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Results of 1992 Seismic Reflection Experiment in Lake Baikal

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Lake Baikal, at more than 600 km long and 1632 m deep, covers the central third of the Baikal Rift (Figure 1). It is the world's most voluminous lake, containing 20% of the world's surficial freshwater, and it is probably also the oldest lake, at >15 Ma. The Lake Baikal Rift occupies the boundary between the Precambrian Siberian craton and several microplates of south-central Asia [*Zonenshain and Savostin*, 1981] (Figure 1). Topics of current geoscience research in Lake Baikal include the nature and history of extension and subsidence in the region, deep lithospheric structure, the paleoclimate record of central Asia, and the history of sedimentation and water level fluctuation in the lake. Another topic of recent debate is whether the rift formed actively via mantle doming [*Logatchev and Florensov*, 1978], or passively as a result of distant plate interactions [e.g., *Tapponnier and Molnar*, 1979].

In August and September 1992, a joint Russian-U.S. team conducted an extensive multichannel seismic reflection (MCS) survey in Lake Baikal focusing on two structurally elevated regions of the Lake Baikal Rift. The Baikal Rift system of southern Siberia is often cited as one of the best examples of an active continental rift system. The data collected reveal considerable information on the extensional tectonics of the upper crust in the region and on the effects of tectonism on sedimentation during the accumulation of the rift's thick syn-rift fill. Primary objectives of the collaborative studies are to develop a detailed sequence stratigraphic framework and to augment and support paleoclimate studies and deep drilling efforts now underway in the lake [e.g., *Lake Baikal Paleoclimate Project Members*, 1992]. Here we present selected lines from the 2200 km of multichannel seismic reflection data acquired during the 1992 field program and highlight our initial results.

Recent Seismic-Reflection Investigations

Prior to 1989, the Lake Baikal Rift was examined through analog single-channel reflection studies of the upper sedimentary section [e.g., *Nikolayev et al.*, 1985], analog Deep Sounding Seismic profiles, and refraction and seismicity studies [e.g., *Krylov et al.*, 1981], and thermal, gravity, and magnetic studies [e.g., *Zorin et al.*, 1989]. In 1989, the southern branch of the Shirshov Institute of Oceanology conducted a major field program, collecting more than 1500 km

