
Methods¹

Expedition 310 Scientists²

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Introduction

This chapter documents the primary procedures and methods employed by various operational and scientific groups during the offshore and onshore phases of Integrated Ocean Drilling Program (IODP) Expedition 310. This information concerns only shipboard and Onshore Science Party methods described in the site chapters. Methods for postcruise research conducted on Expedition 310 samples and data will be described in individual scientific contributions to be published after the Onshore Science Party. Detailed drilling and engineering operations are described in the “Operations” sections in the individual site chapters.

Shipboard scientific procedures

Numbering of sites, holes, cores, and samples

Expedition numbers for IODP expeditions are sequential, starting with 301. Drilling sites are numbered consecutively, and for a European Consortium for Ocean Research Drilling (ECORD) Science Operator (ESO)-operated platform, numbering starts with Site M0001 (the “M” indicates the ESO-operated mission-specific platform). For Expedition 310, the first site was Site M0005. Multiple holes may be drilled at a single site. For all IODP drill sites, a letter suffix distinguishes each hole drilled at one site. The first hole drilled is assigned the site number with the suffix “A,” the second hole takes the site number and the suffix “B,” and so forth.

The cored interval is measured in meters below seafloor. Depth below seafloor is determined by subtracting the initial drill pipe measurement to seafloor from the total drill pipe measurement. For Expedition 310, the cored interval normally consisted of the entire drilled section, but in some cases the upper interval was drilled without coring.

If necessary, recovered core is split into sections with a maximum length of 1.5 m and numbered sequentially from the top, starting at 1 (Fig. F1). By convention, material recovered from the core catcher of a sedimentary core is treated as a separate section labeled “CC” (core catcher) and placed below the last section recovered in the liner. The core catcher is assigned to the top of the cored interval if no other material is recovered.

When recovered core is shorter than the cored interval, the top of the core, by convention, is equated to the top of the cored interval to achieve consistency in reporting depth-in-core. Any sample

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²Expedition 310 Scientists' addresses.



removed from a core is designated by distance measured in centimeters from the top of the section to the top and bottom of the sample removed. A full identification number for a sample consists of the following information: expedition, site, hole, core number, core type, section number, piece number (for hard rock), and interval in centimeters measured from the top of section. For example, a sample identification of “310-M0005A-3R-3, 80–85 cm,” represents a sample removed from the interval 80–85 cm below the top of Section 3, Core 3R (“R” designates that this core was taken using the rotary core barrel [RCB]), from Hole M0005A during Expedition 310 (Fig. F1).

All IODP core identifiers indicate core type. For Expedition 310, the following abbreviations are used:

- R = RCB, and
- M = hammer sample.

Core handling during the offshore phase of Expedition 310

As soon as a core was retrieved on deck, it went through a sequence of processing steps. The core catcher was given to the sedimentologists and coral specialists for description. With the exception of interstitial water (IW) and microbiology, no sampling of the core catchers was undertaken during Expedition 310. Next, the core was marked into section lengths by the curator, each section was labeled, and the core was cut into sections. Samples for IW (using rhizon syringes) and microbiological (by using a spatula through a small window cut in the liner) analyses were taken. Each section was sealed at the top and bottom by attaching color-coded plastic caps: blue to identify the top of a section and clear at the bottom. A yellow cap was placed on section ends where a whole-round sample was removed, and the sample code was written on the yellow cap. Caps were usually secured to liners by coating the liner ends and inside rims of caps with acetone before attaching the caps. Core section liners were permanently labeled with an engraving tool. The length of the core in each section and the core catcher sample were measured to the nearest centimeter; this information was logged into the Offshore Drilling Information System (OffshoreDIS).

No core splitting took place during the offshore phase of Expedition 310. Whole cores were saturated with seawater prior to running through the multi-sensor core logger (MSCL). Cores that contained unlithified sediments were not saturated. After the MSCL, lithological and sedimentological observations through plastic liners were carried out. Cores

were then drained before being stored in the refrigeration container.

Core handling procedures changed partway through Expedition 310, during coring of Hole M0015B: it was decided to use split steel liners instead of regular plastic liners. Cores had to be removed from the steel liner for curation and were carefully transferred into plastic liners by splitting one side of the liner, wedging it open, and sliding the cored material inside. After sealing the split side of the liner with heavy-duty tape, cores were curated and handled as normal.

Core handling during the Expedition 310 Onshore Science Party

After being taken out of refrigerated storage, cores were split lengthwise into working and archive halves. Sections containing significant lengths of massive coral were treated slightly differently (see “[Specialist sampling of massive *Porites*](#)”). Harder cores were split with a diamond saw. Softer cores, less common in this expedition, were split with a wire or saw, depending on the degree of induration. Wire-cut cores are split from bottom to top, so investigators should be aware that older material could have been dragged up the core on the split face of each section.

Archive halves were described visually. Thin sections were made from specific samples when requested by the scientists. Digital images of archive halves were made with a digital imaging system followed by discrete color reflectance measurements. Archive halves were then photographed using a color digital camera. Close-up color photographs were taken of particular features for illustrations in the summary of each site, as requested by individual scientists.

The working half of the core was sampled for both the Onshore Science Party and postcruise studies. Each sample was logged into OffshoreDIS by location and by the name of the investigator receiving the sample. The IODP curator and database maintain information about all samples taken. Samples are sealed in plastic vials, cubes, or bags, labeled, and stored as appropriate. Samples were routinely taken for Onshore Science Party physical property studies, which are described below.

Following initial Onshore Science Party measurements and sampling, both halves of the cores were shrink-wrapped in plastic to prevent rock pieces from vibrating out of sequence during transit. Both halves were then placed in labeled plastic D-tubes, sealed, and transferred to refrigerated storage at the Bremen Core Repository.

Operations equipment

Drilling platform

Water depths at the drill sites ranged from 41.65 to 117.54 m and required the use of a mission-specific platform. The *DP Hunter*, a dynamically positioned (DP) vessel with a large moonpool, was contracted as the drilling vessel (Fig. F2). The drilling contractor was Seacore of Gweek, Cornwall (UK), who installed a drilling rig on the *DP Hunter* over the moonpool and onto part of the aft deck. The *DP Hunter* is a Class 2 DP vessel, and as such has a minimum dual redundancy in propulsion and navigation systems that met IODP and international environmental requirements for the coring operation.

Coring system

From the outset, it was determined by the Operations Superintendent that the coring tools used during Expedition 310 should be of mining type, suitably prepared and installed to operate from a heaving vessel holding station using DP. This decision was based on the previous operational experiences of coring coral formations at Enewetak in the Marshall Islands and on the Great Barrier Reef in Australia and from stationkeeping using DP while coring in various water depths worldwide.

Seacore was contracted to carry out all drilling operations. They installed and operated their R100 rig, previously constructed for IODP Expedition 302, together with a Wirth mining-style rig suitably adapted for offshore and piggyback coring (where the mining coring rig is installed on top of the conventional R100 rig) (Fig. F3). An American Petroleum Institute (API) drill string set by the R100 was used as the conductor pipe for all operations. A drilling and reentry template (DART), constructed for earlier works in high tidal regimes, was deployed on the API pipe as the seabed connector and reaction force for the secondary drill string (Fig. F4).

Drilling and reentry template

The DART is a heavy circular template with a hollow internal section and cutting teeth on the basal circumference to allow the DART to be drilled into the seabed for stability (Fig. F4). The DART is attached to the API drill string to form a connection between the vessel and the seabed that can be held in tension to allow a mining drill string to pass through it and core the formations below. Two different configurations of the DART were used. The first was with three legs sitting on the seabed, but this proved to be too unstable. The second, more stable, configuration was with a short stinger fitted through the DART and attached to the API pipe. The whole assembly was then

drilled ~1 m into the seabed. This effectively leveled the DART and allowed it to lock into the seabed.

Drill string/Conductor pipe

A 5 inch API drill string with 4½ inch internal flush tool joints was used between the DART and the R100 top drive. This was deployed conventionally and used to drill the DART into the seabed in all but the first borehole (see “[Drilling and reentry template](#)”). The drill string was tensioned between the DART and the top drive, under compensated conditions, to stabilize the conductor pipe into which the coring string was run. Approximately 8 T of pullback was held in compensation, allowing 8 T of reaction force for the coring rig. Heave conditions were variable from 0.5 to 3.5 m stroke on the compensator.

Coring tools

A standard Longyear HQ3 3 m long core barrel assembly was used. This comprised an outer core barrel and a wireline interchangeable inner assembly fitted with a plastic liner. This was run on HRQHP drill pipe set in stands of two for running pipe.

The coring bits used with the system were all standard HQ3 pattern with a 96 mm outer diameter and 62 mm inner diameter. A corresponding reaming shell was also fitted to the outer core barrel above the bit. A selection of natural, synthetic, and impregnated diamond bits was carried to allow for optimum coring in any formation. Core was initially collected in an industry-standard HQ3 polyvinylchloride (PVC) liner tube, which served as the triple tube of the HQ3 system. However, because of the nature of the coral formation, this plastic liner was often crushed or torn and contributed to early bit blocking. After discussion with the expedition scientists, a traditional stainless steel or chromed steel split liner insert was trialed. The trials were successful, with demonstrable improvements in core recovery, core quality, and rates of penetration. The split liner insert was used for the rest of the expedition.

A hammer sampler was made up from a spare HQ overshot assembly to allow attempts to be made to clear the bit while coring and to remove bridges while logging. Normally, such a tool is always carried for geotechnical operations, and its successful use during the expedition suggests it is a useful and versatile tool and should be carried at all times, whatever suite of coring equipment is being deployed.

Incorporated into the landing/latching assembly of the inner core barrel was a ball valve that had to be pressurized and then released to indicate that a positive latch had been made between the outer and inner core barrels. This system worked well and dra-

matically reduced mismatching problems associated with wireline operations.

Combinations of bits and catchers were used to maximize core recovery as the expedition progressed and more knowledge was gained about the lithologies being cored. Impregnated diamond bits of medium to medium-hard matrix were used together with a corresponding reaming shell.

Combination basket/core spring catchers were used in the top-hole sections, core springs with a small finger set of catchers were used in friable formations, and conventional core springs were used in competent formations. In all cases, a clear PVC liner or a split steel liner was used to collect the core, but core was always curated and stored in a plastic liner. Two core barrel assemblies were set up for running to minimize changeover time during trips. Variable-length liners and spacers were used to keep from wasting plastic liner if it was used in short core runs.

For open-hole drilling, where there was a danger of bit blocking, a full-face insert bit was carried, allowing retention of the coring facility further downhole. This technique was used on a number of occasions and worked effectively.

Wireline retrieval was by means of a standard Long-year HQ overshot deployed by wire from a hydraulic wireline winch. An overshot release sleeve system was also carried for “dry hole” emplacement of the core barrels.

Downhole logging tools

Downhole logging services were contracted and managed by the European Petrophysics Consortium (EPC). Details and results of the expedition logging program are given in “[Downhole logging](#)” and in the “Downhole logging” sections in the individual site chapters.

Through-pipe underwater video camera

The IODP Environmental and Pollution Safety Panel (EPSP) specified that ESO should have a facility to inspect the seabed before and after coring to ascertain that minimal damage would be done to any living coral present at the drill site. In addition, EPSP also allowed a “clearance zone” with a 150 m radius for drilling around each proposed site (which was increased to 350 m around proposed Site TAH-02A 4) so that patches of living coral could be avoided while drilling proceeded.

The British Geological Survey (BGS) provided an underwater color video camera system and manufactured a deployment frame to allow it to work inside the drill pipe. It is based on diver helmet-operated systems. The system worked well, and good video

coverage was obtained from a number of sites. Importantly, the video demonstrated that it is possible to drill in a reef setting with minimal disturbance to the environment. Additionally, the camera was used for pipe and seabed slope examination when there were technical issues associated with deployment at a particular site. A similar camera system was carried by Seacore as a backup. The Seacore cable was used until an issue with the resistance of the ESO cable was resolved.

The camera could be further developed to provide scale, direction, and possibly an angled view. Assuming that proper site surveys have been conducted, this is a more cost effective tool to carry than a remotely operated vehicle (ROV), which requires more expenditure, additional organization, and an infrastructure (including deck space) to meet the same objective.

Echo sounder

It became obvious partway through the expedition that site survey information was not detailed enough and was often misleading. Various attempts were made by the Co-Chief and Staff Scientists to obtain both further data and the parameters surrounding collection of the previous data. Much of this was forthcoming and allowed laybacks of seismic lines to be calculated and better images to be made of the bathymetry from additional raw data.

However, even after additional refinements, the mapped bathymetry did not agree with manual spot checks (using the tautwire and lead line) at many sites, especially on the shelf edge. With the help of the Co-Chief Scientists, a high-resolution shallow-water echo sounder was located onshore and purchased by the Operations Superintendent for the expedition. A transducer pole was made up on board from which to deploy the transducer in the moon-pool. After some trials to obtain the best settings, the echo sounder was used systematically across survey grids, and the data collected allowed suitable drilling sites to be located.

Data handling, database structure, and access

Data management during offshore and onshore phases of Expedition 310 had two overlapping stages. The first stage was the capture of metadata and data during the expedition (offshore and onshore). Central to this was OffshoreDIS, which stored drilling information, core curation information, and primary measurement data. The second stage was the longer term postexpedition archiving of Expedition 310 data sets, core material, and samples. This

function was performed by the World Data Center for Marine Environmental Sciences (WDC-MARE) and the Bremen Core Repository (BCR).

Offshore drilling information system

OffshoreDIS is a flexible and scalable drilling information system, originally developed for the International Continental Drilling Program (ICDP). The underlying data model for OffshoreDIS is compatible with Janus, the BCR, PANGAEA, and the Lac-Core in Minneapolis (Minnesota, USA). For the specific expedition platform configuration and offshore and onshore workflow requirements of Expedition 310, the OffshoreDIS data model, data pumps, and user interfaces were adapted. Offshore, the system was used to capture basic information related to core and sample curation, core photographs, and section and sample label printing. In addition, the database also stored primary data measurements. These included

- Geophysical downhole logging data (from the EPC management office, carried out by University of Montpellier II, ISTEEM),
- MSCL data,
- Visual core descriptions (VCDs) of core sections (in liner) and core catchers,
- IW analysis, and
- Microbiological data.

Also, scientists produced a variety of spreadsheet files, text documents, and graphics containing data, descriptions, and interpretations in different formats. Therefore, in addition to OffshoreDIS, all data files were stored in a structured file system on a shared hard drive. A specific Web interface for OffshoreDIS (XDIS) was used to distribute OffshoreDIS content via an intranet to all networked computers.

Expedition 310 data were then transferred to the information system of WDC-MARE during the second phase. WDC-MARE was founded in 2000 and is a member of the International Council of Scientific Unions World Data Center system. PANGAEA is the geoscience information system used by WDC-MARE. It has a flexible data model that reflects the information processing steps in the earth science fields and can handle any related analytical data (Diepenbroek et al., 1999, 2002). It is used for processing, long-term storage, and publication of georeferenced data related to earth sciences. Essential services supplied by WDC-MARE/PANGAEA are project data management and distribution of visualization and analysis software. Data management functions include quality checking, data publication, and metadata dissemination that follows international standards. Data captured by OffshoreDIS were transferred to this long-term archive following initial validation procedures as soon as they became available; data transfer

was completed by the time of publication of this volume. Until the end of the moratorium period, the data were not public and access was restricted to the expedition scientists. However, following the moratorium, the data were published on the Internet (www.wdc-mare.org), and WDC-MARE will continue to acquire, archive, and publish new results derived from Expedition 310 samples and data sets.

Hardware installation

OffshoreDIS was implemented in SQLServer-2000 with Microsoft-based client PCs connecting to the system through a Microsoft Access-like user interface. For the offshore phase of the expedition, OffshoreDIS was installed on a server on the *DP Hunter*. A second server was used as a hot-standby and data backup system. Incremental backups and full backups were made regularly, along with additional tape backups. These backups comprise OffshoreDIS and the shared file server.

