

Historical storm frequency on the Shetland Islands (UK) – Preliminary insights from lake sediment cores and coastal wave modelling



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Background & Aim

Severe storms, their extreme waves and surges pose the greatest natural hazard to the coasts of northwestern Europe. For assessing future risks that may arise from storm surges and assessing whether storm activity has increased in recent decades, **high-resolution records of North Atlantic storminess** are required. However, this information is generally limited to instrumental weather data or historical documentation from the last few centuries. Understanding **long-term patterns of storm frequency and intensity**, proxy records from geoarchives of more than 200 years must be used. Since the most destructive storms passing over Europe originate in the North Atlantic, the **Shetland Islands** serve as a window to cyclogenesis in this region. In our research, we extracted lacustrine sediments of the small (16 ha) freshwater lake Loch of Flugarth on Mainland, that is separated from the ocean by a low sand and gravel barrier (**Fig. 1**). Vatsendi Burn from the SW and another unnamed small inflow from the W are the only tributaries into the lake.

This pilot study is carried out in the framework of the **GEN-EX project** and aims to **identify and to date storm-induced overwash** processes in the two sediment cores FLUG 2 and FLUG 3 by intercalated distinct sand layers in the otherwise fine-grained, organic-rich lake deposits (**Fig. 2**). This further implies a better understanding of the recurrence pattern of extreme storm events on the Shetland Islands and the parameters driving extra-tropical storms in the wider region as well as the role and variability of the North Atlantic Oscillation over the past 1500 years.

