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**First pollen record from the Late Holocene forest environment in the Lesser Caucasus**

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**Running Head:** Late Holocene forest reconstruction in Caucasus

**Abbreviations:**

AMS=accelerator mass spectrometry

MC=master core

PCA=Principal Component Analyse

XRF=X Ray Fluorescence

AP=arboreal pollen

NAP=non arboreal pollen

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## Abstract

Pollen-based vegetation change has been inferred from sediments in Kalavan Red Lake. This small lake is placed in the beech-oak-hornbeam forest, about three kilometres away from archaeological remains. It has the potential to document the Holocene forest history and climate and human impacts on the Lesser Caucasus. However, this lake happens to be formed by a large landslide.

Pollen and XRF analysis are provided over the last 3800 years. The basal age of the Kalavan sediment approximates the landslide age. This created a not vegetated slope including the lake catchment. Erosion and sedimentation processes brought coarse and heavy minerogenic elements, decreasing with the catchment revegetation by tall-grassland. This shift in the sedimentation continues, suggesting less erosion in the catchment when an admixture of *Quercus* and grasslands settled. Starting from 2000 cal. BP, arboreal pollen increases successively thanks to the step afforestation of *Quercus*, *Carpinus orientalis* and *Fagus*. The comparison with available pollen reconstruction illustrates the uniqueness of the vegetation dynamic recorded at Kalavan. However, the duration of this succession is also questionable. An intermediate hypothesis is proposed: the Kalavan's dynamic is first initiated

by the landslide with the tall-grass development, then paced by the regional vegetation dynamic.

Linking vegetation history and erosion with regional climate and archaeological data helps to evidence short-term climate change and human impact. Antique arid phase (2000-1600 cal. BP), the Medieval Warm Period and Little Ice Age affect the vegetation, while demography variations during the Medieval period and Modern Age are shown by pastoral activity.

## 1. Introduction

Located between the Black and Caspian Seas, the Lesser Caucasus was formed by the collision of the Arabian and Eurasian plates since the Neogene (Mitchell and Westaway, 1999; Sugden et al., 2021; Figure 1). The formation of the Lesser Caucasus offers varied and numerous topographies, climates, and landscapes (Karakhanyan et al., 2017; Meliksetian et al., 2021), conducive to floristic diversity (Volodicheva, 2002), many of these areas are classified as biodiversity hotspots (Cromar and Kvavadze, 2009; Solomon et al., 2014) and today harbour relict Arcto-Tertiary vegetation (Ghorbanalizadeh and Akhiani, 2022; Joannin et al., 2010). Trees are mostly confined to montane forest, an altitudinal zone embedded in lowland steppe and highland grassland. They grow mainly in Eastern Armenia and Western Azerbaijan, usually on the northeastern slopes. Forest-steppe/grassland are common ecozones (Volodicheva, 2002).

We know almost nothing about the past of these forests because there are no pollen analyses located only in the forest zone. The best approximation comes from the distant signal recorded by the sedimentary archives located in the steppe zone (Cromartie et al., 2020; Joannin et al., 2014a; Leroyer et al., 2016; Robles et al., 2022; Figure 1). These recent studies have made it possible to review the hypothesis that these steppe and open

formations are secondary successions initiated by human activities (Volodicheva, 2002 and reference therein). It was based on pollen studies conducted in the 1970s that determined the presence of the forest on the shores of Lake Sevan in the middle Holocene. While the proportion of forest cover (35%) given by Sayadyan (2011) is highly debatable, its regression is a common feature documented in the Lesser Caucasus mountain ranges (Cromartie et al., 2020; Joannin et al., 2014a; Messenger et al., 2013; Robles et al., 2022), the Alborz (Alinezhad et al., 2021; Homami Totmaj et al., 2021; Ramezani et al., 2021), the Zagros (Stevens et al., 2006, 2001) and Anatolia (Roberts et al., 2011; Wick et al., 2003).

#Figure 1

Climate is among the forcing for this level of duration and superficialities. It has stabilised on the current climate since the Early-Middle Holocene transition, including precipitation regime shift linked to North Atlantic Ocean circulation and northern atmosphere circulation (Joannin et al., 2014a). However, climate records do not show a clear trend over the last millennia.

The Lesser Caucasus is a geographical area where the landscapes are extremely fragile (mountains, plateaus, lakes, river valleys) and sudden changes have a strong impact on societies. And indeed, rapid climatic events of aridification are reported by climatic reconstructions carried out on pollen and molecular biomarkers (Robles et al., 2022). These events are perfectly echoing the abandonments of settlements from the shores of Lake Sevan and on the dynamics of the populations of the Lesser Caucasus (Palmisano et al., 2021).

The impact of humans is also suspected. The open landscapes of the Caucasus have offered human ideal spaces for pastoralism and agriculture since the Neolithic period (which

incidentally corresponds to the Early-Middle Holocene transition). We can therefore wonder if the forest heart of the Lesser Caucasus was an area coveted by the populations.

Fragmentary studies document some use of these forests. The Aghstev Valley was occupied in the Chalcolithic by hunter-gatherers, or pastoral nomads (day-to-day herding or transhumance) (Arimura et al., 2014). Admittedly, the use of wood, which has intensified for the mining activities (Smith et al., 2009; Stöllner, 2021), may have marked a turning point, but it is especially during the last centuries that the forest of the Lesser Caucasus has the most regressed and has deteriorated (Goginashvili et al., 2021). In Armenia, the forest has gone from 18% in the 18th century to 7-8% today (Sayadyan, 2011).

Placed to the northeast of Lake Sevan (Figure 2a), midway between the plains of the Araxes and the Kura, the penetrating valleys of the mountain range could have served as a shortcut, being at the centre of the Bronze Age populations (Kuro-Araxes; Badalyan, 2014) and Iron (Urartu empire and Lchashen-Metsamor culture; Badalyan et al., 2008). These areas were already used as summer- autumn hunting areas in the Palaeolithic (Malinsky-Buller et al., 2021; Montoya et al., 2013), and later as a summer transhumance areas in the high grasslands (Arimura et al., 2014). There are therefore many reasons to be interested in the history of these forests. This study presents the first reconstitution of the forest vegetation in the lesser Caucasus. The pollen and geochemical analysis document the story of the watershed of the red lake of Kalavan to document climate and human impacts. However, despite all the quality of its forest environment, presents a questionable specificity. It is the product of a massive landslide that affected the entire northern slope of Gora (peak) Dzhantapa. This peak is only completely forested on this side (Figure 2a). In this study, we will test the hypotheses of vegetation dynamics initiated by the landslide or echoing the regional evolution of the vegetation.

#Figure 2

## 2. General settings

### 2.1. Presentation

The lesser Caucasus is affected by on-going active tectonics and seismicity and by volcanism of even recent activity (dated to 4 ka cal. BP according to Karakhanian et al. (2002). This has deeply modified the Caucasian landscape since the Pliocene (Ollivier et al., 2010; Sherriff et al., 2019).

From a geological point of view, the Sevan-Shirak region is made of Eocene tuff and sandstone with andesite. Along the Pambak-Sevan-Syunik fault, the basin of the River Getik is an active fault where numerous landslides occurred (Karakhanian et al., 2002; Matossian et al., 2020). Gravitational hazard is characterised by boulder and block falls, mudflows and huge landslides within the middle- and high-mountain belt, where volcanogenic-sedimentary rocks and tectonic faulting zones have been evidences (Boynagryan et al., 2018).

#Figure 3

Kalavan Red Lake (N 40°39.254 ; E 45°08.773 ; 1912m a.s.l.) and its catchment lie inside a landslide area on the northern side of the Miapor mountain ridge, north of Gora (peak) Dzhantapa (2427m, Figure 3a). According to Boynagryan et al. (2018), it is an old large landslide created by a strong earthquake that affected the Paleogene substratum (sandstone-tuff and porphyries). These authors describe a small size of vertical displacement (100–200 m), but the amplitude of horizontal displacement reaches 0.5–1 km. We evaluate a



sizing of about 0.86 km<sup>2</sup>. It primarily resulted from combining water saturation in the superficial cover and slope steepness (average 24% with maximum at 50% today in the erosion zone). The water sourcing is from artesian and hydrothermal origin along the fractured area related to the main potential fault observed. Fracturing and fault kinematics measurements in Eocene formation provide evidence for a single tectonic event in agreement with the dominant strike-slip tectonic regime. Below the erosion zone is the accumulation zone where probably tectonically emplaced depressions, by folding and faulting, are today occupied by Kalavan Red Lake and Kalavan Peat (Figure 3a). There, the potential faulting orientated NW-SE created the shoulder on which declining steepness favoured landslide deceleration and accumulation (slope basement at around 1850m a.s.l.). No evidence of active faulting has been observed in the field, may be due to the poor outcrop quality and condition (dense vegetation, no accessibility), however, morphology of an apparent escarpment could be responsible for the disconnection of the Peat / Lake indicating a potential recent fault activity. We named the lake by the closest village's name.

## **2.2. Archaeological findings in the nearby**

During the Early Bronze Age (about 5500–4200 cal BP; Cherkinsky and Chataigner, 2010), the Southern Caucasus area became closely tied into a regional “ecumene,” termed the Kura-Araxes culture or the Early Transcaucasian culture (Smith, 2005). Only a few sites have been uncovered until now in the forested mountains of the Lesser Caucasus, north of Lake Sevan (Figure 2a). Kalavan-1 is located at 1600 m altitude, on the right bank of the Barepat River, a couple of hundred metres away from the Palaeolithic open-air site Kalavan-2 (Gasparyan et al., 2008; Ghukasyan et al., 2011; Malinsky-Buller et al., 2021). At Kalavan 1, two phases of occupation have been uncovered (Liagre et al., 2009). The Epipalaeolithic layer (layer 7)

contains a lot of lithic material and bones, belonging exclusively to ovi-caprines. This occupation was presumably a hunting camp site (Ghukasyan et al., 2011; Montoya et al., 2013). Arimura et al. (2014) and Tornero et al. (2016) hypothesised that interest in this area arises from the closeness (through Aghstev Valley) with lowlands (Kura Basin) today situated in Azerbaijan.

Kalavan-1 served during the early Bronze Age as a funeral site (Montoya et al., 2013). Down the Barepat river is a small cave (1700 m a.s.l.) which contains artefacts (obsidian, pottery) mixed with bone remains ( $5360 \pm 40$  yr BP). Regarding the final stages of the Barepat River valley occupation, on-going archaeological excavations of the Barepat-1 and Barepat-2 caves relate to the High Medieval Period. At Kalavan-2, the remains of large walls are present. They are not formally attributed to the Medieval Period. After the Russian reattachment in 1840 and Soviet dominance, the former village Anirkher (densely populated by Azeris), was transformed in the 1980s into Kalavan (which population stands at under 200). The Department of Cartography and Geoinformatics of Erevan reports that, before this population migration, summer camps of shepherds at elevation 2130 m, were located one kilometre away from the Kalavan Red Lake (Figure 3a). Only the shape of buildings or livestock rocky walls can be seen on satellite imagery.

