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Stratigraphy and age of a Neoglacial sedimentary succession of proglacial outwash and an alluvial fan in Langedalen, Veitastrond, western Norway

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This study presents the sedimentary succession of an outwash plain and an alluvial fan located along the valley Langedalen at the south-eastern side of the Jostedalsbreen ice cap in inner Sogn, western Norway. A newly exposed ~2.8-m-high section along the southern riverbank of Langedøla river shows alternating layers of minerogenic sediments and peat layers with tree logs, identified as *Salix* sp. The section is situated in the distal part of an alluvial fan built out from the southern slope of Langedalen. Six AMS radiocarbon dates of tree fragments indicate that the accumulation of the fine-grained sediments in the lower part of the section was initiated earlier than the basal radiocarbon date of 914–976 calibrated years CE (1σ age range). These basal, fine-grained sediments are interpreted as proglacial outwash deposited in a floodplain depression or abandoned river channel in a low-energy glaciofluvial environment. Periods of low glacier cover, low river discharge or low-water stands over the floodplain allowed peat formation and the growth of trees and shrubs in the valley. The radiocarbon dates further indicate relatively rapid sediment accretion (~2.7–3 cm a^{-1}) between 190 and 125 cm below the sediment surface, equivalent to approximately 1220 to 1250 cal. a CE (1σ age range). At ~60 cm depth below the surface, dated to approximately 1590 to 1620 cal. a CE (1σ age range), a transition to more coarse-grained, sandy and gravelly sediments indicates increased sediment supply and distal expansion of the alluvial fan. This occurred most likely as a consequence of increased sediment yield from expanding glaciers along the southern valley side of Langedalen as a response to the initial Little Ice Age glacier growth. Based on these results, the accretion and progradation of glacier-fed alluvial fans mainly occur during periods of glacier advance rather than during glacier recession.

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Alluvial fans are common depositional landforms in many proglacial environments (e.g. Glasser *et al.* 2005; Hornung *et al.* 2010; Cable *et al.* 2018; Strzelecki *et al.* 2018). Alluvial fans record the relative importance of fluvial and colluvial processes, which can be related to changes in climate and sediment supply (Dorn 1994). However, proglacial alluvial fans are complex dynamic landforms, and their architecture may depend on glacier fluctuations, glacial erosion and paraglacial activity (McEwen *et al.* 2020). The construction of chronologies has been applied to relate the timing of proglacial alluvial fan development to sediment transport processes and sedimentary records in many mountainous regions such as Sierra Nevada, California (Benn *et al.* 2006; Owen *et al.* 2014), the Andes (Terrizzano *et al.* 2017), the European Alps (Sanders & Ostermann 2011), the Tibetan Plateau (An *et al.* 2021) and the Himalayas (Barnard *et al.* 2006; Ganju *et al.* 2018). A particular interesting question is whether the accretion of sediments and progradation of alluvial fans are associated with glacier build-up and advance or related to phases of glacier retreat. In a Neoglacial context, this may be translated to whether the growth of proglacial alluvial fans occurs primarily as a response to pre- or post-Little Ice Age processes. To elucidate these changes in erosion and sedimentation regimes, it is important to establish a chronological framework using absolute or relative age dating methods (Bowman 2019). It may also be relevant to couple evolution of alluvial fans to adjacent sedimentary archives such as moraines and proglacial outwash deposits (McEwen *et al.* 2011; Kociuba 2021).

The Holocene glacier chronology from the Jostedalsbreen ice cap region demonstrates that the Little Ice Age was the most prominent Neoglacial event, culminating in the mid-18th century (Nesje *et al.* 1991, 2000, 2001, 2008a, b; Nesje & Kvamme 1991; Nesje & Dahl 1993; Nesje 1994, 2009; Vasskog *et al.* 2012). The glacier forelands surrounding Jostedalsbreen are characterised by marginal moraines, tills, alluvial fans and glaciofluvial plains (e.g. Winkler 2020). The Little Ice Age moraines are clear evidence of the maximum glacier positions and subsequent advance/still-stand phases during the general retreat following the Little Ice Age maxima (Grove & Battagel 1983; Grove 1988, 2001, 2004; Bickerton & Matthews 1993; Matthews & Briffa 2005; Imhof *et al.* 2011; Carrivick *et al.* 2022). During this period, there was also increased colluvial and fluvial activity. In particular between the mid-17th and 18th centuries, there were increasing numbers of debris-flows, rockfalls and avalanches in the Jostedalsbreen region (Grove 1972), most likely associated with extreme weather (rainfall) events (Blikra & Nesje 1997; Matthews *et al.* 1997a, b, 1999, 2020; Blikra & Nemec 1998; Blikra & Selvik 1998).

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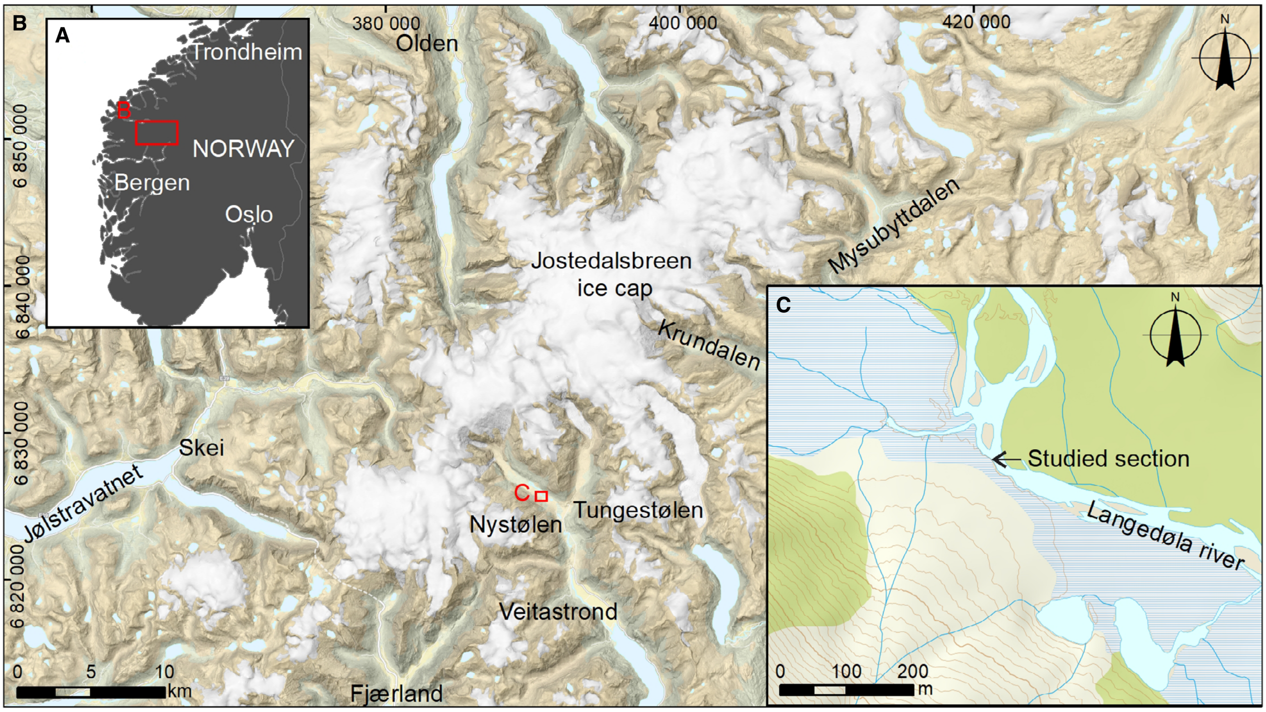

