An NSF/ICDP Workshop on
Scientific Drilling on Lakes Malawi and Tanganyika

October 10-16, 1999

Club Makakola, on the southwestern lakeshore of Lake Malawi

Workshop Report
EXECUTIVE SUMMARY

Introduction

During the week of October 10, 1999, a group of 47 scientists, engineers, local institutional representatives, and funding agency administrators met at Club Makakola, Malawi, on the shore of Lake Malawi, to review the prospects for scientific drilling on Lakes Malawi and Tanganyika. The meeting was opened by the Hon. Harry Thomson, Minister for Natural Resources and Environmental Affairs of Malawi, and was followed by an open discussion of the natural resources of Lake Malawi. Participants included representatives from Malawi, Tanzania, the United States, and 8 other nations in Africa and Europe. Support for the workshop was provided by the U.S. National Science Foundation (Paleoclimate, Continental Dynamics, and Geology and Paleontology programs), and from the International Continental Scientific Drilling Program.

Major topics considered during the meeting included reviews of the major scientific themes to be addressed through drilling, roles of local institutions, engineering and logistical concerns, and the funding environments within likely target funding agencies.

Workshop Agenda

Many of the workshop discussions were centered around the current proposal submitted to the ICDP and NSF for the GLAD800 drilling rig, a lightweight coring system designed for sampling lake basins to a total drilling depth of 800-1200 meters. Administrative, financial and engineering infrastructure of the GLAD800 concept were considered during this opening session.

Following brief summaries of the existing science programs, several speakers presented science reviews in the areas of crustal structure and rift basin evolution, paleoclimatology, environmental background to human origins, paleoecology and evolutionary biology, and geochronology and paleomagnetic studies in lacustrine basins. Several breakout sessions provided the opportunity for international groups to consider key questions to be addressed during scientific drilling. Summary white papers on the four main scientific themes are presented following this summary. A 1-day field trip to the Lake Malawi port facility and shipyard at Monkey Bay, the container port at Chipoka, and to the Limnological Field Station at Senga Bay provided participants with a sense of local infrastructure around the lakeshore.

Plenary Sessions

Following the science reviews, there were several plenary discussions covering the following topics: Roles for Local Institutions, Reviews of Seismic Reflection Site Survey Data, Engineering and Logistical Issues, and Funding Conditions within Target Funding Agencies.

<u>Roles for Local Institutions</u>

Developing opportunities for capacity building within the geosciences community in East

Africa is a high priority objective of the local institutions that were represented at the workshop. The drilling program should develop a plan for expanding educational opportunities at various levels, including training of graduate students at local universities and abroad, and enhancing professional growth of the present staff of professionals in University and government positions. In addition to training, it is important for the project to explore opportunities for improving the equipment and instrumentation infrastructure at Universities and within government-supported laboratories.

In addition to capacity building, a top priority for local governments is to expand the understanding of the regional geology of Lakes Malawi and Tanganyika. In order for countries such as Malawi and Tanzania to best manage their natural resources, it is critical to improve the state of knowledge of the subsurface structure, stratigraphy and lithofacies variability of the lakes of the western branch of the rift valley.

Reviews of Seismic Site Survey Data

Considerable amounts of seismic reflection data of different type and vintage have been acquired on Lakes Malawi and Tanganyika. In the mid-1980's Project PROBE acquired about 4500 km of 24-fold seismic reflection data on the two lakes, in reconnaissance grids with line spacing s of 8-16 km. These data show that the lakes are each underlain with upward of 5-6 km of syn-rift lacustrine sediment. In the case of Lake Malawi, which has the greatest concentration of data, it appears that the sedimentary section thins from a maximum of 5-6 km in the northern part of the rift valley to a few hundred m thickness at the southernmost part of the lake. Since 1992, several medium-resolution single-channel seismic surveys have been undertaken over selected areas on both lakes. These seismic images provide information on the seismic stratigraphy of the lakes to 1-2 km sub-bottom, at a vertical resolution of 1-2 m. These data reveal the complex facies geometries evidently inherent on such tropical lakes, and reveal that several unconformities exist in the stratigraphic section. In the case of Lake Malawi, shallow unconformities produced by dramatic drops in lake level are observed in water depths of more than 500 m, suggesting that it will be necessary to drill in water depths >500 m in order to obtain a continuous stratigraphic record in that lake.

Engineering, logistics, and drilling strategies

Several engineering presentations covered the proposed GLAD 800 lake drilling rig, Ocean Drilling Project- type drilling tools, and deployment of this equipment on a modular barge system with dynamic positioning. The GLAD 800 concept was originally proposed for small-medium lakes, but is also adaptable for large lake drilling, including extending the drill string to 1200 m from 800 m, through use of a narrower-diameter drill string. Thus the GLAD rig appears to be adequate for subsurface sampling to depths of several hundred meters in both Malawi and Tanganyika. ODP drilling/sampling tools, including the Advanced Piston Corers, are effectively off-the-shelf technology and are easily fit to the GLAD rig.

Adapting local vessels for drilling operations is probably the most economical means of providing a drilling platform for a single drilling operation. However it was demonstrated that over the lifespan of several large lake projects it may be cost effective to acquire a modular (@C-Float@) barge system to serve as a drilling platform on successive lake drilling projects. Options for positioning the drilling platform included an anchor mooring system, dynamic positioning system, or hybrid system involving a combination of dynamic positioning and anchoring technologies. Whereas anchoring/mooring systems are simple and robust, they are slow to deploy and require a large anchor-handling tug for mooring deployment. Dynamic Positioning Systems involve large up-front costs and require careful maintenance and oversight during operations, but offer the greatest flexibility and rapid deployment capability. Given the rapidly changing sea states on the lakes, this may be the most advisable choice of positioning technology, according to the engineering team present at the workshop.

Several strategies were discussed for initial drilling, which will likely be proposed first for Lake Malawi, on account of its favorable infrastructure and thorough site survey geophysical data sets already in-hand. Since distances across Lake Malawi are significant, it is likely that 2 support vessels will be required for servicing the drilling platform. Additionally, drilling operations will likely be carried out on a 24 hour per day, 7 day per week basis during the favorable weather window (December-March). It is unlikely that the GLAD drilling rig will be able to operate in sea states greater than 1-2 m, therefore it will be necessary to factor in weather delays when developing drilling operation time lines.

Reviews of funding environments at NSF and ICDP

Several presentations considered the state of funding of the Earth System History Program at the U.S. National Science Foundation, and at the International Continental Scientific Drilling Program. These presentations placed the proposed scientific effort into a realistic fiscal framework. The ICDP will fund up to 1/3 of total operational costs for any given drilling program, with the balance of the funds to be derived from national science agencies. In addition, ICDP is able to provide additional funding for ancillary tasks such as downhole geophysical logging. It is expected that the total drilling budget for a 4-site project will be in the vicinity of $2M, USD.

Excursions to scientific staging sites

On October 14, we ran an excursion to the potential engineering staging sites at Monkey Bay, Chipoka, and to the Lake Malawi Biodiversity Project lakeside facility at Senga Bay, a possible site for core handling and conducting preliminary whole-core analyses. All three sites were observed to be highly suitable. In Monkey Bay, local engineers provided a tour of the local shipyard with its machine ships, slipway, two main piers, and dry-dock facility. Three possible support vessels were in port in Monkey Bay, and seen by the participating scientists. These vessels included the *S/V Timba* (Dept. of Surveys), the *R/V Usipa* (Lake Malawi Biodiversity Project) and the *R/V Ndunduma* (Dept. of Fisheries). In addition, two other vessels were inspected as possible drilling platforms: the barge Viphya (52 m), and the container ship Katundu (~70 m), operated by Malawi Lake Services. The initial impression of the engineer from Seacore Ltd., was that the barge Viphya, with modifications, would be an adequate drilling platform for Lake Malawi.

