# Sensitivity of Alpine fluvial environments in the Swiss Alps to climate forcing during the Late Holocene

**L. SCHULTE[1], R. JULIÀ[2], M. OLIVA[1], F. BURJACHS[3], H. VEIT[4] & F. CARVALHO[1]**

1 *Department of Physical and Regional Geography and Laboratory of Landscape Research, University of Barcelona, Carrer de Montalegre 6, E-08001 Barcelona, Spain*
schulte@ub.edu

2 *Institute of Earth Science "Jaume Almera", CSIC, C/Lluis Sole i Sabaris s/n., E-08028 Barcelona, Spain*

3 *Catalan Institution for Research and Advanced Studies at the Department of Prehistory, University Rovira i Virgili, Plaça Imperial Tarraco 1, E-43005 Tarragona, Spain*

4 *Institute of Geography, University of Bern, Hallerstrasse 12, CH-3012 Bern, Switzerland*

**Abstract** The variability of Late Holocene fluvial dynamics in the Swiss Alps is traced from fan delta deposits using a multi-proxy approach. The spatial coexistence of wetland, alluvial and fluvial environments on the low-gradient Lütschine fan delta provides a high-resolution fluvial record. The sedimentary record shows seven major aggradation pulses from 3600 cal year BP to the present. Furthermore, 19 minor burial episodes occur between 3600 and 1050 cal year BP at intervals of between 100 and 130 years, suggesting that aggradation during the period of interest was triggered by centennial flood events. Nine coarse-grained flood layers, deposited at a recurrence interval of between 200 and 600 years, coincide with positive radiocarbon anomalies and cold phases in the Alps. The solar influence on the regional hydrological regime is proposed as the main factor triggering the flooding events.

**Key words** Late Holocene; fluvial environments; multi-proxy record; solar forcing; climate; fan delta; Swiss Alps

## INTRODUCTION

Fluvial sedimentation is discontinuous in time and space, and sediments may be eroded by subsequent reworking phases. Despite the resulting discontinuity of sediment records, specific fluvial archives such as fan delta deposits provide accurate data about terrestrial environmental change, including changes in the hydrological regime and sediment supply (Migowski *et al.*, 2006).

At present, the significance of flood magnitude, frequency and forces in mountain regions is discussed in the context of global change (Kääb *et al.*, 2005). Since the 2005 Lütschine flood event, these variables have also been discussed on a local scale. The Alps are especially sensitive to changes in the circulation of the atmosphere at the global scale and to events of extreme precipitation and floods. Floods are known to have resulted from extreme rainfall intensity and frequency, snowmelt, glacier outburst, precipitation combined with frozen soils, and other phenomena. Land use can modify mountain ecosystems and river dynamics considerably.

We address the influence of external factors, such as climatic variability and land use, on aggradation processes and palaeofloods. The variability of fluvial environments of the Lütschine catchment in the Swiss Alps during the Late Holocene is traced from fan delta deposits using a multi-proxy approach integrating data from other case studies of fluvial environments in the Alps.

## REGIONAL SETTING

Since the retreat of the Aare Glacier system during the Late Glacial period, the Lütschine has been draining the northern slope of the Jungfrau Massif (46°40′N, 7°53′E; 4158 m a.s.l.) to the Aare River and has built up the fan delta that separates Lake Thun from Lake Brienz (Fig. 1). Layers of fluvial gravel, sand and silt intertongue with organic-rich fine material and peat horizons. Today, the water level of Lake Brienz at 563.70 (+1.63/–1.25) m a.s.l. defines the base level of erosion of the Lütschine River.

Alpine-type glaciers (e.g. Lower Grindelwald Glacier) and smaller hanging glaciers (e.g. Eiger Glacier) cover 17.4% of the 379-km$^2$ Lütschine catchment. In the northern Swiss Alps,