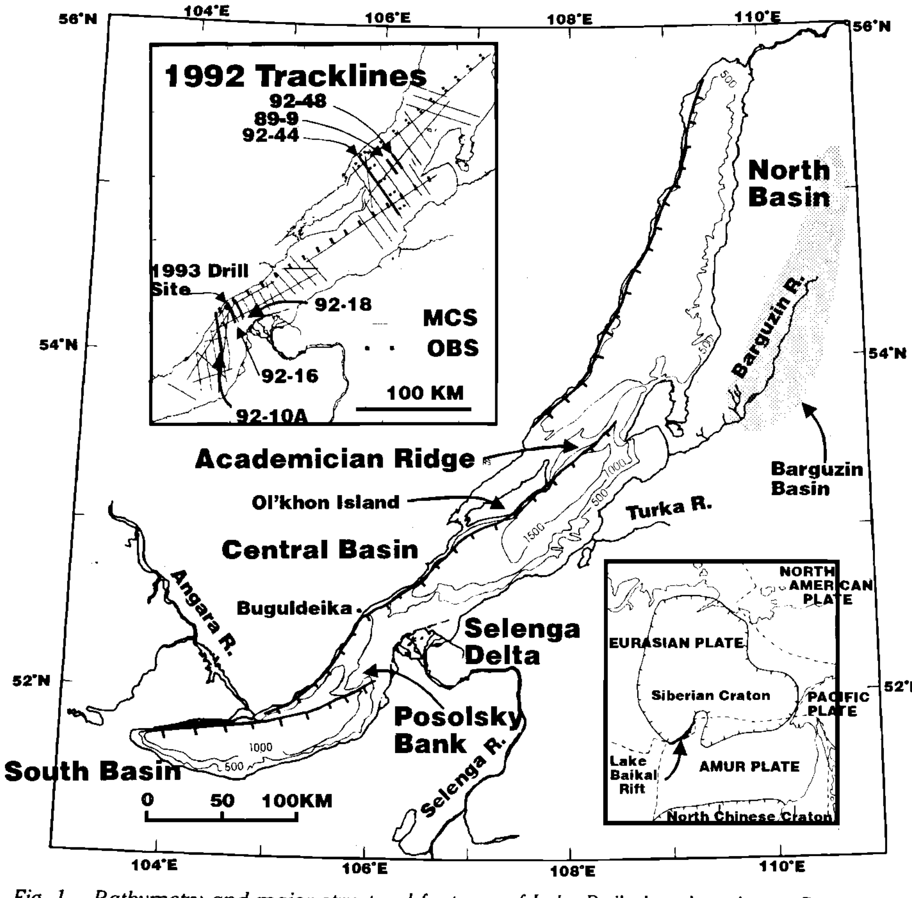

Fig. 1. Bathymetry and major structural features of Lake Baikal and environs. Contour interval is 500 m. Lower inset shows location of Baikal Rift in Central Asia (after Zonenshain and Savostin, *1981.) Upper inset indicates 1992 trackline coverage; lines shown on subsequent figures are highlighted. MCS = multichannel seismic survey, OBS = wide angle reflection survey using ocean bottom seismometers.*

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of 6- and 12-fold multichannel seismic data, which were then jointly processed by U.S. Geological Survey and Russian scientists in 1990 and 1991 (Table 1). This survey, which consisted of sixteen widely spaced dip lines and a single strike line, revealed information on rift-wide structural and stratigraphic trends and provided images of the syn-rift depositional sequences down to the crystalline basement in many localities. The joint U.S.-Russian interpretive effort of the 1989 data revealed that the three bathymetric basins of the lake are each underlain by separate sedimentary depocenters, and that a fourth small, thick sedimentary basin is present along the western edge of the Selenga Delta [*Hutchinson et al.*, 1992a]. The resolution of the 1989 data was inadequate to permit a detailed analysis of the seismic sequence stratigraphy, but three acousto-stratigraphic units could be discerned based on relative differences in acoustic character and the stratigraphic extent of fault groups that internally deformed the basins. Each of these units has been tentatively correlated with a recognized phase of rift development [e.g., *Logatchev and Florenzov*, 1978]. The limited resolution of the 1989 data indicated that a broad-band seismic source and a longer-offset receiving array were required to adequately image details of the syn-rift structure and stratigraphy within the basin fill, particularly in the deeper parts of the basins [*Hutchinson et al.*, 1992b].

The more comprehensive multichannel seismic survey was conducted in August and September 1992 with financial support from the U.S. Geological Survey, U.S. National Science Foundation, and the Russian Academy of Sciences. Details of the acquisition program are presented in Table 1.

Initial Results

The 1992 field program focused on two areas, the Selenga Delta and the Academician Ridge (Figure 1), whereas the previous MCS survey collected widely spaced regional lines along the length of the lake. We concentrated limited time and resources on these two areas of greatest complexity because they represent major tectonic boundaries most likely to reveal information about key rifting processes and critical events in the rift's history. Each is a region of transitional tectonics connecting two of the asymmetric basins that comprise the Lake Baikal part of the rift (Figure 1); both are basement highs of the type commonly referred to as accommodation zones or transfer zones [e.g., *Rosendahl*, 1987].

The 1992 MCS and wide-angle data provide considerable velocity information and indicate that an even thicker pile of syn-rift sediment may underlie Lake Baikal than had been estimated from the 1989 MCS data. In the north end of the Central basin, crystalline basement is observed at depths of 5–6 s on Line 92–44 (Figure 2). Interval velocities derived from stacking velocities and other refraction data were used to estimate sediment thicknesses, which on this profile reach a maximum of about 5 km. Maximum accumulations of sediment >8 km are found on Line 92–10A in the small basin west of the Selenga Delta (Figure 3) and may exceed 10 km in other parts of the Selenga Delta area and in the Central basin. Unlike the earlier MCS data, the 1992 data contain numerous continuous reflections throughout the syn-rift section.

