Integration of ground-penetrating radar, high-resolution seismic and stratigraphic methods in limnogeology: holocene examples from western Swiss lake deposits

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Abstract

Cette étude porte sur l’enregistrement sédimentaire de quelques lacs de Suisse occidentale ainsi que sa relation avec les changements hydrologiques et climatiques durant l’Holocène. Cette recherche intègre des informations géomorphologiques continues, du domaine terrestre au domaine lacustre profond, fournies par deux méthodes d’imageries géophysiques et une analyse "multiproxy" de carottes sédimentaires. Les données géophysiques ont été calibrées par des descriptions sédimentologiques détaillées et des mesures pétrophysiques haute résolution afin de déterminer les facteurs de production et de distribution des sédiments lacustres. De plus, les analyses minéralogiques, physico-chimiques et minéralogiques magnétiques permettent de déterminer les paramètres contrôlant les conditions paléoenvironnementales. Cette thèse comporte trois parties: 1) une phase de tests des méthodes géophysiques ; 2) une application de ces dernières sur le "site calibré" de la Baie de Genève (Léman) ainsi qu’une 3) étude intégrée complète (géophysique, sédimentologique et stratigraphique) du "site [...]"

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Chapter 5

Holocene hydrological and climatic changes inferred from an integrated multiproxy analysis of Lakes Joux and Brenet sedimentary records

5.1 Introduction

The high-quality GPR and HRS data obtained during the geophysical test phase (see chapter 3) guided the selection of certain sites at Lakes Joux and Brenet (Joux Valley) for a ‘fully integrated’ limnogeological study. The term ‘fully’ is related to the present work and is employed here in the sense that all methods described in chapter 2 are applied in order to interpret the extracted/measured proxies in terms of their climatic and hydrological significance. Because only few sedimentological studies have been published on these lakes (two on Lake Joux and none on Lake Brenet, see section 5.1.7), they are considered as ‘exploration sites’.

5.1.1 Geographical setting

The Joux Valley is situated in the Jura Mountains of western Switzerland, 50 km north of Geneva and at an altitude of about 1000 m amsl (Figure 5.1). Surrounded by the Risoux mountain range (1419 m amsl) to the northwest and the Mont Tendre mountain range (1679 m amsl) to the southeast, this valley is oriented southwest-northeast and extends over ca 30 km from Lake Les Rousses (1059 m amsl, France) to the Pierre Punex Pass (1060 m amsl) and the Dent de Vaulion mountain (1483 m amsl). Its thalweg is about 1 km wide and is occupied by a wide area of meadows and peat-bogs scoured by the Orbe River in the southwest.

Two freshwater lakes are located in its northeastern part:

- Lake Joux lies between 46°40'05" N/6°19'51" E and 46°36'41" N/6°14'27" E (169127/515220 and 162932/508272 in Swiss coordinates);

- Lake Brenet is located between 46°40'44" N/6°19'51" E and 46°39'57" N/6°19'01" E (170396/515278 and 168894/514169 in Swiss coordinates).
5.1.2 Geological setting

The valley is characterised by a series of parallel crests and valleys of an anticline-syncline system oriented southwest-northeast. This regularity is disrupted in the northeast by the Dent de Vaulion fault zone which closes the valley, allowing Lakes Joux and Brenet to develop (Aubert, 1941a,b). These two tectonic lakes are located in thalwegs of synclines filled with glacial sediments. The anticlines of the Risoux and Mont Tendre mountain ranges consist of an Upper Jurassic calcareous complex. The Cretaceous formations generally shape the bottom of the valleys and fill the main synclines (Figure 5.2).

Stratigraphy

The stratigraphy of the Joux Valley is dominated by Mesozoic limestones. The oldest rocks cropping out in the valley are the Argovian limestones (Upper Jurassic).

Mesozoic

Jurassic formations mainly consist of richly fossiliferous marine limestones and marls, except for the Purbeckian which is represented by freshwater marly limestones with fine sandstones and breccias.

Cretaceous formations are represented by fossiliferous limestone and marl alternances, except for the glauconitic sandstones of the Upper Aptian and Albian. The Cretaceous formations are generally thinner, less strong, richer in iron oxides/hydroxides (yellowish-beige color) and more marly than the Jurassic ones.

Tertiary

Eocene formations consist of dark clays containing iron oxide nodules.

Oligocene and Miocene formations contain various lacustrine molassic sediments including marls, limestones, conglomerates, clayey siltstones and “gompholite” (Jurassian calcareous conglomerate).

Quaternary

Glacial sediments in the valley are of Jurassic origin. This autochthonous material has a relatively uniform aspect. In the synclines, it mainly comprises plastic clayey ground-moraines containing small striate rocks. Lateral and superficial moraines forming vallums and hills are less clayey and enriched in striate boulders of different sizes.

Post-Glacial sediments have many origins. Deltaic gravels derived from fluvioglacial and glaciolacustrine processes, rockfall debris and alluvial fans. Lacustrine chalk consists of greyish-white chalky marl rich in freshwater mollusk shells. Peat-bog deposits are found in morainic lakes and in small glacial-clay basins.

Tectonics

This region can be tectonically divided into two different zones:

- The Joux Valley proper outlined by the continuous and regular Mont Risoux and Mont Tendre mountain ranges;
- The Dent de Vaulion fault zone in the northeastern end of the Joux Valley.

Joux Valley proper

This region is characterised by parallel and continuous folds. It includes the following five main tectonic units from southeast to northwest:

- The tectonic unit of the Mont Tendre mountain range is composed of the small Crosets Cretaceous syncline and two anticlines (Mont Tendre and Bucley). The latter is deformed by transcurrent faults;
- The Joux syncline forms the depression zone of the Joux Valley and is filled by Lake Joux, alluvium, glacial and peat-bog deposits;
- The Côte anticline has a strike fault crossing its summit;
- The Lake Brenet or Solliat syncline is a Cretaceous depression compressed between two faults and filled by Lake Brenet;
- The Risoux anticline is a relatively flat anticline more than 10 km long.

Dent de Vaulion fault zone

The Dent de Vaulion fault zone is a complex tectonic dislocation that affects all the anticlines and synclines mentioned above. This dislocation results from two successive tectonic influences: numerous transcurrent faults (e.g. Pontarlier-Vallorbe, Pierre Punex and La Dernier) and the Dent de Vaulion overthrust, which displaces the Lake Brenet portion of the Cretaceous content of the Joux syncline.
5.1.3 Glacial history

Glacial deposits in the Joux Valley originate exclusively from the Jura Mountains. The lack of alpine material implies that the Rhône glacier never entered the valley. Therefore, all of the morainic material is the result of indigenous glaciers (Agassiz, 1843; Venetz, 1843) and is apparently all of Wurmian age.

Wurmian glaciation

The elevation of Wurmian glacial deposits in the valley implies that the Joux glacier reached an altitude of ca 1250 m asl with an ice thickness of at least 350 m (Aubert, 1938, 1943). It was fed
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Figure 5.3: Quaternary glaciers of the Joux Valley (after Aubert, 1938)

by many secondary glaciers from the Risoux and Mont Tendre mountain ranges (Figure 5.3). The continuous northeastward flow of the ice led to the convergence with the Rhône glacier through the higher Mollendruz, Pétra Félix and Pierre Punex passes. This flow was blocked at the Rhône glacier confluence, making the Joux glacier a nearly stagnant, flat icecap with fluctuations directly related to those of the Rhône glacier.

Recurrence phases are associated with the Rhône glacier retreat. The flow of the Joux glacier accelerated when the alpine dam disappeared, ensuing ice discharge from the Joux Valley.

The break-up of the glacier was obstructed by the Pierre Punex Pass (1060 m amsl), behind which the ice altitude remained at ca 1100 m amsl for a relatively long period. The subsequent retreat caused the formation of submerged promontories or "monts" (mounts) along the shores of Lake Joux. Some of these mounts are interpreted as retreat moraines, while others as "roches moutonnées" (Aubert, 1938). Later, the glacier stagnated in the upper part of the valley, about 6 km southwest of Lake Joux at le Bas du Chenit. During this time, the northeastern part of the thalweg was occupied by the “1060 m Lake”. Many small deltaic deposits confirm the existence of this high lake level. The opening of new sinkholes down valley probably led to the lowering of the lake down to its present level at ca 1004 m amsl (Aubert, 1943).

5.1.4 Climate

The Joux Valley has a humid and cool continental climate with a mean annual temperature of 6 °C. The mean annual precipitation ranges from 1500 mm to 2000 mm, ca 30 % of which is snow. Natural drainage dominates evaporation processes (Aubert, 1969). About 30 % of the annual precipitation is returned to the atmosphere by evapotranspiration (Burger, 1959). The valley encapsulates an air mass of 28.5 km long, ca 1.5 km wide and up to 58 m thick (Bouët, 1972). During calm and clear weather, nocturnal radiation can cool this immobile mass enough to create a thermal inversion. In winter, under continental high-pressure conditions, the valley is particularly cold. Oriented along the valley’s axis, the dominating winds are:

- The “Bise” is a cold and dry wind blowing from the northeast with frequency and duration that increase in winter;
- The “Sudois” or “Vent” is a relatively warm wind that comes from the southwest. It blows in all seasons and is generally associated with precipitations.

There is snow in the valley during about five months per year. The lakes freeze every winter
but during warm winters, some parts of Lake Joux freeze later because of underwater warm springs (Aubert, 1912). These springs have been observed in the northeastern (Forel, 1898) and southern (Aubert, 1912) parts of the lake.

5.1.5 Hydrography

With dimensions of ca 30 km long and ca 9 km wide and a surface watershed area of 211 km², the Joux Valley is the largest hydrological closed basin of the Swiss Jura Mountains (Jacot-Guillarmod, 1909). The main inflow is the Orbe River, which has its source at Les Rousses in the French Jura. This river flows through Lake Rousses and feeds Lake Joux some 15 km downstream. The mean annual discharge of the Orbe River before entering Lake Joux is 2.2 m³/s (Paquet, 2002). The discharge from the valley is exclusively underground seepage by the karstic hydrogeology of the region. This complex drainage system extends the surface watershed area into the subsurface. The water-retaining stratum is principally created by glacial clays and the younger Hauterivian marls and secondarily by the Purbeckian, Kimmeridgian and Sequanian marls.

The main hydrographical characteristics of Lakes Joux and Brenet are given in Table 5.1. Lake Joux, the largest lake in the Joux Valley, is about 9 km long and 1 km wide (Figure 5.4). The lake bottom has an irregular morphology with a wide platform at the mouth of the Orbe River in the southwest and numerous sublacustrine mounts (see Section 5.1.3) located close to the shores. The lake is fed by the Orbe River in the south, the Lyonne River in the east and several brooks and underwater springs. Except for the northward outlet via Lake Brenet, the water is drained via sinkholes beneath the southwestern part of the lake. Lake Brenet is about 1.6 km long and 0.5 km wide and has a regular bathymetry. The lake is fed by the channel from Lake Joux, a few brooks and underwater springs. The water outflows through sinkholes beneath the southern and northwestern parts of the lake.

The water lost via sinkholes emerges at the Vaulclusian Spring of the Orbe River about 2.5 km NE from Lake Brenet (Forel, 1899). Since 1901 the overflow of the two lakes runs through the underground drainage system of la Tornaz, which feeds the hydroelectric plant of La Dernier near Vallorbe. The construction of this plant is responsible for sealing most of the sinkholes and replacing the natural channel between the two lakes by an artificial watercourse1. The latter, built in 1901, was replaced in 1942 by a fender wall in order to allow a differential control of the level of these lakes (Figure 5.5). Despite the sealing of the sinkholes and the general lowering of the lake levels, Aubert (1948) estimated a natural water leakage of more than 0.5 m³/s.

5.1.6 Limnology

Thermal stratification

The portion of the solar radiation absorbed as heat in a lake affects the thermal structure of water masses. The thermal stratification of Lakes Joux and Brenet is typical of cool temperate regions that undergo strong contrasts in seasonal conditions (Figure 5.6). These lakes are dimictic with turnover periods in April and October, a direct stratification in summer and an inverse stratification in winter. The Lake Joux summer thermocline lies between 9 m and 13 m depth (SESA data).

Chemical stratification

Chemical stratification occurs when the physical stratification is well established. Solar energy is converted into chemical energy by photosynthetic processes that release oxygen as a waste product. Like irradiance, photosynthesis decreases nearly exponentially with depth. The photic zone of Lakes Joux and Brenet extends down to ca 10 m depth. The rate of photosynthesis in this zone is limited by the supply of nutrients to macrophytes, algae and phytoplankton. Eutrophication of these lakes is caused by high concentrations of phosphorus. In the upper layers, the excess of this nutrient causes significant algal growth and an increase in dissolved

1http://www.romande-energie.ch
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Figure 5.4: Hydrographical map of lakes Joux and Brenet. The background map is the LiDAR DEM image of Vaud (2002). The X and Y axes show Swiss coordinates [m].

Figure 5.5: Lake-level fluctuation curves for the period 2002-2005 (MeteoSuisse¹ and SESA² data).
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Figure 5.6: Temperature vs depth curve for Lake Joux, 1995-2004 mean values (after Fiaux et al., 2006). The thermocline gradually sinks during the autumn cooling.

Table 5.2: Littoral zone characteristics of Lakes Joux and Brenet (after Lods-Crozet et al., 1995). * Percentages of lake surface, ** Macrophytes types.

