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A ~ 4500-yr record of river floods obtained from a sediment core in Lake Atnsjøen, eastern Norway

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Abstract

To extend the historical record of river floods in southern Norway, a 572-cm long sediment core was retrieved from 42 m water depth in Atnsjøen, eastern Norway. The sediment core contains 30 light gray clastic sediment layers interpreted to have been deposited during river floods in the snow/ice free season. In the upper 123 cm of the core, four prominent flood layers occur. The youngest of these overlap with the historical record. The thickest (flood layer 5) possibly reflects a general increase in river-flood activity as a result of the post-Medieval climate deterioration (lower air temperatures, thicker and more long-lasting snow cover, and more frequent rain/snow storms) associated with the 'Little Ice Age'. The most pronounced pre-historic flood layers in the core were, according to an age model based on linear regression between eleven bulk AMS radiocarbon dates, deposited around 4135, 3770, 3635, 3470, 3345, 2690, 2595, 2455, 2415, 2255, 2230, 2150, 2120, 1870, 1815, 1665, 1640, 1480, 1400, 1380, 1290, 935, 885, 670, 655 and 435 cal. BP (BP = AD 1950). The mean return period of the river flood layers is, according to the linear regression age model, ~ 150 ± 30 cal. yr (mean ± 1 S.E.).

Introduction

River floods are among the most common and widespread of all natural hazards on Earth (e.g., Baker, 1988; Hupp, 1988; Komar, 1988). Numerous intense weather events with consequences for humans have attracted public attention over the past yrs. A series of large floods in northern Europe and elsewhere in the world during the 1990s has triggered a debate whether the causes of such flood events are due to changes in human-induced land use and/or climate change. It is, however, problematic to separate natural climate change from human-induced climate variations. The latter will be superimposed on the natural changes occurring at varying time scales and with an uneven geographical distribution. Climate change due to human activities has been assessed by the Intergovernmental Panel on Climate Change (IPCC, 1995). The main conclusion in their report is that there is a human component in the mean global temperature rise of 0.3–0.5 °C since AD 1860. During the instrumental period, precipitation has increased over the mainland at northern latitudes, especially during the winter season and there has been a general increase in climate variability and weather extremes over the later decades. Changes in the amount, frequency, and intensity of precipitation have an effect on the magnitude and timing of runoff and the intensity of floods and droughts. Great uncertainties, however, make it difficult to translate these results to a regional scale.

An analysis carried out on twenty-four Nordic historic flood series (AD 1931–1990) shows a de-

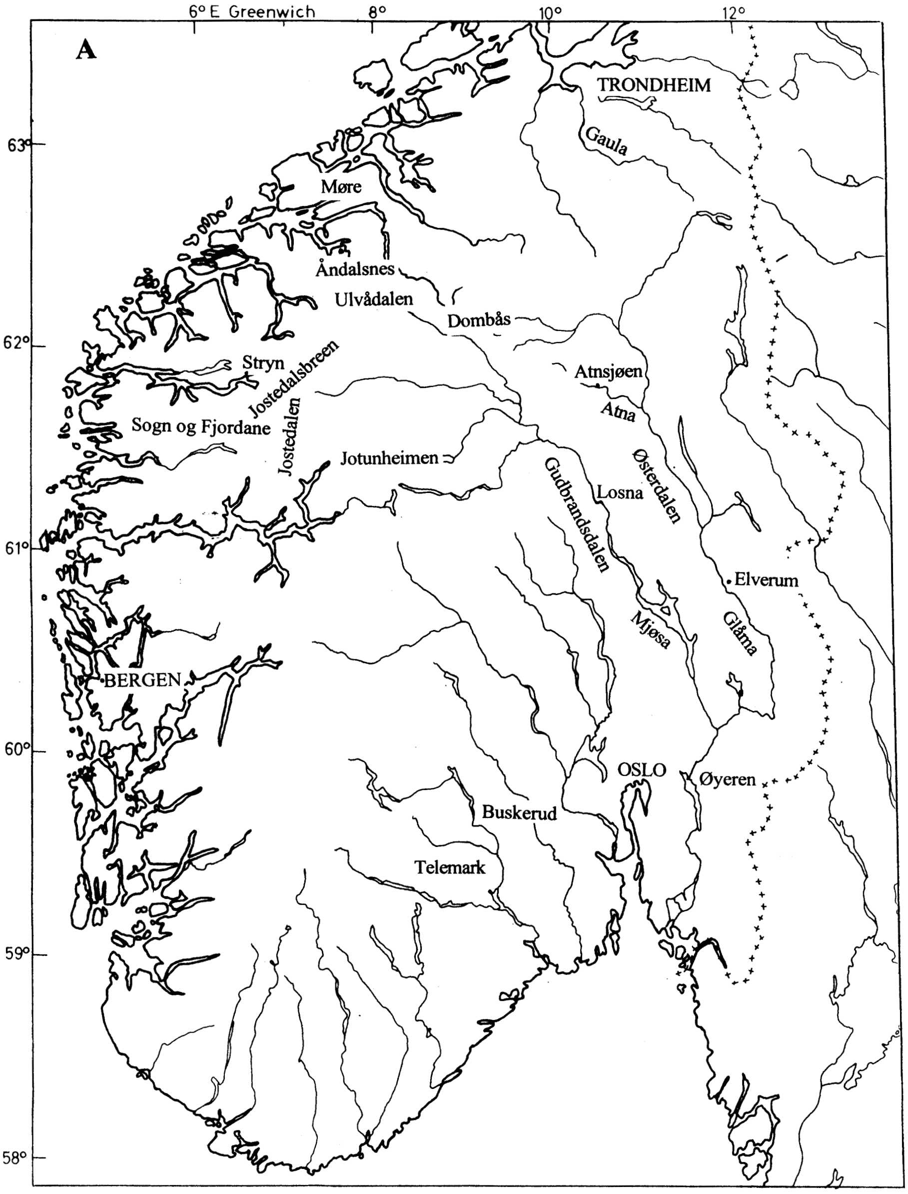


Figure 1. (A) Location map southern Norway and (B) Atnsjøen and its catchment.

clining trend in maximum winter water discharge and the autumn floods in most of Sweden and central parts of Norway (Hisdal et al., 1995). In Scandinavia, the weather records obtained during the historic and instrumental periods show extreme weather events, such as high precipitation (snow and rain) intensity, windstorms, snowstorms, cold periods and droughts (Nyberg & Rapp, 1998).

