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► **To cite this version:**

Manon Bajard, Jérôme Poulenard, Pierre Sabatier, Yann Bertrand, Christian Crouzet, et al.. Pastoralism increased vulnerability of a subalpine catchment to flood hazard through changing soil properties. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 2020, 10.17632/j9x7yhev4.1 . hal-02395553

HAL Id: hal-02395553

<https://hal.science/hal-02395553>

Submitted on 7 Mar 2022

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1 **Pastoralism increased vulnerability of a subalpine catchment to flood hazard**
2 **through changing soil properties**

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13

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15 **Abstract**

16 Soil erosion is strongly linked to both precipitation patterns and land-use. We examine the
17 effects of erosion and its drivers (*i.e.* human or/and climate) on soil evolution from the study of
18 lacustrine archives in the northern French Alps. Multi-proxy analyses of the Lake Gers sediment
19 sequence combined with the study of soils and rocks of its catchment allowed to reconstruct its
20 evolution over the past 4.6 kyr. This included ¹⁴C dating, short-lived radionuclides, geochemistry, loss
21 on ignition, grain-size analyses, as well as plant and mammal DNA analyses. A total of 127
22 instantaneous deposits were identified among the continuous sedimentation in the lake and 93 were

23 interpreted as flood deposits. Erosion was quantified for the whole catchment considering both the
24 continuous sedimentation and the flood deposit thicknesses.

25 The catchment is mainly formed by andesitic sandstones over which Andosols and Podzols
26 can develop. However, low weathered materials from colluviation constitute the main input to the
27 lake.

28 Four main phases of changes in soil weathering were recorded by increases in K_2O/TiO_2
29 ratios, associated with an increase in both erosion and flood-frequency. Two phases were associated
30 with climate cooling in the Western Alps, from 2.65 to 2.5 and from 1.45 to 1.3 cal kyr BP. The two
31 others (1.9-1.75 and 0.9-0.4 cal kyr BP) were triggered with deforestation, with cow grazing during
32 the Roman period, and with grazing of cows, sheep and goats during the Medieval period, amplified
33 by the onset of the Little Ice Age. The increase in erosion and flood frequency after 950 cal yr BP
34 indicates substantial damages to soils of the catchment including increase of their erodibility over the
35 last millennia.

36

37 Key-words: lake sediments, pedogenesis, weathering, pastoralism, climate, erodibility.

38

39 1. Introduction

40

41 Erosion is a natural process, commonly occurring in mountain areas due to steep slopes and high
42 precipitation (Verheijen et al., 2009). Torrential flooding transport mechanisms are often studied for
43 flood hazards and for climatic impacts, which are exacerbated by snow melting in spring or intense
44 stormy rainfall in summer and fall (Noren et al., 2002; Wilhelm et al., 2012; Sabatier et al., 2017;
45 Wilhelm et al., 2018). Few studies focus on the long term effects of flood-triggered erosion on soil
46 evolution despite the fact that landscape, that are based on the soil cover, may be threatened by

47 flood events. Soils provide numerous ecosystem services, including supporting, provisioning and
48 regulating services, as food production, regulation of climate disruption by carbon storage and flood
49 mitigation (Daily et al., 1997; MEA, 2005; Adhikari and Hartemink, 2016). The loss of soil thickness is
50 frequently associated to loss of soil properties like structure or organic matter content (Stacy et al.,
51 2015; Wang et al., 2017). This can decrease the potential of water infiltration and storage and favor
52 surface runoff, through Horton overland flow, thus further increasing erosion (Bailey et al., 1934).
53 The loss of soils in upstream mountain catchments induces more direct and rapid concentration of
54 waters and thus can have strong effect on valley flooding, where infrastructures and housing are
55 concentrated. This displacement of soil and sediments can also result in deep hydrological changes in
56 the catchment. The consequences of floods are thus doubled, with the potential mobilization of large
57 amount of soil associated with ecological and economical losses, as well as the transfer of large
58 amount of water downstream, threatening societies. If flooding are necessary triggered by
59 precipitation, their effects on erosion can be increased according to the conditions of the catchment,
60 especially in response to human-induced modifications (Cosandey et al., 2005; Giguët-Covex et al.,
61 2011; Brisset et al., 2017). Therefore, it is necessary to dissociate what is climate or human induced
62 in flood related erosion, and take interest in land use modifications.

63 Both the number and intensity of extreme precipitations and thus, flood events, are expected to
64 increase with the climate warming in several places in the world and especially in mountainous areas
65 (Giorgi et al., 2016). Consequences of the global warming will also affect lands and agriculture
66 systems as highlighted recently by the IPCC Special Report on Climate Change and Land (IPCC, 2019).
67 In this context, it becomes essential to understand how soils can react and be disrupted by flood and
68 land use change to adapt environmental practices and management in the upstream, thereby
69 ensuring safe living accommodation and sustainability of the agro-pastoral practices. Upstream areas
70 are usually neglected in risk prevention plans or adaptation to climate change because they are
71 considered as natural areas and located usually far from human properties values.

72 Paleo-environmental reconstructions from lake sediments offer the opportunities to study at the
73 same time soil evolution, flood-frequency and effect of human activities on long time-scale (Giguet-
74 Covex et al., 2011, 2014; Arnaud et al., 2016; Brisset et al., 2017). Lake sediment archives are useful
75 to reconstruct past flood events, especially in mountainous areas (Noren et al., 2002; Moreno et al.,
76 2008; Wilhelm et al., 2012; Wirth et al., 2013; Sabatier et al., 2017; Fouinat et al., 2017a; Wilhelm et
77 al., 2019). They also can be used to reconstruct past land use and agricultural activities from pollen
78 and non-pollen palynomorph analyses (Doyen and Etienne, 2017) and from plant and mammal DNA
79 (*e.g.*, animal husbandry) (Giguet-Covex et al., 2014; Parducci et al., 2017; Sabatier et al., 2017; Bajard
80 et al., 2017b). Soil evolution is reconstructed from the comparison between the lake archives and the
81 current soils (Ewing and Nater, 2002; Mourier et al., 2008; Giguet-Covex et al., 2011; Bajard et al.,
82 2017b).

83 Here we present a study based on a lake sediment sequence of the Northern French Alps with
84 the objectives to i) identify flood deposits and establish a flood chronicle, ii) understand the soil
85 evolution, applying a source-to-sink approach (*i.e.*, combining catchment samples and lake sediment
86 analyses) and to iii) link soil evolution and flood-frequency with external anthropic and/or climate
87 forcing.

88

89 2. Materials and methods

90 2.1 Study site

91 Lake Gers (46°1'36"N, 6°43'45"E, 1540 m a.s.l.) is located in the Northern French Alps (Fig.
92 1a) on the municipality of Samoëns in the Giffre river Valley. The area of the lake is 0.05 km² and its
93 maximum depth is 5.6 m (Sesiano, 1993). The lake level decreases of 2 m between spring and
94 summer because of loss of water under the lake (Fig. 1b). The lake is fed by a temporary stream that
95 mainly drains the west side of the catchment. The catchment covers an area of 5 km² and rises up to
96 2385 m a.s.l. (Fig. 1c). The lake is of glacial origin and is part of the Giffre river catchment.

97 According to the weather observation network of the alpine massif (ROMMA), the mean
98 temperatures at Arâches-La Frasse, located at 8 km west from Lake Gers at 1120 m and corrected of
99 an altitudinal gradient of $-0.5^{\circ}\text{C}/100\text{ m}$ for Lake Gers altitude, range from -1.2°C in winter to 13.0°C in
100 summer (these values represent averages for 2011-2017). Precipitations are approximately 1500 mm
101 per year. Snow covers the area from December to April, and the lake is ice-covered during winter.
102 Avalanches fall out every winter and early spring, especially from the west side of the lake, and can
103 reach the lake.

104 The bedrock of the catchment is dominated by Taveyannaz sandstones of Eocene-Oligocene
105 ages (Fig. 1c), which are composed by approximately 80 % of volcanic materials associated with a
106 carbonated matrix (Martini, 1966). Within the sandstones, carbonated marly levels can outcrop in
107 some points of the catchment (*e.g.*, GERS3, GERS4).

108 *Picea abies* is the main tree species covering the east side of the lake (Fig. 1c and 1d).
109 Pastured grasslands cover the south edge of the lake and the upstream of the catchment with
110 punctual areas colonized by *Ericaceae* (*Vaccinium myrtillus*, *Vaccinium uliginosum*, *Rhododendron*
111 *ferrugineum*). Alder (*Alnus viridis*) concentrates in the middle of the catchment and in avalanche
112 areas (Figs 1c and 1d).