<table>
<thead>
<tr>
<th></th>
<th>L. Joux</th>
<th>L. Brenet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural coastline [%]</td>
<td>91</td>
<td>99</td>
</tr>
<tr>
<td>Wide littoral [%]</td>
<td>76</td>
<td>23</td>
</tr>
<tr>
<td>Macrophytes * [%]</td>
<td>21</td>
<td>35</td>
</tr>
<tr>
<td>Emergent ** [%]</td>
<td>7.2</td>
<td>18</td>
</tr>
<tr>
<td>Floating-leaved ** [%]</td>
<td>&lt; 0.5</td>
<td>0</td>
</tr>
<tr>
<td>Submersed ** [%]</td>
<td>92.5</td>
<td>82</td>
</tr>
</tbody>
</table>

Littoral flora

The littoral configurations of Lakes Joux and Brenet (Table 5.2) allow the prolific expansion of macrophyte vegetation. The exuberant development of this flora is an indication of the eutrophic state of the lakes. Depending on the depth of the photic zone and on the lake-bottom texture, macrophyte populations in Lakes Joux and Brenet reach a maximum depth of 4.5 and 6 m, respectively (Lods-Crozet et al., 2006).

Macrophyte distribution in shallow water is often used for littoral lake-bottom zonation (Figure 5.7). The eulittoral zone encompasses the region of seasonal water level fluctuations and is subject to wave disturbances. The infralittoral zone is subdivided into three zones according to the macrophyte types. Emergent macrophytes live on aerial or submersed soils, from the point at which the water table is about 0.5 m below the soil surface to about 1.5 m water depth (upper littoral). Lakeward, water depths from 0.5 to 3 m are the host of the floating-leaved macrophytes of the middle littoral. Beyond this area, the lower littoral, from about 0.5 m depth to the lower limit of the photic zone, is the region of submersed macrophytes. The submersed macrophytes constitute the dominant vegetation, comprising 60 % and 49 % of Chara spp in Lakes Joux and Brenet, respectively (Lods-Crozet et al., 1995). Below the littoral zone (combined eulittoral and infralittoral zones), the littoriprophundal transition zone is colonised by scarce photosynthetic forms of green plants. Finally, the profundal zone is characterised by the absence of vegetation.

Macrophytes play an essential role (physical, chemical and biological) in littoral lacustrine environments. The most important contributions are the following:

- Sediment stabilisation: the sediment distur-

oxygen content. The subsequent oxydative breakdown of dead algal material (mineralisation) leads to oxygen depletion. Despite the biannual turnover period, the end of summer and the fall are characterized by a lack of oxygen, frequently lower than 4 mg/l, in the deep layers of Lake Joux (Fiaux et al., 2006). The carbon dioxide (CO$_2$) content increases by the oxidative mineralisation, causing the pH to decrease in the hypolimnion.

In the geological context of the valley, the waters of Lakes Joux and Brenet are enriched in calcium carbonate (CaCO$_3$). These hardwater lakes contain relatively large concentrations of alkaline earth elements derived from the drainage of the calcareous bedrock. The alkalinity is also governed by contributions from atmospheric precipitation and evapotranspiration. The valley is characterised by abundant rainfall in proportion to the supply of dissolved salts from rocks and evaporation processes. Electrical conductivity values, an indirect estimation of the total dissolved solids (TDS or salinity) are relatively low in the lakes. Between rather uniform values during the spring and fall turnover periods, a conspicuous stratification in TDS can be observed.
bance induced by mechanical stresses from wind and water movements is strongly attenuated by the extensive rhizome system of anchorage, which also favors sedimentation;

- Oxidation of organic matter: the oxygen released by photosynthesis favors the oxidative mineralisation of the organic matter. This complex process is responsible for the lacustrine chalk formation;

- Primary production: macrophytes are among the main primary producers and their maximum biomass is reached in summer. Their presence creates a rich variety of environmental microzones sheltered from wave action. Intense biological activity occurs in these microzones, which includes dense populations of epiphytic complex of algae, mollusks and bacteria.

Phytoplankton

The pelagial phytoplanktonic population is dominated by the toxic cyanobacteria *Planktothrix rubescens* and *P. agardhii* (Lods-Crozet et al., 2006). Favored by the eutrophic conditions, the cyanobacterial biomass reaches its maximum in winter under the ice cover. “Sang des Bourguignons” is the local name given to red-tide blooms of this cyanobacteria.

5.1.7 Previous studies

The only published sedimentological studies of Lake Joux are those of Creer et al. (1980) and Magny et al. (2008).

Creer et al. (1980) studied the Late- and Post-Glacial sedimentary sequences from the deepest parts of Lake Joux, on which they measured the palaeomagnetic secular variation record. Core n°3, the longest sediment core (5.5 m long), was interpreted as Late-Glacial clay from 5.5 to 4.5 m, Late-Glacial clay and lime from 4.5 to 3.25 m and Post-Glacial banded lime in the uppermost part of the core. Palynological studies of the core samples allowed the determination of eight local biozones (*Joux 1* - *Joux 8*). The positive correlation between local biozones and pollen stratigraphy in the southeastern part of the Jura Mountains (Wegmüller, 1966 and Matthey, 1971) revealed two biostratigraphical hiatuses: the lack of the Older-Dryas-Allerød complex in the nearby core n°4 and a hiatus in core n°3 at around 3.3 m depth. The latter was then linked to the complex processes of ice retreat in the Joux Valley which apparently lasted about 1,000 years. Tephra from the Luacher See Volcano (East Eifel Volcanic Field, Germany) was found below a high positive peak in the magnetic susceptibility curve and aided the sediment dating.

Paleomagnetic data from their study includes magnetic susceptibility and natural remanent magnetization (NRM). The authors point out the over-
all correlation between the susceptibility and the colour of the sediment. Susceptibility data show relatively stable values except for a minimum encountered in the first half of the Post-Glacial sequence and a maximum peak at the Late-Glacial / Post-Glacial boundary. Susceptibilities and NRM intensities are similar for the Late-Glacial where Q-ratios (intensity / susceptibility) are low, but quite different for the Post-Glacial where Q-ratios are high. Inclination and declination logs show larger amplitude oscillations in the Late-Glacial sediments. ‘Magnetic’ ages of the inclination and declination features appear consistent with the biostratigraphical 1,000-year hiatus at 3.3 m in core n°3. Moreover, some discrepancies between ‘magnetic’ and ‘pollen’ ages through the uppermost 2 m of this core imply different sedimentation rates in the Joux 6,7 and 8 biozones. Despite the proximity among the different coring sites, the sediment cores indicate significant lateral sediment variations. Nevertheless, a detailed comparison of the directional signals of Lake Joux and Lake Windermere (United Kingdom) shows a notable similarity.

Magny et al. (2008) present a high-resolution record of lake-level and vegetation changes for the last millennium inferred from sedimentary and pollen analyses of a radiocarbon-dated sediment sequence from the southernmost part of Lake Joux. The evidenced multicentennial-scale lake-level fluctuations of this lake suggest that the Little Ice Age (LIA) period in the European mid-latitudes is associated with wetter climatic conditions and possible increased summer precipitation. Moreover, they propose a correlation between these variations in the hydrological cycle with changes in the general atmospheric circulation and the variation in both the oceanic circulation and solar activity. They distinguish 10 successive phases of high and low water-table levels. The periods of low water-table are marked by the deposition of organic sediments (e.g. the Medieval Warm Period) and closely coincide with phases of maximal solar activity. The opposite case (e.g. the LIA) coincides with the deposition of carbonate lake-marls.

Bruder (2003) studied the recent Quaternary deposits of the Lake Joux area. Petrophysical (MSCL) and sedimentological (WC, LOI_{560}, LOI_{1000} and hydrogen/oxygen indexes (HI/OI) of organic matter (OM)) analyses of eleven short cores led to the recognition of seven lithological units that correspond to climatic variations since 3500 yr BP. The longest core jo2001-7 (108 cm long) was extracted at the same location as core n°3 of Creer et al. (1980) and its chronological interpretation was based on the sedimentation rates calculated by the latter authors. These units comprise, from base to top:

- **Unit VII (3450-3000 yr BP)**, relatively coarse, dark-beige sediments (ca. 65% WC, 70% CaCO$_3$ and 4.5% OM) with highly variable densities and HI/OI values indicating an allochthonous origin. This unit was deposited under a warm and dry climate;
- **Unit VI (3300-3200 yr BP)**, finely laminated, light-coloured sediments showing the highest density and carbonate values and the lowest OM content (mainly allochthonous) and mean grain size. Although much evidence indicates a cold climate coincident with the Löbben glacial advance (Austrian and Swiss Alps), the presence of autochthonous rhomboedral calcite crystals indicate relatively warm water;
- **Unit V (3200-2900 yr BP)**, dark-coloured, coarse laminated sediments enriched in OM (> 6%) with many plant and wood remains and low CaCO$_3$ content (< 50%). A warm and humid depositional climate is proposed for this unit;
- **Unit IV (2900-2350 yr BP)**, faintly laminated, beige-brown sediments. Compared to unit V, the deposits are coarser, have higher CaCO$_3$ and lower OM contents. This unit indicates a gradual transition to colder and dryer climatic conditions (i.e. Subboreal to Subatlantic), less drastic but synchronous to the Gösgen I glacial recurrence (Austrian and Swiss Alps);
- **Unit III (2350-825 yr BP)**, light-beige, homogeneous to faintly laminated sediments. HI/OI ratio indicate a mixed origin (allochthonous and autochthonous). From bottom to top, CaCO$_3$ content increases (60% to 70%) while OM values decrease (4% to 2.5%). The climatic conditions were getting warmer and dryer;
- **Unit II (825-475 yr BP)**, fine-grained, homogeneous and light-coloured sediments with very high CaCO$_3$ (> 80%) and low OM (ca. 2%) contents. The latter has an autochthonous origin and the dominance of micritic calcite are compatible with the LIA climate;
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- Unit I (475 yr BP-present), dark brown, homogeneous sediments with a grain size slightly coarser than that of unit II. CaCO$_3$ content is high and stable (> 80%) while OM content shows an upward increase (from ca. 2% to 4.5%). The latter reflects the lake eutrophication in conjunction with the appearance of anthropogenic activity.

This study also provides the first known seismic data from Lake Joux: ca. 20 km of profiles acquired using a single-channel ‘impactor’ (hammer system) source with a bandwidth ranging from 1000- to 3000-Hz (Pugin et al., 2003). The recognised seismic sequences/facies are, from bottom to top:

- Acoustic basement (glacial diamicton), high-amplitude and discontinuous to chaotic reflections. The undulating surface of this sequence displays domes and depressions;

- Sequence I (deposits from the main and/or secondary glaciers), the high-amplitude reflections are more continuous than those of the acoustic basement, and the distinction between both facies is based on morphologic criteria. The dome morphology of this sequence does not draping the underlying basement and is not present throughout over the basin area;

- Sequence II (sub-glaciolacustrine deposits), chaotic and low-amplitude to transparent reflections. Represented in the northeastern part of Lake Joux, this sequence (up to 18 m thick) irregularly fills the depressions of the basement and/or sequence I;

- Sequence III (glaciolacustrine unit), the low-to-high-amplitude, semi-continuous and sub-parallel reflections of this sequence drape and fill the underlying depressions and display some bevelling structures;

- Sequence IV (lacustrine deposits), medium- to high-amplitude, continuous and parallel reflections. This sequence is between 0.3 and 7.5 m thick

According to the interpretation of the alignment of the sublacustrine mounts in the southern part of the Lake (Figure 5.4), which are interpreted as retreat moraines (Aubert, 1938), and to the seismostratigraphical analysis/interpretation, Bruder (2003) proposes a reconstruction of the deglaciation of the Joux glacier. He describes the following four stages prior to the present in chronological order (from northeast to southwest):

1. Mont des Ecuelles - Mont de l’Abbaye
2. Mont de la Capite - Mont Rond
3. Mont de la Roche-Fendue - Groenrroux
4. Mont de Pré-Lionnet - Mont Chez-la-Musique

Finally, a petrophysical, sedimentological, palaeoecological and stable-isotope ($^{18}$O/$^{16}$O and $^{13}$C/$^{12}$C ratios) study based on ostracods from Lake Joux was conducted by Whittle (2006). High-resolution analyses were done on the topmost 40 cm of core JO-N1 from this study (see section 5.3.3). This portion has the following chronological markers:

- 4.5-5.5 cm depth, the maximum $^{137}$Cs activity peak of the 1986 Chernobyl accident;
- 12.5-13.5 cm depth, the beginning of the $^{137}$Cs radioactive fallout in 1955;
- 18.5-19.5 cm depth, a silty/sandy layer corresponding to the 1943 construction work (second) of the hydroelectric power plant of La Dernier;
- 26.5-29.5 cm depth, a density peak attributed to the first construction work of the hydroelectric plant of La Dernier in 1901.

The last two are clearly visible in the ostracod abundance curve as important negative shifts (i.e. for Limnotheca sanctipatricii, Candona candida, Candida ophtalmica). Moreover, the author points out the inverse relationship between the ostracod abundance and the evolution of the trophic state of the lake.

The following sections present the results of the integrated study of the lakes from the Joux Valley. These include the geophysical investigations (section 5.2), the sedimentological investigations (section 5.3) and the constructed chronological framework (section 5.4). Each of these sections are intimately related to one another and share key informations that are compiled and discussed in the conclusions.
5.2 Geophysical investigations

This section presents the radar and seismic stratigraphy of Lakes Joux and Brenet, based on a large set of profiles (Figures 5.8 and 5.9). The geophysical investigations included two stages. First, GPR surveys were conducted in onshore and offshore settings in order to evaluate potential sites for limnogeological studies. Second, offshore HRS profiles were acquired to complement the imaging of sediment stratigraphy in the deepest parts of the lakes. The geophysical data also helped to select coring sites as well as to optimise the number of cores (Section 5.3). Thereby, the location of all recovered sediment cores is indicated on the related geophysical profiles (GPR or HRS) presented in this section.

The sedimentary sequences of Lakes Joux and Brenet were subdivided into 3 seismic units and 4 radar units, defined on the basis of strong reflections, unconformities or sudden changes in the facies. Each unit is interpreted within the stratigraphical context and depositional setting and represents a volume of sediments with similar electrical / acoustical properties (e.g. continuity, amplitude, geometry and interval velocity / density). Using sediment core data, these units can be interpreted within the chronostratigraphical context of the radar / seismic framework (Mitchum Jr. et al., 1977).