Recommendations

- Several general recommendations to the scientific community arose out of the workshop.
- An initial drilling program be proposed for Lake Malawi, given its favorable local infrastructure and extensive seismic and sediment core datasets.

- Engineering scoping of possible platforms should continue. Cost/benefit analyses should be carried out on platform options including 1) modification of the existing barge *Vipyha* on Lake Malawi and 2) acquiring a modular C-Float type barge. This should be completed within the context of a single Lake Malawi program, and alternatively, using a scenario that includes drilling both Lake Malawi and Lake Tanganyika.
- A local planning committee be established for prioritizing local needs.
- A European scientific participant committee be establish to explore avenues of additional support from European science agencies.
- Likely scenarios for a Lake Malawi drilling program include proposals for 4 or 8 site drilling program. A four-site drilling program would include 1) a southern basin site that would sample the southern lake/ southern latitude response to paleoclimate change, provide nearshore sequences for evolutionary biology studies and also serve as an initial test site for coring operations; 2) a central basin site that will penetrate through the Bruhnes-Matayama paleomagnetic reversal and provide an undisputed chronology for the existing stratigraphic framework, and 3) two northern basin sites that sample the rich upwelling regions of the Livingstone Basin, along an offset drilling transect to extend the record back beyond the Pleistocene. In an 8 site scenario, the offset transect would be extended to include an additional 3-4 sites to provide a record of continuous stratigraphic section back through the Pliocene.
- Following final agency decisions on the GLAD 800 proposal to ICDP/NSF, consult with agency program managers and DOSECC on the best proposal framework for the project.
- Explore funding options for additional site survey activity on Lake Tanganyika. Because of the greater depth and volume of Tanganyika, it was likely to have been a much more substantial lake than Malawi during the severe arid intervals of the Pleistocene.

Thematic Science Summaries

The following pages contain four separate thematic summaries covering areas of Paleoclimate Studies, Basin Evolution Studies, Evolutionary Biology, and Environmental Background to Human Origins

Paleoclimate Studies

The large lakes of the East African Rift Valley are unique among the large lakes of the world in terms of their sensitivity to climate change and their long, continuous, high-resolution records of past climate change in the tropics. The paleoclimate group identified three main questions to be addressed by deep drilling in Lake Malawi:

• What is the climatic linkage between tropical Africa and the high latitudes at orbital and longer-period timescales?

- Did tropical African climate predominantly respond to changes in low-latitude precessional insolation (23-19 kyr) or high-latitude ice volume (100 kyr and 41 kyr) forcing?
- Has Lake Malawi always responded to southern hemisphere insolation forcing, as data for the period since the last 40 ka suggest?

• Are high-frequency climate variations (analogous to Dansgaard-Oeschger or Heinrich events) superimposed on glacial-interglacial timescale variations in wet and dry conditions, and how have these varied over time?

• How has interannual African climate variability changed in association with longer-term climate variations?

- What are the dominant interannual modes of variability (ENSO, NAO)?
- How have these modes changes in association with changes in African climate?

• What is the long-term evolution of tropical East African climate?

- What is the dominant Milankovitch frequency back through time? i.e. do we see a shift from the present day 100 ka dominance to 41 ka dominance to 21 ka dominance, as observed in the marine record?
- In this region of tropical Africa, do we see a significant change in vegetation as the Earth shifted from a 41-ka world to a 100 -ka world?

Elaboration:

• What is the climatic linkage between tropical Africa and the high-latitudes?

Terrestrial and marine records of subtropical African paleoclimate variability during the late Pleistocene document the dual but separate influences of high- and low-latitude processes (deMenocal et al., 1993; deMenocal, 1995; Clemens et al., 1996). The evolution of African climate over the last five million years reflects changes in the relative influence of these end-member climate forcing factors. Prior to the onset of Northern Hemisphere glacial cycles near 2.8 Ma, African climate evidently responded primarily to variations in monsoonal circulation due to orbital changes in low-latitude insolation. Following the growth of Northern Hemisphere glacial cycles after 2.8 Ma, African climate was evidently subjected to periodic and large amplitude cool, dry cycles which were in-phase with high-latitude glacial maxima. The coupling between high- and low-latitude climate increased toward the present, with significant increases in the amplitude of glacial arid cycles in subtropical African occurring at ~1.7 Ma and ~1.0 Ma (deMenocal, 1995). These observations are based on ODP cores from the deep sea off Africa, and reflect a broad-scale integration of signals from across much of the African continent. However there are regional differences in climate evolution within east Africa on orbital time scales. One example of this is the out-of-phase relationships in lake level between Malawi and the large lakes to the north (Finney and Johnson, 1991; Finney et al., 1996; Johnson, 1996). Such regional variability can only be detected by drilling the individual lakes across a latitudinal gradient of the African continent.

African paleoclimate variability during the late Pleistocene also exhibited strong millennial-scale variability, also associated with changes in high-latitude temperature changes. In the North Atlantic this variability consists of ~1.5 ka Dansgaard-Oeschger cycles, which are bundled into longer, larger amplitude Heinrich events, which recur every 5-10 ka (Bond et al., 1993). These same millennial-scale variations are also observed in subtropical Africa (e.g. Younger Dryas in Lake Albert – Beuning et al., 1998 and in Lake Magadi – Roberts et al., 1994), and in marine sediments from the Atlantic Ocean and Arabian Sea, again documenting the close linkage between high- and low-latitude climates, although the causal mechanisms of this linkage remain obscure.

Finally, well-dated, detailed reconstructions of African paleoclimate variability indicate that the climate transitions themselves are extremely rapid, with large transitions occurring within decades to centuries (Gasse and VanCampo, 1992; Johnson et al., 1996; deMenocal et al., 1999; Street-Perrott and Perrott, 1990).

• Are high-frequency climate variations (analogous to Dansgaard-Oeschger or Heinrich events) superimposed on glacial-interglacial timescale variations in wet and dry conditions?

Grounds for anticipating centennial- to millennial-scale variations are provided by records of the transition from LGM and Holocene conditions in Lake Malawi and other lakes of tropical Africa. Geomorphological evidence (strandlines, deltas, incised fluvial channels, etc.) indicate generally low-lake or dry basin conditions at the LGM and rising levels from 15 to 12 ka in equatorial Africa. This rising trend was interrupted by a number of short-lived reversals, which are also reflected in palynological records and several geochemical and biological palaeolimnological proxies preserved in lacustrine sediments. These indicate regional excursions in temperature, P/E balance or wind-driven vertical mixing of the water bodies. Interglacial conditions, as reflected in Holocene proxy records, also contain evidence of short-term climatic reversals. Some of these began and ended abruptly. The transition to drier conditions that led to early Holocene low levels in L. Malawi seems to have occurred within a few hundred years around 9.8 14C ka (Ricketts and Johnson, 1996), while the period of particularly high early to mid-Holocene levels in most north African lakes ended equally abruptly around 4.0 14C ka. Some events seem to be local equivalents of high-latitude climatic excursions, such as the Younger Dryas and "8.2 ka event" (Alley et al., 1997), but others have as yet no recognized equivalents outside Africa.

• How does interannual African climate variability change in association with longer-term climate variations?