113 **[insert FIGURE 1]**

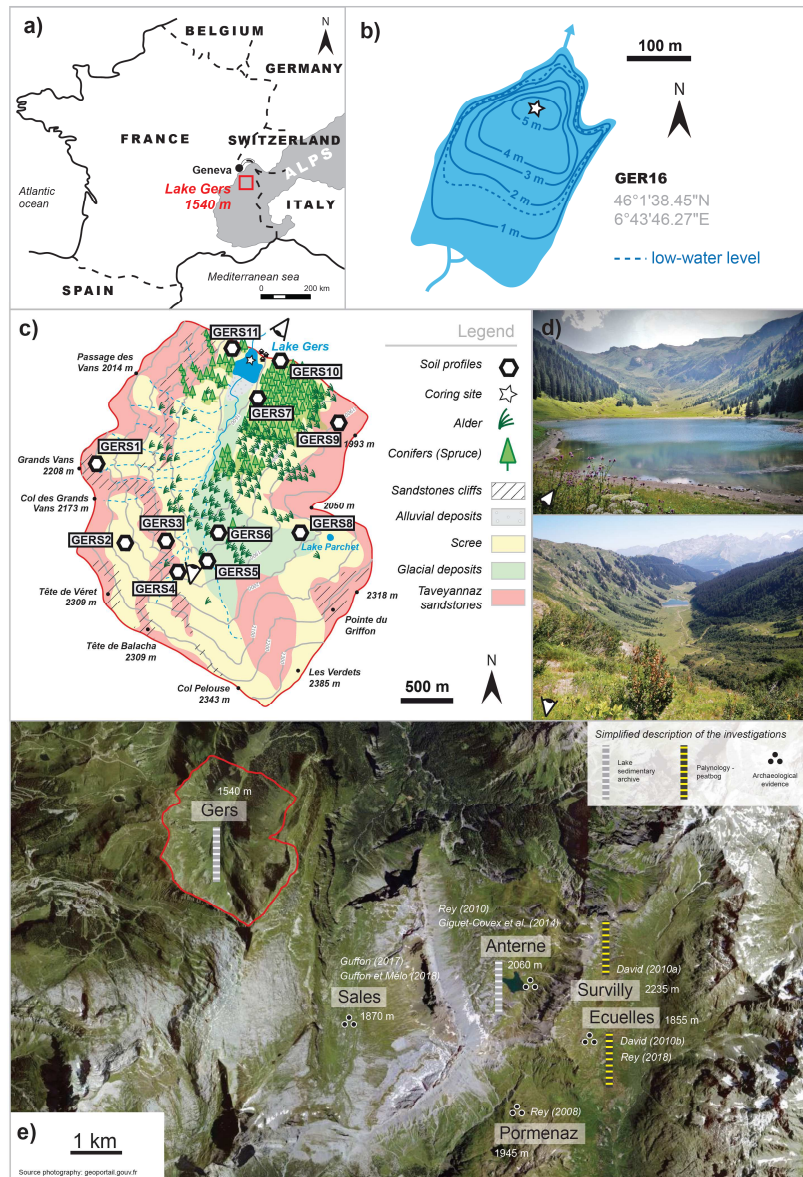


Figure 1. Location of Lake Gers in the Western Alps (a) with the bathymetry of the lake (b) adapted from Sesiano (1993), the simplified geological map of the catchment with the location of the soil profiles (c), the views from the north and south sides of the lake catchment (d) and locations of the nearest sites referenced in the discussion (e).

114

115 2.2 Soil sampling

116 Eleven soil profiles (GERS1 to 11) were realized in Lake Gers catchment to characterize the
 117 major soil types. Soil profiles were described with color, texture, structure and HCl effervescence
 118 test. The FAO (Food and Agriculture Organization) soil classification (WRB - FAO, 2014) and the
 119 Guidelines for soil description (FAO, 2006) were used for horizon and soil denominations. At least
 120 one sample was collected per horizons and sieved to 2 mm for further laboratory analyses. When it
 121 was possible, samples for density estimation were taken with a cylinder. Parent materials from these

122 soils were also collected for geochemical comparison. Soil pH (n=3) were measured for each horizon
123 with a 1:5 soil-water ratio.

124 *2.3 Lake sediment cores*

125 Two coring campaigns were undertaken to retrieve sediments from the deepest part of Lake
126 Gers in winter 2015 and winter 2016. Short gravity cores were taken in 2015 from the ice-covered
127 surface to provide a well-preserved water-sediment interface. Two longer overlapping sections
128 (GER16-I and GER16-II) that are approximately 6 m each in length were retrieved in 2016 (Fig. 1b)
129 using an Uwitec piston coring device. The cores were split into two halves. Each half was described in
130 detail, and pictures were taken with a 20-pixel.mm⁻¹ resolution. The lithological description of the
131 cores allowed the identification of different sedimentary units. A composite profile of 5.8 m (GER16)
132 was built with lithological correlation from a short gravity core (GER15_P3) obtained in 2015 (IGSN
133 code: IEFRA05HV; *IGSN codes refer to an open international database, www.geosamples.org*) and the
134 two sedimentary sections obtained during the 2016 coring. One half of the core was used for non-
135 destructive analysis (*i.e.*, XRF core scanner) and the other half for sampling and performed
136 destructive analysis.

137 *2.4 Analysis performed on both catchment and lake sediment samples*

138 *2.4.1 Loss on ignition*

139 Loss on ignition (LOI) analysis was performed on both the soil samples and sediments, every
140 2 cm all along the sediment sequence to estimate the organic matter (OM) and carbonate contents
141 following the procedure described in Heiri et al. (2001). A measure of density was also realized every
142 2 cm on the sediment core, by sampling and weighting known volume of sediment before the LOI
143 measures.

144 *2.4.2 P-XRF mineral geochemistry*

145 A portable ED-XRF spectrometer (S1 TITAN Bruker) was used on soils, rocks and lake
146 sediments to have a quantitative and comparative measurement of major elements, which were

147 expressed as relative percentages of oxides. Analysis of gently crushed soil and sediment and crushed
148 rocks samples was performed through a 4- μ m-thick Ultralene film in a 32-mm-diameter plastic cup.
149 The samples were triplicated and analyzed over 60 s using the GeoChem Standard instrument's
150 internal calibration mode (Shand and Wendler, 2014). The standard deviations of the replicates were
151 lower than the instrument errors, which were thus conserved as measurement uncertainties. The
152 total contents of Si, Fe Al and Mn were estimated from SiO₂, Fe₂O₃, Al₂O₃ and MnO contents,
153 respectively. Principal component analysis (PCA) was performed on the P-XRF geochemical data from
154 rock and soil samples in order to identify similar rock samples and associated similar soil processes.
155 Analyses were performed using R 2.13.1 (R Development Core Team, 2011).

156 *2.5 Analysis performed only on lake sediments*

157 *2.5.1 XRF Core Scanner*

158 The relative contents of chemical elements were analyzed by X-ray fluorescence (XRF) at high
159 resolution (2 mm sampling step) on the surface of the sediment core with an Avaatech core scanner
160 (EDYTEM Laboratory, CNRS-Université Savoie Mont-Blanc). The core surface was first covered with a
161 4- μ m-thick Ultralene film to avoid contamination and desiccation of the sediment. The element
162 intensities were expressed in counts per second (cps). Geochemical data were obtained with
163 different settings according to the elements analyzed. These settings were adjusted to 10 kV and 1.5
164 mA for 10 s to detect Si, Ca, Al, Fe, Ti, K, Mn, and S. For heavier elements (*i.e.* Sr, Rb, Zr, Br, and Pb),
165 measurements were performed at 30 kV and 1.0 mA for 40 s.

166 *2.5.2 Sedimentary environmental DNA (sedDNA)*

167 To reconstruct the past vegetation dynamic and the nature of herds (*i.e.*, cows, sheep and
168 goats) by DNA analysis, we sampled 35 slices of 1 to 2-cm thickness covering the whole sediment
169 core, following the strict laboratory precautions described in Giguet-Covex et al. (2014). Extracellular
170 DNA was extracted from the sediment, amplified within 8 PCR replicates and sequenced as described
171 in supplementary materials. The sequence analyses were performed using the Obitools software

172 (<https://git.metabarcoding.org/obitools/obitools/wikis/home>) (Boyer et al., 2016). For mammals, we
173 only kept sequences with a match >97 % with the sequences in the reference database and removed
174 all the sequences assigned to hominidae. Results are given in number of positive PCR replicates. For
175 plants, we only considered sequences with a match >95 % with the sequences in the reference
176 database. Then, several filtering steps were applied to remove the potential contaminants (see
177 supplementary materials for more details). The contribution of each taxon and then of vegetation
178 types were obtained by doing the sum of the number of reads from each replicate and for each
179 taxon. Then, we log-transformed these numbers ($\log(N \text{ reads} + 1)$) to correct from the exponential
180 increase of DNA sequences during the PCR amplification. We calculated the taxon contribution from
181 these log-transformed read numbers.

182

183 *2.5.3 Chronology*

184 The chronology of the sediment sequence is based on ten ^{14}C measurements performed on
185 terrestrial plant macroremains, as well as on short-lived radionuclide measurements (^{210}Pb and ^{137}Cs).
186 AMS (accelerator mass spectrometer) radiocarbon dates were performed by the Poznan Radiocarbon
187 Laboratory and the Laboratoire de Mesure ^{14}C (LMC14) ARTEMIS at the CEA (Atomic Energy
188 Commission) Institute of Saclay. The ^{14}C ages were calibrated using the IntCal13 calibration curve
189 (Reimer et al., 2013). Short-lived radionuclides were used to date the most recent sediments. They
190 were measured on the upper 24 cm of GER15_P3 gravity core at the Modane Underground
191 Laboratory (LSM). Measurements were performed by gamma spectrometry, using high-efficiency,
192 very low-background, well-type Ge detectors (Reyss et al., 1995). ^{137}Cs was first introduced in the
193 environment at the end of the 1950s as by-product of atmospheric nuclear weapons tests (maximum
194 peak at AD 1963 in the Northern Hemisphere). The Chernobyl accident in 1986 also dispersed ^{137}Cs
195 into the Northern Hemisphere (Appleby et al., 1991). ^{210}Pb excess activities ($^{210}\text{Pb}_{\text{ex}}$) are calculated in
196 the sediment as the difference between total ^{210}Pb (mixing of erosion and atmospheric deposits) and

197 ^{226}Ra activities at each levels (Goldberg, 1963). Then, we used the Constant Flux/Constant
198 Sedimentation (CFCS) model and the decay of $^{210}\text{Pb}_{\text{ex}}$ to calculate the mean sedimentation rates. The
199 uncertainty of sedimentation rates obtained with this method is derived from the standard error of
200 the linear regression of the CFCS model. The age–depth model for the entire sequence associating
201 short-lived radionuclides and ^{14}C was then generated using R software and the R code package ‘Clam’
202 version 2.2 (Blaauw, 2010).

