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Invited review article

# Scientific drilling projects in ancient lakes: Integrating geological and biological histories

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ABSTRACT

Sedimentary sequences in ancient or long-lived lakes can reach several thousands of meters in thickness and often provide an unrivalled perspective of the lake's regional climatic, environmental, and biological history. Over the last few years, deep-drilling projects in ancient lakes became increasingly multi- and interdisciplinary, as, among others, seismological, sedimentological, biogeochemical, climatic, environmental, paleontological, and evolutionary information can be obtained from sediment cores. However, these multi- and interdisciplinary projects pose several challenges. The scientists involved typically approach problems from different scientific perspectives and backgrounds, and setting up the program requires clear communication and the alignment of interests. One of the most challenging tasks, besides the actual drilling operation, is to link diverse datasets with varying resolution, data quality, and age uncertainties to answer interdisciplinary questions synthetically and coherently. These problems are especially relevant when secondary data, i.e., datasets obtained independently of the drilling operation, are incorporated in analyses. Nonetheless, the inclusion of secondary information, such as isotopic data from fossils found in outcrops or genetic data from extant species, may help to achieve synthetic answers. Recent technological and methodological advances in paleolimnology are likely to increase the possibilities of integrating secondary information. Some of the new approaches have started to revolutionize scientific drilling in ancient lakes, but at the same time, they also add a new layer of complexity to the generation and analysis of sediment-core data. The enhanced opportunities presented by new scientific approaches to study the paleolimnological history of these lakes, therefore, come at the expense of higher logistic, communication, and analytical efforts. Here we review types of data that can be obtained in ancient lake drilling projects and the analytical approaches that can be applied to empirically and statistically link diverse datasets to create an integrative perspective on geological and biological data. In doing so, we highlight strengths and potential weaknesses of new methods and analyses, and provide recommendations for future interdisciplinary deep-drilling projects.



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**Contents**



## 1. Introduction

The vast majority of the world's lakes has existed or will exist for up to a few ten thousand years (e.g., Brooks, 1950). Primarily due to sediment infill, they become progressively shallower and subsequently vanish. Ancient or long-lived lakes, on the contrary, exist for over 100,000 years (100 ky), sometimes millions of years (My) (Brooks, 1950; Gorthner, 1994; Martens, 1997). They typically occur in settings where sedimentation rates are low or balanced by subsidence (Cohen, 2012). Accordingly, most of today's ancient lakes are oligotrophic and situated in active tectonic graben settings, karst systems or impact craters with low sediment supply from the catchment.

Because of the long-term availability of accommodation space (Jervey, 1988), sediment sequences in ancient lakes can reach several hundreds to thousands of meters in thickness (e.g., Scholz et al., 1993, 2011; Lindhorst et al., 2015). Lake deposits contain material that mostly derives from the lake proper and the catchment area and, hence, provide an unparalleled perspective of the lake's history through time (O'Sullivan, 2004). Combining the paleolimnological records from different lakes permits the reconstruction of continental and global environmental, and climatological histories. It is this potential, captured in the often continuous lacustrine sedimentary archives, that has inspired several deep-drilling projects in ancient lakes (reviewed in Cohen, 2012; Fig. 1).

However, over the past decades, drilling operations became increasingly interdisciplinary, as data bearing on physical, chemical, biochemical, and biological research questions can also be obtained from sediment cores. Because of a wealth of new information, scientists from different fields, such as sedimentology, climatology, geochemistry, paleolimnology, paleontology, biochemistry, microbiology, evolutionary biology, physics, and modeling, currently aim to use ancient lakes as paradigms to interactively look into natural phenomena from various angles, emphasizing the need for truly interdisciplinary collaborations (sensu O'Sullivan, 2004; Birks and Birks, 2006).

Multidisciplinary and interdisciplinary studies enable a more holistic approach to scientific problems, provide excellent opportunities for hypothesis-driven research, and are likely to have greater success in generating a widespread interest in the broader scientific community. However, these projects pose several challenges for the diverse science teams. The interests of the various groups involved need to be aligned; participants may lack the required knowledge of other disciplines; traditions and common practices may differ widely between disciplines. Finally, larger teams increase the challenge to communicate and coordinate efforts effectively. The various goals of individual teams call for compromises on several levels, such as drill site selection, subsampling strategies, and choice of analyses (see Section 2.1.1). Life scientists are typically not familiar with drilling operations and often lack basic geological knowledge whereas earth scientists may not be acquainted with biochemical or biological procedures. More practically, the difficulty arises that life scientists do not know exactly how to retrieve the archives they hope to study, and that earth scientists cannot evaluate applicability and performance of biological methods. Similar problems persist on smaller scales, and given the rapid advancement of many of the individual fields, specialists may even struggle with methodological innovations in their field over the often year-long duration of deep-drilling projects, involving the planning, the actual drilling campaign, and the interpretation of the final datasets. These issues are also relevant for core storage, which may affect geological and biological properties differently. Sedimentologists are typically acquainted with long-term changes in sediments after core retrieval, but others may draw erroneous conclusions when linking biological and geological data without accounting for potential contamination, drilling artifacts, decay processes, and other complications (see Section 2.1.2). In general, greater logistic, communicative, and administrative efforts are required with increasing complexity of interdisciplinary projects, and drilling methods may have to be optimized to guarantee the required data quality.

Perhaps the most challenging task, however, is to integrate the diverse datasets various teams collect from drilling cores. These datasets typically have differences in resolution, data quality, and dating uncertainty, but combining them is required to answer interdisciplinary questions. While the physical linkage of information directly obtained from sediment cores is, in most cases, relatively straightforward due to the