address an ever-broadening range of scientific problems. The United States, Germany, and China have pooled resources to establish the International Continental Drilling Program. This program is administered by Geo-Forschungs-Zentrum Potsdam in Potsdam, Germany (WWW home page located at <http://www.gfz-potsdam.de/icdp>).

Among the many projects being considered for international support are a sequence of coreholes in the Chicxulub impact basin of the Yucatan Peninsula, Mexico; an inclined hole across the San Andreas Fault in California; drilling the Unsen Volcano in Japan; and drilling Late Quaternary lake sediments to improve the understanding of past global change.

A trend in scientific drilling projects is to couple them with the research interests of companies. Project Uppercrust collected basement samples of the U.S. midcontinent in oil exploration wells; drilling in the Newark Basin was materially assisted by Amoco. DOSECC encourages the broadening of scientific investigations in each hole drilled and promotes the continued study of samples collected from previously completed holes.

Grant Heiken
Los Alamos National Laboratory, EES-1, MS D462, Los Alamos, N.M. 87545
Heiken is a volcanologist at Los Alamos National Laboratory and chairman of the board of DOSECC. He has participated in a number of continental scientific drilling projects, including the Valles caldera, N.M., Creede caldera, Colo., and Inyo Domes, Calif.

Dennis L. Nielson
Energy and Geoscience Institute, Department of Civil and Environmental Engineering, University of Utah, 423 Wakara Way, Salt Lake City, Utah 84108
Nielson is a research professor at the Energy and Geoscience Institute, University of Utah. He has participated in a number of scientific drilling projects and is currently the principal investigator for DOSECC at the University of Utah.

Roland P. Lawrence
Texas A&M University, 1000 Discovery Dr., College Station, Texas 77845
Lawrence is a drilling engineer at Texas A&M University. He is responsible for planning, budgeting, and supervising drilling operations on behalf of DOSECC.

Low-Temperature Isotope Geochemistry

The application of isotope systematics to studies of low-temperature geologic processes has increasingly widened. These geochemical tools can apply unique constraints to tracing the transport of water, sediment, and dissolved materials through the hydrologic and sedimentary cycles; investigating ecosystem dynamics; and establishing the chronology of the rock record, climate variability, and fluid-rock interaction. Examples of recent applications of stable and radiogenic isotopes to this range of surficial processes are examined below.

Surface water

The lithium isotope composition of stream water in an agricultural catchment in Maryland increased by 25 parts per thousand during the peak of a major rainfall event, indicating the potential of this isotope system for tracing the sources and fate of contaminants that contribute to storm flow vs. base flow (Tomascak and others, University of Maryland). In the drainage of the Darling River, which supports a large portion of Australia's agricultural base, the contrasting geochemical behaviors of neodymium and strontium isotopes are being used to track sources of suspended and dissolved loads, respectively, as means to infer predominantly natural vs. anthropogenic sources of neodymium, strontium, and by implication phosphorus (Martin and McCulloch, Australian National University).

Groundwater

Large enrichments of radium-226 in coastal waters of the South Atlantic Bight indicate that groundwater flux to coastal waters in this region is about 40 percent of the river flux, suggesting that continental groundwater may be a much more important player in global geochemical cycles than previously believed (Moore, University of South Carolina). The isotopic compositions of hydrogen, helium, boron, carbon, nitrogen, oxygen, sulfur, chlorine, chromium, strontium, and uranium are being applied to groundwater systems as powerful tracers of the sources of organic and inorganic contaminants, saline water intrusion, fluid mixing, mineral weathering, atmospheric deposition, and groundwater flow paths and transit times (Kendall, Zielinski, Rowe, Bullen, Thomas, McKnight, and others, U.S. Geological Survey; Rose and others, Lawrence Livermore National Laboratory; Oetting and others, University of Texas; Beneteau and others, University of Waterloo; Barth and others, Eidgenössische Technische Hochschule, Zürich). Numerical modeling of isotope variations that occur during these multiple processes offer quantitative constraints on determining controls on compositional pathways that groundwaters follow (Johnson and DePaolo, University of California, Berkeley).

