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Paleoenvironmental potential of lacustrine sediments in the Central Highlands of Vietnam: a review on the state of research

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ABSTRACT

Global warming enhances atmospheric moisture loading and will likely affect monsoon strength in Vietnam. Without a long written history in Vietnam, we need to rely on geoarchives such as lake sediments to reconstruct past monsoon variability and regional paleoenvironmental fluctuations and evaluate current climatic trends. Natural lakes in the Central Highlands of Vietnam have the potential to have recorded shifts of the monsoon belt over glacial/interglacial cycles. Since 2016, the EOS Geoscience Research Group at Vietnam National University, Hanoi (EOS group) has collaborated with international partners to collect and analyze Vietnamese lake sediments to reconstruct the Pleistocene-Holocene climate history. Numerous sediment cores have been retrieved from Biển Hồ, Ia Bang, Ea Tyn, Ea Sno and Lak lakes between 2016 and 2022. Of special importance is a 25 m long sediment core from Biển Hồ Lake (Gia Lai province) covering the last 57 ka, which the team retrieved in April 2021. Sediment cores were analyzed for geochemistry, sedimentology, magnetic susceptibility, and radiocarbon dating. This paper reviews the status of our currently available sedimentary records to assess the paleoenvironmental potential of lacustrine sediments in the Central Highlands of Vietnam. Current data suggest that the lakes in the Central Highlands provide reliable sedimentological and geochemical records and bear the potential to reconstruct the paleoenvironmental and paleoclimatic conditions in Vietnam across several glacial periods, with a high-resolution record at least in the Holocene. The records contribute to quantifying the effects of monsoon variability and assessing the changes in hydrological conditions before and after the onset of human land use by comparing different lakes in the region. Future fieldwork will focus on retrieving longer lake sediment sequences from the Central Highlands, possibly covering the full interglacial-glacial cycle (i.e. the last 125 ka, back to MIS-5e), and on the assessment of comparable lake archives in other parts of Vietnam where the timing and character of monsoon-related climatic variations may have differed.

Keywords: sediment coring, maar lake, tectonic lake, paleoclimate, Asian monsoon, Pleistocene, Holocene.

1. Introduction

Current trends in global warming will likely increase atmospheric humidity and affect the East-Asian monsoon system across Vietnam (Loo et al., 2015). It is essential to evaluate current and potential future trends in global climate change to properly understand past climatic variability at the regional to local

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scale. Without a long written climate history and instrumental records in Vietnam, we must rely on geoarchives, such as lake sedimentary records, recording the paleoenvironmental history. Scientific, political, and public attention on the effect of climate change on ecosystems, including lake ecosystems, is growing. Lacustrine sediments have long been used worldwide for high-resolution palaeoenvironmental reconstruction and environmental monitoring (e.g., Zolitschka et al., 2015; Jenny et al., 2016). Comparative quantitative and qualitative analyses on current hotspots of climate change research show that a total of 10,296 papers associated with climate change and lakes were published in 1266 SCIE-indexed journals from 1991 to 2015 (Deng et al., 2017). Rapid development occurred during these past 25 years and the number of published papers has considerably increased since the 2000s. Before the 2000s, most studies focused on paleolimnology. Specifically, researchers searched for evidence of climate change in lake sediments using traditional paleoclimate proxies such as diatoms and pollen. In more recent studies, the focus shifted towards the multidisciplinary effects of climate change on lake ecosystems (Deng et al., 2017) using a combination of bio-geochemical proxies. However, in a recent study, Escobar et al. (2020) show that the tropics are strongly under-represented in climate-related paleolimnological studies. Even though approx. 40% of the lakes on the Earth, representing almost one-third of the global lake surface area, lie within tropical latitudes, most studies have been carried out in high-latitude regions of the Northern Hemisphere (Kilian and Lamy, 2012; Zolitschka et al., 2015; Jenny et al., 2019). In recent years, some paleoclimatic and paleoenvironmental records from different archives around Southeast Asia have been published, such as pollen records from a Cambodian lake (e.g. Hamilton et al., 2020, 2019), multiproxy records from lakes in Thailand based on pollen, isotopes (e.g. Chawchai et al., 2016, 2013), and leaf waxes (Yamoah et al., 2016), high resolution geochemical records from a varved lake in Myanmar (Sun et al., 2016), and many records from Southern China, for example, lake sediment records based on pollen (e.g. Yang et al., 2016), or stable isotopes (Hillman et al., 2017) and several stalagmite records (e.g. Liang et al., 2020). All these records focus to a large extent on the variability, position, and strength of the main Asian monsoon systems at different timescales from modern records (Loo et al., 2015) over the last 500 years (Sun et al., 2016) to the last 15,000 years (Yang et al., 2016). Yet, comparable palaeoclimate records from Vietnam are almost entirely lacking. Pioneering research on Vietnamese paleoclimate based on tree ring records has been published by Buckley and colleagues in recent years, covering a maximum of the last 1,000 years (Buckley et al., 2010, 2014, 2017, 2019). Hoang-Van et al. (2021) analyzed geochemistry and mineralogy of Vietnamese clay and calculated chemical index of alteration for reconstruction of Quaternary climatic conditons. The first Vietnamese paleolimnological record of hydroclimatic changes inferred from $\delta^{18}O$ values of lacustrine carbonate from a lake in northern Vietnam covers only the last 650 years (Stevens et al., 2018). So far, very few paleoenvironmental studies from Vietnam existing for the Quaternary period focus on the Holocene delta development of the Mekong (Proske et al., 2011), the Red River (Duong et al., 2020; Funabiki et al., 2007), and offshore Southeast Vietnam (Hoang-Van et al., 2021). However, they provide no detailed paleoclimatic reconstructions comparable to lake and stalagmite records from neighboring countries, and the river sediments are chronologically only poorly constrained. Overall, lacustrine sediment cores have not yet been adequately utilized for reconstructing paleoclimate and paleoenvironment in Vietnam due to a lack of coring equipment and analytical capabilities.

Our research exploits a particular lacustrine environment that has been accumulating sediment potentially for at least ~200 ka. The EOS team has collected sediment cores from lakes that were formed in a variety of ways, including filling craters formed in explosive volcanic eruptions in Vietnam's Central Highlands (i.e. maars), lava-dammed waterways and lakes formed by faulted and rifted rock basements (Figs. 1, 2, and 7). The lakes are natural sediment traps, with every monsoon season washing sediment into the lakes and adding to the top of the sedimentary record. The severity of rainfall directly correlates to the amount of sediment transported into lakes. In 2016, Biển Hồ Lake in Gia Lai Province was the first location targeted for the recovery of lacustrine sediment cores. Between 2017 and 2022, we managed to repeatedly retrieve sediment cores from different lakes in the Central Highlands (e.g. Biển Hồ, Ia Bang, Ea Tyn, Lak and Ea Sno lakes) (Fig. 1). The length, depth, and integrity of retrieved sediment cores from the lakes gradually increased over time using our customized piston corer along with improved sampling techniques. In 2021, we reached ~25 m sediment depth in Biển Hồ lake and collected two parallel, overlapping sediment cores. During the latest coring expedition in Ia Bang Lake in April 2022, we retrieved an 18.5 m long sediment core. This paper provides an overview and preliminary results of our research to address the complexity of paleoenvironmental and climatic reconstruction of the monsoon in Vietnam's Central Highlands in the late Pleistocene - Holocene period.