203 *2.5.4 Estimating erosion*

204 The erosion was estimated from the lake filling considering the volume of each layer of sediment
205 in the lake, their dry densities, their corresponding sedimentation rate and the surface of the
206 catchment (5 km²), following the method described in Bajard et al. (2017). We estimated the volume
207 from the surface corresponding to the current higher lake level of the lake (0.05 km²) and the depths
208 in the core, assuming the sediment is equally distributed on the entire surface area of the lake
209 (Enters et al., 2008). The approximations made on the calculation of the volume are expected to
210 overestimate the accumulated mass of sediment, because of the higher accumulation in the deepest
211 part of the lake, where the core was taken. However, the progradation of the delta should cause the
212 opposite effect and reduce the overestimation. The mass of sediment was then calculated for each
213 sampled depth, using the dry density. Only the non-carbonate terrigenous mass of the sediments
214 was considered, using the Non-Carbonate Ignition Residue (NCIR) of the LOI. The terrigenous masses
215 of each depth were then integrated according to the time, using the age-depth model, and divided by
216 the surface of the catchment to estimate the erosion rate per unit area.

217

218 3. Results

219

220 **3.1 Identification and formation of soils of the catchment**

221 Three main types of pedogenetic processes, *i.e.*, andosolization, podzolization and
222 colluviation were identified in the catchment of lake Gers (Fig. 2 and Table 1). A complete description
223 of the soils is presented in supplement material.

224 Cambisols (GERS1, GERS2, GERS11 and GERS5) present mainly a succession of different
225 brown horizons. They are characterized by low pH increasing with depth and decreasing OM content
226 (Fig. 2 and Table 1). Andosols as GERS8 present a darker color due to high OM content throughout
227 the profile and their pH is low (Fig. 2). They develop on Taveyannaz sandstones which are made of 80
228 % of volcanic materials (Martini, 1966) that make possible the andosolization in this area. They also
229 displays the lowest K_2O/TiO_2 ratio (Table1). Podzols as GERS6, GERS7, GERS9 and GERS10 are
230 characterized by low pH and decreasing OM content in the profile. Colluviation is characterized by
231 lots of coarse elements, higher pH and low OM contents (GERS3, GERS4 and GERS11 in Fig. 2). These
232 soils also display the highest K_2O/TiO_2 ratios (Table1).

233

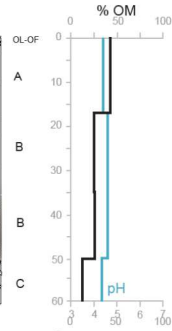
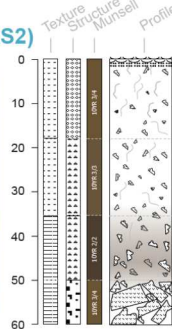
234 **[insert FIGURE 2]**

ANDOSOLIZATION

Andic Cambisols (GERS1 and GERS2)

GERS2

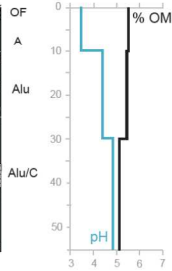
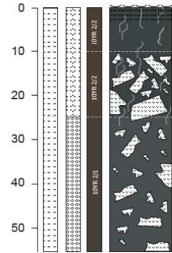
46° 0'43,60"N
6°43'1,50"E
2085 m
Vaccinium



Andosols

GERS8

46° 0'0'46,1" N
6°44'7,7" E
2016 m
Vaccinium

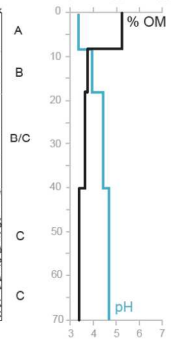
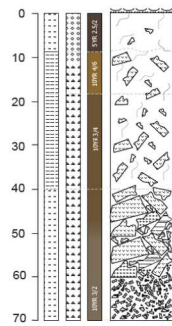
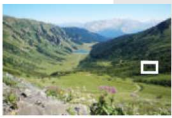


PODZOLIZATION

Cambisols (GERS5) to Entic Podzols (GERS6, GERS7, GERS10)

GERS6

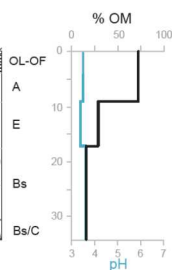
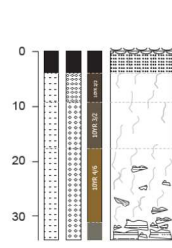
46° 0'45,00"N
6°43'35,40"E
1880 m
Alder



Podzols

GERS9

46° 1'16,20"N
6°44'23,20"E
1990 m
Matgrass

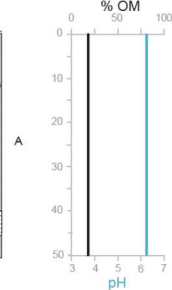
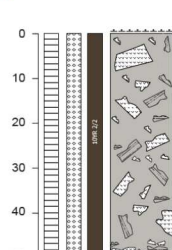


COLLUVIATION

Colluvic Regosols (GERS3, GERS4) and Colluvic Cambisols (GERS11)

GERS11

46° 1'40,60"N
6°44'39,80"E
1573 m



Legend

Texture

- Silty Loam
- Clay Loam
- Silty Clay

Structure

- Lumpy
- Subangular blocky
- Blocky
- Smeary

Artefacts

Coarse elements

- Taveyannaz sandstone with decarbonation halo
- Marly carbonated facies within Taveyannaz sandstone

Roots : fine, medium, coarse

235

236 [insert TABLE 1]

237

238 **TABLE 1. Soil horizon analyses**

| Sample | Top depth (cm) | Bottom depth (cm) | Horizon | pH _{water} | Bulk density | OM % (LOI 550°C) | Al ₂ O ₃ % | SiO ₂ % | K ₂ O % | CaO % | TiO ₂ % | MnO % | Fe ₂ O ₃ % | Zr % | Total % | K ₂ O/TiO ₂ | |
|--------------|----------------|-------------------|---------|---------------------|--------------|------------------|----------------------------------|--------------------|--------------------|-------|--------------------|-------|----------------------------------|-------|---------|-----------------------------------|-----|
| GERS1 | | | | | | | | | | | | | | | | | |
| GERS 1-1 | 1-1 | 0 | 17 | A | 4.0 | 0.5 | 57.0 | 7.62 | 23.85 | 1.07 | 0.62 | 1.03 | 0.08 | 7.75 | 0.03 | 99.1 | 1.0 |
| GERS 1-2 | 1-2 | 17 | 45 | B | 4.2 | - | 26.2 | 18.31 | 38.39 | 1.79 | 1.18 | 1.49 | 0.15 | 11.29 | 0.04 | 98.9 | 1.2 |
| GERS 1-3 | 1-3 | 45 | 65+ | C | 5.0 | - | 7.8 | 19.65 | 57.04 | 2.28 | 2.31 | 1.12 | 0.10 | 9.10 | 0.04 | 99.5 | 2.0 |
| GERS2 | | | | | | | | | | | | | | | | | |
| GERS 2-1 | 2-1 | 0 | 17 | A | 4.4 | - | 43.3 | 10.71 | 32.34 | 1.31 | 0.80 | 1.10 | 0.17 | 9.44 | 0.04 | 99.2 | 1.2 |
| GERS 2-2 | 2-2 | 17 | 35 | B | 4.6 | - | 25.1 | 16.51 | 41.95 | 1.65 | 1.20 | 1.36 | 0.22 | 11.15 | 0.04 | 99.2 | 1.2 |
| GERS 2-3 | 2-3 | 35 | 50 | B | 4.6 | - | 25.8 | 20.44 | 38.27 | 1.71 | 1.86 | 1.18 | 0.13 | 9.77 | 0.05 | 99.2 | 1.5 |
| GERS 2-4 | 2-4 | 50 | 60+ | C | 4.3 | - | 13.0 | 22.03 | 48.87 | 2.26 | 3.00 | 1.08 | 0.10 | 9.19 | 0.04 | 99.6 | 2.1 |
| GERS4 | | | | | | | | | | | | | | | | | |
| GERS 4-1 | 4-1 | 0 | 20 | A/C | 6.1 | - | 17.1 | 15.54 | 50.99 | 3.12 | 2.58 | 0.84 | 0.18 | 8.01 | 0.03 | 98.4 | 3.7 |
| GERS 4-2 | 4-2 | 0 | 10 | A/C | 6.7 | - | 11.9 | 16.57 | 53.78 | 3.44 | 2.57 | 0.88 | 0.20 | 8.45 | 0.04 | 97.8 | 3.9 |
| GERS5 | | | | | | | | | | | | | | | | | |
| GERS 5-1 | 5-1 | 0 | 15 | A | 4.1 | 0.8 | 28.0 | 13.55 | 45.46 | 2.42 | 0.55 | 1.01 | 0.09 | 8.11 | 0.04 | 99.3 | 2.4 |
| GERS 5-2 | 5-2 | 15 | 45+ | B/C | 4.5 | - | 13.8 | 18.15 | 52.02 | 2.93 | 0.72 | 1.14 | 0.12 | 9.00 | 0.04 | 98.0 | 2.6 |
| GERS6 | | | | | | | | | | | | | | | | | |
| GERS 6-1 | 6-1 | 0 | 8 | A | 3.3 | - | 55.7 | 5.99 | 29.17 | 1.21 | 0.60 | 0.90 | 0.03 | 5.64 | 0.05 | 99.3 | 1.3 |
| GERS 6-2 | 6-2 | 8 | 18 | B | 3.9 | - | 18.5 | 15.19 | 51.45 | 2.34 | 0.19 | 1.37 | 0.14 | 10.32 | 0.06 | 99.6 | 1.7 |
| GERS 6-3 | 6-3 | 18 | 40 | B/C | 4.4 | - | 16.0 | 15.19 | 51.48 | 3.15 | 0.13 | 1.67 | 0.24 | 11.76 | 0.09 | 99.8 | 1.9 |
| GERS 6-4 | 6-4 | 40 | 70+ | C | 4.7 | - | 9.5 | 21.86 | 53.26 | 3.15 | 0.66 | 1.06 | 0.14 | 8.63 | 0.04 | 98.3 | 3.0 |
| GERS7 | | | | | | | | | | | | | | | | | |
| GERS 7-1 | 7-1 | 0 | 5 | OH | 3.3 | - | 87.2 | 0.00 | 7.60 | 0.18 | 2.48 | 0.38 | 0.00 | 1.87 | 0.02 | 99.7 | 0.5 |
| GERS 7-2 | 7-2 | 5 | 10 | A | 3.5 | - | 25.8 | 12.03 | 46.73 | 1.76 | 0.85 | 1.27 | 0.07 | 11.13 | 0.04 | 99.6 | 1.4 |
| GERS 7-3 | 7-3 | 10 | 25 | B | 3.8 | - | 18.8 | 17.54 | 46.53 | 2.00 | 0.97 | 1.35 | 0.13 | 10.35 | 0.05 | 97.7 | 1.5 |
| GERS 7-4 | 7-4 | 25 | 50+ | C | 4.3 | - | 15.3 | 18.17 | 51.31 | 2.11 | 1.05 | 1.23 | 0.15 | 10.06 | 0.04 | 99.5 | 1.7 |
| GERS8 | | | | | | | | | | | | | | | | | |
| GERS 8-1 | 8-1 | 3 | 10 | A | 3.5 | 0.3 | 62.5 | 4.91 | 21.73 | 0.76 | 0.80 | 1.28 | 0.02 | 7.43 | 0.04 | 99.5 | 0.6 |
| GERS 8-2 | 8-2 | 10 | 30 | Alu | 4.4 | - | 60.1 | 10.23 | 13.82 | 0.57 | 0.72 | 1.03 | 0.10 | 12.56 | 0.03 | 99.2 | 0.6 |
| GERS 8-3 | 8-3 | 30 | 55+ | Alu/C | 4.9 | 0.4 | 52.5 | 13.57 | 18.34 | 0.66 | 1.10 | 0.98 | 0.18 | 11.64 | 0.03 | 99.0 | 0.7 |
| GERS9 | | | | | | | | | | | | | | | | | |
| GERS 9-1 | 9-1 | 4 | 9 | A | 3.5 | - | 72.2 | 3.40 | 18.91 | 0.89 | 0.38 | 0.51 | 0.02 | 2.78 | 0.04 | 99.1 | 1.7 |
| GERS 9-2 | 9-2 | 9 | 17 | E | 3.4 | 0.6 | 28.5 | 10.22 | 50.51 | 2.19 | 0.07 | 1.27 | 0.02 | 5.60 | 0.07 | 98.5 | 1.7 |
| GERS 9-3 | 9-3 | 17 | 31 | Bs | 3.6 | 0.7 | 16.0 | 16.47 | 51.66 | 2.99 | 0.13 | 1.04 | 0.06 | 8.89 | 0.03 | 97.3 | 2.9 |
| GERS 11 | GERS11 | 0 | 50+ | A | 6.2 | - | 19.7 | 12.65 | 51.42 | 3.01 | 4.39 | 0.86 | 0.13 | 7.38 | 0.04 | 99.6 | 3.5 |

