Limnogeological cruise on Lake Geneva: geological history of the Lake Geneva basin and human settlements

GIRARD CLOS, Stéphanie, CORBOUD, Pierre, WILDI, Walter.

Available at: http://archive-ouverte.unige.ch/unige:39357
19TH INTERNATIONAL SEDIMENTOLOGICAL CONGRESS FROM 18 TO 22 AUGUST 2014 IN GENEVA, SWITZERLAND

SEDIMENTOLOGY AT THE CROSSROADS OF NEW FRONTIERS

Limnogeological cruise on Lake Geneva: geological history of the Lake Geneva basin and human settlements
Stéphanie Girardclos, Pierre Corboud, Walter Wildi (University of Geneva)
Limnogeological cruise on Lake Geneva: geological history of the Lake Geneva basin and human settlements

By Stéphanie Girardclos*, Pierre Corboud** and Walter Widi***

*Section of Earth and Environmental Sciences and Institute for Environmental Sciences, **Institut F.-A. Forel, ***honorary professor, Institut F.-A. Forel

Table of content

Abstract, map of the tour.......................................................................................................................... 1
1. Technical data of Lake Geneva ........................................................................................................... 2
2. Winds and currents of Lake Geneva .................................................................................................. 3
3. Limnology of Lake Geneva .............................................................................................................. 4
4. Regional Chronology ......................................................................................................................... 5
5. Tectonic, geological and sedimentological setting ........................................................................... 6
6. Formation of Lake Geneva basin ...................................................................................................... 8
7. Glacial stages and sediment infill of Western Lake Geneva ............................................................... 9
8. The Rhone delta and canyons ........................................................................................................... 14
9. Extreme events and tsunamis in Lake Geneva .................................................................................. 18
10. Evolution of Lake Geneva level between glacial retreat and the present........................................ 21
11. Holocene vegetation and landscape history ................................................................................... 23
12. Human occupation of the Geneva basin, relations with the environment ..................................... 25
13. Construction of Geneva city with local georesources ................................................................... 26
14. Bibliography ................................................................................................................................... 28

Addresses of authors:
Stéphanie Girardclos • stephanie.girardclos@unige.ch
Department of Earth Sciences
University of Geneva
Rue des Maraichers 13
CH-1205 Geneva
SWITZERLAND

Pierre Corboud • pierre.corboud@unige.ch
Institut F.-A. Forel
Route de Suisse 10 - CP 416
CH-1290 Versoix
SWITZERLAND

Walter Wildi • walter.wildi@unige.ch
Institut F.-A. Forel
Route de Suisse 10 - CP 416
CH-1290 Versoix
SWITZERLAND

Thank you to our co-authors: Katrina Kremer, Guy Simpson, Juan Pablo Corella, Michael Hilbe, Jean-Luc Loizeau, Angel Arantegui, Anne-Marie Rachoud Schneider, Flavio Anselmetti, François Marillier, Frédéric Arlaud and Tonya DelSontro.

Thank you to our financing institutions: Swiss National Science Foundation, Fondation Ernest Boninchi, Fondation Ernest and Lucie Schmidheiny.

This document is published thanks to the financial support of the Société de physique et de science naturelle de Genève (SPHN)

Abstract

Lake Geneva became famous in the scientific world since the publication of the pioneer limnology book "Le Léman" by François-Alphonse Forel (Forel 1892-1904). We will take you onboard the Neptun, a boat constructed in 1904, the same year Forel's book was published, for a short journey through the geological and sedimentological history of the lake. We will show you how the Leman and humans societies, including the palafittes (UNESCO world heritage), interacted through time and how two tsunamis swept over the lake. We will also take the opportunity of the breathtaking view over the surrounding landscape to give an overview of the regional geology (Prealps, Jura) and discuss how the Rhone glacier shaped the Geneva basin during the last glaciation (Last Glacial Maximum ca. 20'000 BP).