Fig. 1. A, B. Location maps of Jostedalsbreen Ice Cap. C. Langedalen and the studied section at the river side of Langedøla river. Map source: norgeskart.no.

Matthews *et al.* (2020) investigated the evolution of sub-alpine alluvial fans in the Austerdalen/Tungestølen area, southeast of Jostedalsbreen. Schmidt-hammer exposure ages obtained on boulders on the surfaces of the fans range from 9480±765 to 1955±810 years ago. After the deglaciation approximately 9700 years ago, the highest number of boulder deposits, peak debris-flood activity and maximum fan aggradation took place around 9000–8000 years ago. This was most likely a result of paraglacial processes owing to rock-slope adjustment and unstable till and colluvial deposits along the steep valley sides. From around 8000 years ago, the alluvial fans aggraded less because the sediment sources probably diminished. In addition, precipitation decreased during the Holocene Thermal Maximum, and the tree cover increased as the tree line advanced vertically. After around 4000 years ago the fan surfaces became more stable, but towards the mid-18th century Little Ice Age maximum, the climatic deterioration (i.e. increased precipitation and lower air temperatures) caused glacier advance, accompanied by more active processes on the fans.

This study describes the development and sedimentary succession of an alluvial fan built out from the southern valley side in Langedalen north of the village of Veitastrond in inner Sogn, western Norway. We present sedimentological and age results from a newly exposed section along the southern riverbank of the Langedøla river, showing alternating layers of minerogenic sediments and peat layers with tree fragments. These results are complemented with data from previous studies from the same area by Lewis & Birnie (2001), McEwen *et al.* (2011) and Øygard (2013). This evidence forms the basis for describing the Neoglacial, including the Little Ice Age, deposition of the proglacial outwash in the valley bottom and the development of the alluvial fan built out along the southern valley side of Langedalen.

Study site

The study section (61°13′38.2″N, 07°04′57.8″E, 271 m a.s.l.) is located in the distal part of an alluvial fan in Langedalen, a valley southeast of Jostedalsbreen that coalesces with Austerdalen at Tungestølen (Fig. 1). The Langedøla river flows from Langedalsbreen, an outlet glacier from the Jostedalsbreen ice cap in the west (Fig. 2A). Lateral, southward migration in the outer riverbank has caused erosion and undercutting, exposing a section that contains distal sediments from an alluvial fan that has been built out from a tributary glacier meltwater stream from Opptaksbreen, an outlet glacier from a small ice cap (Fig. 2B). Figure 2C shows an old picture of the riverbank at the study section location. The year of the picture is unknown, but it is likely from the late 19th or early 20th century.

The alluvial fan covers an area of 93 630 m^2. The apex is located at an elevation of 356 m a.s.l. and the most distal part, truncated by the Langedøla river, lies at

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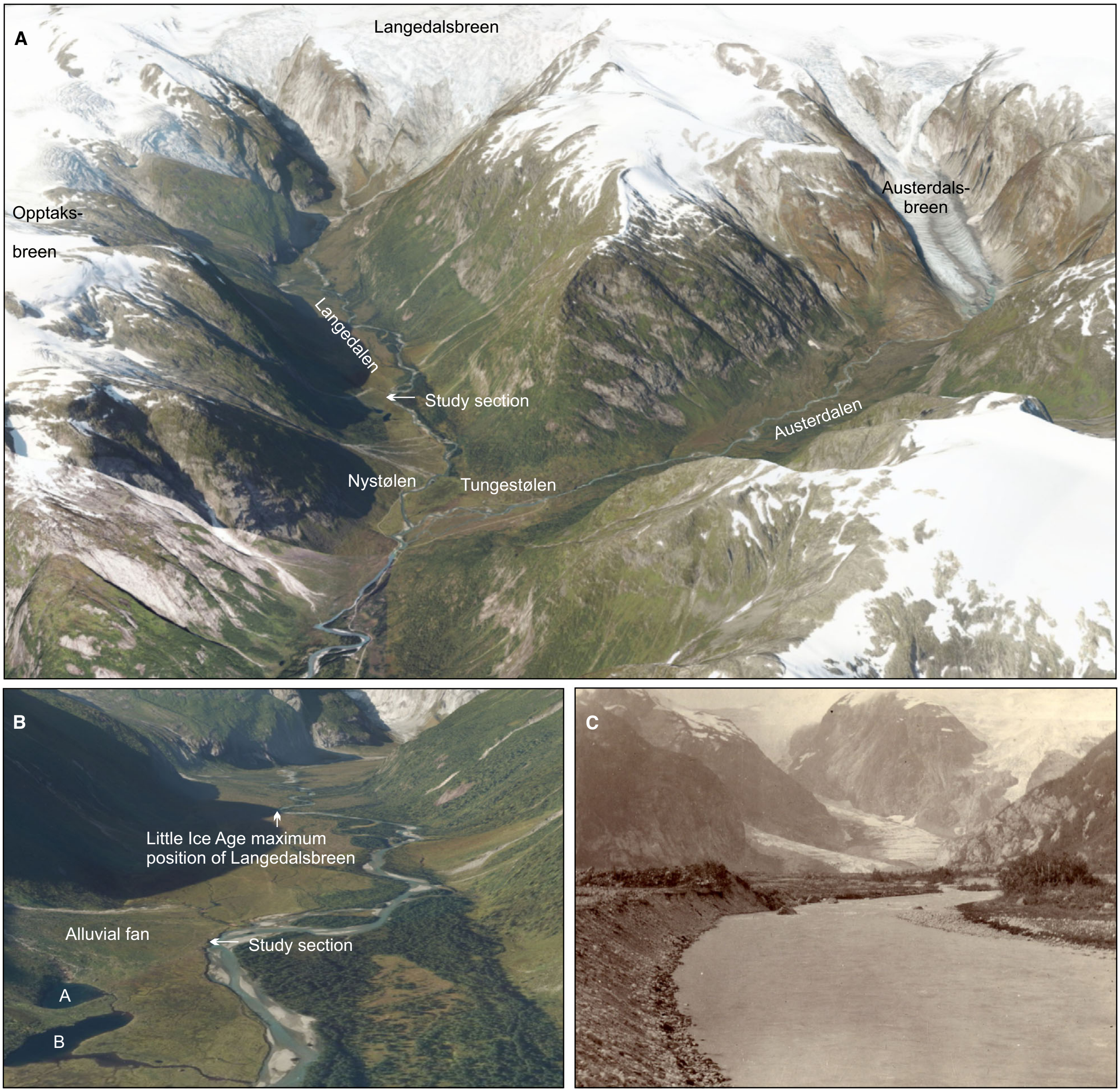