2. Study region

Vietnam's modern climate is generally divided into a temperate North (Köppen-Geiger regimes Cwa, Cwb; Beck et al., 2018) and a tropical South (regimes Am, Aw), with the Hai Van Pass forming a climatic divide. Additionally, the large-scale climate regime is modulated in the highland areas, creating a temperate climate of the Cwb-type in the Lam Dong Province in the Southern Central Highlands. In contrast, in the middle of the Central Highlands, the Aw-type (dry winter) tropical savanna climate is prevalent in Gia Lai and Đắk Lắk provinces. This proximity between temperate and tropical climate zones makes the Central Highlands region particularly sensitive to hydrological climate changes. In a continental-scale context, the Central Highlands are at the heart of the intersection zone of the East Asian Summer Monsoon (EASM) and the Indian Summer Monsoon (ISM). This climate system is socio-ecologically essential but still poorly understood. Some studies hint at teleconnections to El Niño-Southern Oscillation (ENSO) patterns via the Inter-decadal Pacific Oscillation (IPO) (Buckley et al., 2019). Others indicate the impact of the Siberian High (SH) on the East Asian Winter Monsoon (EASW) (Loo et al., 2015), which produces immense precipitation when arriving at the Vietnamese coast, mainly at the windward-facing slopes of the Truong Son mountain range.

The collision between the Indian and Asia continents in the Cenozoic induced widespread pull-apart rifting, strike-slip faulting, and basalt eruptions in Vietnam territory. In the Central Highlands, the eruptions began at ca. 17 Ma and ceased at ca. 0.2 Ma, which built up a thick shield of basaltic rocks and formed volcanic plateaus, including Pleiku and Buôn Mê Thuột at the heart of the highlands (Nguyễn et al., 2013, Nguyen et al., 2019). Distribution of the strike-slip faults and pull-apart basins in South-Central Vietnam shows their systematic relationships to volcanism at the Pleiku and Buôn Mê Thuột basaltic centers.

Our present research focuses on four lakes in the basaltic centers, including two volcanic crater lakes in the Gia Lai province, (1) Biển Hồ Lake (Fig. 1) and (2) Ia Bang Lake (Fig. 2); and two tectonics lakes in Đắk Lắk Province, (3) Ea Tyn Lake and (4) Lak Lake (Fig. 7). Biển Hồ and Ia Bang are typical maar lakes located at the margin of Pleiku volcanic center. Ea Tyn and Lak lakes are located in the southeastern part of the Buôn Ma Thuột volcanic center. The elongated shape of Ea Tyn suggested that the lake developed along a fault, possibly a normal fault which was caused by an east-west directed extensional force. A cluster of Pleistocene volcanoes is about 5 km west of the lake. Therefore, post-eruption thermal cooling of the Earth's crust may also contribute to the subsidence of the lake basement. The origin of Lak Lake is unknown, but it is presumably formed due to pull-apart rifting related to the nearby Neogene-Quaternary volcanism. Additionally, Ea Sno Lake, a lava-dammed lake located west of Ea Tyn Lake, appears as a suitable archive after an initial survey in 2020 (Fig. 7).

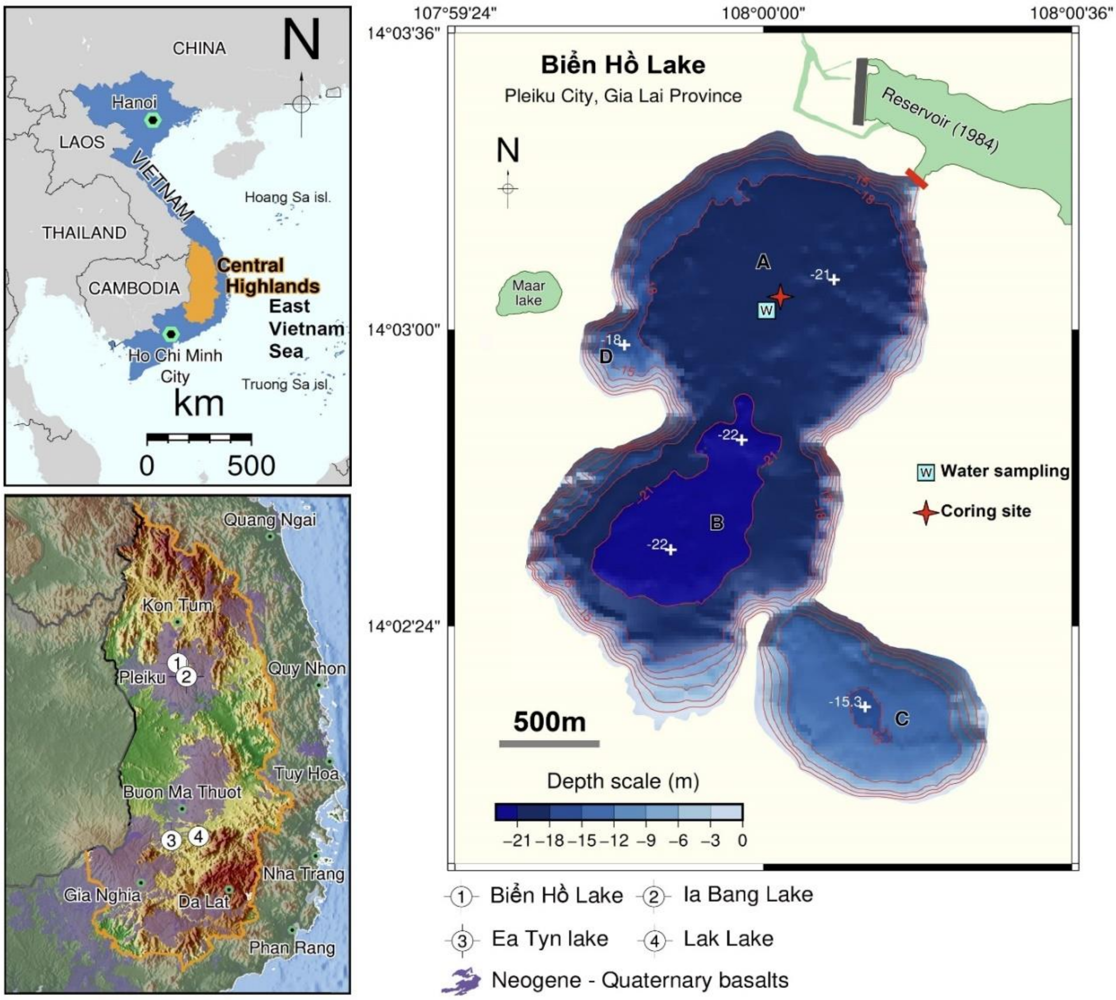

Figure 1. Cenozoic volcanic centers in Vietnam with numerous volcanic craters (e.g. Biển Hồ and Ia Bang) and tectonic basins (e.g. Ea Tyn, Lak and Ea Sno) formed at 17.0-0.2 Ma ago which were filled in with sediment. The right panel shows a bathymetry map with the location of the volcanic crater (A, B, C, and D), and locations of water sampling and sediment coring in Biển Hồ Lake

