**Late Holocene changes on erosion pattern on a lacustrine environment: landscape stabilization by volcanic activity versus human activity**

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**Abstract**The most recent eruption of Mt. Fuji (Japan), the VEI 5 Hōei plinian eruption (CE 1707) heavily impacted Lake Yamanaka, a shallow lake located at the foot of Mt. Fuji. Here, we discuss the influence of the Hōei eruption on the lacustrine sedimentation of Lake Yamanaka using high resolution geophysical and geochemical measurements on gravity cores. Hōei scoria fall-out had two major impacts on Lake Yamanaka: (i) reduction of the sedimentation rate (from ~0.16 cm/yr to ~0.09 cm/yr); and (ii) the increase of in-situ lake productivity. Sedimentation rates after the eruption were relatively low due to the thick scoria layer, trapping underlying sediments in the catchment. The lacustrine system took over more than ~170 years to begin to recover from the Hōei eruption: sedimentation recovery have been accelerated by changes in land use. Since the beginning of the 20th Century, vegetated strips delimited cultivated parcels, trapping sediment and minimizing the anthropogenic impacts on the sedimentation rate. Over the last decade, the decline of agriculture and the increase of other human activities led to an increase in the sedimentation rate (~1 cm/yr). This study highlights the effect of the grainsize of the volcanic ejecta on the sedimentation rate following a volcanic eruption. Coarse-grained tephra are difficult to erode. Therefore, their erosion and remobilization is largely limited to intense typhoons when porous scoria deposits are saturated by heavy rains. Moreover, this study suggests that recent anthropogenic modifications of the catchment had a greater impact on the sedimentation rate than the Hōei eruption.

*Keywords:* *sedimentation rate, volcanic impact, scoria, the Hōei eruption, Mt. Fuji, Lake Yamanaka*

1. **Introduction**

Large explosive Plinian eruptions are known to cause landscape changes and sedimentological processes over extended areas. Intense erosion and deposition occurs following major eruptions (e.g. Collins *et al.,* 1983; Collins and Dunne, 1986; Hayes *et al.,* 2002). Large volumes of unconsolidated ash fall deposits are easily remobilized by fluvial and mass-flow processes, the vegetation cover is destroyed and drainage networks are modified following an eruption (e.g. Ollier and Brown, 1971; Pierson *et al.,* 1992; Major *et al.,* 1996; Hayes *et al.,* 2002; Pierson et al., 2013; Pierson and Major, 2014; Major et al., 2016). Landscape recovery and its duration depend on different controlling factors such as the pre-eruption geomorphology, the volume, type and distribution of erupted materials and the local climatic conditions (Manville and Wilson, 2004; Manville et al., 2009a, 2009b). Erosion is influenced by the thickness and the grain size of the tephra deposit (Folsom, 1986). Following an eruption, thick and coarse-grained tephra deposits are difficult to erode due to their high permeability and resistance to rain splash erosion. White et al. (1997) show that deposits of the CE 1886 Mt. Tarawera eruption (New Zealand) remained in place until 18 years later, when break-out flood from volcanically-dammed Lake Tarawera initiated large scale erosion and redeposition. The latter suggest that high energy events are required to induce the erosion of coarse well sorted and highly permeable tephra deposits. The above mentioned studies discuss the role fluvial and mass transport processes play in post-eruption landscape recovery. However, at present the short-term and long-term impact of coarse scoria fall deposits on lacustrine sedimentation processes and lake recovery is unknown. Here we document the first example of an explosive volcanic eruption that increased landscape stability and reduced erosion and sedimentation rates.

We study Lake Yamanaka, part of the Fuji Five Lakes region (Japan), an area that is both affected by large Plinian eruptions from Mt. Fuji and high energy events (typhoons and earthquakes). Due to the westerly wind direction and its proximity to the volcano, Lake Yamanaka and its catchment have been repeatedly strongly impacted by scoria fall-out. The last eruption of Mt. Fuji, called the Hōei eruption, occurred in CE 1707 and lasted 16 days from the 16th of December 1707 until the 1st of January 1708 (Tsuya, 1955). In total 1.8 km3 of scoria fallout were ejected from three vents located in the south-eastern flank of the volcano (Fig. 1; Miyaji *et al*., 2011). The thickness of the scoria deposit varies from 5 to 37 cm around Lake Yamanaka and reaches up to 64 cm (on average) at the south-west extremity of its catchment (Miyaji *et al*., 2011). Lake Yamanaka and its catchment have also been affected by an increase in human occupation and activities over the last century. The primary objectives of this study are (1) to study the influence of a Plinian eruption (i.e. Hōei eruption) on the sedimentation of Lake Yamanaka and (2) to assess the process of sedimentation recovery following a major eruption and (3) to evaluate recent anthropic effects on the lacustrine sedimentation of Lake Yamanaka. We present a detailed study of the sedimentation history of Lake Yamanaka since the Hōei eruption (CE 1707).