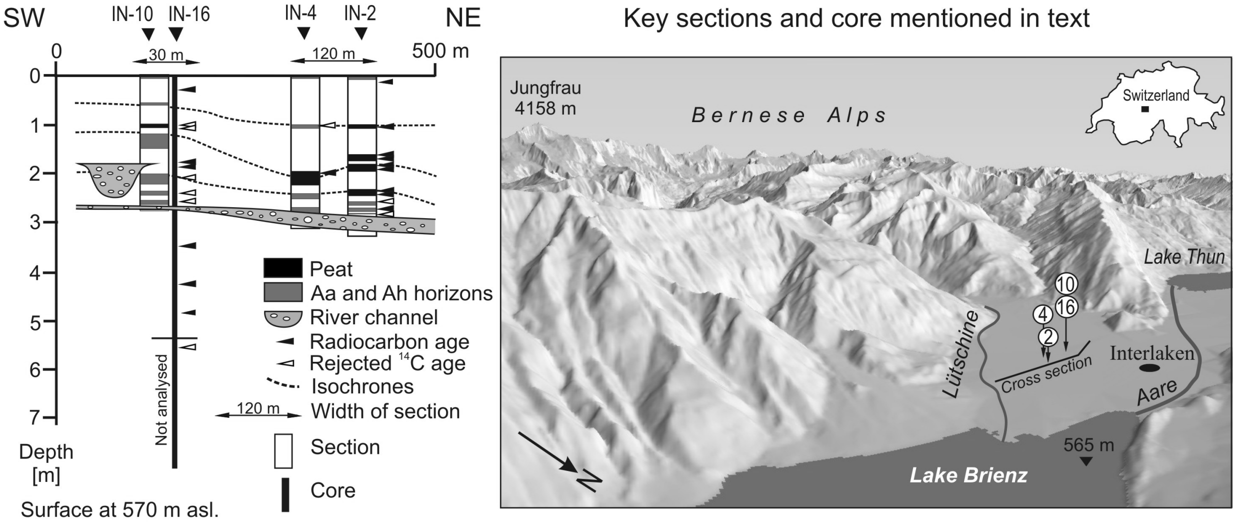


**Fig. 1** Location of the key sections and cores on the Lütschine fan delta.

floods, such as the 2005 Lütschine flood (264 $m^3 s^{-1}$), were triggered by precipitation anomalies, pronounced snowmelt caused by warm fronts, and glacier outbursts. The lithology of the drainage basin can be subdivided into three major areas: the northern area, with elevations below 2100 m a.s.l., mainly made up of carbonated rocks; the central sector, with maximum elevations between 2343 and 2928 m a.s.l., consisting of carbonated rocks, sandstones and marls; and the southern part, with limestone at lower altitudes and crystalline rock reaching up to 4158 m a.s.l. in the summit area of the Aare Massif.

## METHODS

Our research project on fluvial variability in the Swiss Alps combines different methods from several disciplines such as sedimentology, geomorphology, geography, palynology, and geochronology (Schulte *et al*., 2007, 2008). This paper focuses on sedimentological and geocronological methods applied to the fluvial records of key section IN-2 and core IN-16 (Fig. 1) located in the central area of the Lütschine fan delta.

The alluvial fan deposits were sampled at various intervals. The core IN-16 was sampled at 1-cm resolution from 560 to 270 cm depth. Above 270 cm, the fan deposits are exposed in a 30-m wide section (profile IN-10, Fig. 1). According to the continuous lateral extension of the litho-stratigraphic units, the IN-10 section can be traced to the 120-m wide and 330-cm thick IN-2 outcrop which shows a well differentiated sequence of peat and organic-rich horizons, gastropod-rich beds, silt layers, sand beds and coarse-grained channel deposits.

Sediments and soil horizons were described, and trunk, plant and mollusc fragments were collected and classified. To study the geochemical variability of the alluvial fan sediments, major and trace elements of 48 samples extracted from the IN-2 key section were determined by conventional X-ray fluorescence using a Philips PW 2400 spectrometer. With regard to the geochemical record of the IN-16 core, Ca, Ti, K, Fe, Cu and Sr were determined at the Geosciences Department of the University of Bremen, Germany, using a XRF core scanner according to Jansen *et al*. (1998). Organic carbon was performed by loss on ignition (LOI) at 1-cm (IN-16) and 5-cm (IN-2) intervals. Radiocarbon dates were calibrated using the CALIB 5.0.2 Program (Stuiver *et al*., 2005).

Finally, the obtained alluvial fan proxies, i.e. lithology and geochemistry, were correlated with global proxies such as $^{14}C$ residuals (Reimer *et al*., 2004) and delta $^{18}O$ records from GISP2 (Stuiver *et al*., 1997).

