Contributions: The manuscript was written by Nore Praet. The seismic data were collected by Michael Strupler, Jasper Moernaut, Adrian Bender and Peter Haeussler. The multibeam survey was conducted by Nore Praet, Elke Vandekerkhove, Thomas Vandorpe, Peter Haeussler, Robert Witter, Maarten Van Daele and Koen De Rycker. The coring campaign was carried out by Nore Praet, Philipp Kempf, Maarten Van Daele, Richard Johnson and Koen De Rycker. The statistical analysis was done by Nore Praet and Tim Collart. The study was outlined and the results were discussed by Nore Praet, Tim Collart, Maarten Van Daele, Jasper Moernaut and Marc De Batist.

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4.1 Introduction

Proglacial lacustrine sediment sequences are valuable **natural archives** because their annual laminations, or **varves**, allow not only paleoclimate and paleoenvironmental reconstructions to be made (e.g. Kaufman, 2009; Boes et al., 2018), but also provide a high-resolution age framework for these reconstructions (e.g. Ojala et al., 2012; Zolitschka et al., 2015).

The often varved sediment sequences in glacier-fed lakes may be interrupted by flood-generated turbidites, which result from heavy precipitation, rapid meltwater runoff, or glacial lake outburst **floods** (Gilbert et al., 1997; Boes et al., 2018). Upon entering the lake, sediment-laden stream waters can evolve into interflows that transport suspended sediment across the lake, and underflows that deposit a turbidite (Sturm and Matter, 1978; Gilli et al., 2013; Wilhelm et al., 2015; Vandekerkhove et al., 2020). Such turbidite records have been used to construct flood records throughout Europe (Nesje et al., 2001; Gilli et al., 2003; Arnaud et al., 2005; Vasskog et al., 2011; Wilhelm et al., 2013; Wirth et al., 2013; Wilhelm et al., 2016b; Sabatier et al., 2017) and North America (Noren et al., 2002; Mazzucchi et al., 2003; Osleger et al., 2009; Parris et al., 2010). In seismically active settings, lacustrine turbidites may also be produced as a consequence of **seismic shaking**. As such, turbidite records are also useful for paleoseismological reconstructions (e.g. Moernaut et al., 2014; Van Daele et al., 2015; Howarth et al., 2016; Wilhelm et al., 2016a).

Proglacial lakes are thus unique settings that are capable of offering both **paleoflood and paleoearthquake histories**. A critical step in building these lake sedimentary records is the distinction of turbidites from the background sedimentation and, more importantly, deciphering the triggering mechanisms. The sediment's organic-geochemical (e.g. Osleger et al., 2009; Simonneau et al., 2013; Howarth et al., 2014; Howarth et al., 2016; Hage et al., 2017) or elemental signatures (Petersen et al., 2014; Avşar et al., 2015; Kremer et al., 2015; Wilhelm et al., 2016b; Sabatier et al., 2017) are commonly used in temperate regions to discriminate between earthquake-generated and flood-generated turbidites, but are not diagnostic in proglacial lakes with (clastic) glacio-lacustrine sedimentation (Vandekerkhove et al., 2020). Instead, grain-size parameters (especially of the basal part of the turbidites) and spatial

thickness distribution are better suited for distinguishing earthquake-generated from flood-generated turbidites in proglacial lakes, which are dominated by clastic sedimentation (Beck, 2009; Wilhelm et al., 2012; Wilhelm et al., 2017; Van Daele et al., 2019; Vandekerkhove et al., 2020).

The causal relationship between flow characteristics and textural evolution makes grain-size variables effective proxies to infer **turbidite origins** (e.g. Passega, 1964; Beck, 2009; Wilhelm et al., 2013; Sabatier et al., 2017; Vandekerkhove et al., 2020). Floods typically induce turbidity currents that are generated by gradual flow evolution and moderate peak energy, while earthquake-triggered hemipelagic and tributary slope failures produce flows with fast flow evolution and high peak energy. Consequently, a coarser, poorly sorted base often characterizes earthquake turbidites. Proxies reflecting the spatial turbidite distribution are also significant in distinguishing between triggering mechanisms (Vandekerkhove et al., 2020). The strong thermal stratification in summer allows the creation of interflows in addition to underflows. Interflows allow even distribution of the suspended sediments over the entire basin. As a result, flood turbidites show a uniform distribution across the lake basin. In contrast, earthquake turbidites typically pond in the deepest parts (Beck, 2009; Wilhelm et al., 2013; Van Daele et al., 2019; Vandekerkhove et al., 2020). Furthermore, the prolonged exposure to light and oxygen of organic matter in hemipelagic slope sediments, before entrainment in earthquake-induced turbidites, can cause a higher degree of pigment degradation compared to flood-induced turbidites. The initial higher amount of organic matter and the better preservation of its pigments in flood turbidites is then reflected by a browner color (Vandekerkhove et al., 2020). Consequently, visible-range scanning reflectance spectroscopic proxies are also useful for discriminating between turbidite origins.

Despite the presence of numerous **proglacial lakes in Alaska**, these lakes have rarely been investigated for paleoflood or paleoseismological purposes. Vandekerkhove et al. (2020) performed an earthquake-versus-flood fingerprinting study in Eklutna Lake, a proglacial lake in south-central Alaska, which lays the groundwork for the work presented here. The study focused on the multi-proxy analysis of three historical turbidites that could be attributed to known historical events (i.e. one earthquake in AD 1964 and two floods in AD 1989 and AD 1995) based on the concurrence of their varve ages with the years in which these events took place. The present study applied the findings of Vandekerkhove et al. (2020) to the study of much longer (i.e. prehistoric, *ca* 2250 year long) turbidite records that were retrieved in five long sediment cores from Eklutna Lake (**Fig. 4.1 and 4.2**). A novel method was developed to objectively identify turbidites within the varved sediment sequence by performing a statistical outlier analysis based on varve-thickness distributions. This is especially relevant for those core sections for which chronological concurrence with documented events is not possible. While Vandekerkhove et al. (2020) conducted a multi-proxy analysis on 25 short cores to characterize three turbidites, collecting and analyzing a similar amount of proxy data on long prehistoric sedimentary records is simply not feasible. In order to study the large multivariate

and multi-core dataset, the present work developed an approach that makes use of a principal component analysis (PCA) and k-means clustering. Finally, the triggering mechanisms were ascertained by calibration with the properties of the historical events described in Vandekerkhove et al. (2020). This study demonstrates that a statistical approach allows for an efficient and objective assessment of triggering mechanisms in Eklutna Lake and, by extension, proglacial lakes worldwide.

4.2 Setting

4.2.1 Study area

Eklutna Lake is a proglacial lake, located 45 km north-east of Anchorage, Alaska, on the north-west side of the Chugach Mountains (**Fig. 4.1A to 4.1C**). The lake has an elongated shape with an average width of 1.4 km and a length of 10.5 km. Repeated glaciations scoured two sub-basins, which are naturally dammed by a Pleistocene terminal moraine at the north-western end (Karlstrom, 1964; Reger et al., 2007). The deep [58 m when lake level is 258 m above sea level (a.s.l.)] proximal south-eastern sub-basin is bounded by moderately steep underwater slopes (10 to 18°), which are covered by a thin sedimentary drape. The smaller and shallower (50 m when lake level is 258 m a.s.l.) distal north-western sub-basin shows north-westward-decreasing slope angles ranging between 15° and 5° (Chapter 3) (**Fig. 4.1D**).

The **catchment area** of Eklutna Lake (311 km², **Fig. 4.1B**) consists of two sub-catchments, i.e. the East Fork and the West Fork Eklutna Creeks, flowing through mountains with structurally complex, dominantly low-metamorphic grade sedimentary and minor igneous rock (Winkler, 1992). Sediment deposition at the mouths of these tributaries created a single delta complex at the inlet at the south-eastern end of the lake. Minor tributaries bring additional sediment from the surrounding mountains into the lake and form several alluvial fans along the shores (Brabets, 1993).

The primary water source for the lake is the 12 km long **Eklutna Glacier**, which occupies almost half of the West Fork basin (Larquier, 2010). The retreating glacier terminus lies now 8.5 km upstream of the lake's main inlet.

The lake outflow is regulated since the construction of a **dam**, which converted the lake into a hydroelectric reservoir in AD 1929. As a result, lake level fluctuates seasonally (ca 11 m), typically reaching a maximum elevation at the end of summer and a minimum in the spring (Brabets, 1993; Loso et al., 2017). When lake level is at the spillway elevation (265 m a.s.l.), the lake reaches its maximum depth.

Located along the **Alaska-Aleutian subduction zone**, the region surrounding Eklutna Lake experiences megathrust, intraslab and crustal earthquakes. The most recent megathrust

earthquake occurred on 27 March 1964. This M_w 9.2 Great Alaska Earthquake ruptured an 800 km long segment of the megathrust (**Fig. 4.1A**), extending from Prince William Sound (PWS) to Kodiak Island (Plafker, 1969).

