EARLY HISTORY OF THE ATLANTIC OCEAN AND GAS HYDRATES IN THE BLAKE OUTER RIDGE

Results of the Deep Sea Drilling Project

by

Robert E. Sheridan and Felix M. Gradstein*

Leg 76 of the international Deep Sea Drilling Project (DSDP) has yielded a plethora of new and exciting scientific data that may revolutionize some concepts in the geological sciences. In this article, the chief scientists of the cruise summarize the remarkable results obtained from continuous and painstaking coring at Site 534 in the Blake Bahama Basin in the Western North Atlantic Ocean - the second deepest hole drilled below the abyssal seafloor, which penetrated the oldest sediments (~ 155 Ma) yet recovered, and those of Site 533 in the Blake Outer Ridge "contourites", which quantitatively and qualitatively proved the existence of gas hydrates.

Introduction

Leg 76 of the Deep Sea Drilling Project (DSDP) on board the D/V Glomar Challenger began on 11 October, 1980 in Norfolk, Virginia and ended on 21 December, 1980 in Fort Lauderdale, Florida, U.S.A. The cruise operated in the same area (Fig. 1) as DSDP Legs 1, 11 and 44 and concentrated on scientific and potentially economic objectives not accomplished previously.

The two principal goals of drilling in this part of the western North Atlantic Ocean were:

- (1) To continuously core in Upper and Middle Jurassic strata below reflector D, and for the first time, reach ocean-type basement in the M-28 marine magnetic anomaly zone in the Blake Bahama Basin (Site 534);
- (2) To sample with the pressure core barrel and to study geologically, geochemically, and geophysically gas hydrates in the Upper Tertiary sediments above the bottom simulating seismic reflector in the Blake Outer Ridge (Site 533).

Both of these objectives were successfully achieved. This paper incorporates both the shipboard interpretations made at the time of the cruise and shore-based study results obtained since.

Site 533 - Gas Hydrates in the Blake Bahama Outer Ridge

The Blake Bahama Outer Ridge constitutes an unusual topographic feature, extending SE as a spit-like extension of the continental rise sedimentary prism and rising up to 1500 m above the abyssal plain (Fig. 1). Extensive studies have shown that the Ridge formed in Late Cenozoic time through accretion of hemipelagic mud by contour following currents. DSDP Leg 11 established sedimentation rates as high as 5-15 cm/10³ years and found very gassy sediments.

A fundamental phenomenon also discovered during Leg 11 was the time transgressive nature of the Bottom Simulating Seismic Reflector (BSR; Fig. 2). One explanation is that solid gas hydrates, which would be stable under the temperature and pressure regime in the uppermost few hundred meters of Ridge sediment, change to a fluid gas phase below a phase boundary at the BSR. Although the acoustic evidence for a BSR is supported by the theoretical considerations of the gas hydrate stability field and by preliminary geochemical observations made during Leg 11, the hypothesis concerning gas hydrates needed in situ testing and further geochemical analysis. This was accomplished at Site 533.

Operations

The site was occupied from 13 to 19 October, 1980. Two holes were drilled at the same location (533 and 533A) in 3190 m of water, which took 41 hydraulic piston cores (0-167.5 m), 24 rotary cores, four pressure core barrel (PCB) cores (141.5-399.0 m) and three heat probe measurements to reach total depth. Both the PCB and heat probes were successful, with total sediment recovery at 82%. Reflection seismic profiles, and the bottom depth recording by the

Figure 1. Location of DSDP Leg 76, Site 533 on the Blake Outer Ridge and of Site 534 in the Blake Bahama Basin.

*Although this article was prepared for publication in EPISODES by Dr. Sheridan and Dr. Gradstein, it is based on work conducted by the Scientific Team of Leg 76, whose names appear at the end of the article.

Challenger are in excellent agreement with survey data for the originally proposed site. Two near-site sonobuoy experiments complement the detailed geological, geochemical, and geophysical studies made in Holes 533 and 533A. Logging of Site 533 was prevented by the failure of the bit release mechanism.

