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Practical Guide for Description and Analysis of Sedimentary Cores: Practices Developed aboard the *JOIDES Resolution* during ODP and IODP

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Preface

The 1988 *Handbook for Shipboard Sedimentologists* (ODP Technical Note 8) was published just 3 years after the transition from the Deep Sea Drilling Project (DSDP) to its successor phase of scientific ocean drilling, the Ocean Drilling Program (ODP). Authored by Jim Mazzullo and Ann Gilbert Graham, the Handbook included a section on sediment classification by Audry Meyer and Robert Kidd. This document served as the guide for shipboard sedimentological core description on the *JOIDES Resolution* from 1988 to 2023, extending from ODP through the two phases of IODP (Integrated Ocean Drilling Program followed by International Ocean Discovery Program). During the IODP programs the influence of the 1988 Handbook expanded to sedimentary core description on the drillship *Chikyu* and mission-specific platforms (MSPs).

Over the 35 years of ocean drilling since this landmark publication, it became clear that the 1988 Handbook was increasingly disregarded because of its perceived shortcomings, at the risk of reduced programmatic consistency in core description. It did not cover new shipboard technologies that provide a wide array of new imaging and petrophysical data, all digital, in support of core description. Currently, much of core description itself can be recorded digitally with tremendous benefits for data preservation and integration. At the same time, there has been a revolution in muddy sediment classification because high-resolution electron beam imaging in land-based laboratories around the world has transformed our basic understanding of primary versus secondary components in fine-grained sedimentary materials that dominate marine deposits. For all these reasons, an update of the 1988 Handbook was widely seen by the marine sedimentology community as overdue.

Previously, the authors created three IODP Technical Notes to support particular aspects of sedimentary core description, which were intended for use in conjunction with the original handbook: two books on smear-slide analysis are published as IODP Technical Notes 1 and 2, and an atlas of sedimentological core photos is published as IODP Technical Note 3 (**https://www.iodp.tamu.edu/publications/TN.html**). These technical notes were first utilized as instructional tools in 2015 at an IODP workshop: “Short course on shipboard sedimentology: Data collection, interpretation and integration.” This workshop, held at IODP’s Gulf Coast Repository at Texas A&M University (College Station, Texas) was meant to provide updated training to a new generation of shipboard scientists. During preparation of course materials it became clear that Mazzullo and Graham (1988), then only available as grainy photocopy images, was not suitable for instructional purposes. This short course was in many ways the instigation of our plans to create a formal revision, and soon after, we began a proposal to United States Science Support Program (USSSP) to fund the endeavor.

Construction of this revised document was funded by USSSP in two phases, each phase being preceded by review and input from the marine sedimentology community, as well as staff groups at IODP. Phase 1 (beginning in mid-2018) was an analytical phase, focused on review of all published ODP and IODP reports (1988–2018) to identify trends in sedimentological techniques and classification schemes. These results (included here in an appendix) identified a selection of “best practice” classification schemes for the revised handbook. Phase 2 (commencing in early 2020) utilized the results of Phase 1 for construction of the full revised document. In late 2021, comment on the near-final Phase 2 version was requested from IODP staff groups, including curators, editors, and science operations, and then, in late 2022 it was reviewed by a panel with experience in shipboard sedimentological core description. Revisions in response to this panel were reviewed for a final time by another panel of sedimentologists before going to technical editing under the auspices the IODP Publication Services Department. The acknowledgments section lists many of the individuals who have contributed their time and expertise to this document.

During revision of this document, it became apparent that we needed to clarify our perceived future audience. As with our other IODP products (Technical Notes 1, 2, and 3) we realized that we were writing not only for IODP’s *JOIDES Resolution*–centric legacy, but also for any shipboard, shore-based, or classroom study of marine sedimentary core. This is reflected in our title: *Practical Guide for Description and Analysis of Sedimentary Cores: Practices Developed aboard the JOIDES Resolution during ODP and IODP*. We hope these tools will be used by sedimentology educators to create stimulating core-based laboratory exercises to help fill the pipeline with budding marine sedimentologists wanting to probe the secrets of the deep; graduate students as they visit core repositories or peruse online core images during their thesis/dissertation research; shipboard scientists at sea and in the laboratory, describing cores of any kind: box, Kasten, piston, or rotary drilled; and any scientist working on core samples and wanting to understand more about the description process and report content from ODP and IODP.

Thus, this Guide presents recommended best practices designed to make sedimentology data for ocean-drilling cores accessible and useful to the widest possible community, now and in the future, whether the core description takes place at sea or on shore. As this Guide is being written, scientific ocean drilling is looking ahead to a major period of transition. Through 2024 the *JOIDES Resolution* remains the primary drillship used by the program (>75% total IODP expeditions) and the methods described here were developed in large part in the laboratories of the *JOIDES Resolution*. It is likely that future programs will use a different mix of well-established, newly developed, and as-yet-to-be devised methods. With the growing use of mission-specific platforms (MSPs) and because of the occasional need to reduce the size of shipboard parties, core description is carried out increasingly in onshore settings, such as core repositories, using analytical techniques that may have both similarities and differences to ones that are available shipboard. Keeping this in mind, this manual provides a framework for sedimentologists to follow in any setting. While details of core description practice may change and evolve, our hope is that the broad principles and goals that are served by core description practices as outlined in this handbook will remain well-served in the future.

Acknowledgments

We acknowledge with gratitude Jim Mazzullo and Anne Gilbert Graham, authors of the original Handbook, as well as classification scheme contributors Audrey Meyer and Robert Kidd, who created a document that has been used by generations of shipboard science parties. Their system of descriptive practice underlies our current understanding of sediments in the world ocean. This revised Handbook incorporates modern digital methods of data acquisition, while retaining a focus on the fundamental and inescapable value of direct visual observation. This revised document benefited tremendously from review by shipboard colleagues who, collectively, have centuries of experience with description of marine sediments: Ivano Aiello, Peter Blum, Laurel Childress, Peter Clift, Kirsty Edgar, Larry Krissek, Steffen Kutterolf, Cecilia McHugh, David Mallinson, Suzanne O'Connell, Donald Penman, Rebecca Robinson, Brian Romans, and Michael Whalen. Additional input from other core describers, Leah Levay and R. Mark Leckie (paleontology), Tobias Hoefig (igneous petrology), was critical to making this document accessible to core describers with diverse experience. Angela Slagle and Carl Brenner (USSSP, Columbia University) were particularly helpful in the realization of this document. Liselle Persad assisted with drafting of figures and text organization. We are very grateful to IODP Publication Services, for final editing and production of this Guide.

Funding for development of this interactive digital guide was provided by the US Science Support Program for the International Ocean Discovery Program (USSSP-IODP) through Columbia University. USSSP-IODP is sponsored by the National Science Foundation. Thanks to the hundreds of shipboard sedimentologists whose work on Ocean Drilling Program Legs and IODP (Integrated Ocean Drilling and International Ocean Discovery) Expeditions was used in the design and content of this document, as well as the hundreds of shipboard drillers and technicians (notably Gus Gustafsen) who did their best to supply quality core to the core table for sedimentologists to enjoy.

Our approach to sedimentary core description reflects the excellence of our mentors, those who took the time to teach us both in the lab and at sea. For example, Kathie learned to describe core on the JR during ODP Leg 126, under the excellent tutelage of sedimentologist Rick Hiscott (Professor Emeritus, Memorial University) and volcanologist Kelvin Rodolfo (Professor Emeritus, University of Chicago), then sailing with Rick again on Leg 210 at the very end of ODP in 2002. In 1989, Rick had just co-authored *Deep Marine Environments: Clastic Sedimentation and Tectonics* (Pickering, Hiscott and Hein, 1989) and then went on to update and write another book some 25 years later with Kevin Pickering in 2015 entitled *Deep Marine Systems: Processes, Deposits, Envi-*

ronments, Tectonics and Sedimentation, arguably the best current textbook on the subject. On Kitty's first ODP Leg (149) she sailed with Kathie and both were educated by Dr. Chris Wilson (Open University, Emeritus deceased). Kathie later sailed with both of her main mentors (Hiscott and Wilson), in 2003 on ODP Leg 210 off Newfoundland, her sixth ODP cruise and the last before IODP. Kathie and Kitty continued to learn from fellow shipboard sedimentologists as they participated in Integrated Ocean Drilling Program Expeditions on the *JOIDES Resolution* and *Chikyu*, and served on the readiness assessment team for the refurbished *JOIDES Resolution* on the shakedown cruise (320T) starting the second phase of IODP in 2009. During the International Ocean Discovery Program, they have continued to participate, Kitty on Expeditions 316, 338, and 362 and Kathie on 351 and 385.