Figure 4.1: (A) Tectonic setting of south-central Alaska with the location of Anchorage, Cook Inlet, the AD 1964 earthquake epicenter (yellow star) and rupture zone (in red, e.g. Plafker, 1965; Freymueller et al., 2008) with respect to the Alaska–Aleutian megathrust (green line). The region of Eklutna Lake—red rectangle in inset (B)—is situated near the Castle Mountain fault (CMF) (Haeussler et al., 2002). (B) Catchment of Eklutna Lake in the Chugach Mountains with indication of the Eklutna Glacier. Background: ASTER Global Digital Elevation Model (LP DAAC, 2009; <https://lpdaac.usgs.gov>). (C) Multibeam bathymetry of Eklutna Lake with indication of a seismic profile (grey line), core locations (2, 3, 4, 20, and 21), main river inflows and outflows and the dam infrastructure, superimposed on a combination of an ASTER Global Digital Elevation Model (Hill Shade view) (LP DAAC, 2009; <https://lpdaac.usgs.gov>) of the lake’s region and lidar (DGGS elevation portal, 2018; <https://elevation.alaska.gov>). The measured depths in the bathymetry maps represent the depth values from 14 July through 17 July 2016 when the lake reached an elevation of 258 m. Seismic-reflection profiles in the distal (D) and proximal (E) sub-basin of Eklutna Lake with indication of piston core locations and depth. The indicated landslide deposit in the proximal basin is visible in core location 21 and represents event Ek-3 (Chapter 3).

It is the only well-documented historical megathrust earthquake for the PWS region. Coastal paleoseismic records date the penultimate megathrust earthquake along this segment as AD 1020 to 1150 and propose a mean recurrence rate for such megathrust earthquakes of *ca* 550 yrs (Combellick, 1993; Carver and Plafker, 2008; Shennan et al., 2014). Other potential earthquakes affecting the study area are shallow, upper-plate (or crustal) earthquakes, originating from the Castle Mountain fault (**Fig. 4.1A**) (*ca* 30 km N of Eklutna Lake; Haeussler et al., 2002) or intermediate-depth earthquakes within the subducting plate. These intraslab earthquakes commonly occur in the region (**Fig. 4.1A**). The most recent of such events was the M_w 7.1 Anchorage Earthquake on 30 November 2018.

4.2.2 Annual sedimentation

Seasonal variations in lake stratification and river discharge build the typical **glacial varve architecture** in Eklutna Lake (Boes et al., 2018). After glacial melt initiation in spring, clastic sediments enter the cold lake water producing a small overflow plume (Brabets, 1993). At the end of summer, heavy rain events (Johnson, 1947) and maximal glacier melt cause peak discharge pulses. High amounts of coarse sediments flush into the lake, which result in the formation of **underflows**. When thermal stratification is strong, the finer-grained suspended material may evolve into interflows. These processes in spring and summer distribute sediments throughout the lake basin and deposit a dark-colored coarse sediment layer. In winter, the lake surface consistently freezes and discharge is minimal, allowing the deposition of suspended clay particles (Brabets, 1993), forming a light-colored clay cap. Modern sedimentation rates in Eklutna Lake decrease from the south-eastern delta towards the north-western distal basin, with sedimentation rates ranging from *ca* 1.0 to 0.2 cm yr⁻¹, respectively. Boes et al. (2018) observed increased varve thicknesses during the nineteenth century (33 to 62% higher than after the nineteenth century), which was attributed to increased sediment input as a result of **glacier expansions** during the second advance phase of the Little Ice Age (LIA). The combination of expanding and eroding ice masses and the proximity of the glacier's terminus to the lake promoted an increase in sediment discharge into the lake. Fortin et al. (2019) extended the chronology of Boes et al. (2018) and constructed a continuous *ca* 2250 year varve chronology, corroborated by the identification of four tephra beds, which serve as marker layers that are traceable across coring sites.

4.2.3 Event sedimentation

The varved steady-state background sediment is occasionally interrupted by **event deposits**, such as tephra beds, mass-transport deposits and turbidites. The historical turbidites are characterized by their homogeneous appearance and by a locally erosive base that is enriched in coarse clastic material, overlain by a fining-upward sequence and concomitantly upward-decreasing magnetic susceptibility (MS) values (Boes et al., 2018; Vandekerckhove et al., 2020). Most of these turbidites were attributed to **flood events** (Boes et al., 2018). Periods of heavy

precipitation or rapid snowmelt can produce sediment-loaded streams that may evolve into underflows when entering the lake. The resulting intravarve turbidites lead to the formation of thick **multipulsed varves**, especially in the proximal basin. Apart from these high-energy flood events, **seismic shaking** during the AD 1964 megathrust earthquake triggered synchronous landsliding across the lake basin (Chapter 3) and deposited a turbidite in the deepest part of the basin, which is characterized by a coarse erosive base. More recently, the AD 2018 intraslab earthquake triggered delta failures across the basin, which resulted in the deposition of a basin-wide turbidite (Van Daele et al., 2020). Finally, the construction of the dam infrastructure in AD 1929 caused a modification in the lake's hydrology, which resulted in a shift towards darker and less pronounced varves in the last century (Boes et al., 2018). Furthermore, **dam failure** in that same year also left a distinct homogenous turbidite in the sedimentary record (Boes et al., 2018; Vandekerckhove et al., 2020).

Figure 4.2: Examples of earthquake-generated and flood-generated turbidites in Eklutna Lake. A selection of prehistoric turbidites, which are caused by flooding or earthquake shaking, are displayed. The AD 1964 earthquake and AD 1995/1989 flood turbidites represent historical examples and are shown for comparison. See Fig. 4.4 for the location of the turbidites within the stratigraphy.

4.3 Methods

4.3.1 Multibeam bathymetry

In the summer of 2015, **bathymetric data** were acquired using a pole-mounted ELAC SeaBeam 1050 multibeam sonar (ELAC Nautik GmbH) on the USGS research vessel *Lutris II*. This sonar consists of two 50 kHz transducer arrays, operated with a 120° combined swath angle. Sound velocity profiles of the water column were measured multiple times a day with a CastAway® CTD (depths up to 100 m; SonTek) and a CTD 48M (Sea & Sun Technology GmbH). The bathymetric data processing included outlier cleaning with HDPedit (ELAC Nautik GmbH) and incorporating the sound velocity profiles using HDPpost (ELAC Nautik GmbH). Visualization in the IVS 3D Fledermaus™ software (QPS BV) enabled detailed bathymetric data editing. The final high-resolution bathymetry map has a 4 m grid spacing and a vertical accuracy of a few decimeters. Because the **lake level** seasonally fluctuates with maximum lake level at the end of summer and a minimum lake level around spring (Brabets, 1993; Loso et al., 2017), the measured depths in the bathymetry maps are in reference to the lake level elevation of 258 m a.s.l. during acquisition.

4.3.2 Sediment cores

In the winter of 2014, five long piston and short gravity **cores** were collected from five coring sites (**Fig. 4.1C**) using a UWITEC coring platform (Uwitec Sampling Equipment) operated from the frozen lake surface. The long piston-core sequence in each site was acquired in overlapping 3 m long cores from two holes, located about 0.5 m apart. Each 3 m long core was divided in two *ca* 1.5 m long sections for further processing. **Three-dimensional imaging** of all sediment cores was performed using a Siemens SOMATOM Definition Flash X-ray computed tomography (CT) scanner at the Ghent University Hospital. The CT scanner was operated using a voltage of 120 kV, an effective tube current time product of 200 mAs and a 0.45 pitch. The reconstruction of each core into a DICOM (Digital Imaging and Communications in Medicine) image stack obtained a down-core resolution of 0.6 mm and cross-core resolution of 0.16 mm. After import of the DICOM images, the VGStudio 2.2 software (Volume Graphics GmbH) was used to image the digital core volume. The contrast in the exported two-dimensional CT images is a function of density and effective atomic number of the sediment (Cnudde et al., 2006). After CT scanning, the split core surfaces were cleaned, described and imaged with a linescan camera on a Geotek **multi-sensor core logger** (MSCL) (Geotek Limited). Magnetic susceptibility values (Bartington MS2E point sensor) and spectrophotometric properties (Konica Minolta CM-2600d) were measured every 2 mm with the MSCL. Cross-correlating overlapping core segments yielded a continuous composite core for each core site. The resulting composite cores in sites 2, 3, 4, 20, and 21 have lengths of 15.3 m, 15.1 m, 16.6 m, 8.5 m, and 8.4 m, respectively.

4.3.3 Outlier study

Differentiation between a thick varve and a thin turbidite is dubious in proglacial lakes as these turbidites are texturally and compositionally similar to clastic varves, i.e., they are both composed of a coarser base that gradually transitions into a fine-grained top. In order to identify varves that potentially include a turbidite, an **outlier study** was performed (Fig. 4.3) on varve thickness records from Fortin et al. (2019).

Figure 4.3: Methodology flow chart explaining the construction of an earthquake record from proglacial varved sediments.