Stratigraphy and Depositional History

Preliminary biostratigraphic analysis of the cores from Site 533 allowed recognition of ten or more Pliocene-Pleistocene nannofossil zones and an equal number of foraminiferal datums. We found two well identified lithologic units in Site 533. The oldest, Unit 2, is a dark, greenish-grey calcareous clay and mud of Middle to Late Pliocene age, which shows a general lack of bedding structure and indicates a high mid-Pliocene sedimentation rate of $21 \text{ cm}/10^3 \text{ years}$, decreasing to $8 \text{ cm}/10^3 \text{ years}$ in Late Pliocene time. A very low sedimentation rate of $1 \text{ cm}/10^3 \text{ years}$ during latest Pliocene to earliest Pleistocene time indicates sediment bypassing or erosion. This would agree with the seismic interpretation of a hiatus between Units 1 and 2 (Fig. 2), which spans the interval of 2.1 - 1.8 Ma ago and is believed to be related to the rapid escalation of northern hemisphere glaciation in mid-Pliocene time (around 3.5 Ma), which enhanced deep circulation and deep basin erosion.

Figure 2. North to south running seismic profile over the Blake Bahama Outer Ridge at DSDP Site 533 in 3190 m of water. The Bottom Simulating Seismic Reflector (BSR) is thought to represent the phase change from hydrated to non-hydrated sediments. Geochemical and thermal observations during drilling confirm the presence of some hydrates and explain the position of the BSR. The Ridge was built from contourite current activity but the cored sediments showed little visual evidence of the ubiquitously laminated sediments which signal typical contourites.

Unit 1 is a light grey green and rose-coloured nannofossil-rich clay and mud of Pleistocene through Holocene age. Deposited at relatively high sedimentation rates of $7 \text{ cm}/10^3 \text{ years}$, this unit shows striking variations in microfossil assemblages, calcium carbonate content and colour that are associated with the climatic variations during the Pleistocene. Unexpectedly low levels of reworked nannofossil point to predominantly Quaternary sources of the clastics, such as found along the continental slopes to the north. The continuously cored and geographically oriented record (in the hydraulic piston cores only) makes Site 533 ideal for detailed investigations of the Quaternary deep ocean.

The Blake Bahama Outer Ridge is commonly thought to have been formed by sediment transported by geostrophic contour currents. While there is substantive evidence based on geomorphologic and seismic data for this conclusion, we observed almost no current-derived structures in the cores at

Site 533. The Quaternary unit is apparently almost structureless except for some layers of very fine silt with no visible lamination. These thin beds, however, do not appear to be common but are rather the exception at Site 533, whereas contourites* are supposed to be "ubiquitously laminated". The Pliocene unit exhibits what appears to be "fissile" structure throughout, probably the result of compaction. Because of the absence of visible structures and textures in the sediments, we lack direct evidence of contourite deposition at Site 533. The lack of structure and texture, however, does not preclude such a mechanism of deposition and this discrepancy is being investigated in detail.

Geochemical Measurements

The organic geochemical sampling at Site 533 consisted of vacutainer bleeding of gases from the cores, extracting of gas from a sediment segment into a helium headspace, as well as quantitative pressure and volume measurements on gas hydrates with pressure containers and the PCB. These measurements indicated the usual decrease in C_1/C_2 ratio with depth, probably caused by early diagenesis.

The most significant result of the quantitative organic geochemical measurements was the documentation of gas hydrates. We measured a 13:1 volumetric expansion of a gas hydrate sample in core 13, indicating abnormally high volumes of methane, higher than they could be in solution with normal pore water. Even more important, the composition of the gas hydrate excluded the higher hydrocarbons (normal butane and higher $>C_4$), which do not fit in the hydrate cage structure. This is the first empirical proof that gas hydrates in the marine environment follow such a predicted behaviour.

Four successful PCB samples maintained sediments under high pressure, $\sim 4500 \text{ psi}$, and permitted experimental measurements of gas pressure as a function of temperature and time (Fig. 3). On two of the PCB cores, the pressure time curves follow the saw tooth pattern expected for gas hydrates decomposing under increases in temperature and step-wise decreases in pressure. Again, it was the first time that such evidence has been obtained for gas hydrate in this marine environment.