Laminated sediments recovered in box cores and multi-cores from northern Lake Malawi consist of alternating bands of diatom ooze (light laminations) and silty clays (dark laminations), representing the dry, windy season (June-September) and the warm, rainy season (December-March), respectively. Pb-210 dating of several cores has demonstrated that the laminations are varves. Similar annually-laminated sediments occur in deep water cores from Lake Tanganyika. The thickness of the light layers and dark layers can be measured quite precisely using computerized image enhancement and analysis tools. Presumably, the thickness of the light layers is linked to upwelling intensity and diatom productivity, whereas the thickness of the dark layers is a proxy for annual rainfall intensity. Spectral analysis of lamination thickness variability over the past 300 years reveals significant cyclicity at ENSO frequencies (Barry, in prep).

The sediments in the north basin of Lake Malawi are almost continuously varved from the present back to about 2000 ybp, and between 6500 and 10000 C-14 ybp. Within these time windows, varve thickness analyses will provide insight into the existence of climate cycles on an interannual scale. Will the ENSO-scale cycles also dominate the early Holocene record or will the early Holocene climate record be devoid of such variability, as appears to the case in the Peruvian Andes (Rodbell et al., 1999). And with deep drilling in this part of Lake Malawi, will we find similar inter-annual variability in the varved record further back in time?
While short, discrete intervals of piston cores from sites further south in Lake Malawi are laminated, the sediments are mostly homogeneous, even though they accumulated in anoxic deep waters. This is probably due to long sediment transport pathways from the major rivers in the north, resulting in a blurring of seasonal variability as the sediments settle, get re-suspended and ultimately arrive at their final burial site.

• What is the long-term evolution of tropical East African climate?

Evolution of the Milankovitch climate spectrum has been observed in both the marine record (deMenocal and Bloementhal, 1996) and the record of continental lakes (Williams et al., 1998) during the last three million years. The first major change in both records occurs between 3.0 and 2.5 Ma, when power in the obliquity band (41 ka) increases at the expense of power in the precessional band (21 ka). A second major change occurs at about one million years ago when power in the eccentricity band (100 ka) increases at the expense of the obliquity band. Pronounced depositional cyclicity, produced by high-amplitude changes in lake level, is observed in both the Lake Malawi and Lake Tanganyika seismic reflection records over the last half of the Pleistocene (Scholz, 1995; Lezzar et al., 1996). These acoustic facies couplets consist of hemipelagic high-stand deposits and coarse-grained lowstand deposits, and are accumulating in both lake basins with a frequency of about 100 kyr (Figure 1). Drilling in Lakes Malawi and Tanganyika will test this depositional model and constrain both the timing and phasing of these coupled highstand/lowstand packages. We will determine if changes in the cyclicity of the sedimentary record of these lakes are similar to those changes observed in the marine record.

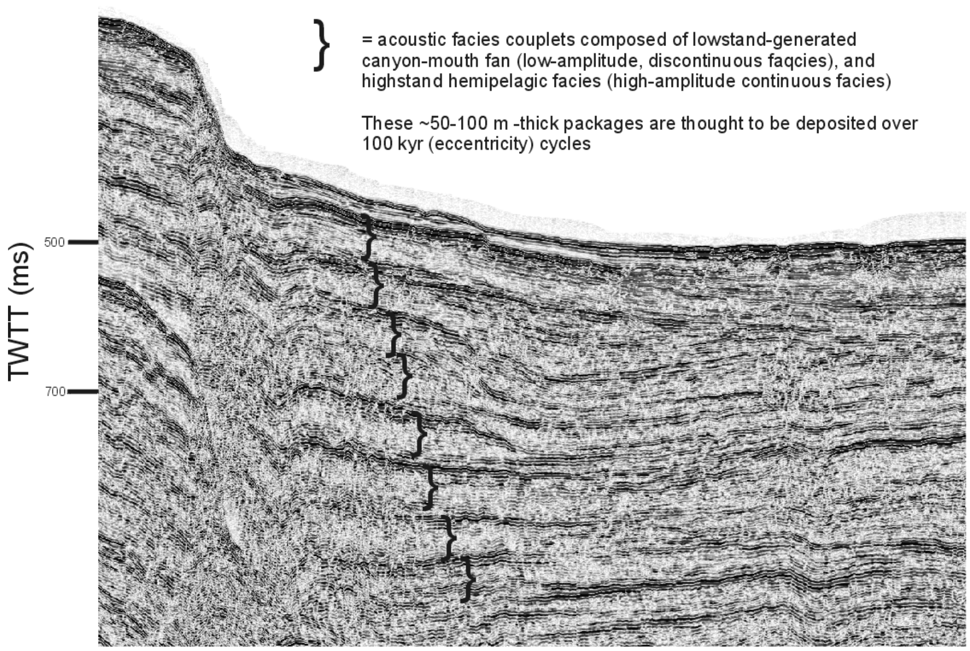

Figure 1. Acoustic Facies Couplets observed on central L. Malawi seismic profile, suggesting 100 kyr lake level and depositional cyclicity.

Geochronology:

We are confident that the suite of geochronometers available in Lake Malawi sediments will provide sufficient control to develop a rigorous age-depth model. Magnetostratigraphic and low-field-susceptibility measurements will provide the backbone of our geochronological work. These techniques have been applied successfully in other ancient lakes (i.e. Lake Baikal). This record will be calibrated using a series of horizons dated by a range of independent techniques. Reliable radiocarbon chronologies using woody material and charcoal exist for the last 20 ka. We anticipate that this approach will provide age control to 40 ka. In addition, there are a series of carbonate-rich horizons deposited during periods of evaporative concentration of lake waters. These have the potential to be dated by uranium series techniques (isochron method, e.g. Bischoff and Fitzpatrick, 1991), developing chronologies for the last 400 ka. Finally, the numerous volcanic ash layers present, particularly in the northern basin, provide opportunities for Ar-Ar dating. This should be possible for sediments older than 25 ka, given the abundance of crystalline material in some of the young ash layers in the northern basin. In addition, trace element fingerprinting of these ash layers will provide a means of developing stratigraphic linkages among cores.

References

Alley, R.B., P.A. Mayewski, T. Sowers, M. Stuiver, K.C. Taylor, and P.U. Clark, Holocene climatic instability: A prominent, widespread event 8200 yr ago, *Geology*, *25* (6), 483-486, 1997.

Barry, S., in prep. The high resolution stratigraphy of sediment cores from the northern basin of Lake Malawi: varves, turbidites and tephras. M.S. thesis, Water Resource Sciences, University of Minnesota.

Bond, G., W.S. Broecker, S. Johnsen, J. McManus, L. Labeyrie, J. Jouzel, and G. Bonani, Correlations between climate records from North Atlantic sediments and Greenland ice, *Nature*, *365*, 143-147, 1993.

deMenocal, P.B., Plio-Pleistocene African Climate, *Science*, *270*, 53-59, 1995.

deMenocal, P.B., W.F. Ruddiman, and E.M. Pokras, Influences of high- and low-latitude processes on African climate: Pleistocene eolian records from equatorial Atlantic Ocean Drilling Program Site 663, *Paleoceano.*, *8* (2), 209-242, 1993.

deMenocal, P.B., and J. Bloemendal, Plio-Pleistocene subtropical African climate variability and the paleoenvironment of hominid evolution: A combined data-model approach, in *Paleoclimate and Evolution With Emphasis on Human Origins*, edited by E. Vrba, G. Denton, L. Burckle, and T. Partridge, pp. 262-288, Yale University Press, New Haven, 1995.

Finney, B. P. and Johnson, T. C., 1991. Sedimentation in Lake Malawi (East Africa) during the past 10,000 years: a continuous paleoclimate recod from the southern tropics. Palaeo-3, v. 85, 351-366.

