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Impact of human activities and vegetation changes on the tetraether sources in Lake St Front (Massif Central, France)

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The distribution of branched glycerol dialkyl glycerol tetraethers (brGDGTs) has been shown to correlate with mean annual air temperature and is increasingly used for paleoclimate reconstructions, in particular in lakes. Numerous studies have reported in situ production of brGDGTs in lakes. These brGDGTs have different distributions compared with those produced in soils and their mixing hampers paleoclimate reconstructions. Very few tools exist to determine brGDGT sources in the present and to trace their changes in the past linked with environmental changes of climatic or anthropogenic origin. While human activities are known to affect both soil and aquatic ecosystems, particularly bacterial communities, the specific impacts on brGDGT distributions are poorly investigated. High resolution analyses of brGDGTs were carried out on Holocene sediments and catchment soils of Lake St Front (Massif Central, France) in association with sedimentological, palynological, and geochemical analyses. Comparison of brGDGT distributions in sediments and soils revealed their mixed origin. For the first time, we tested the reliability of the $R_{IIIa}/R_{IIa}$ ratio in lakes which indicated a gradual shift from aquatic to terrigenous brGDGT sources over the Holocene. This shift was supported by sedimentological and geochemical indices. Three events with a high proportion of terrigenous brGDGTs (6–5.5, 2.8–2.5, and 2–0.2 kyr cal BP) coincide with changes in vegetation in the catchment area, driven by climate and/or human activities. This suggests that vegetation modifications in the watershed impact brGDGT distributions and may thus bias brGDGT-based paleoclimatic reconstructions.

1. Introduction

Mid-altitude lakes like Lake St Front (Massif Central, France) are subject to extreme environmental conditions which make them particularly sensitive to climatic and landscape changes. Human activities can disturb ecosystems. Deforestation increases runoff and destabilizes soils as does agriculture and pastoralism (e.g., Dearing and Jones, 2003; Lotter and Birks, 2003; García-Ruiz, 2010). These activities thus substantially increase the sediment delivery to lakes through soil erosion by runoff (e.g., Dearing and Jones, 2003). Nutrient inputs to the lakes also increase and can lead to eutrophication of the lake (e.g., Lavrieux et al., 2013a). Multiproxy studies of lacustrine sediments enable the reconstruction of such changes and provide insights into the long-term interactions between earth, climate, and humans (e.g., Birks and Birks, 2006).

The first evidence of human incursion into the Velay region (eastern part of Massif Central; Fig. 1A) dates back to the Mousterian at the beginning of the last glacial period and occurred in the valleys (Philibert et al., 1986; Daugas and Raynal, 1989). Late-glacial and Holocene climatic improvements allowed humans to populate higher altitude regions, predominantly during the Mesolithic and Neolithic (Daugas and Raynal, 1989). Archeological evidence supports the existence of regional settlements in the Massif Central as early as 7.5 kyr cal BP (Georjon et al., 2004; Pouenat, 2007; Macaire et al., 2010) and, more specifically, 6.9 kyr cal BP for the Velay region (Daugas et al., 1983; Miall, et al., 1983). After about 6 kyr cal BP, evidence of human occupation became more frequent. From the Final Neolithic (4.7–3.7 kyr cal BP) and particularly the Ancient Bronze Age (3.7–3.4 kyr cal BP)
onward, the archeological and palynological records indicate continuous human occupation and active landscape management (Coûteaux, 1984; Reille, 1992; Miras et al., 2004; Lavrieux et al., 2013a,b). Proxies based on branched glycerol dialkyl glycerol tetraethers (brGDGTs), biomarkers of bacterial origin, have been recently developed from soil analyses (Weijers et al., 2007). These compounds are increasingly studied in many environments, particularly in lakes (e.g., Buckles et al., 2014a,b; Miller et al., 2018; Russell et al., 2018). The producers of these bacterial membrane lipids remain mostly unknown except for subdivisions of Acidobacteria (Weijers et al., 2006, 2009; Sinninghe Damsté et al., 2011, 2014, 2018). They are transported via soil erosion through runoff to aquatic systems where they can be preserved in the sediments (e.g., Hopmans et al., 2004). A variety of structures have been identified in brGDGTs including a varying number (0–2) of methyl branches and cyclopentane moieties (0–2; Supplementary Fig. S1). This structural variability is associated with the ability of the brGDGT producers to modify the composition of their cellular membrane lipids in response to specific environmental parameters such as temperature and pH (e.g., Weijers et al., 2007). Two indices were defined: the cyclization ratio of branched tetraethers (CBT), which is correlated with soil pH, and the methylation index of branched tetraethers (MBT) which is correlated with mean annual air temperature (MAAT) and soil pH (Weijers et al., 2007; Peterse et al., 2012). Recently improved chromatography techniques separate the 5-, 6- and 7-methyl (Me) isomers of penta- and hexamethylated brGDGTs which co-eluted with the traditional method (De Jonge et al., 2013, 2014a; Ding et al., 2016). This new technique thus improves the quantification of the different brGDGT forms (De Jonge et al., 2013, 2014a; Ding et al., 2016).

Many lake studies have shown that brGDGT distributions differ between lake sediments and catchment soils (e.g., Tierney and Russell, 2009; Tierney et al., 2012; Wang et al., 2012; Buckles et al., 2014a,b; Russell et al., 2018). These studies suggest production of brGDGTs in water column and/or sediments which hampered paleoclimate reconstructions from lake sediments. Several tools have been developed to determine brGDGT sources and to allow their use as terrigenous input tracers. These include the BIT index (Hopmans et al., 2004), the weighted average number of cyclopentane moieties and the degree of methyl branching of the brGDGTs (Sinninghe Damsté, 2016), the $\Sigma$Illa/$\Sigma$Illa ratio (Xiao et al., 2016) and the stable carbon isotope composition ($\delta^{13}C$) of brGDGTs (e.g., Weber et al., 2015, 2018). Among these tools, the BIT index and the $\delta^{13}C$ of brGDGTs were already applied for lake studies (e.g., Niemann et al., 2012; Colcord et al., 2017), but the
tools recently proposed by Sinninghe Damsté (2016) and Xiao et al. (2016) were developed in the oceanic realm and their applicability in lakes has yet to be tested. Many studies have demonstrated the impact of human activities on bacterial and phytoplanktonic communities (e.g., Moon et al., 2016; Murphy et al., 2016; Lambert et al., 2018), but fewer studies have considered the potential direct and indirect impacts of human occupation and activities on CDGT distributions (Das et al., 2012; Naehr et al., 2014; dos Santos and Vane, 2016; Chen et al., 2018; Song et al., 2018).

Palynological reconstructions are extensively used to reconstruct past environmental changes (e.g., Reille and de Beaulieu, 1990) at a regional and at the local scale. As vegetal taxa are adapted to specific climate conditions, pollen assemblages can give information on climate changes (e.g., Birks et al., 2011; Gambin et al., 2016). Anthropogenic disturbances can be demonstrated thanks to some specific markers like changes in the sum of arboreal pollen and the rate of cultivated, ruderal and nitrophilous plants (e.g., Lavrieux et al., 2013b; Shumilovskikh et al., 2016).