5.2.1 GPR stratigraphy

A dense grid of onshore and offshore GPR data was acquired using unshielded 100- and 200-MHz and shielded 250-MHz antennas at different and/or coincident sites (Figure 5.9). The surveys comprised:

- Lake Brenet - 40 onshore (including 1 CMP profile, Figure 2.4) and 51 offshore profiles with a mean length of ca. 80 m;
- Lake Joux - 10 onshore (including 2 CMP profiles), 4 offshore and 7 amphibious (under frozen-lake conditions) profiles with a mean length of ca. 90 m.

The radar stratigraphy of the littoral environments of Lakes Joux and Brenet includes 4 main GPR facies (G-0, G-1, G-2 and G-3) that were calibrated with the core data presented in Section 5.3 (i.e. onshore cores BR-V1 to -V5, and offshore cores BR-N2 to -N5 and JO-N3 and -N4). The geometry and electrical properties of each radar unit are presented from bottom to top in Figure 5.10 and are illustrated by a selection of key transversal and longitudinal GPR profiles in Figures 5.11 to 5.22. Within a given unit, distinct radar facies and stratigraphical subdivisions are given with a letter suffix.

In all transversal GPR profiles, the lakeward direction is to the right, the horizontal scale represents the distance in metres (m) and the vertical scales indicate both two-way traveltime (TWT) in nanoseconds (ns) and depth in metres (m). Offshore velocities of 0.033 and 0.055 m/ns were used for the calculation of water and sediment depths, respectively. This indicates a vertical exaggeration of the water column of about 1.6 x. On the basis of CMP data, a velocity of 0.062 m/ns was used for calculating the onshore sediment depth. Each GPR profile is presented with the uninterpreted data in the upper portion of the figure and its interpretation in the lower portion.

Glacial - Lateglacial GPR unit G-0

The lowermost unit G-0 is detected in almost all GPR profiles and is subdivided into two subfacies: G-0a and G-0b.

Subfacies G-0a shows high- to medium-amplitude, chaotic to subparallel reflections. The upper boundary of subfacies G-0a is distinguished by an extremely high-amplitude reflection. The presence of pebble clasts on top of this unit impeded the penetration of core BR-V3 (Figure 5.11). The lithological analysis of core JO-N4 indicates compacted diamicton (Figure 5.31E). Thus, subfacies G-0a is interpreted as melt-out till deposits.

The overlying subfacies G-0b displays low-amplitude to semi-transparent, subparallel, partially continuous reflections, which gently dip towards the lake centre (e.g. Figure 5.12). The lithology comprises faintly to finely laminated, relatively compact clayey sediments (Figure 5.31D), and the subfacies is thus interpreted as glaciolacustrine sediments.

Holocene GPR units G-1 to G-3

Unit G-1 generates low- to high-amplitude, parallel and continuous reflections that are inclined
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Figure 5.8: Maps of Lakes Brenet (a) and Joux (b) showing the geophysical tracklines (HRS and GPR) and sediment cores location. X and Y axes show Swiss coordinates.
towards the lake centre (e.g., Figures 5.21 and 5.22). The lithology consists of relatively fine-grained faintly laminated sediments (see Figure 5.31C). This unit is interpreted as macrophyte-colonised prograding littoral marl bench deposits.

**Unit G-2** onlaps unit G-1 and is characterised by low- to high-amplitude, continuous to semi-continuous sigmoidal reflections that are steeply inclined towards the lake centre (e.g., Figure 5.20). Lithological analysis reveals medium-sized, layered sediments containing very abundant macroscopic components (Figures 5.30 and 5.31B). This unit is also interpreted as prograding macrophyte-colonised littoral marl bench deposits. A good example of these deposits is in the longitudinal profile BRE-9 (Figure 5.14), where dome-shaped reflections are visible at ca. 20 m distance. With the help of the interpretation of the transversal offshore profile BRE-50 (Figure 5.15), acquired a few tens of metres north of profile BRE-63, they are interpreted as a macrophyte-colonised bench spit. We can clearly see prograding fronts on both sides of this spit.
Unit G-3 is encountered within unit G-2 and produces low- to medium amplitude, partially continuous dome-shaped reflections (e.g. Figure 5.11). The cores reveal coarse sandy sediments (Figure 5.31A) that indicate beach ridge deposits.

Discussion of GPR stratigraphy

The quality of the GPR response is intimately linked to the grain size of the sediment. According to Powers et al. (1999), the radar signal is strongly attenuated in the presence of water and fine-grained sediments (e.g. subfacies G-0b). Coarse-grained deposits are well suited for GPR probing (e.g. facies G-1 and G-2). The fact that reflections from facies G-2 are less continuous compared to those of facies G-1 can be explained by its more heterogeneous lithological composition (Figures 5.32 and 5.36).

The images of the prograding littoral marl bench as well as its associated sedimentary facies confirm the existing sedimentological and facies models of ‘bench margins’ studied in Lake Littlefield (e.g. Murphy & Wilkinson, 1980) and Sucker Lake (e.g. Treese & Wilkinson, 1982), Michigan. Examples of the ‘low energy, bench-type lake margins’ (Murphy & Wilkinson, 1980) are illustrated by the GPR profiles BRE-55, -58 and -89 (Figures 5.20, 5.21 and 5.22, respectively). Examples of ‘high energy (wave dominated), bench-type lake margins’ (Swirydczuk et al., 1980) are illustrated by the profiles BRE-11+12 and -63 (Figures 5.11 and 5.17). The GPR stratigraphy also confirms the lake-infilling models proposed by Dustin et al. (1986) and Platt & Wright (1991): the high sediment production rates in shallow water imply that most marl lakes are filled with sediments deposited in shallow benches and lakemounds.

On the basis of the presented GPR stratigraphy, the sediment core information and the radiocarbon ages obtained from these cores, the following chronostratigraphical model and markers are pro-
Profiles BRE-55 and -58 (Figures 5.20, 5.21) reveal changes in the reflection inclinations at the transition between unit G-1 and G-2. The stratigraphical architecture changes laterally from a prograding system to a mixed prograding-aggrading system. Dipping values measured on profile BRE-58 indicate a change from ca. 10° (unit G-1) to ca. 20° (unit G-2). According to Vail et al. (1977), while coastal toplap indicates relative stillstand conditions of water level, a transition from parallel to sigmoidal-shaped reflections can reflect changes in sediment supply, lake hydrodynamics and/or shorter-term fluctuations of the lake level. The latter hypothesis is confirmed by the radiocarbon age of 5844 ± 102 cal yr BP obtained in core BR-V1 at 116.5 cm depth (see Figure 5.21 for location). On a regional scale, this age coincides with the increasing frequency of lake-level fluctuations recorded in many lakes from the Jura and the northern Subalpine region (Magny, 1992) as well as a tripartite climate reversal (three episodes of successively higher lake levels) recorded in the sediments from Lake Constance (Magny et al., 2006b). Moreover, this period coincides with the ‘mid-Holocene climate optimum’ (7000 to 5000 years ago) (see Davis et al., 2003 for review), a period during which temperate latitude regions experienced a dry period followed by increasingly cool and wet conditions (Steig, 1999). This warming initiated during the early Holocene and reached a maximum ca 6000 BP before declining through the remainder of the Holocene (Davis et al., 2003). According to Magny & Haas (2004) this major event marks the Hypsithermal/Neoglaciation transition, possibly resulting from a combination of different factors including orbital forcing, changes in ocean circulation and variations in solar activity.

The beach ridges of facies G-3 were probed by (1) cores BR-N2 and BR-N3 (see Figure 5.11) and (2) core BR-N5 (see Figure 5.17). Beach ridges are known to provide information on the upper physical limit of the lake level (Thompson, 1992). (1) The beach ridges imaged on profile BRE-11+12 (see Figure 5.11) indicate a lake level of ca. -3 m depth, with respect to the present lake level. The landward amalgamation/shifting of beach ridge deposits indicates ‘in-place drowning’ mechanism characteristic of transgressive conditions (see section 3.1.6). The dates obtained from cores BR-N2 and BR-N3 provided ages of 520 ± 41 cal yr BP, 510 ± 49 cal yr BP and 714 ± 65 cal yr BP. These ages coincide with the warm and dry Medieval Warm Period (MWP) that span the milder few centuries prior to the LIA (between ca 1450 AD to 1900 AD). This warming was evidenced, for example, by several short-lived glacier retreat phases (Holzhauser, 1988), negative trends in both the bulk carbonate and ostracode calcite values in $\delta^{18}$O in Lake Neuchâtel (Filippi et al., 1999) as well as short-lived lake-level lowering recorded in sediments from Lake Joux (Magny et al., 2008). (2) The beach ridge and associated complex recognized in profile BRE-63 (Figure 5.17) indicate a low lake level of ca. -4.5 m, with respect to the present lake level. Three radiocarbon ages could be obtained: 2575 ± 146 cal yr BP, 3310 ± 102 cal yr BP and 3723 ± 140 cal yr BP. This period coincides with a phase of glacier recession between the Löbben and Gösgen 1 cold periods (Hornes et al., 2001). According to Magny (1992), the middle Subboreal hosts the best recorded lake-level lowering of the Holocene and is represented in several cases by major erosion of littoral sediments.

Thus the following chronostratigraphical model is proposed:

- unit G-0 corresponds to glacial (facies G-0a) and lateglacial glaciolacustrine deposits (facies U-0b);
- unit G-1 represents prograding macrophyte-colonised littoral marl bench deposits of the postglacial period prior to the ‘mid-Holocene climate optimum’ (7000 to 5000 years ago);
- unit G-2 is interpreted as prograding macrophyte-colonised littoral marl bench deposits from the second half of the Holocene;
- unit G-3 corresponds to beach ridges deposited during specific Late Holocene (unit G-2) lowstand events.

All other radiocarbon dates obtained from the cores of the littoral area of Lake Brenet (see tables 5.6 and 5.7) are in agreement with this chronostratigraphical model. The exceptions are the dates obtained from onshore core BR-V3 in unit G-1 (Figure 5.11). These ages are too young (1015 ± 81 cal yr BR and 1407 ± 111 cal yr BP at 118 and 152 cm depth, respectively) with respect to their stratigraphic location (only a few centimetres above the contact with the glacial/lateglacial unit G-0). This ‘error’ is attributed to the contamination of the sediments by younger carbon that may...
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Figure 5.11: 200-MHz amphibious GPR profile BRE-11+12 from Lake Brenet showing the location of cores BR-N2, BR-N3, BR-V2, BR-V3 and BR-V5. See Figures 5.8a and 5.9 for location. Vertical exaggeration is ∼5.8 x and ∼8 x for onshore and sublacustrine sediments, respectively.
Figure 5.12: 200-MHz transversal offshore GPR profile JOU-5 from Lake Joux showing the location of core JO-N4 (black and white one-metre-long portions). See Figure 5.8b for location. Vertical exaggeration is $\sim 1.5$ x.

Figure 5.13: 200-MHz transversal offshore GPR profile JOU-3 from Lake Joux showing the location of core JO-N3 (black and white one-metre-long portions). See Figure 5.8b for location. There is no vertical exaggeration.
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Figure 5.14: 200-MHz longitudinal offshore GPR profile BRE-9 from Lake Brenet. See Figures 5.8a and 5.9 for location. Vertical exaggeration is $\sim 9.7 \times$.

Figure 5.15: 250-MHz transversal offshore GPR profile BRE-50 from Lake Brenet. See Figures 5.8a and 5.9 for location. Horizontal exaggeration is $\sim 1.1 \times$. 
Figure 5.16: 200-MHz transversal offshore GPR profile BRE-4 from Lake Brenet showing the location of core BR-N4 (black and white one-metre-long portions). See Figures 5.8a and 5.9 for location. Vertical exaggeration is $\sim 3.6 \times$.

Figure 5.17: 100-MHz transversal offshore GPR profile BRE-63 from Lake Brenet showing the location of core BR-N5 (black and white one-metre-long portions). See Figures 5.8a and 5.9 for location. Horizontal exaggeration is $\sim 2 \times$. 
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Figure 5.18: 100-MHz longitudinal onshore GPR profile BRE-59 from Lake Brenet showing the location of the crossing transversal GPR profiles BRE-58 and BRE-89. See Figures 5.8a and 5.9 for location. Vertical exaggeration is ~ 6.5 x.

Figure 5.19: 250-MHz longitudinal onshore GPR profile BRE-28 from Lake Brenet showing the location of the crossing transversal GPR profiles BRE-58 and BRE-89. See Figures 5.8a and 5.9 for location. Horizontal exaggeration is ~ 12.9 x.
5.2. GEOPHYSICAL INVESTIGATIONS

Figure 5.20: 100-MHz transversal onshore GPR profile BRE-55 from Lake Brenet showing the location of core BR-V4 (black and white one-metre-long portions). See Figures 5.8a and 5.9 for location. Vertical exaggeration is $\sim 3.5 \times$.

Figure 5.21: 100-MHz transversal onshore GPR profile BRE-58 from Lake Brenet showing the location of core BR-V1 (black and white one-metre-long portions) and the location of the crossing longitudinal GPR profiles BRE-28 and BRE-59. See Figures 5.8a and 5.9 for location. Horizontal exaggeration is $\sim 2.3 \times$. 
arise from root penetration. Other incoherent ages with respect to the stratigraphy (above and below) were not retained and their lab. number is followed by a sharp sign (Tables 5.6 and 5.7).

5.2.2 HRS stratigraphy

The HRS surveys comprised 7.3 km and 19.5 km of lake-crossing profiles from Lakes Brenet and Joux, respectively (Figure 5.8). Lake Joux HRS facies (3.5-kHz pinger) were compared with the ‘impactor’ seismic facies of Bruder (2003) (see section 5.1.7 for description).

The seismic stratigraphy of the deep basinal environments of Lakes Joux and Brenet includes three main HRS facies (U0, U1 and U2), which were calibrated with the core data presented in Section 5.3 (i.e. offshore cores BR-N1 and JO-N1 and -N2). The geometry and acoustical properties of each seismic unit are presented from bottom to top in Figure 5.23 and are illustrated by a selection from key transversal and longitudinal HRS profiles in Figures 5.24 to 5.27.