Map of the tour

Departure: 10h
Arrival: 13h
1. Technical data of Lake Geneva

Average altitude of the lake: ........................................... 372.05 m (1943-2008)
mini: 371.78 (1949)
maxi: 372.19 (1977)

Extreme levels (after the regularization of Lake Geneva, 1887): .................................
mini: 370.85 (1921)
maxi: 372.91 (1937)

Surface water level: ........................................................................... 580.1 km²
Catchment area: ............................................................................... 7'419 km² (less the lake)
Average altitude of the watershed: .................................................. 1'670 m
Average volume: ............................................................................... 89 billion m³ (89 km³)
Average total flow of the tributaries of Lake Geneva: .............................
mini: 127 m³/s (1976)
maxi: 227 m³/s (1999)

Medium flow of the Rhone River upstream (at Porte du Scex Station): ...........
mini: 127 m³/s (1976)
maxi: 227 m³/s (1999)

Percentage of the contribution of the Rhône River: ........................................ 83% of total of the tributaries
Medium outflow of the Rhone River (Geneva): ........................................
mini: 166 m³/s (1976)
maxi: 327 m³/s (1995)

Theoretical retention time of water: .................................................... 11.3 years (volume/medium flow)
Maximum depth: ............................................................................ 308.9 m (updated)
Length of shoreline: ................................................................. 200.2 km

2. Winds and currents of Lake Geneva


3. Limnology of Lake Geneva

Lake Geneva, also known in French as Le Léman, is a large deep-water basin in central Europe, on the border between Switzerland and France. The lake is characterized by thermal stratification of the water column from spring to autumn and homogenization from the end of winter to the beginning of spring. Lake Geneva is a "monomictic" lake according to the classification of Hutchison.

The annual thermal cycle begins with isothermal conditions in winter, followed by thorough mixing in late winter, and by stratification from May to October. The annual cycle of temperature distribution in the Grand-Lac shows strong seasonal trends. Depending on the difference in volume and morphology of the basin, cooling and warming during the transition periods (spring and fall) are slower in the Grand-Lac than in the Petit-Lac. Minor differences within the basins could be linked to local circulations between coastal areas and deep areas, as well as the influence of fluvial input, including the Rhone.

Over much of the year, the waters of Grand-Lac circulate in a gyre turning counterclockwise (Le Thi et al. 2012). The size and lifetime of the vortex varies depending on weather conditions. Appendices of the main gyre are found in major bays of the northern shore, in Morges and Vidy (Lausanne). These are less stable than the main gyre and their direction may switch depending on wind direction. In the transitional area between the Grand-Lac and the Petit-Lac a gyre oriented clockwise is established. The western end of the Petit-Lac is characterized by a counterclockwise circulation system. In the Petit-Lac, flow towards the Rhone outlet mainly occurs in surface waters and along the borders of the basin, while the return currents to the Grand-Lac are deeper-water currents and found in the central part of the basin. In the Grand-Lac, the downstream flow from East to West follows the northern edge of the basin, while the return current, from the western to the eastern part of the basin, predominantly follows the southern border.

Temperature contours maps from monthly-observed data (left panel) and modeled data (right panel) at the GE3 monitoring site in Petit-Lac (Le Thi et al. 2012).
## 4. Regional Chronology

<table>
<thead>
<tr>
<th>Seismic units</th>
<th>Seismic Reflections</th>
<th>Swiss Plateau Biozones (Lotter 1999; Ammann et al. 1996)</th>
<th>Cal. kyr BP</th>
<th>Cal. kyr BC</th>
<th>Archaeological cultures</th>
</tr>
</thead>
<tbody>
<tr>
<td>14 D</td>
<td>8</td>
<td>Younger Subatlantique X</td>
<td>1 AD</td>
<td>0</td>
<td>Modern period</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Older Subatlantique IX</td>
<td>1 AD</td>
<td>0</td>
<td>Roman times</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Subboreal VIII</td>
<td>2</td>
<td>1</td>
<td>Iron Age</td>
</tr>
<tr>
<td>C3</td>
<td>-10/9</td>
<td>Younger Atlantique VII</td>
<td>3</td>
<td>2</td>
<td>Bronze Age</td>
</tr>
<tr>
<td>13 C2</td>
<td>-11</td>
<td>Older Atlantique VI</td>
<td>4</td>
<td>3</td>
<td>Neolithic</td>
</tr>
<tr>
<td></td>
<td>-12</td>
<td>Boreal V</td>
<td>5</td>
<td>4</td>
<td>Mesolithic</td>
</tr>
<tr>
<td></td>
<td>-13</td>
<td>Preboreal IV</td>
<td>6</td>
<td>5</td>
<td>Neolithic</td>
</tr>
<tr>
<td></td>
<td>-14</td>
<td>Younger Dryas III</td>
<td>7</td>
<td>6</td>
<td>Epipaleolithic</td>
</tr>
<tr>
<td>C1</td>
<td>15</td>
<td>Allerød II</td>
<td>8</td>
<td>7</td>
<td>Modern period</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>Bølling lb</td>
<td>9</td>
<td>8</td>
<td>Roman times</td>
</tr>
<tr>
<td>12.2 B3 B2</td>
<td>17</td>
<td>Oldest Dryas Ia</td>
<td>10</td>
<td>9</td>
<td>Iron Age</td>
</tr>
<tr>
<td>12.1 B1</td>
<td>19</td>
<td>Nyon stage</td>
<td>?</td>
<td>?</td>
<td>Neolithic</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>Coppet stage</td>
<td>?</td>
<td>?</td>
<td>Mesolithic</td>
</tr>
<tr>
<td>11 A2</td>
<td>20</td>
<td>Rhone glacier deglaciation</td>
<td>?</td>
<td>?</td>
<td>Neolithic</td>
</tr>
<tr>
<td>10 A1</td>
<td>21</td>
<td>Reposoir stage</td>
<td>?</td>
<td>?</td>
<td>Mesolithic</td>
</tr>
<tr>
<td>8</td>
<td>22</td>
<td>Geneva stage</td>
<td>ca. 22</td>
<td>ca. 20</td>
<td>Modern period</td>
</tr>
<tr>
<td>7</td>
<td>End of last glacial maximum</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2-6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Glacio-lacustrine and lacustrine units: age and correlation of units and reflections with the Swiss Plateau chrono-biozones and archeological cultures. Fiore et al. 2011 modified.
5. Tectonic, geological and sedimentological setting


