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environments in
Svalbard**

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**Sedimentological characteristics of
ice-wedge polygon terrain in Adventdalen
(Svalbard). Environmental and climatic
implications for the Late Holocene**

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Received: 31 March 2014 – Accepted: 9 April 2014 – Published: 7 May 2014

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Published by Copernicus Publications on behalf of the European Geosciences Union.

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decades several studies have focused on the interaction between air and soil temperatures in the process of cracking (Burn, 1990; Mackay, 2000; Christiansen, 2005; Fortier and Allard, 2005). Other papers have examined the sedimentary record in areas where terrestrial polygonal networks are well-developed (Fortier and Allard, 2004; Fortier et al., 2006) as well as the isotopic composition of the ice (Schwamborn et al., 2006; Opel et al., 2011) as two complementary sources to infer past environmental conditions.

This research is focused on Adventdalen valley (Spitsbergen island, Svalbard), an area where ice-wedge polygon terrains are widespread. The High Arctic is precisely one of the areas on Earth that has recorded the strongest warming trend over the last decades: since the beginning of the 20 century mean annual air temperature (MAAT) in Svalbard increased 0.23 °C per decade (Humlum et al., 2011a). In parallel, ground temperatures have shown a gradual increase during the last decade in Svalbard, the region recording the warmest permafrost temperatures in the High Arctic (Christiansen et al., 2010). Thus, significant changes on the dynamics of the terrestrial ecosystem are expected in response to this climate trend. The formation of ice-wedges may be also affected by this fast-changing climate scenario; in this context, over the recent years, several studies have monitored the cracking process in Svalbard (Christiansen, 2005; Watanabe et al., 2013).

In order to better understand the environmental dynamics in ice-wedge polygon terrains it is of crucial importance to take into account the topographical and geomorphological characteristics of these areas as well as the sedimentological properties and past environmental evolution in the area where polygons are distributed. Present-day landscape in Adventdalen is a consequence of Pleistocene glaciations and post-glacial (Holocene) environmental dynamics. The Lower Adventdalen valley remained covered by ice with at least c. 1000 m of thickness during the Last Glaciation (Lønne and Nemeč, 2004). Enhanced orbital forcing during the Early Holocene induced higher temperatures in the High Arctic that produced shrinking and upvalley retreat of Svalbard glaciers. This process favoured the post-glacial rebound of the valley bottom, which

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has been quantified in 60–70 m over the Holocene (Lønne and Nemeč, 2004). Evi-
dences of warmer conditions in Svalbard until 4 kaBP come from a wide range of sed-
imentary records, such as marine cores (Salvigsen, 2002; Forwick and Vorren, 2010),
lacustrine records (Birks, 1991; Svendsen and Mangerud, 1997; Snyder et al., 2000)
or glaciers (Liestøl, 1988; Humlum et al., 2005). Humlum (2005) proposes MAAT as
high as 0–3 °C for coastal areas, which means that permafrost conditions at lower alti-
tudes should have developed only during the Mid and Late Holocene. According to data
retrieved from lake sediments, warm conditions extended from 8 to 4–5 kaBP (Birks,
1991; Holmgren et al., 2010), with a maximum of ca. +2 °C around 6 kaBP (Wanner
et al., 2008; Sundqvist et al., 2010). After 4 kaBP, temperatures started dropping in
the Northern Hemisphere, particularly in the North Atlantic Region, as reflected by
Greenland ice cores (Vinther et al., 2006), with a declining linear temperature trend
of –0.52 °C per 1000 years (Humlum et al., 2011b) and enhanced climate variability
(Moberg et al., 2005). Over the Late Holocene ocean circulation changes have deter-
mined a succession of colder and warmer periods in the High Arctic (Skirbekk et al.,
2010; Moros et al., 2012), which favoured glacier advances and retreats in Svalbard
(Hald et al., 2001; Grinsted et al., 2006; Divine et al., 2011; Velle, 2012) as well as
landscape changes in the major valleys (Härtel, 2011).

The study of the sediments in areas with ice-wedge polygonal networks provides
insights on their formation and physical and chemical weathering processes, allowing
to understand the local palaeoenvironmental and palaeoclimatic evolution. There is
no agreement if in cold regions weathering is mainly driven by temperature or water
availability. According to Hall et al. (2002) the weathering processes are more limited
by moisture availability than by temperatures, therefore, weathering can be intense
even at low temperatures (Hall, 1997, 2004; Matsuoka and Murton, 2008). The water
fluxes in cold-climate environments are assumed to be important because weather-
ing is dominated by physical processes (Egli et al., 2014), thus the intensity and the
frequency of freeze–thaw cycles are factors of critical importance. Chemical weather-
ing in periglacial areas is also an important mechanism in terms of geomorphic work

(Allen et al., 2001; Thorn et al., 2001), being controlled by the type of lithology, biological activity, organic matter, topography, aspect, water availability, the structure of the hydrologic system and the age of exposure/deglaciation (Egli et al., 2014). Previous works developed indexes to assess soil weathering based on geochemical properties, such as the case of the chemical index of alteration (CIA) (Daviel et al., 2011).

The purpose of this paper is to present new data about the environmental dynamics in the ice-free area of Adventalen valley floor during the Mid and Late Holocene and its connection with climate variability. To do so, this research aims at:

1. characterizing the sedimentological record and weathering processes in two exposures from both the northern and southern banks of the Adventelva river where polygonal networks are present.
2. Characterizing the geochemical record in one of the studied profiles (ADV.20).
3. Reconstructing the environmental evolution in the area and its connection with palaeoclimatic trends in Svalbard.

