Holocene debris flows recognized in a lacustrine sedimentary succession: sedimentology, chronostratigraphy and cause of triggering

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Abstract: This study focuses on the sedimentary characteristics and the chronostratigraphy of Holocene massflow deposits recognized in a lake-fill sedimentary succession. These deposits in lake Ulvådalsvatnet, western Norway, are discrete, sharp-bounded units of sand-sized sediment, running from gravelly and graded to silt-rich, and characterized by low total carbon and water contents. They are rich in terrestrial macroflora detritus, dark brown in colour, and interpreted as high-density turbidity current deposits attributed to subaerial debris flows that plunged into the lake. Thirty-three ^{14}C AMS dates were derived from three cores, and though the ages are somewhat inconsistent (macroflora invariably younger than bulk sediment samples), they indicate a marked increase in debris-flow processes after *c*. 2200 cal. yr BP, considered to reflect increased occurrence of heavy rainstorms.

Key words: Debris flows, lacustrine record, sedimentary facies, chronostratigraphy, triggering causes, Holocene, Norway.

Introduction

An apparent increase in extreme weather events, such as heavy rainstorms, has been widely attributed to anthropogenically induced climatic change towards warmer conditions (e.g., RegClim, 2000; 2002; Houghton *et al.*, 2001; Palmer and Räisänen, 2002). However, before stating such conclusion, the natural variability of extreme weather events must be examined. The record of debris-flow activity may be particularly useful in recognition of past rainstorm events because: (1) debris flows are generally caused by intense rainfall (Prior *et al.*, 1970; Govi and Sorzana, 1980; Van Asch, 1997; Blikra and Nemec, 1998; 2000); (2) repetitive debris flows can occur on sediment-rich slopes, so long as the triggering events recur; and (3) colluvial debris-flow deposits have a high preservation potential in both terrestrial and subaqueous settings. Moreover, organic deposits are commonly preserved buried below debris-flow sediments, allowing their radiocarbon chronology to be established (Matthews *et al.*, 1997; Blikra and Nemec, 1998; Blikra and Sæmundsson, 1998). However, apart from a few pioneering studies (e.g., Jonasson, 1991; 1993; Matthews *et al.*, 1997; Blikra and Nemec, 1998), the chronostratigraphic record of Holocene debris-flow activity in Scandinavia remains sparse.

This paper reports the results of a stratigraphic study designed to identify major periods of Holocene debris-flow activity from the sedimentary record of lake Ulvådalsvatnet in western Norway (Figure 1). The paper focuses on: (1) the description and interpretation of sedimentary facies in cores recovered from the lake floor, with special emphasis on the diagnostic features of subaqueously emplaced deposits of terrestrial debris flows; (2) the temporal distribution of debris-flow events; and (3) the triggering causes of debris flows in the study area.

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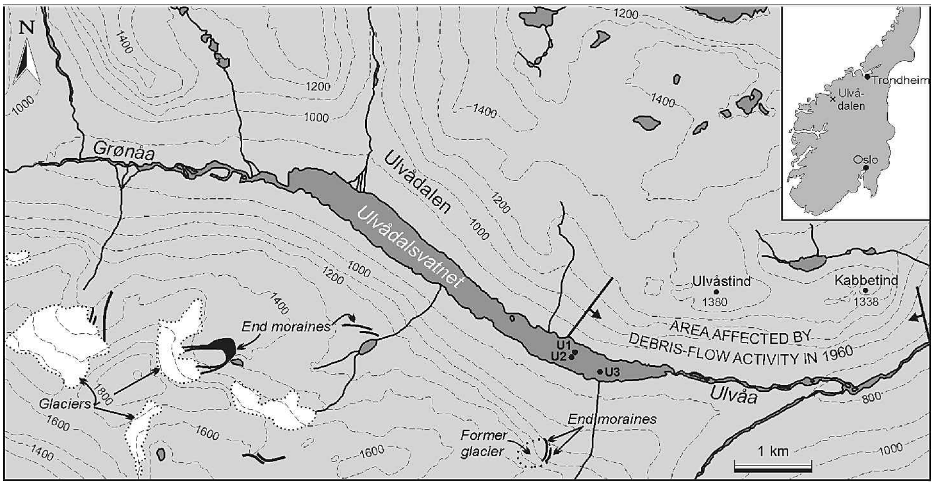

Figure 1 Locality map of the study area in western Norway. Note the valley-side area affected by debris-flow activity in 1960, and the three coring sites (U1, U2 and U3) in lake Ulvådalsvatnet.

Study area

Lake Ulvådalsvatnet is located at 850 m altitude in Ulvådalen, a tributary valley of Romsdalen in western Norway (Figure 1). During an intense rainstorm on 26 June 1960, 26 debris flows occurred along a 5 km long stretch of the slopes of Ulvåstind and Kabbetind (Figures 1 and 2). The slope failure stripped soil and vegetation cover from an area of 780 000 m^2, with an estimated 40% of this material emplaced directly into Ulvådalsvatnet (Rapp, 1963). The causes and effects of this event were studied in detail by Rapp (1963).

Ulvådalen is an east-trending glacial trough with steep, largely drift-free upper slopes. The mid-slope zone supports a coarse rockfall colluvium overlying a thin (0.5–1.0 m) till mantle (Figure 2). Below abandoned lake shorelines or ice-marginal meltwater channels at *c.* 1000 m altitude, the more moderate slope (15–35°) supports a cover of thick till with a fine-grained matrix. Gullies that cut through the till to the underlying gneiss bedrock indicate a till thickness of 3–8 m (Rapp, 1963).

Ulvådalsvatnet is 6 km long, 200–500 m wide, no deeper than 10 m, and is located 9 km east of the water divide, within the limits of the Younger Dryas glaciation (Sollid and Sørbel, 1979; Svendsen and Mangerud, 1987). Several small cirque glaciers occur on high ground within the lake catchment area of *c.* 100 km^2 (Figure 1). Several influent streams of variable size supply water and sediment to the lake; the largest of these is the Grønåa river (Figure 1). Additional sediment is derived by snow avalanches and debris flows from adjacent slopes. The evidence of broken trees and of clasts resting precariously on vegetation indicates that snow avalanches are more frequent on the NE-facing valley side, reflecting steeper slopes and greater accumulation of snow deposited by westerly and southwesterly winds. All debris flows released in 1960 occurred on the opposite, SW-facing slope, and photographs taken prior to 1960, together with mapping of pre-1960 debris-flow deposits on land, indicate that the SW-facing slope, adjacent to the eastern part of Ulvådalsvatnet, was the site of major debris flows prior to 1960. There are several small debris-flow tracks on the slopes west of the area affected by the 1960 event and on the NE-facing valley side, but there is no morphological evidence in these areas for major debris flows, equal to those triggered during the 1960 event.

Long meteorological records from the region are available; precipitation measurements have been carried out at the Verma station, 12 km NE of Ulvådalsvatnet, since 1895, and air tempera-

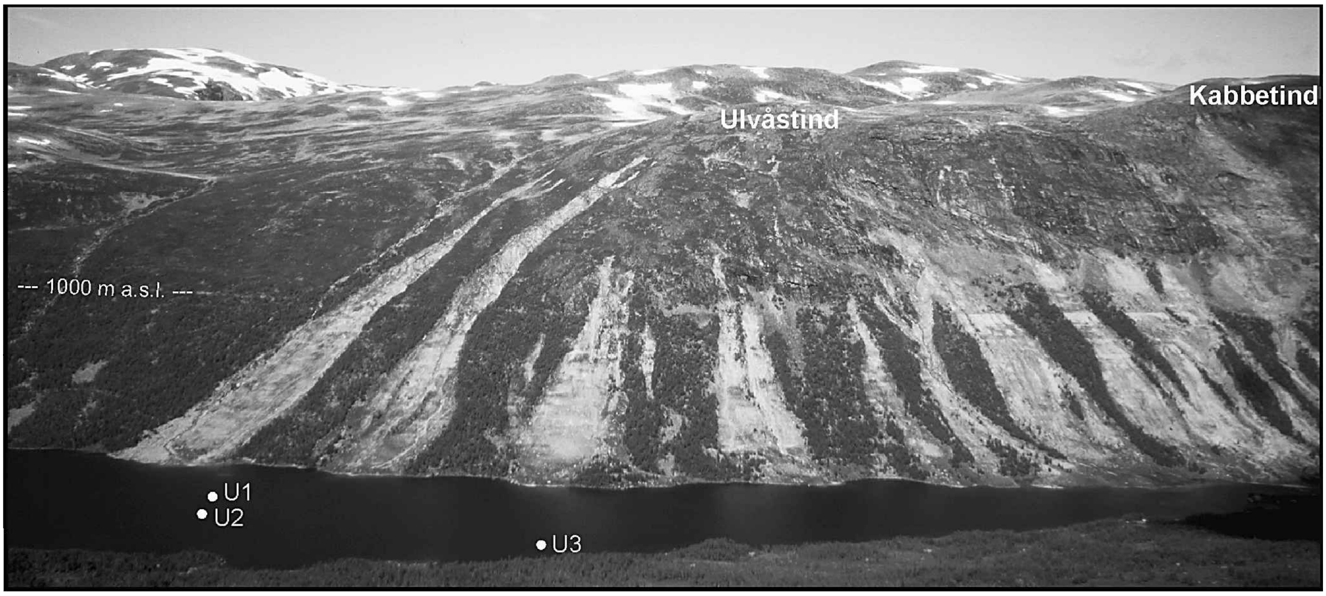

Figure 2 Debris-flows tracks of the 1960 slope-wasting event on the northern side of lake Ulvådalsvatnet. Note the locations of coring sites. Photograph taken in July 1998.

tures have been measured at Kjøremsgrende, 55 km ESE of Ulvådalen since 1864. Rapp (1963) estimated that mean annual precipitation in Ulvådalen is *c*. 1000 mm.