Geological profile through the southern Geneva basin. The Tertiary Molasse basin (yellow) was formed at the end of alpine formation. Gorin and Moscariello 2013.
Lake Geneva lies between the Jura mountain and Prealps in a Tertiary Molasse basin which was deposited in the alpine foreland on top of Lower Cretaceous formations. Its basin was carved during Quaternary glaciations. In the Petit-Lac a deep and undulating valley typical of 'tunnel valleys' (Fiore et al. 2011) built in its southwestern part. Lake Geneva Quaternary sediment infill is maximum 400 m thick in the Grand-Lac and consists mainly of glacial and glacio-lacustrine deposits from the last deglaciation deposited by the Rhone Glacier (Girardclos et al. 2005). The Holocene lacustrine sediment infill is complex and varies greatly depending on currents (Girardclos et al. 2003; Lemmin 1998; Le Thi et al. 2012) and on clastic input from nearby rivers. Where hemipelagic processes are dominant, Holocene sediment infill is only 5-10 m thick but it reaches over 100 m in the Rhone delta.

Geneva geologic basin is formed by three main geologic and tectonic units: sedimentary rocks of the Jura mountain in the NW, Tertiary sandstone ('Molasse') in the centre, and thrust Molasse in the SE. The thrust Molasses is topped by ultrahelvétique and Prealps units which rim the eastern end of the lake.

Seismic and drilling data show that the formation of Molasse basin is younger than folding of Salève and Jura mountains dated at the end of Miocene or at the beginning of Pliocene (between 10 to 2 millions years). But as Molasse basin formation is a consequence of alpine tectonics, it originated much earlier and still presently continues to change at slower rate.
6. Formation of Lake Geneva basin

In the region of Ecoteaux (Prealps units, 10 km north of Vevey) glaciolacustrine sediments at 800 m asl show that a periglacial lake was present in the area indicating a first origin of Lake Geneva basin ca. 730'000 years ago (Pugin et al. 1993). With time, this basin evolved from a wide and relatively shallow depression into the present narrower and deeper Lake Geneva basin.

During the late Pleistocene glacial cycles, Lake Geneva basin deepened into the Molasse bedrock to reach a maximal depth of 500-560 m offshore Lausanne and Meillerie (Grand-Lac : Dupuy 2006). During the phase of Last Glacial Maximum, most of the former sediment infill was removed by Rhone glacier and only rare and compacted sediment patches were preserved from former glaciations (Wildi and Pugin 1998 ; Wildi et al. 1999).

Profile of Lake Geneva basin 730'000, 120'000 years ago, 20'000 and at present (Corboud et al. 2006 ; from Wildi and Pugin 1998).

Ecoteaux : laminated distal glacio-lacustrine sediments with organic layers.
Situation before the Last Glacial Maximum, at ca. 40'000-37'000 BP (38'000-35'000 BC) thick units of sand and gravels deposited in the Geneva basin in more than 10 km-sized sandur, forming the 'Alluvion ancienne' deposit (in grey).

Last Glacial Maximum in Switzerland around 22'000-20'000 years BP (20'000-18'000 BC). Modified from Bini et al. 2009. Red lines indicate present lakes. Ice altitudes are in m asl. © 2014 swisstopo.
Reconstruction of the Last Glacial maximum in the Geneva area with arrows representing main ice fluxes.