Differences in acoustical response and penetration depth of the seismic signal, as well as differences in sedimentological properties allow the subdivision of the units into lake-specific HRS facies. The latter are named JH and BH for Lake Joux and Lake Brenet facies, respectively. Within a given unit, distinct HRS facies and stratigraphical subdivisions are given a letter suffix.

Compared to the Brenet profiles, the Joux profiles show deeper signal penetration and the reflections are more continuous. Due to higher gas content in the sediments from Lake Brenet (Figure A.2), the continuity is slightly disturbed. Despite these differences, both facies correlate well.

For all the HRS profiles the horizontal scale represents the distance in metres (m) and the vertical scales indicate both two-way traveltime (TWT) in milliseconds (ms) and depth in metres (m). A mean velocity of 1480 m/s was used for the calculation of onshore sediment depth. Each seismic profile is presented with the uninterpreted data in the upper portion of the figure and its interpretation in the lower portion.

Bedrock and Glacial HRS unit U0

U0 is the lowermost unit, recognised across the entire Lake Joux basin (JH-0) but never reached in Lake Brenet. It consists of high-amplitude, wavy to chaotic reflections (Figures 5.24 and 5.26). This
5.2. GEOPHYSICAL INVESTIGATIONS

Figure 5.23: Seismic stratigraphy of Lakes Joux and Brenet with image, facies description and interpretation.

Unit displays a high contrast in amplitude with the overlying units and its top displays sharp reflection truncations in places. This unit thus represents the undifferentiated bedrock and moraine deposits.

**Lateglacial HRS unit U1**

Unit U1 is divided into two main subfacies: U1a and U1b.

**U1a** was only observed in the profiles from Lake Joux (JH-1a) and shows the following northeastward lateral and vertical (from bottom to top) succession (Figure 5.24):

- ‘sub-subfacies’ **JH-1a** displays semi-transparent to low-amplitude, chaotic reflections. This subfacies thickens towards the northeast and is interpreted as subglacial melt-out till deposited in front of the receding glacier;
- medium- to high-amplitude, subparallel, wavy
Figure 5.24: Deep offshore longitudinal profile HRS_JOUX-1 / p1 from the central part of Lake Joux. The interpretation of this profile is given on next page (b). Vertical exaggeration is \( \sim 32 \) x.
Figure 5.24: Interpretation of profile HRS_JOUX-1 / p1 of the previous page (a). Vertical exaggeration is $\sim 32 x$. The boxed area at ca 800 m distance is enlarged in Figure 5.25
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Figure 5.25: Detail of glacially-deformed glacio-lacustrine deposits of the seismic unit JH-1 (see Figure 5.24 b for location). Vertical exaggeration is \( \sim 17 \times \).

and continuous reflections that are interpreted as deformed glaciolacustrine proglacial sediments. These deformations indicate small-scale readvances of the glacier (Figure 5.25);

- ‘sub-subfacies’ JH-1a** produces low- to high-amplitude, parallel and continuous reflections. This subfacies thickens northeastward and is interpreted as glaciolacustrine proglacial deposits.

The deposition of unit U1a is influenced by the presence of the glacier. It corresponds to sediments deposited in a subglacial lake (JH-1a* in the southwest) and the associated proglacial lake sediments (JH-1a** in the northeast). The southwestward thinning of the latter indicates a glacier retreat interrupted by small-scale glacier readvances (deformed subfacies). This ‘deformation front’ is interpreted here as part of ‘sub-subfacies’ JH-1a*.

Subfacies U1b is represented in both lakes. The recovery of a longer sediment core in Lake Brenet allows to subdivide this subfacies into two ‘sub-subfacies’ (BH-1b* and BH-1b**). BH-1b* is characterised by low- to medium-amplitude parallel and continuous reflections (Figure 5.27). Lithological observations reveal massive and homogeneous beige clays (Figure 5.31I). It is overlain by the equivalent subfacies BH-1b** and JH-1b, which generate low- to high-amplitude parallel and continuous reflections. The core data indicate black-pigmented to finely laminated (rhythmites) clays (Figure 5.31G and H). The whole subfacies U1b is thus interpreted as glaciolacustrine deposits.

Holocene HRS unit U2

Unit U2 (subfacies JH-2 and BH-2) is characterised by medium- to high-amplitude, parallel and continuous reflections (Figures 5.26 and 5.27). Lithological core descriptions indicate homogeneous to faintly laminated clays (see figure 5.31F). The carbonate content curve of core BR-N1 shows a major and abrupt positive shift (from ca 60% to 90%), particularly for magnesium calcite (Figure 5.37). Thus, this unit is interpreted as Holocene lacustrine deposits. The fine subdivisions of subfacies JH-2 and BH-2 are based on detailed sedimentological descriptions as well as on the analysis of petrophysical, mineralogical and physicochemical properties. These are described in section 5.3.

Discussion of HRS stratigraphy

The conducted high-resolution seismic 3.5-kHz surveys revealed the glacial and postglacial sedimentary infill of Lakes Joux and Brenet, and allowed the study of sedimentary processes and their evolution through the deglaciation. The seismic stratigraphy and the resulting interpreted sedimentary sequences of Lakes Joux and Brenet are similar to those of other lakes from the perialpine area (e.g. Lake Annecy: van Rensbergen et al., 1998; Lake Bourget: van Rensbergen et al., 1999; Lake Zürich: Hsü et al., 1984; Lake Neuchâtel: Gorin et al., 2003 and Lake Geneva: Fiore, 2007). Such lakes result from deep glacial scouring (Pleistocene glaciations) and all exhibit elongated shapes (fjord-lake type). They are characterised by thick sedimentary infill deposited during the relatively short period of deglaciation. The main seismic facies comprise, in chronological order:

- unstratified or poorly-stratified glacial deposits imaged by high amplitude to semi-transparent, wavy to chaotic reflections (unit U0 and subfacies JH-1a*);
- stratified glaciolacustrine deposits defined by low- to high-amplitude, parallel and continuous reflections (Figures 5.26 and 5.27) that are interpreted as glaciolacustrine deposits.
Figure 5.26: Deep offshore longitudinal profile HRS_JOUX-1 / p2 from the central southwestern part of Lake Joux showing the location of core JO-N2. Vertical exaggeration is $\sim 17.7 \times$. 
Figure 5.27: Lake-crossing profile HRS_BRENET-p2 acquired in the central part of Lake Brenet showing the location of core BR-N1 (black and white one-metre-long portions). Vertical exaggeration is $\sim 7.8 \times$. 
5.3 SEDIMENTOLOGICAL INVESTIGATIONS

According to the seismic and radar stratigraphies, five onshore cores (measuring between 1.30 and 1.795 m), five offshore cores (from 2.76 to 10.99 m long) were extracted from the Lake Brenet area and four offshore cores (measuring between 0.85 and 3.26 m) were collected from Lake Joux. They helped to interpret the GPR and HRS data, to characterise the sedimentary stratigraphy, to identify the sediment distribution (following onshore to deep offshore transects) and to collect datable material. Thus, after characterising the main stratigraphic units, this section presents detailed core descriptions followed by a discussion of the sedimentary stratigraphy.

All the core details, including core location, labelling, length, samples location, photography and data of all laboratory measurements described in this section are given in Appendix B.

The legend of the detailed sedimentary description (Figure 5.28) comprises, from left to right:

- **Grainsize classes** ranging from clay to gravel, including 7 classes, are represented by both a ruler scale and a colour scale. The only represented figured elements are dropstones, which generally consisted of ca. 3 mm diameter grains;
- **Grading** including fining upward (normal grading) and coarsening upward (inverse grading) evolutions;
- **Surfaces and structures** are put in the same column (see also Figure 5.29). **Surfaces** include erosive and straight (conform) surfaces and the three observed **structures** consist of laminated (5mm to cm-thick laminae), finely laminated (1-3 mm thick laminae) and faintly laminated;
- **Macroscopic descriptive elements** (see also Figure 5.30) include fragments or entire shells

<table>
<thead>
<tr>
<th>Unit</th>
<th>Subfacies</th>
<th>Bruder (2003)</th>
</tr>
</thead>
<tbody>
<tr>
<td>U0</td>
<td>JH-0</td>
<td>Acoustic basement</td>
</tr>
<tr>
<td>U1</td>
<td>JH-1a*</td>
<td>Sequence II</td>
</tr>
<tr>
<td></td>
<td>JH-1a**</td>
<td>Sequence III</td>
</tr>
<tr>
<td>U2</td>
<td>JH-1b</td>
<td>Sequence IV</td>
</tr>
<tr>
<td></td>
<td>JH-2</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.3: Correlation between the seismic units from this work (3.5-kHz pinger) and those proposed by Bruder (2003) (‘impactor’ 1 to 3 kHz). This correlation is essentially based on the comparison between profile HRS_JOUX-1/p1 (Figure 5.24) and ‘Detail n°3’ of longitudinal profile ‘long3’ from Bruder (2003).

The coastal environment provides relatively clear GPR information of heterogeneous geomorphology. In contrast, informations provided by the HRS response of relatively conformable, continuous and homogeneous profundal lacustrine drapes are more muted.
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of mollusks (i.e. *bivalvs* and *gastropods*), *gastropods* *operculums*, charophyte remains, plant/wood remains and carbonate concretions (*oncoids*, *plate-like concretions* and *tube-like concretions*). The shape of these three concretions are directly related to the nature of their nuclei (Figure 5.30 d, e and f);

- Core petrophysical data (MSCL) including *P*-wave velocity, *Wet bulk density* and *Magnetic susceptibility*;
- Physico-chemical proxies including *Water content*, *Organic matter* or *LOI*$_{500}$ and carbonate content or *LOI*$_{1000}$ indicated as *CaCO$_3$*;
- Calcimetry data including *Calcite* and *Magnesium calcite* (only measured for core BR-N1),
- Corresponding GPR or HRS facies whose attributed colour is presented in the background of the entire figure.

Additionally, the obtained radiocarbon ages are indicated on the left of each lithological log.

### 5.3.1 Sedimentary facies

According to the seismic and radar stratigraphy described in section 5.2 as well as on the basis of sedimentological/lithological core description, five recurring coastal sedimentary facies (key stratigraphic unit) and three recurring deep-basinal sedimentary facies are distinguished. The sedimentary facies names are in capital letters indicating interpretation of either GPR or HRS facies. The synthetic lithological description of each sedimentary unit is presented from bottom to top in Figure 5.31 and illustrated by a selected portion of core photograph.

#### Facies from the coastal/marginal realm

**Glacial-Lateglacial sedimentary units A-B**

**Unit A** was penetrated by core JO-N4 (Figure 5.12) and the coring of BR-V3 was stopped by the presence of pebbles clasts of this facies. It consists of very compacted heterogeneous gravels and pebbles in a beige clayey matrix (diamicton) and is interpreted as melt-out till corresponding to GPR unit G-0a.

**Unit B** was penetrated by cores JO-N3, N4 and BR-N4 (Figures 5.13, 5.12, 5.16). It consist of relatively compacted clays. Generally, the colours and structures change upward from (left to right in Figure 5.31):

- greenish grey-beige and faintly laminated;
- greenish grey and beige black-pigmented. This subfacies correspond to facies H encountered in the deep/basinal realm;
- beige and cream finely laminated (rhythmites), which is identical to facies G from the deep/basinal environment.
5.3. SEDIMENTOLOGICAL INVESTIGATIONS

Figure 5.29: Description of the surfaces (top) and structures (bottom) observed in the onshore and offshore cores from Lakes Brenet and Joux. Examples of (A) straight surface from core BR-N2 between 11 and 15 cm depth, (B) erosive surface from core JO-N1 between 17 and 21 cm depth, (C) laminated structure from core BR-N4 between 98 and 102 cm depth, (D) fine laminations from core BR-N3 between 157 and 161 cm depth and (E) faint laminations from core JO-N3 between 111 and 115 cm depth.

These sediments are interpreted as lateglacial glaciolacustrine deposits that give the GPR reflection pattern of unit G-0b.

Both of these units have high P-wave velocities and densities, low water contents and contain none of the main macroscopic components.

Holocene sedimentary units C, D and E

Unit C is encountered in cores BR-V1, -V3, -V4 and JO-N3 (Figures 5.21, 5.11, 5.20 and 5.13). Sediments are composed of homogeneous to faintly laminated, beige-coloured silty clays. Macroscopic components include a few mollusk-shell debris, charophyte and plant remains. This unit is dated to the first half of the Holocene and corresponds to macrophyte-colonised littoral marl bench deposits imaged by GPR facies G-1. The calibrated radiocarbon age of 5844 ± 102 cal yr BP obtained from the top of this unit (116.5 cm depth in core BR-V1) indicates that it was deposited prior to the ‘mid-Holocene climate optimum’ (around 6000 BP), as discussed in section 5.2.1).

Unit D is observed in all the cores extracted in the littoral environment of Lake Brenet. It consists of medium-sized sediments (from silt and clay to silts), which are layered (alternances) and faintly laminated or homogeneous. Macroscopic components are generally abundant to very abundant. This unit is interpreted as macrophyte-colonised littoral marl bench sediments deposited during the second part of the Holocene (see discussion in section 5.2.1).

Unit E was penetrated by cores BR N2, -N3 and -N5 (Figures 5.11 and 5.17). This unit has coarse-grained sediments, which are faintly laminated to massive, and the observed structures show systematically erosive surfaces. It typically contains more plant, charophyte and mollusk remains than unit D. The attribution of this unit to Late Holocene beach ridge deposits is discussed in section 5.2.1.