Core, section, and sample curation using OffshoreDIS

Expedition 310 followed IODP procedures and naming conventions in core, section, and sample handling (see “[Shipboard scientific procedures](#)”). OffshoreDIS handled data curation and printed the appropriate labels also to IODP standards. The curation data comprise

- Expedition information,
- Site information (latitude, longitude, water depth, start date, and end date),
- Hole information (hole naming by a letter, latitude, longitude, water depth, start date, and end date),
- Core data (core number, core type, top depth, bottom depth, number of sections, core catcher availability, curator, core on deck, date and time, and additional remarks),
- Section data (section number, section length, curated length, curated top depth of section, section length, and curated length),
- Sample information (repository, request, request part, code observer, expedition, site, hole, core, section, half, sample top, sample bottom, and sample volume),
- Calculated core recovery percentage on the basis of the drilled or cored length and the curated recovery, and
- Calculated section recovery on the basis of the section length and the curated length.

No correction was made in cases where the recovery exceeded 100%. Top and bottom depth of the section (in meters below seafloor) was calculated from

core-top depth. The section and sample label formats follow the standard Ocean Drilling Program (ODP)/IODP convention. They include barcodes of the section/sample code and the complete section/sample code (Expedition-Site-Hole-Core-Core type-Section-Half-Interval and sample request code). This standardization guarantees data exchange among the repositories and enables information flow between the implementing organizations.

Sedimentology and biological assemblages

Visual core descriptions

Expedition 310 sedimentologists were responsible for visual descriptions of the archive halves of cores recovered during the expedition. Archive halves were examined by eye and with hand lenses, and for further analysis of corals, bioclasts, and volcanic rock, binocular microscopes were used. Observations were recorded on VCD forms with the high-resolution line scan of the core section already printed on it. Thus, individual elements in these cores could be marked directly, granting later identification of individual corals and other components in the scans. VCD forms were scanned in order to archive them, and data were entered into OffshoreDIS. Section description barrel sheets (Figs. F5, F6) were computer generated from the information entered into Offshore DIS.

Section units were defined on the basis of general lithology changes and/or changes in the dominant hermatypic coral type (genus and/or growth form). One core section can be composed of several core-section units.

The following properties were given attention:

- Core disturbance,
- Overall lithology,
- Major component of unit,
- Detailed list of other components,
- Description of individual corals,
- Description of microbialites,
- Bioerosion intensity,
- Breaks in sedimentation, and
- Other properties.

Core disturbance

Highly disturbed intervals were marked on VCD forms. Strongly crushed intervals were described as “crushed.”

Overall lithology

Overall lithology was defined (for the carbonate sediments following Dunham’s [1962] classification as

modified by Embry and Klovan [1972]) by distinguishing between

- Different types of boundstone (e.g., framework, bindstone),
- Carbonate sediment types (rudstone, floatstone, grainstone, packstone, wackestone, mudstone) and their nonlithified equivalents,
- Volcanic sediment and their nonlithified equivalents, and
- Volcanic rocks (e.g., basalt).

A section unit with in situ corals that are encrusted with thick microbialites is termed a “framework,” even where corals only make up a small volume percentage of the entire rock (see “**Major component of a section unit**”). That is, a generic term is used (framework), and the terminology is *not* based on the most voluminous component (microbialite).

Unconformities

Unconformities were noted because of their potential significance as boundaries. Bioerosion and other hardground properties were noted, as well as stains and diagenetic properties such as cementation and dissolution.

Other properties

Where applicable, properties such as open vugs, geopetal infills, color stains, cementation including marine cement linings, and diagenetic alteration of components were noted.

Major component of a section unit

The major component of a section unit highlights the component with the highest volume percentage of that section unit. For example, a section unit with an overall lithology of “framework” with a coral framework can be composed of the major component “microbialite.” Common major components are corals, microbialites, and volcanoclastic sediment. Components in the cores included the following components listed for each individual section unit:

- Basalt pebbles,
- Basalt sand grains,
- Bivalves,
- Branching coralline algae,
- Bryozoans,
- Corals (for details on the determination of the corals, see “**Description of corals**”),
- Coralgal bindstone (CAB; finely interlayered encrusting corals and coralline algae),
- Echinoderms,
- Encrusting coralline algae (ECR),
- Foraminifers,
- Gastropods,

- *Halimeda*,
- Intraclasts,
- Microbialites (MB),
- Rhodoliths,
- Rubble (carbonate rubble),
- Unknown lithoclasts,
- Unknown bioclasts, and
- Vermetid gastropods.

Carbonate components

Description of corals

The following is a summary of the coral description procedure and the data recorded in the VCD forms and OffshoreDIS.

Identification of corals and coral-bearing horizons

Onshore description of the coral fauna within each cored interval was based on observations of the archive half. The sample half was also examined if coral features were obscured in the archive half. A high-resolution line scan of each core was printed directly onto the VCD sheet. This allowed the coral specialists, along with the sedimentologists, to map the stratigraphic positions of all visible corals precisely on the VCD forms. Each coral specimen was numbered individually (C1, C2, C3, etc.) from top to bottom in the core, and its growth direction, context, and general appearance were described. Core intervals composed of numerous colonies of the same genus were also numbered (C1, C2, C3, etc.) and used to define discrete section intervals that were then entered into OffshoreDIS.

Coral growth forms

Using standard nomenclature (Veron, 2000), coral growth forms were described as massive (>2 cm thick), robust branching (>2 cm maximum branch diameter), branching (<2 cm maximum branch diameter), tabular, foliaceous, and encrusting (<2 cm thick; in contact with basal substrate).

Coral taxonomy

Coral taxonomy followed standard taxonomic references (Veron, 2000). During the Onshore Science Party, coral identifications were carried out at the genus level because taxonomic details were not commonly preserved. All intact corallite surfaces were subsampled for more detailed laboratory investigation and species-level identifications.

Coral context

Special attention was given to establishing the context of each coral within each cored section. A combination of criteria (Blanchon and Blakeway, 2003;

Webster and Davies, 2003; Webster et al., 2004) was used to distinguish in situ corals from allochthonous rubble and/or drilling disturbance. This included identifying

- Whether the coral displayed fresh breakage surfaces,
- Presence or absence of severe surface abrasion and rounding of coral colonies,
- Orientation of well-preserved corallites,
- Orientation of coral skeletal characters,
- Whether the tips of branching corals were capped by thicker (>5 mm) coralline algal crusts, and
- Presence of macroscopic sediment geopotals in cavities within the corals.

Description of microbialites

Cores generally show abundant laminated or clotted micritic sediment interpreted as microbialites (Camoin and Montaggioni, 1994; Camoin et al., 1999, 2006). In split cores, three general morphologies were distinguished: laminated, thrombotic, and dendritic. For microbialites that grew into open vugs, the morphology of the surfaces (knobby versus smooth) was also distinguished. For example, in many cases a succession of laminated followed by dendritic morphology and knobby surface was observed.

Volcaniclastic sediments

Definition and classification

Volcaniclastic sediments contain at least ~50% by volume (vol%) of volcanic lithic components. The terms sand and silt were used in place of “ash,” and sandstone and siltstone were used in place of “tuff,” if lithified. The terms granule and pebble (granule conglomerate and pebble conglomerate, respectively, if lithified) were used in the “lapilli” size category. Cobbles of larger volcanic clasts (“volcanic breccias”) were encountered as components of the rubble in several of the core catchers, between some of the carbonate units, and as occasional components of the carbonate sediments. A large basalt boulder (drilled section = ~65 cm) occurs in Sections 310-M0008A-7R-CC through 8R-1. Lithic fragment size divisions are those of Wentworth (1922) (see Table T1). The main reasons for the use of this set of terrigenous sediment terminology are the following:

- Carbonate debris is ubiquitously intermixed with volcanogenic lithic components.
- Volcaniclastic sediment units are almost always massive and only weakly lithified and in several cases are completely unconsolidated.

- Units contain occasional skeletal-rich, rip-up clasts.
- Units lack volcanic glass shards that are typical of many tephra deposits.
- In the thick sequence of volcanoclastic sediments in Hole M0008A, the bottom volcanic sandstone and siltstone units contain occasional wood fragments and fine, delicate plant roots. These indicate that the volcanoclastic sediments are not primary products of explosive volcanic eruptions but instead are epiclastic sediments produced from erosion of volcanic terrains composed of extrusive volcanics and/or pyroclastics in Tahiti.

The volcanoclastic sediment names we applied were based entirely on hand-specimen observations. As in other sedimentary rocks (see “**Overall lithology**”), volcanoclastic sediment section units were defined on the basis of general lithologic changes.

VCD forms were used to document each section of the volcanoclastic sediment cores. Based on visual and hand lens/binocular microscope observation, volcanoclastic sediments were described according to the following sequence of characteristics:

- Structure,
- Lithic fragment size,
- Sorting and grading,
- Sphericity or angularity, and,
- Composition of the components.

Structure was determined by whether the rock is massive or stratified and whether it is composed of unlithified/nonconsolidated lithics or the lithics are well lithified/consolidated. As noted earlier, lithic fragment size divisions are shown in Table T1. Sorting refers to variations of size distribution, with unsorted referring to large lithic size variation within an interval and well sorted referring to lithic fragments that have almost the same size. Grading refers to change of size distribution with depth within an interval, with normal grading referring to fragment sizes become coarser toward the bottom and reverse grading referring to the opposite. Sphericity refers to degree of roundness of the lithic fragments, from angular to well rounded. The composition of the component lithic fragments was based on hand-specimen observations using hand lens and binocular microscope.

In order to describe the igneous rock boulder in Hole M0008A, individual cobbles (>64 mm), and pebbles (4–64 mm) that are enclosed within volcanoclastic and carbonate units as well those in the rubble in several core catchers, the following sequence of characteristics were used:

- Size and sphericity of the lithic fragment,
- Granularity or grain size,
- Texture,
- Vesicularity, and
- Alteration.

The size (Table T1) and sphericity of lithic fragments were described to produce an integrated picture of the distance of transport and possible depositional environment of fragments at their respective sites. Sphericity of fragments ranges from angular to rounded. Sizes of mineral components within the rocks are fine grained (<1 mm; used here synonymously to the term aphanitic), medium grained (1–5 mm), or coarse grained (>5 mm). Grain-size variations within units were also noted. Texture is mainly whether a rock contains “phenocrysts,” which is a term used here to describe a crystal that is significantly larger (typically 5 times) than the average size of the groundmass crystals (or matrix) and generally subhedral to euhedral in shape. Based on this term, we used the following descriptors:

- Aphyric (or nonporphyritic): phenocryst content <1% of the volume of the rock;
- Sparsely phyric (or porphyritic): phenocryst content 1%–2%;
- Moderately phyric (or porphyritic): phenocryst content 2%–10%; and
- Highly phyric (or porphyritic): phenocryst content >10%.

If the rock is phyric, then size range (in millimeters), mineral type, amount of alteration of the phenocrysts, and further comments, if appropriate, were noted. Phenocrysts are predominantly the typical ferromagnesian minerals in a basalt (i.e., mainly pyroxenes and olivine) with subordinate amounts of feldspars (plagioclase and alkali feldspar) or feldspathoids. Owing to their generally fine to medium crystal size, slightly to highly altered state, and in particular the known tholeiitic to highly alkalic volcanic rock varieties in Tahiti (e.g., McBirney and Aoki, 1968; Cheng et al., 1993), feldspars and feldspathoids were not differentiated; hence, the term “feldspars/foids” was used. Vesicles were described based on their abundance, size (in millimeters), and shape (sphericity and angularity). Secondary minerals (amygdules) lining the walls of or completely filling vesicles were also noted. Abundance categories are sparsely vesicular (1–5 vol%), moderately vesicular (>5–20 vol%), and highly vesicular (>20 vol%). Degree of alteration is unaltered (<2 vol% of alteration products), slight (2–10 vol%), moderate (10–40 vol%), high (40–80 vol%), very high (80–95 vol%), or complete (>95 vol%).

Onshore volcanoclastic sediment analyses

Five representative samples of volcanoclastic sandstone/siltstone, seven volcanic cobbles, and two small portions of the boulder from Hole M0008A were selected for analyses of major and trace element contents using a Spectro XEPOS portable energy dispersive polarization X-ray fluorescence analyzer (EDP-XRF) using the procedure described in Wein et al. (2005). Approximately 10 cm³ aliquots of the volcanoclastic sediments were frozen, freeze-dried to remove water, and ground by hand with an agate mortar and pestle. Rock samples were air dried, broken into smaller chips, and then ground using a Fritsch Pulverisette 7 tumble mill equipped with a zirconium oxide beaker. Approximately 5 grams of dried powder from each sample was poured and then compressed with a pestle in a volumetrically calibrated sample cup consisting of top and bottom rings and 4 µm prolene foil sides and bottom. A total of 5–6 cups of samples were then placed in an autosampler along with 3–4 cups of different rock standards to assess accuracy and precision. Results of the analyses of international and University of Bremen internal standards are presented in Table T2, together with previous analyses of these standards using the same instrument. All sample preparation and analyses were performed at the Department of Geosciences, University of Bremen (Germany).

Petrophysics

Offshore, the petrophysics program involved wireline logging and collecting high-resolution, nondestructive measurements on whole cores using the Geotek MSCL. While offshore, the MSCL was outfitted with four sensor types in order to measure gamma density, magnetic susceptibility, transverse compressional wave (*P*-wave) velocity, and electrical resistivity.

Onshore, the MSCL was used for the acquisition of digital line scan images. Other onshore measurements include lower resolution moisture and density, color reflectance, and full-probe needle-point thermal conductivity measurements that were routinely performed manually. A helium gas pycnometer was used to measure the volume (for density determinations) of discrete samples at an approximate resolution of one per section from the working half of split cores. This allowed independent determination of bulk density, dry density, grain density, water content, porosity, and void ratio, which were used to calibrate the high-resolution, nondestructive measurements made with the MSCL. *P*-wave velocities were measured on the same samples used for density

determination at an approximate resolution of one per section from the working half of split cores.

Multisensor core logging

The MSCL has four physical property sensors mounted on an automated track that sequentially measure gamma density, *P*-wave velocity, noncontact electrical resistivity, and magnetic susceptibility. Whole-core round sections were measured with the MSCL in horizontal setup mode. Standard mode measurements on all cores were undertaken on temperature-equilibrated cores. All core sections and sections from the core catcher were logged on the MSCL. Data quality is a function of both core quality and sensor precision, which is partly a function of measurement time for gamma density and magnetic susceptibility (but not for *P*-wave velocity). Optimal measurements require a completely filled core liner; additional notes are provided regarding core quality. Fully water-saturated cores provide optimal conditions for *P*-wave velocity and gamma density measurements. In sections where the core liner was insufficiently saturated, the resultant *P*-wave measurements were either unreliable or unobtainable (see more detailed notes in “[Compressional wave velocity](#)”). The downcore measurement spacing interval selected was 1 cm for all sensors.

Calibration procedures for all sensors were performed prior to the start of core logging. Repeat calibrations were conducted by repeatedly logging (one run per ~5–6 core sections) three selected calibration pieces (water-saturated gamma calibration section, resistivity calibration section, and magnetic susceptibility section), providing a check on the calibration. Only if the values departed from an acceptable range was a repeat calibration performed.

Density

Gamma ray attenuation (GRA) density is measured by determining the attenuation of gamma rays that pass through the cores and is used to estimate bulk density. The degree of attenuation is proportional to the electron density in the gamma path. Gamma attenuation coefficients vary as a function of atomic number, but, as most earth-forming minerals have similar and low atomic numbers, the correlation between gamma density and bulk density is generally very good. A small (370 MBq) ¹³⁷Cs source (half life = 30.2 y) was used to produce a gamma beam with primary photon energies of 662 keV. Two collimators of 2.5 and 5 mm were available. The maximum measurement resolution obtainable by the sensor is 0.5 cm (using the 2.5 mm collimator), and the minimum integration time for a statistically significant measurement is 1 s. Measurement intervals were set

at 1 cm with the count time set at 10 s (the same as for the magnetic susceptibility sensor), and the 5 mm collimator position was selected in order to maximize gamma counts.

Calibration of the system was completed using known water/aluminium density standards. Initial calibration was performed using a standard core liner (~0.3 m length) containing a stepped aluminium calibration piece centered within the liner and filled with water. Gamma counts were taken through each stepped piece of aluminium (of different, known thickness) for 30 s. This calibration procedure was repeated as necessary following checks by logging the calibration piece at regular intervals during the logging process (1 calibration run per ~5–6 core sections). In cases where the core was left unsaturated with water, “dry” calibrated processing parameters were used and a cautionary note was added to the file.