After the Last Glacial Maximum, the Rhone glacier retreated to form a moraine near Laconnex around 20'000 BP (18'000 BC) with a lake level at 475 m asl.
Geological history of the Lake Geneva basin and human settlements

It was followed by a glacial stage in Geneva city which formed the Old Town hill. The final deglaciation history is recorded in the seismic and sedimentary infill of western Lake Geneva.

In the city harbor next to the Neptune, the so-called “Pierres du Niton” (Niton rocks) represent additional traces of the Rhone and Arve glaciers pathway as they were also deposited during the last deglaciation. They are foliated porphyritic granites of Mont Blanc mountain dated at 303 ± 2 million years (Sesiano et al. 2011). These stones were used since 1845 as altitude reference level for topographic maps and still serve as base level mark for the entire geodesy of Switzerland (373.6 m above sea level, Repère de la Pierre du Niton : RPN).

Till-tongue model with debris-flow lenses coming from the downstream flank of a subaqueous moraine formed by the pushing of proglacial sediments (Stravers and Powell 1997).
The deglaciation happened in a fjord-like environment occupied by a glacier with a steep, calving ice front. The lake-level decreased from an altitude of 430 to 380 m in a few steps but this chronology is still not well known.

Seismic reflection data present the bedrock lake basin (unit U0) as well as sismostratigraphic units with glacial- (U1-11), glaciolacustrine- (U8,10,12) and lacustrine facies (U13-14). The facies and geometry of U9 and U11 indicate re-advances of the Rhone glacier. Units U9b and U11b are interpreted as till-tongues (Fiore et al. 2011; Stravers and Powell 1997). Data points to at least three stages/readvances during the deglaciation process (Reposoir stage, Coppet and Nyon re-advances). Four drillings (S1-S4) done in 2010, 34 to 74-m-deep, confirm the seismic interpretation.

Palynological data from core (S3) show that ca. 60 m of sediment, out of the 75-m-thick infill, were deposited during the Oldest Dryas. The asymmetry of unit U7a also shows that the glacier melted first in the central and eastern part of the lake basin while it was still lying on the Molasse 'ramp' in the West. Glacio-lacustrine deposits (U8-12) consist of variable sedimentary facies, alternating between massive and laminated clayed silt with rare sand layers. Gravels of alpine origin and 'galets mous', interpreted as ice-rafted debris, point to the recurrent presence of icebergs over the lake.

Late Glacial and Holocene infill of Geneva Bay was massively reworked as large mass transport deposit in Bronze Age (3415 ± 35 14C BP; see 'catastrophic events' chapter). Remaining Holocene infill of the Petit-Lac is largely influenced by river input and strong underwater currents (Girardclos et al. 2003; Girardclos et al. 2005).

$$\text{SSW} \quad \text{Rhône glacier} \quad \text{Reposoir stage}$$

$$\text{Distance (km)} \quad 10 \quad 15$$

$$\text{ICE/WATER FLOW}$$

$$\text{Rhône glacier} \quad \text{Coppet readvance} \quad \text{Nyon readvance}$$

$$\text{U0: Molasse bedrock}$$

Synthesized compiled profile along the thalweg showing the entire Quaternary record of western Lake Geneva. Note the numerous till sequences (units U1-U5, U7, U9 and U11), separated by compaction levels corresponding to glacial readvances. The main esker (sub-unit U6a) is not located in the thalweg and is projected from the NW. The latest two glacial readvances in the area ("Coppet" and "Nyon") have built large push moraines (subunits U9a and U11a) and associated proglacial debris-flow fans (sub-units U9b and U11b). Left axis is in TWT (s) and depth scale (right axis) is estimated using seismic velocities of 1500 m/s for water (down to 100 ms) and 1800 m/s for sediments (Fiore et al. 2011).
Lithology of drilled sediment core S3 from the ‘Petit Lac’ at 40 m water depth. The lower part (17-71 m depth) belongs to the Oldest Dryas Ia chronobiozone and consists of a glacial sequence with compacted till (U6b), melt-out till linked to the Reposoir stage (U7a) and glacio-lacustrine deposits (U8-10). Unit U12 (7-17 m) is characterised by a mix of sand layers, pebbles, entire and broken shells and vegetal remains interbedded with silty – clayey lacustrine sediment which is interpreted as a mass transport deposit and dated at 3415 ± 35 14C BP. (Modified from Kremer et al. 2014.)
8. The Rhone delta and canyons

Lake Geneva being a prominent landscape feature in Central Europe already figures in road map of the Roman Empire and on early World map from the 10th century. The first scientific report of water depth measurements in Lake Geneva was written by Horace-Bénédict de Saussure in 1779. The first comprehensive bathymetric map of Lake Geneva, a compilation from measurements made from 1873-1889 by various authors, was published in 1892 by F.-A. Forel. This map was later published in various versions (including Delebecque 1898) and for all official topographic maps of the Swiss Federal Office of Topography (at present too!).