Fig. 2. A. Overview of Langedalen and adjacent locations (source: norgeibilder.no). B. Oblique image of the location of the study section, the alluvial fan and the Little Ice Age maximum position of Langedalsbreen. Ponds ‘A’ and ‘B’ are interpreted to be snow avalanche impact craters (source: norgeibilder.no). C. An old photograph of the study section at the bank of Langedøla river (NGU photo archive).

264 m a.s.l. The transverse profile across the alluvial fan shows a convex surface (transect a–a′ in Fig. 3). The alluvial fan, which is slightly concave along its longitudinal profile (transect b–b′ in Fig. 3), is 440-m long, giving an average surface gradient of 20.9%. The alluvial fan has been formed by sediments transported by the river down the tributary gorge on the southern side of the main valley. Southeast of the alluvial fan, there are two water-filled depressions (Ponds ‘A’ and ‘B’ in Fig. 2B), interpreted to be impact craters formed by snow avalanches from the southern valley side (for details about formation of snow avalanche impact craters in Norway, see Matthews *et al*. (2017) and references therein). Depression ‘A’ measures 80 × 60 m, whereas depression ‘B’ measures 146 × 50 m. Linear surface features upslope from the depressions (towards the SW) and isolated ‘fresh’ boulders on the surface of the alluvial fan and in the gentle valley bottom indicate active snow avalanche processes in the area.

The study site is located beyond the outer Little Ice Age moraine of Langedalsbreen, which Øygard (2013) dated lichenometrically to 1769 CE (Fig. 2B). The basal sediments, below the alluvial fan sequence, at the study site are therefore most likely related to proglacial outwash

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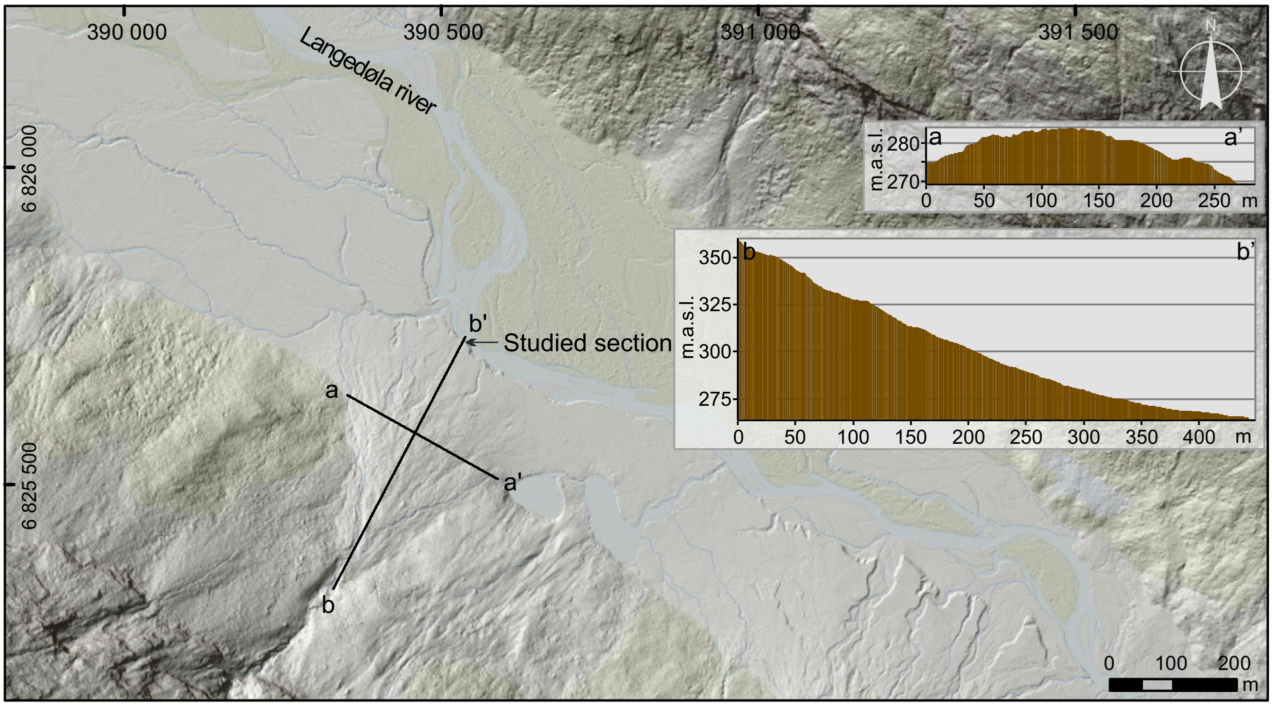

Fig. 3. Hillshade map for the study area with transverse (a–a′) and longitudinal (b–b′) profiles of the alluvial fan. Map source: hoydedata.no.

associated with Holocene, and in particular Neoglacial (including the Little Ice Age) advance and retreat phases of Langedalsbreen. Marginal moraines show that Langedalsbreen was significantly larger (27.2 km^2) during the Little Ice Age than at present (20.9 km^2; Carrivick *et al.* 2022). Also, the Little Ice Age glacier front of Opptaksbreen above the alluvial fan was located further downslope just above the apex, indicating a reduction in area from 9.5 to 7.7 km^2 at present (Carrivick *et al.* 2022). As a result, the fan was directly affected by variations in water discharge and sediment yield. Carrivick *et al.* (2022) calculated the equilibrium line altitude depression during the Little Ice Age at Langedalsbreen to ~250 m, as compared with the equilibrium line altitude in 2006.