***P*-wave velocity**

Transverse *P*-wave velocity was measured using two *P*-wave transducers aligned perpendicular to the core axis with *P*-waves passing through the core horizontally (in whole-core setup). A compressional wave pulse centered on a frequency of 320 kHz was transmitted through the core. A pair of displacement transducers monitored the separation between the *P*-wave transducers so that variations in the outside diameter of the liner did not degrade the accuracy of the measured velocities. Measurement spacing was set at 1 cm.

This measurement is critically affected by the quality of the core, such that undersized core, where the core is not directly in contact with the liner, severely reduces the quality of this measurement. Water-saturated cores allow optimum quality of *P*-wave measurements; accordingly, Tahiti cores were seawater-saturated prior to measurement on the MSCL. This was carried out only after considering the effect on the geochemistry of the core; it was thought to be negligible because the highly porous cores were inundated with seawater during drilling. In cases where the core was insufficiently water-saturated and/or contact with the liner was poor, the quality of the *P*-wave data was considered to be unreliable and either the data were deleted from the processed data or a cautionary note was added to the file.

Initial calibration was performed using a distilled water-saturated standard core liner piece (length = ~0.3 m) at known temperature. This calibration procedure was repeated as necessary following checks by logging the calibration piece (for time considerations, the end of the water-saturated gamma calibration piece was used if it was of sufficient length) at regu-

lar intervals during the logging process (1 calibration run per ~5–6 core sections).

Electrical resistivity

Electrical resistivity of sediment cores was measured using the noncontact resistivity (NCR) sensor. The sensor operates by inducing a high-frequency magnetic field in the core, which in turn induces electrical currents in the core. The small magnetic fields generated by these induced electrical currents are measured on a receiver coil and normalized with a third set of identical coils operating in air. The spatial resolution of measurement is ~2–4 cm. The measurement interval selected was 1 cm, as for the other sensors.

Initial calibration was performed using five standard core liner sections (length = ~0.3 m) containing water of varying but known salinity. The five standards were made up to concentrations of 35 (35,000 ppm), 17.5, 3.5, 1.75, and 0.35 g/L from an initial concentration of 35 g/L that was successively diluted. This calibration procedure was repeated as necessary following checks by logging a piece of core liner filled with water of a salinity in the middle of the anticipated salinity range of the logged core at regular intervals during the logging process (1 calibration piece per ~5–6 core sections).

Magnetic susceptibility

Whole-core magnetic susceptibility was measured on the MSCL using a Bartington MS2 meter coupled to a MS2C sensor coil. The loop sensor had an internal diameter of 80 mm, corresponding to a coil diameter of 88 mm. It normally operates at a frequency of 565 Hz. As a result of the requirements for Expedition 302, two nonstandard loops at slightly offset frequencies were used, and, although this two-loop sensor system was not required for Expedition 310, one of these same loops was used. The loop therefore operates at a slightly offset frequency (513 Hz). This necessitates a correction factor ($\times 0.908$) to be applied to the processed data. The MS2 system operates on two fixed sensitivity levels ($\times 0.1$ and $\times 1$), corresponding to 10 and 1 s sampling integration periods, respectively. The higher sensitivity (0.1 range) setting results in measurements to the first decimal place, and the resolution of the loop is 2×10^{-6} SI on this range with an effective sensor length of 4 cm. Measurements were made at a spacing of 1 cm on the 0.1 range. The sensor automatically zeroes and takes a free air reading at the start and end of each run in order to account for instrument drift (by subtraction of a linear interpolation between these two readings). magnetic susceptibility data were recorded as corrected volume specific units ($\times 10^{-5}$ SI).

The accuracy of the magnetic susceptibility sensor was checked using a calibration standard with a bulk susceptibility of 213×10^{-6} cgs. This calibration piece was centered within a core liner and logged at regular intervals during the core logging process (1 calibration run per ~5–6 core sections).

Digital color imaging system

While onshore, systematic high-resolution line-scan digital core images of the archive half of each core were obtained using the Geotek X-Y digital imaging system (Geoscan II). This system collects digital images with three line-scan charge-coupled device arrays (1024 pixels each). The image resolution is controlled by the height of the camera and width of the core. The standard configuration for the Geoscan II produces a 100 pixels per centimeter (ppcm) resolution downcore, but for Expedition 310 cores this was increased in order for the line scans to be used more effectively for core description. Thus, settings used were 200 ppcm downcore resolution and 130 ppcm crosscore resolution, with the exception of the first cores scanned (Cores 310-M00023A-1R through 12R), where a resolution of 100 ppcm downcore and 83 ppcm crosscore were used. Synchronization and track control are better than 0.02 mm. The dynamic range is 8 bits for all three channels. The framestore card has 48 MB of onboard random access memory (RAM) for the acquisition of images with an ISA interface card for personal computers. The system was calibrated at the start of each day using color and gray scale. Output from the digital imaging system includes a Windows bitmap (.BMP) file and a compressed (JPEG) file. The bitmap file contains the original data with no compressional algorithms applied. These were processed using a height reduction of 56% in order to obtain the correct image proportions. All cores were imaged using an aperture setting of $f/4.7$.

Diffuse color reflectance spectrophotometry

Archive halves were typically measured at 5 cm intervals using a handheld Minolta spectrophotometer (model CM-2600d). Interval spacing was adjusted appropriately depending on the nature of the core. Black and white calibration of the spectrophotometer was performed every 24 h. Prior to measurement, the core surface was covered with clear plastic wrap to maintain a clean spectrometer window.

Spectrophotometric analysis produced three types of data:

- L^* (lightness), a^* , and b^* values, where L^* is a total reflectance index ranging from 0% to

100%, a^* is the green (–) to red (+) chromaticity, and b^* is the blue (–) to yellow (+) chromaticity;

- Munsell color values; and
- Intensity values for 31 contiguous 10 nm wide bands across the 400–700 nm interval of the visible light spectrum.

When utilizing the spectrophotometric measurements, it is recommended that detailed examination of core photos/images and disturbance descriptions/tables is undertaken in order to cull unnecessary or spurious data.

Moisture and density

Moisture and density (MAD; bulk density, dry density, grain density, water content, porosity, and void ratio) were determined from measurements of the wet and dry mass of core plugs and dry volume. Discrete samples were taken from the working half of split cores, typically at an interval of one sample per section, where core recovery allowed.

These samples were dried in an oven at $105^\circ \pm 5^\circ\text{C}$ for 24 h followed by cooling to room temperature in a dessicator. Samples were weighed to a precision of 0.001 g using an electronic balance to determine the dry sediment mass (M_{dry}). Dry volume (V_{dry}) was determined using a Quantachrome pentapycnometer (helium-displacement pycnometer) with a precision of 0.02 cm³ capable of measuring five samples per run. The volume measurements were repeated a maximum of five times, or until the last three measurements exhibited <0.02% standard deviation, with a purge time of 1 min. A reference volume was included within each sample set and rotated sequentially among the cells to check for instrument drift and systematic error. Salt precipitated in sample pores during the drying process is included in the M_{dry} and V_{dry} values.

Procedures for the determination of MAD comply with the American Society for Testing and Materials (ASTM) designation (D) 2216 (ASTM International, 1990). Samples were water-saturated in a vacuum for 24 h and their wet mass (M_{wet}) measured on an electronic balance to a precision of 0.1 g.

The mass of the evaporated water (M_{water}) and the salt (M_{salt}) in the sample are given by

$$M_{\text{water}} = M_{\text{wet}} - M_{\text{dry}}, \text{ and}$$

$$M_{\text{salt}} = M_{\text{water}} [s/(1 - s)],$$

where s = the assumed seawater salinity (0.035) and corresponds to a pore water density (ρ_{pw}) of 1.024 g/cm³ and a salt density (ρ_{salt}) of 2.257 g/cm³. The corrected mass of pore water (M_{pw}), volume of pore water (V_{pw}), mass of solids excluding salt (M_{solid}), volume

of salt (V_{salt}), volume of solids excluding salt (V_{solid}), and the wet volume (V_{wet}) are, respectively,

$$\begin{aligned} M_{\text{pw}} &= M_{\text{water}} + M_{\text{salt}} = M_{\text{water}}/(1 - s), \\ V_{\text{pw}} &= M_{\text{pw}}/\rho_{\text{pw}}, \\ M_{\text{solid}} &= M_{\text{dry}} - M_{\text{salt}}, \\ V_{\text{salt}} &= M_{\text{salt}}/\rho_{\text{salt}}, \\ V_{\text{solid}} &= V_{\text{dry}} - V_{\text{salt}} = V_{\text{dry}} - M_{\text{salt}}/\rho_{\text{salt}}, \text{ and} \\ V_{\text{wet}} &= V_{\text{solid}} + V_{\text{pw}}. \end{aligned}$$

For all sediment samples, water content (w) is expressed as the ratio of the mass of pore water to the wet sediment (total) mass:

$$w = M_{\text{pw}}/M_{\text{wet}}.$$

Wet bulk density (ρ), dry bulk density (ρ_d), sediment grain density (ρ_g), and porosity (ϕ) are calculated from

$$\begin{aligned} \rho_w &= M_{\text{wet}}/V_{\text{wet}}, \\ \rho_d &= M_{\text{solid}}/V_{\text{wet}}, \\ \rho_g &= M_{\text{solid}}/V_{\text{solid}}, \text{ and} \\ \phi &= V_{\text{pw}}/V_{\text{wet}}. \end{aligned}$$

Thermal conductivity

Thermal conductivity was measured with the TeKa TK04 system using the needle-probe method in full-space configuration for soft sediments (Von Herzen and Maxwell, 1959). The needle probe contains a heater wire and calibrated thermistor. It is assumed to be a perfect conductor, as it is significantly more conductive than the unconsolidated sediments that it is measuring. Cores were brought into the laboratory and allowed to equilibrate to room temperature over a 12 h period. Thermal conductivity was measured by inserting the needle probe into the sediment subsequent to removal of either the top or bottom end cap. Generally, thermal conductivity (k) is calculated from the following:

$$k(t) = (q/4\pi) \times \{[\ln(t_2) - \ln(t_1)]/[T(t_2) - T(t_1)]\},$$

where

- T = temperature,
- q = heating power (heat input per unit length per unit time), and
- (t_1, t_2) = is a time interval along the heating (normally 80 s duration) curve.

The correct choice of t_1 and t_2 is complex, and commonly thermal conductivity is calculated from the maximum interval (t_1, t_2) along the heating curve where $k(t)$ is constant. In the early stages of heating, the source temperature is affected by the contact resistance between the source and the full space, and in later stages it is affected by the finite length of the heating source (assumed infinite in theory). The special approximation method (SAM), employed by the

TK04 software, is fitted to the heating curve for all of the time intervals where $20 \leq t_1 \leq 40$, $45 \leq t_2 \leq 80$, and $t_2 - t_1 > 25$. In a good measurement, several hundred time intervals along the heating curve can be matched. The best solution is the one that most closely corresponds to the theoretical curve, and this is the output thermal conductivity. Ten measuring cycles were automatically performed at each sampling location and, when obtained, the closest three were used to calculate an average thermal conductivity. Thermal conductivity measurements were taken where material was suitable, in soft sediments, into which the TK04 needles could be inserted without risk of damage.

Compressional wave velocity

Measurements of P -wave velocity were made using a P -wave sensor (PWS3) on a modified Hamilton frame velocimeter (Boyce, 1976).

Calibration of the system was performed in accordance with Blum et al. (1997). The separation between transducers was calibrated with four polycarbonate standards with varying thicknesses (10–40 mm). The delay time was determined by a linear regression of traveltime versus thickness (15.4–57.5 mm) of aluminum standards.

The PWS3 system uses a vertically oriented transducer pair capable of measuring sample cubes or cylinders. P -wave velocity measurements (V_p) were measured on discrete samples where cylindrical core plugs could be drilled from the reefal material, typically at a frequency of one per section. An acoustic signal of 500 kHz was transmitted and received by the two transducers. Analog to digital transformation of the signal allowed the seismic signal to be displayed on a digital oscilloscope with the first-arrival waveform automatically picked and velocity calculated. To improve the coupling between the transducer and sample, distilled water was applied to the transducer/receiver heads. First-arrival waveforms from samples where the signal was weak were manually picked.

Measurements were performed first on samples dried in the oven for 24 h followed by measurement of the water-saturated sample. Saturation of pore spaces was achieved by placing the sample in a saline solution of 35 g/L (“seawater”) for 24 h while in a vacuum.

Downhole logging

Downhole geophysical logs provide continuous information on physical, chemical, textural, and structural properties of geological formations penetrated

by a borehole. In intervals of low or disturbed core recovery, downhole geophysical logs provide the only way to characterize the borehole section. This is especially true when recovery is poor and when comparable measurements or observations are obtained from the core, as downhole geophysical logs allow precise depth positioning of core pieces by visual (borehole images) or petrophysical correlation.

All measurements were performed under open borehole conditions (no casing) with the exception of a few of the spectral gamma ray logs (see the “Downhole logging” sections in the individual site chapters). After coring was completed, the drill string was pulled and the coring bit was changed to an open shoe casing to provide borehole stability in unstable sections and allow smooth exit and entry of logging tools. In addition, a wiper trip was performed with fresh seawater (no drilling mud was used). Borehole conditions were extremely hostile, and very often boreholes had to be logged in intervals where the drill string was used as a temporary casing. To be able to record ultra high-resolution geophysical downhole logging data, acquisition was done in the rooster box, which in the piggyback drilling system is heave compensated.

Wireline logging measurements are recorded in depth (meters below seafloor) while the tools are pulled to the surface. The logging speed depends on the physics of the specific tool deployed. For example, to obtain spectral gamma radioactivity data without excessive statistical variations, the tool needs to record a certain number of counts per second. Therefore, more time is needed between sampling points when logging low-gamma formations such as carbonates than when logging high-gamma clays and shales. During Expedition 310, not all tools were deployed in each borehole (see the “Downhole logging” sections in the individual site chapters for details of logging tools deployed). With a shallow depth of penetration below seafloor (<100 m) and small-diameter holes drilled (near 100 mm), slimline downhole instruments were used during Expedition 310. These slimline tools were run individually (no logging tool strings).

Borehole geophysical instruments

The set of borehole geophysical instruments was constrained by the scientific objectives and the geological setting of the expedition. A suite of downhole geophysical methods was chosen to obtain high-resolution images of the borehole wall, characterize the fluid nature in the borehole, measure borehole size, and measure or derive petrophysical or geochemical properties of the formation such as porosity, electrical resistivity, acoustic velocities, and natural gamma

radioactivity. Because of environmental constraints, no nuclear tools were deployed during Expedition 310. Most probes were run with Advanced Logging Technologies, Ltd. (ALT) surface recording systems, others with Mount Sopris (Mount Sopris Instrument Company, Inc.) recording systems (see Table T3; also see the “Downhole logging” sections in the individual site chapters for details on the systems deployed).

Optical borehole televiewer (OBI40)

The ALT OBI40 (Fig. F7) produces a millimeter-scale, high-resolution image of the borehole wall, similar to an endoscope. A reflection cone placed at the bottom of the tool enables a vertical charge-coupled device (CCD) camera located inside the tool to image the borehole wall directly. A 360° image is collected and recorded simultaneously. An incorporated lighting system illuminates the borehole wall, and centralizers center the tool for optimal image precision. The resolution of the image is user defined. The highest quality images are obtained with a vertical sampling of 1 mm and 720 pixels taken around the borehole (every 0.5°). A set of triaxial magnetometers allows positioning of measurements relative to magnetic north. Data quality is monitored in real time from a computer display. The precision of measured inclination is 0.5°, and the precision measured azimuth is 1.5°.

Subsequent processing can improve color contrast, and interpolation may be necessary over data transmission errors. The resulting continuous digital image (in RGB color, calibrated from a Kodak reference plate) of the borehole is essential for geological facies recognition and precise core-depth positioning. Consequently, it can be used for sedimentological and structural interpretation, as well as for meso- to macro-scale porosity quantification.

The downhole measurement spacing interval selected was 2 mm × 360 pixels per circumference.