The water discharge in a river is mainly dependent on the size of the catchment and the amount of precipitation. In southern Norway, the annual precipitation varies from about 5000 mm at the coast of western Norway to 200–300 mm in the upper Gudbrandsdalen region. In western Norway, it has been calculated that the precipitation increases 8–10% per 100 m increase in altitude (Haakensen, 1989; Dahl & Nesje, 1992; Laumann & Reeh, 1993). In central eastern Norway, the amount of water stored as snow during the winter accounts for about one half of the annual precipitation, in the mountains even more (Wold, 1992). In the coastal regions, this amounts to approximately 25%. The water stored as snow is normally released during the spring

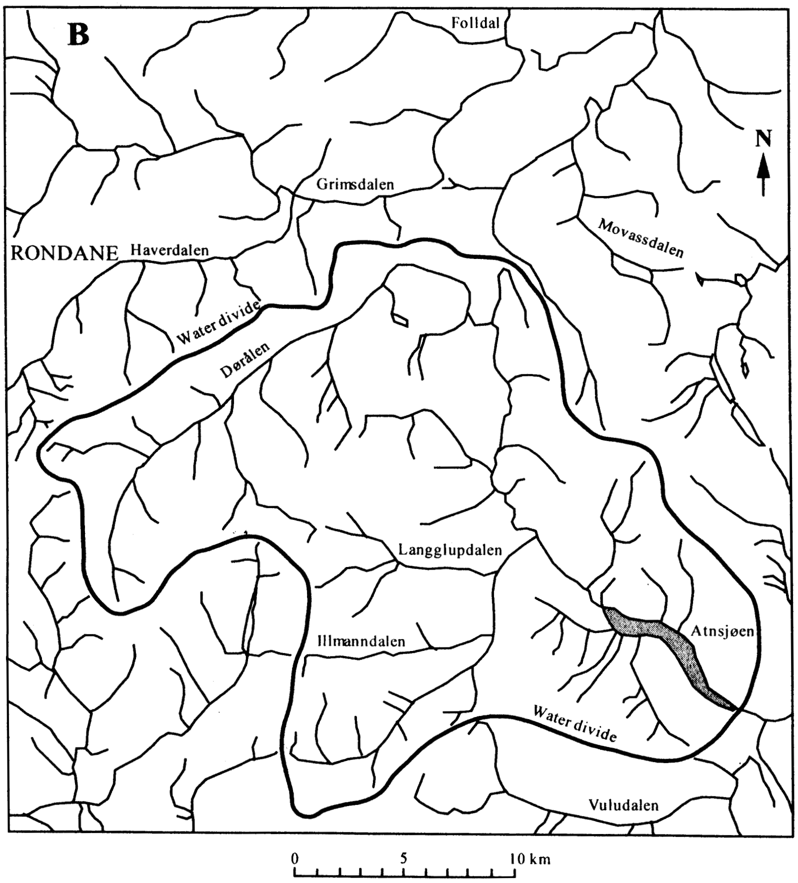


Figure 1. Continued.

flood. The spring flood in southern Norway occurs normally two months later in the inland than at the coast. A topographic effect on the timing of the floods is the delay with increasing altitude and increasing latitude (Wold, op. cit.). In the continental, eastern part of southern Norway, floods and debris flows are frequent in late April, May, and early June. Warm weather, causing rapid snowmelt in combination with high rainfall intensity, is commonly the main trigger of these floods. In the western, maritime areas, September through December is normally the period of the largest floods and associated debris flows due to high precipitation (Nyberg & Rapp, 1998).

Historic river floods in southern Norway

A flood monument at Elverum (Figures 1A and 2) shows a record of historic floods along the Glåma river since AD 1675. Figure 3 shows the relative flood heights and the age distribution of the twenty floods recorded during the historic time period. At Elverum damaging floods (ranked in order of decreasing size) occurred AD 1789, 1995, 1773, 1675, 1717, 1724, 1749, 1827, 1934, 1850, 1916, 1846, 1760, 1966 and 1967 (NOU, 1996). The mean return period of the historically recorded floods at Elverum is 17 ± 3 yrs (mean ± 1 S.E.). Figure 4 shows the annual maximum water level along river Glåma at Elverum between AD 1872 and 1995. At lake Øyeren (Figure 1A) damaging floods occurred AD 1789, 1860, 1853, 1995, 1967, 1927, 1910, 1934, 1966 and 1916. The ranking of the floods in Øyeren after AD 1860 is, however, somewhat uncertain due to regulation works (NOU, 1996). At Losna in Gudbrandsdalen (Figure 1A), floods above 5 m on a water gauge are considered to cause damaging floods. Floods above this level (ranked after size) occurred in AD 1938, 1995, 1939, 1934, 1910, 1897, 1924, 1916, 1958 and 1909. In lake Mjøsa, floods above 7.5 m on the water gauge there is considered to

Figure 2. A flood monument at Elverum (for location, see Figure 1a). The insert photo shows the water level during the 1995 river flood. Photo: O.T. Ljøstad – Dag Stenhammer.

trigger damaging floods, and ranked after size, this level was exceeded in AD 1789, 1860, 1827, 1808, 1927, 1995, 1863, 1846, 1967, and 1850.

The largest flood recorded historically was 'Stor-ofsen', the flood peaking on the 22nd of July 1789 (e.g. Sommerfeldt, 1943). The autumn AD 1788 was cold and the ground was frozen when the snow fell in November. The winter was characterized by deep snow and the snow melted late in spring. Warm weather arrived in May, but because the ground was frozen, little water penetrated the surface ground layer. This caused a long-lasting, but not devastating flood. Large peatbog areas and flat wooded areas were flooded and lakes and ponds were full. On 1 July it started to rain more-or-less continuously for three weeks. The rain culminated on July 21 with extreme rainfall intensity. This resulted in thousands of debris flows, erosion and a flood larger than anybody could remember. In Gudbrandsdalen more than 3000 houses disappeared, 10,000 acres cultivated land was eroded, and 68 persons were killed. In Østerdalen, more than 400 farms were destroyed, and 2700 cows, 250 horses and 3500 sheep were killed. All bridges across the main and tributary rivers were destroyed. For Norway, this flood became an enormous economic burden and the majority of the affected persons had to move to northern Norway (mainly inner Troms) to resettle.

At the end of June AD 1918, rain and snow melt caused a large flood in the river Gaula, Trøndelag (Figure 1A). Houses, parts of the railroad, and roads were swept away. The largest flood in Gaula occurred, however, on the 24th of August 1940. One person and a lot of cattle were killed, and buildings were subject to severe damage. In 1934 a large spring flood hit a large part of southern Norway, causing damages along Glåma and Øyeren, in Telemark and Buskerud, and inner parts of Sogn og Fjordane (Stryn) (Figure 1A). On 14 and 15 August 1979, rain and snowmelt caused a large flood in Jostedalen, western Norway. The flood was one meter higher than a floodmark from AD 1898. One hundred houses and fourteen bridges were damaged. In 1987 and 1988 large floods occurred in several tributary rivers in eastern Norway (NOU, 1996).

