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1. Leg 185 Synthesis: Sampling the Oldest Crust in the Ocean Basins to Understand Earth's Geodynamic and Geochemical Fluxes[1]

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ABSTRACT

During Ocean Drilling Program (ODP) Leg 185, two sites were sampled in the oldest crust of the western Pacific Ocean. The scientific objectives were twofold: (1) to characterize the nature of the oldest in situ oceanic crust on Earth in terms of its formation and subsequent sedimentation and alteration and (2) to determine the bulk geochemical characteristics of crust being subducted into the Izu-Bonin and Mariana trenches, as part of a larger global experiment aimed at understanding geochemical budgets at subduction zones.

This synthesis summarizes results presented in more than 35 papers published not only in this Leg 185 *Scientific Results* volume but also in several journal articles and, specifically, in a special thematic series of articles on Oceanic Inputs to the Subduction Factory published in *Geochemistry, Geophysics, and Geosystems* (G^3). Leg 185 science also supported the theses of 12 students in universities around the world.

The oldest of the two basement sites drilled (Hole 801C) has been dated at 167 Ma and preserves late Bajocian to middle Bathonian fauna. It is thus the oldest crust yet sampled in the oceans. Hole 801C marks the birth of the Pacific plate at a time immediately following Pangaea breakup and increased subduction magmatism. Hole 801C basement is considered to represent a section of crust formed at a fast spreading ridge, and its structure, preservation of hydrothermal zones, and lava stratigraphy are interpreted as being typical of such an environment.

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Site 801 also provided a key location to study the unusual nature of the Jurassic magnetic field. The basement section of Hole 801C records at least six polarity intervals over ~50,000 yr, representing an order of magnitude higher sustained geomagnetic reversal frequency than at any other time in the past 300 m.y. of Earth history. The Jurassic "quiet" zone thus results in part from very high reversal frequency, likely coupled with a relatively low dipole field intensity.

Hole 801C also permitted geochemical and mineralogical characterization of altered oceanic crust being subducted into the Mariana Izu-Bonin arc system. For the first time, ODP scientists worked on a series of composite and common samples, coupled with an extensive set of downhole logging data, to define the bulk chemical composition of altered oceanic crust. These data are compiled as part of a reference suite in the Geochemical Earth Reference Model (GERM). They provide important constraints not only on the integrated fluxes of elements during seawater-seafloor interactions but also for the bulk geochemistry for key anions in the ocean–continent geochemical flux. Some of the very first measurements of Fe isotopes have been made on hydrothermally altered crust from Hole 801C, along with a larger suite of other stable (O, C, S, and Li) and radiogenic (Sr, Nd, Pb, and Hf) isotopes. The Hole 801C composites have enabled the first quantitative constraints on the parent/daughter ratios of the U-Th-Pb isotopic system through the entire cycle from mantle melting at mid-ocean ridges, to seafloor alteration, processing through the subduction zones, and final impact on the Pb isotopic evolution of the mantle.

Site 1149 is the first complete sedimentary section outboard of the Izu-Bonin Trench. Seismic stratigraphy and core-logging integration have been used to correlate sedimentary sequences and develop the sedimentation history across the western Pacific. Site 1149 sediments record the global Valanginian Weissert marine anoxic event, as well as an excellent Pliocene–Pleistocene record of eolian dust and ash deposition. Representing a classical sequence of oceanic pelagic sedimentation, the Site 1149 sedimentary section has also been the target of exploratory work on novel stable isotopes (including those of N, Se, Sb, and Fe). Extensive geochemical logs and core analyses define a detailed geochemical stratigraphy, reflecting a clear hydrothermal signal at the base of the section and Asian dust and ash sources at the top.

The geochemical variations in Site 1149 sediments can be compared with regional stratigraphic variations to predict the bulk sediment flux along the entire Izu-Bonin-Mariana Trench. Most notable is the northward increase in eolian input and southward increase in Cretaceous volcaniclastic sources. These sedimentological changes are recycled through the subduction zone and emerge as sympathetic latitudinal variations in the Mariana-Izu-Honshu arcs in key geochemical tracers such as Th/La and Pb isotopes. The Izu arc, however, is impoverished in the absolute abundance of subducted sediment material, which nonetheless appears in the Izu backarc region, thus demonstrating a delayed delivery response for this cold slab.

Thus, one of the principal outcomes of Leg 185, as part of the "Subduction Factory" experiment, has been to quantify better than any other convergent margin to date both the flux of altered oceanic crust and the overlying sediments into the subduction system. These data constrain the "input function" of the subduction factory regionally in the western Pacific basin and globally as part of the bulk mass balance of subduction processes on Earth.

Finally, Leg 185 played a pioneering role in ODP's burgeoning study of the ocean's deepest biosphere. A series of contamination tests on sediment and basement cores demonstrated their viability in conducting biological studies. These tests and some of the preliminary results have paved the way for biological studies as part of the new Integrated Ocean Drilling Program.

INTRODUCTION

This synthesis summarizes results presented in more than 35 papers published not only in this Leg 185 *Scientific Results* volume but also in several journal articles (Table T1) and, specifically, in a special thematic series of articles on Oceanic Inputs to the Subduction Factory published in *Geochemistry, Geophysics, and Geosystems* (G^3) (Table T2). Leg 185 science also supported the theses of 12 students in universities around the world (Table T3).

T1. Publications in peer-reviewed journals, p. 32.

T2. Publications in G^3 special theme volume, p. 33.

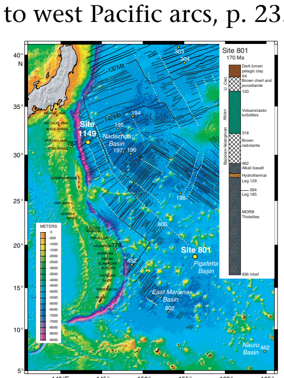
T3. Student theses, p. 34.

Drilling at Sites 801 and 1149 during Ocean Drilling Program (ODP) Leg 185 (Plank, Ludden, Escutia, et al., 2000) has resulted in dating of the oldest basement and sediments in the western Pacific. Penetration into old Pacific crust has helped scientists solve some fundamental problems, such as the nature of the Earth's magnetic field during the Jurassic "quiet" period and the temperature of the Pacific mantle prior to the arrival of the Cretaceous superplume.

As much of the oldest seafloor on Earth is close to subduction zones, the principal aim of Leg 185 was to quantify the geochemical composition of the basement and sedimentary sections being subducted at the Izu-Bonin-Mariana Trench. This effort is part of the U.S. National Science Foundation (NSF) MARGINS and Geochemical Earth Reference Model (GERM) initiatives.

This paper is divided into four sections. The first deals with the history of drilling into Jurassic basement in Hole 801C, our current knowledge of this basement, and new perspectives that Leg 185 has opened on the world's oldest oceanic crust. The second section deals with the sedimentary history of the western Pacific, based in large part on the reference site drilled at Site 1149. In particular, this information helps define the quantity and types of sediments that are being subducted into the west Pacific arcs. The latter is particularly important for the third section of this paper, which deals with the bulk geochemistry of basement and sediments as input to subduction zones and how this material is recycled through the solid Earth. The final section outlines the role Leg 185 played in developing new protocols to study microbial life in deep ocean sediments and crust.

F1. Locations of drilling sites relative to west Pacific arcs, p. 23.



A LEGACY SITE IN JURASSIC CRUST

Historical Summary

The oldest oceanic crust is Jurassic seafloor in the western Pacific Ocean Basin (Fig. F1). Sampling deep ocean basin sites at water depths of >6000 m involves drilling the hard Cretaceous chert sequences that lie a few hundred meters above basement. This technical challenge is part of an unfolding drama of three decades of drilling by the Deep Sea Drilling Project (DSDP) and ODP in the western Pacific abyssal plains. The most recent penetration of the ~170-m.y.-old crust by ODP involved the reentry of Hole 801C during Leg 185 as part of the "Subduction Factory experiment."

Much of the following historical summary is taken from the Acknowledgments of the Leg 129 *Initial Reports* volume (Lancelot, Larson, et al., 1990). DSDP Legs 6 and 7 in 1969 were the first to search the western Pacific for the Earth's oldest oceanic crust and sediments. The search ultimately took 20 yr and 10 cruises of DSDP/ODP (Legs 6, 7, 17, 20, 32, 33, 60, 61, 89, and 129) to achieve the final goal. Many people were involved; the most persistent members of the "Old Pacific Club" included B.C. Heezen, E.L. Winterer, S.O. Schlanger, R. Moberly, I. Premoli Silva, R. Larson, Y. Lancelot, W. Sliter, D. Bukry, R.G. Douglas, and H.P. Foreman. During the early legs, drilling sites were targeted with single-channel seismic records characterized by acoustically opaque chert layers that obscured the underlying volcanic basement. Often, coring was frustrated by these impenetrable cherts, as well as by volcaniclastic sediments and basalts of Cretaceous age. To those who shipped out repeatedly and returned home with more questions than answers, what had started as an oceanographic exercise turned into an ongoing quest for the "old Pacific."

Leg 129 brought the *JOIDES Resolution,* with improved drilling capabilities, where the *Glomar Challenger* failed. Also, preparations for Leg 129, led by Yves Lancelot and Roger Larson, included four multichannel seismic expeditions to the area searching for seismic "windows" through the Cretaceous volcaniclastic sediments and solid basalts.

This combination of improved science and technology was finally successful in 1989 at Site 801 in the Pigafetta Basin, where Jurassic sediments of Bajocian–Bathonian age were discovered overlying ~170-Ma oceanic crust (Lancelot, Larson, et al., 1990).

During Leg 185, Hole 801C was deepened by 340 m into basement, providing a total basement section of 470 m, making it the sixth deepest drill site into normal oceanic crust. Recovery of oceanic basement was very good (47%) and included fresh basaltic glass, which has enabled study of the primary basalt chemistry (Fisk and Kelley, 2002). A high-quality set of logs were run to 388 m in basement and, with the extended core penetration, have revealed a remarkable record of magnetic reversals in the Jurassic section (Tivey et al., 2005; Steiner, 2001). The hole is in good condition, and it remains a legacy site into the world's oldest oceanic crust.

The primary motivation for returning to Hole 801C, seaward of the Mariana Trench, was to sample the upper oxidative zone of alteration of this oldest in situ oceanic crust. Previous drilling during Leg 129 only penetrated 63 m into "normal" Jurassic basement. Based on basement rocks from Hole 504B and other basement sites with sufficient penetration, the upper oxidative zone of alteration, which contains the overwhelming majority of some element budgets (e.g., K, B, etc.), lies in the upper 200–300 m of the basaltic crust.

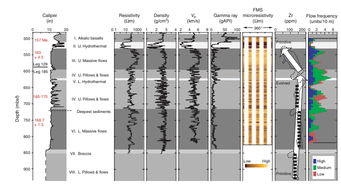
Age and Nature of Basement

An important objective of Hole 801C in the Pigafetta Basin and Hole 1149D close to the Izu-Bonin subduction zone in the Nadezhda Basin was the establishment of their radiometric and biostratigraphic ages, hence providing constraints on the birth of the Pacific plate. Combined with previous results from Pringle (1992) for Holes 801B and 801C, Koppers et al. (2003) arrived at a multistage history for the site. The oldest part of the Pacific plate was formed at the spreading ridges at 167.4 ±

1.4/3.4 Ma. Alkaline volcanics, which compose the upper unit sampled in basement, were erupted at ~7 Ma after the tholeiites at ~160.1 ± 0.6 Ma. The older age for the tholeiitic basement has been confirmed by radiolarian ages, which range from late Bajocian to middle Bathonian (167–173 Ma) (Bartolini and Larson, 2001).

This difference in age between the lower tholeiitic unit and the upper alkaline unit was recognized based on differences in the structural characteristics of this basement section (Pockalny and Larson, 2003) (Fig. F2). Thin layers comprising hydrothermal deposits separate these sequences, which, in addition to the difference in isotopic age, show distinct major and trace element compositions (Fisk and Kelley, 2002). Using a half-spreading rate of 60–70 km/m.y. and the ages given above, the younger volcanic sequence and hydrothermal activity took place as much as 500 km away from the spreading ridge that formed the basement at Site 801.

F2. Physical and geochemical properties for Site 801 basement, p. 24.



As discussed by Koppers et al. (2003), the ages defined at Site 801 provide a calibration point on the geological reversal timescale, as this site is located at the oldest point for Mesozoic magnetic anomalies. Hole 1149D basement potentially gives another important calibration point of 127.0 ± 1.5/3.6 Ma for Anomaly M12, which is younger than current timescale compilations (134.2 ± 2.1 Ma) (Gradstein, 1995). This might suggest that the dated basalt was not formed at a spreading center but was erupted slightly off-axis (Koppers et al., 2003).

Bartolini and Larson (2001) show that the age of Site 801 constrains the time of formation of the Pacific plate to 175–170 Ma, just after the initial separation of the Pangaea supercontinent in the central Atlantic at 190–180 Ma. The authors also identify a time of extensive subduction zone magmatism (175–159 Ma) at the eastern and western edges of Pangaea and suggest that the initial plate separation of Pangaea increased subduction rates along its outer margins and altered the plate boundaries in the Pacific superocean, ultimately leading to formation of the Pacific plate.