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Introduction

The exciting announcement "Core on Deck!" sets in motion a myriad of shipboard measurements and activity. Foremost is describing the lithology and defining the lithostratigraphy of the recovered sediments and sedimentary rocks as first laid out by Mazzullo and Graham (1988) in the inaugural *Handbook for Shipboard Sedimentologists* (MG Handbook) (**Appendix A**). This is the major responsibility of the shipboard sedimentologists, their focus, and legacy, because core descriptions provide shipboard and shore-based scientists a framework for reporting data and a guide for further sampling and study. As emphasized in the MG Handbook, "Shipboard sedimentologists have a tremendous responsibility to the greater scientific community, for they are commonly the only lab team who have the opportunity to see and thoroughly examine all cores from each drilling site and provide vital first-order observations that guide other scientists in sampling those cores. Thus, it is extremely important that the sedimentologists describe the lithology and stratigraphy of sediments and sedimentary rocks in a manner that is both complete and consistent across expeditions."

Through the years, routine core description procedures, methodology, and data collection have evolved from the Deep Sea Drilling Project (DSDP) to Ocean Drilling Program (ODP) and into the subsequent phases of the IODP (Integrated Ocean Drilling and International Ocean Discovery Programs), with certain standards expected for shipboard description on every expedition, as summarized in this Guide. These procedures are based on a review of methods from legs and expeditions from 1988 to 2018, the period during which the original MG Handbook was the guiding document for core description. Many long-standing procedures are retained and new ones are added to better align this Guide with current practices. The advent of modern petrophysical tracks and other methods of digital data acquisition and management have transformed sedimentologic analysis, making this major revision necessary.

The target audience for this Guide is not only trained sedimentologists. The makeup and responsibilities of the shipboard scientific party are determined by the Co-Chief Scientists and Expedition Project Manager (EPM, formerly Staff Scientist). Depending on the cruise objectives and expected lithologies and their degree of deformation, the "Core Description team" can be general or specialized including a mix of sedimentologists, igneous petrologists, geochemists, paleontologists, and structural geologists. In some cases, igneous petrologists or hard-rock structural geologists may describe sedimentary units, including deformation, that are immediately above or within the acoustic basement. Sedimentologists may need to describe an unexpected (sill) or expected (top of oceanic basement) igneous interval and/or include tectonic structures (bedding attitudes, faults, folds) within their general core description, especially if there are no igneous or structural petrologists on board. Those sailing as sedimentologists with expertise in geochemistry, paleontology, physical properties, seismic processing, petrology, structural geology, or microbiology may have little to no prior sedimentary core description experience. This Guide is written to cover all these possibilities: sedimentologists, both trained and untrained in core description, as well as nonsedimentologists. It is meant to be used shipboard (e.g., IODP, other coring vessels), at the well site (e.g., International Continental Scientific Drilling Program [ICDP] expeditions), in core repositories (e.g., mission-specific platform (MSP) expeditions), and in the classroom.

As there are no formally published manuals for marine core description, this document fills a void in the literature. For example, Kennett (1982) only addresses coring methodology. Most workers rely on the description of sediment and sedimentary rocks as laid out in sedimentary geology textbooks like Boggs (2011) or specialty reference books (e.g., Pickering and Hiscott, 2015). Many undergraduate geoscience students never have the opportunity to describe a core, and even fewer go on to describe core in their graduate research or in professional settings. Much core description is done in laboratories using internal protocols and techniques (e.g., Mazzullo and Graham, 1988), including government and energy research laboratories and core service companies where core description protocols may be proprietary. We hope that this document in conjunction with Marsaglia et al. (2013, 2015a, 2015b) can be applied to description of marine sediments and rocks in any context by both students and professionals. It is also meant to summarize and document well-honed techniques developed by shipboard sedimentologists over 50 years of scientific ocean drilling and description of hundreds of kilometers of recovered core: a monumental collective accomplishment documenting the history of the world's ocean basins.

In a practical sense, the creation of a searchable and manipulatable database of core description information (currently IODP's GEODESC [formerly DESClogik]) has been a major accomplishment of the most recent phase of IODP's *JOIDES Resolution* Science Operator (JRSO). It is important that the quality of these first-hand macroscopic and microscopic observations be of the highest caliber, as they are critical to interpretations that have global implications. To this effect, this Guide is the culmination of several previous efforts to support consistent core description, preceded by educational publications on microscopic component identification (Marsaglia et al., 2013, 2015a; **Appendix B**, **Appendix C**) and macroscopic structures and lithology definitions (Marsaglia et al., 2015b; **Appendix D**).

In this document we emphasize the process of sedimentological core description as traditionally practiced on core description sheets. The ability to recast key elements of this description into a searchable database format, of course, is a tremendous advance for integrating core description with modern petrophysical tracks and a wide array of other digital data that are commonly collected shipboard. Today, where such a process serves the needs of a given expedition, shipboard core describers may choose to insert core description information directly into the database, entirely forgoing the use of descriptions sheets. In the broader world of sedimentologic core description, no particular digital product has come to dominate the practice of sedimentologists, and paper-based descriptions are still the main approach. We hope our coverage of traditional core description methods will assist in training and collection of high-quality sedimentological description, to the benefit both those who choose to work solely with digital data as well as those who continue to rely upon description sheets.

A note on naming of roles and program areas

As mentioned above, the procedures described in this Guide were developed during three previous phases of scientific ocean drilling. The naming of roles, for example, "Staff Scientist," "Expedition Project Manager," "Curatorial Specialist," etc., have changed over time and are expected to do so in the future. Similarly, there are specialty groups that have formal designations (e.g., "sedimentologist," "paleomagnetist") that sometimes do not actually match the trained specialty of the scientists carrying out a given activity. For these reasons, we do not emphasize naming usage when referring to these roles, but rather we have endeavored to use more generic descriptions that we hope will have some longevity and also some specificity to the function being described.

1. Overview of shipboard sedimentology activities

1.1. Sedimentologist duties and goals of shipboard core description

As summarized by Mazzullo and Graham (1988), "the primary responsibility of shipboard sedimentologists is to describe the lithology and stratigraphy of sediments and sedimentary rocks in cores" as well as to provide a preliminary written interpretation about the geologic history of the drilling site. It is important to remember that "The shipboard sedimentologists also pursue their own scientific interests but their first obligation is to describe the cores and provide some preliminary interpretation."

1.1.1. Sedimentology team tasks: overview and checklist

The specific duties of the sedimentology team, depending on the platform and/or onshore vs. offshore status of the expedition, are the following:

1. Establish a sedimentology methods description for the expedition (**Chapter 2**, **Chapter 3**).
2. Provide general visual descriptions of sedimentologic and other core features (**Chapter 4**).
3. Petrologically describe sedimentary materials (**Chapter 5**).
4. Enter data from visual and petrologic core descriptions into the core description database (currently GEODESC [formerly DESClogik], DIS, or other similar), which will be used to generate the Visual Core Description (VCD) form (**Chapter 4**).
5. Acquire digital data from the archive half of the core on appropriate core logging tracks. At the time of this writing, on the *JOIDES Resolution* (JR) these are the high-resolution image track (linescans) and point-source magnetic susceptibility (MS) and color reflectance tracks (**Chapter 6**).
6. Integrate data to establish a draft lithostratigraphic framework based on the core descriptions.
7. Collaborate with other laboratory groups to verify lithostratigraphic units (**Chapter 7**).
8. Write the lithostratigraphy section for each of the site reports (**Chapter 7**).