Finney, B. P., Scholz, C. A., Johnson, T. C., Trumbore, S. and Southon, J., 1996. Late Quaternary lake level changes of Lake Malawi. In Johnson, T. C. and Odada, E. O. (eds.), The Limnology, Climatology and Paleoclimatology of the East African Lakes: Gordon and Breach, Amsterdam, 495-508.

Gasse, F., V. Lédée, M. Massault, and J.C. Fontes, Water level fluctuations of Lake Tanganyika in phase with oceanic changes during the last glaciation and deglaciation, *Nature*, *342*, 57-59, 1989.

Gasse, F., R. Téhet, A. Durand, E. Gibert, and J.C. Fontes, The arid-humid transition in the Sahara and Sahel during the last deglaciation, *Nature*, *346*, 141-146, 1990.

Gasse, F., and E. Van Campo, Abrupt post-glacial climate events in West Asia and North Africa monsoon domains, *Earth and Planet. Sci. Lett.*, *126*, 435-456, 1994.

Johnson, T. C., 1996. Sedimentary processes and signals of past climatic change in the large lakes of the East African Rift Valley. In Johnson, T. C. and Odada, E. O. (eds.), The Limnology, Climatology and Paleoclimatology of the East African Lakes: Gordon and Breach, Amsterdam, 367-412.

Lezzar, K.E., Tiercelin, J.-J., De Baptist, M., Cohen, A.S., Bandora, T., Van Rensbergen, P., Le Turdu, C., Mifundi, W., and Klerx, J., 1996, New seismic stratigraphy and late-tertiary history of the north Tanganyika basin, East African Rift system, deduced from multichannel and high-resolution reflection seismic data and piston core evidence, Basin Research 8: 1-28.

Ricketts, R. D. and Johnson, T. C., 1996. Early Holocene changes in lake level and productivity in Lake Malawi as interpreted from oxygen and carbon isotopic measurements of authigenic carbonates. In Johnson, T. C. and Odada, E. O. (eds.), The Limnology, Climatology and Paleoclimatology of the East African Lakes: Gordon and Breach, Amsterdam, 475-493.

Rodbell, D.T., G.O. Seltzer, D.M. Anderson, M.B. Abbot, D.B. Enfield, and J.H. Newman, An ~15,000-year record of El Niño-driven alluviation in southwestern Equador, *Science*, *283*, 516-520, 1999.

Scholz, C.A., 1995, Deltas of the Lake Malawi Rift, East Africa: Seismic Expression and Exploration Implications, AAPG BULLETIN, v. 79, p. 1679-1697.

Street-Perrott, F.A., and R.A. Perrott, Abrupt climate fluctuations in the tropics: the influence of Atlantic Ocean circulation, *Nature*, *343*, 607-612, 1990.

Basin Evolution Studies

Lakes Malawi and Tanganyika are among the largest Aclosed@ sedimentary systems on earth, and hence are ideal sites for evaluating processes of basin evolution. Their stratigraphic record contains a rich history of interplay between surface, near-surface, and crustal processes ranging from climatic forcing of sediment loadings (e.g. Soreghan et al., 1999) to deep-crustal control of extensional deformation and associated vertical movements that impact regional climate. There are three main sets of questions to be considered under the framework of Basin Evolution: Chronology and Active Tectonics, Lithofacies Calibration, and Thermal Structure.

I. Chronology and Active Tectonics

Using dated drill cores, extensive seismic reflection grids (e.g. Rosendahl, 1987; Scholz, 1995), and information on footwall uplift and denudation and catchment evolution (e.g. van der Beek et al.,1998), we can generate well-constrained models of sediment mass and flux rates unavailable from other sedimentary systems. In order to accurately study tropical paleoclimate history and evolutionary biological records on a time scale of 10-1000 kyr it is necessary to determine the morphotectonic boundary conditions for the rift basins. Additionally, a well-constrained basin chronostratigraphy will allow us to assess with high temporal precision the evolution of linked fault systems (e.g. Anders and Schlische, 1994) within the basin at different scales in space and time.

The main question: What are the rates of fundamental basin-forming and basin-filling processes (e.g. subsidence, heat flow, extension, margin uplift, sediment supply, lake level change, sediment compaction) in continental rifts and how episodic or continuous are these processes? In order answer this question, we set the following goals:

<u>GOALS</u>

- Establish the chronostratigraphy of the sedimentary section. Place the current sequence stratigraphic framework, determined from seismic reflection data, into a rigorous chronostratigraphic context. (i.e. expand the chronology determined from the cores into the seismic reflection grid.)
- Quantify rates of footwall uplift and associated subsidence in the vicinity of the drill core, and assess the episodicity of these rates and their sedimentary response.
- Active tectonics controls the development of the watershed of the basin, at the regional and local scale. We intend to quantify denudation rates and the response time of the uplift/denudation/sedimentation system (e.g. Foster and Gleadow, 1993).
- Changes in the basin drainage networks will be characterized through sediment provenance studies, and reflect forcing by tectonic and climatic processes on the scale of 10 kyr to 5 myr.
- Improve models of sediment flux and mass balance in continental extensional basins.
- Assess the development of topographic highs and determine their impact on local climatic

and depositional conditions.

TOOLS

- Radiocarbon, paleomagnetics, tephrachronology (Ar-Ar), and U-Th as our first-order dating techniques.
- Physical properties measurements of continuous core and down-hole geophysical data to correlate drill cores and seismic reflection data sets.
- Expand basin evolution studies beyond the borehole using the following techniques:
  - Fission track thermochronology (e.g. Foster and Gleadow, 1993)
  - U-Th-He thermochronology
  - Cosmogenic exposure age-dating for estimation of denudation rates and sediment transport times
  - GPS campaigns for estimating instantaneous extension rates
  - Volumetric modeling of basin infill using DEM=s and seismic reflection data
  - Construction of temporally calibrated balanced-cross sections, to determine rates of extension and subsidence

A stratigraphic test of the major part of sedimentary section (through the Pliocene) in these lakes is the highest priority for local institutions, and will provide the principal basis for renewed capacity-building in the East African regional geoscience community.

II. Lithofacies calibration, Sedimentology and Sedimentary Geochemistry

The first-order indicator of environmental change in the Lake Malawi and Lake Tanganyika rift basins is sediment lithology (texture and composition) (Soreghan and Cohen, 1996; Soreghan et al., 1999; Wells et al, 1999). High-amplitude and high-frequency shifts in lake water levels exert extreme forcing on sediment character (Scholz and Rosendahl, 1988; Scholz et al., 1990); this is accomplished through changes in base level, sediment supply, catchment area conditions, and limnological and biotic boundary conditions. Rapid facies variations, both laterally and vertically are the paradigm in these basins.

The main question: What are the principal controls on the deposition of the main sedimentary facies in tropical rift basins, what are the first-order characteristics of these lithofacies, and how do they accumulate in space and time?

Deriving the three-dimensional variability of depositional facies in rift basins is fundamental for extracting paleoclimate and deformational histories. This 3-D geometry is well-established from existing seismic reflections data. However the seismic facies framework must be calibrated using continuous sediment cores, and down-hole geophysical data.

Principal goals are to :

- Calibrate and refine existing lithofacies and sequence stratigraphic models for lacustrine rift basins based on continuous sediment cores, and down-hole geophysical data.

- Characterize and calibrate the distinctive acoustic facies couplets observed in reflection records and determine the timing of the observed cyclicity.
- Quantify organic matter content both down-core and spatially, around the basin, and determine the origin of the organic matter in space and time.
- Geochemical characterization of the sediments, with respect to provenance and diagenetic processes
- Assess the diagenetic history of the sediments as a function of lake water chemistry and geothermal conditions.