Temporal variability in the hydrologic cycle and global change

New applications of isotope geochemistry have been a catalyst in integrating more accurately dated (via protactinium-231, thorium-230, and carbon-14 by mass spectrometry) natural records (corals, aragonitic deep-sea sediments, foraminifera, varved sediments, tree rings, ice cores, ice-rafted detritus, and speleothems) with a range of geochemical proxies (oxygen, carbon, lead, and strontium isotopes, and high-precision uranium/calcium and strontium/calcium ratios). These integrated approaches advance the sensitivity with which environmental parameters such as precipitation, sea level, temperature, and salinity can be reconstructed. They provide ground-truth data for evaluating such questions as:

- How fast did the last ice age end?
- What triggers abrupt changes between cold and warm climates?
- What is the relationship between insolation forcing and monsoon intensity and sea level on millennial time scales?
- What drives interannual shifts in the far-reaching teleconnections of the El Niño/Southern Oscillation system?

These questions have been addressed by Dunbar and others, Rice University; Cheng, Min, and others, University of Minnesota; Slowey and others, Texas A&M University; Overpeck and others, University of Colorado; Mayewski and others, University of New Hampshire; Alley and others, Pennsylvania State University; de Vernal and others, University of Quebec; Gwiazda and others, Lamont-Doherty.

Temporal variations in groundwater chemistry, reconstructed from cave calcite deposits (speleothems), are being used to study the links between climate and hydrology. Bar-Matthews and others (Geological Survey of Israel) have demonstrated the importance of considering the controls on isotopic fractionation in modern karst systems for oxygen and carbon isotope studies of speleothems as temporal records of atmospheric temperature, rainfall, soil p_{CO_2}, and vegetation. The application of strontium isotopes to speleothems has the potential for reconstructing flow routes and recharge rates with negligible isotope fractionation effects (Banner and others, University of Texas).

Groundwaters from low-latitude continental settings in North and South America have carbon-14 contents that are consistent with recharge occurring from around the last glacial maximum through the Holocene. Concentrations of the noble gases neon, argon, krypton, and xenon (which have different solubility-temperature relationships) in these waters indicate 5° to 6° C cooler temperatures during the last glacial maximum (Stute and others, Lamont-Doherty). These results call for reevaluation of climate models based on marine records that indicate low-latitude regions have experienced relatively stable climates.

Oxygen isotope variations in Quaternary lacustrine faunas have been used to study the feedbacks between climate, hydrology, and terrestrial ecosystems. They indicate temporal and spatial patterns of moisture transport and water balance (Smith and others, Kent State;

Ito and others, University of Minnesota; Allen and Anderson, University of New Mexico; Dettman and others, University of Arizona). In particular, the ubiquitous ostracodes of lakes, wetlands, streams, and groundwater may play a role similar to that of foraminifera in studies of the deep-sea record.

Carbon isotope variations in marine sediments, paleosols, fossil vertebrate teeth, and oolitic goethite reflect changes in the global carbon cycle from the Precambrian to the Cenozoic that indicate major shifts in atmospheric CO_2 levels, weathering rates, plant types, glaciations, and ocean circulation (Cerling and others, University of Utah; Quade and others, University of Arizona; Kaufman and others, Harvard University; Derry and others, Cornell University; Raymo and others, Massachusetts Institute of Technology; Lea and others, University of Chicago; Yapp and Poths, University of New Mexico).

The cosmogenically produced nuclides chlorine-36, beryllium-10, aluminum-26, silicon-32, and neon-21 provide ages of exposure of loess, soils, paleosols, moraines, and ice that can be used to reconstruct climatic patterns. These patterns provide insight into (1) variations in rainfall between glacial and interglacial periods back to 5 Ma (Gu and others, Scripps Institution of Oceanography), and (2) the extent to which the timing and driving mechanisms of shifts in continental glacial/lacustrine records correspond to marine climate chronologies of sea-level stages and Heinrich ice-rafting events (Phillips and others, New Mexico Tech; Phillips and others, University of Arizona; Gillespie and others, University of Washington; Gosse and others, University of Kansas).

Other systems

Oxygen isotope compositions of carbonate phases from a martian meteorite were used as one of several lines of evidence to support a low-temperature origin for the carbonates and the suggestion that life could have existed on Mars (Romanek, University of Georgia, and others, NASA).

Dating the rock record

Precise uranium-lead dating of paleosol calcite has potential for dating sedimentation because paleosol horizons are common and early diagenetic features in sedimentary sections. Rasbury and others (State University of New York, Stony Brook) have dated Early Permian paleosol calcite at 298±1 Ma using the $^{238}U/^{207}Pb$-$^{206}Pb/^{207}Pb$ isochron. This age is within uncertainty of the previously accepted 290±20 Ma age for the Pennsylvanian-Permian boundary, and suggests the prospect of vastly improving the time resolution of the rock record, which has uncertainties greater than 10 Ma for Paleozoic biostratigraphic boundaries.