1. Outlier analysis on varve thickness records based on Fortin et al. (2019) detects outliers by fitting the varve thickness data within quantile limits 0.95 and 0.75 to a lognormal model distribution (blue line). Outliers (in yellow) are displayed on a Quantile–Quantile (QQ) plot in which predicted versus observed probability functions are compared by plotting their quantiles against one another (van der Loo, 2010b).
2. Cross-correlation of the (outlier) turbidites in each core location defines lake-wide event deposits that are caused by past earthquakes or floods in the lake's history.
3. The distinction between earthquake-generated and flood-generated turbidites is based on a combination of principal component analysis (PCA) and k-means clustering. The multivariate dataset consists of a selection of measured variables for each turbidite based on the study of Vandekerkhove et al. (2020).

The preferred approach herein was to use the varve thickness as a proxy instead of grain size, because continuous grain-size sampling is intensely time consuming for *ca* 15 m long sediment cores. Furthermore, the varve thickness was already measured for the construction of the varve chronology. The current working hypothesis is that a varve containing an extra turbidite (or a slump deposit) would be characterized by an **anomalous varve thickness**—an outlier—in comparison with the steady-state or background bulk varve thickness distribution. Fortin et al. (2019) measured varve thicknesses on a two-dimensional cross-section of the CT scan, in the middle of the split core to minimize the effect of core deformation caused by the piston coring system. Here, this dataset was revised by using a combination of CT and linescan images and then fine-tuning the position of some varve boundaries. This revised varve thickness dataset was used for every coring site.

In order to avoid the effects of human-induced lake level change and associated sedimentary processes, the outlier study only incorporates varves below the turbidite caused by the AD 1929 dam collapse (Boes et al., 2018) and extends down core from there. Although historical turbidites, for example AD 1995, 1989 and 1964 turbidites (Vandekerckhove et al., 2020), were not used for the outlier study, they were later incorporated in order to compare the outcome of the study with historical counterparts.

Core sections affected by strong deformation, as well as individually strongly deformed layers were also excluded from the dataset in order to avoid bias. In location 2, the dataset ends at a depth of *ca* 12 m because varves become indistinguishable and deformation increases. As such, the zone below *ca* 12 m was not incorporated in the outlier analysis. However, layers in this zone that are thicker than the minimum outlier thickness determined by the outlier analysis in location 2 (from 0 to 12 m) were also regarded as outliers.

In order to objectively identify the outliers in varve thickness, the dataset was analyzed with the “outlier detection method I”, described in van der Loo (2010b) and implemented in the “extremevalues” R-package (Appendix 9.7 and available on GitHub; Collart and Praet, 2020) (van der Loo, 2010a). First, a lognormal distribution model was fitted to the data falling below the 0.95 or 0.75 quantile (**Fig. 4.3**). An outlier varve was then defined as having a thickness value within the tail of the distribution where, according to the fitted model, less than one observation is expected to occur given the original number of data points. Hence, a varve is identified as an outlier when its thickness is larger than what can be expected based on 95% or 75% of the data, respectively. Outliers determined with a quantile range of 0.95 and 0.75 will be further referred to as **0.95 outliers** and **0.75 outliers**, respectively. In order to account for errors in thickness due to coring artefacts and measurement inaccuracies, the threshold thickness value derived from the outlier analysis was lowered by 1 mm. Important to note is that every outlier varve holds a turbidite (or slump deposit), but not every turbidite is identified as an outlier.

4.3.4 Event stratigraphy

This procedure resulted in identifying “outlier” turbidites in each core location that are considered to represent an earthquake or flood event in the lake’s history (**Fig. 4.3**). In order to turn this site-specific turbidite record into a lake-wide event stratigraphy, an initial **core-to-core correlation** was established using the physical appearance of the sedimentary sequences and their magnetic susceptibility (MS) peaks. Four tephra beds (see Tephra 5, 7, 10 and 12; Fortin et al., 2019) across different core locations independently corroborate this correlation. Subsequent correlation of each outlier turbidite was performed in detail with linescan images and CT scans. The overall north-westward thinning trend corresponds with the seismic stratigraphy (Chapter 3).

4.3.5 Earthquake versus flood deposits

The methodology developed here builds on the findings of Vandekerkhove et al. (2020), i.e., that turbidity currents caused by earthquakes or floods differ in their flow evolution and result in turbidites with distinctly different characteristics. Here, a **multivariate dataset** of grain-size, thickness, spatial, MS and spectral variables (Appendix 9.8 and available on GitHub; Collart and Praet, 2020) of each event measured throughout multiple cores was constructed to investigate whether different triggering mechanisms can be inferred from these properties throughout the prehistoric record. **Principal component analysis** (PCA) was used to visualize the multivariate dataset and investigate which variables are diagnostic for the discrimination between earthquake-generated and flood-generated turbidites: **k-means clustering** ($k = 2$) was used to objectively distinguish between two different turbidite types based on similarities in event properties (**Fig. 4.3**). The classification of historical turbidites (Vandekerkhove et al., 2020) was used to assign a trigger mechanism to each cluster.

4.3.5.1 Dataset

The **grain-size distribution** of the turbidite base (lowest 3 mm of the turbidite) was determined with a Malvern Mastersizer 3000 (Malvern Panalytical) equipped with a Hydro MV Module, allowing small sample sizes. Pretreatment of the sample (in 10 ml deionized water) included boiling with H_2O_2 (2 ml, 35%) to remove organic material and to isolate the terrigenous fraction [procedure adapted from Vandekerkhove et al. (2020)]. Grain flocculation was avoided by shortly boiling the sample in sodium hexametaphosphate (Calgon®). A measuring time of 12 s with 10% sonification was applied in order to assess the particle-size distribution. The Malvern software provided a range of mass division diameter (D)-values (D10, D50, D80, D90, and D99). Afterwards, mean and sorting were calculated with particle analysis software (GRADISTAT) (Blott and Pye, 2001). The relative basal D80 (RB-D80) was also determined, which is the ratio of D80 to turbidite thickness and was described by

Vandekerkhove et al. (2020) as an approximation for the ratio of the maximum turbidity current energy to the amount of mobilized material.

Turbidite thicknesses were measured by visual inspection excluding the varve base (or top if applicable). **Spatial trends** of thickness, D80, D10, and basal sorting were calculated for all event deposits that are present in more than one location. For event deposits that are present in all locations, the standard deviation between sites 2, 3, 4 and 2, 3, 4, 20, 21 was determined. Minimum, maximum and mean **MS-values** were computed from turbidite base to top. The (normalized) Relative Absorption Band Area between wavelengths 400 nm and 560 nm, (n)RABA₄₀₀₋₅₆₀, was calculated with the **spectral reflectance** data obtained from the core logging (Vandekerkhove et al., 2020; and references therein). This proxy can be linked to a combination of total organic carbon (TOC), type of organic material and/or pigment degradation (Vandekerkhove et al., 2020). For each turbidite a minimum, maximum and mean (n)RABA₄₀₀₋₅₆₀ was calculated. Because the water content and preservation of sediments typically change with depth, a down-core trend for the MS and (n)RABA₄₀₀₋₅₆₀ values can be expected. Therefore, a linear and lognormal distribution is fitted to the MS and (n)RABA₄₀₀₋₅₆₀ curve in order to detrend the data using the fit-curve with the higher correlation coefficient.

4.3.5.2 Statistics

The aim was to define two “populations” of flow-specific characteristics (i.e. earthquake and flood turbidites) (Appendix 9.9 and available on GitHub; Collart and Praet, 2020). The variables were normalized in order to stabilize the variance and limit the bias introduced by the different magnitudes of the variables with larger scales. As most variables are not symmetrically distributed, but lognormal, normalization would bias the data. Therefore, the authors first visually checked for normality and log transformed in case of a skewed distribution.

The **PCA algorithm** was implemented in the R “stats” package (RCoreTeam, 2018) and the results were visualized using the “factoextra” package (Kassambara and Mundt, 2017). For the **k-means clustering**, the algorithm by Hartigan and Wong (1979) was used, also implemented in the R “stats” package (RCoreTeam, 2018). The parameter k was set to 2 in order to distinguish between either earthquake-generated or flood-generated turbidites. In order to minimize noise and prevent bias by the difference in magnitude of the variables, the clustering algorithm was performed on the PCA scores of the observations.

4.3.5.3 Subsets

The presence of **missing values** in a dataset compiled by core data is inevitable, for example, the maximum age of each composite core is usually different. Because the PCA cannot deal with this reality of missing values, the complete dataset was divided into different selections

(Appendix 9.10), from youngest to oldest: selection 1 (all locations), selection 2 (locations 2, 3 and 4) and selection 3 (only location 2).

Some events within selections 1 and 2 contain missing values due to instrumental errors. In order to study these events, **subsets** were created that retain as much information as possible for these particular events. In every subset, the historical events of AD 1995, 1989 and 1964 were also incorporated.