Rapp (1963) argued that the catastrophic scale of slope wasting in June 1960 reflected a combination of three factors. First, and most important, was the unusual high intensity of the convectional rainstorm that occurred over a relatively small area. The lack of precipitation at the Verma weather station on 26 June illustrates the localized nature of the rainstorm. Second, he considered that the development of a thick podzolic soil layer above compact till had permitted rapid infiltration of water and buildup of porewater pressure in the failure zone. Finally, he suggested that the shear strength of the upper soil layer had been reduced by release of water during the spring thaw that preceded the rainstorm event.

Lake coring and core analyses

Bathymetric survey was used to establish the depth of the eastern part of Ulvådalsvatnet, where three sediment cores were retrieved (Figures 1 and 2), using a modified piston corer equipped with a 6 m long, 110 mm diameter PVC sampling tube (see Nesje, 1992, for details). The three cores were labelled U1 (sediment thickness 217 cm), U2 (264 cm) and U3 (245 cm); all reached a layer of dense grey sediment that underlies the Holocene sedimentary succession. Water depths at the coring sites were 630 cm, 640 cm and 560 cm, respectively. Cores U1 and U2 were taken near the two westernmost debris-flow tracks of the 1960 event (Figure 2), with U2 in a slightly more distal position to allow lateral variation in sediment characteristics to be recognized. Core U3 was taken *c*. 400 m further east, to assess the lateral consistency of the stratigraphic succession.

Following extraction, the cores were stored at 4°C. Magnetic susceptibility was measured at 2 cm intervals along the unextruded cores using a core scanner sensor type MS2C, and relative density was measured continuously using X-ray analysis. The cores were then halved lengthwise and the sediment characteristics systematically logged. The total carbon (TC) and water content were measured at 0.5 cm intervals in the upper, brown-coloured part, and at 2 cm intervals in the grey-coloured lower part of each core. Both TC and total organic carbon (TOC) content were measured also on 18 samples from selected levels in the three cores, and on two till samples from the northern valley side. The carbon content was determined using the Leco-SC-444. Grain-size distribution was determined by wet-sieving and with Coulter Laser Granulometer for sediment finer than 2 mm. Samples for this purpose were mostly extracted at 1 cm intervals from the brownish upper parts of the cores (0.5 cm intervals in thin layers, and 2–3 cm intervals in some thicker ones), and at 10 cm intervals in the underlying grey deposits. TOC, TC, water, sand and gravel content values are given in wt % in the text. In order to establish whether plant fragments in massflow deposits are of terrestrial provenance, 10 samples of such deposits, and one gyttja sample containing macrofossils were analysed (Table 1). This analysis also allowed the identification of terrestrial macroflora species submitted for radiocarbon dating.

A total of 33 samples were extracted from selected levels of the three cores and submitted for AMS dating at the Radiocarbon Dating Laboratory in Trondheim/T. Svedberg Laboratory in Uppsala and the Van de Graaff Laboratory in Utrecht (Table 2). Most samples corresponded to 4–10 mm thick sediment layers, although thicker samples were taken from basal deposits with lower organic carbon content, and six dates were obtained from macroflora detritus. Standard chemical preparation methods for elimination of contamination and for separation of characteristic fractions were used. The radiocarbon dates were calibrated to calendar years according to Stuiver and Reimer (1993).

Lithostratigraphic units and sedimentary facies

Lithostratigraphic units

Cores U1, U2 and U3 from Ulvådalsvatnet all contain a basal unit of massive, grey silty deposits, overlain by organic-rich gyttja interlayered with dark brown, sandy sediment and light grey silt bands. The sedimentary succession in each core has been divided into units defined by colour changes and visible textural differences, and these units have been labelled alphabetically in their ascending stratigraphic order (Figures 3, 4 and 5). Units which show grading in grain size, or are interrupted by intervening units, are further divided into subunits. The validity of the macroscopic distinction of lithostratigraphic units is strongly supported by the laboratory data, which show that the visible changes coincide with marked changes in grain-size distribution, total carbon content and water content (Figures 3, 4 and 5). Only the magnetic susceptibility shows little correspondence with the macroscopic changes, probably because the magnetic field of the measuring spool is influenced by sediment in a radius of 6–7 cm. The susceptibility curves are thus smoothed, but relatively high values of magnetic susceptibility correspond to the high concentration of minerogenic sediment at the base and near the top of the cores, compared to the organic-rich gyttja. Scattered gravel-sized clasts are evident in X-ray images (Figures 3, 4 and 5).

Sedimentary facies

The sedimentary succession sampled by the three cores has been further divided into five facies on the basis of the macroscopic characteristics, including grain size, sedimentary structures, colour and macrofossil content. Their stratigraphic distribution in the core profiles is shown in Figures 3, 4 and 5. The letter code is modified from Eyles *et al.* (1983). Lower-case letters after the hyphen refer to the sediment colours brown (b) and grey (g).

Facies Fsc-g: grey or light grey silt

This facies constitutes the basal minerogenic unit A in all cores, and forms also the thin (<1 cm) units C_1, C_2 and C_3 in the gyttja succession in cores U1 and U2, and unit E in core U3. The thick, compact silt unit A contains some gravel-sized clasts and some lenses and interlayers of fine sand (<3 cm thick), and is characterized by low water content (<30%) and negligible TC content. The thin layers of light grey silt intercalated with the gyttja deposits resemble the basal silt. They are poor in sand (0.6–2.3%), and are associated with a drop in water content to 40–60% and a marked drop in organic carbon content to 0.6–2.7%. The silt layers have sharp boundaries, and only the isolated silt layer E in core U3 contains an admixture of sand (5%).

The basal unit of inorganic silt is interpreted to have been deposited in Ulvådalsvatnet during the early-Holocene deglaciation, which is consistent with the radiocarbon age of 10 689–10 557 cal. yr BP of a sample from the lowermost gyttja deposit in core U1 (Figure 3). The similarity of the thin silt layers in the gyttja succession to the basal silt unit suggests that they represent phases of increased fluvial runoff associated with the rapid retreat of periodically expanding cirque glaciers in the lake's catchment (cf. Karlén and Matthews, 1992; Matthews and Karlén, 1992; Nesje *et al.,* 1991; 2000; 2001; Dahl and Nesje, 1994; Matthews *et al.,* 2000). The higher sand content of unit E in core U3 only may indicate proximity to a local glacier on the southern side of the valley where two nested end-moraines are evidence of a former small glacier (Figure 1). The meltwater from this glacier would have discharged into Ulvådalsvatnet about 150 m west of the coring site U3, and as far as *c*. 300 m east of the coring sites U1 and U2. The eastward draining of the lake would have spread the local plume of sediment suspension over the coring site U3 only.

Table 1 Aquatic and terrestrial macrofossils in samples from cores U1, U2 and U3. Those identified as aquatic/terrestrial may indicate either or both habitats. All the samples are from dark brown massflow units, except for the sample from gyttja unit B_1 in core U1. An asterisk indicates macroflora used for radiocarbon dating. The unit symbols and depths are as in Figures 3, 4 and 5