239

240 The PCA performed on the geochemistry of both the rocks and soils samples allowed to
 241 better understand the soil formation and identify different geochemical sediment sources (Fig. 3).

242 Dimensions 1 and 2 (denoted as *Dim 1* and *Dim 2*) of the PCA from the geochemical data of
 243 the parent materials represent 75.6 % of the total variability (Fig. 3a). Three end members were
 244 identified on the correlation circle. The first one includes TiO₂ as well as Fe₂O₃ and SiO₂ and is
 245 positively correlated with the first dimension of the PCA. It concerns rocks from GERS1, GERS2 and
 246 GERS8 (Fig. 3a). Al₂O₃ forms a single end member, positively correlated with the second component
 247 of the PCA. This second end member contains the parent materials of GERS5, GERS6 and GERS9. The
 248 third one is negatively correlated with both components and give positive loading between K₂O and
 249 CaO. This third end member contains the rocks sample of GERS3 and GERS4. Parent materials of
 250 GERS11 is located between these three end-members (Fig. 3a).

251 The PCA performed with soil samples includes the same geochemical elements than the rock
 252 sample PCA (SiO_2 , Al_2O_3 , TiO_2 , Fe_2O_3 , CaO) and the OM content (Fig. 3b). Dimensions 1 and 2
 253 represent 78 % of the total variability of this dataset. Dimension 1 gives positive loading to Fe_2O_3 and
 254 negative loadings to K_2O . TiO_2 and the OM content are correlated to both dimensions. Dimension 2
 255 (Dim 2) gives negative loading to Al_2O_3 and CaO but CaO is poorly representative in the soil dataset
 256 (Fig. 3b). SiO_2 is positively correlated to Dim 2 and negatively to Dim 1. Surface horizons are
 257 associated with OM direction and conversely, the deepest horizons are anticorrelated to OM.
 258 Samples from GERS9, GERS6 and GERS5 are mainly associated with Dim 2 and form a “Podzolic”
 259 endmember. GERS4 and GERS11 are anticorrelated to Dim 1 and closely associated to K_2O (Fig. 3b).
 260 They form an end-member of low weathered soils, with the deepest horizons of other soils. GERS1,
 261 GERS2 and GERS8 appear to be mainly associated to Fe_2O_3 and Al_2O_3 and form an “Andic”
 262 endmember. GERS7 is in the center of the PCA.

263 [insert FIGURE 3]

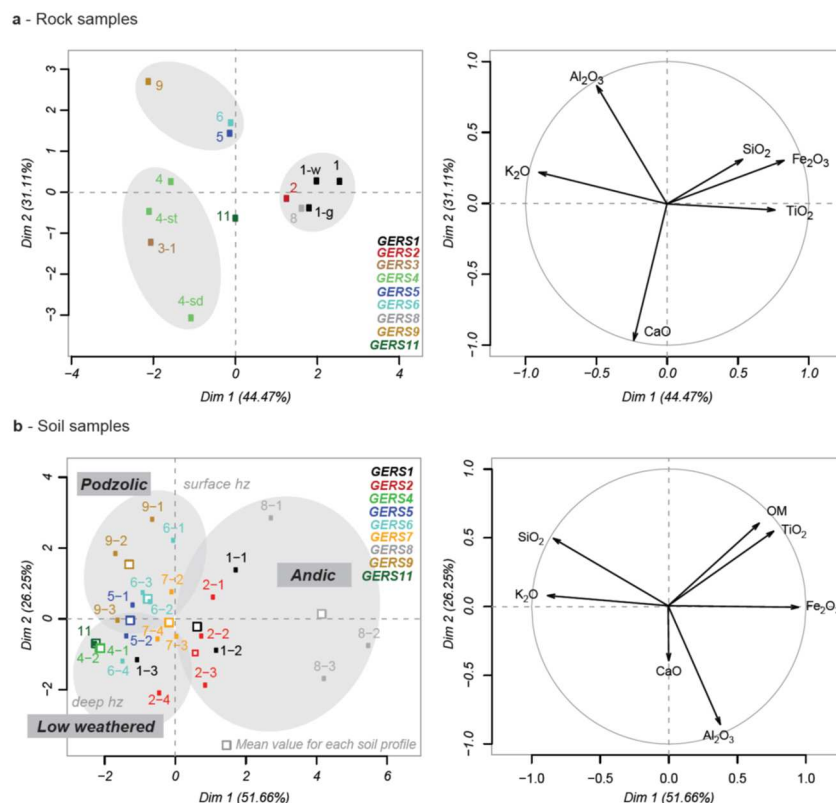


Figure 3. Biplots of dimensions 1 and 2 and correlation circles of the principal component analysis realized with the rock-parent material of soils (a) and with the soil horizon samples (b).

264

265 3.2 Core description and lithology

266 The continuous sedimentation of the 5.8 m of the sequence consists mainly of dark medium
267 silts, with a higher variability between 3 and 1.25 m. The organic matter content is 11 % in average
268 and the carbonate content is 3 % in average.

269 The sedimentary sequence is interrupted by 127 individual layers that are interpreted as
270 short-term depositional events according to Sturm and Matter (1978) and Arnaud et al. (2002). 93 of
271 these deposits are darker graded beds with a coarse and no erosive base and present thicknesses
272 ranging from the millimeter to the dozens of centimeters. The thickest deposits occur at 5.20 m (12
273 cm), 3.90 m (9.5 cm), 3.02 m, (13.5 cm), 1.73 m (6.5 cm) and 1.31 m (11 cm). Between 1.80 and 2.00
274 m, deposits are thinner and more numerous (approximately 30 between 2 and 8 mm of thickness).

275 The 34 other deposits are very fine sand layers from less than 1 mm to 5 mm, located only in
276 the bottom part of the core, between 4.8 and 5.8 m.

277 A more complete description of the sediment analyses according to depth is presented in the
278 supplementary materials.

279 3.3 Age-depth model and instantaneous deposits

280 3.3.1 Short-lived radionuclides

281 The measurement of short-lived radionuclides allowed the dating of the uppermost 16 cm of
282 the core. A logarithmic plot of $^{210}\text{Pb}_{\text{ex}}$ activity (Fig. 4a) shows a downward decrease from the surface.
283 The three deepest points measured were rejected because of their distance from the main
284 logarithmic trend (reach the secular equilibrium). In the same way, the $^{210}\text{Pb}_{\text{ex}}$ measures realized in
285 the 9.6-12.5 cm and 12.5-15.5 cm deposits present lower activities and were excluded from the
286 construction of an event-free sedimentary record because they were considered as instantaneous
287 deposits (Arnaud et al., 2002). The depth-corrected plot of $^{210}\text{Pb}_{\text{ex}}$ activities (*i.e.* depth without
288 instantaneous events) shows two logarithmic relationships providing two mean sedimentation rates:
289 $2.9 \pm 0.5 \text{ mm.yr}^{-1}$ above 5 cm and $1.3 \pm 0.2 \text{ mm.yr}^{-1}$ below. Ages were then calculated using the

290 'constant flux, constant sedimentation rate' (CFCS) model (Goldberg, 1963; Krishnaswamy et al.,
 291 1971) applied to the original sediment depth to provide a continuous age-depth relationship.