Material and methods

After an initial survey of the site on 6 September 2019, the study section was described, photographed and logged on 15 October 2020. The employed logging scheme (Krüger & Kjær 1999) was supplemented by symbols for peat and logs (Fig. 4). Tree fragments from six peat horizons were extracted for AMS radiocarbon dating, put in plastic bags and sealed. At the EarthLab sediment laboratory at Department of Earth Science, University of Bergen, the tree fragments were dried overnight at 90 °C. Subsamples of the retrieved tree fragments were submitted to the Poznan Dating Laboratory for standard AMS radiocarbon dating. The radiocarbon dates were calibrated with the Calib 8.20 calibration program, using the IntCal20 Northern Hemisphere radiocarbon age calibration curve (Reimer *et al.* 2020). The median probability calibrated ages, 1σ age range (68.3%) and 2σ age range (95.4%), are presented. In the case of several possible calibrated age options, the calibrated dates with the highest probability were used. However, for Langedal-4 (Poz-130 765), the date with the lower probability was chosen because the age is most likely younger than the dated sample below (sample Langedal-3, Poz-130 547).

Results

Stratigraphy

A near vertical, ~280-cm-deep section in an exposure along the southern outer riverbank was excavated and logged (Fig. 4A). The section extends at least another ~80 cm below the water level in the Langedøla river. The surface at the site consists of a grass- and moss-dominated vegetation cover with mountain birch and other willow shrubs. The sedimentary log of the section is presented in Fig. 4B. Based on lithostratigraphic observations we divide the section into three units.

Unit A: Alluvial fan deposits with soil development. – Between 44 and 2 cm there is a diamicton with gravelly sand matrix and stones/cobbles with a diameter of up to 10 cm, whilst the upper 2 cm consist of topsoil. Roots reach down to at least 20 cm below the surface. Based on the occurrence of cobbles and the unsorted nature of

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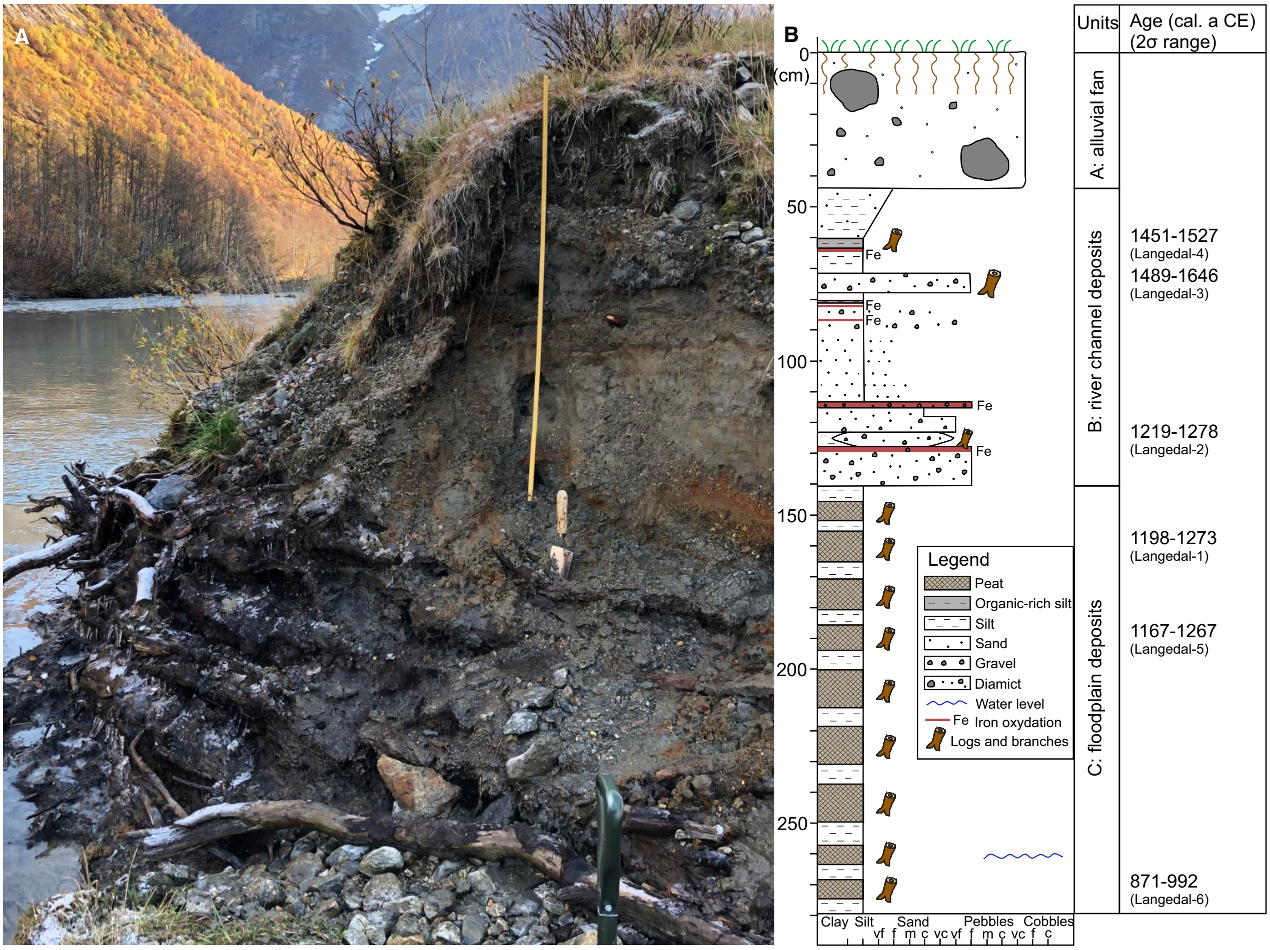

Fig. 4. Photograph (A) and sedimentary log (B) of the vertical section at the bank of the Langedøla river.

this uppermost deposit, we interpret it to reflect a progradation of the alluvial fan over the study site. Large parts of this unit are also influenced by soil formation processes.