Methological setting used to establish the bathymetric map of Lake Geneva (Forel 1892 ; Delebecque 1898). 1880-1890 (date undetermined).
Under the pressing need of updated and more detailed bathymetric data, a Digital Terrain Model (DTM) and corresponding bathymetry map of eastern Lake Geneva were recorded with multibeam echosounding methods in 2008 (Sastre et al. 2010). This dataset truly revealed the underwater Rhone river delta morphology, showing numerous unknown canyons and structures such as slide scars and dredging traces. Presently inactive canyons (Corella et al. 2014) are interpreted as traces of the former Rhone river mouthing (Sastre et al. 2010), as shown by ancient map from 1781.

Bathymetric map recorded in 2008 with shaded relief of NW Lake Geneva and sublacustrine Rhone delta morphology. Modified from Sastre et al. 2010.

Left : Map of the lower Rhone valley and the terrestrial part of the Rhone Delta by Mallet 1781.

Right : Comparison with modern coastline and sublacustrine canyons (C1-C8). Modified from Sastre et al. 2010.
Rhone delta dynamics are mainly controlled by three sedimentation processes, which mainly depend on the river discharge and water density. When discharge is low, suspended particles deposit as delta foreset near the river mouth. If the incoming river flow density is comprised between the one of the epilimnion and the one of the hypolimnion, it propagates along the thermocline, and brings fine silt particles to the northern part of the delta. In contrast, when river inflow is denser than the hypolimnion, underflow currents build up a distal delta morphology with canyons, levee and fans, thus transporting coarse silt- and fine sand-sized sediment up to 15 km to the west. The turbidite record of distal Rhone delta is due to both flood and slope failure events (Lambert and Giovanoli 1988; Corella et al. 2014).

The Rhone delta model with three types of sedimentation:

1. the proximal sedimentation builds a delta foreset;
2. the erosion, transport and deposition by underflow currents form channels and distal fan;
3. the interflow fine sediment transport is deflected to the North.


The recent sedimentary infill of deep Lake Geneva (Grand-Lac) is characterized by hemipelagic sediments intercalated with smaller turbidites originating from either the Rhone or Dranse delta area (floods or delta collapses). The frequency of turbidites is varying spatially and temporally. From the 6th century until 1675 ± 125 cal AD, the infill is dominated by turbidites from the Dranse delta most probably because the Rhone was mouthing in the northern canyons too. Since 18th/19th century, deep Lake Geneva sediment record shows an apparent ‘progradation’ of the Rhone turbidites (Kremer 2014). Additionally, a decrease in the frequency of turbidites upwards along the active canyon (C8) wall suggests a progressive confinement of the flow through time (Corella et al. 2014). Both distal turbidite progradation and decrease of proximal upwards turbidite frequency are interpreted as consequences of the inland channelizing of the Rhone River between 1870-1880 and point to possible ongoing lengthening and deepening of the underwater channel (Kremer 2014; Corella et al. 2014).

Evolution of the canyon activity in the Rhone delta area and in the distal deposition zone of the Rhone turbidites since 563 AD.

A. Between 563 AD and 1675 ± 125 cal AD (Unit 1), the main active canyon is C5 with a sedimentation zone located in the northern part of the basin.

B. Between 1675 ± 125 cal AD to present (Unit 2) the main active canyon is C8 with a sedimentation zone located in the southern part of the basin. C5 was cut from the Rhone River between 1870 and 1880 AD. From Kremer 2014.
Comparison of multibeam bathymetry datasets recorded in 2008 and 2012 show that the sublacustrine Rhone canyon is currently very active: up to 4 m of sediment is either deposited or eroded on the canyon floor in these 4 years. In the same time interval, floor erosions are associated to new slide scars formed in the canyon walls and thus certainly triggered by strong (mud?water?) flows in the canyon (Girardclos et al. 2012).

