ODP's GREATEST HITS

CONTRIBUTIONS FROM THE U.S. SCIENTIFIC COMMUNITY

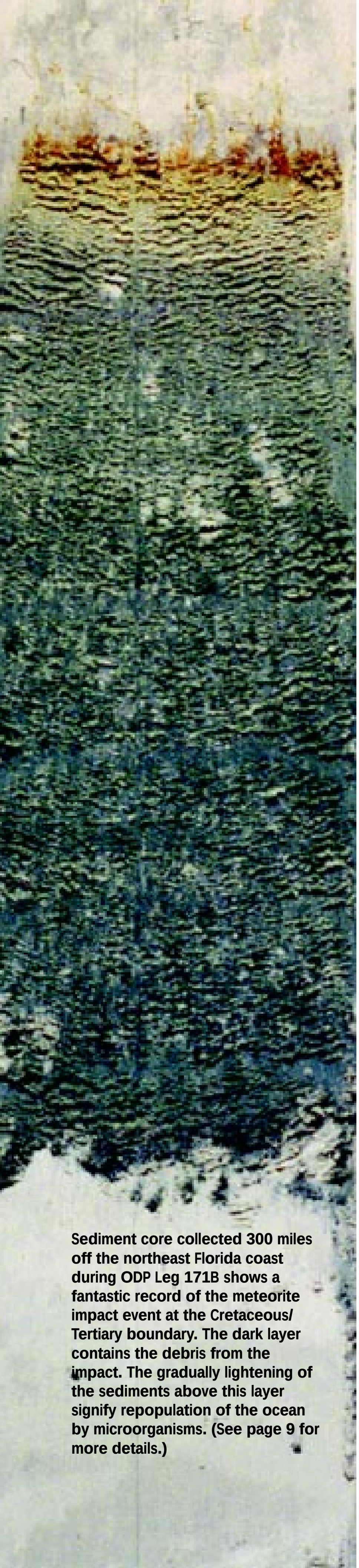
The centerpiece of the Ocean Drilling Program is the 143-meter long drillship, *JOIDES Resolution.* With this ship ODP can drill cores — long cylinders of sediment and rock extracted from beneath the seafloor — in water depths up to 8.2 kilometers. The ship is equipped for scientific drilling in all but the very deepest parts of the world ocean, and the shipboard laboratories are among the world's finest. The ship carries a crew of 52 and accommodates a scientific and technical complement of 50.

THE OCEAN DRILLING PROGRAM

Exploring Earth through scientific ocean drilling

The Ocean Drilling Program is an international partnership of scientists and research institutions organized to explore the evolution and structure of Earth. ODP provides access to a vast repository of geological and environmental information recorded far below the ocean waves in seafloor sediment and rock. By studying ODP cores and downhole logs we gain a better understanding of Earth's past, present, and future. Many outstanding scientific discoveries have been made through ocean drilling. In this brochure we present just a few of ODP's "greatest hits," highlights of the rich diversity of accomplishments by the U.S. scientific community.

Scientists aboard *JOIDES Resolution* describe and sample sediment cores.



Sediment core collected 300 miles off the northeast Florida coast during ODP Leg 171B shows a fantastic record of the meteorite impact event at the Cretaceous/Tertiary boundary. The dark layer contains the debris from the impact. The gradually lightening of the sediments above this layer signify repopulation of the ocean by microorganisms. (See page 9 for more details.)

Scientific Ocean Drilling

A brief history

The Ocean Drilling Program is the direct successor of the Deep Sea Drilling Project (DSDP). DSDP, which began in 1968, was the first scientific effort to sample the global seafloor by deep ocean coring and downhole logging, and its accomplishments were striking. Research based on the samples strongly supported the hypotheses of seafloor spreading — the relationship of crustal age to the record of Earth's magnetic reversals — and plate tectonics.

The DSDP began as a U.S. program but quickly evolved into an international effort in which five partner countries (France, West Germany, Japan, the United Kingdom, and the USSR) became full participants, and were responsible for scientific decision-making and financial support. The international organization created by the partner countries, Joint Oceanographic Institutions for Deep Earth Sampling (JOIDES), continues to be the scientific advisory mechanism for the Ocean Drilling Program. By 1981, as the DSDP drillship *Glomar Challenger* was reaching the end of her useful life, 150 of the world's leading earth scientists met and created a blueprint for the future of ocean drilling. They recommended support for the Ocean Drilling Program. This new program began in 1985 when the larger and more capable *JOIDES Resolution* was modified to meet the special requirements of scientific ocean drilling. Scientists were now able to drill deeper, in more difficult rock formations, and with a more comprehensive set of logging tools.

Funding for the Ocean Drilling Program is currently provided by seven international partners representing 21 countries. Partners include: the Australia/Canada/Chinese Taipei/Korea Consortium for Ocean Drilling; the European Science Foundation Consortium for Ocean Drilling which includes Belgium, Denmark, Finland, Iceland, Italy, Norway, Portugal, Spain, Sweden, Switzerland, the Netherlands, and Turkey; France; Germany; Japan; the United Kingdom; and the United States of America. Joint Oceanographic Institutions (JOI) is the prime contractor. JOI subcontracts to Texas A&M University, which, as science operator, leases, operates, and staffs the drillship and maintains facilities for storage and study of ODP cores. Lamont-Doherty Earth Observatory houses the logging services contractor responsible for downhole measurements and the ODP's Site Survey Data Bank.

Scientists from the ODP partners review drilling proposals, and participate in each ODP research cruise. This unique format brings together researchers from universities, industry, and government laboratories in the member nations to work in a state-of-the-art ship-board laboratory on focused scientific goals. Students also participate in drilling expeditions, working with some of the world's leading scientists and becoming part of the intellectual fabric essential for future advances in the earth sciences. The results of research based on ODP data are published openly in leading scientific journals and in the archival *Proceedings of the Ocean Drilling Program.*

CORE ON DECK

On board *JOIDES Resolution*

At odd intervals of the day and night, routine operations aboard *JOIDES Resolution* are shattered by the welcome cry, “Core on deck!” With that summons, crew, technicians, and scientists rush to the drilling deck as a 9.5-meter section of ocean sediment or rock is hoisted from the water. Carefully, they carry the plastic-sheathed cylinder to the first of many shipboard laboratories in which the core will be studied.

At the first stop, a precise routine ensures that the core will be marked with its original location on the seafloor, coded to distinguish top from bottom, measured, and cut into smaller sections for study and storage. Each segment is sliced lengthwise. One half is used for nondestructive analyses before being stored in the ODP archives. The other half is ready for scientists to begin to reconstruct another chapter in Earth history.

Paleontologists examine fossils in the cores to determine the age of the material; other scientists measure physical properties such as density, strength, and ability to conduct heat. Other specialists use state-of-the-art equipment to read the record of Earth’s magnetic field changes, information that helps determine the ages and latitudes at which rocks were formed. Within minutes, scientists in *JOIDES Resolution’s* seven levels of shipboard laboratories have begun to analyze the core. No aspect of the core is overlooked. The challenging process of interpretation begins.

Each 9.5-meter segment comprises only a small part of the entire length of core that will be extracted from the hole, so this sequence is repeated many times. The scene aboard *JOIDES Resolution* is far removed from the normal routines in researchers’ land-based laboratories, but then, the ODP has always been a breed apart.

Scientific investigation does not stop with the cores. Once they have been extracted from the drill hole, this empty column itself becomes a laboratory. In a process called downhole logging, scientists lower instruments into the drill hole to record the physical and chemical properties of the surrounding rock. Afterwards, some boreholes may be sealed off to become sites of long-term observatories. Instruments that measure temperature and pressure, and that take water samples, remain in the borehole for several years after *JOIDES Resolution* has left the site. Data can be retrieved from these observatories by remotely operated vehicles or submersibles.

The seven-member drilling crew uses a variety of mechanical and hydraulic devices to extend the drill string to the seafloor. Lengths of pipe exceeding 28 meters and weighing 874 kilos are lifted by the draw works at the base of the derrick, threaded onto the drill string, and lowered through the moon pool in the bottom of the ship. In 5,500 meters of water, it takes 12 hours for the drill bit to reach the seafloor where drilling can begin.

Facts and Figures

ODP leg locations and statistics

Since ODP's inaugural expedition in 1985, *JOIDES Resolution* has traversed the world's oceans collecting sediment and rock samples, recording downhole geophysical and geochemical information, and establishing long-term borehole observatories. The ship has drilled in water depths of up to 5,980 meters in the oldest part of the Pacific Ocean, and the Program's deepest hole has been drilled 2,111 meters below the seafloor through the upper layers of the oceanic crust. ODP has collected over 138 km of core and has provided over 1,700 shipboard scientists with more than 1,000,000 samples for further laboratory study.

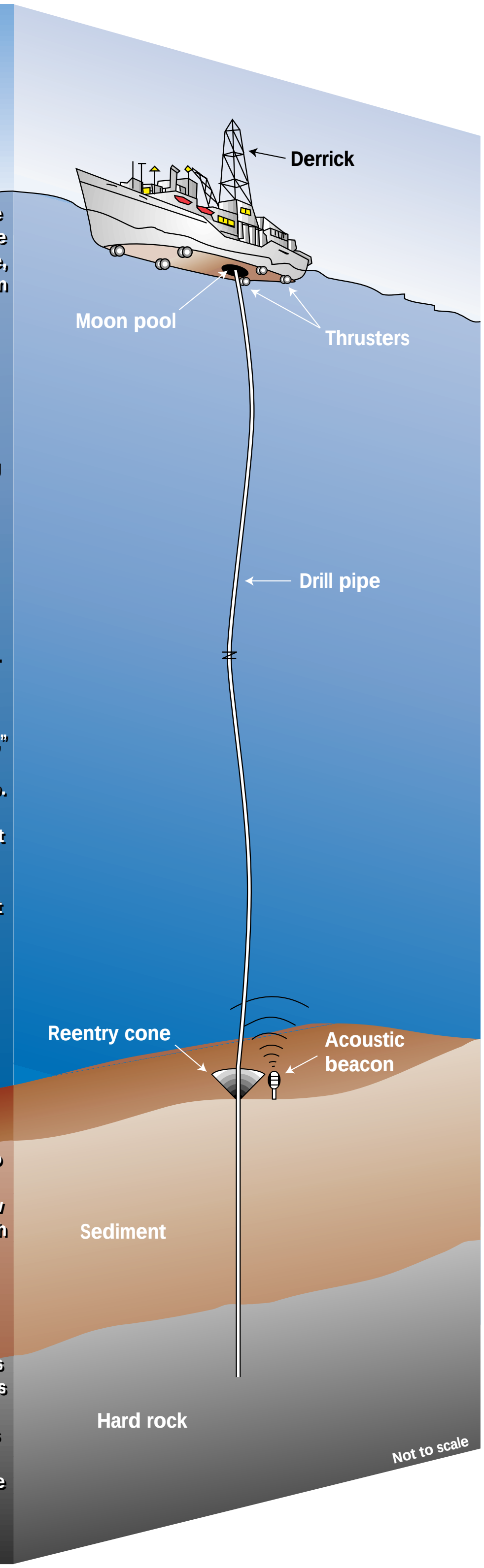
JOIDES Resolution is outfitted with the most modern laboratory, drilling, and navigation equipment. The ship is 143 meters long and 21 meters wide, and its derrick rises 61.5 meters above the water line. The drilling system can handle 9,150 meters of drill pipe, long enough for drilling in 99.9% of the world's oceans.

A computer-controlled system regulates 12 powerful thrusters in addition to the main propulsion system. Using an acoustic beacon set near the drill site on the seafloor, this system keeps the ship stabilized over the borehole despite wind and waves, allowing drilling in water as deep as 8,235 meters.

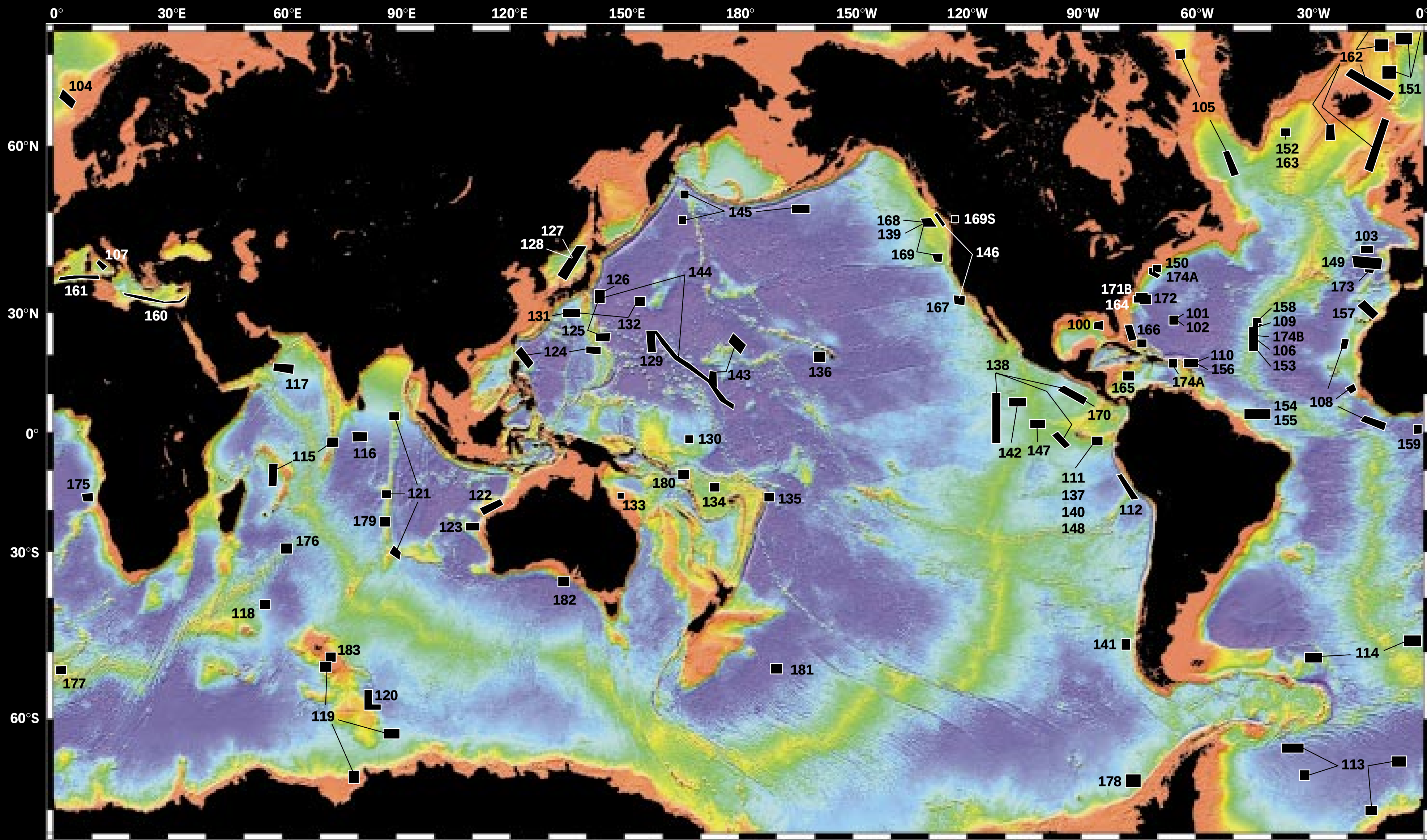
The drill pipe is lowered from the steel derrick through the "moon pool," a seven-meter-wide hole in the bottom of the ship. A heave compensator in the derrick acts as a giant shock absorber, so that the up and down movements of the ship are not transferred to the drill pipe. Thus cores can be cut and lifted smoothly.

To drill through soft sediment or mud, a hydraulic piston corer is used. This device uses compressed seawater to drive a steel barrel through the sediment. To penetrate into harder sediment and rock below the seafloor, drill bits with cutting heads are used.

As the drill bit or hydraulic piston corer cuts through layers of sediment and rock, cores of subseafloor material as long as 9.5 meters are collected in plastic tubes and returned to the ship on a wire cable inside the drill pipe.