Sample	Aquatic habitat	Terrestrial habitat	Terrestrial/aquatic habitat
U1, unit L 47–47.4 cm			Moss stems and leaves
U1, unit J 50.5–51 cm		*Salix herbaceae* leaf, leaf fragments	*Sphagnum* leaves, stems and leaves of other mosses
U1, unit I 64–64.5 cm		*Polytrichum* leaf, *Empetrum* leaves, roots	*Sphagnum* leaves, stems and leaves of other mosses
U1, unit H 66–67.3 cm	*Isoëtes lacustris* spores	*Calluna* stem with leaves, *Empetrum* leaf, *Betula* leaf part, twig, leaf veins, leaf stalk, roots, *Selaginella* spores	*Sphagnum* leaves, other mosses
U1, unit F_2 76–77 cm	*Isoëtes lacustris* spores, *Coenococcum* sclerotia, Chironomid head capsules, *Plumatella* statoblasts	Other moss leaves and parts of stems*, *Dicranum*, *Polytrichum*, *Empetrum* leaves and seeds*, *Betula* fruit, leaves, budscale, male and female catkin scales*, pieces of bark probably *Betula**, *Viola* seeds*, *Calluna*/Ericaceae (?) flower*, twigs, leaf fragments*, bark fragments*, roots, *Selaginella* spores*	*Sphagnum* leaves*, *Sphagnum* stem with leaves*
U1, unit B_1 138–139.5 cm	*Nitella,* Chironomid head capsules, Trichoptera, *Plumatella* statoblasts	*Betula* catkin scale, leaf fragments	*Sphagnum* leaves, leaves and detritus of other mosses
U2, unit H 43.5–44 cm	*Isoëtes lacustris* spores	*Empetrum* leaf, twig with leaves, twigs, leaf fragments, root parts, *Selaginella* spores	*Sphagnum* leaves, other moss leaves and stems
U3, unit I_3 23.5–24 cm		Twigs, leaf fragments, bark fragments, moss leaves	
U3, unit I_3 27.5–28 cm		*Dicranum* stems with leaves*, twigs*, roots, leaf fragments*, bark fragments*	*Sphagnum* stems with leaves*, other moss leaves
U3, unit G 58.5–59.3 cm	*Isoëtes lacustris* spores	*Polytrichum* stem with leaves, *Betula* fruits and leaf, *Empetrum* leaves, *Rumex acetosa,* leaf fragments, leaf stalk, roots, *Selaginella* spores	*Sphagnum* leaves, stems and leaves of other mosses, unidentified species of liverwort
U3, unit D 72–72.4 cm		Piece of bark*	

Facies O-bg: organic-rich gyttja

This facies forms units B, D, E, G, K and N in cores U1 and U2 (Figures 3 and 4) and units B, C, F, H and K in core U3 (Figure 5). The units are 0.5–20 cm thick, composed of silt and clay with low or negligible sand content, and characterized by consistently high water content (50–88%) and moderate to high TC content (2–14%). Only the lowermost gyttja, near the contact with the basal silt unit, shows lower carbon and water content in the three cores. The TC content varies considerably in the gyttja profile (Figures 3, 4 and 5) and the colour ranges from olive-grey and olive-brown to dark grey and dark or very dark greyish brown. The vertical changes in the gyttja colour are gradational, whereas the contacts with other facies are sharp. In Table 1, the macrofossil species identified are grouped by habitat (aquatic versus terrestrial). The gyttja sample from unit B_1 in core U1 is rich in *Nitella* and chironomid head capsules, also contains other aquatic species, and is poor in terrestrial species. The uppermost gyttja unit N in core U1 is disturbed and contains sand derived from the underlying unit M. Similarly, the uppermost part (9 cm) of unit K in core U3 is disturbed and contains inclusions of dark brown sand, probably derived from an overlying deposit that was lost during the coring. Scattered clasts (<2 cm in diameter) occur in some of the gyttja units as revealed by X-ray images (Figures 3, 4 and 5), particularly in cores U2 and U3.

The gyttja facies constitutes most of the upper part of the core profiles and apparently represent the slow ‘background’ sedimentation of organic and fine-grained minerogenic matter throughout the Holocene. The varying colour and TC content of the gyttja units may reflect long-term climatic changes, possibly controlled by expansion and melting of local glaciers in the lake catchment. The scattered pebbles, more common in cores U2 and U3, can be attributed to snow avalanches derived from the southern slope and emplaced subaqueously. Some of the clasts may be dropstones shed by floating ice during the spring.

Facies Sn-b: dark brown sand, rich in macroflora detritus

This facies forms units F and M in cores U1 and U2 and unit I in core U3 (Figures 3, 4 and 5), in the upper part of the gyttja succession. The units are 5–28 cm thick, dominated by sand and containing minor admixture of fine gravel. They have generally lower, water content (14–67%) and variable, but generally lower, TC content (0–8%) than the gyttja. Their very dark brown colour is due to the high content of macroflora detritus, and Table 1 shows that these deposits are much richer in terrestrial species, and relatively poor in aquatic species, compared to the gyttja. A notable feature of these units is the distinctive upward fining in particle size, accompanied by an increase in both water and TC contents (Figure 6). The unit’s lowest part is distinctly coarse-grained (up to 27% gravel), with a low water content and low TC content, whereas the upper part is finer-grained, sandy, with higher TC and water contents and abundant macroflora remains. Unit I in core U3 comprises two such graded beds (Figure 5). The number of samples taken from the lower bed (I_1) for grain-size analysis was insufficient to reveal its normal grading, but the basal part is clearly rich in gravel. The upper, thicker and normal-graded bed is subdivided into a predominantly minerogenic lower part (I_2) that grades into a finer-grained, macroflora-rich upper part (I_3). The units of facies Sn-b have sharp bases and tops. The boundary between unit M and gyttja unit N in core U1 is irregular, probably disturbed by coring.

The units of this gravel-bearing, macroflora-rich sandy facies, isolated in the upper part of the gyttja succession, are interpreted as representing abrupt incursions of coarse terrigenous sediment onto the lake floor. The normal grading indicates sediment deposition by turbulent flows, whereas the lack of stratification points to highly concentrated, non-tractional massflows. The flows are unlikely to have been generated by river floods, because the distance from the coring sites to the main river outlets is too large (4–5 km). The associated lake-floor slopes are probably too gentle

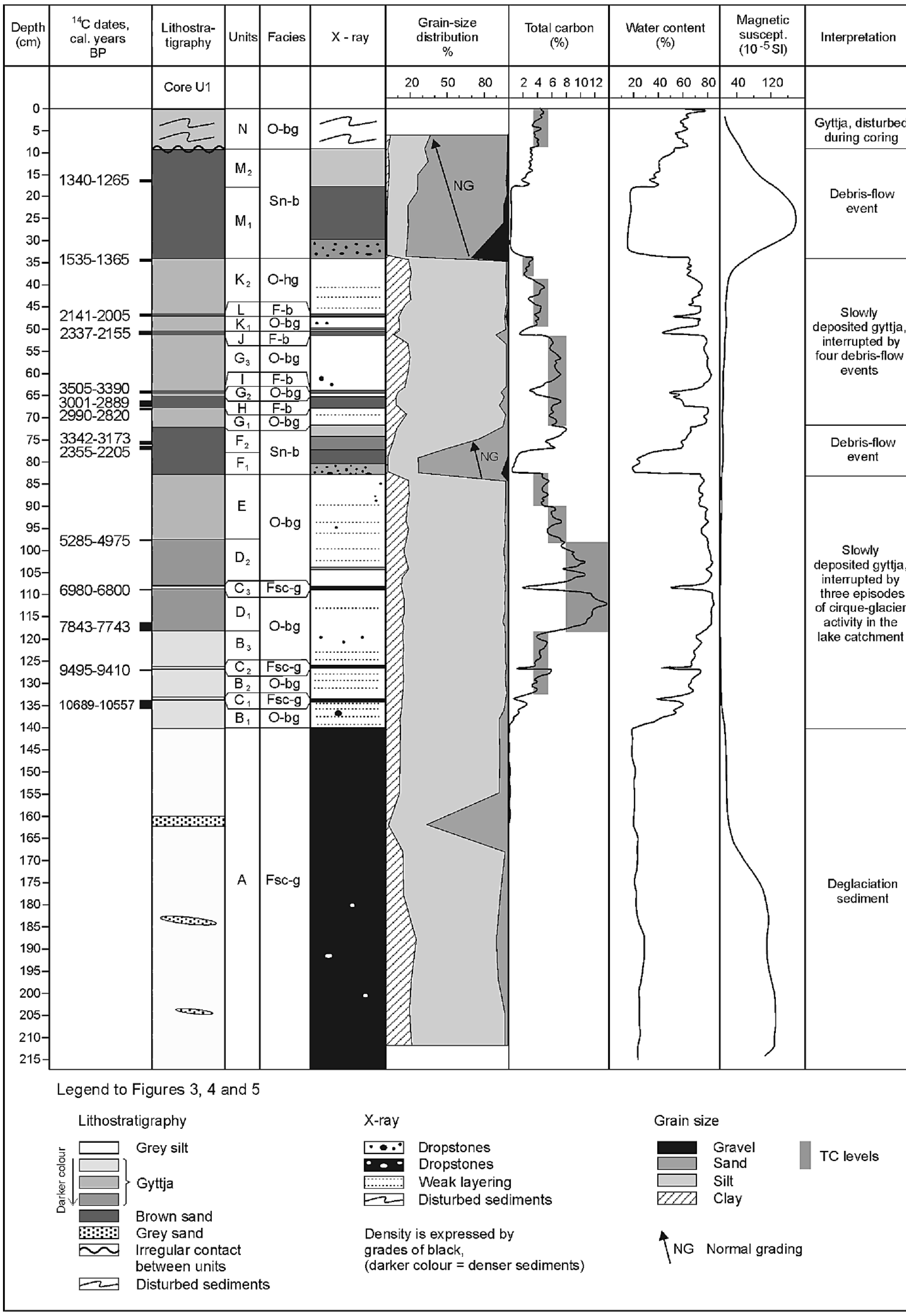

Figure 3 Profile of core U1 from Ulvådalsvatnet. The data include radiocarbon dates, lithostratigraphy (facies symbols as used in the text), X-ray image, content of gravel, sand, silt and clay, total carbon content, water content, magnetic susceptibility curve and interpretation of the deposits.