III. Thermal Structure of the Rift Basin

The main question:
What is the nature of heat flow across the Lake Malawi rift basin, and how has the thermal history impacted the evolution of extensional faults in the rift basin.

In this project, we propose to use new heat flow observations obtained from the drill holes in Lake Malawi to critically evaluate models for the structural development of rift faults. Although there is a large volume of scientific literature on continental rifting, substantial gaps still remain in our understanding of how continental rifts form and evolve structurally. In particular, little is known about fault growth during the earliest stages of rifting, in part because fault growth is directly linked to the thermal and mechanical structure of the lithosphere (Cowie, 1998; Jackson and Blenkinsop, 1997; Hayward and Ebinger, 1996; Ebinger et al., 1999; Scholz and Contreras, 1998), for which we have few constraints. Heat flow observations provide a first-order constraint on the thermal structure of the lithosphere, and without such constraints it is not easy to assess the mechanical state of the lithosphere at the time of rifting.

While heat flow measurements have been made in other areas of East Africa, they either come from unrifted parts of the East African Plateau (Nyblade et al., 1990, Nyblade, 1997), or else from regions of the Kenya rift where the crustal thermal regime has been hydrologically disturbed (Whieldon et al., 1997). Marine type heat flow measurements were made several decades ago in Lakes Malawi, Tanganyika, and Kivu (Von Herzen and Vacquier, 1967; Degens et al., 1971; Degens et al., 1973), but the uncertainties associated with these measurements are so large (>50%) that the data provide only weak constraints the thermal structure of the rifted lithosphere. Nonetheless, they suggest that crustal temperatures beneath the rift are elevated, while most fault models assume that the crust is cold and brittle (Cowie, 1998; Jackson and Blenkinsop, 1997; Hayward and Ebinger, 1996; Ebinger et al., 1999; Scholz and Contreras, 1998). The proposed drill holes in Lake Malawi would afford us an opportunity to make high quality conventional heat flow determinations that would indicate to what extent the rifted crust is thermally modified.

Heat flow observations can be made in the drill holes by logging temperatures several times after drilling is complete. From the multiple measurements, the disturbance to the thermal field around the drill hole can be determined and an estimate of the equilibrium temperatures can thus be obtained. In addition to temperature measurements in the drill holes, core samples will be needed to measure thermal conductivities.

References

Anders, M. H. and Schlische, R.W., Overlapping faults, intrabasinal highs, and the growth of normal faults, *Journal of Geology*, v.102, 165-179, 1994.

Cowie, P.A., A healing-reloading feedback control on the growth rate of seismogenic faults, *J. Struct. Geol., 20*, 1075-1087, 1998.

Degens, E.T., R.P. Von Herzen, and H.K. Wong, Lake Tanganyika: water chemistry, sediments and geologic structures, Naturwissenschaften, 58, 229-240, 1971.

Degens, E.T., R.P. Von Herzen, H.K. Wong, W.G. Denser, and H. W. Jannasch, Lake Kivu: structure, chemistry and biology of an East African rift lake, Geol. Runsch., 62, 245-277, 1973.

Ebinger, C.J., J.A. Jackson, A. N. Foster, and N.J. Hayward, Extensional basin geometry and the elastic lithosphere, *Phil. Trans. R. Soc. Lond. A, 357,* 741-765, 1999.

Foster, D.A.and Gleadow, A.W., Episodic denudation in East Africa; a legacy of intracontinental tectonism, *Geophysical Research Letters*, v. 20, n. 21, p. 2395-2398, 1993.

Hayward, H., and C. Ebinger, Variations in the along-axis segmentation of the Afar rift system, *Tectonics, 15,* 244-257, 1996.

Jackson, J. and T. Blenkinsop, The Bilila-Mtakataka fault in Malawi: an active, 100 km long normal fault segment in thick seismogenic crust, *Tectonics, 16,* 137-150, 1997.

Nyblade, A.A., H.N. Pollack, D.L. Jones, F. Podmore, and M. Mushayandebvu, Terrestrial heat flow in east and southern Africa, *J. Geophys. Res., 95*, 17371-17384, 1990.

Nyblade. A.A., Heat flow across the East African Plateau, *Geophys. Res. Lett., 24,* 2083-2086, 1997.

Rosendahl, B.R., Architecture of continental rifts with special reference to East Africa, Reviews of Earth and Planetary Sciences, 15, 445-503, 1987.

Scholz, C.A., Deltas of the Lake Malawi Rift, East Africa: Seismic Expression and Exploration Implications, *AAPG BULLETIN*, v. 79, p. 1679-1697, 1995.

Scholz, C.A., Rosendahl, B.R. and Scott, D.L. Development of Coarse-grained Facies in Lacustrine Rift Systems: Examples from East Africa. *GEOLOGY*, v. 18, pp. 140-144, 1990.

Scholz, C.A. and Rosendahl, B.R., Low Lake Stands in Lakes Malawi and Tanganyika, East Africa, Delineated with Multifold Seismic Data. *SCIENCE*, V. 240, pp. 1645-1648, 1988.

Scholz, C.H., and J.C. Contreras, Mechanics of continental rift architecture, *Geology, 26,* 967-970, 1998.

Soreghan M.J., and Cohen, A.S., Textural and compositional variability across littoral segments of Lake Tanganyika: The effect of asymmetric basin structure on sedimentation in large rift lakes, *AAPG Bulletin*, 80, 382-409, 1996.

Soreghan, M.J., Scholz, C.A., and Wells, J.T., Coarse-grained deep-water sedimentation along a border fault margin of Lake Malawi, Africa: Part 1- Seismic Stratigraphic Analysis, Journal of Sedimentary Research, V 69, p 832-846.

Wells, J.T.,, Scholz, C.A, and Soreghan, M.J. Processes of sedimentation on a Lacustrine border fault margin: Interpretation of cores from lake Malawi, East Africa. Journal of Sedimentary Research, 69, p. 816-831.

Wheildon, J., P. Morgan, K.H. Williamson, T.R. Evans, and C.A.Swanberg, Heat flow in the Kenya rift zone, Tectonophysics, 236, 131-150, 1997.

Van der Beek, P. Mbede, E., Andriessen, P., and Delvaux, D., Denudation history of the Malawi and Rukwa Rift Flanks, (East African Rift System) from apatite fission track thermochronology, Jrnl. Afr. Earth Sciences, 26, 363-385, 1998.

Von Herzen, R.P., and V. Vacquier, Terrestrial heat flow in Lake Malawi, Africa, J. Geophys. Res., 72, 4221-4226, 1967.

EVOLUTION of BIODIVERSITY and ECOLOGY in ANCIENT LAKES: BIOLOGICAL OBJECTIVES of DEEP DRILLING
in LAKES MALAWI and TANGANYIKA

The Biological Significance of Lakes Malawi And Tanganyika

Lakes Malawi and Tanganyika are aquatic island systems of elevated endemic biodiversity, unparalleled for their potential to test hypotheses of comparative evolution on large scales. The sedimentary record of these lakes offers us the opportunity to resolve both evolutionary and ecological changes in their biota at time scales of decades, over hundreds of thousands to millions of years.