## **2.3. Present phytogeography and climate**

### ***2.3.1. Present phytogeography***

Volodicheva (2002) provided the description of the Central Transcaucasia vegetation which can be adapted with field observation (Figure 2b). Lake Kalavan is surrounded by a forest of oak (*Quercus macranthera*)-beech (*Fagus orientalis*)-hornbeam (*Carpinus orientalis*) sometimes mixed with other trees (*Acer platanoides*, *Sorbus* sp., *Salix caprea*) and open land

areas where develop tall grasslands partly used for hay-making (Figure 3a). Tall grasslands are composed predominantly of broad-leaved herbaceous plants which often reach 1.5-2 m in height with a high endemic rate (*Heracleum* sp.; *Senecio* sp.). Downward the lake is an admixture of beech and oriental hornbeam. Close to the bottom valley of Barepat stand oak forests (*Quercus iberica*) admixed with *Carpinus caucasica* (*C. betulus*) and patches of pines. The last may have been planted during the late soviet programs (1980) for afforestation; a practice largely seen in Armenia. Upward is a birch tree-line (*Betula litvinii*) which stands between 2200 and 2300 m a.s.l. on the northern slope of the Gorn Dzhantapa. On the southern slope settled a tree-line of oak (*Quercus macrocarpa*) sparse woodland mixed with grasslands at around 2050 m of elevation.

Considering the Kalavan Red Lake itself, today's vegetation forms a belt dominated in three areas by *Sphagnum* on which stands birch (*Betula* sp.) wood. However, in two areas (outlet and creek mouth) only dead trunks of birch stand (sometimes sporadically surviving) (Figure 3b). There, young birches are now sprouting on a yellow/brown *Sphagnum* peat. This acidophilous plant association is replaced near free shallow water by patches of sedge taxa (such Cyperaceae: *Cyperus*, *Scirpus*). The lake never dries. Water pH was 3.57 in June 2012. Kalavan Peat (Figure 3a) shows successive belts of *Sphagnum*-birch and semi-aquatic association of *Juncus communis* and *Phragmites* and *Galium palustre*.

### **2.3.2. Climate**

The Kalavan area is characterised by a thermo-moderate and humid mountain climate with mild summers and extremely cold and snowy winters. The meteorological station of Chambarak city is the closest station to Kalavan (N40° 35' 45"; E45° 21' 20"; 1845 m a.s.l.). It is expected to document rather similar climatic conditions (though warmer because of

elevation difference), i.e. a low annual temperature (5 °C on average), with a minimum in January (-5.2 °C on average) and a maximum in July (14.7 °C on average). Annual precipitation is about 583 mm on average, with a minimum in January (20.3 mm on average) and a maximum in June (93.1 mm on average) (Figure 2c). Mountain-valley circulations, due to differential heating, can produce thundershower activity, particularly in late spring (i.e. May-June) when snow retards the rise of air temperature.

### **3. Material and methods**

#### **3.1. Core sampling**

A coring campaign was done in June 2012 in the framework of the Caucasus mission (CNRS, MAEE, and Institute of Archaeology of Yerevan). Coring tests were done in the Kalavan Peat (eastward to the lake) and in the lake's outlet and creek mouth (Figure 3a). The creek delta (Figure 3b), which offers greater potential considering deepness and lithology, was then cored in twin cores using a Russian corer (chamber length 56 cm). A 502 cm long core was retrieved, and recovered in 14 sections.

The master core (MC), i.e. the ideal and complete lithological sequence using both parallel cores, was established based on the visual description of lithological changes combined with X-Ray Fluorescence (XRF) core scanner profiles. The grain size distribution of each sedimentary unit was performed by a laser diffractometer (Malvern Mastersizer 2000G).

#### **3.2. Geochemical sediment studies**

##### **3.2.1. Quantitative and semi-quantitative sediment methodologies**

The lake's reddish shores, shown in Figure 3b, indicate the presence of iron oxides.

Concretions can be observed at the water-air interface. They often embed wood

macroremains (beech leaves and fruits mainly). Quantitative measurement of metallic elements (Zn, Fe, Pb, Cu, Cr, Cd, Ni) was performed using atomic absorption spectrometry (AAS). Five stratigraphic samples, two shore samples, and one sample from the main tributary were analysed to compare current metallic concentrations of Kalavan Red Lake with past concentrations.

The running chemical composition of sediment cores was performed using an Avaatech XRF (EDYTEM Laboratory) core scanner at a 0.5 cm interval (presented here: Si, Zr, K, Ti, Sr, Al, S, Fe, Ca). The XRF measurements were carried out on split cores with a measurement duration of 10 s. A 10 kV voltage and a 1000  $\mu$ A current were applied to detect elements. Because of the influences of variable water content and grain size on the sediment matrix, the XRF scanner provides an estimate of the geochemical composition, and the acquired counts are semi-quantitative.

### **3.2.2. Radiocarbon dating**

Chronological information was obtained using  $^{14}\text{C}$  dating on plant macrofossils processed by accelerator mass spectrometry (AMS) (Table 1). Macroremains were collected from sediment samples sieved with a 100  $\mu\text{m}$  mesh screen. Samples were processed at the  $^{14}\text{C}$  laboratory in Poznan. Radiocarbon ages were calibrated in cal. BP using the calibration curve IntCal20 (Reimer et al., 2020). Dates are expressed as intercepts with  $2\sigma$  ranges.

#Table 1

## **3.3. Plant studies**

### **3.3.1. Pollen analysis**

Samples of around 1 cm<sup>3</sup> of sediments were treated chemically (HCl, KOH, HF, acetolysis) and physically (sieving between 200 and 10 µm) following standard procedures (Moore et al., 1991). A total of 66 pollen samples were analysed under a light microscope at a standard magnification of × 400. Pollen flora is identified using photo atlases (Beug, 2004; Reille, 1992). The pollen cumulated diversity is established to 103 taxa.

A minimum of 20 taxa (excluding wetland plants, i.e. mainly Cyperaceae) and an average sum of 366 terrestrial pollen grains were counted. Percentages were calculated based on the total terrestrial pollen sum. Using the Psimpoll program, the main pollen taxa are represented in percentages. Local pollen assemblage zones are defined using the CONISS function of Psimpoll.

Five moss samples were collected from both the surroundings of Kalavan Red Lake (forested area) and the Kalavan Peat (not forested area; Figure 3a). They were treated both chemically (NaOH, HCl, HF, acetolysis) and physically (sieving between 200 and 10 µm) to extract pollen. According to Pardoe et al. (2010), pollen proportions from moss samples represent the pollen deposition of one area over several years. Moss samples are used to emphasise the correlation between pollen rain and vegetation.

### **3.3.2. Dendrochronology**

A short dendrochronology survey was conducted in July 2017 by drilling some of the oldest birches (dead or only regenerating from a few branches) to estimate their ages and study their ring sizing.

## **4. Results**

### **4.1. Sedimentology**

#### 4.1.1. Lithology and sediment units

The sediment core is characterised in terms of colour description and grain-size distribution and allowed to define five sedimentary units from base to top (Figure 4). Unit A (507 – 427 cm) is a light grey silty mud. Unit B (427 – 328 cm) contains an alternation of brownish to greyish muddy layers and one piece of birch wood (B5 55-56; Table 1). Unit C (328 – 280 cm) is grey-dark mud. Unit D (280 - 150 cm) starts with a compacted gyttja layer followed by light brownish mud. Unit E (150 – 0 cm) is mainly of gyttja including a *Sphagnum* peat layer.

#Figure 4

However, the textural group for all units is a sandy mud with a median grain size (D50) ranking from 8,5  $\mu\text{m}$  to 74,3  $\mu\text{m}$ . Important proportions of the clay fraction are reported in the bottom A and B units (respectively up to 18,5 and 8,0 %) compared to C, D, and E units (< 2,5 %). The grain size distribution is mainly bi- or tri-modal. Since no protocol for organic matter destruction has been implemented, the increase in the sand fraction in the samples is attributed to the higher proportion of plant macroremains. This is consistent with the stratigraphic description of the sediment sequence where more organic-rich sediment (gyttja facies) in the upper part of the core is deposited.

#### 4.1.2. Sediment composition

Only quantitative measurements of the metallic Fe element are provided here to highlight processes causing the lake to have reddish shores and the presence of iron oxides. Fe dataset is shown in **Error! Reference source not found.** and Figure 4. It shows a very high

concentration of Fe on today's shores and in the main tributary (80g/kg DW) compared to sediment.

#### #Table 2

Sediment composition from XRF measurements provided semi-quantitative values for Si, Zr, K, Ti, Sr, Al, S, Fe, and Ca (Figure 4). Correlation values, variable's factors weight, and map issued from a Principal Component Analyse (PCA; Figure 5) on raw data were performed using Past software (PAleontological STatistics 3.17; Harner et al., 2001). It indicates three major components (>10% of the variance): PC1: 56.4% variance, PC2: 18.8% variance, PC3 (not shown): 11.6% variance. Geogenic elements (Al, Si, K, Ti) are one pole of component 1. They are correlated ( $r = 0.92$  on average) thus suggesting a common source and depositional process. The opposite pole of component 1 is sulphur (S). This element increases during sedimentary units B, D, and E of enhanced organic matter accumulation.

#### #Figure 5

The second component opposes Fe, S to Ca, Mn. Except for detrital sediment units (A and C), organic-reach sediment units (B and E) show high Fe and S content. Interestingly, the Fe semi-quantitative XRF measurement pattern is validated by the quantitative Fe concentrations (brown square dots in Figure 4). The third component (not shown) is mainly forced by peaks of high Ca content occurring at negative values of PC2.

#### 4.1.3. Age model



The age-depth model is constructed using an interpolated linear curve (Figure 4) by the 'Clam' model developed by Blaauw (2010). One  $^{14}\text{C}$  age (Poz-76962,  $2450 \pm 30$  BP; Table 1) was excluded, being birch roots (possibly belonging to the contemporary birch wood Poz-76961 dated at  $2460 \pm 30$  BP). The average sedimentation rate ( $13 \text{ cm} \cdot 100 \text{ a}^{-1}$ ) accelerated during the last millennium. The Kalavan record covers about 3800 cal a BP. The average temporal resolution for the pollen analysis is estimated to be 75 years between samples.

## 4.2. Vegetation analysis

### 4.2.1. Pollen analysis

#### *Pollen from moss polsters*

The pollen results from the five moss samples have been averaged for selected taxa (Figure 6) and individual % values are found in Supplementary Table S1. The pollen diagram records terrestrial plants' pollen with trees (AP) on the left and herbs (NAP) on right.