The next highest historic flood in Østerdalen occurred on the 2nd of June 1995 (Figures 2 and 3). The weather was quite cold in May 1995 with some snow in higher regions and snow melt only in the lowland areas. Weather records and data on snow depth from meteorological stations in the region show that this flood occurred as a result of rising temperatures from 22nd of May, causing accelerating snow melt from both wooded areas (300–1000 m a.s.l.) and mountains. It has been estimated that 4000 mill m^3 of snow melted during the period from 25 May to 2 June, corresponding to a precipitation of 100 mm over the catchment in addition to rainfall precipitation of 50–70 mm between 28 May and 3 June (NOU, 1996). Daily precipitation maxima occurred on 2, 5, and 6 June. The maximum water discharge at Elverum of about 3500 m^3 sec^{-1} occurred on 2 June. At Elverum, the maximum flood level in 1995 was approximately 60 cm below 'Stor-ofsen' in AD 1789 (Figure 2). Erichsen (1995) calculated the return period of the 1995 flood to 100–200 yrs, which is in close agreement with the flood frequency presented by Tvede (1989).

One of the most spectacular events, and the largest case in Scandinavia described by eye-witnesses, took place 26 June 1960 in Ulvådalen between Åndalsnes and Dombås (Figure 1A). A convectional rainstorm of unknown intensity lasted for about 2 h and caused

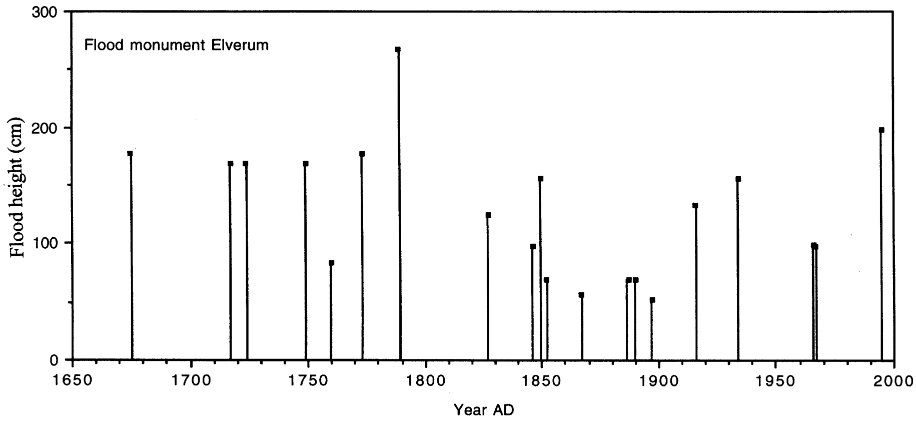


Figure 3. Time distribution and flood heights (in cm) of the individual floods recorded on the Elverum flood monument.

30 large debris slides and flows along the valley sides.

In order to extend the historical record of river floods in southern Norway, we present an approximately 4500-yr history of river floods in the Atnsjøen catchment, a part of river Glåma's drainage basin (Figures 1A and 1B) in eastern Norway, as recorded in lacustrine sediments in lake Atnsjøen.

The Lake Atnsjøen sediment core

Sampling procedure and methodology

Lake sediments provide an archive for reconstructing the history of floods in a river system (Thorndycraft et al., 1998). These sediments commonly consist of fine sand and silt deposited from suspension where flood flow velocities are rapidly diminished. The coring of the Atnsjøen sediments was carried out from lake ice during the spring of 1995 about 2 months before a large flood in late May and early June 1995. The core was retrieved by means of a piston corer with diameter 110 mm constructed to obtain up to 6 meters of sediments from deep water (Nesje, 1992). The core was stored in a cold room (+4 °C). After opening, the outer sediment layer closest to the tube was removed and the sediment surface was cleaned carefully. Visual lithofacies, structures and textures were logged before the cores were split into 1-cm discs placed in plastic bags and stored in a cold room.

The amount of organic carbon in lake sediments is a function of autochthonous and allochthonous organic production and clastic sediment input. Weight loss-on-ignition (LOI) is a method to determine the organic content of lacustrine sediments. The LOI samples (normally 1–3 g dry sample) were dried overnight at 105 °C in ceramic crucibles before the dry weight was measured. The samples were then subject to gradually rising temperatures for half an hour and ignited at 550 °C for 1 h (Dean, 1974). After ignition, the samples were placed in a desiccator and weighed at room temperature (18–20 °C). The weight loss-on-ignition was calculated in percent of dry weight.

Eleven AMS radiocarbon dates (Table 1) were carried out at Beta Analytic Inc., Florida, USA, while the basal date in the sediment core was carried out at Swansea Radiocarbon Dating Laboratory (Department of Geography, University of Wales at Swansea, UK) according to standard procedures for 'conventional' radiocarbon dating. The radiocarbon ages are corrected for $^{12}C/^{13}C$. Calibration of the radiocarbon ages to calendar years BP (BP = AD 1950) is according to the calibration program of Stuiver & Reimer (1993).

Lake Atnsjøen catchment physiography

Lake Atnsjåen (701 m a.s.l.) is located along the Atna river, a tributary to river Glåma flowing through Østerdalen (Figure 1A). The catchment area of Lake Atnsjøen is 457 km^2 and drains the eastern part of Rondane (Figure 1B). A major part (85%) of the lake catchment is above 1000 m, with the highest point 2178 m (there is no glaciers in the catchment). The total catchment area of Glåma, the longest river in Norway (580 km), is 42,000 km^2. The bedrock in the Atnsjøen catchment consists of feldspar-bearing quartzite with chlorite-sericite schists and conglomerate (Sigmond et al., 1984).