Facies from the deep/basinal realm

Lateglacial sedimentary units F, G and H

Unit F is the deepest cored sedimentary facies (observed from 5.865 to 10.99 m in core BR-N1, Figures 5.27 and 5.37) and consists of massive homogeneous beige clays with very faint and irregularly dispersed medium- to light-greyish laminae of ca. 1 mm thickness. All petrophysical and physico-chemical data are relatively stable and characterised by:

- high P-wave and density values as well as high calcite content;
Figure 5.30: Main macroscopic components found in the onshore and offshore sedimentary cores from Lakes Brenet and Joux. (a) Bivalve, (b) gastropod operculum, (c) charophyte oogone and (d to f) carbonate concretions. Oncoids are sub-rounded particles of many mm in diameter (d1) with nuclei consisting of gastropod fragments (d2) or entire shells (d3). Plate-like concretions (e1, upper view) have nuclei made of macrophyte leaves (e2, cross section), while those of tube-like concretions (f1) consist of charophyte stems (f2).
Figure 5.31: Atlas of sedimentary facies and associated GPR and HRS facies of the subsurface beneath Lakes Joux and Brenet. Typical coastal (left side) and basinal (right side) facies are selected from the following core intervals: (A) core JO-N4 from 180 - 186 cm; (B) from left to right (downward relative to the stratigraphy) core BR-N4 from 326 - 332 cm, core JO-N3 from 240 - 246 cm and core JO-N4 from 150 - 156 cm; (C) core JO-N3 from 86 - 92 cm; (D) core BR-N4 from 72 - 78 cm; (E) core BR-N2 from 136 - 142 cm; (F) core BR-N1 from 714 - 720 cm; (G) core BR-N1 from 522 - 528 cm; (H) core BR-N1 from 362 - 368 cm and (I) core BR-N1 from 51 - 57 cm. A correspondence between the coastal and basinal facies is indicated by the dotted line.
• relatively high magnetic susceptibilities ($\kappa$);
• medium carbonate contents;
• low water, organic matter and magnesian calcite contents.

This unit is interpreted as glaciolacustrine clays (corresponding to seismic facies BH-1b*), which seems to result from glacial slurry decantation processes.

Both facies G and H consist of clay deposits containing some gravel-sized dropstones. This allows to interpret these sediments as glaciolacustrine deposits. They produce the HRS reflection pattern corresponding to seismic facies BH-1b** (Brenet) and JH-1b (Joux) (Figures 5.37 and 5.38).

Facies G is a very finely laminated facies observed at the bottom of the unit (from ca. 4.8 down to 5.8 m depth in core BR-N1). It is interpreted as glacial rhythms and closely resembles those observed by Baster (2002) in core Bl18 from Lake Geneva. The latter author attributes this sedimentary feature to the Oldest Dryas - Bølling chronozone. A similar lithology was described in Geneva Bay (Moscarrello, 1996; subunit D3, Table 4.2) and at the base of the Hauts-Monts promontory slope, Lake Geneva (Girardclos, 2001). The interpretations proposed by the latter authors are diverse and range from aeolian loess, underflow, microturbidites to annual varve deposits.

Facies H consists of black-pigmented to faintly laminated clays observed at the top of this unit (i.e. from 2.85 to 5.8 m depth in core BR-N1). Few mollusk shell debris are present at the top of this facies. Again, such deposits were observed in Lake Geneva by Baster (2002) and were palynologically dated to the Allerød.

The comparison of the ages obtained by Baster (2002) on facies similar to G and H are globally in good agreement with the age calibration provided by the comparison between the S-ratio and GISP2 $\delta^{18}$O data discussed in sections 5.2.2 and 5.4.3.

The smooth positive trends observed in the P-wave, density and magnetic susceptibility curves of facies G and H result from the presence of dropstones. Water and organic matter contents display very discrete upward increasing values in opposition to carbonate and calcite contents. The magnesium calcite curve is stable at low values.

Holocene sedimentary unit I

This unit is characterised by grey to brown, homogeneous to faintly laminated clays and corresponds to the seismic unit U2. Mollusk shell debris are present along the entire unit and all the measured parameters show high-amplitude and high-frequency oscillations that contrast with the relative stability beneath. The most remarkable shift is observed in the carbonate and magnesium calcite curves. Such results are a typical response to the climatic changes of the Lateglacial - Holocene transition and are in good agreement with other records, such as those from Lake Zürich, Switzerland (Thompson & Kelts, 1974), some lakes in southern Sweden (Hammaklund, 1993) and from Lake Annecy, France (Brauer & Casanova, 2001). According to Thompson & Kelts (1974), this shift in carbonate content is attributed to low detrital inputs due to heavy forestation as well as to high planktonic biogenic activity induced by warm climatic conditions.

5.3.2 Description of onshore cores

All onshore cores were extracted from the reed marsh environment in the southwestern area of Lake Brenet (Figures 5.8 and 5.9).

Core BR-V1

Core BR-V1 was collected at about 22 m landward from the shoreline. It measures 147.5 cm long and consists of a coarsening upward sequence of high carbonate sediments (mean CaCO$_3$ content of ca. 91%) ranging from silty clays to gravels (Figures 5.32 and B.5). The lower portion contains many mollusk shells while the upper portion is characterised by very abundant charophyte and plant remains.

This core can be subdivided into five units (see section B.2.1).

Core BR-V2

Core BR-V2 was collected at the shoreline, ca. 1 m lakeward. It measures 179.5 cm long and the sediment is mainly dominated by mixed silts and clays and silty clays with high carbonate contents (mean value of 90.6%, Figures 5.33 and B.5). Many small coarsening- and fining-upward sequences can be identified. The content of macroscopic components is generally high and increases with grain size.

P-wave velocity, density and magnetic susceptibility curves shows similar trends and correlate
Figure 5.32: Core BR-V1: Sedimentology (grain size, structure, descriptive elements), MSCL (P-wave velocity, wet bulk density and magnetic susceptibility), water content, loss on ignition (LOI_{560} and LOI_{1000}) data and corresponding GPR facies.
positively. P-wave velocities are generally high and vary from 1580 to 1630 m s\(^{-1}\).

This core can be subdivided into two units (see section B.2.2).

Core BR-V3

Core BR-V3 was extracted at about 45 m west of the shoreline (ca. 46 m landward from core BR-V2). It measures 163.5 cm and exhibits a coarsening upward sequence grading from clays to sands and ‘diamicton’ (Figures 5.34 and B.5). The uppermost 60 cm consist of topsoil humus and embankment material, which was drilled with an auger. From 101.5 cm depth to the bottom of the core, the sediment contains very abundant charophyte remains.

Scarce reliable P-wave velocity information indicates mean values of 1517 m s\(^{-1}\).

The carbonate content curve shows steadily increasing values downward. Water content values display a similar but smoother trend, while the organic matter curve correlates negatively with the two latter datasets.

This core can be subdivided into four units (see section B.2.3).

Core BR-V4

Core BR-V4 was collected on the shoreline, ca. 1 m lakeward (about 25 m eastward from core BR-V3). This 136 cm long core globally exhibits a coarsening upward sequence grading from clay to sand and ‘diamicton’ interrupted by a mixed silt and clay interval (Figures 5.35 and B.5). At this site again, the uppermost 60 cm of topsoil humus and embankment material were drilled with an auger. The coarser sediments are enriched in charophyte and plant remains as well as oncoids.

Reliable P-wave velocity information is scarce (from 110.5 to 126 cm depth) and decreases downward from 1536 to 1463 m s\(^{-1}\). The density curve correlates positively with grain size.

This core can be subdivided into five units (see section B.2.4).

Core BR-V5

Core BR-V5 was collected at the shoreline, ca. 1 m lakeward (about 20 m southeast from core BR-V2). It is 130 cm long and the sediments are dominated by silt with generally high carbonate content (mean value of 91.2%, Figures 5.36 and B.5). Many small coarsening- and fining-upward sequences can be identified. Mollusk remains are present along the entire core (especially between ca. 80 cm and 108 cm depth), while charophyte remains are abundant to very abundant (particularly from ca. 30 to 73 cm depth). Plant remains are abundant to very abundant along the entire sediment core. Oncoids are regularly present from 70 cm to the bottom of the core, while some plate-like carbonate concretions are present in the deepest 40 cm.

P-wave velocity data are relatively stable with a mean value of about 1537 m s\(^{-1}\).

This core can be subdivided into six units (see section B.2.5).

5.3.3 Description of offshore cores

The offshore cores were collected from both shallow-water (BR-N2 to Br-N5, JO-N3 and JO-N4) and deep-water (BR-N1, JO-N1 and JO-N2) environments of Lakes Brenet and Joux (Figures 5.8 and 5.9). The locations of core BR-N1 and JO-N2 were selected on the basis of conformable and continuity factors in HRS data. Moreover, in order to better calibrate the sedimentological and geophysical data, core JO-N2 was extracted at approximately the same location as core n°3 of Creer et al. (1980) (see section 5.1.7).

Core BR-N1

Core BR-N1 was extracted from the central part of Lake Brenet, in a water depth of ca. 12 m. It measures 10.99 m and the sediments are dominated by clay (Figures 5.37 and B.3). Sediments are faintly laminated from the top of the core down to ca. 4.75 m depth and followed by a very finely laminated (rhythmites or varves, Figure 5.38) interval of ca 1 m thick. Below, the sediments have many straight surfaces or very faint rhythmites. The topmost ca. 3.5 m contain few mollusk shell debris and very scarce plant remains.

P-wave velocity and density curves show the lowest and slightly increasing downward values until ca. 3.5 m depth. This trend steadily intensifies from 3.5 to ca. 5 m depth and then reverses until 5.8 m depth. Further downward, the values again increase slightly.

Magnetic susceptibilities are low and variable in the uppermost ca. 2.5 m. Then a high value peak is reached at about 2.9 m. Finally, from ca. 3.3 m depth down to the bottom of the core the magnetic
Figure 5.33: Core BR-V2: Sedimentology (grain size, structure, descriptive elements), MSCL (P-wave velocity, wet bulk density and magnetic susceptibility), water content, loss on ignition (LOI_{560} and LOI_{1000}) data and corresponding GPR facies.
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Figure 5.34: Core BR-V3: Sedimentology (grain size, structure, descriptive elements), MSCL (P-wave velocity, wet bulk density and magnetic susceptibility), water content, loss on ignition (LOI$_{560}$ and LOI$_{1000}$) data and corresponding GPR facies.
Figure 5.35: Core BR-V4: Sedimentology (grain size, structure, descriptive elements), MSCL (P-wave velocity, wet bulk density and magnetic susceptibility), water content, loss on ignition (LOI560 and LOI1000) data and corresponding GPR facies.
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Figure 5.36: Core BR-V5: Sedimentological (grain size, structure, descriptive chronology) MSCL (P-wave velocity, bulk density and magnetic susceptibility) data.
5.3. SEDIMENTOLOGICAL INVESTIGATIONS

Figure 5.37: Core BR-N1: Sedimentology (grain size, structure, descriptive elements), MSCL (P-wave velocity, wet bulk density and magnetic susceptibility), water content, loss on ignition (LOI560 and LOI1000), calcimetry (calcite vs. magnesian calcite) data and corresponding HRS facies.
susceptibility curve shows similar trend as those of P-wave velocity and density.

Water and organic matter contents correlate positively, while carbonate content shows an opposite trend. The uppermost 1.5 m of the core displays high-amplitude and high-frequency variations in these data. The ca. 1.5 m of underlying sediments are characterised by more stable intermediate values of water and organic matter content and very high carbonate content (ca. 90%). The deepest 8 m of the core generally displays stable and low values of these parameters and the carbonates are dominated by calcite.

This core can be subdivided into three units (see section B.2.6).

Core BR-N2

Core BR-N2 was extracted from the southwestern part of Lake Brenet in a water depth of ca 3 m and ca 90 m lakeward from the shoreline. It measures 282.5 cm and contains a wide spectrum of grain sizes (from clay to gravel, Figures 5.39 and B.4). The sediments are faintly laminated in the uppermost ca 50 cm, faintly laminated down to ca 2.1 m and finely laminated below. Few dispersed gravel-sized clasts are observed inside or near some coarser layers. Many small coarsening- and fining-upward sequences can be identified. Macroscopic components are present to very abundant along the entire sedimentary column (especially in the coarser layers), while carbonate concretions are only observed in the two gravel units at the base of the core.

All measured parameters shows major variations along the entire core.

P-wave velocities in the uppermost ca 1 m have a mean value of 1483 m s⁻¹ and correlate positively with the density data. Below, many anomalous positive and negative high-amplitude P-wave velocity values are attributed to the presence of entrapped gas in the sediment. Densities range from 1.08 to 1.84 g cm⁻³. Magnetic susceptibility values are low, stable and lie between -1.3 and 4.4 SI.

Water and organic matter and carbonate contents range from 30.54 to 66.97%, 1.43 to 11.9% and 62.94 to 90.35%, respectively.

In general, this core contains heterogeneous alternations of layers up to ca 20 cm thick, which can be separated into two groups:

1. **Fine-grained layers** (clay and silty clay) of varying colours, including dark grey, grey, light and dark greenish grey, light grey, grey-beige, beige, brown-grey and brown, and presenting many types of laminations. They generally have relatively low P-wave velocities, densities and carbonate contents, and relatively high water and organic matter contents.

2. **Coarse-grained layers** consisting of light grey and beige-grey massive/homogeneous sediments ranging from silt and clay to gravel. They generally have relatively high P-wave velocities, densities and carbonate contents, and relatively low water and organic matter contents.