Tree pollen diversity is close to vegetation description and observations (illustrated in Figure 2b), while pollen-based tree proportions are higher than forest superficies. Arm6 and 7, taken from an open peat-land with few birches (*Betula*), show about 76% AP while oaks (*Quercus macranthera*) are distant by approximately 50m. Inversely, pollen-based herb diversity is considerably low and percentages of grass (Poaceae) and tall grass (Asteroideae, Apiaceae) are underrepresented compared to observed superficies. Steppe meadow which is present at higher altitudes is poorly recorded. A higher % of *Betula* is seen in the pollen from moss polster (Arm8) from the birch stand at the main creek delta of Kalavan Red Lake. Pollen diversity recorded by moss polsters is close to the upper paleo samples of the diagram. Percentage values are also closed for most taxa (*Fagus*, Poaceae, and *Betula* for

example). Only *Quercus* is superior in moss samples (40 %) and reinforces forest total (AP; around 80 %).

### ***Terrestrial pollen (TP) sequence***

Vegetation zone TP-1 (507-505 cm; 3800-3700 cal. BP; Figure 6) concerns one sample only with medium forested landscape (AP = 40 %) of *Quercus* (oak) and *Carpinus betulus* and *C. orientalis* (European and oriental hornbeam). The NAP includes a high percentage of the Caryophyllaceae family.

Vegetation zone TP-2 (505-345 cm; 3700-2200 cal. BP) represents an open landscape (NAP around 70 %) with grass or tall grass meadows of Poaceae, Asteroideae, and Apiaceae.

Forest taxa are mainly of *Quercus* and *Carpinus betulus*. *Pinus diploxylon*, mixed deciduous forest (*Salix*, *Fraxinus* sp., *Acer*, *Tilia*, *Ulmus*), *Juglans*, and shrubs are present with low rates.

Other trees (*Picea*, *Abies*, *Alnus*) are sometimes recorded. Open landscape also includes humid taxa (*Ranunculus*) and other herbs (Lamiaceae, Apiaceae). The Steppe meadow is represented by stable rates of *Artemisia*.

Vegetation zone TP-3 (345-262 cm; 2200-1400 cal. BP) marks fluctuating values of AP rates.

On average, this rate increases (AP around 42 %) but the forest composition remains stable except for *Carpinus orientalis* which disappears in the record from 340 to 310 cm. The observed afforestation affects the grass meadows (decreasing values of Poaceae and Asteroideae mainly) but not the steppe (*Artemisia*).

Vegetation zone TP-4 (262-155 cm; 1400-600 cal. BP) illustrates bi-phased afforestation

(around 60 %) with oaks (*Quercus*), hornbeams (*C. orientalis* and *C. betulus*), and beech

(*Fagus*) in the recent one. A temporary return to a more open landscape that benefits both

grass and steppe meadows. It is recorded between 210 and 190 cm.

Vegetation zone TP-5 (155-36 cm; 600-59 cal. BP) shows the most recent pollen records but the sampling resolution is affected by sterile samples in the gyttja facies. A forest landscape (AP around 70%) of oak, beech, and the 2 hornbeams is recorded. Grass and steppe meadows have similar values to today's average surface sample.

#Figure 6 (Full page in portrait)

### **Lake vegetation sequence**

Non Terrestrial Pollen (NTP) diversity is much lower than the terrestrial one (Fig. 6). Zonation is based on semi-aquatic and non-vascular plants, while algae are not recorded. Today's observation of birch stands (*Betula*) and Cyperaceae/*Scilla* rafts find an echo in the pollen diagram which opposes phases with higher *Betula* values (NTP-1, -3, -5) or higher Cyperaceae values (NTP-2, -4). *Sphagnum* pollen is sporadically recorded, even in the compacted sphagnum deposit. Monolete spores (fern) are Non Terrestrial Pollen but are not associated with wetlands. Higher amounts characterise NTP-1-2-3 and decrease afterward.

### **4.2.2. Birch dendrochronology**

Dendrochronological survey was conducted in July 2017. The oldest birches grew since 1970 at late and their rings started to decline in 2007-2009, some of them died afterward while the others survived till 2015 or up to now.

## **5. Discussion**

### **5.1. Modern and past environment of Kalavan Red Lake**

#### **5.1.1. Modern and past sediment**

According to Graupner (1982), iron from mire is common in tidal zones of surficial waters with a duration of formation extending from centuries to millennia. In Kalavan however, such Fe concentrations are much higher on the shore and in the main creek than those measured in the sediment core (Table 2 **Error! Reference source not found.**). According to this data, the anomaly comes from a recent iron input. It had a negative effect on semi-aquatic plants (*Sphagnum*-birch) in the creek delta and lake outlet, but not on the westward connected *Sphagnum*-peatland which is fed by an independent creek. The dendrochronological survey reveals a decline in birch growth in 2007-2009 possibly dating this iron excess anomaly. As some of the birches survived and young are sprouting, they suggest a normalisation of the situation. However, the *Sphagnum* layer in the creek delta has not yet recovered. Two iron sources (geological and biological) are possible. They may come from pyrite rocks and leaching seen in a small landslide further in the catchment. According to Google Earth satellite images (2001, 2006, and 2011), this landslide happened between 2001 and 2006. Geothermal oversaturated waters may add too. Many can be seen on the opposite slope of the Gora Dzantsha. The second possibility is the large biomass amount from tree leafs (beech mainly) decaying upward in several depressions of the main creek. This creates anoxic conditions and low pH favouring Fe accumulation (see below).

The proportion of heavy minerogenic elements (Al, Si, K, Ti) is the most pronounced in sediment units A and C (Figure 4) suggesting erosional phases in the catchment (Figure 5). They oppose S content which increases during sediment units B, D and E of enhanced organic matter accumulation. According to Holmer and Storkholm (2001), the majority of sulphur in lakes originates from the weathering of sulphur-containing rocks in the catchment and from the oxidation of organic sulphur from terrestrial sources. The second sulphur

sourcing dominates as it occurs with weaker erosion and forest development in the catchment.

Except more detrital input in sediment units A and C, organic-reach units B and E show high Fe and S content while organic-reach unit D relates on the Mn and Ca pole of PC2 (Figure 5). The second component may be related to biogeochemistry of shallow water and water/sediment interface. Fe and S may be positively related through anoxic conditions due to organic matter decay; sulphate-reducing bacteria produce hydrogen sulphide reacting with metal to produce metal sulphides (FeS and FeS<sub>2</sub>; Choi et al., 2006), which are not water-soluble. Moreover, trace metals, such as Fe and Mn, have a redox-sensitive behaviour in aquatic environments (e.g. Naeher et al., 2013 and reference therein). As Fe oxidises faster than Mn, high Mn accumulation occurs only under oxic conditions. Organic-reach units (B and E) show high Fe and S content due to (h<sup>+</sup>po<sup>-</sup>), anoxic conditions in shallow water and water/sediment interface and low pH. Light brown clay deposits in unit D therefore characterised oxic conditions possibly related to deeper water supported by increase in Cyperaceae (NTP-4, Figure 6). Carbonates may also react to anoxia (and its relation with pH) therefore linking Ca with Mn in Component 2. The third component only relates to Ca. This may indicate again the relation between carbonate deposits during oxic phases with more neutral pH.

### 5.1.2. Past lake vegetation

Today's lake vegetation belt is dominated by *Betula* (Birch) growing on *Sphagnum* moss in the creek delta and on a westward connected peat. They are both implanted over the tidal zone of the lake itself where patches of Cyperaceae/*Scilla* can be seen but do not form tussocks. Difficulty rises here for *Betula* and *Sphagnum*. The first is also present at the

timberline but, as birch remains were found at 372.5 cm depth, we postulate that *Betula* pollen comes from the closest trees. The second taxa can be underrepresented by its spores because of its tendency to reproduce vegetatively or to be destroyed by acetylation effect (Charman, 1992). *Betula* and Cyperaceae eventually relate on lake vegetation belt and anti-correlated along pollen stratigraphy. Birch/Cyperaceae ratio show higher values during erosional sediment units A and C. Based on the pollen from moss polsters, high-values ratio are also seen for the last decades.

### 5.1.3. Formation and development of the lake and its catchment: two related histories

The basal age of Kalavan sediment (3800 cal. BP) may approximate the landslide age. This slide is related to a combination of water saturation in the substratum, and slope steepness, in the active tectonic context of the Pambak-Sevan-Syunik fault. The large landslide erosion zone north of Gora Dzhantapa (2427m, Figure 2a) produces a new, not vegetated slope, which includes the lake catchment. Erosion and sedimentation processes brought at first coarse and heavy minerogenic elements illustrated by positive values of principal component (PC) 1 (Unit A; Figure 5,

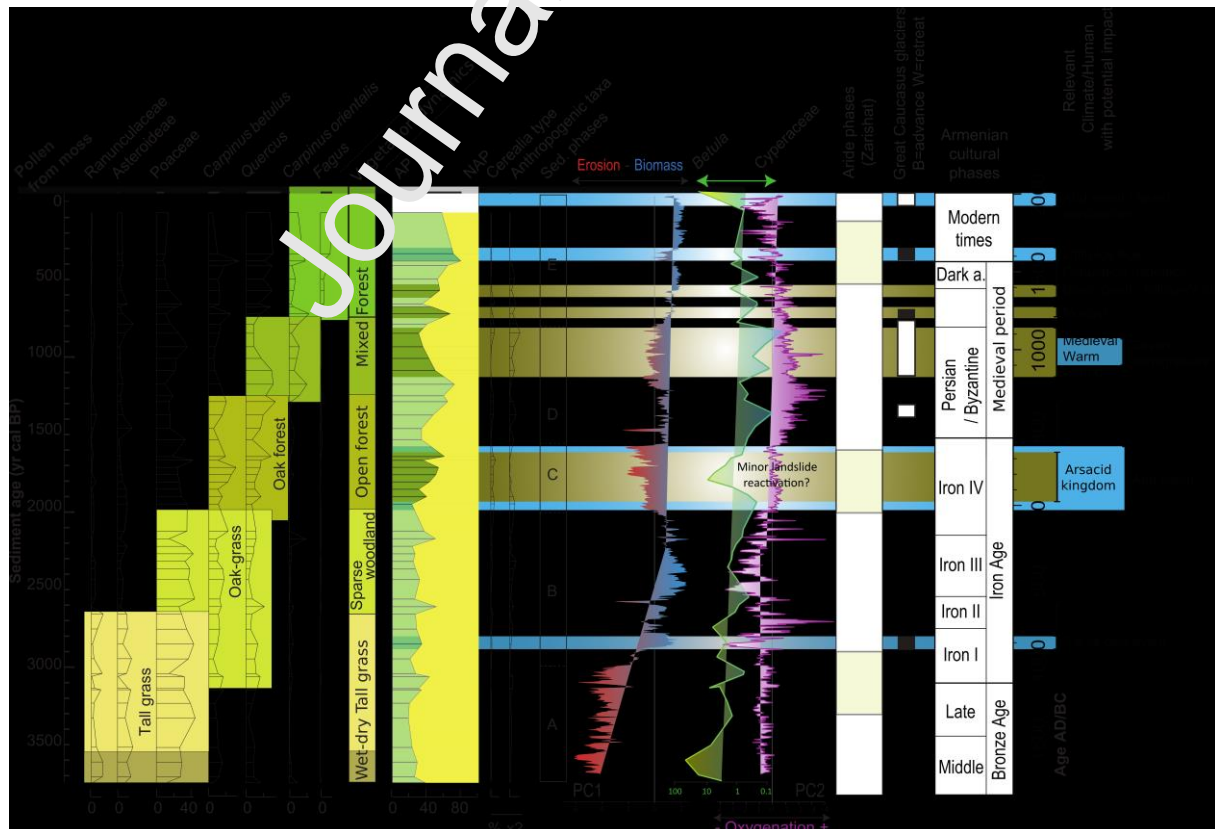


Figure 7). Along the 3800 years of Kalavan record, erosion in the catchment decreased operating a shift in the sedimentation. Lower detrital inputs benefited semi-aquatic plant growth (Cyperaceae) and biomass accumulation (PC1 negative values;