2 Study area

This research is focused on the Lower Adventdalen valley, in the centre-west of Spitsbergen island (Svalbard archipelago). The study area is located in the proximities of Longyearbyen, the largest settlement of the archipelago, at latitude 78° N (Fig. 1). Climate corresponds to a polar tundra climate (ET) in the Köppen climate system. The MAAT between 1961 and 1990 in Longyearbyen was -6.7°C rising to -4.6°C between 1981 and 2010, with a large interannual variability, especially during winter months (Førland et al., 2011). No significant trends have been inferred for precipitation over the last decades, with a mean annual precipitation of 190 mm mainly concentrated during the summer season.

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Topography in the study area consists of peaks, ridges and plateaus cut by the Adventdalen valley, which runs SE–NW towards Isfjorden. Adventdalen is a typical U-shaped glacial valley covered by unconsolidated glacial, colluvial, alluvial, marine and aeolian deposits Holocene in age. Tertiary coal seams are exposed on the slopes composed mainly of Jurassic to Triassic deposits (Major et al., 2001). Tributary streams draining to Adventelva river have built large alluvial fans along the valley sides. One of the study areas is precisely located in Todalen alluvial fan, on the left margin of the river (Fig. 1).

The Equilibrium Line Altitude of the glaciers in Svalbard varies from 200 m a.s.l. along the coast to > 600 m in the central-eastern parts of Spitsbergen (Hagen et al., 1993). In the ice-free areas of Svalbard (~ 40 % of the island) permafrost is continuous, reaching a thickness of ~ 100 m in coastal areas up to ~ 400–500 m in the highlands (Liestøl, 1976). Permafrost in the valley floors and coastal areas is probably dated of the Late Holocene whereas in the mountains it dates back from the Last Glaciation or is even older (Humlum et al., 2003). The warmest permafrost conditions in the High Arctic are recorded in Svalbard despite a significant temperature increase detected during the last years (Christiansen et al., 2010).

Vegetation in the valley floor is typical of high-arctic tundra environments, with a mixture of grasses. Aeolian sediments cover the lowest glaciofluvial terraces of the Adventelva river (Fig. 1), where ice-wedge polygonal networks are a highly common patterned ground (Sørbel and Tolgensbakk, 2002; Ulrich et al., 2011; Pina, 2014). Here, the thermal contraction cracking of the ground is responsible for the formation of ice-wedge polygonal networks. This process occurs during cold spells in winter when air temperatures drop to below -20°C and ground temperatures to below -15°C near the top of the permafrost above the ice-wedge (Christiansen, 2005). Between 2000 and 2007 the thickness of the active layer at the end of the summer season in the bottom of Adventdalen valley oscillated between 74 and 104 cm (Christiansen and Humlum, 2008).

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The average dimension (mean axis) of the polygons in the study areas is about 12 m, but their sizes range from ca. 2 to 70 m. Also, most of the polygons are low-centred and have 5, 6 and 7 neighbours, although polygons with a number of neighbours in the range of 3 to 11 have been identified. The majority of networks exhibit a non-orthogonal pattern, but spatial clusters of orthogonal behaviours of the troughs were also detected in some networks. Consequently, the vertices of trivalent nature (intersection of 3 troughs) prevail largely against the tetravalent ones (4 troughs) on the analyzed networks (Saraiva et al., 2012).

Two sites have been examined, corresponding to: (1) a sedimentary sequence on the lowest part of the Todalen alluvial fan, in the southern bank of the Adventelva river; (2) a sedimentary sequence located in a glaciofluvial terrace on the northern bank of the river (Fig. 2).

The first area, where the alluvial fan of Todalen river meets Adventelva river, constitutes a case study where several ongoing experiments are conducted at a very detailed scale to identify the factors conditioning the distribution of periglacial landforms and to understand the process of ice-wedges and mudboils formation. Their distribution shows a consistent spatial pattern across the study area and is well-related to changes in the sedimentological properties across the alluvial fan (Watanabe et al., 2012a). The topographical position with respect to Todalen and Adventelva rivers conditioned the sources of the sediments as well as the geomorphological features distributed in this alluvial fan (Härtel, 2011). Todalen alluvial fan is a high-energy environment where coarse sediments (gravels and boulders) were deposited throughout the Holocene; in fact, the formation of alluvial fan deltas in Adventalen valley is thought to have started during the Early Holocene (Lønne and Nemeč, 2004). While in the upper part of the alluvial fan tens of mudboils are distributed, in the distal part ice-wedge polygons are abundant. Recent investigation has shown that the areas where mudboils are present experienced large amount of frost heave associated with intensive ice segregation in comparison with the ice-wedge polygon sites (Watanabe et al., 2012a). Therefore, gravels are expelled to the surface and generate these mudboils.

At specific study-sites Watanabe et al. (2012b) have shown that soil composition, soil moisture conditions, winter ground thermal regime together with snow depth are crucial factors controlling the formation of mudboils and ice-wedge polygons in this Arctic tundra landscape.

3 Materials and methods

Fluvial erosion has exposed sections on the river terraces where sediment exposures can be examined at high resolution. Samples from two sections in the northern (ADD.4) and southern margins (ADV.20) of the river were collected according to the different lithostratigraphic units observed in the field and characterized for palaeoenvironmental reconstruction.

3.1 Laboratory analysis

Soil organic matter content was determined by Loss on Ignition (LOI) at 550°C (3 h). For grain size measurements, samples were first pre-treated with hydrogen peroxide (H₂O₂) to eliminate the organic fraction and subsequently analysed with a Malvern Mastersizer 2000. Analyses were undertaken at the laboratory of the Geology Center of the University of Lisbon. Ten samples (plant fragments) from both sedimentary sequences were AMS ¹⁴C dated at the Centro Nacional de Aceleradores of Sevilla (Spain) in order to establish the geochronological time frame. The geochemical composition of ten samples (fine-grained fraction (Ø < 2 mm)) from different lithostratigraphical units of the ADV.20 section was acquired by X-ray fluorescence (XRF) at the Institute of Geosciences of the Federal University of Rio Grande do Sul (Brazil) following standard analytical procedures. The chemical index of alteration was calculated using the following formula: $CIA = [(Al_2O_3 + CaO + Na_2O + K_2O)/Al_2O_3] \times 100$ (Nesbit and Young, 1982).

