Progress in Global Lake Drilling Holds Potential for Global Change Research

During the past decade, numerous international investigations of past global change have focused on particular time intervals, or “Time Streams,” suggested by the Past Global Changes (PAGES) Project of the International Geosphere-Biosphere Programme (IGBP). Time Stream 1 encompasses the last 2000 years, and Time Stream 2 encompasses at least the last 250,000 years. Geographically, many of these studies have been grouped into north-south transects of continental global change records known as the Pole-Equator Pole (PEP) transects [Bradley et al., 1995]. These continental transects have been complemented by the study of marine records included in the International Marine Global Change Study (IMAGES) transects and high-latitude ice core records such as those from the U.S. Greenland Ice Sheet Project 2 (GISP2) and the European Greenland Ice-core Project (GRIP).

Using conventional marine piston coring equipment, maximum core lengths are limited to about 20 m. Such a core might collect sediments spanning the entire Stream 2 time frame in slowly accumulating pelagic sediments, but not in nearshore, rapidly accumulating hemipelagic sediments. The marine coring community solved this problem over 30 years ago with drill ships, first the Glomar Challenger and then the JOIDES Resolution. Probably the most revolutionary invention for obtaining undisturbed Quaternary sediments from a drill ship was the hydraulic piston corer. In addition, the flagship of IMAGES, the French RV Marion Dufresne, is capable of handling a coring device heavy enough to obtain single-entry cores of up to 50 or 60 m in length.

Coring in pursuit of continental global change records has had a very different history. Lake sediments offer tangible advantages over other continental climate archives. Both modern and ancient deposits are widely distributed over the continents. Sedimentation typically is highly resolved and continuous at 0.1 to 1.0 mm/yr. Sequences contain a variety of sensitive internal and external regional environmental signatures of changes in the geosphere, hydrosphere, and biosphere. Reconstructing paleoclimate from lake cores requires an understanding of each unique lake system. A truck-mounted drill rig can be driven out on a dry lake bed, but if the lake still has water in it, obtaining long cores is more difficult. Existing lakes are attractive targets for paleoceanographic and paleoclimatic studies, because their modern depositional systems provide calibration for past processes and conditions. Like conventional marine coring systems, conventional lake coring systems—for example, the Livingstone piston corer—are limited to a maximum of about 20 m. The lake coring community has long recognized the need for a lake-going JOIDES Resolution with hydraulic piston coring capabilities, but one that was easily transportable and inexpensive to operate. With the development of the PEP transects and other projects designed to investigate global change within PAGES Time Stream 2, the need for long continental paleoclimate records accelerated.

To assess this need for long continental records, a workshop titled “Continental Drilling for Paleoclimate Records” was held at GeoForschungsZentrum (GFZ), Potsdam, Germany, from 30 June to 2 July 1995. The workshop was sponsored by PAGES and GFZ in cooperation with the International Continental Drilling Program (ICDP), also housed at GFZ. The recommendations from this workshop were published as a PAGES Workshop Report [Colman, 1996], beginning a long collaboration between PAGES and ICDP. The participants in the workshop also organized a Lake Drilling Task Force to assess the potential for lake drilling. To this end, the Task Force solicited two-page proposals from the international continental paleoclimate community to be considered for support by ICDP. More than 60 mini-proposals were received, and more complete proposals were requested by the Task Force for those sites that were evaluated as having the highest priority. These materials were compiled into a 5-year drilling plan that was presented at the VIII International Continental Drilling Symposium, which was held in February 1996 in Tsukuba, Japan. The plan, “Prospectus for a Global Lake Drilling Initiative,” was submitted to ICDP in April 1996. Thus, the concept of Global Lake Drilling was born, although the acronym (GLAD) would come later. Now all that was needed was that lake-going JOIDES Resolution!

Several years of discussions and workshops involving the lake coring community and engineers from ICDP and the U.S. non-profit scientific drilling corporation (Drilling, Observation, and Sampling of the Earth's Continental Crust; or DOSECC) ensued. A contracted engineering feasibility study resulted in a design for an oil field-scale drilling system.

