

A 500,000-Year-Long Sediment Archive Drilled in Eastern Anatolia

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Sedimentary archives host a wealth of information that can be used to reconstruct paleoclimate as well as the tectonic and volcanic histories of specific regions. Long and continuous archives from the oceans have been collected in thousands of locations by scientific ocean drilling programs over the past 40 years. In contrast, suitable continental archives are rare because terrestrial environments are generally nondepositional and/or subject to erosion. Lake sediments provide ideal drilling targets to overcome this limitation if suitable lakes at key locations have existed continuously for a long time.

Lake Van, a large terminal lake in eastern Anatolia (Turkey), holds a key position within a sensitive climate region between the Black, Caspian, and Mediterranean seas. Lake Van extends more than 130 kilometers on a high plateau; lake level at present is 1665 meters above sea level. The lake water, up to 450 meters deep, is alkaline (pH ~ 9.8) and saline (~21.4%). Its long and partly annually laminated sedimentary record provides an excellent palaeoclimate archive because it yields a long and continuous continental sequence that covers several glacial-interglacial cycles spanning more than 500,000 years. Lake Van is therefore a key site for constructing Quaternary climate evolution in the Near East. The geochronological precision on a decadal or even annual scale will allow comparisons with not only astronomical cyclicity but also frequencies below Milankovitch cycles, such as the North Atlantic Oscillation, which may have also affected the past climate system of the eastern Mediterranean region. Moreover, being located in a tectonically active area bordered by two historically active volcanoes, it holds a unique paleoseismic and volcanic archive. In fact, a magnitude 7.1 earthquake on 23 October 2011, with its epicenter located just north of the city of Van, caused more than 600 casualties and major infrastructural damage, reflecting the high seismic risk for this region.

Continental Drilling: The Paleovan Project

As a closed and saline lake, Lake Van reacts very sensitively to lake level changes caused by any alterations in the hydrological regime in response to climate change. Because the lake is the deepest lake in Anatolia and in contrast to other more shallow lakes, likely never dried out in its history, it was identified as the most promising candidate to contain a long and continuous sediment archive. Starting with international pilot campaigns in the 1970s, several geophysical and sediment-coring operations were conducted. Cores were retrieved and dated back 20,000 years, showing the large paleoclimatic

and paleoenvironmental potential of Lake Van sediments. Moreover, the proximity to two large historically active volcanoes promised a wealth of tephra layers in the sedimentary record, allowing the evolution of Lake Van to be dated in some detail. To retrieve the full sediment record down to the basement, a working group within the framework of the International Continental Scientific Drilling Project (ICDP) was established to initiate a new project, called Paleovan.

On the basis of the results from a site survey (short cores and seismic survey) carried out in 2004 [Litt *et al.*, 2009] and discussions during an international workshop focused on drilling at Lake Van, a full drilling proposal was submitted to ICDP in 2007, which was accepted in the same year.

The main objectives of the Paleovan project are the recovery and analysis of a long continental paleoclimate record in a sensitive, semiarid region. Lines of inquiry include exploring the dynamics of lake-level fluctuations and hydrogeological development. Further scientific goals are the temporal, spatial,

and compositional evolution of explosive volcanism as reflected in the succession of tephra deposits, as well as the reconstruction of earthquake activities. In addition, the sediments host key pathways for migration of continental and mantle-derived noble gases to be analyzed in pore waters.

On the basis of the seismic site survey, several potential sites were selected from which two were finally drilled in summer 2010. The “Ahlat Ridge” site (AR) was drilled on a low ridge in the deep basin to recover a complete sedimentary section. The “Northern Basin” site (NB) is located close to the northern shore of Lake Van. The proximity to the historically active volcanoes Nemrut and Süphan, which supplied numerous tephra layers to the lake sediments, allows scientists the opportunity to reconstruct the temporal and compositional evolution of volcanic activity and associated volcanic hazards.