to have promoted such sediment-gravity flows, and it should be emphasized that the organic detritus in facies Sn-b represent predominantly terrestrial macroflora (Table 1), which indicates sediment derivation from subaerial slopes. The emplacement of the deposits of facies Sn-b is attributed to major terrestrial debris-flow events that caused widespread erosion of soil and vegetation cover from slopes adjacent to the lake. The debris flows are thought to have become turbulent when accelerating on the steep mountain slopes, entering the lake and incorporating more water. As such, these turbulent subaqueous flows should be classified as high-density turbidity currents (*sensu* Lowe, 1982), generated by direct transformation of subaerial debris flows (see Weirich, 1989). The contrasts noted above between the lower parts of the units of this facies (F_1 and M_1 in cores U1and U2, and I_1 and I_2 in core U3) and the upper parts (F_2, M_2 and I_3) are related to an initial deposition by the waning flow, followed by slower settling of suspended fine-grained particles and macroflora detritus. The composite unit I in core U3 may represent two consecutive surges of one debris flow, or alternatively two successive debris-flow events with no intervening deposition of gyttja, though it is possible that an intervening gyttja layer may have been removed by the later event. The youngest massflow unit M (Figures 3 and 4) represents probably the 1960 catastrophic debris-flow event.

Facies F-b: dark brown sandy silt, rich in plant macroflora detritus

This facies constitutes units H, I, J and L in cores U1 and U2 (Figures 3 and 4) and units D and G in core U3 (Figure 5). These units are 0.2–2.5 cm thick and show affinities with those of facies Sn-b, because they are discrete, sharply bounded layers associated with an influx, albeit minor (0.8–18.1%), of sand-sized sediment, and lower content of water (44–69%) and total carbon (2–6%) than in the overlying and underlying gyttja. Abundant terrestrial macroflora detritus (Table 1) gives the deposit its very dark brown

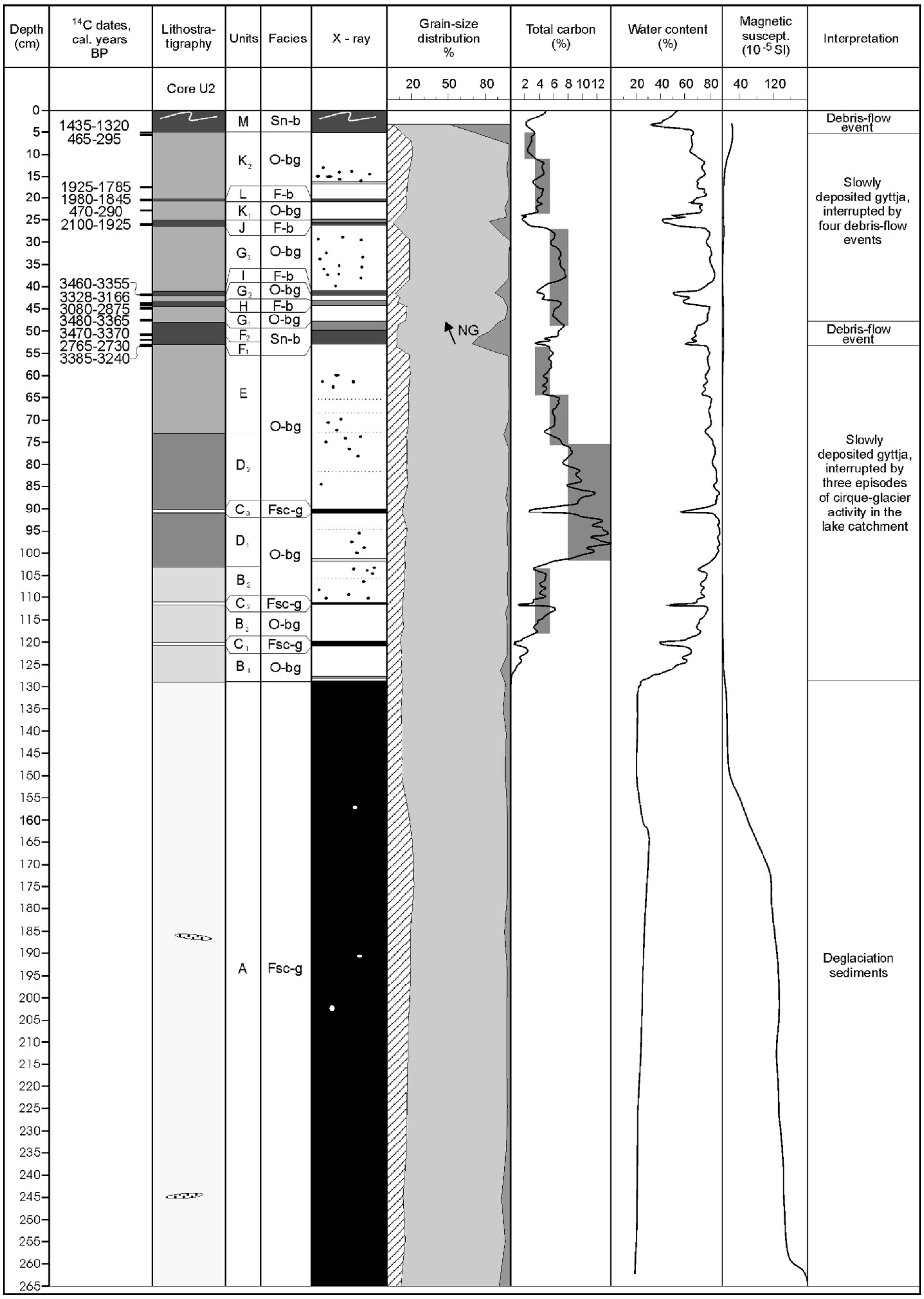

Figure 4 Profile of core U2 from Ulvådalsvatnet. The data include radiocarbon dates, lithostratigraphy (facies symbols as used in the text), X-ray image, content of gravel, sand, silt and clay, total carbon content, water content, magnetic susceptibility curve and interpretation of the deposits. Legend is in Figure 3.

colour. There is, however, some variation in the units of this facies. Unit H in cores U1 and U2 and particularly unit G in core U3 show a higher TC content than that of the surrounding gyttja. The colour of unit G is almost black. Unit L in core U2 is nearly devoid of sand.

The affinities with facies Sn-b suggest that these thin dark brown layers may be of similar origin. If this interpretation is valid, the units of facies F-b reflect either relatively small-scale debris-flow events or they are the distal, downflow equivalents of the facies Sn-b. Anyway, their environmental significance would be similar. The parental debris flows were apparently derived from different parts of the mountain slope, some flows being exceptionally rich in plant detritus (unit H in core U1 and U2, unit G in core U3) and some others losing sand before waning in the vicinity of the coring sites (unit L in core U2).

Facies F-g: grey sandy silt

This facies form unit J in the uppermost part of core U3 (Figure 5). The unit is 1 cm thick and consists of grey, massive silt relatively rich in sand (14%), poor in water (33%) and markedly poor in TC (1%). Its contacts with the overlying gyttja and the underlying dark brown sandy unit are sharp.

This isolated unit of facies F-g differs from all other units, and the interpretation is necessarily more speculative. The sharp-bounded layer of sandy silt indicates an abrupt incursion of minerogenic sediment, perhaps similar to the deposition of facies F-b, except that the sediment has a lighter, grey coloration and its TC content is very low. The fact that this layer overlies directly deposits inferred to have been emplaced during a major debris-flow event (unit I), suggests, however, that they may have a joint origin. The debris flow could remove soil along its track and be