Drilling results into basement in the western Pacific basins have provided the ground truth for the geologic timescale, global plate reconstructions, and mapping magnetic reversals in a critical period of Earth's history.

Crust Structure and Accretion

During ODP, few deep holes have been drilled into oceanic crust. Hole 504B, the most renowned of the deep crust drilling sites of ODP, is located on 5.9-Ma crust in the Panama Basin south of the Costa Rica Rift axis (Alt et al., 1996). Drilling this hole occupied seven ODP legs and penetrated >2000 m into oceanic basement, reaching close to the Layer 2–3 transition zone. On the other hand, two other sites (DSDP Site 534 and ODP Site 765) in addition to Site 801 have sampled the oldest crust in the oceans (Table T4). Given the range in crustal age and spreading rate, these sites have proved invaluable in understanding the geochemical balance between altered basaltic crust and seawater involved in global continent–ocean geochemical cycles.

T4. The oldest crust drilled by ODP, p. 35.

In addition to being the oldest oceanic crust, Hole 801C deeply samples crust formed at fast spreading rates (130–140 km/m.y. whole rate) (Tivey et al., 2005). Thus, Site 801C provides a unique record of crustal structure and accretionary process of oceanic crust formed in a fast-spreading environment.

Pockalny and Larson (2003) used downhole logging data and basement stratigraphy to determine the spreading environment and crustal accretion history of the ocean basement cored in Hole 801C. High-resolution microresistivity data obtained with the Formation MicroScanner (FMS) were used to measure the dip of the extrusive layers and indicate a 10°–30° increase in dip downhole with lava flow contacts dipping back toward the original ridge axis. This structural pattern and the high proportion of massive flows relative to pillow units are consistent with prevailing crustal accretion models proposed for faster spreading ridges (e.g., >60 km/m.y.). Combined with geochronological, geochemical, and structural information (Fig. F2), these authors defined the emplacement history of the lavas erupted at Site 801: the shallowest 100 m of the drilled section (e.g., Sequences I–III) were emplaced just off the ridge (Sequence III) or significantly farther off-axis up to 5–15 m.y. later (Sequences I and II). The remainder of the drilled section (Sequences IV–VIII) has geochemical, lithological, and physical trends that are assumed to be representative of crust created at fast-spreading ridges.

The composition of the basement in terms of proportions of massive vs. pillowed lavas and interflow breccias, hyaloclastites, and sedimentary horizons is one of the major challenges when drilling a "one-dimensional" hole in ocean crust. In addition to the problem of lateral extrapolation of the lithologies, the extent of recovery during coring is highly variable. For Leg 185, determining the proportion of basement lithologies was fundamental to reconstruction of the bulk geochemistry for global flux studies. For example, interflow segments are often poorly sampled by drilling but richly are concentrated in alteration phases (carbonate and alkali-bearing clay minerals). The primary data used to reconstruct the bulk composition of the site include the alteration mineralogy (Talbi and Honnorez, 2003), chemical analyses of core materials (Kelley et al., 2003), and geochemical and geophysical logs. Of particular note are two studies (Barr et al., 2002; Revillon et al., 2002) which integrated downhole logging data, geochemistry, and formation structures using data from the FMS. The reconstructed logging-based lithological sequence consists of thick massive flow units (27.4%), pillow units (33%), breccia units (31%), sediments (1.4%), and hydrothermal deposits (1.3%), with 5.9% unclassified due to unreliable tool response in intervals where hole conditions were poor. The proportion of pillow basalts doubled and the amount of breccia increased sixfold from that reported using core description alone, demonstrating convincingly that core-logging integration is essential to providing an accurate representation of the ocean crust section and the input flux to subduction zones (see also **"Site 801: A Geochemical Reference Site for Global Budgets and the Aging of Oceanic Crust,"** p. 13, in "Geochemical Sinks and Recycling in Subduction Zones.").

Magnetic Properties of Oceanic Crust

The magnetic properties of the basement section of Hole 801C were determined from borehole measurements down to 837 meters below seafloor (Tivey et al., 2005) as well as paleomagnetic and rock magnetic measurements on 480 individual samples and continuous core segments (Steiner et al., 1999; Steiner, 2001). The results from these different data sets support a remarkable paleomagetic history for Hole 801C.

The rock-magnetic properties of the Jurassic tholeiitic basalts are unusual in their excellent state of preservation (except near the zones of hydrothermal alteration). The iron oxides are ordinary titanomagnetite with iron/titanium ratios identical to those in modern, normal mid-ocean-ridge basalts (N-MORB). The basalt remanent intensities and Curie temperatures are the same as those of very young (e.g., 8 Ma) ocean crust. The logging data observed that the horizontal and vertical field measurements are “in phase,” unambiguously demonstrating that the site formed in the Southern Hemisphere at a paleolatitude of 22.7° ± 5°S (Tivey et al., 2005). The paleomagnetic data demonstrate that after crustal formation in the Middle Jurassic, the site first moved north, approximately to the paleoequator by the Oxfordian, reversed direction, and transited south to ~15°–20°S by the Albian–Aptian, and reversed direction again to transit monotonically northward across the paleoequator to its present location at 18.6°N.

These observations at Site 801 demonstrate that the Jurassic magnetic quiet zone (JQZ) does not result from either low-temperature oxidation of the magnetic minerals due to their great age or from originally anomalous magnetic mineralogy. Instead, the JQZ most likely results from anomalous behavior of the geomagnetic field in the Middle Jurassic, from excessively fast reversing of the geomagnetic field, and possibly also accompanied by abnormally low geomagnetic field intensity.

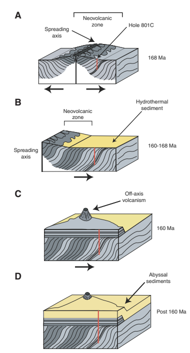
The Jurassic basement of Hole 801C contains evidence for multiple geomagnetic field reversals, with six polarity reversals in the drilled volcanic crust (Tivey et al., 2005; Steiner et al., 1999). An appreciable portion of the section recorded transitions of the magnetic field from one polarity interval to the other. Because of potential hiatuses in the basement section and likely changes in the rate of crustal construction during volcanic episodes, an estimate of reversal frequency or polarity interval duration is necessarily imprecise. However, the vertical extrusive volcanic section probably was constructed in ~50,000 yr at this spreading rate (130–140 km/m.y.), and probably the majority of the extrusive section has been penetrated and sampled. Hence, the logging studies suggest an average reversal period of 10,000–15,000 yr (Tivey et al., 2005), which is consistent with that estimated from the paleomagnetic data (Steiner, 2001) This represents approximately an order of magnitude higher sustained geomagnetic reversal frequency than observed at any other time in the past 300 m.y.

This reversal frequency alone could produce the quiet anomaly signature by cancellation of the magnetic signal by stacked opposite-polarity basalt segments. Tivey et al. (2005) calculated the average magnetic moment of the crustal section to be 1930 Am^2, assuming an average magnetization of 5 A/m, but when alternating polarity is taken into account this is reduced to an effective moment of ~650 Am^2. This moment is equivalent to a 500-m-thick source layer with a magnetization of only ~1 A/m, which also provides a possible explanation for the appreciable reduction in magnetic anomaly amplitude over the area including Site 801.

Studies of contemporaneous stratigraphic sequences (Steiner et al., 1987) also observed an abnormally high frequency of reversals during the same portion of the Middle Jurassic and led Steiner et al. (1987) to suggest at that time, that rapid reversing of the geomagnetic field might be the explanation of the minimal magnetic anomaly signature within the JQZ. McElhinny and Larson (2003) summarized paleointensity studies and concluded that this is also a time of anomalously low dipole field intensity. However, the common observation of very reduced geomagnetic field intensity during reversals (~10%) suggests that a sustained lower geomagnetic field intensity during the extent of the JQZ is quite probable. Thus, the paucity of a magnetic anomaly signature over the JQZ crust may result from the combination of very high reversal frequency with relatively low dipole field intensity.

Finally, the magnetic logging data demonstrated that the appreciably altered tholeiites adjacent to the upper and lower hydrothermal units correspond to a paleolatitude of ~16°S for normally magnetized rocks. Moreover, sedimentary, radiometric, and paleomagnetic data demonstrated that the alkalic basalts overlying tholeiite basement were emplaced when the site was in an approximately equatorial location; hence, the hydrothermal activity was not contemporaneous with alkalic basalt emplacement. Instead, the site occupied a paleolatitude of ~16°S at two different times, several million years after crustal construction and in the mid-Cretaceous. Because midplate volcanism was widespread throughout the western Pacific Basin during the mid-Cretaceous, the polarity changes suggested that the hydrothermal deposits were precipitated in Site 801 tholeiitic crust in association with that activity, ~60 m.y. after construction of the oceanic crust. The evolution of the volcanic units and the magnetic stratigraphy at Site 801C are illustrated in the cartoon depicted in Figure F3 and taken from Tivey et al. (2005).

F3. Magnetic and extrusive volcanic history of the crust, Hole 801C, p. 25.



Petrology of Mesozoic Pacific Oceanic Crust

More than 50 samples of fresh basaltic glass were recovered from Sites 1149 and 801, providing pristine samples of the igneous liquid that forms Jurassic Pacific crust. These valuable samples record mid-ocean-ridge processes, mantle composition, and mantle temperature at a time preceding the Cretaceous "superplume" event in the Pacific (Fisk and Kelley, 2002). Hole 801C records higher Fe8 (10.77 wt%) and marginally lower Na8 (2.21 wt%) compared to MORB from the modern East Pacific Rise (EPR), suggesting deeper melting and a temperature of initial melting that was 60°C hotter than today. Trace element ratios such as La/Sm and Zr/Y, on the other hand, show remarkable similarities to the modern southern EPR, indicating that Site 801 was not generated on a hotspot-influenced ridge and that mantle of similar composition has fed spreading ridges over the past 170 m.y. Hole 801C basalt chemistry indicates that higher temperatures of mantle melting beneath Pacific ridges may have preceded the initiation of the Cretaceous superplume.

SEDIMENTATION HISTORY OF THE WESTERN PACIFIC

Site 1149 is the first complete section through the pelagic sediments (~400 m) of the Nadezhda Basin, a ~1000 km × 1000 km region in the northwestern Pacific Basin. More than 90% of the sedimentary section was either recovered or logged, and ~50 km of 80-in^3 water gun data were seismically recorded across the site and in the vicinity. Site 1149 is an important reference site for Mesozoic equatorial sedimentation since the late Valanginian and for sediment that is being subducted along the entire Izu Trench. The original objectives for drilling at Site 1149 involved the following:

1. Estimating geochemical fluxes from sediments subducted into the Izu subduction zone. Tests of differences in sediment inputs

in the Izu and Mariana trenches lead to geochemical differences in volcanic outputs at the two arcs. The paleolatitudes of formation of the sediments are important as the different sources of sediment, from pelagic, from eolian, or from volcaniclastic inputs will result in different sediment source compositions in the subduction zone;
2. Improving the Early Cretaceous paleomagnetic timescale; and
3. Providing constraints on mid-Cretaceous carbonate compensation depths and equatorial circulation.

Western Pacific Sedimentary/Seismic Sequence

Site 1149 is representative of the seismic and thus presumably sedimentary stratigraphy of the vast northwestern Pacific Basin (**Abrams,** this volume), which forms the primary input into the subduction zones at the western edge of the Pacific plate. Core-logging integration produced the following sedimentary and seismic section at Site 1149 (**Abrams,** this volume). An upper seismic transparent layer correlates with Unit I and II ash and pelagic clays. At 180 meters below seafloor (mbsf) and a two-way traveltime of 226 milliseconds below seafloor (msbsf) is the top of an upper seismic opaque layer, corresponding to the top of Unit III interbedded radiolarian cherts, porcellanites, and siliceous clay of early Aptian–Albian age. The strong velocity and density increase here produces a prominent seismic reflection that can be traced regionally (Ewing et al., 1968) and separates predominantly eolian deposits (above) from predominantly biogenic deposits (below). Below the uppermost cherts, velocity and density both increase more linearly, giving way to a lower transparent layer, corresponding to Unit IV cherts and carbonates of Early Cretaceous age (late Valanginian–late Hauterivian). At 410 mbsf (438 msbsf), basaltic basement is encountered, producing another impulsive increase in velocity and density and a strong seismic reflection. The cherts and carbonates deposited between the two prominent seismic reflectors mark the paleoequatorial passage of the Pacific plate regionally (Lancelot and Larson, 1975). This seismic sequence can be traced along the entire Izu-Bonin Trench and permits confident extrapolation of the detailed geochemical and sedimentological data collected at Site 1149 (**Abrams,** this volume; Plank et al., 2002a).

