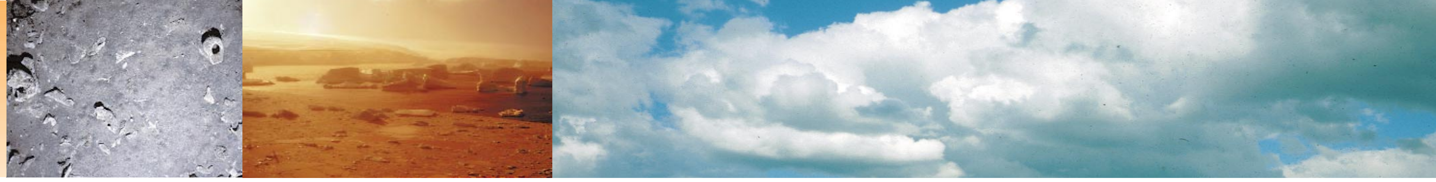
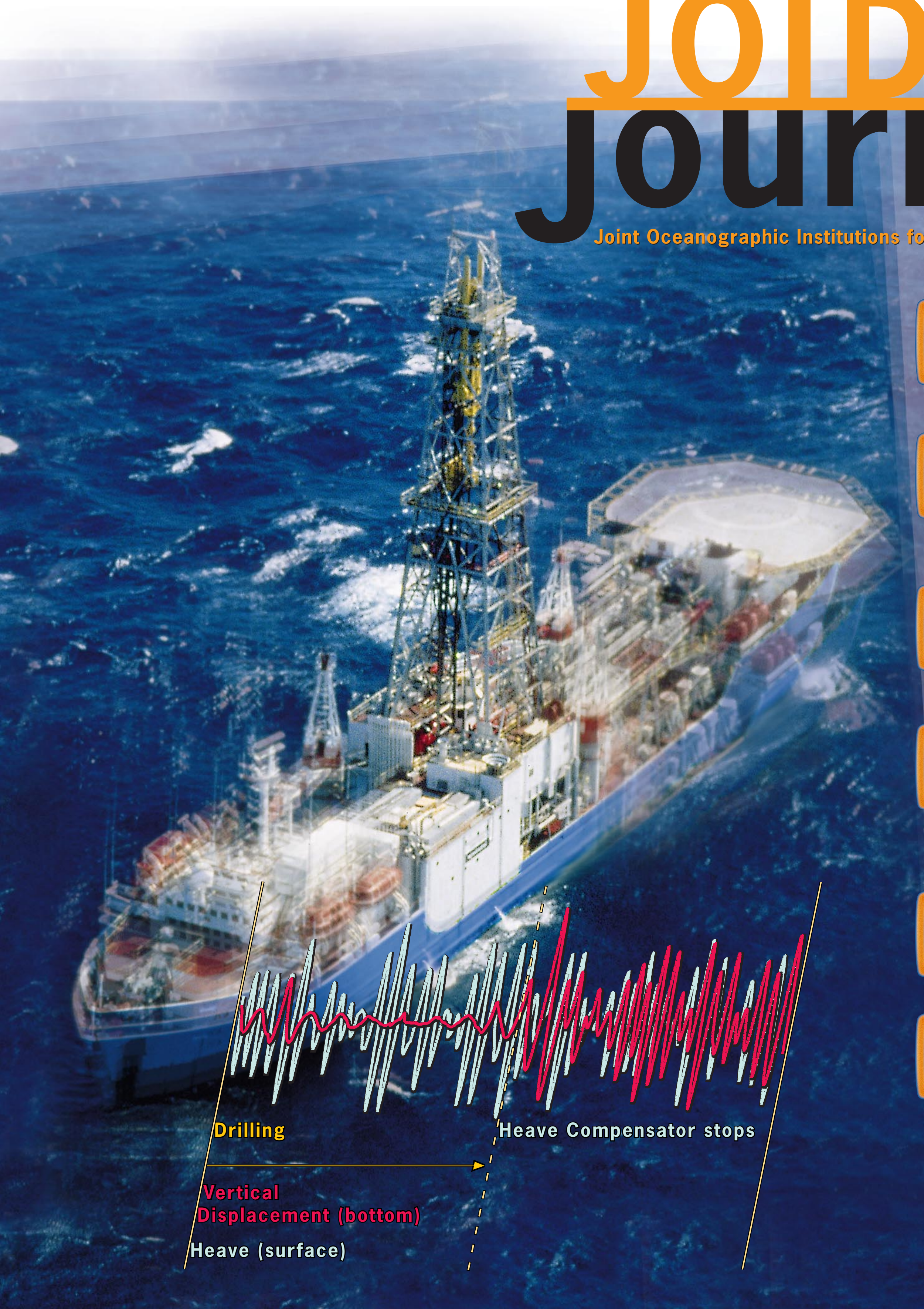
OCEAN DRILLING PROGRAM



Vol. 26 No. 2-2000

JOIDES journal

Joint Oceanographic Institutions for Deep Earth Sampling



Preliminary Results from Leg 188 Drilling in Prydz Bay Antarctica

The Opening of the Tasmanian Gateway: Results of Leg 189

Deformation and Fluid Flow Processes: ODP Leg 190

Ship Heave Effects: Observations from Legs 185 and 188

Core-Log Integration Platform Update (SAGAN)

Excerpts from the Final Report of JOIDES Gas Hydrate Program Planning Group

ODP welcomes Dr. Steven R. Bohlen as new President of JOI

Dr. Steven R. Bohlen, the new President of JOI and Executive Director of the ODP

It is with great pleasure that we announce the appointment of Dr. Steven R. Bohlen to the position of President of the Joint Oceanographic Institutions and Executive Director of the Ocean Drilling Program. Dr. Bohlen was Associate Chief Geologist at the U.S. Geological Survey (USGS), joined JOI/ODP on November 27, 2000. He succeeded Admiral James Watkins (USN retired) who stepped down as President of JOI on October 1. Dr. John Orcutt of the Scripps Institution of Oceanography and Director of the Cecil and Ida Green Institute of Geophysics and Planetary Physics had served as interim President.

In addition to serving as Associate Chief Geologist at USGS, Dr. Bohlen has also served as consulting professor at Stanford University (1989-1995), Associate Professor (tenured) at the Department of Earth Sciences and Space Sciences at the State University of New York at Stony Brook (1985-1988) and postdoctoral research fellow at the University of California Los Angeles Institute of Geophysics and Planetary Physics.

As Associate Chief Geologist for Science in the Geologic Division of USGS, Dr. Bohlen was responsible for the research funded by 10 line items (USGS scientific programs) in the federal budget totaling $240 million. Those funds support the work of 1,800 scientists and scientific support personnel.

The scientific work directed by Dr. Bohlen included coastal and marine research, global change and climate history, earthquake, volcano, landslide hazards reduction programs, geomagnetic and space weather programs, energy and mineral resources programs and geologic mapping and ecosystem programs.

Dr. Bohlen also oversaw the International Programs Unit of the USGS and presented scientific findings and defended budgets within the USGS before the Administration (the Department of the Interior, Office of Science and Technology Policy, Office of Management and Budget) and the US Congress.

He developed budget initiatives and performance plans relating to the Government Performance and Results Act, set scientific priorities and supervised peer review of USGS work through the National Research Council of the National Academy of Science.

ODP welcomes Dr. Bohlen in his new position as Director, and is looking forward to his input and energy into management and planning issues for ODP's future.

NOTICE TO POTENTIAL CRUISE APPLICANTS

This is to advise you that a problem occured in the ODP/TAMU web-based Cruise Application system last fall. The problem has now been fixed, but an unknown number of applications submitted in October and November may have failed to reach ODP/TAMU.

If you submitted a cruise application to ODP/TAMU in October or November and have not received an acknowledgement, please send us a brief e-mail to muston@odpemail.tamu.edu to let TAMU know.

ODP/TAMU can then verify whether or not your application has been received.

Thank you!

In this issue

Leg Reports

Milestones in Antarctic Ice Sheet History – Preliminary Results from Leg 188 Drilling in Prydz Bay Antarctica 4

The Opening of the Tasmanian Gateway Drove Global Cenozoic Paleoclimatic and Paleoceanographic Changes: Results of Leg 189 11

Deformation and Fluid Flow Processes in the Nankai Trough Accretionary Prism: ODP Leg 190 18

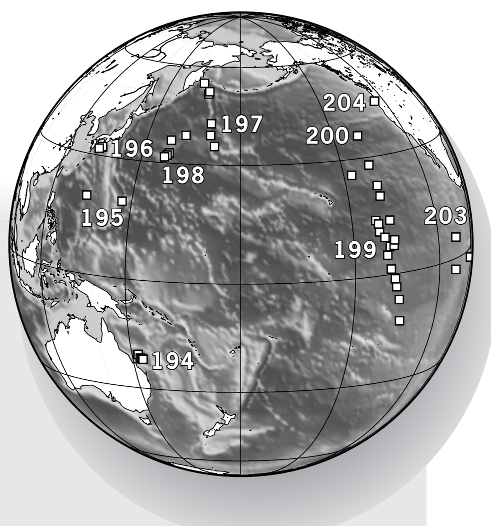
Technology

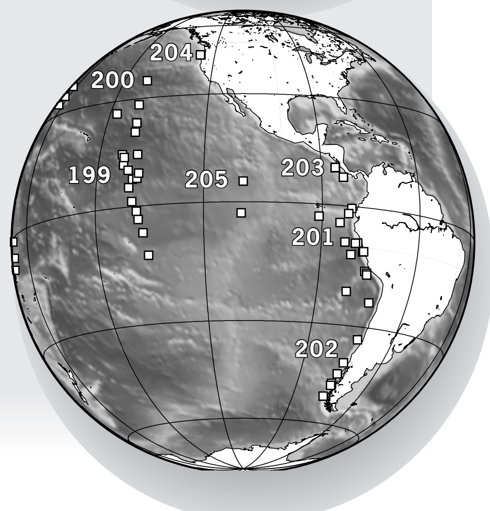
Ship Heave Effects While Drilling: Observations from Legs 185 and 188 26

Core-Log Integration Platform Update (SAGAN) 30

Panel Reports

Excerpts from the Final Report of JOIDES Gas Hydrate Program Planning Group 33





Scheduled Legs until November 2002

LEG	TITLE	DEPARTURE	DATES
194	Marion Plateau	Townsville	01/06/01 – 03/05/01
195	Mariana/West Pacific ION	Guam	03/05/01 – 05/03/01
196	Nankai II	Keelung	05/03/01 – 07/02/01
197	Hawaiian HS-Emperor Seamounts	Yokohama	07/02/01 – 08/28/01
198	Shatsky Rise	Yokohama	08/28/01 – 10/24/01
199	Paleogene Equatorial Pacific	Honolulu	10/24/01 – 12/17/01
200	H2O ION Site	Honolulu	12/17/01 – 02/07/02
201	Peru Margin Microbiology	Panama City	02/07/02 – 04/08/02
202	SE Pacific Paleoceanography	Valparaiso	04/08/02 – 06/07/02
203	Costa Rica Subduction Factory	Panama City	06/07/02 – 08/06/02
204	Hydrate Ridge	San Francisco	08/06/02 – 10/04/02
205	Equatorial Pacific ION	San Francisco	10/04/02 – 11/09/02

Milestones in Antarctic Ice Sheet History – Preliminary Results from Leg 188 Drilling in Prydz Bay Antarctica

P. E. O'Brien[1], A. K. Cooper[2], C. Richter[3], M. Macphail[4], E. M. Truswell[1] and Leg 188 Shipboard Scientific Party

The Antarctic Ice Sheet is one of the great features of our planet. It plays a pivotal role in global atmospheric circulation and the sea-ice zone around it produces cold waters that control much of the ocean's deep circulation. The Antarctic Ice Sheet is also the largest store of fresh water on earth and controls short-term sea level changes. The history of the Antarctic Ice Sheet has been pieced together from various sources. For the late Quaternary, ice cores contain a detailed record of accumulation, air temperature and atmospheric composition. For the Cenozoic, information has come from distal marine oxygen isotope records, records of detrital output from the continent and fragmentary outcrops in ice-free areas on the continent. These records have been augmented by drilling on the Antarctic continental margin to try and recover direct evidence of glacial ice and to investigate the transition from pre-glacial to the full polar glacial conditions that we see today.

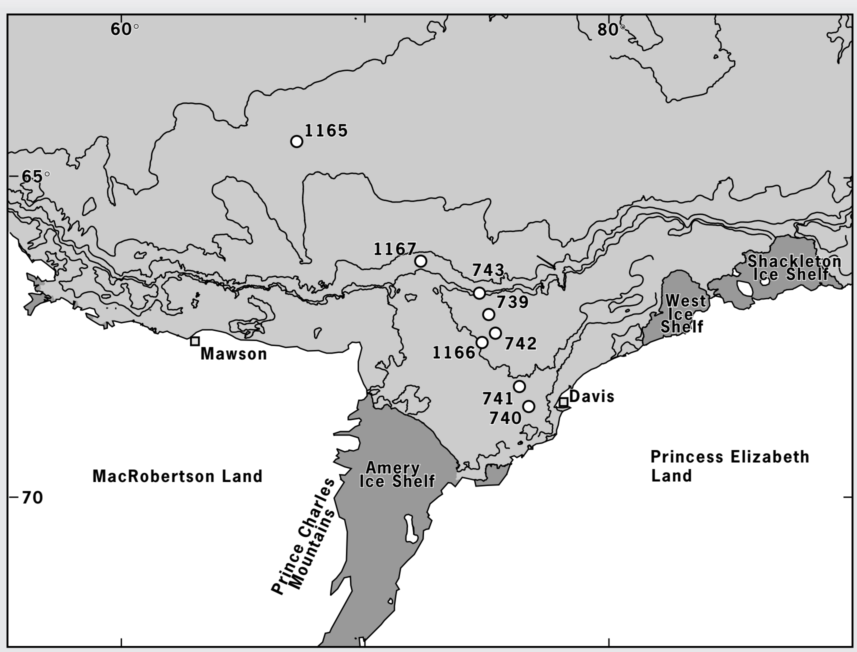
Direct evidence from Antarctica is required because distal proxy records still contain ambiguities. For example, the age of significant growth of ice on Antarctica during the Paleogene is estimated using $\partial^{18}O$ curves from deep sea sections distant from Antarctica. Zachos et al. (1996) describe a section that indicates that a major shift in $\partial^{18}O$ values commences at about 33.6 Ma (earliest Oligocene). Other studies have inferred significant ice volumes earlier in the Eocene (49 Ma, Abreu and Anderson 1998). Miller et al. (1999) suggested that a rapid sea level fall observed in the North American continental margin implies the existence of significant ice as far back as the Maastrichian.

ODP Leg 188 started as one of a series of drilling proposals by the Antarctic Offshore Stratigraphy project (ANTOSTRAT) sponsored by the Scientific Committee for Antarctic Research (SCAR). ANTOSTRAT aims to understand major events in the development of the Antarctic Ice Sheet by synthesising seismic data and then drilling. Major events targeted are the earliest Paleogene ice sheet development, the expansion of ice onto the continental shelf, variously thought to be Oligocene to mid-Miocene and the development of the cold, polar ice sheet of today through the Pliocene and Pleistocene.

Proposal development for Prydz Bay involved scientists from Australia, USA, Norway, Russia and Japan who contributed ideas and data. Extra site-survey data were collected on two Australian National Antarctic Research Expedition voyages in 1995 and 1997. Phil O'Brien of the Australian Geological Survey Organisation led the formulation of the drilling proposal and was co-chief scientist with Alan Cooper in affiliation with Stanford University. Leg 188 took place from January to March 2000.

Operations experienced the usual range of Antarctic scenarios of fast-moving storms, eratic icebergs and reloca-

FIGURE 1 *Location of ODP sites drilled by Leg 188 in Prydz Bay. Sites 739 to 743 were drilled by Leg 119.*



[1] Australian Geological Survey Organization
GPO Box 378
Canberra, ACT 2601, Australia

[2] U.S. Geological Survey,
345 Middlefield Road, MS 999
Menlo Park, CA 94025

[3] ODP/Texas A&M University
1000 Discovery Drive
College Station, TX 77845-9547

[4] Department of Archaeology & Natural History,Research School of Pacific and Asian Studies, Canberra ACT 0200, Australia

tion of a drill site because of pack ice. At times, drilling equipment was encrusted with ice and snow blanketed the ship. Many staff were also tempted to stop work to admire the acrobatics of humpback whales that visited the ship on several occasions.

Prydz Bay was chosen because it lies at the downstream end of the Lambert Glacier-Amery Ice Shelf drainage system, the largest single ice stream flowing from the interior of East Antarctica (Fig. 1). The glacier flows within a major graben that has been active since the Permian. Part of the ice originates from the subglacial Gamburtsev Mountains, the area where some models of ice sheet growth suggest that the Antarctic Ice Sheet first developed. Thus, Prydz Bay was thought likely to contain the earliest evidence of Cenozoic glaciation in Antarctica. The large size of the drainage basin (20% of East Antarctica) and the focussing of the ice into one massive ice stream means that major changes in the East Antarctic Ice Sheet should be seen as fluctuations of the Lambert-Amery system.

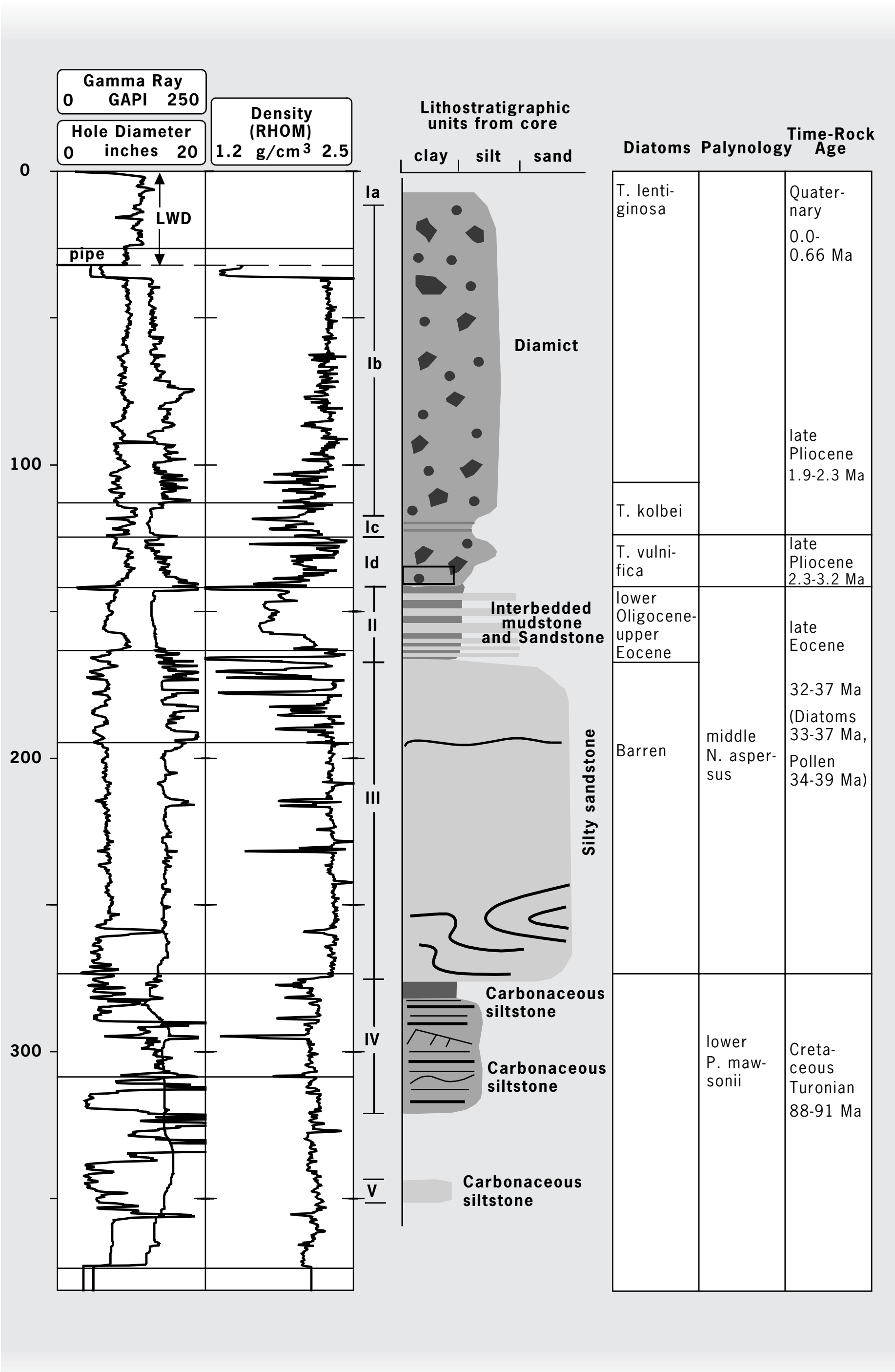
Three holes were drilled, each one aimed at providing insights into different aspects of Antarctic glacial history.

GLACIAL ONSET – SITE 1166

Site 1166 was drilled on the continental shelf in 486 m of water and was intended to sample the earliest Cenozoic glacial sediments, to date glaciation onset and determine what the pre-ice-sheet environment was like. It penetrated 381 m of pre-glacial, early glacial and glacial rocks of Cretaceous to Holocene age (Fig. 2). Since the cruise ended, Mike Macphail and Liz Truswell of the Australian National University have studied the palynology of key samples that could not be dated during Leg 188. The oldest dated rocks, which they believe are Turonian age, are claystone and sandstone with carbonaceous material and wood, indicative of an alluvial environment with vegetation. Unconformably overlying these sediments are deltaic deposits with abundant spores, pollen and marine dinoflagellates. A disconformity separates these rocks from overlying transgressive sandstone and mudstone and open marine mudstone with ice-rafted dropstones near the upper part of the unit. The deltaic and mudstone units also contain diatoms and dinoflagellates of mid to Late Eocene age (34 to 37 Ma).