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3.2 Statistic analysis

Some descriptive statistics of the studied variables were examined, specifically: mean (M), minimum (Min), maximum (Max), standard deviation (SD) and coefficient of variation (CV). The normal data assessment was carried out with the Shapiro-wilk test.

- 5 Since not all distributions respected the Gaussian distribution, data were transformed using logarithms in order to meet normal distribution requirements. A one way-anova was carried out in order to identify significant differences between soil profiles in LOI, sand, silt and clay percentages. With the transformed data, Pearson correlation coefficients were calculated to identify relations between depth and the studied variables.
- 10 Significant differences between soil profile and correlations between variables and soil depth were considered at a $p < 0.05$.

4 Results

4.1 Sedimentological characteristics in the northern bank of Adventelva river (ADD.4)

- 15 The studied sedimentary sequence has a thickness of 1.3 m, since permafrost was found at 1.2 m depth and it was not possible to examine the deeper lithostratigraphic units. Three very different units were observed in this section (Fig. 3):

- Unit A: 82–130 cm.

The basal layer of this section is constituted by a slightly decomposed peat layer with very high organic matter content (LOI > 50 %). The mineral particles existing in this unit correspond mainly to silts, which constitute ca. 70 % of the total.

- Unit B: 41–82 cm.

The intermediate unit contains an alternation of more organic layers (15–20 % LOI) and silty loess layers with lower organic matter proportion (10–15 %). These

size changes were observed along this unit, with a proportion of sands ranging from 25 to 30 %.

– Unit B: 0–95 cm.

The upper meter is composed by a silty matrix that shows a gradual increase in sand content towards the surface, reaching 30–35 % of the total. Some pockets of sand were also observed in the uppermost sediments, constituting 40 % of the sediments in these layers. Here, cracks related to frost and desiccation cracking are very common. In this unit the LOI percentages are even lower than at the base (2–4 %), with very few plant fragments.

Only 2 samples from this section were ^{14}C dated. The bottom organic band reported an age of 3913 ± 81 years calBP and the upper organic layer yielded an age of 1008 ± 75 years cal BP.

Soil organic matter content was significantly higher in ADD.4 than in ADV.20 section ($F = 15.76$, $p < 0.001$). Sand content was much higher in ADV.20 ($F = 9.46$, $p < 0.01$) and silt proportion was more abundant in ADD.4 ($F = 10.19$, $p < 0.01$). No significant differences were observed in the percentage of clay between the two soil profiles ($F = 3.26$, $p > 0.05$). The CV of these parameters was higher in ADD.4 than in ADV.20. Regarding to the evolution of these variables with soil profile depth, significant positive correlations were observed in LOI, silt and clay percentages in ADD.4, while sand content showed a significant negative correlation. In ADV.20 only a significant positive correlation of LOI with soil depth was identified (Table 2).

Geochemical properties were only analyzed in ADV.20. On average, SiO_2 and Al_2O_3 were the most abundant minerals in the ADV. 20 sequence, with percentages of 73.1 % and 11.3 % respectively, while MnO (0.04 %) and Cr_2O_3 (0.01 %) were the less abundant. With regards to the trace elements, sediments were richer in Ba (539 ppm) and Sr (161.3 ppm), and poorer in Sc (8.4 ppm).

The CIA ranged from 71.39 to 73.30, with an average of 72.44. The CV (%) was higher in P_2O_5 (26.93) and MnO (14.34) and lower in SiO_2 (1.51). A significant positive

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correlation of CaO and CIA with soil depth was detected as well as a significantly negative correlation in the case of SiO₂ (Table 3). The distribution of the elements along this section is shown in Fig. 5. Regarding the CIA index, there was a clear decreasing trend from the bottom layers upwards, though it increased sharply from 65 cm depth to the surface (Fig. 5c).

5 Discussion

Previous research has already identified a large number of periglacial landforms in the landscape of Adventdalen valley – such as pingos, palsas, sorted circles and ice wedges – which are indicative of permafrost conditions in the area (Humlum et al., 2003). In both margins of the Adventelva river, where the relief is relatively flat, polygonal networks of different size and morphologies are distributed. These areas hide a complex internal sedimentary structure of Holocene age (Härtel, 2011).

5.1 Palaeoenvironmental evolution in the Adventalen valley floor

The research presented in this paper focuses in the Lower Adventdalen valley, an area that has been ice-free since the beginning of the Holocene (Lønne and Nemec, 2004). Ice-free areas in Svalbard have experienced significant environmental changes during the Middle and Late Holocene (Birks, 1991; Svendsen and Mangerud, 1997; Humlum, 2005).

The sedimentological characteristics of two long sedimentary sequences located in two areas where ice-wedge polygonal terrains are widespread morphological features have been studied. The bases of these sequences correspond to the level of the frozen ground at the beginning of September 2011. Permafrost was found at 1.9 m in the southern site ADV.20 and at 1.3 m in the northern site ADD.4. Apart from differences in aspect, the presence of a peat layer in ADD.4 contributed to thermally insulate the ground and favoured the presence of the permafrost table closer to the surface than

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in ADV.20, where no peat layer was observed. The two exposures include sediments deposited since the transition from the Middle to the Late Holocene until present-day. According to the basal datings, ADD.4 encompasses the last 3.3 kcalBP and ADV.20 the last 3.9 kcalBP.