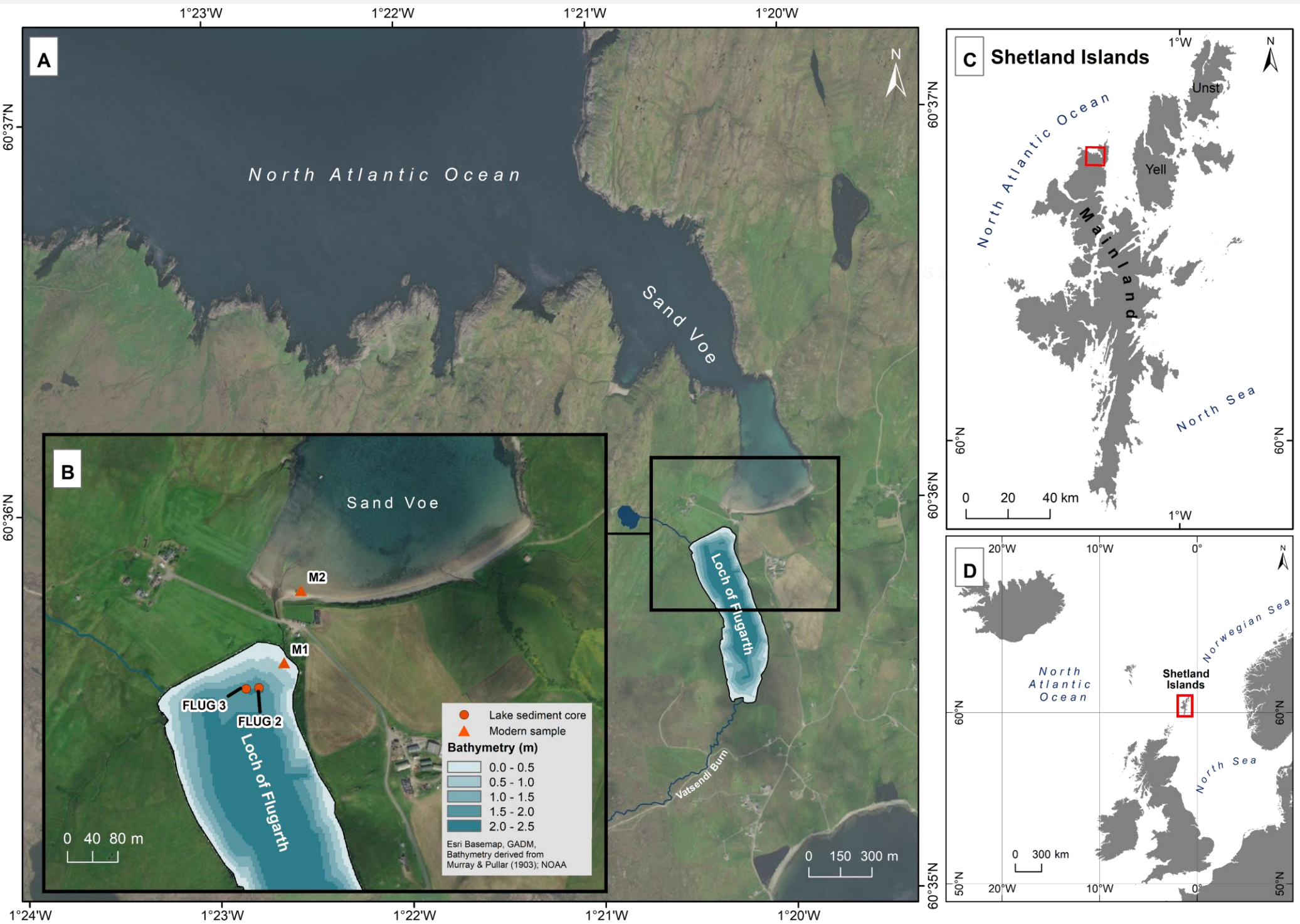


Fig. 1: Study area: A) Bay of Sand Voe. B) Location of the lake Loch of Flugarth and position of the two lake sediment cores FLUG 2 and 3 and the modern environmental samples M1 and M2. C) The Shetland Islands with the study area in the North of Mainland. D) The Shetland Islands border the North Atlantic, the Norwegian Sea and the North Sea. Since cyclones regularly form near Iceland and move southeast, storms moving towards mainland Europe often cross the Shetland Islands first.

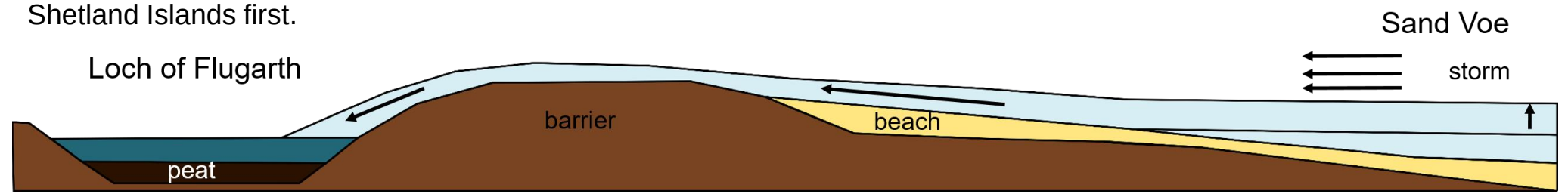


Fig. 2: Sketch of the assumed overwash process during a storm surge after Chaumillon et al. (2017). The sediment from the shallow bay (<2 m depth) and the beach is carried over the barrier into the lake by the rise in sea level due the storm surge and the breaking waves as a result of the passage of a cyclone and the fetch of the storm from the open sea.

Methodology

Sedimentology

Storm-induced marine flood layers can be identified, e.g. by sedimentology through micromorphological analysis, grain-size analysis, magnetic susceptibility and density. Total organic carbon (TOC) and element ratios based on handheld micro-X-ray fluorescence analysis (μ XRF) also reflect the sediment source (**Fig. 4**). The occurrence of marine microfossils (e.g. foraminifera) and similar geochemical signals from the lake sediment cores and the sediment from the beach and barrier (sample: M1 and M2, **Fig. 1 B**) point to the origin of the layer.

Geochronology

In order to assign the individual sediment layers to periods of increased storm activity, five different plant/wood remains from FLUG 2 and FLUG 3 were dated by AMS- ^{14}C (**Fig. 3**). Data were calibrated using Intcal20 (Reimer et al., 2020) and a Bayesian age-depth model was calculated with *rBACON* (Blaauw & Christen, 2011). Further ^{14}C , ^{210}Pb and ^{37}Cs dating may refine the age-depth model, while (crypto)tephra from historical Icelandic eruptions may provide additional age constraints.