Core BR-N3

Core BR-N3 was extracted from the southwestern part of Lake Brenet in a water depth of ca 2 to 2.5 m and ca 70 m lakeward from the shoreline (ca 20 m southwest of core BR-N2). It measures 276 cm and has sediments of many grain sizes (from clay to gravel, Figures 5.40 and B.4). The sediments are faintly laminated within 0-30 / 110-147 / 170-180 / 187-215 and 222-270 cm depth, laminated within 30-110 and 180-187 cm depth, and finely laminated between 147 and 170 cm depth. Many small coarsening- and fining-upward sequences can be identified. Macroscopic components are present to very abundant along the entire sedimentary column (especially in the coarser layers), and tube-like carbonate concretions are only observed between ca 200 and 235 cm depth.
5.3. SEDIMENTOLOGICAL INVESTIGATIONS

Figure 5.39: Core BR-N2: Sedimentology (grain size, structure, descriptive elements), MSCL (P-wave velocities, wet bulk density and magnetic susceptibility), water content, loss on ignition (LOI560 and LOI1000) data and corresponding GPR facies.
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Figure 5.40: Core BR-N3: Sedimentology (grain size, structure, descriptive elements), MSCL (P-wave velocity, wet bulk density and magnetic susceptibility) data, and corresponding GPR facies.
P-wave velocity, density and magnetic susceptibility curves show similar trends, the higher values being associated with the coarser deposits, and range from 1458 to 1525 m $s^{-1}$, 1.23 to 1.89 g cm$^{-3}$ and 0 to 7.9 SI, respectively.

Water and organic matter contents respectively range from 29.26 to 64.49% and 1.65 to 10.23%, the higher values being associated with the fine-grained sediments. Carbonate contents are between 66.65 and 89.20%, the lowest values corresponding to the finer sediments.

In general, this core shows heterogeneous alternations of layers up to ca 24 cm thick and grain-size classes from clay to gravel. The colours include black, brown, dark grey, grey, light grey, light greenish grey, grey-beige, beige and cream.

**Core BR-N4**

Core BR-N4 was obtained in the western part of Lake Brenet in a water depth of ca 2 m and ca 65 m lakeward from the shoreline (ca. 370 m north of core BR-N2). It measures 350.5 cm and includes relatively thick layers of sediments ranging from clay to silt (Figures 5.41 and B.4). As mixed silt and clay dominate the upper 227 cm and overlie clay to silty clay sediments, the entire core represents a coarsening upward sequence. Also, the upper unit is darker than the lower one. The sediments are faintly laminated within 0-15 and 157-350.5 cm depth, and laminated from 21 to 153 cm depth. Some coarsening- and fining-upward sequences can be identified. Except for carbonate concretions, all macroscopic components are present (very abundant in places), and their content increases upward.

All the parameters have relatively stable values along the entire sediment column, apart from an isolated high value peak in the magnetic susceptibility at 1 cm depth.

This core can be subdivided into two units (see section B.2.7).

**Core BR-N5**

Core BR-N5 was collected in the western part of Lake Brenet in a water depth of ca 3 m and ca 20 m lakeward from the shoreline (ca 300 m north of core BR-N4). It measures 351 cm and the sediments are dominated by mixed silt and clay (Figures 5.42 and B.4). Coarsening- and fining-upward sequences can be identified. Except for carbonate concretions, all macroscopic components are present (very abundant in places, especially in the silty and sandy layers) and their content increases upward.

This core can be subdivided into three units (see section B.2.8).

**Core JO-N1**

Core JO-N1 was extracted from the northernmost-centre part of Lake Joux in a water depth of ca 26 m. It measures 85 cm and consists of faintly laminated clay containing two subordinate silty layers from 18 to 19 and 83.5 to 84 cm depth (Figures 5.43 and B.6). The two latter have an erosive base and present straight surfaces at their top. Moreover, the upper silty layer contains abundant mollusk shell debris and plant remains as well as very abundant charophyte remains. The sediment colours comprise black, dark brown, dark grey, dark greenish grey, grey and light grey.

The mean value of P-wave velocity is 1457 m $s^{-1}$ and the anomalously low values measured between 40 and 55 cm depth are attributed to the presence of gas in the sediment. Densities and magnetic susceptibilities range from 1.11 to 1.47 g cm$^{-3}$ and from 4 to 17.6 SI, respectively.

Both water and organic matter content curves show the lowest values for the upper silty layer (respectively 47.8% and 2.86%), but these data generally are between 55.76 and 74.06% and between 4.8 and 11.06%, respectively.

**Core JO-N2**

Core JO-N2 was obtained about 1.2 km southwest of the geographic centre of Lake Joux in a water depth of ca 20 m. It measures 326 cm and consists of massive/homogeneous to faintly laminated clays (Figures 5.44 and B.6). The upper 150 cm of sediments display brown-tinted colours (dark brown, brown, brown-grey and beige), followed by grey- to grey-beige-coloured sediments down to 250 cm depth, then by black-tinted (black, dark grey and dark greenish grey) sediment and finally by black-pigmented beige sediments. Mollusk shell debris are scarcely present between 190 and 240 cm depth.

P-wave velocities are relatively stable with a mean value of 1451 m $s^{-1}$, and they display maximum values in the uppermost 110 cm (1483 m $s^{-1}$) and the deepest 35 cm (1497 m $s^{-1}$). Densities increase downward from 1.22 to 1.81 g cm$^{-3}$,
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Figure 5.41: Core BR-N4. Sedimentology (grain size, structure, descriptive elements), MSCL (P-wave velocity, wet bulk density and magnetic susceptibility), water content, loss on ignition (LOI) and LOI data and corresponding GPR facies.
5.3. SEDIMENTOLOGICAL INVESTIGATIONS

Figure 5.42: Core BR-N5. Sedimentology (grain size, structure, descriptive elements), MSCL (P-wave velocity, wet bulk density and magnetic susceptibility), water content, loss on ignition (LOI100 and LOI500) data and corresponding GPR facies.
CHAPTER 5. HOLOCENE HYDROLOGICAL AND CLIMATIC CHANGES INFERRED FROM AN INTEGRATED MULTIPROXY ANALYSIS OF LAKES JOUX AND BRENET SEDIMENTARY RECORDS

Figure 5.43: Core JO-N1: Sedimentology (grain size, structure, descriptive elements), MSCL (P-wave velocity, wet bulk density and magnetic susceptibility), water content, LOI data and corresponding HRS facies.
5.3. SEDIMENTOLOGICAL INVESTIGATIONS

Figure 5.44: Core JO-N2: Sedimentology (grain size, structure, descriptive elements), MSCL (P-wave velocity, wet bulk density and magnetic susceptibility), water content data and corresponding HRS facies.
the minimum measured value being attributed to the presence of gas bubbles at ca 289 cm depth. The magnetic susceptibility curve ranges from 1.8 to 11.7 SI and displays the highest values (up to 67.2 SI at 278 cm depth) from ca 250 to 293 cm depth.

Water content values decrease downward and range from 76.30 to 30.14%.

Core JO-N3

Core JO-N3 was extracted from the centre southeastern shore of Lake Joux, in a water depth of ca 3 m and about 40 m lakeward from the shoreline. It measures 263.5 cm and the sediments are dominated by clay and silty clay (Figures 5.45 and B.6). The observed macroscopic components are mollusk shell debris, plant remains and oncoids, all of these being sparsely present in the upper part of the core.

This core can be subdivided into eight units (see section B.2.9).

Core JO-N4

Core JO-N4 was acquired about 1.2 km southwest of the geographic centre of Lake Joux, in a water depth of ca 2 m and about 50 m lakeward from the shoreline. It measures 223.5 cm and contains very heterogeneous lithologies dominated by clay and gravel (Figures 5.46 and B.6). Scarce mollusk shell debris and plant remains were observed in the uppermost sediments. All the measured parameters (P-wave velocity, density, magnetic susceptibility and water content) display highly fluctuating values.

This core can be subdivided into four units (see section B.2.10).

5.3.4 Discussion of sedimentary stratigraphy

The ground-truthed littoral environments of Lakes Joux and Brenet typically display high lateral and vertical variability in the sediment composition. Even by including all the measured parameters, a simple visual correlation between two closely spaced cores remains difficult to perform. However, the combination of detailed geophysical and sedimentological analysis permits the characterisation of five key coastal stratigraphical units (see correlation Table 5.4 and Figure 5.47). As already discussed in section 5.2.1, sedimentological analysis of coastal deposits provides ‘instantaneously read-able’ information. Direct indicators of past lower lake levels such as coarse-grained beach ridge deposits were identified on the basis of combined geomorphological and sedimentological methods. Yet, because of the high hydrodynamical actions (causing e.g. many erosional surfaces) that characterize the littoral environment, the littoral platform gives a discontinuous / incomplete sedimentary record.

In order to overcome this chrono-morphological hiatus, the deep-water conformable sedimentary record can provide continuous and high-resolution information. Both the seismic and the sedimentary stratigraphies of Lakes Joux and Brenet show typical fjord-type glacial and postglacial sedimentary infill and allow the study of the sedimentary processes and their evolution through the deglaciation. The three main sedimentary units interpreted from the deep offshore core BR-N1 from Lake Brenet (Figure 5.48) comprise, in chronological order:

- unstratified or poorly-stratified glacial deposits comprising massive and compact beige clay (unit F);
- stratified glaciolacustrine deposits containing very finely laminated clay (rhythmites from the Oldest Dryas - Bølling, facies G) and black-pigmented to faintly laminated clay (Allerød, facies H). The whole unit contains gravel-sized dropstones along nearly the entire length.
- lacustrine deposits consisting of homogeneous to faintly laminated, highly carbonated clay deposits (unit I).

By analogy (Table 5.4), the characterised coastal sedimentary facies succession can be correlated with the depositional chronology of the profundal
Figure 5.45: Core JO-N3: Sedimentology (grain size, structure, descriptive elements), MSCL (P-wave velocity, wet bulk density and magnetic susceptibility), water content data and corresponding GPR facies.
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Figure 5.46: Core JO-N4. Sedimentological (grain size, structure, descriptive elements), MSCL (P-wave velocity, wet bulk density and magnetic susceptibility), water content data and corresponding GPR facies.
5.3. SEDIMENTOLOGICAL INVESTIGATIONS

<table>
<thead>
<tr>
<th>UNIT</th>
<th>RADAR FACIES</th>
<th>SEDIMENTARY FACIES</th>
<th>INTERPRETATION</th>
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<td><img src="image2" alt="Image" /></td>
<td>Beach ridge deposits (coarse-grained sediments)</td>
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<tr>
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<td><img src="image3" alt="Image" /></td>
<td><img src="image4" alt="Image" /></td>
<td>Steeply prograding macrophyte-colonised littoral marl bench deposits (medium-grained sediments)</td>
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<td>Prograding macrophyte-colonised littoral marl bench deposits (relatively fine-grained sediments)</td>
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<td><img src="image8" alt="Image" /></td>
<td>Glaciolacustrine deposits (clay-sized sediments)</td>
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<td><img src="image10" alt="Image" /></td>
<td>Melt-out till (clastic)</td>
</tr>
</tbody>
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Figure 5.47: Correlation of the radar and sedimentary stratigraphy. The detailed description and interpretation of radar and sedimentary stratigraphies are given in Figures 5.10 and 5.31, respectively.
Typical deglaciation sedimentary infill $\Rightarrow$ profoundal facies $\Rightarrow$ coastal facies

| Unstratified or poorly-stratified glacial deposits | Massive, compact clay | compact diamicton |
| Stratified glaciolacustrine deposits | finely laminated, black-pigmented to faintly laminated clay | finely laminated, black-pigmented to faintly laminated clay |
| Lacustrine deposits | faintly laminated, highly carbonated clay | faintly laminated silty clay, layered silt and clay, homogeneous sand |

Table 5.5: Correlation of the profundal and coastal sedimentary facies of Lakes Joux and Brenet with typical fjord-type sedimentary infill.

5.4 Chronological framework

The objectives of this section are to analyse the results of different dating methods in order to build a precise and complete age model for the Holocene lacustrine deposits of the Joux Valley.
5.4. CHRONOLOGICAL FRAMEWORK

5.4.1 Radiocaesium-137

Detailed $^{137}$Cs activity profiles were obtained from the uppermost 20 cm of cores BR-N1 and JO-N1 (Figure 5.49).

Lake Brenet. The $^{137}$Cs profile of core BR-N1 (Figure 5.49a) has a background concentration (measured from 19.5 to 14.5 cm depth) ranging from 0.93 to 4.88 Bq/kg and is directly overlain by the ‘significant’ value of 10 Bq/kg at 13.5 cm depth. The curve then increases exponentially until the high activity of 154 Bq/kg is reached at 8.5 cm depth. Further upward, values increase slightly to attain the highest value of 181 Bq/kg at 4.5 cm depth. Finally, the curve decreases slightly down to 120 Bq/kg at the sediment surface.

Lake Joux. Core JO-N1 (Figure 5.49b) displays a $^{137}$Cs background concentration ranging between 0.69 to 6.5 Bq/kg (measured from 19.5 to 14.5 cm depth). A first ‘significant’ value of 15.1 Bq/kg is encountered at 13.5 cm depth. The shape of the activity curve displays a double increasing trend (141 and 173 Bq/kg at 11.5 and 8.5 cm depth, respectively) before it reaches the highest value of 330 Bq/kg at 4.5 cm depth. Above, core data show a downward trend to reach ca 102 Bq/kg at the surface.

The curves from both lakes show similar trends as well as peaks at the same depths, except for the ‘high’ activity measured at 11.5 cm for core JO-N1. The peaks measured at 4.5, 8.5 and 13.5 cm are attributed to the time markers 1986, 1963 and 1954 AD, respectively (see section 2.5.1 for radiocaesium basics). As the only ‘well-defined’ peak is encountered at 4.5 cm depth (corresponding to the Chernobyl accident), the two deeper sedimentation rates may not be representative and are only given here as rough indications. Indeed, the diffusion of the two lower peaks can be due to mixing by physical, biological (e.g. bioturbation) or chemical processes. Thus, sedimentation rates calculated for the periods 2004-1986, (1986-1963) and (1963-1954) are 2.50 mm yr$^{-1}$, (1.74 mm yr$^{-1}$) and (5.55 mm yr$^{-1}$), respectively.

5.4.2 Radiocarbon-14

All of the obtained radiocarbon ages are given in the Tables 5.6 and 5.7. For each core, these ages are plotted in a depth/age relationship in order to provide an age model and to determine the variations in the sedimentation rates among the different sedimentary units (Figures 5.50a and b). The analysis of these plots does not allow the attribution of specific sediment rates for a particular sedimentary facies. Despite this, all radiocarbon age models illustrate the high sedimentation rates of the littoral environment (Figure 5.50 A to F) compared to those of the deep basinal environment (Figure 5.50 G).