Section ADD.4 shows two very different sedimentological environments separated by a transition period, denoting that significant environmental changes have occurred in this area over the last three millennia. The stabilization of geomorphic activity at the distal part of alluvial fans in contact with the Adventelva river around 3.6 kaBP favoured peat formation in these areas (Jeppesen, 2001; Härtel, 2011). According to data obtained in ADD.4, the combination of climate and topographical conditions in the northern margin of the river continued to be favourable to peat development until ca. 3.3 kcalBP. The two basal ^{14}C dates in ADD.4 yielded similar ages despite being vertically separated 30 cm (3322 ± 80 yearscalBP and 3321 ± 76 yearscalBP, respectively). These dates fit within the range of 2.8–3.4 kcalBP reported in other sites of Adventalen valley for the formation of this widespread thick peat layer (Härtel, 2011). A very rapid peat growth is assumed during this period probably driven by a warmer climate regime. Favourable climate conditions for peat growth in the High Arctic are strongly controlled by temperatures and soil moisture content (Ellis and Rochefort, 2006). Evidences from marine records indicate warmer temperatures in Svalbard from the beginning of the Holocene until ca. 3.5 kaBP due to increased inflow of warm Atlantic water with summer sea surface temperatures probably 1–3 °C warmer than today (Salvigsen et al., 1992; Salvigsen, 2002).

Around 85 cm depth there is a clear change, with a sharp decrease in the organic matter content (LOI drops from > 50 % to 15 %). A sample from this level was radiocarbon dated of 3739 ± 103 yearscalBP. However, this age is too old with respect to the chronological sequence and should be rejected. According to the lower (3322 ± 80 yearscalBP) and upper ^{14}C datings (3095 ± 172 yearscalBP) this change with significant environmental consequences in the area must have occurred around 3.2 kcalBP. This time frame is consistent with other records in Svalbard that indi-

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cate a deterioration of the warm conditions: evidences of glacier expansion starting at 3 kaBP until 2.5 kaBP have been inferred from proglacial lake sediments (Svendsen and Mangerud, 1997) and fjords in western Svalbard (Kempf et al., 2013).

Climate variability and possible modifications in the local geomorphological setting must be taken into account when interpreting sedimentological changes in site ADD.4. The changing fluvial activity in Adventelva river during the last millennia may have entailed variations on the deflation processes reaching ADD.4 since this fluvial braided system constitutes the source of the uppermost aeolian sediments of this sequence. Variations in the source of the sediments with respect to the location of the site ADD.4 may have favoured peat formation or aeolian deposition. However, the fact that other regional proxies point to a change in the climate conditions prevailing in Svalbard until ca. 3 kaBP (Svendsen and Mangerud, 1997; Kempf et al., 2013) suggests that this change towards less dense vegetation cover and increased aeolian deposition may be rather connected to climate variability. From 3 kaBP onwards climate conditions turned to be progressively more favourable to tundra-type vegetation, with no peat development, less grass cover and increasing mineral sedimentation. However, this long-term pattern was stepped through a series of short periods alternating soil formation and others with prevailing aeolian sedimentation. A similar sedimentological pattern is observed in ice-wedge polygons between 2.75 and 2.35 kaBP in the eastern Canadian Arctic (Fortier et al., 2006). Probably, in Svalbard these phases were driven by changing in moisture conditions. Marine records show changing patterns on ocean circulation in the North Atlantic region during this period (Skirbekk et al., 2010; Moros et al., 2012). These changes must have brought about environmental shifts in the terrestrial ecosystem. Birks et al. (1991) also detected a change in the vegetation zones around 2.5 kaBP due to increasing climatic severity. A change towards declining sedimentation rates is also recorded in proglacial lakes around 2.4–2.5 kaBP (Svendsen and Mangerud, 1997).

However, the samples at 50 and 60 cm depth did not yield consistent ^{14}C ages and, therefore, an accurate calendar for the moment in which aeolian deposition become

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dominant at ADD.4, with no development of organic-rich soils, can not be provided. For this specific site we can only assume that it took place after 2.5 and before 0.6 ka cal BP. Since then, aeolian processes have deposited a 40–45 cm thick loess cover on this glaciofluvial terrace where ice-wedge polygons are nowadays well-developed.

5 In the southern margin of Adventelva river the thick aeolian deposit covering the lowest terraces has buried the coarser sediments of the Todalen alluvial fan. Deeper levels in ADV.20 show a rather homogeneous lithostratigraphical sequence with little variations in terms of grain size and organic matter content. Only four levels were identified with slightly higher organic matter percentages but without significant grain size
10 changes. The basal layers for ADV.20 reported an age of 3913 ± 81 years cal BP. This date may appear to be too old since the widespread peat layer dated 2.8–3.4 ka BP in other sites from Adventalen valley was not found in the first 1.9 m depth examined in this section. Uncertainties with ^{14}C dating are common in this area and have been already described in other Quaternary chronological studies due to the presence of Tertiary coal strata contaminating the samples, thus providing older ages than expected
15 (Humlum et al., 2005; Härtel, 2011).

In section ADV.20 a sample at 105 cm depth yielded an age of 1008 ± 75 years cal BP, which suggests a deposition rate of 1 m yr^{-1} for the upper sediments. An increase of the loess accumulation rates has been inferred for the last millennium in parallel to
20 colder and possibly windier and dryer conditions in Svalbard (Härtel, 2011). A windier climate must have also entailed higher evaporation rates, thus reinforcing the effect of aeolian processes. This colder climate regime has been more intense during the winter season (Divine et al., 2011), and particularly between AD 1500 and the end of the 1800 (Isaksson et al., 2005). This cooling favoured widespread glacier growth in Svalbard
25 during the Little Ice Age (LIA), particularly since the 13–14th centuries (Svendsen and Mangerud, 1997; Hald et al., 2001; Humlum et al., 2005).