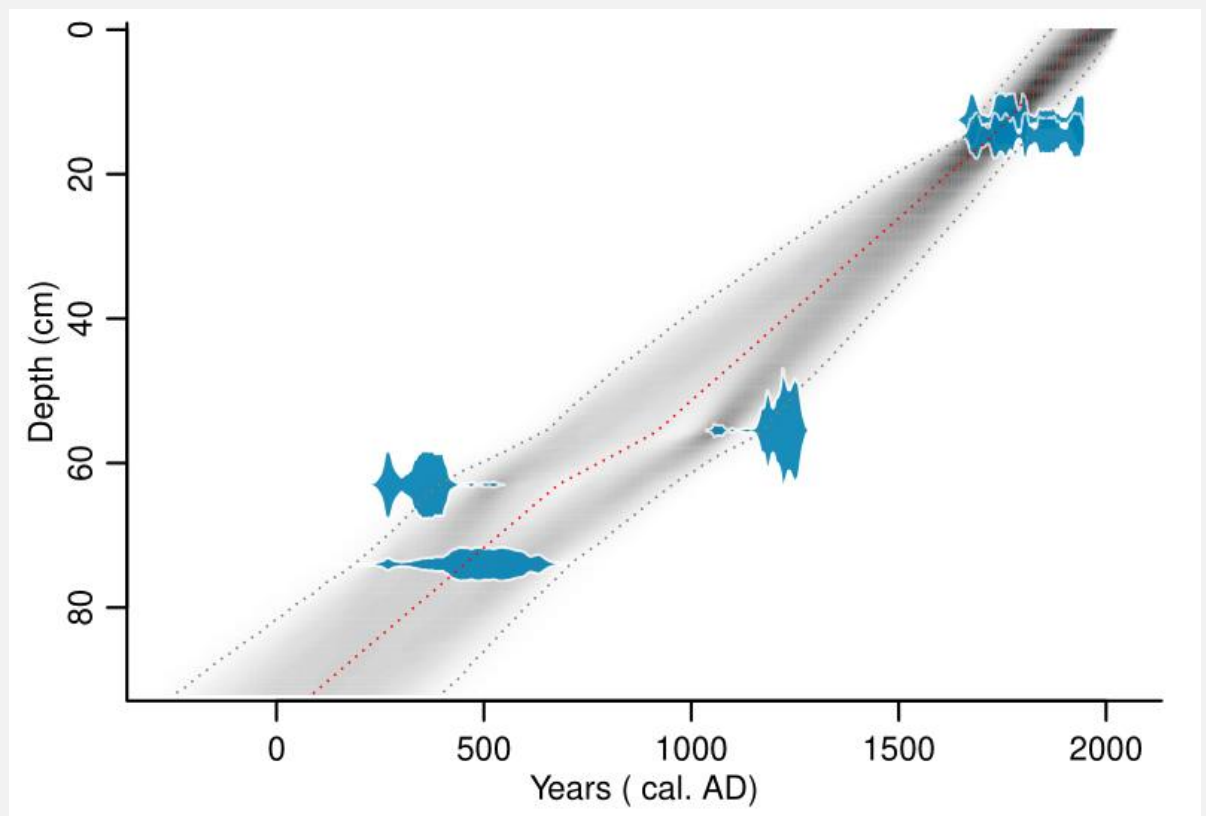


Fig. 3: Bayesian age-depth model of FLUG 3. The accumulation rate is c. 20 yrs/cm, assessed by Markov Chain Monte Carlo (MCMC) iterations.

Hydrodynamic Modelling

The intensity of the storms cannot be derived directly from the thickness of the intercalated sand layers and not every storm causes a flood event. Instead, the sensitivity and thus the critical threshold height of a storm-induced wave that reaches the lake is assessed using a hydrodynamic model in DELFT3D-Flow.

Historical Documentation

Lamb (1991) documented and described catastrophic storm events and their tracks across the Atlantic Ocean on synoptic weather maps around the British Isles for the past approx. 500 years. This historical information will help to calibrate the sedimentary record and multiproxy data of this study.