Fig. 1. The GLAD800 rig and platform (R/V Kerry Kelts) are shown on Lake Titicaca, Bolivia, in May 2001.
but such a system was quickly judged to be prohibitively expensive. Finally, the concept of “GLAD20-200” emerged. This would be a rig and platform that could collect a sequence of cores of lake floor sediments ranging in total length from 20 m to 200 m from any one hole. The rig and platform would be transportable to anywhere in the world and would cost less than $1 million. DOSECC engineers met with representatives of the scientific community at the University of Minnesota in September 1998 and presented a plan for a rig and platform that could handle a drill string of not just 200 m, but for only slightly more money and size, a total drill string length (water plus sediment) of 800 m. Floation for the platform would be provided by inflatable pontoons. The workhorse would be a modified Christensen CS1500 diamond coring rig. Drilling tools, including a hydraulic piston corer, would be designed and built by DOSECC engineers, modified after Ocean Drilling Project (ODP) wireline tools. Initially, core barrels would be 3 m long and use standard ODP plastic liners (6.2 cm in diameter). If the platform only operated in water depths of less than 200 m, then it could be held on site with four anchors, and dynamic positioning would not be needed. If it only operated in reasonably good weather, then heave compensation would not be needed.

The rig and platform would be built by a DOSECC contractor in Rexburg, Idaho. Research projects on Great Salt Lake, Utah, and Bear Lake, Idaho/Utah, were being conducted jointly by the U.S. Geological Survey (USGS) and a number of academic institutions, and both projects were in need of longer cores. Therefore, it was suggested that the system be tested on these lakes close to DOSECC and other facilities in Salt Lake City. From this meeting, the concept of GLAD800 emerged. A proposal-writing workshop was hosted by USGS in Denver in December 1998. Proposals were completed over the holidays, and one was submitted to ICDP in January 1999 to fund the construction of the GLAD800 platform. At the same time, a second proposal was submitted to the Earth System History Program of the National Science Foundation (NSF-EH) to fund coring on Great Salt and Bear Lakes as tests of the system.

Funding for scientific drilling on Great Salt and Bear Lakes was approved by ESH, with NSF and USGS splitting the cost of drilling on Bear Lake. The platform design that was finally presented to ICDP consisted of eight, 20-foot-long international shipping containers fastened together at the corners and turned upside down because the floors are stronger than the roofs. Each container would hold foam at the top for flotation, water in the bottom for ballast, and an airbag in between for trim. This design (Figure 1) was approved, and funding recommended, by ICDP in December 1999. The platform was built in the spring of 2000. The rig was tested on a truck mount in Hawaii in June 2000. The rig and all of the associated gear was loaded into the shipping containers (“platform modules”) and shipped from Rexburg to Salt Lake City in early August. The first leg of the RV Kerry Keels (GLAD1) began on Great Salt Lake on 12 August 2000. It is the lake-going Jolles Resolution.

GLAD1 Coring on Great Salt Lake

Great Salt Lake is a perennial brine body that is a remnant of Pleistocene pluvial Lake Bonneville. As a closed-basin lake, the level of the lake has responded sensitively to climatic and environmental changes. A long history of scientific inquiry, beginning in the late nineteenth century with the pioneering work of G.K. Gilbert [1890], has provided a solid framework of knowledge to identify promising locations for drilling activities. This information underlies the hypotheses about climatic change and tectonic evolution since the Tertiary that can be addressed by drilling.

Prior investigations of Late Pleistocene and Holocene sediments from cores and outcrops form the basis of much of our understanding of climate and hydrologic history in the Lake Bonneville basin [e.g., Spencer et al., 1984; Morrison, 1991]. These studies document features of lake-level changes and associated sedimentological and geochemical responses, particularly over the past ~40 k.y. They also document links between the history of this lake and climatic forcing in the region during the last glacial maximum and the period of deglaciation. However, most of the research data has been of relatively low temporal resolution.

In the 1970s, AMOCO conducted a program of petroleum exploration across the Great Salt Lake. Fifteen exploration wells ranging between 640 m and 3700 m in length were drilled, accompanied by the acquisition of 2700 km of multifold seismic reflection data. Collectively, these wells and seismic data demonstrate that the Bonneville basin contains the most continuous record of Neogene climate change in North America [Davis and Moutoux, 1998; Koukalovska and Cohen, 1998]. Most of the record has been analyzed from samples of well cuttings, which are homogenized over large stratigraphic intervals; and thus, the record is of too low a resolution to unambiguously determine climatic and lake histories.