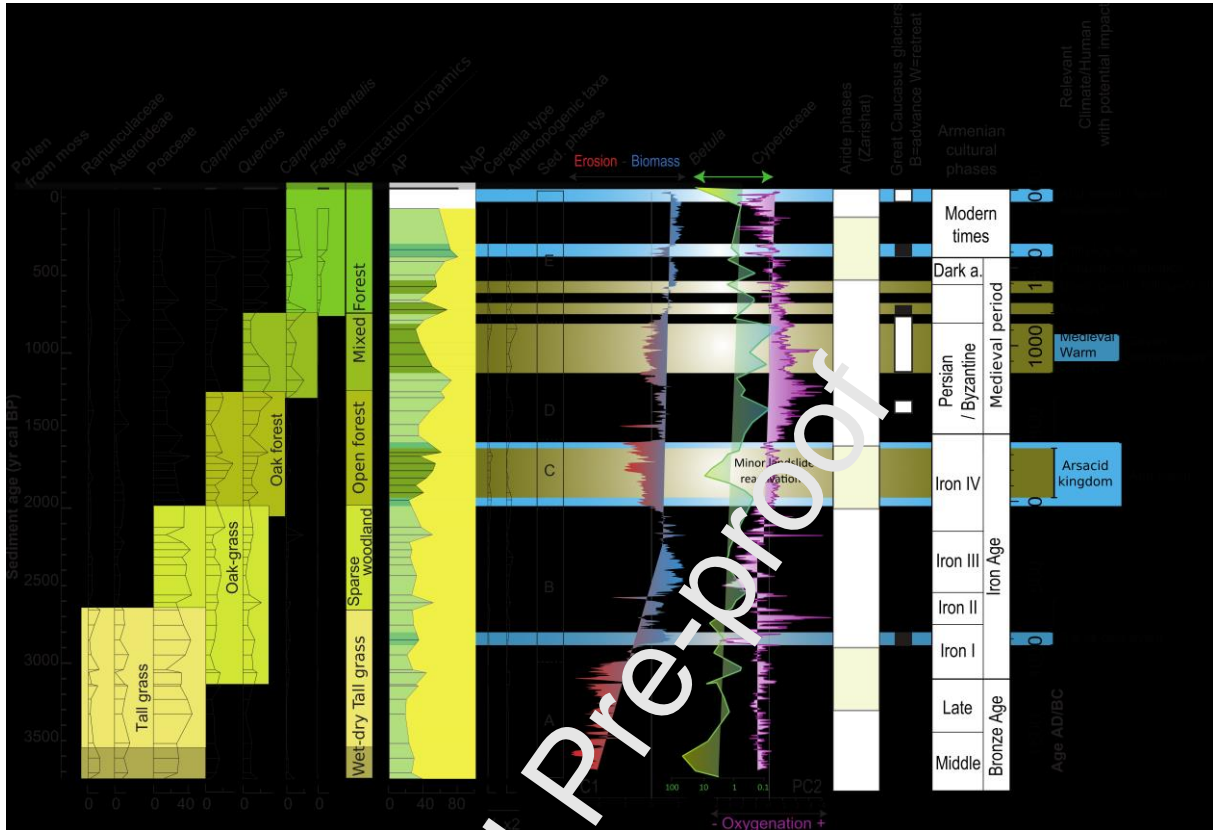


Figure 7). This coherent pattern is challenged by Unit C, which shows afforestation but also more erosion in the catchment with birch benefiting more detrital sediment in the creek delta. This afforestation is likely to disqualify a new large landslide event hypothesis but cannot exclude a minor surface landslide reactivation, or a gravity adjustment of the accumulation zone. The detrital character of this phase is also questioned, by means of a lesser production of organic matter during a lake lowering phase. Concomitantly occurs an arid phase recorded in the wetland sediment archive and the regional pollen-based climate reconstruction from Zarishat (Joannin et al., 2014a).

## 5.2. Pollen-based vegetation

### 5.2.1. Pollen representation in modern vegetation

Studying the relationship between pollen rain and actual vegetation is essential for the interpretation of fossil pollen spectra (Fall, 1992; Sugita, 1994). The pollen rain depends primarily on the internal parameters of the plant (production potential and dispersion; Holmes, 1990) and external factors (topography and climate; Joannin et al., 2012; Odgaard, 1999). Moreover, these parameters are not stable over millennia. Pollen rain integrates local to regional vegetation (Prentice, 1985). In Armenia, a recent study from Robles et al. (2022) compared modern pollen assemblages and botanical relevés along an altitudinal transect. This study complements the study of Connor and Kvavadze (2009) for Georgia. These authors found that when largely open, vegetation contributes to a greater pollen dispersion but the main pollen taxa are representative of their altitudinal zone.

In general, the underrepresentation of herbs is caused by their bee-dispersal strategy, lower pollen production, and lower buoyancy of wind-dispersed pollen. This particularly affects grass (Poaceae), tall grass (Asteroideae, Apiaceae) and the distant steppe meadows (*Artemisia*). On the opposite, tree pollen representation is favoured by their wind-dispersal strategy and high pollen productivity. In addition to taphonomic processes, the taxonomic level of pollen identification ranges from species (the two hornbeams can be identified, i.e. *Carpinus orientalis* and *C. betulus*) to genus (the two oaks cannot be separated, i.e. *Quercus* sp. groups *Q. iberica* and *Q. macranthera*), to family [Poaceae groups *Stipa* grass from steppe meadow (Bohn et al., 2000) with grasses from lower altitude meadows]. This reduces diversity in the pollen assemblage compared to the original landscape.

Assemblages issued from averaged pollen from moss polsters and the most recent paleo samples are very close both in diversity (composition) and proportion (structure) (Figure 6).

The Azeris population migration in the 1980s and associated pastoral demise (in the former village' name Amirkher) accounts for the small difference of  $\Delta 20\%$  in oak and AP. Therefore,



considering permanent biases, pollen assemblages are suitable to reconstruct vegetation composition and structure.

### 5.2.2. Terrestrial vegetation dynamics

Along the whole stratigraphy, it is noteworthy that arboreal pollen (AP) increases thanks to the increasing rates of *Quercus* (oak), *Carpinus orientalis* (oriental hornbeam) and *Fagus* (beech) (

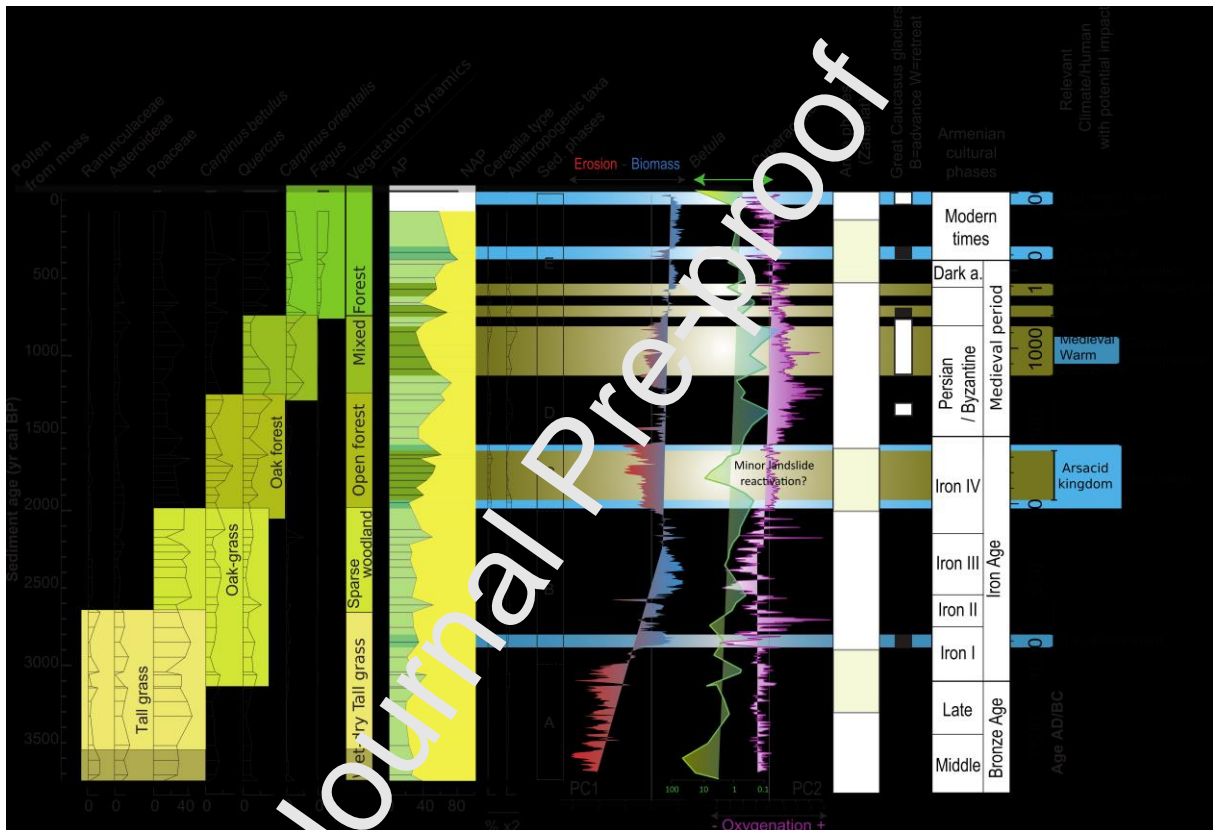


Figure 7) while *Carpinus betulus* dynamic (Caucasus Hornbeam) is stable. This afforestation expands on the grass meadows (Poaceae, Asteroideae). Zonal steppe meadows remain stable.

