Tracing earthquakes through lake sediments for better prediction

Dada Yan[1,2,*] **and Hao Long**[3]
[1]Institute of Geosciences, Friedrich-Schiller-Universität Jena, Jena 07749, Germany
[2]Faculty of Geosciences and Environmental Engineering, Southwest Jiaotong University, Chengdu 611756, China
[3]State Key Laboratory of Lake Science and Environment, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences (NIGLAS), Nanjing 210008, China
*Correspondence: dada.yan@uni-jena.de

Received: January 26, 2024; Accepted: May 20, 2024; Published Online: May 22, 2024; https://doi.org/10.59717/j.xinn-geo.2024.100077

Citation: Yan D. and Long H. (2024). Tracing earthquakes through lake sediments for better prediction. The Innovation Geoscience **2(3)**: 100077.

Intensive climatic extremes and frequent earthquakes, both in China and other regions, have captured public attention recently. The Tibetan Plateau at middle northern latitudes boasts large glacier and snow coverage, coupled with frequent tectonic activities, exerting profound yet poorly understood influences on zonal atmospheric motion and energy flux during interhemispheric coupling. This study proposes a comprehensive process-based approach involving multi-proxies focused on alpine lakes to illuminate the intricate interactions among tectonics, glacial processes and hydro-climatic variations. This perspective can enhance our understanding of the spatiotemporal diversity of the local-to-global hydro-climatic change pattern, particularly forced by Tibetan Plateau, and suggests to consider its combined summer thermal and tectonic forcing. Additionally, the approach provides unbiased geological data extracted from lakes, contributing to the optimization of hazard and climate models for better predictions of tectonics, abrupt and irreversible climate tipping points with confidence.

Lake sediments can uniquely archive strong seismic shaking as specific deposits or deformation structures within the lacustrine sedimentary infill, and therefore they are considered as high-quality 'natural seismographs', a concept initiated in the pioneer studies during the 1970s to 1990s.[1] Many deep lakes exhibit continuous sedimentation, allowing the preservation of earthquake-induced deposits and structures in a continuous long-sequence. During the last decade, publications on lacustrine paleoseismology have increased notably fast. The primary objective is to ascertain potential scenarios of paleo-earthquakes in terms of magnitude and rupture location, while also constraining the frequency and temporal variability of strong earthquake recurrence near plate boundaries.[1,2] This thriving discipline is widely applied in tectonic domains, including subduction, transform and intraplate zone. Despite this, geological evidence of small and moderate-sized earthquakes with high recurrences is rarely created or preserved near the surface. Identifications of seismogenic turbidites through strata comparison in multiple lake