Detailed shaded multibeam bathymetry maps of the Rhone main channel, with panels of the February 2008 (a, c and e; from Sastre et al. 2010) and March 2012 (b, d and f) channel morphology. Colored isolines indicate erosion (-) and deposition (+) in meters. New slide scars appear close to areas of strong bottom erosion (d). Refer to upper panel for channel overview, panel location and contour lines color scale. From Girardclos et al. 2012.

Geological history of the Lake Geneva basin and human settlements
9. Extreme events and tsunamis in Lake Geneva

In the Grand-Lac, high resolution seismic reflection data (pinger 13 kHz) indicate that in the upper 30-m-thick sequence consists of five large Mass Transport Deposits (MTD, lenses of transparent facies) which alternate with the normal lacustrine sediment infill (Kremer et al. submitted).

MTD A (volume $130 \times 10^6 \text{ m}^3$), which is interpreted as a slump deposit starting offshore Lausanne at 100 m water depth, happened at the same event horizon than MTD C (volume $22 \times 10^6 \text{ m}^3$) which started on the opposite (southern) shore. Both failures left scars on the topography which are still visible on multibeam bathymetry data. These mass transport deposits are dated from Early Bronze Age (3395 ± 35 14C BP) and might have happened coevally with the mass transport deposit in Geneva Bay (see core S3, chapter 7) pointing to a possible earthquake trigger. Taking into account a minimum VII intensity to trigger coeval slope failures in both the ‘Grand’ and ‘Petit-Lac’, the Early Bronze Age event of Lake Geneva could be explained by a Mw ~ 6 earthquake potentially located south of the lake, where magnitudes of historical events reached already Mw 4.6-5.5 during the last 200 years. Independently of its trigger, MTD A displacement by itself induced a minimum 4-6 m high tsunami near Lausanne and Evian and thus certainly impacted local palafitte settlements (Kremer et al. 2014).

MTD D to MTD F started in the area of the Rhone delta and are interpreted as delta failures (maybe linked to sediment accumulation). Their trigger is unknown but their volume and comparison with numerical modeling show that they were all large enough to produce m-sized tsunami waves over Lake Geneva (MTD D volume $30 \times 10^6 \text{ m}^3$; MTD E volume $46 \times 10^6 \text{ m}^3$; MTD F volume $83 \times 10^6 \text{ m}^3$ (Kremer et al. submitted). MTD G, with its volume of $250 \times 10^6 \text{ m}^3$, is the largest mass transport deposit in our record. It happened in 563 AD, during the so-called ‘Tauredunum’ event (Montandon 1925) and when a large aerial landslide of aseismic origin fell onto the former Rhone delta to destabilized its slopes and trigger a huge sublacustrine failure. This failure induced a giant tsunami over Lake Geneva and deposited as a large turbidite bed at the bottom of the Grand-Lac (Kremer et al. 2012).

Core data confirm the seismic interpretation and date MTD events thanks to radiocarbon dating and the correlation with historical data for the 563AD event. (Kremer et al. 2012; 2014; submitted).
Photographs and lithology of Ku-IV sediment core with turbidite and mass transport deposits outlined in grey. MTD A, interpreted as a slump, is composed of deformed and folded laminated sediment layers, topped by mudclasts incorporated in a muddy matrix and a homogeneous layer. The dashed black line indicates the age-depth curve in calibrated years BP and in AD/BC. Turbidite of 563 AD (Kremer et al. 2012) corresponds to MTD G on seismic line (from Kremer et al. 2014).
Sketch of the geological and limnogeological process describing the main phases of the 563 AD event, from the aerial rockfall in the Rhone valley (1), to the sublacustrine Rhone delta collapse, followed by turbiditic and debris flow propagation with wave generation (2), ending with water wave passing over the old city walls of Burgundian Geneva (3).

Possible inundated zone for an 8 m wave in the reconstructed Burgundian city of Geneva (in white) with 6th century buildings, walls and bridge, and the past lake border (thick black line) with background aerial photograph of Geneva. Inundated region was estimated taking account of the first arrival wave height (at the lake shore) and the current topography without estimation of the wave runup (from Kremer et al. 2012).

The displacement of MTD G was simulated by numerical modelling and confirms historical data on the Tauredunum event. Historical reports mention waves entering the Geneva Burgundian city (located on the hill of the present Old City) and killing people (Montandon 1925; Kremer et al. 2012).
10. Evolution of Lake Geneva level between glacial retreat and the present

After the retreat of the Rhône glacier, and from the Mesolithic period (ca. 6500 BC), the level of Lake Geneva stabilised at a mean water level close to the present lake-level. However, climatic variations and geological events have caused secular and seasonal fluctuations within an interval of ca. 9 m.