Unit B: River channel deposits. – Between 141 and 44 cm the sequence consists of interbedded silt, sand and gravel. In the lower part of this unit, from 141 to 113 cm, the sequence is dominated by coarse sand and gravel. The lowermost gravel bed from 141 to 128 cm has iron oxidation sustained over the top 5 cm. Between 128 and 123 cm we found a thin layer of unsorted gravel with wood fragments, which lenses out towards a laminated silt layer to both sides of the section. This lens was dated based on a wood fragment identified as willow (*Salix*). The upper part of this unit, from 113 to 44 cm, is more fine-grained and consists of silt intercepted by sand and gravel layers and lenses. Starting from 113 to 78 cm, silt dominates, but is interbedded with thin layers of sand and sand–gravel lenses with iron precipitation. Between 78 and 72 cm, there is an unsorted diamicton with a matrix of sandy gravel containing a tree branch which has been dated and was identified as willow (*Salix*). From 63 to 60 cm, the silt is organic rich containing wood fragments and branches, and iron oxidation is found in the layer immediately below. A wood fragment picked from this level for dating is identified as aspen (*Populus* sp). In the uppermost bed, between 60 and 44 cm, we find inversely graded silt to fine sand.

Based on the layered nature and alternating layers of silt sand, and gravel with subrounded to subangular clasts, this unit is interpretated as river channel deposits. Iron precipitation and oxidation indicate that the river channel was at times abandoned and groundwater levels may have varied. It seems that the energy level was highest in the lowermost part of this unit from 141 to 113 cm when the main river transport was probably located at the studied section. Later, the section had a more distal position with respect to the main river transport, or higher elevation owing to aggradation, restricting the deposition of sand and gravels to flood events throughout the upper part of this unit from 113 to 44 cm.

Unit C: Floodplain deposits. – The basal sequence contains organic, fine-grained sediments of silt and clay

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Fig. 5. Photographs of the radiocarbon-dated wood samples.

inter-bedded with peat horizons. The peat resembles grass-bound topsoil which was drowned by silty flood deposits. Several of these peat layers have abundant logs and branches up to 10 cm in diameter deposited in their upper part. We dated twigs and roots of willow (*Salix*) on three levels throughout this unit: 275–268, 195–185 and 165–155 cm.

This basal, fine-grained sediment sequence is interpreted as proglacial outwash deposited in a floodplain depression (pond), an abandoned river channel or on an inner river point bar in a low-energy glaciofluvial environment. Variations in water level in Langedøla river and periods of low water stands over the floodplain allowed peat formation and growth of trees and shrubs.

Radiocarbon dates

New radiocarbon dates. – Samples for radiocarbon dating from the section were collected at six levels (Langedal-1 to -6; Fig. 5; Table 1). The calibration curves of the individual dates are shown in Fig. 6. The age–depth relationship of the radiocarbon dates is shown in Fig. 7, and the mean accumulation rates between the radiocarbon dated levels are displayed in Fig. 8.

Table 1. Radiocarbon ages from the study site in Langedalen. The radiocarbon dates have been calibrated with the Calib 8.20 calibration program using the IntCal20 Northern Hemisphere radiocarbon age calibration curve (Reimer *et al.* 2020). 1σ age range = 68.3% and 2σ age range = 95.4%. Calibrated ages with highest probability are underlined. BP = Before present (=1950 CE); BCE/CE = Before Common Era/Common Era; RAUPD = relative area under probability distribution.

Sample no.	Depth below surface (cm)	Laboratory reference	^{14}C age BP ($\pm 1\sigma$)	Cal. age (a CE) (median probability)	Cal. age (a CE) (1σ age range)	RAUPD	Cal. age (a CE) (2σ age range)	RAUPD	Tree species
Langedal-4	60–63	Poz-130 765	370±30	1518	1459–1515 1590–1620	0.655 0.345	1451–1527 1552–1633	0.547 0.453	*Salix*/*Populus*
Langedal-3	72–78	Poz-130 547	315±30	1561	1519–1590 1020–1639	0.793 0.207	1489–1646	1.000	*Salix*
Langedal-2	123–128	Poz-130 764	785±30	1247	1228–1247 1253–1271	0.506 0.494	1219–1278	1.000	*Salix*
Langedal-1	155–165	Poz-130 546	820±30	1233	1218–1263	1.000	1175–1196 1198–1273	0.108 0.892	*Salix*
Langedal-5	185–195	Poz-130 548	830±30	1223	1181–1187 1212–1262	0.083 0.917	1167–1267	1.000	*Salix*
Langedal-6	268–275	Poz-130 549	1140±30	922	776–780 883–902 914–976	0.029 0.225 0.746	775–787 828–859 871–992	0.056 0.087 0.857	*Salix*

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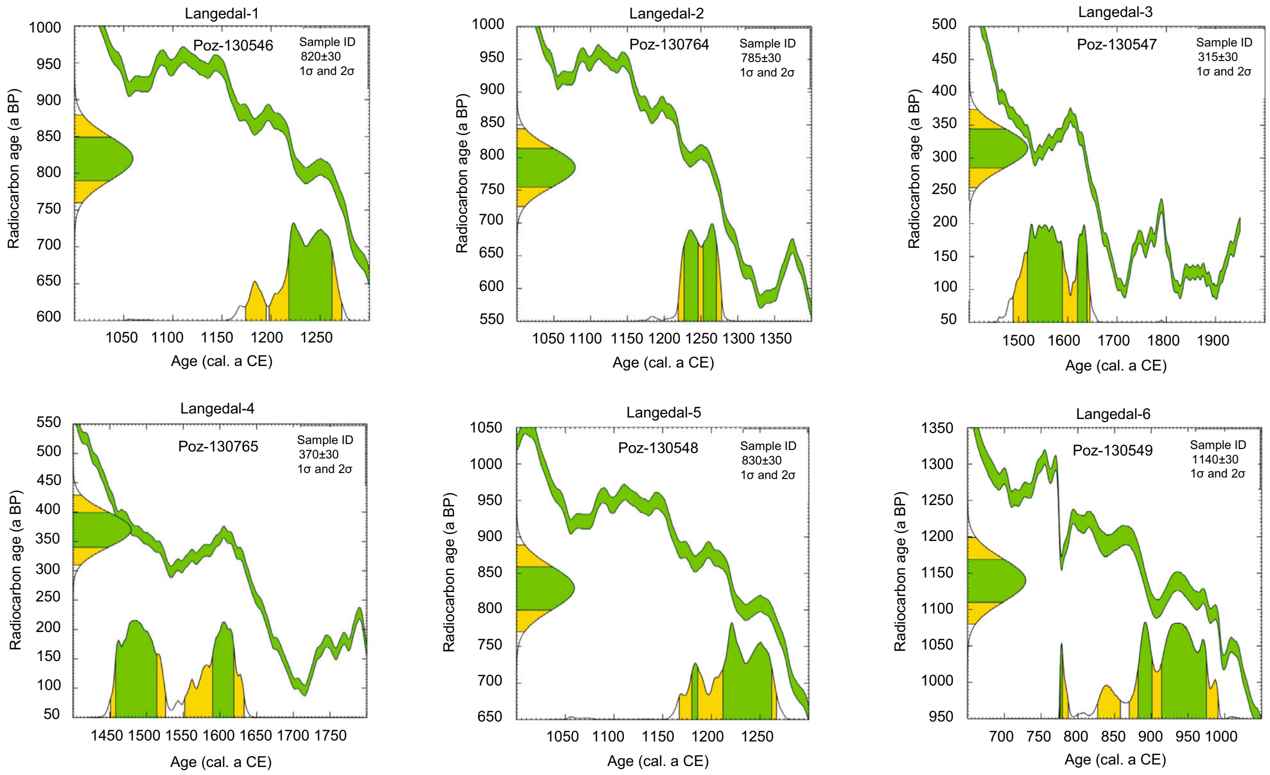