Caryophyllaceae was the first to develop on the ground area after the landslide. No indication of development by arboreal pioneer elements such as *Betula*, shrubs or heath is observed but instead, pollen data document for a tall-grass phase. Ranunculaceae may suggest a wetter environment than the following Poaceae. The tall grass and grass

assemblage is completed by monolet ferns. Such grass and tall-grass meadow only root down 10-30cm deep, favouring high erosion in the catchment. During this phase, arboreal pollen grains (*Quercus* and *Carpinus betulus*) likely come from outside the landslide area, probably from lower altitude forested zone where today *Q. iberica* and *C. caucasica* admixed (Figure 2b). This lower altitude zone was not affected by the landslide (below the altitude of the accumulation zone). Increase in *Quercus* and AP rate and *Carpinus orientalis* continuous appearance around 3100 cal. BP suggests a slight afforestation in the catchment associated with less erosion. Around 2600 cal. BP, an oak-grass environment is possibly documented. Soils and substratum being more protected from erosion by tree roots, afforestation is closely followed by a shift in PC1 values indicating less erosion. Starting from around 2000 cal. BP is an oak open forest development surprisingly related with more erosion during four centuries. *Carpinus orientalis* and *Fagus* appear first as single stands at 1700 cal. BP. Upward, two forested phases are observed. One is centred on 1200 cal. BP and is characterised by oriental Hornbeam development. The other starts 700 years ago with beech development. This last phase is similar to today's forest, both in composition and proportion issued from pollen in moss polsters.

#Figure 7

### 5.2.3. Comparison of Kalavan's vegetation dynamic in the lesser Caucasus

In Armenia, and more generally in the lesser Caucasus, there is no reconstruction of past vegetation resulting from a pure forest environment. The most recent pollen studies all report a steppe environment since the Lower Holocene in Western Armenia (Zarishat, Joannin et al., 2014a; Shenkani, Cromartie et al., 2020; Vanevan, Leroyer et al., 2016; Robles

et al., 2022). This contradicts studies carried out in the 1970s which indicated a forest environment on the shores of Lake Sevan in the middle Holocene (e.g. Sayadyan et al., 1977). In addition, these sedimentary archives record part of the long-distance pollen signal. This signal echoes the evolution of the diversity and structuring of the vegetation of the North of the Lesser Caucasus (Zarishat, Shenkani, and in Georgia: Tsavkisi, Connor, 2006; Jvari, Connor et al., 2020; Paravani, Connor and Kvavadze, 2009; Messenger et al., 2013) and the East (this study, Vanevan).

In all these sites, the forest signal (AP) describes a decrease since 4ka (also seen in Lake Van record; Wick et al., 2003) to which oppose Kalavan's afforestation trend. Only Zarishat, Tsavkisi, and Shenkani record an AP increase over the last 2000 years. The NAP signal is mainly carried by Poaceae which has been increasing for 4ka in Georgia (Connor and Kvavadze, 2009, Paravani) and in Vanevan. Looking at the diversity of these forests, it has been documented that *Fagus* is recorded from the middle Holocene in Paravani, Tsavkisi, Zarishat, and Shenkani and very rarely in Vanevan. The increase in AP at Zarishat, Tsavkisi, and Shenkani since 2ka is mainly driven by *Pinus* and *Quercus*. It is a similar pattern which is recorded in Dagestan (Arkiaa, Ryabogina et al., 2022), while Kalavan records a richer forest with *Quercus*, *Carpinus orientalis* and *Fagus*. We find that the development of *Carpinus betulus* is typical of the middle Holocene at Shenkani, Zarishat and Vanevan.

#### **5.2.4. Is the Kalavan's vegetation dynamic regional or a response initiated by the 4000 yrs old landslide?**

The comparison of vegetation records in the Lesser Caucasus illustrates the uniqueness, in the current state of knowledge, of the vegetation dynamic recorded at Kalavan. Looking in

detail, this dynamic is divided into four phases (

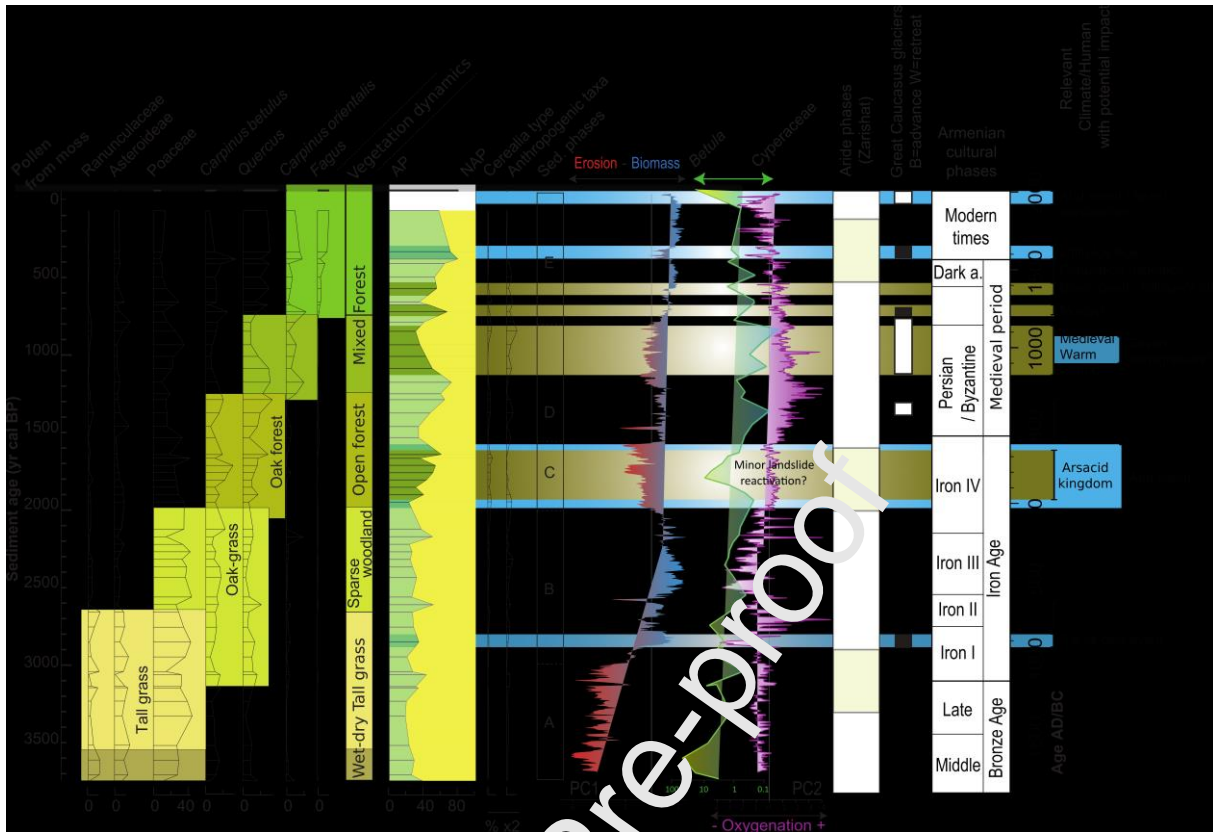


Figure 7):

- First, a tall-grass phase in the Lukse catchment with Caryophyllaceae, then Ranunculaceae, and then with Asteroideae, Poaceae and Monolete ferns. According to Volodicheva (2002), tall grasslands develop on the North-facing slopes with fertile and well-moistened soils. They can be part of primary successions or replace subalpine woodlands in which herbaceous tier is formed by the same species (broad-leaved herbaceous plants such as the Apiaceae *Heracleum* sp. and the Asteroideae *Senecio* sp.). Tall herbaceous plants provide strong below and above the ground competition to woody seedlings, impeding the regeneration of woodlands (Volodicheva, 2002).
- Second, sparse woodland of oak and grass. This finds an echo today in the south-oriented slope of the Gora Dzhantapa, where oaks (*Q. macranthera*) are distributed

as single stands over the grassland. But there, human impact through pastoralism can also provide grazed wooded meadows. Kalavan's pollen assemblage differs from the mosaic vegetation pattern observed in Kasakh valley, where *Q. macranthera* colonised north-oriented slopes as forest and grassland developed on other slopes (Cromartie et al., 2020).

- Third, the development of oak proportion at around 2000 cal. BP suggests a shift from sparse woodland to a more forested catchment, probably of open forest with patches of tree stands. *Carpinus betulus* might benefit from the landscape structure change to be more represented at the lake altitude.
- Fourth, at 1300 cal. BP, is the addition of oriental hornbeam in the pollen assemblage. This taxon regularly mixes with oriental beech to form mixed beech natural forests in Armenia (Figure 2b Vojudicheva, 2002) and in Iran (Sefidi and Mohadjer, 2010). Then, is the beech development in the catchment for about 300 years as *Fagus orientalis* has a low wind-transported pollen potential according to Kvavadze and Stuchlik (2002). This shade-tolerant tree is known for its competitiveness (operating through forest densification).

The question arises whether this vegetation dynamic is unique to the landslide-affected lake catchment or common at the scale of the forest zone in North-East Armenia. On the one hand, the opposition between erosion and vegetation cover, as well as the absence of a clear trend in regional climate records over the last millennia call for a landslide driven dynamic. On the other hand, the long duration of this dynamic is questionable because it is too long for a secondary succession (estimated duration: decennial to secular; Walker et al., 2010; Wardle et al., 2004). This duration is more specific of a "chronosequence", a term that groups known patterns of primary successions which have a longer duration estimated to

millennia (Birks et al., 2016; Chapin et al., 2002; Pickett et al., 2013). Therefore, Kalavan's vegetation dynamic would not fit either into these definitions. One can thus envisage the Kalavan's dynamic to be first initiated by the landslide with the tall-grass development on bare ground, with high erosion, then by the regional tree dynamic. Following this hypothesis, the about 2000 years long phase of tall-grass development could be the strong competitive inhibitor that delays afforestation (Volodicheva, 2002).

### 5.3. Climate and human impact

The Kalavan vegetation can also be affected by climate change and Human activities. Indeed, rapid climatic changes and phases of human impact were imposed on long-term trends in tree vegetation. This is why this can be discussed here (i.e. after the discussion part on forcing factors of the vegetation dynamic).