Acoustic borehole televiewer (ABI40)

The ALT ABI40 (Fig. F8) produces millimeter-scale, high-resolution images of the borehole surface and can be directly used for sedimentological and structural interpretation, as well as for meso- to macro-scale porosity quantification. It is less affected by suspended sediments in the borehole fluid than the OBI40.

A voltage is applied in the piezoelectric ceramic to produce acoustic waves (1.2 MHz) at regular intervals. On hitting a focalizing mirror, these waves are deflected perpendicularly to the wave source and toward the borehole wall. The focal point corresponds to the point of maximum energy, giving an ~4 mm

diameter footprint on the wall in a 100 mm diameter borehole. To obtain a 360° image, the mirror pivots on a central axis. The resolution is user defined and depends on the number of measurements made in one rotation and on the vertical sampling interval. The highest quality images are obtained with a vertical sampling of 2 mm and a radial sampling with 288 shots per circumference.

The ABI40 produces two distinct images of the borehole wall. First, an acoustic impedance image (from the contrast between the borehole fluid and wall) is derived from the reflected wave amplitude obtained around the hole. The amplitude ratio between the emitted wave and the reflected wave provides information on the formation's capacity of absorption (low returned amplitude corresponds to a high capacity of absorption, i.e., soft formation). Second, a travelttime image is derived from the reflected wave travelttime from the ceramic transducer to the borehole wall and back. The travelttime is directly proportional to the distance between the borehole wall and the probe. Like the OBI40, the tool is equipped with magnetometers and accelerometers for tool orientation with respect to north. The precision of measured inclination is 0.5°, and the precision of the measured azimuth is 1.5°. For each of the two images, a set of false colors is assigned. From the measurements, a virtual image of the borehole wall depth is produced. This image is displayed as an unfolded representation of the 360° view. The FAC40 tool of ALT is used as a backup for the ABI40. The ABI40 is a second-generation FAC-40 tool. The operating principles are the same; only the output parameters of the FAC are slightly different. The downhole measurement spacing interval selected was 4 mm × 288 pixels per circumference.

Hydrogeological probe (IDRONAUT)

The ALT IDRONAUT (Fig. F9) measures hydrogeological properties of borehole fluid, which are explained below.

Borehole fluid pressure and temperature

Analysis of fluid temperature could help to locate inflows of water coming from the main island into the borehole and is necessary to derive salinity of the fluid from electrical conductivity. Fluid pressure provides an indirect assessment of the tool's progress down and up the hole. It can also be integrated to obtain fluid density in the hole. The tool was calibrated for temperature by the manufacturer and checked on site using a thermometer. The precision of measured pressure is 0.01 dbar, and the precision of measured temperature is 0.004°C.

Electrical conductivity (C and C₂₀)

Conductivity is measured using seven platinum electrodes grouped within a cell, a central electrode that emits an alternating current, and six peripheral electrodes for current return and potential measurements. Electrical conductivity provides a means to identify different fluid types and derive fluid salinity. In the case of freshwater circulation through the reef and into the borehole, it may record lower values than background seawater (where $C_w = 50$ mS/cm on average, at 20°C). The precision of measured conductivity is 0.004 mS/cm.

Hydrogen concentration (pH)

The pH is obtained using two electrodes, one of which is a reference. An electrical current is created between the electrodes. The current is a function of the number of H⁺ ions in the water. The resulting value is then amplified to acquire a precise signal. The precision of measured pH is 0.01 units.

Oxydo-reduction potential (Eh)

This sensor functions in the same way as the pH sensor with a two-electrode setup. The reference electrode is the same electrode as for pH. The measured potential is that of the redox couple located between the two electrodes. The precision of measured Eh is 1 mV.

The tool as a whole was calibrated by the manufacturer prior to the expedition. On site, temperature was checked using a thermometer, and electrical conductivity, hydrogen concentration, and oxydo-reduction were checked using special reference liquids. Finally, the oxygen concentration was checked in air. The downhole measurement spacing interval selected was 0.1 mm.

Spectral natural gamma probe (ASGR)

Unlike other slimline instruments recording total gamma ray emissions, the ANTARES ASGR (ANTARES Datensysteme GmbH) (Fig. F10) allows identification of individual elements that emit gamma rays. Naturally occurring radioactive elements such as K, U, and Th emit gamma rays with a characteristic energy. K decays into two stable isotopes (Ar and Ca), and a characteristic energy of 1.46 MeV is released. U and Th decay into unstable daughter elements. In nature, U and Th decay chains contain many radioactive elements of which the final daughter elements are stable isotopes of Pb. For both U and Th decay, a characteristic energy is also produced. The most prominent of the gamma rays in the uranium series originate from decay of ²¹⁴Bi and in the Th series from decay of ²⁰⁸Tl. Because there is an equilibrium

relationship between the daughter product and parent, it is possible to compute the quantity (concentration) of parent ^{238}U and ^{232}Th in the decay series by counting gamma rays from ^{214}Bi and ^{208}Tl , respectively, if the probe has been properly calibrated.

The ASGR detector for gamma rays is a bismuth germanate (BGO) scintillation crystal optically coupled to a photomultiplier. The BGO detector has an absorption potential eight times greater than a more classic NaI crystal. As most of the spectral discrimination is performed in the high-energy range, only instruments equipped with BGO detectors prove to be reliable in the slimline tool domain.

As the probe moves up the borehole, gamma rays are sorted according to their emitted energy spectrum (the tool has 512 reference spectra in memory) and the number of counts in each of three preselected energy intervals are recorded. These intervals are centered on the peak values of ^{40}K , ^{214}Bi , and ^{208}Tl . Tool output comprises K, U, and Th in becquerel per kilogram, and total gamma ray (GR) counts in counts per second (cps). K, U, and Th values can also be presented as percent K and parts per million U and Th values. The vertical resolution of the tool is ~15 cm.

In reefal carbonates, the ASGR provides a means to identify the presence of clays (usually K and/or Th rich) from terrestrial (nearby island) erosion and organic matter by the U band (or Th/U ratios).

The instrument was master-calibrated by the manufacturer. On site, the stability of the sensor was checked using a volume of purest potassium. The downhole measurement spacing interval selected was 0.1 mm.

Induction resistivity probe (DIL 45)

The ALT DIL 45 (Fig. F11) provides measurements of electrical conductivity. Variations in electrical conductivity correspond to variations in, among other things, lithology (composition and texture), formation porosity and saturation, and interstitial fluid nature. It can, for example, be used to derive porosity from borehole fluid identification when the pore fluid nature is known independently.

An oscillator sends an alternating current through an emitting coil. The resulting alternating electromagnetic field induces Foucault currents in the formation. These induced currents then generate their own electromagnetic fields, which are detected by a solenoid (receiving coaxial coil). This secondary field induces an electromotive force proportional to the flow running through the coil. The alternating current is of constant amplitude and frequency; thus, the Foucault current is proportional to the formation

conductivity and to the electromagnetic field induced in the solenoid.

The electromagnetic field, created by the emitting coil, induces an alternating current as it runs through the receiving coil. This current is out of phase by 90° . The field, created by the Foucault currents, creates an alternating current when it is run through the receiving coil. This current has a phase in opposition with that of the emitting current. The Foucault currents are also out of phase by 90° with the emitting current.

A phase sensitive detector (PSD) enables the elimination of the “reactive” signal and therefore only keeps the signal induced by the field linked to the Foucault currents. In addition to the main receiving and emitting coils, induction probes also possess other secondary emitting and receiving coils (focalization solenoids). Their characteristics and position vary from tool to tool and are selected to reduce the effect of formations and drilling mud located above and below the probe.

The output of the tool comprises two logs:

- Induction electrical conductivity of medium investigation depth (ILM, 0.57 m), and
- Induction electrical conductivity of greater investigation depth (ILD, 0.83 m).

Measured conductivity is finally converted into electrical resistivity. The instrument was calibrated against a Wenner array in a reference hole located in Campos, Mallorca (Spain). Stability of this calibration is checked on site using a reference coil. The downhole measurement spacing interval selected was 0.05 mm.

Full waveform sonic probe (SONIC)

The Mount Sopris 2PSA-1000 sonic probe (Fig. F12) measures compressional wave velocities of the formation. When bulk density is known (from core), elastic properties (bulk and shear moduli) and an estimate of porosity can be derived from sonic measurements. In addition, the analysis of surface waves in the borehole (i.e., Stoneley waves) can be indicative of formation permeability.

This downhole instrument is composed of an acoustic transmitter and four receivers. The transmitter transmits an acoustic signal that propagates through the borehole fluid to the rock interface where some of the energy is critically refracted along the borehole wall. As a result of wavefront spreading (Huygens principle), some of the refracted energy is transmitted back into the borehole. At some point, energy will be transmitted back into the borehole adjacent to a receiver. Each receiver picks up the signal, amplifies it, digitizes it, and then sends the digitized signal

to the surface. The recorded waveforms are then examined and wave arrival times are selected (picking). Arrival times are the transit times of the acoustic energy. By measuring the acoustic transit time and knowing the distance between receivers (1 ft), fluid velocity, and borehole diameter, the sonic velocity of the rock is calculated. Consequently, three interval velocities values are generated at each sampling point. In specific configurations *P*-wave (10 kHz monopole survey), *S*-wave (10 kHz dipole survey), and Stoneley wave (1 kHz monopole survey) were recorded. Calibration of the tool is performed either in water (1500 m/s for *P*-wave; freshwater at 28°C) or into a steel pipe (5440 m/s) while running downhole. For processing purposes, data were filtered (frequency filter) in such a way that only the energy around the induced frequency was analyzed. Waveform picking was done manually to ensure good quality data. Where no clear arrivals in the waveform were present in at least two receivers, a value of zero was entered in the database. The precision of acoustic traveltime measurements is ~5%. The downhole measurement spacing interval selected was 0.05 mm.

Caliper probe (CAL3)

The Mount Sopris 2PCA-100 (Fig. F13) is a three-arm caliper tool that measures borehole diameter. The caliper measurement is made with the three arms attached to a mechanical assembly that drives a linear potentiometer. Because the three arms are linked mechanically, only a minimum diameter value is obtained for a particular hole size. A constant reference voltage is applied across the potentiometer. The direct-current output voltage from the wiper of the potentiometer is converted to frequency. A microprocessor applies a quadratic correction to this frequency so that the frequency is linearly related to borehole diameter. Calibration of the caliper tool is done using two cylindrical rings with known diameters before and after a logging run. The precision of the measurement is ~1 mm. The caliper log is essential for the processing of other logs and can be directly used in sedimentological and structural interpretation of the formation. The downhole measurement spacing selected was 1 cm.

Data recording, processing, and quality

Each logging run was recorded and stored digitally. Data flow was monitored for quality in real time using tool-specific acquisition boxes and software. Table T3 summarizes the acquisition system for each tool. WellCAD software was used for processing, visualization, and plotting the data. Sonic data were processed using LogCruncher (Mercury Geophysics)

software. The quality of downhole logging data may be degraded by rapid changes in borehole diameter. Deep-investigation measurements such as induction resistivity are least sensitive to borehole conditions.

While deploying all the tools separately, a fixed zero depth position is maintained at the top of the drill pipe. Ship heave was minimized by attaching the winch to the conductor pipe (coupled with the seafloor via the DART) and the upper sleeve to the heave-compensated rooster box. Additional processing on the accelerometer data of the image tools allowed (by a double integration of the acceleration), whenever needed, a detailed repositioning of the recorded image data to its correct position with respect to the seafloor.

Geochemistry

Offshore interstitial water sampling

Effect of drilling procedure and core flow on pore water quality

Drilling was generally performed with the RCB. In order to minimize damage to the reef and improve the quality of the cores, cuttings were flushed from the pipe with seawater instead of drilling mud. Seawater from the ship's firepump system was constantly supplied into the Seacore mud-pump container pool. The tank level was controlled by an overflow pipe that drained back into the sea. From this pool, seawater was pumped into the drill pipes with the pump system normally used for drilling mud. During the drilling process, seawater flushes the barrel from the outside and leaves the pipe through a small gap between the barrel shoe and the inner side of the drill bit. Thus, porous or coarse sediments are expected to contain pore waters that consist mainly of exchanged seawater from the drilling process. Loose fine-grained material in cavities or large pores is expected to be flushed away or moved downward the core sequence.

Although plastic-lined core barrels were used, most of the water stayed in the liner until it was capped and sealed in the curation container. After several problems with jammed plastic liners, a test with split-spoon stainless steel liners revealed that the quality of the cores could be significantly improved with their use. Subsequently, an increasing number of cores (see remarks field in OffshoreDIS individual core runs) were drilled using this method, and the cores were transferred on the deck from the split-spoon stainless steel liners into a plastic liner that was cut on one side along its length. The plastic liner was eased open at the cut, and the core and the lower spoon half were inserted. After turning every-

thing upside down so that the cut in the liner pointed upward, the stainless steel spoon was pulled out toward the top. This way, even fragile cores were transferred from split-spoon liners to plastic liners with minimum disturbance. From a geochemical point of view, however, this included the possibility of contamination because the stainless steel liners were reused and the plastic liners were opened. Care was taken to clean the split-spoons from the outside as they were driven out of the barrel with pressurized drilling water. Even so, small amounts of rust, grease, or other contaminants from the outside of the split-spoon may have been transferred to the inner wall of the plastic liner.

After microbiology and pore water sampling, the core was curated, sealed with tape, and refilled with seawater for physical property measurement. Only cores with obvious contents of loose sediments were not refilled. After physical property logging, refilled cores were drained and finally sealed. One of the tap-water outlets in the curation container was connected to the mud container pool so that the same water used for drilling was used to refill cores for physical property measurement. The seawater tap was left running 24 h a day to avoid alteration on the supply tube. During the first days of operation, seawater sampled with a clean bucket from over the ship's side was used to refill the cores because the drill-water supply was not immediately operational. Because of the open Pacific location, the seawater around Tahiti is extremely clean and low in microbial activity.

One obvious alteration of the seawater used as drilling fluid is that some iron content was acquired in the mud pool, evidenced by brownish stains that developed in the sink after a few days of constantly running seawater. Both seawater and drill water from the mud container pool were sampled several times for reference.

Although this procedure has many potential problems and would perhaps be inappropriate for handling normal marine sediments, it preserved in situ drilling conditions for these very coarse and porous reef materials.

Pore water sampling

During Expedition 310, the priority was to sample good-quality, undisturbed coral reef sequences. In the Expedition 310 *Scientific Prospectus*, extraction of pore water was planned only for soft-sediment sequences beneath or within the reef sequences (Camoin et al., 2005). Generally, very few of these sediments were sampled. Most of the recovered material was very porous carbonates or coarse volcanoclastic material with cavities, which were flushed with sea-

water during the drilling process as described above. In some cases, short sequences of fine nonencrusted sediments were sampled that allowed extraction of pore waters.

Preparation

The pH electrode was calibrated, and rhizons were placed in a beaker with pure water. Sample vials were prepared with preservatives as described below.

Pore water sampling using rhizon samplers

For closed liners, a standard 3.8 mm diameter drill bit was used to drill a hole in the plastic liner. A spacer on the drill bit prevented it from going into the core material. The half-split liners were sampled through the split before sealing. Core catcher samples were sampled in a split liner after they were delivered from the drill floor. If necessary, a 2.5 mm wide stainless steel stick was used to prepare a hole in the sediment. A rhizon sampler was carefully pushed into the sediment and connected to a 50 or 20 mL disposable syringe. Because rhizons with female Luer adapters were used, no Luer-Luer adaptors were necessary. Vacuum was established by pulling the syringe plunger and keeping it open with a wooden spacer. In most cases, the syringe was filled after 30 min. If there was still pore water flow, the syringe was emptied into a 20 mL scintillation vial (Greiner, polypropylene) and reattached. If the pore water flow through the rhizon was slow, the syringe was taped to the liner in order to allow core-curation procedures to continue. Filtering was generally not necessary because the maximum pore width of the rhizons is 0.2 μm . The samples were filtered with 0.45 μm disposable syringe filters (Nalgene 25 mm, nylon) if the rhizons turned out to be broken. Broken rhizons can easily be detected, as the vacuum can not be maintained when the porous tube is damaged. If detected early enough, these rhizons were replaced. When pore water collection was very slow, two rhizons were used in the same sampling interval to speed up the sampling procedure. Rhizons retain 130 μL of liquid when wet and are readied for use by being left in a beaker with pure water. Usually the first drops are discarded to avoid collecting this water and rinsing the system. However, at very low expected sample volumes it was decided to leave this water in the sample and allow for the dilution.