Still uncertain are the quantities of gas hydrates present at Site 533. Our direct observations of the hydrates in the opened cores amounted to several thin icy and fizzy layers in Core 13; it is not known what amounts of hydrates (perhaps finely distributed) in the six-meter-long pressurized section of the PCB were producing the pressure effects observed. Gas hydrates may only be present in cm or mm thin layers which decompose rapidly upon release of pressure.

Figure 3. Graphic evidence for gas hydrates in pressure core barrel No. 5 at 390 m, Site 533, Blake Bahama Outer Ridge. The distinctive saw-tooth pattern of pressure change recorded is typical of gas hydrate decomposing under increasing temperature and step wise decreasing pressure (that is, the gas is vented several times, and each time the pressure is allowed to build up again).

* Contourites are deposits which form under the influence of bottom currents which follow the topography of the slope and rise of continental margins.

Acoustic Properties and Seismic Stratigraphy

Measurements with well-positioned sonobuoys made by Glomar Challenger at Site 533 yielded compressional wave velocities of approximately 2.3 km/sec above the BSR. These relatively high velocities contrast with the more normal sediment velocities, approximately 1.8 km/sec, measured for the interval below the BSR (Fig. 2). Such occurrences of velocity inversions at the BSR have been observed elsewhere on the Blake Outer Ridge, and it is thought to be a real situation over most of the area. The higher velocities above the BSR can be attributed to the presence of thin layers of gas hydrates interlayered with normal sediments. The spatial distribution and actual thickness of the gas hydrate beds is still enigmatic, as is the actual amount of gas hydrate layers needed to cause these higher seismic velocities.

Temperature

Temperatures are well documented at Site 533 by well-equilibrated measurements at three different depths. These measurements reveal temperatures as high as 19°C at 400 m depth and a near linear temperature gradient of 3.9°C/100 m near the bottom of the hole. (A slightly higher gradient of 5.1°C/100 m in the upper part of the hole has several possible explanations.)

Extrapolation of these temperature measurements to the depth of the BSR, approximately 600 m, indicates that the temperatures would be in the range at which methane gas hydrate would decompose. The temperature measurements agree with the interpretation that the BSR is a phase change boundary between gas hydrated sediments and normal sediments.

Site 534 - Early History of the Western North Atlantic Ocean

The North American Basin, off the eastern seaboard of the U.S.A., is in proximity to one of the oldest passive continental margins of the modern oceans. The history of this ocean basin is thought to span in excess of 160 million years. Drilling during Legs 1, 2, 11, 43 and 44 with D/V Glomar Challenger has provided fundamental knowledge of the sea-floor spreading, sedimentary and paleoceanographic processes and history of this basin over the last 145 million years. The lack of solid information on the earliest history of the North Atlantic Ocean led to the planning of a drill site where pre-reflector D sedimentary strata overlying ocean crust in excess of 150-160 million years old (Middle Jurassic), are within reach of D/V Glomar Challenger's drill string. Thus, the larger part of Leg 76 was devoted to this objective at Site 534, where basement was interpreted to be as shallow as 1800 m below the seafloor in 4970 m water depth.

The dynamically positioned Deep Sea Drilling Vessel Glomar Challenger has been used in the DSDP since 1969. Funds are currently provided by U.S.A., U.K., France, Federal Republic of Germany, Japan, and the U.S.S.R. The ship is capable of drilling in water depths of almost seven km.

Operations

Site 534 was occupied from 21 to 22 October, 29 October to 29 November, and from 5 to 19 December, 1980 - a total of 44 days. Hole preparations were completed on 5 November; this included the emplacement of 531 m of casing string below the re-entry cone in 4976 m (below rig floor) of water. Hole 534A was then drilled to a depth of 1590 m, using five drill bits. Re-entries varied from easy to very difficult to achieve, depending on the apparent presence of variable deep currents. Coring was continuous from 536 m to 1590 m, and recovery was at 54%. We completed continuous coring into basement on 12 December, to the total depth of 1666.5 m. Logging of the hole, which necessitated another (the seventh) re-entry, was accomplished on 18 December; surveys include density, sonic velocity, temperature, natural gamma radiation and hole diameter. Leg 76 terminated on 21 December, 1980 in Fort Lauderdale, Florida.