The overall geometry observed on the 1992 data is that of a series of deeply subsided half-grabens or tilted full-grabens. The primary border faults in each basin are on the northwestern shore, and thus the syn-rift strata typically dip to the west or northwest. The geometry of the North basin stands in sharp contrast to that of the Central and South basins, however. The North basin is less subsided (that is, basement is at a maximum of about 2.6 s subbottom on the 1992 data), has a thinner syn-rift fill, and may not have been active during all of the rifting phases recognized in the Central and South basins. The main basin boundary faults within these basins have relatively steep dips, generally >65° (see Figure 2, Line 92–44); thus, the basin geometries may be incompatible with simple orthogonal extension [*Etheridge et al.*, 1988]. These geometries and results of earlier modeling analyses [*Balla et al.*, 1991] suggest that oblique extension has dominated much of the evolution of the Lake Baikal Rift. This is corroborated by analysis of seismicity in the northeast part of the rift [*Doser*, 1991].

Selenga Delta

The Selenga River is the largest source of freshwater and sediment to Lake Baikal, and its delta is the one of the most prominent features of the shoreline (Figure 1). Information from the upper 1 s of MCS data and from high-resolution seismic surveys (S. M. Colman, personal communication, 1993) indicates that relatively little material is deposited off the central delta front; rather, most riverine sediment is channeled through fault-controlled canyons into the basins to the northeast and southwest sides of the delta. This is manifested on the MCS data as regions of pronounced surficial channeling and slumping (Figure 3). In general, the thick deposits forming the delta are well imaged in the MCS data and clearly show intrabasinal faults, unconformities, stratal relationships, and strong basement reflections. Locally, the quality of the deeper seismic data diminishes in regions of the deeply incised channels and downslope from the channelized area, where there is mass wasting and turbidity current activity.

Data from the 1989 program indicated that the bathymetric saddle in front of the Selenga Delta is a result of a pronounced basement high between the South and Central basins, rather than deltaic accumulation [*Hutchinson et al.*, 1992a]. The 1989 data imaged the delta along a strike line; the de-

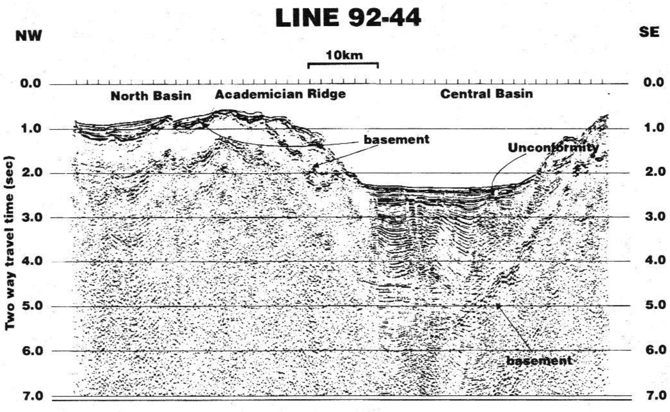

Fig. 2. Multichannel line 92–44. Profile extends from the southern end of the North basin, over the Academician Ridge, and into the northern part of the Central basin. Note the thick section of syn-rift sediment in the Central basin relative to other areas. The main basin boundary fault of the Central basin is located on the southeast side of the Academician Ridge.

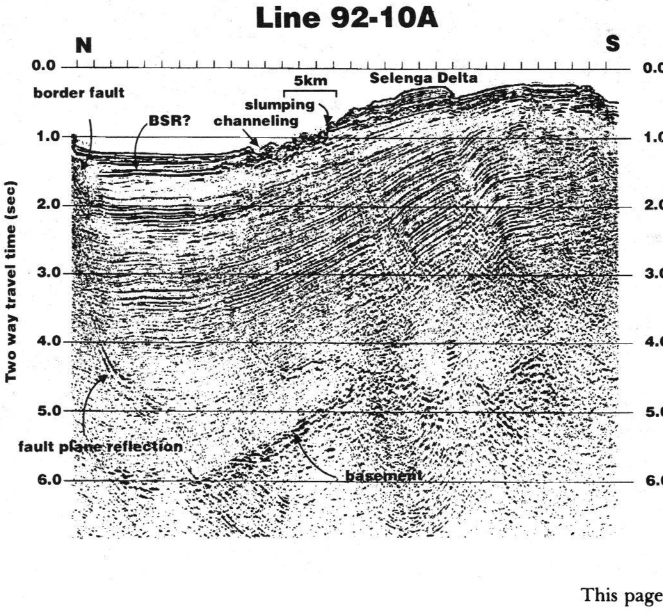

Fig. 3. Multichannel line 92–10A located on the southwest side of the Selenga Delta. Profile shows the thick accumulation of sediment adjacent to the Selenga Delta. Main basin border fault is observed on the north side of the profile. Note bottom simulating reflector at about 300 ms subbottom on the north side of the profile.