Spores and pollen are representative of a stunted, "rainforest scrub" like that in

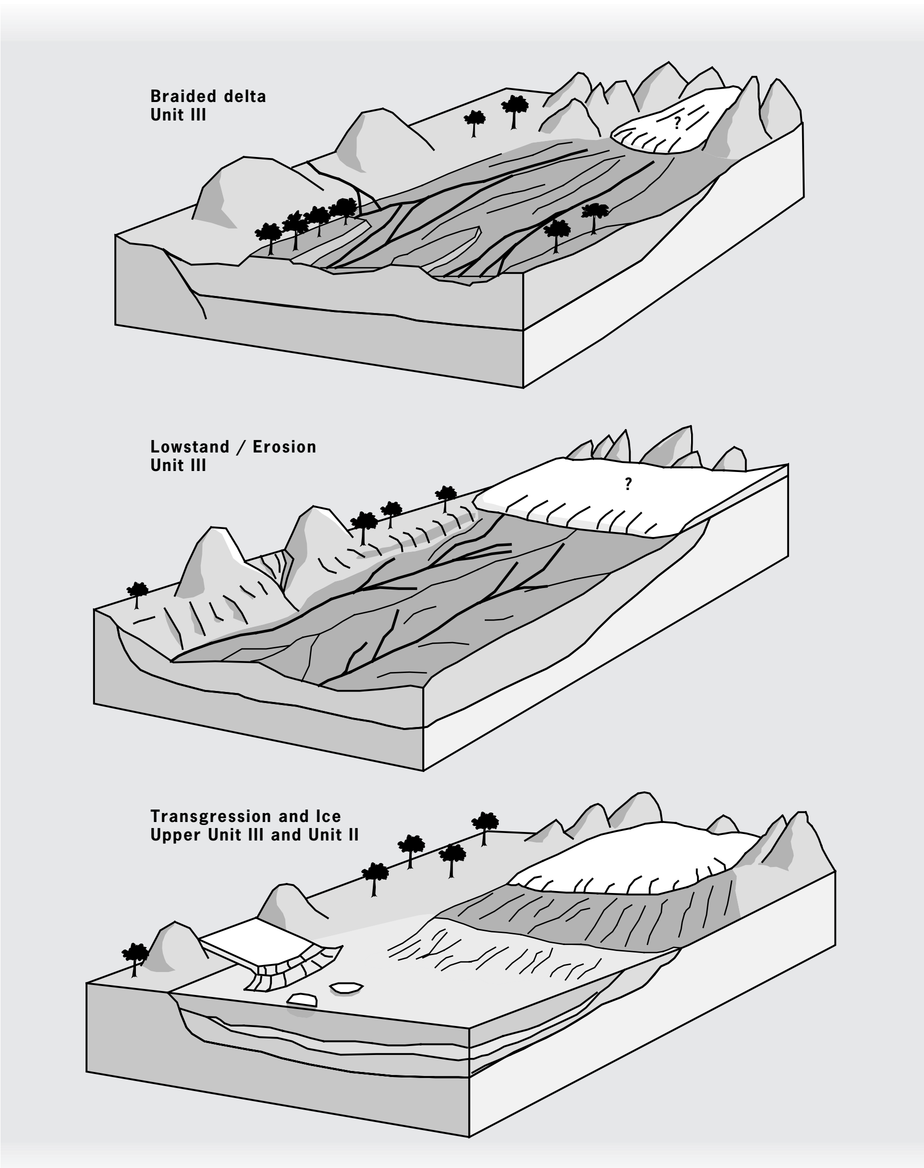
FIGURE 2 *Lithological units of Site 1166, and ages of the units based on diatom biostratigraphy and palynology.*



alpine areas of Tasmania and Patagonia. This scrub consisted of stunted trees around 1 m tall with no understory plants. The dominant plants were *Nothofagus* (southern beach) species and gymnosperms. A major unconformity separates these marine strata from diamicts of late Pliocene to Pleistocene age. The diamicts are mostly subglacial deposits, but interbeds of diatom-bearing silts are present in both the Pliocene and Pleistocene sequences that probably formed during warmer, interglacial phases.

Site 1166 showed that, during the late Eocene, Prydz Bay was a site of shallow marine to deltaic deposition in a cold-temperate environment (Fig. 3). The area was vegetated by plants stunted by the cold but not reduced to tundra. Floating ice was present in the sea, but whether that ice came from glaciers at sea level has yet to be determined. Further work will be needed to decide whether the rivers flowing into Prydz Bay were in fact glacial outwash streams. Further comparisons with ODP sites drilled in Prydz Bay on Leg 119 will bracket more closely the time at which the stunted forests of the late Eocene were finally overwhelmed by the developing East Antarctic Ice Sheet.

FIGURE 3 *Depositional model for Paleogene sedimentation at Site 1166. Unit III was deposited on a vegetated alluvial plain, probably in braided streams. The existance of ice in the hinterland is conjectural. The erosion surface in the upper part of Unit III formed during a relative lowstand, possibly related to the first expansion of ice on the continent, but evidence of glacial erosion of detritus has not been detected yet. Cold-temperate rainforest-scrub vegetation existed on the alluvial plain. The upper part of Unit III and Unit II formed during a marine transgression on the coastal plain. Floating ice delivered lonestones to the marine embayment and the rainforest-scrub persisted.*



NEOGENE EXPANSION – SITE 1165

Site 1165 was located on the continental rise on a large sediment drift. It was intended to drill through the Neogene to a surface that marks a change in seismic geometry that Kuvaas and Leitchenkov (1992) interpreted as representing either a major change in oceanic circulation or the first arrival of ice on the continental shelf inferred to be around the Oligocene-Miocene boundary. Site 1165, drilled in 3537 m of water, penetrated a mostly-continuous 999 m section of early Miocene-Holocene age hemipelagic and contourite deposits (Fig. 4).

The lowest unit penetrated (Unit III) is a thick contourite deposit of dark gray claystone with silt partings and scattered interbeds of massive green-gray claystone. Scattered sand grains are found throughout from 307.8 m to 999.1 mbsf. Seismic lines across the site display sediment waves through this interval. Diatoms, radiolaria and paleomagnetic data suggest an early to middle Miocene age for this unit. We interpret the thick fine contourites as formed from detritus supplied to the continental rise by temperate

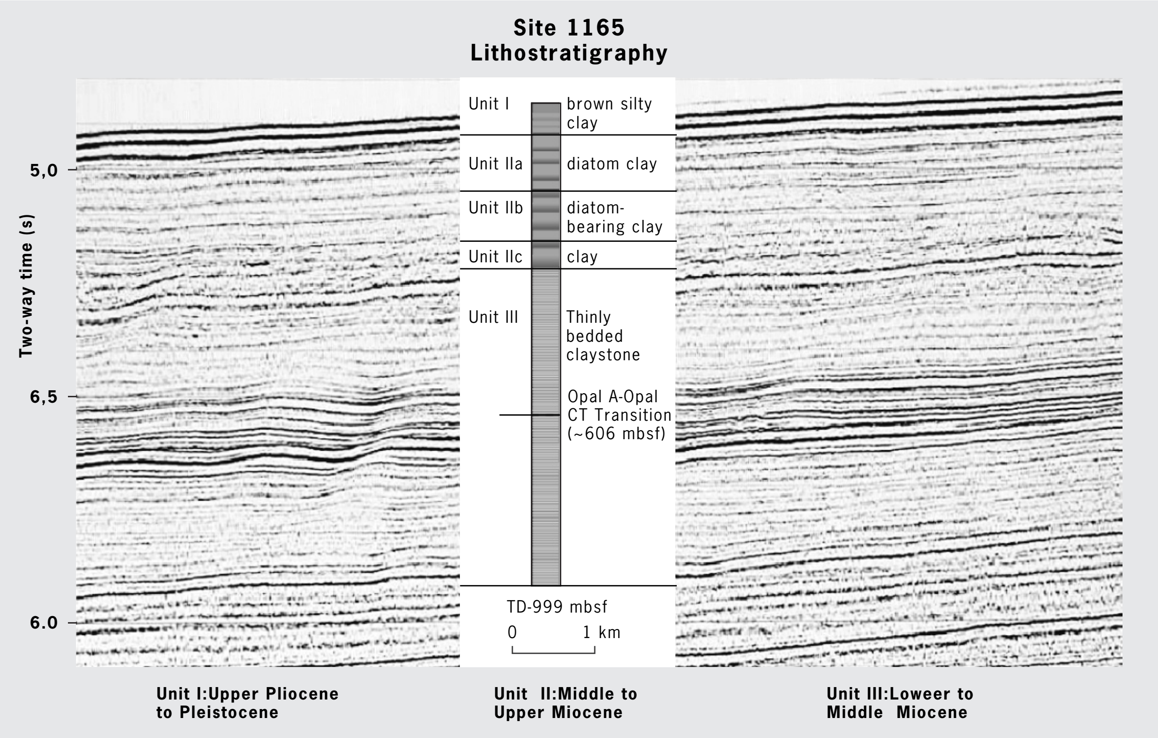


FIGURE 4 *Lithological units in Site 1165 superimposed on seismic section.*

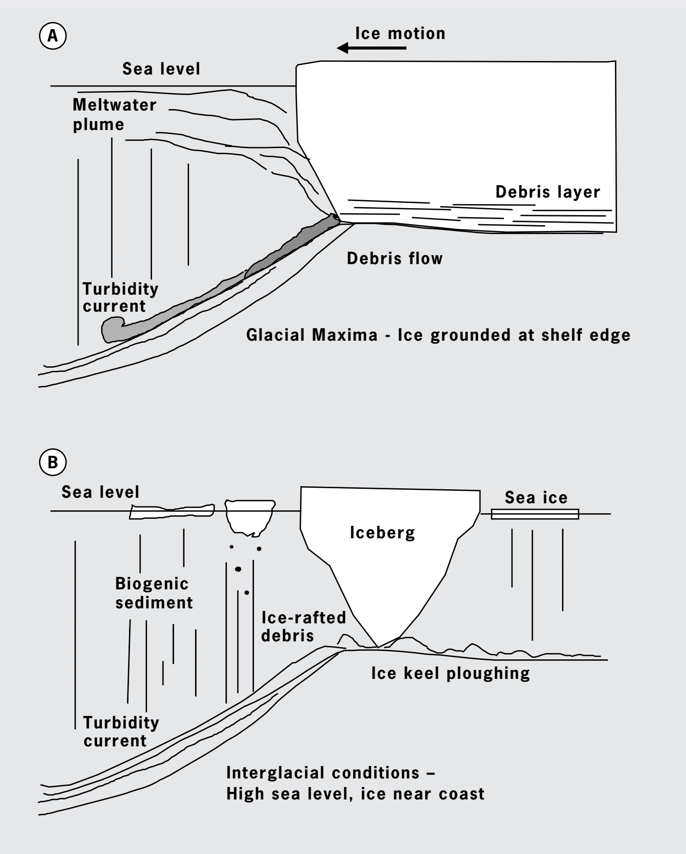


FIGURE 5A *Model of trough mouth fan sedimentation. When ice expands to the shelf edge, basal debris melts out at the shelf edge and debris flows, tubidity currents and sediment settling from meltwater plumes prograde the fan.* **5B** *When the ice is not grounded at the shelf edge, the fan recieives a drape of hemipelagic sediment and dropstones with minor turbidity current deposition.*

glaciers on Antarctica. Such glaciers are highly erosive and produce abundant meltwater and fine erosion products. Sediment waves suggest strong, west-flowing currents in the area. The reflection surface originally thought to be at the Oligocene-Miocene boundary is likely to result from carbonate diagentic changes that accentuate a gradational change of facies in early Miocene contourites.

Overlying Unit III is an unit composed of interbeds of structureless greenish-gray diatom clay and dark gray diatom-bearing clay. A few beds of massive nannofossil chalk < 0.5 m thick are also present. Ice-rafted coarse sand and pebbles are more abundant and glauconite and reworked

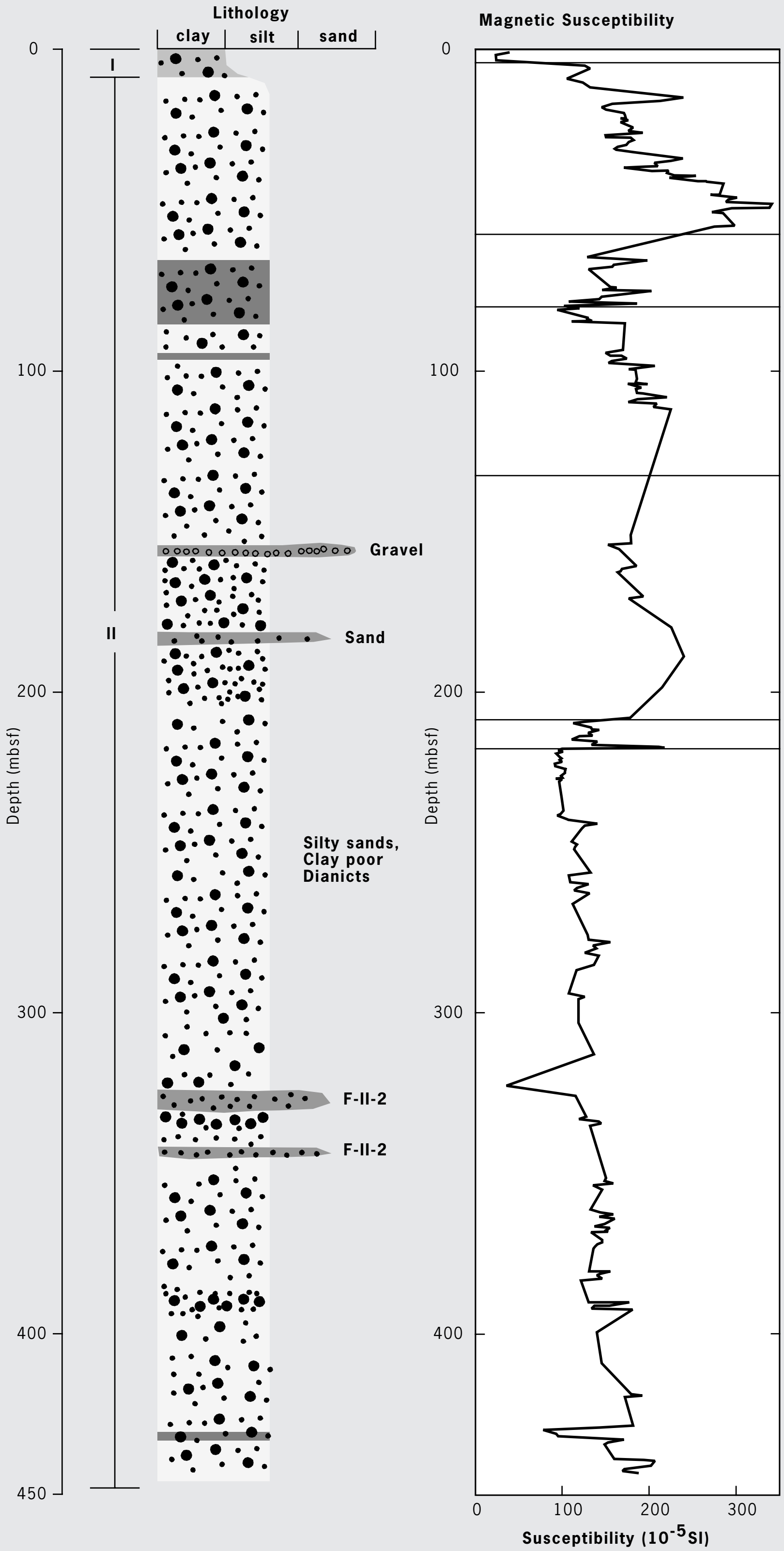


FIGURE 6 *Lithological log of site 1167 with magnetic susceptibility data. The susceptibility data show a series of falling intervals separated by abrupt increases. These trends may reflect long term, systematic changes in provenance that may relate to ice volume changes.*

benthic foraminifers appear in the core. Clay minerals make up a higher proportion of the fine fraction than in Unit III. Our initial interpretation of Unit II is that it comprises mostly hemipelagic sediments with minor contour current deposits and represents an upward change to a colder, less active ice sheet. Furthermore, the presence of glauconite, reworked microfossils and a greater abundance of clay minerals suggests that the ice sheet expanded onto the continental shelf, eroding older, shallow marine sediments and delivering the recycled detritus to the rise. The greater abundance of ice-rafted detritus (IRD) also suggests that ice masses were at sea level, where they produced more icebergs than previously. The nannofossil chalk beds suggest brief blooms of coccoliths. The age model for the hole indicates that the notable transition to a large ice sheet took place in the Middle Miocene.

The uppermost unit in Site 1165, from 0 to 63.8 mbsf, comprises interbedded structureless greenish-grey diatom clay and yellowish gray to brown diatom clay that pass upward into grayish brown diatom ooze. Ice-rafted granules and pebbles, diatoms, sponge spicules and radiolarians are abundant and foraminifers are common. Bioturbation is pervasive. Fossil content and palaeomagnetic data indicate Unit I was deposited from the early Pliocene to Pleistocene. This unit is interpreted as hemipelagic sediment deposited at relatively slow sedimentation rates. The slow sedimentation rates and abundant IRD suggest cold, polar conditions with relatively slow-moving ice sheets eroding the continent more slowly than during the lower Miocene.

The sediments at Site 1165 document changes in Antarctic palaeoenvironments from times of temperate glaciers with fluvial systems and large sediment supply to the rise (Unit III), to more polar conditions with glacial erosion of the shelf, increased ice rafted detritus (IRD) and lower sediment supply (Unit II), to polar conditions like today with IRD and little sediment reaching the rise at this site (Unit I). Cyclic sedimentation between terrigenous-dominated and biogenic-rich facies, is observed throughout the hole, and appears (where color variations are most evident, in the upper 300 mbsf) to have Milankovich periodicities that imply orbital forcing of the sedimentation processes.

PLIO-PLEISTOCENE FLUCTUATIONS – SITE 1167

Site 1167, in 1649 m of water, penetrated the Prydz Channel trough mouth fan. This fan is a sediment body constructed of debris brought to the shelf edge in the base of the Lambert Glacier during periods of maximum advance. At the shelf edge, the debris melts out and slumps down the continental slope, or rises in turbid meltwater plumes before settling out (Fig. 5). During times when the ice is grounded inshore from the shelf edge, hemipelagic muds and minor turbidites formed by iceberg reworking and slumping of the shelf edge drape the fan surface. Studies on the Prydz Bay shelf demonstrated, however, that the Last Glacial Maximum grounding line of the Lambert Glacier was well inboard from the shelf edge (Domack et al., 1998, O'Brien et al., 1999). Drilling a hole in Prydz Channel fan would answer the question: which glacial episodes produce ice advances to the shelf edge?

The hole sampled a 448 m thick section of Pleistocene debris flows with

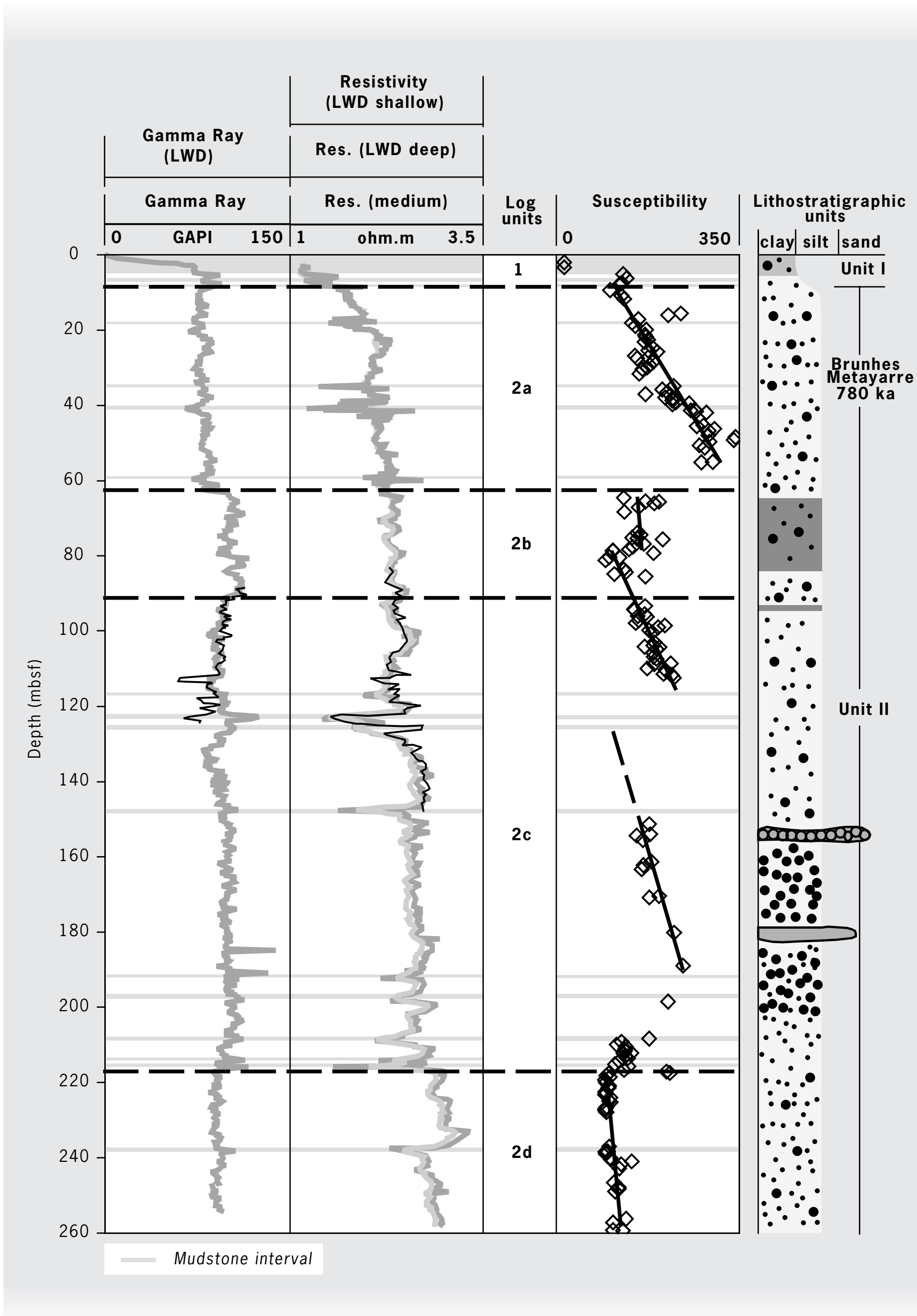


FIGURE 7 *Lithological log of the upper 260 m of site 1167 with geophysical (LWD) logs showing mudstone interbeds. Preliminary position of age datums also shown. Mudstone interbeds represent sedimentation during periods when the ice was not grounded at the shelf edge.*

minor interbedded and laminated mudstone (Fig. 6). The debris flows comprise poorly sorted sandy silt, silty sand, clayey sand and clast-poor diamicts. Lonestones are common throughout. Mudstone beds are dark gray, with some silt interbeds and greenish gray sandy clay with foraminifers and nannoplankton. Recovery of mudstone intervals was poor and hole conditions prevented wireline logging of the hole. However, Logging While Drilling (LWD) of the top 260 m of the hole indicated interbedding of thick debris flow intervals with thin mudstone units.

Ages derived from paleomagnetic data and calcareous nannoplankton suggest that the Lambert Glacier reached the shelf edge only 5 times in the last 800,000 years (Fig. 7), despite the fact that distal $\partial^{18}O$ records suggest about 10 major increases in global ice volume over that period (Williams et al. 1988).

Unexpected features of the cores are several large-scale (up to hundreds of meters thick) cycles of systematic variation in magnetic-mineral content and detrital sediment composition (Fig. 6). Our initial interpretation is that they probably reflect cyclic changes in erosion of the ice-source areas, possibly with contributions from several different source areas. Drilling at Site 1167 is the first deep sampling of upper-slope fans around Antarctica, and the first observation of such cycles in a glacial trough mouth fan. Post-cruise work will aim to understand the significance of these cycles.

CONCLUSION

Leg 188 is one of a series of ODP legs aimed at understanding the role of the Antarctica in global climate. Leg 178 drilled on the Antarctic Peninsula and obtained a record from part of the continent that is occupied by small ice masses that respond rapidly to climate change. The following Leg 189 drilled part of the South Tasman Rise that was attached to Antarctica until the Oligocene (Shipboard Party, 2000). Leg 119 first explored Prydz Bay in 1987/88 and demonstrated the presence of Paleogene glacial rocks (Barron, Larson et al., 1991). Leg 188 has now extended the record back to the late Eocene, demonstrating the presence of floating ice in association with a terrestrial flora stunted by cold temperatures. Leg 188 drilling on the rise has increased the evidence for the existence of a more temperate glacial regime in Antarctica until the middle Miocene, when the ice advanced onto the continental shelf and started eroding it. From then on, a cooling trend produced more polar conditions, reducing erosion rates and sediment delivery to the ocean. This trend to colder, less active ice continued through the Plio-Pleistocene, with evidence that the Lambert Glacier has not advanced to the shelf edge in step with global ice volumes as indicated by $\partial^{18}O$ records recorded by others.