Lithostratigraphy and Biostratigraphy

The lithological units penetrated in Site 534 between 0 and 1496 m subbottom are readily assigned to the formations erected for the North American Basin (Fig. 4). Exceptions are the dark coloured claystone, olive grey limestone and radiolarian silt and claystone between 1496 m and 1635 m on M-28 oceanic basement, which are quite different from (and older than) the oldest Formation (Cat Gap) known so far in the Atlantic Ocean. In descending order, we encountered (Fig. 4):

- 0-2.8 m, Core 534-1: 2.8 m (2.8 m; 100% recovered) of grey nanofossil ooze and silty clay - Blake Ridge Formation, Quaternary. This unit was sampled before the casing string to 531 m was placed.
- 545-696 m, Cores 534A, 1-18: 165.5 m (83.5 m; 50% recovered) of chalks and intraclast chalks and dark-green mudstones - Great Abaco Member of the Blake Ridge Formation, Middle and Lower Miocene.
- 696-741 m, Cores 534A, 19-23: 45 m (7.6 m; 17% recovered) of interbedded zeolitic and siliceous, variegated mudstone, graded sandstone and porcellanite - Bermuda Rise Formation, Late Eocene.
- 741-764 m, Cores 534A, 24-26: 23 m (9.5 m; 41% recovered) variegated claystone - Plantagenet Formation, early Maastrichtian.
- 764-950 m, Cores 534A 27-46: 186 m (83.2 m; 45% recovered) of black to green carbonaceous claystone - Hatteras Formation, Cenomanian through early Aptian.
- 950-1342 m, Cores 534A, 47-91: 392 m (298.4 m; 76% recovered) of bioturbated and laminated radiolarian-rich nanofossil limestone and chalk, grading upward in calcareous claystone and carbonaceous claystone - Blake Bahama Formation, Barremian through early Berriasian.
- 1342-1496 m, Cores 534A, 92-111: 154 m (74.6 m; 48% recovered) of greyish-red, calcareous claystone underlain by dark greenish-grey claystone with interbedded limestone - Cat Gap Formation, Tithonian through Oxfordian.
- 1496-1635 m, Cores 534A, 112-127: 139 m (39.8 m; 29% recovered) of dark-coloured variegated claystone underlain by olive-grey, pelletal limestone and radiolarian claystone, underlain by greenish-black to brown nanofossil claystone (Photograph 3). Unnamed lithostratigraphic unit of early-middle Callovian through early-middle Oxfordian age.
- 1635-1666.5 m, Cores 534A, 127-130: 31 m (17.3 m 60% recovered) of dark-grey, aphyric to sparsely microporphyrific basalt (Photograph 4). Green claystone and reddish-brown siliceous limestone with "filaments" fill some 1-5 m thin fractures.

The preliminary chronostratigraphy of the Jurassic, Cretaceous and Lower Tertiary sedimentary section is based on the inter-relation of zonations using nanofossils, foraminifers, dinoflagellates and calpionellids and resembles the one in DSDP Site 391C. The abyssal nature of the hemipelagic

Figure 4. Stratigraphic summary of hole 534A Leg 76 of the DSDP and correlation to the seismic record over the site, using shipboard data. The formations are those used in this part of the western North Atlantic Ocean. The unnamed unit seven is older than and different from any previously drilled sediment on oceanic basement. The Callovian age for sediment on basement is 10-30 Ma younger than previously estimated and leads to a recalibration of the scenario of events prior to and during early opening of the Atlantic Ocean.

A portion of Core 126, Site 534 in the western North Atlantic Ocean composed of dark-colored, laminated shale with horizons of elongated clasts due to local slumping. This sediment was deposited in Callovian time almost immediately above oceanic basement and is older than any other sediment drilled in the oceans. It is difficult to judge if such lithology reflects a widespread low oxygen event or a lack of bottom circulation or just local conditions. There is similarity to the Bathonian-middle Oxfordian "Terres Noires", a sequence of pelagic, dark-colored calcareous, silty claystone with interbeds of calcareous turbidites, deposited along the northern margin of Tethys in SE France. The overlying Kimmeridgian-Tithonian sediments with reddish-brown calcareous claystone and greyish limestone of the western North Atlantic Cat Gap Formation resemble the Rosso and Aptychi facies in Tethys.