Core Recovery and Analysis

The drilling campaign, operated by the U.S.-based company Drilling, Observation and Sampling of the Earth's Continental Crust (DOSECC; <http://www.dosecc.org/>), was carried out in July and August 2010. DOSECC developed and assembled a new Deep Lake Drilling System (DLDS) specifically designed

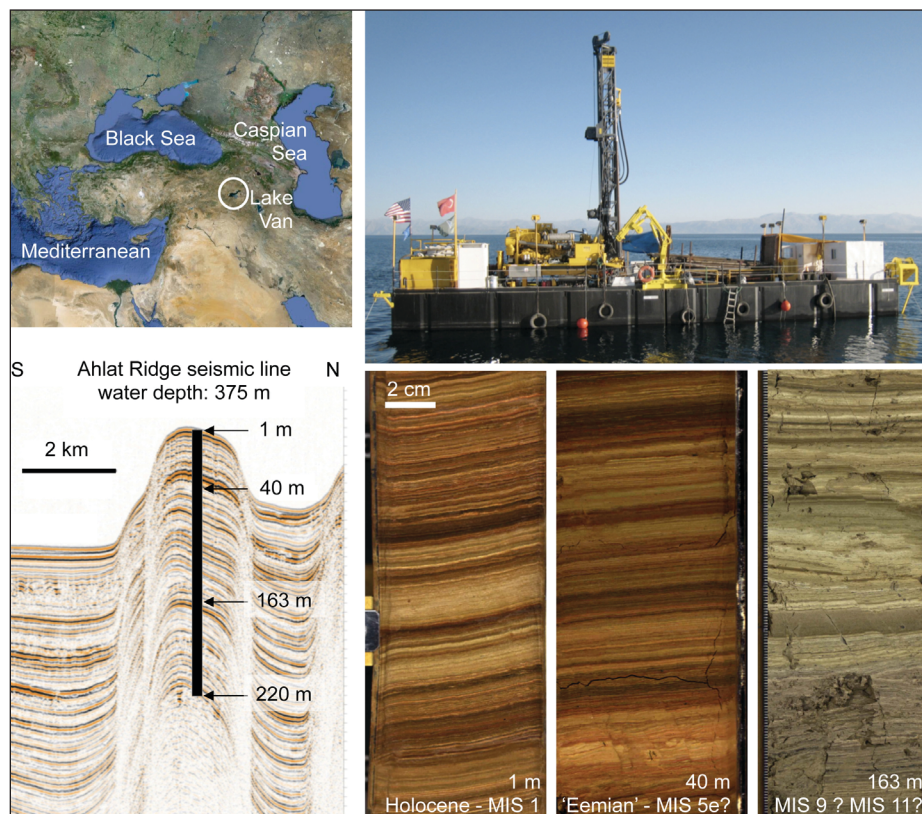


Fig. 1. (clockwise from top left) Location of Lake Van in eastern Anatolia (Google Earth imagery ©Google Inc. Used with permission). The new Drilling, Observation and Sampling of the Earth's Continental Crust (DOSECC) drill rig and barge, optimized for deep drilling from lakes. Three core photographs of annually laminated lithologies from marine isotope stages (interglacial periods); detailed layer analysis at submillimeter resolution will allow researchers to compare the annual/seasonal cycles of past warm periods. Seismic line of the Ahlat Ridge (AR) showing where the AR core was taken; note how the drill site penetrates the complete sediment succession down to the acoustic basement at 220-meter sediment depth.

for coring sediments from deep lakes that was first operated in Lake Van. The DLDS worked at water depths of up to 360 meters (as used for AR; seismic data showed that deeper water depths were not ideal for getting a full sedimentary record), and cores from 140 meters (NB) and 220 meters (AR) below the lake bed depth were retrieved. To obtain a complete sedimentary section, the two sites were cored multiple times (average recovery, 91% and 71% at AR and NB sites, respectively). Total length of all parallel cores recovered at the two sites is over 800 meters, allowing a consistent look back in time at the scale of several glacial-interglacial cycles. Where possible, one hole at each site was wireline-logged using petrophysical and geochemical sensors lowered through the hole to complete sections with low recovery.

