited in the present study by the very small sample quantities available.

The Middle Jurassic-Lower Cretaceous sediments at Andøya occupy an area of about 8 km^2 along the north the northeast coast (Dalland 1975). The thickness of the sequence is more than 650 metres, but the coal layers are limited to the lower part (Manum *et al.* 1991; Birkelund *et al.* 1978; Vajda & Wigforss-Lange 2009). Mesozoic rocks also occur in very near shore positions to Andøya and in half-graben systems in fjords further south (Bøe *et al.* 2010). The preserved sedimentary deposits are probably a remnant of a more extensive Mesozoic sedimentary basin located along the western margin of northern Norway (Brekke 2000). The sedimentary rocks were preserved due to downfaulting during Late Jurassic-Early Cretaceous tectonic activity, thus escaping late Tertiary-Pleistocene erosion.

Andøya, a probable provenance area for parts of the vegetation on Svalbard

The extensive glaciers on Svalbard started to retreat before 20 kyr BP (Mangerud & Svendsen, 1992; Mangerud *et al.* 1992, 1998; Svendsen *et al.* 1992; Jessen *et al.* 2010; Hughes *et al.* 2016). The northwestern part of Europe was also glaciated during Late Pleistocene, but as shown by Vorren (1978), Vorren *et al.* (1988, 2015), Parducci *et al.* (2012) and Hughes *et al.* (2016), the northern part of Andøya, North Norway, was an ice-free refugium as early as ~22 kyr BP except for some cirques and lowland valleys occupied by local glaciers isolated from the mainland ice sheet (Nesje *et al.* 2007; Vorren *et al.* 2015). Birks *et al.* (1994) indicated that the climate was high Arctic continental with sparse, discontinuous vegetation dominated by grasses and a high percentage of small crucifers (Vorren *et al.* 1988). However, Parducci *et al.* (2012) have also given evidence for the presence of conifers although this hypothesis has been questioned by Birks *et al.* (2012).

Vorren *et al.* (2013) showed that *Aulacomnium turgidum* is a characteristic macrofossil in postglacial sediments from the northern tip of Andøya where it was especially abundant about 17.8–16.5 kyr BP. The presence of *A. turgidum* indicates a polar desert environment where the plants probably grew in moistier depressions, or places with some snow cover (Vorren 1978).

Already, Alm & Birks (1991) suggested that Andøya may have served as a spreading centre for long-distance dispersal of vascular plants, but at that time, they lacked adequate observations which could support this hypothesis. Later comprehensive palaeobotanical and biogeographical molecular analysis have supported the view that the plant colonization of Svalbard was due to migration also from other areas (Gabrielsen *et al.* 1997). Genetic studies by Alsos *et al.* (2007) have shown that long-distance plant colonization on Svalbard has occurred repeatedly and from several source regions, including Andøya and other parts of North Norway. It was assumed that the dispersal of plants could have been caused by floating icebergs and/or strong winds across the winter sea ice of the Norwegian Sea. We agree with the principle of these dispersal theories, but we will point out some important factors for explaining the dispersal.

1. It is well known that wind dispersal of plant material from snow-free areas is an important agent for mobilization of organic matter during winter in Arctic areas, when the landscape is smoothed by snow cover and winds are very strong (Bonde 1969; Glaser 1981). Saville (1972) suggested that seeds could be blown for a very great distance. As shown by Clark (1988) sand-sized charcoal particles can also be transported some distance downwind. However, they are often too big to be suspended at typical wind speeds, but move by saltation with trajectories rarely more than one metre above the surface (cf. Bagnold 1941). During this transport process the particles strike both the ground and each other leading to mechanical abrasion and rounding.

   The distance between Norway and Svalbard is about 1000 km, which is too far to explain dispersal by wind alone. Probably the plant material has been blown onto sea ice along the coast which later broke up and drifted northwards with the prevailing currents. Recent investigations have shown that material transported by sea ice can be quite significant, and the surface of sea ice in the eastern Arctic and in the Barents Sea can be discoloured by accumulations of lithogenic and biogenic material (Pfirman *et al.* 1990; Nürnberg *et al.* 1994). In this way drift ice is important in dispersal of plant material from Siberia and Northwest Russia to Svalbard; see e.g. Häggblom (1982) and Johansen & Hytteborn (2001).
2. Our finds of coal and botanical material in deep-sea sediments west of Svalbard indicate that a late glacial current system flowed along the ice margin of the Norwegian coast and further up along the west coast of Svalbard. This current system has also been reconstructed by Ślubowska-Woldengen *et al.* (2007), and Ślubowska-Woldengen *et al.* (2008) showed that the West Spitsbergen current was flowing parallel with the glaciated coast of west Spitsbergen (Fig. 11).
3. The distance between Andøya and the Vestnesa area is in excess of 1000 km. Recent transport time for passively drifting material in the surface water layer from Andøya to W Spitsbergen was simulated by Berge *et al.* (2005), and these estimates indicate that surface-layer transport could require up to 3–4 months. The late glacial current speed is not known, but it is reasonable to believe that it might have been of the same magnitude as at present or even somewhat slower.
4. The density of charcoal is c. 0.4–0.6 g/cm^3 (Patterson *et al.* 1987; Clark 1988). Although fresh charcoal floats very well, experiments indicates that the rate of waterlogging is dependent both on the temperature of charring, original fragment size, and species (Vaughan & Nichols 1995, Nichols *et al.* 2000, Scott *et al.* 2000). Within a single species the