We studied Lake St Front, a maar located at an altitude of 1230 m in the eastern Velay region (Massif Central, France), in a climatic transition zone between Atlantic and Mediterranean influences. It has a small catchment area and a high potential for the accumulation and preservation of sedimentary organic matter due to a relatively high sedimentation rate. A 65 m depth core was recovered from the lake in 1991 which contained deposits dating back to the penultimate glacial cycle (i.e., between 130 and 180 kyr BP; Vlag et al., 1997). Due to human occupation of the immediate surroundings of Lake St Front since the Neolithic (e.g., Dendievel, 2012 and References therein), this study site offered a good opportunity to test the anthropogenic impacts on brGDGT distributions.

We identified and quantified the brGDGTs present in the catchment soils and in the Holocene sedimentary sequence of Lake St Front in order to: (1) determine the sources of brGDGTs present in modern lake sediments using the available source indices and by comparing the brGDGT distributions between catchment soils and lake sediments, and (2) reconstruct the changes in brGDGT sources during the Holocene in relation to vegetation changes and anthropogenic impacts.

2. Material and methods

2.1. Site description

Lake St Front (44°58’N, 4°10’E, 1234 m) occupies a sub-circular crater located on the Meygal-Mézenc plateau (eastern Velay, Massif Central, France; Fig. 1A). The crater was cut through Quaternary basalts by a phreatomagmatic explosion (maar; Mergoil, 1987; Teulade et al., 1991). The lake diameter is 600 m and its maximum depth is 6 m. The 1.5 km² lake catchment area (Fig. 1B) contains numerous streams. Currently, the two main environment types are coniferous and deciduous forests with Pinus sylvestris and Quercus pubescens dominant (Carles, 1956) and grassland areas that are used as cattle pasture (Fig. 1B and C). A peat bog located on the northern shore documents high lake level deposits dating from the Holocene (Florschutz, 1954; Bout, 1973). The lake is eutrophic and, apart from rainfall/runoff, it is supplied by surface and probably groundwater springs fed by a groundwater table located at around 20 m (Mergoil et al., 1993). A small outlet was dug in recent historical times at the southwestern shore to control the lake water level.

Mean annual temperature ranges from 6 °C to 9 °C with a mean value of 7 °C. Average winter temperature is 1 °C and average summer temperature is 15 °C with daily maxima that can exceed 25 °C. The average annual precipitation is 1000 mm. Rainfall originates from Atlantic or Mediterranean humid air masses pushed by winds. Snowfall occurs more than 50 days per year on the Eastern Velay plateau. The lake is usually frozen for at least three months each year (Fillod, 1985). Modern climatic parameters were obtained from the instrument database of Météo-France (https://donneespubliques.meteofrance.fr) at the nearby (11 km) station of Mazet-Volamont and the nearest altitude (1130 m) for the period 2009–2017. Data for longer periods were from the stations of Saint Julien Chapteuil (distance 9 km, altitude 810 m, period 1995–2017) and Le Puy en Velay (distance 22 km from Lake St Front to the northwest, altitude 833 m, period 1981–2010). Temperature values were corrected using an altitudinal gradient of 0.6 °C/100 m (Gandouin et al., 2016).

Lake St Front presents ideal conditions to provide continuous sedimentary records for the last climatic cycle. It has a shallow bathymetry allowing water column mixing by the wind, a simple water supply system and a relatively simple limnology. Archeological evidence shows human presence in the immediate surroundings of Lake St Front since the Neolithic (e.g., Dendievel, 2012 and References therein). This relatively simple system in a temperate climate was appropriate for the study of brGDGTs and the potential impact of anthropogenic activities on their distribution.

2.2. Sampling

Lake sediment cores were recovered during two coring campaigns in 1991 and 2016 (Fig. 1B, Table 1). In 1991, three parallel cores SFA, SFB, and SFC were collected down to depths of 45 m, 65 m, and 18 m, respectively (Rhoujjati, 1995). Piston core sections of 1 m length and 8 cm diameter were recovered from the top 35 m of the SFA core and from the top 22 m from both the SFB and SFC cores. Since their collection, the cores were stored refrigerated and no significant alterations have been detected (Supplementary Text 1 and Supplementary Fig. S2). For this study, a composite sequence was reconstructed from cores SFB and SFC.

Additional cores were collected during July 2016 using UWITEC equipment (corers and coring platform) with the 2 m long hammer piston corer at sites SF16-2 (19 m) and SF16-3 (13 m; Fig. 1B). They were used to fill the hiatus of the SF-1991 cores (Andrieu et al., 1996, 1997) and to obtain a continuous composite sequence. A 60 cm gravity core was collected across the water–sediment interface in the central part of the lake (SF16-1A; Fig. 1B), while other shallow interface cores (50 cm maximum depth) were recovered from several shoreline sites (Fig. 1B, Table 1). Soil samples (2–5 cm depth), upper sediments of catchment streams (0–2 cm depth), and shoreline surface sediments were also collected from around the lake (Fig. 1B, Table 1).

2.3. Core description and preliminary analyses

We focused on the upper 13 m long part of the core covering the Holocene. The sediment sequence consisted of organic “gyttjas”, an accumulation of vegetable fibers packed into a clay matrix that is formed under temperate climatic conditions by autochthonous organic matter (OM) and soil degradation products (Fig. 2; Rhoujjati, 1995). This top organic unit contained dissolved gas formed by OM degradation and possibly by deep gas sources of volcanic origin.

In the field, low field magnetic susceptibility (MS) was measured at 2 cm intervals using the MS2 Bartington susceptibility meter connected to a 90 mm diameter MS2C probe, enabling correlations with the MS profiles between the SF-2016 and SF-1991 cores (Vlag et al., 1996, 1997). Magnetic susceptibility is a dimensionless quantity expressed in SI units. Matter can become magnetized under the influence of a magnetic field. In volcanic geological contexts, where magnetite and titanomagnetite are the main
Table 1
Sample locations, positions of stream, shoreline, and lake sediments and soil samples.