Basalt breccia in Core 129 of Site 534, Leg 76 in the western North Atlantic Ocean is well cemented with calcite which points to the slow healing of old crust.

sediments just above or below the Carbonate Compensation Depth (CCD) for foraminifers resulted in a stratigraphically patchy and often much impoverished foraminiferal record, without much of planktonic forms. Nannofossils were most consistently present through the Jurassic to Lower Tertiary, except in Jurassic and mid-Cretaceous dark shales. In those intervals organic walled microfossils and radiolaria assist in stratigraphic assignments.

Key biostratigraphic information in Site 534 comes from (1) the eleven nannofossil zones of *S. hexum* through *P. cretacea* in cores 127 to 44 which allow an eleven-fold subdivision in early Callovian through Albian strata; (2) a Callovian age in one of the lowermost cores based on tethyan radiolarian biostratigraphy; (3) the *L. quenstedti*, *E. aff. uhligi* foraminifer assemblages of the *E. mosquensis* Zone in and below Core 99 which is not younger than Early Tithonian in age; (4) the presence of *Calpionella* B Zone markers in Cores 92-90 indicative of latest Tithonian-earliest Berriasian beds; (5) Aptian-Albian dinoflagellate stratigraphy in the dinoflagellate stratigraphy in the Hatteras shales, and (6) a presumably in situ *Globotruncana* foraminifera assemblage in Cores 24-26 of early Maastrichtian age, and the Late Eocene nannoflora assigned to the *D. barbadiensis*/*G. saipanensis* Zones in Cores 19 to 21.

The Miocene stratigraphy in Site 534, as in Site 391C, uses a combination of standard nannofossil and planktonic foraminiferal zonations; resolution is above that obtained in the older beds.

Physical Properties, Seismic Stratigraphy and Magnetostratigraphy

Comparison of the laboratory velocity measurements and in situ impedance calculations with the correlation of seismic reflectors to drill hole lithologies and hiatuses has been very satisfactory. Seismic stratigraphic correlations (Fig. 4) were made with bedding impedance contrasts for Horizons A^C (Upper Eocene cherts), β (Barremian limestone), C (Tithonian red shaly limestone), and D (lower Oxfordian limestone). Other reflections were attributed to possible unconformities, such as Horizon A^U (Lower Miocene/Upper Eocene), β' (lower Albian/upper Aptian), C' (upper Berriasian/lower Berriasian), and D' (middle to upper Oxfordian/lower to middle Oxfordian).

The ages of Horizons A^C, β, and C at Site 534 agree with previously published correlations. The age of Horizon D, drilled for the first time at Site 534, is younger than the basal Callovian age and older than the Tithonian age predicted in the literature.

The magnetostratigraphy of the sedimentary column could not be ascertained onboard. The assignments of the basal beds to the *"S. hexum"* nannofossil zone of early-middle Callovian age, which is currently being verified by radiolarian stratigraphy, gives us a minimum age for basement anomaly M-28. We take into account that D/V Challenger hit basement at a slightly higher level than anticipated. The

discrepancy is the result of local small-scale basement relief and of a slight over-estimate of (basal) sediment velocities. Given uncertainty in geographic positioning relative to the seismic record across the site in the order of 0.5 mile, we apparently hit a little "hill" next to the target valley (Fig. 4). Also, the lower velocities of the sediments encountered than estimated prior to drilling, have a tendency to "pull up" the basement. We assume that the hemipelagic sediment cover on the basement formed more or less simultaneously in troughs and on highs, aided in this by intermittent, weak bottom circulation. As a result we are confident that the chronostratigraphy of the basal sediments provides a reliable estimate of the minimum age for the basement at Site 534.