Selection 1: All locations (events E1 to E36)

- Subset 1A has no missing values and comprises 28 events. Nine events within this range have missing values and therefore they were analyzed in other subsets (1B, 1C, 1D, 1E, and 1F).
- Subset 1B (MS and (n)RABA₄₀₀₋₅₆₀ of location 2 excluded): E7-1, E28, E32-1, E35, and Subset 1A.
- Subset 1C (MS and (n)RABA₄₀₀₋₅₆₀ of location 3 excluded): E6-3, E33, and Subset 1A.
- Subset 1D (MS and (n)RABA₄₀₀₋₅₆₀ of location 2 and 3 excluded): E6-2 and Subset 1A.
- Subset 1E (all variables of location 2 excluded): E32-2 and Subset 1A.
- Subset 1F (MS and (n)RABA₄₀₀₋₅₆₀ of location 2 and all variables of location 21 excluded): E36 and Subset 1A.

Selection 2: Locations 2, 3 and 4 (events E37 to E73)

- Subset 2A has no missing values and consists of 28 events. Ten events with missing values were analyzed in subsets 2B and 2C.
- Subset 2B (MS and (n)RABA₄₀₀₋₅₆₀ of location 2 excluded): E37, E38, E44, E49-2, E50, and Subset 2A.
- Subset 2C (all variables of location 4 excluded): E68, E69, E70, E71, E73, and Subset 2A.

Selection 3: Location 2 (events E74-1 until E94)

- Subset 3 comprises 19 events; spatial variables were not included, as these events are only present in location 2.

Clustering is only meaningful for subsets 1A, 2A and 3, as they hold the most variables. Because the analysis of subset 1A is based on a complete dataset, the PCA and clustering analysis is the most significant and allowed for detailed interpretations. Events with missing values (contained in subsets 1B, 1C, 1D, 1E, 1F, 2B, and 2C) were not classified by clustering. Instead, their classification was based on their proximity to previously clustered events on the PCA plots of these subsets.

Figure 4.4: Stratigraphic correlation between piston sediment cores from Eklutna Lake. Core locations are displayed with increasing distance from the delta (from right to left) with location 2 located in the distal basin and locations 3, 4, 20, and 21 located in the proximal basin. Outlier turbidites and a slump deposit in location 21 interrupt the varved “background” sediments. The correlation of earthquake-generated and flood-generated

turbidites establishes an event stratigraphy, which consist of 0.75 events (event with only 0.75 outliers) or 0.95 events (event with 0.95 outlier in at least one of the locations). Turbidites related to historical events in AD 1995, 1989 and 1964 are included in the stratigraphy (Boes et al., 2018; Vandekerkhove et al., 2020). Magnetic susceptibility (MS) peaks pinpoint the presence of (crypto) tephra T5, T7, T10, and T12 (Fortin et al., 2019). Zones with deformed sediments are indicated and result in tentative correlations (dashed lines). Zones with prominent presence of gravel levels are visible in the deepest parts of locations 2, 3 and 4.

4.4 Results and interpretation

4.4.1 Core description

The sediment cores consist predominantly of **glacial varve sequences**. The varved background sediment is locally interrupted by **event deposits** such as tephra beds and turbidites (**Fig. 4.4**). Turbidites are defined by a fining-upward trend, but they exhibit great variability in color (brownish to greyish; **Fig. 4.2**), grain size, thickness, and the presence of an erosive base. At location 21, at a burial depth of 2.7 m, a *ca* 42 cm thick slump deposit is present. From a depth of *ca* 8.0 m, *ca* 9.5 m and *ca* 11.5 m in locations 2, 3 and 4, respectively, gravel size rock fragments are occasionally discernible on the CT scans based on their high-density values (**Fig. 4.4**).

The **varve thickness** (VT) varies throughout the core, which is demonstrated for location 4 (**Fig. 4.5**). In order to better quantify the down-core varve-thickness distribution, the y-axis was rescaled (normalized varve thickness) by dividing the varve thickness by the average varve thickness in location 4, which is 7.0 mm. The running average (window: 15 varves) of the varve thickness is higher than the average varve thickness in location 4 from *ca* 0.6 to *ca* 4.5 m, from *ca* 6.3 to *ca* 7.3 m and from *ca* 16.4 m onward.

Figure 4.5: Down-core varve thickness data (excluding earthquake turbidites) in location 4 and distribution of 0.75 and 0.95 event deposits of Eklutna Lake. The running average (window: 15 varves) is indicated in purple. The y-axis was rescaled by dividing the varve thickness by the average varve thickness (green line, VT = 7.0 mm) in location 4 (i.e. normalized varve thickness). Zone 1 (events E7-2 to E4), zone 2 (events E22 to E17-1) and zone 3 (events E32-2 to E28) show a noteworthy higher abundance of 0.75 event deposits in the sedimentary sequence and correspond to an interval with overall thicker varves (more than average VT).

4.4.2 Outlier study

The outlier study yields **outlier varves** for locations 2, 3, 4, 20, and 21 when the varve thickness exceeds 15.5 (n = 27), 19.2 (n = 66), 24.6 (n = 45), 29.3 (n = 16), and 29.3 mm (n = 18), respectively (**Tab. 4.1**; **Fig. 4.4**), using a 0.75 quantile range. When a larger quantile range of 0.95 was applied to fit the model distribution, the minimum varve thickness necessary to be identified as an outlier increases and the number of outliers decreases (**Tab. 4.1**). In locations 2, 3, 4, 20, and 21, a 0.95 outlier is identified when the varve thickness exceeds 18.0 (n = 24), 24.8 (n = 40), 30.3 (n = 30), 33.1 (n = 14), and 34.9 mm (n = 12), respectively.

Table 4.1: Results of the outlier analysis in locations 2, 3, 4, 20, and 21 in Eklutna Lake, based on varve thickness records from Fortin et al. (2019): minimum outlier thickness and number of outliers for quantile limits $F_{max} = 0.95$ (0.95 outlier) and $F_{max} = 0.75$ (0.75 outlier).

	Minimum outlier thickness (mm)		Number outliers	
	$F_{max}= 0.75$	0.95	0.75	0.95
Location 2	16.5 (-1)	18.0	27	24
Location 3	20.2 (-1)	24.8	66	40
Location 4	25.6 (-1)	30.3	45	30
Location 20	30.3 (-1)	33.1	16	14
Location 21	30.3 (-1)	34.9	18	12

The individual QQ-plots for each location can be consulted in Chapter 9 (Appendix 9.11) and on GitHub (Collart and Praet, 2020). The present study only focuses on singular events that exhibit an anomalous thickness. Outliers representing multipulsed varves with more than two coarse-grained pulses (Boes et al., 2018) (E54, E21, E13-1, and E14), were indicated on **Fig. 4.4** but are not incorporated in the following analyses. In the zone below *ca* 12 m in location 2 (**Fig. 4.4**), an additional 16 layers have a thickness that exceeds the boundary calculated by the outlier analysis for the upper 12 m. These extra layers were further included for subsequent analyses.

4.4.3 Event stratigraphy

Cross-core correlation of those turbidites with outlier thicknesses resulted in a lake-wide event stratigraphy with **94 prehistoric events** (**Tab. 4.2**). As deformed zones complicate correlations, tentative correlation lines were indicated in **Fig. 4.4**.

An event deposit is defined here as a **0.95 event deposit** (n = 26) if the corresponding varve is a 0.95 outlier in at least one of the (maximum five) records, while **0.75 event deposits** (n = 68) are only represented by 0.75 outliers. The distinction between 0.75 and 0.95 event deposits enables straightforward comparison of the spatial distribution in the sediment record. From **Tab. 4.2**, it is inferred that several 0.95 event deposits, such as E11, E16 and E34, show a 0.95 outlier in each location, hinting at lake-wide, high volume events, while 0.75 outliers seem

more restricted to locations 3 and 4. An interesting observation is that a 0.95 outlier in location 2 mostly implies the presence of 0.95 outliers in each location.

Table 4.2: Event stratigraphy of Eklutna Lake sediments with indication of 0.75 events indicated in bold. Voluminous, lake-wide 0.95 events that show a 0.95 outlier in every location are indicated in grey. The dark grey zone represents missing values due to differences in composite core length.