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Sample type – provenance</th>
<th>Latitude (°N)</th>
<th>Longitude (°E)</th>
<th>Depth (m)</th>
<th>Profile depth (cm)</th>
<th>Sampling interval (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>a Soil – Coniferous forest</td>
<td>44°58’51.05”</td>
<td>4°10’26.4”</td>
<td>0.02</td>
<td>2-5</td>
<td>Bulk</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td>44°58’47.52”</td>
<td>4°10’26.58”</td>
<td>0.02</td>
<td>2-5</td>
<td>Bulk</td>
</tr>
<tr>
<td>S2</td>
<td>a Soil – Deciduous forest</td>
<td>44°58’51.66”</td>
<td>4°10’29.4”</td>
<td>0.02</td>
<td>2-5</td>
<td>Bulk</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td>44°58’49.02”</td>
<td>4°10’30.24”</td>
<td>0.02</td>
<td>2-5</td>
<td>Bulk</td>
</tr>
<tr>
<td>S3</td>
<td>a Soil – Grassland, peaty</td>
<td>44°58’59.7”</td>
<td>4°10’21.06”</td>
<td>0.02</td>
<td>2-5</td>
<td>Bulk</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td>44°58’59.1”</td>
<td>4°10’26.4”</td>
<td>0.02</td>
<td>2-5</td>
<td>Bulk</td>
</tr>
<tr>
<td>S4</td>
<td>Soil – Peat bog</td>
<td>44°58’48.84”</td>
<td>4°9’54.72”</td>
<td>0.02</td>
<td>2-5</td>
<td>Bulk</td>
</tr>
<tr>
<td>S5</td>
<td>Soil – Grassland</td>
<td>44°58’47.88”</td>
<td>4°9’54.12”</td>
<td>0.02</td>
<td>2-5</td>
<td>Bulk</td>
</tr>
<tr>
<td>S6</td>
<td>Soil – Forest</td>
<td>44°58’42.96”</td>
<td>4°10’4.74”</td>
<td>0.02</td>
<td>2-5</td>
<td>Bulk</td>
</tr>
<tr>
<td>S7</td>
<td>Soil – Marsh</td>
<td>44°58’57.6”</td>
<td>4°10’27.72”</td>
<td>0.02</td>
<td>2-5</td>
<td>Bulk</td>
</tr>
<tr>
<td>R1</td>
<td>a Stream sediment – Grassland/forest</td>
<td>44°58’46.17”</td>
<td>4°10’22.84”</td>
<td>0</td>
<td>0-2</td>
<td>Bulk</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td>44°58’46.22”</td>
<td>4°10’23.37”</td>
<td>0</td>
<td>0-2</td>
<td>Bulk</td>
</tr>
<tr>
<td>R2</td>
<td>a Stream sediment – Grassland/forest</td>
<td>44°58’51.66”</td>
<td>4°10’28.5”</td>
<td>0</td>
<td>0-2</td>
<td>Bulk</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td>44°58’51.54”</td>
<td>4°10’29.1”</td>
<td>0</td>
<td>0-2</td>
<td>Bulk</td>
</tr>
<tr>
<td>R3</td>
<td>a Stream sediment – Grassland</td>
<td>44°59’2.7”</td>
<td>4°10’21.06”</td>
<td>0</td>
<td>0-2</td>
<td>Bulk</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td>44°59’5.10”</td>
<td>4°10’2.64”</td>
<td>0</td>
<td>0-2</td>
<td>Bulk</td>
</tr>
<tr>
<td>R4</td>
<td>Stream sediment – Grassland/forest</td>
<td>44°59’5.10”</td>
<td>4°10’26.46”</td>
<td>0</td>
<td>0-2</td>
<td>Bulk</td>
</tr>
<tr>
<td>R5</td>
<td>Stream sediment – Grassland/peat bog</td>
<td>44°59’3.78”</td>
<td>4°10’8.28”</td>
<td>0</td>
<td>0-2</td>
<td>Bulk</td>
</tr>
<tr>
<td>D1</td>
<td>a Sediment – Shoreline</td>
<td>44°58’47.88”</td>
<td>4°9’54.12”</td>
<td>0</td>
<td>0-2</td>
<td>Bulk</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td>44°58’48.84”</td>
<td>4°9’54.72”</td>
<td>0</td>
<td>0-2</td>
<td>Bulk</td>
</tr>
<tr>
<td>F</td>
<td>Short sediment core near forest shore</td>
<td>44°58’53.4”</td>
<td>4°10’22.26”</td>
<td>2.5</td>
<td>0-25</td>
<td>2</td>
</tr>
<tr>
<td>P</td>
<td>Short sediment core near peat bog shore</td>
<td>44°58’57.72”</td>
<td>4°10’21.12”</td>
<td>3.2</td>
<td>0-30</td>
<td>2</td>
</tr>
<tr>
<td>O</td>
<td>Short sediment core near outlet</td>
<td>44°58’30.58”</td>
<td>4°9’55.8”</td>
<td>3.2</td>
<td>0-45</td>
<td>2</td>
</tr>
<tr>
<td>G</td>
<td>Short sediment core near southern grassland shore</td>
<td>44°58’47.34”</td>
<td>4°10”</td>
<td>2.4</td>
<td>0-17.5</td>
<td>2</td>
</tr>
<tr>
<td>SF16</td>
<td>1A Short sediment center of the lake</td>
<td>44°58’53.4”</td>
<td>4°10’14.1”</td>
<td>4.2</td>
<td>0-65</td>
<td>2-10</td>
</tr>
<tr>
<td></td>
<td>2 Long sediment core</td>
<td></td>
<td></td>
<td></td>
<td>17-1860</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td>100-1300</td>
<td>10</td>
</tr>
<tr>
<td>SF91</td>
<td>B Long sediment core</td>
<td>44°58’42.96”</td>
<td>4°10’23.4”</td>
<td>5.5</td>
<td>105-945</td>
<td>10</td>
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<td></td>
<td>C</td>
<td></td>
<td></td>
<td></td>
<td>900-1215</td>
<td>10</td>
</tr>
</tbody>
</table>

Fig. 2. Age-depth model and accumulation rate for the Lake St Front sediment core. A. Age-depth model obtained with the Bacon software (Blaauw and Christen, 2011). The grey dotted lines indicate the 95% confidence limits and the red dotted line shows the weighted mean ages for each depth. The shaded area indicates the density of individual age-depth iterations. The calibrated age range of 14C-dated samples is indicated in blue. B. 210Pb ages for the upper 30 cm of the core. C. Lithology of the sedimentary sequence of Lake St Front. D. Accumulation rate for the last 12,000 years cal BP obtained with the Bacon software (Blaauw and Christen, 2011). The shaded area indicates the probability density. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

ferrimagnetic minerals present, MS mainly measures the concentration of these magnetic minerals in the sediment mixture. This reveals physical and/or chemical conditions from the erosion to the diagenesis that are related to the environment and/or climate.

2.4. Age model

The age control of the upper 20 m of the sequence was performed with radiometric methods. Lead-210 (210Pb) activity was measured in the upper 30 cm of the composite sequence at GEO-TOP Montreal (Table 2, Fig. 2B). The constant flux constant sedimentation model (CFCS), a particular case of the constant initial concentration model (CIC) (Ghaleb, 2009), was used to interpret the 210Pb profile. AMS 14C dating of total OM and organic macrofossils was carried out on an ARTEMIS accelerator mass spectrometer (Gif-sur-Yvette, France). Five radiocarbon age estimates (Table 3, Fig. 2A) were available on the SFA core from Rhoujjati (1995). We added nine 14C age estimates on the SFB and SFC cores (Table 3, Fig. 2A). Twenty 14C age estimates were obtained for SF16-2 and SF16-3 cores (Table 3, Fig. 2A). Radiocarbon age estimates (14C year BP) were converted to calendar years before 1950 (cal yr BP) using the IntCal13 calibration curve (Reimer et al., 2013). The age model was developed using the Bayesian model of the Bacon program (version 2.2; Blaauw and Christen, 2011) implemented in R (version 3.3.2; R Development Core Team, 2015). Ages were interpolated using the weighted mean within a 95% confidence interval.