## RESULTS AND DISCUSSION

Several logs were obtained from the central Lütschine fan delta. Key section IN-2 and the core IN-16 (Fig. 1 for location) record the aggradational evolution during the last 3500 years. Figure 2 shows the lithology, the obtained radiocarbon ages, the Ca/Ti relationship, the Ca content reported as CaO percentage for IN-2 and as counts per second (cps) for IN-16, the Cu content as ppm for IN-2 and as cps for IN-16, and the percentages of organic carbon (OC).

The radiocarbon dates were used for the chronological model of the aggradational pulses. The four radiocarbon ages obtained from the bottom and top of the two thicker peat layers of IN-2 provide information about the elapsed time without accumulation (bottom and top of the same peat layer) and the elapsed time between the occurrence of an aggradation and the formation of the next peat layer. According to these dated samples, about 15 cm of peat were deposited between 40 and 90 years, whereas a period of 70 years was required to re-establish similar peat environments after deposition occurred.

The lithology (Fig. 2) shows the different aggradational pulses characterized by predominant upward thinning sequences, where the organic beds correspond to relatively stable conditions in the general aggradational dynamics of the Lütschine fan delta. Gravel beds correspond to channel or crevasse splay deposits, whereas sand and silt are interpreted as overbank deposits.

The calcium content shows its lower values during the peat deposit formation, probably due to the acidic waters of these environments, whereas its higher values correspond mainly to silty deposits. The Ca/Ti in general highlights the gravel deposits, probably as a consequence of grain size distribution because the Ti content is closely related to fine phyllosilicates (Schulte *et al.*, 2008). This fact evidences minor aggradational pulses inside the overbank deposits, which are characterized by the progressive decline in the Ca/Ti and a slight increase in organic matter at the top of each pulse.

The Cu content is used here as an indicator of major mining activity in the Lauterbrunnen Valley (lead, zinc, iron and baryte mining). In steep mountain areas, mining can supply large amounts of incoherent material, which can easily be introduced to the river channel. Nevertheless, the high Cu content can also be interpreted as a consequence of pyrite oxidation and the formation of acidic waters, mainly during peat formation. Thus, the high Cu content in peat beds is not taken into account as an indicator for mining.

The organic carbon content (OC in Fig. 2) was drawn in logarithmic scale due to the high values recorded in the peat layers compared with the low values found in sandy or silty beds. The peaks of organic matter, correlating to the minima values in Ca/Ti, were used to model the main aggradational pulses.

At least seven major aggradation pulses can be differentiated from the bottom to the top (Fig. 2):

Pulse I (Fig. 3, Ca/Ti anomalies log): From the gravel bed recorded at 5.3 m depth in the IN-16 core to the organic layer dated at 3005 ± 35 year BP.

Pulse II: From 3005 ± 35 year BP to the organic layer dated at 2700 ± 45 year BP. During this aggradational period four minor pulses can be differentiated on the basis of Ca/Ti and organic carbon content.

Pulse III: From 2700 ± 45 year BP to the peat layer dated at 2305 ± 45 year BP. Ca/Ti content shows five minor aggradational pulses.

Pulse IV: From 2305 ± 45 year BP to the peat layer dated at 1980 ± 30 year BP. During this period, the lithology differentiates three further aggradational pulses. The occurrence of four peaks of Cu content suggests mining activities in the Lütschine catchment. The upper metal anomaly could be related to the Roman mining activities found in the Alps (Morin *et al.*, 2007).

Pulse V: From 1980 ± 20 year BP to the peat layer dated at 1650 ± 20 year BP. The upper part of this main pulse is characterized by the occurrence of two thick peat layers separated by silts which represent a flood event. Two more pulses can be differentiated by the lithology and Ca/Ti. The Cu content is the highest of the section although its interpretation could be ambiguous due to the peat formation.