Event name	Location 2	Location 3	Location 4	Location 20	Location 21
1995	0.95	0.95	0.95	0.95	0.75
1989	no	0.95	no	no	no
1964	no	0.95	0.95	0.95	0.75
E1	0.95	0.95	0.95	0.95	0.95
E2	no	0.95	0.95	0.95	0.75
E3	no	no	no	no	0.95
E4	no	no	0.75	no	no
E6-1	no	0.75	no	0.95	0.75
E6-2	no	no	0.75	no	no
E6-3	no	0.75	no	no	no
E7-1	no	no	0.75	no	no
E7-2	no	0.75	no	no	no
E8	0.95	0.95	0.95	0.95	0.95
E10	no	0.95	no	no	no
E11	0.95	0.95	0.95	0.95	0.95
E12	no	0.95	0.95	no	no
E13-2	no	0.95	0.95	0.95	0.95
E15	no	0.95	0.95	0.95	0.75
E16	0.95	0.95	0.95	0.95	0.95
E17-1	0.75	no	0.75	no	no
E17-2	no	no	0.75	no	no
E18	no	0.95	no	no	no
E19	no	0.75	no	no	no
E20	0.95	0.95	0.95	0.95	0.75
E22	no	no	0.75	no	no
E23	no	0.95	no	no	no
E24	no	no	no	no	0.95
E25	0.95	0.95	0.95	0.95	0.95
E26	no	0.95	0.95	0.95	0.95
E27	0.95	0.95	0.95	0.95	0.95
E28	no	no	0.75	no	0.75
E29	no	0.95	0.75	no	no
E30	no	0.75	0.75	no	no
E31	no	0.75	no	no	no
E32-1	no	0.75	no	no	no
E32-2	no	0.75	no	no	no
E33	no	0.95	no	no	no
E34	0.95	0.95	0.95	0.95	0.95
E35	no	0.95	no	no	no
E36	no	0.75	0.95	0.95	
E37	no	0.75	no		
E38	no	0.95	0.95		
E39	0.95	0.75	0.75		
E40	no	0.75	0.95		
E41	0.95	0.95	0.95		
E42	0.95	0.95	0.95		
E43	no	0.95	no		

4 EKLUTNA LAKE RECORD: DECIPHERING TRIGGER MECHANISMS

E44	no	no	0.95
E45	no	0.95	no
E46	0.95	0.95	0.95
E47	0.95	0.95	0.95
E48	no	0.95	no
E49-1	0.95	0.95	0.95
E49-2	no	0.75	no
E50	no	0.75	no
E51	no	0.95	no
E52	0.75	0.95	0.95
E53	no	0.95	no
E55-1	0.95	0.95	no
E55-2	no	0.75	no
E56	0.95	0.95	0.95
E57	0.95	no	no
E58	0.95	0.95	0.75
E59	0.95	0.75	no
E60	0.95	0.95	0.95
E61	no	0.75	0.95
E62	no	0.75	0.95
E63	0.95	0.95	0.95
E64	no	no	0.75
E65-1	no	0.75	0.95
E65-2	no	0.75	no
E66	no	0.95	no
E67	no	0.75	no
E68	no	0.75	
E69	no	0.75	
E70	no	0.95	
E71	no	0.95	
E73	0.95	0.95	
E74-1	0.95		
E74-2	0.75		
E75	0.95		
E77	0.95		
E78-1	0.95		
E78-2	0.75		
E79	0.95		
E80	0.95		
E81	0.95		
E82	0.95		
E83	0.95		
E84	0.95		
E85	0.95		
E86	0.95		
E87	0.95		
E88	0.95		
E90	0.75		
E91	0.95		
E94	0.95		

4.4.4 Principal component analysis and clustering: classification earthquake and flood events

4.4.4.1 Selection 1

The principal component 1 (PC1) versus principal component 2 (PC2) plot for **subset 1A** is shown in **Fig. 4.6**: PC1 explains 33.6% of the variability, while PC2 describes 11.6%. The relatively low values underscore the complexity of the relations in this dataset. The clustering assigned each event to a cluster that shares similar characteristics (indicated in blue and red). The blue cluster consists of numerous events with significant internal variability, whereas the red cluster contains only six events and is less variable. The PC1, which is primarily related to basal grain size and thickness, defines a clear separation between the blue and red clusters.

Figure 4.6: Biplot between PC1 and PC2 (upper plot), and between PC1 and PC3 (lower plot) of subset 1A, which display 28 prehistoric events and three historical events (1995, 1989 and 1964 events, Vandekerckhove et al., 2020). The k-means clustering defines a red (earthquakes) and a blue cluster (floods) with six earthquake and 25 flood events, respectively. Detailed photographs of event deposits E1, E11, E15, E16, E20, and E22 (in italics) are shown in Fig. 4.2.

The interpretation of each cluster, and thus the determination of the trigger mechanism of each event is inferred from the classification of the 1964 earthquake and 1989/1995 flood turbidites (**Fig. 2**). The 1964 earthquake event was assigned to the **red cluster (Fig. 4.6)**, which can thus be interpreted as representing past earthquakes. Likewise, historical flood events in 1989 and 1995 fall within the **blue cluster (Fig. 4.6)**, which may be interpreted to represent flood events.

The presence of a **slump** underlying the turbidite of event E11 (**Fig. 4.2**) in location 21 corroborates the interpretation that this turbidite—which plots in the earthquake cluster—originates from earthquake-induced underwater slope failures. A comparison with the seismic reflection data reveals that the burial depth of the slump in location 21 (i.e. 2.3 m; **Fig. 4.4**) roughly corresponds to the burial depth of event horizon Ek-3 (i.e. *ca* 3.3 m) in the seismic stratigraphy of the Eklutna proximal basin (Chapter 3, **Fig. 4.1E**), which is also the only landslide that reaches that location.

The **earthquake cluster** primarily distinguishes itself by coarse basal grain size and large thickness. However, this is less pronounced for E22 (**Fig. 4.2**), which primarily loads on RB-D80 (PC3). Although the earthquake cluster shows high basal sorting values in locations 2, 3 and 4, the values in locations 20 and 21 are rather low (**Fig. 4.6**), which leads to a large standard deviation of sorting. The D10 values are often high in locations 4, 20 and 21 (Appendix 9.8), which results in a large standard deviation of D10.

The variability within the **flood cluster** is captured by the first three components and thus represents a relatively wide range of parameters. The PC1 describes the thickness and grain-size variability, while PC2 and PC3 represent mainly spectral variables ((n)RABA₄₀₀₋₅₆₀), but also spatial (standard deviation of D80 and thickness), MS and RB-D80 variables (**Fig. 4.6**). The biplot between PC1 and PC2 shows that within the flood cluster there is a clear difference between turbidites characterized by high RABA_{400-560_max} values, a coarse base in location 3, and subsequently a high RB-D80 and spatial variability of thickness and D80 (**Fig. 4.6**) (for example, event deposits E1 and E15; **Fig. 4.2**), and event deposits with low spatial variability of the thickness and D80 and RB-D80 (for example, event deposits 1995 and 1989). The biplot between PC1 and PC3 differentiates in the flood cluster between larger and coarser turbidites with high (n)RABA₄₀₀₋₅₆₀ values (for example, event deposits 1995 and E1; **Fig. 4.2**) and turbidites with low (n)RABA₄₀₀₋₅₆₀ variables and a smaller thickness and basal grain size (for example, event deposit 1989). As PC1 and PC2 describe most variability, only PC1 versus PC2 plots will be discussed in the following paragraphs.

Events E7-1, E28, E32-1, and E35 plot within the flood cluster (**subset 1B, Fig. 4.7**), which argues for a classification as floods. Likewise, events E6-3 and E33 plot within the flood group (**subset 1C, Fig. 4.7**). Event E6-2 belongs to the earthquake group (**subset 1D, Fig. 4.8**) and plots close to the peculiar event E22 (**Fig. 4.2**). In contrast to the other events from the earthquake cluster, these earthquake turbidites are thin and show high values of RB-D80 and standard deviation (thickness and D80), and low RABA₄₀₀₋₅₆₀ values. Not including the

variables of locations 2 and 21 for the analysis of subsets 1E and 1F, respectively, clearly reduces the separation between the groups, and thus the diagnostic potential, which stresses the importance of incorporating as many coring locations as possible. Event E32-2 represents a flood event (**subset 1E, Fig. 4.8**) as it plots in the flood cluster close to the 1989 flood event. Event E36 (**Fig. 4.2**) most likely belongs to the flood group (**Subset 1F, Fig. 4.8**), as it shares most similarities with the already classified flood events. However, due to high values of grain size, RB-D80 and spatial variables (D80, D10 and sorting) and lower RABA₄₀₀₋₅₆₀ variables, this event plots at the edge of the cluster.

Figure 4.7: Biplots between PC1 and PC2 of subset 1B (MS, (n)RABA₄₀₀₋₅₆₀ of location 2 excluded; upper plot) and subset 1C (MS, (n)RABA₄₀₀₋₅₆₀ of location 3 excluded; lower plot). Historical events (1995, 1989 and 1964 events, Vandekerkhove et al., 2020) are also included. Events E7-1, E28, E32-1, E35 (subset 1B) and E6-3, E33 (subset 1C) are classified as part of the red (earthquake) or blue (flood) group, based on the spreading of previously clustered events of subset 1A.

4.4.4.2 Selection 2

The PC1 and PC2 of **subset 2A** explain 28.4% and 15.5% of the variability, respectively (**Fig. 4.9**). Ten events are clustered in the red cluster, which is clearly different from the events in the blue cluster. In this subset, the distinction between the blue and red cluster is captured by a combination of the first two principal components. The red cluster is associated with higher values for certain grain-size variables, especially D99, D90 and D80 (**Fig. 4.9**) and high spatial variability of D10, sorting and thickness. These turbidites are thicker, particularly in location 4, which explains the low RB-D80 values for this location while the RB-D80 of locations 2 and 3 is typically high (**Fig. 4.9**). The blue cluster is mostly characterized by higher RABA₄₀₀₋₅₆₀ values.