From the 19th century dams were built in Geneva on the Rhone River to ‘feed’ the hydraulic machines of the local industry. These facilities caused important lake-level variations so that the Canton of Vaud opened a court case against Geneva at the Swiss Federal Supreme Court. The «Lake Geneva trial» was solved in 1884 by the signature of a Convention between both cantons that defined the limits of possible lake-level variations. The construction of sluice gates of Pont-de-la-Machine aimed at applying this convention. Since 1887, Lake Geneva was regulated by the Pont-de-la-Machine dam and since 1995 by the downstream and present Seujet dam.
Lake Geneva regime, which is largely influenced by glaciers from the upstream Rhone River catchment, can change rapidly if the balance between precipitation, glacier melting and evapotranspiration changes. Small variations in temperature and rainfall can cause rapid fluctuations of mean level, that can happen at the scale of the half-century, with average levels between 367 and 372 m at least. On the other hand, highest lake-levels during prehistoric and Roman times were probably caused by geological accidents, occurring downstream at the junction between the Rhone and Arve River in Geneva.

Around 1000 yrs BC (3000 BP), at the time of pile dwellings settlements, the lake level lies below 369 m asl.

During Roman times (58 BC to 476 AD), the lake level lies around 375 m asl (thus higher than today).

Low lake-level during summer 1921 (370.85 m), with view on the coastal bank with boat lying on it. In the background: Chillon, Montreux and Clarens. La Patrie Suisse no 719, 13 avril 1921, p. 91.
11. Holocene vegetation and landscape history

Landscape of Geneva Bay at the time of the glacial retreat (approximately 15'000 years BC/ 17'000 BP). The hill of Geneva, a glacier-linked feature, emerges as a peninsula. Boulders are deposited on the edges and at the bottom of the lake like the «Pierres du Niton», which were transported from the Mont-Blanc area to Geneva by the Arve glacier. The lake level lowers progressively, approximately to 470, 430 m, then to 405 m. During the Late Glacial period, fauna, attracted by the grass, appears along juniper (*Juniperus*), dwarf birch (*Betula nana*) and other rare pioneer vegetation. In this context, we can imagine that the last Ice Age mammoths were coming to drink waters of the Geneva Bay. Around 14'000 BC the Rhone glacier left the lake basin with a water level 33 to 36 m higher than at present. (Drawings Yves Reymond, from Corboud et al. 2006, 2008).

Forest of birches and pines in Geneva Bay during the Bølling, approximately 12'000 years BC (14'000 BP). The lake level stabilises at ca. 380 m asl, i.e. 8 m higher than at present. In this period, the first phase of steppe reforestation happens, first with trees and shrubs, then birches settle. During Allerød, (between 12'000 to 11'000 BC) dense pine and birch forests establish. During the climate cooling of Younger Dryas (between 11'000 to 9500 BC) herbaceous and shrub vegetation increase with linked forest opening.
Landscape of the Geneva Bay at the beginning of the middle Neolithic (Younger Atlantic). A forest of leafy trees, mixed oak grove, develops. The lake-level is approximately 372 m asl, like at present. At that time, the mixed oak forest gradually loses ground and is replaced by beech and fir trees. From the Neolithic (5000 to 4000 years BC), the presence of man becomes more evident, with remains of pile dwellings prehistoric villages in the Geneva Bay and with a settlement found beneath the Saint-Gervais church. The discovery of cultivated cereal pollens, dated from the middle of the fifth millennium BC, confirms agriculture practices. The presence of Neolithic farmers-breeders in the area is attested at least around 4500 years BC.

During the Late Bronze Age, around 1000 BC, pile dwellings occupations are numerous. During the lake low levels (about 3 m lower than at present) the Rhone river didn't flow out of the bay of Geneva. Several villages were built next to others on the «Banc de Travers», a sandy and clayed shoal. At the end of Bronze Age, the vegetation is enriched by new species such as white alder, maple and ash. The forest extends, with a majority of oaks, hazel trees, as well as beeches. On surfaces released by water, willows colonize the ground, while flooded banks are occupied by reeds which leave a little higher, for bordering alders and ashes forest.
12. Human occupation of the Geneva basin, relations with the environment

After the glacial retreat, the pioneer herbaceous vegetation occupies the territory of the Geneva basin which is favourable to the passage of reindeer and wild horses. This fauna attracts the first Upper Paleolithic hunters in shelters under blocks collapsed from the Salève limestone cliffs. In addition to reindeer and horse, Magdalenian of Veyrier were hunting many additional species such as hares, marmots and ibex. Overall, with the climatic optimum of the Atlantic, at ca. 4500 BC, human influence is growing in Geneva region.