Table 1.* Acquisition Parameters
1989 and 1992 Lake Baikal Multichannel Seismic Reflection Field Programs

	1989 Survey	1992 Survey
Seismic Source	Single, 1000 in^3 (17 litre) airgun, fired on time	Tuned array of 10 Sleeve guns, total volume = 1665 in^3 (27.31 litres). Fired on time. Two 60 litre guns for wide-angle lines.
Hydrophone Streamer	1200 m long, 50 m groups, 24 channel, ballast depth control	2400 m long active section, 2870 m total offset, 25 m groups, 96 channel, dynamic streamer control system
Acquisition System	Russian Institute of Oceanology system	Texas Instruments DFS-V
Data Coverage	1500 km of 6- and 12-Fold coverage; regional lines along the entire lake	2200 km total MCS coverage 24-Fold, except on selected Selenga delta lines which were 12-Fold. Profiles concentrated near accommodation zones.
Navigation	Radar, Dead Reckoning	Ashtec Global Positioning System satellite receiver in autonomous mode
Quality Control	None	Demux and record section display on MASSCOMP computers using SIOSEIS software
Wide-Angle Data	None	Four wide-angle reflection lines using a maximum of six USGS Ocean Botton Seismometers
Magnetometer	None	Towed magnetometer
Participating Institutions in Field Program	Southern Branch, Shirshov Institute of Oceanology (Gelendzhik, Russia); Institute of Limnology (Irkutsk, Russia)	Southern Branch, Shirshov Institute of Oceanology (Gelendzhik, Russia); Institute of Limnology (Irkutsk, Russia); USGS - Branch of Atlantic Marine Geology (Woods Hole, Mass.); Duke University (Beaufort, N.C.)

**Klitgord et al.*, 1993; *Nichols et al.*, 1992; *Ten Brink et al.*, 1993

tailed 1992 grid indicates that a complex tectonic regime underlies the subaqueous delta, consisting of many fault blocks and localized deep basins. Figure 4 shows how on adjacent profiles separated by less than 8 km, basement depths change from about 5.5 km (3.5–4 s on line 16) to >10 km (5–6.5 s on Line 92–18). The 1992 data also indicate that Posolsky Bank (Figure 1) is underlain by more than 4 s of parallel-layered rift fill. These data show clearly that the Posolsky Bank is an enormous fault block, back-tilted to the northwest (Figure 1). Though the delta is located upon a basement high, about 5 s of sedimentary section are observed on Line 92–10A on its southwestern flank, equating to syn-rift deposits over 8 km thick. Across most sections in Lake Baikal, as in places in East Africa, basins show wedge-shaped cross-sections with sediments thickening toward the main basin border fault. Off the front of the Selenga Delta, a distinct reversal in sediment thickening is observed on Line 92–18 (Figure 4). The thickening of section toward the base of the delta sequence indicates that the locus of most rapid subsidence is adjacent to the delta, not along the border fault.

The first Bottom Simulating Reflector (BSR) recorded in a lacustrine setting is observed in Lake Baikal MCS data (Figure 3) and is particularly evident over the subaqueous areas of the Selenga Delta [*Hutchinson et al.*, 1991]; the 1992 data show that the BSR is regionally extensive and that it coincides with deep zones of low-coherency reflections and poor data quality. Although the BSR tends to have variable amplitude and depth below the water bottom, the manner in which it crosscuts regional stratigraphy is generally similar to marine BSRs. Preliminary indications are that cold bottom water temperatures, water depths >700 m, and possibly enhanced terrestrial carbon inputs from the Selenga River produce favorable conditions for generating a methane hydrate. Further complicating the stratigraphy of the upper sedimentary section is an angular unconformity seen at about 300 ms below the water bottom in many areas, which is about the same depth of occurrence of the BSR.

Academician Ridge

Academician Ridge is a major physiographic and tectonic feature of the Baikal Rift that separates the Central and North basins of Lake Baikal (Figure 1). In part a submerged extension of Ol'khon Island, it also separates a zone of concentrated oblique extension and deep subsidence in the Central basin from a region of more limited subsidence and possibly more diffuse extension across the lake's North basin and the Barguzin basin to the east (Figure 1). Profiles across the Academician Ridge and into the basins on either side show a much thicker sedimentary section on the Central basin side of ridge. The sedimentary section in the Central basin has been severely deformed by a series of intrabasinal faults (Figure 2).