1.2. General core laboratory procedures (outside of sedimentology team)

Sedimentologists must be aware of the broader aspects of the core and sampling processes, as they must be prepared to share observations with other teams, integrate data from other working groups, provide a sedimentologist's perspective, and assist with other scientific and curatorial duties. Sedimentologists may be called upon to describe nonsedimentary materials and structural features that occur within sedimentary sections (e.g., sills, small faults). The EPM, Lab Officer (LO), and onboard Curator are points of contact for information about procedures and workflows that are outside the direct scope of core description team activities (e.g., general core handling, sampling, computer use, etc.).

The flow of core from the drill floor, through the laboratories, and ultimately into cold storage is a complex and carefully choreographed process. The JR core flow diagram is shown Figure **F1.1**. Core flow for MSP onshore science parties is shown in Figure **F1.2**.

Processing and sampling of core on the JR proceeds generally as follows:

1. A 9.5 m liner with retrieved core is taken from the drilling rig floor to the core receiving platform (catwalk) outside the laboratory. Within the plastic core liner, recovered core materials may be condensed, and less than (or sometimes more than) 9.5 m of core may be present. On the catwalk, whole-round subsamples are taken from the core for a variety of purposes. Sedimentologists may be involved in activities on the core receiving platform, for example, choosing whole-round intervals and placing section breaks to target or avoid certain lithologies or key contacts. Once whole-round samples are taken, if at all, the 9.5 m core is cut into sections of 1.5 m or less and laser-scribed with identifiers, and the ends are capped by the Curator and core technicians.

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2. Whole-round core sections (~1.5 m) are thermally equilibrated in a rack by the entrance to the catwalk inside the laboratory.
3. Once equilibrated, the whole-round core sections are run through a series of petrophysical core logging tracks to measure whole-round natural gamma radiation (NGR), gamma ray attenuation (GRA) bulk density, magnetic susceptibility (MS), and *P*-wave velocity.
4. The whole-round core sections are then sliced lengthwise into archive and working halves using a wire or a saw, depending on the lithification state of the core.
5. The archive half of the core is delivered to the core description table for sedimentologic description. Specific sedimentologic core analyses are described in **Chapter 4**, **Chapter 5**, and **Chapter 6**. Smear slide samples are taken from the archive half (**Appendix B**, **Appendix C**).
6. The working half of the core is made available for limited shipboard sampling, principally by the scientific teams for physical properties (moisture and density [MAD] and geotechnical properties), paleomagnetism (discrete samples for natural remanent magnetization [NRM] and Kappa Bridge MS), and geochemistry (bulk carbonate and organic matter), but also by the sedimentologists (X-ray diffraction [XRD] bulk carbonate). Sedimentologists should provide input on the locations of these samples in the cores in consultation with the physical properties, geochemistry, and micropaleontology teams. Sampling for postcruise studies may also occur.
7. Once description and shipboard sampling are complete and paleomagnetic analyses on the archive halves have been conducted, core halves are wrapped, placed in plastic "D-tubes," and transferred to refrigerated storage on the ship. After the expedition, the cores are shipped to

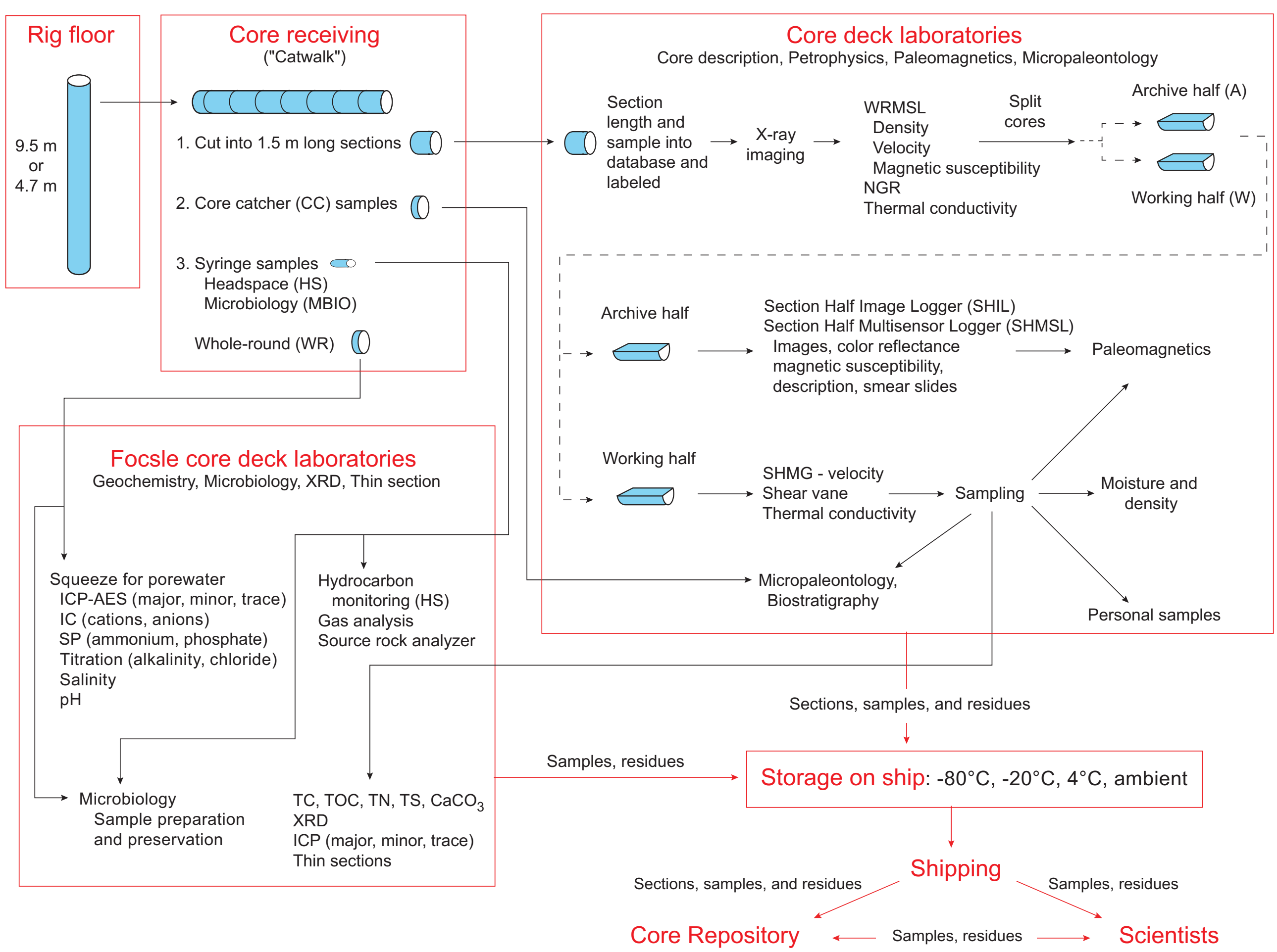

Figure F1.1. Example of core flow aboard the *JOIDES Resolution* (from Expedition 396: Planke, Berndt, Alvarez Zarikian, et al., 2023).

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one of the IODP core repositories according to established regional conventions, where they are made available for study.

8. Nondestructive X-ray fluorescence (XRF) core scanning has been added as a shipboard measurement undertaken postcruise at the IODP Gulf Coast Repository.

1.3. Team and workflow organization on the *JOIDES Resolution*

Shipboard sedimentologists are usually divided into two teams working on opposite 12-hour shifts (noon–midnight; midnight–noon). In rare cases, a scientist may straddle shifts, working 6–6, for example, if only one sedimentologist is familiar with smear slide characterization. There may be one or two (one per shift) designated lead sedimentologists who also serve as liaisons with the Co-Chief Scientists because of their experience or familiarity with the drilling proposal.

Sedimentologists (core describers) are most productive if provided with tasks that utilize or build on their expertise. The lead sedimentologist(s) should survey the group to evaluate the experience or special interests of each person and then assign the various core description tasks accordingly. It is important that each team member has the opportunity to assist with site chapter preparation and presentation at science meetings at some point during the cruise.