Paleoenvironments, Paleoclimate, and Paleoceanography

The seismic sequence outlined above results from the northward migration of Site 1149 by as much as 40° of latitude through most of its history across several oceanographic provinces (the following summary is from Plank, Ludden, Escutia, et al., 2000). Site 1149 was formed in the Valanginian (**Bartolini,** this volume) at low latitudes south of the equator (~5°–10°S), crossed the equator during the mid-Cretaceous (~100 Ma), and continued north to its current latitude (~31°N) in the western Pacific. The cherts and carbonates that make up the lower half of the site (Units IV and III) record biological events at equatorial paleolatitudes. The brown pelagic clays of Unit II record in a short interval (~60 m) most of the site's history (~100 m.y.) in sediments that are metal rich but largely barren of microfossils (with the exception of ichthyoliths). Unit I records ~6.5 m.y. of eolian deposition within the westerly wind belt and western boundary currents. This sedimentary section has led to definition of a global anoxic event in the Valanginian, as well as a high-resolution eolian record for the Pliocene–Pleistocene.

The uppermost Valanginian sediments in Hole 1149B contain biotic changes in nannofossils and radiolarians associated with the Valanginian $\delta^{13}C$ anomaly, which are coeval with and similar to those previously documented in the Tethys (Erba et al., 2004). This suggests a global perturbaton of marine ecosystems. A marked increase in abundance of *Diazomatholithus,* absence of nannoconids (**Lozar and Tremolada,** this volume), and a Pantanellium peak coincident with high concentrations of barium (**Bartolini,** this volume) characterize the Valanginian $\delta^{13}C$ excursion. Such changes were interpreted as being due to global enhanced fertility and a biocalcification crisis under conditions of excess CO_2. The presence of organic carbon–rich black shales in the Southern Alps and in the Pacific in this interval further suggested a Valanginian oceanic anoxic event (OAE), which Erba et al. (2004) named the "Weissert OAE" in recognition of Helmi Weissert's pioneering work on Lower Cretaceous sedimentary successions (Weissert, 1989). There is no paleontological or $\delta^{18}O$ evidence of warming during the Weissert OAE. On the contrary, both nannofossils and oxygen isotopes record a cooling event at the climax of the $\delta^{13}C$ excursion. Possibly, weathering of basalts and burial of organic carbon–rich black shales were responsible for CO_2 drawdown and establishment of reversed Greenhouse conditions.

A recent study (**Escutia et al.,** this volume) focuses on the Miocene to Pleistocene volcanic ash record in Unit I and Subunit IIA sediments at Site 1149, along with a companion site ~10° farther north (ODP Site 1179; Kanazawa, Sager, Escutia, et al., 2001), within the context of the paleoceanographic and paleoclimatic evolution of the northwestern Pacific. Detailed $^{40}Ar/^{39}Ar$ analyses of ash samples, combined with magnetostratigraphy, yield a refined chronology that will be invaluable for future geochemical studies aimed at the evolution of arc volcanism in the northern circum-Pacific (**Escutia et al.,** this volume). The new chronology also reveals peaks in ash frequency and cumulative ash thickness. Because both sites show correlated increases in ash accumulation rates, Sager and Escutia (2005) hypothesize increased transport of sediment may be associated with cooling climate events and stronger trade winds carrying both dust and ash from an increasingly arid Asia. This is supported by the position of dated ash layers at both Sites 1149 and 1179 for the last 2.1 m.y., which correlate with cold stages or cooling trends in the isotopic variations.

Lower Pliocene to Quaternary silicoflagellate biostratigraphy allowed **Lozar and Mussa** (this volume) to track the increasing warming of surface waters due to the diverted Kuroshio Current in relation to the Middle Pliocene closure of the Central American Seaway using three closely spaced events: the asperoid/fibuloid reversal, the change in the *Distephanus*/*Dictyocha* ratio, and the last occurrence (LO) of *Distephanus Boliviensis*. Diatom stratigraphy studies by **Olschesky and Laws** (this volume) show that zonal indicator species for the lower Pliocene–upper Pleistocene zones for both the equatorial Pacific and the North Pacific zonations are present in Hole 1149A. Additionally, the presence of coastal and benthic taxa in the diatom flora from Unit I strongly suggests some onshore to offshore transport of material to Site 1149 either by aqueous or eolian mechanisms.

The Pleistocene section of Hole 1149A provides an expanded record of eolian dust (supplied from the Asian continent), changing volcanic ash input, and siliceous plankton accumulation, with recurrent diagenetic intervals in a deep-sea environment. Urbat and Pletsch (this volume) developed a scheme for the late Pleistocene section using geochemical normative calculations on the basis of Al and Cr contents to discriminate between the major groups of components (terrigenous, volcanogenic, biogenic, and diagenetic) in combination with magnetic variations to quantify the eolian input of continental material to Site 1149.

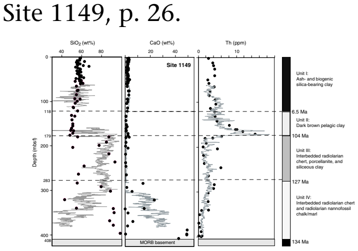
Textural variations and other physical properties, such as electrical resistivity, of the sediments that are being subducted within the Pacific plate provide important information on mass transfer properties of fluids. A series of studies that will provide important constraints to future Integrated Ocean Drilling Program (IODP) experiments, such as for fluid evolution in Nankai sediments, were carried out on the Site 1149 sedimentary sequence (**Hirono,** this volume; **Hirono and Abrams,** this volume; **Kawamura and Ogawa,** this volume; **Tanaka and Ogawa,** this volume).

Geochemical Stratigraphy and Novel Stable Isotope Systematics

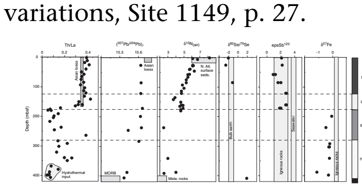
The primary objective of drilling at Site 1149 was to create a geochemical reference site for subduction at the Izu Trench, and so this ~400-m sedimentary section has been the target of a remarkably comprehensive set of geochemical studies. A great variety of elemental and isotopic measurements have been made, in many cases on the same sample powders. This is too often not the case, and so Site 1149 studies provide a rare opportunity to relate many geochemical systems. In addition to enabling precise mass flux estimates for the Izu margin (see **"Geochemical Sinks and Recycling at Subduction Zones,"** p. 13), the geochemical data for Site 1149 sediments help define the sedimentation history for the Nadezhda Basin, as well as first-order systematics on some new isotopic systems.

The combination of geochemical logging data and comprehensive core analyses creates a useful geochemical section for Site 1149 sediments. Unit I is characterized by the intermediate silica and low CaO typical of pelagic clays, whereas Unit II is characterized by a dramatic increase in the concentration of hydrogenous elements like Th in brown clays (Fig. **F4**) (Plank and Kelley, 2001). Unit III is clearly identified by a rise to silica values >80% due to the appearance of chert and Unit IV by a more gradual rise in CaO due to the abundance of chalks (Fig. **F4**). Other geochemical tracers record the detailed motion of the site relative to different oceanographic provinces. Th/La maps several geographic transitions (Fig. **F5**), as it is sensitive to eolian dust and ash (high Th/La), hydrothermal inputs (rare earth element [REE] rich and low Th/La), and biogenic fluxes (phosphate and REE rich and low Th/La). Thus, as the site begins in the south in low-latitude, high-productivity zones, Th/La is initially low due to hydrothermal and biogenic inputs then rises dramatically when the site moves northward into the central gyre (near the Unit III/II boundary), and rises further to high values typical of eolian dust (loess) as the site moves into the influence of the westerly winds (Plank et al., 2002a) (Fig. **F5**). Pb isotopes also map similar variations, with low MORB-like values at the base, reflecting hydrothermal inputs, rising to high values throughout the rest of the site, reflecting eolian and seawater inputs (Hauff et al., 2003) (Fig. **F5**). Thus, geochemical variations both define the stratigraphic units

F4. Chemostratigraphic section, Site 1149, p. 26.



F5. Trace element and isotopic variations, Site 1149, p. 27.



and record the site's migration from equatorial regions to western Pacific mid-latitudes. Such systematic geochemical variations, clearly tied to lithological and latitudinal variations, make Site 1149 a useful reference site for calculating geochemical inputs into the Honshu-Izu-Bonin-Mariana Trench (see **"Site 1149: A Geochemical Reference Site for Sediment Recycling at the Izu-Bonin-Mariana Margin,"** p. 15, in "Geochemical Sinks and Recycling at Subduction Zones").

In contrast to geochemical tracers that reflect the primary sedimentation history of the site, carbon and nitrogen isotopes in Site 1149 sediments record predominantly diagenetic effects (Sadofsky and Bebout, 2004). The uppermost 100 m of the site shows systematic decreases in $\delta^{15}N$ (Fig. **F5**), as well as in $\delta^{13}C$, and in N and organic carbon concentrations. Although some of this variation may relate to an increase in biologic productivity as the site moves into the influence of the western boundary currents, Sadofsky and Bebout (2004) interpret the changes largely as diagenetic. Significantly, this study is one of the first to document $\delta^{15}N$ variations in a section of deep-sea pelagic sediments, and the observed ~3‰ decrease in $\delta^{15}N$ downcore may help to relate high marine organic values to the low values typical of metasedimentary rocks (Sadofsky and Bebout, 2004) (Fig. **F5**). This early diagenetic shift in N isotopes may be representative of the first step in the progressive metamorphism of deep-sea sediments during subduction. These data, taken together, provide the basis for global subduction flux estimates for nitrogen and carbon (Sadofsky and Bebout, 2004).

Site 1149 sediments represent a classical sequence of oceanic pelagic sedimentation, including type examples of chalk, chert, brown clay, and eolian deposition. Thus, they make a convenient target for developing new stable isotope systems in geochemistry (Rouxel et al., 2002, 2003a, 2003b). Figure **F5** includes a summary of these works, with some of the first data published on Se, Sb, and Fe isotopes in deep-sea sediments. More than revealing anything unusual about Site 1149 sediments, these measurements help to define the marine processes that lead to significant fractionation in these new stable isotope systems.

Se isotopic compositions of Site 1149 sediments show significant shifts in $^{82}Se/^{76}Se$ relative to bulk earth (Fig. **F5**), to both low values (at <25 mbsf) and high values (basal carbonate). In accord with the interpretations in Rouxel et al. (2002), the low $\delta^{82}Se/^{76}Se$ ratios in the upper 25 m of the site may result from reduction of seawater Se(IV) and Se(VI) oxyanions, since this is the region of active organic matter degradation and suboxic diagenesis at the site (Sadofsky and Bebout, 2004; **Cragg et al.,** this volume). The positive shift in the basal carbonate marks the heaviest $\delta^{82}Se/^{76}Se$ composition in any earth (or meteoritic) material measured by Rouxel et al. (2002). Based on neighboring samples, this sediment contains a significant fraction of Fe-rich hydrothermal precipitate and may reflect the complement to low-$\delta^{82}Se/^{76}Se$ sulfide-rich hydrothermal deposits reported by Rouxel et al. (2002).

Sb isotopic compositions of Site 1149 sediments generally fall within the range defined by igneous rocks (Fig. **F5**), and indeed, Rouxel et al. (2003b) use Site 1149 in part to define continental crust values. Nonetheless, there is a range of almost 2‰ in $\varepsilon^{123}Sb$ in Site 1149 sediments, with the lowest values corresponding to a Unit I sample with abundant arc-derived ash (as revealed in its high εNd) (Hauff et al., 2003). The highest values, which are shifted toward seawater, are in Unit II samples that have the greatest hydrogenous Mn oxyhydroxide contribution (as revealed in their high Mn/P and positive Ce anomalies) (Plank and Kelley, 2001).

Rouxel et al. (2003a) measured the Fe isotopic composition of cherts and chalks from Units III and IV and found $\delta^{57}Fe$ shifted to values up to 1‰ lower than the igneous value. In fact, the Site 1149 sediments are used in part to define a chert average of –0.11‰, which Rouxel et al. (2003a) argue is shifted toward likely seawater values of approximately –1.0‰. The lowest values at the site are for a basal carbonate, which may reflect the input of hydrothermal Fe (based on its high Fe/Al).

Other studies in progress on Site 1149 sediments include a focus on cosmogenic ^{10}Be (Valentine et al., 2002), Li isotopes (Valentine et al., 2001), Hf-Nd isotope systematics (Marini and Chauvel, 2001), and high-precision Pb isotope systematics in the hydrothermally dominated basal sediments (V.M.C. Chavagnac, C.R. German, unpubl. data).

GEOCHEMICAL SINKS AND RECYCLING AT SUBDUCTION ZONES

Site 801: A Geochemical Reference Site for Global Budgets and the Aging of Oceanic Crust

Holes 801C and 1149D in the western Pacific Ocean provide well-described sections into Mesozoic fast-spreading crust, Layer 2A. This ocean crust has acted as a "sponge" and soaked up elements during alteration by warm hydrothermal fluids and, later, cold seawater. Much of this alteration occurs early in the history of the cooling of the plate as it moves away from the spreading center, but chemical exchange may continue for tens of millions of years and may be reactivated by later volcanic and hydrothermal activity or by fracturing during flexure of the crust into the trench. This crust is then transported into the subduction zone, where it dewaters and melts, providing fluids that lubricate the subduction system and drive melting in the mantle. These transformations to the downgoing plate ultimately lead to arc volcanism and mantle heterogeneity.