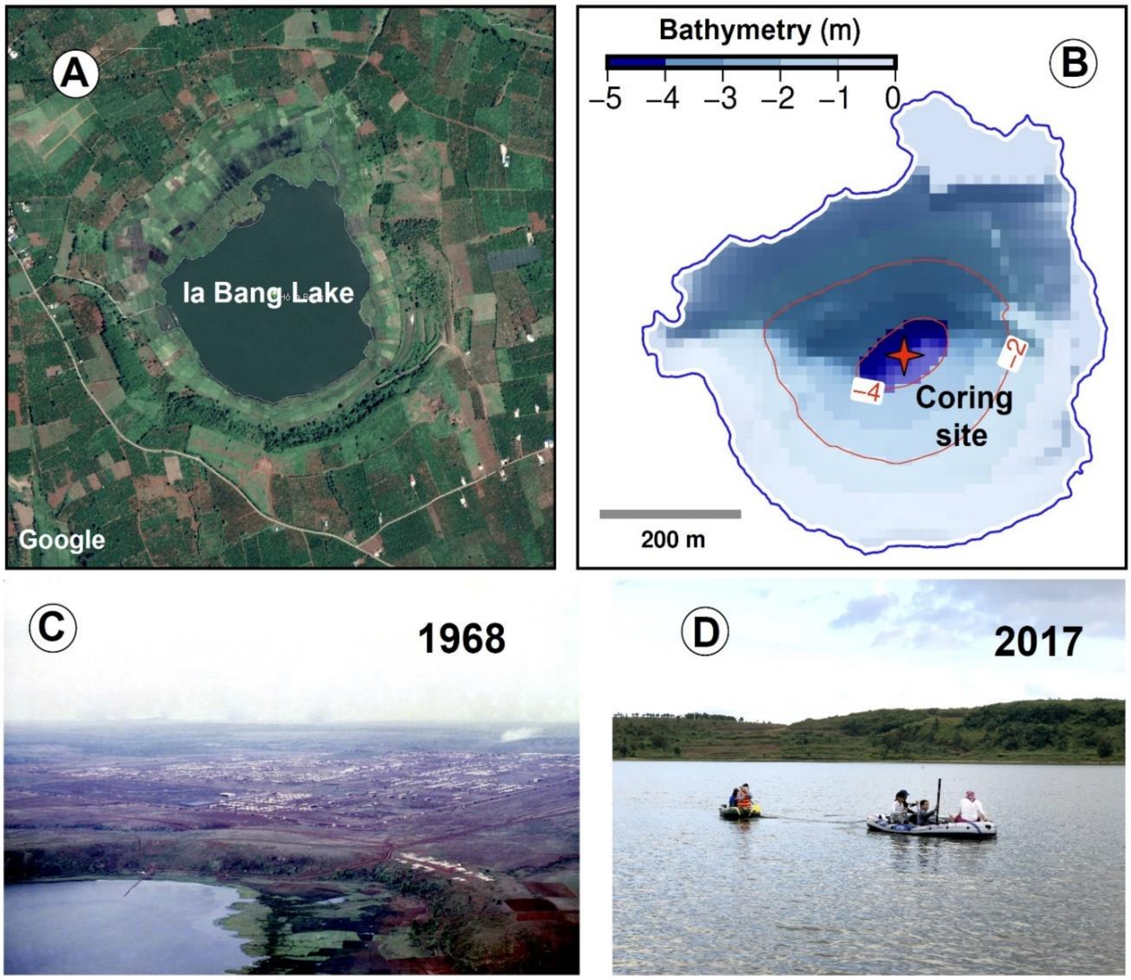

Figure 2. Google image (A) and bathymetric map (B) of Ia Bang volcanic crater lake south of Pleiku City, Gia Lai Province. The lake's bathymetry was mapped from depth measurements taken in November 2017. (C) An aerial view (1968) from the northeast towards Ia Bang demonstrates military use of the area by "Camp Enari" (Image courtesy of Bill Lathan). (D) Sediment coring and bathymetric survey near the deep center of Ia Bang Lake (November 2017, Image courtesy of Minh Ngọc Schimmelmann)

3. Sampling and methods

3.1. Fieldwork

Bathymetric surveys in the Central Highland's lakes were done with a Garmin STRIKE 4 fish finder. The instrument includes a Garmin CHIRP (77/200 kHz) dual-beam transducer and provides reliable bathymetric data throughout our lake coring expeditions. For shallow coring down to ca. 0.8 m, we built an affordable and lightweight Autonomous Gravity Corer (AGC) with a pneumatic core catcher, which we successfully employed for the recovery of undisturbed short sediment cores from Biển Hồ Lake at water depths up to 21 m (Schimmelmann et al., 2018). In Ia Bang, Ea Tyn, Lak, and Ea Sno lakes with water depth shallower than Biển Hồ, we used a Wildco® hand core sediment sampler to obtain surface cores for initial analyses quickly. The sediment/water interface of cores recovered with the hand core sampler was not as well preserved as cores recovered with the AGC.

However, the cores were still sufficient for initial examinations.

A stable coring position is mandatory for taking deeper cores. During the deep coring expeditions in Biển Hồ and Ia Bang lakes between 2016 and 2022, we used a mobile floating platform that was constructed from welded steel pipes and wooden planks (Nguyễn-Văn et al., 2022). Six inflated inner tubes of truck tires were tied to the bottom of the platform for flotation. Anchors for the coring platform were made from metal-wire chicken coops filled with ~25 kg of rocks each and tied to the platform with polyethylene ropes. We successfully held our position in about 19-20 m deep water after dropping four anchors at distances of ~50 m from the platform's four corners in Biển Hồ Lake. Ea Tyn Lake is located in an area that is more difficult to access, so we designed a new coring platform using lightweight materials. For the new platform, the welded steel pipes were replaced with acrylonitrile butadiene styrene (ABS) coated steel pipes connected *via* metal joint sets.

In contrast, wooden planks were replaced with composite plates. Two or three long polyethylene ropes connected the platform to trees on shore and facilitated the movement of inflatable supply vessels between the platform and the shore. The long ropes were an essential support for maintaining a steady coring position in shallow lakes such as Ia Bang and Ea Tyn where chicken-coop anchors occasionally moved when the wind was moderate, even if they drooped at distances further than 100 m from the platform.

For deeper coring, we designed and built a customized piston corer that uses a steel pin to lock the movable piston into the bottom of the core liner before lowering the device into the water column (Nguyễn-Văn et al., 2022). Several segments of metal rods with quick-release threads manually lower the piston core to a pre-determined depth just above or within the sediment. A sharp pull on a steel cable releases the pin, followed by tying the steel cable to the coring platform to keep the piston at a pre-determined depth. Further pushing of the metal rods inserts the core liner into the sediment. At the same time, the piston is kept at a stationary depth, generating a vacuum in the upper portion of the core liner. As a result, the sediment core does not suffer from 'core compression' when sediment enters the core liner. Coring at each lake site involved the retrieval of two parallel cores with a 50 cm vertical offset to close gaps in the entire sediment sequence due to the incremental coring of 1 m piston segments. The piston corer successfully recovered sediment segments down to ca. 25 m depth in sediment in April 2021 in Biển Hồ Lake.

Along with bathymetric surveys and sediment coring, physical and chemical parameters of lake water, including pH, temperature, dissolved oxygen (DO), and electric conductivity (EC) were also measured. In October 2018 and March 2019, Biển Hồ and Ea Tyn Lake water was sampled using a custom-built Van Dorn-type bottle and then measured for DO, EC, turbidity, temperature, and pH with an YSI™ ProDSS digital. In April 2022, the parameters of Biển Hồ Lake water were measured with the same type of instrument but with a long cable which provided more accurate *in-situ* measurements and reduced time consumption.

3.2. Analytical methods

Initial core analyses: Sediment cores have been split, subsampled, and mainly analyzed at Vietnam National University, Hanoi (VNU). Initial core analyses include core photography, magnetic susceptibility, sedimentology, and loss-on-ignition. Correlations between different cores and a master depth-profile were generated for the cores based on the sedimentological description (i.e. sediment components and lithology, structures, color, unconformity surfaces), color photographs, and most importantly downcore variation of magnetic susceptibility. Magnetic susceptibility was logged with a Bartington MS2E surface-scanning sensor at 1 cm resolution. The profiles of pore water and organic matter (OM) contents (wt. %) were determined *via* the weight loss after freeze-drying or 100°C heating and 550°C heating.