2.5. Pollen analyses

Pollen analyses were conducted on 106 samples from the SFA profile (Supplementary Table S1). Pollen and spores were extracted using a flotation liquor (d = 2; Nakagawa et al., 1998). Identification of sporopollen material was carried out using a photonic microscope at 500 x magnification. Standard palynological identifications were based on the pollen reference collection of the
Mediterranean Institute of Biodiversity and Marine and Continental Ecology (CNRS, Aix-en-Provence, France) and pollen photographic atlases (Reille, 1992, 1995, 1998; Beug, 2004). Pollen percentages were calculated based on a pollen sum (PS) including all plants except for aquatics, ferns, and bryophytes. Different assemblages of taxa were considered in this study. The arboreal pollen sums all the tree taxa and among these taxa, two ensembles assemblages of taxa were considered in this study. The arboreal taxa included in the thermophilous forest were 

Acer, Corylus, Hedera, Ilex, Lonicera, Ostrya, deciduous Quercus, Quercus ilex, Pistacia, Sambucus, Sorbus, Tilia, Ulmus, Viburnum and Viscum. The taxa forming the mesophilous forest were Abies, Carpinus and Fagus. The anthropogenic taxa linked with human occupation and activities were also studied and separated into three groups. The nitro-philous taxa associated with farming were Plantago lanceolata, P. major, Rumex, Chenopodiaceae and Urtica; the cereals, markers of agriculture, included Cerealia and Secale and the pollen of Juglans was representative of arboriculture.

2.6. BrGDGT analysis

The sedimentary sequence was sampled at 10 cm increments and stored in a freezer prior to being freeze-dried and powdered. Before powdering, soils and interface samples were sieved to remove macro-remains and roots. After adding the internal standard C46 GDGT (Huguet et al., 2006), the lipids from 1 to 2 g of each sample were extracted using the accelerated solvent extraction method (ASE 350 Dionex system) with dichloromethane (DCM): methanol (MeOH) (90:10, v/v) at 120°C.

The lipid extracts were then separated into apolar and polar fractions using Al2O3 columns and hexane:DCM (1:1, v/v). After adding Al2O3 columns and hexane:DCM (1:1, v/v) to eluate, respectively, the apolar and polar fractions following the method described by Sanchi et al. (2013). Polar fractions were analyzed with high-performance liquid chromatography–atmospheric pressure chemical ionization–mass spectrometry (HPLC–APCI-MS) using an Agilent 1260 Infinity HPLC coupled to an Agilent 6120 quadrupole mass spectrometer.
following the new method described by Hopmans et al. (2016) with the modifications reported by Davtian et al. (2018). The analyses were carried out at the CEREGE (Aix-en-Provence, France).

Soil and sediment samples were run at least in duplicate. Peak areas of GDGTs were determined by manual integration of the peak areas of [M+H]+ ion traces of GDGTs (m/z 1292.3, 743.7, 1050.0, 1048.0, 1046.0, 1036.0, 1034.0, 1032.0, 1022.0, 1020.0, 1018.0 according to Davtian et al., 2018; Supplementary Table S2) using the Agilent Chemstation chromatography management software. GDGT concentrations were obtained by relating chromatogram peak areas to the known concentration of the internal standard C_{46} GDGT (Huguet et al., 2006; Supplementary Table S2). The relative response factor (RRF; Huguet et al., 2006) was inferred by running mixed samples of C_{46} and GDGT-0 (caldarchaeol, 1:1). One sample was chosen as an external standard and was run at the beginning and at the end of each batch to test the reproducibility for instrument drift.

2.7. Statistical analysis and calculation of brGDGT-based indices

We used CoDaPack software (version v2) to perform compositional analyses (Comas-Cufí and Thió-Henestrosa, 2011). This method accounts for the compositional nature of geochemical data which are constrained as their sum is equal to 1 (100%), using the Aitchison geometry (Aitchison, 1986). This geometry works into the simplex S^3, a generalization to D dimensions of the ternary diagram concept (D = 2; Aitchison, 1986). Log-ratio techniques transfer the information from the simplex to a Euclidian space where standard non-constrained multivariate statistics can be used while conserving the relationship between the components (Aitchison, 1986; Filzmoser and Hron, 2011; Pawlowsky-Glahn and Buccianti, 2011; Reimann et al., 2012; van den Boogaart and Tolosana-Delgado, 2013; McKinley et al., 2016). Prior to performing principal component analysis (PCA), we applied the centred log-ratio (clr) transformation (Aitchison, 1986; McKinley et al., 2016). All the other statistical tests were performed using R (version 3.3.2; R Development Core Team, 2015) and PAST software (version 3.04; Hammer et al., 2001).

Several indices were calculated using the relative abundances of brGDGTs which correspond to the proportion of each brGDGT compared to the sum of all brGDGTs. Roman numerals in the following equations refer to the different brGDGT forms described in Supplementary Fig. S1.

We measured crenarchaeol to determine the branched and isoprenoid tetrateraether index (BIT) values, using a modified version of the definition by Hopmans et al. (2004) to include the 6-, 7- and 5-Me penta- and hexamethylated brGDGTs and was calculated using a modified version of the definition by De Jonge et al. (2014b):

\[ R_{6Me} = \frac{IIa + IIb + IIc + IIIa + IIIb + IIIc}{\Sigma \text{pentamethylated brGDGTs} + \Sigma \text{hexamethylated brGDGTs}} \]

(3)

\[ R_{7Me} = \frac{IIa + IIIa + IIb}{\Sigma \text{pentamethylated brGDGTs} + \Sigma \text{hexamethylated brGDGTs}} \]

(4)

These isomer ratios allow comparison of the relative abundances of the different isomers; the lower the ratio’s value, the lower the fractional abundances of the considered isomer compared to the other isomers.

3. Results

3.1. Age-depth model

\(^{210}\text{Pb}\) activity decreased steadily with depth in the upper 30 cm except for the top 0.5 cm (Table 2). The estimated sedimentation rate was 0.37 ± 0.05 cm/yr. This result is consistent with the rate of 0.40 cm/yr obtained from \(^{14}\text{C}\) measurements in the upper 5 m. The sedimentation rate increased slightly during the Holocene (from 0.04 to 0.4 cm/yr) with an average value of 0.33 cm/yr. Two peaks were recorded at 5.5 kyr cal BP and between 1.4 and 2 kyr cal BP with means of 1.0 and 1.6 cm/yr, respectively (Fig. 2D). The average temporal resolution for the brGDGT analyses was 90 years, 100 years for pollen counts and 28 years for magnetic susceptibility measurements.

Age estimates obtained from \(^{14}\text{C}\) and \(^{210}\text{Pb}\) measurements for the upper core yielded a discrepancy of around 800 years with \(^{14}\text{C}\) providing an older age estimate (Tables 2 and 3). Plant macrofossils and bulk sediment from 1.90 m showed an offset of only 200 years (Table 3). Thus, the reservoir effect is not constant over time which precludes application of a constant correction factor.