5.4.3 Palaeomagnetism

All the data presented in this section are first compared with those measured by Creer et al. (1980) on the lacustrine sediments from Lake Joux. Initial magnetic measurements comprise the NRM stepwise AF demagnetisation of randomly chosen pilot U-channels. The results show a high directional stability (Figure 5.51). The intensity curves reveal median destructive fields (AF required to reduce remanence intensity of half the initial value) ranging from ca. 40 to 50 mT (Figure 5.51A). The orthogonal projection diagrams attest to a good directional stability (changes are limited to a few degrees during the entire treatment in all cases) after the initial removal of a weak viscous component of up to 10-20 mT (Figure 5.51B). All samples lost a soft component of magnetisation by ca 20 mT and thereafter demagnetised linearly toward the origin (Figure 5.51C). Considering these
### Table 5.6: Radiocarbon dates of the onshore cores from Lake Brenet. The lab. number of unused data is labelled with a sharp sign.

<table>
<thead>
<tr>
<th>Core Section</th>
<th>Section Depth</th>
<th>Total Depth</th>
<th>AMS Calibrated Age (2σ range)</th>
<th>Lab. Number</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>BR-V1</td>
<td>92-104.5</td>
<td>98</td>
<td>4154-4210 AD</td>
<td>ETH-32149</td>
<td>charcoal</td>
</tr>
<tr>
<td></td>
<td>129.5</td>
<td>129.5</td>
<td>5319-5488 BC</td>
<td>ETH-33248</td>
<td>wood</td>
</tr>
<tr>
<td></td>
<td>112.5-115</td>
<td>118</td>
<td>5185-5215 2σ</td>
<td>ETH-32148#</td>
<td>wood</td>
</tr>
<tr>
<td></td>
<td>116.5-118.5</td>
<td>115</td>
<td>5129-5145 2σ</td>
<td>ETH-32147</td>
<td>wood</td>
</tr>
<tr>
<td></td>
<td>112-115</td>
<td>118</td>
<td>5185-5215 2σ</td>
<td>ETH-32146</td>
<td>wood</td>
</tr>
<tr>
<td></td>
<td>106.5</td>
<td>116.5</td>
<td>4838-5064 2σ</td>
<td>ETH-32144</td>
<td>wood</td>
</tr>
<tr>
<td></td>
<td>111.5-1150</td>
<td>1115</td>
<td>4370 ± 55 2σ</td>
<td>ETH-33245#</td>
<td>wood</td>
</tr>
<tr>
<td></td>
<td>392-412.5</td>
<td>412</td>
<td>3900 ± 55 2σ</td>
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<td></td>
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<td>38.5</td>
<td>3765 ± 95 2σ</td>
<td>ETH-32147#</td>
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<tr>
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<td>30-31</td>
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<td>ETH-33246</td>
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<td></td>
<td>92</td>
<td>92</td>
<td>3450-3500 BC</td>
<td>ETH-33245</td>
<td>wood</td>
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<td>122</td>
<td>122</td>
<td>3050-3100 BC</td>
<td>ETH-33244</td>
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</tr>
<tr>
<td></td>
<td>112</td>
<td>112</td>
<td>2920-2970 BC</td>
<td>ETH-33243</td>
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<td></td>
<td>106</td>
<td>106</td>
<td>2790-2840 BC</td>
<td>ETH-33242</td>
<td>wood</td>
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<tr>
<td></td>
<td>90</td>
<td>90</td>
<td>2660-2710 BC</td>
<td>ETH-33241</td>
<td>wood</td>
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</tbody>
</table>
### 5.4. CHRONOLOGICAL FRAMEWORK

Table 5.7: Radiocarbon dates of the offshore cores from Lake Brenet. The lab. number of unused data is labelled with a sharp sign.

<table>
<thead>
<tr>
<th>Core</th>
<th>Section</th>
<th>Section depth [cm]</th>
<th>Tot. depth [cm]</th>
<th>AMS $^{14}$C age [yr BP]</th>
<th>$\delta^{13}$C [%]</th>
<th>Calib. age (2σ range)</th>
<th>Lab. Number</th>
<th>Material</th>
</tr>
</thead>
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<td></td>
<td></td>
<td></td>
<td>cal yr AD/BC</td>
<td></td>
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<tr>
<td>BR-N1</td>
<td>1A</td>
<td>14.5</td>
<td>24.5</td>
<td>265 ± 45</td>
<td>-22.6 ± 1.2</td>
<td>(0)-13 1937-1951 AD</td>
<td>ETH-33249</td>
<td>wood</td>
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<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>148-188 1762-1802 AD</td>
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<tr>
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<td></td>
<td></td>
<td></td>
<td>198-211 1739-1752 AD</td>
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<td></td>
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<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>269-466 1484-1681 AD</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1B</td>
<td>33</td>
<td>43</td>
<td>1320 ± 70</td>
<td>-23.8 ± 1.2</td>
<td>1071-1345 605-879 AD</td>
<td>ETH-33250</td>
<td>wood</td>
</tr>
<tr>
<td></td>
<td>1C</td>
<td>65.5</td>
<td>27.1</td>
<td>11900 ± 130</td>
<td>-33.6 ± 1.2</td>
<td>1348-14023 12014-1196 AD</td>
<td>ETH-33251</td>
<td>wood</td>
</tr>
<tr>
<td>BR-N2</td>
<td>1B</td>
<td>25.5</td>
<td>132</td>
<td>495 ± 45</td>
<td>-21.6 ± 1.2</td>
<td>480-561 1389-1470 AD</td>
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<td>wood</td>
</tr>
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<td></td>
<td>1C</td>
<td>77</td>
<td>183.5</td>
<td>3630 ± 50</td>
<td>-25.5 ± 1.2</td>
<td>3830-4090 2141-1881 BC</td>
<td>ETH-33253#</td>
<td>wood</td>
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<td></td>
<td>1C</td>
<td>48</td>
<td>210.5</td>
<td>960 ± 45</td>
<td>-20.9 ± 1.2</td>
<td>775-957 993-1175 AD</td>
<td>ETH-33254</td>
<td>wood</td>
</tr>
<tr>
<td>BR-N3</td>
<td>1B</td>
<td>10.5</td>
<td>111.5</td>
<td>480 ± 45</td>
<td>-19.8 ± 1.2</td>
<td>342-346 1694-1698 AD</td>
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<td>wood &amp; charcoal</td>
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<td>1C</td>
<td>11</td>
<td>195</td>
<td>755 ± 50</td>
<td>-19.1 ± 1.2</td>
<td>568-583 1367-1382 AD</td>
<td>ETH-30468</td>
<td>wood &amp; charcoal</td>
</tr>
<tr>
<td>BR-N4</td>
<td>1B</td>
<td>64.5</td>
<td>225.5</td>
<td>1755 ± 50</td>
<td>-28.0 ± 1.2</td>
<td>3617-3624 1675-1668 BC</td>
<td>ETH-33259</td>
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<td></td>
<td></td>
<td></td>
<td>3629-3898 1949-1679 BC</td>
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<td></td>
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<tr>
<td></td>
<td>1C</td>
<td>87.5</td>
<td>248.5</td>
<td>3485 ± 55</td>
<td>-23.9 ± 1.2</td>
<td>3169-3179 1230-1256 BC</td>
<td>ETH-33260</td>
<td>wood</td>
</tr>
<tr>
<td>BR-N5</td>
<td>1C</td>
<td>54.5</td>
<td>309.5</td>
<td>3100 ± 50</td>
<td>-23.5 ± 1.2</td>
<td>3208-3412 1463-1259 BC</td>
<td>ETH-33261</td>
<td>wood</td>
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<td>3422-3442 1493-1473 BC</td>
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<td></td>
<td>3584-3863 1914-1635 BC</td>
<td>ETH-30471</td>
<td>wood</td>
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</table>

Table 5.7: Radiocarbon dates of the offshore cores from Lake Brenet. The lab. number of unused data is labelled with a sharp sign.
Figure 5.50: Radiocarbon-based age model and estimated sedimentation rates for Lake Brenet cores (A) BR-V2, (B) BR-V5, (C) BR-N2 and (D) BR-N5. The corresponding GPR facies are indicated in large grey letters. Except for core BR-V5, radiocarbon ages are mean values of the maximum probability interval of the 2 sigma age ranges (Tables 5.6 and 5.7).
Figure 5.50: Radiocarbon-based age model and estimated sedimentation rates for Lake Brenet cores (E) BR-N4, (F) BR-N5 and (G) BR-N1. The corresponding GPR (for E and F) and HRS (for G) facies are indicated in large grey letters. Radiocarbon ages are mean values of the maximum probability interval of the 2 sigma age ranges (Table 5.7).
pilot results, the NRM direction was taken as free of viscous magnetisation and thus representative of the primary component of the original NRM after/under AF demagnetisation at 20 mT.

Mineral-magnetic data

The hysteresis ratios (Mrs/Ms versus Hcr/Hc) of sediment samples from Lakes Joux and Brenet are plotted on a Day plot (Day et al., 1977) in Figure 5.52. Samples from different cores and core depths are plotted with different symbols and show a clustering according to their time period (Late Glacial - Holocene transition at ca. 3 m sediment depth, see figure 5.54). The general trend shows a typical hyperbolic distribution. All points fall into an apparent pseudo-single domain (PSD) range. The Holocene samples possess a strong and stable characteristic remanent magnetisation apparently by PSD magnetites, while Lateglacial sediment sample values from Lake Brenet (i.e. H23, H26 and H29, Table C.2) plot close to the MD range. This indicates a different behavior between warm and cold climatic stages. Similar trends were observed in Swiss Alpine lake sediments by Lanci et al. (1999) and Lanci et al. (2001).

The values of the $\kappa$, NRM intensity and Q-ratio data show a good and positive correlation with those published by Creer et al. (1980) (Figure 5.53). First, with regard to the proximity of the two cores from Lake Joux (JO-N2 and core n° 3), the difference in the depths (ca. 40 cm) at which the trends and peaks are observed is surprising. Indeed, seismic data in the region of the core location indicate...
conformable and continuous lacustrine drapes. On the other hand, this confirms the observations of Creer et al. (1980) concerning the significant lateral sediment variations as well as the presence of hiatuses in the sedimentary records attributed to complex processes of ice retreat in the Joux valley. Nevertheless, an overall positive correlation of the isolated parameters is shown by the parallelism of the drawn tie-line frameworks. The sharp transition observed in all data at the Lateglacial - Postglacial transition probably indicates changes in the magnetic concentrations along the core and is attributed here to changes in the climatic conditions.

These results agree with the complete rock-magnetic dataset presented in Figure 5.54. This figure compares the mineral magnetic data obtained from both lakes and includes $\kappa$, $\kappa_{ARM}$, SIRM, SIRM/$\kappa$, $\kappa_{ARM}/\kappa$ and S-ratio. Despite a constant upward shift of a few centimetres in the data from Lake Joux compared to those of Lake Brenet, the trends in all curves are similar throughout the core. Magnetic mineral data obtained from core BR-N1 (the longest core) allow the dating of certain important hydrological and climatic changes. The S-ratio curve shows a positive correlation with $\delta^{18}O$ data from the ‘GISP2 ice core record’ and evidences the cold and dry event of the Younger Dryas as well as the Bølling - Allerød warmer period. According to Rolph et al. (1996), these periods are characterised by a gradual decrease in the supply of magnetic material, reflected by lower values of $\kappa$ and SIRM. As all the presented data show similar trends, this event is attributed to a decrease in the input of catchment material.

An additional tentative correlation allows to identify the Older Dryas period and the Last Glacial Maximum (LGM at ca 21 kyr BP) and to eventually assign a maximum age of core BR-N1 of ca 36 kyr BP. Such rough indication could signify that Lake Brenet acted as a subglacial lake since this time. This indication agrees with the stable density curve of the core (Figure 5.37). Indeed, the weight of a glacier at this time would have leave a significant shift in the density values.

Magnetic susceptibilities ($\kappa$), SIRM and SIRM/$\kappa$ show three distinct positive peaks at 292.5 cm, 371.0 cm and 417.0 cm depth. Thin sections from these intervals indicate changes in the mineralogy (appearance of quartz, plagioclase, amphibole and sanidine). Moreover, in analogy to published limnogeological studies of marl lakes from the French Jura, positive magnetic susceptibility peaks correspond to tephra layers. Thus, on the basis of the ages provided by the S-ratio curve, it is proposed that the peak at 292.5 cm depth could represent the Ulmener Maar Tephra (Eifel Volcanic Field, Germany) dated to 9560 $^{14}$C yr BP (end of Preboreal) (Zolitschka et al., 1995). The intermediate peak at 371 cm should then correspond to the Laacher See Tephra (Eifel Volcanic Field, Germany) dated to $12'900 \pm 560$ yr BP (van den Bogaard, 1995) (Allerød - Younger Dryas transition). Due to the scarcity of extracted mineralogical material and historical data, the deepest peak can not be reasonably attributed to a specific tephra.
CHAPTER 5. HOLOCENE HYDROLOGICAL AND CLIMATIC CHANGES INFERRED FROM AN INTEGRATED MULTIPROXY ANALYSIS OF LAKES JOUX AND BRENET SEDIMENTARY RECORDS

Figure 5.53: Comparison of the mineral-magnetic record from cores JO-N2 and BR-N1 to the (*) Lake Joux record from core n° 3 of Creer et al. (1980). (A) magnetic susceptibility ($\kappa$), (B) NRM intensity and (C) Q-ratio.
Figure 5.54: Lithology and variations in mineral magnetic parameters ($\kappa$, $\kappa_{\text{ARM}}$, SIRM, SIRM/$\kappa$, $\kappa_{\text{ARM}}$/SIRM, $\kappa$ and S-ratio) from cores BR-N1 and JO-N2 (thin grey curves), and comparison of S-ratio data from core BR-N1 with the oxygen isotope record from the Greenland Ice Sheet Project 2 (GISP2, Grootes et al., 1993 and Stuiver & Grootes, 2000). LGM = Last Glacial Maximum, OD = Oldest Dryas, BØ-AL = Bølling - Allerød warming and YD = Younger Dryas cold period. T1, T2 and T3 represent tephra horizons (UMT = Ulmener Maar Tephra and LST = Laacher See Tephra) detected on core BR-N1.
Geomagnetic secular variations from Lake Brenet

As the successive sections of the cores were not oriented with respect to the north azimuth, the mean declination of the NRM record was established by considering the mean declinations for each successive section as equal to zero (relative declination). For the cleaned declination record, the successive sections were also connected by matching the declinations at their ends. Due to problems during laboratory procedures, the NRM information of U-channel J2 (see section C.3) from the Lake Joux core JO-N2 was lost. Thus, the following paragraphs exclusively compare the data from Lake Brenet core BR-N1 and the displayed Joux data only give indications.