Dating techniques: Samples of macrofossil terrestrial plant fragments and total organic carbon (TOC) from our 2016-2022 sediment cores were selected for Accelerator Mass Spectrometric (AMS) radiocarbon age measurement. The radiocarbon dating for Biển Hồ and Ea Tyn sediment cores were performed at National Ocean Sciences Accelerator Mass Spectrometry (NOSAMS) facility at Woods Hole Oceanographic Institution and the ^{14}CHRONO Centre for Climate, the Environment and Chronology at Queen's University Belfast. Ia Bang sediment core was radiocarbon dated at Nagoya University. Additionally, the youngest sediments up to a sediment depth of ~1.3 m from Biển Hồ and Ea Tyn lakes were dated with ^{137}Cs (cesium-137) at the Geological Survey of Finland using a fully digital BrightSpec bMCAUSB pulse height analyzer coupled to a well-type NaI(Tl) detector. After the availability of the ^{14}C dates an age-depth model of the respective core is established using the R-package *rbacon* (Blaauw and Christen, 2011). The models are usually created in 1 cm intervals with the default settings of *rbacon*. While the radiocarbon dates are implemented for the international calibration curve IntCal20 (Reimer et al., 2020), the ^{137}Cs dates are already included as calendar years. All dates are reported with 1σ-uncertainty ranges following (Mook and van der Plicht, 1999) and as calibrated calendar years before the present (cal BP), where the present is 1950 CE (Fig. 5). Paleomagnetic dating and tephrochronology for the Biển Hồ sequence are currently being analyzed, which we hope will further refine and extend the ^{14}C-based age-depth modeling. The evaluation of these data, especially correlations with known periods of climatic variability, was then defined as the sampling strategy for the destructive analyses.

4. Preliminary records

4.1. Biển Hồ Lake

Biển Hồ is a cluster of at least four fused volcanic craters (A, B, C, and D in Fig. 1) forming a maar lake about 7 km north of Pleiku City, Gia Lai Province. It is a flat-bottomed lake characterized by a large depositional basin. Biển Hồ serves as the main freshwater source for the provincial capital Pleiku and local agriculture around the western rim of the maar. Photographs taken in the 1970s by U.S. military personnel occasionally indicate low water levels allowing heavy military vehicles to drive onto dry, exposed terraces in the maar. The lake was also used for recreational purposes, which led to severe environmental degradation. Our combined data from our 2016-2021 bathymetric surveys at Biển Hồ lake show that the current maximum water depth is ~21 m (Fig. 1).

Physical and chemical parameters of Biển Hồ water, including dissolved oxygen (DO), electric conductivity (EC), turbidity, temperature, and pH were measured repeatedly in October 2018 and April 2022 for the entire water column at 1 m resolution at three sites in the lake. Profiles of pH, temperature, DO, and EC along the water column in both October 2018 and April 2022 portray consistent lake water composition and stratification (Fig. 3). Notably, the DO and temperature profiles indicate a significant thermocline and a steep oxycline occurring at ~8 to 10 m water depth (Fig. 3). The observations also indicate that a stronger thermocline occurs in April 2022 compared to October 2018 due to warmer surface water heated by stronger summer insolation, which may prevent the wind-driven mixing of surface and deep water in Biển Hồ. The depletion of DO in Biển Hồ Lake's protects modern laminated sediment from macrobenthos and bioturbation.

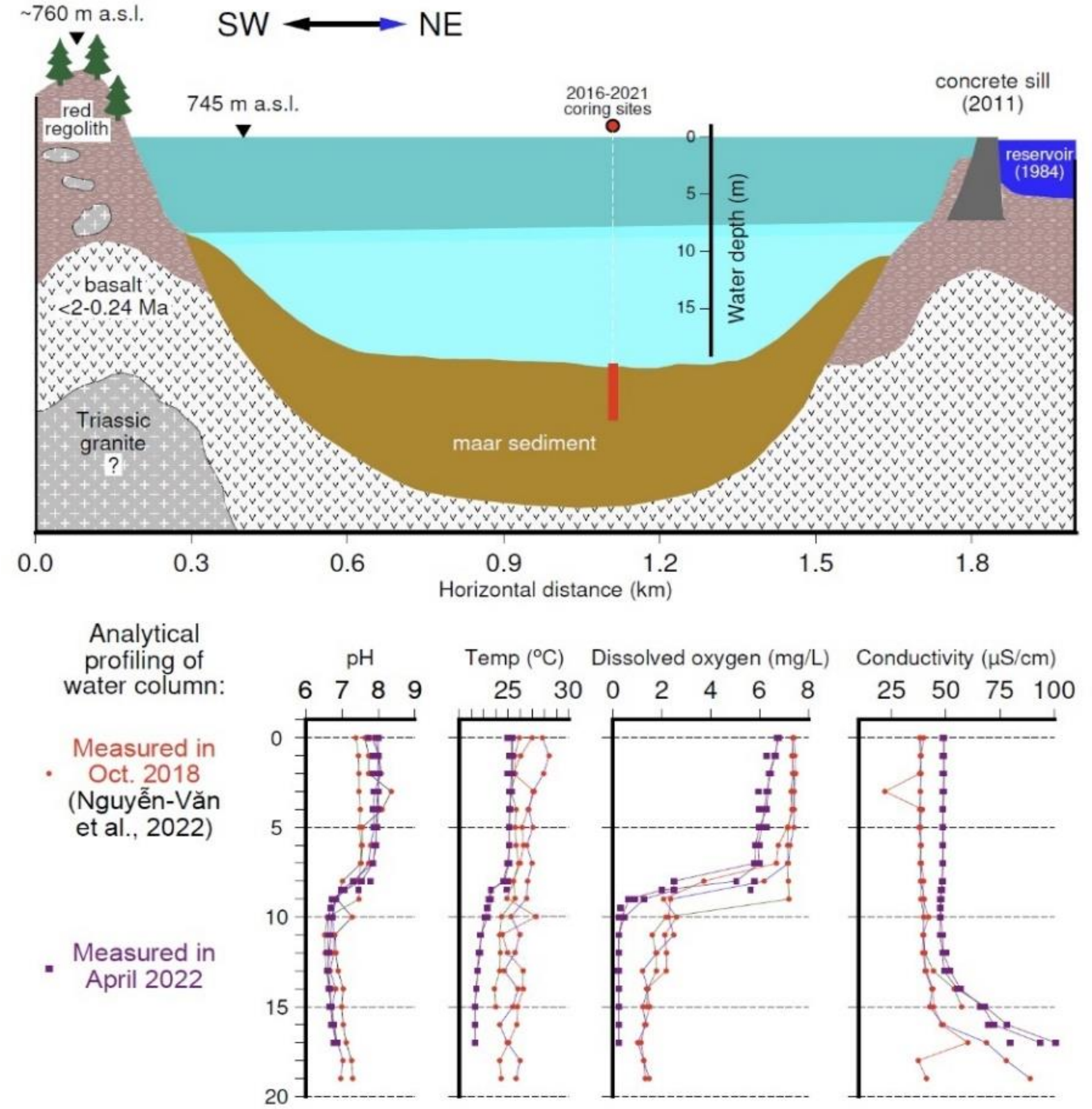

Figure 3. The pH, temperature, dissolved oxygen (DO) profiles, and electric conductivity (EC) along the Biển Hồ water column were repeatedly measured at three locations in October 2018 and April 2022. The two water colors indicate the relative position of oxycline and thermocline. Schematic geo-hydrology of the lake and the October 2018 data is reproduced from Nguyễn Văn et al., 2022

In field campaigns between 2016 and 2021, numerous gravity and piston cores were recovered with lengths of up to ~25 m (Fig. 4). The Biển Hồ sediment sequence has a homogenous sediment composition with a high water content (~70-85 wt. %) and can be divided into two main lithofacies, (1) dark olive silty clay and (2) olive-gray diatom-rich silty clay. Dominance of clay was observed in the upper approximately

6 m. In the uppermost 0-6 m, magnetic susceptibility varies widely between 40 and 180 SI×10^{-5} and organic matter varies similarly within 10-30 wt. %. Below ~6 m sediment depth, magnetic susceptibility varies only between 20 and 80 SI×10^{-5}, while organic matter remains relatively stable around 10 wt. %.