As the forest occupies much of the plain, first farmers and stock breeders clear woodland with polished stone axes to create proper land for agriculture. First pile dwellings settlements are known at 4000 BC and certainly linked to a significant decrease in the lake-level.

The next climate phase (Subboreal, 3400 to 800 BC) corresponds to the final Neolithic and the Bronze Age human occupations. The western part of the Geneva basin is still dominated by mixed oak forest. Changes in the lake-level induce village displacements, from terraces overlooking the lake to coastal banks, emerged during low waters (Corboud 1998; 2009).

Model of a pile dwelling settlement, during the Late Bronze age (ca. 1050-850 BC)

1. Between 1200 and 1100 BC, a significant drop of lake-level, known throughout all Swiss Plateau lakes, also happens in Lake Geneva. This important regression results in a lowering of at least 3-m down, to 369 m. In Geneva Bay, two villages are built and occupied as early as 1067 BC (Corboud 2003).

2. Most probably, Bise windstorms damage initial buildings which require the building of an extra palisade against wind waves, a few meters away from houses toward the lake at around 993 BC. During summers, when waters are particularly high, these fences act as protection for the slightly raised house floors from flooding by strong wind waves.

3. Before 858 BC, the lake-level becomes higher during summer. In the following years, the lake transgression is too great to allow further human occupation, villages are abandoned and constructions are quickly destroyed by severe Bise windstorms. The level of Lake Geneva then reaches an altitude of 370 to 371 m asl.

4. The level of water still regularly rises. Each storm demolishes ancient architectural structures and erodes remaining vertical piles. Soon, all construction elements are dispersed by waves, excepted piles which are firmly planted in compacted clayed sediment.

At present in Geneva Bay, with the artificial lake-level management at ca. 372 m asl, only wooden piles resist wave erosion. But they are often broken at the sediment level and are accompanied by only few archaeological bronze and stone objects, which concentrate at the interface between sand and glaciolacustrine clay layers.

In 2011, the prehistoric pile dwellings around the Alps were nominated as UNESCO World Heritage. A representative selection of 111 prehistoric pile dwellings sites from six countries (France, Germany, Austria, Italia, Slovenia and Switzerland) is listed by UNESCO.

For more information: www.palafittes.org
13. Construction of Geneva city with local georesources


Geneva Harbor with limestone transported on boat from Meillerie (June 1899). BGE, Centre d'iconographie genevoise.

The Palais Wilson, a former hotel on the right bank of the Geneva Bay, was built between 1873 and 1875 with Molasse sandstone. From 1920 to 1936, it became headquarters of the 'League of Nations', until they moved to the new Palais des Nations. At present, the Palais Wilson serves as Office of the High Commissioner for Human Rights. Photo taken between 1905 and 1919. BGE, Centre d'iconographie genevoise.
11. Bibliography


Bini (A.), Buoncristiani (J.-F.), Coutterand (S.), Ellwanger (D.), Felber (M.), Florineth (D.), Graf (H.R.), Keller (O.), Kelly (M.), Schlüchter (C.), Schoeneich (P.). 2009. Die Schweiz während des letzteiszeitlichen Maximums (LGM) = La Suisse durant le dernier maximum glaciaire = La Svizzera durante l'ultimo massimo glaciale = Switzerland during the last glacial maximum. Wabern : Bundesamt für Landestopografie Swisstopo.


Fiore (J.), Girardclos (S.), Pugin (A.), Gorin (G.), Wildi (W.). 2011. Würmian deglaciation of western Lake Geneva (Switzerland) based on seismic stratigraphy. Quaternary science review, 30, 3-4, 377-393.


Kremer (K.), Marillier (F.), Hilbe (M.), Simpson (G.), Dupuy (D.), Yrro (B.J.F.), Rached-Schneider (A.-M.), Corboud (P.), Bellwald (B.), Wildi (W.), Girardclos (S.). 2014. Lake dwellers occupation gap in Lake Geneva (France-Switzerland) possibly explained by an earthquake-mass movement-tsunami event during Early Bronze Age. Earth and planetary science letters, 385, 28-39.

Geological history of the Lake Geneva basin and human settlements


Lotter (A.F.). 1999. Late-glacial and Holocene vegetation history and dynamics as shown by pollen and plant macrofossil analyses in annually laminated sediments from Soppensee, Central Switzerland. Vegetation history and archaeobotany, 8, 165-184.