ODP Leg Locations: 1985-1998



Seafloor topography map courtesy of Walter H.F. Smith and David T. Sandwell, Seafloor Topography Version 4.0, SIO, September 26, 1996, © Walter H.F. Smith and David T. Sandwell, 1996

Year	ODP Leg		# of drill sites	# of drill holes	meters cored	meters recovered	% recovered	deepest penetration (m below seafloor)	max water depth (m)
1985	100	Gulf of Mexico	1	3	325	281	87%	235	900
	101	Bahamas	11	19	2977	1429	48%	535	3581
	102	Western Atlantic	1	1	0	0	0%	0	5505
	103	Galicia Bank	5	14	1460	594	41%	547	5321
	104	Norwegian Sea	3	8	2419	1695	70%	1229	2780
	105	Labrador Sea/Baffin	3	11	2960	1884	64%	1147	3870
	106	Mid-Atlantic Ridge	2	12	92	12	13%	33	3529
	107	Tyrrhenian Sea	7	11	3297	1908	58%	721	3606
1986	108	Northwest Africa	12	27	4244	3842	91%	381	4750
	109	Mid-Atlantic Ridge	4	5	102	12	12%	93	4494
	110	Lesser Antilles	6	10	2404	1898	79%	691	5018
	111	Panama Basin	3	5	641	428	67%	1562	3474
	112	Peru Margin	10	27	4710	2666	57%	779	5093
	113	Weddell Sea	9	22	3361	1944	58%	646	4665
1987	114	South Atlantic	7	12	3602	2297	64%	672	4637
	115	Mascarene Plateau	12	22	3955	3075	78%	353	4440
	116	Bengal Fan	3	10	2299	992	43%	961	4747
	117	Oman Margin	12	25	5847	4367	75%	994	4045
	118	SW Indian Ridge	4	20	780	447	57%	501	5219
	119	Prydz Bay	11	22	3652	2102	58%	716	4093
1988	120	S Kerguelen	5	12	2140	1082	51%	935	2041
	121	Broken Ridge	7	17	2722	1824	67%	677	2937
	122	Exmouth Plateau	6	15	3911	2446	63%	1037	2710
	123	Argo Abyssal Plain	2	5	1793	1080	60%	1195	5758
	124	SE Asia Basins	5	13	3115	2122	68%	1271	4916
	124E	Luzon Strait	6	15	264	156	59%	532	5811
1989	125	Bon/Mar I	9	15	2917	1019	35%	829	4912
	126	Bon/Mar II	7	19	4737	2128	45%	1682	3269
	127	Japan Sea I	4	10	2917	1655	57%	903	3311
	128	Japan Sea II	3	9	2044	1548	76%	1083	2820
	129	Old Pacific Crust	3	5	1708	469	27%	594	5980
1990	130	Ontong Java Plateau	5	16	5889	4822	82%	1528	3873
	131	Nankai Trough	1	7	1463	736	50%	1327	4696
	132	West/Central Pacific	3	11	205	165	80%	325	4682
	133	NE Australia	16	36	7973	5505	69%	1011	1650
	134	Vanuatu	7	16	4831	2044	42%	1107	3101
	135	Lau Basin	8	18	3356	1249	37%	834	4814
1991	136	OSN-1	2	6	129	66	51%	764	4441
	137	Hole 504B	1	1	49	9	18%	1622	3475
	138	Eastern Pacific	11	42	5542	5537	100%	394	3873
	139	Sedimented Ridges I	4	23	2656	933	35%	936	2457
	140	Hole 504B	1	1	379	48	13%	2000	3474
	141	Chile Triple Junction	5	13	2515	1019	41%	743	2760

Year	ODP Leg		# of drill sites	# of drill holes	meters cored	meters recovered	% recovered	deepest penetration (m below seafloor)	max water depth (m)
1992	142	East Pacific Rise	1	3	2	0.5	25%	15	2583
	143	Atolls & Guyots I	6	12	3995	1076	27%	1744	4838
	144	Atolls & Guyots II	11	21	3205	1088	34%	910	5685
	145	N Pacific Transect	7	25	5015	4322	86%	930	5726
	146	Cascadia	7	20	2266	1190	53%	600	2675
	147	Hess Deep	2	13	487	123	25%	155	3874
1993	148	Hole 504B	2	2	385	81	21%	2111	3474
	149	Iberian Abyssal Plain	5	10	2687	1532	57%	838	5331
	150	New Jersey Margin	5	11	4602	4035	88%	1150	2709
	151	Atl. Arctic Gateways	7	18	4211	3005	71%	1062	3330
	152	East Greenland Margin	6	13	2906	1257	43%	1310	2100
	153	MAR/Kane F.Z.	5	15	798	261	33%	201	3343
1994	154	Ceara Rise	5	19	6161	5808	94%	930	4369
	155	Amazon Fan	17	36	5117	4053	79%	434	4149
	156	N Barbados Ridge	3	8	469	267	57%	592	5024
	157	VICAP/MAP	7	12	4091	3090	76%	1159	5449
	158	TAG	1	17	436	55	13%	126	3657
	Transit		1	2	143	142	100%	133	3789
1995	159	Eq. Atlantic Transform	4	13	3167	1878	59%	1159	4657
	160	Mediterranean I	11	48	4802	3362	70%	600	3942
	161	Mediterranean II	6	16	4591	3875	84%	929	3470
	162	Atl. Arctic Gateways II	9	30	7708	6731	87%	965	2799
	163	SE Greenland Margin	3	4	294	205	70%	325	542
	164	Gas Hydrates	7	17	2786	1974	71%	751	2810
1996	165	Caribbean Ocean History	5	13	4178	3359	80%	1066	3260
	166	Bahamas Transect	7	17	5255	2934	56%	1300	658
	167	California Margin	13	52	7710	7502	97%	449	4215
	168	Juan de Fuca Ridge	10	19	2071	1571	76%	595	2614
	169	Sedimented Ridges II	7	25	3267	1204	37%	546	3302
	169S	Saanich Inlet	2	9	642	657	103%	118	229
	170	Costa Rica	5	17	2052	1464	71%	665	4353
1997	171A	Barbados-LWD	5	5	0	0	0%	832	5056
	171B	Blake Nose	5	16	366	360	98%	685	2671
	172	NW Atlantic Sed. Drifts	11	42	5689	5765	101%	418	4786
	173	Iberia Margin	6	6	1188	453	38%	2994	5333
	174A	New Jersey Margin	3	12	1544	946	61%	664	100
	174B	CORK Hole 395A	2	2	70	72	103%	70	4485
	175	Benguela Current	13	40	8211	8003	98%	605	3007

Amazing Sea Stories

An introduction to ODP's greatest hits

Before writing this preface I opened an old paperback book of early stories by Isaac Asimov, always one of my favorite science fiction writers. In *his* preface, Asimov described his experiences peddling 1930s-vintage stories to magazines named *Astounding Science Fiction, Amazing Stories,* and *Thrilling Wonder Stories.* While wallowing in this charming nostalgia I also marveled at the audacity of the magazine titles, designed to literally leap off the bookseller's shelf into the hands of an over-intelligent teenager like Asimov, or indeed like many of us. Titles help to sell the works within, and I like the title *ODP's Greatest Hits* for this abstract volume. However, I thought I'd go it one better and call this preface *Amazing Sea Stories,* although this implies that at least some of them may not be true. Well, let's face it, maybe some of them aren't. With more time, more data, more models, and more thought, some of our current ideas will be discarded, although they were not originally conceived as science fiction.

I think that I was initially attracted to science by my teenage love of science fiction, especially books by Asimov, Robert A. Heinlein, and Arthur C. Clarke. These writers established an unreal set of circumstances, often set in the future, and tried to reason what would happen inside that unreal, but logical construct. Trying to create a novel geological concept is not too different, except that we are trying to reason logically within what we hope is a factual framework, and we are trying to predict not the future but the past. When we do that, we demonstrate over and over that "truth is stranger than fiction." For example, within this volume you will find evidence for the present-day formation of huge, ore-grade deposits of iron, copper, and zinc precipitated out of hydrothermal fluids heated to over 300°C and rising as hot springs from the center of spreading ridges. Perhaps even more astonishing is the evidence for much larger amounts of lesser-heated water percolating through the ridge flanks. Earth was even more thermally active in the Cretaceous than now when enormous plumes of mantle rock rose beneath the lithosphere and triggered the formation of individual volcanoes and volcanic plateaus at rates unknown in today's world. We know that large volumes of natural gas (methane) are frozen within deep-sea marine sediments as gas hydrates and now we've discovered that there is enough locked

Photograph taken from the *Alvin* submersible in 1993 showing a bacterial mat covering the data logger, which was bathed in hydrothermal fluid leaking from the bottom of the Hole 858G borehole seal, or CORK (see pages 24-25). Subsequent observation of the hole with the drillstring TV camera prior to reCORKing on Leg 169 showed that the bacterial mat had disappeared and that hydrothermal venting had ceased sometime between 1993 and 1996. Photo courtesy of Keir Becker.

***JOIDES Resolution* passes by an iceberg in the North Atlantic during ODP Leg 105 in Baffin Bay.**

up in a hydrate field off the Carolinas to supply U.S. needs for over 100 years. It appears likely that the oceanic crust is home to an unforeseen microbial community called the deep biosphere whose concentration is small, but because oceanic crust is the most common rock sequence on Earth, may contain a significant fraction of Earth's biomass. Throughout all of this, the periodicities of Earth's orbit about the Sun have hammered out a climatic rhythm like a snare drummer keeping the beat in a tune with seemingly endless verses. This rhythm becomes more obvious in times of climatic stress like the present, but the beat goes on no matter what.

All of this would have been considered science fiction 30 years ago, but after over 170 legs of DSDP and ODP drilling, we now believe that many of these "amazing sea stories" and more as well are true. Conversely, in the spring of 1967 when I was a graduate student and a year before Leg 1 of DSDP left the dock, one of our professors offered to bet anyone in the room $20 that DSDP would recover a continuous Phanerozoic sediment section and bottom out in Precambrian basement beneath the deep seafloor. In doing this he echoed the views of the famous American geologist James D. Dana more than 100 years earlier who also believed in the fixity of continents and ocean basins. In addition to that he demonstrated it is hard to make major advances in scientific thinking without improved technology. As Bertolt Brecht put it, "Astronomy did not progress for 1,000 years because astronomers did not have a telescope."

For the past 30 years, scientific ocean drilling has been the inward looking "telescope" for the integrated study of how Earth works as a dynamic planet. Future studies will bring more startling and unexpected discoveries that were not part of anyone's "Long-Range Plan," for certainly no one predicted any of the just-cited examples 30 years ago. This recalls a remark made by Wilbur Wright in about 1908: "We can see enough now to know that the next Century will be magnificent; only let us be the first to open the roads."

Roger L. Larson
Chairman, U.S. Science Advisory Committee
1996-1997

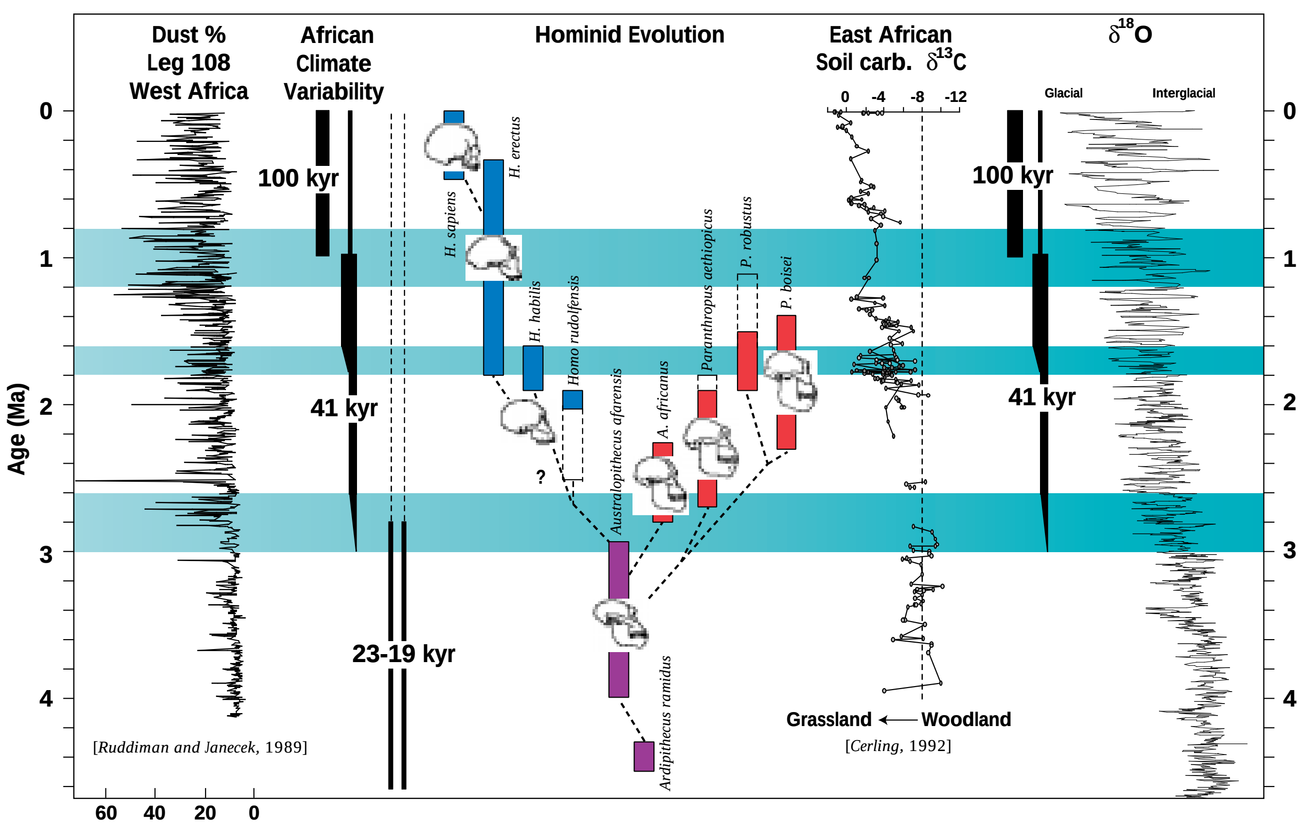
AFRICAN CLIMATE & HUMAN EVOLUTION: THE LAND-SEA CONNECTION

Peter B. deMenocal, Lamont-Doherty Earth Observatory, Columbia University

A comparison of ODP results with anthropological studies suggests that human evolution in Africa may have been influenced by climate change. Detailed records of African climate change during the Pliocene-Pleistocene are rare from geological sequences on land. However, in 1986, ocean drilling on the western marine margin of Africa during ODP Leg 108 recovered a continuous and well-dated record of wind-borne dust, an indicator of atmospheric conditions. Because the export of dust to the ocean is linked to regional precipitation patterns, this record constrains subtropical African climate variability over the past 5 million years. The East African fossil chronology is primarily based on geochemically dated volcanic ash layers. Ash shards from these same eruptions are also found within the marine paleoclimate records providing a correlation between marine and land records.

The monsoonal climate regime of Africa before 2.8 Ma was paced by 21,000-year cycles in low-latitude incoming solar radiation (Earth's orbital precession). Marine records document a shift toward prolonged and seasonally more arid conditions, favorable to grasslands, after 2.8 Ma. (See figure and *deMenocal,* [1995]. All subsequent citations are referenced therein). Other paleoclimate data (e.g., $\delta^{18}O$) and climate modeling results suggest that this shift was the result of cooler North Atlantic sea-surface temperatures associated with the onset of significant Northern Hemisphere glaciation [*Rind et al.,* 1986; *deMenocal et al.,* 1993]. Major steps in the evolution of African hominids [*Wood,* 1995] and other vertebrates [*Vrba,* 1995] coincide with shifts to more arid and open conditions near 2.8, 1.7, and 1.0 Ma, suggesting that the extinction of some species and the evolution of new ones during the Plio-Pleistocene may have been climatically mediated.