Geochemical alteration of the volcanic section in Hole 801C occurs in several discrete zones, associated with ocherous Si-Fe hydrothermal deposits and thick massive flows and breccias. These zones control the alteration pattern of crust and contrast with previous models for a gradual decrease downhole in the alteration of oceanic basement. The pattern of alteration at Site 801, controlled by local pathways for hydrothermal fluids, may be a feature of fast-spreading crust (Alt and Teagle, 2003).

It is a great challenge to calculate the bulk geochemical composition of such a heterogeneous section. The approach taken by Leg 185 scientists was to combine representative samples into physical composite mixtures, ultimately leading to a "super" composite that approximates the bulk composition of the site in a single sample powder (e.g., Staudigel et al., 1995; Kelley et al., 2003). Preparation of these composites was guided by the abundance of data on the proportions of alteration zones (e.g., alteration halos, numbers of veins, and types of vein fillings logged by shipboard scientists) (Plank, Ludden, Escutia, et al., 2000), alteration mineralogy (Alt and Teagle, 2003; Talbi and Honnorez, 2003), and reconstruction of core types and compositions from logging data (Barr et al., 2002; Révillon et al., 2002; Jarrard et al., 2003). The basic major and trace element compositions of these composites are described in Kelley et al. (2003), and below are descriptions of the many other studies that have used the Site 801 basement samples and composites to provide first-order constraints on the composition of old oceanic crust.

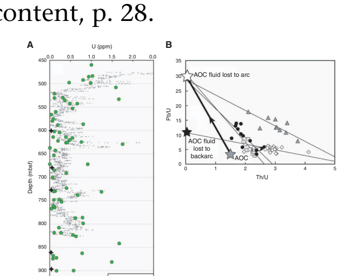
Rouxel et al. (2003a) conducted one of the first detailed studies of Fe isotope fractionation during oceanic crust alteration, using primarily Leg 185 material. Although the Site 801 composites show little variation in δ^{57}Fe from average igneous rocks, different alteration domains show large shifts, with both positive and negative δ^{57}Fe, up to a total range of 4‰. The proposed processes of isotopic fractionation include formation of secondary minerals, Fe oxidation, preferential leaching of Fe^{2+} and, possibly, microbial mediation. These results are among the first produced for this system and provide a reference for future studies of reservoirs of fresh and altered basalts in the modern Earth for comparisons with the ancient Earth, the moon, and terrestrial planets.

Alt (2003), Alt and Teagle (2003), and Jarrard (2003) used samples from Hole 801C to define the concentrations and stable isotopic ratios of the major anions of O, C, and Cl in ocean crust with respect to estimates from other deep ocean crust sections. The oxygen isotopic composition of Hole 801C secondary minerals records temperatures from 5° to 100°C, increasing downhole through the ~500-m basement section in Hole 801C (Alt and Teagle, 2003). The δ^{13}C composition of Hole 801C carbonates reflect incorporation of oxidized organic carbon, as well as δ^{13}C changes in seawater since the Jurassic (Alt and Teagle, 2003). One of the important differences in the basement alteration of Hole 801C relative to other drilled basement sections is the order-of-magnitude lower abundance of brown oxidation halos, probably due to smooth basement topography and high sedimentation rate restricting access of oxygenated seawater (Alt and Teagle, 2003). The "super" composite for Hole 801C also appears to have higher δ^{18}O than other upper oceanic crustal sections, even when corrected for δ^{18}O-rich sediments (Alt, 2003). These observations could lead to a more detailed understanding of the oxidation state and δ^{18}O composition of the suprasubduction zone mantle. Finally, Jarrard (2003) uses physical properties of Hole 801C sediments (Jarrard et al., 2003) in part to develop a strategy for calculating the subduction flux of H_2O, CO_2, Cl, and K worldwide.

The radiogenic isotopes of Sr are reset by the circulation of seawater (e.g., Staudigel et al., 1995; Alt and Teagle, 2003), and this effect is well identified in fluid transfer as contributing a radiogenic isotope signature to arc lavas during dewatering at subduction zones (e.g., Elliot et al., 1997). The detailed sampling approach has permitted quantitative estimates of radiogenic isotope compositions of Sr, Pb, Nd, Hf, and Os of the altered oceanic crust being subducted into the Izu-Mariana system. These results have been used to quantify the different components involved in the generation of arc magmas (Hauff et al., 2003; Marini and Chauvel, 2001).

One of the most significant geochemical transfers in low-temperature alteration of oceanic crust is the uptake of U from seawater and its consequent disruption to the coupled ^{238}U-^{206}Pb, ^{235}U-^{207}Pb, and ^{232}Th-^{208}Pb isotopic systems (Hart and Staudigel, 1989). One of the major achievements of Leg 185 was to define the U and Pb content of altered oceanic crust (Révillon et al., 2002; Kelley et al., 2003) (Fig. F6A) and thus provide a realistic estimate for modeling subduction fluxes (Fig.

F6. Estimation of crustal uranium content, p. 28.



F6B) (Kelley et al., 2005). Alteration in the upper 500 m of the oceanic crust leads to more than a fourfold increase in U/Pb, and if crust of this composition were subducted and incorporated into the mantle over Earth history, it would lead to mantle compositions that are never observed (Hart and Staudigel, 1989; Kelley et al., 2005). Thus, the subduction zone must further modify subducting slab compositions, and indeed, mass balance calculations of oceanic crust input with Marianas arc and backarc output predict shallow loss of 45%–75% of the slab Pb to the arc and deeper loss of 20%–40% of slab U to the backarc, with the net effect producing a source capable of evolving to compositions typical of the modern oceanic mantle (Kelley et al., 2005). These studies on Hole 801C sediments have thus quantified for the first time a whole-Earth geochemical cycle that has long been argued as critical in the development of mantle heterogeneity (e.g., Hofmann and White, 1982).

Studies are still in progress on the isotopic and elemental distribution of Li and B in the ocean crust (Valentine et al., 2001). Boron, and probably to a lesser extent Li, are dewatered at an early stage of subduction and are commonly enriched in fluids emanating from forearc regions (e.g., Benton et al., 2004). Quantification and modeling of these lower-temperature slab fluxes require an understanding of their distribution in the altered oceanic crust.

Many of the accomplishments of Leg 185 have stemmed from the attempt to use the same sample suite for all geochemical analyses. Such a practice should serve as a model for future IODP efforts. The composite sample suite from Leg 185 is already a valuable reference for the geochemical community, and samples remain for further study.

Site 1149: A Geochemical Reference Site for Sediment Recycling at the Izu-Bonin-Mariana Margin

One of the primary goals of drilling during Leg 185 was to test whether chemical contrasts between the Marianas and Izu volcanic arcs derive in part from different input fluxes to the respective trenches. Different basement sections may contribute some variability (Hauff et al., 2003), but the different sedimentary sections create the largest chemical contrast in input fluxes along the margin. Site 1149 was chosen primarily to provide such a reference site for sediment recycling at the Izu-Bonin margin.

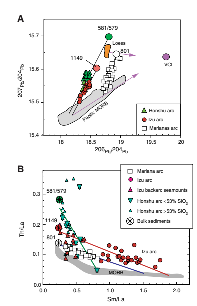
Subduction recycling studies are impossible without attacking systems on both sides of the trench. At the same time that Leg 185 postcruise activities focused on oceanic input to the trench (also see the contents of the G^3 special volume on this theme; Table T2), many complementary studies have been carried out to characterize the composition of Izu-Bonin-Mariana (IBM) volcanic output through time, including new results from the submarine portions of the arcs (Hochstaedter et al., 2000, 2001; Ishizuka et al., 2003), as well as detailed marine ash records (Straub, 2003; Straub et al., 2004; Bryant et al., 1999, 2003). Site 1149 also preserves a well-dated volcanic ash record (**Escutia et al.,** this volume), some of which derives from the Izu arc (based on preliminary laser inductively coupled plasma–mass spectrometry [ICP-MS] analyses of ash shards, T. Plank and Mordick, unpubl. data). The uppermost 120 m at Site 1149 contains 94 discrete ash layers, some light and some dark (**Escutia et al.,** this volume; Sager and Escutia, 2005), much like material recovered in the Izu forearc basin (Fujioca et al., 1992). Nonetheless, layers at Site 1149 may have been windblown from multiple volcanic sources, and future geochemical analyses will resolve the provenance of the ash record. Such arc ash also contributes significantly to the subducted input flux. Discrete ash layers make up a minimum of 5% of the total sediment deposited over the last 7 m.y. (Sager and Escutia et al., 2005), whereas dispersed ash may make up as much as 35%–50% (based on Al- and Nb-based calculations in Plank, Ludden, Escutia, et al., 2000). Thus, Site 1149 is uniquely situated to provide both an input and an output record to the Izu subduction recycling problem.

At a regional scale, the combination of Legs 185 and 129 have given us an unprecedented understanding of subducted sediment fluxes along >1000 km of plate boundary at the IBM margin. Key in this endeavor are the seismic correlations that permit interpolation between widely spaced drill sites (**Abrams,** this volume). In contrast to the sediments subducting at the Marianas Trench (based on Sites 801 and 800), sediments in the Izu-Bonin Trench lack a mid-Cretaceous volcaniclastic section and contain more siliceous and carbonate-rich biogenic material due to a longer residence of the site beneath zones of high biological productivity. The more northerly latitude of Site 1149 leads to its Cenozoic passage into the westerly wind belt, resulting in a significant section of eolian dust of similar composition to Asian loess, as well as arc ash, both of which are largely absent from Site 801. As biogenic sediments are impoverished in most trace elements of interest to subduction cycling (Plank and Ludden, 1992; Plank and Langmuir, 1998), the most significant chemical difference is the abundance of eolian dust and ash at Site 1149 (Izu) vs. ocean-island volcaniclastics at Site 801 (Marianas).

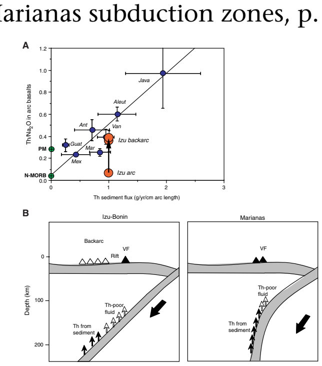
The impact of such differences in sediment input have now been looked for and found in corresponding volcanic output. Eolian-dominated (for Izu) and volcaniclastic-dominated (for Marianas) sediments lead to different Pb isotopic sediment mixing end-members for the two arcs (Fig. **F7A**). For example, the entire Mariana arc is shifted to higher ^{206}Pb/^{204}Pb, which is largely due to the high ^{206}Pb/^{204}Pb volcaniclastics subducted there, combined with different components from the basement and mantle (Hauff et al., 2003). Another useful tracer in the recycling problem is Th/La, which is uniquely high in continental detritus (e.g., eolian dust) (see Fig. **F5A**) and is efficiently recycled through subduction zones (Plank, 2005). The IBM arcs mix toward sediment with progressively higher Th/La (Marianas to Izu to Honshu) as the seafloor enters the westerly wind belt and receives increasing amounts of high-Th/La eolian dust to the north (Fig. **F7B**). The IBM system thus illustrates for the first time how latitudinal variations in sedimentary stratigraphy can be linked to latitudinal variations in arc geochemistry on a regional scale (~1500 km). This experiment in the spatial coherence of sediment-arc recycling complements another recent experiment finding such coherence through time at the Nicaragua margin (Plank et al., 2002b).

Although there has been considerable success in tracing regional sediment inputs to IBM arc outputs, there remains a problem in the absolute mass fluxes involved. The most trenchward line of volcanoes that define the Izu arc (the "volcanic front") is highly deficient in the concentration of slab tracers, such as Th, relative to the Marianas arc and the rest of the global arc array (Fig. **F8A**). Results of Leg 185 demonstrate clearly that this deficiency in the Izu volcanic front is not caused by a deficiency in the sediment input flux to the Izu Trench. The mass flux delivered by Site 1149 is broadly comparable to that delivered by

F7. Examples of sediment recycling at the Izu-Bonin-Marianas-Honshu margins, p. 29.



F8. Th recycling at the Izu and Marianas subduction zones, p. 30.

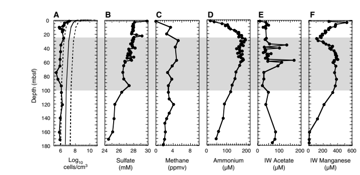


Site 801 for K, Th, and U, which are robustly calculated from downhole natural gamma logging data (Fig. F8A). Thus, while the Th deficiency indicates that there is a clear sediment contribution at the Izu volcanic front, the amount it is too low. However, submarine lavas erupted 100–150 km behind the Izu volcanic front (Hochstaedter et al., 2001) have the appropriate composition for the sediment input fluxes (Plank and Kelley, 2001; Straub, 2003). This suggests that the Izu subduction factory has a delayed delivery system, with most sedimentary slab material missing the main arc but feeding the backarc region. Both the Izu and Mariana arcs are consistent with subducted sedimentary components derived from deeper than 175 km in these cold slabs but the near vertical slab beneath the Marianas, allowing multiple components to contribute to the volcanic front (Fig. F8B). Drilling along the IBM margin has thus revealed new dynamics within the subduction factory relating to dip and thermal structure of the downgoing plate, which can be tested at other margins.