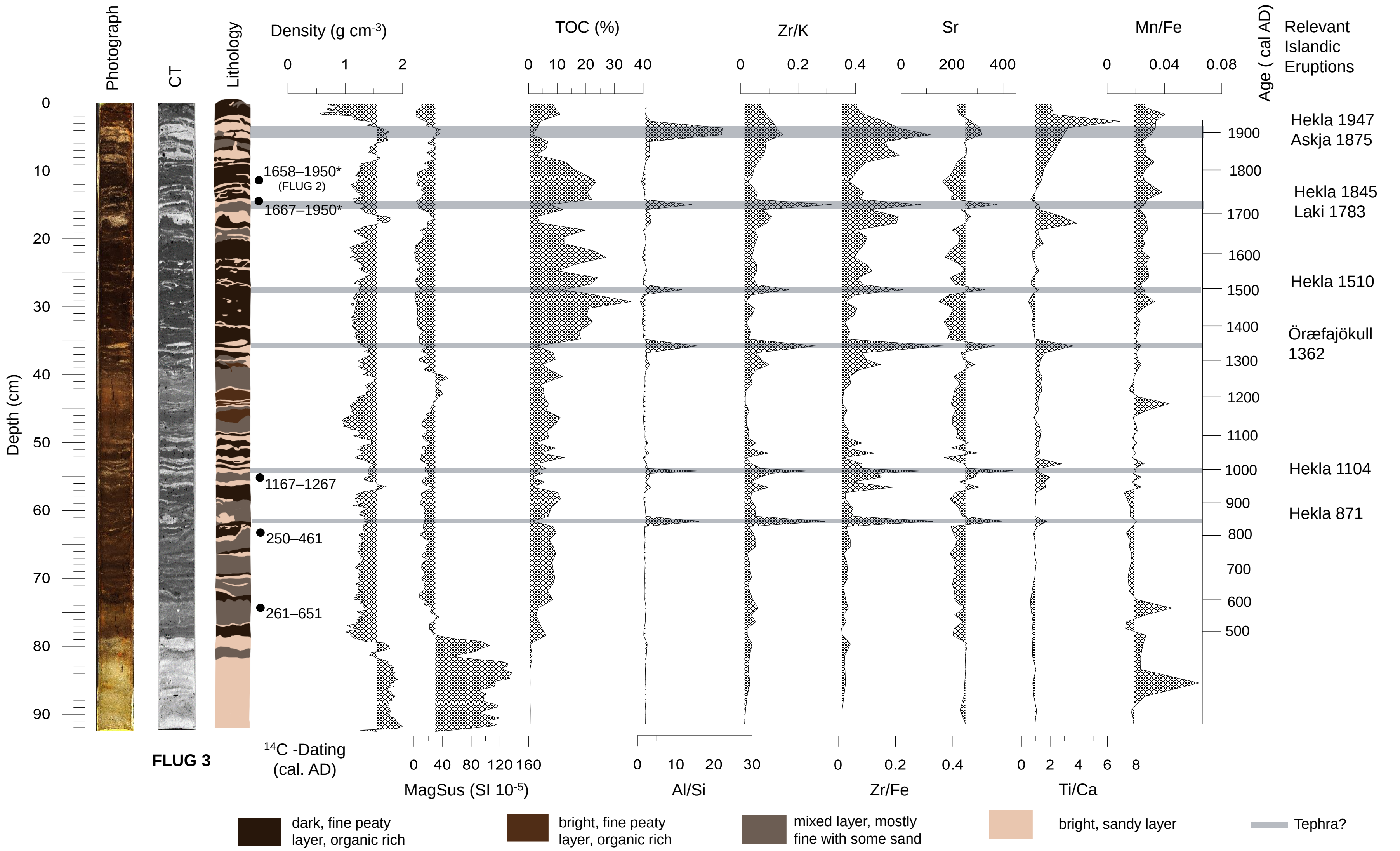


Fig. 4: Preliminary sedimentological and geochemical results of FLUG 3. From left to right: Real-colour photograph; Computed tomography (CT) scan; schematic lithology; calibrated samples for ^{14}C -dating (2 σ), the upper date is derived from FLUG 2; density; magnetic susceptibility (MagSus); Total organic carbon (TOC); μ -X-ray Fluorescence (μ XRF) proxies and ratios expressed as intensity (Al/Si, Zr/K, Zr/Fe, Ti/Ca, Sr, Mn/Fe); mean ages calculated with *rBacon* (Blaauw & Christen, 2011), as the event layers are not considered in the model, the ages have a wide range; relevant major volcanic eruptions from Icelandic volcanoes as tephra sources.

Preliminary Results & Interpretation

The calculated age-depth model (**Fig. 3**) depicts an accumulation rate of c. 0.5 mm/yr. Hence, FLUG 3 is a non-varved sediment core with distinct bright event layers as shown by density and magnetic susceptibility (**Fig. 4**). The background sediment is darker, organic-rich as revealed by the TOC content and in some sections (39–49 cm) it is brighter. This section is dated to the **Medieval Warm Period** (from c. 950 to c. 1250). The darker sediment layers above (10–36 cm) can be dated to the **Little Ice Age** (from c. 1500 to c. 1850). In the transition time in between there seem to be a particularly large number of event layers presumably created by marine overwash (**Fig. 2**). The XRF-based ratios Zr/K and Zr/Fe are indicators for coarser grain sizes. Van Daele et al. (2014) identified tephra layers in lake sediments with the Al/Si ratio. Since all these ratios show peaks in six different

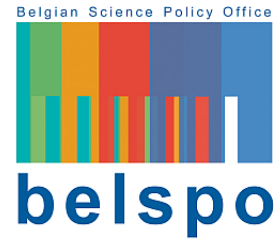
depths and Sr and Zr are often elevated in tephra, the peaks may be related to **(crypto)tephra** from volcanic eruptions (Davies et al., 2015) such as those of Hekla, Askja, Laki or Öræfajökull on Iceland (Newton et al., 2007). Further microscopic analyses are still pending. Increased values for the Ti/Ca ratio can be interpreted as increased detrital input. Higher values for the Mn/Fe ratio indicate oxic conditions that can be caused by increased lake mixing as a result of a lower lake level or higher wind speed (Davies et al., 2015) associated with overwash. Historical maps show that the barrier has existed as it does today since at least the middle of the 19th century. The bright, sandy section below 78 cm could reveal that the lake was directly connected to the sea at that time. The tides also have an influence on the development of the storm surge and must be considered in the hydrodynamic model.



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