The cores are stored at an Integrated Ocean Drilling Program core repository located at the University of Bremen's Center for Marine Environmental Sciences (MARUM), in Germany. This repository's ideal sampling and preparation facilities have been used for splitting, photographic and X-ray fluorescence (XRF) scanning of the core halves, writing core descriptions, and taking samples during spring 2011. Samples have been taken to analyze a variety of characteristics, including paleomagnetism, sedimentology, inorganic geochemistry, black carbon concentrations, pollen species and abundances, isotopes and biomarkers, general composition, and tephra layers, the latter of which can be dated using single-crystal analysis based on the argon isotope fractions present.

Preliminary single-crystal argon dating of anorthoclase in the tephra, XRF scanning results, as well as pollen analyses, suggest that the AR record encompasses more than 500,000 years of paleoenvironmental and volcanic/geodynamic history. In addition to the current interglacial stage (marine isotope stage 1), three to four interglacial stages can be identified on the basis of annually laminated lithologies and higher amounts of pollen from trees such as deciduous oak, which favor warmer

environments. These submillimeter-scale annual laminations reflect strong seasonal fluctuations in particle supply resulting in alternations of aquatic biomass, authigenic carbonates, and detrital constituents. These warm phases must have coincided with bottom water anoxia and probably coincide with the past interglacials (marine isotope stages 5, 7, 9, and 11 or 13) that dot the past 500,000 years of paleoclimate history. Cold stages are characterized by nonlaminated, banded lithologies and the predominance of pollen types related to steppe plants.

The pore water chemistry as well as the occurrence of freshwater mollusks in sediments from the very bottom at the AR site suggest the initiation of Lake Van as an open freshwater body having an outlet at that time; when it became a terminal lake is not well known. The recovery of several-meter-thick tephra layers allows correlation to major dated and compositionally fingerprinted fallout tephra deposits studied on land during the presite survey, allowing for concrete time markers throughout the core. Numerous small-scale sediment deformations and seismoturbidites were identified that record earthquake history of this seismically active area so that an unprecedented history of seismic hazards can be established. Further pore fluid analysis will yield data of paleo-lake water evolution, reflecting the hydrologic changes in the past, and transport of mantle-derived noble gases, which will allow scientists to study terrestrial helium emanation and crustal fluid transport. The measured concentration profiles of atmospheric noble gases will be used to reconstruct changes of temperature, salinity, and lake-level fluctuations throughout the lake's history.

A Window Into the Past

The Lake Van sedimentary record is considered a treasure for high-resolution paleoenvironmental, paleoclimatic, volcanologic, and paleotectonic research because it encompasses a much more

extended sequence than all other continental records in the entire Near East obtained to date. The understanding of environmental and climate changes reflected in past lake-level fluctuations together with the now unraveled knowledge of the seismic and volcanic history of the Lake Van basin will provide the necessary tools of scientific and societal significance to establish frequencies and intensities of natural hazards for this sensitive and populated area.

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—THOMAS LITT, Steinmann Institute of Geology, Mineralogy and Paleontology, Bonn University, Bonn, Germany; E-mail: t.litt@uni-bonn.de; FLAVIO S. ANSELMETTI, Eawag: Swiss Federal Institute of Aquatic Science and Technology, Dübendorf, Switzerland; M. NAMIK CAGATAY, Department of Geological Engineering and Eastern Mediterranean Centre for Oceanography and Limnology, Istanbul Technical University, Istanbul, Turkey; ROLF KIPFER, Eawag: Swiss Federal Institute of Aquatic Science and Technology; SEBASTIAN KRASTEL and HANS-ULRICH SCHMINCKE, Helmholtz-Zentrum für Ozeanforschung Kiel, Forschungszentrum für Marine Geowissenschaften, Kiel, Germany; and MICHAEL STURM, Eawag: Swiss Federal Institute of Aquatic Science and Technology