Sampling of exchange water

Because of the lack of proper pore water samples to test the equipment, drainage water from the core after physical property measurement was collected in a beaker, sampled with a disposable syringe, and filtered with 0.45 μm Nalgene nylon filters. Because

the refill seawater had some time (generally >2 h) for diffusive exchange with smaller pores even from very porous cores, the measured data were recorded and entered into OffshoreDIS with the remark “exchange water after flushing and draining cores with drill water” and a sampling depth that covered the whole-core section length. Some indication of the in situ pore water conditions may be extracted from this procedure if the exchange waters significantly differ from the refill water.

Sampling with the Bremen squeezer

The Bremen pore water squeezer was set up and operational, but no suitable samples of stiff but compressible material were recovered that would have given better pore water extraction than with the rhizons.

Labeling

Both the syringes and sample vials were first hand-labeled with hole, core, section, and sampling depth information, and then the sample was entered into OffshoreDIS. The primary bar code sample label was used for the 20 mL scintillation vial. Samples were split and labeled using the following abbreviations:

- DW = drilling water (seawater) from the mud pool tank/seawater tap;
- SW = seawater taken from over the ship’s side; and
- TW = tap water from the ship’s freshwater supply.

Samples were measured for pH, alkalinity, ammonia, and chlorinity in the curation container. The results were entered into a worksheet to calculate alkalinities and both calibrated ammonia and chloride concentrations. The results, the total sample and split-sample volumes, and the type and amount of added preservatives were entered into OffshoreDIS. Split-sample labels from OffshoreDIS were glued to the appropriate vials and lined with transparent tape (Tesa-film). If label fields failed to print correctly, they were hand-corrected with a permanent marker. Samples other than pore water were only hand-labeled.

Sample splitting

If possible, sample splits were filled straight from the syringe. Where exact amounts were needed (alkalinity and sulfide splits), a 1000 μ L Eppendorf adjustable pipette was used to transfer samples from the primary sample vial. Table T4 shows the sample-split priority.

Samples for isotope analysis were put into vials and sealed without headspace. The sample split for oxygen isotope analysis was taken only if a sufficient

amount of sample was collected. Because the exact amount of acid added, and thus the sample dilution, is known, alkalinity splits were labeled and stored as well, especially when the total sample volume collected was low. Wheaton ampules were sealed by welding the glass with a small torch.

The minimum sample amount from which all offshore parameters were measured was 400 μ L. In this case, pH and alkalinity were measured from a 185 μ L sample split, and ammonia and chloride were measured from a 1 in 5 dilution (100 μ L sample + 400 μ L pure water). Because rhizons contain 130 μ L of pure water when wet, this had to be considered as dilution of the original sample.

Pure water

Pure water was generated in the curation container from the ship’s tap water with a Seradest USF 3000 purifying cartridge. The conductivity of the water was controlled to be <0.1 μ S (>10 M Ω) by a LFM C1 conductivity detector. For microbiological use, an Aquafine SL-10 A ultraviolet sterilization unit and a Seralplus 0.2 μ m filter cartridge served as extra purifying steps. Pure water for laboratory use was produced in batches of 10 L and stored in a carboy. On 3 November 2005, the ship received new freshwater supplies, which turned out to have a much higher chloride content (>1000 ppm compared to 300 ppm Cl before). This was possibly due to seawater contamination in the tank of the supply ship. Whatever the cause, no change in the purified water quality was detected. On 11 November, the ship’s freshwater supply was switched to another tank, which had even lower chloride contents (25 ppm).

Sample temperature

In situ temperatures of the sample could not be measured. From logging data we learned that they differ little from the water temperature, which is between 26° and 28°C in the working area. During core retrieval from the barrel, there may have been significant warming on the deck for daytime samples (0900–1800 h) because of outside temperatures of up to 40°C in the shade. In the curation container, samples were thermally equilibrated to temperatures between 23° and 26°C. Apart from some air conditioning failures, the curation container temperatures were constant at 25° \pm 1°C.

pH value

The pH value was measured with a Mettler Toledo InLab 423 microcombination glass electrode with a 3 mm tip. In 2 mL Eppendorf cups, the pH value and the alkalinity were determined from 1 mL of sample.

When the sample volume was low, the amount needed could be reduced to 185 μL using a conical 1.5 mL Eppendorf cup. A constant reading was achieved by turning the vial around the electrode with a special magnetically driven vial holder rather than stirring the sample with a perfluorotetrafluoroethylene (PTFE)-coated stir bar. The pH meter was calibrated twice a day using Merck Certipur pH buffer solutions (pH = 4.01, 7.01, and 10.03). Temperatures were measured prior to pH measurement and manually entered into the pH meter. The instrument shows the pH with a resolution of 0.001 pH units. The measurement has an accuracy of better than ± 0.02 pH units.

Alkalinity

Alkalinity was determined by titration with 0.01M HCl. The equivalence point was detected by titrating a 1 mL sample with 0.01M HCl while controlling the pH value. Titration was stopped at pH < 3.9. An Accustep digital burette with a 5 mL tip was used for titration. With this setup, a minimum of 10 μL increments may be titrated at an accuracy of ± 5 μL when using a small-diameter tube that is placed in the solution to be titrated. The algorithm used to calculate alkalinity accounts for the activity of seawater and dilution by the titration solution so that the results are stable for different endpoint pH values. The measurement has an accuracy of better than 0.2 mmol/L. For the titration, a 0.3 mm internal diameter PTFE tube from the digital burette was placed in the liquid before the titration started. Both the PTFE tube and the pH electrode were rinsed with pure water and carefully dried with lab tissues before the measurement. The magnetically driven rotating vial holder is described in more detail in the ESO curation container cookbook, and the algorithm is derived from Grasshoff et al. (1983).

Ammonia

Ammonia was detected using the PTFE tape gas separator technique as described in the curation container cookbook. With this technique, ammonia is stripped from a 100 μL sample by an alkaline carrier solution (0.2M Na citrate in 10 mM NaOH), passes a 200 mm \times 5 mm PTFE membrane area as NH_3 , and is redissolved as NH_4^+ in an acidic solution (1 mM HCl). The NH_4^+ causes a conductivity signal in the acidic carrier that is detected with an Amber Science 1056 conductivity meter with a model 529 temperature-compensated micro flow-through cell. The conductivity signal was recorded with a Knauer strip-chart recorder, and peak height was analyzed manually. This method is very precise and stable, practically insensitive to matrix changes, and shows

a linear conductivity response for ammonia concentrations between 10 and 1000 μM . The detection limit is 5 μM , and accuracy is better than 2%. Generally, measurements were made with the original sample. Only if the sample volume was extremely low was the sample diluted to gain a sufficient amount of sample for analysis. Ammonia calibration standards were freshly prepared from a 5.56 mM (100 ppm) standard solution. In order to avoid unnecessary time for preparation of calibration standards and calibration prior to measurements, only one standard was measured to check instrument function and a proper calibration was performed only if samples showed a signal above the detection limit.

A 300–400 μL sample split was taken from the primary sample vial with a Hamilton 1000 μL precision glass syringe and injected onto a 100 μL loop with a Rheodyne high-pressure liquid chromatography (HPLC) valve. The valve was then opened to the carrier solution stream to start analysis. The Hamilton syringe was rinsed with pure water before and after analysis.

Chlorinity

Although chloride content is not an ephemeral parameter and may be measured months later without loss in precision, it is usually measured offshore because freshwater influence from meltwater, decay of gas hydrates, or submarine freshwater supplies may be of major scientific interest. Chloride content of samples was detected from a 100 μL split by titration with AgNO_3 using a $\text{KCrO}_4/\text{K}_2\text{Cr}_2\text{O}_7$ indicator solution. A total of 5 mL of pure water and 100 μL of indicator solution were placed in a glass beaker on a magnetic stirrer with a white surface. Using an Eppendorf EDOS digital burette system with a 2 mL tip, 0.1M AgNO_3 was titrated into the solution until a color change from milky yellow to orange brown was detected visually. The instrument and operator titration factor was determined by repeated measurement of International Association of Physical Sciences Organizations (IAPSO) seawater standard (556.8 mM). The accuracy of this method is $\pm 2\%$, which is in the range of the total variation of chloride contents in the samples, so it is recommended that the samples be remeasured onshore with a more precise method (i.e., ion chromatography).

Onshore interstitial water analyses

Using analytical equipment housed in the Department of Geosciences, Bremen University (www.geochemie.uni-bremen.de/koelling/index.html), aliquots of IW samples taken during drilling operations were analyzed for a suite of dissolved species to comple-

ment shipboard analyses. Detection limits and reproducibility of IAPSO seawater measurements are given for each analyte in Table T5.

Cations measured by inductively coupled plasma–optical emission spectrometry

Dissolved cations were measured using a Perkin-Elmer Optima 3300 R simultaneous inductively coupled plasma–optical emission spectrometry (ICP-OES). All samples used for these analyses were acidified directly following shipboard sampling with concentrated HNO₃. Samples were diluted 1:10 using 0.65% (0.14M) HNO₃ prepared with subboiling distilled HNO₃ and 18 MΩ water. First, sample aliquots were analyzed for major elements utilizing a cross-flow nebulizer for B (249.772 nm), Ca (317.933 nm), K (766.490 nm), Mg (279.077 nm), S (181.975 nm), Si (251.611 nm), and Sr (421.552 nm), measuring the intensity at each wavelength in triplicate. In a second run, the same sample aliquots were analyzed for trace elements using a CETAC USN 5000AT ultrasonic nebulizer for Al (396.153 nm), Ba (455.403 nm), Cd (228.802 nm), Co (228.616 nm), Cr (267.716 nm), Cu (324.752 nm), Fe (239.562 nm), Li (670.784 nm), Mn (259.372 nm), Mo (202.031 nm), Ni (231.604 nm), U (385.958 nm), V (310.230 nm), and Zr (343.823 nm), measuring the intensity at each wavelength in triplicate.

Calibration standards for the major elements were prepared with high-purity single-element standards (Spectrascan by Teknolab, Norway) using a 0.5M NaCl (Merck certipur) solution as the matrix, as shipboard salinity measurements had determined all samples had seawaterlike salinities. Calibration standards for the trace element analyses were prepared by multiple dilutions of a multielement standard (Merck Certipur multielement standard IV) prepared with a 0.6M NaCl solution as the matrix.

Bromide, chloride, and sulfate by ion chromatography

Bromide, chloride, and sulfate were measured using a Metrohm Advanced Compact IC 861 ion chromatography system with chemical suppression comprising a Metrohm 837 eluant degasser, a 4 mm × 100 mm MetrosepA Supp5 anion column, and a wide-range conductivity detector. The eluant used in this system was a 3.2 mM sodium carbonate/1 mM sodium hydrogen carbonate solution. IW samples were diluted 1:150 with 18 MΩ water. Concentrations were determined by comparison to IAPSO seawater and dilutions of this standard.

Phosphate by photometry

Dissolved phosphate was analyzed by the molybdenum blue method using a Merck portable photometer SQ118. A 1 mL aliquot of sample was placed in a microcuvette, and 50 μL of ammonium molybdate solution and 50 μL of ascorbic acid solution were added. Samples were shaken and placed in the dark for 10 min and then analyzed at a wavelength of 820 nm. Concentrations were determined by comparison to a curve defined by seven dilutions of a phosphate standard (Merck Certipur).

In addition to the above measurements, aliquots that received zinc acetate were examined for precipitates. None of the samples showed any traces of precipitate, indicating that hydrogen sulfide was below the detection limit in all samples.

Microbiology

During Expedition 310, various methods were applied to quantify bacterial abundance, diversity, and activity. This combined approach included cell counting by 4',6-diamidino-2-phenylindole (DAPI) staining, adenosine 5'-triphosphate (ATP) activity measurements, and cultivation of microorganisms. To guarantee that we were indeed investigating indigenous microorganisms, samples were obtained only from selected attached biofilms that showed a high degree of activity as measured by ATP.

Core handling and sampling

Samples for microbial studies were collected based on microbial activity measurements using the ATP test, which is described in “[Activity test by ATP monitoring.](#)”

Because of the nature of modern environments, special sampling precautions against oxygen, temperature, and pressure changes were not necessary because the physiochemical conditions on deck were similar to in situ conditions. Microbiological samples were taken systematically from cavities in the core material wherever high activities could be measured by the ATP test.

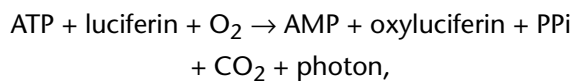
Because of the drilling approach and the nature of the sediments, it was difficult to collect sterile samples. In order to quantify the degree of contamination of the drilling fluid (seawater), water samples collected from the core liner were measured by the ATP test and compared with sterile water and seawater (see Table T6). Results show extraordinarily low activity of microorganisms in the drilling fluid compared with those of the control samples (tap water and seawater).

During the first part of Expedition 310, samples were obtained from small windows opened in the plastic liners (Fig. F14). Only biofilms attached to pieces of coral or microbialites were used for cultivation, identification, activity experiments, and deoxyribonucleic acid (DNA) analysis. In order to avoid microbial degradation, samples were immediately chemically fixed and/or frozen at -60°C . Because of technical problems with ruptured plastic liners, split metal liners were used instead. This change exposed the cores to more sources of microbial contamination on deck. ATP measurements and sampling were therefore completed before the cores were transported to plastic liners for curation.

Precautions, such as the use of sterile spatulas, forceps, pincers, small chisels, and gloves, were taken during sampling to reduce external contamination. The nature of the samples (biofilm, unconsolidated sediment, and crusts) dictated the best technique to use to obtain aseptic samples. Samples of unconsolidated sediment were taken immediately after core recovery; the underlying 0.3–0.5 cm of sediment was removed with a sterilized spatula, leaving behind an uncontaminated surface.

Activity test by ATP monitoring

ATP is the universal energy-transferring intermediate molecule in all organisms. ATP is stable inside cells but becomes unstable outside living organisms; thus, the presence of ATP acts as a marker molecule for living cells. This is affirmed by the fact that ATP is not known to form abiotically. ATP can be easily detected with high sensitivity and high specificity using an enzymatic assay (luciferase):



where

AMP = aminomonophosphate, and
PPi = pyrophosphoric acid.

A photon is emitted as a result of the reaction, which is detected by a photomultiplier. In principle, the detection limit is a photon produced by a single molecule of ATP. Typical sensitivity (significant above background) of commercially available instruments is 0.01 attomoles/mL (0.01×10^{-18} mol/mL) water, corresponding to about five *Escherichia coli* cells.

Detection of ATP during Expedition 310 was used for two purposes: (1) detection of living biofilms in the reef framework and (2) assessment of microbial contamination by drill waters, equipment, and other sources.

In order to test microbial activity immediately after coring, a quick activity test, which is commercially

available for industrial hygiene monitoring, was applied. The Uni-Lite NG luminometer (Biotrace International Pl., Bridgend, UK), in combination with the “Clean-Trace” and “Aqua-Trace” swab kits, measures ATP concentrations by a firefly enzyme-based test. The sensitivity of the test is on the order of 20–40 microbes, expressed in relative light units (RLU). Previously, tests carried out in the Geomicrobiology Laboratory, Swiss Federal Institute of Technology (ETH), Zurich (Switzerland), proved that this method could be applied on geological material, such as rock surfaces and environmental biofilms. Additionally, application of this test to water samples can aid evaluation of the degree of contamination of the drilling water, which percolated inside the core liner.

The following procedures were used to measure microbial activity. Using the Clean-Trace surface test kits, ~ 1 cm² of the rock surface was sampled, which provided results within a 30 s analysis. For water samples, an Aqua-Trace test stick utilizes a test tube with a 0.1 mL water sample, providing an activity measurement using the same method as above and also expressed in the same units (RLU). The ATP test can be calibrated using a sample with a known density of microbes. However, the ATP content of microbes can vary according to their feeding status.

Measurements for ATP were performed on the surfaces of sedimentary rocks, in the cavities of the reef framework, on percolated drilling water, and on seawater collected 10 m below sea surface. Additionally, purified water for analysis and chemical solutions from the shipboard geochemical laboratory were monitored for the degree of contamination.