LEG 188 SCIENCE PARTY

Alan K. Cooper and Philip E. O'Brien, Co-chief scientists, Carl Richter, Staff Scientist, Samantha Barr, Steven M. Boharty, George E. Claypool, John E. Damuth, Patrick S. Erwin, Fabio Florindo, Carl Fredrick Forsberg, Jens Grützner, David A. Handwerger, Nicole N. Janusczak, Alexander Kaiko, Kelly A. Kryc, Mark Lavelle, Sandra Passchier, James J. Pospichal, Patrick G. Quilty, Michele Rebesco, Peter Sammann, Kari Strand, Brian Taylor, Kevin Theissen, Detlef A. Warnke, Patricia Whalen, Jason Whitehead, Trevor Williams.

REFERENCES

Abreu, V. S. and Anderson, J. B., 1998. Glacial eustacy during the Cenozoic: sequence stratigraphic implications. *American Association of Petroleum Geologists Bulletin*, 82: 1385–1400.

Barron, J., Larsen, B. et al., 1991. *Proceedings of the Ocean Drilling Program*, *Scientific Results*, College Station, TX (Ocean Drilling Program), 119: 1003 pages.

Domack, E., O'Brien, P. E., Harris, P. T., Taylor, F., Quilty, P. G., DeSantis, L. and Raker, B., 1998. Late Quaternary sedimentary facies in Prydz Bay, East Antarctica, and their relationship to glacial advance onto the continental shelf. *Antarctic Science*, 10, 227–235.

Kuvaas, B. and Leitchenkov, G., 1992. Glaciomarine turbidite and current controlled deposits in Prydz Bay, Antarctica. *Marine Geology*, 108: 365–381.

Miller, K. G., Barrera, E., Olsson, R. K., Sugarman, P. J. and Savin, S. M., 1999. Does ice drive Maastrichtian eustacy? *Geology*, 27: 783–786.

O'Brien, P. E., De Santis, L., Harris, P. T., Domack, E and Quilty, P. G., 1999. Ice shelf grounding zone features of western Prydz Bay, Antarctica: sedimentary processes from seismic and sidescan images. *Antarctic Science*, 11: 78–91.

Shipboard Scientific Party, 2000. Leg 189 The Tasmanian gateway between Australia and Antractica – paleoclimate and paleoceanography. *Ocean Drilling Program*, *Preliminary Report*. College Station, Texas, 123 pages.

Williams, D. F., Thunnell, R. C., Tappa, E., Rio, D., and Raffi, I., 1988. Chronology of the Pleistocene oxygen isotope record: 0-1.88 m.y. B. P. *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*, 64: 221–240.

Zachos, J. C., Quinn, T. M. and Salmy, K. A., 1996. High resolution (104 years) deep-sea foraminiferal isotope records of the Eocene-Oligocene climate transition. *Paleoceanography*, 11: 251–266.

The Opening of the Tasmanian Gateway Drove Global Cenozoic Paleoclimatic and Paleoceanographic Changes: Results of Leg 189

N. Exon[1], J. Kennett[2], M. Malone[3], and the Leg 189 Shipboard Scientific Party

The major ice sheets of the Cenozoic Era are unusual in geological history. Progressive cooling at high latitudes during the Cenozoic eventually formed major ice sheets, initially on Antarctica and later in the Northern Hemisphere. In the early 1970s it was proposed that climate cooled and an Antarctic ice sheet (cryosphere) developed as the Antarctic Circumpolar Current (ACC) progressively isolated Antarctica thermally (Kennett et al., 1975). This current resulted initially from the opening of the Tasmanian Gateway, and the history of this opening was the main focus of ODP Leg 189. Early ocean drilling in the Tasmanian Gateway between Australia and Antarctica (Deep Sea Drilling Project Leg 29: Kennett, Houtz et al., 1975) provided a basic framework of paleoenvironmental changes associated with the opening, but was of insufficient quality and resolution to fully test the potential interrelationships of plate tectonics, circum-polar circulation and global climate. Until now, the timing of events has remained inadequately constrained.

The opening of the Tasmanian Gateway in the latest Eocene and the only other important ACC constriction, the Drake Passage, in the earliest Neogene (Fig. 1), had enormous consequences for global climate. These consequences came by isolating Antarctica from warm gyral surface circulation of the Southern Hemisphere oceans, and also by providing the conduits that eventually led to ocean conveyor circulation between the Atlantic and Pacific Oceans. Both factors, in conjunction with positive feedbacks and other changes in the global system, have been crucial in the development of the polar cryosphere, initially in Antarctica in the Paleogene and early Neogene, and later in the Northern Hemisphere in the late Neogene (Shackleton and Opdyke, 1977; Ruddiman et al., 1989). Furthermore, the continued expansion of the Southern Ocean during the Cenozoic because of the northward flight of Australia from Antarctica, has clearly led to further evolution of the Earth's environmental system and of oceanic biogeographic patterns.

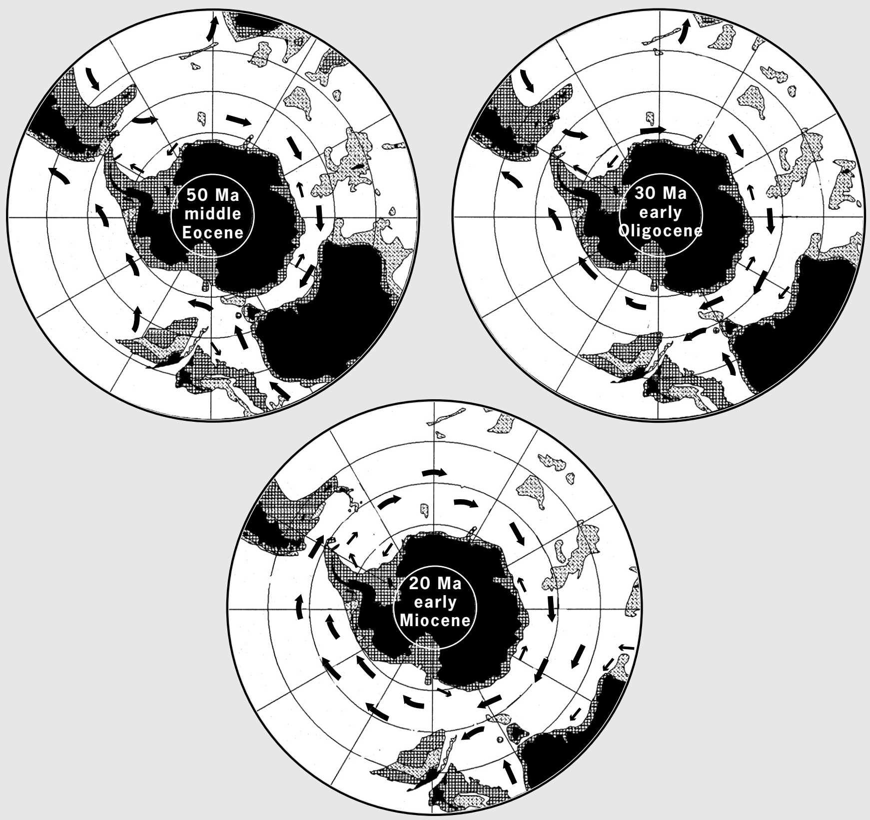


FIGURE 1 *Antarctica and surrounding continents in middle Eocene, early Oligocene and early Miocene times, showing the change from meridional to circum-Antarctic current circulation that brought about the thermal isolation of Antarctica (after Lawver et al., 1992; Shipboard Scientific Party, 1999). Leg 189 was in the plateau areas around Tasmania.*

[1] Australian Geological Survey Organisation, PO Box 378, Canberra, ACT 2601, Australia

[2] Department of Geological Sciences and Marine Science Institute, University of California, Santa Barbara, California 93106, U.S.A.

[3] Ocean Drilling Program, Texas A&M University, 1000 Discovery Drive, College Station, Texas 77845, U.S.A.

The five Leg 189 drill sites, in water depths of 2475 to 3579 m (Fig. 2), tested the above hypothesis and refined and extended it, greatly improving understanding of Southern Ocean evolution and its relation with Antarctic climatic development. The focus of the expedition was to better document the climatic and oceanographic consequences of the opening of the gateway during the transition from warm Eocene climates to cool Oligocene climates. The relatively shallow region off Tasmania (Exon and Crawford, 1997) is one of the few places where well-preserved and almost complete marine Cenozoic carbonate-rich sequences can be drilled in present-day latitudes of 40–50ºS, and paleolatitudes of up to 70ºS. The broad geological history of all the sites was comparable. However, the Paleocene-Eocene separation of the three Indian Ocean sites from the two Pacific Ocean sites by the Tasmanian land bridge led to important differences. Depositional conditions in the restricted Australo-Antarctica Gulf (AAG), west of the land bridge, contrasted with those in the more open Pacific Ocean. There are also differences from north to south related to proximity to the opening gateway and to major land masses.

In all, 4539 m of core was recovered (overall recovery 89% despite some real Southern Ocean weather), with the deepest core taken 960 m beneath the seafloor. The sedimentary sequence cored is entirely marine, and contains a wealth of microfossil assemblages that record marine conditions from the Late Cretaceous (Maastrichtian) to the late Quaternary, with major terrestrial input until the earliest Oligocene. The drill sites are on submerged continental blocks, which were at polar latitudes in the Late Cretaceous when Australia and Antarctica were still united, although rifts had developed as slow separation and northward movement of Australia commenced. The cores indicate that the Tasmanian land bridge completely blocked the eastern end of the widening AAG until the late Eocene, during both slow and fast (from 43 Ma) spreading phases.

THE SEQUENCES DRILLED

The stratigraphic results of the expedition are summarised in Figure 3. In general, terrigenous sedimentation in a shallow marine deltaic setting dominated until the late Eocene, and pelagic carbonate deposition in deep waters thereafter. Distance from the ACC strongly affected the nature of sedimentation in the late Eocene.

Three sites were west of the Tasmanian land bridge, and hence in the AAG until the Oligocene. Site 1168 on the west Tasmanian margin cored to 883 metres below the sea floor (mbsf). This site recovered an almost complete sequence of Oligocene to Recent chalk and ooze, and some late Eocene shelf mudstone. Site 1169 on the western South Tasman Rise cored to 249 mbsf and recovered only chalk and ooze, with an expanded early Pliocene to Recent sequence, and small parts of the late and middle Mio-

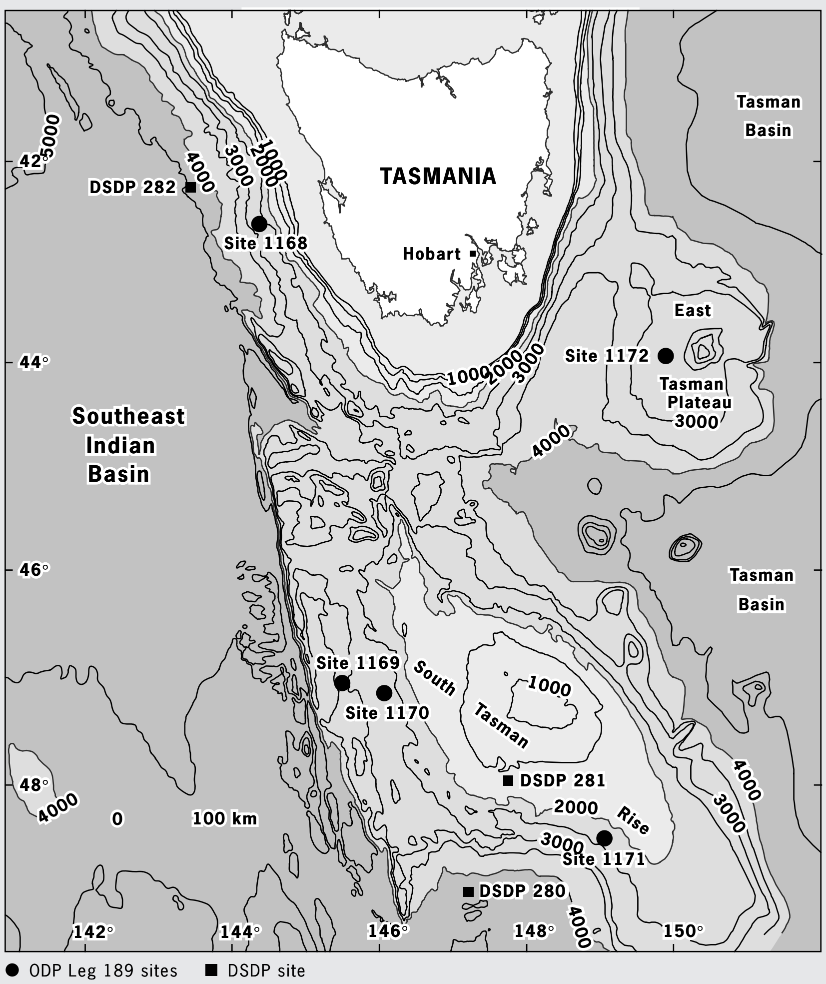


FIGURE 2 *Bathymetry of the offshore Tasmanian region, making use of extensive swath-bathymetry (Hill et al., 1997). Leg 189 sites are solid circles, and DSDP sites are squares. Contours in meters.*

cene. Site 1170, 40 km east of Site 1169, cored to 780 mbsf and recovered early Oligocene to Recent chalk and ooze, and middle to late Eocene shelf mudstone. This site lay close to the developing ACC, which caused erosion or non-deposition of most of the mid-Oligocene and the late Miocene.

Two sites were always in the Pacific Ocean (in the initially narrow Tasman Sea) and east of the Tasmanian land bridge until the Oligocene. Site 1171, on the southernmost South Tasman Rise, cored 959 mbsf and recovered an almost-complete late Oligocene to Recent chalk and ooze sequence, and much of a late Paleocene to late Eocene shelf mudstone sequence. Several time breaks in the Eocene and Oligocene, and the late Miocene, can be related to the nearby ACC. Site 1172, on the East Tasman Plateau, was also on the Pacific side of the land bridge, but further from the Antarctic Circumpolar Current. It recovered almost-complete sequences of Oligocene to Recent chalk and ooze, and Late Cretaceous to late Eocene shelf mudstones. Short time breaks were identified in the earliest Paleocene, early middle Eocene and earliest Oligocene.

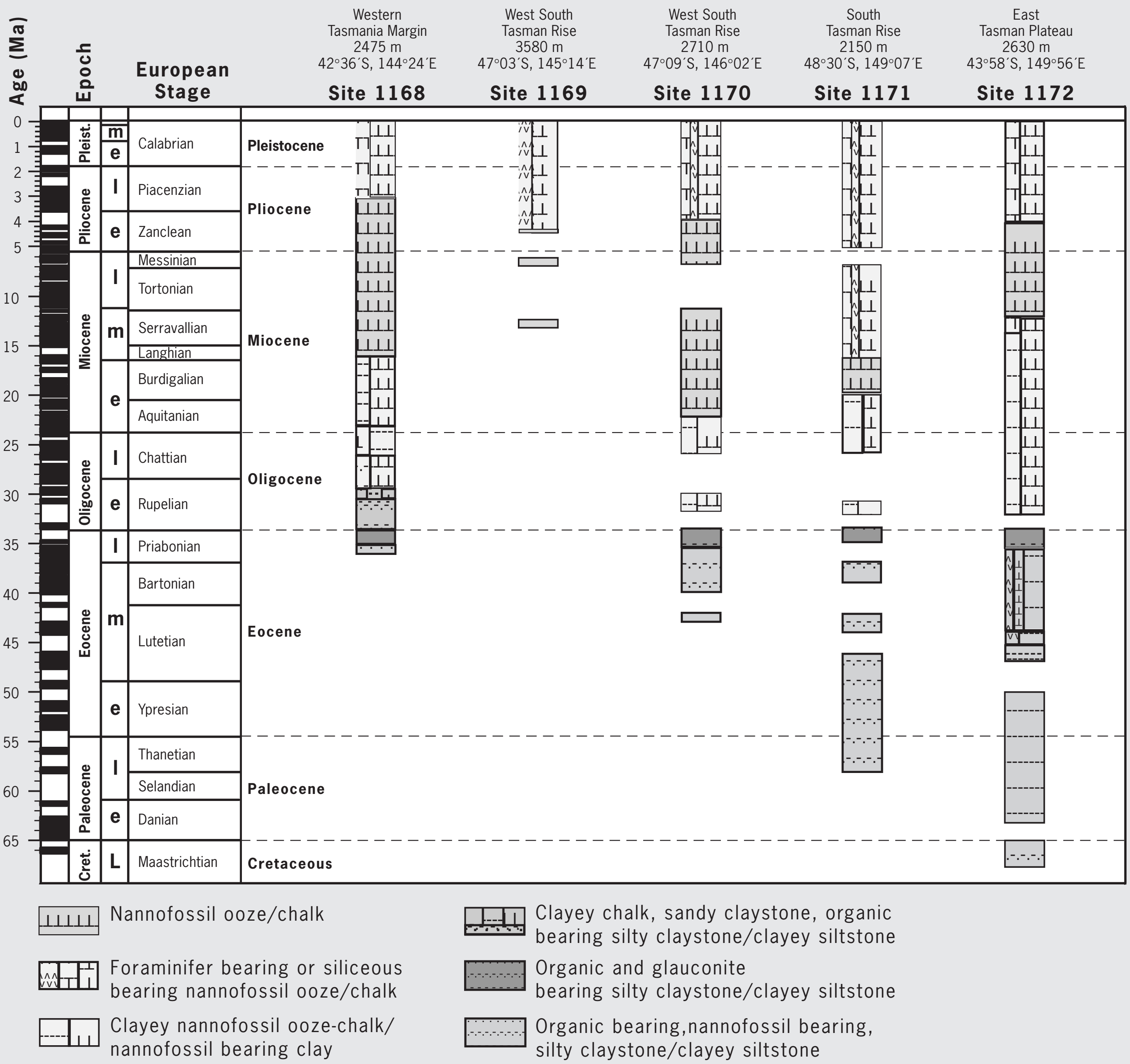


FIGURE 3 *Summary stratigraphy and sediment facies for all sites drilled during Leg 189 arranged against time, from west to east.*

HIGHLIGHTS

Sedimentation rates depended on local tectonics, distance from source, sedimentation patterns, and by-passing and current erosion, and vary among the sites (Fig. 4). Apatite fission track dating indicates that west and east Tasmania were subject to regional cooling in the late Paleocene to early Eocene, indicating tectonic uplift and erosion (O'Sullivan and Kohn, 1997). West of Tasmania, Site 1168 continuously received sediment from Tasmania, and sedimentation rates were moderate and fairly constant from the late Eocene onward (3-5 cm/ky), with little change as terrigenous sedimentation gave way to carbonate sedimentation. On the South Tasman Rise, Sites 1170 and 1171 were part of the tectonically active borderland between Antarctica and Australia in the Paleocene and Eocene, but were isolated from major landmasses thereafter, with the local hinterland sinking and diminishing. Thus sedimentation rates were relatively high (5-10 cm/ky) during terrigenous deposition in the early and middle Eocene, and generally low thereafter. Sedimentation rates were low in the late Eocene (1-2 cm/ky) as the sites were current-swept by the developing ACC, and later during pelagic carbonate deposition. On the East Tasman Plateau, sedimentation rates at Site 1172 were generally low from the Maastrichtian onward (1–2 cm/ky) for both terrigenous and carbonate sedimentation, suggesting that the terrigenous source was relatively limited until it vanished in the Oligocene.

Four key observations come from the geochemistry (Fig. 5). First, in Sites 1170, 1171 and 1172, Paleogene sediments are generally carbonate-poor, and Neogene sediments carbonate-rich. Second, the transition from carbonate-poor to carbonate-rich sediments is quite abrupt, except at Site 1168. Third, carbonate and total organic carbon contents are antithetic: Paleogene sediments usually contain greater than 0.5 % TOC, whereas Neogene sediments contain little TOC. Fourth, organic matter type (primarily Rock Eval pyrolysis), and paleosalinity characterizations (C/S ratios), identify geochemical facies. The facies show distinct changes at the Paleocene-Eocene boundary, in the middle Eocene, and near the Eocene-Oligocene boundary. Fifth, at Sites 1168, 1170 and 1171, methane content from headspace gas measurements increases abruptly downward into the organic carbon-containing Paleogene sediments, which contain thin, almost-mature hydrocarbon source rocks.

Prior to the late Eocene, marine siliciclastic sediments, largely silty claystone, were deposited in a relatively warm sea on broad, shallow tranquil shelves. Sediment supply was rapid and despite the rifting, drifting, and compaction, deltaic deposition kept up with subsidence. Calcareous and siliceous microfossils are sporadically present, and dinocysts, spores and pollen are always present. The spores and pollen show that, throughout this time, this part of Antarctica was relatively warm with little ice, and supported temperate rain forests with southern beeches and ferns – part of the "Greenhouse" world. Differences in the claystones indicate that the eastern AAG was more poorly ventilated than the gradually widening Pacific Ocean with its western boundary current, the East Australian

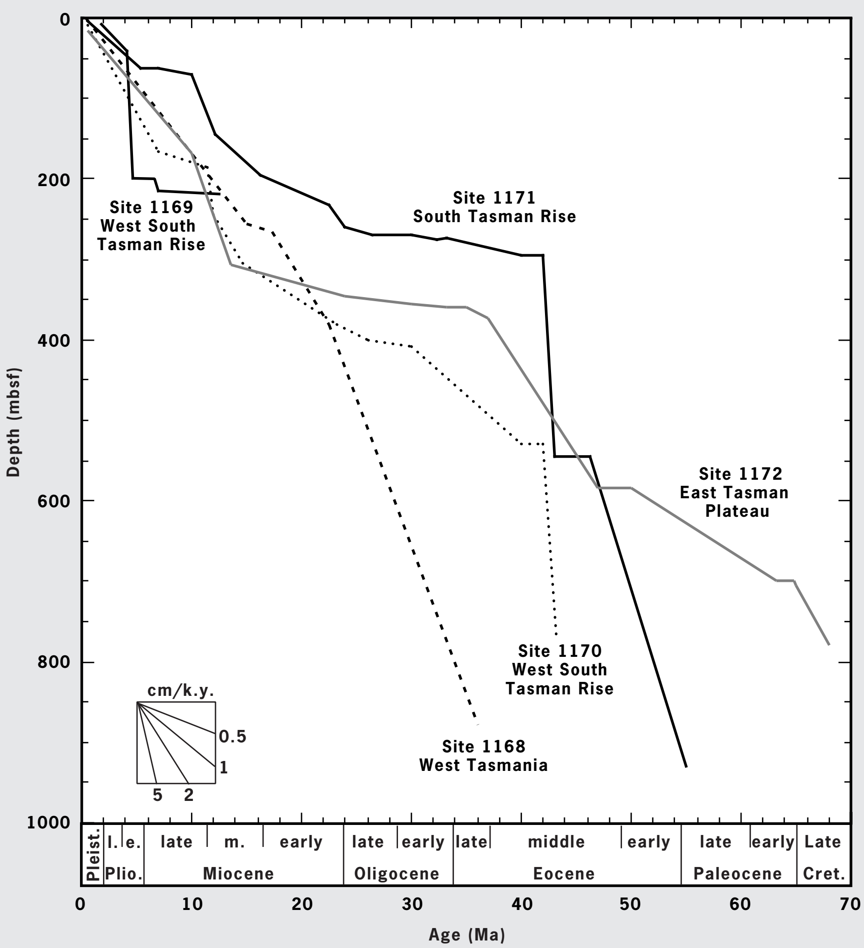


FIGURE 4 *Sedimentation rate summary curves for all sites drilled during Leg 189.*

Current. However, currents from low latitudes warmed both sides of the land bridge.