THE DEEP BIOSPHERE

The deep water (~6000 m) and proposed penetration into old oceanic basement provided an intriguing target in the search for hidden bacterial life forms. Leg 185 was the first ODP leg to incorporate microbiology as a major new initiative. The microbiology objectives for Leg 185 resulted in the determination of the amount of biological contamination created by the advanced piston corer (APC), extended core barrel (XCB), and rotary core barrel (RCB) coring processes and the development of a sample-handling strategy for routine microbiological sampling (Fisk, 1999; Smith et al., 2000). Contaminant tests using perfluorocarbon and fluorescent microspheres showed that several APC core interiors were entirely free of contaminants and RCB core interiors were free of microspheres (Smith et al., 2000). Culturing experiments were undertaken, and bacterial populations of Site 1149 are now part of the global compilation of the subseafloor microbiological diversity (Fig. F9) (Cragg et al., this volume).

F9. Total bacteria and IW geochemistry, Site 1149, p. 31.



Textural evidence for bacterial activity in Hole 801C volcanic glasses bear a remarkable resemblance to such features in modern ridge axis environments (Fisk, 1999) and may record long-term biological activity in seafloor volcanic systems. Research on the subsea biosphere is now a major part of IODP. Pioneering studies by the Leg 185 scientists helped pave the way for this initiative.

CONCLUSIONS

Leg 185 revisited and redefined an ODP legacy site on the western Pacific plate. Hole 801C is now a reference site for a number of key physical and chemical features of the planet, most notably for the birth and structure of the Pacific plate, the variation of the magnetic field in the Jurassic, and the bulk geochemical composition of oceanic crust. For the latter, the crust not only acts as a sink for major and trace elements in global fluxes between seawater and the continents but also as an important part of the input into the subduction factory for key chemical components. When subducted, these elements play a key role in the global fluxes of the planet through mobilization during subduction metamorphism and melting and final recycling into the mantle.

Leg 185 also permitted the quantification of sediment input into the subduction system along a north-south transect where the components show an extreme variation, largely controlled by the wide range in paleoenvironments traversed by the plate. These different sediment inputs are recorded in the outputs of nearby volcanoes and also in components that will be recycled into the mantle and may be sampled later in Earth's history by mantle melting and magmatism.

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Figure F1. Locations of the ODP Sites 1149 and 801 and other ODP drilling sites relative to the west Pacific arcs (from north to south: Honshu, Izu, and Marianas arcs). The predicted topography of the northwest Pacific is taken from Smith and Sandwell (1997) and magnetic lineations of the western Pacific are compiled from Nakanishi et al. (1989) and the PLATES Project (1998). Ages of selected lineations (solid black lines) are given using the timescale of Channell et al. (1995). Open circles = locations of selected DSDP/ODP sites. Site 1149 is located 2200 km northwest of Site 801 along a fracture zone bounded flow line spanning ~36 m.y. White dashed lines = locations of fracture zones (GMT software; Smith and Wessel, 1990). The section shown on the side of the figure represents a simplified stratigraphic section of ODP Site 801. MORB = mid-ocean-ridge basalt.

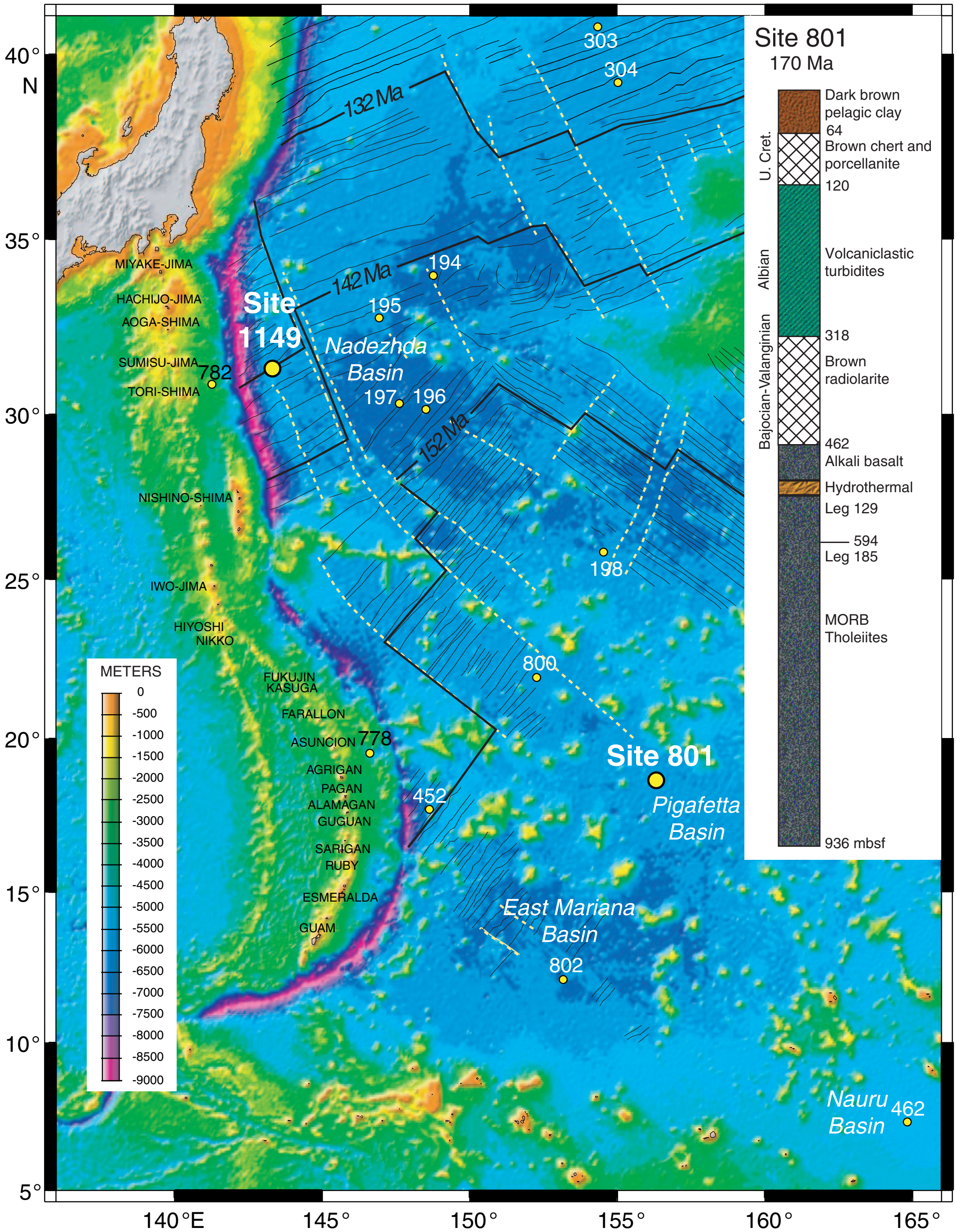

Figure F2. Compilation of physical and geochemical properties for Site 801 basement (Pockalny and Larson, 2003). The volcanic section is divided into eight units (left column) on which the ages of the basement have been superimposed (Koppers et al., 2003). Representative geophysical logging measurements are shown overlain on basement stratigraphy to illustrate the correspondence between the various parameters. Sequences I–III are interpreted as being erupted slightly off-axis, while the deeper sequences IV–VIII are assumed to be more characteristic of ocean crust emplaced at a fast spreading ridge axis. Zirconium compositions (Kelley et al., 2003) have been used to define the basement sequences. Note the trend toward low Zr (more primitive compositions) in sequences IV–II (no Zr abundances are given for the alkaline lavas in sequence I). Lava flow frequency (number of volcanic units per 10-m section) is calculated from Formation MicroScanner (FMS) data (Pockalny and Larson, 2003).

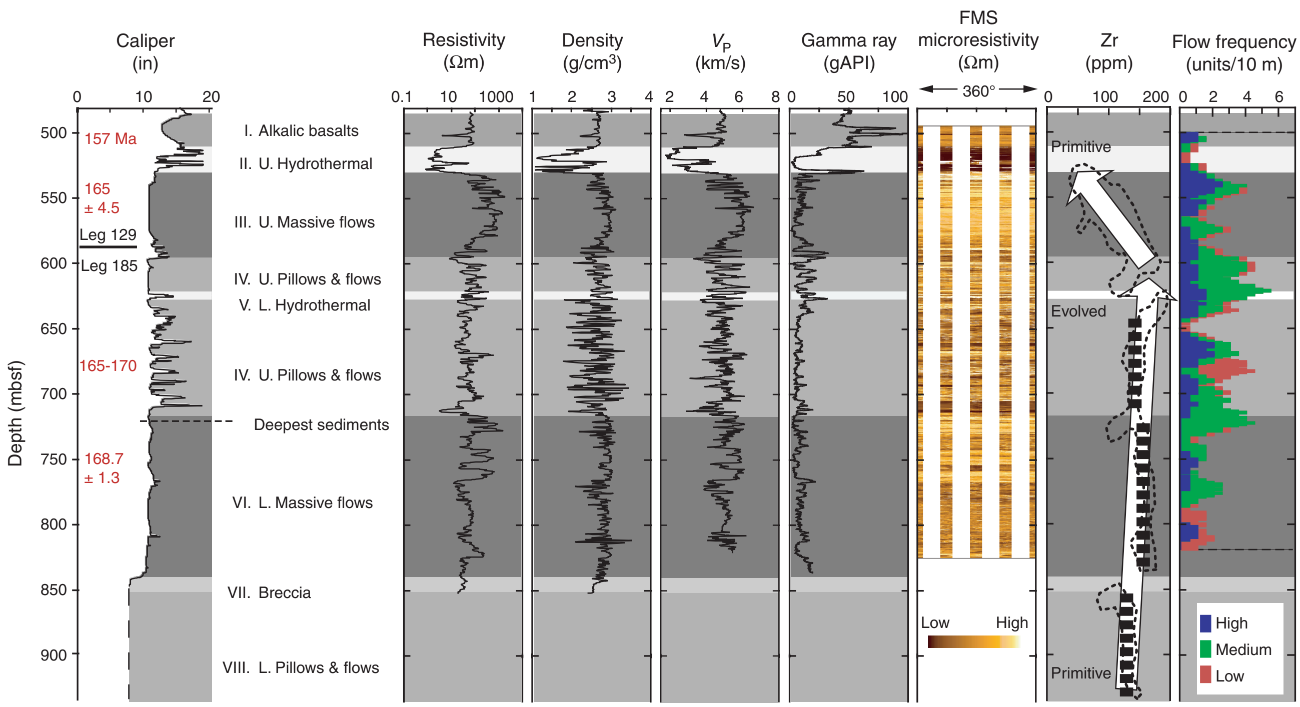

Figure F3. Details of the magnetic and extrusive volcanic history of the crust in Hole 801C. This illustration of the superposition of the volcanic units and the magnetic stratigraphy is taken from Tivey et al. (2005).