1. **Study Area**

Lake Yamanaka (35.4185° N, 138.8787° E at the center of the lake; 981m asl) (Fig. 1) has a maximum depth of 14.3 m and is located at the foot of the ENE flank of Mt. Fuji (3776 m asl). Lake Yamanaka covers a surface area of 6.89 km2 and is fed by underground water originating from the Mt. Fuji and Tanzawa mountains aquifers via springs located at its bottom (Koshimizu and Tomura, 2000; Hirabayashi *et al.,* 2004). The lake receives additional water inputs by ephemeral rivers, active during typhoons, spring time (snow melting) and torrential rain episodes. The Katsura River, located at the north-western end of Lake Yamanaka, is fed by the lake and flows into Sagami Bay (Pacific Ocean).

The catchment of Lake Yamanaka has an asymmetric shape with an area of 69.81 km2. The ENE flank of Mt Fuji constitutes 51 % of the catchment and is characterized by gentle slopes (~2-5°). Towards the north, the watershed is limited and has steep slopes (~13-18°). The catchment is mainly composed of basalt lava flows, lahar and pyroclastic fall deposits.

1. **Materials and Methods**
   1. **Sediment cores**

The core data set is composed of five short gravity cores (YAM14-1A, YAM14-2A, YAM14-3B, YAM14-4B and YAM14-5B) collected using a gravity Uwitec corer system during October 2014 (Fig. 1). The length of the cores ranges between 39.9 cm and 66.5 cm: all the cores terminated in the top of a coarse scoria layer. The cores were split, described and scanned for imagery (linescan) and physical properties using a Geotek MSCL core scanner. Core to core correlations were done based on magnetic susceptibility (Fig. 2). X-ray radiography was performed on all the cores to identify sedimentary structures not visible to the naked eye.

We selected core YAM14-2A, located in the deepest part of the lake, to perform high-resolution measurements. This core is inferred to be representative of the background sedimentation (i.e. hemipelagite). Due to its distal location from sedimentary sources, it only records major sedimentary disturbances. Grain-size analysis was performed using a Malvern 2000 at a 0.5 cm sampling interval. To avoid clay flocculation, 2 ml of 0.5g/L sodium hexametaphosphate was added. Scanning Electron Microscopy (SEM) as well as smear slides were carried out on selected samples to characterize the background sedimentation. Semi quantitative elemental composition was done using an Avaatech XRF core scanner at a resolution of 2 mm and under two different conditions (for light elements: 0.1 mA, 10 s count time and 10 kV; for heavier ones: 0.75 mA, 45 s count time and 30 kV). Only significant chemical elements (more than 1000 counts per second (cps)) are considered. Data were not smoothed allowing the detection of minor shifts along the core. Reliable data were obtained for Al, Si, S, Ca, Ti, Mn, Fe, Cu, Zn, Br, Sr, Zr and Pb. The Si/Zr ratio was employed to estimate the biogenic silica content relative to material (Cuven *et al.,* 2011) and Br/Ti as a proxy for organic productivity (e.g. Agnihotri *et al.,* 2008). We built a correlation matrix for each sedimentary unit to assess the quality of the correlation between pairs of elements (Kylander *et al.,* 2011; see supplementary data 1). R values greater than 0.7 or lower than -0.7 were considered as strong correlations. The disadvantage of the Avaatech core scanner is that Al is the lightest element which can be measured under reasonable exposure times (Tjallingii et al., 2007) and elements present at low concentrations are poorly constrained. In order to validate the elemental variations measured by the Avaatech core scanner, major (Si, Ti, Al, Fe, Mn, Mg, Ca, Na, K) and trace elements above 500 ppm (Ba, Cr, Cu, Ni, Sr, P, Zr, Zn, Co, Pb) were measured in 10 selected samples using X-ray fluorescence spectrometry (PERFORM’X) on pressed powdered pellets.

XRD spectra were acquired at 1 cm resolution using a PANalytical Empyrean XRD and were processed with DIFFRAC.EVA software. Clay analysis was performed on selected samples. For that purpose, the clay fraction (< 2 µm) was separated by settling in a water column and mounted as oriented aggregates on glass slides (Moore and Reynolds, 1989). Three X-ray spectra were acquired on slides prepared under different experimental conditions: (i) air-dried, (ii) ethylene glycol solvated for 24 h and (iii) heated at 500°C for four hours.