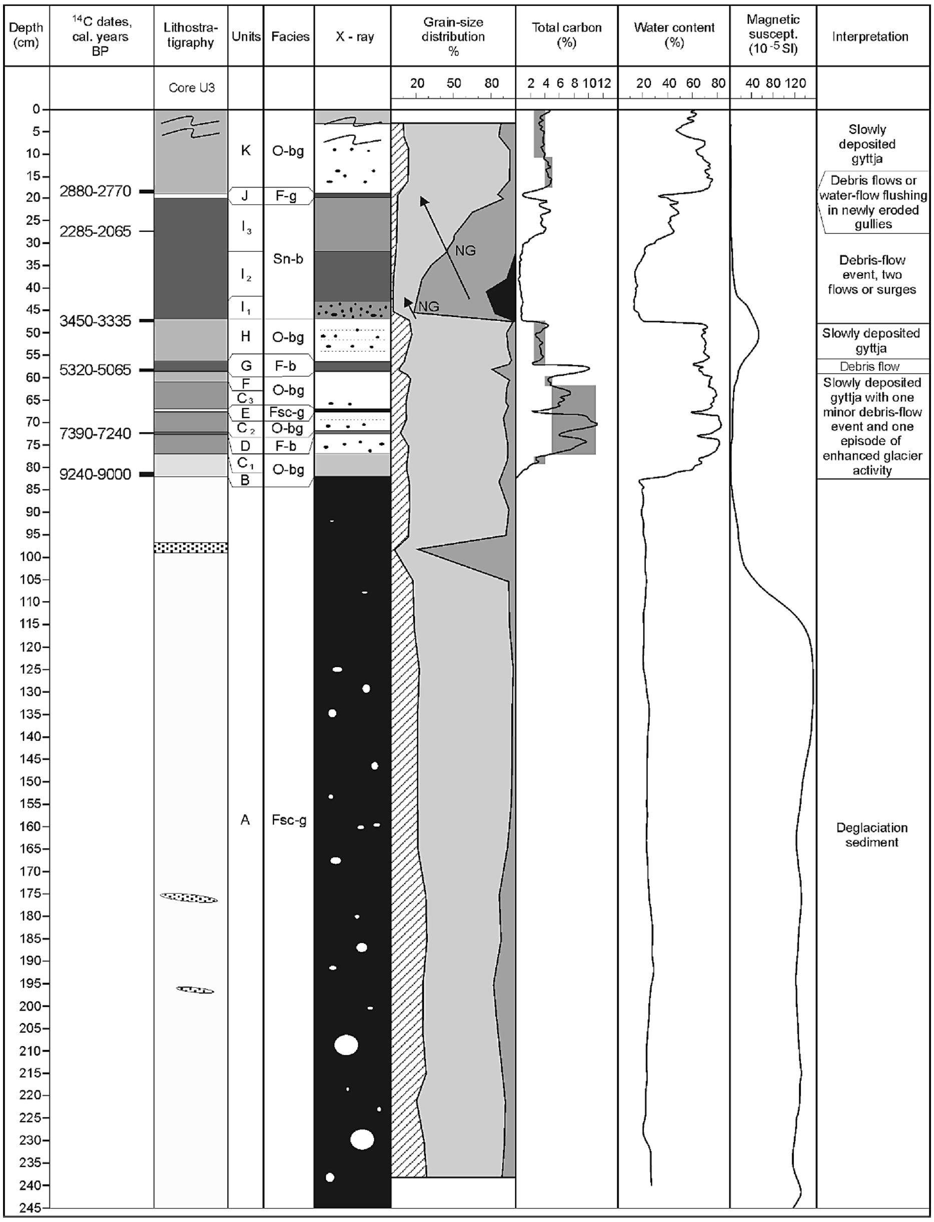

Figure 5 Profile of core U3 from Ulvådalsvatnet. The data include radiocarbon dates, lithostratigraphy (facies symbols as used in the text), X-ray image, content of gravel, sand, silt and clay, total carbon content, water content, magnetic susceptibility curve and interpretation of the deposits. Legend is in Figure 3.

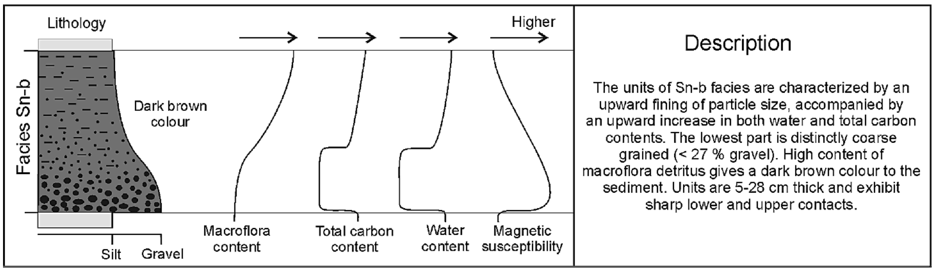

Figure 6 Typical characteristics of facies Sn-b units, including mean grain size, macroflora content, total carbon and water content, and magnetic susceptibility.

followed by runoff that flushed minerogenic sediment from the resulting gully.

Radiocarbon dates and chronostratigraphy

Dating of samples

Three types of samples from the sediment cores were dated (Table 2): (1) bulk samples of gyttja; (2) bulk samples of massflow deposits; (3) samples of terrestrial macroflora remains, of which two contained a mixture of identified plant fragments (Table 1), three contained unidentified twigs and one was an unidentified piece of bark. The 33 dates obtained are not quite consistent, because 10 of them deviate from the chronostratigraphic order of the samples (Figure 7). Closer examination shows that the dates of all gyttja samples increase in age with depth, except for a sample from the depth of 47.6–48.1 cm in core U2, which is older than implied by its stratigraphic position (Table 2).

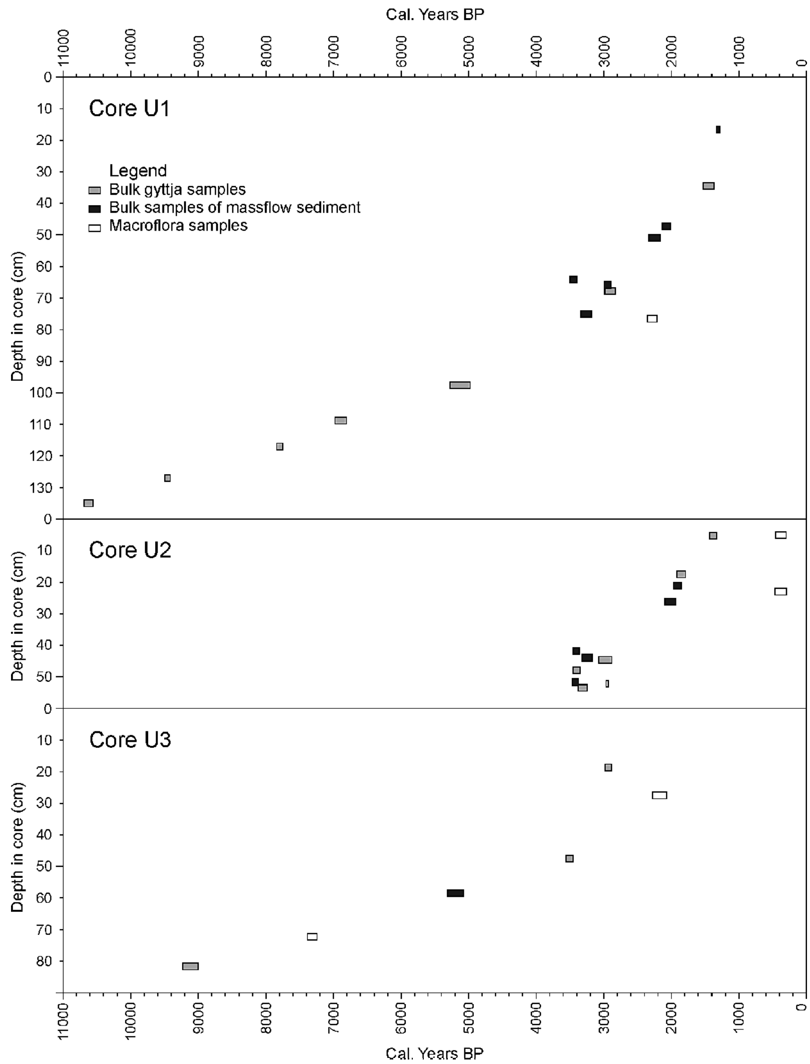

Figure 7 Radiocarbon dates from cores U1, U2 and U3 plotted against the sample depths in the cores. Note that only the upper 140 cm of core U1, upper 60 cm of core U2 and upper 90 cm of core U3 are shown.

This date is, however, not significantly different from the date of the underlying gyttja (sample depth of 53.0–53.5 cm), if the criterion of one standard deviation is used. The dates of bulk massflow samples are also progressively older with depth, except for a sample from the depth of 64.0–64.6 cm in core U1 and a sample from the depth of 41.5–42.1 cm in core U2, which appear to be older than expected from their stratigraphic positions (Table 2). Notably, the massflow dates show reasonable conformity with the gyttja dates. The six dates of terrestrial plant remains are also consistently older with depth, except for the young age of a 2 cm long twig from the depth of 23.0 cm in core U2 (Table 2). However, the macroflora remains appear to be *c.* 550–1200 years younger than the bulk gyttja and massflow samples from similar or adjacent stratigraphic levels in the upper (massflow dominated) part of the cores. For instance, the two samples of terrestrial macroflora from massflow unit F in cores U1 and U2 have both yielded ages that are *c.* 600–1000 years younger than those of the corresponding bulk sediment samples. This suggests that the decomposed organic matter in the parent soil, and thus in the bulk massflow samples, are older than the identifiable terrestrial plant remains within the same deposit.

Similar problems with dating of lacustrine deposits have arisen in other studies, where terrestrial macroflora remains commonly yield younger ages than bulk-sediment samples (e.g., Nesje *et al.*, 1994; 2000; Helle *et al.*, 1997). The age discrepancies encountered in the present study make it crucial to consider the nature of organic material used for dating to assess the validity of the dates obtained.