Because the 1964 earthquake event plots in the **red cluster** of the plot of subset 2A (**Fig. 4.9**), this cluster can be interpreted to represent earthquakes. Likewise, the 1989 and 1995 historical flood events plot in the lower part of the **blue cluster**, and this cluster is therefore interpreted to represent flood events.

Both of these clusters show a large degree of **internal variability**. The earthquake cluster ranges from a group of thick turbidites with a very coarse base, for example E49-1 and E63 (**Fig. 4.2**), to thinner turbidites with lower basal grain-size values, for example E62 and E65-1 (**Fig. 4.2**). On the other hand, event deposits E51, E60, E52, and E42 from the flood cluster are thicker and coarser, while E67 and 1989 mark the other side of the spectrum.

Event E38 (**Fig. 4.2**) plots in the earthquake group (determined by clustering for subset 2A), while E37, E49-2 and E50 most likely represent flood events (**subset 2B, Fig. 4.9**). The classification of event E44 (**Fig. 4.2**) is enigmatic, as this event plots in between the earthquake and flood group (subset 2B, **Fig. 4.9**). The low RABA₄₀₀₋₅₆₀ values argue for an earthquake origin. This event probably plots outside the earthquake group because it only produced a thick coarse turbidite in location 4 (high basal grain-size, MS and RB-D80 values), while the turbidites in locations 2 and 3 are rather thin. For the analysis of **subset 2C** only the variables of locations 2 and 3 are used, but nevertheless the clusters remain well-separated data clouds. Events E68, E69, E70 and E71 are classified as flood events, while E73 (**Fig. 4.2**) is interpreted as an earthquake event, especially since it is located in the vicinity of events that were already unambiguously classified in the earthquake cluster of subset 2A, for example, E49-1 and E73 (subset 2C, **Fig. 4.9**).

4.4.4.3 Selection 3

The PCA of **subset 3** (**Fig. 4.10**) renders two main clusters and two outliers (i.e. events E82 and 1989). The PC1 explains 38% of the variability while PC2 represents 31.1% of the variability. Although only the variables of location 2 were used for this analysis, the spreading between

both clusters is very distinct. In subset 3, the distinction between the blue and red cluster does not depend on thickness variables.

Figure 4.9: Biplots between PC1 and PC2 of subset 2A (upper plot), subset 2B (MS, (n)RABA₄₀₀₋₅₆₀ of location 2 excluded; middle plot) and subset 2C (variables of location 4 excluded; lower plot). The plots also show historical events (1995, 1989 and 1964 events, Vandekerckhove et al., 2020). The k-means clustering defines a red (earthquakes) and blue cluster (floods) for subset 2A with 11 earthquake and 20 flood event deposits. Events E37,

E38, E44, E49-2, and E50 (subset 2B), and events E68, E69, E70, E71, and E73 (subset 2C) are classified as part of the red (earthquake) or blue (flood) group, based on the spreading of previously clustered events of subset 2A. Detailed photographs of event deposits E38, E40, E44, E46, E47, E63, E65-1, E66, and E73 (in italics) are shown in Fig. 4.2.

The event deposits in subset 3 are located in the zone below *ca* 12 m burial depth of location 2 where the sedimentation pattern is clearly different, i.e., varves are indistinct and turbidite thickness and frequency increases (**Fig. 4.4**). All historical events (1964 earthquake and 1989/1995 floods) fall within the same cluster and, hence, the changed sedimentation conditions may make the comparison with recent turbidites not meaningful here (**Fig. 4.10**).

Low $RAB_{400-560}$ values and a coarse, poorly sorted turbidite base suggests an earthquake origin for the events in the red cluster, while the other events are mainly characterized by high $RAB_{400-560}$ values, which are typical for flood turbidites. These flood turbidites are very thick, especially at location 2 where turbidites are typically thin. The extremely coarse (basal grain size up to 0.738 mm) and erosive base of event deposit E82 is responsible for the distinct shift in the direction of PC1 on the PCA plot. The high (n) $RAB_{400-560}$ values suggest a flood origin, but the trigger mechanism behind event deposit E82 remains a point of discussion.

Figure 4.10: Biplot between PC1 and PC2 of subset 3. Historical events (1995, 1989 and 1964 events, Vandekerckhove et al., 2020) are also included. The k-means clustering defines a red (possibly earthquake) and blue cluster (possibly flood) for subset 3, which renders six and 16 events, respectively. Detailed photographs of event deposits E84, E85 and E86 (in italics) are shown in Fig. 4.2.

4.5 Discussion

4.5.1 Earthquake versus flood events

Significant clustering and comparison with historical events demonstrate that earthquake and flood deposits can be confidently discriminated using the presented method. The prehistoric

Eklutna Lake record comprises **24 earthquake** and **70 flood turbidites**. An earthquake origin is favored for thick turbidites with a poorly sorted, coarse base suggesting high peak energies and fast flow evolution, which is characteristic for earthquake-induced turbidity flows (Beck, 2009; Wilhelm et al., 2013; Sabatier et al., 2017; Van Daele et al., 2019; Vandekerkhove et al., 2020).

In agreement with the results of Vandekerkhove et al. (2020), the base of **earthquake turbidites** is remarkably well-sorted in the most proximal locations, because in high-energy conditions only coarse fractions (sand) can be deposited. Because the cores were collected in the central, deepest part of the basin, the standard deviation of the thickness for earthquake turbidites is not as high compared to the results in Vandekerkhove et al. (2020). Their transect perpendicular to the lake's long axis reveals better the ponding character of the turbidite and thereby increase the standard deviation values. Compared to earthquake turbidites, **flood turbidites** have a well-sorted, finer-grained base, and show overall less spatial variability. The higher RABA₄₀₀₋₅₆₀ values for flood events explain the browner color of these turbidites. This observation is in accordance with the results of Vandekerkhove et al. (2020) that relate these RABA₄₀₀₋₅₆₀ values to a combination of total organic carbon (TOC), type of organic material and/or pigment degradation.

4.5.2 Intra-cluster variability

The large multivariate dataset also reveals variability within the earthquake and flood clusters. The variability in the **earthquake events** is limited to slight differences in thickness and basal grain size. The characteristics of the remobilized slope sediments (location, volume, and type) and the induced turbidity flows (path, peak energy, flow evolution, and interaction) likely define depositional features such as thickness, coarseness, sorting and spatial variability of these events.

The substantial variability within the **flood cluster** is best demonstrated for subset 1A (**Fig. 4.6**). The spreading hints at different source, transport and depositional mechanisms. Flood events may generate turbidites with a quite uniform spatial distribution (of thickness and D₈₀), for example, the 1995 and 1989 event deposits. These historical events were initiated by heavy rainfall in two consecutive days during fall storms, which is demonstrated by instrumental precipitation records (Boes et al., 2018; Vandekerkhove et al., 2020). Other flood events that share similarities with these historical counterparts probably indicate similar conditions. The uniform spatial distribution suggests that interflows developed due to strong thermal stratification at the end of summer and redistributed the suspended sediment load across the lake (Fig. 13 in Vandekerkhove et al., 2020).

On the other hand, the Eklutna Lake record also shows evidence of thick flood turbidites with an intense brown color and a coarse base, especially in location 3, for example, event deposits E27, E1 and E15 (**Fig. 4.2**). Because closely spaced deltas and alluvial fans surround location 3,

tributary slope failures due to severe floods are a possible cause of these turbidites. This interpretation is supported by the fact that event E1 represents, according to Vandekerkhove et al. (2020), a flood-induced delta collapse that occurred in AD 1917.

Thorough examination of the thickness and D99 (Appendix 9.8) throughout the lake basin indicates that the “uniform” flood events display in fact slight spatial variations, suggesting that these turbidites are the product of a complex interplay of different factors. The presence of **interflows** typically results in a uniform spatial distribution but depends on the seasonal lake’s thermal stratification. The lack of interflow processes might explain why some event deposits show only a large thickness and coarse base in the locations close to the main delta (proximal locations), for example, event deposit E28. Turbidites with a coarse base (high D99, D90 and D80) in locations other than the proximal locations argue for other source areas, especially when accompanied by a slightly larger thickness. For example, the 1995 event produced a coarse turbidite in locations 2 and 3 beside locations 20 and 21. This indicates that extra coarse material may have washed in from deltas and alluvial fans surrounding the distal basin. The lake **bathymetry** may also influence the flow dynamics in the lake basin. If an underflow originates from a tributary source in the proximal basin, then this flow plunges towards the deeper depocenters in locations 3 and 4. In that case, no coarse material (or oxygen) will reach the distal basin.