δ13C, δ15N, TOC (total organic carbon) and TN (total nitrogen) analyses were performed on bulk sediments at a 1 cm resolution. C/N values were derived from the total organic carbon (TOC) and the total nitrogen (TN) data. The C/N atomic ratio provides information about the origin of the organic matter. Terrestrial plants are characterized by C/N value around 20 or greater whereas lacustrine phytoplankton show low C/N ratio, between 3 and 9. A mixed source has generally C/N value ranging from 10 to 20 (e.g. Meyers, 1994). Every centimeter of the core was sampled for loss-on-ignition (LOI). The samples were dried at 105°C for 24 hours and then heated at 550°C for 24 hours. The water and organic matter (OM) content were calculated following Heiri et al. (2001).

* 1. **Chemostratigraphy**

Four sedimentary units (from A to D) were defined based on lithology, magnetic susceptibility, XRF and isotopic measurements. The oldest sedimentary unit, unit D, corresponds to a black scoria layer deposited during the last eruption of Mt. Fuji, the CE 1707 Hōei eruption. Its identification was done based on its stratigraphic position and on the isopach map of the Hōei tephra fall-out (Fig. 1A). The absence of organic matter and silt intercalated within the scoria deposits suggest that the scoria has not been reworked. The primary deposit nature is also supported by high resolution seismic reflection profiling where the Hōei scoria deposits appear as undisturbed and continuous strong reflective horizons (Lamair et al., in press). The boundary between unit D and unit C is defined by a change in lithology (from scoria to lacustrine sediments). The boundary between unit C and unit B is marked by a significant minimum in the magnetic susceptibility depth profile. The boundary between unit B and unit A corresponds to an increase of δ15N. This boundary is supported by a change of slope in 210Pbxs depth profile (see the following section).

* 1. **Age-depth model**

Short lived radionuclides (210Pb, 226Ra and 137Cs) were used to define the chronology of the sedimentary infill of Lake Yamanaka over the last century by sampling selected 1cm thick layers in the upper 32 cm of core YAM14-2A. Activities of 210Pb, 226Ra and 137Cs were measured by gamma spectrometry using a high-efficiency, well type detector (Ge volume 280 cm3, CANBERRA; Schmidt and De Deckker*,* 2015). Activities are expressed in mBq g-1 and errors are based on one standard deviation counting statistics. Excess 210Pb (210Pbxs) was calculated by subtracting the activity supported by its parent isotope, 226Ra, from the total 210Pb activity in the sediment.

In order to estimate the sedimentation rate and the age of the lacustrine sediments, two models were applied: the Constant Flux Constant Sedimentation model (CF/CS; Oldfield and Appleby, 1984) and the Constant Initial concentration (CIC model). In addition to 210Pb and 137Cs dating, the Hōei scoria layer was used as a temporal marker (CE 1707). The age of the upper boundary of Unit C was deduced from the sedimentation rate obtained for Unit B.

1. **Results**
   1. **Description of the sedimentary deposits**

The sedimentary sequence recovered in the cores consists of homogenous grey-brown silt. A thick black basal scoria layer of 6.4 cm is recorded in core YAM14-5A as well as in all core catchers (Fig. 2). No cores penetrate to the base of this scoria layer. Based on its stratigraphic position, the scoria deposit is associated with the last eruption of Mt. Fuji, the Hōei eruption (CE 1707). The water content of the short cores ranges from 76 to 80% of the sediment weight.Core YAM14-2A, located in the central part of the lake, has a stable grain size content with an average d90 of 54 µm ± 9 µm.In core YAM14-1A, sedimentation is interrupted at a depth of 47.7 cm, by a 3 cm thick coarser grained-layer showing cross-lamination interpreted as an instantaneous sedimentary event deposit (Fig. 2). The background sedimentation consists of a high percentage of amorphous material (60-70%; Fig. 3), which comprises a mixture of biogenic silica (diatoms) and allophane derived from weathering of volcanic tephra. The crystallized fraction is composed of total clays (24.3 – 36.5 %), K-feldspar (37 – 52 %; Fig. 4), plagioclase (13 – 19 %; Fig. 4) and cristobalite (4 – 9 %) which composed the terrigenous fraction of the sediment. The correlation matrix shows a positive correlation (r≥0.7) between plagioclase, total clays, K-feldspar and cristobalite. The clay fraction consists of illite and chlorite. A low proportion (<5 %) of quartz, magnetite, calcite and dolomite is also identified. The C/N ratio indicates that most of the organic matter present in the center of the Yamanaka basin is related to lake productivity (Fig. 5). OM content calculated by LOI (550°C) shows a good correlation with TOC (r=0.71) and TN (r=0.80). By removing the TOC outlier value (at 8.5 cm depth), the correlation improves (r=0.87).

* 1. **Core stratigraphy**

The core stratigraphy is subdivided into four units on the basis of chemostratigraphy and magnetic susceptibility. Starting at the bottom of each core, Unit D is a layer of black scoria inferred to represent primary airfall tephra from the CE 1707 Hoei eruption. Unit C, B and A are described in more detailed in the following.