Exoenzyme activity

Hydrolytic exoenzymes are indicators of metabolically active bacteria. Exoenzyme activity can be measured very sensitively by fluorescent-labeled substrate analogs (Coolen and Overmann, 2000). The result gives an idea of which substrates are used by microbial communities living in the reef subsurface. The activity of three exoenzymes was measured during Expedition 310:

- Alkaline phosphatase, cleaving inorganic phosphate from organic molecules such as phospholipids;
- β -glucosidase, cleaving sugar molecules from polysaccharides; and
- Aminopeptidase, cleaving proteins and peptides into smaller fragments.

As the measurement of exoenzyme activity is a common method in marine seafloor environments, data can be compared with existing databases.

Exoenzyme activity in sediment samples was determined by the fluorogenic substrate analogs for the hydrolytic exoenzymes alkaline phosphatase (EC 3.1.3.1), β -glucosidase (EC 3.1.2.1), and leucine aminopeptidase (EC 3.4.1.1). Alkaline phosphatase and β -glucosidase were assayed with MUF-phosphate (4-methylumbelliferone-phosphate) and MUF- β -D-glucoside (4-methylumbelliferone-glucoside, obtained from Sigma). Aminopeptidase activity was measured with MCA-labeled leucine (7-amino-4-methylcoumarin-leucine, obtained from Sigma).

Fresh samples (~0.5 g) were weighed and incubated in 2 mL reaction vials with 1.5 mL sterile filtered seawater. Substrate analog solution (5 μ L), required to yield a final concentration of 33 μ M, was added to initiate the enzymatic reaction. Samples were incubated for 30 and 90 min at a temperature of 28°C. For each substrate analog, a control of the same sediment material was inactivated by boiling in distilled water for 20 min to assess the nonenzymatic hydrolytic cleavage of the substrate analogs. This procedure represents a reliable control for abiotic cleavage of fluorogenic substrates in various samples.

After the incubation time, NaOH was added to increase the pH of the solution to 11, together with 1.7M (final concentration = 0.1M) of tetrasodium ethylenediamine tetraacetic acid (EDTA) to prevent carbonate precipitation. The assays were centrifuged for 5 min, and the concentration of free dissolved fluorophores was determined fluorometrically by a LS-5B luminescence spectrometer (PerkinElmer), with excitation wavelength of 360 nm and an emission wavelength of 450 nm. Depending on exoenzyme activity, samples were diluted 1:10 to 1:100.

For calibration, MUF and MCA standards in artificial seawater at concentrations of 10–2000 nM were used. The exoenzymatic activity is expressed as nanomol per hour per gram of substrate analogue cleaved.

Microscopy: DAPI staining

Microscopic cell counting by DAPI is a standard technique to stain DNA of an entire microbial community in environmental samples (Hobbie et al., 1977). This technique was applied to attached biofilms recovered in Tahiti reef cores to quantify microbial communities.

Samples were obtained directly from cores with aseptic tools and transferred into sterile 2 mL reaction vials. Samples were fixed with 1 mL 3% formaldehyde solution and washed with marine PBS buffer (phosphate buffered saline + 2.7 g/L NaCl).

To remove fine carbonate debris and detach cells from mineral surfaces, 1.5 mL of EDTA solution was

added (0.3M EDTA; pH 7.3; 2.7 g NaCl/L), mixed and incubated for 1–2 h. Following this procedure, samples were placed in an ultrasonic bath for 3 s and vortexed. Supernatants were transferred to another vial and incubated for 1 h to obtain a solution that is nearly free of carbonate particles. The EDTA solution was removed from the solid phase using a 10 min centrifugation. The supernatant was discharged and the pellet suspended in 0.1 mL saline PSB (NaCl, 2.7 g/L) concentration. A 10 μ L aliquot of each sample was spread on gelatin-coated multiwell microscope slides (3 g gelatin; 0.5 g CrKSO₄/L) and left to dry for 10 min. DAPI (250 ng/mL; 5 μ L) staining was applied to each sample, and samples were incubated for 5 min. Slides were washed in a PBS NaCl solution for 15 min. To avoid bleaching, 5 μ L “Citifluor” was added to each well and covered with a slide cover.

Samples were examined using a Zeiss AxioskopII microscope with a 100 \times objective, equipped with a 50 W ultraviolet lamp and appropriate filter. Images were recorded by a Zeiss MRC5 digital camera.

Because of the vibration caused by the ship's engines, it was often impossible to obtain sharp pictures with 100 \times objective.

Fluorescence in situ hybridization

Fluorescence in situ hybridization (FISH) can be used to identify and quantify specific microbial cells in environmental samples. Oligonucleotides are used to stain selective microbial cells according to their phylogenetic affiliation. Samples were fixed onboard for future application of specific probes during shore-based studies.

Cultivation of microorganisms

In order to identify the microorganisms occurring in biofilms and understand their function by investigating their metabolism, aerobic microorganisms were cultivated. Subsamples of biofilms growing on reef material were incubated on board. Biofilm material was diluted in a sterile PBS saline solution, inoculated on agar plates, and incubated at in situ temperature (24°C). Unfortunately, only a small fraction of the in situ microbes can be cultivated on a selective medium.

Isolation of microorganisms

After 15–30 days incubation, individual colonies were sampled and inoculated on new agar plates. These cultures were identified by 16S ribonucleic acid (RNA) analysis and could be preserved for further investigations concerning microbially mediated mineral precipitation.

The 16S ribosomal ribonucleic acid gene

Molecular phylogenetic analyses are based on 16S ribosomal ribonucleic acid (rRNA) sequence analysis. The sequence of the 16S rRNA molecule is highly preserved among all organisms. Thus, rRNA is an excellent molecule to detect evolutionary relationships among prokaryotic organisms. Ribosomal RNA is phylogenetically ancient, functionally constant, universally distributed, and preserved across broad phylogenetic distances.

Scanning electron microscopy: fixing of samples

For scanning electron microscopy (SEM) studies, a fresh sample (~0.5 g) was taken from the core material, transferred in a sterile reaction vial, fixed with a 3.5% glutaraldehyde solution, washed two times in marine PBS, and stored in a 80% ethanol:20% PBS solution at -70°C.

Culturing

From selected samples where a high cell density and a high ATP signal was observed, culturing of aerobic microbes was done on marine cell preserved solution (CPS) agar plates. The composition of the CPS agar was artificial seawater supplied with soluble starch and peptone.

Specialist sampling of massive *Porites*

Identification of massive *Porites*

Massive colonies of *Porites* suitable for paleoclimatic studies were visually identified in core sections through the transparent liners prior to core splitting. Those core sections containing massive *Porites* longer than the core diameter (or shorter but apparently in good condition) were labeled to prevent them from being split using the regular core-splitting procedure. The major goal was to recover pristine, long, continuous intervals of the *Porites* skeleton from individual colonies along the major axis of growth. The regular core-splitting procedure does not take account of the major growth direction of *Porites* colonies, which can be different from the core axis, or holes within a colony as a result of bioerosion, which can interrupt an otherwise continuous interval of the *Porites* skeleton. Therefore, the liner was split for core sections containing *Porites* colonies using a handheld electric saw. One half of the liner was removed, and photographs of the colonies within the core were taken for reference.

Splitting of massive *Porites*

Massive *Porites* were taken out of the core liner and split along the plane of the corals' major growth direction using a rock saw with a 1 mm thick blade and tap water. This resulted in two nonequal parts, so the procedure outlined in Figure F15 was followed to preserve 50% of the core volume for the archive half. One part was declared to be the archive half of the *Porites* colony and the other the working half. A 1 cm thick slab was cut from the working half of the *Porites* colony for paleoclimatic studies. A second 0.8 cm thick slab was cut from the working half for other purposes (e.g., dating, further geochemical studies). In cases where the 0.8 cm thick slab appeared to provide the better sample, it was selected for paleoclimatic studies and the 1 cm thick slab was used for other purposes. The parts of the core without *Porites* colonies were then cut in half, and the archive and working halves were placed in their respective D-tubes.

Washing and drying of *Porites* slabs for paleoclimatology

After slicing, *Porites* slabs for paleoclimatic studies were washed with tap water and dried at 50°C in an oven for ~24 h.

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Figure F1. Schematic of recovery and naming conventions used by IODP and during Expedition 310.

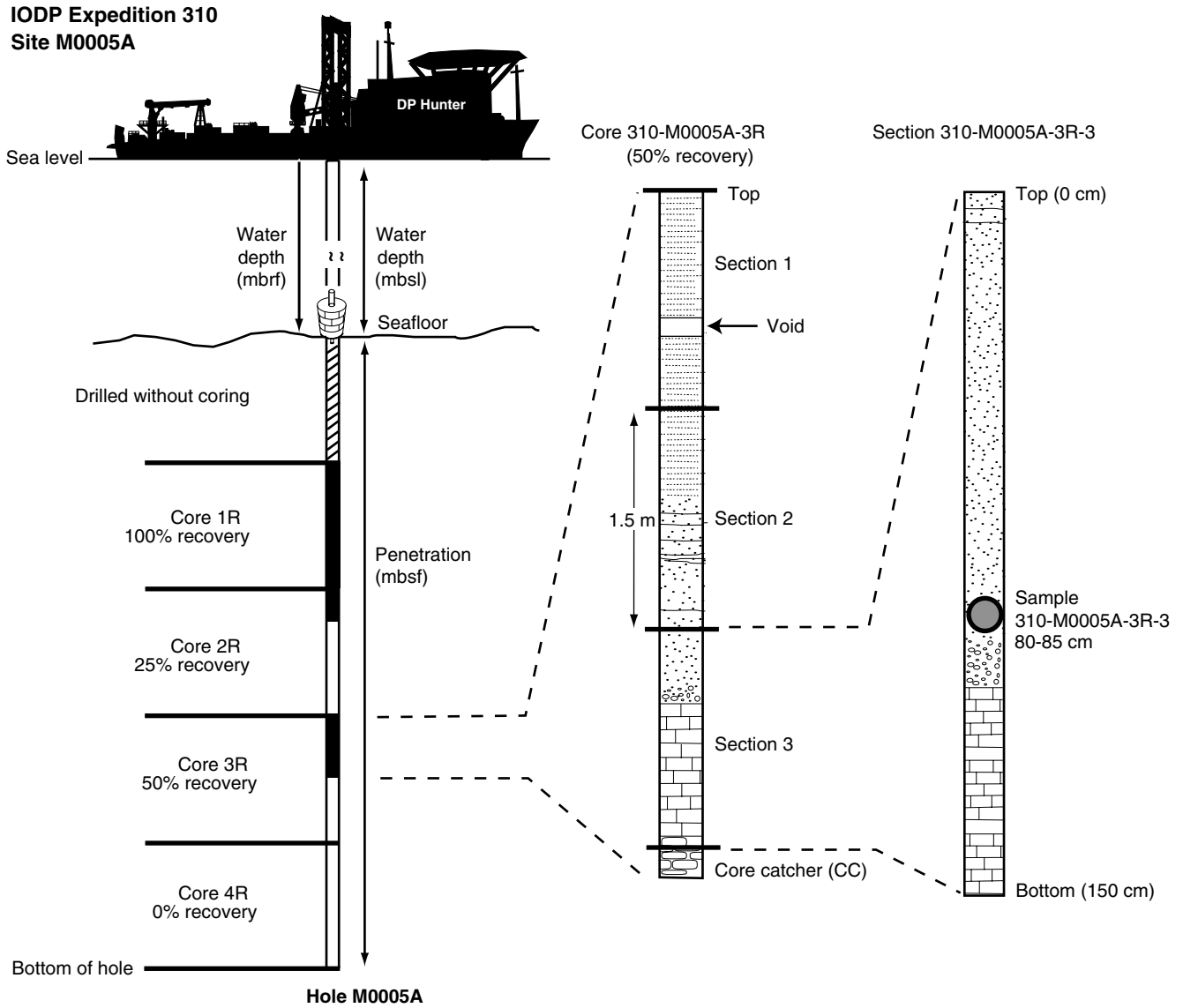


Figure F2. The *DP Hunter*, Papeete.



Figure F3. R100 rig, taken from outside core curation container.



Figure F4. DART seabed template in the moonpool.

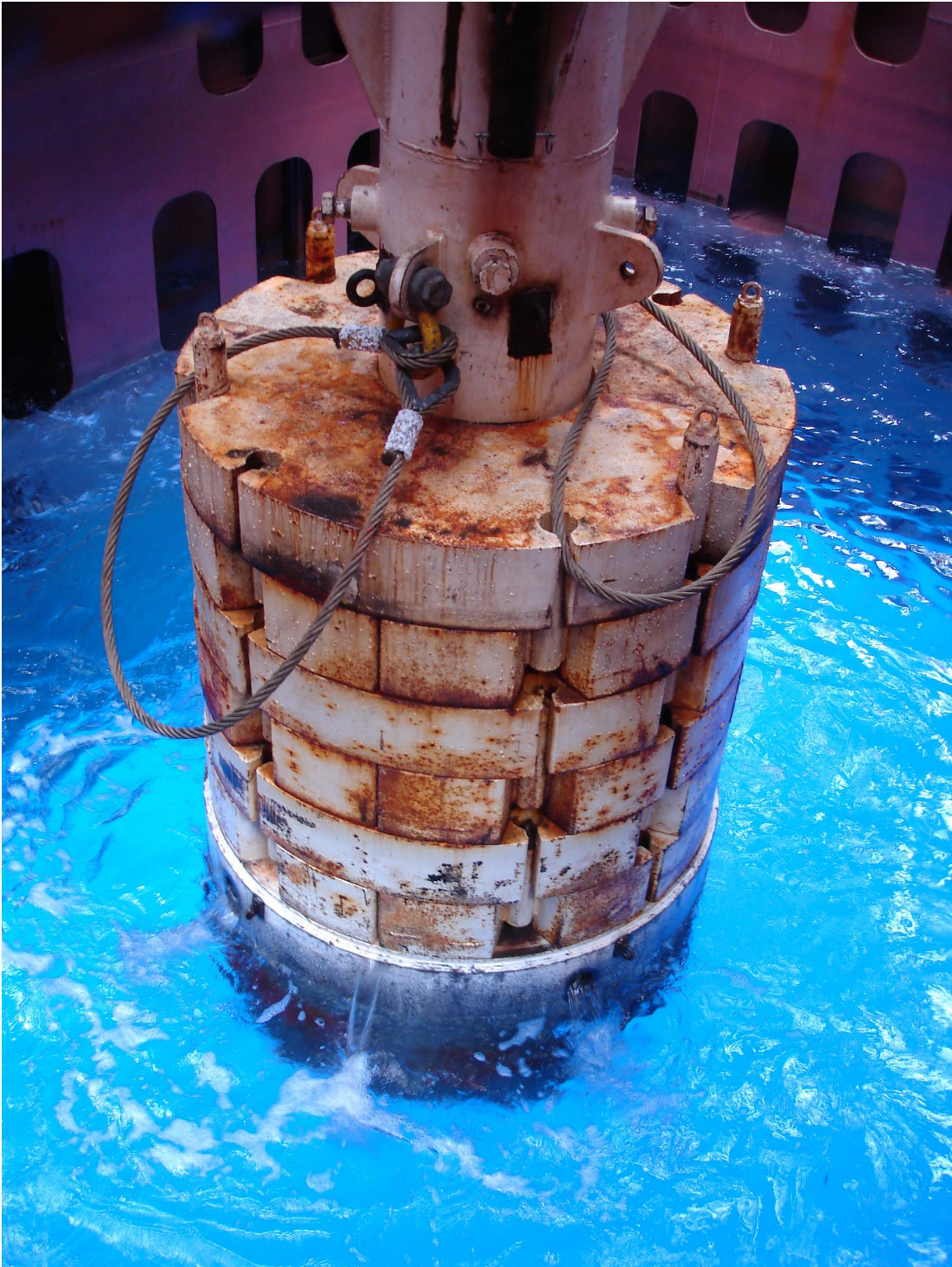


Figure F5. Example of a visual core description (VCD).