The increase of the mean annual temperatures recorded after the LIA as well as the significant warming of the last decades (Humlum et al., 2011a) led to important environmental changes in the terrestrial ecosystem in Svalbard (Lønne and Lyså, 2005).

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However, the impact of these higher temperatures is not detected in the sedimentary record of the two studied sections. The pattern of the prevailing sedimentological processes is the same than during the LIA, with high loess deposition enhanced by the sparse vegetation cover in these areas.

5.2 Site-specific controls on sedimentological processes

Significant differences on the studied variables are observed between the two sections, which may be attributable to diverse environmental responses in both local settings. ADV.20 section is located in a south facing bank of the river, contrary to ADD.4 that is located in a northern slope exposition. The aeolian cover in the southern bank is constituted by sediments 40–45 cm thick, while in the northern site this layer can reach a thickness of 1.5–2 m. A deposition rate of 1 mm yr^{-1} has been calculated for the upper aeolian sediments in ADV.20, which is in agreement with OSL datings from neighbouring sites (Härtel, 2011). Therefore, loess sedimentation rates in the lowest terraces of the southern side of Adventalen valley are much higher than in the northern side.

Furthermore, the fact that ADV.20 had significantly higher percentages of sand content and ADD.4 showed larger proportions of silt content may be an evidence of the different sources and/or energy of transport prevailing in both areas. Aeolian transport is not a uniform process and can occur in different forms depending on the source area characteristics and transport height and distance (Vandenberghe, 2013). Changes in wind strength are very likely the responsible for the different grain size transport in loess environments (Zech et al., 2008). At local scale wind circulation is very complex especially in irregular topographic areas, which can increase or decrease wind intensity (Jonassen et al., 2012). Previous works on loess deposits observed that local wind systems in valleys can be important in the formation of aeolian deposits (Sun and Liu, 2000).

Indeed, slope position and exposure have implications in the process of soil formation in loess areas (Finke, 2012; Finke et al., 2013). At microscale level this fact has implications on soil development and on the degree of surface vegetation cover. Weak

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soil formation and sparse vegetation cover facilitate the sediment transport (Vandenberghe, 2013), enhanced by favourable wind circulation. These environmental conditions must have facilitated the transport and deposition of fine-grained sediments from the Adventelva floodplain, especially in ADV.20 area with a higher percentage of sands in this sequence.

The correlations between soil depth and LOI, silt and clay in ADD.4 profile were significantly positive, while sand showed a significant negative correlation. Regarding the ADV.20 section, only LOI had a significant positive correlation. No significant correlation was observed for the other variables. These results showed high LOI values in the bottom than in the top of both section (Figs. 3 and 4). However, in ADD.4 the positive significant correlation in silt and clay, showed that they were predominant in the bottom layers, while sand was common in the top layers. In relation to ADV.20, no correlations were observed. The CV (%) of LOI, sand, silt and clay was higher in ADD.4 showing that variability of sediments organic matter and texture was higher than in ADV.20. Thus, grain size variations reflected the changes between accumulation rate and pedogenesis in the period after the deposition (Huang et al., 2012).

5.3 Geochemical properties of the sediments

The major elements concentration in loess and paleosols reflect their properties directly from the source, but also their evolution after deposition (Jahn et al., 2001). Silica and Al_2O_3 were the most common minerals in ADV.20 profile, denoting the presence of aluminosilicate minerals such as micas and feldspars (Ujvari et al., 2008). The predominance of these elements in loess deposits was observed in previous studies in similar regional settings (Drewnik et al., 2014; Gallet et al., 1998). The variability of the studied geochemical elements showed little variations along the section. This is indicative of no major changes in the pedogenic processes at this site, as well as estability in the source of the sediments deposited in ADV.20 during the last millennia.

Regarding the weathering processes, high values of CIA are related to strong chemical weathering, while low values are connected with weak soil formation (Zech et al.,

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2008). Previously, Gallet et al. (1998) observed in a meta analysis of loess deposits in several parts of the world that CIA values were in the range of 50–70. The authors concluded that these deposits had a similar alteration history and were subjected to a moderate weathering. For cold-climate regions, Daviel et al. (2011) inferred an average value of 74.4 in a paleosol located in central Yukon; these authors propose that values near 75 show a considerable proportion of primary minerals converted into clay minerals. In Siberia, Zech et al. (2008) identified values of CIA > 63 that they interpreted as being related to intense weathering processes. For this site in Svalbard, the average of CIA gives a value of 72.44. Taken into account the limited literature on these topics, weathering at the ice-wedge polygon terrain in Adventalen can be considered moderate or slightly high. The variability of CIA was reduced (89 % of CV) suggesting that the chemical alteration was almost homogeneous along all profile, confirming small variations in pedogenic intensity during the time span covered in this section. However, a significant positive correlation with depth is detected, which suggests that weathering processes were slightly more active in the sediments located in the deeper layers. In our case, the high levels of CIA in the bottom layers may be related with the presence of higher soil organic matter concentrations during periods of weak soil formation.

In ADV.20, on average, the most common trace element was Ba. Previous works in loess deposits also observed that Ba was in higher content in relation to other trace elements (Gallet et al., 1998, 2001; Jahn et al., 2001; Varga et al., 2011). In this case, the high content of Ba in ADV.20 can be strongly influenced by the deposition of marine aerosols from the adjacent sea and an in situ enrichment due the higher mobility of other elements (Zach et al., 2008). The distribution of Ba can be also related to the intensity of the soil formation. The accumulation of Ba is supported by illuviation including the formation of new clay minerals, variation of redox conditions and translocation of elements and minerals (Galovic et al., 2011). The low variability of this element across the profile is an evidence that weathering process and soil formation was not variable (Bokhorst et al., 2009).