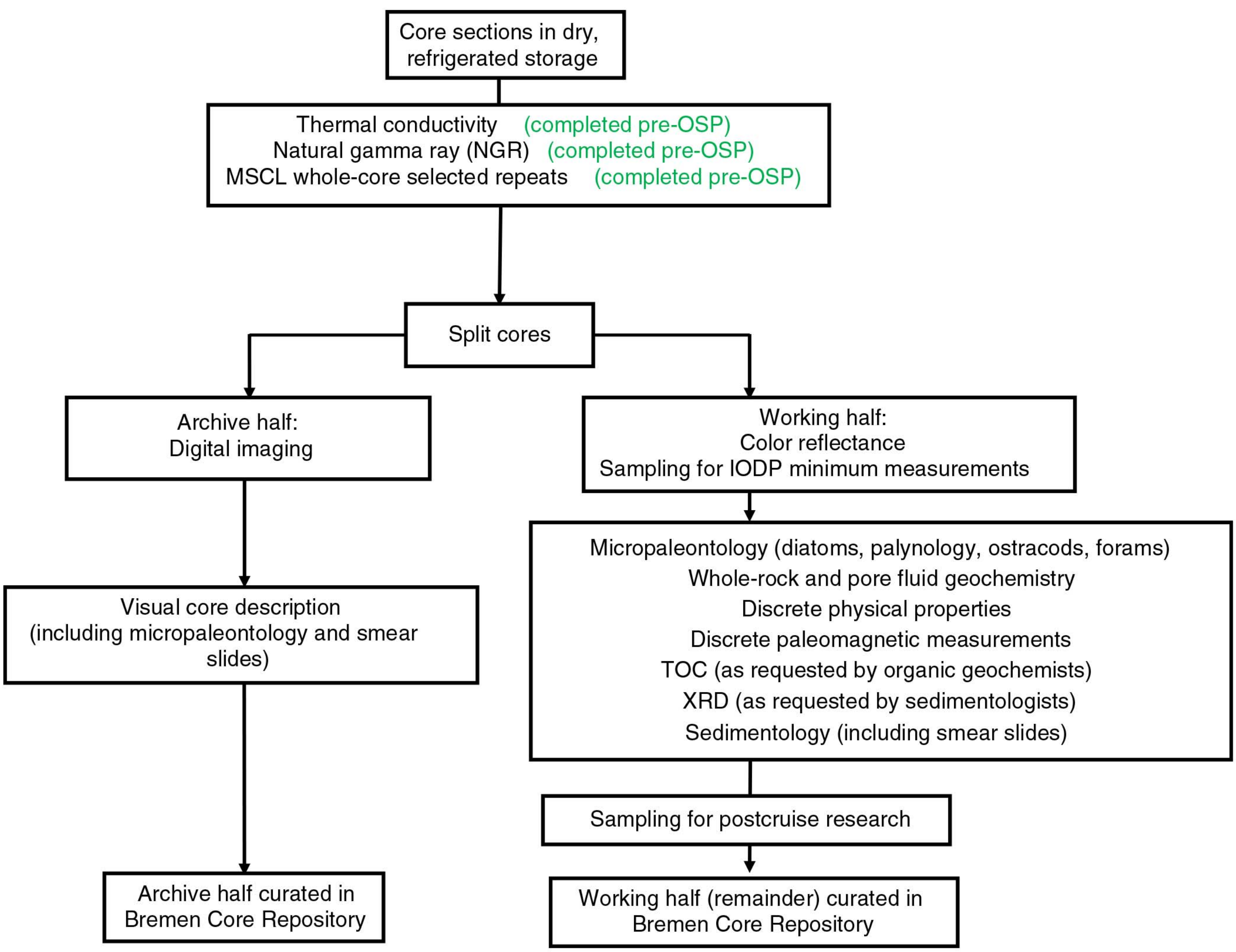

Figure F1.2. MSP onshore science party core flow (**https://www.marum.de/en/Research/Core-flow-and-procedures.html**)

Prime areas that need attention in terms of team assignments leading up the writing of the methods section include the following:

- **Macroscopic core description** (**Chapter 4**) includes aspects that vary in terms of the sedimentological expertise required. Determination of Munsell color, grain size, and drilling disturbance are simple and more quickly learned tasks. Determination of bedding and recognition of sedimentary structures and depositional units (e.g., Bouma sequences) requires varying degrees of experience (e.g., comparison to images in Technical Note 3 [Marsaglia et al. 2015b; **Appendix D**] and other references).
- **Petrographic data** (**Chapter 5**). Microscope skills are necessary for petrographic work. Fine-grained lithologies are defined using smear slide techniques. Uniformity of technique is necessary to ensure consistency and quality. Usually, one person is designated as the smear slide petrographer for each shift. This person needs to be familiar with IODP Technical Notes 1 and 2 (Marsaglia et al., 2013, 2015a; **Appendix B**, **Appendix C**). Experience shows that assigning 1–2 tasks per sedimentologist is the most efficient and consistent way to optimize core flow. Although teams often discuss alternating between macroscopic and microscopic tasks, this rarely happens (and is rarely successful).
- **Track core logging** (**Chapter 6**). IODP technicians can quickly train scientists to acquire track data, and track operation may become the purview of other core describers (e.g., igneous petrologists or structural geologists prior to retrieval of hard rocks or if structures are not encountered) or other available staff.
- **Data entry** into the core description software is an essential task and may be shared by the whole or a part of the sedimentology team. Data entry by only one person per shift or a few people in general may benefit consistency. Note that data may also be directly entered as acquired, individually or in description teams, without the use of paper description sheets.
- **Construction of figures** for the methods and site chapters using provided applications (e.g., stratigraphic columns with core recovery, age, lithology, etc., XRD data summaries, and correlation figures with simplified columns to show relationships among holes at a given site).
- **Presentations for shipboard science meetings** during the course of the expedition.
- **Writing site reports** (**Chapter 7**). Sedimentologists often take turns being the lead author on site lithostratigraphy chapters.

Once the tentative order in which the proposed sites will be drilled is established at the start of the cruise, the sedimentologists may wish to organize and initiate a system of designating one lead sedimentologist per shift and alternating responsibility for each site report among rotating team members. Responsibilities may also be divided by hole or unit or age in the case of single-site expeditions. This format can be modified depending on the number of sedimentologists, their expertise and interests, and the needs of the expedition. The lead organizes and writes the first draft of the site report with support from their shift (may include paragraphs of text) and continues to revise the draft as it is reviewed first by the sedimentologists individually, then by the EPM and Co-Chiefs. Figures and tables for the site are discussed and designed within the entire group of sedimentologists. Commonly, individuals take on responsibilities for creating drafts of certain figures for each hole, replicating a design set up for the first hole into the second: stratigraphic columns, smear-slide or thin section imagery (petrography), XRD analyses, scanning electron microscopy (SEM) images, and/or core images illustrating inferred depositional processes. Assignment of these tasks depends on the expertise and/or willingness of the sedimentologists to learn new things. The lead sedimentologist for a given site may also be designated to give update presentations (or verbal summaries) at crossover meetings of the full contingent of shipboard scientists and at the final site summary meeting.

The order of leads is best switched between shifts, with a day shift sedimentologist taking the first site lead and the night shift a second site lead, and then back to the day shift, and so on. Depending on the number of sites, it is customary to ask every sedimentologist to take responsibility for a site, with the more experienced often taking on the first sites. The site lead distribution should be discussed with and condoned by the Co-Chiefs. The site chapters are under continuous production, review, and revision as new sites are drilled, so having different lead contacts for the sites facili-

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tates organization and spreads the responsibility and effort among the sedimentology group and the shifts. Again, the lead is to be supported by their shift team, another reason for alternating responsibilities between shifts. Organization and communication are the keys to success.