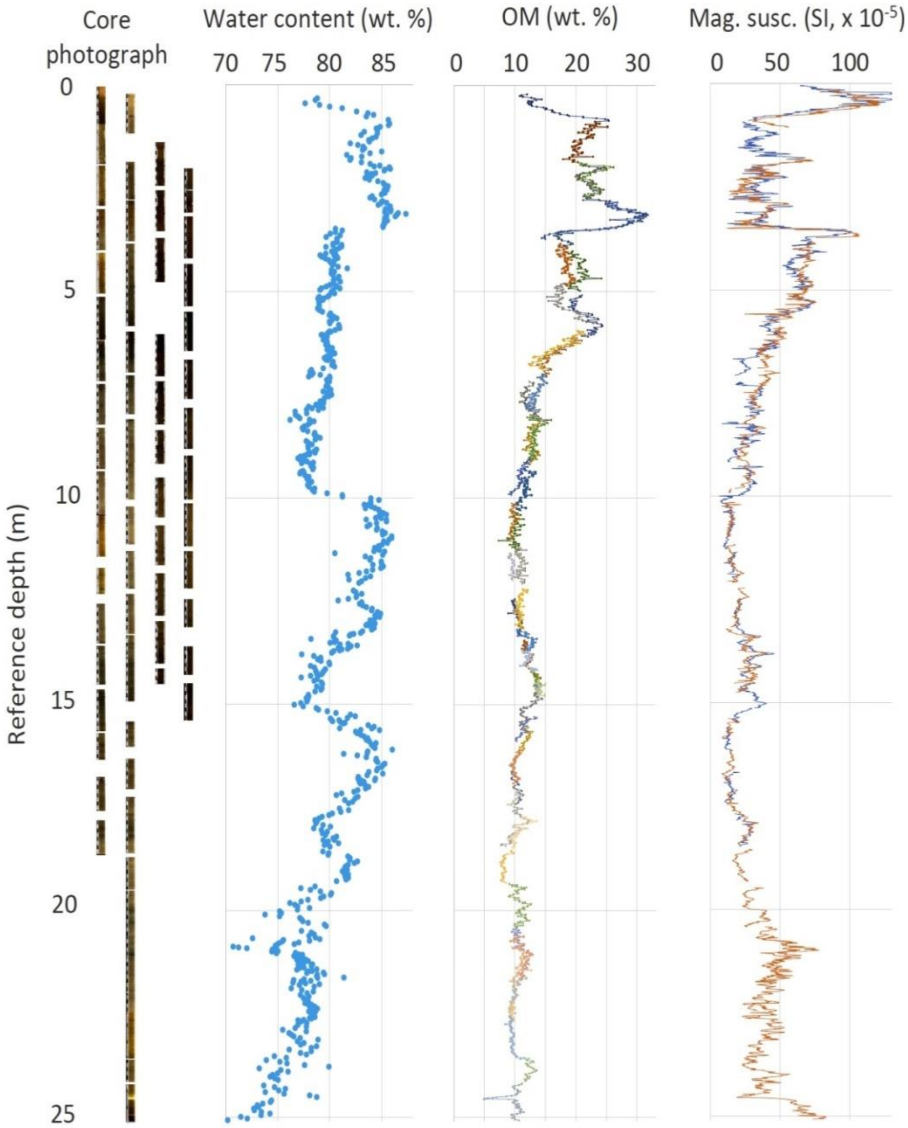

Figure 4. Overlapping piston cores retrieved in Biển Hồ Lake in 2018 and 2021 and downcore variations in water content, organic matter (OM) and magnetic susceptibility (Location indicated in Fig. 1)

Despite limited airborne fallout in Vietnam from nuclear testing and accidents, 4 events were identified based on our ^{137}Cs stratigraphy in Biển Hồ core (Nguyễn-Văn et al., 2022; Ojala, Nguyễn-Văn et al., in review). The dating indicates a significant increase in sedimentation in recent decades due to anthropogenic activities. ^{14}C ages of terrestrial plant fragments and bulk organic carbon suggest continuous sedimentation across the currently available 25 m core length, corresponding to an age of 57 ka BP (Ojala, Nguyễn-Văn et al., in review). This translates into an average sedimentation rate as low as 0.044 cm/yr (Table 1).

Table 1. Summary of the paleolimnological research sites in the Central Highlands of Vietnam

No.	Lake with maximum water depth	Coring campaign	Core depth (m)	Lithology	Average organic matter (wt. %)	Magnetic susceptibility (SI × 10^{-5})	Date of core bottom based on ^{14}C age-depth-model	Average sedimentation rate
1	Biển Hồ (21 m)	2016 2017 2018 2021	0-1.0 0-4.2 0-15.3 0-25.1	Silty clay and diatom-rich silty clay	15	20-180	57 ka cal BP	0.044 cm/yr
2	Ia Bang (5 m)	2017 2022	0-0.8 0-18.5	Organic- rich silty clay	25-35	5-35	22.5 ka cal BP	0.085 cm/yr
3	Ea Tyn (5 m)	2019 2020	0-0.5 0-8.7	Clayey silt	11	15-50	1.25 ka cal BP	0.7 cm/yr
4	Lak (2 m)	2019	0.5	Organic-rich silty clay		3-10		
5	Ea Sno (8 m)	2020	0.5	Clay		100-200		

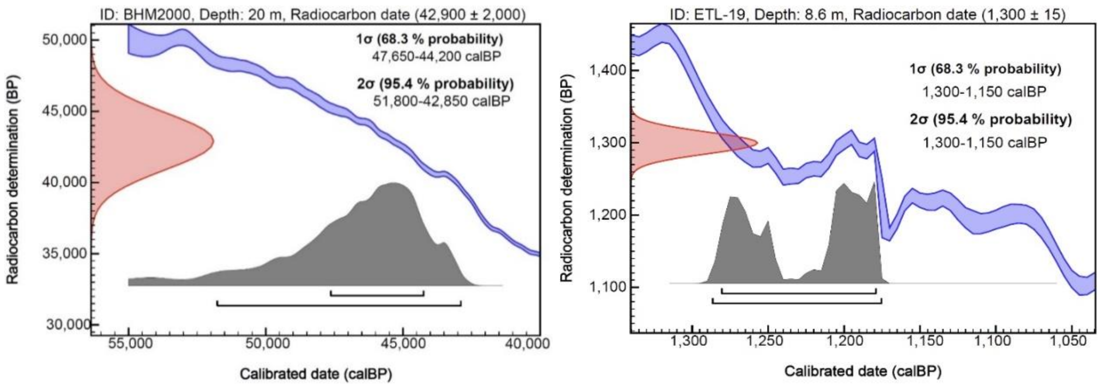

Figure 5. (Left) A ^{14}C date of Biển Hồ sample located at a reference depth of 20 m in the sediment core represents the huge 2σ uncertainty range of nearly 3,000 years (1 σ range) or 9,000 years (2σ range) after calibration. (Right) A ^{14}C date of Ea Tyn was sampled at a reference depth of 8.6 m near the core bottom. Both samples were calibrated with respect to the calibration curve IntCal20 (Reimer et al., 2020) using OxCal 4.4 (Bronk Ramsey, 2009)

4.2. Ia Bang Lake

Ia Bang Lake is a crater lake located in Gia Lai province, surrounded by steep and forested crater-wall slopes with the maximum depth ca. 5 m in the central area (Fig. 2). A 0.8 m surface sediment core was collected in November 2017 showing dark olive clay with low magnetic susceptibility at the top half of the core and grayish laminated clay at the bottom half (Fig. 6). During a field campaign in April 2022, two parallel and overlapping piston cores were retrieved to a sediment depth of 18.5 m. The sediment cores were split, described, and analyzed for sediment characteristics, loss-on-ignition, and magnetic susceptibility. We divided the Ia Bang sediment sequence into two main lithofacies: dark olive organic-rich silty clay and light gray laminated clay. Sediment units with dark olive color have a high organic matter content (~40-50 wt. %) and very low magnetic susceptibility (~5 SI × 10^{-5}). On the contrary, laminated sediment units with light gray color contain 20 wt. % of organic matter and higher magnetic susceptibility (~35 SI × 10^{-5}) 26 ^{14}C samples were taken along the 18.5 m long Ia Bang sediment core. The age-depth model produced in *rbacon* yielded a basal age of 21.7 ka cal BP. This corresponds to an average sedimentation rate of 0.085 cm/yr, approximately twice as high as in Biển Hồ Lake (Table 1).