* + 1. **Unit C**

Unit C is characterized by a decreasing trend of magnetic susceptibility (Fig. 4). The δ15N values are relatively low (2.4 ± 0.4 ‰). Through Unit C, the Br/Ti ratio, OM and TOC content tend to increase (Fig. 3).

In this unit, Al, Si andCa are strongly correlated as well as Ca and Ti. Cu is associated with Zn, Sr and Zr (Supplementary data 1). The base of Unit C presents low values of Ca, Sr and Zr (Fig. 4). Positive peaks of Ti, Ca, Sr and Zr are observed at 44.6-45.6 cm, 42-43.2 cm, 38.6-39.6 cm depth. Additionally, Ti and Sr show positive peaks at 36.0-37.2 cm depth (Fig. 4). Within this sedimentary unit, Ca content shows a general decreasing trend until the upper boundary of the unit. Similarly to Ca, Si/Zr tends to decrease within the unit; three peaks of Si/Zr are identified at 46.8-49.2 cm depth, at 45-46.2 cm depth and from 39.6 cm to the beginning of Unit B (33.2 cm) (Fig. 4). The first peak of Si/Zr is associated with a peak of TOC (Fig. 5) and high Br/Ti content (Fig. 4). The thicker one is correlated with a peak of OM content (Fig. 5) and highest Br/Ti values (Fig. 3). In the unit, Pb, Zn, Na (wt%), Mg (wt%), K (wt%) and S (wt%) are very stable (Fig. 6).

* + 1. **Unit B**

Unit B is defined by higher and stable magnetic susceptibility (Fig. 4). Up to the upper boundary of Unit B, the δ13C values tend to decrease. δ15N values tend to increase upward from 2.5 ‰ to 4.0 ‰ with two positive peaks at 30.5 cm and 21.5 cm depth. Br/Ti tends to be constant (Fig. 3). TOC and OM content increase through the unit. OM content reaches 14.2% at the upper boundary. In Unit B, there are two distinct associations of geochemical elements: (i) Ca, Si, Al; (ii) Ca, Al and Ti (Supplementary data). A global slight increase of Ca with several small peaks is observed. Ti, Sr and Zr contents are mostly characterized by stable values with two low levels (Fig. 4). From 34.4 cm depth up to the upper boundary of Unit B (19.8 cm), the profiles of Na (wt %), Mg (wt %), K (wt %) and S (wt %) present a global increase whereas Pb and Zn profiles tend to slightly increase up to 19.8 cm depth (Fig. 6). The Si/Ti ratio (Fig. 3) indicates a long-term increase trend, starting at 30 cm depth and continuing up to the top of the core (Unit A).

* + 1. **Unit A**

Unit A presents stable magnetic susceptibility values (Fig. 4) and OM content (from 13% to 14.2% - Fig. 5). The high OM content in the upper part of the sedimentary infill is supported by smear slides which show an enrichment of OM particles. The δ15N values are generally stable and on average higher than in the previous units (3.9 ± 0.2 ‰). Like in Unit B, Br/Ti tends to be constant (Fig. 3). In Unit A, a good correlation between Fe, Ti, Ca, Cu, Sr, Zr is observed (Supplementary data 1). Unit A is characterized by a global decrease pattern for Ca as well as Sr and Zr (Fig. 4). However, for Sr and Zr, the XRF results indicate that Sr (wt%) and Zr (wt%) content have highest values in Unit A (Fig. 4) and remain stable suggesting that the top of the core is affected by a dilution effect related to organic matter content. We observe a decreasing trend of Ti (Fig. 4). Pb, Zn, Na (wt%), Mg (wt%) and K (wt%) have the highest values. Pb slightly decreases upward with an exception for the upper 5 cm. Zn shows a decrease in the upper part of Unit A. However, similar to Sr and Zr, the decrease of Zn is not supported by XRF measurements, which show a stable behavior followed by an increase in the upper 5 cm. Na (wt%) and Mg (wt%) are stable whereas K (wt%) and S (wt%) continue to increase (Fig. 6).

* 1. **Age-Depth Model**

The chronology of the sedimentary infill of Lake Yamanaka is based on (i) 210Pb dating and (ii) the presence of the Hōei scoria identified at the bottom of the cores.