In the late Eocene (37–33.5 Ma), the Tasmanian land bridge separated from Antarctica, the bridge and its broad shelves began to subside, and cool surface currents started to circulate around Antarctica from the west. These swept the still-shallow offshore areas, and glauconitic siltstones were deposited very slowly, as condensed sequences. Palynological and other evidence suggests that there were considerable fluctuations in temperature superimposed on a general cooling, and the amount of upwelling also fluctuated in response to changing oceanic circulation. Calcareous microfossils are rare, but diatoms and foraminifers indicate that there was minor deepening in the latest Eocene (33.5 Ma) at some sites.

The most conspicuous change of the entire 70 million year sequence in this region occurred over the Eocene-Oligocene transition, when Australia and Antarctica finally separated: shallow to deep, warm to cold, dark siliciclastic to light pelagic carbonate deposition, palynomorph dominated to pelagic microfossil dominated, poorly to well ventilated, organic-rich to organic-poor.

By the early Oligocene (Fig. 6), warm currents from the tropics were cut off from some parts of Antarctica by the developing ACC, now with both shallow and deep circulation, leading to global cooling and some formation of ice sheets. In the Tasmanian offshore region, conditions were significantly cooler and there is no positive evidence of land vegetation, although plant material would have been oxidised in well-ventilated waters.

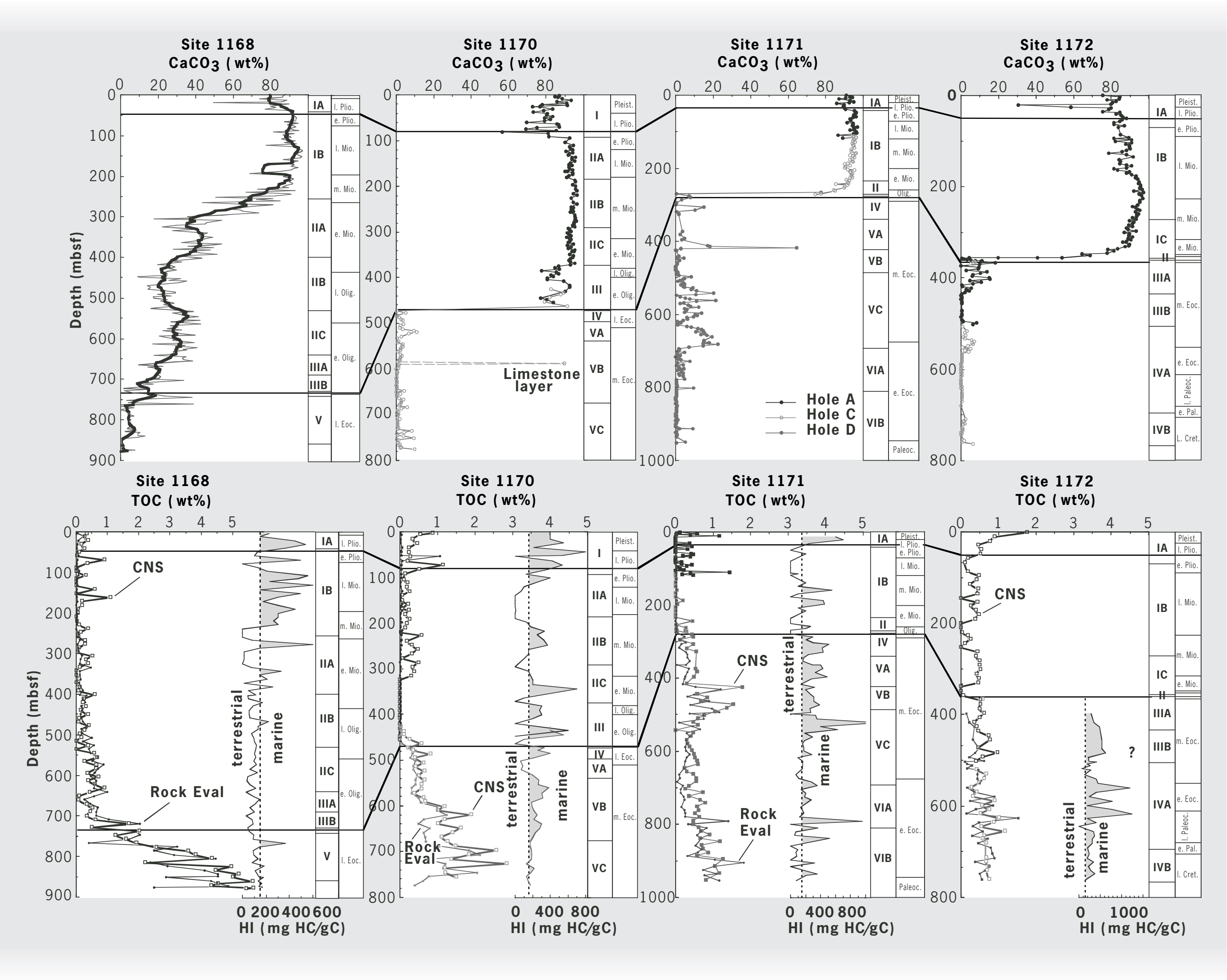


FIGURE 5 *Summary of organic geochemistry results. The upper panel shows carbonate content (weight percent $CaCO_3$), whereas the lower panel shows total organic matter content and hydrogen indices. Also shown are regional correlations and approximate location of lithostratigraphic units and age.*

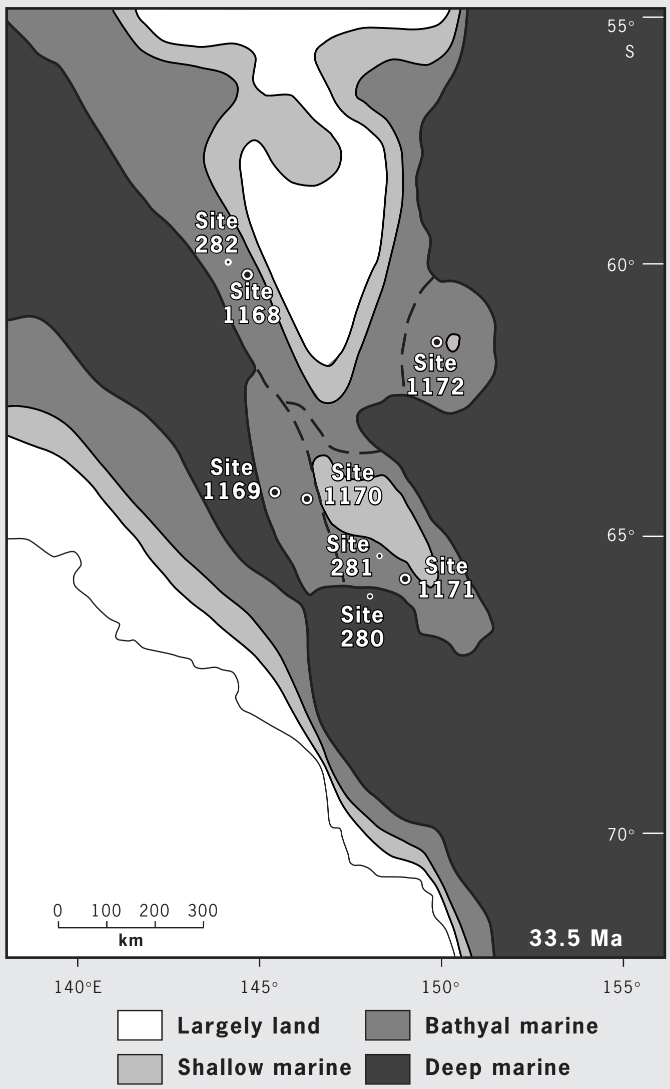


FIGURE 6 *Paleogeographic map of the Tasmanian and South Tasman Rise region in the earliest Oligocene (33.5 Ma), based partly on Royer and Rollet (1997, Fig. 8) and on Leg 29 and Leg 189 results. A deep-water connection had just been established south of South Tasman Rise, between the restricted Australo-Antarctic Gulf to the west and the Pacific Ocean, allowing the onset of deep circum-Antarctic circulation. Most of the continental margin was covered with bathyal seas, and most oceanic crust with deep water. Dots = DSDP Leg 29 Sites. Open circles with dots = Leg 189 Sites.*

Much of the land bridge had subsided beneath the ocean so there was a smaller hinterland to supply sediment. Furthermore the colder ocean provided less moisture, decreasing precipitation and erosion. Altogether, far less siliciclastic sediment was transported from the land, and generally slow deposition of deep-water pelagic sediments set in on the starved Antarctic and Tasmanian margins. However, the East Australian Current and currents flowing down the western Australian margin kept the Tasmanian region relatively warm, resulting in carbonate deposition rather than the siliceous biogenic deposition that marks much of the Antarctic margin. In the offshore Tasmanian region, and even in the Cape Adare region on the conjugate Antarctic margin (Piper and Brisco, 1975), there is no sign of glaciation in the early Oligocene. However, mountain glaciers existed on Tasmania in the earliest Oligocene (Macphail et al., 1993).

Drake Passage opened fully early in the Neogene (Lawver et al., 1992), and the Tasmanian Gateway continued to open, strengthening and widening the ACC, and strongly isolating Antarctica from warm water influences from lower latitudes. The east Antarctic cryosphere evolved into ice sheets comparable to the present ones at about 15 Ma (Shackleton and Kennett, 1975; Kennett, 1977). This intensified global cooling and thermohaline circulation: the “Ice House” world had arrived. However, temperatures and current activity fluctuated, and dissolution and erosion varied over time. The Tasmanian region had been moving steadily northward so its sediments were never south of the Polar Front, and pelagic carbonate continued to accumulate in deep waters at average rates of 1–2 cm/ky. The late Neogene sequences contain windblown dust from Australia, which was progressively moving northward into the drier mid-latitudes. Along with global climate change associated with high latitude ice sheet expansion, this led to massive aridity on Australia, and an increase in dust abundance in some Leg 189 sequences after 5 Ma.

Comparisons with sequences drilled elsewhere on the Antarctic margin (e.g. Prydz Bay ODP Leg 188: O’Brien, et al., 2000) will further improve our understanding of these momentous changes in the Earth’s history, and some of the constraints on modern climates. If Australia had not broken away from Antarctica and moved northward, global climate may well have remained warm. We can now document in some detail the changes related to that tectonic movement. Our results identify three important Cenozoic tectonic events: Paleocene strike-slip movement on the southeast South Tasman Rise (STR) terminated at 55 Ma by seafloor spreading to the south; Eocene strike-slip movement along the western boundary between STR and Antarctica, terminating in the latest Eocene around 34 Ma; and early Oligocene subsidence and collapse of the continental margin around Tasmania. The early Oligocene subsidence and collapse also occurred in the Victoria Land Basin east of the rising Transantarctic Mountains (Cape Roberts Science Team, 2000), and along the Otway coast on mainland Australia, northwest of Tasmania (Heggie et al., 1988).

Post-cruise studies and comparisons will better define and explain regional similarities and differences in tectonism, sedimentation and climate. Initial studies of physical properties, wireline logs, and microfossils all show that climatic cycles of varying length are present throughout the entire sequence, and present studies will better define Milankovitch and other cycles. In the Neogene pelagic carbonates, the excellent preservation and high depositional rates will allow detailed isotope studies to determine surface and bottom water temperatures through time. There is a unique opportunity to build Southern Ocean correlations between various microfossil groups – calcareous nannofossils, planktonic foraminifers, diatoms and radiolarians, and dinocysts, spores and pollen.

CONCLUSIONS

Leg 189 results essentially encapsulate the Cenozoic evolution of the Antarctic system from "Greenhouse" to "Ice House". The changes recorded in the cores reflect the evolution of a tightly integrated, and at times dynamically evolving, system involving the lithosphere, hydrosphere, atmosphere, cryosphere, and biosphere. Major successes included establishing differences for most of the Cenozoic between the Indian and Pacific Oceans, and also from north to south, by recovering relatively complete sequences, which will allow us to establish an unprecedented integrated biostratigraphic framework for the region. We expected to penetrate only to the middle Eocene, but in fact drilled Paleocene sediments in the southernmost site, which greatly improved our understanding of South Tasman Rise tectonic history, and Paleocene and Cretaceous sediments in the eastern site, revolutionising our understanding of the geological history of the East Tasman Plateau.

LEG 189 SHIPBOARD SCIENTIFIC PARTY

Neville Exon and Jim Kennett, Co-Chief Scientists; Mitch Malone, Staff Scientist; Henk Brinkhuis, George Chaproniere, Atsuhito Ennyu, Patrick Fothergill, Michael Fuller, Marianne Grauert, Peter Hill, Tom Janecek, Clay Kelly, Jennifer Latimer, Kristeen McGonigal, Stefan Nees, Ulysses Ninnemann, Dirk Nuernberg, Stephen Pekar, Caroline Pellaton, Helen Pfuhl, Christian Robert, Ursula Röhl, Stephen Schellenberg, Amelia Shevenell, Catherine Stickley, Noritoshi Suzuki, Yannick Touchard, Wuchang Wei, Tim White.

REFERENCES

Cape Roberts Science Team, 2000. Studies from the Cape Roberts Project, Ross Sea, Antarctica. Initial Report on CRP-3. *Terra Antarctica* 7, 1/2.

Exon, N. F. and Crawford A. J., eds., 1997. West Tasmanian margin and offshore plateaus: geology, tectonic and climatic history, and resource potential. *Australian Journal of Earth Sciences* 44 (5), 540–710.

Heggie, D., McKirdy, D., Exon, N. and Lee, C.-S., 1988. Hydrocarbon gases, heat-flow and the development of the offshore Otway Basin. *PESA (Petroleum Exploration Society of Australia) Journal* 13, 32–42.

Hill, P. J., Exon, N. F., Royer, J.-Y., Whitmore, G., Belton, D. and Wellington, A., 1997. Atlas of the offshore Tasmanian region: swath-mapping and geophysical maps from AGSO's 1994 Tasmante survey. *Australian Geological Survey Organisation*, 16 sheets.

Kennett, J. P., 1977. Cenozoic evolution of Antarctic glaciation, the Circum-Antarctic Ocean, and their impact on global paleoceanography. *Journal of Geophysical Research* 82, 3843–59.

Kennett, J. P., Houtz, R. E., Andrews, P. B., Edwards, A. R., Gostin, V. A., Hajos, M., Hampton, M. A., Jenkins, D. G., Margolis, S. V., Ovenshine, A. T. and Perch-Nielsen, K., 1975. *Initial Reports of the Deep Sea Drilling Project*, 29, Washington, DC (U.S. Government Printing Office), 1197.

Kennett, J. P., Houtz, R. E., Andrews, P. B., Edwards, A. R., Gostin, V. A., Hajos, M., Hampton, M. A., Jenkins, D. G., Margolis, S. V., Ovenshine, A. T. and Perch-Nielsen, K., 1975. Cenozoic paleoceanography in the Southwest Pacific Ocean, Antarctic glaciation, and the development of the Circum-Antarctic Current. In Kennett, J. P., Houtz, R. E., et al., *Initial Reports of the Deep Sea Drilling Project*, 29, Washington, DC (U.S. Government Printing Office), 1155–1169.

Lawver, L. A., Gahagan, L. M. and Coffin, M. F., 1992. The development of paleoseaways around Antarctica. In Kennett, J. P. and Warnke, D. A., eds., The Antarctic paleoenvironment: A perspective on global change, I, *Antarctic Research Series*, 56: Washington, DC (AGU), 7–30.

Macphail, M. K., Colhoun, E. A., Kiernan, K. and Hannan, D., 1993. Glacial climates in the Antarctic region during the late Paleogene: evidence from northwest Tasmania, Australia. *Geology*, 21, 145–148.

O'Brien, P. E., Cooper, A. K., Richter, C ., Macphail, M., Truswell E. M. and

Leg 188 Shipboard Scientific Party, 2000. Milestones in Antarctic ice sheet history – preliminary results from Leg 188 drilling in Prydz Bay, Antarctica. *JOIDES Journal* 26 .

O'Sullivan, P. B. and Kohn, B. P., 1997. Apatite fission track thermochronology of Tasmania. A*ustralian Geological Survey Organisation Record* 1997/35, 61p.

Piper, D. J. W. and Brisco, C. B., 1975. Deep-water continental margin sedimentation, DSDP Leg 28, Antarctica. *Initial Reports of the Deep Sea Drilling Project*, 28, Washington, DC (U.S. Government Printing Office), 727–755.

Ruddiman, W. F., Raymo, M. E., Martinson, E. G., Clement, B. M. and Backman, J., 1989. Pleistocene evolution: Northern Hemisphere ice sheets and North Atlantic Ocean. *Paleoceanography*, 4, 353–412.

Shackleton, N. J. and Kennett, J. P., 1975. Paleotemperature history of the Cenozoic and initiation of Antarctic glaciation: oxygen and carbon isotope analyses in DSDP Sites 277, 279 and 281. In J.P. Kennett, R.E. Houtz, et al., *Initial Reports of the Deep Sea Drilling Project*, 29, Washington, DC (U.S. Government Printing Office), 801–807.

Shackleton, N. J. and Opdyke, N. D., 1977. Oxygen isotope and palaeomagnetic evidence for early Northern Hemisphere Glaciation. *Nature* 270, 216–219.

Shipboard Scientific Party, 1999. Leg 181 summary: Southwest Pacific Paleoceanography. In Carter, R. M., McCave, I. N., Carter, L., et al., *Proceedings of the Ocean Drilling Program, Initial Reports, 181*, College Station, TX (Ocean Drilling Program), 1–80.

Deformation and Fluid Flow Processes in the Nankai Trough Accretionary Prism: ODP Leg 190

G. Moore[1] and A. Taira[2], A. Klaus[3], and Leg 190 Shipboard Scientific Party

The Nankai Trough accretionary prism represents an "end-member" prism accreting a thick terrigenous sediment section in a setting with structural simplicity and unparalleled resolution by seismic and other geophysical techniques (Aoki et al., 1982; Moore et al., 1990, 1991). It therefore represents a superb setting to address ODP's Long Range Plan objectives for accretionary prism coring, *in situ* monitoring, and refinement of mechanical and hydrological models. Additional interest has recently been focused on this portion of the Nankai Trough because it has experienced major, catastrophic earthquakes along its seismogenic zone (Ando, 1975; Hyndman et al., 1995; Park et al., 2000; Kodaira et al., 2000).

Our approach for drilling at the Nankai margin includes sites for coring, *in situ* observation, and long-term monitoring to (1) constrain prism hydrology, mechanical properties, and deformational styles and (2) test existing models for prism evolution. Leg 190, the first of a two-leg program, concentrated on coring and sampling two transects of sites across the prism. Leg 196, planned for 2001, will use logging-while-drilling technology to collect *in situ* physical properties data and will also install advanced CORKs (Davis et al., 1992) for long-term *in situ* monitoring of prism processes including pressure, temperature, fluid geochemistry, and strain.

The Nankai Trough (Fig. 1) is the subducting plate boundary between the Shikoku Basin and the southwest Japan arc (Eurasian plate). The Shikoku Basin is part of the Philippine Sea plate, which is subducting to the northwest under southwest Japan at a rate of 2–4 cm/yr (Karig and Angevine, 1986; Seno, 1977), slightly oblique to the plate margin.

The goals of Legs 190/196 are to: (1) understand the structural and hydrologic evolution of the décollement zone; (2) delineate chemical gradients and fluid flow paths; (3) contrast the stratigraphic and deformational framework along strike; and (4) document the Miocene to Recent evolution of the accretionary prism.

DRILLING RESULTS

During Leg 190, we successfully cored six sites (Figs. 1 and 2), meeting most of the leg objectives and also revealing some surprising new findings.

CHANGES IN PHYSICAL PROPERTIES

Lithostratigraphy and sediment diagenesis vary markedly in three dimensions throughout the Nankai-Shikoku Basin system. These variations in turn exert considerable influence on physical properties, hydrology, fluid-sediment geochemistry, and microbial activity. Discontinuities in porosity, P-wave velocity, electrical conductivity, and grain density generally correspond to lithologic and diagenetic boundaries.

[1] Dept. Geology & Geophysics
University of Hawaii
Honolulu, HI 96822, U. S. A

[2] Ocean Research Institute
1-15-1, Minamidai, Nakano-ku
Tokyo 164-8639, Japan

[3] Texas A & M, Ocean Drilling Program
1000 Discovery Dr.
College Station, TX 77845, U. S. A.

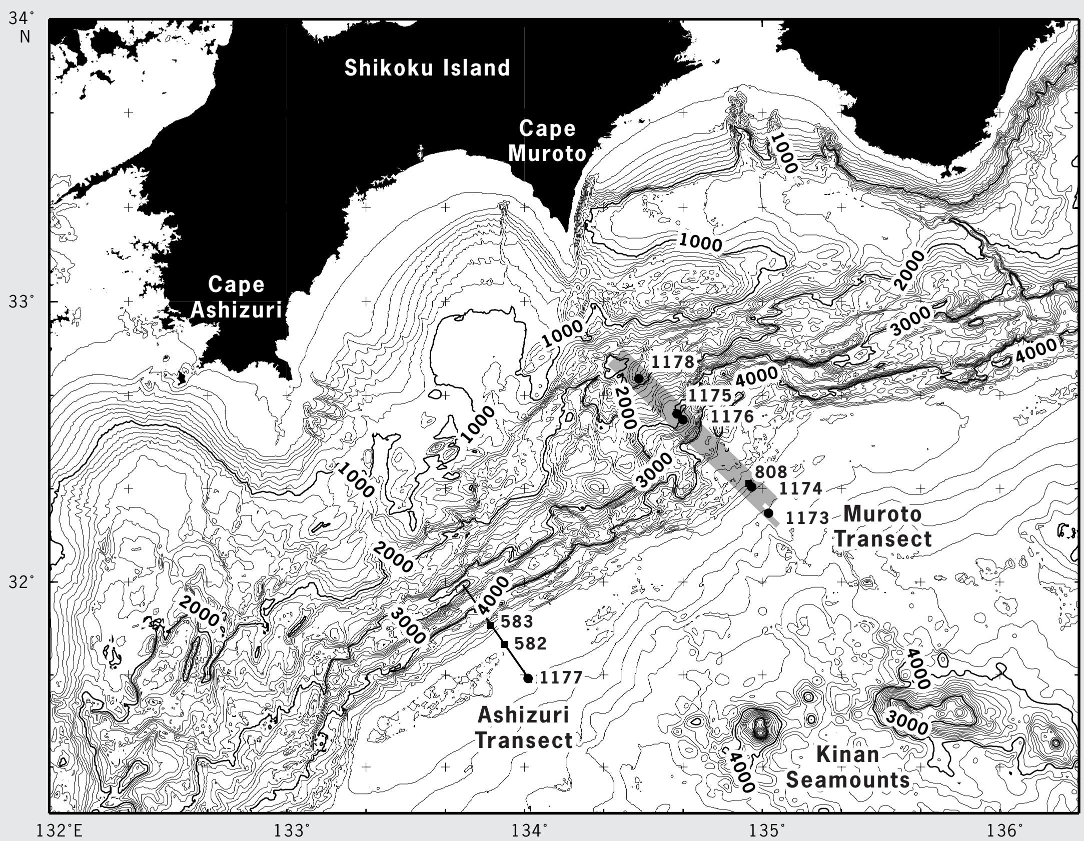


FIGURE 1 *ODP Leg 190 (solid circles) and previous ODP/DSDP drill sites (solid squares) in Nankai Trough. The shaded outline shows the 3-D seismic survey of Bangs et al. (1999) and Moore et al. (1999). Contour interval = 100 m.*

We demonstrated that there is a large contrast among many key properties, including the diagenetic, lithologic, and geochemical (including microbial activity) character of the incoming sequences, between the Muroto and Ashizuri Transects. Such contrasts may be tied to variations in mechanical, structural, and hydrologic behavior along the strike of this margin. In spite of these contrasts, we found that the décollement at both transects occurs at the level of an almost coeval horizon (6–7 Ma). As at Site 808, the décollement marks an abrupt increase in porosity (and a corresponding decrease in P-wave velocity), suggesting some combination of undercompaction below and overcompaction above (Taira et al., 1992).