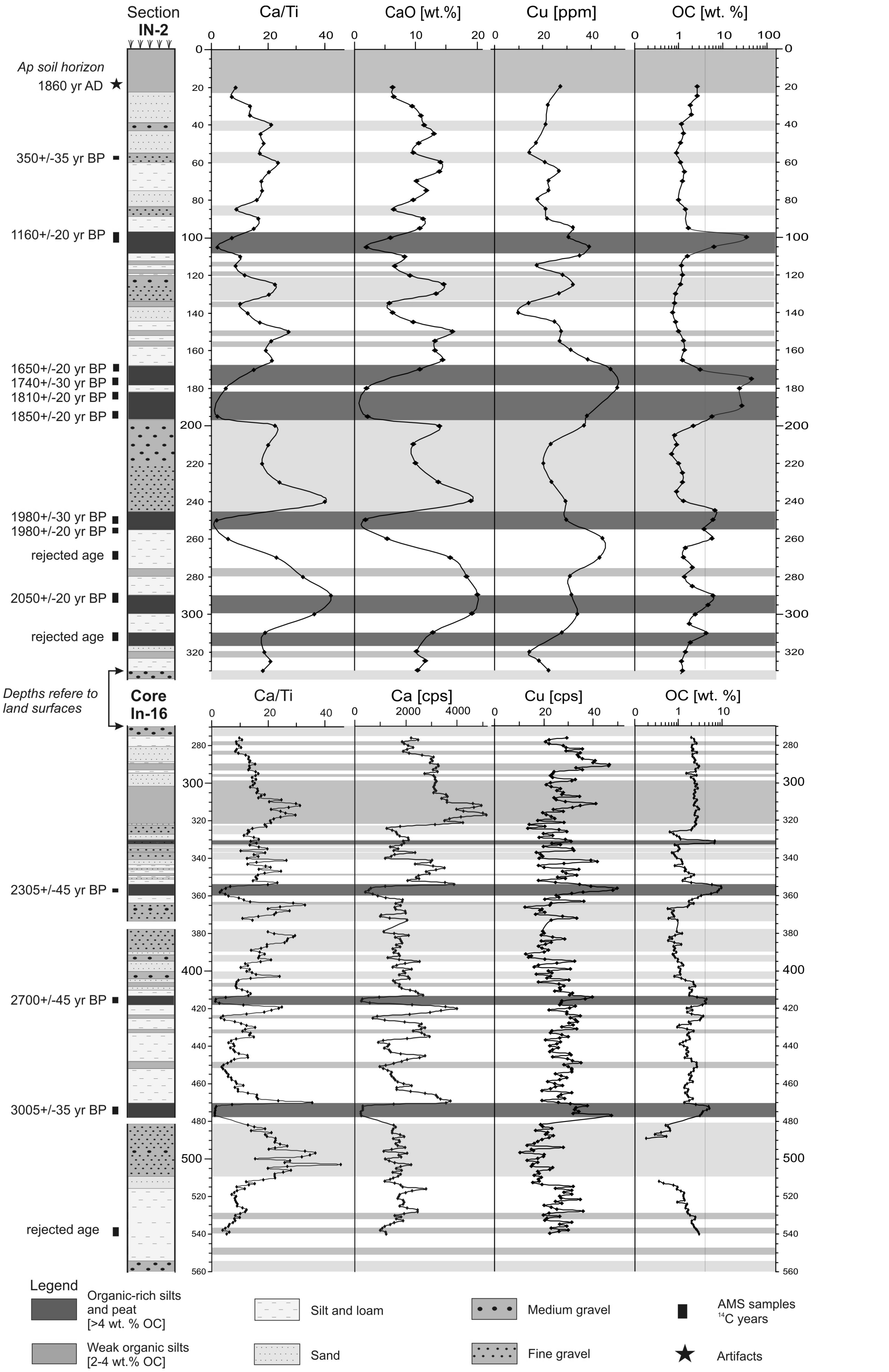


**Fig. 2** Lithology and chronology of the IN-2 key section and IN-16 core, central Lütschine fan delta, Swiss Alps.

Pulse VI: From 1650 ± 20 year BP to the peat layer dated at 1160 ± 20 year BP. Ca/Ti relations also suggest the occurrence of four minor pulses not reflected by organic carbon oscillations. The copper content peaks at the beginning of the eighth and ninth centuries, suggesting Middle Ages mining activities in the Lütschine catchment.

Pulse VII: From 1160 ± 20 year BP to the top of profile IN-2. No sensitive aggradation pulses were recorded. Land-use changes related to the establishment and prosperity of the Monastery of Interlaken in 1133 AD (Affolter *et al*., 1990), detected by pollen records from site IN-2 (Schulte *et al*., 2008), and channel management changed the sedimentation pattern.