1.4. Team strategies for core description

High core recovery strategies (also if there are too few core describers per shift or time constraints for shore-based description) should be defined according to the objectives of each expedition:

1. Minimize and simplify description as needed (e.g., simplify to sand vs. very fine to coarse sand; note as interbedded *x* and *y* lithologies with relative proportions and average/max/min stratification thicknesses for each lithology instead of individual beds or laminae).
2. Conscript other personnel to help with core scanning and data entry.
3. Use a longer, full-core description sheet (see **Chapter 4**) instead of individual section sheets.
4. Use first hole descriptions (Hole A) as a guide for color and lithology on overlapping multihole sites with simple lithologies; refer to specific core/section descriptions if correlations can be made; direct input of data without paper copies may be warranted for the third or fourth holes if there is little lateral variability in the section.
5. Decrease smear slide frequency to key intervals marking unit/subunit boundaries or tests for mineralogy/chemistry (XRD and CARB samples).
6. Bypass sedimentary core description forms (CDFs) entirely and enter data directly into the core description software.

1.4.1. Meeting strategies

It is important that scientists hold routine crossover meetings 15–20 min prior to or after shift changes to minimize errors, communicate core description or core-flow issues and, most importantly, exchange scientific findings and exciting discoveries. These meetings effectively increase shift length, and when combined with science party meetings (varies from cruise to cruise; can be daily), can lead to 13+ hour shifts. It is helpful if one scientist per shift, perhaps the group leader, is tasked with preparing information for crossover to make the process as efficient as possible.

1.4.2. VCD strategy recommendations

Keep a uniform text format and style for VCDs. Formulaic style is good. Refer to the *IODP Shipboard Writing Guide* (**http://iodp.tamu.edu/publications/resources/IODP_shipboard_writing_guide.pdf**) and consult with the Publications Specialist early in the expedition to make sure there are no issues.

- Assign one (or two) people to proof VCDs. Ideally, it should seem like one person wrote them.
- Keep a list of day shift and night shift core description responsibilities, preferably listing who wrote and entered text into the database.
- Highlight intervals that have extensive drilling disturbance—essential information for those requesting samples later. Identify major and minor lithologies.
- Do not include interpretation or use interpretive terms in the text (e.g., turbidite, contourite). However, apparent depositional units or bedsets can be described; these may not be readily apparent in the column.
- Add intervals for minor critical/unique lithologies (e.g., volcanic ash layers, sand beds, macrofossils, wood fragments) in text to make sampling easier for (visually oriented) future scientists. Sample lists can be made of trace lithologies from old Ocean Drilling Program (ODP) and Deep Sea Drilling Project (DSDP) VCDs, whereas newer IODP VCDs may require viewing images in the IODP Laboratory Information Management System (LIMS) database. It is best to have a user-friendly format for future samplers.
- Ensure that the differences between units and subunits are adequately characterized in the series of VCDs: demonstrate lithologic breaks in the lithology symbols in the columns and in the lithology names and descriptions.

2. Writing lithostratigraphic methods

Prior to describing core, shipboard sedimentologists (and the Co-Chief Scientists and EPM) must agree on description methodology. Writing the lithostratigraphic methods draft can occur via email prior to the cruise, during the port call, or during the transit, if time allows. The *IODP Shipboard Writing Guide* is an important resource for preparing all types of expedition documents (**http://iodp.tamu.edu/publications/resources/IODP_shipboard_writing_guide.pdf**).

The MG Handbook (**Appendix A**) makes no specific mention of methods section development, as it was assumed that the Handbook itself would serve such a purpose. Many expeditions did utilize the MG Handbook in this manner and presented details of methods taken directly from that document. Deviations from the methods presented in the MG Handbook have also occurred over the years, in some cases meticulously documented in the Methods chapter of a given leg/expedition and in other cases not. This Guide assumes expedition-specific methods customizations, and many options for this are presented here. Sedimentology teams that go beyond the methods given in this new Guide are cautioned that careful documentation, citation, and justification of any new methods need to be included in the expedition Methods chapter. Wholesale use of previous methods sections is discouraged, as it favors propagation of errors. Again, if nonstandard methods are taken from a previous expedition the *primary* origins must be cited.

Selection of a sediment classification scheme is one of the major decisions made by the shipboard sedimentologists as a prelude to core description. This scheme is often chosen based on the expected main lithologies (e.g., siliciclastic, volcaniclastic, calcareous) as prognosticated by seismic-reflection data interpretation in the expedition *Scientific Prospectus* (e.g., sediment drift deposits, submarine fan, carbonate reef). Any previous drilling in the region can be used as a guide. Though it is not required, there could be substantial value in using the same classification scheme as previous legs/expeditions in the area to make synthesis more straightforward. A different classification scheme can be used if there are reasons to do so, but this decision should be made carefully (see further discussion in **Chapter 3**).

In other cases, paleoceanographic or tectonic setting can be used to infer likely sediment types. There are often surprise components and/or lithologies that require modification of the scheme during an expedition. Final usage and application should be verified prior to publication of the expedition *Preliminary Report*.

The important components of a lithostratigraphic Methods chapter are listed here and in Table **T7.1**. Figures for possible use in a methods section can also be selected from materials presented in **Chapter 3**, **Chapter 4**, and **Chapter 5**. The Methods chapter is likely to be used by other scientists in addition to sedimentologists (e.g., geochemists, geophysicists, geomicrobiologists, igneous petrologists), both shipboard and postcruise, so these methods must be explained in a manner that is accessible to a broad audience. We emphasize that modifications to any of the description schemes in this Guide should be explicitly explained in the methods section. For example, changes in percentage boundaries, grouping of components, addition of components, or definitions of components must be clearly explained with graphics. The methods section must address each of the attributes listed in the visual core description within **Chapter 4**, as well as each of the track systems utilized (**Chapter 6**).

2.1. Key points with respect to methods

- Methods should align with the goal of the particular expedition (e.g., refer to *JOIDES Resolution* Standard Measurements Policy: **https://www.iodp.org/jr-facility-policies-procedures-guidelines/117-jr-measurements-final/file**).
- Specify sources for methods (including the use of this Guide). If methods outside of this Guide are employed, detailed justification should be given and documented with appropriate references and figures.
- For sedimentary deposits, use descriptive characterization (e.g., graded to laminated bed with abrupt base and bioturbated top) rather than genetic characterization (e.g., “turbidite,” or “ice-

rafted debris"), as established in the MG Handbook with the understanding that definitions of "interpretation" vs. "description" are subject to some degree of debate and depend somewhat on the experience of the practitioner. Careful oversight by the EPM is critical to maintaining this important principle in preparing VCDs. We support inclusion of preliminary interpretation of the recovered sequences at the end of the lithostratigraphy sections of site reports; well-documented, nongenetic descriptions leave the door open to future workers to make alternative interpretations from the basic data and observations gathered by shipboard scientists.
- Description of texture (grain size and grain sorting) should be included for all granular sediments regardless of composition (terrigenous, biogenic, volcaniclastic). A figure outlining the Udden-Wentworth (Udden, 1898; Wentworth, 1922) numerical grain size scale and its verbal transformations (e.g., gravel, sand, silt, clay, and further subdivisions) should be included in every Methods chapter.
- Compositional classification should be separate from textural description.
- The MG Handbook was a good effort, but there is no universal compositional classification that can be applied to all marine sediments, especially given their diverse components and common mixtures. Compositional classifications should be customized for broadly different sediment types. We present in this Guide selected good examples of these from previous cruises that should cover the range of world sediments.
- Compositional classifications should focus on the grain assemblage, to the degree that it can be observed shipboard. Diagenetic overprints should be ignored to the extent possible in classification, with the exception of a few lithologies for which the diagenetic overprint is profound (e.g., chert, dolomite). In general, diagenetic features should be described as modifiers of the main sediment class.
- Clear criteria must be set for assignment of names as sediments vs. rocks (e.g., sand vs. sandstone; gravel vs. conglomerate; ooze vs. chalk or chert, etc.). Mechanical rock properties are of particular interest to the physical properties and structural geology teams, so consultation with these groups on this point is advised. The science goals of the expedition may enter into the choice of lithification criteria, depending on the reasons that lithification to some particular level may be of interest.
- Careful and repeated oversight during the cruise and immediate postcruise period will ensure that the lithostratigraphy methods section is uniformly followed and is ultimately a good representation of the rock description performed on board the ship.