The trench-wedge facies thickens substantially from the basin to the trench. This rapid sedimentation may affect the pore pressures and the compaction state of the underlying sediment. Within the trench-wedge facies, porosities exhibit high scatter, probably because of lithologic variability. In general, porosities decrease with depth within this section at Sites 1173 and 1174 but show no distinct trend at Site 808. Some of the difference in the porosity trend may be attributed to offset along the frontal thrust at Site 808, which would disturb the pre-existing porosity profile.

At Site 1177, the lowermost ~100 m of the upper Shikoku Basin facies exhibits nearly constant porosities of 60%–65%, whereas the P-wave velocities increase slightly with depth (Fig. 3). At Site 1173, porosities increase slightly with depth from 57%–65% at ~102 mbsf to 62%–69% at ~340 mbsf. These values are surprisingly high for a burial depth of 300–400 m, and the porosity within the upper Shikoku Basin facies at both reference sites deviates significantly from normal compaction trends for silty clays. Velocities at Site 1173 remain relatively constant to ~240 mbsf and increase below this, despite the increasing porosity. This behavior suggests cementation. At Sites 808 and 1174, a slight porosity increase with depth is observed in this unit but is less distinct than at Site 1173. Porosities within the upper Shikoku Basin facies at Sites 1174 and 808 range from ~35% to 45%. The difference in porosity values between the reference sites and those in the deformed wedge imply that either compaction, collapse, and dewatering of the sediments has occurred during accretion, or the sites within the accretionary wedge have a different diagenetic, cementation, and burial history than the current reference sites. High-velocity lay-

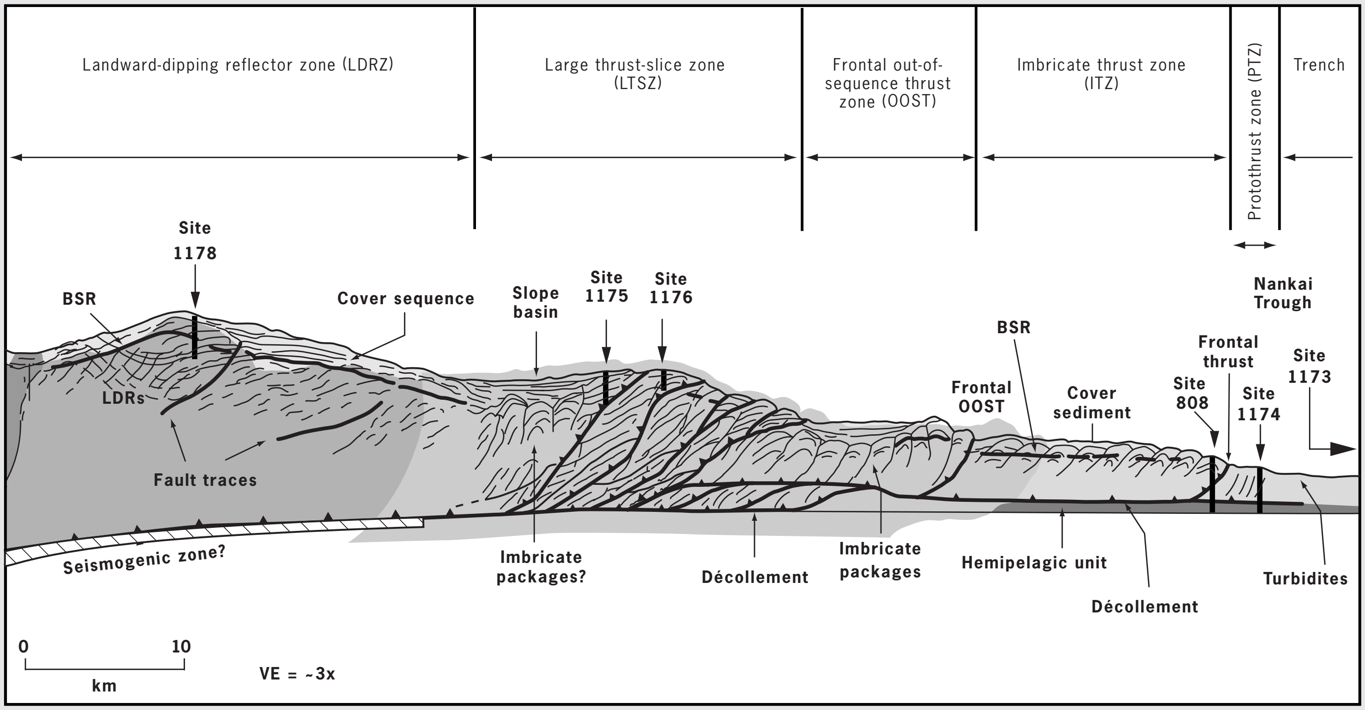


FIGURE 2 *Schematic interpretation of seismic line 141-2D in the Muroto Transect showing tectonic domains and location of Leg 190 drill sites.*

ers occur near the top and bottom of the upper Shikoku Basin facies, which is otherwise characterized by gradually increasing velocities with depth.

Along the Muroto Transect (Sites 1173, 1174, and 808), porosities within the lower Shikoku Basin facies decrease with depth and follow a compaction trend typical of fine-grained marine sediments. At Site 1173, porosities within this unit decrease from ~50% at the top to ~36% at its base. At Sites 1174 and 808, porosities decrease from 34%–40% to 30%–35%, with a sharp offset to greater porosity across the décollement. At Site 1177, the lower Shikoku Basin facies includes a thick turbidite sequence that does not correlate with the stratigraphy observed along the Muroto Transect. Porosities within the upper hemipelagic portion of the lower Shikoku Basin facies at Site 1177 (400–449 mbsf) decrease with depth from 60%–65% to 46%–54%. The porosity decrease within the lower Shikoku Basin sequence from Site 1173 to Sites 1174 and 808 may be explained by compaction and dewatering of these sediments with progressive burial. Alternatively, the lower Shikoku Basin sediments at Sites 1174 and 808 may have initially had lower porosities than Site 1173 because of factors such as greater overburden or lithologic differences.

At both Sites 808 and 1174, porosities increase sharply across the décollement zone, whereas velocities decrease. This probably reflects a combination of (1) rapid, partially undrained burial of the underthrust sequence resulting in underconsolidation and (2) higher mean stress and tectonic compaction of the accreted sediments. At Site 1174, porosities directly below the décollement zone are slightly lower than at Site 808. This observation suggests that simple progressive compaction of underthrust sediments may not adequately explain the porosity-depth trends and that other factors (such as initial sediment thickness and heterogeneity in mechanical strength) are also important. At Site 1173 the stratigraphic equivalent interval of the décollement zone (~390–420 mbsf) corresponds to the base of an anomalous zone in which velocities decrease with depth. A similar, considerably smaller amplitude velocity excursion correlates with the stratigraphic equivalent of the décollement at Site 1177 (~430 mbsf).

DEVELOPMENT OF THE DÉCOLLEMENT ZONE, MUROTO TRANSECT

Leg 190 completed a transect of the basal décollement of the Nankai accretionary prism from an undeformed state at Site 1173 to the well-developed fault zone landward of the deformation front documented at Sites 1174 and 808 (Fig. 3).

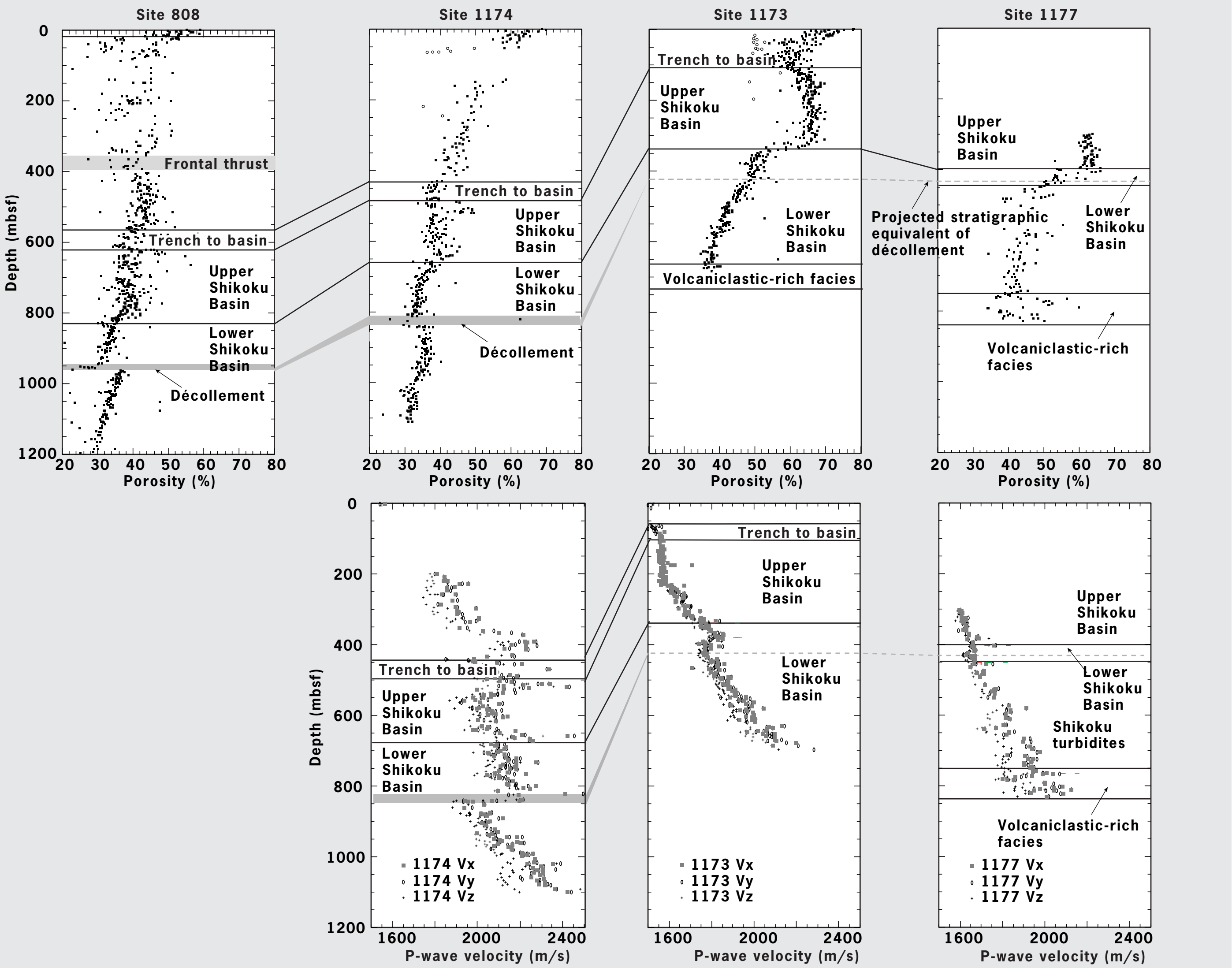


FIGURE 3 *Porosities and velocities across the Muroto Transect (Sites 1173, 1174, and 808) and Ashizuri reference site (Site 1177). Lithologic units and major structural features are shown. The décollement location is shown by gray shading where it was observed and by a dashed line at the stratigraphically equivalent depth at the reference sites.*

At Site 1173, there is little evidence from the structural geology or physical properties for a proto-décollement zone, i.e., incipient deformation indicative of a major fault. The stratigraphic equivalent to the Site 1174 décollement interval indicated in Figure 3 is based on correlation of core magnetic susceptibility. This interval is part of a thicker domain of increased bedding dip, but shows no localized increase in observed deformation. However, a marked downhole decrease in P-wave velocity and a slight porosity increase at the top of the interval (~389 mbsf) suggest that a subtle mechanical strength discontinuity could contribute to the localization of the décollement in this interval. Pore fluid chlorinity also shows a small low-chloride excursion above this interval and an abrupt transition to higher values at ~390 mbsf; however, there is no corresponding feature in the Sites 1174 or 808 chlorinity data. It is unknown, of course, whether in the future the décollement actually will propagate along this particular stratigraphic horizon to the position of Site 1173.

The hallmark of the décollement zone at Sites 808 and 1174 is intense brittle deformation, manifested as finely spaced fracturing that breaks the mudstone into millimeter- to centimeter-scale fragments.

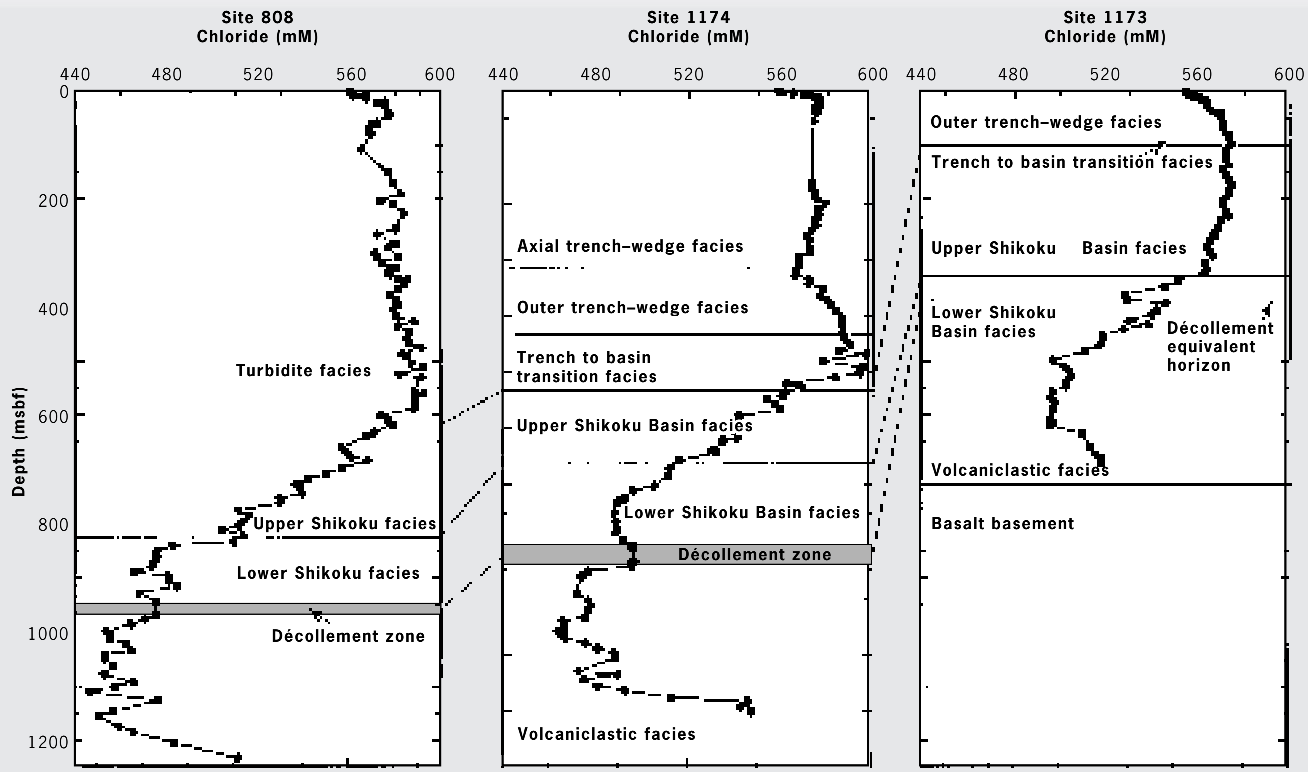


FIGURE 4 *Chloride concentrations in interstitial water samples from the Muroto Transect reference (Site 1173) and prism toe sites (Sites 1174 and 808).*

The fragments have polished and slickenlined surfaces, showing complex and heterogeneous slip directions, but they do not exhibit obvious internal deformational structures at the core scale. At Site 1174, the upper limit of the décollement zone is marked by a sharp downward increase in the intensity of brecciation, although the lowermost prism section above exhibits distributed fracturing as well. Within the décollement zone, there is a downward increase in intensity of the brecciation, peaking in a 7-m-thick zone of fine comminution of the mudstone just above the very sharp base of the décollement zone. Within the fault zone, there are several intervals, up to tens of centimeters thick, of unbroken mudstone, which are interpreted as intact blocks in a multistranded shear zone.

It is remarkable that the décollement zone at Site 1174 appears to be at least equally well developed as it is at Site 808. It is thicker at Site 1174 than it is at Site 808 (32.6 vs. 19.2 m thick, respectively). It is also brecciated to a finer scale, despite the more landward – thus presumably more structurally evolved – position of Site 808. Differences in the observed structures could be explained by differences in core recovery; however, the greater thickness at Site 1174 could not. Notable at both sites is the complete absence of veins, alteration zones, or other evidence of past fluid-rock interaction specific to the décollement.

The development of the décollement and the strain discontinuity across it are clearly exhibited in the core physical properties data. At Site 1174, there is a sharp porosity increase and P-wave velocity decrease immediately below the structurally defined décollement. These same features are even more pronounced at Site 808. Site 808 exhibits evidence of a porosity minimum within the décollement, whereas no clear evidence for such a minimum exists at Site 1174. However, the most prominent feature at both sites is the discontinuity across the base of the zone crossing into the underthrust section. This discontinuity is likely due to a combination of undercompaction of the rapidly loaded underthrust section (e.g., Saffer et al., 2000) and enhanced tectonic compaction of the prism and décollement caused by the imposition of lateral tectonic stress (Morgan and Karig, 1995).

In summary, the décollement beneath the toe of the Nankai accretionary prism develops from an unremarkable and homogeneous interval of hemipelagic mudstone into a 20- to 32-m-thick zone of intense brittle deformation, the base of which marks a boundary between the distinct physical/mechanical regimes of the prism and the underthrust section. The two drilling penetrations of the fault zone suggest an anastomosing system of discrete brittle shears, similar to faults observed in mudrocks on land. Despite a major effort to detect localized fluid flow along the fault, there is no unambiguous evidence for flow of a chemically distinct fluid in the décollement zone along the transect defined by these three sites.

Correlation of the décollement horizon between Muroto and Ashizuri Transects imposes an intriguing question on the localization of the décollement in the lower Shikoku Basin mudstone. Although DSDP/ODP drilling has not penetrated the décollement at the Ashizuri Transect, a clear and continuous seismic reflector allows us to correlate the décollement horizon at the toe region to Site 1177. At Site 1177 this reflector is at 420 mbsf and coincides with the identical horizon of the décollement of the Muroto Transect based on chronological and magnetic susceptibility correlations. This raises an important question as to why the décollement stays at the same stratigraphic horizon despite the fact that there is a major difference in the thickness of turbidites and the lithology and diagenesis of the Shikoku Basin sediments between the two transects. This question should be addessed by further shore-based study.

GEOCHEMICAL GRADIENTS, MUROTO TRANSECT

The shipboard geochemical data provide insight on the origin of fluids and the depth intervals and paths of possible recent fluid flow. In addition, abiogenic and microbially mediated diagenetic reactions that have modified fluid composition have been characterized and quantified.

The most interesting and pronounced feature of the pore fluid concentration-depth profiles in the Muroto Transect from Site 1173 through Site 1174 to Site 808 is the ~350-m-thick low-Cl zone within the lower Shikoku Basin unit (Fig. 4). It has a clear concentration minimum ~140 m below the décollement (or its equivalent at Site 1173). At Sites 1173 and 1174, this low-Cl zone decreases in intensity gradually upsection to the sediments overlying the upper Shikoku Basin facies. Additionally, the extent of Cl dilution relative to seawater Cl concentration systematically differs among the sites; it has evolved from 8%–9% at reference Site 1173 to 16%–17% at intermediate Site 1174 to 20%–21% at adjacent (<2 km) Site 808 (Kastner et al., 1993). Based on the residual smectite content of the sediment section at Site 808, some of the freshening may not be due to local smectite dehydration but could result from transport of freshened fluids from greater depth. It is important to note, however, that the original smectite concentration and clay-sized fraction are not known. The low-Cl concentrations most likely reflect some combination of (1) in situ clay dehydration and other reactions, (2) the transport of freshened water from dehydration reactions at greater depth, and (3) the uptake of Cl by deep-seated hydrous silicate reactions; for example, serpentine, chlorite, talc, or amphibole incorporate considerable amounts of Cl in their structure. These reactions occur at temperatures of >250° and up to ~450°C. Thus, the broad low-Cl zone possibly carries a signal from Cl uptake by high-temperature reactions in the seismogenic zone. The relative contributions of these processes may be resolved by rigorous mass-balance calculations, modeling of the physical and chemical hydrology, and shore-based measurements of Cl, Br, and F concentration and Cl and Br isotope analyses. The origin of slightly higher Cl concentration within the décollement zone, observed at Sites 1174 and 808 is unclear.

Other potential fluid flow horizons characterized by sharp changes in downhole geochemical profiles are: (1) At Sites 1173, 1174, and 808, the boundary between the trench-wedge and upper Shikoku Basin sediments. The sharp reversal of the Cl gradient at this boundary may be maintained by flow of a slightly more saline fluid than seawater or by in situ hydration reactions that outpace diffusion. (2) Along the protothrust (~470 mbsf) at Site 1174, as particularly indicated by the Cl, Na, Ca, and K concentration profiles. (3) At Site 1176, the Cl, Na, Ca, and K concentration profiles suggest communication with a deep fluid source, possibly associated with the out-of-sequence thrust.

It is interesting to note that the chemical characteristics of fluids from the protothrust at Site 1174 and the source potentially associated with the out-of-sequence thrust fault at Site 1176 are similar to the characteristics of the fluid in the low-Cl zone centered below the décollement. The composition of the fluid along the trench wedge/Shikoku Basin boundary is, however, distinct.

Another distinct characteristic of the Muroto Nankai Transect, not observed at any of the other drilled DSDP and ODP subduction zone sites, is the elevated (up to 10 mM) dissolved sulfate zone found at depth. It is beneath the near surface sulfate reduction zone, and prevails from the boundary between the upper and lower Shikoku Basin facies to oceanic basement and probably deeper. The fact that microbial activity has not reduced it over the past 0.5 m.y. indicates that the amount of labile organic matter available for microbial activity (for sulfate reducers and/or methane oxidizers) above the proto-décollement and décollement zones, where temperatures do not limit bacterial activity, is extremely low. Thus, dissolved sulfate may persist into the seismogenic zone; it can only be reduced inorganically at temperatures of 250°–300°C. The presence of dissolved sulfate in an anaerobic environment affects the oxidation state of the system and should influence sediment magnetic properties as well as inorganic reactions with transition metals, such as Fe and Mn.

The dominant diagenetic processes are ash alteration to clays and zeolites and silicate (mostly clay) reactions at the deep water sites and carbonate reactions at the shallow water sites; carbonate diagenesis, however, also occurs at the deep water sites. Opal-A dissolution controls the Si concentration profiles at each of the sites in the top few hundreds of meters, and other silicate reactions control it deeper in the sections.