Depositional History

The thick Jurassic, Cretaceous and Tertiary-Quaternary stratigraphic sequence is the result of "continuous" slow and periodically fast sedimentation. There was largely continuous, quiescent, 0.1 cm/10³ years or less, hemipelagic "background" sedimentation between the CCD for foraminifers and nannofossils. On this is superimposed periodic sedimentation by turbidite, debris flows or current mechanisms of slope or shelf carbonate and carbonaceous claystone at average rates as high as 4 cm/10³ years (Fig. 5). Three quarters of this sediment (decompacted thickness) deposited in the first 50 million years after the site appeared at the mid-ocean ridge approximately 155 Ma ago. The overlying section is largely of Miocene and younger age and accumulated in the last 20 million years. The main periods of redeposited carbonates are in the early part of the Early Cretaceous and in the Miocene; carbonaceous claystones overwhelmed the basin in mid-Cretaceous time. Redeposited sand and silt form a minor constituent of the cored section; this can be explained by their general absence on the carbonate platform-type of hinterland to the west and SW of the basin combined with the very distal location of the site.

The Middle and Late Jurassic brown and green-black, radiolarian-rich claystone and redeposited limestones indicate hemipelagic sedimentation, interrupted by slope and shelf derived turbidites. If we assume no drastic diagenetic alteration to the original state of the sediment, then the colour changes can reflect alternating oxidizing and reducing conditions, becoming more continuously oxidizing in latest Jurassic time. The Middle Jurassic Atlantic Ocean basin may have had limited bottom circulation leading to alternating organic-rich and more oxidized sediments, as occurred again in Middle-Late Cretaceous time.

In this scenario, alternation of oxidized and reduced sediment points to a delicate balance in the Jurassic ocean of (terrestrial) organic input and oxygen depletion as a function of weak bottom circulation and probably a wet climate. The Jurassic ocean surface waters sustained rich radiolarian faunas and nannofloras indicative of continuous open marine connection to Tethys and probably the Pacific as well. This is also shown by the presence of Oxfordian age primitive planktonic foraminifers, some of the oldest known, which

correlates to an abundance peak in the Mediterranean basin margins.

The massive influx of redeposited and pelagic carbonates in Berriasian to Barremian (Early Cretaceous) time, gradually changed to predominantly carbonaceous claystone accumulation during Aptian-Cenomanian time. The CCD shoaled sharply in Barremian through Aptian time to leave a carbonate-depleted sediment. The carbonaceous claystone was deposited by turbidites. The organic matter is mostly terrigenous and less marine in origin, reflecting a wet climate. Organic content is high enough for petroleum generation but is of too low maturity. There are distinct alternations (cycles) of marine and terrestrial (dominance of quartz with kaolinite, smectite, attapulgite) clay minerals and distinct peaks in organic abundance; a Cenomanian marine organic matter peak correlates to a similar peak at other sites in the Atlantic Ocean. The variegated, oxidized (mid-) Aptian age sequences contain minor silt layers and weathering-resistant clay minerals which indicate a marked change in environment with improved bottom circulation and slower accumulation or winnowing.

A surprising find was several tens of m of thin, variegated claystone and interbedded zeolitic-siliceous mudstone, sandstone and porcellanite of Maastrichtian and Late Eocene age (Fig. 4) where the Miocene/Cenomanian discontinuity (of nearby Site 391) drilled during Leg 44 was expected. The postulate of up to 800 m of (mostly Oligocene) erosion, which is based on apparently somewhat tenuous coalification data in the Aptian/Albian and Miocene strata, may need revision. We prefer to conclude that there was extensive sediment starvation in the Late Cretaceous and Paleogene Blake Bahama Basin.

In the lower Miocene debris flows, one continuously graded unit over 30 m thick was observed which may derive from the same slumping event as observed at Site 391, 22 km south-eastward. Rather similar and coeval deposits have been found during Deep Sea Drilling cruises off Morocco, which suggests common cause(s) for their formation. We are not sure if oversteepening of the shelf terrace due to the

Oligocene eustatic sea level fall, or Alpine tectonics (in the Atlas Mountains and Cuba-Antilles), would cause Early, Middle and Late Miocene slumping.