Fig. 6. Calibration curves of the individual radiocarbon samples obtained from the radiocarbon calibration program Calib 8.20 (Reimer *et al.* 2020).

The radiocarbon dates of the tree fragments imbedded in peat horizons representing former river bar or floodplain surfaces indicate that the accumulation of the fine-grained sediments in the lower part of the section (275–268 cm below the surface) started prior to the basal radiocarbon date of 914 to 976 cal. a CE (1σ age range). The radiocarbon dates further show rapid accumulation of minerogenic sediments (on average on the order of 2.7–3 cm a^{-1}) between approximately 1220 and 1250 cal. a CE (190–125 cm below the sediment surface). This is significantly higher than the base sediment accumulation rate throughout the profile of approximately 0.25 cm a^{-1} and probably an effect of the thickness of the woody layers (Fig. 8). At a depth of about 60 cm below the surface, a transition to more coarse-grained sandy and gravelly sediments indicates increased sediment supply and distal expansion of the alluvial fan from about 1590 to 1620 cal. a CE (1σ age range). This is most likely a result of increased sediment delivery from the growing glaciers along the southern valley side in Langedalen as a response to the climate deterioration during the Neoglacial (Little Ice Age). This suggests that this accretion phase of the alluvial fan most likely occurred simultaneously with the initial expansion of Opptaksbreen and Langedalsbreen before their Little Ice Age maxima during the mid-18th century.

Previous radiocarbon dates from Langedalen. – Our results from the newly exposed site can be combined with previous observations in Langedalen by Lewis & Birnie (2001) and Øygard (2013). Lewis & Birnie (2001) radiocarbon dated four samples with the conventional dating technique from a section in the same area as the present study along the Langedøla river. The oldest date indicates that the deposition of fine-grained facies beneath the more coarse-grained, alluvial fan deposits started before 1278–1422 CE (2σ age range). We re-calibrated the dates presented by Lewis & Birnie (2001: table 2, p. 187), using 1 and 2σ age ranges (Table 2). From the re-calibrated ages, the deposition of fine-grained facies beneath the more coarse-grained, alluvial fan deposits started before 1351 to 1395 cal. a CE (1σ age range) or 1275 to 1411 cal. a CE (2σ age range). The formation of the distal alluvial fan deposits may have occurred after 1735 cal. a CE.

Along the escarpment on the southern side of the Langedøla river close to the studied section, Øygard (2013) obtained three AMS radiocarbon dates on organic material imbedded in the minerogenic material at three different depths: 'Langedalen-1' was sampled at a site ~10 m away from 'Langedalen-2' and 'Langedalen-3' (Table 2). The dates indicate that the three organic horizons with wood remains formed around 1100, 1220, and 1510 cal. a CE. However, as

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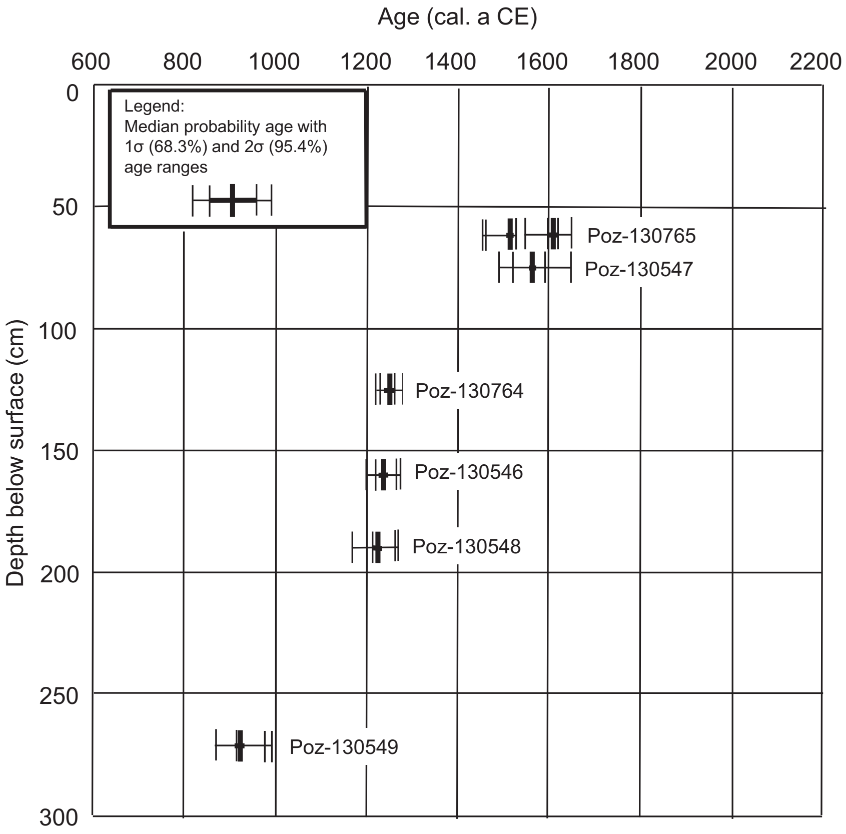

Fig. 7. Age–depth relationship of the study site (see Tables 1 and 2).

the uppermost date at 125 cm below the surface is the oldest, Øygard (2013) suggested that the dated wood fragment has been subjected to re-deposition. This discrepancy may, however, also be related to differences between the sampling sites.