3.2. Modern brGDGT distribution in Lake St Front sediments and catchment soils

All the brGDGTs described thus far, including 7-Me brGDGTs (see Supplementary Text 2), were present in both catchment soils and surface sediments (0–10 cm) of Lake St Front, except for brGDGT IIa which was not detected in soils (Fig. 3). The summed concentrations of brGDGTs ranged from 0.8 to 29 μg/g in soils (mean = 7 μg/g) and from 1 to 15 μg/g in lake sediments (mean = 6 μg/g; Tables 4 and 5). While brGDGTs without cyclopentane moieties (brGDGTa, 88% for soils and 83% for sediments) and pentamethylated brGDGTs (II, 48% for both soils and sediments) were dominant in both surface sediments and catchment soils,
the fractional abundances of the other brGDGTs exhibited a different pattern (Fig. 3, Table 4). Soils contained higher abundances of tetramethylated brGDGTs (I, 34%) than sediments (19%), and in particular brGDGT Ia (28% vs 14%, respectively). Sediments contained higher abundances of hexamethylated brGDGTs (III, 33%) than soils (18%), especially for brGDGT IIa (11% vs 4%, respectively). The relative abundance of pentamethylated brGDGTs was similar for both soils and sediments, but brGDGT IIa was more abundant in soils (35%) than in sediments (22%) while brGDGT IIa’ was more abundant in sediments (13%) than in soils (8%). The distribution patterns of the 5- and 6-Me forms also differed in that the relative abundance of 6-Me over 5-Me brGDGTs (IR_{6Me}) ranged from 0.03 to 0.3 in soils (average of 0.19) and from 0.3 to 0.4 in sediments (average of 0.36; Table 4). IR_{6Me} was significantly higher in sediments (0.05) than in soils (0.02; Table 4, t-test \( p < 0.0001 \)). The BIT index was very close to 1 in sediments and soils (Fig. 3). The \( \Sigma IIIa/\Sigma Ila \) values ranged from 0.2 to 0.6 in soils (average = 0.4; Fig. 3, Tables 4 and 5) and from 0.6 to 1 in lake sediments (average = 0.8).

The first axis of the covariance biplot (not shown), computed after a clr-transformation of the dataset, explained 96% of the variance in the dataset and is linked to the presence or absence of brGDGT IIIa’. In a second compositional analysis where brGDGT IIIa’ had been removed, the two principal components (PC) explained 66 and 15% of the variance. BrGDGTs Ia, Ila, and Ila’ scored positively on PC1 whereas the 6- and 7-Me forms, except Ila’, scored negatively (Fig. 4A). Considering the sample scores on PC1 and PC2, soils and sediments appeared to form two separated groups, scoring positively and negatively on PC1, respectively (Fig. 4B). Scores for catchment samples were more heterogeneous than for sediments, despite minor differences between cores.

We observed three groups in the compositional analysis (Fig. 4B). The first group corresponded to samples collected in deciduous forest (S2a and S2b; Table 1) and was distinct from the other two groups by its low negative values on PC2 and its maximum on PC1; the second group corresponded to samples collected in coniferous forests (S1a and S1b), streams, and grassland (except S3a) and had intermediate values on PC2; the third group contained samples collected in the peat bog, the marsh, streams, and the grassland sample S3a, and exhibited high values on PC2 and relatively lower values on PC1. Grassland samples were spread across the last two groups. The waterlogged soils formed a cluster with streams (S4, S7, S3a and S3b, and the streams R1–R5) and scored positively on PC2 while all the other soils (except sample S6) scored negatively (Fig. 4B).

Considering the surface sediments only (0–3 cm), the differences between cores were very small for all cores except for the G core. Samples D1a and D1b, corresponding to surface sediments from the lake’s water edge, and sample 1A-55 had slightly less-negative scores on PC1 than the other sediment samples (t-test \( p < 0.0001 \)) and was set apart from the group of the other sediment samples (Fig. 4B).

### 3.3. Sedimentological, geochemical, and palynological evolution through time

Magnetic susceptibility (MS) at the beginning of the Holocene presented relatively high values (\( 47 \cdot 10^{-5} \) SI units) which decreased rapidly to 0 SI units (Fig. 5B). MS slightly increased around 7 and 6 kyr cal BP before decreasing to negative values. MS slightly increased from 2.5 kyr cal BP, then abruptly from 1.8 kyr cal BP and remained high until 0.2 kyr cal BP (until 36 \( \cdot 10^{-5} \) SI units; Fig. 5B).

Through the Holocene and until 2 kyr cal BP, the Arboreal Pollen (AP, see Section 2.5 for definition) percentages remained at an almost constant high level (near 90% of the pollen sum, PS; Fig. 5D and Supplementary Table S1), except for a decrease from 7.3 to 5.5 kyr cal BP (minimum of 64% of PS reached at 6.7 kyr cal BP). At about 2.8 kyr cal BP, AP values rapidly decreased by almost 50% in as little as 1000 years (Fig. 5D and Supplementary Table S1).
However, its value slightly increased with two abrupt drops at 1.8 and 0.1 kyr cal BP (Fig. 5G). From 2 kyr cal BP, the values of the BIT index decreased to increasing again until 2 kyr cal BP with a rapid drop at 5.5 kyr cal BP (–0.19). Then, the ratio values increased until 5.1 kyr cal BP and decreased again until 2.7 kyr cal BP when they abruptly dropped and reached their minimum prior to a rapid increase until 2 kyr cal BP (to 0.87). The values again dropped abruptly and remained low before increasing from 0.2 kyr cal BP.

### 4. Discussion

#### 4.1. Heterogeneity of catchment samples

We found a large diversity of brGDGT distribution patterns in the catchment area. On a global scale, brGDGT distribution is correlated with air temperature and soil pH (e.g., Weijers et al., 2007; De Jonge et al., 2014a). The restricted sampling area (1.5 km²) leads to minimal spatial air temperature variations. The diversity of brGDGT distribution patterns may reflect the different environment types found there: coniferous and deciduous forests, grassland used as cattle pasture, peat bog, and marsh (Figs. 1 and 4B;
Compositional analysis of brGDGT distributions from catchment and sediment samples. Compositional analysis based on the fractional abundances of the 18 brGDGTs in the surface samples (IIIa\(^0\) was not considered) at Lake St Front including catchment soils and surface and sub-surface sediments (0–50 cm, \(n = 37\)). A. Scores of the brGDGT compounds on PC1 and PC2. B. Scores of the surface sediment (circles), waterlogged (filled diamonds), and other soil (open diamonds), stream (squares), and shoreline samples (crosses) along with their reference names (see Table 1). The environment of the samples has been identified as woodland (dark green), grassland (light green) or peaty (brown). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Weijers et al., 2011; Ayari et al., 2013; Huguet et al., 2013; Naehler et al., 2014; Liang et al., 2019). Nonetheless, the variability observed, even within each type of environment, suggests that this factor may not have the greatest influence (Weijers et al., 2010; Buckles et al., 2014b).

The proximity of high water content samples on PCA (Fig. 4B) and their brGDGT distributions similar to sediments (Table 5) suggests that soil water content may be an additional factor influencing brGDGT distributions (Weijers et al., 2010; Loomis et al., 2011; Buckles et al., 2014b; Naehler et al., 2014; Dang et al., 2016). However, Dang et al. (2016) found an opposite tendency in brGDGT distributions in humid soils (higher brGDGT I abundance and lower brGDGT III abundance), which suggests that water content may not be the most determinant factor of brGDGT distribution. Instead, pH is a better candidate to explain the diversity of brGDGT distribution patterns observed in catchment samples.