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



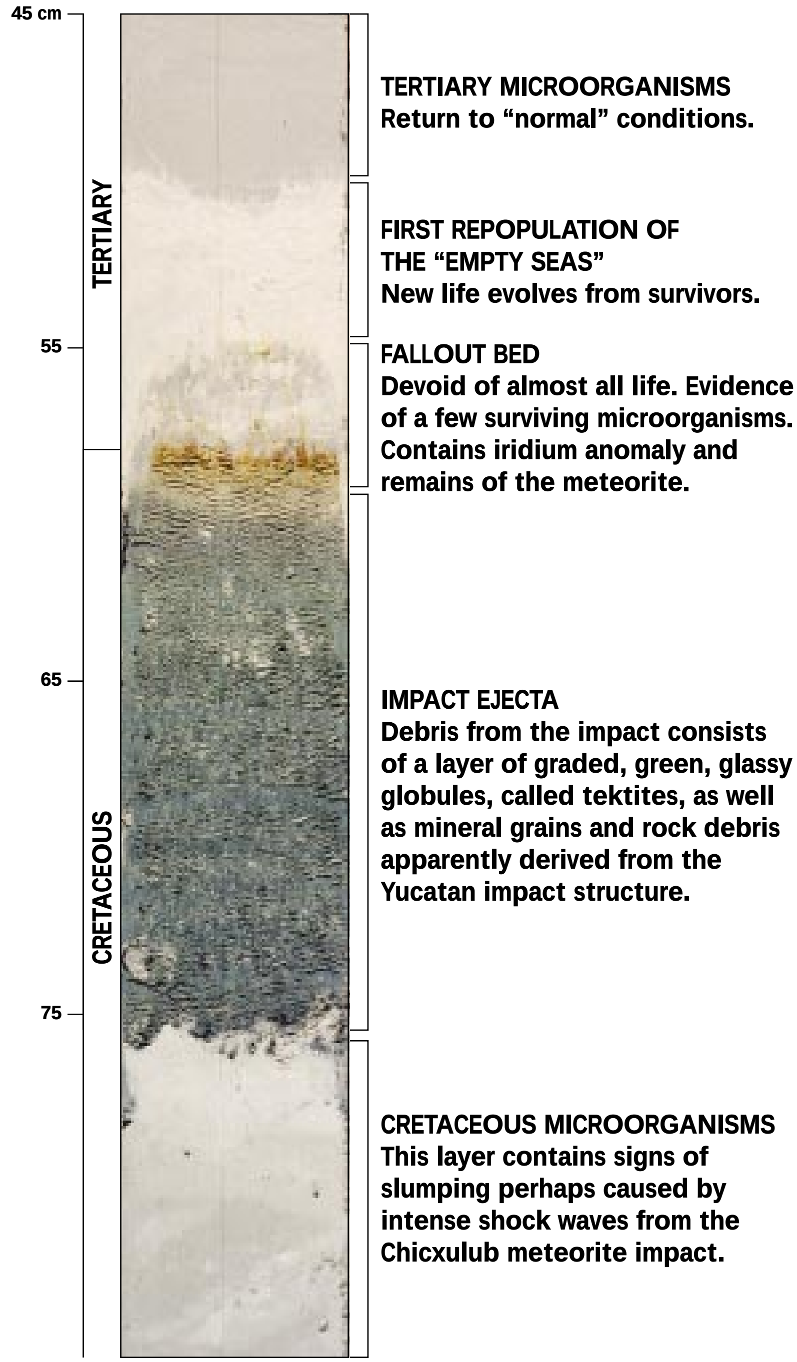
RECORDS OF THE APOCALYPSE: ODP DRILLS THE K/T BOUNDARY

Richard D. Norris, Woods Hole Oceanographic Institution
and the ODP Leg 171B Scientific Party

ODP results from the Atlantic Ocean, 300 miles off northeastern Florida, provide dramatic support for the long-standing theory that a large extraterrestrial object slammed into Earth about 65 million years ago at the Cretaceous-Tertiary (K/T) boundary. This event caused widespread extinctions of perhaps 70 percent of all species, including the dinosaurs. By drilling multiple holes at Site 1049 in 1997, ODP Leg 171B recovered three cores containing sedimentary layers that reveal — in beautiful detail — a cataclysmic story of destruction and biotic upheaval (see photograph). The lowermost impact layer contains a graded bed (6 to 17 cm thick) of green, silica-rich globules produced by the large meteorite impact. This spherule layer, which contains Cretaceous planktic foraminifera, forms a sharp contact with underlying nannofossil ooze (soft, microfossil-rich sediment) that was deposited before the catastrophe. The spherule layer also contains mineral grains and rock debris from the Chicxulub crater on Mexico's Yucatan Peninsula, the site of the presumed meteorite impact, over 1500 km away from Site 1049. The thin, rusty brown layer and the dark gray layer of bioturbated nannofossil ooze above it passes upwards into white nannofossil ooze of early Tertiary age, when survivors of the fireball repopulated the oceans. Notably, the dark gray ooze atop the rusty horizon contains only a few species of minute Cretaceous planktonic foraminifera suggesting that the spherule bed, and the bolide impact that produced it, were associated with a massive collapse of the oceanic ecosystem. Spherules were not observed at the K/T boundary at nearby Sites 1050 and 1052, although rocks from both the earliest Tertiary and the latest Cretaceous were recovered. The impact debris at these sites may have slumped into deeper water shortly after the impact debris fell from the sky, settled through the ocean, and arrived on the seafloor. These new ODP cores hold great research potential because unlike most K/T layers, those from Leg 171B are soft, unlithified, and the microfossils are extremely well preserved. This will enable scientists to conduct high-quality geochemical and paleontological studies of the post-apocalyptic repopulation of the ocean.

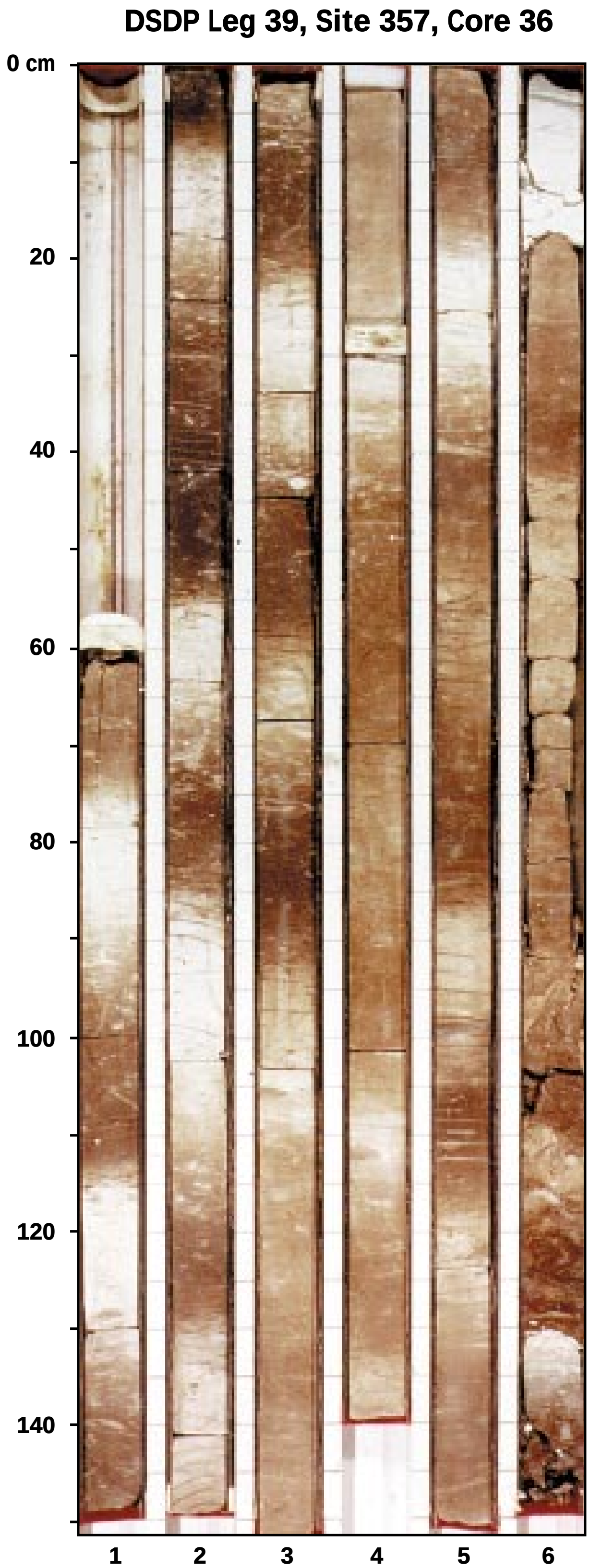
Cretaceous/Tertiary Boundary meteorite impact

ODP Leg 171B, Site 1049, Core 1049A, Section 17X-2



CLIMATE PERIODICITY IN "ICEHOUSE" AND "GREENHOUSE" WORLDS

Timothy D. Herbert, Department of Geological Sciences, Brown University



Campanian age (circa 75 Ma) carbonate cycles at DSDP Site 357 (Rio Grande Rise, Atlantic). Sediment variability reflects periods of enhanced carbonate production (light beds) and clay mineral deposition (dark beds) paced by Earth's 23,000-year precessional cycle.

Deep-sea sedimentary records show shifts between glacial and warmer climates that are surprisingly periodic, and even predictable, over the last two to three million years of so-called "icehouse" conditions on Earth. Statistical analyses link these climatic cycles to periodic variations in seasonal heating resulting from, and indeed paced by, subtle changes in Earth's orbital geometry. These results beg the question, "What kind of cycles are observed in the much more ancient past, when factors controlling the climate system were operating in a significantly different manner?" To address this, we analyzed DSDP cores from the late Cretaceous (84 - 65.5 Ma), a time of warm "greenhouse" conditions, when Earth was essentially ice-free. Variations in Cretaceous climate modulated the types of sediment that formed, thus affecting sediment color (see photo). We measured variations in light intensity of these colors and observed a dominating cycle with a 23,000-year periodicity. This cycle, which closely matches Earth's precessional orbital cycle, is also observed in geologic records from the more recent "icehouse" world. The causal link between the sedimentary and orbital cycles is supported by the fact that this Cretaceous cycle shows amplitude modulations — patterns of constructive and destructive interference — that are characteristic of Earth's precessional cycle. These oscillations have been observed continuously for stretches as long as 20 m.y., and have been correlated among widely disparate drill sites using magneto- and biostratigraphy. Such observations tell us that Earth's ancient climate was sensitive to small changes in incoming solar radiation, even without the amplifying effects of continental ice sheets that exist in today's "icehouse" world. In addition, the cycles act as celestial "clocks" enabling geologists to measure time in the rock record at high precision, and across critical events, such as the biological upheaval at the Cretaceous-Tertiary mass extinction [*Herbert and D'Hondt,* 1990].

Reference:

Herbert, T.D., and S.L. D'Hondt, Precessional climate cyclicity in late Cretaceous-early Tertiary marine sediments: A high resolution chronometer of Cretaceous-Tertiary boundary events, *Earth & Planetary Science Letters, 99,* 263-275, 1990.

ODP AT THE WATER'S EDGE: DEFINING THE HISTORY OF SEA-LEVEL CHANGE

Gregory Mountain, Lamont-Doherty Earth Observatory, Columbia University, and
Kenneth G. Miller, Lamont-Doherty Earth Observatory, Columbia University, and Department of Geological Sciences, Rutgers University

The stratigraphic record is replete with evidence that ocean shorelines have advanced and retreated throughout geologic time, with large consequences for nearshore ecosystems, material and chemical balances of the ocean, and global climate. Available data cannot determine whether these changes occurred synchronously around the globe, implying a mechanism that drives planetary sea level, or were the result of local processes such as tectonism and sediment supply. ODP is uniquely suited to address this question, and a plan is underway to: (1) date sea-level changes caused by fluctuations in global ice volume by using $\delta^{18}O$ (an ice-volume proxy) studies of deep-sea sediments, (2) determine the magnitudes of global sea-level ("eustatic") changes by drilling carbonate platforms and passive margins, and (3) evaluate relationships between local and eustatic variations by drilling thickly sedimented continental margins.

In 1993, Leg 150 exploited the latter strategy by drilling into the New Jersey continental slope as part of a multi-leg transect from the continental rise to the coastal plain (see figure and *Miller et al.*, [1996]). Major Oligocene-Neogene gaps in sediment deposition on the slope, determined from analysis of ODP cores, were found to match the age of ice buildups determined by $\delta^{18}O$ measurements, which correspond to sea-level lowerings. These breaks in sediment deposition are typically overlain by redeposited sediment, which was transported downslope during times of lowered sea level. These same gaps have been cored on shore in locations beneath the New Jersey coastal plain, but the most sensitive and instructive record of sea-level change is buried within the intervening shelf, some of which was drilled by ODP in 1997. We expect that shelf drilling results will substantiate an ice-based mechanism for global sea-level change since 33 Ma, but they may also reveal leads and lags between the time of eustatic changes and their effects on sediment deposition. These phase relationships and the spatial distribution of sediments during sea-level oscillations must be understood to accurately interpret the geologic record of sea-level changes observed elsewhere. A future challenge will be to examine times when Earth was probably ice-free (e.g., the mid-Cretaceous) to learn why stratigraphic gaps were as widespread and frequent then as they have been since 33 Ma.

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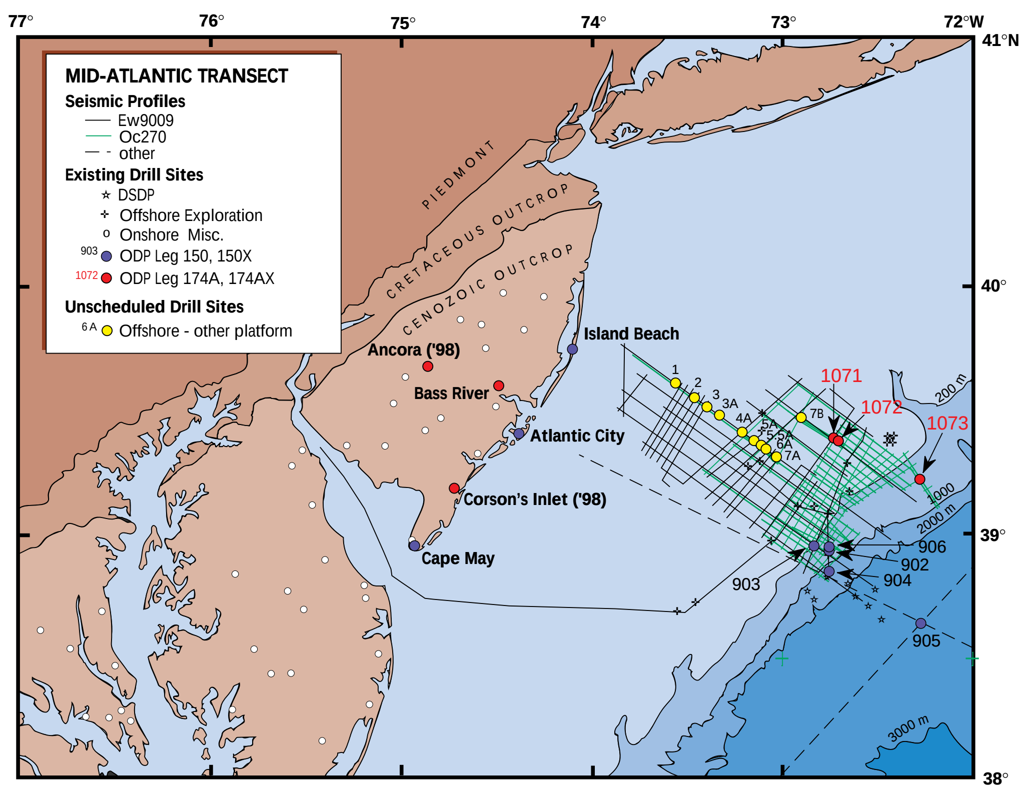


Location map of Mid-Atlantic Transect drill sites. Each offshore site is tied through the 120-channel *Maurice Ewing* seismic grid that is shown. Legs 150 (1993) and 174A (1997) were drilled by ODP. Onshore boreholes, legs with the "X" designation, are part of this sea-level transect, and were drilled from 1993 through 1997. Sites designated as *other platform* locations have not yet been drilled, and will require a platform other than *JOIDES Resolution* to complete.