Subsidence patterns and boundary fault activity in the Central basin have changed markedly over time. For instance, the lowermost sediments tend to thicken to the northwest, whereas most of the upper section thickens toward the southeast. Yet the very upper 100–200 ms of sediment appear to thicken again to the northwest. These alternating depocenters indicate that subsidence and extension have not remained concentrated along the main border fault in this basin but instead have shifted from one side of the basin to the other. Onshore studies in the Ol'khon region of the border fault identified a similar shift in deformation to the northwest during the most recent rifting phase. Based on similarity of acoustic character alone, the MCS data suggest that the thickest section of young sediments is in the North basin, and thus most recent subsidence is focused on the northwestern side of that basin. However, recent seismicity tends to be concentrated on the southeastern side of the Central basin [*Doser*, 1991].

Several pronounced unconformities are recognized in the profile on top of Academician Ridge (Figures 2 and 5), and the lower sequences thin considerably toward the center of the North basin. The depositional sequences bounded by those unconformities have variable thicknesses and distributed depocenters on top of the ridge. This distribution and the complicated fault pattern (Figure 5) reflect the complex history of relative uplift of this large basement high. These unconformities and depositional sequences define at least three depositional phases in the Central basin but only two phases in the North basin. Figure 5 shows some of the details of this anomalous sediment accumulation as well as the significant improvement in seismic resolution in the 1992 data compared to the earlier survey.

Discussion

In February 1993, a drilling barge operated by the Russian deep drilling program NEDRA was frozen into the ice about 6 km offshore from the Buguldeika delta (Figure 1). Using Advanced Piston Corer technology adapted from the Ocean Drilling Program, the Baikal Drilling Project completed two 100 m boreholes and recovered nearly 175 m of core as of late March 1993. This is the site of the first of several drill holes that will be used to reconstruct the paleoclimate of central Asia during the late Cenozoic [*Lake Baikal Paleoclimate Project Members*, 1992]. The site chosen is within 1 km of the northeast side of Line 92–16 (Figure 4). Both MCS and high-resolution seismic records (S. M. Colman, personal communication, 1993) show a laterally homogeneous section of high-amplitude, continuous reflections in

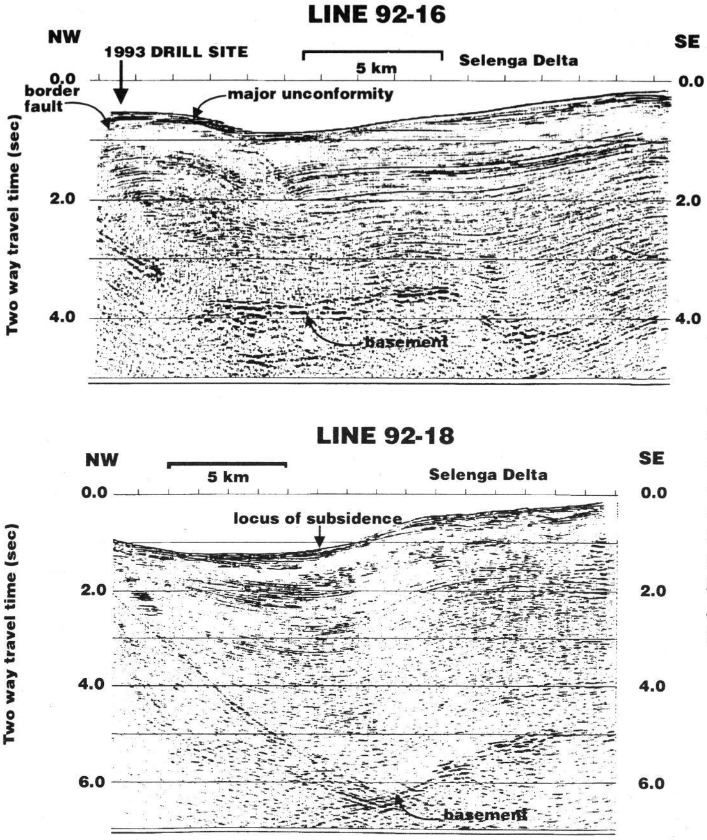

Fig. 4. Multichannel lines 92–16 and 92–18. Note increase in depth to basement from 92–16 to 92–18, and the reversal in dip of reflections in the syn-rift sedimentary section on the northwest side of line 92–18. Line 92–16 shows the location of the 1993 drill holes.