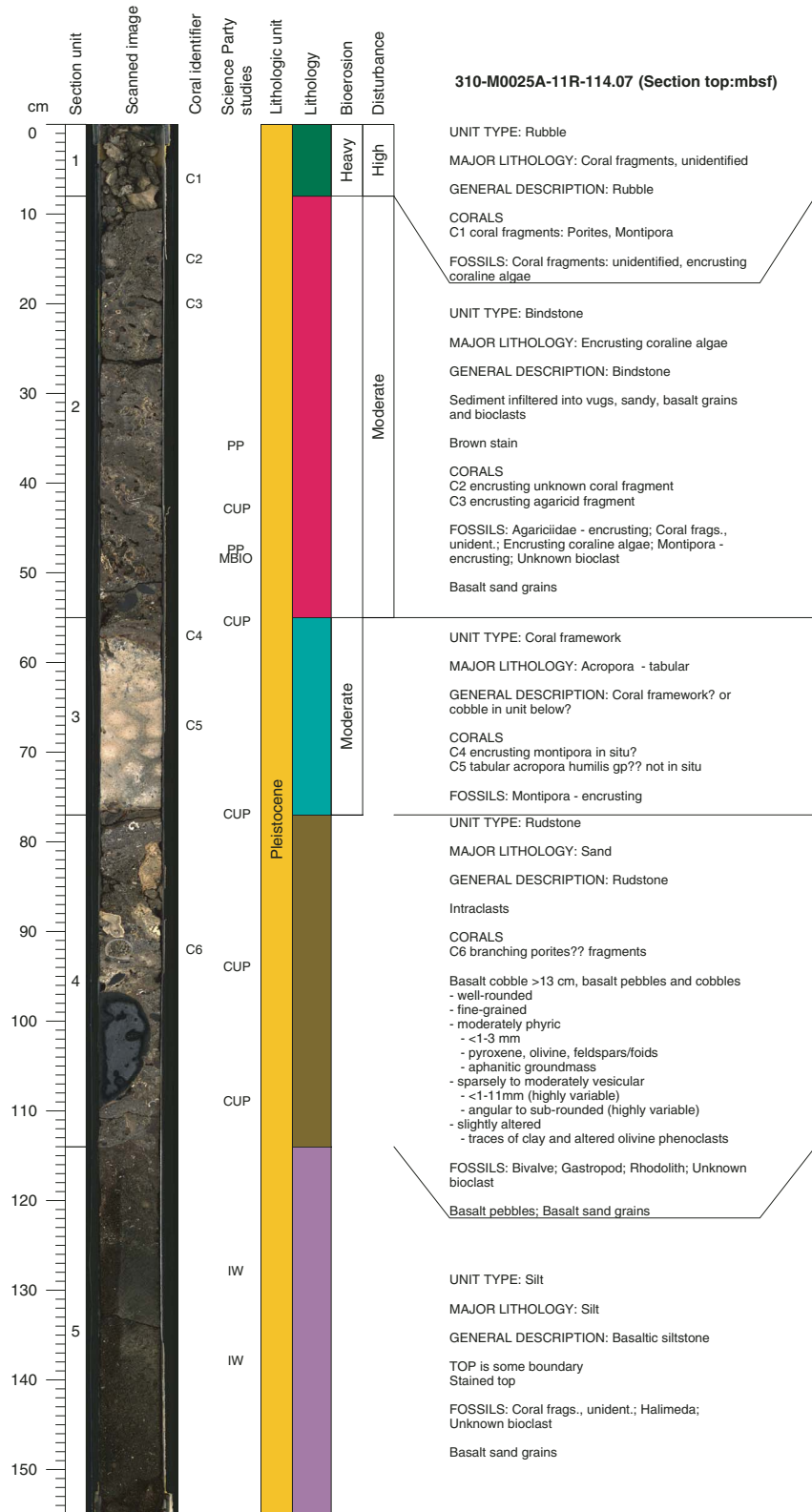


Figure F6. Visual core description definitions.

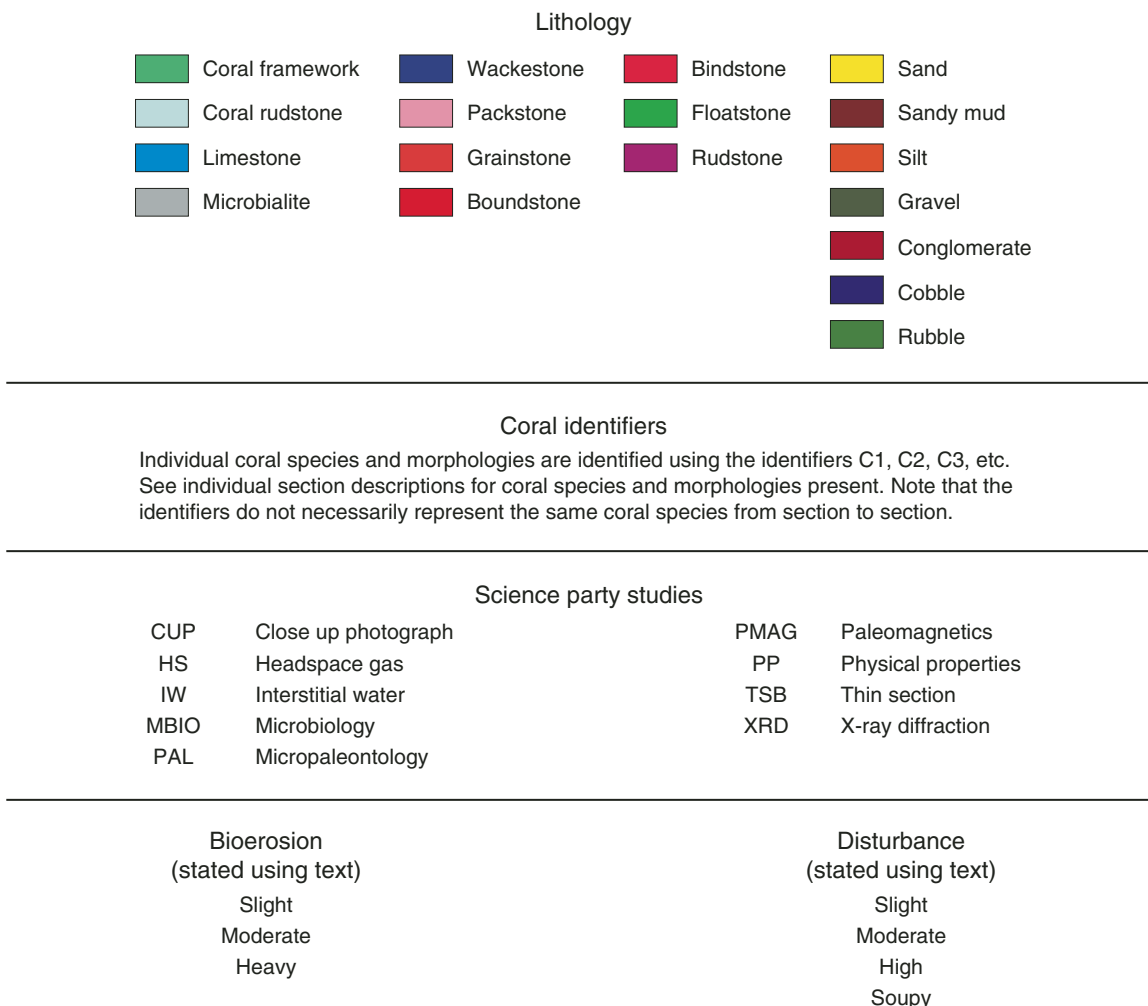


Figure F7. OBI40 tool diagram.

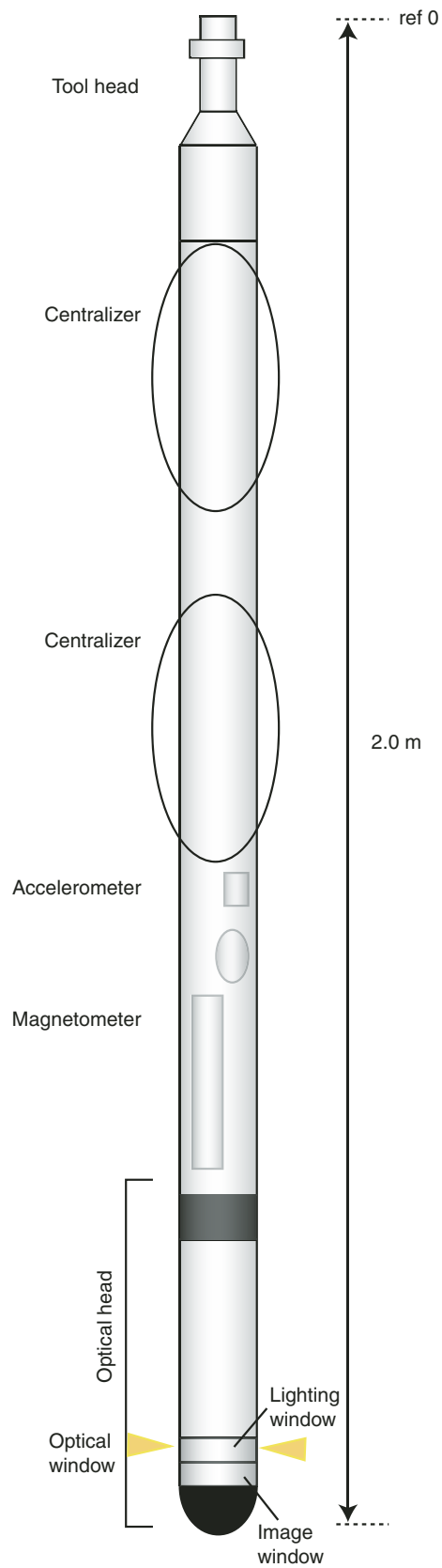


Figure F8. ABI40 tool diagram.

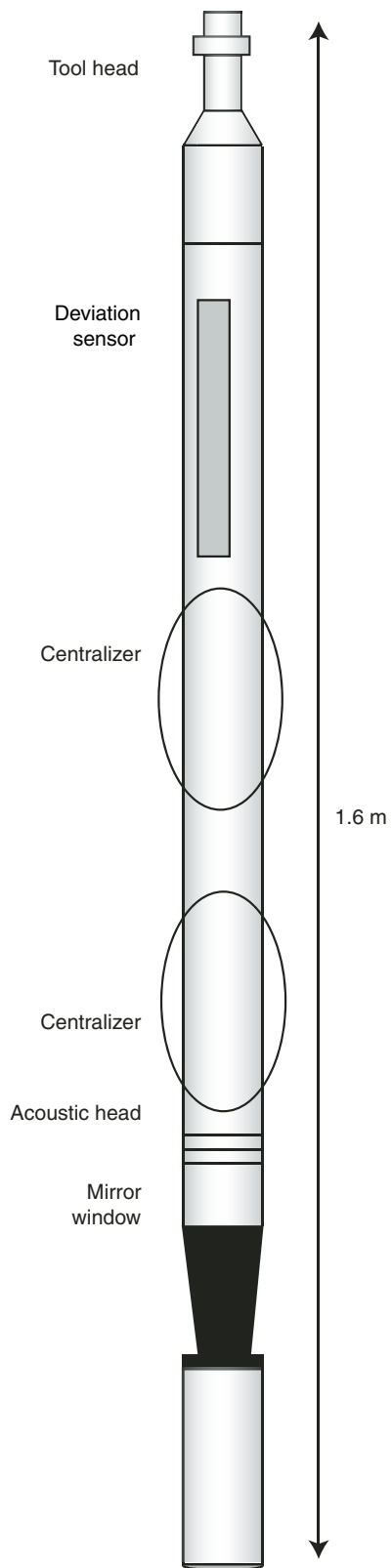


Figure F9. IDRONAUT tool diagram.

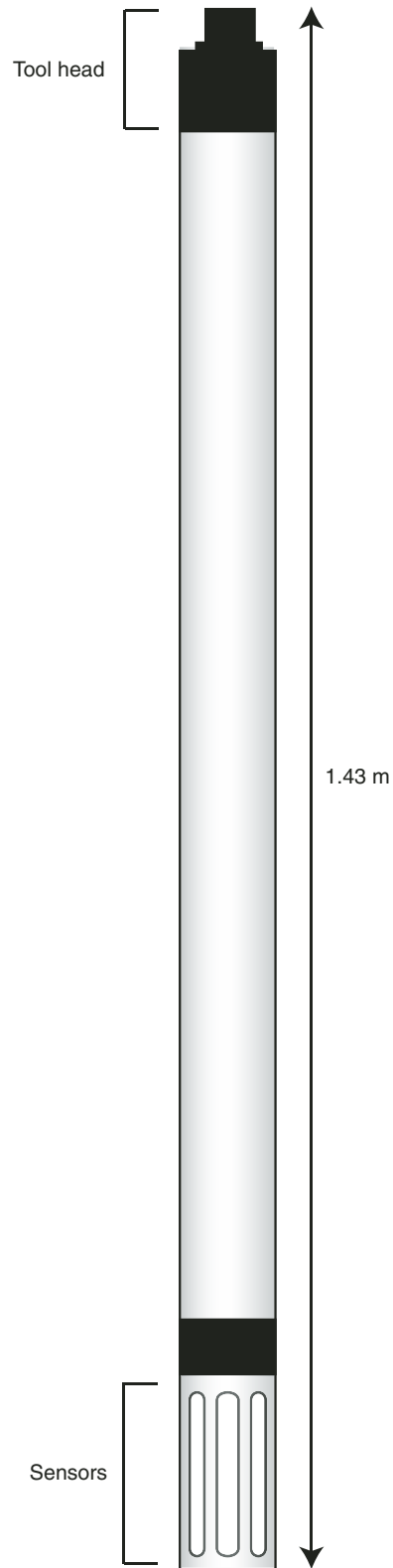


Figure F10. ASGR tool diagram.

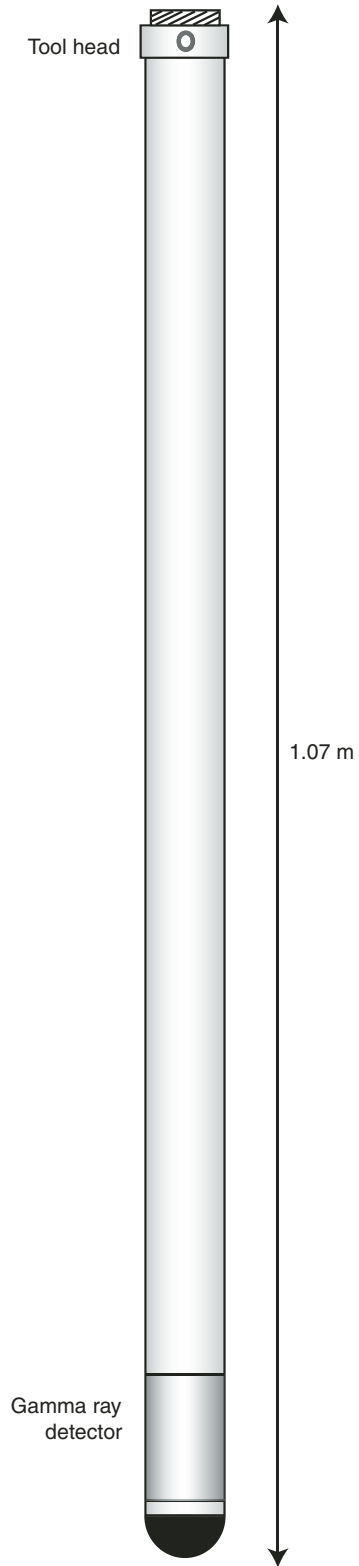


Figure F11. DIL45 tool diagram. ILD = induction electrical conductivity of greater investigation depth, ILM = induction electrical conductivity of medium investigation depth.