EVOLUTION OF THE ACCRETIONARY PRISM

We also documented the accretionary history of the Nankai Trough prism for the first time and revealed a phenomenally rapid rate of growth of the prism during the Pleistocene. Basal sediments in the slope basin at Sites 1175 and 1176 are all younger than 2 m.y., so the underlying material must have been accreted within the last 2 m.y. This is a major revision to previous estimates of the accretionary wedge growth and shows that the outer 40 km of the accretionary prism has been added to the Nankai margin over only 2 m.y. This finding has important ramifications for structural and hydrologic models of this margin. Our results will provide a basic framework for further mechanical, hydrogeological, and geochemical studies of this accretionary prism. Leg 190 results will also be useful for understanding the tectonics of accretionary prism evolution, thus providing a link between prism-toe processes and highly deformed accretionary complexes, the dominant components of orogenic belts.

MICROBIAL ACTIVITY AND BIOGEOCHEMISTRY

Bacteria are responsible for shaping many of the chemical profiles within deep marine sediments through their metabolic activity. The distribution of the microbial community was characterized and their impact on deep marine sediments was investigated using the new microbiology lab on the JOIDES Resolution. The apparent environmental controls on bacterial distribution varied among sites from physical (temperature) to geochemical. Overall, the total numbers of bacteria at these sites were either at the low end, or below the range predicted by a general model constructed from bacterial distributions in deep marine sediments at previous ODP sites (Parkes et al. 1994). This is consistent with observations made at a previous accretionary prism site - Cascadia margin.

LEG 190 SHIPBOARD SCIENTIFIC PARTY

Gregory Moore and Asahika Taira, Co-chief Scientists; Adam Klaus; Keir Becker, Luann Becker, Babette Boeckel, Barry Cragg, Allison Dean, Chris Fergusson, Pierre Henry, Satoshi Hirano, Toshio Hisamitsu, Sabine Hunze, Miriam Kastner, Alex Maltman, Juli Morgan, Yuki Murakami, Demian Saffer, Mario Sánchez-Gómez, Elizabeth Screaton, David Smith, Arthur Spivak, Joan Steurer, Harold Tobin, Kohtaro Ujiie, Michael Underwood, Moyra Wilson.
For more information see Shipboard Scientific Party (2000).

REFERENCES

Aoki, Y., Tamano, T., and Kato, S., 1982. Detailed structure of the Nankai Trough from migrated seismic sections. In Watkins, J. S., and Drake, C. L. (eds.), Studies in Continental Margin Geology. *American Association of Petroleum Geologist*, *Mem*., 34:309–322.

Ando, M., 1975. Source mechanisms and tectonic significance of historical earthquakes along the Nankai Trough, Japan. *Tectonophysics*, 27:119–140.

Bangs, N. L., Taira, A., Kuramoto, S., Shipley, T. H., Moore, G. F., Mochizuki, K., Gulick, S. S., Zhao, Z., Nakamura, Y., Park, J.-O., Taylor, B. L., Morita, S., Ito, S., Hills, D. J., Leslie, S. C., Alex, C. M., McCutcheon, A. J., Ike, T., Yagi, H., and Toyama, G., 1999. U.S.-Japan Collaborative 3-D seismic investigation of the Nankai Trough plate-boundary interface and shallowmost seismogenic zone. *EOS*, 80:F569.

Davis, E. E., Becker, K., Pettigrew, T., Carson, B., and MacDonald, R., 1992. CORK: a hydrologic seal and downhole observatory for deep-ocean boreholes. In Davis, E. E., Mottl, M. J., Fisher, A. T., et al., *Proceedings of the Ocean Drilling Program*, *Initial Reports*, 139: College Station, TX (Ocean Drilling Program), 43–53.

Hyndman, R. D., Wang, K. and Yamano, M., 1995 Thermal constraints on the seismogenic portion of the southwestern Japan subduction thrust. *Journal of Geophysical Research*, 100:15373–15392.

Karig, D. E., and Angevine, C. L., 1986. Geologic constraints on subduction rates in the Nankai Trough. In Kagami, H., Karig, D. E., Coulbourn, W. T., et al., *Initial Reports of the Deep Sea Drilling Project*, DSDP, 87: Washington (U.S. Govt. Printing Office), 789–796.

Kastner, M., Elderfield, H., Jenkins, W. J., Gieskes, J. M., and Gamo, T., 1993. Geochemical and isotopic evidence for fluid flow in the western Nankai subduction zone, Japan. In Hill, I. A., Taira. A., Firth, J. V., et al., *Proceedings of the Ocean Drilling Program, Scientific Results*, 131, College Station, TX (Ocean Drilling Program), 397–413.

Kodaira, S., Takahashi, N., Park, J., Mochizuki, K., Shinohara, M., and Kimura, S., 2000. Western Nankai Trough seismogenic zone: results from a wide-angle ocean bottom seismic survey. *Journal of Geophysical Research*, 105:5887–5905.

Moore, G. F., Shipley, T H., Stoffa, P L., Karig, D. E., Taira, A., Kuramoto, S., Tokuyama, H., and Suyehiro, K., 1990. Structure of the Nankai Trough accretionary zone from multichannel seismic reflection data. *Journal of Geophysical Research*, 95:8753–8765.

Moore, G. F., Karig, D. E., Shipley, T. H., Taira, A., Stoffa, P .L., and Wood, W. T., 1991. Structural framework of the ODP Leg 131 area, Nankai Trough. In Taira, A., Hill,I.A., Firth, J.V., et al., Proc. ODP, *Proceedings of the Ocean Drilling Program*, *Initial Reports*, 131: College Station, TX (Ocean Drilling Program), 15–20.

Moore, G. F., Taira, A., Kuramoto, S., Shipley, T. H., and Bangs, N. L., 1999. Structural setting of the 1999 U.S.-Japan Nankai Trough 3-D seismic reflection survey. *EOS*, 80:F569.

Morgan, J. K., and Karig, D. E., 1995. Kinematics and a balanced and restored cross-section across the toe of the eastern Nankai accretionary prism. *Journal of Structural Geology*, 17:31–45.

Park, J.-O., Tsuru, T., Kodaira, S., Nakanishi, A., Miura, S., Kaneda, Y., and Kono, Y., 2000. Out-of-sequence thrust faults developed in the coseismic slip zone of the 1946 Nankai earthquake (Mw = 8.2) off Shikoku, southwest Japan. *Journal of Geophysical Research*, *Letters*, 27:1033–1036.

Parkes, R. J., Cragg, B. A., Bale, S. J., Getliff, J. M., Goodman, K., Rochelle, P. A., Fry, J. C., Weightman, A. J., and Harvey, S. M. 1994. A deep bacterial biosphere in Pacific Ocean sediments. *Nature*, 371:410–413.

Saffer, D. M., Silver, E. A., Fisher, A. T., Tobin, H., and Moran, K., 2000, Inferred pore pressures at the Costa Rica subduction zone: Implication for dewatering processes, *Earth and Planetary Science Letters*, 177:193–207.

Seno, T., 1977. The instantaneous rotation vector of the Philippine Sea Plate relative to the Eurasian Plate. *Tectonophysics*, 42:209–226.

Shipboard Scientific Party, 2000. Leg 190 Preliminary Report: Deformation and fluid flow processes in the Nankai Trough accretionary prism. *Ocean Drilling Program*, *Preliminary Report*, 190 [Online]. Available from World Wide Web: http://www-odp.tamu.edu/publications/prelim/190_prel/190PREL.PDF.

Taira, A., Hill, I., Firth, J., Berner, U., Brückmann, W., Byrne, T., Chabernaud, T., Fisher, A., Foucher, J.-P., Gamo, T., Gieskes, J., Hyndman, R., Karig, D., Kastner, M., Kato, Y., Lallement, S., Lu, R., Maltman, A., Moore, G., Moran, K., Olaffson, G., Owens, W., Pickering, K., Siena, F., Taylor, E., Underwood, M., Wilkinson, C., Yamano, M., and Zhang, J., 1992. Sediment deformation and hydrogeology of the Nankai Trough accretionary prism: synthesis of shipboard results of ODP Leg 131. *Earth and Planetary Science, Letters*, 109:431–450.

Ship Heave Effects While Drilling: Observations from Legs 185 & 188

D. Goldberg[1], G. Myers[1], G. Guerin[1], D. Schroeder[2]

and the Legs 185 and 188 Scientific Parties

The JOIDES Resolution routinely encounters waves on the sea surface that generate both vertical heave and torsional motions of the ship. Typically, the vertical heave varies from several cm to a few m. New downhole observations of this motion in deep and shallow waters are presented in this article. They illustrate the difficult conditions imposed on piston and rotary coring while drilling without a riser. As a result, we gain new insight into the dynamics of drilling with the JOIDES Resolution and also present basic methodologies that could be used to evaluate the dynamics of drilling and coring with a riser or with another drilling platform. Two pressing needs for ODP, to evaluate the effectiveness of the current heave compensation systems on the JOIDES Resolution and to minimize the effects of ship heave on core recovery, are also addressed.

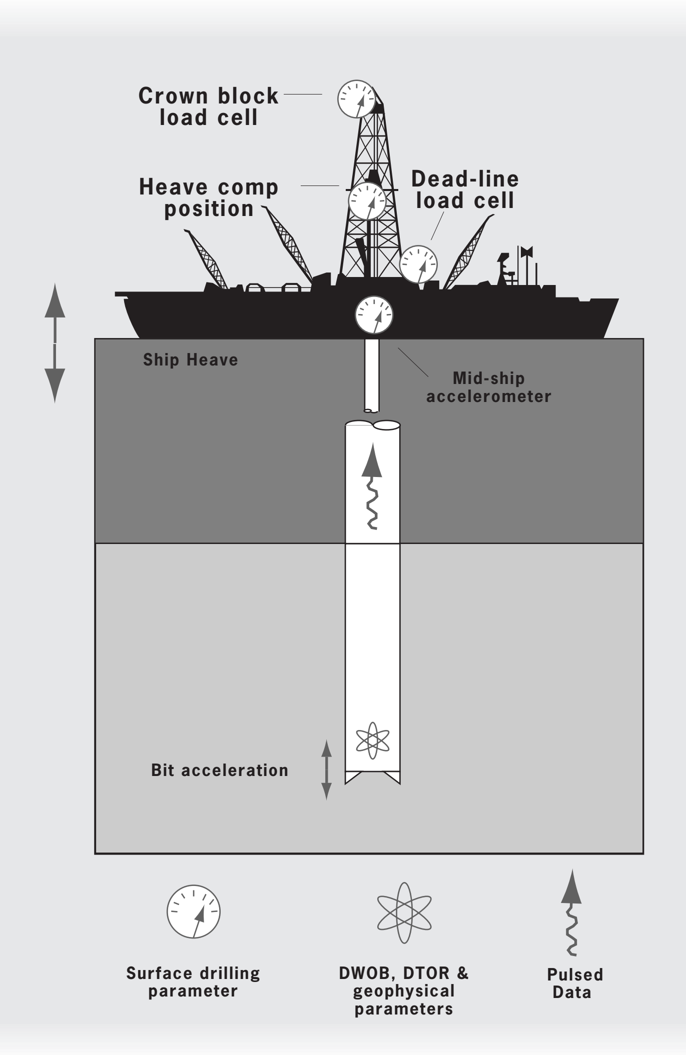


FIGURE 1 *Cartoon of rig instrumentation on the ODP ship D/V JOIDES Resolution, illustrating sensor locations for surface (SWOB) and downhole weight-on-bit (DWOB), heave, and acceleration that were used in these experiments.*

The effect of variations in weight on bit and drill string accelerations on the coring process has long been of concern to DSDP and ODP scientists (e.g. Kidd, 1979; Francis, 1981). Only recently, however, has new technology been developed that allows for the dynamic parameters of a drill string to be recorded both at the rig floor and at the drill bit. Figure 1 illustrates the locations of several instruments, some of them in common use by industry, which have been installed on the JOIDES Resolution. Results from two ODP cruises in the western Pacific near Japan (Leg 185) and in the Southern Ocean near Antarctica (Leg 188) are discussed below. These experiments provide critical information about the dynamics of the drill string during ODP coring operations.

The first experiment was conducted using a downhole accelerometer developed at Lamont Doherty Earth Observatory. This instrument is placed on conventional ODP rotary and piston coring tools to measure downhole bit acceleration and pump pressure. With this efficient and economical device, heave effects can be evaluated "while coring" without interfering with normal ODP operations. It contains three-axis accelerometers, a high-resolution pressure sensor, batteries, and digital memory. Sufficient battery power and memory exists for up to 2.5 hours of continuous data acquisition at the highest data sampling rates of up to 100 samples per second. During May 1999, the downhole accelerometer was deployed at ODP Site 1149 in the western Pacific (Plank et al., 2000). Four rotary and one piston coring runs were made at depths ranging from 5800 to 6200 m below the sea surface. Ship heave during these runs was typical of ODP operations. The heave period of the JOIDES Resolution is consistent under most sea conditions (8–10 seconds) and the heave height at this time was approximately +/-2 m at mid-ship. The forma-

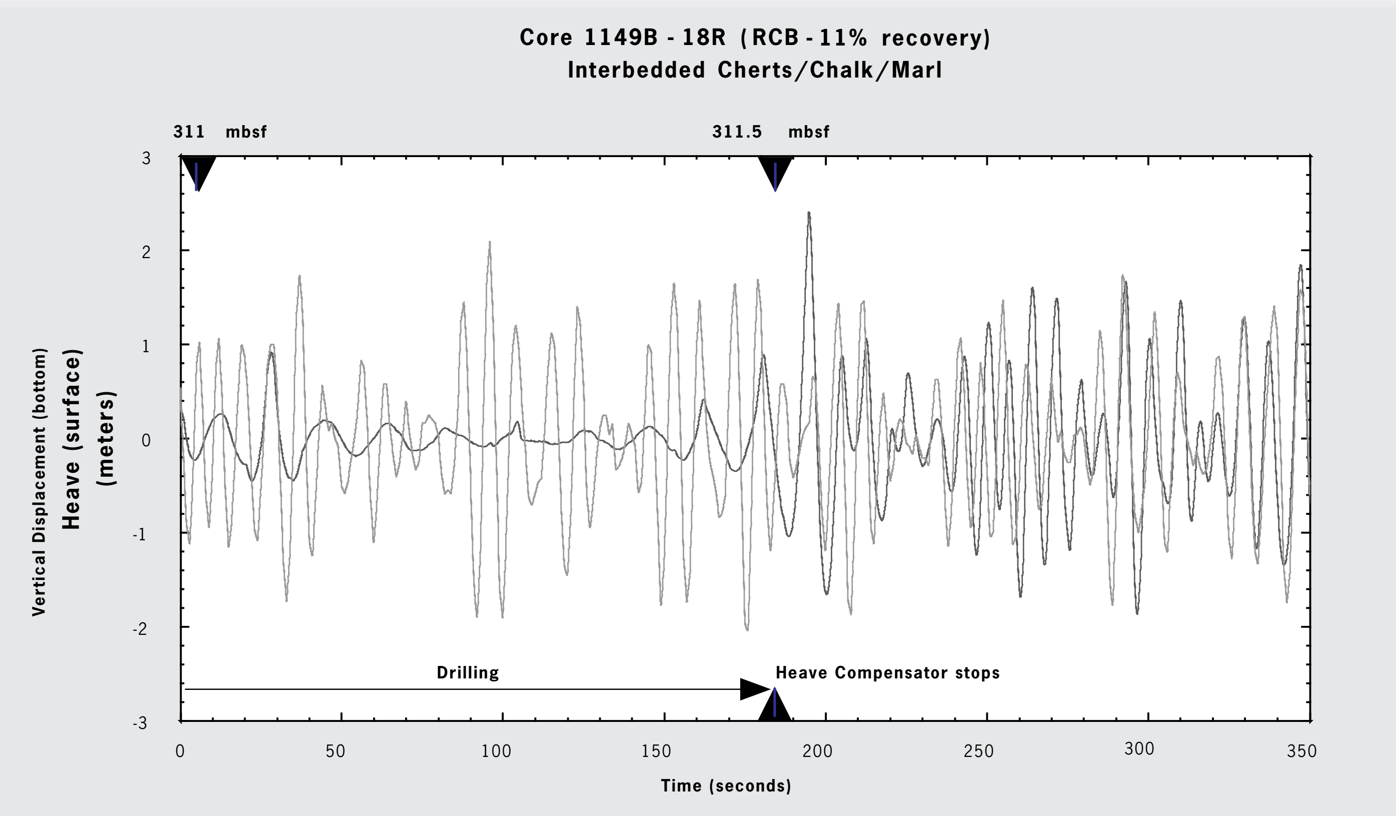
[1] Lamont-Doherty Earth Observatory, Borehole Research Group, Palisades, NY 10964

[2] Texas A&M University, Engineering Services Group, College Station, TX 77845

tions encountered at Site 1149, thin layered cherts within surrounding chalk and marl, were particularly difficult to core and resulted in sediment recovery often less than 15% (Plank et al., 2000). Results from the downhole accelerometer shed light on the heave effects and low core recovery. Vertical acceleration reaches a maximum value of 3G as the core barrel penetrates into the formation and then varies while coring progresses over several minutes. Figure 2 shows the downhole acceleration and heave data recorded over a 6-minute interval as the last section of a rotary core is taken from 311-311.5 m depth below the seafloor in 5800 m of water. Vertical acceleration has been converted to displacement and then filtered to pass only the low frequencies that include the heave motion of the ship. While coring, the measured displacement indicates vertical oscillation of the bit by less than +/-0.25 m as the passive heave compensator was operating. After approximately 3 minutes, both coring and the heave compensator stop and the bit displacement immediately increases to more than +/-2 m, reflecting the motion of the ship at the surface. In this case, the heave compensator damps almost 90% of the ship motion but does not improve core recovery in the layered chert and chalk formation. Significant displacements are translated to the bit in this hole despite the benefit of a passive heave compensator.

The second experiment used commercially-available Measurement-While-Drilling (MWD) tools to record weight-on-bit, rate of penetration, torque, and pump pressure (e.g. Murphy, 1993). Because MWD instruments cannot be used while coring they are not routine in ODP operations. Commercial drilling with these devices from fixed marine platforms, however, is quite common (Kashikar, 2000). MWD tools also transmit information from the bit to the surface using mud-pulse systems, providing the driller with the advantage of viewing some data in real time. Data sampling with current technologies are limited by pump volume and allow for maximum rates of 5-10 samples per second. Although this is insufficient to resolve wave periods of 8-10 seconds, longer wavelength changes can fortunately still be observed.

FIGURE 2 *Data recorded while recovering the last section of a rotary core at ODP Site 1149 over a 6-minute interval. Vertical acceleration is transformed to displacement and filtered to pass only the low frequencies including ship heave. Peak-to-trough displacements increase from less than +/-0.25 m, indicating vertical oscillations of the bit, to more than +/-2 m after coring and heave compensation stop, which reflects the surface motion of the ship.*



In January 2000, MWD tools were deployed at ODP Sites 1166 and1167 in approximately 380 m and 1640 m of water, respectively, on Leg 188 off Antarctica (Shipboard Scientific Party, 2000). Downhole and surface measurements of weight-on-bit were recorded for the first time in the ODP. Only the passive heave compensator was available during this leg, although heave reached up to 4 m at mid-ship. This is quite high and atypical of ODP drilling operations, yet the dominant heave period remained 8-10 seconds. The formation drilled at this location was soft sandy clay with some diamict layers. Average core recovery was about 40% (Shipboard Scientific Party, 2000). Figure 3 shows the heave height at Site 1167 over a 10-minute interval and the corresponding records of surface and downhole weight-on-bit. Due to the superposition of large swells on the sea surface, heave height varies significantly over long periods (~20 seconds) which correlate with similar changes in weight-on-bit measured at the surface. The ship's motion is directly transmitted to weight on the drill bit. Downhole weight-on-bit varies similarly over long periods and corresponds, after a 20-30 second time lag, to changes in the heave height. The time lag is due to mud pulse transmission and signal propagation delays along the drill string. Heave compensation of the drill string to reduce variation in weight-on-bit is advantageous because consistent downhole weight improves core quality and core recovery in most lithologies. At both Sites 1166 and 1167, however, weight-on-bit variations appear often to be as large or larger downhole than at the surface, perhaps due to the interaction of the passive heave compensator and the high sea state. Understanding the dynamic motion of the drill string is the first step towards evaluating the performance of the heave compensator and may assist in controlling weight on the surface by allowing prediction of the effects of ship heave downhole.

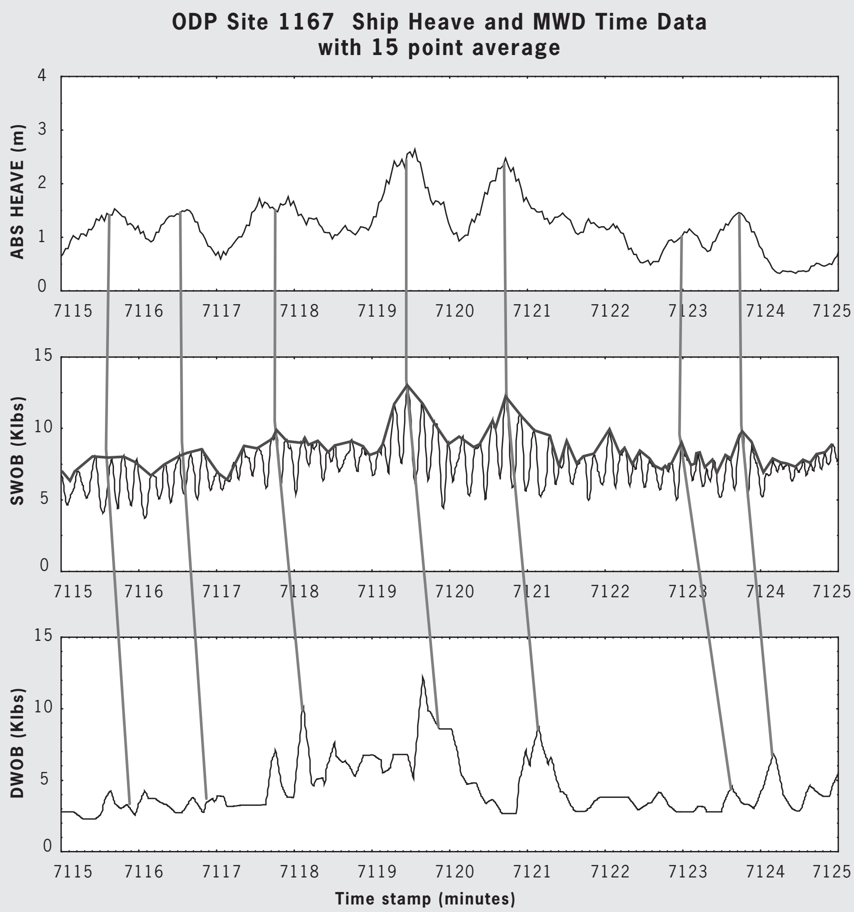


FIGURE 3 *Data recorded at ODP Site 1167: (a) heave records at mid-ship, (b) surface weight-on-bit (SWOB), and (c) downhole weight-on-bit (DWOB). Both weight-on-bit records were measured by Schlumberger-Anadrill using commercial technology. The good correlation at long periods (> 20 seconds) indicates a downhole/surface lag due to mud pulse transmission and signal propagation along the drill string.*

Figure 4 shows a correlation of the mean weight-on-bit measured at the surface to the spectral ratio of downhole/surface weight-on-bit for each drilling interval between pipe additions. The spectra are used to filter out periods shorter than 20 seconds where the downhole sampling is aliased and longer than 100 seconds where there are no significant effects of ship heave. This relationship indicates that variation in weight-on-bit due to long-period ship heave is 2-6 times greater downhole than it is at the surface. The spectral ratios and standard deviations (vertical bars) increase as weight-on-bit increases. Data from Site 1166 and 1167 show similar results, even though Site 1166 drilled in shallower water and made less penetration. Using weight-on-bit measured at the surface, such relationships allow for prediction of weight at the bit for a given range of sea states, hole penetrations, and water depths.