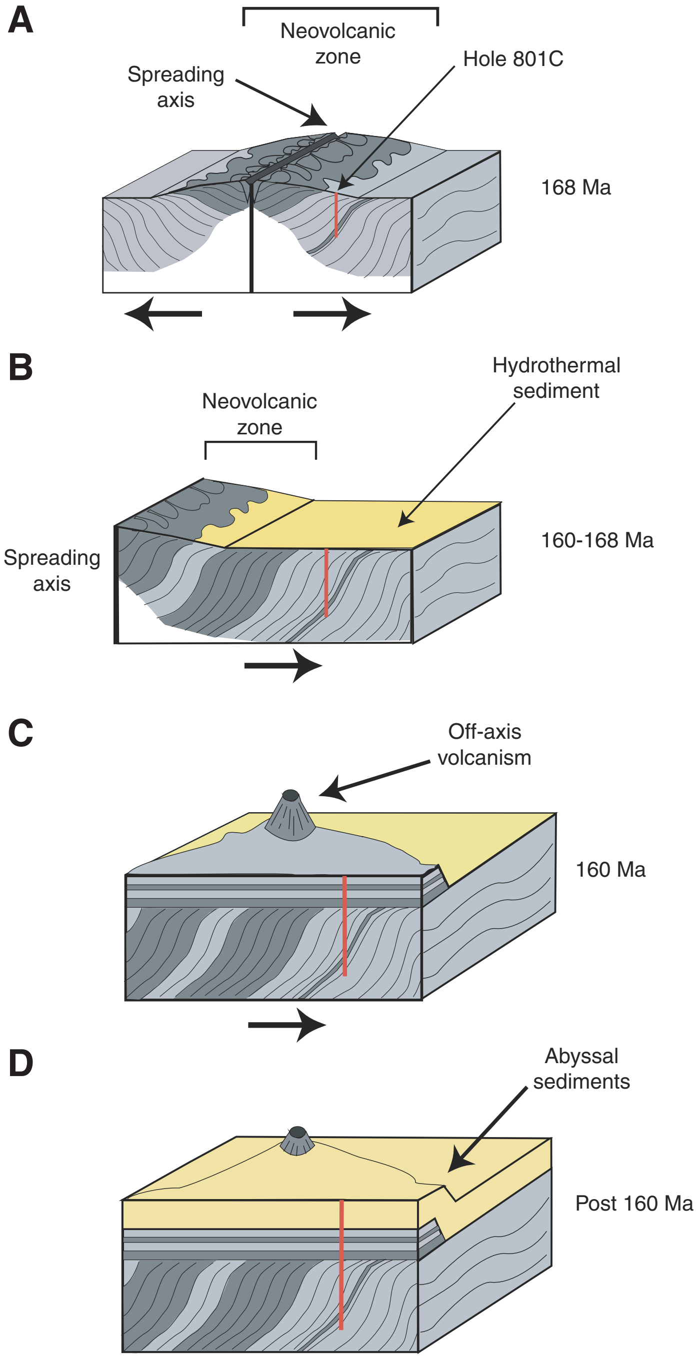

Figure F4. Chemostratigraphic section at ODP Site 1149, based on logging data in Hole 1149B (gray line) and chemical analyses of core samples from Holes 1149A and 1149B (solid circles; Plank and Kelley, 2001). Oxide data are from geochemical logging tool, renormalized to 100% to include all major element oxides and H_2O. Thorium data are from the Hostile Environment Gamma Ray Spectrometry tool and core data, corrected to in situ concentrations. Note good agreement between borehole and sample data, except in chert-rich lithologies, where larger footprint (tens of centimeters) of borehole logs averages thin layers of dramatically different composition (e.g., chert vs. clay vs. carbonate). Age boundaries are as follows: I/II (paleomagnetic stratigraphy; Plank, Ludden, Escutia, et al., 2000), II/III (middle Albian radiolarian zones; Bartolini, this volume), III/IV (Hauterivian/Barremian radiolarian zones; Bartolini, this volume), and basement age (assuming M12 chron; Bartolini, this volume). Ages based on timescale of Gradstein (1995). MORB = mid-ocean-ridge basalt.

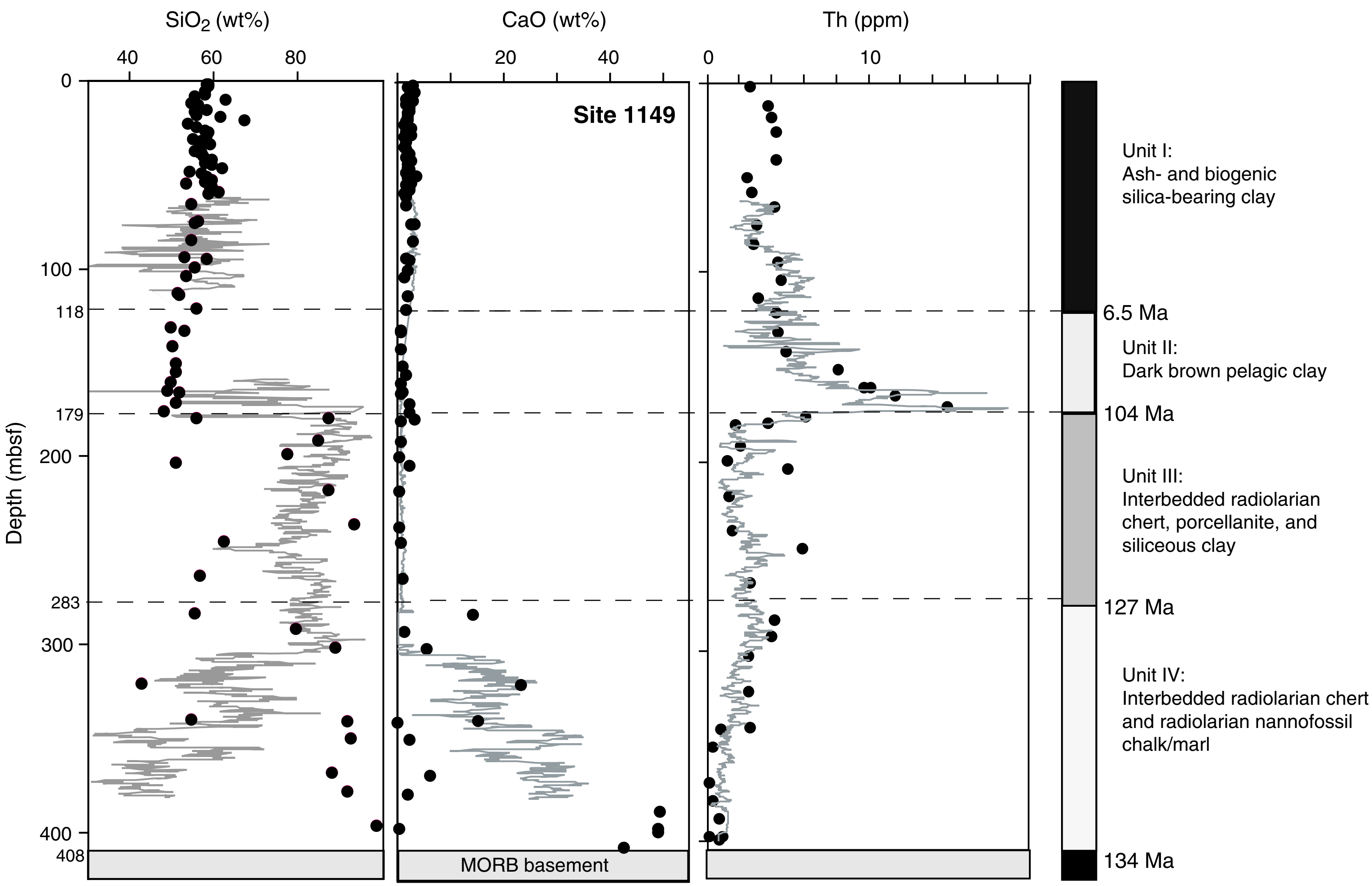

Figure F5. Trace element and isotopic variations in sediments from ODP Site 1149. From left: Th/La variations showing dominance of eolian dust source at the top of the site, and REE-rich biogenic and hydrothermal material in the lower part of the site (Plank et al., 2002a; Asian loess from Jahn et al., 2001). Initial Pb isotopic variation, showing nearly uniform, continental values through most of the site but approaching mid-ocean-ridge basalt (MORB) values in sediments at the base, due to hydrothermal inputs (data from Hauff et al., 2003, corrected for ingrowth based on measured U/Pb and ages interpolated between unit boundaries as in Figure **F4,** p. 26. Diagenetic processes decrease nitrogen isotopes by several permil downcore, to values typical of low-grade metamorphic rocks (after Sadofsky and Bebout, 2004). Selenium isotope variations, lower than bulk earth values at the top of the core (possibly due to organic matter degradation) and greater than bulk earth in basalt sediments with hydrothermal inputs (after Rouxel et al., 2002). Antimony isotope variations, lying generally within the values for igneous rocks but shifted toward seawater in Unit II (after Rouxel et al., 2003b). Iron isotope variations, showing values lower than igneous rocks, in chert- and carbonate-dominated lithologies of Units II and III (after Rouxel et al., 2003a).

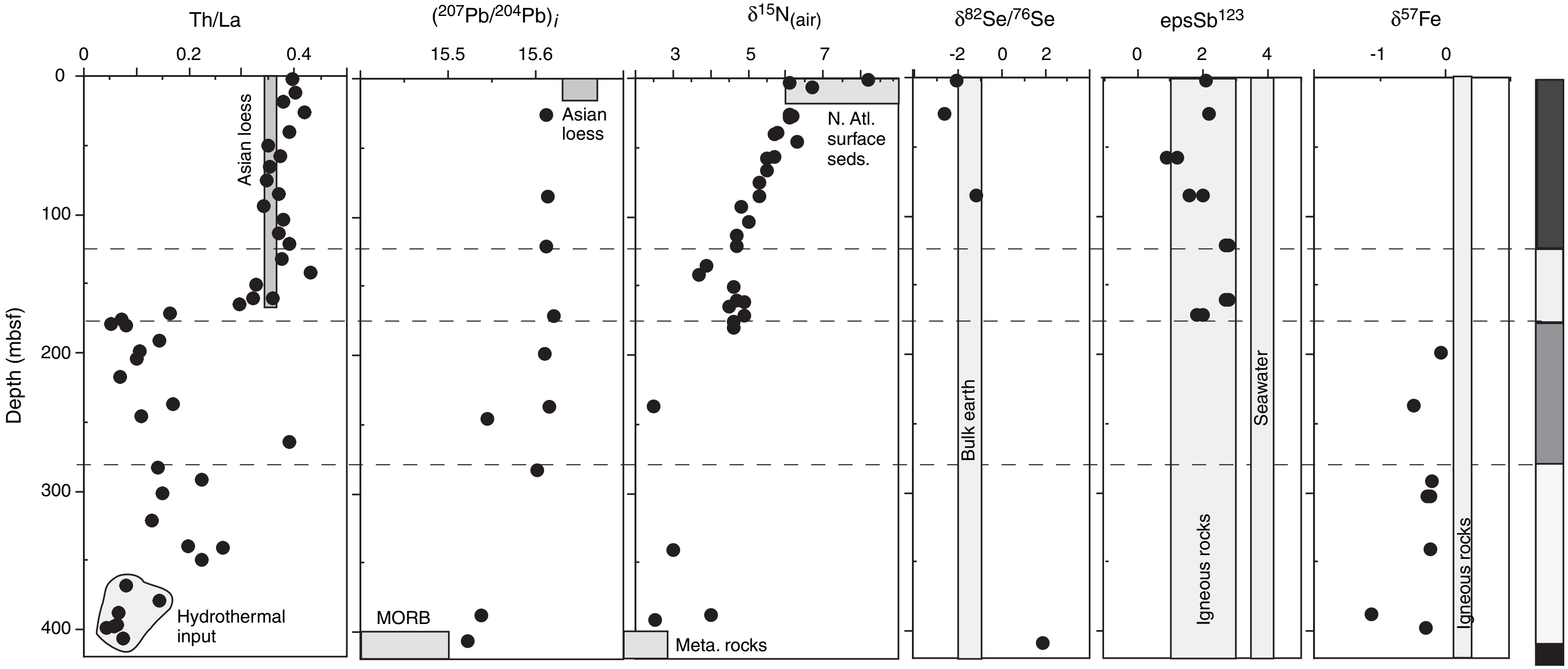

Figure F6. A. Natural Spectral Gamma Ray Tool logging data and inductively coupled plasma–mass spectrometry (ICP-MS) analyses of discrete samples to obtain an estimate for the uranium content of the oceanic crust (from Kelley et al., 2003). **B.** Pb/U vs. Th/U in arc basaltic lavas (all ICP-MS data). Triangles = Honshu (Gust et al., 1995), squares = Aleutians (Plank, 2005), circles = Marianas (Elliott et al., 1997), diamonds = Mariana backarc (Pearce et al., 2005). Thin black lines are RMA linear regressions through data.Thick black line illustrates the difference between bulk altered oceanic crust (AOC) (based on ODP Site 801 composites) and the AOC-derived fluid, demonstrating a common enrichment in Pb over U in the fluid component that recycles to volcanic arcs (figure from Kelley et al., 2005).