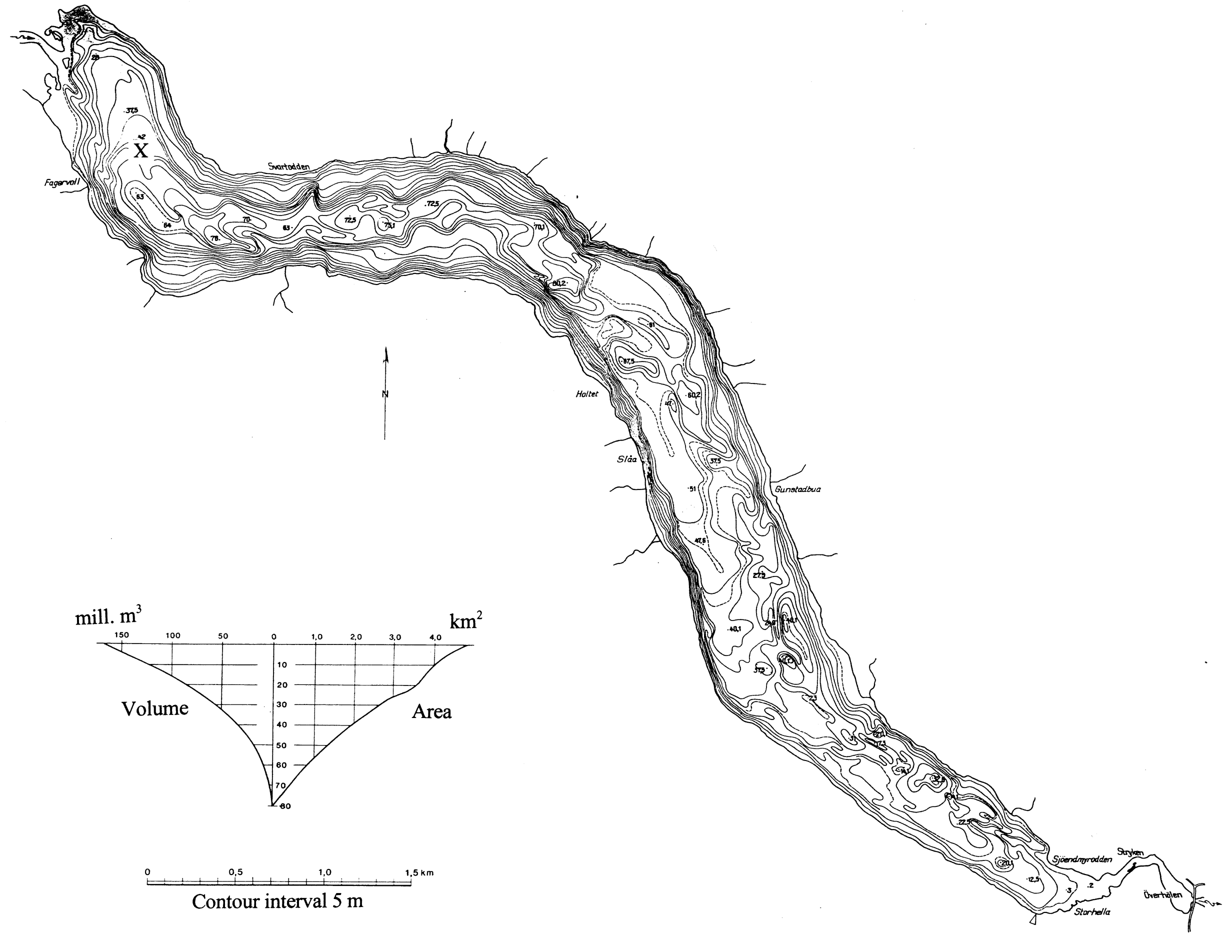


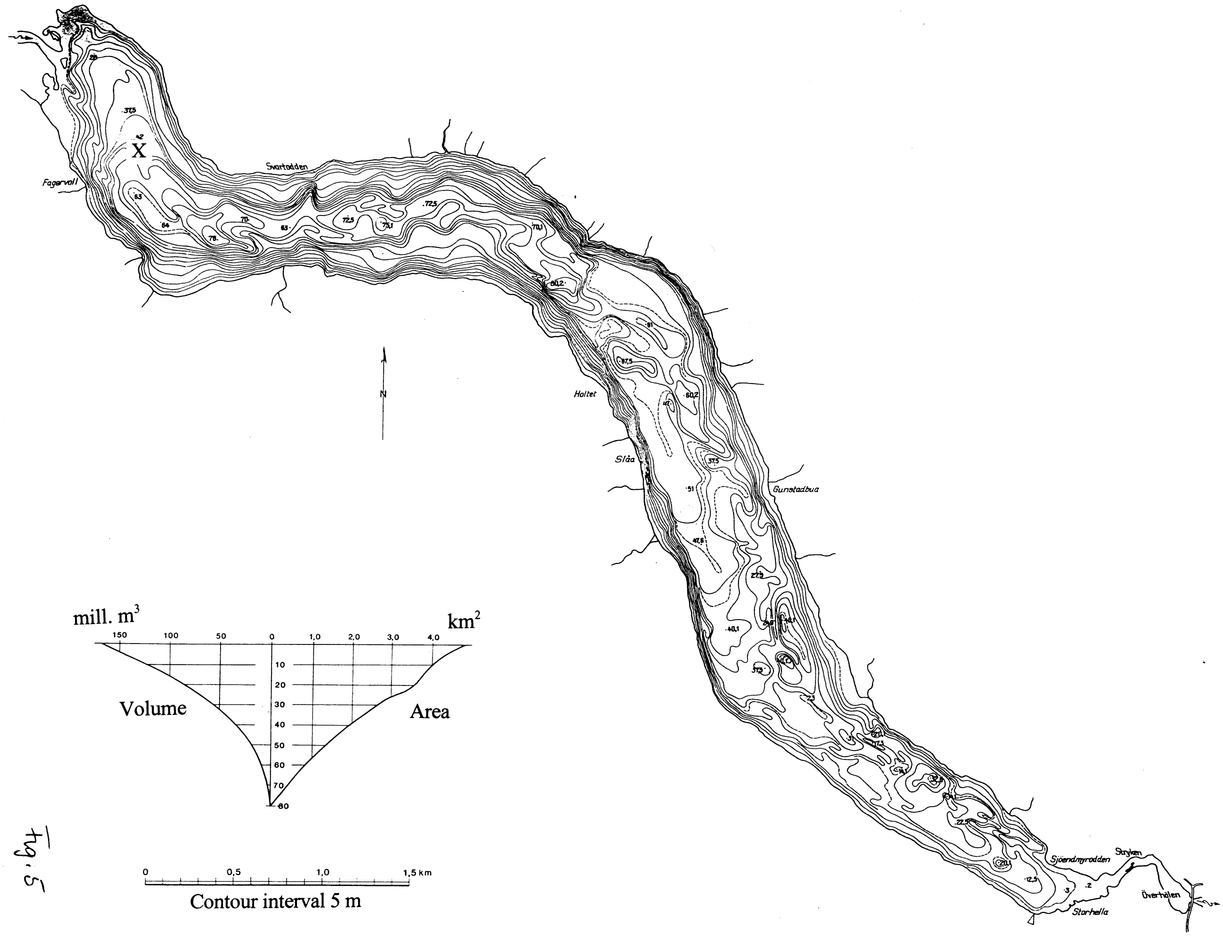
Figure 5. Bathymetric map of lake Atnsjøen (adapted from NVE, 1984). X – Coring site.