In the future, ODP will continue experiments similar to those discussed here. A digital recording system for rig floor parameters and an active-control heave compensator have both been installed for routine use. These advances will undoubtedly yield insight into the dynamics of drilling and allow for design improvements in heave compensator systems. Drilling and coring performance with the JOIDES Resolution should improve dramatically. Continued experimentation will also help quantify the effects of ship heave for other non-stationary drilling vessels, resulting in similar relationships between ship heave and downhole weight-on-bit. An empirical approach can be extended in this way for practical application to drilling under a variety of conditions and in different geological environments.

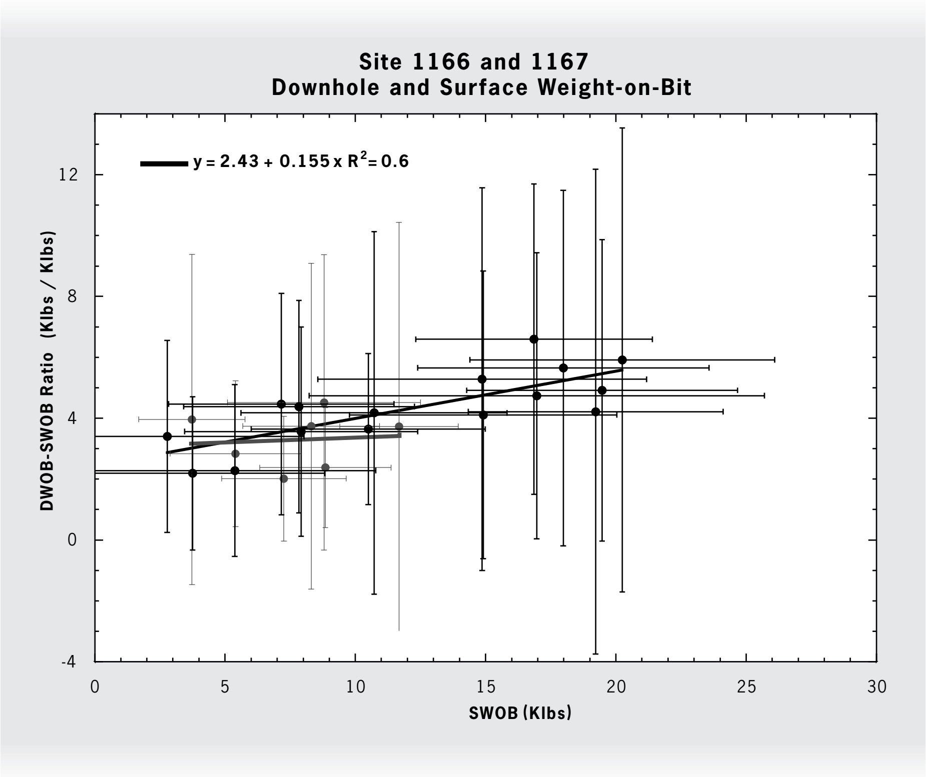


FIGURE 4 *Comparison of surface weight-on-bit (SWOB) to the ratio of surface/downhole weight-on-bit (DWOB/SWOB) at long periods (20-100 seconds) at Sites 1166 and 1167. Data points represent mean values; error bars indicate +/- 1 standard deviation. The regression equation is given for Site 1167. These results indicate that weight-on-bit due to ship heave is 2-6 times greater downhole than it is at the surface and that the ratio increases as weight-on-bit increases. Using such relationships, a prediction of weight at the bit can be made from surface measurements in similar drilling environments.*

REFERENCES

Francis, T. J. G., 1981, Effect of drill string movement on shape of the hole and on cored rocks at Hole 459B. *Initial Reports of the Deep Sea Drilling Project*, 60, Washington, DC (U.S. Government Printing Office), 835–840.

Kashikar, S., 2000, MWD/LWD practices in ultra deep water. *Offshore Magazine, Ultra DEEP Engeneering Supplement*, 60–10, 14–16.

Kidd, R. B., 1979, Core discing and other drilling effects in DSDP Leg 42A Mediterranean sediment cores, *Initial Initial Reports of the Deep Sea Drilling Project*, 42, Washington, DC (U.S. Government Printing Office), 1143–1149.

Murphy, D. P., 1993, What is new in MWD and formation evaluation, *World Oil*, 214, 47–52.

Plank, T., Ludden, J.N., Escutia C., et al., 2000, in press. Proc. ODP, *Proceedings of the Deep Sea Drilling Project* 185 [Online].

Shipboard Scientific Party, 2000, Leg 188 Preliminary Report, Prydz Bay-Cooperation Sea, Antarctica: Glacial History and Paleoceanography, Ocean Drilling Program http://www-odp.tamu.edu/publications/prelim/188_prel/188toc.html

ACKNOWLEDGEMENTS

We wish to thank the shipboard and scientific staff aboard the D/V JOIDES Resolution during ODP Leg 185 and Leg 188 for their efforts in collecting these data.

Core-Log Integration Platform Update (SAGAN)

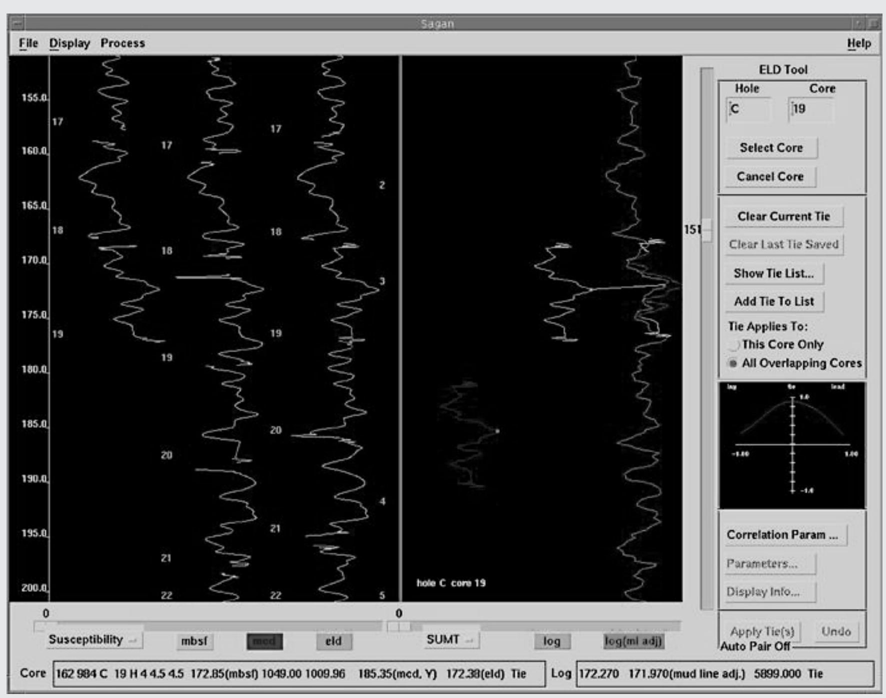
U. Ninnemann[1], T. Janecek[2], and P. de Menocal[1]

The recovery of complete stratigraphic sequences has become an essential element of most paleoceanographic drilling legs. Obtaining a continuous paleo-environmental record is a prerequisite for fully understanding the frequency and evolution of climatic variability. Despite its importance, the continuity of the recovered sequence was commonly assessed only well after drilling had been completed. Leg 138 marked the first systematic effort to establish stratigraphic continuity between multiple holes at a given drill site (Hagelberg et al., 1992). The continuous composite sequences generated from Leg 138 eventually led to significant improvements in the late Neogene geological time scale (Shackleton et. al., 1995). Following these initial successes, the software program Splicer 1 was developed to provide a standard, integrated platform for rapidly generating composite depth scales and spliced sections.

Splicer is a graphical and interactive program for depth-integrating (depth-shifting) multiple-hole lithologic data for building composite sections and developing age models. Up to ten different physical property measurements (e.g. magnetic susceptibility, GRAPE density, P-wave velocity, natural gamma activity, color reflectance) can be used to simulateously establish interhole correlations. The program uses an optimized cross-correlation routine for determining the best interhole depth correlation and depth offset. Once the correct depth offset is determined it is applied to the entire core and the user proceeds iteratively core-by-core until all cores of all holes at a given site are optimally depth-correlated. Metadata files generated by this program are now formally included in the JANUS database and with the recent upgrade to version 2.2, Splicer can directly open JANUS output files. Since it's introduction on Leg 151 (1993) Splicer has been used routinely on the JOIDES Resolution to provide a real-time assessment of the continuity of the recovered sediment sections and provide feedback to guide further drilling.

In addition to guiding drilling efforts and providing a continuous section for paleoceanographic studies, the process of compositing and splicing recovered sediment sequences also has highlighted some of the effects drilling and coring operations have on the recovered sediments. As shared stratigraphic features between holes are tied together and cores are shifted from their standard meters below sea floor depth (mbsf) so that the features are aligned, a new composite depth scale (mcd, meters composite depth) is created. The composite depths are commonly 10% greater than mbsf depths due to a variety of factors not accounted for in original mbsf depths, including coring gaps (Hagelberg et al., 1992), and elastic rebound (Moran, 1997).

FIGURE 1 *An example of core-log integration in Sagan using core and downhole log magnetic susceptibility records. A common feature is chosen for manually assigning a tiepoint between the core and log records.*



[1] Borehole Research Group
Lamont-Doherty Earth Observatory
Palisades, NY 10964, U.S.A.

[2] Antarctic Research Facility
Florida State University
108 Carraway Building
Tallahassee, FL 32306-4100, U.S.A.

Although compositing allows the complete section to be reconstructed, the final sequence is no longer representative of the original drilled depth, thus making estimates of sedimentation rates and mass fluxes problematic. In addition, because the same offset is applied to a given core when transforming to mcd, differential amounts of within core distortion are not accounted for, often resulting in identical events having slightly different mcd's in different holes. The expanded mcd depth scale also makes direct core-log data comparisons difficult since the reconstructed composite depth scale is no longer simply related to drilling or logging depths.

Fortunately, a number of borehole measurements routinely conducted during downhole logging are directly comparable to the shipboard core physical property measurements (e. g. natural gamma, bulk density, porosity, magnetic susceptibility, sonic velocity). These continuously measured, *in situ* logs provide a reference for mapping the composited sediment sequences back to their original stratigraphic positions. Sagan 1, a companion program to Splicer, was created in order to standardize and expedite this mapping process. Using the same graphical interface as Splicer, Sagan is designed to work seamlessly with Splicer output files to generate a single metafile that defines a set of precise depth correlations between core and log datasets at any given site. This metafile provides the foundation for core-log data integration as it establishes the unique mapping function linking the two independent depth scales. The program merges the core-log depths using physical parameters measured both on cores and downhole. The core-log depth correlations are conducted either manually (e.g., core-by-core from single or multiple holes, Figure 1) or automatically (e.g., an entire composite record from a given hole is correlated). Sagan can also perform smoothing, decimation, and culling procedures to modify

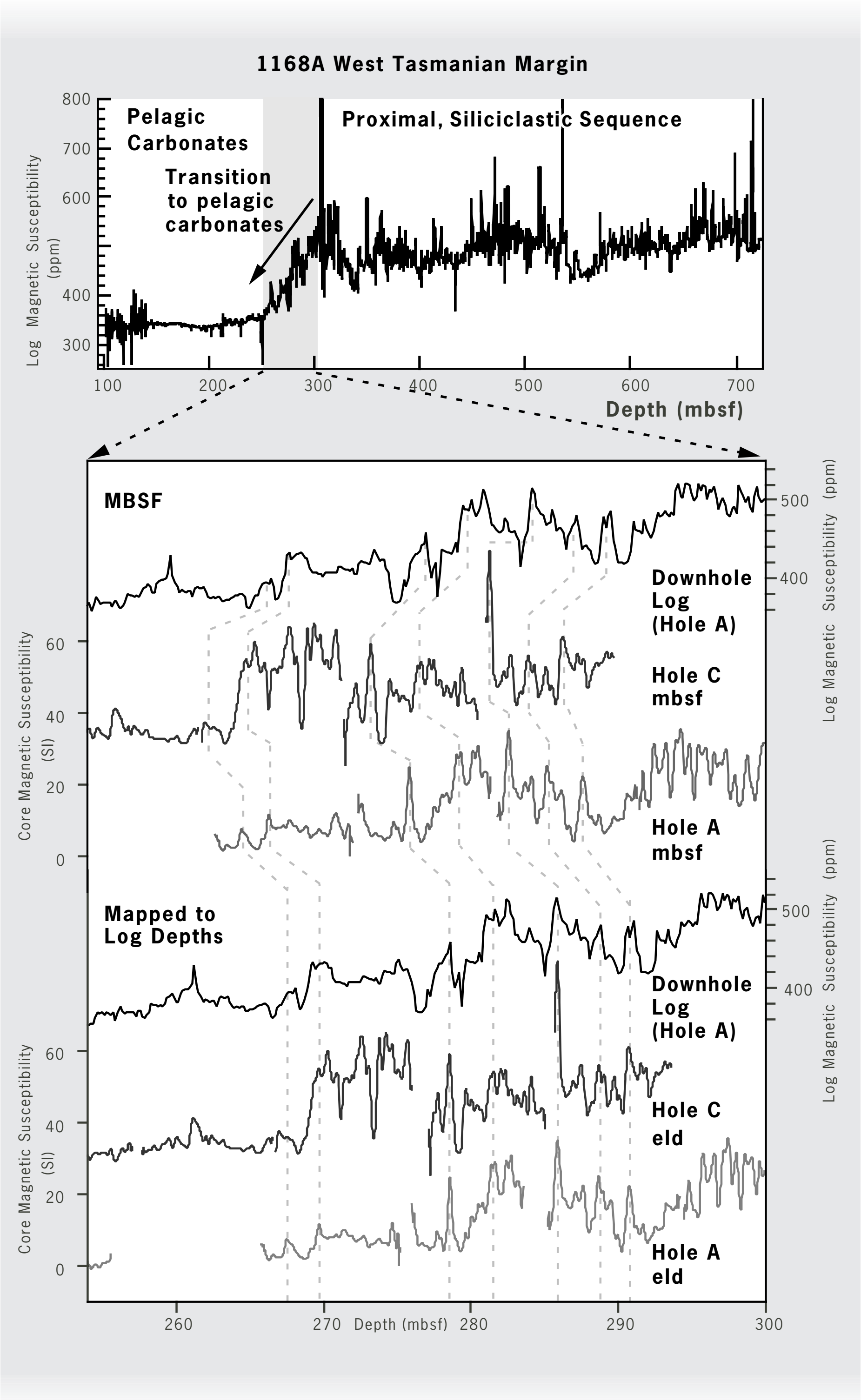


FIGURE 2 *Shown is an example of core log integration using magnetic suseptibillity over just 25 m of Site 1168 which penetrated >883 mbsf. The size and positions of the core gaps are much more accurately placed after correlation with the logs.*

the data. The program can manage up to 10 holes of core data, 5 data types per hole, nearly an infinite number of cores (limited only by computer memory) and data points and up to 3 reference log curves. Data management and computation is very efficient in Sagan (and Splicer) due to the use of dynamic memory allocation. The resulting core-log tielines can be applied across equivalent mcd depths in different holes or just for individual cores. Because multiple ties can be applied to a single core, the downhole logs can be used as a reference to compensate for differential inter-core distortion to improve inter-hole correlations. Finally, in environments where the resolution of the downhole logs captures the dominant lithologic variability, the completeness of the original splice can be assessed.

In intervals where core recovery is low or multiple holes are not drilled, core-log integration still has significant benefits. For instance, detailed core-log integration allows a much more accurate estimate of the size and position of coring gaps. One example from ODP Leg 189 where the most recent version of Sagan (version 2.2) was first deployed is shown in Figure 2. The data plotted versus mbsf (top) illustrate the original inter-hole offsets and estimated core gaps versus those after core-log integration using Sagan (bottom). Despite the lower resolution of the downhole logs, the adjustments in the size of core gaps suggested by the correlation can exceed the length of a typical lithologic event. Thus, at sites where sediment cyclicity or cyclostratigraphy are of interest, core-log integration is a valuable step in both verifying the original splice and extending the stratigraphy beyond the splice.

Splicer and Sagan were developed by Peter deMenocal and Ann Esmay. ODP Logging Services provides support for both programs and download files are available at http://www.ldeo.columbia.edu/BRG/ODP/ODP/CLIP.

ACKNOWLEDGEMENTS

We thank the Leg 189 shipboard scientific party for providing the data used in Figure 2.

REFERENCES

Hagelberg, T. K., Shackleton, N. J., Pisias, N. and shipboard scientific party, 1992. Development of composite depth sections for site 844 through 854. In: L. Mayer, Pisias, N., Janecek, T., Palmer-Julson, A. and van Andel, T. H. (eds.), *Proceedings of the Ocean Drilling Program, Initial Reports*, College Station, TX (Ocean Drilling Program), pp. 79–85.

Moran, K., 1997. Elastic property corrections applied to Leg 154 sediment, Ceara Rise. In: N. Shackleton, W. B. Curry, C. Richter and T. J. Bralower (eds.), *Proceedings of the Ocean Drilling Program, Initial Reports*, College Station, TX (Ocean Drilling Program), pp. 151–155.

Shackleton, N. J., Crowhurst, S., Hagelberg, T., Pisias, N. G. and Schneider, D. A., 1995. A new Late Neogene time scale: Application to ODP Leg 138 sites. In: N. G. Pisias, L. A. Mayer, T. R. Janecek, A. Palmer-Julson and T. H. van Andel (eds.), *Proceedings of the Ocean Drilling Program, Scientific Results*, College Station, TX (Ocean Drilling Program), pp. 73–101.

Excerpts from the Final Report of JOIDES Gas Hydrate Program Planning Group

C. Paull[1] (Chair), G. Bohrmann[2], P. Brewer[1], P. Cochonat[3], T. Collett[4], N. Edwards[5], M. Hovland[6], A. Johnson[7], K. Kvenvolden[8], R. Matsumoto[9], D. Sloan[10], A. Tréhu[11], and G. Westbrook[12]

SUMMARY

Three meetings of the Gas Hydrate PPG were held (June 23-24, 1998 in College Station, Texas; December 11-13, 1998 in Monterey, California; and September 27-29, 1999 in Berlin, Germany). Discussions focused on the relevance of gas hydrate research, the geologic environment of gas hydrate deposits, the tools needed for gas hydrate evaluation, and the approach necessary to meld a series of legs to form a unified program.

RECOMMENDATIONS

The panel recommends that the JOIDES advisory structure concentrate resources on the following:

- At least three more interrelated ODP legs be devoted to gas hydrate research. They should fit together into a sensible unified program.
- Greater efforts to develop new down-hole tools that detect and retrieve gas hydrate and to optimize the use of the existing tool. Current capabilities to detect the presence of gas hydrate in boreholes are extremely limited. We specifically recommend that both the existing ODP Pressure Core Sampler (PCS) and the Hydrate Autoclave Coring Equipment (HYACE) tool that is under development be supported strongly. Attempts to develop other new tools and techniques to detect gas and gas hydrate also need to be encouraged and supported.

FUNDAMENTAL OBJECTIVES OF A GAS HYDRATE RESEARCH PROGRAM

SCICOM established a Program Planning Group (PPG) for Gas Hydrate research and set as its goals 1) development of a plan of drilling and sampling to: study the formation of natural gas hydrates in marine sediments; 2) determination of the mechanism of development, nature, magnitude, and global distribution of gas hydrate reservoirs; 3) evaluation of the source of the gas locked up in hydrates; 4) investigation of the gas transport mechanism and migration pathways through sedimentary structures from site of origin to reservoir; and examination of the effect of gas hydrates on the physical properties of the enclosing sediments, particularly as it relates to the potential relationship between gas hydrates and slope instability.

In this context, SCICOM's mandate to the PPG was as follows:

To work with other appropriate international geoscience initiatives to:

- Develop the drilling strategy to complete the defined goals.
- Identify geographic areas appropriate to meet the scientific objectives.
- Advocate new and/or better technologies to achieve the objectives.
- Organize and nurture the development of specific drilling proposals.

INTRODUCTION

Answering the question of the mass and distribution of gas hydrate has many impacts and consequences that are of both practical and scientific interest. These include the following:

- Gas hydrates represent a very large and dynamic reservoir of natural gas. Understanding the amounts and associated reservoir characteristics are required to evaluate the possibility that parts of this reservoir may be a future energy resource.
- Because methane is a greenhouse gas, atmospheric release of large quantities of methane from gas hydrates could seriously affect climate. Knowledge of the amount of methane in hydrate is important in understanding how the planet sequesters carbon.
- Changes in bottom water temperature or changes in pressure (sea level) can destabilize hydrate layers, and potentially can result in large landslides and massive methane release. Any human activity on the seafloor (drilling, laying pipelines) can also change hydrate stability leading to significant environmental hazards.

---

[1] MBARI, U. S. A.
[2] GEOMAR, Germany
[3] IFREMER, France
[4] USGS, U. S. A.
[5] University of Toronto, Canada
[6] Statoil, Norway
[7] Chevron, U. S. A.
[8] USGS, U. S. A.
[9] University of Tokyo, Japan
[10] Colorado School of Mines, U. S. A.
[11] Oregon State University, U. S. A.
[12] University of Birmingham, U. K.

- Because gas hydrate acts as a pore-filling material and its dissociation can increase fluid pressure, gas hydrates can influence sediment physical properties, diagenetic pathways, and even sedimentary tectonics.

A successful research program on gas hydrates will require investigation of the interrelated processes that affect the formation and dissociation of hydrate within its sedimentary host rock. Thus, proposals should focus on several of the following general themes:

- Determining the partitioning of the sedimentary gas into the dissolved, gas hydrate, and free gas phases.
- Identifying and quantifying the diffusive and advective processes that move gas into and out of the pressure and temperature conditions of the gas hydrate stability field.
- Defining where gas hydrate develops within the host sediment and its habit.
- Documenting the effect that the presence of hydrate has upon the diagenesis of the host sediment.
- Understanding how gas hydrate changes the physical properties of the sediment.
- Refining and calibrating remote detection techniques to quantify gas hydrate amounts.
- Establishing whether significant transfers of methane from the geologic reservoirs to the ocean and atmosphere system are possible.
- Determining whether gas hydrate plays a role in slope failure on continental margins.
- Learning how bodies of gas hydrate evolve with time (grow or diminish).
- Documenting the geomicrobiological and biogeochemical activity that produces gas (especially methane) in marine sediments. (See Deep Biosphere section below.)

Finally, it is critical to understand how the importance of these processes varies among different geological settings.

CHARACTERISTICS OF A GENERIC GAS HYDRATE PROGRAM

To assure a maximally successful program, careful application of existing techniques, clever drilling strategies, development of new techniques, and innovative technology to document the in-situ nature of gas and gas hydrates will be required.