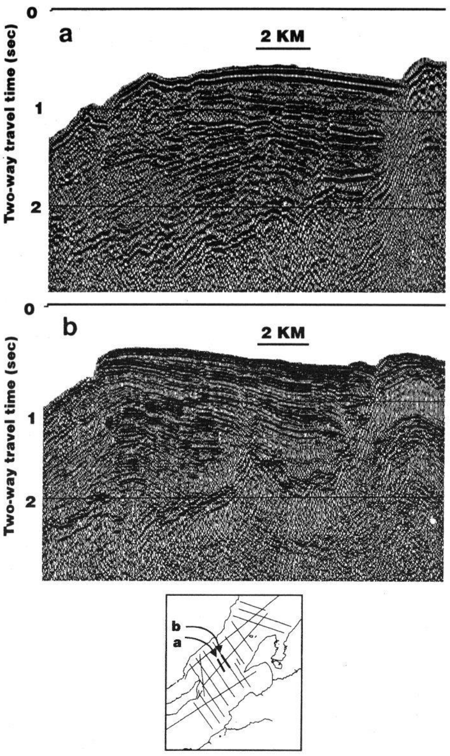

Fig. 5 Profiles over the Academician Ridge a) line 89–9; b) line 92–48. Note complex fault pattern on top of ridge and improved resolution in 92–48.

this area, indicating an environment of hemipelagic, lacustrine sedimentation, although an unconformity at about 100 ms subbottom suggests a possible hiatus in the recent past. This is predominantly a well layered sequence of fine-grained muds, material well suited for extracting paleoclimate proxy records. We anticipate that the siting of future drill sites will rely heavily on the recently acquired MCS data.

Estimating the age of large lake systems is often problematic because datable sediments are extremely difficult to recover from the base of thick lacustrine sections. A commonly applied technique, however, is to estimate the age of the lake by extrapolating ages and sedimentation rates determined from ^{14}C-dated sediment cores to the base of the sedimentary section, the thickness of which is estimated from seismic reflection data [e.g., *Cohen et al.*, 1993]. Sedimentation rates in profundal areas of Lake Baikal average about 0.5 mm/yr or less [e.g., *Edgington et al.*, 1991]. If we neglect the effects of compaction and use 8 km for a typical sediment thickness in the deeper parts of the Central and South basins of Baikal, a minimum estimate for the age of the lake is 16 Ma. To approach the problem rigorously, however, spatially coincident decompacted thicknesses and sedimentation rates must be estimated at many sites in various water depths and depositional environments.

Conclusions

The 1989 and 1992 multichannel seismic reflection data sets indicate that the Lake Baikal part of the Baikal Rift is composed of three asymmetric basins (South, Central, North) that all have their respective basin-bounding faults on the northwestern side of the rift, and a smaller basin (Selenga) that may be an arm of the South basin. The three major basins are separated by two basement highs commonly referred to as accommodation zones or transfer zones. The basement high underlying the Selenga Delta is a complex amalgamation of faulted basement blocks. Initial interpretations suggest that the syn-rift fill in the basins may be as much as 10 km thick in some localities. The North basin is less deeply subsided, contains a thinner sediment fill, and is probably younger than the Central and South basins. The cross-sectional geometry of the North basin bears the most resemblance to a typical half-graben. The data indicate that all three basins have been modified by oblique-slip tectonics, although extension directions may have varied considerably during the rift's development. Several well developed unconformities, defined by both erosional surfaces and onlap surfaces, are seen in several localities and at various stratigraphic levels within the sedimentary section. The acoustic stratigraphy is further complicated by a BSR in many areas where water depths exceed 700 m. Detailed structural and seismic-stratigraphic sequence analyses tied to "ground-truth" studies of drill core material and outcropping lacustrine sediments may reveal to what extent the observed unconformities formed as a result of tectonic activity, and also how sedimentation patterns have varied due to past climatic variations.