292 The ¹³⁷Cs activity profile (Fig. 4a) has a peak beginning at a depth of 16.5 ± 0.25 cm and
 293 reaches a maximum at 13.5 ± 0.25 cm, interpreted respectively as the beginning of atmospheric
 294 production of ¹³⁷Cs, in AD 1955 due to nuclear weapon test in the Northern Hemisphere and its
 295 maximum fallout in AD 1963 (Robbins and Edgington, 1975). The good agreement between the ages
 296 of the beginning and maximum artificial radionuclide fallout inferred from the ²¹⁰Pbex-CFCS model
 297 (1952 and 1965) and their known ages (1955 and 1963) supports the validity and the accuracy of our
 298 age-depth model in the upper 16 cm of the sediment sequence.

299 *3.3.2 Radiocarbon dating*

300 A total of 10 radiocarbon analyses were performed on selected macrofossils collected from
 301 the 5.8-m length of the sediment core (Table 2). These data and those from the short-lived
 302 radionuclides measurements were incorporated into Clam to generate the age–depth model of the
 303 whole core (Fig. 4b). SacA42472 sample appear too old. It was taken only a few millimeters from an
 304 instantaneous deposit. Macrofossils had thus probably been reworked, explaining the age obtained.
 305 In consequence, this radiocarbon date was not considered for age–depth modeling. Nevertheless, its
 306 high uncertainty, due to its young age, stays in the smooth model computed (Fig. 4b).

307 **[insert TABLE 2]**

Table 2. Radiocarbon ages for Lake Gers sediment sequence

| Sample name | Lab. Code | Depth (mm) | Sample type | Age (yr BP) | Min. age (cal yr BP) | Max. age (cal yr BP) |
|-------------|------------------|------------|---------------------|-----------------|----------------------|----------------------|
| GER1 | SacA42472 | 465 | Herbs, seeds | 315 ± 30 | 303 | 463 |
| GER2 | SacA42473 | 1155 | Herbs | 620 ± 30 | 552 | 657 |
| GER3 | SacA42474 | 2180 | Bark, herbs | 1125 ± 30 | 960 | 1172 |

| | | | | | | |
|---------|-----------|------|----------------------------|-----------|------|------|
| GER16-1 | Poz-81888 | 2395 | Herbs, moss, twigs | 1345 ± 30 | 1186 | 1308 |
| GER16-2 | Poz-81889 | 2862 | Bark, twigs | 1885 ± 30 | 1733 | 1888 |
| GER16-3 | Poz-81890 | 3347 | Wood, bark | 2145 ± 30 | 2009 | 2303 |
| GER16-4 | Poz-81891 | 3911 | Wood, bark | 2475 ± 30 | 2382 | 2719 |
| GER16-5 | Poz-81892 | 4576 | Bark | 3270 ± 30 | 3411 | 3570 |
| GER16-6 | Poz-81894 | 5206 | Twigs, herbs, bark, leaves | 3830 ± 35 | 4100 | 4405 |
| GER16-7 | Poz-81895 | 5706 | Herbs ,twigs, bark | 4020 ± 35 | 4418 | 4570 |

Bold samples correspond to excluded dates from age-depth modeling.

308

309 The 127 deposits interpreted as instantaneous events represent a total of 163 cm that were
310 removed from the main continuous sedimentation. The remaining 4.2 m of sediment were used to
311 build an event-free sedimentary record (Bøe et al., 2006; Wilhelm et al., 2012). We then calculated
312 an age-depth relationship by a smooth spline interpolation (Fig. 4c). This age-depth model was used
313 to date all instantaneous deposits.

314 **[insert FIGURE 4 – Age model]**

315 The 5.8 m of sedimentary sequence cover the last 4.6 kyr. The sedimentation varies from 0.5
316 to 2 mm.yr⁻¹ with maxima between 4.6 and 4.3 cal kyr BP (1.2 mm.yr⁻¹), 2.5 and 1.9 cal kyr BP (1
317 mm.yr⁻¹), 900 and 500 cal yr BP (1.7 mm.yr⁻¹) and over the last century (2 mm.yr⁻¹).

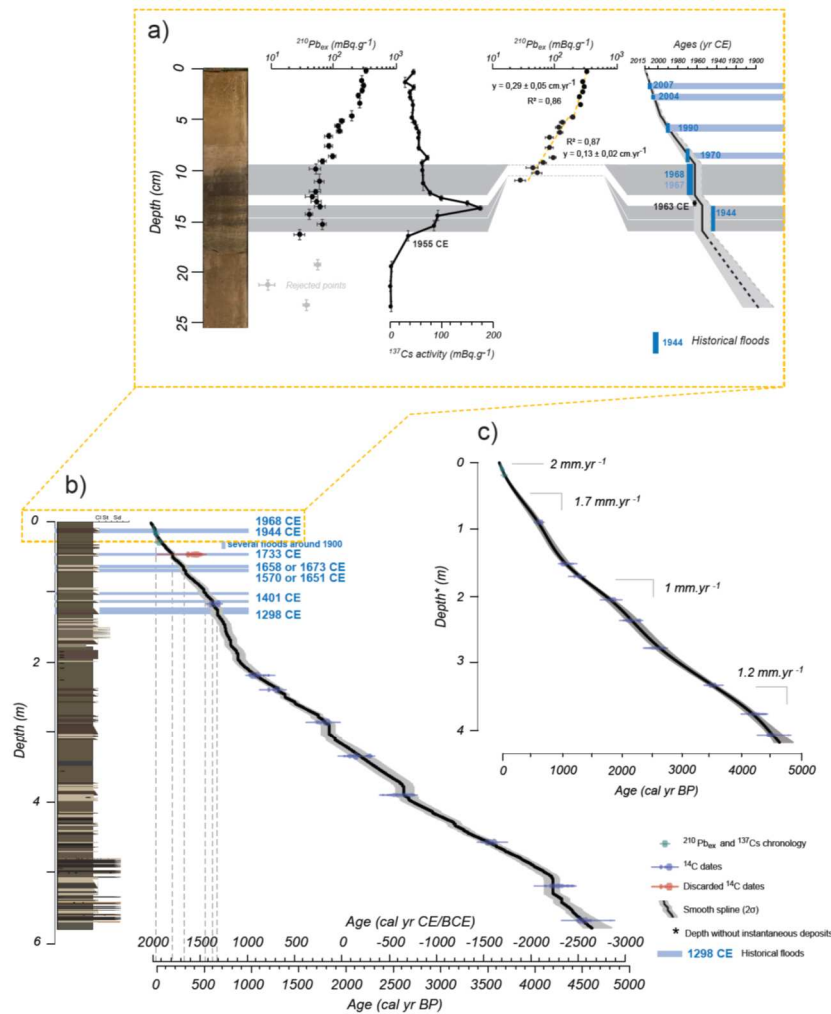


Figure 4. Age-depth model of Lake Gers sediment sequence including ^{210}Pb / ^{137}Cs chronology (a) and ^{14}C ages (b). Uncertainties are included in the ^{137}Cs activity dots. (c) corresponds to the continuous age-depth model, without instantaneous deposits. Historical floods were collected from Mougín (1914) for the Giffre valley, from RTM online database (<http://rtm-onf.ifn.fr>) and from municipal documents. CE= Common Era, BCE= Before Common Era.

318

319 3.4 Sedimentary DNA

320 DNA analysis were performed only in the continuous sedimentation to avoid possible
 321 taphonomic biases especially due to grain-size effects that might occurred in instantaneous deposits.
 322 Extracellular DNA is expected to be more concentrated in the clayey part than in the sandy/coarse
 323 silts part of the flood deposit (Giguët-covex et al., 2019).

324 The DNA of six mammalian taxa was detected in the sediments of Lake Gers, specifically *Bos*
 325 sp. (cattle), *Canis* sp. (dog/wolf), *Capra* sp. (goat), *Felis* sp. (cat), *Ovis* sp. (sheep) and *Sus* sp. (pig). We
 326 only focus on the three taxa associated with grazing activities: *Bos* sp. *Ovis* sp. and *Capra* sp. (Fig. 5a).
 327 *Bos* sp. was detected in two samples at 2000 and 1750 cal yr BP, but in only one replicate over eight.
 328 It was then recorded in all samples younger than 850 cal yr BP, except in the youngest sample. The

329 highest number of positive PCR replicates was measured at 850, 700 and 400 cal yr BP (3, 6 and 4
330 positive PCR replicates over 8, respectively, Figure 5a). *Ovis* DNA was detected in the two samples
331 between 850 and 800 cal yr BP (4 and 5 positive replicates over 8) and in the two samples between
332 700 and 550 cal yr BP (2 and 1 replicates). *Capra* DNA was detected in two samples between 850 and
333 750 cal yr BP in 1 or 2 PCR replicates and in the two samples between 400 and 200 cal yr BP in 1 PCR
334 replicates each (Fig. 5a).

335 For the plants, after the filtering steps, 99 taxa (MOTU) were obtained and classified
336 according to the vegetation stratification and types (*i.e.*, tree layer, shrub layer, herbaceous layer,
337 moss and ferns). We only present in Figure 5b the tree layer which includes *Prunus*, *Maleae*,
338 *Aquifoliaceae*, *Betulaceae*, *Populus*, *Picea*, *Pinaceae*, *Ulmaceae*, *Alnus* and *Acer*. The sample at 4.2 cal
339 kyr BP was removed from our analysis because it contained only 2 taxa detected in 1 or 2 replicates
340 (*Apioidaeae* and *Polytrichaceae*) any tree sequence, whereas all the other samples older than 1.9 cal
341 kyr BP contain between 15 and 56 % of tree DNA sequences (32 % in average).

342 From 4.6 to 1.9 cal kyr BP, the DNA of trees represents 31,5% in average, and 13,5% from 1.9
343 to the present day (Fig. 5b). During this last period we identified a period of higher tree DNA
344 between 1300 and 900 cal yr BP with 25% in average. The complete sedDNA study combined with
345 pollen analysis of the Lake Gers sediment sequence has been presented by Blanchet et al. (2019) and
346 is subject of a publication in preparation.