5.4 Implications for ice-wedge polygon terrains

In Adventalen valley the lowest glaciofluvial terraces covered by loess close to the Adventelva braided plain are the environments where ice-wedge polygon terrains are more abundant. The fact that today the process of craking in ice-wedge terrain in Svalbard is active under present-day climate conditions (Christiansen, 2005; Watanabe et al., 2012a, 2013) suggests that these flat areas covered at present by a thick layer of aeolian sediments constitute very appropriate environments for the development of ice-wedges.

Studies in other areas of the High Arctic have shown that the development of ice-wedge polygon terrains during the Holocene is strongly conditioned by the characteristics of the sediments as well as by climate variability (Fortier and Allard, 2004; Fortier et al., 2006). The properties of the host sediments may conditioned the geometry of the polygons: homogeneous host-material generate hexagonal intersections while heterogeneous sediments form orthogonal intersections (Lachenbruch, 1962; Härtel, 2011).

In Svalbard, for the southern Adventalen area, Härtel (2011) has detected the presence of a segregated ice-layer marking a transient-layer at the level of the peat layer. This indicates that permafrost was present at the time that peat was forming. The formation of permafrost in a peaty environment may also act as a feedback process to maintain the permanent frozen conditions in the ground thanks to the insulator effect of the overlying peat layer. This, in turn, also favours ice-wedge formation. Therefore, it is likely to interpret that in the northern terrace ice-wedges could have started developing when peat was forming at 3.3 kcalBP. This process continued throughout the Late Holocene and reinforced particularly during the last millennium, with the environmental shift towards prevailing aeolian deposition and thick loess accumulation. Indeed, colder conditions, particularly in winter (Divine et al., 2011), must have reinforced the process of ice-wedge formation.

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In this paper, two sedimentary sequences located in the northern and southern glaciofluvial terraces of the Adventelva river where ice-wedge polygonal networks are abundant have been examined. The northern section (ADD.4) is much more heterogeneous than the southern one (ADV.20), where sediments show little variations in grain size or organic matter content. Climate conditions must have been decisive to imprint these changes on the sedimentation processes, together with the geomorphological setting, which may also explain the differences observed between the two sections.

In ADD.4 the existence of very different lithostratigraphic units must be a consequence of environmental changes in this periglacial environment during the last three millennia. A period of widespread peat formation in Adventdalen valley took place until 3.3 kcalBP. This period of geomorphic stability was driven probably by warmer conditions than today. After 3.2 kaBP a phase with alternating soil formation and loess deposition took place, subsequently changing to a period of predominance of aeolian deposition. Unfortunately, our records do not allow to establish a precise timing for this change (between 2.5 and 0.6 kcalBP), although other studies indicate that this pattern intensified during the last millennium (Härtel, 2011). In both sections a thick loess cover constitutes the uppermost sediments, ranging from 40–45 cm thickness in the northern site to 1–2 m in the southern bank of Adventelva river. Here, the upper 1 m of loess sediments have been deposited during the last 1 kcalBP. The post-LIA warming has not promoted any significant change on the sedimentological processes prevailing in both areas.

In the eastern Canadian Arctic syngenetic ice-wedge polygons developed in wind-blown silt and organic sediments during the Late Holocene (Fortier and Allard, 2004). In Adventalen valley floor recent studies suggest that the formation of ice-wedges could have started when peat was forming (Härtel, 2011). Therefore, the landscape of the present-day ice-wedge polygonal terrains may have its origin in the transition from the Middle to Late Holocene; gradually, as environmental conditions shifted to prevailing

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aeolian deposition the process of ice-wedge formation become more intense in the lowest glaciofluvial terraces in Adventalen valley.

Soil organic matter content and grain size differences between ADD.4 and ADV.20 suggest that their development was dependent on the topographical and geomorphological characteristics at microsite level. The location of the two sites conditioned soil formation and/or aeolian deposition in both banks of the Adventelva river where ice-wedges polygons are distributed. Regarding the geochemical composition in site ADV.20, the most abundant major minerals were SiO₂ and Al₂O₃ and Ba the was the trace element found in higher amounts. However, the magnitude of the changes detected in the studied variables is generally small. This fact can be interpreted as a consequence of little variations in the intensity of the pedogenic processes at this site as well as in the sediment sources prevailing in the area during the Late Holocene.

Acknowledgements. The first author thanks the Agency for the Management of University and Research Grants (AGAUR) of Catalonia and AXA research fund for funding a post-doctoral fellowship during which this paper was written. This research has been supported by the Portuguese Science Foundation (FCT) under the project ANAPOLIS (PTDC/CTE-SPA/99041/2008). We would like to acknowledge the logistic support in field activities provided by The University Centre in Svalbard through Hanne Christiansen as well as Adriane Machado (University of Coimbra) for carrying out the XRF measurements.

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Table 1. AMS ^{14}C datings performed on the samples. Radiocarbon ages have been calibrated using the CALIB 7.0 program and the IntCal13 curve (Reimer et al., 2013).

Sample	Laboratory code	Dated material	Depth (cm)	Conventional age (BP)	Calibrated age
ADD4.1a	CNA1401	Plant fragments	115	3108 ± 33	3321 ± 76
ADD4.1d	CNA1402	Plant fragments	85	3111 ± 35	3322 ± 80
ADD4.3	CNA1403	Plant fragments	81	3468 ± 41	3739 ± 103
ADD4.11	CNA1405	Plant fragments	73	2935 ± 65	3095 ± 172
ADD4.14	CNA1404	Plant fragments	65	2507 ± 106	2562 ± 219
ADD4.18	CNA1406	Plant fragments	57	3495 ± 31	3772 ± 82
ADD4.26	CNA1407	Plant fragments	50	–	–
ADD4.27D	CNA1408	Plant fragments	20	583 ± 28	616 ± 33
ADV20.3	CNA1409	Plant fragments	165	3612 ± 38	3913 ± 81
ADV20.7	CNA1410	Plant fragments	105	1107 ± 36	1008 ± 75

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Table 2. Descriptive statistics of the studied elements (% of LOI, sand, silt and clay) in sections ADD.4 and ADV.20. Significant differences at $p < 0.05^a$, $p < 0.01$, n.s. not significant at a $p < 0.05$.