4.2. Significant brGDGT in situ production in the lake

Numerous studies have reported discrepancies in brGDGT distributions between surface sediments and soils (Tierney et al., 2010; Loomis et al., 2011, 2014; Sun et al., 2011; Wang et al., 2012; Buckles et al., 2014a,b; Günther et al., 2014; Naehler et al., 2014; Hu et al., 2015; Cao et al., 2017), suggesting that in situ production can occur in a wide range of lacustrine environments. The main distinguishing feature for brGDGT distributions between catchment samples and sediments in Lake St Front is the presence of brGDGT IIIa only in the latter (Fig. 3). The brGDGT IIIa has never been found above detection limits in soils (De Jonge et al., 2014a; Weber et al., 2015, 2018) which suggests that this brGDGT results from in situ production in the lake (Weber et al., 2015). In situ production is also evidenced by the clustering on PCA (Fig. 4B) revealing different overall brGDGT distribution patterns between surface sediments and catchment samples (lower abundances of brGDGT I, higher abundances of brGDGT III, and higher IR\(_{Me}\) and IR\(_{Me}\) in sediments than in soils; Fig. 3, Table 4). The brGDGT distribution pattern in sediments in Lake St Front is consistent with those found in cold lakes (Sun et al., 2011; Zink et al., 2016) and some Chinese lakes (Dang et al., 2018).

Additional evidence for the in situ production of brGDGTs in Lake St Front is provided by the relative homogeneity of the surface sediment group, which contrasts with the heterogeneity of the soil signatures in the catchment area (Fig. 4B). A locally higher proportion of detrital inputs gave a brGDGT signature slightly different in three surface and sub-surface sediment samples which was illustrated by the lower value of the \(\sum \)IIIa/\(\sum \)Ia ratio (1A-55, D1a and D1b; Fig. 4B, Table 5).

Preferential transport or degradation seem unlikely since similar chemical structures probably have similar degradation rates (Schouten et al., 2004; Xiao et al., 2016). BrGDGTs share the same molecular structures with only minor variations and thus they should have similar degradation rates. This assumption was confirmed by a thermal degradation experiment (He et al., 2012) which showed a decrease of brGDGT concentrations with increasing temperature without a change in relative abundances. So, despite the low surface and shallow depth of Lake St Front, in situ production of brGDGTs is significant and confirms the necessity of testing for brGDGT origin in all lake studies.

4.3. Test of the existing tools to discriminate brGDGT sources

A comparison of brGDGT distributions in soils and sediments leads to the conclusion that there is in situ production in Lake St Front. We compared these results with those of the existing tools for brGDGT source determination. The weighted average number of cyclopentane moieties for the brGDGTs I and II of our soil and sediment samples did not exceed 0.4, which corresponds to the range of values of global soils. This indicates a terrigenous source for branched tetraethers present in sediments (Sinninghe Damsté, 2016; Table 5). The degree of methyl branching of the brGDGTs in our samples supports the same conclusion: the fractional abundances of tetra-, penta- and hexamethyl brGDGTs correspond with those in global soils (Sinninghe Damsté, 2016; Table 5). The tools developed in the marine realm by Sinninghe Damsté (2016) do not discriminate sediments and soils of Lake St Front.
Fig. 5. Sedimentological, geochemical, and palynological evolution of the Holocene recorded at Lake St Front. A. Simplified sedimentation rate obtained from the Bacon program. B. Magnetic susceptibility. C. Total Organic Carbon (TOC, Rhoujaji, 1995). D. Percentage of arboreal pollen (brown curve) and percentages of pollen from thermophilous (beige area, sum of Acer, Corylus, Hedera, Ilex, Lonicera, Ostrya, deciduous Quercus, Quercus ilex t., Pistacia, Sambucus, Sorbus, Tilia, Ulmus, Viburnum, Viscum) and mesophilous (green area, sum of Abies, Carpinus, Fagus) tree pollen. E. Cumulative percentages of pollen of nitrophilous taxa (light green area, Plantago lanceolata, P. major, Rumex, Chenopodiaceae, Urtica), cereals (orange area, Cerealia, Secale), and Juglans (burgundy area). F. C/N ratio (Rhoujaji, 1995); note that the axis has been reversed for improved readability. The dashed line represents the upper limit of production in the aquatic realm. G. BIT index with analytical errors (1σ values); note that the axis has been reversed. H. Fractional abundance of IIa′ with analytical errors (1σ values). I. IIIa/IIa ratio (red curve) with analytical errors (1σ values). The dashed lines represent the upper limit of production in the terrestrial realm and the lower limit of production in the aquatic realm defined by Xiao et al. (2016). J. 14C calibrated ages and 210Pb dates. Shaded rectangles highlight the periods when ΣIIIa/ΣIIa values are below the upper limit for soil origin. The period of permanent human occupation is marked by a hatched symbol. RP: Roman Period, MP: Modern Period. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
St Front, possibly due to the reduced size of the watershed and the shallow depth of the lake which guarantee very similar conditions for brGDGT-producing bacteria.

The BIT index values in surface sediments (0–10 cm) were close to 1 (Table 5) indicating that brGDGTs predominate over crenarchaeol. This also denotes a prevailing terrigenous source of branched tetraethers in Lake St Front sediments or a water depth that is too shallow for crenarchaeol production (Tierney et al., 2010; Wang et al., 2019). However, the use of the BIT index as a tool to discriminate brGDGT source is questioned, in particular due to the existence of in situ production (e.g., Sinninghe Damstè, 2016).

All existing GDGT source indices point to a terrigenous source of brGDGTs except the \([\text{IIa}/\text{IIa}]\) ratio which suggests a mixed origin. Xiao et al. (2016) used this ratio to distinguish brGDGT origins. When comparing soils and marine sediments, 90% of the soils from the global soil database had a ratio lower than 0.59 and 90% of the marine sediments tested had a ratio higher than 0.92. While the \([\text{IIa}/\text{IIa}]\) ratio has never been used in the lacustrine realm (Xiao et al., 2016), it offers a contrasting picture when soil and lake samples are considered and provides evidence for the mixed origin of brGDGTs in surface sediments. The catchment samples exhibited values below the limit for terrigenous origin, except the stream sample R3 which showed slightly higher values, while surface sediment samples showed values above the soil limit and below the limit for aquatic origin consistent with a mix of aquatic and soil production (Table 5).

In the modern situation, brGDGTs in Lake St Front sediments have thus a mixed origin: aquatic and terrigenous. Analysis of catchment samples and surface sediments revealed that their brGDGT distribution patterns were significantly different. This constitutes a major problem for paleotemperature reconstructions. In fact, such reconstructions rest on the use of two indices, the methylation index of branched tetraethers (MBT) and the cyclization ratio of branched tetraethers (CBT) calculated from the brGDGT abundances (see Supplementary Text 3). In sediments, the mixing of brGDGTs of distinct origins characterized by significantly different brGDGT distribution patterns can thus introduce a bias in paleotemperature reconstruction (see Supplementary Fig. S3 and Supplementary Text 3). Prior to any attempt of paleotemperature reconstruction from brGDGTs in lake sediments, it is necessary to determine the brGDGT origin and if mixed origin is detected, to evaluate the proportion of each source to correct the bias. In the present situation, the \([\text{IIa}/\text{IIa}]\) ratio appears to be the single tool based on brGDGT abundances able to discriminate soil and aquatic sources. It can thus be applied in the past to reconstruct past changes of brGDGT sources.