Despite their long histories and geological similarities, the patterns of diversity and genetic differentiation of the biota differ dramatically between Lakes Malawi and Tanganyika. Both lakes were colonized by cichlid fishes, thiarid gastropods and ostracode crustaceans, but these exemplar taxa currently have contrasting aspects in the two lakes. Approximately 1000 fish species are estimated to have evolved within the cradle of Lake Malawi, which is approximately 10% of all freshwater fish species in the world. Despite their astonishing multitude, these species encompass a rather modest degree of molecular genetic and morphological change (Kornfield, 1978; Moran *et al.*, 1994; Parker and Kornfield, 1997). The fishes in Tanganyika are genetically and morphologically much more diverse than those in Malawi (Sturmbauer and Meyer, 1992, 1993)., yet total only 300 species (which is still more than all the species in the 10s of thousands of North American lakes combined). In Lake Tanganyika, about 240 out of 250 species of prosobranch gastropods and ostracode crustaceans are unique to that lake, and like the cichlid fish, form numerous distinct, divergent lineages (Michel, 1994; Park and Downing, in press). The living prosobranch gastropod fauna of Lake Malawi has undergone only limited differentiation and few if any endemic ostracodes are reported from this lake (Martens, 1994; Michel, 1994).

Understanding the history of the Malawi and Tanganyika radiations, their similarities and differences, represents an extraordinary opportunity for evolutionary biology.
In these lakes we have a unique opportunity to investigate the dynamics of evolutionary and ecological change. Patterns of speciation, the origin of major morphological evolution, and the origin of major reorganizations in community structure can all be investigated in a comparative setting in these two lakes, in the context of high resolution, long stratigraphic records. Paleoenvironmental, tectonic and climatic reconstructions obtained from other components of

this drilling program will provide the context for interpreting those dynamics.

MAJOR QUESTIONS TO BE ADDRESSED IN EVOLUTIONARY BIOLOGY AND PALEOECOLOGY

For our purposes of evolutionary studies the most promising groups of fossil organisms are the gastropod molluscs and ostracode crustaceans. In addition to their preservation potential these animals are small (easily obtained in cores), can be identified to species level as fossils, and provide interesting targets for evolutionary studies.

- **Timing of diversification of the endemic radiations in Lakes Malawi & Tanganyika.**

We propose to determine the duration and extent of evolutionary radiations in target groups of readily preserved fossil lineages. We will test the hypothesis that the Lake Malawi biota has undergone more frequent resetting of its evolutionary clock than the biota of Lake Tanganyika, as a result of more frequent and profound disruption of the Lake Malawi ecosystem by climatically-driven lake level fluctuations and perhaps salinity crises. As a result of its lesser depth and simpler tectonic configuration (fewer basins), habitat stability is predicted to have been much less in Lake Malawi and the lake may have frequently dried, eliminating nascent evolutionary novelty, similar to Lake Victoria in the Late Pleistocene (Johnson *et al.*, 1996). The more complex basin configuration and deeper waters of Lake Tanganyika provided more time and less severe perturbations to the evolving biota, stimulating greater levels of morphological diversification and genetic differentiation.

From cores in Lake Malawi we will document changes in the *Melanoides* gastropod lineage through time, as this group currently includes 12 extant, endemic species (Brown, 1994). Similarly, the *Gomphocythere* ostracode lineage will be a focal taxon. When drilling moves to its second phase in Lake Tanganyika we will compare these records with the more diverse *Lavigeria* lineage, a related thiarid gastropod, and the *Gomphocythere* lineage for ostracodes (Michel in press; Park and Downing, in press). In both lakes we will compare the records of evolutionary change with our developing understanding of lake level, climate and tectonic history, to determine if more frequent and/or extensive desiccation and disappearance of habitat is characteristic of Lake Malawi, and if those changes are linked to extinction events. Furthermore in Tanganyika we predict that the evolution of multiple basins of the lake (whose age will also be determined by drilling) is linked to episodes of diversification (e.g. Michel *et al.*, 1992; Meyer *et al.*, 1994; Cohen *et al.*, 1997).

- **Rates of diversification in ancient lakes**

Recent phylogenetic studies of living fish and molluscs suggest a "burst-like" pattern of initial radiation in the faunas of Lakes Malawi and Tanganyika (Meyer *et al.*, 1994; Michel, *in press*; West and Michel, *in press*). We will test whether benthic fossil lineages support an interpretation of rapid morphological innovation and species divergence among molluscs and crustaceans. We further predict that these bursts will be linked to significant episodes of tectonic or climatic change (i.e. Verheyen *et al.*, 1996), analogous to the rapid speciation inferred to have

occurred in Lake Victoria subsequent to its Pleistocene desiccation, during its Holocene refilling (Johnson *et al.*, 1996) and Lake Baikal in its basin subdivision (Sherbakov 1999). In contrast, we predict that planktic diatoms will show much less diversification following major tectonic or climatic events because habitat segregation and basin subdivision to will not affect populations of these readily transported species (focussing on the *Aulacoseira* complex, Cocquyt and Vyvermans, 1994).
For both benthic and planktonic organisms we will trace sequences of evolutionary change and extinction through a series of lake level fluctuations. Core data will provide replication and thus statistical rigor to our tests of causal basis of speciation.

- **Evolutionary escalation and predator/prey arms races**

Present-day Lakes Malawi and Tanganyika display strikingly different patterns of predator-prey interactions in their benthic and demersal habitats. In Lake Tanganyika, endemic crabs and fish are specialized for effective predation, and natural selection has resulted in heavily armored gastropods, remarkably convergent on thick-shelled, spinose marine snail morphologies (West *et al.*, 1991; West and Cohen, 1996). The gastropods deposit multiple cross-lamellar layers (up to 4) of skeletal carbonate, strengthening the shell in a fashion analogous to plywood. Furthermore, the Lake Tanganyika gastropods can repair their shells after attack (a trait rarely seen in freshwater snails, but again common in marine ones). None of these characteristics or interactions are well developed in Lake Malawi (Brown, 1994).

The question of why these two similar lakes have undergone such radically different histories of predator-prey interactions can only be answered through a detailed analysis of the history of character acquisition for the heavily-shelled molluscs in modern Tanganyika, and a comparison of this history with that of the fossil molluscs of Lake Malawi. It is entirely possible that similar bouts of coevolutionary "arms-races" have occurred in the past in either lake, only to be eliminated through periodic extinction events. Repeated episodes of escalatory coevolution among fish species have been inferred from the fossils of Pliocene Lake Idaho, but the timing on rates of evolution of these complexes is poorly constrained (Smith, 1987). Viviparid gastropods exhibit anti-predatory morphologies, coincident with increased species diversity, through several sedimentary cycles of the Lake Edward-Albert fossil deposits, but lose both diversity and armor in the relict living fauna (van Damme & Pickford, 1999).

We hypothesize that the modern extreme biotic differences between the two lakes reflects different ages of their respective aquatic ecosystems, Malawi being the younger, less co-evolved system and Tanganyika the older. We can test this hypothesis through the acquisition of shell thickness, repair and cross lamellar count data. Knowing the age of changes in each of these factors will allow us to determine their rates of change. Furthermore, age data can be superimposed on existing phylogenies that map out the acquisition of multiple cross lamellae, telling us what the pattern of evolution of these characters has been (e.g. West and Cohen, 1996). We can then use the shell repair data to determine long-term predation intensity, testing whether the unusual mollusc shell characters in Tanganyika are part of a coevolved complex. Lake Tanganyika promises a clearer documentation of actual rates of predator-prey coevolution than any other biotic system from any environment. In Malawi our interest will be to see if earlier episodes of escalation have occurred during periods of lake-level stability, subsequently eliminated in the modern lake fauna.

- **Community response to environmental change at varying time scales**

Ecologists have grappled with the question of how communities change over time, whether as coordinated groups of organisms responding *en masse* through invasion and local extinction, or through individualistic shifts of species' relative abundances. This problem has been a particularly thorny issue because of our inability to sample community dynamics at a wide and continuous range of time scales. On the one hand, neo-ecological studies are generally performed with an abundance of data but over time intervals encompassing few generations. In contrast, paleoecological studies typically cover much longer intervals but are poorly resolved in time. In Lake Tanganyika "long-term" ecological research on cichlid fish communities, spanning about a decade, supports a model of community coordination and stability, at odds with lower resolution but longer duration ostracode community data within the same lake (Hori *et al.,* 1993; Cohen, *in press*). Are these contradictions real (resulting from differences between organismal groups or habitat) or are they a result of sampling at very different time scales?