A lake bed scarp west of Antelope Island in the Great Salt Lake correlates with the surface projection of the East Great Salt Lake Fault in this area (Figure 2). The siting of GLAD800 cores on both sides of this scarp, coupled with existing high-resolution seismic reflection data that show at least three Holocene surface ruptures on the fault, was designed to constrain
the timing and recurrence interval of major earthquakes along the East Great Salt Lake Fault. Knowledge of the late Quaternary displacement history of the East Great Salt Lake Fault is needed to determine the seismic hazard it poses to cities along the northern Wasatch Front.

Between 12 August and 5 September 2000, cores were collected at four sites in the south basin of Great Salt Lake with over 93% recovery. Sites 1–3 (Figure 2) were sited to collect entire Holocene sequences from the hanging wall and footwall of the East Great Salt Lake fault. This was accomplished at each site with sediment recovery of 61 m, 39 m, and 57 m below lake floor (mblf) at Sites 1, 2, and 3, respectively. A preliminary chronology is provided by the recovery of two volcanic ash layers, Mazama (6.8 ka) and Hansel Valley (25.5 ka), at all three sites. Earthquake event horizons in these cores are currently being dated by radiocarbon geochronology. Sequences of interbedded sapropel and salts (halite and thenardite) were recovered beneath Holocene argonite mud. A successful integrated coring and seismic reflection approach to paleoseismologic analysis of a submerged fault demonstrates that the GLAD800 system provides a powerful new tool for tectonic research in lakes.

Coring at Site 4, located on the southern margin of the northern basin (Figure 2), was designed to produce at least 400 m of core and provide a detailed basinal history extending back into several glacial cycles. Because of lost drilling time due to bad weather, the objective was cut short, but coring did penetrate to a total section of 121 mblf with five offset holes, and provides the longest continuously cored sediment record from Great Salt Lake. It may reach greater than 250 ka, based on local Pleistocene sedimentation rates and limited preliminary dating. Two intervals of bedded salts were recovered below Holocene argonite mud that contains the Mazama ash (Figure 3). The upper salt crust consists of interbedded sapropel and thenardite (NaSO₄) and contains the Hansel Valley ash (Figure 3). The diatomaceous sediments below the upper salt were deposited during the Bonneville Lake highstand (Oxygen Isotope Stage 2). The lower salt sequence (68–71 mblf) is composed of dense halite (NaCl). Based on preliminary volcanic ash and U/Th chronologies, we estimate that the two bedded-salt intervals were deposited during saline lake phases at the transitions between glacial and interglacial periods (Oxygen Isotope Stage 6 to 5 and Oxygen Isotope Stage 2). Finely laminated carbonate and diatomaceous mud below the lower salt sequence to 121 mblf may represent deposition during Oxygen Isotope Stage 6. Ostracodes occur in relatively low abundances throughout much of the section except for a brief interval just below the upper salt horizon (Figure 3), in an interval that probably corresponds with the Bonneville and other late Pleistocene lake high stands. The ostracode fossil fauna is dominated by Limnocythere stapini (Figure 3), a salt-tolerant species typical of sulfate-rich waters.

**GLAD800 Coring on Bear Lake**

The Bear Lake Valley in northeastern Utah and adjacent Idaho (Figure 2) is a half-graben at 1800 m above sea level, containing a mesosaline-alkaline lake (Bear Lake) with an area of 280 km² and a maximum depth of 63 m. Historically, the Bear River did not flow into Bear Lake, but it was diverted in through a series of canals beginning in 1909, making Bear Lake a reservoir. The lake has recently become a focal project of the USGS in collaboration with researchers from a number of universities. Studies of the modern lake and catchment system are being undertaken to complement sediment core interpretations.
Piston coring in 1996 and seismic profiling in 1997 showed a layered sediment package with clear wedging reflectors and erosional unconformities. Previously obtained piston cores contain highly resolved records with excellent definition of geochemical climate proxies and low sedimentation rates. However, these cores are only a maximum of 5 m long and go back to the last glaciation—approximately 25,000 years—when Lake Bonneville was at its highest elevation. The Holocene sediments are carbonate-rich, predominantly aragonite, and the glacial sediments consist of non-carbonate silty clays, probably indicating direct inflow of Bear River into Bear Lake. The history of the thick sedimentary sequence will provide an independent test of wet/arid paleoclimatic cycles and millennial events over several glacial cycles. The Bear River is the major present-day source of freshwater to Great Salt Lake (Figure 2). The possibility of paleo-sources of fresh water from the Bear Lake/River system is controversial.