Gyttja samples

The gyttja consist mainly of fine-grained minerogenic sediment, aquatic plant remains and some terrestrial plant fragments. It has been shown that aquatic plants build into their cellular material the ^{14}C:^{12}C ratio of the lake water (Turney *et al.*, 2000), which may be higher than the atmospheric ^{14}C:^{12}C ratio (MacDonald *et al.,* 1987). This 'hard-water' effect is prominent in areas with carbonate bedrock, but bulk samples of lacustrine sediment may yield anomalously old dates even in soft-water lakes (Oldfield *et al.*, 1997; Barnekow *et al.,* 1998).

The bedrock in the Ulvådalsvatnet catchment consists of gneisses, mainly quartz-dioritic to granitic, with no known occurrences of carbonate rocks. However, analyses show an inorganic carbon content of up to 1.42% in the sediment cores. The content is close to zero in the basal deglaciation deposits, and in the range of 0.1% to 0.5% in the early-Holocene gyttja deposits (dated as older than *c.* 9100 cal. yr BP). The values are higher (0.8% to 1.42%) in the samples of mid- to late-Holocene gyttja deposits (younger than *c.* 6900 cal. yr BP). One possible source for this inorganic carbon is far-travelled carbonaceous matter in the till mantle on catchment slopes, eroded in the Holocene. Two samples from a gully-cut outcrop of the till on the northern valley slope yielded an inorganic carbon content of 0.46% (upper, brown till

Table 2 Radiocarbon dates from cores U1, U2 and U3. The dates are from bulk gyttja samples (g), bulk samples of massflow deposits (mf), and redeposited terrestrial macroflora samples (m). The radiocarbon dates are given with one standard deviation, and calibrated to calendar years according to Stuiver and Reimer (1993)

Core	Depth (cm)	Unit	Laboratory no.	Sample material	Dates (^{14}C yr BP)	Calibrated ages (cal. yr BP)	$\delta^{13}C$ (‰)
U1	16.0–16.5	M_2	TUa-2747A	mf	1400 ± 70	1340–1265	–27.2
	34.0–34.6	K_2	TUa-2975A	g	1565 ± 65	1535–1365	–26.1
	47.0–47.4	L	UtC-9561	mf	2112 ± 40	2141–2005	–27.6
	50.5–51.1	J	UtC-9560	mf	2244 ± 47	2337–2155	–26.2
	64.0–64.6	I	TUa-2746A	mf	3245 ± 65	3505–3390	–26.7
	66.0–67.3	H	UtC-9559	mf	2859 ± 39	3001–2889	–28.3
	67.3–67.7	G_1	TUa-2669A	g	2815 ± 70	2990–2820	–25.3
	75.0–76.0	F_2	UtC-9558	mf	3049 ± 47	3342–3173	–27.6
	76.0–77.0	F_2	TUa-2745	m	2320 ± 80	2355–2205	–27.6
	97.4–97.8	D_2	TUa-2668A	g	4480 ± 75	5285–4975	–24.0
	108.9–109.3	D_1	TUa-2667A	g	6045 ± 75	6980–6800	–25.0
	116.0–118.0	D_1	UtC-9557	g	6980 ± 46	7843–7743	–22.5
	126.7–127.1	B_2	TUa-2666A	g	8480 ± 75	9495–9410	–20.7
	134.0–136.0	B_1	UtC-9556	g	9400 ± 50	10689–10557	–20.8
U2	5.0–5.5	K_2	TUa-2976A	g	1505 ± 65	1435–1320	–25.1
	5.1	K_2	TUa-2977	m (twig)	315 ± 65	465–295	–30.6
	17.5–17.9	K_2	TUa-2767A	g	1925 ± 65	1925–1785	–27.7
	20.7–21.1	L	TUa-2770A	mf	1975 ± 65	1980–1845	–25.9
	23.0	K_1	TUa-2978	m (twig)	310 ± 70	470–290	–25.3
	25.8–26.5	J	TUa-2766A	mf	2060 ± 70	2100–1925	–25.8
	41.5–42.1	I	TUa-2765A	mf	3190 ± 60	3460–3355	–27.1
	43.6–44.1	H	UtC-9562	mf	3031 ± 41	3328–3166	–28.0
	44.1–44.5	G_1	TUa-2670A	g	2865 ± 75	3080–2875	–25.0
	47.6–48.1	G_1	TUa-2979A	g	3205 ± 65	3480–3365	–26.3
	50.5–51.1	F_2	TUa-2764A	mf	3205 ± 55	3470–3370	–26.8
	52.2	F_1	TUa-2980	m (twig)	2610 ± 60	2765–2730	–26.1
	53.0–53.5	E	TUa-2981A	g	3105 ± 70	3385–3240	–23.8
U3	18.3–19.0	K	TUa-2982A	g	2725 ± 70	2880–2770	–29.6
	27.3–27.5	I_3	TUa-2751	m	2175 ± 60	2285–2065	–27.7
	47.0–47.8	H	TUa-2983A	g	3170 ± 65	3450–3335	–24.2
	58.0–58.7	G	TUa-2750A	mf	4555 ± 65	5320–5065	–28.1
	72.2–72.5	D	TUa-2749	m	6440 ± 75	7390–7240	–25.9
	81.0–82.3	B	TUa-2748A	g	8190 ± 65	9240–9000	–20.6

affected by pedogenic processes) and <0.17% (lower, grey and more compact till). These values are lower than those of mid- to late-Holocene lake deposits, but suggest that the carbonate content may vary in the till cover. However, if the till is the source of inorganic carbon, higher values would be expected in the gyttja units in upper part of the cores because of the higher rate of valley slope erosion in the late Holocene, but some of the highest values are obtained from mid-Holocene gyttja sediment. High values would also be expected in bulk massflow samples because the sediment is derived from the till mantle. The inorganic carbon content in massflow units is, however, relatively low, ranging from 0.1% to 1.0%.

Although the source of inorganic carbon is not quite clear, its occurrence in the system could cause the aquatic plant remains in the gyttja to bear a hard-water effect. Furthermore, the gyttja may contain reworked older organic material brought into the lake by Holocene fluvial processes (Törnqvist *et al.*, 1992) and runoff from the valley side, especially in periods after debris-flow events. Also the degradation of peat deposits in the catchment area, caused by changes in groundwater level or drainage pattern, may have introduced relatively old organic material to the lake. It is likely, therefore, that the dates obtained on bulk gyttja samples record anomalously 'old' radiocarbon ages. The bulk dates from the early-Holocene gyttja may be more reliable because the inorganic carbon content in these deposits is low, and also because it is less likely that significantly older plant detritus was washed into the lake immediately after the deglaciation.

Bulk samples of massflow deposits

The massflow deposits consist of minerogenic sediment, terrestrial macroflora detritus and minor aquatic macrofossil fragments. The soils and peat material carried by debris flows may contain organic matter with a very wide age range, especially where derived from a mature soil and/or peat cover. Consequently, ^{14}C ages of bulk massflow deposits should be regarded as maximum dates of the depositional events they represent.

Terrestrial macroflora samples

Terrestrial living species use atmospheric CO_2 and provide a more reliable material for dating (MacDonald *et al.*, 1987). However, the macroflora samples from Ulvådalsvatnet are not necessarily ideal for accurate dating of depositional events. The four dates of macroflora from massflow deposits may possibly be older than the actual debris-flow event. The dates of twigs from gyttja may also be problematic, because such plant fragments can rest on the ground or shallowly buried for decades to centuries before being eventually washed into a lake (Barnekow *et al.*, 1998). With the exception of the anomalously young (470–290 cal. yr BP) twig at 23 cm depth in core U2, which was found close to the core wall and probably displaced there in the coring process, the dates of macroflora samples should be regarded as maximum ages of the host deposits. Notably, a twig extracted from the gyttja immediately below massflow unit M in core U2 (Figure 4) yielded an age of 465–295 cal. yr BP. Based on 95% probability level, however, the age range is 509–5 cal. yr BP, which supports the assumption that unit M in cores U1 and U2 represent the 1960 debris-flow event.

It must be concluded that the inconsistent radiocarbon dates obtained from the core samples and the unknown effect of reservoir age through time have given a far less accurate age control than originally expected. All the dates (apart from that of the twig at 23 cm depth in U2) should be regarded as maximum ages, but the terrestrial macroflora give the youngest maximum dates and thus provide the most reliable information constraining the timing of sediment deposition in the middle and late Holocene. As argued above, the bulk gyttja dates may provide reasonable close limiting ages for the early-Holocene deposits.

Correlation of core profiles

The sedimentary succession in cores U1 and U2 is almost identical (Figures 3 and 4), but shows some differences in core U3 (Figure 5), which renders their correlation somewhat problematic, particularly in view of the dating uncertainties. However, there are two main marker beds in the late-Holocene part of cores U1 and U2, namely the thick massflow units F and M (Figures 3 and 4), and one of these probably corresponds to the thick massflow unit I in core U3 (Figure 5).

The general pattern of TC variation in the three cores is very similar (Figure 8). The most striking are the high TC values in lower to middle parts of the Holocene succession in all cores, interrupted by an abrupt drop in TC content associated with the intervening grey silt band (unit C_3 in cores U1 and U2, and unit E in core U3). Other parts of the TC logs also show marked affinities, implying that the variation in TC content is a valid basis for core correlation (Figure 8).