The sedimentary records of Lakes Malawi and Tanganyika allow sampling of ecological change at annual to decadal resolution, over time intervals spanning hundred of thousands to millions of years, thereby addressing this important question. Analysis of change at varying time scales through a series of cores will allow us to see how our perceptions of change are affected by our scale of observation, an important question for almost all of community ecology. We can extend our analysis from the temporal to the spatial scale through the analysis of adjacent cores (in our proposed drilling program three cores will be routinely collected at each coring site, to provide assurance of complete core recovery). This is also important because much current speculation about community stability or instability rests on an understanding of how adjacent habitat patches and populations interact with one another over time. In Lakes Malawi and Tanganyika we have the possibility of inferring these patch interactions over very long time periods.

We can attack the problems outlined above using ostracode, diatom and palynological records. The former two data sets will give us records of the tempo of community change and patch dynamics in the lakes, and through comparison between the lakes, an understanding of how community change relates to larger-scale differences in lake history. The pollen record will allow us to see vegetational response to shifting climatic variables, and whether these responses differ between the subequatorial climate of the Lake Malawi basin and the equatorial climates of the Tanganyika basin.

- **Regional Research Questions**

In addition to the questions outlined above, all of which have broad significance for evolutionary ecology in general, issues of more regional concern can be tested with fossils in the Malawi and Tanganyika cores. The biogeography of dispersal among freshwater ecosystems of the African

Great Lakes can be addressed for the taxa amenable to core analysis (primarily ostracodes and molluscs, since fish are rarely preserved well enough to identify to species level). Some data suggests that Lake Tanganyika has acted as a long-term crucible or refugium during periods of severe dessication in other lake systems, and that the faunas of the other African Great Lakes are derived from within "Tanganyikan" clades (Meyer *et al.* 1994; Van Damme and Pickford, 1999; Park and Downing, *in press*, West and Michel, *in press*). This hypothesis may be testable with data to be acquired in the combined Tanganyika/Malawi drilling program, in combination with earlier-collected outcrop data from the Kaiso Rift and Lake Rukwa.

Another important regional question for paleobiology is the role that external forcing mechanisms have played in constraining the phylogeny of ostracodes and molluscs. Through close collaboration with our colleagues in paleoclimatology and tectonic interpretation of the cores we hope to be able to provide realistic and detailed scenarios of evolution within different sub-basins of the lakes, relating, for example, the establishment of particular barriers to dispersal with particular diversification events.

The endemic fauna as a tool for paleoclimatic and tectonic data acquisition

Fossil organisms can be powerful tools for paleoenvironmental and chronostratigraphic interpretation. Ostracodes, molluscs and diatoms have all been widely used to infer composition and concentration of water masses, water depths and habitat zonation. Carbonate in ostracode and mollusc shells can also be analyzed for stable isotopes and minor elements, again for the purpose of paleoenvironmental and paleoclimatic interpretation. And finally, ostracodes and molluscs have been a mainstay of chronostratigraphy in the ancient Cretaceous rift lake basins of Brazil and West Africa, a testimony to their rapid evolution in those systems, so similar in many respects to the large rift lakes of Africa. Although these are not, in our view, fundamental questions of ecology and evolution, they are nevertheless of critical importance to the drilling program as a whole.

CONSTRAINTS ON DRILLING TARGETS

As we have alluded to above, not all lacustrine organisms are going to be equally amenable to study in this project. Our best hopes for evolutionary records clearly lie with small, benthic, shelled invertebrates. These organisms are completely restricted to the oxic zones of the two lakes today, and will not be found therefore in deep water sediments, except during periods of significant lake level decline. This assertion is based on considerable coring experience of the authors in Holocene and Late Pleistocene sediments and the observation that deep water transport of dead shell material, while a real phenomenon on steep slopes, is unlikely to be important in the types of locations where we will drill (flat, away from rocky highs). For this reason we strongly advocate that at least some cores in each lakes be taken from relatively shallow, sublittoral sites, or sites that have likely been at such depths over geologic time. We recognize that these areas may not be ideal for other purposes, such as the highest resolution paleoclimate studies. Nevertheless, the added information such shallow sites will provide us for evolutionary ecology studies makes the additional effort of obtaining such records well worthwhile. This justification is further strengthened when one considers the potential of these same, shallow-lake organisms for providing paleoclimatic proxies such as carbonate, growth banding (for bivalves), trace elements and stable isotope records, all of which are unobtainable in deep water.

Our experience suggests that large structural platforms or perhaps distal deltaic environments are the best sites for collecting the types of records we require, with paleowater depths of 0-100m. Clearly depth will change over time, but the lakes seem to return to similar spillway elevations repeatedly, so modern depth ranges are probably realistic guides for locations of abundant fossils in cores.

Our prior experience in the large lake coring in these types of environments suggests that decadal-scale resolution is quite feasible. Bioturbation exists in these water depths, but is relatively unimportant (2-3cm mixing depths) for the likely sampling spacing we would employ. Depositional hiatuses during lake low stands are a greater concern for our records, but these hiatal intervals in the shallow site records would be dovetailed with records from deeper basinal sites, so we can expect a reasonably complete record at the millenial scale considering the lakes in their entirety.

References

Brown, D.S., 1994, *Freshwater Snails of Tropical Africa and their Medical Importance* 2nd ed., Taylor and Francis, London.

Cocquyt, C. and Vyverman, W., 1994, Composition and diversity of the algal flora in the East African Great Lakes: a comparative survey of Lakes Tanganyika, Malawi (Nyasa) and Victoria. *In* Martens, K., Goddeeris, B. and Coulter, G. (eds.) *Speciation In Ancient Lakes*. *Arch. Hydrobiol. Beih. Ergebn. Limnol.* 44:161-172.

Cohen, A.S., Lezzar, K.E., Tiercelin, J.J. and Soreghan, M., 1997, New palaeogeographic and lake-level reconstructions of Lake Tanganyika: implications for tectonic, climatic and biological evolution in a rift lake. *Basin Research* 9:107-132.

Cohen, A.S., *in press*, Linking spatial and temporal change in the diversity structure of ancient lakes: Examples from the ostracod ecology and paleoecology of Lake Tanganyika. *In* Rossiter, A. (ed.) *Biology of Ancient Lakes* Academic Press.

Hori, M.,Gashagaza, M.M., Nshombo, M., and Kawanabe, H., 1993, Littoral fish communities in Lake Tanganyika: Irreplaceable diversity supported by intricate interactions among species. *Conservation Biol.* 7:657-666.

Johnson, T.C., Scholz, C.A., Talbot, M.R., Kelts, K., Ricketts, R.D., Ngobi, G., Beuning, K., Ssemmanda, I. And McGill, J.W., 1996, Late Pleistocene dessication of Lake Victoria and rapid evolution of cichlid fishes. *Science* 273:1091-1093.

Kornfield, I., 1978, Evidence for rapid speciation in African cichlid fishes. *Experientia* 34:335-336.

Martens, K., 1994, Ostracod speciation in ancient lakes: a review. *In* Martens, K., Goddeeris, B. and Coulter, G. (eds.) *Speciation In Ancient Lakes*. *Arch. Hydrobiol. Beih. Ergebn. Limnol.* 44:203-222.