2.2. Lithostratigraphy methods: essential elements

Table **T7.1** outlines the essential elements to be included in the methods section for every expedition. Additional items may be included, customized for the goals and needs specific to a given expedition's objectives.

3. Sediment classification schemes

"In no other science does the problem of terminology present so many difficulties as in geology."
C.K. Wentworth 1922

Prior to publication of his seminal 1954 classification paper, Shepard surveyed a number of sedimentologists who indicated they approved of and would use his sediment scheme so that "in the future it will become possible to describe sediments by these names and have the names denote the same meaning to all readers." This Guide contains summaries of previous lithostratigraphic methods sections (ODP Leg 119 through IODP Expedition 370) (Appendix **A3.1**) and the results of a general survey of experienced shipboard sedimentologists about their preferences for sediment classification schemes (Appendix **A3.2**). We report the group recommendations below and suggest that one of these consensus-based schemes be considered for future expeditions.

If a different scheme is chosen, provide detailed justification along with the published source and details about any modifications made to the original as published in the methods section. This ensures that the applied methods build both on past experience and use practices that are fine-tuned to the expedition. For example, it is important to consider methods used during previous DSDP, ODP, and IODP legs/expeditions in the area of the current expedition to preserve uniformity of methods for later regional comparisons of drilling results. Even minor modifications such as changing the use of a single term (e.g., mudstone) or adding a term to the description options (e.g., diamicton) should be specified in the methods to build on past experience and fine tune best practices.

The first scheme considered here is that first published as an appendix in the *1988 Handbook for Shipboard Sedimentologists* (Mazzullo and Graham, 1988) authored by Jim Mazzullo, Audrey Meyer, and Robert Kidd (abbreviated throughout this document as the MGK Appendix). The MG Handbook is presented in its entirety in **Appendix A**. The MGK appendix (see page 47 in Appendix A) classification is built on several published schemes for sediment classification including Wentworth (1922), Shepard (1954), Dunham (1962), Fisher and Schmincke (1984), and Dean et al. (1985). Appendix **A3.1** presents our analysis of the usage of this scheme by shipboard sedimentologists who sailed during ODP and IODP cruises starting in 1988.

The MGK Appendix scheme (Figure **F3.1**) was created to encompass a large number of different components found in marine sediment, with a special focus on mixing of sediment types. Initially, the complex scheme (four end-members: pelagic, neritic, siliciclastic, volcaniclastic; and a mixed category) was used with minor modifications during ODP Legs 126 (Taylor, Fujioka, et al., 1990), 127 (Tamaki, Pisciotto, Allan, et al., 1990), and 129 (Lancelot, Larson, et al., 1990), but through the years the scheme has been modified. The main areas of modification are in respect to the classifications of mixed, volcaniclastic, carbonate, biosiliceous, and glacial sediments. Most of the modifications described as moderate/significant applied other published schemes, including many created by shipboard sedimentologists during previous cruises. The geographic regions where schemes were most likely to be modified are in higher latitudes (glacial and biosiliceous sediments), those with volcaniclastic input (magmatic arc basins), and carbonate shelf deposits.

The scheme used by the MGK Appendix for granular sediments was simplified most often by shipboard sedimentologists when one or more of the four components was not present in described lithologies (e.g., volcaniclastic or biosiliceous debris was not expected/encountered). Note that oftentimes, if the lithologies could be simplified to three main components, ternary diagrams were devised to aid in the classification process (these are discussed at the end of this report). The unmodified MGK Appendix scheme was most often used when the sediments cored were largely pelagic in nature. Implementations of much more detailed and complex classification schemes are apparent in recent expeditions, after the introduction of the core description database (GEODESC at the time of this writing).

Our approach includes detailed reviews of the classification methods for specific sediment and sedimentary rock types following the MGK Appendix classification scheme (e.g., terrigenous, vol-