In mountainous areas, climate change is generally tracked by pollen variation in the dominance of altitudinal zone (extension, regression), while human impact affects forested landscape by openings through pastoralism, burnings or cuttings (e.g. Joannin et al., 2014b in the Alps). In the climate case it is possible to discuss the Kalavan pattern in light of a regional climate scenario established on the Javakheti Plateau. There, a 10 000 yrs long record provides pollen-based climate quantification and water body fluctuations (Joannin et al., 2014a). A comparison of the Great Caucasus glacier's advance and retreat history is also possible but one must be cautious about dates (Solomina, 1999). In the Human case, European history identifies crops (cereal), silviculture (fruit trees), pastoralism (grazing-favoured plants) and wood cutting (buildings). They are uneasy to apply for the Caucasus from where many plants are native (cereals, Behre, 1981; walnut, Woeste and Michler, 2011). However, taking them all together helps to cross-validate expectations issued from archaeology. Down to Kalavan Red Lake, in Barepat river banks, archaeological remains attest to human seasonal then yearly-around presence since the Epipaleolithic (Montoya et al., 2013) and during the Early Bronze Age (Kura-Araxes culture; Liagre et al., 2009), respectively. The Kalavan record starts during the Late Bronze Age when fortresses and demographic centres were all located in Western Armenia and Western Azerbaijan (Greene

and Lindsay, 2012; Hovsepyan, 2015).

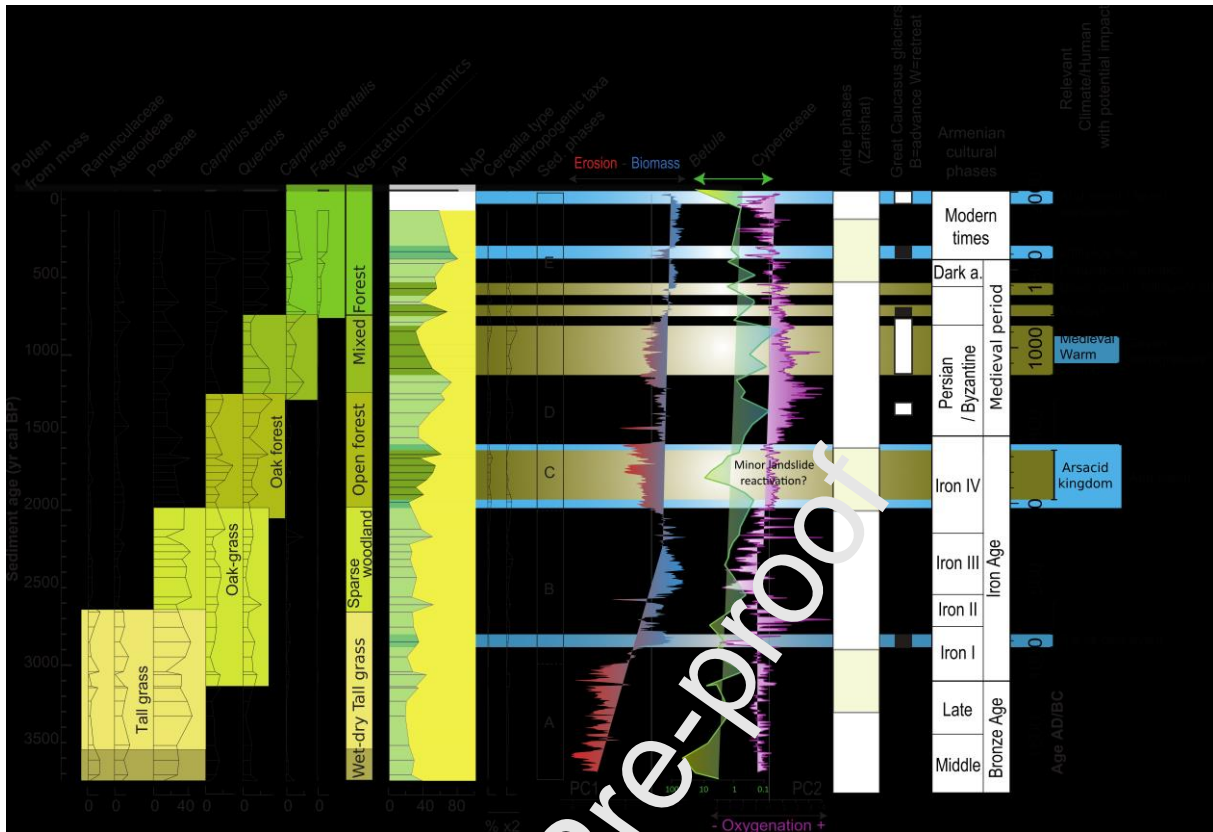


Figure 7 compares Kalavan's catchment history and climate scenario and Human activity.

A strong shift separates high erosion and organic sedimentation at ca. 3000 cal. BP. This shift has no counterpart in the pollen-based vegetation from the catchment. It can be due to less coarse discharge in the lake. It approximately dates the end of the arid phase recorded in the Zarishat and the Vanevan pollen records (Joannin et al., 2014a; Robles et al., 2022) which follows the 2.8 ka cold event defined in Europe (Ivy-Ochs et al., 2009) that also forced glacier advances in the Great Caucasus (Solomina et al., 2015). The Urartu period is usually associated with cereali-culture between 800-650 AD. This population was centered on the north-west of Lake Sevan (Robles et al., 2022; Smith, 2005).

The main event to be seen in the catchment is the return to more erosive activity (PC1) between 2000 and 1600 cal. BP (50-450 AD) and local development of birch on the tributary of the Kalavan Red Lake. AP increase due to *Quercus* development. These proxies, therefore,

contradict since forest development would stabilise erosion in the catchment. This period corresponds in age to the Arsacid period, known from historical resources for laws favouring development of agriculture and preservation of forests.

At the beginning of the Medieval period, a forest drop is recorded in Kalavan's AP percentage. It is contemporary to the Sassanid period (428-651 AD) which population develop agricultural activities.

Upward is a phase between 1150 and 800 cal. BP (800-1150 AD) during which forest regresses a lot (oak mainly) and is replaced by Poaceae meadows and anthropogenic indicators for pastoralism. This is accompanied by a slight increase in erosion proxy (PC1). This period corresponds to the demographic and economic medieval expansion in Europe and Caucasus too during the Medieval Warm Period (MWP). The Medieval Silk Road illustrates this period (Franklin, 2021). At Kalavan, oak selective cutting by the local population may have favoured expansion of Oriental hornbeam, which is for example found as a secondary community after the destruction of oaks in Italy (Blasi et al., 2001). The climate became warmer in Greece and Anatolia (Xoplaki et al., 2016). Volodicheva (2002) reported a possible climate discrepancy with the Great Caucasus glaciers to retreat while Lake Sevan transgressed between the 10<sup>th</sup> and the 12<sup>th</sup> centuries (Solomina, 1999).

According to our pollen diagram and pollen from moss polsters, the Medieval period has been the most impacting Human period over Kalavan's landscape. Forest regresses concomitantly in the Lake Paravani pollen record (Messenger et al., 2013). This period is known for increasing population in highlands organised by Seljuk rulers (Yevadian, 2010). According to the Kalavan age-depth model, from 800 to 450 cal. BP (1150-1550 AD) is a period of Human demise and afforestation in the Kalavan landscape separated by a brief return of wood cuttings (Oak mainly) and pastoralism (and hay-making) between 690 and



600 cal. BP (1260-1400 AD). Despite the  $C^{14}$  uncertainty range, this pattern can settle with a period of unstable politics with the Mongol invasion in the mid-XIII century possibly leading to depopulation. According to Manandyan (1965), the highlands were spared from the destruction, which is contradicted at Kalavan by the afforestation. It is followed by the Black Death in 1349 (Schamiloglu, 2004) and the fall of the Armenian kingdom of Cilicia in 1375 AD when starts the Dark ages of Armenia (decline of society and culture, population migration and transfer during the fifteenth and sixteenth centuries; Kouymjian, 1998). Similarly, the Dark ages are known in Western Europe due to the demographic drop caused by Black Death and famines (e.g. Büntgen et al., 2011) related to the afforestation of the Alps (Joannin et al., 2014b; Tinner et al., 2003). Interestingly, the forest rose to a maximum development at the end of the Dark Ages in Kalavan.

PC1 values show a sharp event from 400 to 300 cal. BP (1550-1650 AD) with more erosion in the catchment. This happens with first a maximum then a massive decline in all major forest elements (beech excepted) but has no counterpart in anthropogenic taxa. A similar forest decreasing trend is also observed on the Javakheti Plateau (Joannin et al., 2014a; Messenger et al., 2013) and correlates with an arid event recorded in Zarishat, despite low temporal resolution in all records. This may therefore illustrate a brief climate event taking place during the Little Ice Age (LIA). In Turkey, cold and dry conditions during the LIA are expected from rock glaciers (Akçar et al., 2007; Hughes, 2014). Dry conditions are revealed in Lake Neor (Iran) through XRF analysis (Sharifi et al., 2015; Sinha et al., 2019). In the Alps, LIA is likely an unstable cold period with agricultural demise and afforestation (e.g. Joannin et al., 2014b).

Despite low pollen resolution, PC1 most recent values (1970-1990 AD) suggest a return to erosive conditions that may have favoured local birch establishment. This change in

sedimentation is contemporaneous with birch seedlings dated by dendrochronology. Birch/Cyperaceae ratio extrapolated from the most recent paleo-sample to pollen from moss peat also suggests the birch development of the delta around this age. The last change is probably both caused by (1) the on-going worldwide climate change identified in the last three decades in meteorological data from Chambarak [and more generally in Armenia (Galstyan et al., 2015) and in the Caucasus (Shahgedanova et al., 2009)] with decreasing annual precipitation and increasing annual temperature, and (2) by the installation of farmers at higher altitude and associated pastoralism and wood exploitation reported in 1976 by the Department of Cartography and Geomorphology of Yerevan.

## 6. Conclusion

Pollen, XRF, dendrochronology and  $C^{14}$  dating studies were applied to the sedimentary archive of Kalavan Red Lake in Armenia. Due to its location within the Lesser Caucasus forest zone, it is the first paleo-record providing a history of this forest.

The first discovery of this study was to better constrain the formation of the lake, due to a massive landslide. The base age of the sediment approaches the age at which this slide occurred, approximately 3000 years ago. The reconstructed vegetation shows vegetation dynamics over time. This begins with a phase dominated by tall grass, gradually colonised by oak, oriental hornbeam and then beech. This succession seems to describe a succession initiated by the landslide exposing the watershed. However, the duration of this succession is challenged by its length. Unfortunately, pollen records from the Lesser Caucasus also fail to identify the dynamics at Kalavan Red Lake as being related to regional tree dynamics. We propose an intermediate hypothesis with a long pioneering phase due to the known competition of tall grasses (Volodicheva, 2002), then a regional tree dynamic, in particular

for the arrival of beech. To be tested it will need additional pollen studies in the forested area of the lesser Caucasus.

Climate and human impacts are discussed in light of the forest management during the Medieval Period and Little Ice Age. Thanks to the interdisciplinary approach, we link Kalavan vegetation history and erosion with regional climate and archaeological data. Antique arid phase (2000-1600 cal. BP), Medieval Warm Period and Little Ice Age affect the vegetation, while demography variations during the Medieval period and Modern Age were illustrated by pastoralism and forestry.