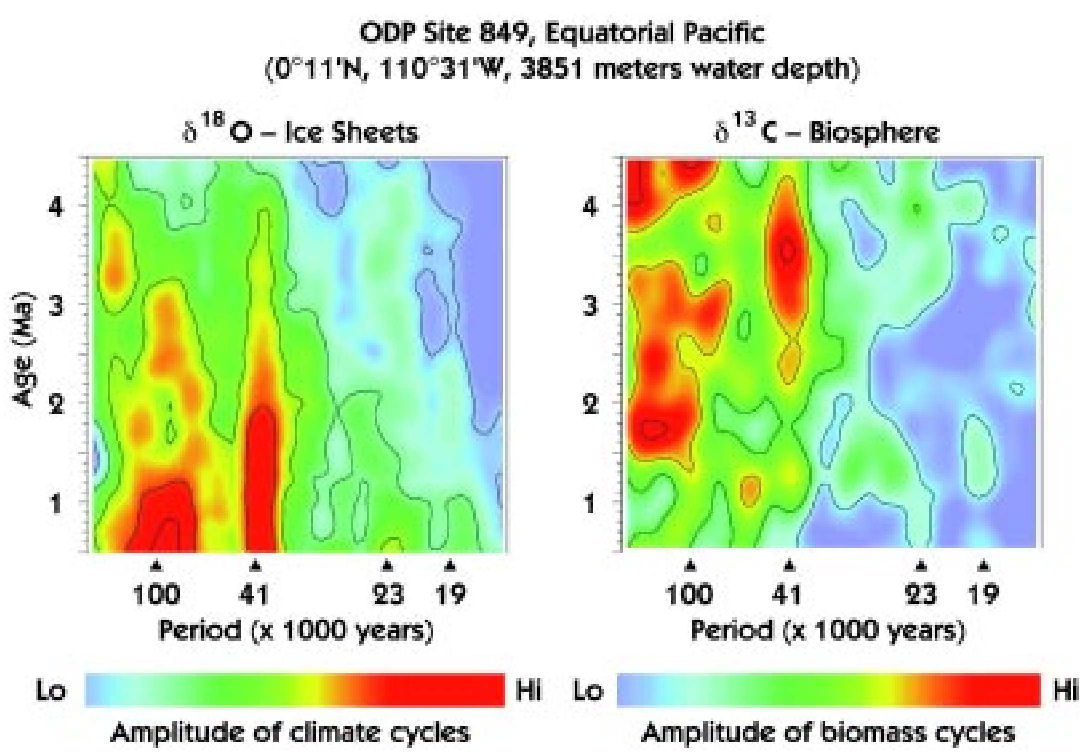
DOES EARTH'S BIOSPHERE SET CLIMATE SENSITIVITY?

Alan C. Mix, College of Oceanic and Atmospheric Sciences, Oregon State University

How did the ice ages begin, and why did they end? Does the biosphere amplify or stabilize climate change? Clues to these questions are found in the isotopic ratios of oxygen ($^{18}O/^{16}O$, or $\delta^{18}O$) and carbon ($^{13}C/^{12}C$, or $\delta^{13}C$) preserved in the skeletal remains of seafloor dwelling microorganisms (foraminifera) recovered from ODP Site 849, in the deep Pacific Ocean [*Mix et al.,* 1995]. Changes in $\delta^{18}O$ primarily track the size of continental ice sheets, while those in the $\delta^{13}C$ mostly reflect global variations in the amount of carbon stored in organic matter — Earth's biomass.

The most persistent signal in ice-sheet fluctuations has a periodicity of 41,000 years, which matches cyclic changes in the tilt of Earth's rotational axis. The amplitude of this climate signal, that is, the size of the undulations from large to small ice sheets, has increased towards the present (see figure). Additional climate periodicities, near 100, 23, and 19 thousand years, which correspond to other changes in Earth's orbital geometry, have also grown stronger through time. On the other hand, a long-period cycle near 400,000, observed prior to 3 Ma, when Earth's only major ice sheet was in Antarctica, weakened after 3 Ma when ice sheets first began to cover the Northern Hemisphere as well. Although isotopic cycles occur throughout the record, their total amplitude has grown over time. Why? Maybe the biosphere ($\delta^{13}C$) is responsible.

Cycles with similar periods are observed in the $\delta^{13}C$ data, but swings in the size of Earth's biomass have decreased with time, unlike those in ice sheet size. For example, at the 41,000 period, the greatest amplitudes in $\delta^{13}C$ predate 3 Ma, while the opposite is true for $\delta^{18}O$. Longer-period $\delta^{13}C$ cycles were also strongest in the distant past, between about 1.5 and 3 Ma and prior to 4 Ma. One explanation for these $\delta^{13}C$ patterns is that global biomass was larger (and thus more changeable) in the past, and herein may lie the link to climate. A more active biosphere might stabilize climate by regulating carbon dioxide, a greenhouse gas, absorbing it when atmospheric and oceanic levels were high, and releasing it when they were low. When ice sheets began to invade the polar regions of North America and Europe, about 3 Ma they stripped off a thick mantle of forests and soils, and desiccated large land masses. This long-term loss of biomass may have sensitized Earth's climate system to change, and over time amplified the ice-age cycles.



Statistical analyses of microfossil isotope data reveal the changing strengths of climate and biosphere rhythms over the past 4.5 m.y. Warmer colors indicate stronger cycles, with larger amplitudes.

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RAPID CLIMATIC AND OCEANOGRAPHIC CHANGE IN SANTA BARBARA BASIN

James P. Kennett, I. Hendy, and Kevin Cannariato,
Department of Geological Sciences and Marine Science Institute, UC Santa Barbara,
and Richard J. Behl, Department of Geological Sciences, California State University, Long Beach

Understanding the nature and mechanisms of rapid climate change and related biospheric responses is critically important to current discussions of global climatic stability and perturbation. Two cores taken during ODP Leg 146 at Site 893 in 1992 represent the highest resolution sedimentary record of oceanic environmental and biotic changes over the last 160,000 years yet recovered from anywhere in the ocean, and provide unique opportunities to study rapid climate change.

The Santa Barbara Basin record shows strong evidence for major instability of the marine environment and ecosystem off coastal California during the late Quaternary [*Kennett & Ingram,* 1995; *Behl & Kennett,* 1996]. This instability occurs over a range of time-scales, but is most dramatically shown in association with a sequence of 18 Dansgaard-Oeschger (D/O) climatic oscillations that occurred during the last 80,000 years [*Behl & Kennett,* 1996]. These extremely rapid and major climatic warming episodes (interstadials) were first recognized in the Greenland Ice Sheet where they have been tied to synchronous CO_2 and methane fluctuations. The Santa Barbara Basin record demonstrates that sea-surface temperatures increased and decreased very rapidly over intervals as short as 50 to 70 years, at both the initiation and termination of the interstadials, as was the case in Greenland. This similarity suggests a remarkably tight coupling between the atmosphere, the Northern Hemisphere cryosphere and hydrosphere. In Santa Barbara, oxygen isotope data indicate that sea-surface temperatures increased up to 7°C in less than 70 years before stabilizing at ~4°C warmer than before the D/O event. An extraordinary feature of this isotopic record are ~0.5‰ $\delta^{18}O$ overshoots occurring near the beginning of the interstadials, producing a sawtooth pattern familiar in other scales of Quaternary climate change. This feature suggests the involvement of brief, strong greenhouse gas feedback mechanisms, associated with the initiation and termination of the interstadials.

The rapid climate changes are linked with equally rapid changes in the oxygenation and ecology of the basin. Upheaval of the benthic (seafloor) ecosystem is reflected by oscillations between laminated and faunally mixed sediments and by changes in benthic foraminiferal species. Benthic assemblages associated with laminated sediments during warm intervals are dominated by taxa that tolerate low oxygen conditions, such as *Bolivina tumida* and *Buliminella tenuata*. Assemblages associated with bioturbated sediments typical of cooler episodes are dominated by taxa typical of oxygenated waters. These fluctuations within Santa Barbara Basin were controlled by oscillations in the oxygenation of intermediate waters along the California margin.

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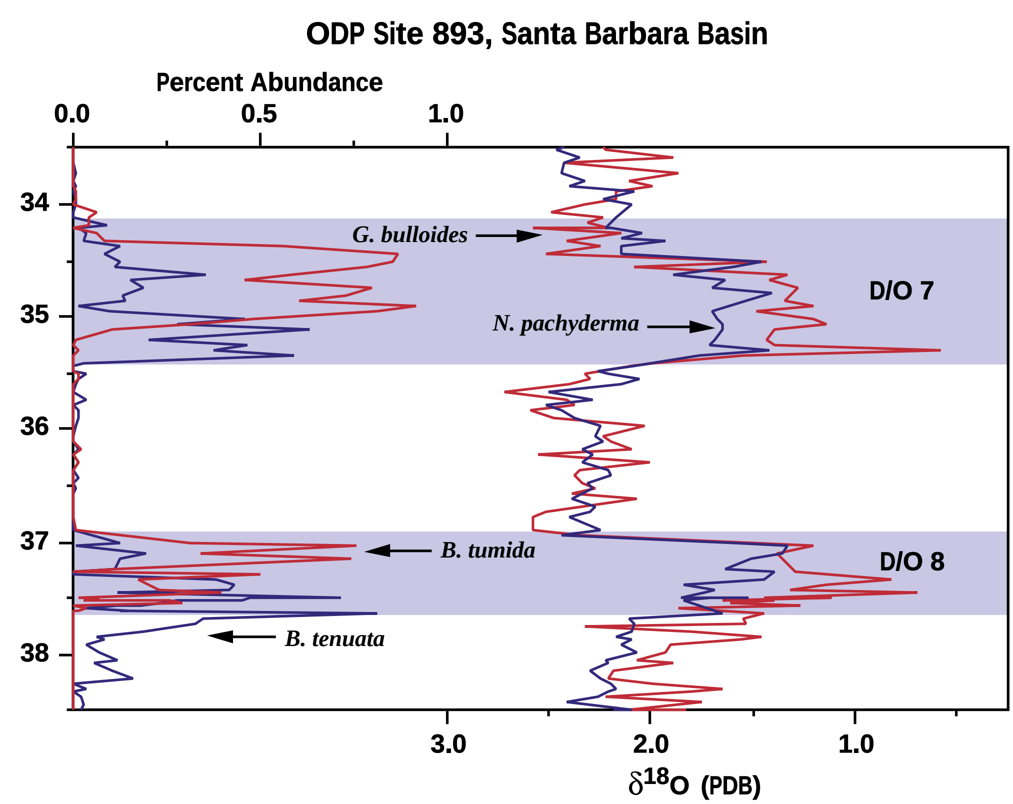
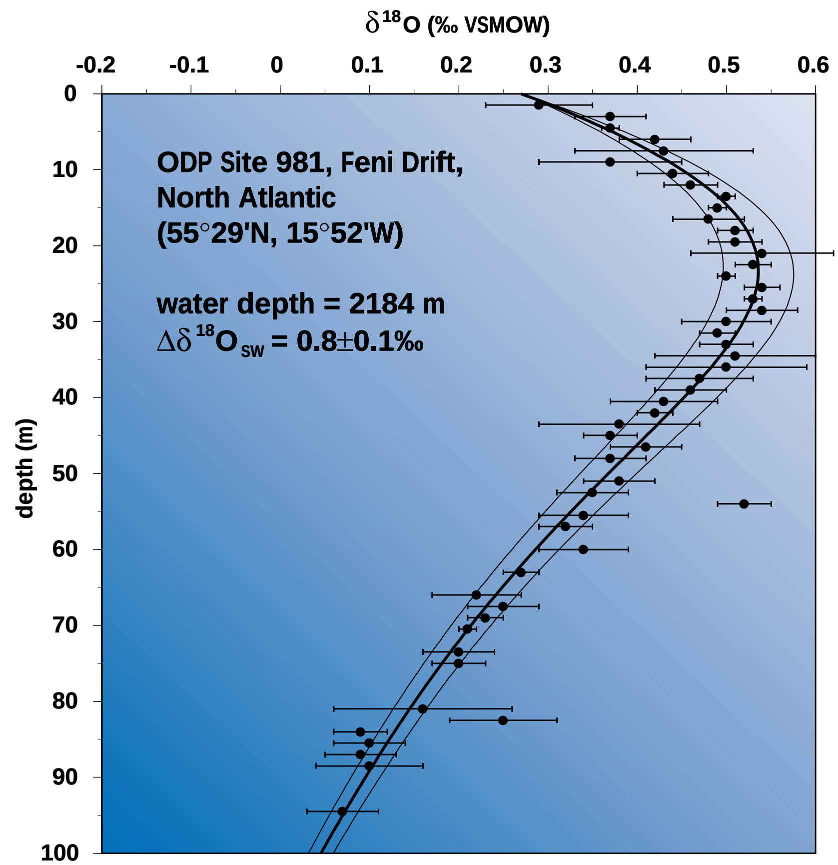


ICE AGE OCEAN TEMPERATURES INFERRED FROM ODP PORE WATERS

Daniel P. Schrag, Department of Earth and Planetary Sciences, Harvard University



To reconstruct past climates and to improve our understanding of climate dynamics, paleoceanographers have focused on key climatic parameters such as ocean temperature and the size of continental ice sheets. To estimate temporal fluctuations in these two, scientists have historically relied upon downcore measurements of the ratio of oxygen isotopes ^{16}O and ^{18}O (i.e., $\delta^{18}O$) in calcareous foraminiferal microfossils. The difficulty of this approach is that foraminiferal $\delta^{18}O$ monitors changes in both temperature and seawater $\delta^{18}O$, the latter of which is primarily due to variations in ice sheet size. Up to now, the challenge has been to disentangle the two signals from the one foraminiferal data set. A new approach — measuring the $\delta^{18}O$ of pore waters squeezed from ODP sediment cores — may resolve the degree to which each parameter contributes to the total change in foraminiferal $\delta^{18}O$. The approach is straightforward. Seawater diffuses into the seafloor leaving a profile of $\delta^{18}O$ versus depth in the sediment column that records the $\delta^{18}O$ history of the overlying seawater, independent of temperature [*Schrag and DePaolo,* 1993]. The depth to which the signal penetrates is determined by the diffusivity of water through the pore spaces. Detailed measurements of pore water $\delta^{18}O$ from the upper 50 m of ODP Site 925 (Leg 154 in 1994), in the tropical Atlantic, enabled us to reconstruct seawater $\delta^{18}O$ during the last ice age [*Schrag et al.,* 1996]. These data suggest that continental ice growth increased the mean $\delta^{18}O$ of seawater by only 1.0‰, 0.3‰ less than previous estimates. New data on North Atlantic samples from Leg 162 (in collaboration with D. Hodell and K. MacIntyre) yield a similar change of 0.9±0.1‰ (see figure). By subtracting these pore water values from the larger foraminiferal values we are able to isolate the temperature component of the isotopic signal. Our data suggest that the deep ocean was ~3°C colder during the ice age and the tropical surface ocean was 2-5°C colder. These results support the argument that the ice age world was colder than some paleoclimatologists previously thought. Detailed sampling of pore waters on future drilling legs will tell us how seawater temperature and $\delta^{18}O$ in the deep ocean varied within and between ocean basins.

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EVIDENCE FOR MICROBES IN OCEANIC BASALTS: GLASS-EATING BACTERIA?

Martin R. Fisk, College of Oceanic and Atmospheric Sciences, Oregon State University

Until recently, conventional wisdom held that Earth's subsurface was a sterile place, devoid of life. Exciting new results, however, indicate that this is far from the truth. Scientists have discovered evidence of organisms deep beneath Earth's crust on both continents and ocean floors. By studying new microbial life-forms, and the incredibly wide range of environments in which they live, we gain a much better understanding of how life began and evolved on Earth, and possibly other planets. To this end, ODP has led the way in collecting subseafloor microbes to evaluate the exciting new paradigm of the so-called deep biosphere. The size of this biosphere is difficult to determine, and will require additional drilling to constrain. The concentration of living material in the oceanic crust is small, but because of the huge global volume of this material, it may contain a significant fraction of Earth's biomass [*Parkes et al.,* 1994]. About 5% of oceanic crust consists of volcanic glass, intuitively a material inhospitable to life. Nevertheless, new microscopic examination and application of molecular genetic techniques on DSDP and ODP basalts collected near the Mid-Atlantic Ridge [*Bougault et al.,* 1985] suggests that the rocks contain ample evidence of microbial life. The idea is that microbial activity, indicated by pitting of the glass, and the formation of intricate and branching burrows, helps weather and erode this volcanically derived material. The microbes may even be "eating" the glass, using it as an energy source. The most typical texture observed microscopically is thin irregular channels, about one µm in diameter and extending 20 to 40 µm into the glass (see photomicrograph). A better understanding of Earth's subsurface biosphere will result by examining other crustal rocks and new samples from future drilling that are free of contamination and are specially preserved immediately after collection. Microbes in volcanic crust may turn out to be important catalysts of chemical change. In this role, they would help regulate the cycling of elements between seawater and the oceanic crust. Microbes that derive their energy from inorganic chemical reactions suggests that life may thrive in previously unsuspected places, such as on Mars and Europa.