The visual comparison between the directional palaeomagnetic oscillations record with the data of Creer et al. (1980) shows also a positive correlation of both the declination (Figure 5.55A) and the inclination (Figure 5.55B). The identification of declination and inclination features was based on both the comparison with existing master curves and the time markers detected by the mineral-magnetic data. Concerning the data from Lake Brenet, changes in declination have peak-to-peak amplitudes of up to 60°, while the inclination changes tend to be smaller with mean peak-to-peak amplitudes of ca. 35°. According to Thompson & Edwards (1982), such difference in amplitudes largely results from trigonometric effects caused by the steep inclination of the geomagnetic field in high to middle latitudes.
5.4. CHRONOLOGICAL FRAMEWORK

<table>
<thead>
<tr>
<th>Greek label</th>
<th>Alphanum. label</th>
<th>Age [cal yr BP]</th>
<th>Depth [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>α (alpha)</td>
<td>1</td>
<td>250</td>
<td>0.14</td>
</tr>
<tr>
<td>β (beta)</td>
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<td>650</td>
<td>0.19</td>
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<td>γ (gamma)</td>
<td>3</td>
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<tr>
<td>δ (delta)</td>
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<td>η (eta)</td>
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<tr>
<td>σ (sigma)</td>
<td>17</td>
<td>*14500</td>
<td>5.24</td>
</tr>
</tbody>
</table>

Table 5.9: Correspondance among the two labeling systems (Greek and alphanumeric), conventional (uncalibrated) radiocarbon ages and depths of the main inclination peaks. Ages are based on the British master record (Turner & Thompson, 1981), Lake Joux * (Creer et al., 1980) and Lake Bouchet ** (Creer et al., 1986).

Inclination data seem to be more reliable than declination data. Concerning the delay of the magnetic blocking recorded in the inclination data, the variation observed between the UMT and LST can be attributed to different sediment sources and processes between Lateglacial and Holocene periods.

Nevertheless, sedimentation rates calculated from declination and inclination palaeomagnetic data are quite similar for the Holocene and the Lateglacial, and both the Younger Dryas and the beginning of the Holocene are characterised by lower sedimentation rates. Such results are consistent with those reported by e.g. Creer et al. (1980) from Lake Joux, Niessen & Kelts (1989) from Lake Lugano and Baster (2002) from Lake Geneva. Concerning Lake Brenet, Lateglacial sedimentation rates estimated from declination and inclination features are ca 0.63 mm yr$^{-1}$ and 0.59 mm yr$^{-1}$, respectively. Sedimentation rates of the Younger Dryas and the Lateglacial-Holocene transition indicate 0.07 mm yr$^{-1}$ and 0.12 mm yr$^{-1}$ (respectively, declination and inclination), and those of the Holocene period are of 0.67 mm yr$^{-1}$ and 0.38 mm yr$^{-1}$ (respectively, declination and inclination). Sedimentation rates estimated from the declination features indicate a sharp increase towards ‘modern’ times (> 1 mm yr$^{-1}$).

5.4.4 Discussion of the chronological framework

The Holocene and Late-Pleistocene sediments of Lake Brenet (and Joux) recorded precisely the past secular variations of the Earth’s geomagnetic field since ca. 18’000 cal yr BP. Despite some discrepancies between magnetic and radiocarbon ages, all of the estimated sedimentation rates are concordant. The discrepancies are attributed to the reworking of terrestrial plant remains, which makes radiocarbon ages of lake sediments too old, and to younger ages induced by magnetic locking-in delays. Sedimentation rates estimated from $^{137}$Cs activity are in agreement with those provided by declination data.
CHAPTER 5. HOLOCENE HYDROLOGICAL AND CLIMATIC CHANGES INFERRED FROM AN INTEGRATED MULTIPROXY ANALYSIS OF LAKES JOUX AND BRENET SEDIMENTARY RECORDS

Figure 5.56: Comparison of the Lake Brenet (core BR-N1) directional palaeomagnetic record with the composite ‘European record’ proposed by Thouveny & Williamson (1987). The ‘European record’ is compiled by the Holocene PSV type curve from the U.K. (Turner & Thompson, 1981; Creer & Tucholka, 1983) and the Late Pleistocene PSV curve from Lac du Bouchet (France) (Thouveny, 1983; Smith, 1985; Creer et al., 1986; Smith & Creer, 1986). The Y axis of the ‘European record’ shows the European original radiocarbon time-scale while that of core BR-N1 represents the sediment depth. The alphanumeric labelling system is used (declination: D1 - D18 and inclination: I1 - I19).
Figure 5.57: Age model based on palaeomagnetic (A) declination and (B) inclination features recorded in core BR-N1 and the related sedimentation rates for the last 20'000 cal yr BP.
CHAPTER 5. HOLOCENE HYDROLOGICAL AND CLIMATIC CHANGES INFERRED FROM AN INTEGRATED MULTIPROXY ANALYSIS OF LAKES JOUX AND BRENET SEDIMENTARY RECORDS
Chapter 6

General conclusions and perspectives

This research was conducted with the following goals in mind:

- to determine the usefulness and limitations of GPR methods in onshore and offshore lacustrine settings;
- to identify and characterise the typical radar facies/patterns in the littoral environment of western Swiss lakes;
- to assess the comparative and complementary aspects between GPR and HRS methods in lacustrine environments;
- to test the joint application of GPR and HRS methods in such environments by studying a ‘calibrated site’: the Geneva Bay area;
- to use some of these results in the integration of geophysics, sedimentology, petrophysics, stratigraphy, physico-chemistry, geochronology and palaeomagnetism in studying the limnogeology at an ‘exploration site’: Lakes Joux and Brenet.

By achieving these goals, Lateglacial and Holocene lacustrine sedimentary models are improved and related to hydrological and climatic changes. The main results are presented and discussed in the following paragraphs.

GPR methods offer the potential to continuously profile the littoral lacustrine environment from onshore to shallow offshore settings. The analysis of the frequency spectra of the returned radar signal in offshore settings indicates that, as water depth increases, the spectra display a downward shift of the centre frequency and a narrowing of the frequency bandwidth. Despite the slow radar velocity through water, a sufficiently high theoretical vertical resolution is possible. Independant of the GPR antenna frequency, onshore and offshore sediments often can be probed through the uppermost 3 m, but below ca 3 m water depth the radar signal is completely dissipated. Moreover, GPR reflections can be followed continuously beneath the lake-bottom multiple and from onshore to offshore. The littoral lacustrine environment can be subdivided into four distinct zones in terms of GPR response: onshore, shoreline adjoining onshore, very shallow water and ‘offshore’ zones. Each one of these zones possess specific investigation depths, noise characteristics and signal-to-noise ratios.

The onshore and offshore GPR reflections are generally continuous and inclined at various degrees towards the lake. Most reflection terminations consist of lakeward downlaps and landward onlaps. Four characteristic littoral radar facies are identified: sheet drapes, flat and lens-shaped beaches, beach ridges and associated complex, and prograding macrophyte-colonised littoral marl benches. All provide key geomorphological information about the palaeoshoreline location and thus changes in lake level. Beach ridges and prograding littoral benches are the dominant imaged coastal landforms.

GPR profiles from onshore areas surrounding Geneva Bay allow the accurate mapping of the landward extent of a beach ridge complex, which corresponds to the known +3 m lacustrine terrace. This terrace was formed during several short-lived highstands since the Late Neolithic Period.

Changes in the inclinations of GPR reflections from the above-mentioned marl benches of Lake Brenet correspond to the increasing frequency of lake-level fluctuations recorded by Magny (1992). These are also coincident with the mid-Holocene climate optimum (for review, see Davis et al., 2003). Other submersed ancient beach ridges im-
aged beneath Lake Brenet indicate lowstands at ca. -3 m and -4.5 m, which are dated to the Medieval Warm Period (WMP) and the middle Subboreal (phase of glacier recession located between the Löbben and Göschenen I cold periods), respectively.

The comparison between GPR and HRS data is restricted to the uppermost first metre of sediments in shallow water settings. Both methods have vertical resolutions in the decimetre range and display similar reflection pattern (geometries and terminations) at similar locations. The comparative and complementary aspects between these two techniques were successfully analysed, and it can be concluded that complete onshore-offshore geophysical profiling of lacustrine sedimentary sequences still remains a difficult task and that these methods are much more complementary.

The joint application of GPR and HRS methods at the ‘calibrated’ site of Geneva Bay (Lake Geneva) improve the understanding of local lacustrine sedimentary processes since the Late Pleistocene. Offshore HRS investigations extend the known seismic stratigraphy of the ‘Petit Lac’ (Moscariello, 1996, Moscariello et al., 1998a and Fiore, 2007) to the city of Geneva. Offshore GPR profiling reveal the present-day 3D geometry and sedimentary dynamics of a Late Holocene ooidal sand body and indicate ancient beach deposits. Onshore GPR profiles of the +3 m lacustrine terrace allow to attribute specific lakeside sediment sources of these beach ridge deposits. The complex reflection geometries observed in the GPR and HRS profiles underline the importance of the ‘Bise’ wind as major agent for erosion and deposition in the Geneva Bay area. Thus, even a limited number of geophysical profiles can contribute to the local sedimentological and climate models.

The ‘complete’ integrated study conducted at the ‘exploration site’ allows to characterise the radar stratigraphy, the seismic stratigraphy and the sedimentary stratigraphy as well as to construct a geochronological model for both Lakes Joux and Brenet.

The GPR stratigraphy comprises four main units G-0 (glacial and lateglacial glaciolacustrine), G-1 (prograding macrophyte-colonised littoral marl benches; first half of the Holocene), G-2 and G-3 (respectively, prograding macrophyte-colonised littoral marl benches and beach ridges; second half of the Holocene).

The HRS stratigraphy includes three main units U0 (glacial), U1 (glaciolacustrine) and U2 (lacustrine).

Sedimentary stratigraphic units comprise unit F (massive and compacted glacial deposits), units G and H (faintly to finely laminated glaciolacustrine clay containing gravel-sized dropstones) and unit I (homogeneous to faintly laminated highly carbonated lacustrine clay).

All three stratigraphies are in agreement with each other and reflect typical fjord-type sedimentary infill. The chronological framework of this study is based on radiocaesium, radiocarbon and palaeomagnetic ages, and it allows the precise dating of different events that correlate with hydrological and climatic changes since the Lateglacial (magnetic ages down to ca 18 cal kyr BP).

Mineral magnetic data obtained from the deep offshore core BR-N1 allow the dating of certain important hydrological and climatic events. The correlation of the S-ratio curve with $\delta^{18}O$ data from the ‘GISP2 ice core record’ (e.g. Grootes et al., 1993 and Stuiver & Grootes, 2000) evidences the cold and dry event of the Younger Dryas as well as the Bolling - Allerød warmer period. Magnetic susceptibility ($\kappa$), SIRM and SIRM/$\kappa$ show three distinct positive peaks at 292.5 cm, 371.0 cm and 417.0 cm depth. On the basis of the ages provided by the S-ratio curve, it is proposed that the peak at 371 cm corresponds to the Laacher See Tephra (LST) dated to 12'900 ± 560 yr BP (van den Boogaard, 1995) (Allerød - Younger Dryas transition) and that the upper peak represents the Ulmener Maar Tephra (UMT) dated to 9560 $^{14}$C yr BP (Zolitschka et al., 1995) (end of Preboreal).

Finally, the palaeosecular variations (declination, inclination and intensity) of the geomagnetic field recorded in the sediments from Lake Brenet correlate positively with the published master curves from Lake Joux (Creer et al., 1980) and the ‘European record’ proposed by Thouveny & Williamson (1987). This allows the construction of a continuous ‘magnetic’ age model, which is enhanced by the addition of $^{137}$Cs, $^{14}$C and deduced tephrachronological ages. Thus, a detailed chronostratigraphical model extending back to ca 18'000 cal yr BP is obtained.

Finally, this local study provides a platform and a promising methodology for further limnogeological investigations that include targets in littoral settings.
Perspectives for future Holocene limnogeological investigations covering the coastal and deep basinal realms include an increase in geophysical surveys in order to enhance the GPR and HRS stratigraphies. Additional amphibious GPR tests are still needed to better characterise the radar response in coastal environments.

Additional frozen-lake GPR surveys in Lakes Joux and Brenet could be helpful, as such methods are very efficient for amphibious profiling. Despite the favorable electrical properties of pure ice compared to those of liquid water (allowing deeper penetration), the reality of variable ice quality in temperate regions confirms that good surveying methods on unfrozen lakes are indispensable. Thus, advances in GPR technology that lead to significant signal strength enhancement in order to provide deeper penetration depths with relatively similar vertical resolutions (even higher).

The retrieval of coastal (onshore and shallow water) and offshore sediment cores of ca 5m and 20m length, respectively, would be necessary to better calibrate the geophysical data as well as to better improve the sedimentary models.

A palynological study as well as a study of the chironomid fossil record from the profundal sediments of Lake Brenet would target Holocene climatic changes and could reveal detailed responses of the lake dynamics to these changes.
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