Discussion

The mostly fine-grained sediments intercalated with peat and wood remains in the lower part of the section indicate the deposition of proglacial outwash along the valley bottom in a low-energy floodplain depression or point bar, as also suggested by Lewis & Birnie (2001). If the Langedøla river had a more southern position upstream of the study site at the time of deposition, the alluvial fan could have acted as an obstacle forcing the river towards the north and forming an inner point bar at the study site where tree fragments could accumulate. This hypothesis is supported by observations of present-day deposition of tree logs on a point bar on the northern side of the river opposite our study site. Alternatively, the tree fragments may have been deposited in a pond or abandoned river channel on the floodplain during flood events or because of glacier advance into a forest (Worsley 2020).

The expansion and accretion of the alluvial fan were represented by deposition of gravelly and sandy facies (the upper ~60 cm) and were most likely a result of increasing sediment supply/yield and glaciofluvial transport as a result of the advancing glacier located on the mountain plateau along the southern valley side of Langedalen during the Late Holocene (Neoglacial). The uppermost Langedalen-4 radiocarbon date of 1590 to 1620 cal. a CE (1σ age range) at 60 cm indicates that the expansion of the alluvial fan probably happened after this age. Thus, the expansion and growth of the alluvial fan coincide with the Neoglacial (Little Ice Age) glacier and climate records established from different proxy and historical data (Grove 1988; Nesje *et al.* 1991, 2001; Bickerton & Matthews 1993; Nesje & Dahl 2003; Nesje 2009), indicating increased winter precipitation and ~1 °C lower summer temperatures compared with the 1961–90 normal. This suggests that the activity on the alluvial fan increased during the Little Ice Age glacier expansion.

A comparison of the new radiocarbon dates obtained in Langedalen with radiocarbon dates obtained on tree remains from two former studies (Lewis & Birnie 2001; Øygard 2013) in the same area along the southern side of the Langedøla river does not show a consistent pattern. Lewis & Birnie (2001) found younger tree remains of

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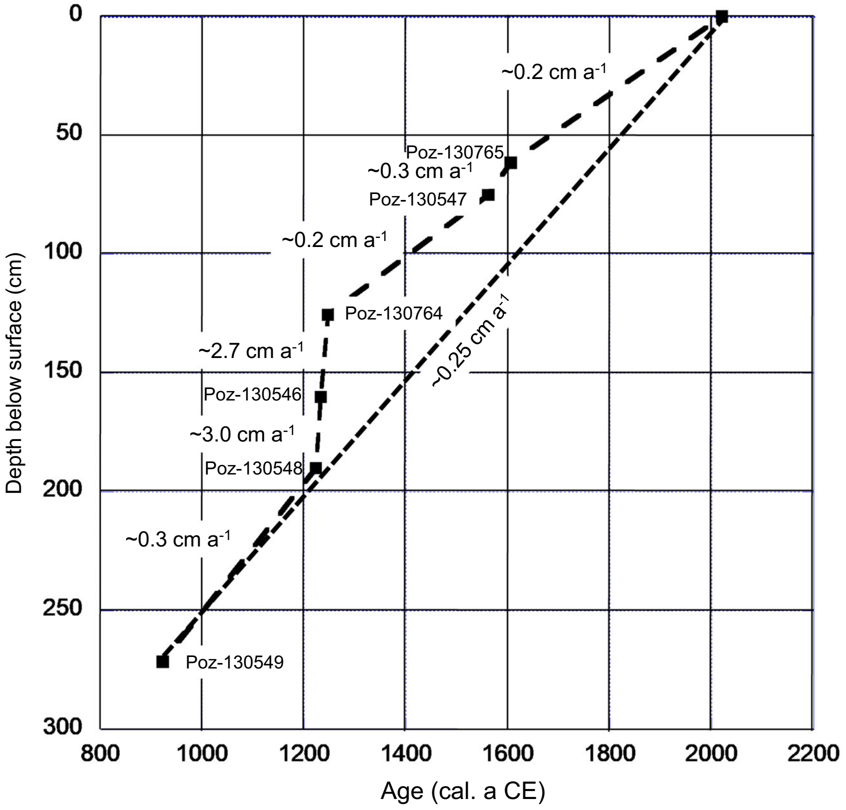

Fig. 8. Mean accumulation/sedimentation rates between the radiocarbon-dated levels (see Tables 1 and 2).

1725 to 1811 cal. a CE (1σ age range) than were found in our section or in the samples by Øygard (2013). A reason for this deviation may be that the samples were collected at different locations along the riverbank, and the influence of the alluvial fan may differ between these locations.

Deposits from the pre-Little Ice Age period have previously been reported from other valleys around the Jostedalsbreen ice cap. Nesje & Rye (1993) radiocarbon-dated tree logs embedded along a vertical section in distal glaciofluvial material at Sandsvora in Sunndalen on the northwestern side of the Jostedalsbreen ice cap. The organic horizons were interpreted to have formed when Sandskardfonna, a cirque glacier above the site, was significantly smaller than at present, or totally melted down. The basal radiocarbon sample dates to ~750 cal. a CE, whereas the upper organic horizon dates to ~1350 cal. a CE, also indicating the initial Little Ice Age expansion of Sandskardfonna. Also, Nesje & Dahl (1991) obtained radiocarbon dates from eight peat horizons embedded along a 1.3-m-deep section in a peat deposit intercalated with distal, glaciofluvial sediments at Rambjørgebotnen in Befringsdalen on the western side of the Jostedalsbreen ice cap. The peat was interpreted to have formed when small local glaciers in Steinbotnen above the site were significantly smaller than at present,

Table 2. Conventional and AMS radiocarbon ages of wood remains and peat obtained by Lewis & Birnie (2001) and Øygard (2013), respectively. The ^{14}C ages are given in 1σ range (68.3%) and 2σ range (95.4%). The calibrated age ranges with the highest probability are selected. The radiocarbon dates have been re-calibrated with the program Calib 8.20 using the IntCal20 Northern Hemisphere radiocarbon age calibration curve (Reimer *et al.* 2020). CE = Common Era.