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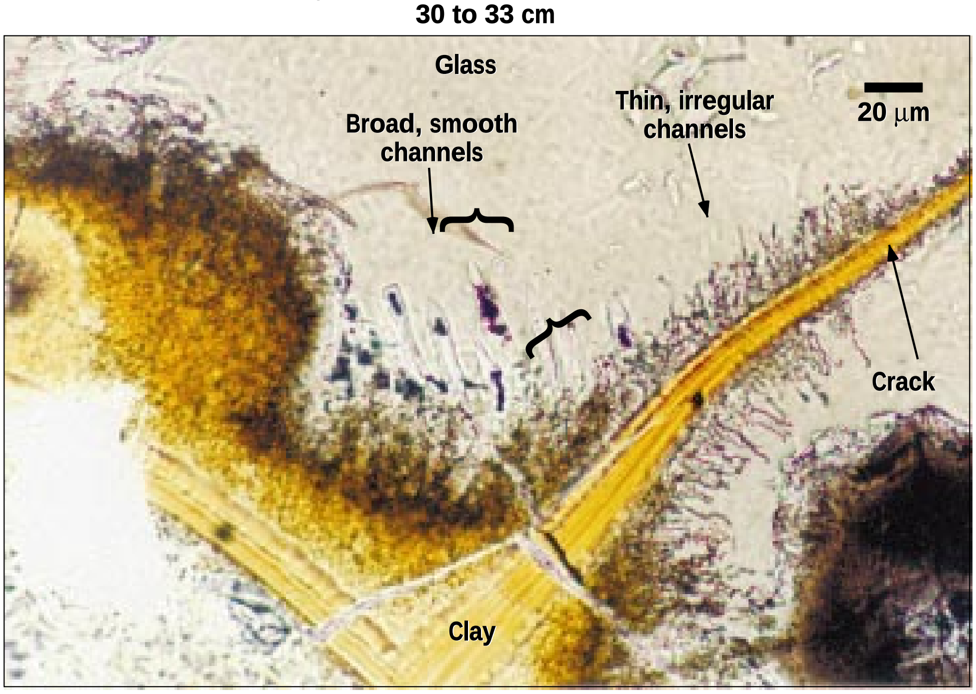
Leg 82, Site 561, Core 1, Section 2
30 to 33 cm



Photomicrograph shows 15 million year old volcanic glass with both thin, irregular and smooth, broad channels thought to have been created by microorganisms [*Furnes et al.,* 1996; *Giovannoni et al.,* 1996]. The volcanic glass also has a crack filled with clay (orange). The sample is from basalt recovered by drilling about 200 km west of the Mid-Atlantic Ridge beneath 400 m of sediment. Rock temperature before drilling was about 40° C.

RECYCLING PROCESSES AND FLUID FLUXES IN SUBDUCTION ZONES

Miriam Kastner, Scripps Institution of Oceanography

Earth's surface is covered by about 43,500 km of active subduction zones, dynamic arcs where one lithospheric plate descends beneath another (see figure). About a dozen of these zones have been sampled by the ODP and imaged by geophysical and geochemical means. The results have advanced our knowledge of (1) the mass fluxes into these systems, (2) the central role fluids play in the mechanical, thermal, and geochemical evolution of subduction zones, and (3) the chemical and isotopic compositions of these fluids. All of these provide new insight into key questions: how does recycling in this tectonic setting affect the chemical budgets of the ocean and mantle on various time scales and what relationships exist between earthquake cycles and the generation and flow of fluids?

The subducting oceanic plate and overlying sediment are porous and contain variable amounts of hydrous and carbonate minerals. With the increasing temperature and pressure that are encountered in subduction zones, compaction, diagenesis, and metamorphism expel fluids at various rates and depths. Chemosynthetic benthic biological communities, sustained by venting volatiles (i.e., H, C, O, N, S), are the most direct evidence that significant amounts of fluids are expelled and returned to the ocean [*Kulm et al.,* 1986]. These fluids are chemically and isotopically very different from seawater, therefore, their fluxes must be known to better understand these communities and global geochemical budgets.

The most important characteristic of these fluids is that they are fresher than seawater. When normal seawater mixes with water that is driven off hydrous minerals, the chloride concentration in the resulting fluid is depleted by 20 to 65 percent [*Kastner et al.,* 1991]. Subduction zone fluids are also enriched in B, Li, Ca, Sr, and Ba and have variable H, O, C, B, Cl, and Sr isotope ratios. High methane concentrations are also characteristic of many subduction zones, often leading to the formation and accumulation of gas hydrate deposits when appropriate temperature and pressure levels are encountered. Methane hydrate is the most common natural gas hydrate in the marine environment, storing about 10,000 gigatons of carbon globally [*Kvenvolden,* 1988]. Subduction zone fluids also reach great depths and have been incorporated in magmas, as demonstrated by ^{10}Be and ^{207}Pb data in volcanic arcs. Such recycling is also reflected in the minor and trace element chemistry of arc magmas [*Tera et al.,* 1986, *Plank and Langmuir,* 1993]. Compared to mid-ocean ridge basalts, these magmas are enriched in water, B, Be, Sr, Ba, K, Rb, Sc, Pb, and U. In the early stages of subduction zone development, the pathways for flow are both diffuse and focused. Over time, however, compaction, deformation, and cementation increase the importance of focused flow, which becomes dominant.

Because the estimated global flux of fluids expelled by tectonic compaction and dehydration of the sediments and oceanic slab is 2 to 3 km^3/yr [*Von Huene and Scholl,* 1991], extrapolation suggests that all seawater in the global ocean cycles through subduction zones within 350 to 500 million years. The chemical and isotopic significance of such a global fluid flux is rather small. For example, this flux has no more than one to two percent of the impact that global networks of rivers and hydrothermal systems have on the rates at which the seawater levels of ^{87}Sr/^{86}Sr and Li change. However, geologists know that hydrologic flow, including the meteoric (e.g., rain) component, which returns to the ocean through continental margins, is much larger. How much of this hydrologic flow occurs through subduction zones is important, yet still entirely underconstrained. If we assume a hydrologic flow of 70 to 100 km^3/yr when constructing a global mass balance, then the chemical and isotopic fluxes of some elements and isotope ratios are considerable, perhaps equal to or even exceeding riverine or hydrothermal fluxes.

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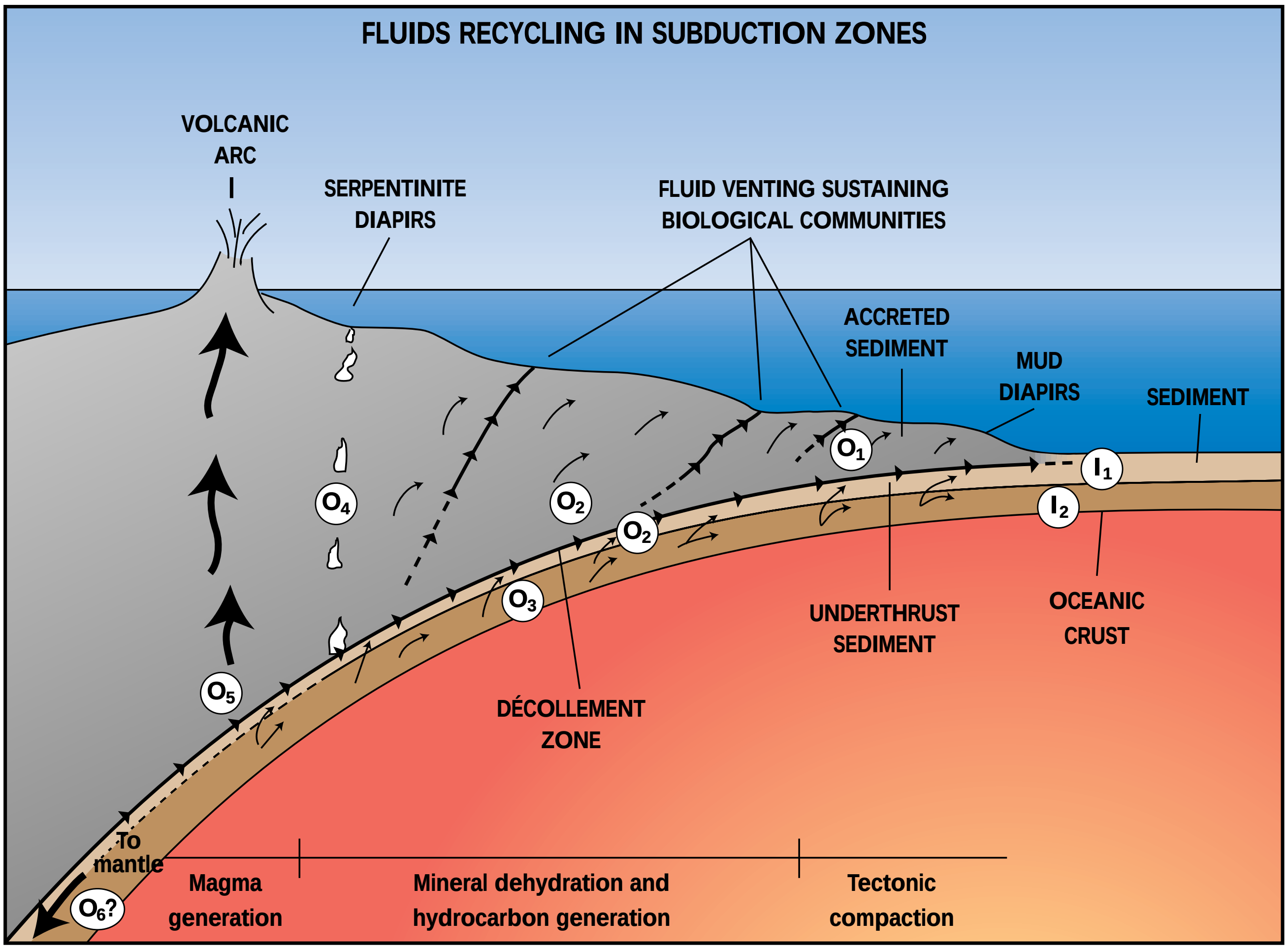


I = Input O = Output

= Diffuse fluid flow

= Focussed fluid flow along the décollement and other high permeability faults

FLUID MASS BALANCE

$I_1 + I_2 = O_1 + O_2 + O_3 + O_4 + O_5 + O_6 + R$

I_1 = Sediment with pore fluid

I_2 = Hydrated oceanic crust

O_1 = Tectonic compaction

O_2 = Dehydration of hydrous minerals and hydrocarbon generation

O_3 = Dehydration of oceanic crust

O_4 = Serpentinization and diapirism

O_5 = Magma generation

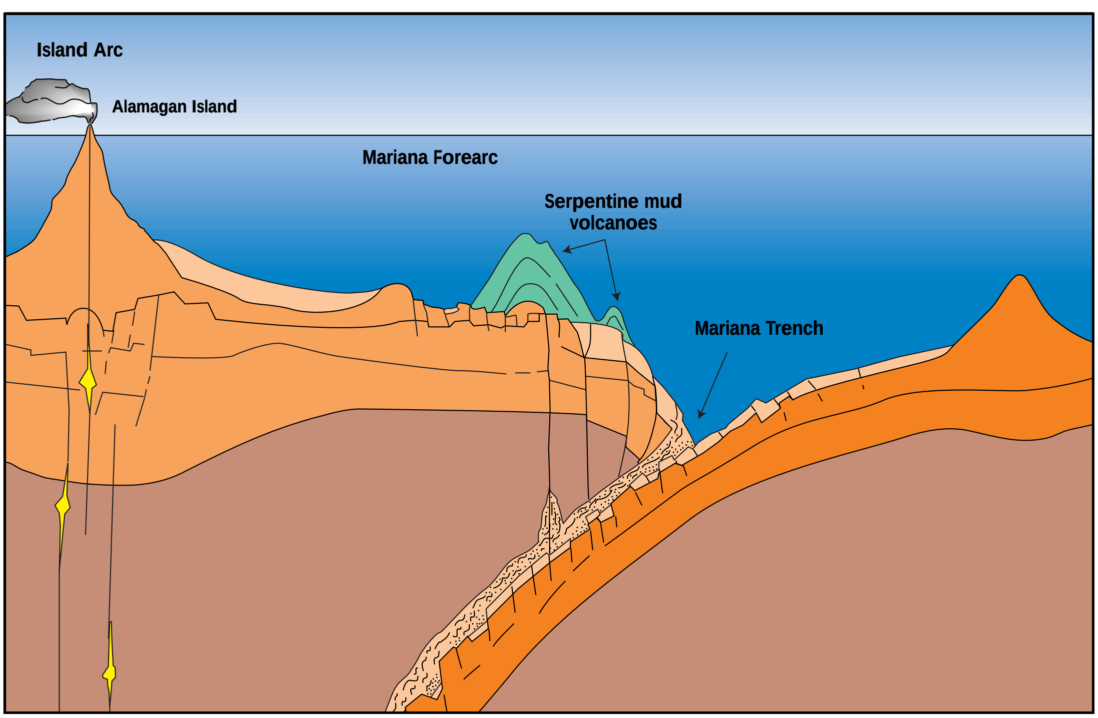
O_6 = To mantle (?)

R = Residual fluid

ODP DISCOVERS MUD VOLCANOES FROM THE MANTLE

Patricia Fryer, Hawaii Institute of Geophysics and Planetology, SOEST, University of Hawaii

Undersea volcanoes, oozing green, asbestos-rich mud, were discovered just west of the Mariana Trench in the western Pacific. Seafloor volcanoes are normally composed of molten lava, but the unusually large (more than 25,000 m in diameter and 2,000 m high) “Conical Seamount” mud volcano was formed by gradual build up of low-temperature, fine-grained, unconsolidated serpentine flows. Serpentine, an asbestos mineral, is formed when water is mixed with rock material originating from the mantle, tens of kilometers below the seafloor. The flows carrying the serpentine and other rocks formed by chemical transformation under elevated temperatures and pressures (metamorphism), move upward to the seafloor along deeply penetrating faults that extend down to the subducting plate. Water, an essential ingredient for metamorphism of the mantle to serpentine, is squeezed from the downgoing slab and percolates upwards, due to its lower density. Our first efforts to sample this volcano, to learn more about its origin, involved shipboard dredging of rocks and muds from the volcano’s surface. Sonar imaging of the seafloor indicated large flows, and submarine investigation proved these to be composed of serpentine muds. However, drilling was required to truly understand the internal mechanics of Conical Seamount, and the origin of the fluid. With these goals in mind, ODP Leg 125 penetrated the summit and flanks of the volcano in 1989 and confirmed that the entire edifice, and not just the surface, was composed of serpentine mud flows. Furthermore, drilling provided the first evidence that fluids derived from the down-going plate were actively emanating from the seamount. The composition of these fluids is unique in the world’s oceans. For example they are more basic (pH of 12.6), than any ever measured from the deep ocean. ODP also recovered rock fragments in the muds that could only have formed at great depths (tens of km), most likely from the subducting plate. This observation proved that the routes for the slab-derived fluids likely penetrate to the décollement, the contact between the overriding and subducting plates. The mantle rock fragments recovered by ODP are remarkably uniform in composition. The important implications of this are that the rising fluids are will be subjected to a less complex range of chemical interactions on their journey to the seafloor than would occur in more lithologically variable regions. As such, the Mariana serpentine seamounts are an excellent place to study slab-derived fluids that are more pristine than those collected elsewhere, such as at accretionary sedimentary wedges. Scientists need to understand the fluxes and compositions of slab-derived fluids from these locations, and others world-wide, in order to determine the subduction-related contribution to global mass balance. Because these seamounts are the only serpentine mud volcanoes known to be active, they provide the optimal site for such studies.