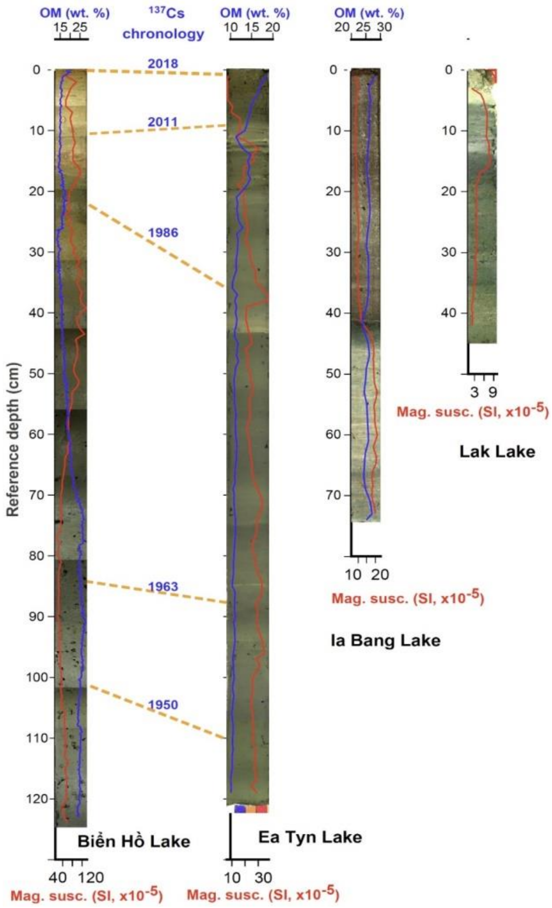

Figure 6. Orthomosaic photographs of surface sediment cores with well-preserved sediment/water interface retrieved from Biển Hồ, Ea Tyn, Ia Bang, and Lak lakes between 2017 and 2020, and downcore variations in organic matter (OM, blue line) and magnetic susceptibility (Mag. Susc., red line) (Locations indicated in Figs. 1 and 7). ^{137}Cs chronology is from Nguyễn-Văn et al., 2022 and Nguyễn-Đình et al., 2022

4.3. Ea Tyn Lake

Ea Tyn Lake is located in the Central Highlands in the center of the Nam Kar Biosphere Reserve, about 30 km south of the City Buôn Ma Thuột in Đắk Lắk Province, at an altitude of about 420 m above sea level. The 3.6 km long lake with an average width of 200-400 m and a catchment size of about 10 km² formed along an east-west directed tectonic fault in an area dominated by Jurassic sandy to silty sedimentary rocks (Nguyễn-Đình et al., 2022). The lake is limited to the north and south by two small mountain ridges, the highest peak reaching ~730 m above sea level. A small ephemeral brook at the valley floor irrigates small rice paddy fields and banana plantations. The lake has a natural outlet in the west toward the Krong No River, flowing at a distance of a few hundred meters.

The morphology fosters precipitation-induced erosion along the hill slopes resulting in a high sedimentation rate in the lake. Local fishermen reported that the lake used to have a "green" color for many years, hence calling the lake also "Bầu Nước Xanh" (green-blue water lake). The modern maximum water depth is ~5 m with small seasonal changes (Fig 7). We surveyed Ea Tyn Lake in March 2019 to collect water parameters and surface sediment cores. The pH of the lake water constantly decreases from the air/water interface to the lake bottom (~4.5 m) water depth. EC and temperature profiles show no significant changes along the water column due to the shallow water level of the lake (Fig. 8). The DO profile indicates a steep oxycline occurring at ~1.5 to 2 m water depth. A distinct smell of hydrogen sulfide in a fresh bottom water sample indicated anoxic bottom water.

In March 2020, we retrieved two parallel sediment cores (ETL-C3 and ETL-C4 cores) with a total depth of 8.7 m from Ea Tyn Lake. The horizontal distance between the two coring sites is about 3 m. ETL-C3 starts at the lake's bottom at 0 cm depth and ends at 774 cm. ETL-C4 starts at 42 cm depth and ends at 877 cm (Fig. 9). The 877 cm long sedimentary sequence was subdivided into 14 sedimentary units based on sedimentological properties, color, texture, and organic macrofossils. The sediment is composed of dark grayish-brown to yellowish-brown clayey silt. The Ea Tyn sedimentary sequence chronology is based on 12 AMS ^{14}C and 4 ^{137}Cs dates derived from plant macrofossils and covers the last 1,250 years (Fig. 5). Hence, with 0.70 cm/yr, the sedimentation rate in Ea Tyn lake is approx. 15 times higher than in Biển Hồ Lake (Table 1).

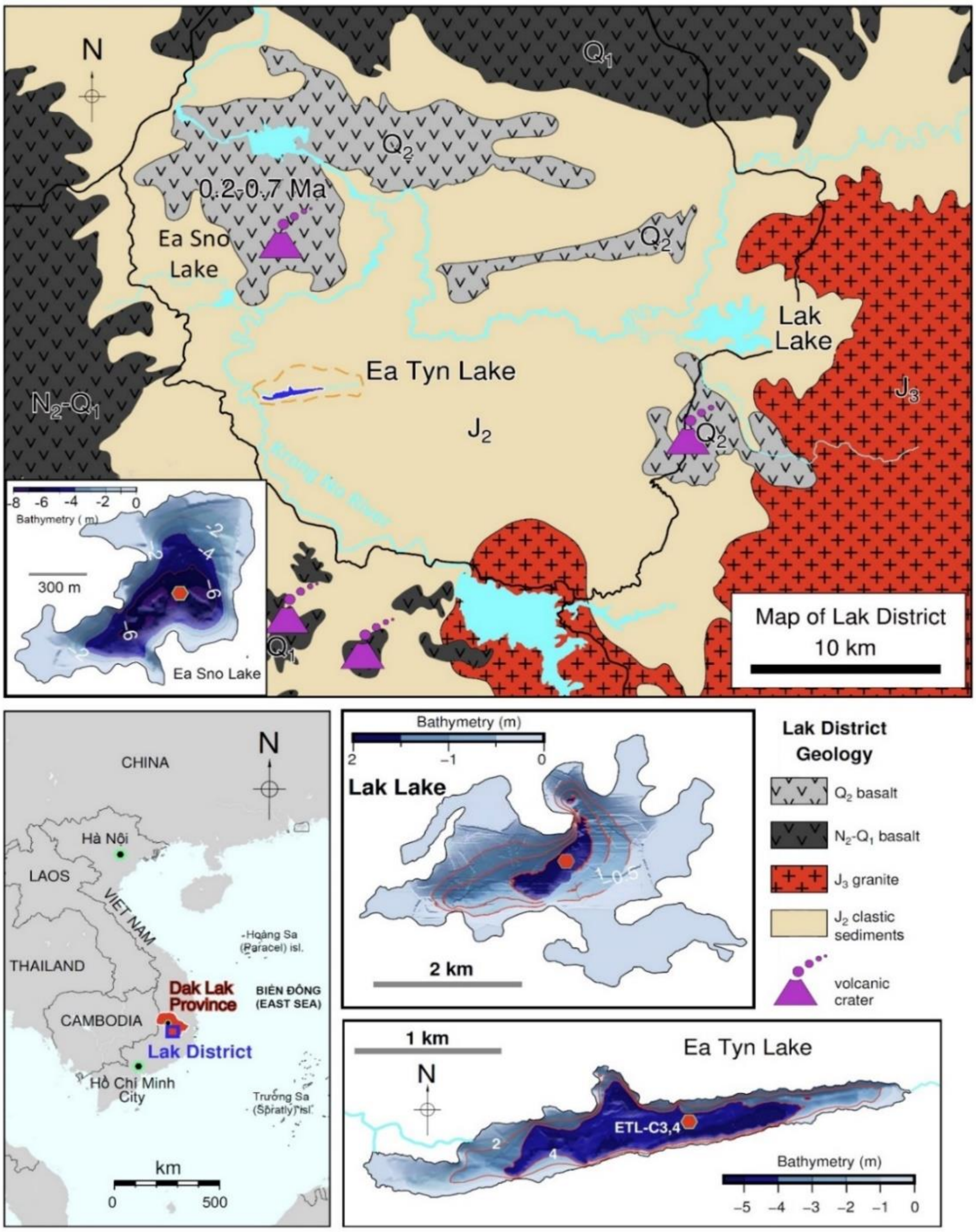

Figure 7. Maps of Ea Tyn, Lak, and Ea Sno lakes in and near Lak district (Đắk Lắk province) and their spatial context in the Central Highlands of Vietnam and Southeast Asia. Bathymetric maps of the lakes with the locations of sediment cores collected in 2019 and 2020. The geological map of Lak District is reproduced from Nguyễn-Đình et al., 2022