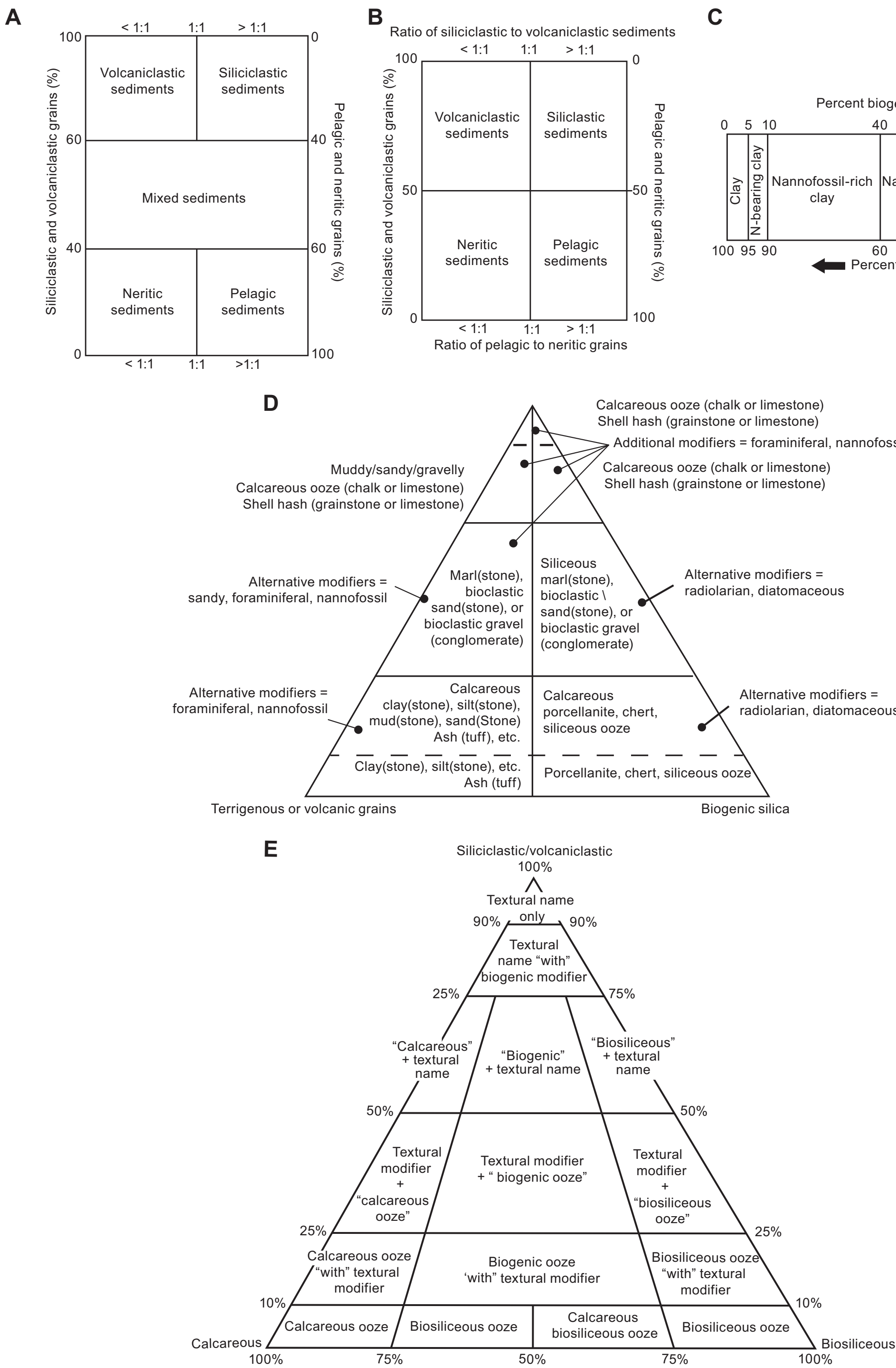

Figure F3.1. Various schemes for sediment classification. A. Mazzullo and Graham (1988; MG Handbook) classification scheme, created to encompass a large number of different components found in marine sediment, including mixtures thereof. B. One simplification is to remove the mixed field (e.g., Leg 136), thereby creating dual ribbon plots between four end-members; top (X, Y); bottom (Z, A). C. Extremely simple (binary) systems can be reduced to a “ribbon plot” with mixtures between two end-members (Leg 201). D. In 3-component systems the ternary plot became the most common form of modification. Some were specific to the main components in the sediment (e.g., Leg 191: radiolarians, diatoms, and clay; Exp. 323: biogenic, siliciclastic, and volcaniclastic debris; Exp. 343: volcaniclastic, siliceous microfossil, and terrigenous debris). Ternary plots have been used for 3- to 4-component systems (e.g., carbonate, biogenic silica, and a combination of terrigenous/volcanic grains); two components represented by one end of the ternary with alternate terms indicated in the fields. The Exp. 317 example is the most complete. E. Another combination of siliciclastic (sometimes with volcaniclastic), biogenic silica, and biogenic carbonate (or calcareous) was used during Exp. 346. References: Leg 119 (Barron, Larsen, et al., 1989); Leg 136 (Dziewonski, Wilkens, Firth, et al., 1992); (Leg 186 (Sacks, Suyehiro, Acton, et al., 2000); Leg 191 (Kanazawa, Sager, Escutia, et al., 2001); Leg 201 (D’Hondt, Jørgensen, Miller, et al., 2003); Exp. 317 (Fulthorpe, Hoyanagi, Blum, et al., 2011); Exp. 323 (Takahashi, Ravelo, Alvarez Zarikian, et al., 2011); Exp. 343 (Chester, Mori, Eguchi, Toczko, et al., 2014); Exp. 346 (Tada, Murray, Alvarez Zarikian, et al., 2015).

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caniclastic, neritic carbonate sediments and rocks, pelagic sediments and rocks, and mixed). We included some new classifications (glacial, serpenticlastic), and we also reconsider certain of the MGK Appendix's chemical sediments and rocks in the above classifications (e.g., for chert, organic-rich sediment, and evaporite) following, in part, from more recent understandings about the nature of diagenesis.

In general, the sedimentology core description must strive to be purely descriptive rather than interpretive. For example, the use of interpretive terms such as turbidite, contourite, and debris flow in barrel sheets and VCDs must be avoided. Mixing description and interpretation in terminology in this way requires combinations of multiple lithologies and associated sedimentary structures and bedding features: for example, interpretation of a "turbidite" relies on identifying sedimentary structures as well as grain size trends over an interval. The practice of mixing description and interpretation in terminology is not accepted in scientific publications and should be avoided in Expedition Reports. The long-lived scientific value of descriptions and data are that they can be interpreted in the future to reflect new knowledge of Earth system processes. Further examples of potential pitfalls are mentioned in the following text.

3.1. Classification of sediment and sedimentary rock types: general

Determination of lithology starts at the core description table with macroscopic observations of grain size and other textural characteristics, followed by smear slide or petrographic techniques, and lastly, SEM observations where appropriate. Examples of core macroscopic and microscopic imagery are shown in **Appendix B**, **Appendix C**, and **Appendix D**. Aspects of diagenesis may play a role in determining lithology names (e.g., sediment vs. -stone, chert, dolomite), though in general, lithology is based solely on the composition of the grain assemblage (see details below). There are some general considerations that variably apply to multiple sediment and sedimentary rock types, such as grain size and degree of lithification.

3.2. Classification based on grain size (texture)

Textural classification mainly concerns the size and size distribution (sorting) of the grain component, though it may also consider grain shape and fabric. "Grain" in this context refers to particulate debris that was mobile in the depositional environment. Textural classification is applied to all sediments independent of the composition of the grain assemblage (e.g., terrigenous vs. marine carbonate) or the grain origin (e.g., pelagic vs. benthic). Diagenetic components (e.g., cements, grain replacements, pores) do not enter into the determination of texture, as they do not reflect conditions of deposition but rather postdepositional modifications. Grain shape, another textural attribute, may also factor in classification (e.g., breccia vs. conglomerate).

Grain size should be determined using the metric scale, specifically the Udden-Wentworth numerical grain-size scale (Wentworth, 1922; Udden, 1898) and its verbal transformations (e.g., gravel, sand, silt, clay, and further subdivisions; Figure **F3.2**). These terms are descriptive only of size class and are not meant to be genetic (e.g., infer terrigenous origin). Blair and Mcpherson (1999) further subdivide the gravel fraction (2 mm–1075 km) into gravel (2 mm–4.1 m; granule, pebble, cobble, and boulder) and megagravel (4.1–1075 km) with perhaps only blocks (4.1–65.5 m) being relevant to core description of mass transport deposits.

Medium to coarse sand and gravel descriptions are best done macroscopically using grain-size comparator cards and metric rulers, commonly with the aid of a hand lens. Very large clasts can exceed the length of a section and even a core, making identification difficult in core section segments. The largest clasts may only be discernible with the aid of seismic reflection data. Other clast measurements can be conducted on gravel, specifically measurement of short, intermediate, and long axes of clasts to better define shape; maximum clast size is often linked to flow competence (Komar and Carling, 1991).

A well-known issue concerns the use of the term "clay" for both an Udden-Wentworth particle size category (<4 µm) that includes particles of any composition but also as a mineralogical class with no specific crystal size implication. Conflating "clay" with "clay mineral" in the context of particle size or with "clay size" in the context of mineralogical composition is a common problem. Particles 4 µm in size are discernible at highest magnifications in smear slides (see IODP Technical Notes 1 and 2; Marsaglia et al., 2013, 2015a; **Appendix B**, **Appendix C**). That 4 µm boundary is used in this Guide for determining clay/silt proportions in fine-grained lithologies. Some workers use a 1 or 2 µm boundary between clay and silt sizes, often in connection with centrifugation for clay mineral analysis, but these boundaries are not used in this Guide. Recent advances in understanding fine-grained sediment include the concepts that sediments dominated by particles of true clay size are rare in the rock record as a consequence of (1) particle clumping (Schieber et al., 2007), (2) the difficulty of sorting the finest silt from clay-size material (McCave et al., 1995), and (3) the

	Millimeters	Phi units	Wentworth size class
	4096	-12	
	1024	-10	Boulder
	256	-8	
			Cobble
GRAVEL	64	-6	
	16	-4	Pebble
	4	-2	
	3.36	-1.75	
	2.83	-1.5	Granule
	2.36	-1.25	
	2.00	-1.0	
	1.68	-0.75	
	1.41	-0.5	Very coarse sand
	1.19	-0.25	
	1.00	0	
	0.84	0.25	
	0.71	0.5	Coarse sand
	0.59	0.75	
	0.50	1.0	
	0.42	1.25	
SAND	0.35	1.5	Medium sand
	0.30	1.75	
	0.25	2.0	
	0.210	2.25	
	0.177	2.5	Fine sand
	0.149	2.75	
	0.125	3.0	
	0.105	3.25	
	0.088	3.5	Very fine sand
	0.074	3.75	
	0.0625	4.0	
MUD: SILT	0.053	4.25	
	0.044	4.5	Coarse silt
	0.037	4.75	
	0.031	5.0	
			Medium silt
	0.0156	6.0	
			Fine silt
	0.0078	7.0	
			Very fine silt
	0.0039	8.0	
MUD: CLAY	0.0020	9.0	
	0.00098	10.0	
	0.00049	11.0	Clay
	0.00024	12.0	
	0.00012	13.0	
	0.00006	14.0	

Figure F3.2. Udden-Wentworth grain size scale and sediment classes (Udden, 1898; Wentworth, 1922).

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potential for generation of substantial amounts of authigenic clay through alteration of unstable grains of silt and sand sizes (Denommee et al., 2020; Rafiei et al., 2020). Sediment rich in detrital clay can also be generated by syndepositional dissolution of carbonate grains below the carbonate compensation depth (CCD), but again, these sediments may not have been dominated by either clay-size particles or clay minerals at the time of deposition.

The MGK Appendix classification scheme uses Shepard's (1954) nomenclature based on sand-silt-clay ratios. The Shepard diagram (Figure **F3.3**) was designed for use with measured grain size data rather than data estimated from a core surface or in smear slides (see DSDP Leg 119; Barron, Larsen, et al., 1989). However, this can be overcome by first estimating sand/mud ratios macroscopically in the core, followed by clay/silt proportions in smear slide using high magnification data (up to 40×) supported by analytical data from bulk chemistry and XRD (e.g., clay-mineral or quartz + feldspar content).