**Environmental controls on the Lütschine fan aggradation**

Sedimentary architecture and facies analyses from chronologically constrained sections provide useful data in defining the environmental variables that control their evolution. Figure 3 shows the composite lithological section (IN-2 plus IN-16), the Ca/Ti anomaly, the Cu anomaly and the organic carbon content compared with two global climate records: delta $^{18}$O records from GISP2 (Stuiver *et al*., 1997) and $^{14}$C residuals (Reimer *et al*., 2004).

Tectonics and climate are the primary variables considered in conceptual models of alluvial fan development. However, in areas formed by glaciers, such as the Lütschine catchment area, glacier dynamics and outbursts, shifts in vegetation densities, snowmelt and rainfall regime seem to be the main variables involved in alluvial fan evolution. Channel profile changes can also be triggered by isostatic re-adjustments on the basis of a large time scale and, furthermore, by lake level changes.

Taking our data into account, the following facts can be highlighted (Fig. 3):

(1) According to radiocarbon dates and lateral extension of lithology, major entrenchment phases are negligible at the studied sites during the last 3600 years.

(2) The gravel deposits mainly occur during positive $^{14}$C residuals (Reimer *et al*., 2004), suggesting more frequent floods during cold periods. The five flood episodes detected during the last two millennia correlate with periods of increased debris flow events recorded by turbiditic layers in lake deposits in the Dolomite Alps (Irmler *et al*., 2006) and in the Lower Tauern (Schmidt *et al*., 2002). These cold phases were also detected in stalagmite records from the central (Mangini *et al*., 2005) and southeastern Alps (Frisia *et al*., 2005).

(3) The major aggradational pulses occur at intervals from 580 years to 200 years.

(4) At least 19 minor aggradational pulses occur at intervals between 100 and 130 years lasting at least from 3005 ± 35 year BP until 1160 ± 20 year BP. These deposition events could be seen as return periods of moderate flood intensity while catastrophic events could be related to the 200–580 year periods. The minor pulses occurring at intervals between 100 and 130 years could be related to the solar forcing cycles detected at the centennial scale, such as the Gleissberg cycle, in other sedimentary records (Castagnoli *et al*., 1994; Versteegh, 2005).

(5) Regarding a possible comparison between the $^{18}$O record from GISP2 and the Ca/Ti log of the fan delta deposits, we consider that it is not possible at present to draw direct correlations due to insufficient precision of the chronology. Despite the different chronological resolution and possible local forcing, similar trends of the 100-year smoothed $^{18}$O and the Ca/Ti plot suggest a response of the alluvial fan aggradation to global climate.

All these facts indicate that the main variable controlling the Lütschine fan evolution is climate.

The regional correlation of Alpine fluvial archives shows a different picture. Sedimentological and geomorphic studies on alluvial fans, considered as a system of sediment storage in Alpine catchments, have been conducted in the High Tauern (Veit, 1988), Inn Valley (Patzelt, 1994), Ötztal Alps (Geitner, 1999), Retic Alps (Burga *et al*., 1997), Allgäu Alps (Jerz *et al*., 2000) and the Bavarian Alps (Schrott *et al*., 2002). The chronologies of Alpine fluvial stratigraphies show a heterogeneous pattern of geomorphic processes due to the following factors: differences in time resolution, configuration of catchments, different environmental forces, and spatial distribution and intensity of rainfall events. However, the sedimentary archive of the Isola fan delta in the Retic Alps records similar aggradation processes during the colder climate phases (Göschen I and Göschen II periods), and peat formation dominance during the Roman Climate Optimum (Burga *et al*., 1997).