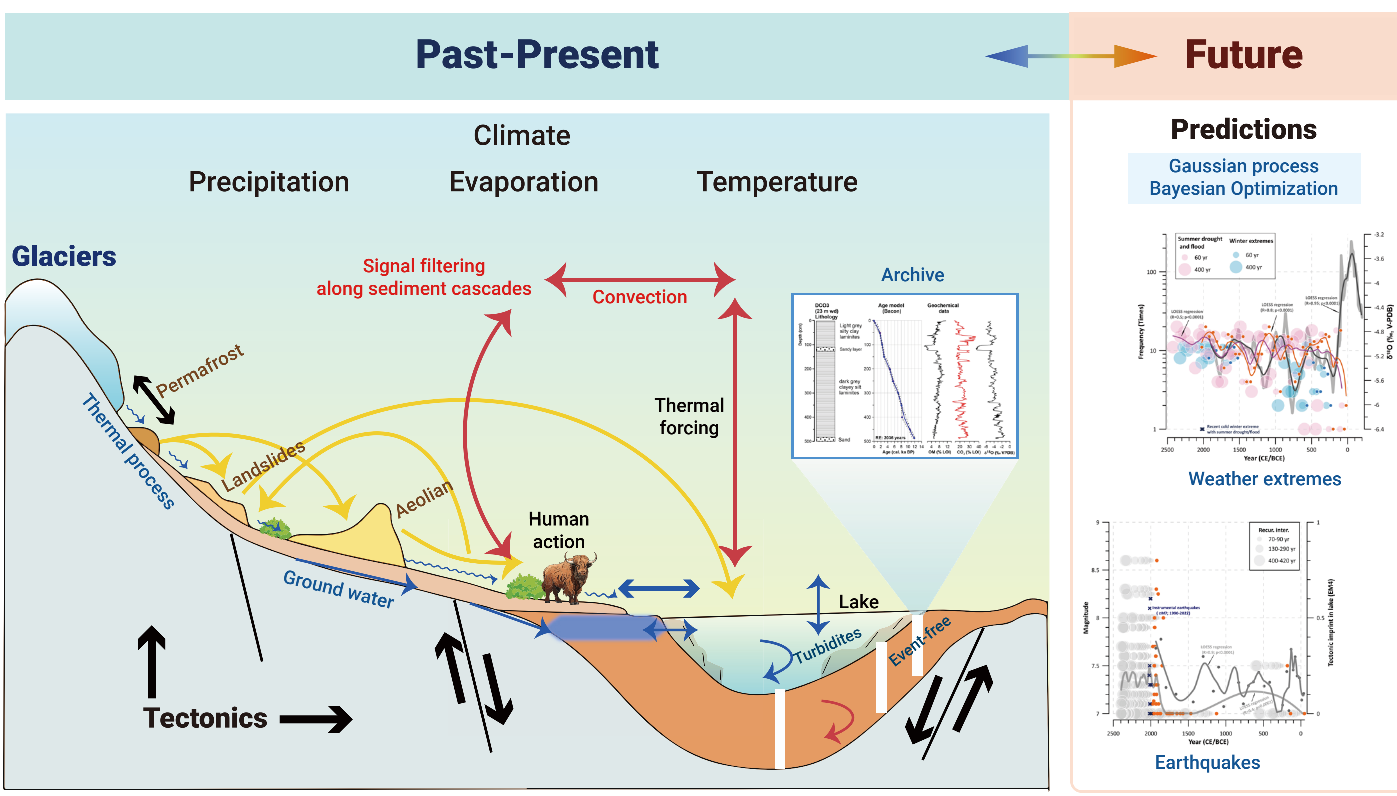

Figure 1. Schematic diagram of multi-process-and-forcing integrated study on lake-catchment interactions on the Tibetan Plateau (The embedded archive and statistical panels are from Yan et al.[9]).

cores, as applied in the Dead Sea,[1] serve to attribute rarely occurring tectonic-induced features and phenomena on land surface to paleoseismic markers in lake sediments with time-dependent sequences. This approach operates under the hypothesis that earthquakes in large magnitudes are rare and follow Poisson distribution within a certain period. However, the low frequency of documented historical and instrumental large earthquakes in most faults until now challenges the Poisson distribution test,[1] rendering it a failure. Thus, it would be of potential shift to binomial distribution, which only reports the frequency of their occurrence, not suitable for time-series analysis for reoccurrence intervals. The absence of a solid basic mathematical foundation raises concerns about the validity of the strata comparison-based approach, questioning whether paleoseismologists are indeed collecting the right type of data to be useful to hazard modelers.[2]

Despite the prevalence of tectonically originated lakes on the Tibetan

Plateau (TP), lacustrine paleoseismology study remains notably absent, extending this gap across the entire expanse of China.[3] Existing research on TP lakes mainly focuses on Holocene climate reconstruction, particularly regarding precipitation and temperature changes, achieved through a simple comparison of stable oxygen isotopes in caves with those in lake records.[4] The poorly constrained spatially variable pattern of moisture sources and the impacts of frequent neotectonics, which may have reshaped the landscape, sediment supply availability, transport routine, and water storage capacity, pose key challenges.[5] The oversight is attributed to the neglect of various surface processes in the catchment and in-lake processes in previous studies. Only a limited number of studies have reported potential seismic-triggered sediments in TP lakes. For example, Wünnemann et al.[6] identified a disturbed layer indicative of mass flow in the sediment core at the centre of Hala Lake, likely triggered by a major seismic event. This determination was achieved through a comprehensive comparison of sediments from different water depths. Additional seismic activities were discerned by comparing shallow seismic profiles and ostracod faunas in the lakes of Nam Co, Tangra Yumco and Donggi Cona on the TP.[7] Given these lake basins exhibit considerable variability in morphology, sedimentation and catchment dynamics, their lake records even in a similar seismotectonic setting can bear very different paleoseismic signatures. Therefore, a comprehensive analysis of each individual lake-catchment system becomes imperative. In particular, the influence of tectonics on lake-processes could result in the relocation and resorting of sediments from the catchment across large and deep lakes, driven by lake hydrology responding to various climate conditions. Moreover, changing sedimentation style, induced by climatic shifts and associated lake level fluctuations and water chemistry alternations, can modify the geotechnical properties of sediments. This, in turn, may impact the capacity of lake sediments to accurately record earthquake shaking.[1] It can finally result in that sedimentary evidence of older earthquakes may be eroded or 'masked', not as a multidirectional sub-deposit, which is considered as a new criterion for stacked turbidites identification.[8] Especially with regard to short recurrence intervals in a slow sedimentation rate setting, muddy turbidity currents as the main type of earthquake evidence are found to be virtually non-erosive at distal depocenters.[1] Accordingly, effective statistics on the sedimentary dataset, such as endmember modelling with full consideration of lake basin morphology and further incorporation with Gaussian process and Bayesian Optimization, can contribute to define climatic and non-climatic impacts on sediment variability and transport in a lake basin.