		<i>M</i>	Min	Max	SD	CV(%)	<i>R</i> : depth
ADD.4 (<i>N</i> = 38)	LOI	15.68	3.15	64.19	15.52	98.97	0.88 ^c
	sand	23.06	5.5	68.43	16.75	72.63	-0.63 ^c
	silt	63.08	25.49	80.94	12.33	19.54	0.76 ^c
	clay	13.83	5.38	25.33	5.46	39.47	0.35 ^a
ADV.20 (<i>N</i> = 27)	LOI	4	2.6	6.8	0.9	21.7	0.62 ^c
	sand	32.7	27.6	47.6	4.3	13.2	-0.11 ^{n.s}
	silt	55.4	42.1	60.3	3.9	7.1	0.21 ^{n.s}
	clay	11.9	8.8	16.2	1.5	12.9	-0.08 ^{n.s}

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Table 3. Descriptive statistics and correlation with the depth of the geochemical oxides and trace elements analyzed in the ADV.20 section. Significant differences at $p < 0.05^a$, $p < 0.01$, n.s. not significant at a $p < 0.05$ ($N = 10$).

	<i>M</i>	Min	Max	SD	CV(%)	<i>R</i> : depth
SiO ₂	73.09	70.45	74.28	1.10	1.51	−0.76 ^b
Al ₂ O ₃	11.25	10.68	11.72	0.35	3.07	0.68 ^a
Fe ₂ O ₃	4.09	4.11	3.80	4.43	3.94	0.32 ^{n.s}
K ₂ O	2.24	2.14	2.31	0.05	2.37	0.20 ^{n.s}
Na ₂ O	1.68	1.53	1.82	0.10	5.83	−0.22 ^{n.s}
MgO	0.70	0.65	0.76	0.03	4.74	0.50 ^{n.s}
CaO	0.36	0.33	0.39	0.02	6.35	0.77 ^b
MnO	0.04	0.03	0.04	0.01	14.34	0.00 ^{n.s}
P ₂ O ₅	0.12	0.07	0.17	0.03	26.93	0.14 ^{n.s}
Cr ₂ O ₃	0.011	0.010	0.012	0.001	6.60	−0.05 ^{n.s}
CIA	72.44	71.39	73.30	0.65	0.89	0.71 ^a
Ba	539	487	583	27.01	5.01	−0.17 ^{n.s}
Ce	54.30	33	96	19.11	35.19	−0.06 ^{n.s}
Cu	16.30	11	20	2.75	16.88	0.45 ^{n.s}
Nb	14.70	7	22	4.62	31.42	0.54 ^{n.s}
Ni	45.78	25	75	15.96	34.87	−0.23 ^{n.s}
Sc	8.40	8	9	0.52	6.15	0.28 ^{n.s}
Sr	161.30	152	171	5.95	3.69	−0.51 ^{n.s}



Fig. 2. Pictures of the two long sections studied: ADV.20 (left) and ADD.4 (right).

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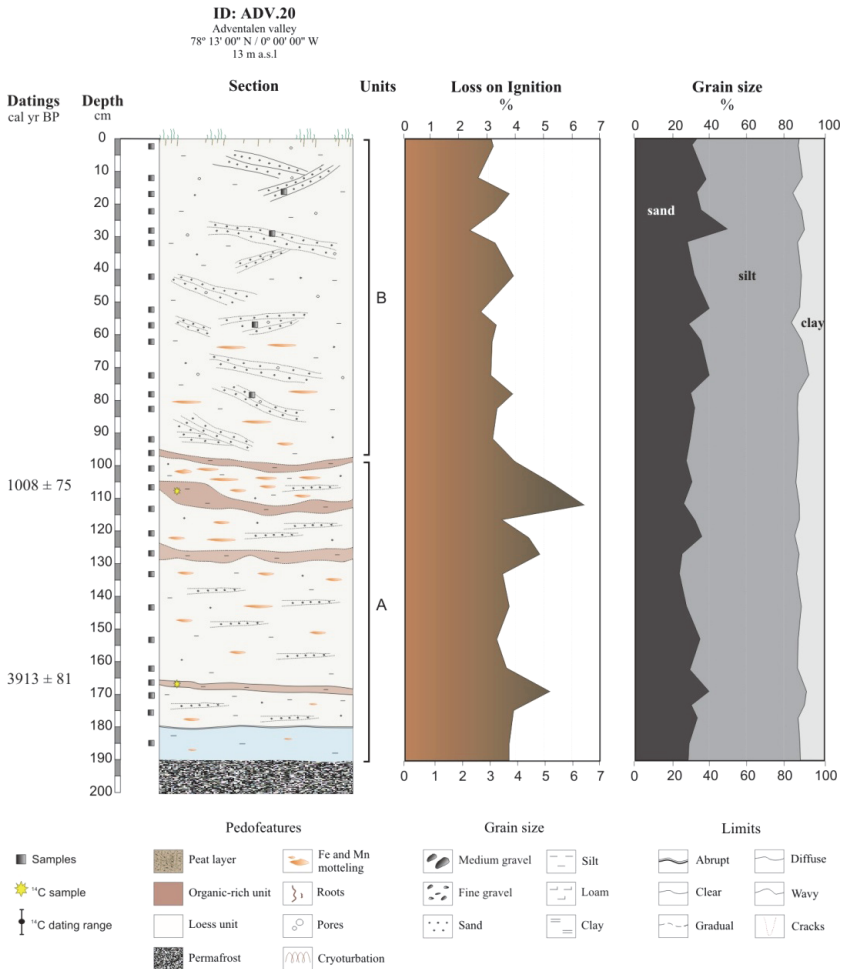


Fig. 3. Lithostratigraphic section ADD.4 together with ¹⁴C datings, LOI and grain size properties.