### **Acknowledgment**

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## Author Contributions

Conceptualization, S.J.; methodology, S.J., A.C., B.B., B.M.; software, S.J.; field investigation, S.J., V.O., P.T., O.B.; resources, A.K., writing—original draft preparation, A.C., S.J., V.O.; supervision, S.J.; funding acquisition, C.C., B.P., V.O., O.B., A.M-B. All authors have read and agreed to the published version of the manuscript.

## Captions

Sample ID	Lab. code	Material	AMS 14C (age BP)	Depth Mt (cm)	Cal yr BP (2 $\sigma$ )
A3 19-20	Poz-76959	Plant fibers, seeds	540 $\pm$ 30	1.55	514–628
B4 37-38	Poz-76060	Plant fibers	1630 $\pm$ 35	2.6	1406–1586
B5 55-56	Poz-76961	Birch wood	2460 $\pm$ 30	372.5	2365–2707
B6 33-34*	Poz-76962	Birch roots	2450 $\pm$ 30	422.5	2361–2703
B7 54-56	Poz-52962	Plant fibers	1450 $\pm$ 35	506.5	3589–3831

\* Age rejected (see text)

Table 1. AMS-radiocarbon dates with 2 $\sigma$  range of calibration from cores of Kalavan Red Lake.

MC=master core.

Fe	Mineralisation (mg/l)	Sample (g)	Total Fe (g/kg DW)
Lake 2	1751.00	0.1022	428.33
Lake 3	1744.00	0.1032	422.48
Creek	351.40	0.1018	86.30
B1 15-16 cm	224.50	0.1007	55.73
B3 44-45 cm	153.70	0.1034	37.16
B4 53-54 cm	60.15	0.1021	14.73
A6 6-7 cm	167.00	0.1024	40.77
B7 49-50 cm	167.60	0.1016	41.24

White	Undef.
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Table 2. Fe measurements in lake shore and main tributary, and lake sediment (graphic representation in Figure 4).

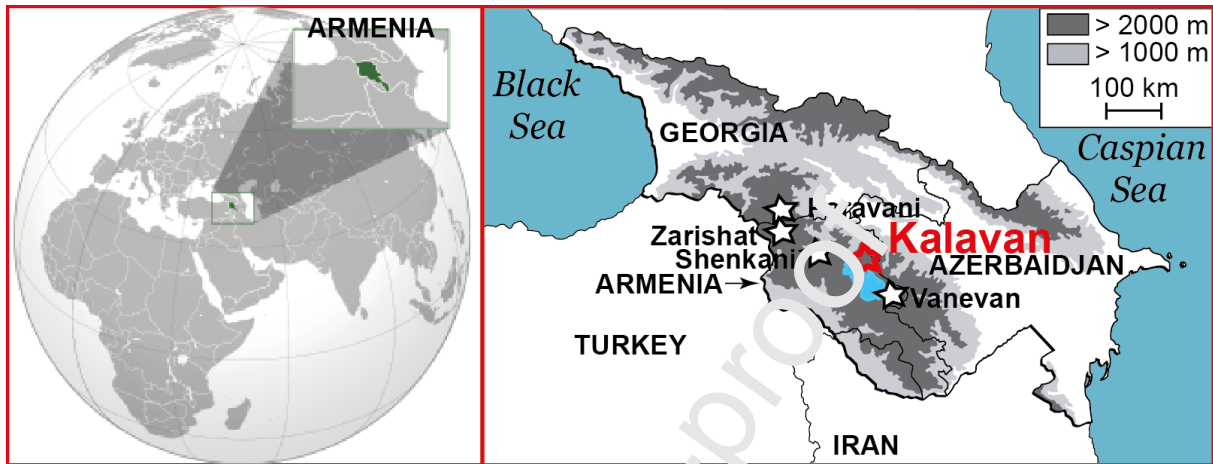


Figure 1. Location map of Caucasus and sites cited in the text.

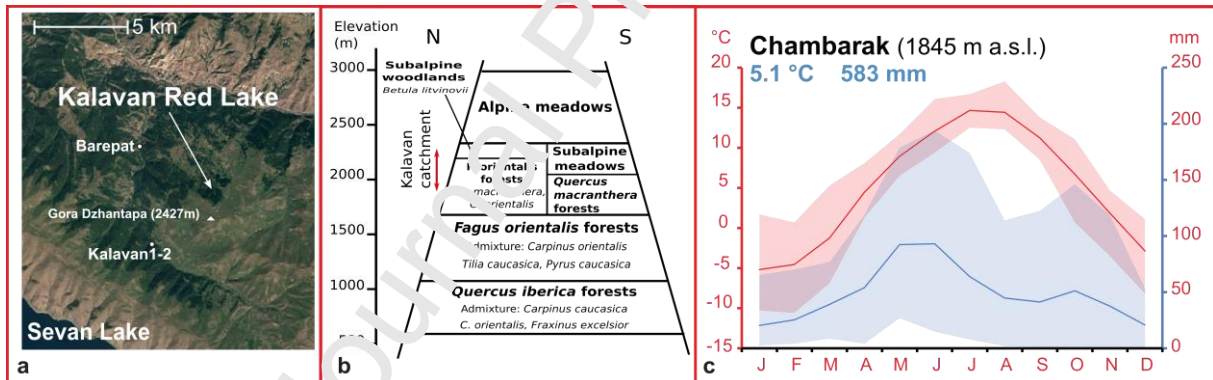


Figure 2. a) location map of Kalavan Site with archaeological sites ; b) Altitudinal sequences of climax vegetation in Central Transcaucasia modified from Volodicheva (2002); c) Ombrothermic diagram of the meteorological station of Chambarak, ca. 18km from Kalavan Red Lake. The temperature and precipitation records span 74 and 67 years, respectively.

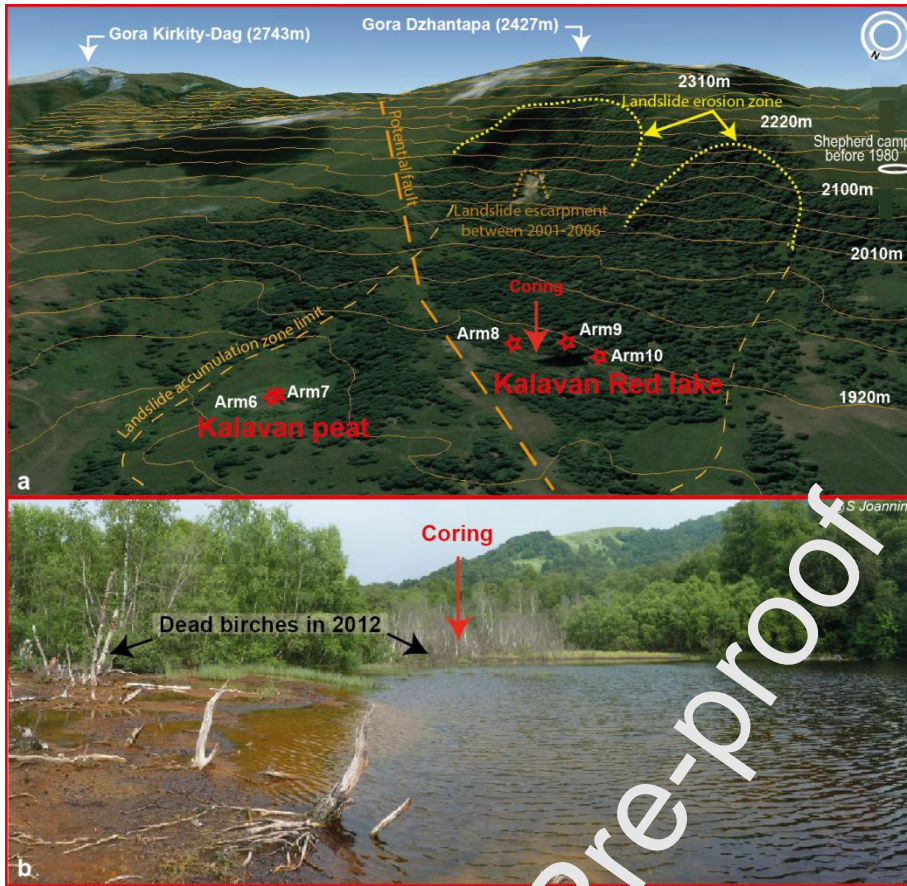


Figure 3. a) Mountain view with location of Kalavan Red Lake, Kalavan Peat and pollen from moss polsters, and elevation indicators, b) photo taken from the north side (lake outlet) showing the coring site under a dead birch stand at the creek mouth.

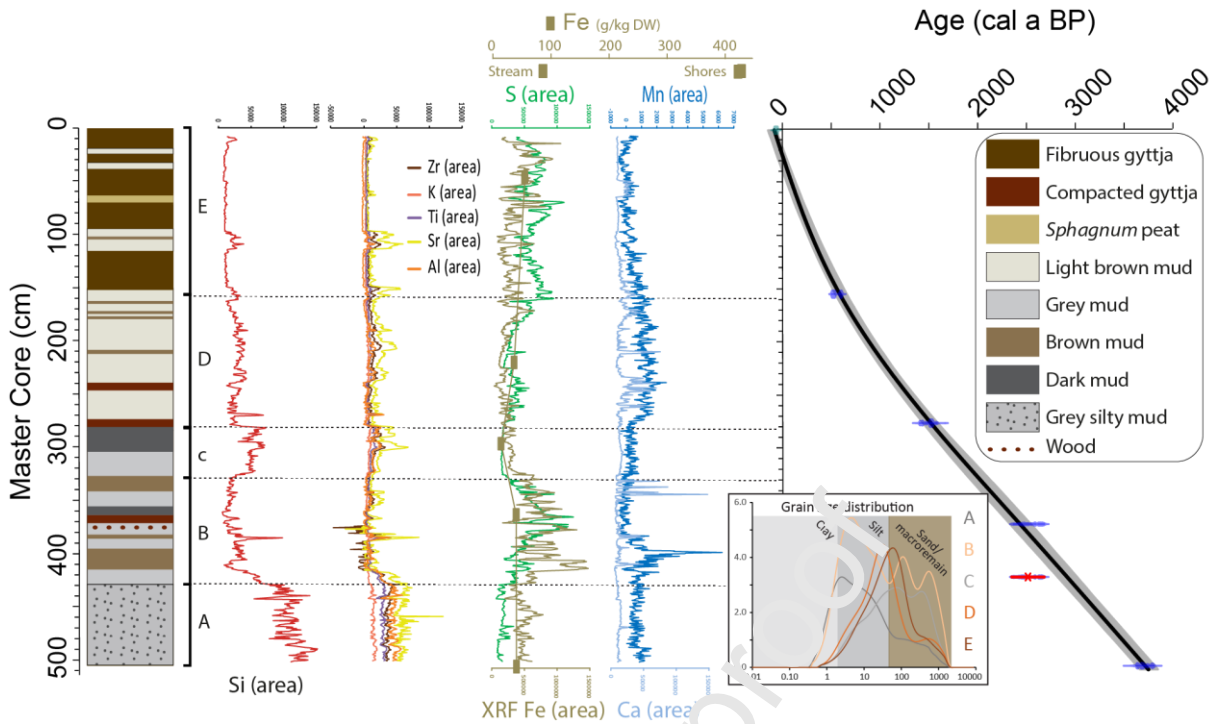


Figure 4. Lithology of Kalavan cores numbered as units (A to E); XRF Core scanner measurements of main antagonist elements (see text); Fe measurements in lake shores and main creek, and lake sediment (see Table 2); Age–depth model based on calibrated radiocarbon ages (with  $2\sigma$  errors) (A to E, see Table 1); Grain size distribution of sedimentary units.