Jay L. Banner
Department of Geological Sciences, University of Texas, Austin, Texas 78712

Banner is an associate professor of geological sciences at the University of Texas. His research interests include the application of field, petrologic, geochemical, and modeling techniques to studies of carbonate diagenesis and the chemical evolution of groundwater and ancient oceans.

Mantle and Core Studies

1996 was a busy year for deep-earth geophysicists with the deepest part of our planet — the inner core — receiving much of the attention. It has been known for some time that the inner core is strongly elastically anisotropic. The geometry is roughly that of a single crystal with hexagonal symmetry whose fast axis is not quite aligned with the rotation axis of Earth. It is this slight departure from axisymmetry that allows differential rotation of the inner core to be detected.

Two detections

X. Song and P. Richards were the first to publish such a detection using body waves recorded at a station in Alaska from events in the South Sandwich Islands spanning a 30-year period. They inferred that the inner core is rotating slightly faster than the mantle at a differential rate of about one degree per year.

A second detection has been published by a group from Harvard and Berkeley (W. Su, A. Dziewonski, and R. Jeanloz) using a different dataset and analysis technique. These scientists inferred a differential rotation rate of about three degrees per year using data from a global network of some 2,000 stations. The individual data are relatively inaccurate, but by processing some 250,000 readings, the authors believe they have identified a robust signal. Only part of this signal can be explained by a simple rigid rotation of the inner core.

Dynamo model predictions

Both of the published values of the rotation rate are close to the predictions of the dynamo model of Glatzmaier and Roberts but are significantly larger than the predictions of the Kuang and Bloxham dynamo. These two dynamo calculations produce very similar magnetic fields external to the core but have very different field geometries within the core.

The Glatzmaier and Roberts dynamo has strong field generation in the polar regions of the outer core, which are within a cylinder that is aligned with the rotation axis and that just encompasses the inner core — the so-called "tangent cylinder." The geometry of convection and the resulting magnetic fields give strong electromagnetic coupling to the inner core resulting in the super-rotation. This mechanism is described in detail in a paper by Glatzmaier and Roberts published in *Science* where they liken the process to a synchronous motor driven by a thermal wind.

The Kuang and Bloxham dynamo is quite different with most of the field generation going on in the outer core outside the tangent cylinder. Their model results in inner-core differential rotation rates that are much smaller than inferred from the seismic studies and which can be either eastward or westward.

Complications

The situation is further complicated by a number of observational studies presented at the fall meeting of the American Geophysical Union. K. Creager and T. McSweeney used an extensive dataset of differential travel times of the type used by Song and Richards to demonstrate that there is quite strong lateral heterogeneity in the anisotropy in the inner core and that the "single crystal" model is a poor approximation in detail. These large local variations in anisotropy could mean that the observations of Song and Richards might be explained by a much smaller differential rotation rate, but such a local anomaly should have been averaged out in the Harvard-Berkeley study. At this point, the temporal variation of travel time residuals for waves travelling through the inner core has clearly been established, but our quantitative understanding of the phenomenon is still at a primitive level.

Yet another complication arises from the fact that we do not yet understand the cause of the strong anisotropy observed in the inner core. Some seismic studies now place the level of anisotropy (as measured by the differences in compressional wave speed in the equatorial and polar directions) at as much as 3 percent. The first-principles calculations of the properties of iron at core pressures by L. Stixrude and R. Cohen predict that iron will be in a hexagonal close packed (hcp) phase with a degree of elastic anisotropy that is comparable to the seismic observations. Of course, this requires an extremely efficient mechanism to align iron crystals, which is difficult to envisage given the fact that the inner core is a complicated chemical system that must include some light impurities.

Recently, a group at the Carnegie Institution under H. Mao have conducted some pioneering experiments to determine elastic anisotropy in the diamond-anvil cell by exploiting the deviatoric stress field. These experiments imply a much stronger degree of anisotropy in iron than previously thought (about 10 percent) and a structure that is not hcp. If these experiments hold up, explaining the anisotropy in the inner core will become a lot easier, but the conflict with the first-principles calculations will require resolution.

We are sure that the inner core will remain the object of intense scrutiny in 1997, and will be the subject of a rather uniquely interdisciplinary research effort involving seismologists, geomagnetists, geodynamicists, and mineral physicists. Combining the efforts of all these