Despite all uncertainties, the radiocarbon dates generally support the inferred correlation of the three cores (Figure 9). The gyttja dates from corresponding levels in cores U1 and U2 (the tops of units G_1 and K_2) are almost identical, which suggests that core U3 can probably be correlated with the two others on the basis of gyttja dates. The date of gyttja directly underlying unit I in core U3 (3450–3335 cal. yr BP) is statistically indistinguishable from the gyttja date directly below unit F in core U2 (3385–3240 cal. yr BP) and the gyttja date from the lowermost part of unit K in core U3 (2880–2770 cal. yr BP) is similar to the ages obtained from gyttja unit G_1 in core U1 and U2 (2990–2820 and 3080–2875 cal. yr BP). These results confirm the inferred correlation of unit I in core U3 with unit F in cores U1 and U2. Furthermore, the date of macroflora in unit I in core U3 (2285–2065 cal. yr BP) is statistically indistinguishable from that of the macroflora in unit F in core U1 (2355–2205 cal. yr BP).

The correlation of core profiles has several implications. First, given that the youngest major massflow unit M in cores U1 and U2 most likely was deposited during the 1960 debris-flow event, it is notable that a corresponding unit is absent from core U3. The lack of this unit is attributed to loss of the uppermost part of this core during extraction, as it is very unlikely that this major debris-flow event did not result in massflow deposits at the U3 site. This interpretation is supported by the presence of incorporated brown sand in the deformed upper part of unit K in core U3. The upper part of unit M in core U2 was probably also lost during coring.

Part of the lowermost deposits in cores U1 and U2 (units B_1, C_1, B_2 and C_2) seems to be missing in core U3. The lake floor at the U3 coring site is located 70–80 cm higher than at sites U1 and U2, which suggests that the thinness of the lowermost gyttja deposits in core U3 may be due to local slumping, and/or lower

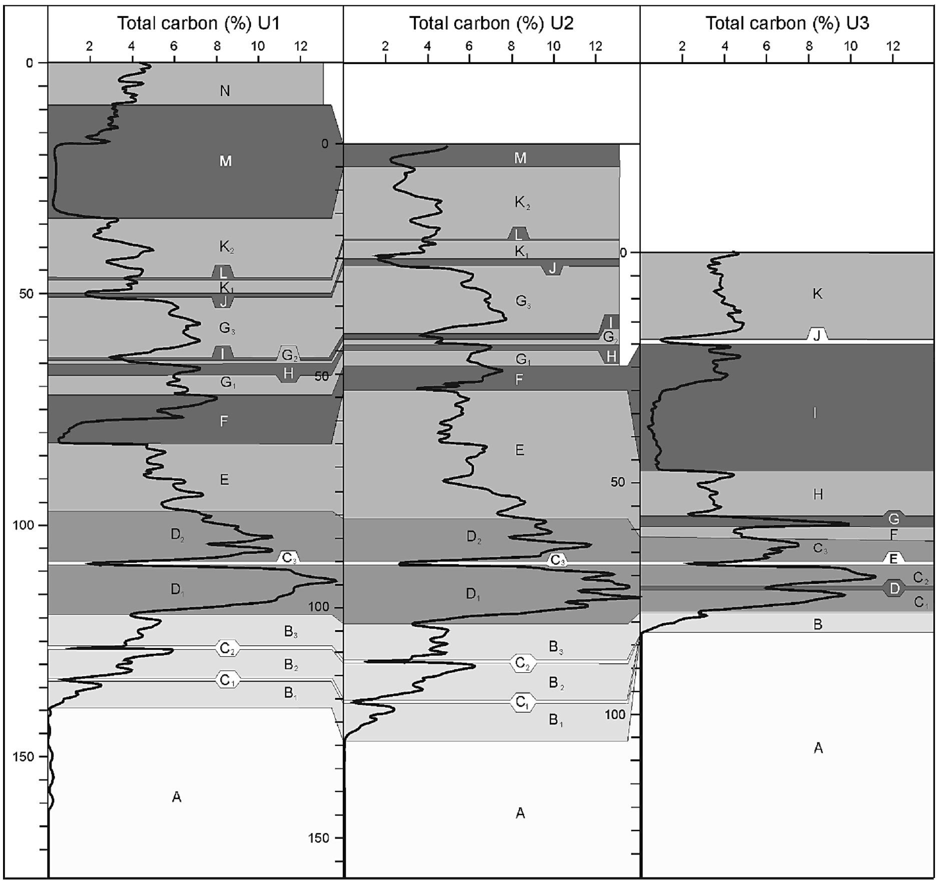

Figure 8 Correlation of the curves of total carbon content of cores U1, U2 and U3. The lithostratigraphic units and their letter codes are the same as in Figures 3, 4 and 5.

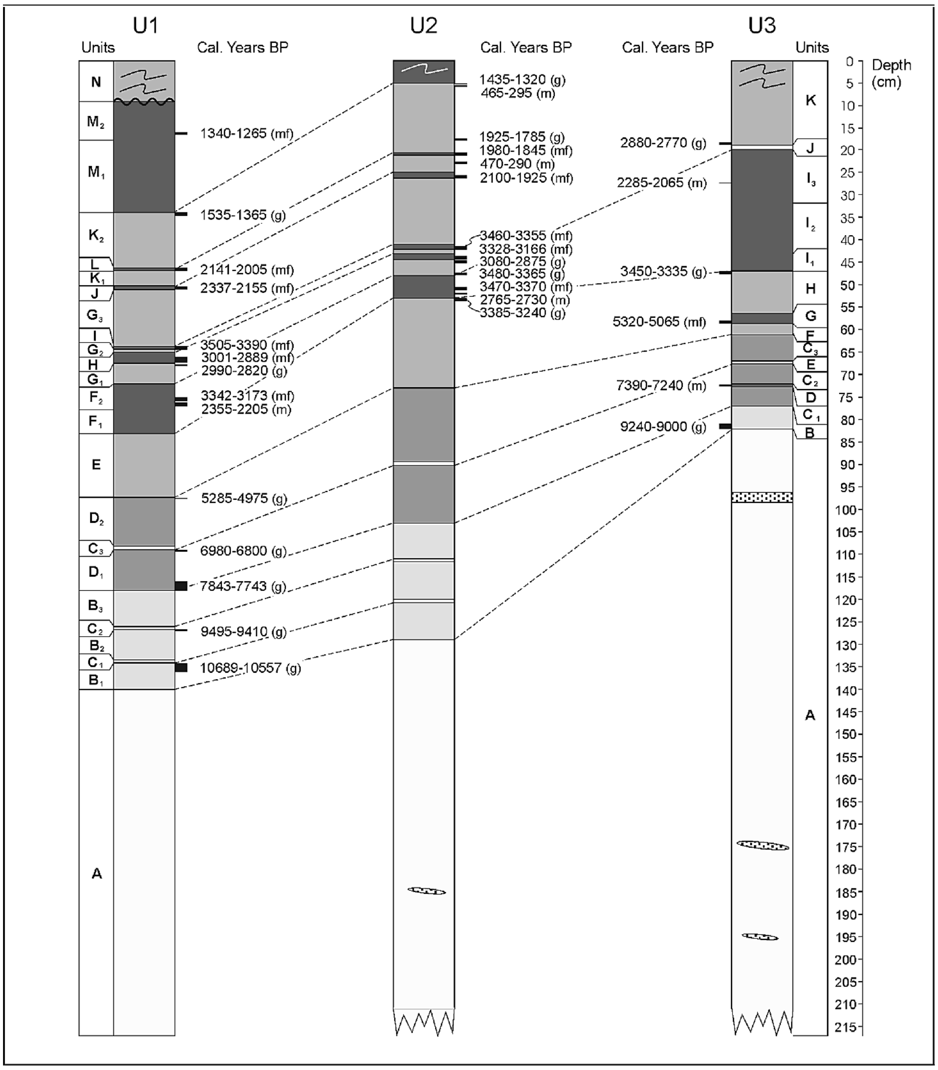

Figure 9 Chronostratigraphic correlation of cores U1, U2 and U3. The radiocarbon dates are from bulk gyttja samples (g), bulk sample of massflow deposits (mf) and redeposited terrestrial macroflora samples (m).

sedimentation rate on the lake-floor high. Our understanding of the lake bathymetry and bottom currents is, however, insufficient to verify this hypothesis.

The thick, dark-brown massflow units F and M (Figures 3 and 4) are both thinner and finer-grained in core U2 than in core U1, which probably reflects primary downflow changes, and implies that the two debris-flow events occurred on the northern side of the valley. Furthermore, the proposed correlation of unit F in cores U1 and U2 with the much thicker unit I in core U3 suggests that the main slope failure leading to this depositional event occurred relatively close to the U3 site. The thin massflow units H and L are both thinner and finer-grained in core U2 than in core U1, whereas units I and J are thicker and coarser-grained. This spatial relationship may similarly reflect downflow changes, suggesting that units I and J were probably derived from the lake's southern side, and units H and L from the northern side.