In core YAM14-2A, the 210Pbxs profile shows two distinct trends with depth (Fig. 7). Firstly, its activity decreases slightly from 192 mBq g-1 at the surface down to 131 mBq g-1 at a depth of 15-16 cm, which indicates a rapid sedimentation accumulation rate. Secondly, the profile presents a rapid decrease of 210Pbxs activities to negligible values (<4 mBq g-1) at a depth of 32-33 cm implying a lower sedimentation rate. The two distinct trends correspond to the boundary between the sedimentary units A and B. The Constant Flux Constant Sedimentation model (CF/CS; Oldfield and Appleby, 1984) was applied for the two distinct units (A and B) resulting in the following apparent sedimentation rate: 1.04 ± 0.14 cm/yr for Unit A and 0.16 ± 0.01 cm/yr for Unit B. 137Cs, a byproduct of nuclear weapons fall-out and nuclear accidents, is present in the atmosphere since 1950. Its high activities in the uppermost layers is associated with the 2011 Fukushima nuclear disaster.137Cs measurement reveals a peak of 56 mBq g-1 at 6.5 cm depth. The CF/CS model gives an age of CE 2009-2010 for the peak of 137Cs and the CIC model dates the peak of 137Cs at CE 2010. The shape of the 137Cs peak suggests either bioturbation or a vertical migration of 137Cs took place. No significant 210Pb and 137Cs concentrations were measured for Unit C. The sedimentation rate of Unit C (~0.09 cm/yr) was estimated based on the occurrence of Hōei tephra at the bottom of the core and the inferred age of the upper boundary of Unit C. In the absence of 210Pb and 137Cs, we made the hypothesis that the sedimentation rate in Unit C in constant. Unit D corresponds to a near instantaneous event deposit, the CE1707 Hōei eruption.

Based on the sedimentation rate obtained for units A and B, the age of each sedimentary unit was defined. Unit C began after the Hōei eruption in CE1707 and ended around CE 1885±14. Unit B started around CE 1885±14 and finished around CE 2000±2. Unit A was deposited over a period of ~14 years, from ca. CE 2000±2 to CE 2014, the year of the coring campaign.

1. **Interpretation and Discussion**
   1. **The impact of scoria fall-out on the lacustrine sedimentation**

The sedimentation rate prior the Hōei eruption can be estimated based on a drilling borehole taken 300 m far from YAM14-2A (see Fig. 1 for the location). The 14C dating done on plant remains indicates a sedimentation rate around ~0.16 ± 0.1 cm/yr for the last ~ 1400 years (Koshimizu *et al.,* 2007). As the sedimentation accumulation rate is lower at the emplacement of the drilling borehole, we estimate that this sedimentation rate corresponds to a minimum (see supplementary data 2). Our results demonstrate that following the Hōei eruption, the post-eruptive sedimentation rate was reduced by a factor two (~0.09cm/yr). This is in contrast with previous studies (e.g. Ollier and Brown, 1971; Pierson *et al.,* 1992; Major *et al.,* 1996; Hayes *et al.,* 2002), documenting the highest sedimentation following an eruption. High-sedimentation rates are mainly linked to remobilization of ash-fallout deposits by fluvial or mass-flow processes. In the sedimentary sequence of Lake Yamanaka, no fine-grained tephra fall-out deposits have been identified, due to its proximal location to Mt. Fuji. After the Hōei eruption, a thick scoria layer (thickness up to 64 cm; Miyaji *et al.*, 2011) covered Lake Yamanaka and its catchment (Fig. 1A). Sr and Zr measurements (Fig. 4), proxies for the presence of a terrigenous signal, indicate very low terrigenous input in the aftermath of the Hōei eruption. During the first ~170 years after the Hōei eruption (Unit C), the sedimentation was detrital driven (cf. detrital pulses identified in Ti, Ca, Sr and Zr peaks in Fig. 4). These detrital pulses are sometimes accompanied by peak measurements of amorphous materials, K-feldspar and/or plagioclase (Figs. 3 and 4). The observed low sedimentation rate and sedimentary pulses over the first 170 years following the Hōei eruption can be explained. Deposition of the up to 64 cm thick Hōei scoria increased the surface permeability, in addition to sealing off erodible and loose volcanic soils from erosion and transport processes. The erosion and transport of scoria deposits require high energy events, such as typhoons or earthquake shaking. During intense episodic typhoons, increased rainfall water percolated through the thick Hōei scoria layer, inducing saturation and decreasing the resistance of the scoria deposits against erosion by surface run-off. In the catchment, surface runoff initiated the erosion and transport of the Hōei scoria and the sediment below, towards Lake Yamanaka. The latter explains the presence of a series of four sedimentary pulses, rich in terrigenous material, recorded in the central part of the lake (Fig. 4). Other mechanisms, such as earthquake shaking and mass movement might also trigger punctual increases in sediment transport towards Lake Yamanaka.

Since CE 1885±14 (base of Unit B), the detrital supplies towards the lake became more important, as indicated in our cores by an increase in the sedimentation rate and magnetic susceptibility and Ca content (Fig. 4) associated with the presence of plagioclase and carbonate. The terrigenous content became more stable, indicating that moderate rainfalls had sufficient energy to erode and transport surface sediment from the watershed towards Lake Yamanaka. The erosion and transport of the Hōei scoria deposits (decreasing its thickness) during typhoons, the development of a new soil on top of the Hōei scoria deposits and agricultural practices influenced sedimentation within Lake Yamanaka. Lake Yamanaka’s sedimentary system needed at least ~170 years, to begin to recover from the deposition of the thick Hōei scoria in its catchment, and to restore the sedimentation rate to pre-CE 1707 levels.