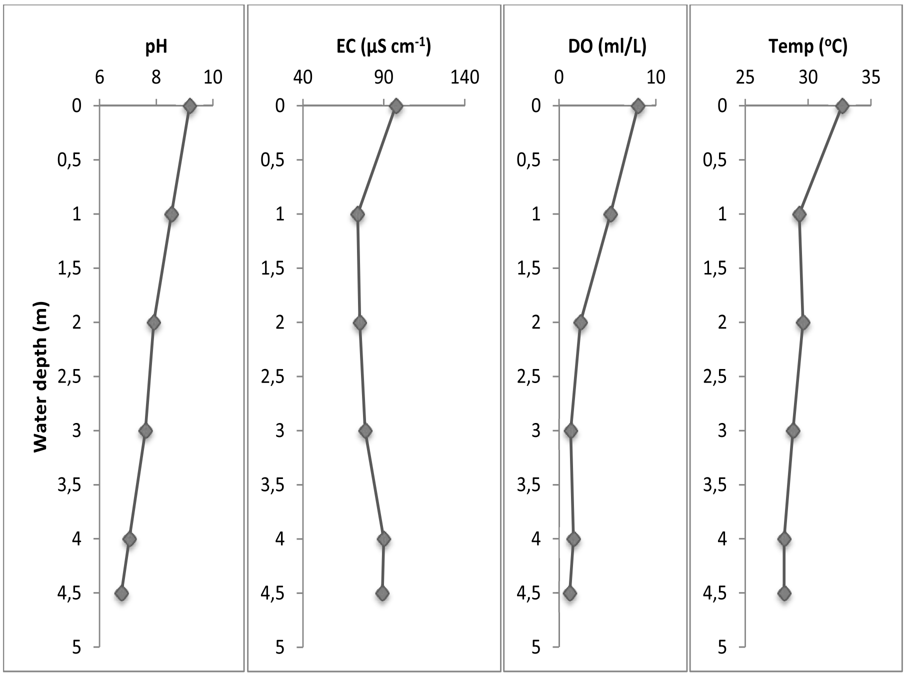

Figure 8. A pH, temperature, DO, and EC profile along the Ea Tyn Lake water column measured in March 2019 (Locations near the coring sites indicated in Fig. 7)

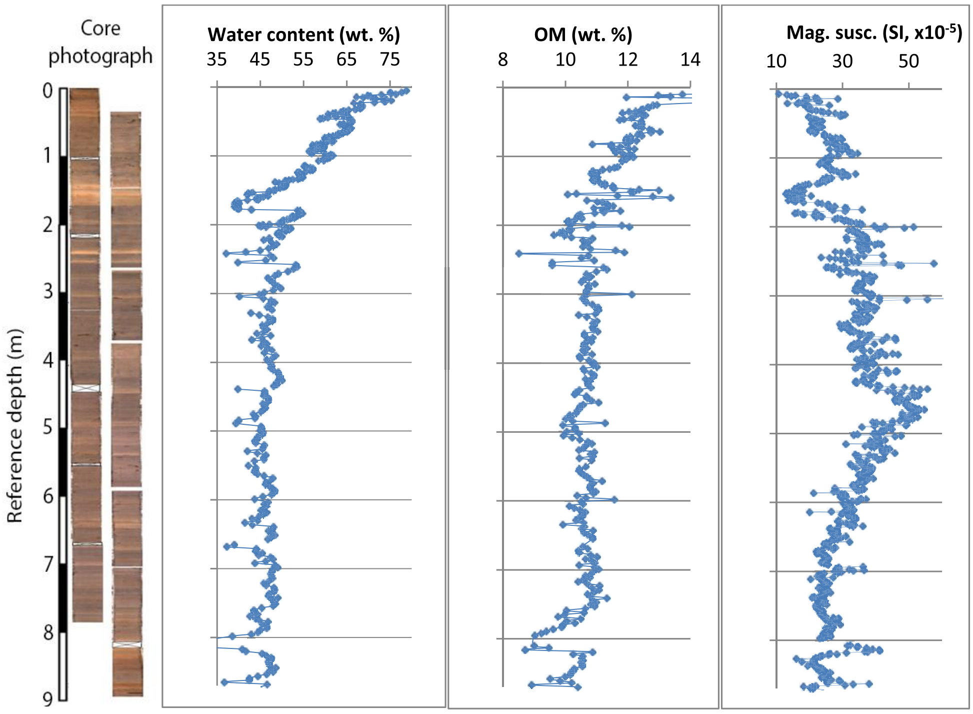

Figure 9. Photographs of sediment core segments retrieved in Ea Tyn Lake in 2019 and 2020 and downcore variations in water content, organic matter (OM) and magnetic susceptibility. (Location in Fig. 7). OM data originated from Nguyễn-Đình et al., 2022

4.3. Lak Lake and Ea Sno Lake

Lak Lake, Vietnam's second largest natural lake was surveyed in March 2019. It is only 1.8 m deep and has a varying size between 7 km² during wet seasons and 4 km² during dry seasons (Fig. 7). The catchment of Lak Lake is significantly larger and flatter than that of Ea Tyn Lake, and is intensively used for agriculture, mainly rice paddy fields. In a recent study, Dao (2016) compared the ecological lake properties of Lak Lake with Biển Hồ Lake, providing modern analogues for comparing the palaeoecological records of both lakes. The results of Dao (2016) show that the current surface water conditions of the two lakes were comparable in terms of physical properties and trace metal concentrations and favored phytoplankton growth. Nitrogen and phosphorus concentrations were generally higher in Lak Lake than in Bien Ho Lake and fostering the development of phytoplankton whereas nitrogen concentration in Bien Ho seemed to limit algal growth. Beyond that, Bien Ho seems to show a stronger seasonal contrast in lake water conditions than Lak Lake (Dao, 2016). Our 50 cm long surface sediment core from Lak Lake consists of dark to grey organic-rich silty clay with low magnetic susceptibility (Fig. 6). The magnetic susceptibility of Lak sediment is the lowest of all investigated lakes in the Central Highlands.

Ea Sno Lake, al lava dammed lake with a maximum depth of 8 m and a surface area of 0.7 km² appears as a further suitable geoarchive in the region and was surveyed in March 2020 with respect to accessibility and bathymetry (Fig. 7). Two 0.5 m long sediment cores were retrieved for initial analyses. The cores consist of light gray clay with high magnetic susceptibility and low organic content (Fig. 6, Table 1). The magnetic susceptibility of Ea Sno sediment is the highest when compared to Biển Hồ, Ia Bang, Ea Tyn and Lak sediments.