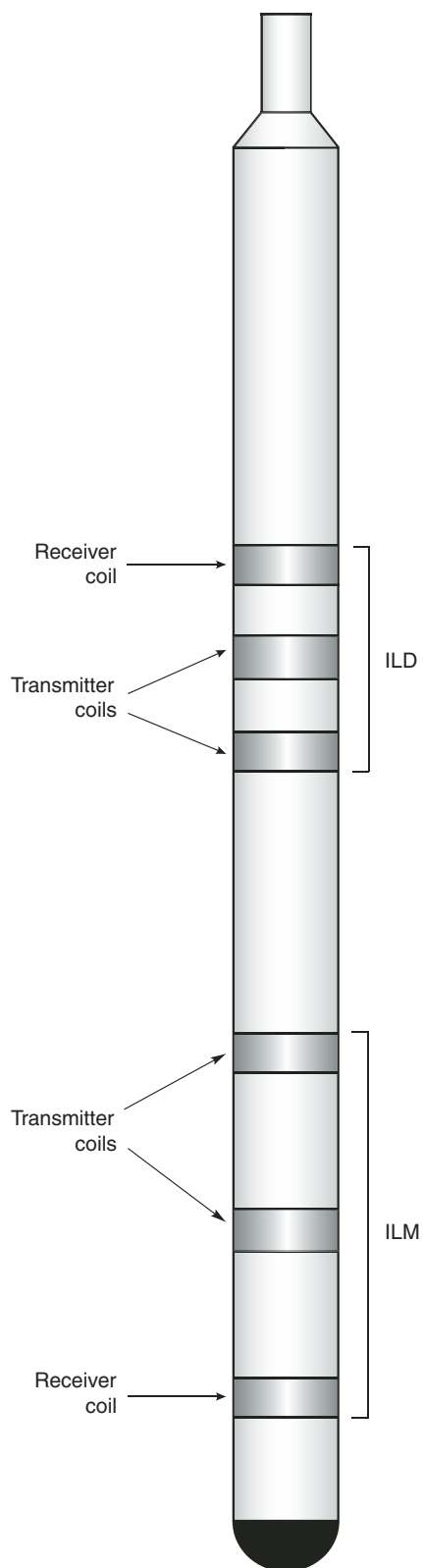


Figure F12. Sonic tool diagram.

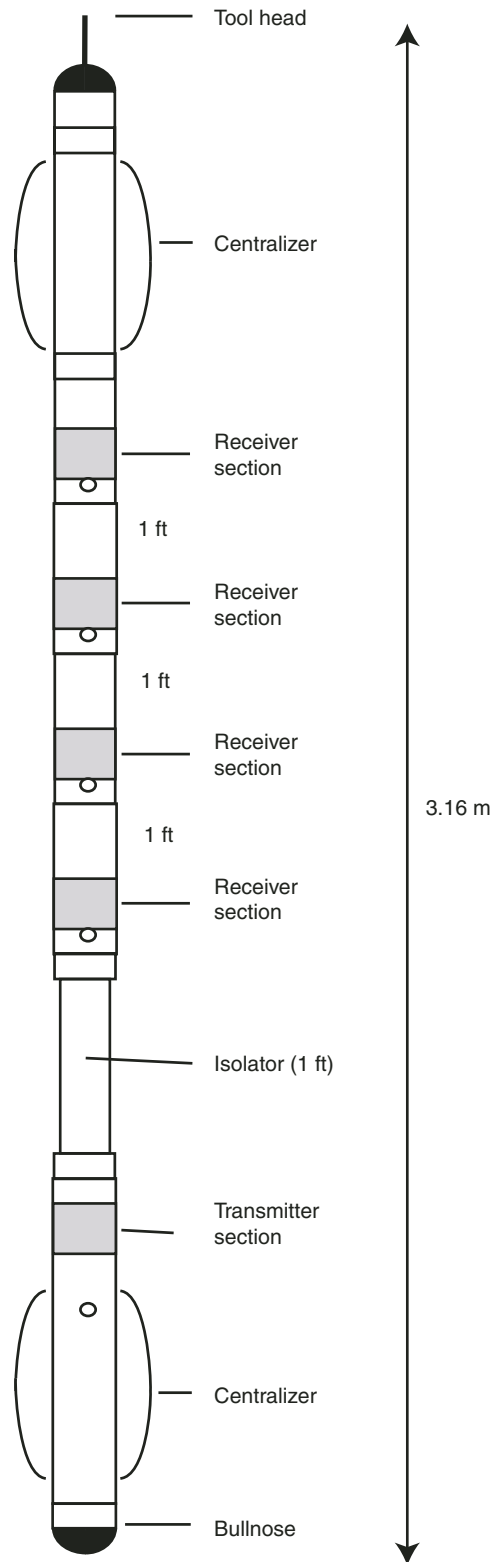


Figure F13. Caliper tool diagram.

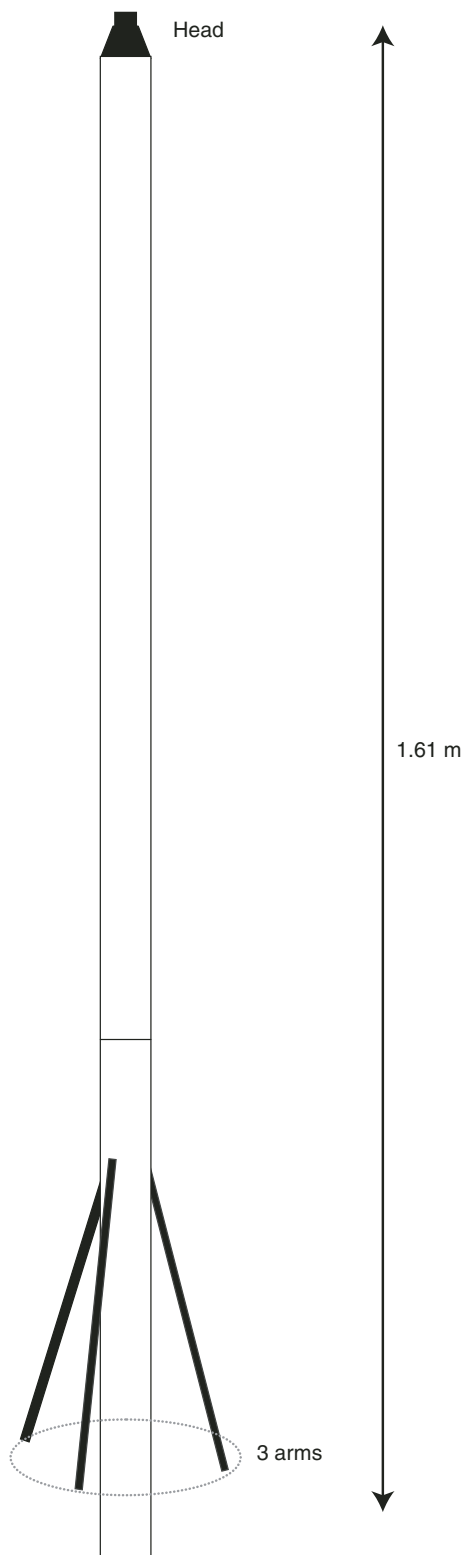


Figure F14. Sampling window in a 6.4 cm core liner.



Figure F15. Schematic diagram describing placement of massive *Porites* pieces after oblique cutting. The corner piece of one half is added to the other half to ensure both archive and working halves contain 50% of the original core volume. A = archive half, W = working half.

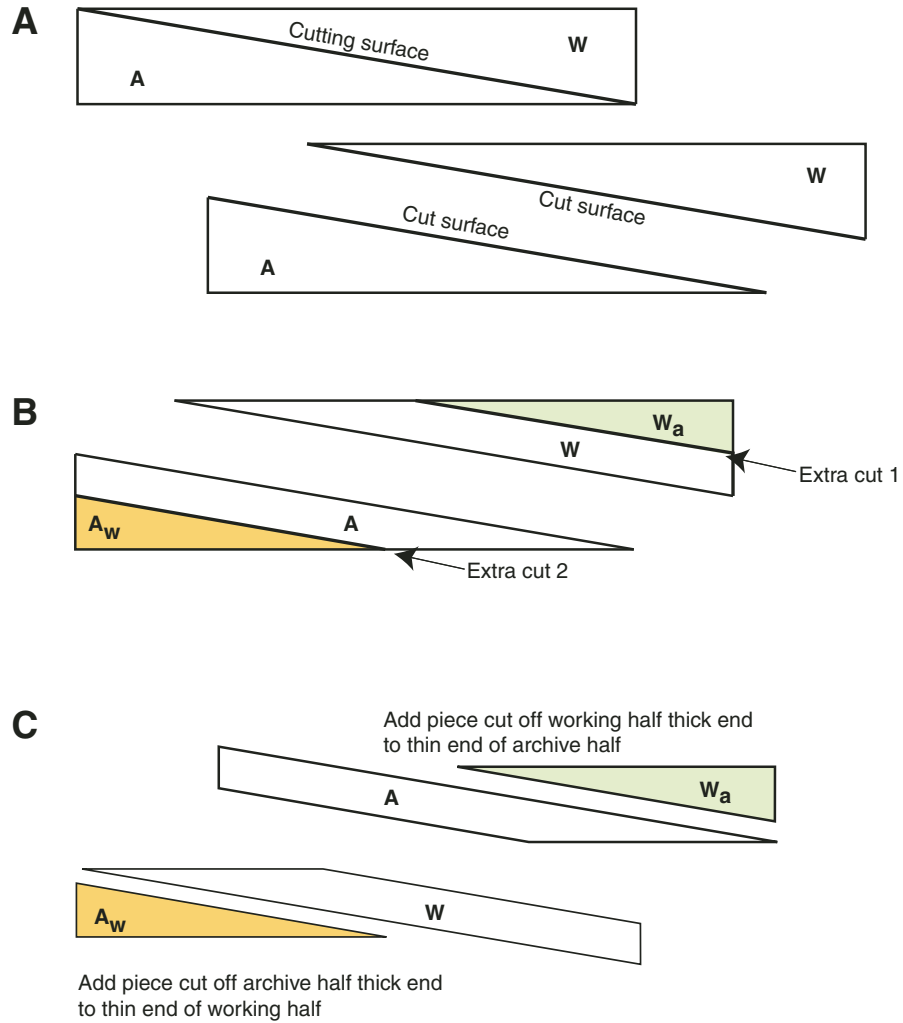


Table T1. Wentworth size class.

Size (mm)	Name
>256	Boulder
64–256	Cobble
4–64	Pebble
2–4	Granule
1/16–2	Sand
1/256–1/16	Silt
<1/256	Clay (mud)

Table T2. Major and trace element analyses of rock standards analyzed by EDS-XRF.

Element	MAG-1			Pacs-1			SDO-8			MAX			CAMAX		
	New analysis (ppm)*	Average (ppm)	RSD (%)	New analysis (ppm)	Average (ppm)	RSD (%)	New analysis (ppm)	Average (ppm)	RSD (%)	New analysis (ppm)	Average (ppm)	RSD (%)	New analysis (ppm)	Average (ppm)	RSD (%)
Si	240,267	240,767	1	251,700	250,817	1	294,300	292,383	1	195,700	194,950	1	216,200	215,983	1
Ti	4,155	4,050	3	3,669	3,717	2	2,817	2,806	2	4,050	4,011	1	4,445	4,430	3
Al	81,860	82,200	1	55,900	54,915	1	34,320	35,537	8	88,940	88,583	1	90,890	90,610	1
Fe	44,757	44,840	0	43,920	43,690	0	32,050	31,872	1	67,650	67,255	1	43,350	43,267	0
Mn	767	743	3	463	446	7	3,028	2,998	1	194	207	11	1,405	1,394	2
Mg	18,033	18,105	4	15,230	14,935	9	15,850	17,888	20	12,730	11,902	5	13,890	14,040	5
Ca	9,297	9,422	1	18,020	18,013	1	43,580	43,290	3	20,240	20,262	1	37,860	37,818	0
K	28,580	28,222	1	11,450	11,332	1	10,530	10,605	7	13,060	13,007	1	12,290	12,572	2
P	847	950	2	957	1,098	7	638	697	42	780	728	6	521	493	19
Sr	124	123	1	244	243	2	280	278	2	131	134	1	222	227	1
Ba	465	473	11	521	508	9	1,198	1,119	3	268	298	18	291	385	12
Rb	132	130	1	36.5	38.3	4.5	40.5	40.4	2.2	74.0	72.1	2.3	71.6	71.6	1.6
Cu	28.5	26.7	8.6	421	411	2	151	143	2	31.1	31.4	13.0	45.1	52.8	7.7
Ni	47.3	47.3	12.2	41.4	42.0	6.5	86.4	78.5	5.6	54.5	55.3	4.0	69.9	80.6	6.4
Zn	122	119	4	608	613	2	84.1	85.1	3.3	118	116	4	111	117	3
S	3,177	3,182	1	11,040	10,897	2	2,003	2,218	22	7,675	7,719	1	4,345	4,348	1
Cl	18,240	18,217	1	20,290	20,117	1	25,280	24,978	2	14,880	14,815	2	14,680	14,770	0
Br	197	197	2	178	174	1	91.6	95.4	1.0	121	120	3	101	101	2

Notes: MAG, Pacs, SDO, MAX, and CAMAX are characterized rock standards. * = average of two new MAG-1 analyses. Average = average of six previous analyses, RSD = relative standard deviation of previous analyses.



Table T3. Logging equipment and software.

Manufacturer	Tool	Recording device	Software	Processing software
Advanced Logging Technologies Ltd.	OBI40	ALT A-BOX	ALTLogger	WellCAD
Advanced Logging Technologies Ltd.	ABI40	ALT A-BOX	ALTLogger	WellCAD
Advanced Logging Technologies Ltd.	IDRONAUT	ALT A-BOX	ALTLogger	WellCAD
ANTARES Datensysteme GmbH	ASGR	ALT A-BOX	ALTLogger	WellCAD
Advanced Logging Technologies Ltd.	DIL 40	ALT A-BOX	ALTLogger	WellCAD
Mount Sopris Instrument Company Inc.	SONIC	MSI MGX II	MSLog	LogCruncher/WellCAD
Mount Sopris Instrument Company Inc.	CAL3	MSI MGX II	MSLog	MSLog/WellCAD

Table T4. Prioritized list of sample splits and geochemical determinations and methods used during Expedition 310.

Priority	Split	Volume (mL)	Preservative		Vial	
			Type and concentration	Volume (μ L)	Type and size	Material
1	pH, alkalinity	1.00	HCl s.p. 0.01 <i>n</i>	Varies	2 mL Eppendorf cup	Polypropylene
2	Ammonia	0.4	—	—	Direct Injection	Hamilton 1 mL glass syringe
3	Anions, archive	2–5	—	—	5 mL ampule	Glass
4	Cations	2–5	HNO ₃ s.p. 65%	100	5 mL ampule	Glass
5	¹³ C	2, no HS	HgCl ₂ 0.25 M	30	2 mL crimp cap	Glass
6	Sulfide	2.00	ZnAc 50 mM	500	8 mL twist cap	Glass
7	¹⁸ O	8, no HS	—	—	8 mL twist cap	Glass
8	DIC, archive	5	HCl 30%	100	5 mL ampule	Glass
9	Archive	Varies	—	—	20 mL scintillation	Polypropylene

Notes: 1 = highest priority, 9 = lowest priority. DIC = dissolved inorganic carbon. HS = headspace. ZnAc = Zn(H₂C₃O₂)₂. s.p. = suprapure.

Table T5. Detection limits and reproducibility of IAPSO seawater.

Element	Unit	Detection limit	IAPSO seawater mean value	Standard deviation 1 σ	IAPSO analyses (N)
Mg	mg/L	—	1293	7.19	6
K	mg/L	—	391	7.12	6
Ca	mg/L	—	396	3.32	6
S	mg/L	—	851	2.45	6
Si	mg/L	—	1.26	10.5	6
Sr	mg/L	—	7.63	6.90	6
Li	μ g/L	0.83	172	1.14	3
P	μ g/L	49.8	75.8	8.95	2
Mn	μ g/L	17.7	*	4.32*	3*
Fe	μ g/L	28.9	*	2.11*	3*
Ba	μ g/L	3.75	88.9	5.08	3

Notes: Detection limit = blank mean + 3 σ . Standard deviation 1 σ is as a percent of the mean. — = not applicable, * = elements below detection in IAPSO seawater. Reproducibility is calculated from repeat analyses of the 50 ppb standard solution treated as unknowns.

Table T6. Water analysis and activity data.

Source	ATP (RLU)
Tap water	84, 67, 70, 22
Seawater	112, 120, 98, 78, 121
Drill water	30, 79, 48, 45
Drill pipe	89, 150, 129
Operators gloves	150, 170
Rod dope (grease)	500, 410

Notes: Drill pipe measured directly in the rooster box. ATP = adenosine 5'-triphosphate. RLU = relative light units.