June the water discharge was reduced to 80 m^3 sec^{-1} (Fagerlund & Grundt, 1997). The Atnsjøen river catchment has normally no autumn floods. The mean water discharge in Glåma is 728 m^3 sec^{-1} with a maximum flood discharge of 3,542 m^3 sec^{-1}. The material brought into suspension during a flood is normally brought through the river system during a few days.

On average, Atnsjøen is partly and totally covered by lake ice for 190 and 180 days per yr, respectively (Wold, 1992); from the end of November (median: 24 November) until end of May (median: 27 May) (observation period 1950–1995, NVE Hydrological Division). The earliest and latest date of ice-covered lake is 7 November (1981) and 10 December (1954/ 1960), respectively. The earliest recorded date of ice-free lake is 12 May (1961) and the latest date 6 June (1979). On average, the lake is ice-free for 184 days a year.

The sediment core

A 572-cm long sediment core (Figure 6) was retrieved from a relatively flat area at 42 m water depth distal to the delta in the NW part of the lake (Figure 5) (c.f., Bogen, 1983). The sediment core consisted of numerous alternating layers of light brown, silty gyttja and light gray, low-organic, silty bands. The light gray clastic sediment layers are deposited during river floods as a result of erosion of minerogenic sediments along the rivers in the catchment during flood periods, bringing clastic sediments consisting of the local, light gray, feldspar-bearing, quartzite in suspension in the lake. During stable periods characterized by little or low flood activity, however, brown-colored organic material (pollen and plant macrofossils) from the lake catchment (allochthonous) and organic material produced within the lake (autochthonous) are deposited



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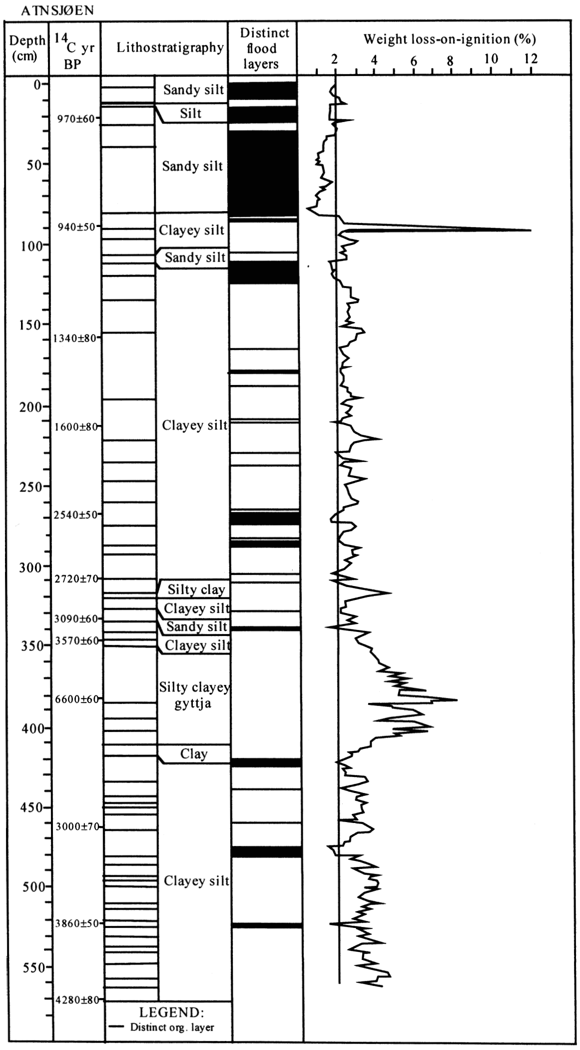

Figure 6. Lithostratigraphy, flood layers, radiocarbon dates, and weight loss-on-ignition (LOI) in the Atnsjøen core.

in the lake (Bogen, 1983; Fagerlund & Grundt, 1997). The sediment texture and the loss-on-ignition (LOI) analyses at 1-cm intervals show that brown-colored sediments yield LOI values > 2%, while the LOI values on the sediment bands interpreted as river flood layers are < 2% (Figure 7). Altogether, 30 distinct flood layers are present in the Atnsjøen core. The thickest and most distinct flood layers in the core are recorded above 125 cm depth in core (Figure 6, Table 2). In the deeper part of the core, flood layers > 2 cm thick occur at 270–272, 274–277, 287–290, 308–310, 314–316, 332–335, 343–346, 426–430, 482–486 and 530–532 cm (Figure 6). Throughout the core numerous thin organic layers (gyttja and plant macrofossils) are present.

Age models

In order to provide age estimates of the river flood layers, altogether twelve radiocarbon datings (eleven AMS and one 'conventional') were obtained on bulk sediments in the Atnsjøen core (Figure 6, Table 1). As seen from Figure 8 (upper panel), several of the radiocarbon dates are not in chronostratigraphical order. The reason for this is probably that during the flood events, the rivers in the catchment erode older organic material which is transported into the lake, thereby giving higher ages than the actual flood event. Therefore, to obtain age estimates for the individual flood layers recorded in the core, two age models were applied. Age model 1 (Figure 8, middle panel) is based on linear regression of the calendar dates (excluding the obvious outlier at 379–385 cm depth, date 6600 ± 60 ^{14}C yr BP, Table 1). In age model 2, interpolation

Table 2. Depth in core and mean age of the Atnsjøen river flood layers according to age model 1 and 2. Dates in calendar yrs BP (BP = AD 1950)

Flood layer no.	Depth in core (cm)	Age model 1 mean age	Age model 2 mean age
1	1–7	See ages of historic floods in text	
2	12–22		
3	24–26		
4	27–28		
5	29–82	435	530
6	83–84	655	795
7	86	670	820
8	110–116	885	990
9	116–123	935	1030
10	165	1290	1300
11	178	1380	1340
12	180	1400	1360
13	190	1480	1390
14	211	1640	1470
15	214–215	1665	1480
16	232–234	1815	1590
17	241	1870	1640
18	270–272	2120	1855
19	274–277	2150	1885
20	286	2230	1960
21	287–290	2255	1980
22	308–310	2415	2125
23	314–316	2455	2165
24	332–335	2595	2290
25	343–346	2690	2370
26	426–430	3345	2955
27	444	3470	3070
28	466–467	3635	3270
29	482–486	3770	3595
30	530–532	4135	4360