5. Perspective

Vietnam is vulnerable to weather-related hazards and the effects of climate change. Storms and floods are the most frequent and severe natural hazards affecting Vietnam. According to the SREX Vietnam report 2015 (IMHEN and UNDP, 2015), Vietnam is targeted by an annual average of 6 to 7 typhoons. Between 1990 and 2010, 74 floods occurred in the river systems of Vietnam. Severe drought, saline water intrusion, landslides, and other natural hazards are also impeding Vietnam's development. Extreme natural disasters have become more frequent in recent years, inflicting hardship for people and negatively impacting the economy (IMHEN and UNDP, 2015). Precipitation in the Central Highlands is sensitive to reorganization of large scale climate patterns, such as the positioning and strength of the Intertropical Convergence Zone (ITCZ) impacting the monsoon system and typhoon strength, the strength and frequency of El Niño Southern Oscillation (ENSO), and related shifts in the Pacific Walker Circulation. The Central Highlands are one of the regions most sensitive to ENSO in Vietnam, with El Niño events causing severe droughts and, thus damage to agriculture and the livelihoods of people in the region (CGIAR, 2016). The drought episode in 2003 reduced coffee production by about 25 % (CGIAR, 2016). Domestic water supplies were also threatened. Main rivers' discharge was reduced by 20 to 90 % during the severe 2015-2016 drought (CGIAR, 2016). By early April 2016, water supplies in most reservoirs in the Central Highlands declined to 10-50 % of their capacity. Hundreds of small lakes in Kon Tum, Gia Lai and Dak Lak provinces ran dry (CGIAR, 2016). Long-term planning by policymakers should be based on a realistic assessment of perceived climatic trends combined with knowledge of the long-term history of monsoon variability and regional rainfall patterns. Unfortunately, Vietnam's historical archives don't reach far enough to provide an adequate picture of historical rainfall and flooding, let alone descriptions of how the environment looked hundreds of years ago before colonialism and incipient industrialization changed the landscape and affected Vietnam's environment. Global data in observing rainfall patterns in Vietnam, such as Global Satellite Mapping of Precipitation, still exhibited high biases in the rainy season and topographically heterogeneous areas (Pham-Thi et al., 2021). The instrumental weather record for Pleiku reaches back only to 1961. The data shows an increase in daily minimum temperature with a warming rate of about 0.21-0.34°C per decade, but it does not show a significant increase or decrease in annual total rainfall in Pleiku (Phan et al., 2013). Over Southeast Asia, the drought characteristics for the mid and late 21st century are projected to become shorter and more severe for Representative Concentration Pathway (RCP) scenarios RCP8.5 in the late 21st century (Nguyen-Ngoc-Bich et al., 2022), but comparison with observations indicates that model uncertainties are high over some regions.

Strong monsoonal rainfall normally occurs between May and October in the Central Highlands, which is the most important reason for sediment transport from catchments into lakes due to the lack of large rivers entering or leaving the catchment of the volcanic lake basins. Sedimentation during the dry winter in such lakes is predominantly organic-rich (autochthonous), whereas the monsoon-related summer sedimentation is mineral-rich (allochthonous) (Nguyễn-Văn et al., 2022). Multiproxy analyses, including sedimentological and geochemical characteristics of the lake sediment records, help reconstruct the local and regional environmental history with respect to both long-term trends and extreme weather events and anthropogenic changes in hydrology across several millennia.

Biển Hồ's fascinating paleoecological history was photographically documented in detail for the past ca. 70 years (Nguyễn-Văn et al., 2022) which provides a robust foundation for the interpretation of Biển Hồ's deeper sedimentary record. The Biển Hồ sediment core currently has the longest and best chronology compared to Ia Bang and Ea Tyn lakes due to a large number of ^{14}C dates combined with paleomagnetic measurements (Ojala, Nguyễn-Văn et al., 2023, in review). However, the bottom of the 2021 Biển Hồ core show huge dating uncertainties as it approach the limits of the ^{14}C dating method around 55 ka BP. In addition to paleomagnetics, it is also desirable to combine with other dating methods such as tephrochronology, or apply wiggle matching with isotope or pollen chronologies to enhance age-depth models of lakes from the Central Highlands that reach well back into the Pleistocene.

Due to the lack of carbonate minerals or shells in Biển Hồ, Ea Tyn and Ia Bang sediments, we cannot rely on $\delta^{18}O$ analysis for paleotemperature reconstruction. Analyses of XRF-based elemental ratios, C/N ratio and $\delta^{13}C$ are currently our most effective approach to document significant paleoenvironmental and paleoclimatic changes. Biomarkers, pollen, and diatom data can supplement the geochemical data. Furthermore, initial, unpublished tests on compound-specific δ^2H values expressing the $^2H/^1H$ ratio of n-alkanoic C_{28} acid from terrestrial plant leaf waxes from Biển Hồ lake point to a potential proxy for paleoprecipitation, evaluating changes in effective moisture availability in the Central Highland (K.E. Doiron and S.C. Brassell, pers. comm.). Our preliminary data also suggest that aquatic sponge-related biomarkers and the excellent preservation of fossil sponge spicules in Biển Hồ sediment contrast with poor preservation of those proxies in other/older lake sediments (Doiron et al., 2019). Thus, for further analyses such as total organic carbon (TOC), total nitrogen (TN), stable isotope ratio of carbon ($^{13}C/^{12}C$), grain size, mineral composition and microfossil analyses, we need to rely on chronological data to determine the subsampling strategy for the sediments.

Ea Tyn Lake has a much higher sedimentation rate (ca. 0.70 cm/yr) compared to Biển Hồ (ca. 0.044 cm/yr) and Ia Bang (ca. 0.082 cm/yr). This high sedimentation rate in Ea Tyn Lake allows paleoclimate reconstructions at least during the late Holocene with a much higher temporal resolution than in the other lakes. However, the total thickness of the lake sediments at Ea Tyn is not known yet; thus, it is not clear how long the climate record reaches. XRF-based elemental proxies and principal component analysis were effectively used with the available Ea Tyn core to reconstruct at least 12 drought events, some of which appear to be of supraregional significance as they coincide with historically documented droughts in India, China, and Cambodia (Nguyễn-Đình et al., 2022). Furthermore, the Rb/Sr elemental ratio along the Ea Tyn sediment sequence reflects long-term monsoon variability throughout the last millennium, which was previously only reconstructed via $\delta^{18}O$ speleothem records from China and India (Nguyễn-Đình et al., 2022). Future analyses of pollen, diatom, and stable isotopes of the Ea Tyn sediment core will contribute to understanding climate history at decadal resolution. For Biển Hồ and Ia Bang sediments, the lower sedimentation rate and dating uncertainty only allow a multidecadal to the centennial resolution of the climate reconstructions. However, the integration of the three lake records from the Central Highlands of Vietnam and their comparison to records from other archives in Southeast Asia provide valuable data for regional-scale modeling of paleoclimate variability for Southeast Asia.

6. Conclusions

Future work can extend the Central Highlands' lakes record further back in time. Studies on changes in land cover and land use in the region may yield information on monsoonal variability on regional vegetation. Our sediment coring in the Central Highlands's lakes is currently limited by the available equipment, which sometimes makes it difficult for the coring team to push deeper into relatively hard sediments manually. We also found it relatively difficult to extract the entire coring string to the platform surface after sampling due to the high friction and the weight of the coring rods. Here, improved piston coring equipment would facilitate extending the sedimentary record back through earlier glacial-interglacial cycles, especially in Biển Hồ. We plan to improve the entire sampling procedure and equipment such as using a tripod with a pulley to reduce manpower consumption in the field, reducing the diameter of core head, and lower the PVC casing further down that will help keeping the metal push rods straight and also let us re-enter the same hole repeatedly. Reaching basaltic bedrock in the center of Biển Hồ would constrain the age of the last volcanic eruption, which is estimated to be roughly 200 ka BP. This estimate would potentially allow a paleoclimate record reaching at least back to the Eemian, i.e. MIS 5e (approx. 125 ka BP).

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