347

348 **[insert FIGURE 5 – Evolution of landscape]**

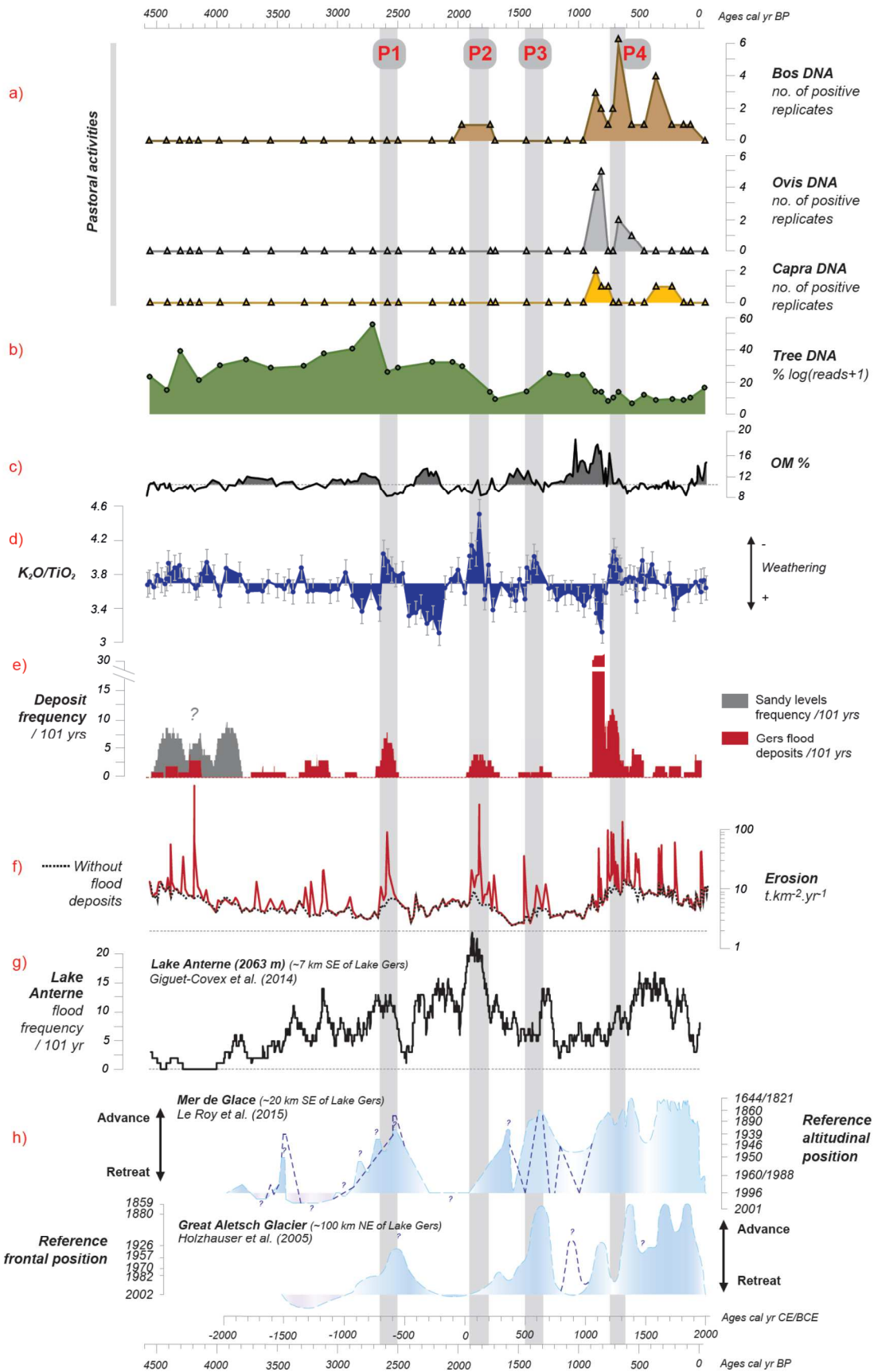


Figure 5. Evolution of agro-pastoral activities, vegetation and erosion in the Lake Gers catchment during the late Holocene as inferred from mammal DNA, including DNA of cow, sheep and goat (a), tree DNA (b), organic matter (OM) content (c), K_2O/TiO_2 ratio (d) measured in the continuous sedimentation, the centennial deposit frequency in Lake Gers (e), erosion in Lake Gers catchment (f), compared to Lake Anterne centennial flood frequency (g) and regional glacier records (h) from Le Roy et al. (2015) and Holzhauser et al. (2005) as climate proxys.

350 4. Discussion

351 4.1 Source-to-sink dynamics

352 4.1.1 Pedological origin

353 PCA for geochemical data from the parent materials (Fig. 3a) highlighted heterogeneity in the
354 geochemistry of Taveyannaz sandstones, especially between the real sandstones characterized by a
355 weathering carbonated aureole found in GERS1, GERS2 and GERS8 and the alternating layer of thick
356 sand and marly levels (GERS3, GERS4). Marly levels were found at lower altitudes than the
357 Taveyannaz sandstones of GERS1, GERS2 and GERS8 (Fig. 1). Considering its colluvial position,
358 GERS11 can be feed by both facies (Fig. 1 and 2). The third main parent material can be associated to
359 glacial deposits in the center (GERS5 and GERS6) and upper part (GERS9) of the catchment (Fig. 1 and
360 2). PCA from the soil samples defined the same groups as the rock sample PCA, with a distinction for
361 surface and deep horizons. This scheme reflects a strong relation between parent material and soil
362 evolution processes in this catchment. GERS1, GERS2 and GERS8 are affected by andic properties,
363 GERS9, GERS5 GERS6, GERS7 by podzolization and GERS3, GERS4 and GERS11 are low developed and
364 affected by erosion and colluviation. The development of Andosols is rare in the Alps and no
365 Andosols has been described in the French Alps to our knowledge. Their development is possible
366 here from the weathering of Taveyannaz Sandstones which formed from sedimentary deposition of
367 old eroded volcanic complex.

368 The less weathered soils of Gers catchment, and the deepest soil horizons present high
369 K_2O/TiO_2 ratios (Table 1). In the sediments, increases in K_2O/TiO_2 ratios will represent less weathered
370 source inputs (young materials, from regular erosion area), or increasingly deep horizons inputs.
371 Values of K_2O/TiO_2 in the sediments are in the higher range, and beyond what is observed in soils
372 (Fig. 7d and Table 1). In summary, the main sources of sediment are low weathered soils such as
373 GERS11 and GERS4.

374 Several phases present high contents of OM when K_2O/TiO_2 ratios, erosion and flood deposit
 375 frequency are the lowest (Fig. 5). These phases can be interpreted or by slight erosion of soil surface,
 376 either as the expression of lacustrine OM that is less diluted than during the periods of higher
 377 terrigenous inputs. Between 900 and 800 cal yr BP, the increase in OM may be also link to grazing on
 378 the delta of the lake, which could have bring lots of organic matter from dungs.

379

380 4.1.2 Flood chronicle

381 Normally graded deposits are common features in lake sediments. There are commonly
 382 associated to turbidity currents triggered by mass movements or by flood events. To verify this
 383 hypothesis, we compared our record with the historical flood calendar of the downstream Giffre
 384 river established by Mougin (1914) and completed by local archives and internet database of RTM
 385 (ONF-RTM database, <http://rtm-onf.ifn.fr>). The comparison allows to associate the thickest deposits
 386 to historical floods from CE 1298 to today (Table 3). The proposed dates fitted within 20 years in
 387 average, throughout the last 650 years. Only three deposits dated at 513 cal yr BP could not be
 388 identified in the historical archives, possibly due to both their low thicknesses and their old age
 389 (Table 3). This good correspondence supports both the assumption of the torrential origin of these
 390 deposits and the chronology of the sequence for this period.

391

392 **[insert TABLE 3]**

393 **Table 3. Comparison of flood deposits recorded in Lake Gers sediments with historical floods of the Giffre River for the**
 394 **last 650 yrs. CE= Common Era.**

| Flood thickness (cm) | Age cal. BP | Age cal. CE | min CE | max CE | Historical flood | Age difference (yrs) | Reference | Historical document |
|----------------------|-------------|-------------|--------|--------|------------------|----------------------|--|---------------------|
| 3 | -14 | 1964 | 1971 | 1956 | 1968 | 4 | RTM archives | |
| 1 | -6 | 1956 | 1964 | 1947 | 1944 | 12 | Municipal archives (Sixt-Fer à Cheval) | |
| 1 | -6 | 1959 | 1964 | 1947 | 1944 | 12 | Municipal archives (Sixt-Fer à Cheval) | |

| | | | | | | | | |
|-----|-----|------|------|------|--------------|----------|---------------|---|
| 0.5 | 79 | 1871 | 1890 | 1856 | 1878 | 7 | Mougin (1914) | Patriote Savoisien, 1878, 2 juin, 21 juin, 4 septembre |
| 1.5 | 204 | 1746 | 1776 | 1716 | 1733 | 13 | Mougin (1914) | Arch. Dép. H.-S. T. P. Fy. Liasses anciennes, 14 juin 1737, n°236 |
| 2.5 | 204 | 1746 | 1776 | 1716 | 1733 | 13 | Mougin (1914) | Arch. Dép. H.-S. T. P. Fy. Liasses anciennes, 14 juin 1737, n°236 |
| 3.5 | 318 | 1632 | 1672 | 1593 | 1658 or 1673 | 26 or 41 | Mougin (1914) | Revue savoisienne, 1898. Gonthier. Eboulements historiques. |
| 3.5 | 338 | 1612 | 1654 | 1572 | 1570 or 1651 | 46 or 39 | Mougin (1914) | Revue savoisienne, 1898. Gonthier. Eboulements historiques. |
| 1 | 513 | 1437 | 1490 | 1390 | ? | - | - | |
| 1 | 513 | 1437 | 1490 | 1390 | ? | - | - | |
| 1 | 513 | 1437 | 1490 | 1390 | ? | - | - | |
| 2 | 534 | 1416 | 1470 | 1369 | 1401 ? | 15 | Mougin (1914) | Acad. Sallès Tome XX. Abbé Feige. Monographie de Mélan. |
| 5 | 595 | 1355 | 1409 | 1307 | 1401 ? | 46 | Mougin (1914) | Acad. Sallès Tome XX. Abbé Feige. Monographie de Mélan. |
| 11 | 641 | 1309 | 1364 | 1258 | 1298 | 11 | Mougin (1914) | Acad. Sallès Tome XX. Abbé Feige. Monographie de Mélan. |