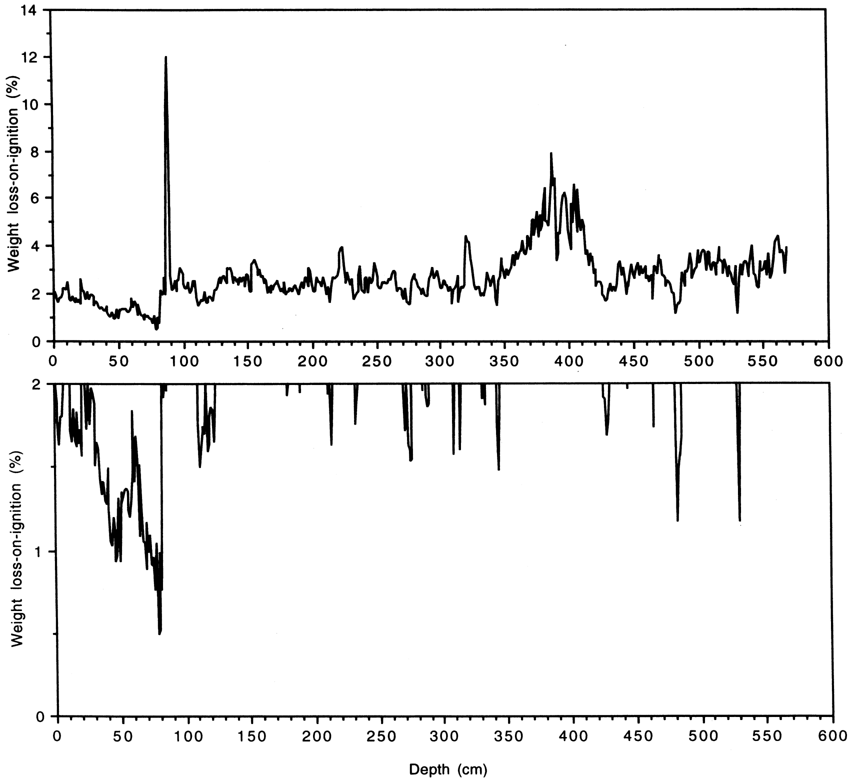

Figure 7. The upper panel shows the weight loss-on-ignition (LOI) in the Atnsjøen core. The lower panel shows the river flood layers.

between the calendar ages at 86–92, 156–162, 219–225, 459–465, 519–525 and 571–572 cm were applied (Table 1). Figure 9 shows the ages (in calendar age BP) of the 30 individual flood layers according to age model 1. Table 2 lists the age estimates (in calendar yrs BP) of the individual flood layers according to the two age models. According to age model 2, the older pre-historic flood layers may be up to about 400 yrs younger, and the youngest layers up to 150 yrs younger (Figure 10).

Sedimentation rates and time resolution

According to the linear regression age model (age model 1), the mean sedimentation rate throughout the core was 1.22 mm yr^{-1} (Figure 11). According to age model 2, the sedimentation rate in the Atnsjøen core may have varied between 0.58 mm yr^{-1} (462–523 cm) and 2.68 mm yr^{-1} (159–222 cm). Age model 1 yields a mean time resolution of 8 yr cm^{-1}. According to age model 2, on the other hand, the time resolution in the core varied between 4 yr cm^{-1} (159–222 cm) and 17 yr cm^{-1} (462–523 cm) (Figure 11).

Late Holocene history of river floods in the Atnsjøen catchment

The sediment core from Atnsjøen shows altogether 30 light gray, low organic sediment layers with LOI values < 2%, which have been interpreted as flood layers, a conclusion also reached by Bogen (1983). Seventeen of the interpreted flood layers are thicker than 2 cm, while thirteen are thinner. Age estimates for the individual flood layers are given in Table 2. The most pronounced pre-historic flood layers in the core were according to age model 1 deposited ~ 4135, 3770, 3635, 3470, 3345, 2690, 2595, 2455, 2415, 2255, 2230, 2150, 2120, 1870, 1815, 1665, 1640, 1480, 1400, 1380, 1290, 935, 885, 670, 655 and 435 cal. BP (BP = AD 1950). In the upper 123 cm of the core, four prominent flood layers occur, of which flood layer 5 probably reflects increased flooding activity as a result of the post-Medieval climate deterioration characterized by lower air temperatures, thicker and more long-lasting snow cover, and more frequent storms associated with the 'Little Ice Age' (e.g., Grove, 1988). The mean return period of the twenty-six pre-historic floods have