In previous records such homogenous signals are of high potential to be misidentified layers as climatic signals. Because impacts of seismic activities and reworking processes on lake record are often excluded in advance in order to obtain a reliable chronological frame based on Bayesian statistics. A recent example is the Jishishan *M*6.2 earthquake on December 20, 2023, and its numerous subsequent aftershocks (423 times until 8 am on December 20) in the joint area of Gansu and Qinghai provinces. Due to their relatively low magnitudes, event-free sediments were observed on land surface. However, several days later, soil-liquefaction-induced land/mud slides and even flash floods occurred over a broad region toward Xining city, coinciding with aftershocks. This real-time simultaneous occurrence cannot be correlated solely to the larger *M*6.2 earthquake using the aforementioned strata comparison approach based on Poison distribution. They even could be erroneously assigned to climate-driven events if found in a core without clear documentation as presently observed. Thus, to define various sedimentary, authigenic and biogenic processes based on multi-proxy and multi-cores and to understand their interaction during lake evolution are of great potential and significance to differentiate climatic and non-climatic factors, leading to a better tracing earthquakes in lake sediments.

Notably, most lacustrine paleoseismic studies concern lake basins that were glaciated during the Last Glacial, therefore, it is proposed that stress changes due to deglaciation and subsequent (still ongoing) isostatic uplift may lead to distinct periods of enhanced seismicity, separated by long periods of relative quiescence.[1] How to dynamically assess and distinguish seismic and nonseismic features according to lake variation responding to glacier activities and climate changes is therefore an urgent challenge on the TP.

Recent findings from Lake Donggi Cona have proposed a complex yet clear pattern to trance the responses and interactions of lake evolution and glacier-climate-tectonics on the north-eastern TP.[9] Unlike the Dead Sea, where modern soft sediment deformation are visible in both the catchment and the lakes, the conventional strata comparison-based approach is deemed unsuitable for the basin. Therefore, the authors developed a novel elimination method to discern seismic influence, considering Gaussian distribution of all tectonics, determined by the large number (2979 times) of aftershocks within a week following the *M*7.4 Madoi earthquake in 2021. By eliminating most or all turbidite/sedimentary change triggers other than earthquakes, such as climate and glaciers, the remaining factor is the tectonic.[2] This method benefits from the better constraint of lake evolution and climatic factors due to (1) high data resolution of multiple proxies and cores, along with robust statistics including endmember modelling and time-series analyses; (2) suitable reference sites from in-lake and nearby region; and (3) comprehensive consideration of various processes, facilitating more accurate proxy interpretations (e.g., $\delta^{18}O$ values) as subsidence-induced lake deepening has increased the water residence time in the lake. Furthermore, this approach reveals a combined Tibetan Plateau summer thermal and tectonic forcing of regional-to-global climate change, particularly in terms of Holocene seasonality variation with multi-cycle and the interannual migration of the northern edge of the Inter-Tropical Convergence Zone.[9,10] The newly initialed pattern, corroborated by historical and instrumental records of tectonics and climatic extremes, indicates an active phase of multi-cycle compounding at present. This phase helps explain the recent high seasonality and frequent earthquakes, and it is projected to persist until 2300 AD.[9]