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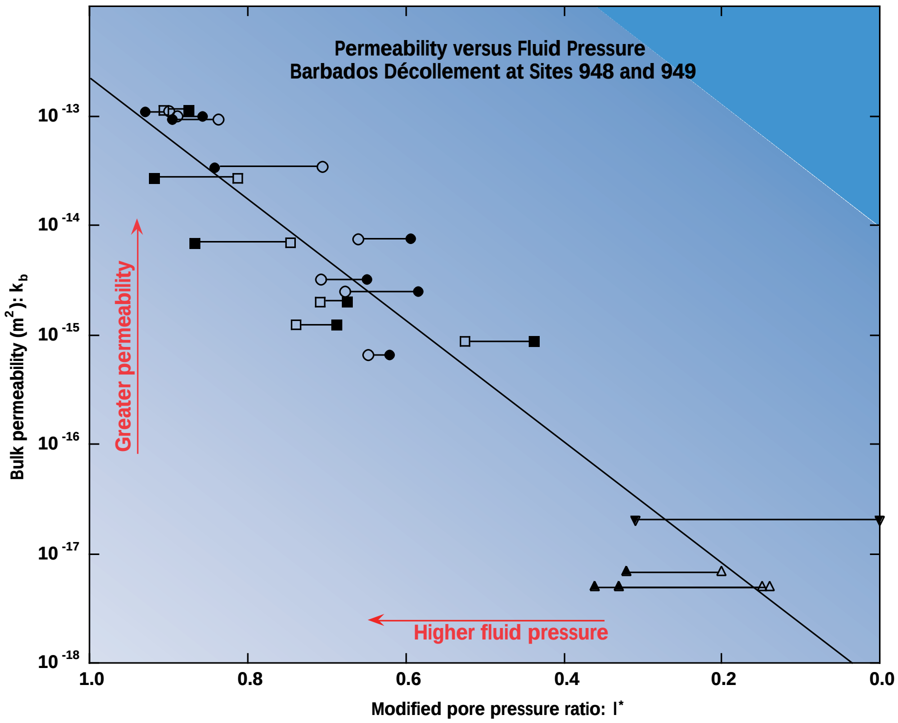
THE ROLE OF WATER WITHIN FAULT ZONES

Andrew T. Fisher, Institute of Tectonics and Earth Sciences Department, University of California, Santa Cruz,
Elizabeth Screaton, Department of Geological Sciences, University of Colorado,
Gretchen Zwart, Earth Sciences Department, University of California, Santa Cruz,
Keir Becker, Department of Marine Geology and Geophysics, RSMAS, University of Miami, and
Earl Davis, Pacific Geoscience Centre, Geological Survey of Canada

Geologists have long been aware that water plays an important role in enabling Earth's tectonic plates to slide past one another. When water is present along a fault, it may help lubricate the fault surface. When water is under pressure within a fault, it may bear some of the load of the overlying sediments and rock, and allow these materials to glide past each other over long distances. This motion takes place with or without earthquakes.

Scientists have examined the roles of water within fault zones in many settings. One area subjected to particularly intense research is the boundary between the North American and Caribbean plates, northeast of Barbados, where the two plates are moving towards each other at a rate of several centimeters per year. As these plates collide, and the North American plate is thrust under the Caribbean plate, a large wedge of sediment is scraped off and piled into a thick wedge. The island of Barbados is the tip of this sediment wedge, or "accretionary complex."

Two geologic properties of great interest to scientists working in this area are fault permeability and fluid pressure below the accretionary complex, along the fault that separates the wedge from the underlying plate. Permeability is a measure of the ease with which fluid can move through rock. It has been hypothesized that the fault below the Barbados wedge is very permeable and that the fluids within the fault are under great pressure.



Effective bulk permeability versus pore-fluid pressure along the décollement of the Barbados accretionary complex. These are results from borehole aquifer tests during ODP Leg 156 (circles and squares used for two different kinds of tests) at Sites 948 and 949, and from CORK tests conducted during a subsequent submersible expedition to Site 949. The range of values shown for each permeability (closed and open symbols joined by a line) indicate the range in fluid pressures during each test. The modified pore pressure ratio is fluid pressure normalized to the weight of the overlying sediment; using this value rather than absolute fluid pressure allows data from the two sites to be combined. The line through the data illustrates the apparent relation between permeability and fluid pressure in this setting.

The first direct measurements of permeability and fluid pore pressure along this fault were completed at two sites during ODP Leg 156 in 1994. These measurements suggest that: (1) fluid pressures are high along the fault, (2) permeability is also relatively high along the fault, and most interestingly, (3) permeability varies with fluid pressure within the fault [*Fisher and Zwart,* 1996 and in press]. Leg 156 test results are also consistent with a variety of independent, but less direct estimates based on chemical and thermal observations and modeling.

These Leg 156 data were complemented by additional information collected from a long-term borehole seal and instrument package that was left in one of the holes during the ODP expedition [*Screaton et al.,* 1997]. This hole was visited by submarine 18 months after the drilling expedition to retrieve the long-term data and to conduct additional hydrologic tests. The long-term record confirms that fluids within the fault below the sediment wedge are under great pressure, and the new tests are consistent with the idea that permeability varies with fluid pressure. These results should help scientists better understand how these kinds of faults work, and how fluid pressures influence tectonic and earthquake cycles.

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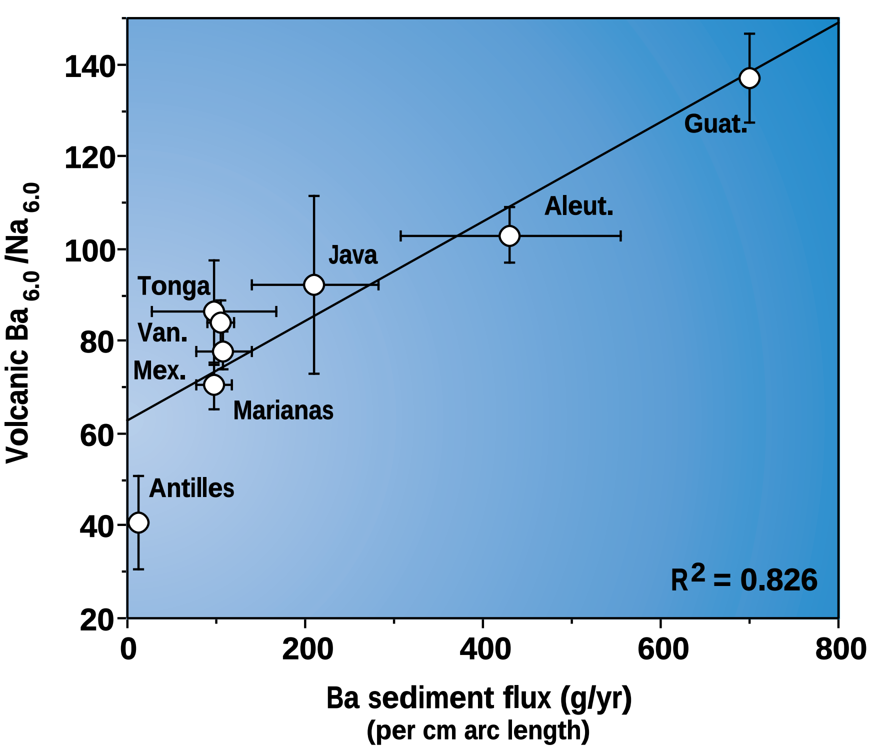
SEDIMENT RECYCLING AT SUBDUCTION ZONES: THE INS AND OUTS OF ARC VOLCANOES

Terry Plank, Department of Geology, University of Kansas, and
Charles Langmuir, Lamont-Doherty Earth Observatory, Columbia University

As the tune goes: "What goes up, must come down..." Deep-sea drilling at trenches, however, shows us that what goes down, must come up. That is, mud and ooze on the seafloor plunge more than 100 km into the mantle at subduction zones, before portions rise again in magmas that erupt around the Pacific, in the Ring of Fire. We can't see the sediment sink all the way into the deep mantle, but we can use chemical tracers to see where they end up. This technique requires drilling, because there are no remote ways to measure chemical tracers in deep-sea sediment. Few ODP or DSDP drill sites have been specifically targeted to address this issue, but many "holes of opportunity" exist near trenches, where sediments begin their descent into the mantle.

Some isotope tracers, such as ^{207}Pb and ^{10}Be, provide strong evidence that sediment components are "recycled" into volcanoes [*Woodhead*, 1989; *Tera et al.*, 1987]. Although volcanic lavas clearly preserve isotopic imprints of marine sediment, strong evidence linking the exact sediment in the trench to the nearby volcanoes has come to light more slowly. Analysis of many drill cores near trenches (ODP Legs 123 and 129 in particular) reveals large ranges in the flux of element tracers (e.g., Ba, Sr, Th), with each sediment column possessing its own geochemical fingerprints [*Plank and Ludden*, 1992; *Plank and Langmuir*, 1997]. For example, the figure shows an order of magnitude variation in the sediment Ba flux for different trenches around the globe [*Plank and Langmuir*, 1993]. By obtaining data for lavas from the nearby volcanoes for the same tracers, we find that the volcanoes are clearly influenced by the sediments. The correlation in the figure shows that where the subduction flux of sedimentary Ba is high, the volcanoes erupt Ba-enriched lavas. Thus some of the geochemical characteristics of arc volcanics are ultimately derived from sedimentological processes in the oceans, illustrating a remarkable linkage of processes across the hydrosphere and lithosphere.

What goes down doesn't all come back up; some keeps going down. A mass balance of the inputs and outputs at several convergent margins suggests that only 20-50% of the subducted sediments are recycled to the arc, with the remainder possibly continuing down into the deep mantle. Because sediments are ultimately derived from the continents, this downward flux is a net loss of mass from the continents, and through time, slows the growth of the continents. Current flux estimates are based on individual element or isotope tracers. We still have a poor understanding of what the sediments actually do when they subduct, how they separate into material that rises in magmas and sinks with the subducting plate [*Scholl et al.*, 1996]. Future drilling will help us move beyond mass balance of tracers, and learn much more about the rock recycling process, or how that spinning wheel goes round...



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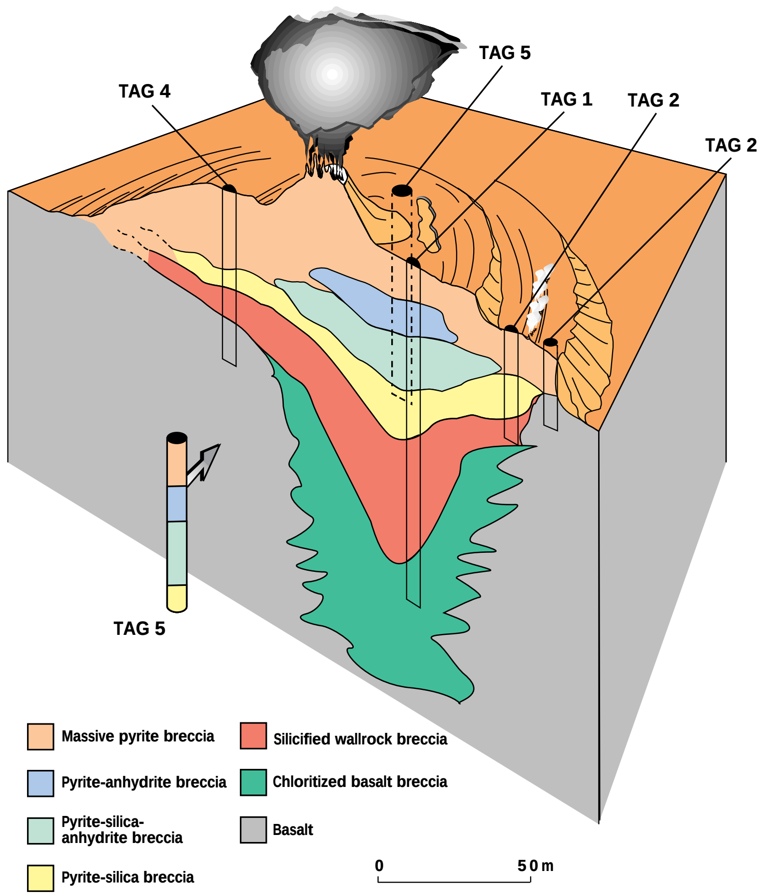
ODP REVEALS THE ANATOMY OF AN ACTIVELY FORMING SEAFLOOR MINERAL DEPOSIT

Susan E. Humphris, Department of Geology and Geophysics, Woods Hole Oceanographic Institution

Metal ore bodies contained within massive sulfide deposits, such as on the island of Cyprus, are thought to have formed long ago and at great depths in the ocean. There, hydrothermal circulation of seawater through oceanic crust at mid-ocean ridges gives rise to complex rock-water interactions that produces sulfide deposits. To better understand their origin, characteristics, and distribution, we study actively forming deposits by drilling into them. Our results enable us to test and revise models that have been put forward to explain the genesis of these sulfide deposits. Such models may be used to prospect for ore bodies**.**

Drilling during ODP Leg 158 in 1994 at the Trans-Atlantic Geotraverse (TAG) site on the Mid-Atlantic Ridge revealed for the first time the size and internal structure of an active massive sulfide deposit and the underlying stockwork that is forming on young, unsedimented oceanic crust. The stockwork is a three-dimensional deposit of dense mineral veinlets. With an estimated 30,000-60,000 metric tons of copper in the deposit, the TAG site is comparable in size to the largest 30% of the Cyprus-type ore deposits. The bulk of the deposit consists of a heterogeneous assemblage of cemented angular rock fragments (breccias) composed of pyrite/marcasite, chalcopyrite, quartz, and anhydrite (calcium sulfate). This deposit records a complex depositional history reflecting multiple cycles of active growth, separated by periods of dissolution of anhydrite, dislodgement and downslope transport, and brecciation [*Humphris et al.,* 1995]. Material deposited during earlier episodes of hydrothermal activity is overgrown by later generations of minerals, and is progressively cemented or replaced by quartz, sulfides, and anhydrite. Over long periods of time, hydrothermal reworking remobilizes metals from the massive sulfides and concentrates them at the top of the deposit.

New evidence from the internal structure of this TAG deposit has been used to reinterpret the origin of several important ore types. A key observation is the abundance of anhydrite, a mineral that is saturated in seawater at temperatures of 150°C or greater, but undersaturated below that. As such, anhydrate is uncommon and poorly preserved in fossil deposits. Circulation of seawater within the deposit, and precipitation of anhydrite as the seawater is heated both by mixing with hydrothermal fluid and by conduction of heat from below, plays a critical role during the construction of the TAG deposit. However, during periods of inactivity and cooling, anhydrite dissolution leads to collapse of the mound and extensive brecciation. The possible magnitude of this effect is indicated by the estimate, based on the drilling results, that the TAG mound currently contains about 165,000 metric tons of anhydrite. This important mechanism for the formation of breccias provides a new explanation for the origin of similar breccia ores observed in ancient massive sulfide deposits.



Sketch of the active Trans-Atlantic Geotraverse (TAG) hydrothermal mound showing the generalized internal structure and mineralogic zones as revealed by drilling (modified from Humphris et al., [1995]).