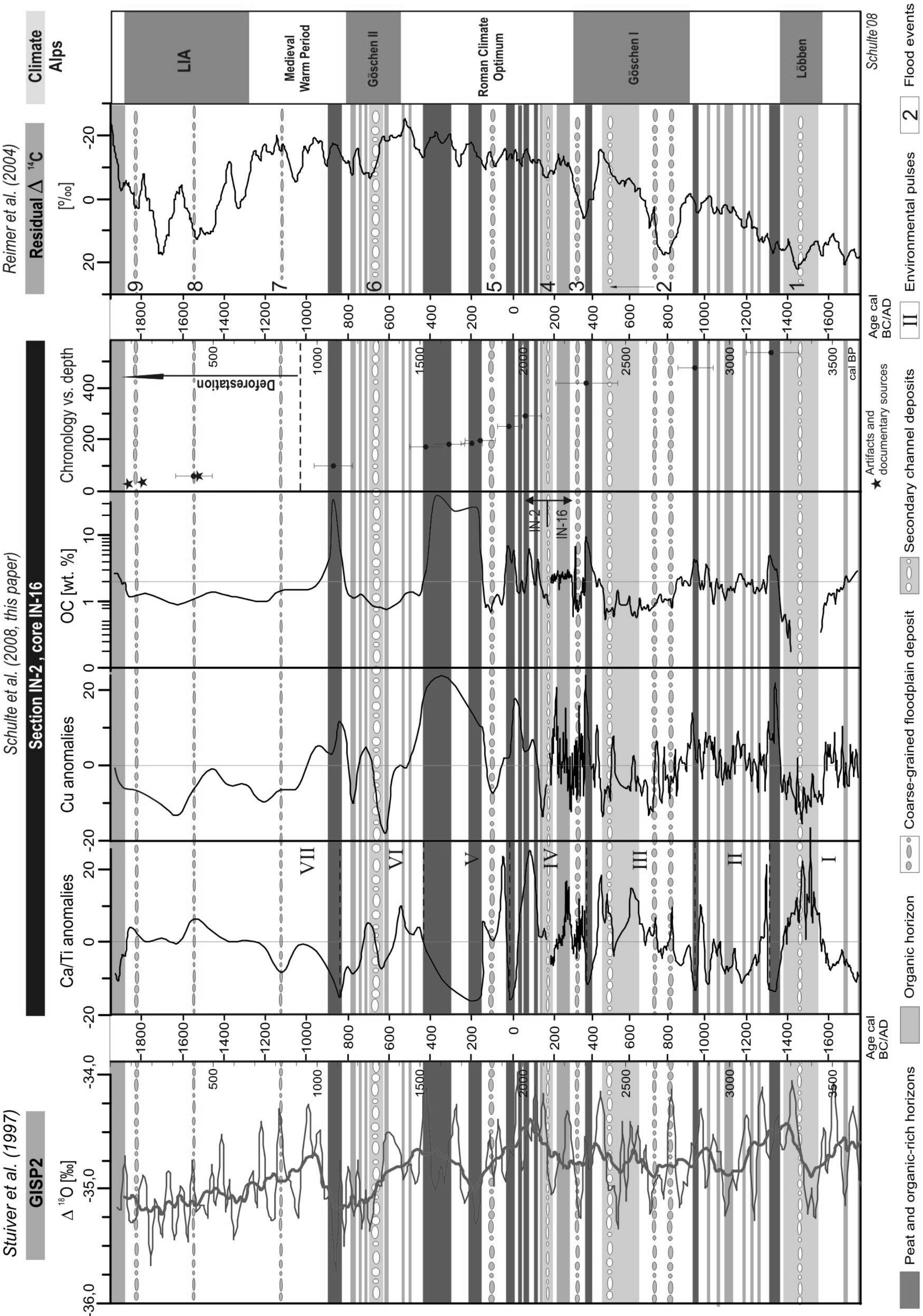


**Fig. 3** Chronostratigraphy of the Lütschine fan delta and comparison between fan delta proxies and global records.

## CONCLUSIONS

The sedimentary record of the Lütschine fan delta shows seven major aggradation pulses between 3600 cal year BP and present. Furthermore, 19 minor burial episodes occur between 3600 and 1050 cal year BP at intervals between 100 and 130 years, suggesting that aggradation during the focused period was triggered by centennial flood events. Nine coarse-grained flood layers, deposited at a recurrence interval of between 200 and 600 years, coincide predominantly with positive radiocarbon anomalies and cold phases in the Alps. We propose the solar influence on regional hydrological regime as the main factor triggering the flooding events. The occurrence of several peaks of Cu content in non-organic sediments suggests intermittent mining activities in the Lütschine catchment since 2300 cal year BP.

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