* 1. **Sedimentation Recovery and Human Impact**

From CE 1885±14 to CE 2000±2, the average sedimentation rate is similar to the one before the Hōei eruption. It is difficult to assess to what extent sedimentation recovery was accelerated by human activities and/or natural processes. Indeed, during this period, Lake Yamanaka’s catchment was the subject of changes in land occupation (i.e. urbanization, deforestation and agriculture).

Especially during the last century, urbanization modified the catchment of Lake Yamanakaand many roads and houses as well as larger infrastructure were built. Since 1936-1938, a military base occupies 12 % of the catchment. Before the 1960's, the base was used by US army mainly for military drills. In the 1980's, a tunnel of 3 km was built in the south-west of Lake Yamanaka. The direct consequence of construction works are the large quantities of sediment available in the catchment due to excavations. Moreover, road surfaces limit the water infiltration and increase the erosion and the transport of fine-grained materials (e.g. Dunne, 1979; Reid and Dunne, 1984; Fahey and Coker, 1989). High sedimentation rates are observed in the years directly following road constructions and decrease over time (Fredriksen, 1970; Megahan and Kidd, 1972).

From 1900 to 1950, timber harvest was a standard forestry practice in Japan (Paletto *et al.*, 2008). Deforestation of coniferous and broadleaf forest took place to provide wood supplies for building and heating. It is well known that deforestation leads to an increase of sedimentation rate in a catchment (Grant and Wolff, 1991). The recovery rate is variable and depends on the nature of the disturbance. Surficial mass movements, related to root decay, can occur decades after harvesting (Grant and Wolff, 1991). Since the 1970’s-1980’s, people began to use fossil fuels instead of wood for heating in Japan, initiating the recovery of forest (Yamamoto, pers. comm. and Fig. 8).

Aerial photographs taken in 1948 (Fig. 8A and G) show numerous small cultivated parcels, delimited by strips of vegetation planted perpendicular to the slopes. The use of vegetated strips reduces surface runoff and soil erosion (e.g. Barfield *et al.,* 1975; Dillaha *et al.,* 1989), slowing down terrestrial inputs of water, trapping sediment and filtering nutrients (Yuan *et al.,* 2009). The vegetated strips present around the Lake Yamanaka, as shown on aerial photographs (Fig. 8A, C and G), trap the sediment in the catchment and reduce the influence of other human impacts (construction of buildings and roads, forest harvesting) on the sedimentation rate. During the second half of the 20th Century, small cultivated parcels progressively disappeared and were replaced by larger cultivated parcels, houses or forest (Fig. 8 A, D-F, H-J). Moreover, the numerous roads parallel to the slope help increase the sediment input from the catchment towards the lake. During the last decade, the decrease of agriculture and vegetated strips combined with the increase of urbanization around Lake Yamanaka lead to an increase in the sedimentation rate by a factor ~ 6. From a sedimentological point of view, the decline of agriculture and the increase of human activities have a larger impact on the sedimentation rate of Lake Yamanaka than the Hōei eruption.

* 1. **Lake Productivity and Volcanic Eruption**

The Hōei eruption did not only affect the sedimentation rate of Lake Yamanaka, but also influenced the lake productivity. Following the Hōei eruption, the presence of peaks of Si/Zr, TOC and the high content of Br/Ti in our measurements indicate the occurrence of algal blooms (Fig. 3). An increase of diatoms concentrations following the deposition of volcanic ash layers has been documented in several paleoenvironmental studies (e.g. Smith and White, 1985; Telford *et al*., 2004). Deposition of volcanic ash into lacustrine environments leads to the dissolution of adsorbed metal salts, acid and aerosols, increasing the concentration of key nutrients (Frogner *et al.,* 2001). Experiments conducted by Jones and Gislason (2008) on several ash layers show that in contact with water, the fluxes of important macronutrients (such as Si, P and Fe) and of key micronutrients (Mn, Co, Ni, Cu, Zn) increases. Bio-incubation experiments have shown that diatoms use nutrients from volcanic ash (Duggen *et al.,* 2007). Considering the deposition of scoria fall-out, similar process may play a role. Nutrient fluxes might be less important than in the case of a fine ash layer, as smaller particles are better scavengers of volatile due to their higher surface area to mass ratio (Oskarsson, 1980). The Hōei eruption induced volcanogenic fertilization of Lake Yamanaka resulting in an increase in diatom concentration in the sediments (evidenced by Si/Zr ratios) recorded for over a period of ≥35 years (Fig. 3).

Around CE 1830, a second increase of diatoms (Si/Zr) and lake productivity (high Br/Ti content and peak of OM) is observed. The presence of a peak in K-feldspar reaching 52% in our measurements (Fig. 4) attest for a strong catchment disturbance.