Rather than relying on a simple approach or single proxy in climate reconstruction in the past, this perspective advocates for an integrated approach (Figure 1). It suggests combining sedimentary characteristics and biological fossils within a lake and its catchment to enhance the understanding of the variable transport and depositional conditions of sediments, along with their relevant processes from source to sink. This approach takes the fluctuation of lake hydrology into account, including seismic/climatic extremes. Afterwards, the interpretation of different isotopes for climatic aspects should consider the variable fractionation processes, accounting for hydrological balance changes coupled to catchment processes such as aeolian flux, river incision, glacier process, and tectonics in the lake basin. Such comprehensive and process-based (re-) evaluation and (re-) interpretation of proxy data are of significance for identifying climatic variation with seasonal differences at high altitudes and predicting seismic reoccurrence in the wide region. These factors influence the water/sediment storage capability in the head water region of China, further regulating local sea level and land-ocean interactions on the western Pacific Ocean in terms of water and sediment availabilities. New climate pattern with multiple cycles by the combined Tibetan Plateau thermal and tectonic forcing[9] points out the significance of moisture contribution within the Plateau and denies the overestimated summer monsoon rainfall to the TP.[4] This pattern might diffuse into a regional feedback loop of climatic events incorporated into other forcings in a wider region. This, in turn, leads to a more accurate prediction of future earthquakes and a projection of climate change by refining hypotheses and optimizing relevant parameters in models based on geological evidence and involving Gaussian process and Bayesian Optimization.

REFERENCES

1. Moernaut, J. (2020). Time-dependent recurrence of strong earthquake shaking near plate boundaries: A lake sediment perspective. Earth-Sci Rev **210**: 103344. DOI: 10.1016/j.earscirev.2020.103344.
2. McCalpin, J.P. (2009).Chapter 9 Application of Paleoseismic Data to Seismic Hazard Assessment and Neotectonic Research. Int Geophys **95**: 1-106. DOI: 10.1016/S0074-6142(09)95009-4.
3. Tapponnier, P., Ryerson, F. J., Van der Woerd, et al. (2001). Long-term slip rates and characteristic slip: Keys to active fault behaviour and earthquake hazard. Earth-Sci Rev **333**: 483–494. DOI: 10.1016/S1251-8050(01)01668-8.
4. An, Z., Colman, S.M., Zhou, W., et al. (2012). Interplay between the Westerlies and Asian monsoon recorded in Lake Qinghai sediments since 32 ka. Sci Rep **2**: 619. DOI: 10.1038/srep00619.
5. Yan, D., Wünnemann, B. and Zhang, Y. (2020). Late Quaternary lacustrine Ostracoda and their implications for hydro-climatic variation on Northeastern Tibetan Plateau. Earth-Sci Rev **207**: 10325. DOI: 10.1016/j.earscirev.2020.103251.
6. Wünnemann, B., Wagner, J., Zhang, Y., et al. (2012). Implications of diverse sedimentary patterns in Hala Lake, Qinghai Province, China for reconstructing Late

Quaternary climate. J Paleolimnol 48: 725–749. DOI: 10.1007/s10933-012-9641-2.
7. Yan, D., Wünnemann, B., Zhang, Y., et al. (2021). Neotectonic subsidence along the Cenozoic Kunlun fault (Tibetan plateau). Geophys Res Lett 48: e2021GL094571. DOI: 10.1029/2021GL094571.
8. Van Daele, M., Cnudde, V., Duyck, P., et al. (2014). Multidirectional, synchronously-triggered seismo-turbidites and debrites revealed by X-ray computed tomography (CT). Sedimentology 61: 861–880. DOI: 10.1111/sed.12070.
9. Yan, D., Wünnemann, B., Zhang, Y., et al. (2024). Holocene climatic and tectonic forcing of decadal hydroclimate variation on the north-eastern Tibetan Plateau. Quat Sci Rev 326: 108514. DOI: 10.1016/j.quascirev.2024.108514.
10. Wünnemann, B., Yan, D., Hu, S., et al. (2023). Seasonal variations in surface processes and hydroclimate on an alpine lake, NE Tibetan Plateau. Quat Sci Rev 300: 107876. DOI: 10.1016/j.quascirev.2022.107876.

FUNDING AND ACKNOWLEDGMENTS

This research was funded by the National Natural Science Foundation of China (42171018). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript. The data about the Shijishan earthquakes are accessible online (www.ceic.ac.cn).

We gratefully acknowledge Prof. Dr. Bernd Wünnemann from Southwest Jiaotong University for his substantial engagements into process-based lake study and also for the fruitful discussions with him on this issue. We also address our appreciations to anonymous reviewers and editors for their constructive suggestions to our manuscript.

DECLARATION OF INTERESTS

Hao Long is an Editorial Board member of The Innovation Geoscience and was blinded from reviewing or making final decisions on the manuscript. Peer review was handled independently of this member and their research group. The other author declares no conflicts of interest.