### 4.4. Evolution of brGDGT sources during the Holocene

We compared the \([\text{IIa}/\text{IIa}]\) values with the C/N ratio, an established tool for determining organic matter origins (e.g., Stein and Littke, 1990). The decrease of \([\text{IIa}/\text{IIa}]\) along the sedimentary sequence, consistent with the other proxies, indicated an increase in the proportion of terrigenous material (Fig. 5). Vegetation cover development (continuous increase of AP percentage; Fig. 5D) and soils limited the erosion of the magmatic bedrock (decrease of magnetic susceptibility; Fig. 5B) and enhanced organic matter (OM) production (increase of Total Organic Carbon, TOC, from 10.5% to 26%; Rhoujjati, 1995). The forest cover also enhanced bacterial community development. During the Early Holocene, the lake became eutrophic and primary production increased as indicated by xanthophyll blooms (Rhoujjati, 1995) and high abundances of IIIa* (Fig. 5H). The proportion of terrigenous OM quickly increased compared to lacustrine OM which was illustrated by the decrease of \([\text{IIa}/\text{IIa}]\) and increase of C/N (Rhoujjati, 1995) until the values of both ratios moved out of the aquatic production realm (\([\text{IIa}/\text{IIa}] < 0.92\) and C/N > 10; Fig. 5F and I; Stein and Littke, 1990).

The overall trend of increasing terrigenous inputs was interspersed by three abrupt events from 6 to 5.5, 2.8 to 2.5, and 2 to 0.2 kyr cal BP which were characterized by a sharp decrease in \([\text{IIa}/\text{IIa}]\) below the limit for a soil origin and a decrease in the fractional abundance of IIIa* (Fig. 5H and I). These events seem to correspond to higher terrigenous inputs as indicated by the higher sedimentation rate, MS, and TOC (Fig. 5A–C; Rhoujjati, 1995) and an increase in primary production (i.e., lower C/N and BIT index, in conjunction with higher \([\text{IIa}/\text{IIa}]\) and fractional abundances of IIIa*; Fig. 5F–I; Rhoujjati, 1995) that followed each decrease in \([\text{IIa}/\text{IIa}]\).

The variation in the \([\text{IIa}/\text{IIa}]\) ratio suggests that the brGDGT sources drastically changed throughout the Holocene. In the late Younger Dryas, brGDGTs were mainly of lacustrine origin (high \([\text{IIa}/\text{IIa}]\) values and fractional abundances of IIIa*; Fig. 5H and I) while during the Late Holocene they mostly originated from the catchment area. These source changes led to changes of the brGDGT distributions which could, by analogy with present situation (see Supplementary Fig. S3 and Supplementary Text 3), bias paleoclimatic reconstructions based on brGDGTs. Thus, it is necessary to test for brGDGT source changes in the past.

#### 4.5. Significance of the \([\text{IIa}/\text{IIa}]\) ratio as a proxy for brGDGT origin

The \([\text{IIa}/\text{IIa}]\) ratio compares the abundances of the brGDGTs containing two methyl groups (hexamethylated forms) with brGDGTs containing one methyl group (pentamethylated forms) and so, it reflects the number of brGDGT methyl groups. Weijers et al. (2007) and Peterse et al. (2012) found a positive correlation between the mean annual air temperature (MAAT) and the methyl indices of brGDGTs (MBT and MBT*). The MBT index corresponds to the proportion of brGDGTs without a methyl group (tetramethylated forms) compared with all forms and reflects the number of methyl groups of the brGDGTs. In contrast, using the global soil database from Peterse et al. (2012), we found a weak negative correlation between \([\text{IIa}/\text{IIa}]\) and MAAT (\(R^2 = 0.17, n = 272, p < 0.0001\); Supplementary Fig. S4). This correlation was mainly due to several MAAT values that were > 20 °C. By removing these values, the correlation was much weakened (\(R^2 = 0.05, n = 227, p = 0.006\)). In conclusion, we found that for soils in temperate climates like Lake St Front there was a very weak correlation between \([\text{IIa}/\text{IIa}]\) and temperature.

To test this correlation in other sediments, we used the global marine database of Xiao et al. (2016). As the sea surface temperatures are not provided in the database, we used latitude since latitude is strongly linked with water and air temperature. Considering all the sediments of the database, the negative correlation between \([\text{IIa}/\text{IIa}]\) and latitude is relatively weak (\(R^2 = 0.16, n = 1261, p < 0.0001\)). Considering only surface and sub-surface sediments, the correlation was weaker (\(R^2 = 0.03, n = 271, p = 0.008\)). The values of \([\text{IIa}/\text{IIa}]\) in marine sediments were weakly correlated with latitude and so with water and air temperature.

We also tested the correlation in lakes using available data from modern surface sediments in lakes (Tierney et al., 2010; Loonism et al., 2011, 2012, 2014; Wang et al., 2012; Günther et al., 2014; Li et al., 2016; Zink et al., 2016; Dang et al., 2018; Russell et al., 2018; Weber et al., 2018; Ning et al., 2019; Supplementary Table S3). Considering all the sediments of the database, we obtained a weak but significant negative correlation between \([\text{IIa}/\text{IIa}]\) and MAAT (\(R^2 = 0.35, n = 359, p < 0.0001\); Supplementary Fig. S4). Once again, this correlation seems to be mainly due to several MAAT values that were > 20 °C, the correlation became...
weaker when removing them ($R^2 = 0.23$, $n = 269$, $p < 0.0001$). Furthermore, the occurrence of in situ production introduces significant variability which seems linked with different mixing percentages of soil and aquatic brGDGT sources rather than with MAAT. The correlation between $\Sigma IIa/\Sigma Ila$ and MAAT for sediments from lakes with in situ production of brGDGTs is very weak ($R^2 = 0.04$, $n = 128$, $p = 0.02$). Shifts in brGDGT sources in temperate environments leads to $\Sigma Ila/\Sigma Ila$ variations more important than $\Sigma IIa/\Sigma Ila$ variations due to temperature changes as the slope of the correlation with temperature is very small and the temperature change during the Holocene limited to a few degrees (e.g., Marcott et al., 2013; Pei et al., 2017).

Furthermore, lake sediment $\Sigma IIa/\Sigma Ila$ ratios show a good correlation with C/N ($R^2 = 0.51$, $n = 135$, $p < 0.0001$), which is also a source indicator, showing that the $\Sigma IIa/\Sigma Ila$ ratio effectively reveals the changes of brGDGT sources (Supplementary Fig. S5 and Supplementary Text 4). The correlation between $\Sigma IIa/\Sigma Ila$ and the fractional abundance of IIa⁺, an indicator of the proportion of in situ production, is weaker but still significant ($R^2 = 0.32$, $n = 143$, $p < 0.0001$). While IIa⁺ may be a reliable indicator for the occurrence of in situ production, it is not an ideal indicator for the proportion of in situ production compared with soil production. IIa⁺ had high variability which may be due to a variable production rate or stem from analytical bias as this brGDGT was only present in low concentrations making its detection and quantification subject to greater error.