Acknowledgments

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NSF to Receive 10% Funding Increase

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Work is almost complete on the fiscal year 1994 funding bill for the National Science Foundation. On October 1, Conference Committee Chairs Louis Stokes (D-Ohio) and Barbara Mikulski (D-Md.) and their colleagues completed work on the final version of HR2491, the VA, HUD, Independent Agencies Appropriations Bill. The House and Senate will soon give their final approval to the conference report for HR2491, after which it will lack only the president's signature. NSF's overall budget increase of 10%, raising total funding to $3,005.3 million, is the highest increase among all departments and agencies. Last year's increase in NSF funding was 6.3%.

Funding for research and related activities will increase 7% to $1,986 million, a compromise between the 10% House increase and the 4% Senate figure. Last year's bill cut research funding. Education and human resources funding will increase 17% to $569.6 million. This is $13.5 million above the Clinton administration's request. Last year's increase for education and human resources was 4.7%.

Perhaps responding to the ever-growing backlog of modernization needs, House and Senate conferees increased funding for academic research facilities and instrumentation by 100% to $100 million, $45 million over the administration's request.—*Richard M. Jones, American Institute of Physics*

Passage Delayed by ASRM Inclusion

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In a late development that will delay but is not expected to seriously affect the NSF funding portion of the appropriations bill, the full House returned the bill to the House-Senate conferees on October 6, refusing to debate the bill because it includes $158 million to fund the shuttle's planned Advanced Solid Rocket Motor (ASRM) project. The House had voted in June to kill this project, but the Senate voted to continue it. The conferees attempted a compromise, involving minimal funding for the ASRM, but the House rejected this attempt. Although some say the ASRM is needed for missions in the same orbital path used by the Russians, the House action is considered one more sign of growing congressional skepticism on space issues.

Union Session to Explore the Mississippi-Missouri River Floods

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The causes and effects of the severe Mississippi-Missouri River floods of 1993 will be the focus of the Fall Meeting Union session U11B. This session should interest geophysical scientists in several disciplines, as it examines the meteorological conditions associated with the floods; their magnitudes and extent; the degree to which the floods represent a statistical extreme; and the role of channel constraints, reservoirs, and reservoir operating policies on flood dynamics and resulting damage. Descriptions of several papers to be presented as part of the session are discussed below.

"The Great Midwestern Flood of 1993—A Description and Some Speculation on Causes," will be presented by Gerald D. Bell, David R. Rodenhuis, and David Miskus of the Climate Analysis Center, Washington, D.C. This paper will examine the persistent circulation pattern that caused a major anomaly in climate conditions covering the upper midwest and north central Great Plains and resulted in the saturation of the Mississippi and lower Missouri rivers. The authors will also investigate hypotheses of global warming, stratospheric aerosols, and El Niño Southern Oscillation as an influence on this weather pattern.

Another paper, "How Rare Were the 1993 Floods in the Upper Mississippi River Valley?," to be presented by K. W. Potter and C. A. Rogers of the University of Wisconsin at Madison and K. Kunkel of the Midwestern Climate Center, Champaign, Ill., will estimate the severity of the floods, by using rainfall and streamflow data that extend back to the beginning of the century.

"Effect of Flood Control Reservoirs on Peak Discharge Along the Kansas River 1993," by C. A. Perry and S. E. Studley of the U.S. Geological Survey, Lawrence, Kans., asserts that flood control reservoirs retained a large volume of runoff and helped reduce flooding along the Kansas and lower Missouri rivers. It compares peak discharge, maximum river stages, and total flood volume on the Kansas River with analyses of the 1951 flood, which had a similar total volume but a substantially larger peak discharge.

This session will be held on Monday, December 6, at 8:30 a.m., in Civic Auditorium room 103.

Environmental Change Profiled in Greenland Ice Core Record

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The longest continuous high-resolution record of climate response available in the Northern Hemisphere, covering approximately 250,000 years, is the focus of Union sessions U31D, U32C, and U41B, "Climate from Central Greenland Core Records I, II, and III." This climate record has been provided by the Greenland Ice Sheet Project 2 (GISP2), which successfully reached bedrock on July 1, and its European-led counterpart, the Greenland Ice Project (GRIP). Presentations will focus on information obtained from analyses of the over 3,000-m-deep ice core samples retrieved by both projects.