Proponents are encouraged to specifically identify how the available techniques will be applied and integrated into a unified research program. The basic components of any dedicated gas hydrate leg should include: 1) remote geophysical data for site characterization (e.g., 2D and/or 3D seismic data, OBS, side-scan sonar, etc.); 2) core recovery and analysis (including the use of pressure core samplers, porewater geochemistry, gas analyses, physical properties, and advanced core analysis procedures); 3) downhole measurements (porewater samples, temperature measurements, conventional wireline logging, logging while drilling, VSP, tomography, etc.); and in some cases 4) long-term monitoring (e.g., CORKS).

An end-member strategy was endorsed by the panel as an approach for selecting geographic regions for individual drilling legs. For example, during the course of the multiple legs that collectively comprise a gas hydrate program, it will be desirable to drill sites with contrasting characteristics such as: high versus low fluid flow; porous versus conduit flow; locally produced versus thermogenic gas; failed versus intact sediment slopes; and distinct sediment facies. It will also be important to ground truth the effects of gas hydrates within typical environments rather than only studying areas where gas hydrates are heavily concentrated. Thus, proponents are encouraged to identify how their proposed sites fit within this end-member concept.

Within individual leg proposals, proponents are encouraged to select sites very carefully and provide clear justification for their selection. For example, one strategy is to select sites where similar formations can be drilled that have distinct remote sensing properties over short lateral distances. At least one hole should be drilled where there is a well-developed bottom simulating reflector. However, it is important to drill reference sites. At each site the entire section should be examined in detail from the surface to at least 200 m below the theoretical base of gas hydrate occurrence.

The development of new tools and techniques may be vital to the success of gas hydrate research. Thus, proponents are encouraged to advance existing techniques by trying new approaches, deploying experimental tools, and developing new technologies.

TARGETS FOR FUTURE LEGS

To accomplish these objectives we recommend at least a three-leg program. A minimum of three legs is required because of the nature of the geologic settings in which gas hydrates are known to occur. Examining the gas hydrate occurrence in diverse settings is the only way to provide a basis for more robust global extrapolations and to provide meaningful insight toward the diverse problems that need to be addressed. Thus, a range of geologic settings should be considered which include: accretionary margin complexes where there is evidence for high fluid flux and significant methane generation; passive margin sites with definable fluid fluxes and indication of high methane levels; a region where thermogenic hydrocarbons are actively seeping from greater depths; and areas where slope instabilities may have occurred because of gas hydrate dynamics. Specific features within these areas which should also be targeted include: near seafloor occurrence of gas hydrate, slump structures, chemosynthetic communities, mud-volcanoes, pockmarks, and faults which are active fluid conduits.

A leg to drill gas hydrate-bearing sediments on Hydrate Ridge off Oregon has been selected for drilling in 2002. Hydrate Ridge drilling will specifically address mechanisms of hydrate formation from methane carried by fluids that are escaping from compacting sediments and where some of the gas may be derived from the decomposition of gas hydrates within tectonically uplifting sea floor. Thus, the Hydrate Ridge leg will address some of the difficult problems associated with the internal dynamics of gas hydrate formation and will provide information on the physical properties of gas and gas-hydrate bearing sediments in an accretionary environment in which methane is abundant. Although it touches on many of the general themes listed above, it samples a limited range of sediment types and tectonic settings. Additional observations in contrasting settings will be needed in order to obtain a generalized understanding of distribution and dynamics of global gas hydrate deposits.

UNADDRESSED QUESTIONS - POST HYDRATE RIDGE DRILLING

The most significant gas hydrate research issues that will remain unaddressed after the Hydrate Ridge leg concern the potential connections between the gas hydrate reservoir and the Earth's climate. Several possible scenarios have been proposed in the literature, leading to both positive and negative feedback between hydrate destabilization and climate. Common among these scenarios are mechanisms to transfer huge volumes of methane between the geologic reservoirs and either ocean or atmosphere. Thus, it is critical that the various mechanisms to release volumes of methane from gas hydrate-bearing sediment sections are assessed. These include the potential for gas release through slope instabilities and through global scale perturbations associated with sealevel and ocean temperature changes (a. and b. below). In addition, significant progress in understanding geohazards is unlikely until an active hydrocarbon province is targeted (c. below). Moreover our understanding of the effects of gas hydrate on sediments will remain poor until appropriate data are also collected away from obviously gas hydrate-dominated areas (d. below).

a. Slope stability and climate connections.

The potential for large-scale catastrophic release of methane is most likely associated with large-scale slope failure because gigatons of methane are available to escape from the sediments during a large slide event in gas hydrate-bearing sediment regions. During massive slope failures, the transported sediments disaggregate into turbidity flows. As this happens pieces of gas hydrate in the suspension are freed from adhering sediments and float upward because of their inherent buoyancy. Free gas will also be released from the transported material and from fractures that are generated in the sole of the slide. Estimates of the loss of methane that occurs during the process of major slope failure events in gas and gas hydrate-bearing sediments can be made by comparing the volumes of gas and gas hydrate in recent slide deposits and under the slide's sole with adjacent intact sediments of similar age and lithology. In the process, valuable information will be gathered about the causes of the failure; another fundamental, but unanswered question that has important ramifications for evaluating and predicting natural hazards related to gas hydrates (e.g., tsunamis generated by slumping, and destruction of offshore structures).

b. Natural perturbations.

The largest non-catastrophic releases of methane are inferred to be associated with thermal or pressure perturbations. For example, a significant warming trend that may be affecting the gas hydrate system is presently occurring in the Arctic. The warming is associated with the flooding of the Arctic shelves after the last glaciation. Thus, a large thermal wave is propagating downward from the relatively warm ocean waters into the gas hydrate-bearing submarine permafrost below. The temperature changes are forcing reductions in the size of the hydrate stability zone and presumably decrease in the gas hydrate reservoir. The dynamics of this ongoing change provide the opportunity to investigate the potential for transferring methane carbon from a progressively decomposing gas hydrate reservoir to the seafloor. While a JOIDES Resolution-like vessel may not be able to operate in the shallow ice bound environments, alternative drill platforms can. (Editorial note: This is currently being investigated by drilling on the Siberian Shelf under the auspices of the Laptev Sea Drilling Project).

c. Drilling in an active hydrocarbon province.

The dynamics of gas hydrate-bearing systems may be different in a thermogenic hydrocarbon province for several reasons: (a) Geohazard issues are most relevant in this environment and thus represent the meeting point for industrial and scientific interests outside the hydrocarbon pipeline. (b) The presence of hydrocarbon gases (in addition to methane) allows gas hydrate of multiple crystal structures to occur. Because both DSDP and ODP have consciously avoided drilling where other gases will be present, all our insight into the behavior of natural gas hydrates is based solely on Structure I methane gas hydrate. However, other gas hydrate structures (e.g., II, H) are nearly as common where thermogenic gases occur.

d. Gas Hydrate distribution away from "bottom simulating relflectors" (BSR's).

Our knowledge of the quantity of hydrates in nature has been driven very strongly by the correlation with seismic detection of BSR's. However, it is likely that large portions of continental margins contain methane hydrates although their presence is not indicated by a BSR. We know almost nothing about the frequency of such occurrences. It would be hard to make a case that a hydrate leg be scheduled where there is no a priori evidence from seismic data. Instead we recommend the development of a set of basic procedures to test for the presence of gas hydrates on legs that do not have gas hydrate research as an objective. The simplest suite of measurements would consist of basic logs (e.g., Dipole Shear Sonic, Density, and Resistivity), routine porewater chloride measurements, and periodic inspection of cores using an infrared scanner.

STATUS OF CRITICAL TOOLS

The research drilling needs for gas hydrate research are unlike those for many of the more traditional ODP objectives because of the ephemeral nature of gas hydrate. Gas hydrate research requires a series of specialized tools that measure *in situ* properties because gas hydrate decomposition and gas escape occur during core recovery. Many of these tools are either not available or are in critical need of improvement. However, since ODP leg 164 (Gas Hydrate Sampling on the Blake Ridge and Carolina Rise) there has been considerable progress on a number of instrument development issues.

PRESSURE CORE SAMPLING SYSTEMS

Continued development of tools that retrieve samples that remain under in situ temperature and pressure conditions are critical for the progress in gas hydrate research. Currently there are two complementary systems, the Pressure Core Sampler (PCS) and the Hydrate Autoclave Coring Equipment (HYACE) tool.

The existing ODP PCS is capable of taking small core samples (42 mm diameter, up to 0.86 m long) from the bottom of a bore hole and sealing the core into a pressure housing so that recovery occurs at near *in situ* pressures. The PCS was used with great success on ODP Leg 164 as a tool to sample the total amount of gas that is contained within the original sediment volume. Repetitive use of the PCS tool is a fundamental aspect of ODP's gas hydrate research.

Currently, only one complete PCS system exists, (plus parts of a second tool). Because even simple degassing experiments take a few hours to perform, and because it takes trained tool specialists ~2-6 hours to prepare the PCS for the next deployment, hardware limits severely restrict deployment. In addition, a functional manifold to degas the PCS does not exist. The core material within the PCS sample chamber cannot be directly accessed or transferred without depressurizing the PCS sample chamber.

HYACE is another tool to retrieve samples under in situ pressures. HYACE incorporates three different wireline coring concepts for sampling gas hydrate in various lithologies: a push corer for soft sediments; a rotary corer for hard sediment; and a percussion corer for sandy sediments. The pressure conservation autoclave function will include specially designed and operated valves which will also permit the largest possible core diameter of at least 50 mm. Temperature conservation will be achieved by an acrylic core liner with three built-in temperature probes for measurement while coring from an electronic chamber where monitoring of pressure and acceleration for tool control is performed. The core of 1 m length will be pulled mechanically into the autoclave downhole core barrel. Onboard evaluation of the sample within the autoclave by core logging with gamma ray and other through-the-casing sensors will be possible. HYACE is being designed for easy transfer of the sample from the downhole autoclave to a laboratory pressure container. Sub-sampling of sediments and or pore waters through ports in the laboratory chamber will be possible. Ultimate gas venting, sediment and water analyses under ambient conditions may follow using traditional methods.

IN SITU PORE WATER SAMPLING

Measurement of interstitial pore water concentration has become a standard and basic measurement to assess the original pre-coring gas hydrate content of sediment samples. However, the calculation requires an understanding of the *in situ* pore water composition. Unfortunately, tools that confidently and reliably retrieve uncontaminated samples from the formation have not been developed. The lack of pristine samples has complicated our interpretations. Thus, we desperately need to make progress on this front. While efforts to refine existing tools should be supported, a fundamentally new tool may have to be designed to provide these samples. Some progress may also come from developing better tracers to improve our understanding of the extent of contamination. Rigorous procedural and multiple tracer regimes will enable the quantification of sample contamination from drilling fluids, side-wall caving, and core processing activities that may compromise sample integrity.

CORE TEMPERATURES

Distinct variations in temperature are commonly observed in freshly recovered core samples from gas-rich sediments. These variations are believed to be due to both the endothermic gas hydrate decomposition and gas expansion, and thus represent fundamental information about the presence and distribution of gas and gas hydrate within cores. Equipment to collect these data (such as an infrared thermoscanner) needs to be available on the drill ship for both fortuitous encounters with gas hydrates and to use in a routine way on gas hydrate-dedicated legs.

Tools that continuously measure temperature, pressure, and conductivity (TPC) inside the core barrel during routine coring operations are needed. Existing ODP technology does not provide any routine data that is readily interpretable concerning the *in situ* volumes of gas and gas hydrate in marine sediments. Unfortunately, because large pressure decreases occur during core recovery, most of the original gas is lost before the core barrel reaches the deck of the JOIDES Resolution. However, TPC sensors in the coring assembly could provide a simple and robust way to monitor the effects of gas loss in cores. Again, significant thermal variations will occur due to both endothermic gas hydrate decomposition and gas expansion. Conductivity measurements will detect whether and when gas bubbles develop in the core barrel headspace (i.e., gas saturation is achieved) during ascent. These data will allow estimates of *in situ* concentrations of methane to be calculated. Variations in these records with successive APC cores will indicate changes in the volume of gas, its vertical distribution in the sediments, and how it is stored in the sediments. This information is needed from many sites to assess the size of the global interstitial gas inventory.

WELL LOGGING

The neutron-density porosity tools have been updated with devices that yield higher quality downhole log-derived sediment porosity data in poor borehole conditions. The downhole acoustic tool has been replaced with the Schlumberger Dipole Shear Sonic Imager, which yields both compression- and shear-wave acoustic velocity data. Logging while drilling technology has also become a critical component of specialized ODP drilling legs when downhole stability problems are expected. Within the near future, pending ODP drilling configuration modifications will allow the deployment of new wireline-conveyed downhole tools including the Modular Formation Dynamics Tester and Nuclear Magnetic Resonance log. Both of these tools have the potential of yielding important gas hydrate data. The panel recognizes the important contribution of the downhole logging program to characterizing the *in situ* nature of gas hydrate occurrences and the panel supports the continued development and modernization of the ODP downhole logging program.

BOREHOLE GEOPHYSICAL EXPERIMENTS

Geophysical experiments are critical for linking the borehole observations to the results of regional surveys. For example, offset VSP experiments, using P-waves and S-waves, define the distribution of hydrate in a cone around the borehole. Borehole-to-surface and cross-hole measurements have the advantage of sensing a larger volume of sediment than can be obtained using traditional borehole logging tools. Additional ways to use the boreholes for geophysical experiments need to be encouraged.

TOOL DEVELOPMENT STATUS SUMMARY:

- Additional components for the existing PCS tool are being made which will make it possible conduct multiple closely spaced deployments.
- HYACE is being built and tested by a group of eight European research institutions and industrial companies. The project is being sponsored by the European Commission's MAST III program and coordinated by the Marine Technology Group at the Technical University of Berlin under the direction of Professor Hans Amman. HYACE will be field tested on the JOIDES Resolution on Leg 194 and available for operational deployment in 2002.
- Improvements to the Fissler porewater sampling tool are underway through USSAC funding.
- Development of infrared thermal measurement systems to scan cores and record catwalk core data is strongly recommended.
- A tool to measure Temperature, Pressure, and electrical Conductivity (TPC) during core recovery (joint project between MBARI and ODP) is being developed with funds from both MBARI and NSF.
- Downhole logging improvements continue to be made that allow better data to be collected under poor bore hole conditions.
- Innovative approaches to using the borehole for high-resolution geophysical imaging of a volume around the borehole are encouraged.

MAINTAINING TECHNOLOGY DEVELOPMENT EFFORTS

The nature of tool development in ODP has always been an iterative process, closely linked to the opportunities to test prototype tools on a drilling leg. Hydraulic piston core development, for example, began in DSDP in the mid-seventies and took nearly ten years and several major design changes before it became the routine operation that sustains paleoceanography today. We stress that the development of gas hydrate tools may be an iterative process too. Regular opportunities to test and refine new downhole tools are essential to maintain the momentum of tool development efforts.

SHIPBOARD STAFF FOR COMPLEX TECHNICAL LEGS

Because ODP is a multi-national program and there is widespread interest in gas hydrate science, the pressures for scientific berths on future gas hydrate legs will be very high. It is important that these pressures do not prevent a proper balance between scientific and technical personnel being achieved. The advent of complex downhole tools changes the balance between scientific and technical personnel on the JOIDES Resolution. On routine legs the operation of the basic tools (APC, XCB, & RCB) depends on the two coring technicians who each work on alternate 12 hour shifts. These technicians can accommodate only one or two additional runs of the ODP supported tools without additional help. However, gas hydrate drilling legs require repetitive operations of multiple complex tools. Many of the tools that are being developed are not supported by the existing staff and will require support of the personnel that are developing them. Thus, some of the normal scientific berths will have to be sacrificed to accommodate the increased technical manning requirements.

LONG TERM OBSERVATIONS

Long-term observations are needed to study changes in the hydrate system over periods of weeks to years, and are vitally important to measure aspects of the hydrate system when it has recovered from the disturbance caused by drilling. These observations include measurements within the borehole, such as those made with CORK's, and on the seafloor. Logging of the data from these measurements can be in self-contained packages that are retrieved during repeat cruises to the site. Alternatively, the data can be conveyed to shore either via fiber-optic cables or through satellite telemetry of data relayed through a surface mooring. These latter approaches provide real-time measurements and provide a link between ODP and other emerging oceanographic initiatives.

1. CORKs:

We encourage further development of CORK technology, as outlined in the report of the "Workshop on Advanced CORK's for the 21st Century", K. Becker and E. E. Davies, 1998 (available from JOI, Inc.). A CORK enables recording instrumentation to be left in boreholes after the hole has been hydraulically sealed and the drill ship has left. By using borehole seals, pressure recording and pump testing, it is possible to establish and monitor downhole pore pressure and to estimate permeability and fluid flow at multiple depth intervals. Accurate measurement of formation temperatures can be obtained after the initial drilling disturbance has decayed away. Mechanical and hydrogeological properties of the hydrate-bearing sediment matrix and the gas-bearing interstitial fluid below the phase boundary can be determined.

2. Fluid Flow/Discharge:

Long-term monitoring of fluid and gas escape around the site is desirable, to be correlated with other measures of flow through the system and the mechanisms driving the flow.

3. Geophysical Monitoring:

Seafloor geodetic measurements may be appropriate in tectonically active environments where vertical movements influencing the gas hydrate system. Microseismic activity should also be monitored in such environments to detect linkages between deformation associated with faulting and fluid flow through the system.

4. Slope Stability:

Monitoring of pore pressures in situations where slope stability is an issue of particular value.

5. Video Monitoring:

Continuous camera monitoring of downhole conditions and of the seabed in the immediate vicinity of the hole could record formation of gas hydrate, biological colonization, and other time varying changes following the drilling of the hole and emplacement of monitoring instrumentation.

6. Repeated seismic experiments:

Carefully calibrated repeated high-resolution seismic surveys provide a potential means of quantifying long-term regional subsurface changes associated with fluid flow and gas-hydrate formation and dissociation.

PERTURBATION EXPERIMENTS

The panel discussed the possibility of conducting a set of perturbation experiments for studies of the response of the hydrate-bearing sediments to external forcing. These perturbations can include chemical, thermal, and mechanical stimuli to force a response that can be measured. The concept can be extended over a range of time and space scales. These studies would extend knowledge of the dynamic response of hydrate systems in ways that are not achievable by other means. Such experiments could be conducted as an add-ons to legs that are located for independent reasons.

DEEP-BIOSPHERE ASSOCIATIONS

Interactions between gas hydrate and deep-biosphere research objectives are strongly encouraged. Needs for collecting and subsampling representative materials with multiple degrees of sample validation in short time-spans while protecting redox chemistry tie gas hydrate and deep-biosphere research together. Many of the procedures, tools, techniques, and issues facing gas hydrate research are inseparable from the needs for deep-biosphere research. Both require extensive solid, liquid, and gas phase geochemical measurements to characterize the basic environment. Both require extensive use of PCS- or HYACE-type coring tools. Both require rigorous sample validation procedures insuring that sub-samples are representative and not compromised chemically or microbiologically by drilling fluids. Ultimately, both research themes also require understanding the natural redox coupling and dynamics of both the mass and energy balances within the shallow subsurface. While considerable advances in understanding gas hydrates could occur without including a biological perspective, the inclusion of microbiological research will greatly expand our comprehension of biogeochemical processes.

PRESERVATION OF GAS HYDRATE-BEARING CORE SAMPLES

When hydrates are cored it is imperative that the samples are preserved as close to the *in situ* conditions as possible. In the past many cores have been pressurized with gases in ways that encourage gas hydrate dissociation. Studies of gas hydrate sample preservation show that the most effective method is to store gas hydrate samples in a dry Dewar container at liquid nitrogen temperatures. Thus arrangements need to be made to have liquid nitrogen and appropriate storage facilities available on the JOIDES Resolution for gas hydrate legs.

INDUSTRIAL AND INTERAGENCY INTERACTIONS

The hydrocarbon industry has long-standing research efforts into pipeline flow assurance problems related to artificially created hydrates. Outside pipelines, gas hydrates are important to industry and governmental agencies as a current safety issue and as a potential resource in the long term. As such there is a natural infrastructure available for interaction with ODP on naturally occurring hydrates. Industry and government agencies have data and technical expertise that may be valuable in ODP efforts. By combining efforts both groups may accomplish more.

CARBON DIOXIDE SEQUESTERING

While natural gas hydrates are the focus of this PPG's mandate, we need to point out that the ODP will be facing another gas hydrate issue-associated with CO_2 sequestering. The Kyoto Protocols have focused international efforts on ways of reducing emissions of CO_2 to atmosphere. Various concepts that involve pumping CO_2 into ocean are being widely discussed. One idea is that the CO_2 could be pumped to an adequate depth to be converted into CO_2-hydrate and that the CO_2-hydrate thus will stay sequestered on the seafloor. While there are some conceptual models to do this, very little empirical data exist. Fundamental and engineering research in CO_2 sequestration could realize a widespread application of great service to society. ODP may play an important role in developing strategies to assess various potential approaches to disposing of CO_2 as CO_2-hydrate.

ODP CONTRACTORS

WEBSITE: www.oceandrilling.org for all contractors

JOINT OCEANOGRAPHIC INSTITUTIONS

Prime Contractor
Program Management
Public Affairs
JOIDES Journal Distribution

1755 Massachusetts Ave., N. W.,
Suite 700
Washington DC 20036-2102, USA
Tel. (202) 232-39 00
Fax: (202) 462-87 54
joi@brook.edu

JOIDES OFFICE

Science Planning and Policy
Proposal Submission
JOIDES Journal Articles

University of Miami - RSMAS
4600 Rickenbacker Causeway
Miami, FL 33149, USA
Tel: (305)-361-4668
Fax: (305)-361-4632
joides@rsmas.miami.edu

ODP SITE SURVEY DATA BANK

Submission of Site Survey Data
Site Survey Data Requests

Lamont-Doherty Earth Observatory
P. O. Box 1000, Rt. 9W
Palisades, NY 10964, USA
Tel. (845) 365-85 42
Fax: (845) 365-81 59
odp@ldeo.columbia.edu

ODP-TAMU

Science Operations
ODP/DSDP Sample Requests
Leg Staffing, ODP Publications
Ocean Drilling Program

Texas A & M University
1000 Discovery Drive
College Station, TX 77845-9547, USA
Tel. (979) 845-84 80
Fax: (979) 845-10 26
moy@odpemail.tamu.edu

ODP-LDEO

Wireline Logging Services
Logging Information
Logging Schools
Log-Data Requests
Borehole Research Group

Lamont-Doherty Earth Observatory
P. O. Box 1000, Rt. 9W
Palisades, NY 10964, USA
Tel. (845) 365-86 72
Fax: (845) 365-31 82
borehole@ldeo.columbia.edu

JOIDES Journal

The JOIDES Journal is published and distributed semi-annually by Joint Oceanographic Institutions, Inc., Washington, DC for the Ocean Drilling Program under the sponsorship of the National Science Foundation and participating member countries. The material is based upon research supported by the National Science Foundation under prime contract OCE-9308410.

The purpose of the JOIDES Journal is to serve as a means of communication among the JOIDES advisory structure, the National Science Foundation, the Ocean Drilling Program, JOI subcontractors thereunder, and interested earth scientists. Any opinions, findings, conclusions or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

The information contained within the JOIDES Journal is preliminary and privileged and should not be cited or used except within the JOIDES organization or for purposes associated with ODP.

This journal should not be used as a basis for other publications.

Editor: William W. Hay, Emanuel Soeding
Design: Martin Wunderlich

Published semi-annually by the JOIDES Office at

JOIDES Office
GEOMAR
Wischhofstr. 1–3
D-24148 Kiel
GERMANY