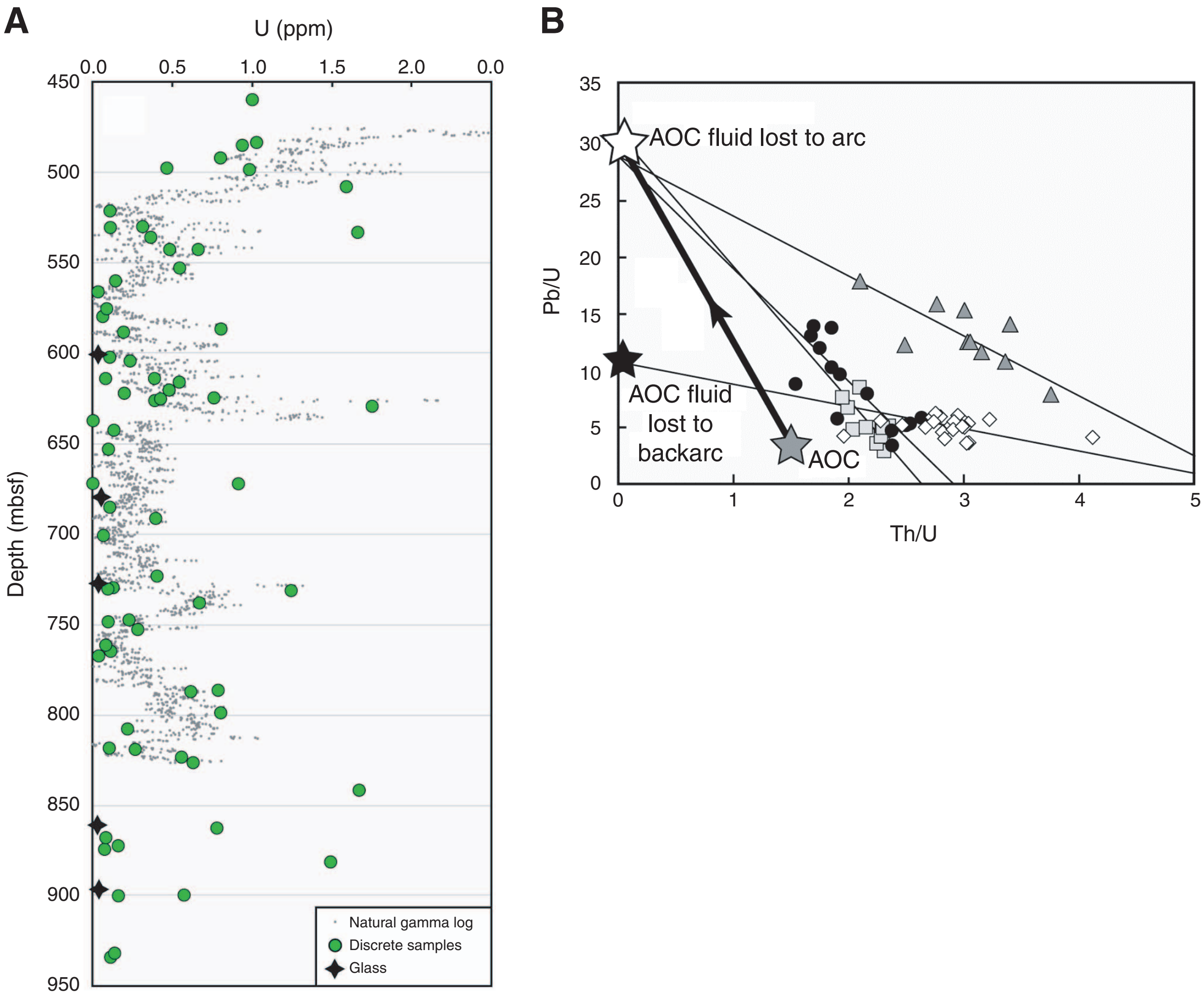

Figure F7. Examples of sediment recycling at the Izu-Bonin-Marianas-Honshu margins. **A.** Pb isotopic composition of different arcs can be resolved into mixing arrays between composition in the Pacific mid-ocean-ridge basalt (MORB) field, and compositions entirely consistent with local bulk sediment subducting at each trench, based on DSDP and ODP drilling: Honshu arc mixes to DSDP Site 579/581 bulk sediment; Izu arc mixes to ODP Site 1149 bulk sediment; Marianas arc mixes to ODP Site 801 bulk sediment. The shift in the Mariana arc to high $^{206}Pb/^{204}Pb$ is quantitatively consistent with a shift toward Cretaceous ocean island volcanics (VCL) that litter the seafloor seaward of the Marianas trench, in both the sediment, from pelagic values near loess toward VCL, and the basement, from low ^{206}Pb Pacific MORB toward VCL. Data sources: Honshu arc (Gust et al., 1995); Site 579/581 (Cousens et al., 1994); Izu arc (Taylor and Nesbitt, 1998); Site 1149 (Hauff et al., 2003); Marianas arc (Elliott et al., 1997); Site 801 sediment and VCL (Plank and Langmuir, 1998). **B.** Th/La and Sm/La systematics also show mixing toward local sediments. Each arc forms a mixing trend between a mantle composition (in the MORB array) and a sedimentary composition, which in each case is nearly identical to the nearby trench sediment (for a global development of this, see Plank, 2005). The western Pacific arcs show systematic regional trends, where arcs mix toward sediment with progressively higher Th/La to the north (Mariana to Honshu) as seafloor enters the westerly wind belt and receives eolian dust with high, continental Th/La (~0.35, see Fig. F5, p. 27). Arc data are from Elliott et al. (1997), Gust et al. (1995), Taylor and Nesbitt (1998), and Hochstaedter et al. (2000). Bulk sediment compositions are from Plank and Langmuir (1998) for Mariana and Honshu. New ICP-MS data for Site 1149 sediments is from Plank and Kelley (2001).

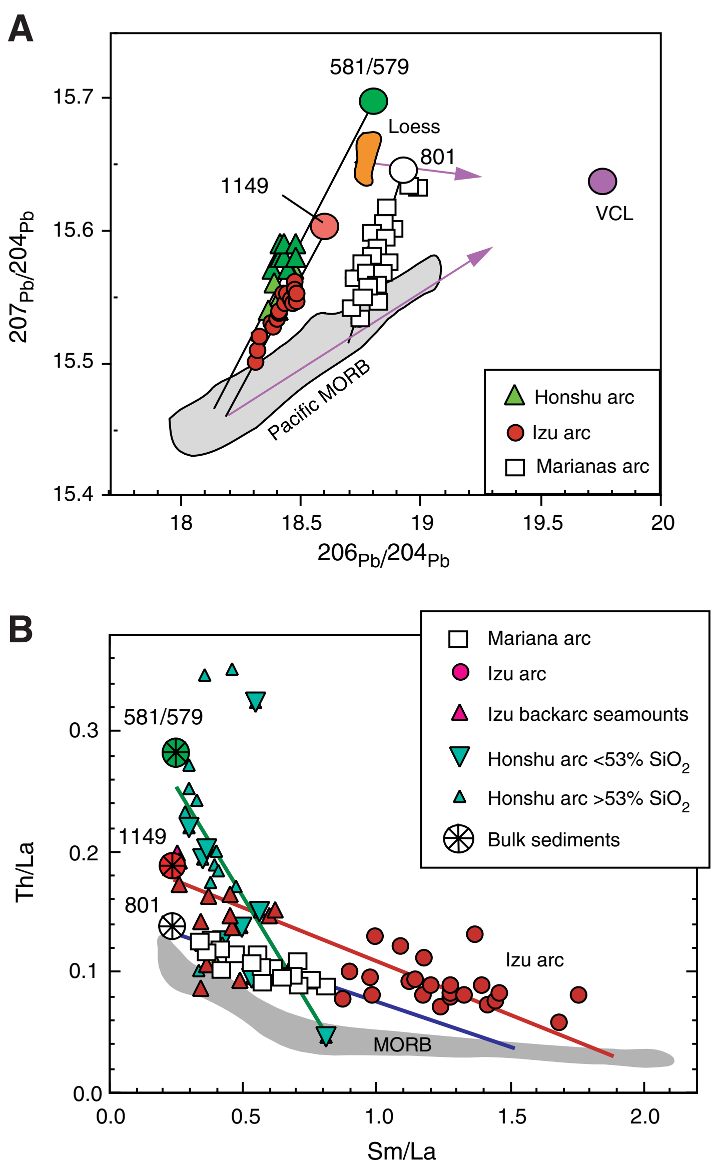

Figure F8. Th recycling at the Izu and Marianas subduction zones. **A.** Izu arc volcanics are deficient in Th relative to Marianas arc volcanics by a factor of ~5 (based on Th/Na). This deficiency in the Izu arc is anomalous with respect to the global array and the Th sediment input flux, based on drilling results reported here for ODP Site 1149 (Plank and Kelley, 2001). Volcanism in the backarc region of Izu, however, does have the appropriate Th concentrations, consistent with this region receiving the dominant sediment recycling flux. PM = primitive mantle, N-MORB = normal mid-ocean ridge basalt. **B.** This suggests a delayed delivery system for the Izu arc, possibly resulting from different dips of the cold Izu and Marianas slabs (cartoon after Straub, 2003). Global array after Plank and Langmuir (1993); Mariana arc data from Elliott et al. (1997); Izu arc data from Taylor and Nesbitt (1998); Izu backarc data from Hochstaedter et al. (2001). Izu Th sediment flux calculated from Site 1149 natural gamma logging data, which agree well with high precision core analyses (Fig. F4, p. 26). VF = volcanic front.

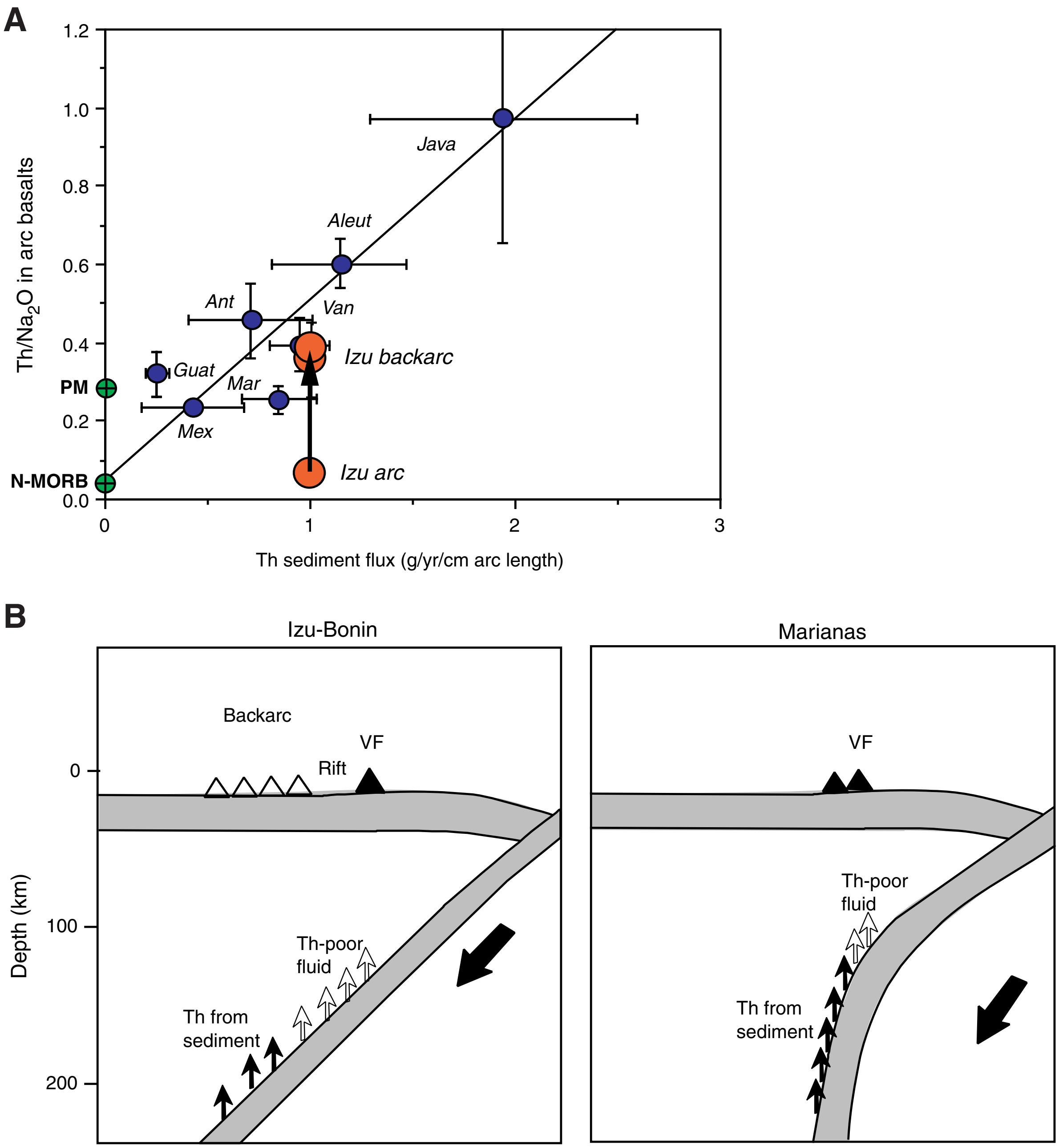

Figure F9. A. Total bacteria at Site 1149 using the acridine orange direct count technique. Solid sloping line = the regression line of best fit derived from 16 ODP legs of deep bacterial profiles, dashed lines = the 95% prediction limits (Parkes et al., 1994) and interstitial water (IW) geochemistry. **B.** Sulfate. **C.** Methane. **D.** Ammonium. **E.** Acetate. **F.** Reduced manganese. The shaded area highlights the broad peak in bacterial manganese reduction activity between 26 and 100 mbsf (from Cragg et al., this volume).