The proposed correlation also suggests that the two thin massflow units D and G in core U3 are not represented in cores U1 and U2, and that the thin massflow units H, I, J and L in cores U1 and U2 have no equivalents in core U3, pointing to lateral pinchout of relatively small massflows (though the lack of units L and J in core U3 may reflect loss of sediment during coring). The correlation thus implies that, although the sedimentary record of major debris-flow events, which probably include several debris flows, is relatively widespread in the studied part of the lake, the record of smaller debris-flow events is limited to the lake-floor area close to the flow's coastal plunging point. A further implication is that an extensive network of cores would be necessary to get a complete record of debris flows that have entered the lake. However, the sedimentary record from Ulvådalsvatnet is thought to be reliable as regards the slope-wasting events in the valley side adjacent to the eastern part of the lake.

Timing of events

The radiocarbon dates suggests that the Ulvådalsvatnet area was deglaciated before *c.* 10 600 cal. yr BP, and that three periods of increased growth and rapid melting of cirque-glaciers in the valley's catchment occurred in the early to middle Holocene (maximum ages *c.* 10 500, *c.* 9400 and *c.* 6900 cal. yr BP). Minor debris flows are recorded by units D and G in core U3 in the middle Holocene. Their maximum ages are *c.* 7300 and *c.* 5200 cal. yr BP respectively. The massflow unit F in cores U1 and U2 and unit I in core U3, if correctly correlated, mark the onset of the main period of debris-flow activity in the late Holocene. Dates of this major debris-flow event range from 2285–2065 cal. yr BP (macrofossils from unit I) to 3470–3370 cal. yr BP (bulk sediment date of unit F). However, because all the dates here must be regarded as maximum ages, the main debris-flow activity most probably did not start earlier than *c.* 2200 cal. yr BP.

A number of other studies from western Norway jointly indicate a regional increase in slope-wasting processes in the late Holocene, and particularly after *c.* 3000 ^{14}C yr BP (*c.* 3200 cal. yr BP) (Blikra, 1986; Matthews *et al.,* 1986; 1997; Nesje *et al.,* 1991; 1995; Blikra and Nemec, 1993a; 1993b; 1998).

Scattered gravel clasts in the gyttja deposits are thought to represent mainly snow-avalanche processes. Notably, the gravel component is rare in the gyttja deposited immediately after the deglaciation, and periods of increased snow-avalanche activity and debris-flow processes tend to alternate with each other in the late Holocene (Figures 3, 4 and 5).

Triggering of debris flows

Reduction of frictional strength by seismic shaking and liquefaction can instantaneously trigger slope failures and debris flows. Western Norway is tectonically stable at present, but the possibility of powerful earthquakes during the Holocene cannot be entirely excluded (see discussion by Blikra and Nemec, 2000). Actually, evidence of neotectonic faulting in southern Norway has recently been documented (Anda *et al.*, 2002). Under conditions of tectonic stability, however, debris flows are almost invariably triggered by an abrupt rise in porewater pressure, which reduces effective normal stress and thus the soil's shear strength (Sandersen, 1997). An abrupt rise in porewater pressure may be caused by intense rainfall or rapid snowmelt, or their combination. Sandersen (1997) found that in the maritime climate of western Norway debris-flow events are most frequent during rainstorms in the autumn, and that the critical factor in triggering soil failures is a high-intensity rainfall lasting for 2–6 hours. The 1960 debris-flow event in Ulvådalen provides a good example of this relationship. Snowmelt probably did not contribute to this slope failure directly, because the snowcover during the preceding winter was thin; moreover, May and June in 1960 were warm and most of the snow on the south-facing valley slope probably melted before the rainstorm event. Notably, the record from Ulvådalsvatnet shows that debris-flow processes are less prominent in periods of high snow-avalanche activity. Because the incidence of snow avalanches depends mainly on high snowfall intensity, this result supports the assumption that snowmelt is not a major factor in triggering of debris flows in Ulvådalen. It seems likely, therefore, that Holocene debris-flow events in Ulvådalen were triggered by unusually intense rains, perhaps with a contribution of snowmelt.

However, the intrinsic shearing strength of soil on steep valley-side slopes is determined by a variety of factors, including the sediment's texture and primary structure, effects of weathering, pedogenic alternation and secondary layering, vegetation cover, and the degree of water saturation and draining rate (Moser and Hohensinn, 1983; Church and Miles, 1987; Johnson and Sitar, 1990; Nyberg and Lindh, 1990). Antecedent soil-moisture conditions may be particularly important in determining whether or not a particular rainstorm generates a debris flow (Govi and Sorzana, 1980; Matthews *et al.*, 1997; Strunk, 1997; Van Asch, 1997). Consequently, depending on these factors, rainstorms of the same intensity and duration may sometimes trigger debris flows and sometimes not.

Sediment availability is not a limiting factor in Ulvådalen, but the soil structure and slope stability may have changed during the Holocene. It cannot be precluded that the late-Holocene debris-flow activity reflects a cumulative effect of progressive pedogenesis (cf. Brooks *et al.,* 1995) and, if valid, the early- and mid-Holocene rainstorms, even if of similar or greater magnitude to the 1960 event, may not necessarily have triggered debris flows. However, a debris-flow record from upper Gudbrandsdalen, eastern Norway, shows that debris flows occurred on till-mantled slopes throughout the Holocene, suggesting that long-term changes in intrinsic sediment characteristics is not a limiting factor for debris flows in the early and middle Holocene (Sletten and Blikra, 2002). There is no sedimentary evidence of debris-flow processes immediately after the deglaciation, when the till-covered slopes were free of vegetation, and potentially in an unstable or metastable state (Ballantyne and Benn, 1994), suggesting less intense rainstorms at that time. The upper limit of pine in western Norway is now lower than earlier in the Holocene (Dahl and Nesje, 1996), but the Ulvådalen slopes presently support birch forest up to an altitude of 1000–1100 m, and it seems unlikely that changes in vegetation cover have significantly affected slope stability after the first forest establishment. Furthermore, the 1960 debris flows originated on a slope densely vegetated by birch, implying that depletion of forest cover was not responsible for reducing the slope stability prior to that event.

In summary, it is possible that factors other than rainfall intensity have influenced the timing of Holocene debris-flow events in Ulvådalen, but the most probable triggering factor responsible for the recorded increase in debris-flow activity after *c.* 2200 cal. yr BP is climatic, namely an increase in the frequency of intense rainstorms.

Conclusions

(1) The sediment cores from lake Ulvådalsvatnet reveal the chronostratigraphy of Holocene debris flows derived from the adjoining mountain slope and spread subaqueously as high-density turbidity currents. These discrete massflow deposits are 0.2–28 cm thick and exhibit sharp contacts with both underlying and overlying lacustrine gyttja. They are associated with an influx of sand-sized sediments, a drop in water and TC contents, and are rich in terrestrial macroflora remains that give the sediment a dark brown colour. The macroflora indicates terrestrial derivation of the sediment and reflects stripping of peat and vegetation cover from the collapsing valley-side slopes. Massflow units 5–28 cm thick may include a minor component of fine gravel and are characterized by an upward fining in particle size accompanied by an increase in both water and TC contents.

(2) The ^{14}C dates show that the terrestrial macroflora detritus in the upper, massflow-dominated part of the Holocene lake-fill succession are consistently younger than the corresponding bulk-sediment samples. The dates obtained are regarded as maximum ages, but the dates of terrestrial macroflora and early-Holocene gyttja are considered to be the most reliable. The inconsistent radiocarbon dates from the lake-fill sedimentary succession point to the need for research designed to resolve the problems related to 'hard-water' effects and redeposition of old terrestrial organic matter in lake sedimentation.

(3) The variation in TC content is a valid basis for correlation between the sedimentary successions in the three cores from Ulvådalsvatnet. This correlation is supported by the ^{14}C dates, and shows that the thinnest massflow units (0.2–2.5 cm) lack lateral continuity over a distance of 400 m, which probably reflects the localized deposition by small debris flows. Consequently, the limited number of cores is unlikely to provide a complete Holocene stratigraphic record of the debris flows that terminated in the lake. However, the record obtained is thought to be reliable as regards the debris-flow activity in the valley side surrounding the eastern part of the lake.

(4) Despite the discrepancies, the dates from the three sediment cores show a consistent pattern of the time-frequency of debris-flow events, with only two small events in the middle Holocene and two major and four smaller events in the late Holocene. The main period of late-Holocene slope wasting is thought to have commenced at *c.* 2200 cal. yr BP.

(5) Intense rainstorms are thought to have triggered the Holocene debris flows in Ulvådalen, although other factors, particularly high antecedent soil moisture due to snowmelt, may have contributed to the slope failures. We therefore suggest that unusually intense rainstorms began to occur more frequently in the Ulvådalen area after *c.* 2200 cal. yr BP. This conclusion corre-

sponds with other studies of the time-frequency of colluvial debris flows in western Norway, indicating a general increase since *c.* 3000 ^{14}C yr BP (*c.* 3200 cal. yr BP).

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