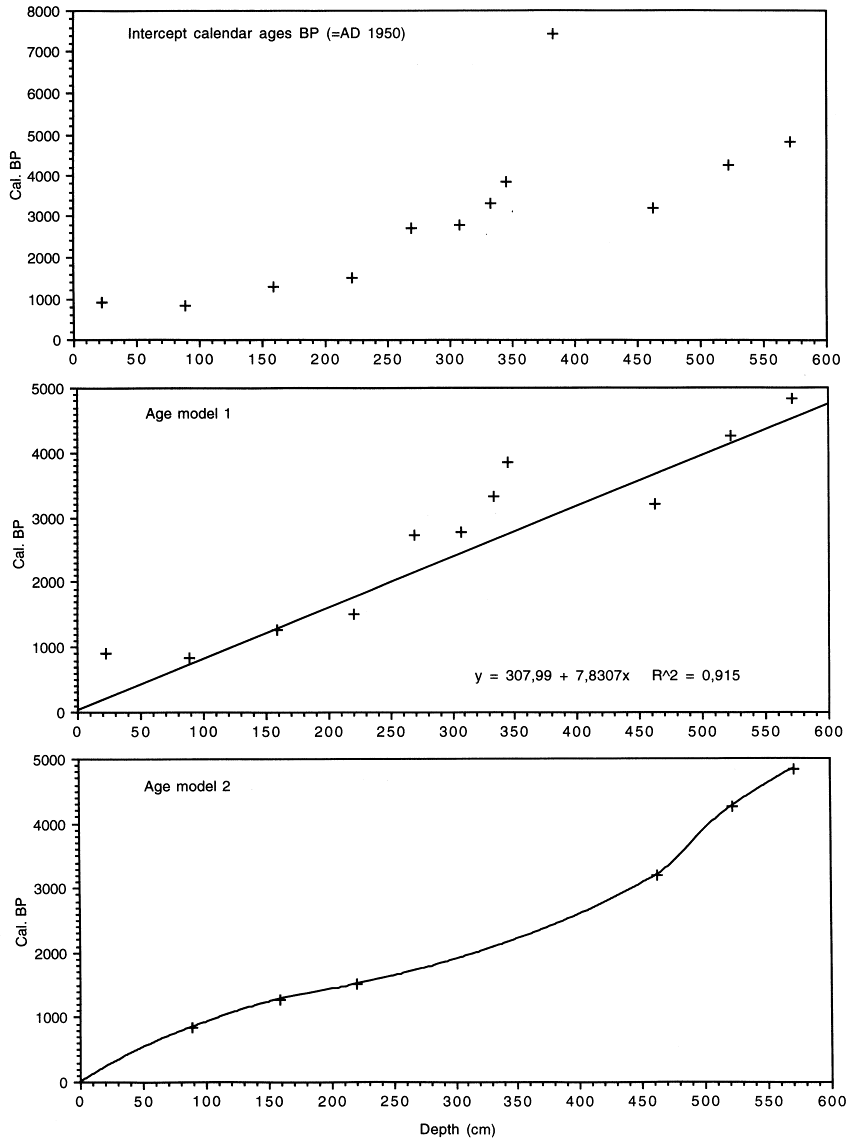

Figure 8. Upper panel: The cal. BP intercept dates in the Atnsjøen core plotted versus depth. Middle panel: Age model 1 of the Atnsjøen core based on linear regression of eleven radiocarbon dated (intercept cal. BP) levels. Lower panel: Age model 2 based on interpolation between six radiocarbon dated (intercept cal. BP) levels.

according to age models 1 and 2 been calculated to ~ 150 ± 30 and 145 ± 35 yrs (mean ± 1 S.E.), respectively.

Comparison between the Atnsjøen river flood history and records of snow avalanches in Møre, debris flows in the Jotunheimen–Møre region, and glacier fluctuations at Jostedalsbreen

The record of pre-historic river floods obtained from the Atnsjøen sediment core provides important additional information on the magnitude and frequency of historic floods in eastern Norway. The temporal distribution of floods is compared with data on debris flows and snow avalanches from the Møre and Jotunheimen regions (Blikra & Nesje, 1997; Matthews et al., 1997; Blikra & Fjeldstad Selvik, 1998) and with glacier activity in the Jostedalsbreen region, as recorded in a proglacial lake at the NW part of Jostedalsbreen (Nesje et al., in press). The increased frequency of floods occurring from about 2500 cal. BP until ca. 1500 cal. BP also occurred in a period of expanding glaciers at Jostedalsbreen, periods of increasing debris-flow activity

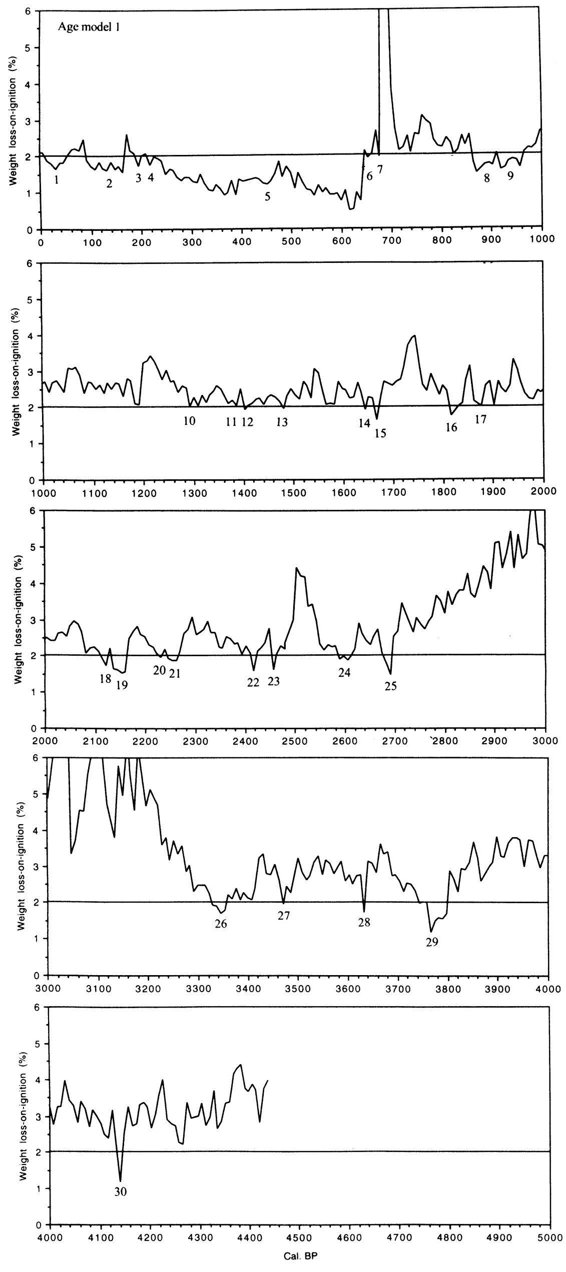

Figure 9. The age of the flood layers in the Atnsjøen core according to age model 1 (see Figure 8).

in Møre/Jotunheimen and increasing snow-avalanche activity in Møre. A period of little flood activity around the Medieval period (AD 1000–1400) correlates with reduced glacier activity at Jostedalsbreen, low debris-flow activity in Møre/Jotunheimen and reduced snow-avalanche activity in Møre. The period of the most extensive flood activity in the Atnsjøen catchment, starting around 800 cal. BP, takes place more-or-less simultaneously with increasing glacier activity at Jostedalsbreen and increasing snow avalanche activity in Møre. The record of debris-flow activity does not, however, indicate a similar increase. From the present data, there seems, despite some coherent events, little common pattern between the four records of debris flows, snow avalanches, glacier fluctuations, and river floods from southern Norway. This is, however, to be expected, since the different types of weather-related phenomena may be triggered by different weather phenomena, commonly of local character, and at different times of the year. This may also partly be due to incomplete records and lack of data, especially for debris flows. The climatic evidence available from modern debris flows and river floods indicates that intense summer or autumn rainfall is a major cause, although snowmelt associated with high temperatures and rain may also be a trigger (e.g. Matthews et al., 1996; Blikra & Nemec, 1998). Snow avalanches, on the other hand, are mostly related to strong winds and high winter precipitation (mild, stormy weather with high precipitation during the winter) (e.g. Blikra & Nesje, 1997; Blikra & Fjeldstad Selvik, 1998; Blikra & Nemec, 1998). The main problem of correlation between regions (Møre, Jotunheimen and Østerdalen) is also the highly local character of precipitation intensity. This may make regional correlations difficult. Glaciers respond to the combined effect of summer temperature and winter precipitation; the western maritime glaciers responding mainly to winter precipitation, while the eastern continental glaciers mostly respond to summer temperature. For future comparisons between the different weather-related phenomena, records of snow avalanches, debris flows, glacier fluctuations, and river floods should preferentially be obtained from the same geographical region with comparable modern climatic characteristics.