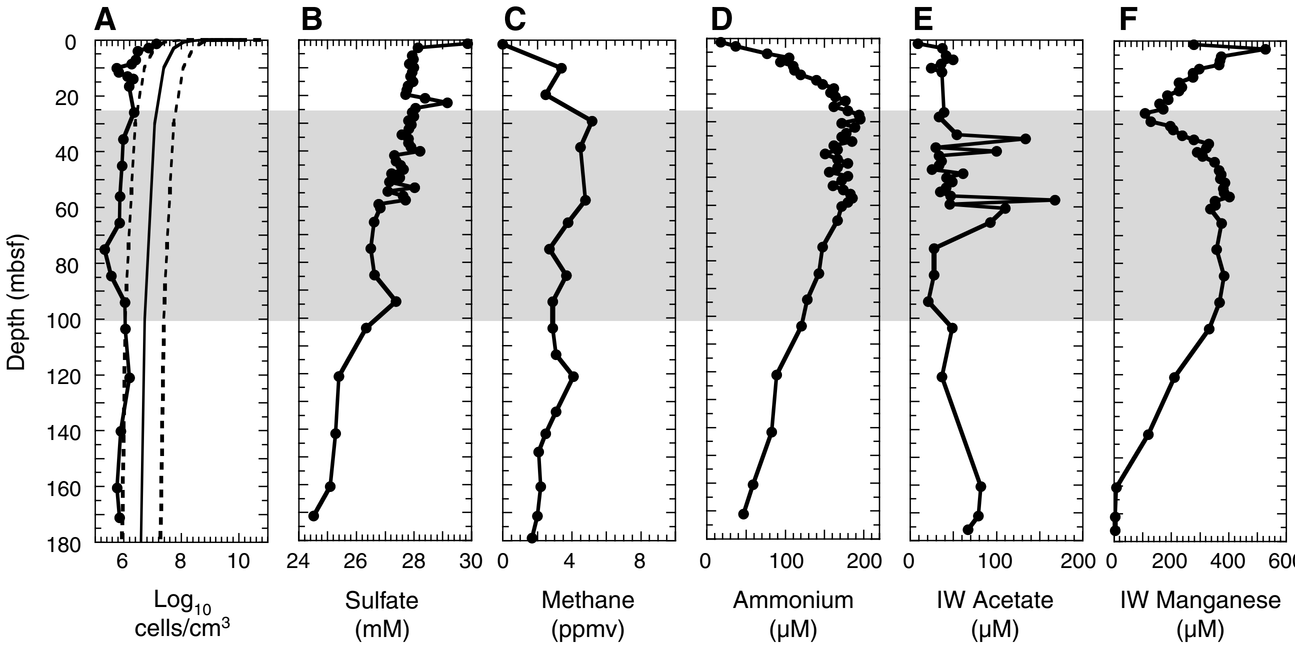

Table T1. Leg 185 science published in peer-reviewed journals (in addition to G^3 theme, see Table T2, pg. 33, and this *Scientific Results* volume).

Authors	Year of publication	Article title	Journal, volume:page range
Alt, J.C., and Teagle, D.A.H.	2003	Hydrothermal alteration of upper oceanic crust formed at a fast-spreading ridge: mineral, chemical, and isotopic evidence from ODP Site 801	*Chem. Geol.,* 201:191–211
Bartolini, A., and Larson, R.L.	2001	Pacific microplate and the Pangea supercontinent in the Early to Middle Jurassic	*Geology,* 29:735–738
Erba, E., Bartolini, A., and Larson, R.L.	2004	Valanginian Weissert oceanic anoxic event	*Geology,* 32:149–152
Fisk, M., and Kelley, K.A.	2002	Probing the Pacific's oldest MORB glass: mantle chemistry and melting conditions during the birth of the Pacific plate	*Earth Planet. Sci. Lett.,* 202:741–752
Fisk, M.R., reporting for Shipboard Scientific Party, Leg 185	1999	New shipboard laboratory may answer questions about deep biosphere	*Eos,* 80:580
Jarrard, R.D., Abrams, L.J., Pockalny, R., Larson, R.L., and Hirono, T.	2003	Physical properties of upper oceanic crust: Ocean Drilling Program Hole 801C and the waning of hydrothermal circulation	*J. Geophys. Res.,* 108 **doi:10.1029/2001JB001727**
Kelley, K.A., Plank T., Farr, L., Ludden, J., and Staudigel, H.	2005	Subduction cycling of U, Th and Pb	*Earth Planet. Sci. Lett.,* 234(3-4):369–383 **doi:10.1016/j.epsl.2005.03.005**
Rouxel, O., Dobbek, N., Ludden, J., et al.	2003	Iron isotope fractionation during oceanic crust alteration	*Chem. Geol.,* 202(1-2):155–182
Rouxel, O., Ludden, J., Carignan, J., Marin, L., and Fouquet, Y.	2002	Natural variations of Se isotopic composition determined by hydride generation multiple collector inductively coupled plasma mass spectrometry	*Geochim. Cosmochim. Acta,* 66(18):3191–3199
Rouxel, O., Ludden, J., and Fouquet, Y.	2003	Antimony isotope variations in natural systems and implications for their use as geochemical tracers	*Chem. Geol.,* 200(1-2):25–40
Smith, D.C., Spivack, A.J., Fisk, M.R., Haveman, S.A., and Staudigel, H.	2000	Tracer-based estimates of drilling-induced microbial contamination of deep sea crust	*Geomicrobiol. J.,* 17:207–219
Sager, W.W., and Escutia, C.	2005	Leg 191 synthesis: summary of scientific results	*Proc. ODP, Sci. Results,* 191:1–19
Tivey, M., Larson, R., Schouten, H., and Pockalny, R.	2005	Downhole magnetic measurements of ODP Hole 801C: implications for Pacific oceanic crust and magnetic field behavior in the Middle Jurassic	*Geochem. Geophys. Geosyst.,* 6:Q04008 **doi:10.1029/2004GC000754**

Table T2. Contents of oceanic inputs to the Subduction Factory special theme volume, *Geochemistry, Geophysics, Geosystems* (2002–2004). Guest editors were Terry Plank and John Ludden.

Authors	Article title	DOI	Date published
Sadofsky, S.J., and Bebout, G.E.	Nitrogen geochemistry of subducting sediments: new results from the Izu-Bonin-Mariana margin and insights regarding global nitrogen subduction	10.1029/2003GC000543	6-Mar-2004
Koppers, A.A.P., Staudigel, H., and Duncan, R.A.	High-resolution $^{40}Ar/^{39}Ar$ dating of the oldest oceanic basement basalts in the western Pacific Basin	10.1029/2003GC000574	25-Nov-2003
Hauff, F., Hoernle, K., and Schmidt, A.	Sr-Nd-Pb composition of Mesozoic Pacific oceanic crust (Site 1149 and 801, ODP Leg 185): implications for alteration of ocean crust and the input into the Izu-Bonin-Mariana subduction system	10.1029/2002GC000421	12-Aug-2003
Gómez-Tuena, A., LaGatta, A.B., Langmuir, C.H., Goldstein, S.L., Ortega-Gutiérrez, F., and Carrasco-Núñez, G.	Temporal control of subduction magmatism in the eastern Trans-Mexican Volcanic Belt: Mantle sources, slab contributions, and crustal contamination	10.1029/2003GC000524	9-Aug-2003
Peucker-Ehrenbrink, B., Bach, W., Hart, S.R., Blusztajn, J.S., and Abbruzzese, T.	Rhenium-osmium isotope systematics and platinum group element concentrations in oceanic crust from DSDP/ODP Sites 504 and 417/418	10.1029/2002GC000414	15-Jul-2003
Kelley, K.A., Plank, T., Ludden, J., and Staudigel, H.	Composition of altered oceanic crust at ODP Sites 801 and 1149	10.1029/2002GC000435	27-Jun-2003
Ruellan, E., Delteil, J., Wright, I., and Matsumoto, T.	From rifting to active spreading in the Lau Basin – Havre Trough backarc system (SW Pacific): locking/unlocking induced by seamount chain subduction	10.1029/2001GC000261	30-May-2003
Alt, J.C.	Stable isotopic composition of upper oceanic crust formed at a fast spreading ridge, ODP Site 801	10.1029/2002GC000400	13-May-2003
Jarrard, R.D.	Subduction fluxes of water, carbon dioxide, chlorine, and potassium	10.1029/2002GC000392	3-May-2003
Talbi, E.H., and Honnorez, J.	Low-temperature alteration of mesozoic oceanic crust, Ocean Drilling Program Leg 185	10.1029/2002GC000405	3-May-2003
Bach, W., Peucker-Ehrenbrink, B., Hart, S.R., and Blusztajn, J.S	Geochemistry of hydrothermally altered oceanic crust: DSDP/ODP Hole 504B – implications for seawater-crust exchange budgets and Sr- and Pb-isotopic evolution of the mantle	10.1029/2002GC000419	7-Mar-2003
Pockalny, R.A., and Larson, R.L.	Implications for crustal accretion at fast spreading ridges from observations in Jurassic oceanic crust in the western Pacific	10.1029/2001GC000274	24-Jan-2003
Révillon, S., Barr, S.R., Brewer, T.S., Harvey, P.K., and Tarney, J.	An alternative approach using integrated gamma-ray and geochemical data to estimate the inputs to subduction zones from ODP Leg 185, Site 801	10.1029/2002GC000344	31-Dec-2002
Barr, S.R., Révillon, S., Brewer, T.S., Harvey, P.K., and Tarney, J.	Determining the inputs to the Mariana Subduction Factory: using core-log integration to reconstruct basement lithology at ODP Hole 801C.	10.1029/2001GC000255	16-Nov-2002

Notes: This theme focuses on the raw materials fed into the subduction factory. Papers may emphasize the geophysical and geochemical aging of the oceanic crust, the composition of marine sediments entering trenches, seawater fluxes into Layers 1–3 of the oceanic plate, novel geochemical tracers, and results from recent ODP drilling. DOI = digital object identifier.

Table T3. Student theses that contributed to ODP Leg 185.

Student	Degree, year	University	Thesis title
Armstrong, Robin N.	Ph.D., 1999	Southampton Oceanography Centre, University of Southampton, UK	Evaluating the ore-forming potential of porphyry copper systems through melt inclusion chemistry
Barr, Samantha	Ph.D., 1999	University of Leicester, UK	Evaluation of subduction accretion as an important crustal growth mechanism: Rhodope, North Greece
Farr, Linda C.	M.S., 2002	Boston University, USA	Mineral hosts of uranium in the altered oceanic crust and mechanisms controlling its distribution: a laser ablation-ICPMS study
Haveman, Shelley A.	Ph.D., 2001	Goeteborg University, Sweden	Subsurface microbial ecosystems: community composition and interactions with the geosphere
Hirono, Tetsuro	Ph.D., 2001	Tokyo Institute of Technology, Japan	Direct imaging and measurement of the pore structure and mass transport properties of rocks
Kelley, Katherine A.	Ph.D., 2003	Boston University, USA	Trench inputs and arc outputs in the Mariana-Izu-Bonin subduction factory
Marini, Jean-Christophe	Ph.D., 2004	University Josef Fourier, Grenoble, France	L'Hafnium dans les zones de subduction: Bilan isotopique des flux entrant et sortant
Quintin, Lacie	M.S., 2003	Boston University, USA	Geochemical studies of Pacific Ocean marine sediments; ICP-emission spectrometry of sediments onboard the *JOIDES Resolution,* and terrigenous input and dispersed ash at Ocean Drilling Program Site 1149, Northwest Pacific
Rouxel, Olivier	Ph.D., 2002	CRPG, Nancy, France	Chalcophile and siderophile isotope systematics
Sadofsky, Seth Joseph	Ph.D., 2000	Lehigh University, USA	Behavior and cycling of volatile elements in the crust and mantle; evidence from field-based studies of nitrogen-isotope geochemistry and high-P/T low-grade metamorphism
Schmidt, Angelika	Ph.D., 2001	Christian-Albrecht-Universitat, Kiel, Germany	Temporal and spatial evolution of the Izu Island arc, Japan, in terms of Sr-Nd-Pb isotope geochemistry
Valentine, Robert	Ph.D., 2004	Washington University, St. Louis, USA	Li, Be and B isotopes in arc magmas and oceanic input

Table T4. The oldest crust drilled by ODP in the different ocean basins.

Leg 185, Site 801: West Pacific, Pigafetta Basin
Water depth (m): 5674
Total depth (m): 6609.7
Penetration (m): 935.7
Basement (mbsf): 461.6
Basement penetration (m): 474.1
Magnetic lineation: >M36
Oldest sediment: Bajocian–Bathonian (166 Ma)
Basement age: Alkalic cap (155 Ma)
Tholeiites: > 155 < 171 Ma
The oldest basement drilled in the oceans.
Leg 76, Site 534: West Atlantic, Blake-Bahama Basin
Water depth (m): 4973
Total depth (m): 6639.5
Penetration (m): 1666.5
Magnetic lineation: M28
Oldest sediment: mid-Callovian (~155 Ma)
Basement: core catcher, no radiometric age
The oldest Atlantic basement drilled.
The deepest penetration.
Leg 123, Site 765: Argo Abyssal Plain, Indian Ocean
Water depth (m): 5713.8
Total depth (m): 6908.7
Penetration (m): 1194.9
Casing string (m): 937
Basement (mbsf): 947.9
Basement penetration (m): 247
Magnetic lineation: M25a
Oldest sediment: early Berriasian (140 Ma)
Basement age: >156 Ma; Ar/Ar fusion
Celadonite age: 155 Ma; K/Ar
The oldest Indian Ocean basement drilled.
The greatest total depth.