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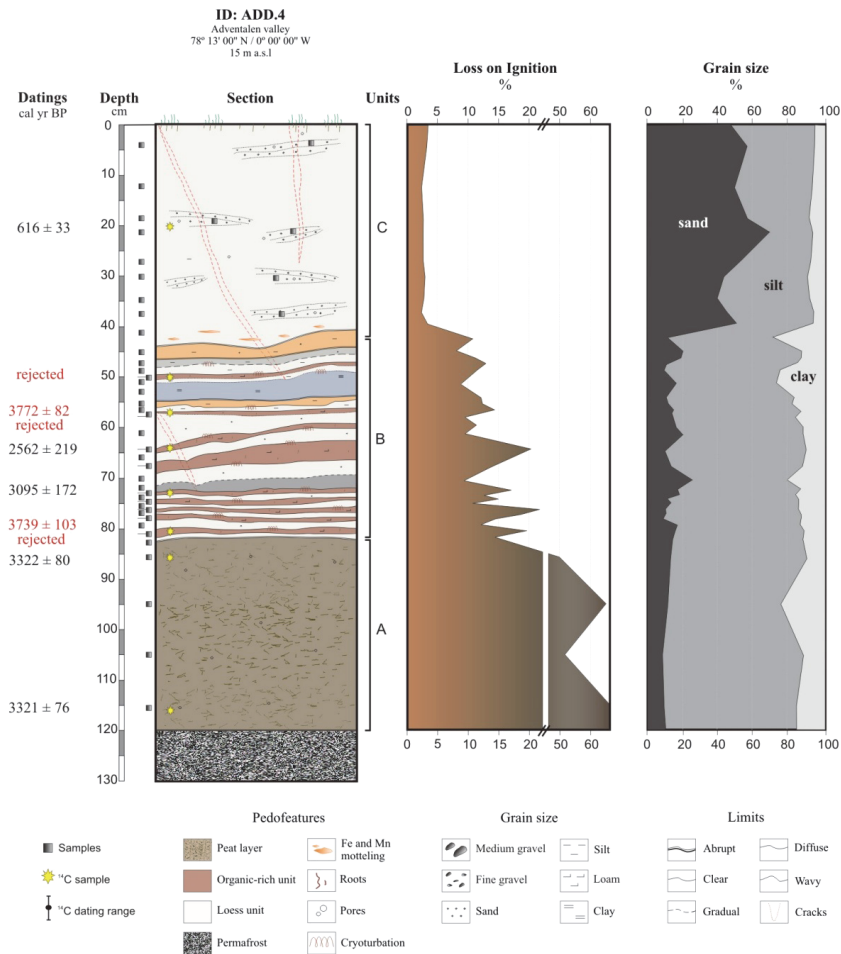


Fig. 4. Lithostratigraphic section ADV.20 together with ¹⁴C datings, LOI and grain size properties.

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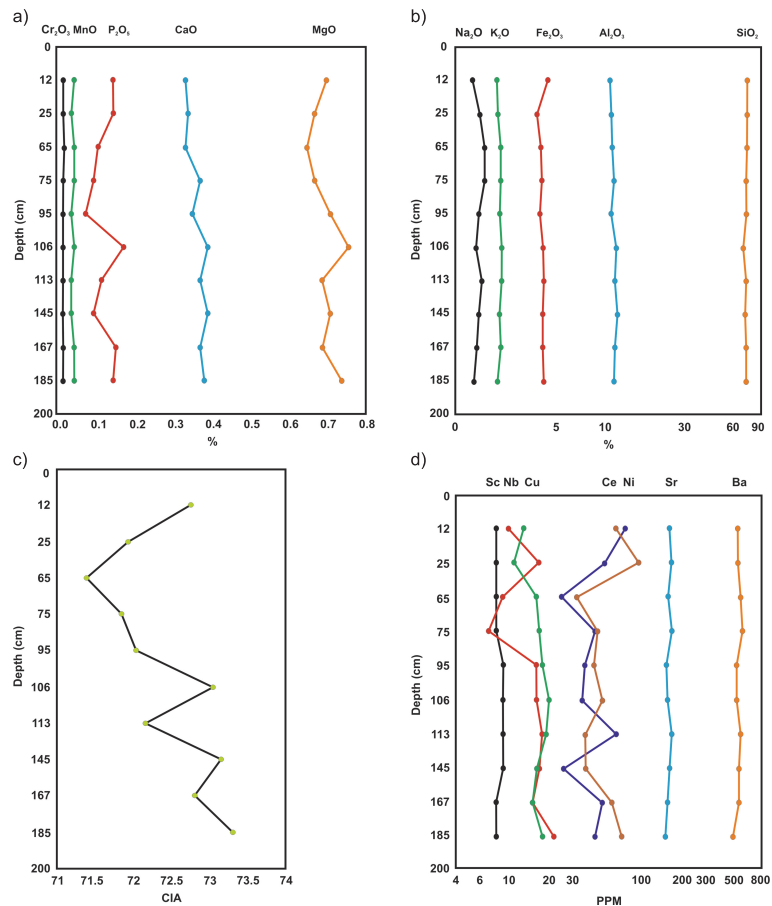


Fig. 5. Profile distribution of the studied geochemical elements.