Although heavy **precipitation** likely caused a large portion of the prehistoric flood events, in accordance with the 1995 and 1989 flood events, intense snow or ice melt or a combination of triggers might be responsible for other flood turbidites. Furthermore, the amount of precipitation or melt, the flood duration, the catchment preconditioning (for example, dry or wet period preceding the flood), and the amount of remobilized sediments may contribute to the variability. The limited instrumental records starting only in the 1940s makes it, however, challenging to study the influence of each factor in detail.

4.5.3 Down-core sedimentation trends

Examination of the down-core distribution of 0.75 and 0.95 event deposits reveals clear trends. For the first 37 event deposits (E1 to E35), there are **three distinct zones** in the sedimentary sequence with a noteworthy higher abundance of 0.75 event deposits (**Tab. 4.2; Fig. 4.5**): zone 1 (events E7-2 to E4), zone 2 (events E22 to E17-1) and zone 3 (events E32-2 to E28). The running average of the varve thickness in location 4 (Fortin et al., 2019, excluding earthquake turbidites) reveals that these zones correspond to an interval with overall thicker varves [more than the average varve thickness (VT), **Fig. 4.5**]. Boes et al. (2018) linked these variations in varve thickness with fluctuations in sediment input due to **glacier dynamics**. Therefore, the authors infer that 0.75 event deposits are more abundant in periods when sediment input is significantly higher.

Interestingly, earthquake turbidites E6-2 and E22 (**Fig. 4.2**) are only recorded as an outlier in location 4 in zones 1 and 2, respectively (**Fig. 4.5**). Their small thickness, high D99, D90, and D80 (and thus very high RB-D80) have resulted in plotting them at a distance from the other (lake-wide) earthquake events in the earthquake cluster (subset 1D, **Fig. 4.8**). It is suggested here that higher sedimentation rates increased the sensitivity to earthquake-triggered slope failure and decreased the intensity threshold for slope instability. The **increased sedimentation rates** are therefore responsible for recording earthquakes of lower macroseismic intensity in the proximal basin of Eklutna Lake. This relationship between the sedimentation rate and the sensitivity to earthquake shaking was already demonstrated in other lakes, for example, in the Alps (Wilhelm et al., 2016a). On the other hand, the authors cannot exclude that the generally increased varve thickness is directly responsible for thicker “event varves” and that therefore events E22 and E6-2 were identified as outliers.

4.5.4 Turning a turbidite record into an earthquake and flood catalogue: quality assessment

4.5.4.1 Evaluation of the outlier study

The outcome of the outlier study depends on the recovered core sections and measured varve thicknesses. The varve thickness was measured instead of the event thickness, and varves with the same thickness may encompass turbidites with a different thickness. However, the **varve thickness** serves as a good approximation of the event thickness, because it can only overestimate the event thickness; consequently, no events will be missed. Furthermore, using the varve thickness is convenient as it can be acquired quickly. The varve thickness dataset in this study is probably a valid representation of the real varve thickness within the sedimentary archive, taking into account possible (piston) coring artefacts and instrumental errors. Moreover, the measurement of the varve thickness on a 2D image is not ideal, because the varve embodies a 3D geometry, i.e., turbidite thicknesses might change within a core section. The present study has tried to counter these issues as much as possible by lowering the outlier boundary in combination with a **multi-core approach**.

The study of Fortin et al. (2019) has shown that the varve thickness has not significantly changed in the last *ca* 2250 yrs. Therefore, the varve thickness record in this study was not **detrended**. Furthermore, flood-generated turbidites will likely thicken in periods with higher sedimentation rates, whereas the thickness of the earthquake-generated turbidites may stay unaffected. Hence, earthquake-generated turbidites may be missed by detrending the thickness record. However, it is possible that during periods with a slight increase in varve thickness (**Fig. 4.5**) more outliers were produced, for example events E22 and E6-2.

The thickness of the **historical turbidites**, studied in Vandekerckhove et al. (2020), might be biased by the change in hydrology due to the dam structure. Therefore, the authors chose not

to incorporate the turbidites younger than the dam construction in the outlier study. The thickness of the historical turbidites does, however, exceed the outlier boundary (**Fig. 4.4**), which further endorses the present method of identifying outliers from the varve thickness data. Nevertheless, the 1964 event, related to the corresponding megathrust earthquake, did not produce an outlier in location 2, in contrast to the lake-wide 1995 flood event. The 1989 event was limited to one outlier in location 3. Finally, the 2018 earthquake turbidite, studied by Van Daele et al. (2020), seems to be slightly above the 0.75 outlier threshold in locations 20 and 21 (even though these thicknesses are an approximation due to turbidite deformation, the incomplete 2018/2019 varve and lack of compaction at the sediment–water interface). These observations emphasize the importance of using a multi-core approach and constructing a lake-wide event stratigraphy, instead of relying on a single core.

The events from subset 1A were studied in all five locations. **Subset 1A** is the most important subset for evaluating which quantile limit range is significant for future studies. Earthquake events predominantly show a 0.95 outlier in all locations (for example, E11, E16, E25 and E34), although the 1964 and 2018 events show that this is not always the case and probably depend on the location of the slope failures and shaking intensity, respectively. Earthquake events E6-2, E22 and 2018 present no 0.95 outlier along their stratigraphic interval. The thickness of E6-2 is within 1 mm of the 0.75 boundary in location 4. This means that in order to capture all earthquakes (reaching a certain shaking threshold), a 0.75 boundary is preferred, especially in proximal locations. Flood events may also represent lake-wide events with 0.95 outliers, as demonstrated by the historical 1995 event. The choice of the **quantile limit** is thus not biased towards a specific trigger mechanism. This very important conclusion implies that the outlier study can be applied to select and study both earthquakes and floods in Eklutna Lake.

4.5.4.2 Evaluation of the event stratigraphy

Core-to-core correlation may pose some challenges especially when sediment sections are affected by deformation. The identification of **tephra beds** across the lake basin are thus necessary to ensure reliable correlations.

The **0.95 events** often show an outlier in every location (for example, E1, E8, E11, E20, E25, E27 and E34), representing high-volume lake-wide events, whereas **0.75 events** only present an outlier in specific locations, often locations 3 and 4 (for example, E7-1, E17-1 and E31) (**Fig. 4.4; Tab. 4.2**). This suggests that the identification of 0.75 events is strongly influenced by the choice of the coring location. Locations 3 and 4 are surrounded by multiple tributary sediment sources and are characterized by high sedimentation rates. Therefore, these locations appear to be the most sensitive and highest-resolution turbidite recorders.

4.5.4.3 Evaluation of the principal component analysis and clustering

In order to test the classification based on the PCA and clustering, the **recurrence intervals** of prehistoric earthquake and flood events were calculated (**Fig. 4.11**) based on the median ages inferred from the age model, provided in Fortin et al. (2019). The earthquake recurrence is best expressed by a **Weibull distribution** (shape parameter >1), which implies a time-dependent recurrence process in which the hazard increases with the elapsed time since the latest event. Flood recurrence intervals best fit with an **exponential distribution** (or a Weibull distribution with shape parameter <1), which implies a time-independent (random) Poisson process, as can be expected (Kirby, 1969). The earthquake recurrence interval distribution is not necessarily conclusive for a specific formation mechanism, as the distribution of earthquakes may vary from clustered (e.g. Marco et al., 1996), supercycle (e.g. Goldfinger et al., 2013), bimodal (e.g. Avşar et al., 2014; Dal Zilio et al., 2019), random (e.g. Lake Tutira, Gomez et al., 2015) to quasi-periodic (e.g. Lake Calafquén, Moernaut et al., 2018) behavior. Moreover, in Eklutna Lake, more than one fault in the vicinity can trigger turbidity currents. The recurrence variability may depend on the number of (subduction zone and intraplate) **earthquake sources** affecting the lake and their activity for the last 2500 yrs, as evidenced by the historical record of both a megathrust (AD 1964; Chapter 3, Vandekerckhove et al., 2020) and an intraslab (AD 1818; Van Daele et al., 2020) earthquake. Nevertheless, the different recurrence-time distribution of the earthquake and flood clusters definitely imply **different triggering mechanisms**, which corroborates the results of the PCA and clustering.

Figure 4.11: Histograms with recurrence intervals of prehistoric earthquake (A) and flood (B) events in location 4 of Eklutna Lake, based on the median ages inferred from the age model, provided in Fortin et al. (2019). An exponential, Weibull and normal distribution are displayed for each histogram. Earthquake recurrence (in red) fits a Weibull distribution, while flood recurrence intervals (in blue) corresponds best with an exponential distribution.

4.5.4.4 Evaluation of the statistical approach to distinguish earthquake and flood origins

Using a statistical approach enables the **objective identification** of turbidites and the **distinction** between earthquake-generated and flood-generated turbidites in varved, proglacial lake-sediment sequences. Furthermore, this study has shown that grain-size and thickness variables alone may suffice to discriminate between both triggering mechanisms (**Fig. 4.6**). However, the outcome of the statistical analyses entirely depends on the **quality of the dataset**. Instrumental errors, sediment deformation by coring artefacts or unequal core lengths are responsible for the lack of certain variables. The reality of missing variables in a dataset compiled by sediment cores hinders statistical analysis; however, the use of different subsets that comprise as much variability as possible has also enabled classification of those events with missing variables. Future studies should try to minimize coring artefacts and instrumental errors. For the PCA, this will lead to an even better significant spreading of the variables in the PCA and thus an improved clustering, as well as a more straightforward identification process.