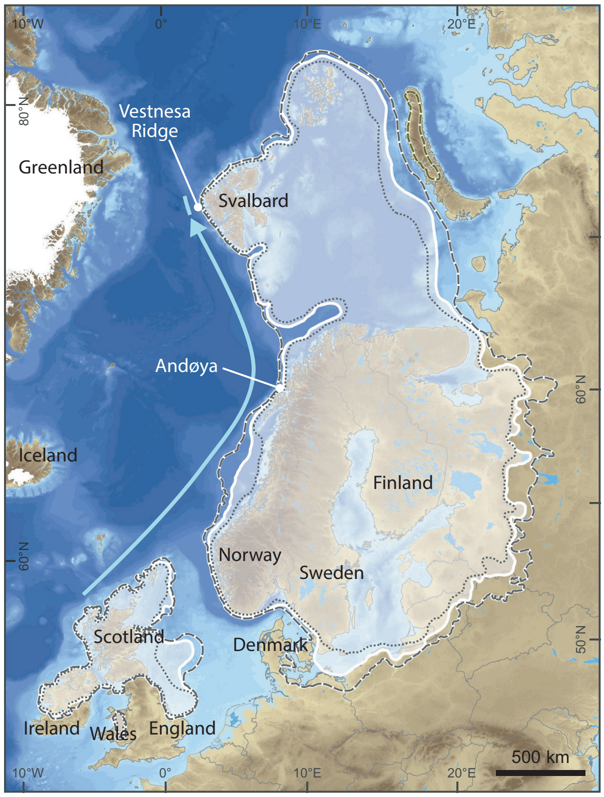


Fig. 11. Reconstruction of the ice sheets in northwest Europe 17 kyr BP. The dashed lines indicate uncertainty of the aerial extent. The arrow indicates the North Atlantic Current flow along the glaciated areas. Modified from Hughes *et al.* (2016) and Ślubowska-Woldengen *et al.* (2008).

waterlogging of different organs shows significant variations (Nichols *et al.* 2000). However, most charcoal becomes waterlogged in less than one week and sinks to the bottom of the water body, indicating that the hydrodynamic properties of the material are important limiting factors with regard to transportation length from the original fire. The rapid waterlogging of charcoal indicates that the only possible way of transporting charcoal northwards for several months, must be that it was transported northwards by ice rafting.

5. Archaeological investigations indicate that the coastal areas in north Norway have only been populated for the last 12 kyr (see summary by Günther *et al.* 2018). This indicates that the charcoal cannot have been derived from an ancient camp fire, but must be due to bush fire caused by lightning. Thus, this charcoal represents the oldest known bush fire in Norway.
6. The buoyancy characteristics of the moss *Aulacomnium turgidum* is not known, but probably this material would also sink fairly soon in salt water if not transported by ice rafting in a similar manner to the charcoal.
7. Coal has a higher density than sea water, and therefore the coal fragments must also have been transported with floating ice. Most seeds die in contact with salt water for extended periods (cf. van der Pijl 1982), but transport with drift ice will eliminate that problem. Seeds might have been deposited along the Svalbard shore during storms when drift ice has been cast ashore above the storm surf limit, analogous to driftwood (e.g. Hanken *et al.* 2012). After melting and releasing their organic material along the shore, some of the seeds could have started germinating in favourable places.
8. The ice cover of Svalbard was so extensive during the last glacial maximum that only nunataks in the northwestern part of Svalbard were exposed (Landvik *et al.* 2003). This could indicate that parts of Svalbard's flora might have survived if conditions for plant refuges were sustained, but as genetic studies by Alsos *et al.* (2007) indicate, colonization occurred repeatedly after glacial retreat with ice-free lowlands in Younger Dryas. There are 165 recent vascular plant species native to Svalbard (Elven & Elvebakk 1996), and the preliminary genetic studies seems to indicate that the dominant source was from northwestern Russia with some minor contribution from Greenland and Scandinavia. Alsos *et al.* (2007) suggested that sea ice could have played an important role in seed dispersal, and our find of plant material derived from Andøya supports this theory.

Conclusions

The discovery of both Upper Jurassic coal and typical tundra vegetation in deep marine Quaternary sediments west of Svalbard is important for a better understanding of the development of the vegetation cover in northwest Europe shortly after the Weichsel maximum, of the ice cover, and the North Atlantic current system. As coal is heavier than sea water and charcoal can only float for about one week, this material must have been transported northwards with drift ice by the North Atlantic Current and released to the sea bottom as the ice melted.

When the coastal areas of Svalbard became ice-free after Younger Dryas, parts of the land vegetation might have been established by seeds floating on drift ice from southern areas. If this ice was cast ashore above the storm surf limit, the seeds would have the possibility to sprout after the ice melted. This spreading mechanism has also been indicated for other islands on the northern hemisphere such as Greenland (e.g. Bennike 1999; Johansen & Hytteborn 2001) and Iceland (e.g. Rundgren & Ingólfsson 1999), and our investigations thus support the theory about ice rafting as an important factor in plant dispersal to remote North Atlantic islands.

Bischof *et al.* (1997) investigating clastic grains, suggested that the small Mesozoic outcrop at the northern part of Andøya was too small to contribute significantly to the clastic dropstone composition. However, this investigation indicates that ice-rafted organic grains might be a valuable tool in achieving more reliable and precise provenance analysis for Late Pleistocene erratics than has previously been possible.

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