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ODP DRILLS GAS HYDRATES, THE WORLD'S LARGEST SOURCE OF FOSSIL FUEL

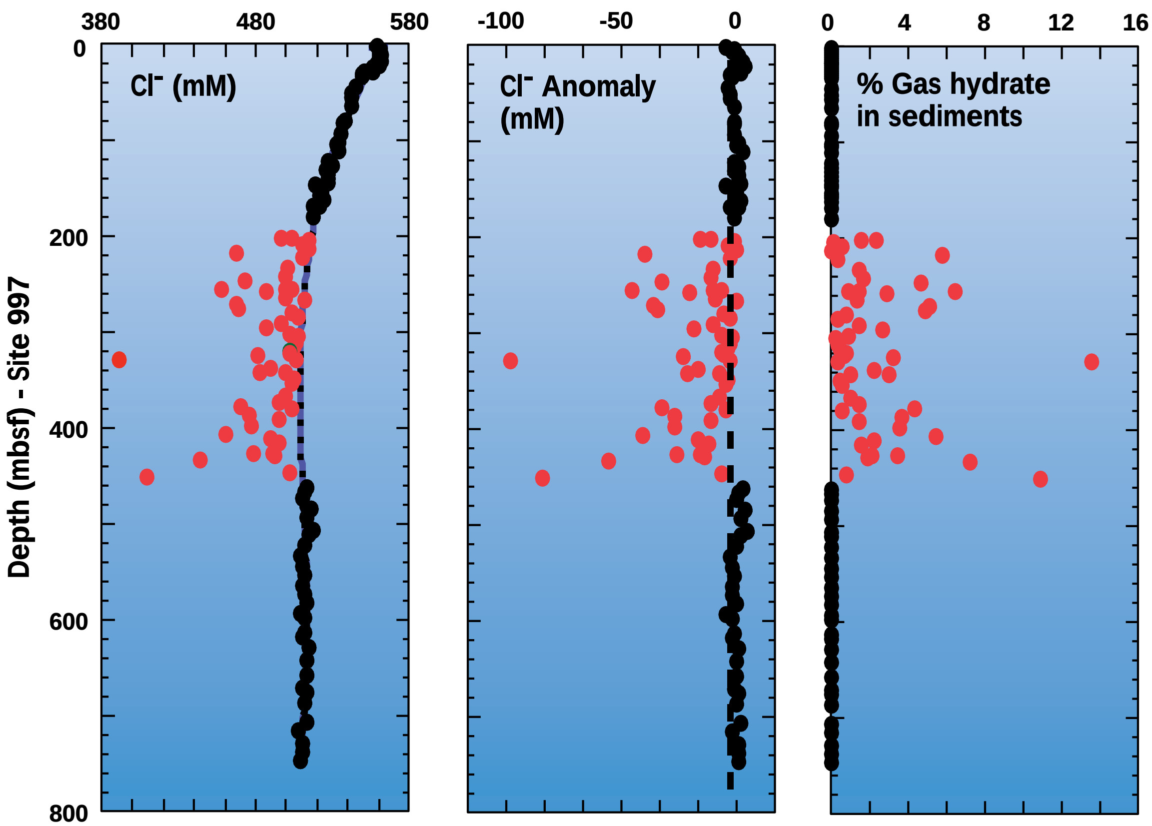
Charles Paull, University of North Carolina, Chapel Hill,
Gerald R. Dickens, University of Michigan (currently at James Cook University),
W. Steven Holbrook, Woods Hole Oceanographic Institution,
Walter Borowski, University of North Carolina, Chapel Hill, and
the ODP Leg 164 Scientific Party

Enormous volumes of natural gas are stored in marine sediments as gas hydrates — ice-like deposits of crystallized methane and water that form under high pressures and frigid temperatures in the deep sea. Large fields of methane hydrates are scattered throughout the world's oceans and are thought to contain about as much energy as all other forms of fossil fuel combined. This unconventional hydrocarbon energy source has remained untapped, however, because traditional sources are still plentiful and less expensive to develop. Nevertheless, scientists have recently been taking a closer look at hydrates, and not only as a possible energy source. Hydrates may affect climate because when warmed or depressurized, they decompose and dissociate into water and methane gas, one of the "greenhouse" gases that warms the planet. Seafloor dissociation of hydrates lowers sediment strength and can lead to sediment failure and slumps, posing a hazard to the safe design and emplacement of offshore drilling/production platforms, subsea equipment, and pipelines [*Borowski and Paull,* 1997]. Despite the tremendous importance of these geological deposits, they remain poorly understood. For example, we don't have accurate estimates of the global distribution of hydrate fields, nor the volume of methane therein, nor the amount of free methane gas often trapped beneath them.

To better understand these mysterious deposits, ODP drilled into a gas hydrate field in the Blake Ridge off the coast of North Carolina in 1995. The Leg 164 scientific party sought to quantify the amount and characteristics of the methane in this area — the size of New Jersey — that lies within a sediment-drift deposit of microfossil-rich clays. Multiple holes were drilled to depths as great as 750 mbsf, and the gas hydrate zone was found between about 200 and 450 mbsf. Finely disseminated gas hydrate pieces were observed within this sedimentary zone and nodules as large as 30 cm thick were recovered. Nevertheless, direct shipboard observation of these deposits is notoriously difficult because warming and depressurizing during the very act of retrieving them from the seafloor causes them to rapidly decompose.

To overcome this problem, ODP has developed and used several clever approaches. The first is direct sampling of the hydrate with a new research tool, called a pressure core sampler (PCS) [*Pettigrew,* 1992], which was successfully used for the first time on Leg 164. This tool enables scientists to take and maintain samples of the hydrates at the *in situ* high pressure conditions in which they form until they are returned to the shipboard laboratory for analysis of gas quantity and composition. Seventeen PCS deployments during Leg 164 were used to construct the first vertical profile of *in situ* methane volumes through a subseafloor sequence containing hydrate, dissolved methane, and free methane gas [*Dickens et al.,* 1997]. Results indicate that hydrate occupies 0-9% of the pore volume in the hydrate zone and that gas comprises up to 12% of the pore volume in the underlying free-gas zone. PCS measurements also demonstrate that the volume of methane in the free-gas zone rivals the amount of methane within the overlying hydrate zone.

Other ways to study hydrates are based on indirect evidence gathered from geochemical measurements, well-logs, and vertical seismic profiling. Because fresh water is released by the dissociation of hydrates, geochemical analyses of the pore waters squeezed from sediment cores recovered from the drill holes can be used to infer the presence of hydrates, even if they are no longer there. Pore water profiles of salinity (indicated by the chloride concentration) show a high variability in the hydrate zone between 200 and 450 mbsf that is characterized by local, anomalously fresh values (see figure), indicating drilling-induced dissociation of the hydrate. Translation of these data suggest that the sediments contain 1-12% gas hydrate in their pore spaces (figure panel c). Well-logs show distinct zones of higher electrical resistivity that coincide with these chloride anomalies. Hydrate abundance has also been estimated from seismic velocities measured in the drill holes. Seismic results of Holbrook and collaborators suggest that hydrate fills 2-7% of the pore volume in the hydrate layer, in close agreement with the independent PCS and chloride anomaly estimates. The seismic data further suggest that free gas bubbles fill 1-2% of the underlying 250 m thick free-gas zone, whereas the PCS and pore water data argue for higher values, up to 12%. The difference between these two estimates of free gas reflect variations in the scale and sensitivity of the seismic and PCS measurements. The seismic data average sonic velocities over a broad, vertical zone, whereas the PCS measurements are from discrete sedimentary layers, and are thus more likely to encounter a range of values. We know from



Downhole geochemical profiles define the gas hydrate zone. Pore water concentrations of chloride (a) show great variability in the hydrate zone between 200 and 450 meters below the seafloor. Low values indicate lower salinity waters indicative of dissociation of gas hydrates into fresh water and methane gas. Deviations from baseline chloride values (b), below and immediately above the gas-hydrate-containing zone, show the hydrate zone more clearly. Chloride dilution is directly related to the amount of gas hydrate in the sediments (c).

the seismic data that free gas is concentrated in specific, heterogeneous layers below the gas hydrate, and that the greatest concentration of free gas occurs in a thin (<20 m) layer directly beneath the hydrate zone, but further research is needed to better define these layers and to determine the amount of gas in each.

Our best estimates suggest that there are about 2.3×10^{15} ft^3 of methane (containing 35 billion metric tons of carbon) in the Blake Ridge hydrate field. Based on a U.S. consumption rate of 2.2×10^{13} ft^3 in 1996, this field alone contains enough methane to supply U.S. needs for 105 years.

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BOREHOLE OBSERVATORIES MONITOR ACTIVE HYDROLOGY BENEATH THE SEAFLOOR

Keir Becker, Division of Marine Geology & Geophysics, RSMAS, University of Miami
Earl E. Davis, Pacific Geoscience Centre, Geological Survey of Canada

A wide range of fundamental geological problems, such as the exchange of mass and heat between Earth's lithosphere and hydrosphere, the origin of valuable metal ore bodies, and even earthquake activity associated with deep-sea trenches, are linked to a common process — the widespread circulation of fluids beneath the seafloor, through oceanic sediments and underlying crust. Near mid-ocean spreading centers, such circulation is driven by thermal energy released by the formation of oceanic crust from magma, and is therefore termed "hydrothermal circulation." Near subduction zones, subsurface fluid flow is largely driven by compressional forces as plates converge, and the circulating fluids are generally lower in temperature than hydrothermal fluids.

Hydrothermal circulation at the crests and flanks of the mid-ocean ridges results in water-rock chemical exchanges that alter the original compositions of both the igneous oceanic crust and the circulating fluids and modulate the chemistry of the oceans. Hydrothermal vents, both at most ridge crests and at cooler seeps at subduction zones, support unique chemosynthetic biological communities on and beneath the seafloor, completely independent from photosynthesis. Therefore, it has been hypothesized that ancient hydrothermal systems may have been associated with the origins of life on Earth, and recent indications of hydrothermal sites elsewhere in the solar system are generating considerable excitement about the possible existence of primitive extraterrestrial life.

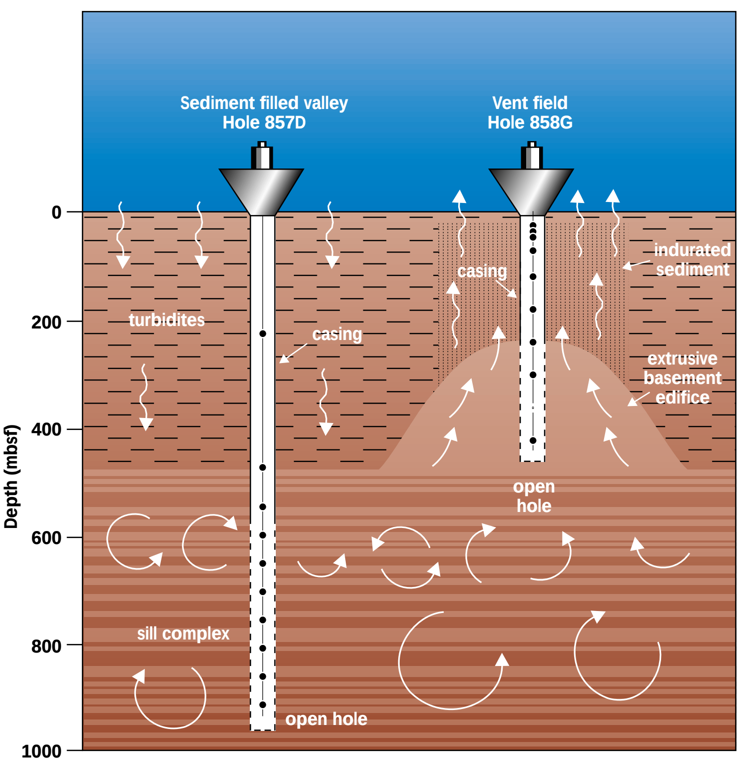

Figure 1: Configuration of the two Middle Valley CORKs, first deployed in 1991, as refurbished in 1996. Lines and dots down the centers of the holes represent thermistor cables and positions.

Present scientific understanding of hydrothermal circulation is largely inferred from the chemistry of fluids exiting the seafloor and from the patterns revealed by heat-flow measurements made just below the seafloor. ODP drilling now provides an innovative means of studying fluid circulation deep beneath the seafloor, by emplacing long-term sensors directly within the formation where circulation occurs. The ODP drilling process uses surface seawater to flush cuttings from the hole, and therefore often disturbs the very hydrothermal system we seek to study. These drilling disturbances make it difficult to conduct meaningful hydrological measurements or to sample pristine, *in situ* fluids from holes that are left open. To overcome this problem, ODP engineers and scientists have developed specialized borehole seals that prevent the flow of water into or out of selected ODP holes after they are drilled, and simultaneously allow emplacement of instruments for long-term use in the sealed holes [*Davis et al.*, 1992; *Davis and Becker,* 1993]. Once these holes are sealed, the hydrological conditions in the rock formation slowly return to the natural state that existed prior to drilling, and the instruments monitor the recovery to true *in situ* conditions as well as any natural hydrologic events that may also occur. Several sites on ridge crests and flanks and in subduction settings have now been instrumented using these so-called "CORK" (Circulation Obviation Retrofit Kit) experiments; ODP installs the instruments, and the data are recovered months to years later from manned or unmanned submersibles.

On the ridge flanks and crests, heat flow surveys dating back to the 1970's clearly demonstrated that hydrothermal systems can extend over large areas — 10's or even 100's of kms. However, we understand little about the subsurface workings of such systems, and this is one of the key objectives of the CORK experiments. A good example is provided by the first two CORKs, which were installed in a sediment-covered spreading center in the Pacific northwest (Figure 1) [*Davis and Becker,* 1994]. One of these CORKs is located in the midst of a hydrothermal-vent field

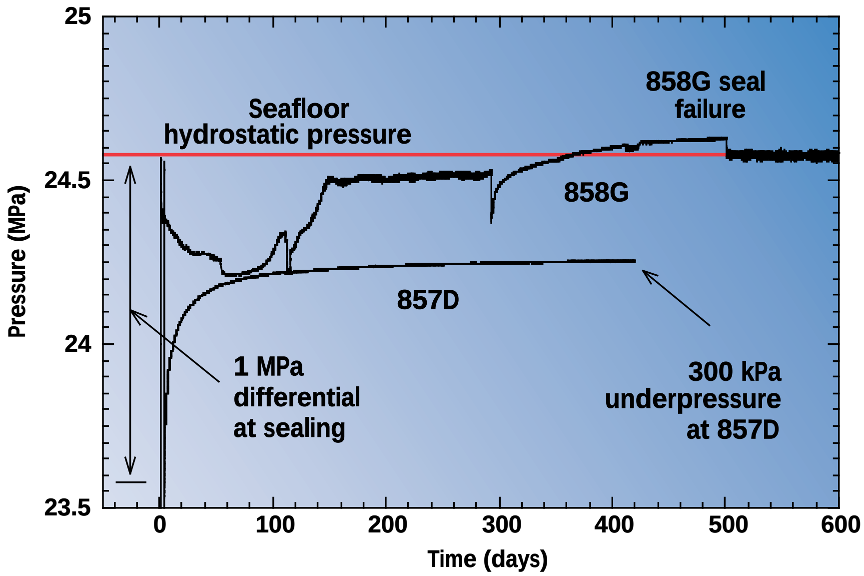

Figure 2: 1991-1993 long-term pressure records from the Middle Valley CORKs.

where fluids at temperatures of 260-270°C are expelled. Here, ODP Hole 858G was drilled through hardened sediments into an underlying volcanic edifice, which is thought to act like a permeable "chimney" in focusing the subsurface hydrothermal flow to produce the seafloor vents. Over a kilometer to the south, well away from the vent field, Hole 857D was drilled into highly permeable rocks that may serve as one of the sources of the fluids that vent near Hole 858G.

The data from these two CORKs show surprisingly different trends over time (Figure 2). In both holes, the earliest segments of the borehole pressure records show brief excursions toward extremely low values, caused by the invasion of cold and dense seawater during drilling. In the months that followed, the Hole 857D record shows a smooth recovery towards *in situ* pressures as the formation recovered from the cooling artifact of drilling. In contrast, the time series of pressure data from Hole 858G in the vent field shows several discrete events, including sudden offsets and distinct changes in trends. Some of these may be associated with natural activity in the vent field, while others were probably linked to hydrologic disturbances via a nearby exploratory drill hole that was inadequately backfilled with cement. A thermally induced failure of the CORK seals caused the event about 500 days after CORK deployment. When the seals failed, fluid pressures dropped suddenly to that of the column of seawater at the site ("seafloor hydrostatic pressure") and a full-amplitude tidal signal was observed.