* 1. **Fertilizers, Lake Productivity and Eutrophication**

Since CE 1880, in-lake productivity (OM content, TOC) increased as well as diatom content (Si/Zr) (Figs. 3 and 5). Moreover, euglenophycean and chlorophycean algae are present in the sediment (Yamagishi *et al.,* 1982). The increase of organic matter produced in Lake Yamanaka can be linked to an increase of nutrient supplies, enhanced by catchment erosion and fertilizers used for the cultivation of rice and mulberries. The δ15N signature (Fig. 5) recorded in the sediment suggests the use of synthetic fertilizers, characterized by values between -4 and +4 ‰ (Kendall, 1998). The increase of Na, Mg and K content is related to the presence of chemical fertilizers (e.g. fused magnesium phosphate) used in Japan during the 1970s (Koshino, 1990).

Despite the decline of agriculture since the second half of the century, the Na, Mg and K contents remained relatively high until the present-day (Fig. 6). For decades, contaminated sediments were trapped in the vegetated strips. With their decrease and the increase of excavations in the 2000's, polluted sediments were remobilized and transported to Lake Yamanaka, explaining the time delay between the period of fertilizer use in the catchment and their recording in Lake Yamanaka. Additionally, fertilizers might have contaminated ground water, which is the main water source of Lake Yamanaka.

The higher concentration of OM since CE 2000±2 and the significant increase of P over the last 5 years suggest eutrophication of Lake Yamanaka. Lake Yamanaka was classified as a mesotrophic lake by Aizaki et al. (1981). Hirabayashi et al. (2004) suggest that the trophic status of the lake should be reconsidered based on an increase of the density of *P. akamusi* larvae and their positive correlation with organic matter. However, no notable change of Chlorophyll-a content is observed for the last 20 years (Yamanashi Prefecture, 2015). The high in-situ lake productivity contributes to the increased sedimentation rate (i.e., increase of the organic compound) recorded in the last decade.

* 1. **Atmospheric Pollution**

The poor correlation between Pb, Ti, Br and organic matter suggests that Pb enrichment is not governed by organic matter concentration and is not related to the catchment area. Therefore, Pb enrichment is directly linked to atmospheric pollution from coal burning and gasoline pollution. The atmospheric pollution (Pb and Zn) started to increase from around ~CE 1885±14 (base of Unit B, Fig. 6). This observation corresponds to the beginning of Japanese industrialization that started around the 1870’s (Hayami *et al.,* 2004). From the beginning of the 1980's, significant enrichment of Pb, Zn and S is noticed in the sediment of Lake Yamanaka. An air monitoring station located at the summit of Mt. Fuji indicates that the troposphere is affected by significant amounts of polluted air from China and from Japan itself (Suzuki *et al.,* 2008). The recent industrialization of China and its growth is probably responsible for the recent increase of atmospheric pollution recorded in Lake Yamanaka.

1. **Conclusions**

This study highlights the impact of scoria fall-out on a lacustrine system. The Hōei scoria fall-out (CE 1707) had two major impacts on Lake Yamanaka: (i) reduction of the sedimentation rate and (ii) a peak of lake productivity. The sedimentation rate after a Plinian eruption is relatively low due to the deposition of a thick scoria layer trapping the underlying sediments. This contrast with previous studies where an increase of sedimentation rate is usually observed following ash fall-out deposits. This study suggests that the sedimentation rate is affected by the grainsize of the volcanic ejecta. Coarse-grained tephra such as scoria are difficult to erode by rain splash and surface runoffs. The erosion of the catchment occurred during intense typhoons when porous scoria layers are saturated by heavy rains. The heavy rains trigger surface runoffs which drained the sediments from the catchment towards the lake. Lake Yamanaka needed more than ~170 years to begin to recover towards similar sedimentation rate (~0.16 cm/yr) that existed before the Hōei eruption. The recovery might have been accelerated by land use changes. During the last decade, the sedimentation rate increased drastically due to the decline of agriculture and planting of vegetated strips, urbanization of the catchment and the increase of in situ-lake productivity. Anthropogenic modifications of the catchment have greater impacts on the sedimentation rate than a major volcanic eruption. Moreover, agriculture and industrialization have severely contaminated Lake Yamanaka.

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**Figure captions**

Figure 1 – General settings. A. Location map of Lake Yamanaka (YA) and Fuji Five Lakes region (MO= Lake Motosu, SH= Lake Shoji, SA= Lake Sai, KA= Lake Kawaguchi). Isopachs represent the direction and the thickness of the tephra fall-out produced by the Hoei eruption (CE 1707) (after Miyaji *et al.* (2011). The Hōei vents are illustrated in white surrounded by an orange line. B. Study area showing geological map (Ozaki *et al.*, 2002) and bathymetric map of Lake Yamanaka (Adhikari *et al.,* 2005). Lake Yamanaka is very shallow with a maximum depth of 14.3 m. Inlets and outlets of Lake Yamanaka are represented with the blue arrow. Its catchment mainly consists of volcaniclastic and pyroclastic deposits.