The **multi-core approach** here provides essential information, which is in agreement with the results from Vandekerkhove et al. (2020). The inter-core variability of certain variables including D10, D80, thickness, and sorting, contributes significantly to the differentiation of triggering mechanisms, as spatial variables insert proxies related to flow-specific processes. The event stratigraphy has also highlighted seemingly conflicting results, for example, the low sorting values in locations 20 and 21 for earthquake turbidites in contrast to high values in other locations.

The **dynamic environment** of proglacial lakes and corresponding sedimentary changes do not affect the ability to cluster the variables, as demonstrated for subset 3 that only contains variables from location 2. However, deriving the trigger behind each cluster is less obvious, especially since the individual importance of certain variables (for example, thickness) changed. Future studies should focus on better comprehending the influence of environmental and climate change on the lacustrine sedimentary processes and the depositional record. This is especially important for proglacial lakes, which are influenced by glacier dynamics.

4.5.4.5 Evaluation of flood and earthquake records

Flood records

Lacustrine flood records that are composed of continuously varved sections over millennial-scale intervals are quite rare (Gilli et al., 2013). **Proglacial lakes** can provide these highly desirable seasonally resolved flood records, even though the construction of such a record from proglacial lake sediments poses some challenges. First, it is important to note that the

definition of a 'flood event' completely depends on the objectives of the study or the parameters one aims to derive. Most paleohydrological studies are interested in finding turbidites that are the result of extreme rainfall, whereas proglacial lakes may also receive floods from additional **sources**, such as rapid meltwater runoff or drainage of ice-dammed lakes.

The present study aimed to capture flood events based on an outlier study of the varve thickness from Fortin et al. (2019). This study revealed that flood events represent both 0.95 and 0.75 events, while the majority of the earthquake events are more consistently classified as 0.95 events. Hence, earthquake turbidites show an abnormal thickness (i.e. 0.95 outlier) in at least one location. This suggests that all earthquake turbidites may have been captured when performing the outlier study, whereas a **thickness-based identification** alone is likely not sufficient for identification of the recorded flood events. This seems reasonable, considering the variability of these complex and continuous processes. Possibly, some smaller flood events were missed because their thickness is mistaken as part of the background varve thickness distribution. For future studies, the authors would recommend fine-tuning this methodology by incorporating **grain-size data**. Continuous down-core grain-size trends can be acquired by time-consuming grain-size sampling and analysis or by—more efficiently—using the Hounsfield units of the CT pictures, which are partly related to grain size (Vandorpe et al., 2019; Vandekerkhove et al., 2020).

Another challenge is that proglacial lakes are highly sensitive to variations in **climate and/or glacier dynamics**. Although glacial activity is mainly controlled by winter precipitation and summer temperatures, while flood occurrence is driven by extreme rainfall events, several studies in the Alps reported a link between floods and periods with favorable conditions for glacier expansion (e.g. Wirth et al., 2013; Amann et al., 2015; Fouinat et al., 2017). Flood occurrence may increase as a result of more frequent heavy rainfall caused by changing atmospheric conditions that also affect glacial activity (e.g. Wirth et al., 2013; Amann et al., 2015). Furthermore, a study by Fouinat et al. (2017) reported that the change in sediment availability also plays a major role in flood generation. As glacial activity enhances abrasion in the watershed, the production of fine sediments will increase the watershed sensitivity to produce flood deposits in the lake. This study demonstrates that significantly more 0.75-event deposits are recorded during periods when sedimentation rates were higher, especially in locations 3 and 4. The change in sedimentation rate may have produced a shift in background sedimentation towards coarser and thicker varves. Consequently, it is very difficult to objectively discern between a varve and a turbidite. The advantage of the continuous sedimentation in proglacial lakes is that it offers the possibility to easily infer these sedimentation rate variations, which ultimately could result in an overestimation of the number of past floods in certain periods. These results are in agreement with the study of Fouinat et al. (2017) and demonstrate that caution must be taken when reconstructing past

flood variability or deriving flood intensities, as environmental changes may influence the frequency and intensity of floods.

Earthquake records

A reliable lacustrine paleoseismic record requires that all past earthquakes that exceeded a certain shaking threshold caused a turbidite and/or an underwater landslide deposit in the lake basin. An earthquake is recorded in the sedimentary sequence when its induced local macroseismic intensity exceeds the **intensity threshold** required for slope instability, typically intensities *ca* VI (Monecke et al., 2004; Moernaut et al., 2014; Van Daele et al., 2015; Wilhelm et al., 2016a), but as low as $V\frac{1}{4}$ to $V\frac{1}{2}$ for failures of deltaic slopes (for example, triggered by the 2018 earthquake in Eklutna Lake) (Moernaut et al., 2014; Van Daele et al., 2020). Indeed, proglacial paleoseismic records, with their **high sedimentation rates**, have the potential to be one of the most sensitive paleoseismic archives. However, the sensitivity to slope failures changes through time in response to a fluctuating sediment input (Wilhelm et al., 2016a). These changing threshold conditions do not necessarily have to pose an issue, as long as the changes in sedimentation rate can be identified.

In contrast to coastal marsh paleoseismic records from subduction zones, which are a function of coseismic relative land-level changes, lacustrine paleoseismic records rely on the **shaking intensity** produced by the earthquake. The turbidite records are directly applicable for seismic hazard analysis, and for inferring information about earthquake ground shaking from megathrust, intraslab and crustal earthquakes. The **robust age control** of proglacial lake sediments opens possibilities for future studies to focus on the identification of these different seismic sources. **Megathrust earthquakes** can be identified based on the modelled age ranges of these earthquakes from coastal paleoseismic and tsunami records, and by comparison with other lake records. However, the paleoseismic record may also reveal information about earthquake ground shaking from **crustal and intraslab earthquakes** (Van Daele et al., 2019). The most recent of such intraslab events, the M_w 7.1 2018 Anchorage earthquake, demonstrates that there is a need for a better assessment of the seismic hazards of these events. The fact that this earthquake did generate a turbidite in Eklutna Lake (Van Daele et al., 2020) indicates that such earthquakes indeed likely represent part of the Eklutna paleoseismic turbidite record. Further paleoseismic studies on proglacial lakes could focus on distinguishing these events, which might be crucial to attain a comprehensive hazard assessment, especially for Anchorage, which is the population and infrastructure center of the state.

4.6 Conclusions

Sediment cores from five sites in Eklutna Lake, Alaska, show a *ca* 2250 year long record with **varved “background” sedimentation** that is frequently interrupted by **turbidites**. A statistical

outlier analysis, based on varve thickness distributions, yields an objective identification of 27, 66, 45, 16, and 18 outlier varves for core locations 2, 3, 4, 20, and 21, respectively.

The statistical approach developed in this study, involving a principal component analysis and a clustering algorithm, transforms a large multivariate [i.e. basal grain-size, thickness, spatial, spectral, relative basal D80, and magnetic susceptibility (MS) variables] **multi-core dataset into two distinct clusters**. Calibration with historical earthquake and flood events ascertains the triggering mechanisms of these clusters and shows that the prehistoric Eklutna Lake record comprises 24 earthquake and 70 flood turbidites.

The causal relationship between **flow characteristics** and **textural evolution** makes grain size and thickness the most effective proxies to discriminate earthquake-generated and flood-generated turbidites. The high peak energy and fast flow evolution of earthquake-induced turbidity flows typically produce thick turbidites with a poorly sorted, coarse-grained base. Earthquake turbidites also show high spatial variability of sorting and D10. The typically browner color of flood turbidites results from higher RABA₄₀₀₋₅₆₀ values, which relate to total organic carbon (TOC), type of organic material and/or pigment degradation.

The spatial distribution of turbidite thickness is an important parameter to discriminate between earthquake and flood turbidites. This emphasizes the necessity of using a **multi-core approach**. Multiple cores provide the necessary spatial information, which contributes significantly to the differentiation of triggering mechanisms, as these variables reflect proxies related to flow-specific processes. Moreover, the construction of a lake-wide event stratigraphy minimizes locally biased results that can lead to missing of events in the record.

Using different subsets counters the presence of **missing variables** in a core dataset; however, the outcome of the statistical analyses becomes more equivocal as the quality of the dataset reduces. The recorded sedimentary changes as a response to glacier variability in time does not affect the clustering but ascertaining the trigger mechanism becomes less straightforward.

This statistical approach represents a powerful method to identify turbidites and their triggering mechanisms in long prehistoric sediment records in an efficient and objective manner. This opens new **prospects for paleoseismological, paleohydrological and paleoclimate studies** in proglacial lakes worldwide.

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