Meyer, A., Montero, C. and Spreinat, A., 1994, Evolutionary history of the cichlid fish species flocks of the East African great lakes inferred from molecular phylogenetic data. *In* Martens, K., Goddeeris, B. and Coulter, G. (eds.) *Speciation In Ancient Lakes*. *Arch. Hydrobiol. Beih. Ergebn. Limnol.* 44:407-423.

Michel, A.E., Cohen A.S., West, K., Johnston, M.R. and Kat, P.W., 1992, Large African lakes as natural laboratories for evolution: Examples from the endemic gastropod fauna of Lake Tanganyika. *Mitt. Internat. Verein. Limnol.* 23:85-99.

Michel, A.E., 1994, Why snails radiate: A review of gastropod evolution in long-lived lakes, both recent and fossil. *In* Martens, K., Goddeeris, B. and Coulter, G. (eds.) *Speciation In Ancient Lakes*. *Arch. Hydrobiol. Beih. Ergebn. Limnol.* 44:285-317.

Michel, E., *in press,* Phylogeny of a gastropod species flock: Exploring speciation in Lake Tanganyika in a

molecular framework. *in* Rossiter, A. (ed.) *Biology of Ancient Lakes*. Academic Press.
Moran, P., Kornfield, I., and Reinthal, P., 1994, Molecular systematics and radiation of the haplochromine cichlids of Lake Malawi. *Copeia* p.274-288.
Parker, A. and Kornfield, I., 1997, Evolution of the mitochondrial DNA control region of the mbuna (Cichlidae) species flock of L. Malawi, E. Africa. *Jour. Mol. Evol.* 45:70-83.
Park, L.E. and Downing, K. *in press,* Implications of phylogeny reconstruction for ostracod speciation models in Lake Tanganyika. *in* Rossiter, A. (eds.) *Biology of Ancient Lakes* Academic Press.
Sherbakov, D.Y. 1999, Molecular phylogenetic studies on the origin of biodiversity in Lake Baikal. Tren. Ecol. Evol. 14:92-95.
Smith, G.R., 1987, Fish speciation in a western North American Pliocene rift lake. *Palaios* 2:436-445.
Sturmbauer, C. and Meyer, A., 1992, Genetic divergence, speciation and morphological stasis in a lineage of African cichlid fishes. *Nature* 358:578-581.
Sturmbauer, C. and Meyer, A., 1993, Mitochondrial phylogeny of the endemic mouthbrooding lineages of cichlid fishes from Lake Tanganyika, Africa. *Mol. Biol. Evol.* 101:751-768.
Van Damme, D. and Pickford, M., 1999, The late Cenozoic Viviparidae (Mollusca, Gastropoda) of the Albertine Rift Valley. *Hydrobiologia* 390:171-217.
Verheyen, E., Ruber, L., Snoeks, J. and Meyer, A., 1996, Mitochondrial phylogeography of rock-dwelling cichlid fishes records evolutionary influence of historical lake level fluctuations of Lake Tanganyika. *Phil. Trans. Roy. Soc. Lond.* B 351:797-805.
West, K., Cohen, A.S., and Baron, M., 1991, Morphology and behavior of crabs and gastropods from Lake Tanganyika, Africa: Implications for lacustrine predator-prey coevolution. *Evolution* 45:589-607.
West, K. and Cohen A.S., 1996, Shell microstructure of gastropods from Lake Tanganyika, Africa: Adaptation, convergent evolution and escalation. *Evolution* 50:672-681.
West, K. & Michel, E. *in press* The dynamics of endemic diversification: Co1 phylogeny suggests explosive origin of the gastropods of Lake Tanganyika (Cerithioidea: Thiaridae).*in* Rossiter, A. (ed.) *Biology of Ancient Lakes.* Academic Press.

Impact of Lake Malawi/Tanganyika Drilling on Issues of Human Origins

A Prospectus

- Lakes Malawi and Tanganyika are centrally located in the geographic belt (Ethiopia to S. Africa) that records the earliest human ancestors (2 to 5 million years old) and the oldest known fossils of our own species, *Homo sapiens* (>100,000 years old).

- Ancient lake basins of eastern Africa preserve the longest and most precisely dated sequences of hominid fossils and archeological evidence bearing on human origins.

- High-resolution study of African lake history is thus directly pertinent to understanding the link between past environmental change and human evolution.

Abstract

Paleoclimate research focusing on Africa has made a rich contribution to the development of hypotheses regarding human evolutionary history.

Two examples: The turnover pulse hypothesis (advanced by E. Vrba, 1980-1995) and the variability selection hypothesis (advanced by R. Potts, 1996-1998) were developed as a direct result of the past two decades of research on global paleoclimates and environmental change in ancient African lake basins.

Turnover pulse means that species origins and extinctions, including episodes involving hominids, were initiated by dramatic climatic change (aridity and cooling) in Africa during the late Pliocene and again in the Pleistocene. Variability selection draws attention to the oscillation evidenced in global and regional sedimentary records. According to this body of evidence, environmental fluctuation caused inconsistencies in the adaptive settings of early humans and thus had a formative impact on the origin of toolmaking, brain enlargement, and other advances

in human adaptability.

So far, these ideas have mainly been tested by looking at evidence of environmental change in terrestrial sediments (e.g., the Turkana and Olorgesailie basins) and deep-sea cores. Terrestrial records, however, have many gaps due to erosional unconformities, while the marine record is rather far removed from the places where hominids lived.

Recovery of high-resolution cores from Lakes Malawi and Tanganyika would provide an unparalleled record of environmental change relevant to the time and place of early human origin and the evolutionary history of our own species. An international contingent of geologists, paleontologists, and archeologists are ready to dedicate themselves to comparing the records from these African lakes to those of past lakes and associated settings inhabited by hominids.

Cores drilled from Lakes Malawi and Tanganyika will offer a body of evidence directly pertinent to the fact that human adaptations have evolved in association with African lakes for over 4.4 million years. This body of evidence signifies an opportunity that is otherwise unavailable for testing the link between human evolution and change in climate and the biota.

Potential Case Studies

- Olorgesailie, a Pleistocene lake basin in southern Kenya, provides the best calibrated record of hominid stone tools, change in the African biota, and climatic fluctuation between 1.2 million and 49,000 years ago. Recent research suggests that environmental variability has escalated through the Quaternary in the Olorgesailie region. One implication is that important changes in hominid technology, formation of the modern suite of large mammals, and perhaps the origin of the modern human lineage, all corresponded with a widening range of habitat perturbation. Comparison with Quaternary cores from modern African lakes would allow us to find out if these perturbations were widespread or local, whether fluctuations in eastern African lakes were tightly correlated, and thus whether early human populations faced inescapable shifts in their survival conditions over a wide geographic area. Testing these ideas would have an immediate impact on our understanding of human evolution.

- Since the early 1990s, considerable effort has been put into examining the record of human evolution against deep-sea dust records (terrestrial material blown from Africa). The reasoning is that if key events in human evolution occurred in response to changes in aridity or monsoons, there should be a strong correlation between these events and environmental markers in the dust record. Drilling of Lakes Malawi and Tanganyika is likely to offer the missing link in this analysis – i.e., the link between the terrestrial records (where evidence of hominids is found), the aquatic lake record on land, and records from the deep sea. Since most hypotheses of human evolutionary history are based on correlation between geological, biotic and anthropological data sets, high-resolution records from modern African lakes will provide a much more sound basis than we presently have for determining any such correlations.

Submitted by Dr. Richard Potts, Director, Human Origins Program, National Museum of Natural History, Smithsonian Institution, Washington, DC 20560, U.S.A. (October 1999)
Environmental background to human origins