Seafloor Spreading

The North Atlantic Ocean is generally thought to have rifted in Triassic to Early Jurassic time, with significant opening beginning not later than late Early Jurassic time. This date of opening is largely derived from estimates for early spreading of 2 cm/yr. Our finding of Callovian sediments on M-28 anomaly basement indicates an early spreading rate that was almost twice as fast.

Extrapolation of the new 3.76 cm/year spreading rate leads us to date the Blake Spur magnetic anomaly as basal Callovian, which is about 20 Ma younger than once thought. This means the major spreading center shift marking the beginning of the "true" modern North Atlantic also occurred much later in time.

Stratigraphically the Callovian deposits around the North Atlantic marked the onset of a rapid, widespread transgression. Generally, the breakup of plates to form ocean crust is punctuated by a pulse of rapid subsidence and rapid transgression over the breakup unconformity on the continental margins. This widespread Callovian transgression would thus be a record of the Blake Spur spreading center jump.

Acknowledgement

The wealth of information unearthed since 1969 from more than 460+ sites drilled by D/V Glomar Challenger has shaped many of our present concepts in geodynamics (including plate tectonics) and has literally revolutionized many aspects of the geological science. Much credit goes to the technical and planning staff of the Deep Sea Drilling Project, administered by the U.S. National Science Foundation, and to the marine crew of the Challenger, for the high performance in achieving the scientific objectives of Leg 76. The D/V Glomar Challenger, which is owned by Global Marine Inc., has pioneered many of the techniques needed to successfully drill in the oceans.

THE AUTHORS:

Co-chief scientists Bob Sheridan (right) and Felix Gradstein, show a piece of the oldest sedimentary formation drilled in the oceans. On the core rack are a slabbed core and a drill bit. On the drill floor, roughnecks are preparing for logging of the record site.

SCIENTIFIC TEAM OF LEG 76

R.E. Sheridan (University of Delaware, Delaware, U.S.A.); F.M. Gradstein (Atlantic Geoscience Centre, Geological Survey of Canada, Canada); L.A. Barnard (Texas A & M University, College Station, Texas, U.S.A.); D.M. Bliefnick (University of California at Santa Cruz, California, U.S.A.); D. Habib (Queens College, Flushing, New York, U.S.A.); P.D. Jenden (University of California at Los Angeles, Los Angeles, California, U.S.A.); H. Kagami (University of Tokyo, Tokyo, Japan); E.M. Keenan (University of Delaware, Newark, Delaware, U.S.A.); J.A. Kostecki (Lamont-Doherty Geological Observatory at Columbia University, Palisades, New York, U.S.A.); K.A. Kvenvolden (U.S. Geological Survey, Menlo Park, California, U.S.A.); M. Moullade (Centre de Recherches Micropaleontologiques, Nice, France); J. Ogg (Scripps Institution of Oceanography, La Jolla, California, U.S.A.); A.H.F. Robertson (University of Edinburgh, Edinburgh, U.K.); P.H. Roth (University of Utah, Salt Lake City, Utah, U.S.A.); T.H. Shipley (Scripps Institution of Oceanography, La Jolla, California, U.S.A.); L. Wells (Scientific Software Corporation, Denver, Colorado, U.S.A.); J.L. Bowdler (Union Oil Company of California, Houston, Texas, U.S.A.); P.H. Cotillon (Université Claude Bernard, Villeurbanne, France); R.B. Halley (U.S. Geological Survey, Colorado, U.S.A.); H. Kinoshita (Chiba University, Chiba, Japan); J.W. Patton (Marathon Oil Company, Littleton, Colorado, U.S.A.); K.A. Pisciotto (Deep Sea Drilling Project, Scripps Institution of Oceanography, La Jolla, California, U.S.A.); I. Premoli-Silva (University di Milano, Milano, Italy); M.M. Testarmata (University of Texas, Galveston, Texas, U.S.A.); R.V. Tyson (The Open University, Milton Keynes, Bucks, England, U.K.); D.K. Watkins (Florida State University, Tallahassee, Florida, U.S.A.)