Figure 2 – Core to core correlations based on magnetic susceptibility (Mag. Sus.). A. From left to right, linescan, X-ray photography, schematic log, magnetic susceptibility depth profile. The sedimentary record are divided into four sedimentary units (A to D). D corresponds to the Hōei scoria deposits and is recorded at the base of YAM14-5A and in all the core catchers (C.C.). B. Grainsize analysis done on YAM14-2A.

Figure 3 – Depth profiles of the elements selected for study measured on YAM14-2A. From left to right, percentage of amorphous materials, Br/Ti ratio, Br (%wt), Si/Zr ratio and P (wt%). On the P (wt%) depth profile, error bars correspond to the instrumental error. Sedimentary boundaries (A, B and C) defined based on the Magnetic susceptibility are also indicated. The peaks mentioned in the main text are highlighted in grey. Peaks of Si/Zr are interpreted as increase of diatoms content. The upper 5 cm of the gravity core present enrichment in P related to recent eutrophication.

Figure 4 – Depth profiles of the elements selected for study measured on YAM14-2A. From left to right, Mag. Sus., Ti, percentage of K-feldpar, Ca (cps), Ca (wt%), percentage of plagioclases and carbonates, Sr (cps), Sr (wt%), Zr (cps) and Zr (wt%). Instrumental errors are represented by error bars on Ca (wt%), Sr (wt%) and Zr (wt%) depth profiles. Sedimentary boundaries (A, B and C) defined based on the Magnetic susceptibility are shown as well. The peaks mentioned in the main text are highlighted in grey. We assume that these peaks are related to detrital pulses.

Figure 5 – Depth profiles of the elements selected for study measured on YAM14-2A. From left to right, δ15N, TOC (%), C/N, δ13C, LOI for 550°C (% OM). Sedimentary boundaries (A, B and C) defined based on the Magnetic susceptibility are also represented. In Unit C, peaks of C/N associated or not with peak in % OM calculated from LOI at 550°C coincide with peak of Si/Zr and are highlighted in grey. These peaks are interpreted as increase of in-situ lake productivity.

Figure 6 –Depth profiles of the elements selected for study measured on YAM14-2A. From left to right, Pb (cps), Pb (wt%), Zn (cps), Zn (wt%), Na (wt%), Mg (wt%), K (wt%), S (wt%). Errors bar indicated in the graph correspond to instrumental errors. Sedimentary boundaries (A, B and C) defined based on the Magnetic susceptibility are shown as well. The recent increase of anthropogenic pollution is highlighted in grey.

Figure 7 – Age-depth model of YAM14-2A. From left to right,210Pbxs depth profile, 137Cs depth profile, CF/CS model and CIC model.

Figure 8 – Landscape evolution and land change occupation. A- Aerial Photograph of the eastern part of Lake Yamanaka in 1948 (GSI, 2017). B- Landsat Photograph of the eastern part of Lake Yamanaka in 2016 (Google Earth, 2016). In the eastern part of Lake Yamanaka, the cultivated parcels present in 1948 were progressively replaced by houses and buildings. In some places, cultivated parcels were merged into bigger parcels. Nowadays, vegetated strips are mostly absent. C- Aerial Photograph of the southwestern part of Lake Yamanaka in 1959 (GSI, 2017). D- Aerial Photograph of the southwestern part of Lake Yamanaka in 1976 (GSI, 2017). E- Aerial Photograph of the southwestern part of Lake Yamanaka in 2001 (GSI, 2017). F- Landsat Photograph of the southwestern part of Lake Yamanaka in 2016 (Google Earth, 2016). From 1959 to 1976, cultivated parcels almost disappeared and were replaced by forest. Occasionally, cultivated parcels were still present. From 1976 to 2016, urbanization grew in the southwestern of the lake. Houses, buildings as well as roads were constructed leading to a decrease of the forest area and cultivated parcels.

Landscape Evolution and Land change occupation. G- Aerial Photograph of the northern part of Lake Yamanaka in 1948 (GSI, 2017). H- Aerial Photograph of the northern part of Lake Yamanaka in 1975 (GSI, 2017). I- Aerial Photograph of the northern part of Lake Yamanaka in 2002 (GSI, 2017). J- Landsat Photograph of the northern part of Lake Yamanaka in 2016 (Google Earth, 2016). In 1948, the north of the lake was entirely cultivated and a small village occupied its border. From 1948 to 1975, cultivated lands were progressively abandoned and replaced by forest. From 1975 to 2016, the north border of Lake Yamanaka has been urbanized.