The most surprising and fundamental result of these observations is the large difference in equilibrium pressures at the two sites. Before the seal failed, the pressure in Hole 858G had become greater than hydrostatic conditions, and was continuing to rise towards a value of about 0.1 MPa above a hydrostatic reference consistent with the local geothermal gradient. This is equivalent to about one bar and represents the excess fluid pressure available to drive water out of the formation at the vent field. In contrast, the long-term record at Hole 857D recovered to about 0.3 MPa below local hydrostatic conditions. This strong "underpressure" indicates that seawater must be slowly percolating down through the sedimentary column to replenish fluids circulating in the subsurface hydrothermal system, possibly linked directly to the vent field near the other hole.

Models using the constraints provided by the CORK data provide one way to quantitatively estimate the extent to which the formation is hydrologically connected. A more direct experiment was conducted when the two drill holes were re-instrumented in 1996 during ODP Leg 169. At that time, a unique cross-hole experiment was carried out to provide an independent estimate of the formation-scale permeability and hydrological connectivity between the holes. (Data from this experiment is scheduled to be recovered in September, 1997, using the remotely operated vehicle, *JASON*.) The high permeability inferred at this site, as well as at other sites instrumented during Leg 168 on the eastern Juan de Fuca ridge flank, suggest that fluids may move through the upper igneous crust at average rates of tens of meters per year, and carry heat and solutes laterally over distances of many tens of kilometers with great efficiency. If this is so, the oceanic crust may be one of the most hydrologically active formations on Earth.

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EVIDENCE FOR VIGOROUS CRETACEOUS MANTLE DYNAMICS FROM LARGE IGNEOUS PROVINCES

Millard F. Coffin, Institute for Geophysics, The University of Texas at Austin, and
Olav Eldholm, Department of Geology, University of Oslo

Conditions on Earth today are dramatically different from those that existed during the Cretaceous Period, which ended 65 million years ago. Widespread evidence indicates that during the Cretaceous, which preceded the Cenozoic Era we are now in, climate was considerably warmer, sea level was significantly higher, episodes of oceanic anoxia were more frequent, and mass extinctions were more common. In addition, seafloor spreading rates were higher, and Earth's magnetic field was uncharacteristically steady in that it did not switch from normal to reversed polarity for ~35 million years. The ODP has made critical contributions to this list of Cenozoic-Cretaceous contrasts. For example, ODP results have demonstrated that the Cretaceous was a time when huge volumes of magmatic material flowed to Earth's surface from the mantle, and not just from the typical seafloor spreading process. Instead, most of the magma was injected upwards through volcanic hotspots. These eruptions formed many features, including two giant oceanic plateaus and several large igneous provinces (LIPs). ^{40}Ar-^{39}Ar dating of basalts recovered by ODP from the two giant submarine igneous plateaus, Ontong Java and Kerguelen-Broken Ridge, show major peaks in magmatism at ~121/90 and ~115/85 Ma, respectively [*Bercovici & Mahoney,* 1995], and many other LIPs, including oceanic plateaus, volcanic passive margins, and continental flood basalts, were emplaced during the Cretaceous. Magmatic fluxes from hotspots at this time accounted for 50% or more of the integrated heat loss from Earth's interior, whereas during the Cenozoic, only 5% of Earth's heat has been lost in this manner. Simple calculations involving estimated volumes of the two giant plateaus and degrees of partial melting (see figure) suggest that the whole mantle convected, if not overturned, during part of the Cretaceous [*Coffin & Eldholm,* 1994]. Convection of the entire mantle may be linked to the higher seafloor spreading rates and unusual magnetic field behavior during the Cretaceous. Furthermore, LIP emplacement episodically altered the geometries of the ocean basins, continental margins, and the continents, as well as affected the chemistry and physics of the oceans and atmosphere, with enormous environmental impact. A major future challenge for ODP is to investigate causal links between Cretaceous mantle dynamics and environmental change.

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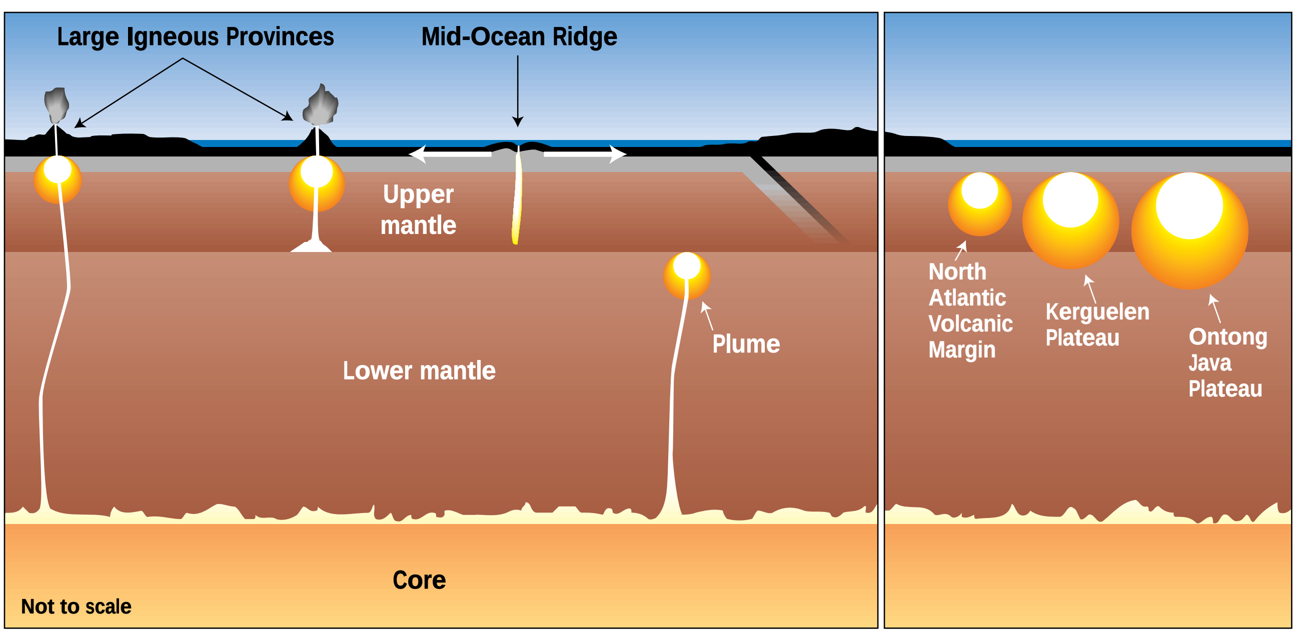
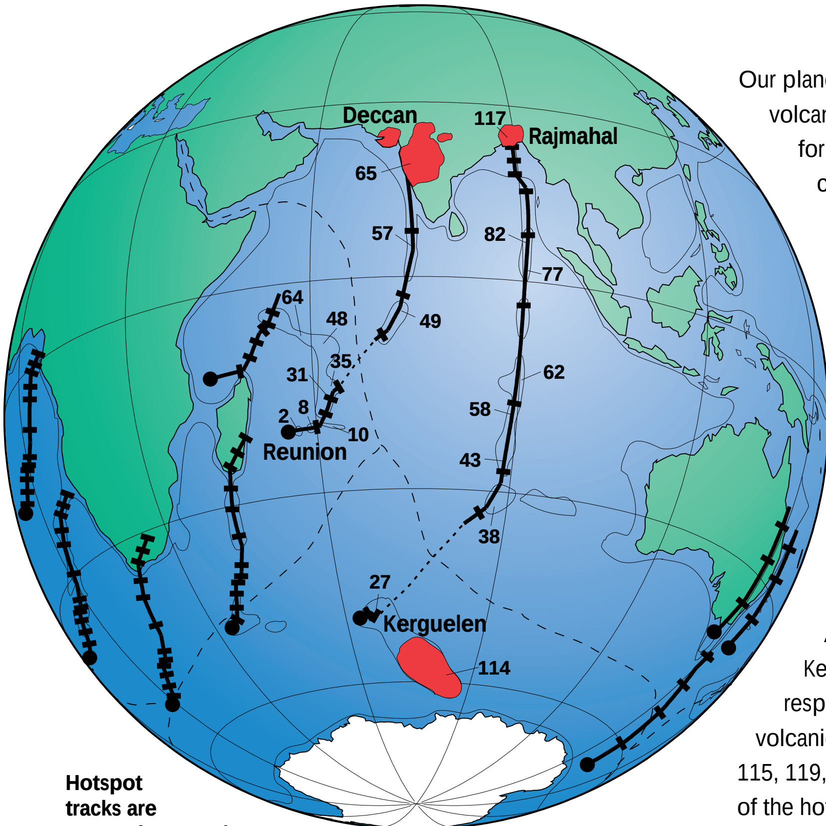


Rising plumes of hot material migrate through Earth's mantle; where the head of the plume reaches the surface, a large igneous province forms (left). Plumes probably originate at the boundary layers between the core and mantle at 2900 km below Earth's surface, and between the upper and lower mantle. The parent plumes of the most voluminous igneous provinces were so huge that they must have originated at least in part in the lower mantle, most likely at the core-mantle boundary. The spheres on the right depict the minimum (white) and maximum (orange) inferred diameters of the plumes associated with five large igneous provinces.

THE LIFE CYCLE OF MANTLE PLUMES

Robert A. Duncan and Martin R. Fisk,
College of Oceanic and Atmospheric Sciences, Oregon State University



Hotspot tracks are mapped across the Indian Ocean by a computer model that incorporates known tectonic plate motions and assumes hotspot immobility. The tracks match observed volcanic ridges, seamounts and islands remarkably well. Radiometrically-determined ages (numbers in m.y.) of ODP samples and terrestrial rocks also fit with model-predicted ages (ticks at 10 m.y. increments). Enormous accumulations of flood basalts at the northern ends of the Reunion and Kerguelen tracks, and the southern Kerguelen plateau (stippled areas) were erupted when mantle plume activity initiated.

Our planet's surface is dotted with hotspots, which are focused volcanic areas, approximately 100-200 km wide, that persist for tens of millions of years. Because these volcanic centers appear to remain at a fixed position beneath the moving tectonic plates throughout their long lifetimes, it is speculated that hotspots are connected to a stable pattern of upwardly flowing plumes of warmer than average material from deep levels of the mantle. This convective circulation may be the major way that heat moves from Earth's interior to its surface. We study these features to better understand the dynamics, kinematics, chemistry, and thermal histories of these fascinating conduits. Nowhere is their behavior more clearly seen than in the Indian Ocean (see figure). Here, drift of the African, Indian, Australian and Antarctic plates over the Reunion and Kerguelen hotspots (formed at about 65 and 117 Ma, respectively) produced linear, age-progressive chains of volcanic ridges, islands and seamounts. Data from ODP Legs 115, 119, 120 and 121 document the continuity and immobility of the hotspots, which provide us with a direct and simple frame of reference to reconstruct plate motions during the opening of the Indian Ocean. The Reunion and Kerguelen hotspots began with extraordinarily extensive eruptions of lava flows that cooled into thick volcanic platforms, called flood basalts, both on continental and oceanic lithosphere. The original eruption rate from these hotspots was at least 10 to 100 times greater than today at the most active hotspots, such as Hawaii and Iceland. This enormous flux was most likely related to new, surfacing plumes that disgorged large volumes of high temperature mantle material. The timing of flood basalt volcanism correlates with environmental crises, such as global warming, ocean anoxia and mass extinctions, implying a strong link between mantle activity and Earth's surface. Hotspots also provide "windows" into the deep mantle. The compositions of volcanic rocks along hotspot trails change with time and reflect varying contributions from the deep vs. the shallow mantle. The compositional variation along the Reunion hotspot trail is consistent with early entrainment of shallow material within the rising plume, and subsequent gradual increase in the proportion of deep material in the source for hotspot melting. A similar evolution in Kerguelen hotspot magmas is observed, with compositional changes related to varying proportions of upper and deep mantle mixing, correlated with the plate tectonic setting. Both hotspots are now located well away from plate boundaries but earlier lay near or at spreading ridges.

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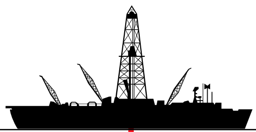
EXPLORING EARTH'S HISTORY

The ocean floor provides an ideal location to explore Earth history because deep-sea sediment and rock layers are generally much more continuous and less disturbed than comparable formations on continents, which are exposed to the erosional forces of wind, precipitation, rivers, and sea level fluctuations. The ODP has recovered sediments ranging in age from the last decade all the way back to the Triassic Period, nearly 227 million years ago.

ODP data span two eras



Era	Period	Period/Epoch	Beginning (million years ago)	Duration (million years)	Development of life on Earth
CENOZOIC ERA	Quaternary Period	Holocene Epoch	0.01	0.01	Humans hunt and tame animals, develop agriculture, use metals, coal, gas, wind, and water power, and other resources
CENOZOIC ERA	Quaternary Period	Pleistocene Epoch	1.8	1.79	Modern humans develop and mammoths, woolly rhinos, and other animals flourish but die out near end of epoch
CENOZOIC ERA	Tertiary Period	Pliocene Epoch	5.3	3.5	Sea life, birds, and many mammals similar to modern ones spread around the world, humanlike creatures appear
CENOZOIC ERA	Tertiary Period	Miocene Epoch	23.8	18.5	Apes in Asia and Africa, other animals include bats, monkeys, whales, primitive bears and raccoons; flowering plants and trees resemble modern ones
CENOZOIC ERA	Tertiary Period	Oligocene Epoch	33.7	9.9	First primitive apes, development of camels, cats, dogs, elephants, horses, rhinoceroses, and rodents; huge rhinoceros-like animals disappear near end of period
CENOZOIC ERA	Tertiary Period	Eocene Epoch	54.8	21.1	Plentiful birds, amphibians, small reptiles, and fish joined by primitive bats, camels, cats, horses, monkeys, rhinoceroses, and whales
CENOZOIC ERA	Tertiary Period	Paleocene Epoch	65.0	10.2	Flowering plants plentiful, invertebrates, fish, amphibians, reptiles, and mammals common
MESOZOIC ERA		Cretaceous Period	142.0	77	First flowering plants; horned and armored dinosaurs common; plentiful invertebrates, fish, and amphibians; dinosaurs disappear at end of period
MESOZOIC ERA		Jurassic Period	205.7	63.7	Dinosaurs at maximum size; first birds, shelled squid; mammals are small and primitive
MESOZOIC ERA		Triassic Period	248.2	42.5	First turtles, crocodiles, dinosaurs, and mammals; fish resemble modern kinds

Time scale adapted from "a Phanerozoic Time Scale" by F.M. Gradstein and J.G. Ogg, *Episodes,* vol 19, no's 1&2, 1996.

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Contacts for more information...

PROGRAM MANAGER:

Ocean Drilling Program and
U.S. Science Support Program
Joint Oceanographic Institutions
1755 Massachusetts Avenue, NW, Ste 800
Washington, DC 20036-2102
Tele: 202/ 232-3900
Fax: 202/ 232-8203
E-Mail: joi@brook.edu
Web Site: www.joi-odp.org

U.S. FUNDING AGENCY:

Ocean Drilling Program
National Science Foundation
4201 Wilson Boulevard
Arlington, VA 22230
Tele: 703/ 306-1581
Fax: 703/ 306-0390

SCIENCE OPERATOR:

Ocean Drilling Program
Texas A&M University
1000 Discovery Drive
College Station, TX 77845-9547
Tele: 409/ 845-2673
Fax: 409/ 845-4857
Web Site: www-odp.tamu.edu

LOGGING OPERATOR:

Borehole Research Group
Lamont-Doherty Earth Observatory
Palisades, NY 10964
Tele: 914/ 365-8672
Fax: 914/ 365-3182
E-mail: borehole@ldeo.columbia.edu
Web Site: www.ldeo.columbia.edu/BRG

The brochure...

EDITORS:

Ellen S. Kappel, Associate Director
Ocean Drilling Programs, JOI

John W. Farrell, Assistant Program Director
Ocean Drilling Programs, JOI

DESIGN:

Johanna M. Adams
JOI Graphic Designer

ODP PHOTOS:
ODP/TAMU Photography Department

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JOINT OCEANOGRAPHIC INSTITUTIONS

1755 Massachusetts Avenue, NW, Suite 800
Washington, DC 20036-2102 USA
Tele: (202) 232-3900; Fax: (202) 232-8203
E-mail: joi@brook.edu
Web Site: www.joi-odp.org

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