Summary and conclusions

A flood monument at Elverum, Østerdalen, gives a record of twenty floods in the Glåma river since AD 1675. At Elverum damaging floods (in order of decreasing size) occurred AD 1789, 1995, 1773, 1675, 1717, 1724, 1749, 1827, 1934, 1850, 1916, 1846, 1760, 1966 and 1967 (NOU, 1996). The largest historically recorded flood, 'Stor-ofsen', culminated on 22nd of July 1789. The flood resulted in thousands of debris flows, erosion and the largest recorded flood catastrophe. In Gudbrandsdalen 3000 houses were

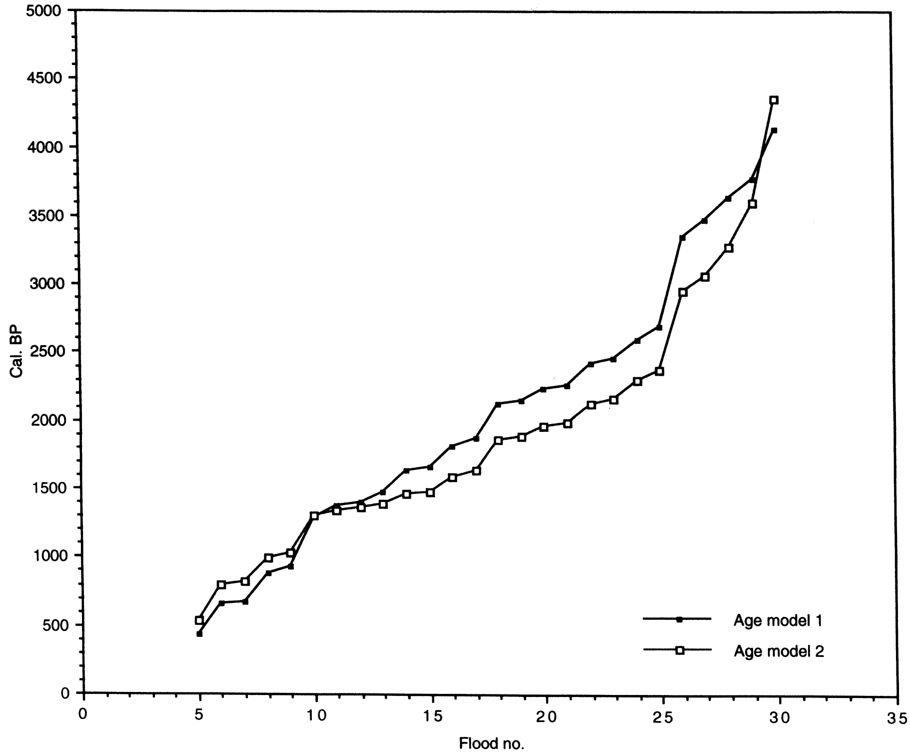

Figure 10. Age difference between the different flood layers according to age model 1 and 2.

destroyed, 10,000 acres cultivated land was eroded and 68 persons were killed. In Østerdalen, 350 farms were destroyed, and 2700 cows, 250 horses and 3500 sheep were killed.

To extend the record of historically reported floods in southern Norway, a 572-cm long sediment core was retrieved from 42 m water depth distal to the inlet delta at the NW end of Atnsjøen. The sediment core shows 30 light gray clastic bands, interpreted as river flood layers.

The history of floods recorded in the Atnsjøen core provides important additional information on the magnitude and frequency of pre-historic floods in southern Norway. The pre-historic river flood layers in the core were according to age model 1 (linear regression between eleven dated levels) deposited approximately 4135, 3770, 3635, 3470, 3345, 2690, 2595, 2455, 2415, 2255, 2230, 2150, 2120, 1870, 1815, 1665, 1640, 1480, 1400, 1380, 1290, 935, 885, 670, 655, and 435 cal. BP (BP = AD 1950). According to age model 2 (interpolation between six dated levels), the older pre-historic flood layers may be up to about 400 yrs younger, and the youngest layers up to 150 yrs younger. The mean return period of the pre-historic floods has been calculated at ca. 150 ± 30 and 145 ± 35 yrs (mean ± 1 S.E.) accord to age models 1 and 2, respectively.

In the upper 123 cm of the core, four marked flood layers occur, which overlap the historic record. Flood layer 5 probably reflects increased flooding activity as a result of the climatic deterioration during the ‘Little Ice Age’ (Grove, 1988) or a single, large event.

Comparison of the flood history with records of debris flows from Møre and Jotunheimen, snow avalanches in Møre, glacier activity at Jostedalsbreen, show different temporal patterns. This is possibly attributed to different trigger factors and local topographical effects associated with different weather-related phenomena.

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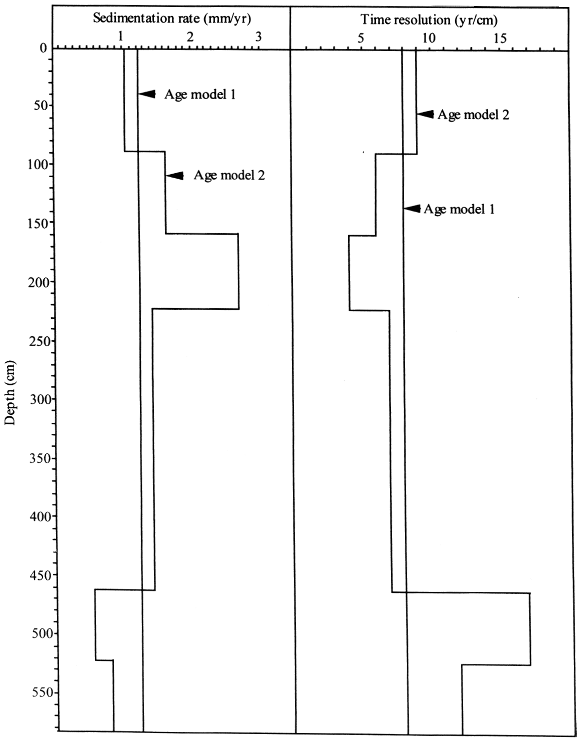

Figure 11. Mean sedimentation rates and time resolution in the Atnsjøen core according to age model 1 and 2.

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