395

396 The frequency of the instantaneous deposits was estimated for a period of 101 years (Fig. 5i)

397 (Fig. 5e). Sandy levels are presented in a different color as they can have a different origin from the

398 other events and are only present from 4.6 to 3.8 cal yr BP (Fig. 5e). Sandy levels occur from 2 to 10

399 deposits per 101 years on this period, with three higher frequency periods around 4.4, 4.15 and 3.9

400 cal kyr BP. The frequency of the other deposits ranges from 0 to 33 events (Fig. 5e). The centennial

401 frequency ranges from 0 to 4 between 4.6 and 2.7 cal kyr BP, with up to 4 events from 4.6 to 4.15,

402 3.7 to 3.5, 3.3 to 3.1 and 2.95 to 2.85 cal kyr BP. The frequency reaches 8 events per 101 years

403 between 2.7 and 2.5 cal kyr BP before a period where no events were recorded between 2.5 and

404 1.95 cal kyr BP. The frequency reaches up to 4 events again from 1.95 to 1.65 cal kyr BP and up to 2

405 events between 1.5 and 1.23 cal kyr BP. The maximum frequency occurs from 900 to 670 cal yr BP

406 with up to 33 events between 900 and 800 cal yr BP (Fig. 5e). The frequency stays between 2 and 4

407 events per 101 yrs until 460 cal yr BP, then between 0 and 2 until the last century.

408 The origin of sandy deposits between 4.6 and 3.8 cal kyr BP is not solved. As two of them are

409 associated to a graded layer, a flood deposit is possible, but can also be due to chance, *i.e.*, a sand

410 deposit followed by a flood deposit. No other proxies analyzed in the sediment core provide

411 information about the disappearance of these deposits after 3.8 cal kyr BP. They correspond to
412 another source which is no longer mobilized or which does not reach the lake since 3.8 kyr. They
413 happen while very low flood-frequency and erosion are recorded at Lake Anterne (Fig. 5g). 3.8 kyr is
414 also considered as a major paleohydrological transition toward wetter regional conditions as
415 evidenced by different studies in the Alps (Nicolussi et al., 2005; Magny et al., 2011; Arnaud et al.,
416 2012; Le Roy et al., 2015; Arnaud et al., 2016; Rapuc et al., 2019). This change in the sedimentary
417 dynamic could be a consequence of the 4.2 kyr event recognized in different types of archives at
418 many global locations. The avalanches that arrive on the lake can also bring sands when ice is
419 melting, especially from the Taveyannaz sandstones cliff above (Fig. 1c). However, they appear to
420 have a constant grain-size, while avalanches bring very different grain-size materials (weak sorting),
421 and usually even coarse (e.g., gravels, pebbles) with dropstones in lake sediments (Fouinat et al.,
422 2017b).

423 *4.1.3 Long-term erosion*

424 Erosion was first calculated without the instantaneous deposits (Fig. 5f, dotted line), and
425 then including each instantaneous deposit (Fig. 5f). Erosion is approximately $10 \text{ t.km}^{-2}.\text{yr}^{-1}$ between
426 4.6 and 4.1 cal kyr BP, with three highest peaks at 30, 50 and $200 \text{ t.km}^{-2}.\text{an}^{-1}$ during the years of
427 instantaneous deposits. Erosion decrease at approximately 4-5 to $3 \text{ t.km}^{-2}.\text{yr}^{-1}$ from 4.1 to 2.6 cal kyr
428 BP, with punctual event induced-erosion peaks until $20 \text{ t.km}^{-2}.\text{an}^{-1}$. Erosion increases at $9 \text{ t.km}^{-2}.\text{yr}^{-1}$
429 between 2.6 and 1.7 cal kyr BP, with two highest periods from 2.6 to 2.5 and 1.9 to 1.7 cal yr BP.
430 Erosion is lower from 1700 to 950 cal yr BP except during the higher event frequency period from 1.4
431 to 1.3 cal kyr BP (Fig. 5ef). Erosion increases up to $15 \text{ t.km}^{-2}.\text{yr}^{-1}$ outside flood deposits and up to 100
432 $\text{t.km}^{-2}.\text{yr}^{-1}$ with flood deposits between 950 and 600 cal yr BP, and slightly decreases from 600 to 0 cal
433 yr BP. The last 65 yrs are characterized by an increase erosion trend.

434 The calculation of erosion is very simplified and absolute values are to be carefully used.
435 Nevertheless, they are in the order of magnitude of erosion modeled and recorded in Europe (Enters

436 et al., 2008; Cerdan et al., 2010; Egli et al., 2014; Vanmaercke et al., 2015). Furthermore, Bajard et al.
437 (2017) showed that the uncertainty of the volume of sediment weakly influenced the amount of
438 erosion. Otherwise, with instantaneous inputs from floods, the erosion triggered at each of these
439 deposits is very depending of the deposit time of the considered “sample depth” below. Without
440 considered the flood inputs, erosion is still higher during higher flood-frequency periods, suggesting
441 an impact of these events on the continuous sedimentation. For example, a part of the material
442 mobilized during an extreme event can be stocked in the catchment before being remobilized with
443 later rainfall. This assumption is strongly supported by the variation of K_2O/TiO_2 that displays always
444 higher values during high flood-frequency periods (Fig. 5de).

445

446 *4.2 Environmental dynamics and agro-pastoral activities in the late Holocene*

447 In the Northwestern Alps, first important developments of pastures happened after 3600 to
448 3000 cal yr BP. In the Anterne mountain (Fig. 1e), palynological studies from Survilly and Ecuellas
449 peat bogs show an expansion of *Alnus* around 3600 and 3000 cal yr BP respectively, and were
450 associated to clear-cutting and grazing activities (David, 2010a, 2010b). Archaeological evidences
451 found close to Lake Anterne confirms, with sedDNA from the lake, the long livestock farming history
452 of this area (Rey, 2008, 2010; Giguet-Covex et al., 2014). Similar observations were made in the Swiss
453 Alps from Lake Sägitalsee at 1935 m a.s.l. (Wick et al., 2003). It is also during this same period that
454 first human clearing and grazing activities were identified in the area of the Petit Saint Bernard pass
455 (2188 m a.s.l, French-Italian border), by independent palynological, DNA, pedoanthracological and
456 archaeological studies (Talon, 2006; Rey et al., 2008; Bajard et al., 2017b).

457 At lake Gers, the period between 4600 and 2700 cal yr BP is characterized by no or low
458 variations of the geochemistry with four periods of low flood-frequency, reflecting constant inputs
459 and slight evolution in the landscape. The catchment was rather forested. No pasture activity was

460 recorded by DNA. At 2700 cal yr BP, the peak in tree DNA (Fig. 5b) is mainly due to *Alnus* (data not
461 shown). This occurrence of *Alnus*, could reflect first development of grazing in lake Gers catchment.

462 After 2700 cal yr BP, both OM contents and K_2O/TiO_2 ratio present higher variations, mainly
463 anticorrelated. The four phases of higher K_2O/TiO_2 ratio (noted P1 to P4, Fig. 5), reflecting the
464 contribution of less weathered materials are associated to higher flood-frequency periods. They
465 appear as ruptures in the evolution of the landscape. Floods had to disrupt the catchment bringing
466 less weathered materials from rejuvenated soils through erosion and colluviation movements, while
467 outside periods of higher flood-frequency, the continuous sedimentation reflected the low erosion of
468 surface soils, with higher OM contents and higher weathered materials.

469 The Roman period is marked a slight decrease of DNA of trees and the first occurrence of
470 cow DNA in the sediments between 2000 and 1700 cal yr BP, suggesting deforestation and
471 development of cattle grazing in the catchment. The rejuvenation of soils between 1900 and 1750 cal
472 yr BP (P2 phase) is associated with this development of grazing activities. On the other hand, cow and
473 bos DNA were detected earlier in the sediments of lake Anterne (Fig. 1e), between 2400 and 1900
474 cal yr BP (Giguët-Covex et al., 2014). This difference could reflect a development of pastoral areas by
475 the areas at higher altitudes.

476 Between 1300 and 900 cal yr BP, a recovery in the forest restored surface soil inputs. No
477 flood deposit was recorded during this period. A similar recolonization of the vegetation was
478 recorded at Lake Verney (2088 m) in the Petit Saint Bernard pass area (French-Italian border),
479 approximately at the same period with evidence of a slight recovery in the podzolic processes in the
480 catchment (Bajard et al., 2017b). The origins of this decrease in pastoral activities could therefore be
481 more global (*e.g.*, climate forcing).

482 After 950 cal yr BP, cattle grazing activities seems to be continuous. Sheep and goat were
483 present especially until 800 cal yr BP. The Gers valley is known to be one of the main route to bring
484 animals to the Sales Vallon (Fig. 1e), which is another pasture located a few kilometers away

485 (Guffond and Mélo, 2018). At Sales, 84 archaeological structures and remains of building were
486 identified (Guffond, 2017). Two animal bones, buried in the buildings, were dated 865 and 675 yr BP.
487 They independently confirm the medieval implantation of these mountains. Moreover, the
488 intensification of agricultural activities in this part of the Alps in the medieval period was also
489 reflected by the expansion and opening of new grazing areas like at Bénit, a pasture located 18 km
490 west of Gers (Bajard et al., 2018).

491 This diversification of the pastoral activities was associated with the expansion of pastoral
492 areas, as suggested by the decrease in the DNA of trees and increase in erosion of OM-rich and highly
493 weathered soils associated with the high frequency of thin flood deposits. They suggest a progressive
494 erosion of soils, from weathered and organic surface horizons to deep, less weathered horizons (P4
495 phase), leading to a more important development of Cambisols, instead of Podzols and Andosols.
496 From 700 cal yr BP to the present, few changes were recorded except the relative decrease in flood-
497 frequency, suggesting a stabilization of the landscape. Historical documents from 1418 CE (532 yr cal
498 BP) attests that animals and heifers were bring to Sales Vallon (Guffond and Mélo, 2018). In 1847,
499 300 cows were grazing below Pointe Pelouse.