Threshold values used to distinguish aquatic, mixed and soil production domains were proposed by Xiao et al. (2016). The value for soil production was obtained from the global soil database and can thus be used confidently here. However, the value used for aquatic production was based on marine sediments and the actual lake values might differ. This should be tested for the use of $\Sigma IIa/\Sigma Ila$ to make quantitative assessment of terrigenous brGDGT proportions.

The influence of temperature on the $\Sigma IIa/\Sigma Ila$ ratio of lake sediments in temperate environments seems too weak to have significantly modified the values of the ratio during the Holocene. Shifts in brGDGT sources have a stronger influence on $\Sigma IIa/\Sigma Ila$ values. The variations of the $\Sigma IIa/\Sigma Ila$ ratio observed in Lake St Front sediment through the Holocene can be reliably interpreted as brGDGT source shifts.

4.6. Impact of anthropogenic activities and vegetation changes on brGDGT distribution

The first decrease in $\Sigma IIa/\Sigma Ila$ values coincides with a shift from a thermophilous to mesophilous forest between 7.4 and 5.6 kyr cal BP (Fig. 5D). This vegetation change is also recorded elsewhere in the Massif Central (Faure, 2012; Lavrieux et al., 2013a; Cubizolle et al., 2014; Miras et al., 2015; Chassiot et al., 2018) and is thought to result from regional climatic change. Such vegetation changes progressively led to soil destabilization and thus increased terrigenous inputs into the lake of OM and magnetic minerals from the magmatic bedrock. As OM was transferred from the catchment to the lake, the proportion of soil brGDGTs increased in the lake until it dominated in situ production.

Palynological and archeological records indicate a gradual increase in human activities and their effects on erosion dynamics in the region since 6 kyr cal BP (e.g., Daugas and Raynal, 1989; Cubizolle et al., 2004; Miras et al., 2004). Pollen assemblages mark the beginning of a permanent human presence around Lake St Front from 2850 to at least 200 yr cal BP, although some phases are visible corresponding more or less with archeological periods. Each period begins with increased deforestation (a decrease of 50% of AP in 1000 years; Fig. 5D) occurring during the First Iron Age (2850–2100 yr cal BP, 900–150 BC), the Gallo-Roman period (2100–1560 yr cal BP, 150 BC–400 AD), the Middle Ages (1560–500 yr cal BP, 390–1450 AD), and during modern times. In addition, each period is associated with increased arboriculture (Juglans; Fig. 5E and Supplementary Table S1), agriculture, and pastoralism in close vicinity of the lake as indicated by the increased occurrence of anthropogenic taxa such as nitrophilous taxa and cereals (e.g., Secale; Fig. 5E and Supplementary Table S1) whose pollen only disperse over short distances (Vuorela, 1973; Broström et al., 2008). Furthermore, at the beginning of each period, $\Sigma IIa/\Sigma Ila$ drops below the limit for a soil origin which points to a mostly terrigenous source for brGDGTs in sediments. The Gallo-Roman period (2100–1560 yr cal BP, 150 BC–390 AD) also shows an increase in sedimentation rate which could mark the period of greatest land use with agricultural production peaking around 1750 yr cal BP (200 AD; Fig. 5A and E). The increase in magnetic minerals in combination with the simultaneous decrease in OM inputs at the beginning of the Middle Ages is characteristic of exhausted agricultural soils, as continued erosion exposes the underlying magmatic bedrock. Archeological records confirm long term human occupation in the direct vicinity of Lake St Front (Dendievel, 2012 and References therein). These phases of intense land use were interspersed by brief decreases in human activity as shown by decrease in anthropogenic taxa, partial recovery of forest cover, and higher $\Sigma IIa/\Sigma Ila$ values.

The simultaneity of the periods of vegetation changes in the catchment area of anthropogenic or climatic origin with the changes of sedimentary fluxes and $\Sigma IIa/\Sigma Ila$ suggests that the changes observed in brGDGT distributions resulted from these vegetation changes. Human activities led to increased erosion by changing soil use and thus increased the quantity of OM and terrigenous brGDGTs transferred to the lake. As brGDGT distributions differ according to their origin (terrigenous vs aquatic), anthropogenic activities and climate-based vegetation changes both impact brGDGT distributions in lacustrine sediments. Changes of sedimentary fluxes thus represent a potential bias for brGDGT analysis in lakes since they are connected with their catchment which can experience vegetation changes of anthropogenic or climatic origin. It appears necessary to understand the evolution of brGDGT sources in the past before reconstructing temperature using brGDGT distributions in lakes to detect this bias.

5. Conclusions

Characterization of brGDGT distributions in and around Lake St Front allowed the determination of their sources (terrigenous vs aquatic). Terrigenous inputs were high but significant in situ production was also detected. This indicated that brGDGTs in Lake St Front sediments have a mixed origin. Different published brGDGT source indices, weighted average number of cyclopentane moieties, degree of methyl branching of the brGDGTs and $\Sigma IIa/\Sigma Ila$ ratio, defined from continental and marine realms, were tested in Lake St Front sediments and nearby soils. Only the $\Sigma IIa/\Sigma Ila$ ratio, applied for the first time in a lake, was able to fully trace the varying abundances of terrigenous brGDGTs. The $\Sigma IIa/\Sigma Ila$ ratio should be tested in other lakes to determine its reliability in a variety of freshwater environments.

When applied to the sedimentary archives, a multiproxy analysis revealed that terrigenous inputs into the lake varied throughout the Holocene. A brGDGT analysis highlighted a gradual shift from aquatic to terrigenous sources with several periods of strong terrigenous inputs. These periods were synchronous with vegetation changes in the catchment area, causing soil destabilization and increased erosion. The two most recent events were associated
with a continuous human occupation of the lake area from 2.8 kyr cal BP, leading to the development of agriculture, pastoralism, and deforestation. Thus, erosion dynamics that were initially driven by climatic changes were increasingly affected by human activities which became the principal forcing factor after 2.8 kyr cal BP. This demonstrated that human activities and vegetation changes could significantly impact brGDGT distributions by modification of erosion dynamics and lead to changes in the relative proportions of terrigenous and aquatic brGDGTs.

Few paleoclimatic studies based on brGDGTs in lakes have involved identification of brGDGT sources and their potential changes over time. Studies should always control this parameter as in situ production can occur in a large range of environments including small and shallow lakes. The brGDGT source can be determined by comparing brGDGT distributions between sediments and catchment soils in the modern sets of data and by using the existing tools to determine brGDGT origin after a test in the present situation. It is also essential to associate brGDGT analysis with a multiproxy study of the evolution of the quantity of eroded soil from the catchment area delivered to the lake to identify potential external perturbations of the lacustrine ecosystem and influences on brGDGT distribution. In particular, pollen analysis can be very helpful to detect anthropogenic perturbations. These controls are necessary to prevent bias which can affect paleoclimatic studies that attempt temperature reconstructions based on lacustrine archives.

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Appendix A. Supplementary material

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