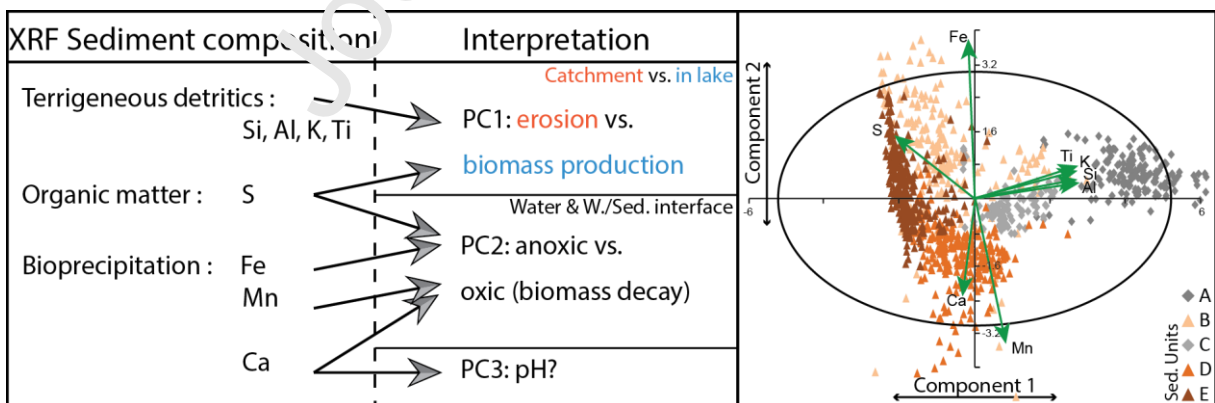


Figure 5. From left to right: sediment chemistry inferred from XRF measurements, sourcing and deposit processes, variables factor map of XRF main elements according to Principal Component Analyse (PCA).

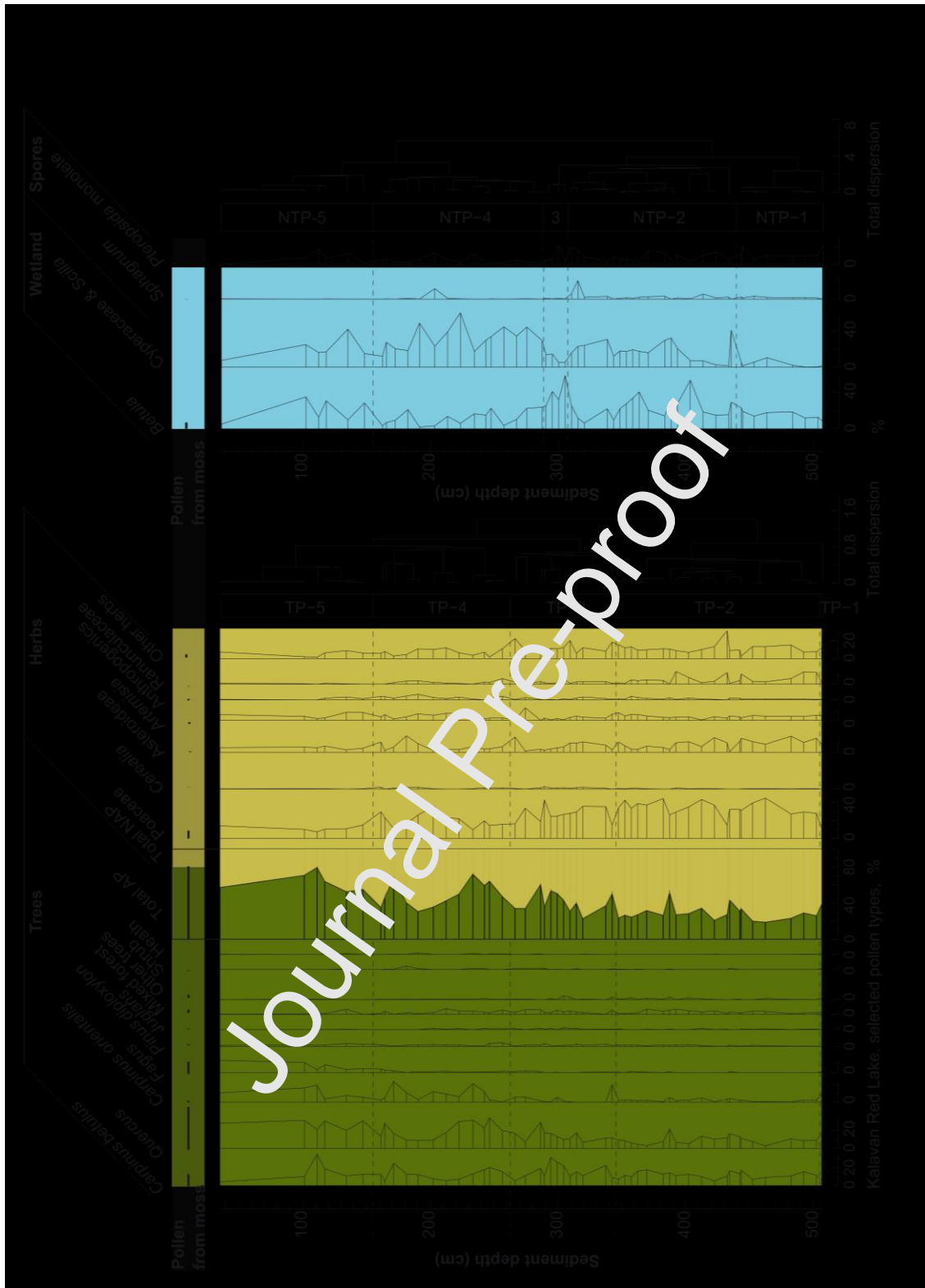


Figure 6. Pollen diagram against depth showing percentages of main pollen and non-pollen taxa. Terrestrial Pollen (TP) zones are based on CONISS. Same for Non Terrestrial Pollen grains (NTP).



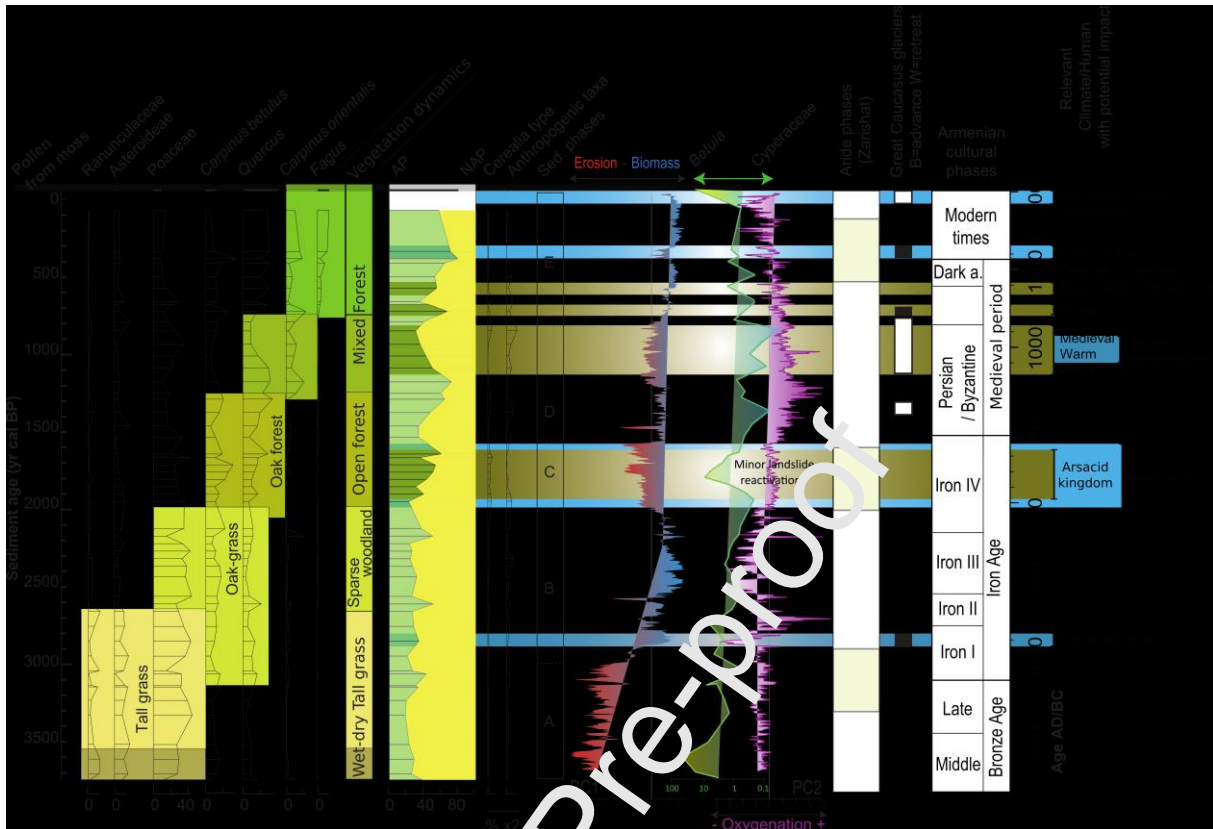


Figure 7. Plotted against age: taxa and vegetation dynamics, forest vs non forested and human-related taxa, sedimentary phases and Principal Components (PC) 1 and 2, *Betula/Cyperaceae* ratio (In representation) from Kalavan record. They are compared to arid phases known for Armenia (Gochinin et al., 2014), Great Caucasus glacier history (Solomina, 1999) and Armenian cultural phases (adapted from Smith et al., 2009). On the right is an attempt to correlate dominant forcing from climate (blue) and Human (brown) to known relevant events in the region.

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**Declaration of interests**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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**Running Head:** Late Holocene forest reconstruction in Caucasus

- The Kalavan red lake is a unique palaeorecord of the forest in the Lesser Caucasus
- The Kalavan red lake was formed 4000 yrs ago thanks to a massive landslide
- Therefore, vegetation dynamics is questionable: is it controlled by regional dynamics or initiated by the opening created by the landslide?
- Climate and human impacts are discussed in light of the forest management during Medieval Period and Little Ice Age.

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