Sample no./ thickness	Laboratory reference	Material	^{14}C age (a BP)	Age (cal. a CE) (median probability)	Age (cal. a CE, 1σ)	Age (cal. a CE, 2σ)	Reference
B4.1	CAR-1470	Wood	640±60	1343	1351–1395	1275–1411	Lewis & Birnie (2001)
B1.2/(2–3 cm)	CAR-1471	Peat	250±60	1658	1622–1682	1477–1695	Lewis & Birnie (2001)
B1.2/(3–4 cm)	CAR-1472	Peat	190±60	1774	1725–1811	1637–1950	Lewis & Birnie (2001)
B1.2/(12–13 cm)	CAR-1473	Peat	260±60	1642	1511–1591	1468–1694	Lewis & Birnie (2001)
B1.2 average			233±60	1735	1640–1672	1632–1689	Lewis & Birnie (2001)
Langedalen-1	Poz-3826	Wood	940±35	1102	1114–1156	1027–1177	Øygard (2013)
Langedalen-2	Poz-3827	Wood	380±35	1509	1454–1512	1445–1527	Øygard (2013)
Langedalen-3	Poz-3828	Wood	830±30	1223	1212–1262	1167–1267	Øygard (2013)

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or totally melted down. The basal radiocarbon sample dates to ~1450 cal. a BCE, whereas the upper peat horizon dates to ~620 cal. a CE (Nesje & Dahl 1991), indicating that the initiation of the latest Neoglacial (including the Little Ice Age) glacier expansion in Befringsdalen occurred during the 7th century. Torske (1993) carried out a palaeobotanical study in a nearby section, which contained mainly peat with macroscopic organic remains in the form of roots, wood fragments and twigs. In addition, there were thin horizons with minerogenic material, interpreted to reflect alluvial (brownish colour) and glaciofluvial (bluish-grey colour) activity along the stream from Steinbotnen. The radiocarbon dates showed that the sequence covered the time span from about 9600 to 2900 cal. a BP, with a modern soil on top. Altogether, a general picture of glacier and alluvial fan expansion in the centuries prior to the Little Ice Age is now revealed from sedimentary records on both sides of the Jostedalsbreen ice cap.

During the Neoglaciation in western Norway, as in many other glaciated regions, the climate showed a cooling trend with several glacier fluctuations, culminating in the Little Ice Age event (Nesje & Kvamme 1991; Nesje & Dahl 1993; Nesje *et al.* 2008a, b). In the centuries prior to the Little Ice Age, the amount of winter precipitation increased (Nesje *et al.* 2001; Bakke *et al.* 2005; Gjerde *et al.* 2016), resulting in a higher frequency of snow avalanches (Vasskog *et al.* 2011; Aa *et al.* 2022). Also, Holocene flood frequency records from non-glacial catchments east of the Jostedalsbreen ice cap show peaks in extreme flood events around 500–600 CE and 1800 CE (Støren *et al.* 2012). The combined effect of glacier re-advance over unconsolidated deposits in valley floors and changes in the hydroclimatic regime probably increased sediment accumulation rates in downstream outwash pools and abandoned river channels. At the same time, climate deterioration also caused glacier advance on the mountain plateau above valleys and forest decline on alluvial fans (McEwen *et al.* 2020), resulting in accretion and progradation of the alluvial fans. This setting is not unique to the Jostedalsbreen ice cap, and the reconstruction of glacier and climate changes may be extrapolated to comparable glaciated mountainous landscapes in other parts of the world, where fewer studies have been conducted.

The question of whether accretion of sediments and progradation of alluvial fans are associated with glacier build-up and advance or related to phases of glacier retreat requires reliable time control on when alluvial fans advanced over the underlying deposits. A potential uncertainty lies in the possibility of redeposition of older wood remains in a younger sediment layer. We assume that Langedalen was forested with willow (*Salix* sp.) and aspen (*Populus* sp.) when Langedalsbreen started to advance through the valley prior to the Little Ice Age. The glacier may have overridden the forest in a way similar to what Worsley (2020) observed at Engabreen. Thus, the source for older wood remains can be from subglacial material or erosion of proglacial sediments containing wood fragments. As the glacier advanced and the climate became colder, the proglacial area between the glacier front and the study section was gradually reduced in size and was probably dominated by grass and shrubs. This may have reduced the likelihood of redeposition of wood fragments towards the peak of the Little Ice Age. Also, our sedimentological observations of the upper part of Unit B indicate that the deposition of sand and gravel was restricted to flood events and our study site had a more distal position to the main river. Based on our observations and assuming that the dating of the tree logs is accurate, we conclude that the alluvial fan expanded simultaneously with glacier advance prior to the regional peak of the Little Ice Age (1740–1750 CE). This is consistent with the recalibrated datings from Øygard (2013) and sample B4.1 from Lewis & Birnie (2001). The 1725 to 1811 cal. a CE dating (sample B1.2) from Lewis & Birnie (2001) may reflect that this location was located at the most distal part of the alluvial fan so that the progradation of the fan reached this site later during the peak of the Little Ice Age.

Conclusions

- Six radiocarbon dates of tree logs (*Salix* sp. and possibly *Populus* sp.) imbedded in peat horizons representing former river bar or floodplain surfaces in the valley Langedalen southeast of the Jostedalsbreen ice cap indicate that the accumulation of the fine-grained sediments in the lower part of the section (275–268 cm below the surface) started prior to the basal radiocarbon date of 914 to 976 cal. a CE (1σ age range).
- At a depth of about 44 cm below the surface, a transition to more coarse-grained sandy and gravelly sediments indicates increased sediment supply and distal, northward expansion of the alluvial fan from about 1590 to 1620 cal. a CE (1σ age range).
- This fan accretion most likely occurred because of increased sediment delivery/yield from growing glaciers along the southern valley side in Langedalen as a response to the climate deterioration during the Neoglacial (including the Little Ice Age).
- The accretion phase of the alluvial fan also most likely occurred simultaneously with the initial expansion of Langedalsbreen towards its mid-18th century Little Ice Age maximum.
- The results from this study indicate that accretion and progradation of proglacial alluvial fans mainly occur during periods of glacier advance rather than during glacier recession.

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Author contributions. – AN made the initial survey and outlined the design of the study. DCR and JCY conducted the fieldwork. DCR constructed the sedimentary log and put together Figs 1–5. AN prepared the radiocarbon samples and created the age model and prepared Figs 6–8. All authors (AN, DCR and JCY) interpreted the data. AN and JCY wrote the text, which was edited and reviewed by all authors (AN, DCR and JCY).

Data availability statement. – The data that support the findings of this study are available from the corresponding author upon request.

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