500 *4.3 Impact of climate and human in the subalpine area*

501 *4.3.1 Erosion and climate patterns at the local scale*

502 For both the Roman and medieval periods (P2 and P4 phases, Figure 5), the increases in
503 erosion, flood-frequency and K_2O/TiO_2 ratio appear to be mostly due to human activities. For the two
504 other periods (P1 and P3 phases), the impact of human activities could be under-recorded, especially
505 at the early beginning of the deforestation process. Changes in vegetation may be partly masked in
506 the first hundred years after landscape modifications, as DNA may be stored in soils, and will only be
507 transferred to the lake with erosion (Parducci et al., 2017; Giguët-covex et al., 2019). The extreme
508 values of K_2O/TiO_2 ratio and the highest flood-frequency recorded in the same way than during P2
509 and P4 phases constitute one more argument in the assumption of human induced flood-frequency

510 increase in P1 and P3 phases, considering that roman and medieval periods were the main periods of
511 pastoral activities in the Alps.

512 In order to verify this hypothesis, we compared the Lake Gers record with regional glacier
513 records (Fig. 5h). Holzhauser et al. (2005) and Le Roy et al. (2015) provide reconstitutions of the
514 dynamics of the Great Aletsch Glacier (100 km northeast of Lake Gers) and of the Mer de Glace (20
515 km southeast of Lake Gers), respectively, throughout the last 3500 yrs. Both P1 and P3 phases are
516 synchronous with glacier advances of both glaciers, suggesting mainly a climate cooling to explain the
517 higher flood-frequency periods and the associated erosion increases. Around the Alps, Arnaud et al.
518 (2016) pointed out that colder periods generally favour higher flood frequency. Indeed, a climate
519 cooling could affect vegetation by reducing its development. But vegetation protects soils from
520 erosion, and soils also absorb precipitation, limiting run off and flooding. So, a cooling of the climate
521 could increase flood events.

522 The P4 phase but also all the last millennia of Lake Gers sedimentary record is also largely
523 associated to glacier fluctuations. The P4 phase could thus be associated to both climate and human
524 forcings. Both effects of substantial land-use and precipitation patterns changes could be responsible
525 for the higher flood-frequency recorded at the beginning of the last millennia.

526 In order to draw the regional pattern of erosion we compared the Lake Gers record with Lake
527 Anterne sedimentary record (7 km southward). At Anterne, both the flood-frequency and
528 sedimentation rate, which present the same variations, were used as proxies of erosion (Giguet-
529 Covex et al., 2011, 2012), as observed in Lake Gers sequence. Higher flood-frequency was recorded
530 at Lake Anterne (max 24/101 yrs, 7 /101 yrs on average) than at Lake Gers (max 33/101 yrs, 2/101 yrs
531 in average). The catchment of Lake Anterne is possibly more susceptible to flood because of both its
532 higher altitude (*e.g.*, difference in vegetation, precipitations and snow melting) and the highest
533 erodibility of the schists, which mainly cover its catchment. Pastoral activities at Anterne were
534 recorded mainly from 2400 to 1900 cal yr BP (cow and sheep) and from 1000 to 200 cal yr BP (mainly

535 cow) (Giguët-Covex et al., 2014). The effects of human activities seem to be more marked at Anterne
536 during the late Iron age and the beginning of roman period, with both cow and sheep grazing,
537 associated with maximum of erosion, while this period is much more weakly marked by human
538 activities at Lake Gers (Fig. 5).

539 The erosion recorded in both lakes display similar variations, especially between 3200 and
540 1000 cal yr BP. After 1000 cal yr BP, both erosion patterns seem more different. At Lake Anterne,
541 erosion increases slightly, and more after 500 cal yr BP in relation with wetter and colder climate
542 conditions of the Little Ice Age (Giguët-Covex et al., 2012). At Lake Gers, erosion was very important
543 after 950 cal yr BP, in relation with human activities, triggering a high destabilization of soils and an
544 increase of flood deposits. Erosion trajectories of soils in both catchments are similar while human
545 impact is moderated, as noticed in the Roman period, and then differ when human pressure
546 strengthens in the Middle Age. This comparison suggests that from the medieval period, human
547 activities overwhelm the impact of climate on erosion in Lake Gers catchment. A similar observation
548 was realized from Lake La Thuile sediment sequence for the same period (Bajard et al., 2016). Both
549 erosion and soil disruption were triggered first by climate forcing (*i.e.*, heavy precipitations, snow
550 cover duration) and strongly increase according to the intensity of human activities that disrupt soils
551 and make them more easily erodible. However, changes in hydrological patterns could be more
552 associated to bare soils than change in vegetation (Cosandey et al., 2005). Such an increase in the
553 erodibility of a catchment with anthropic activities was also recorded in the southern Alps and
554 represent a major threat for the future (Brisset et al., 2017).

555 *4.3.2. Consequences of land use modifications on the vulnerability to climate changes*

556 Long-term changes in land use has led to an increase in transport capacity of water in the
557 catchment (*e.g.* increased of Hortonian flow due to vegetation changes or compaction) and increase
558 in the sediment supply through the erosion initiated by grazing activities and deforestation. These
559 consequences triggers an input of water and sediments more important to downstream areas where

560 human activities take place. In interaction with climate changes and multiplication of extreme
561 events, these consequences increase the vulnerability of population to flood hazards. Therefore,
562 upstream areas should be more taken into account in the adaptation to climate change and risk
563 prevention plans.

564 Effect of floods, favored by human-induced land-use changes increases losses of soils and
565 their associated ecosystem services. Anthropogenic land-use changes are known to be an important
566 way to lose organic carbon (Carcaillet et al., 2002; Kaplan et al., 2011). However, human activities
567 induced-erosion is not well considered in the assessment of organic C losses and in the global C
568 budget (Lal, 2003). Erosion could yet accelerate organic C losses in the atmosphere, by mineralization
569 to CO₂, and strengthen climate warming (Alewell et al., 2009; Wang et al., 2017). The less important
570 OM content in the sediment of Lake Gers (10 % in average) than in soils of the catchment (30 % in
571 average, Table 1) suggests a loss of organic carbon with erosion. However, our data do not allow to
572 assess the location of mineralization, during transport or within the lake. As a result, a larger
573 consideration and management of upstream areas would reduce the vulnerability of population
574 downstream to flood events and participate to carbon storage to limit the global warming.

575

576 5. Conclusions

577 The sediment sequence of Lake Gers (1540 m a.s.l.) in the Northern French Alps provides a
578 continuous record of environmental changes throughout the last 4.6 kyr. The sequence is punctuated
579 by 127 instantaneous deposits, including 93 graded deposits identified as flood deposits. The other
580 deposits are sand layers occurring only from 4.6 to 3.8 cal kyr BP, whose origin was not determined.
581 Multiproxy analyses of the continuous sedimentation, including geochemistry, loss on ignition and
582 DNA analyses, was compared to flood-frequency and to current soils of the catchment. Erosion was

583 quantified from the lake filling, including flood events and compared to regional climate and erosion
584 records.

585 Three potential geochemical sources were identified in the catchment, corresponding to
586 variations in geological formations over which different pedogenetic processes were associated, *i.e.*,
587 Podzolization, Andosolization and colluviation. Colluviation and low weathered material seem to be
588 responsible for the main inputs in the lake. Podzols and Andosols features were not identified in the
589 sediment with our analyses.

590 Four phases of decrease in the weathering of sedimentary inputs were associated to higher
591 flood-frequency periods, suggesting the progressive erosion of soils and their periodic destabilization
592 and rejuvenation. Two of the four weathering decrease phases (*i.e.* increase in K_2O/TiO_2 ratio) were
593 associated with climate cooling in the 2650-2500 and 1450-1300 cal yr BP periods. The two other
594 phases were associated with human activities, *i.e.* deforestation and pastoralism, during the late
595 Roman period and in the Middle Age, mainly with cow grazing. In the last millennia, agricultural
596 activities are diversified with sheep and goats, and combined to climate forcing. Both effect,
597 agriculture and climate, triggered an even higher flood-frequency deposit and higher erosion. This
598 last anthropic phase evidenced higher modifications operated by agro-pastoral activities in the
599 catchment (*e.g.*, vegetation) and a higher sensibility to climate events.

600

601 6. Acknowledgments

602 The authors thank the municipality of Samoens for access and coring authorizations to Lake
603 Gers, and the ski resort of Flaine - Grand Massif for the winter access to the lake by the ski slopes
604 (Malvina Sculo, ski patrols and snow groomer driver). Thanks to Jim Félix-Faure, Laurent Fouinat and
605 Anouk Leloup-Besson for field support and Dominique Navillod for her welcome to the “Gite de
606 Gers”. Thanks also to Sarah Bureau for ICP-AES analyses at ISTERre laboratory. 14C analyses were

607 acquired thanks to the CNRS-INSU ARTEMIS national radiocarbon AMS measurement program at
608 Laboratoire de Mesure du 14C (LMC14) in the CEA Institute at Saclay (French Atomic Energy
609 Commission). The authors thank also the Laboratoire Souterrain de Modane (LSM) facilities for the
610 gamma spectrometry measurements. DNA analyses were supported by AGIR-PAGE Euromont 2016
611 project. We thank Morgan T. Jones for correcting the English of the article and the two anonymous
612 reviewers for advice in improving our manuscript.

613 7. Data availability

614 Datasets related to this article can be found at
615 <https://data.mendeley.com/datasets/j9x7yhcvd4/draft?a=1fbbfa5b-b76e-4d5b-b428-adc496d7c2d4>,
616 (doi:10.17632/j9x7yhcvd4.1) an open-source online data repository hosted at Mendeley Data
617 ([CITATION TO DATASET]).

618 8. References

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