The original objective for coring Bear Lake with the GLAD800 system was to obtain two continuously cored holes from the deepest part of the lake, each 100 m long. In September 2000, two parallel holes were continuously cored with the GLAD800 system at a single site in a water depth of 53 m (Figure 2), one to a sub-bottom depth of 100 m and a second to 120 m. Preliminary results of analyses of core catcher samples indicate the presence of two carbonate-rich, predominantly aragonite, intervals prior to the Holocene aragonite interval (Figure 4). The upper of these intervals is characterized by extremely low magnetic susceptibility values like those observed for the Holocene. Similarities between these intervals and the Holocene sediments suggest that these intervals may represent previous interglacials. Preliminary volcanic ash and U/Th dating (Figure 4) indicate that these intervals probably do coincide with the last two interglacial periods, Oxygen Isotope Stage 5e and 7. The last glacial maximum (Oxygen Isotope Stage 2) is represented by an interval of red silty clay with uniformly high magnetic susceptibility (10–20 mT). Other intervals that contain predominantly siliciclastic material were probably deposited during earlier glacial intervals. In contrast to sediments in Oxygen Isotope Stage 2, these sediments are various shades of gray and have highly variable magnetic susceptibility. These differences reflect variable destruction of detrital Fe-oxides and formation of Fe-sulfides—including the magnetic monosulfide, greigite—in more reducing bottom-water conditions.

**Shore-based Studies**

On board the GLAD800 platform, the core catchers were sub-sampled for various shore-based analyses, and the liners were cut into
1.5-m lengths. On shore, the 1.5-m sections were boxed and stored in a refrigerated van until they could be shipped to the Limnological Research Center (LRC), University of Minnesota. At the LRC, the core sections were scanned with a Geotek multisensor logger that measures porosity, magnetic susceptibility, and P-wave velocity. The core sections were then split, digitally imaged, photographed, and described. Sampling and analyses follow core curation specifications and protocols that were in place before drilling.

Preliminary laboratory analyses are being conducted on core catcher samples that were sub-sampled on board and immediately sent to investigators. For the Great Salt Lake samples, pollen and ostracode analyses are being conducted at the University of Arizona; diatom analyses are being conducted at the University of Utah; and carbon, magnetic, and X-ray diffraction mineralogical analyses are being conducted at the USGS in Denver. For the Bear Lake samples, pollen, ostracode, and amino acid analyses are being conducted at University of Northern Arizona; diatom analyses are being conducted at the University of Utah; and carbon, magnetic, X-ray diffraction mineralogical analyses and inorganic geochemical analyses are being conducted at the USGS in Denver and Menlo Park. Results of these analyses, together with the Geotek logs, digital images, and visual core descriptions for each 1.5-m core section, will form the “Initial Core Descriptions” that will be available in digital form at the World Data Center-A for Paleoclimatology (http://www.ngdc.noaa.gov/wdc/wdca/wdca_paleo.html) and the Index to Marine and Lacustrine Geologic Samples Database (http://www.ngdc.noaa.gov/mgg/curator/curator.html), NOAA-NGDC, Boulder, Colorado.

Use of the GLAD800 system is open to any group, with scheduling priority given to projects in the following order: 1) scientific drilling projects supported by ICDP (see http://icdp.gfz-potsdam.de); 2) scientific drilling projects supported by other science agencies (for example, NSF); and 3) other drilling projects. For further information on use of the GLAD800 system, contact Dennis Nielson at DOSECC (see http://www.dosecc.org).

Note: On 8 February 2001, one of the authors of this article, Kerry Kelts, died after a long battle with Hodgkin's disease. Kerry was a professor in the Department of Geology and Geophysics and director of the Limnological Research Center (LRC) at the University of Minnesota; but more important, he was one of the leading driving forces behind global lake drilling. Kerry was on the deck of the Glomar Challenger in December 1978 when the first hydraulic piston core was taken from the ocean (Gulf of California; DSDP Site 480). From that day, it was his dream to have that capability for lakes. Kerry was on the deck of the GLAD800 platform when the first hydraulic piston core was taken from Great Salt Lake on 12 August 2000. The next day, he returned to Minneapolis to begin the treatment from which he never recovered. In his honor, the GLAD800 platform has been named the R/V Kerry Kelts.

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