The majority of shipboard sedimentologists have used the Shepard plot or modifications thereof for textural classification (Figure **F3.3**). Some (Figure **F3.4**) kept the end-members and grouped the mixture fields (e.g., silty-clay to clayey-silt as a single field). The mixture fields help simplify core description, as end-member lithologies are easier to identify, but the need to determine the precise proportion of clay to silt, often a matter of discussion by shipboard sedimentologists, is eliminated in naming the sediment (note that this determination is made in smear slide using 40×–60× magnification). The problematic naming of a lithology that represents the central sand-silt-clay regions of the Shepard ternary led others to simply divide this field into sandy mud and muddy sand. These alternatives are presented in Figure **F3.4**.

A more radical change to the Shepard plot was made by some high-latitude workers by combining the ternary side categories with a slice of the sand-silt-clay region to form a radial, spoke-like subdivision of the ternary but retaining the three end-member (sand-silt-clay) lithologies. We are not certain of its origin, but it was first used during Leg 188 (O'Brien, Cooper, Richter, et al., 2001), where new classifications for glacial sediments were proposed. This significant modification is less consistent in terms of terminology with Shepard, and the complexity of the central spoked region makes it less useful in that tiny differences in composition can lead to very different sediment names. For this reason, use of this plot should be avoided. We specifically do not display this diagram to dissuade scientists from using it. The Shepard classification does not include gravel, an important component of glacially and volcano-derived sediments. There are also important size terms applied to pyroclastic deposits such as fine and coarse ash, lapilli, blocks, and bombs as

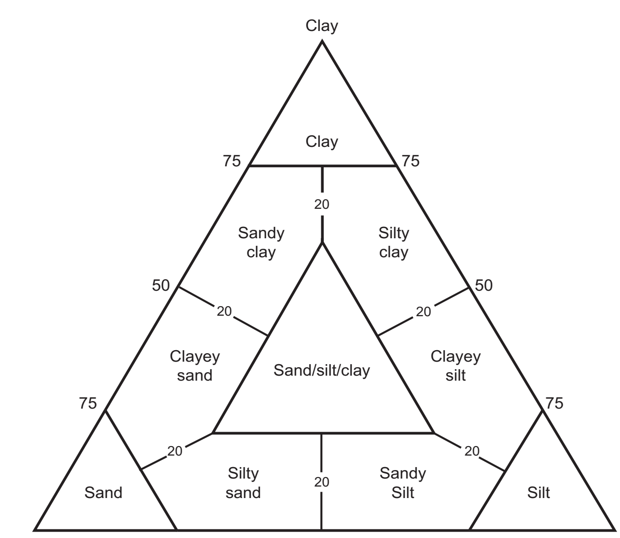

Figure F3.3. Shepard (1954) sediment classification diagram.

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defined by Fischer and Schminke (1984). We address this in separate sections below. There are other important textural and grain properties to be determined.

Visual estimates of sediment sorting can be described during macroscopic and/or microscopic core analysis. Sorting is implicit where percentages of size classes are estimated (e.g., equal percentages of sand/silt/clay is very poorly sorted). A general sorting scale is shown in Figure **F3.5**.

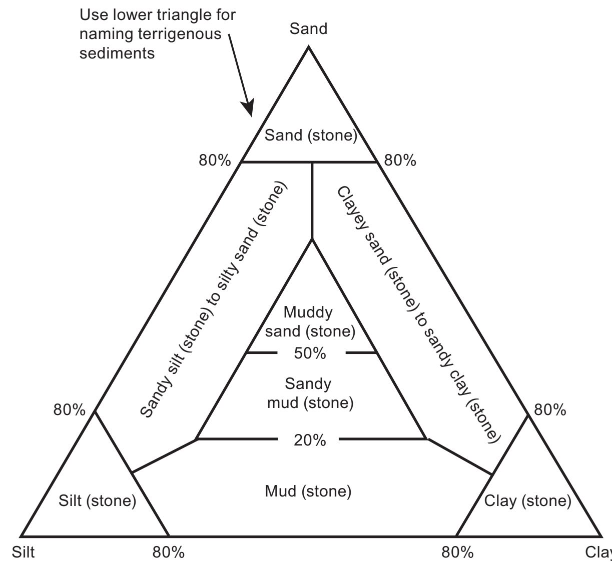

Figure F3.4. Modified Shepard (1954) diagram from Expedition 317 (Fulthorpe, Hoyanagi, Blum et al., 2011).

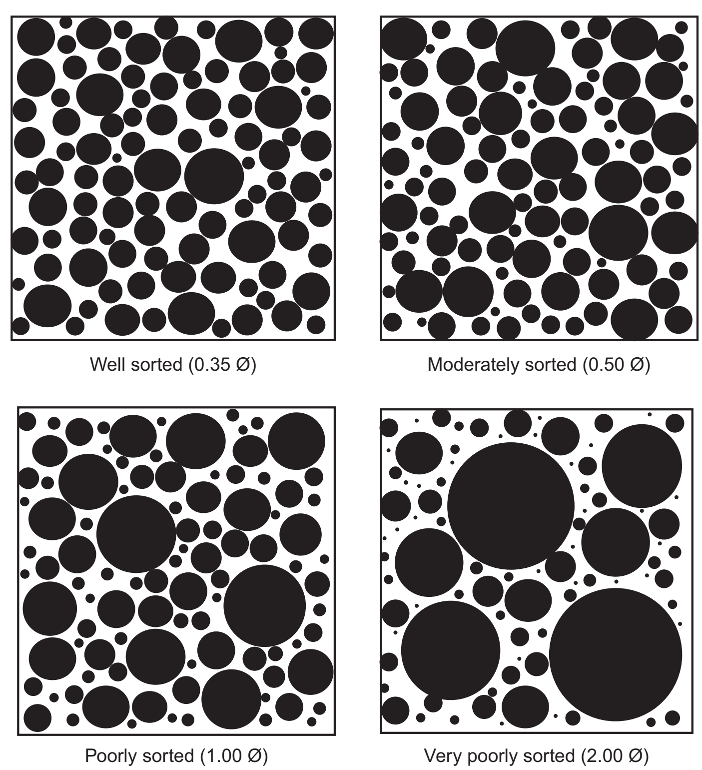

Figure F3.5. Visual images from Harrell (1984) as depicted in Boggs (2011) for estimating grain size and sorting; verbal terms for sorting description (e.g., poorly sorted) are as defined by Folk (for different phi [standard deviation]) values.

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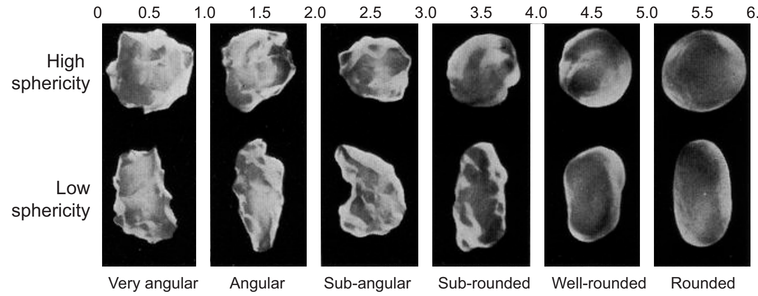


Figure F3.6. Grain rounding scale modified from Powers (1953) with the numerical rounding scale (rho values) of Folk (1955). Grain views provide perspectives on sphericity.

Grain rounding (modes, ranges) also should be included in the description and, in some instances, can be the basis of lithology determination (e.g., breccia [angular] vs. conglomerate [rounded]; Figure **F3.6**).

3.3. Classification based on lithification state

A challenge for assigning names that indicate lithification state is the often gradational and transient nature of this rock property. For example, a sediment that is soft and easily deformed or disaggregated when wet may be very different a few hours later when dry. Muddy sediments and rocks are particularly troublesome in this regard compared to sand-dominated materials.

The transformation of sediments into rocks (lithification or induration) is driven by both mechanical (e.g., compaction) and chemical (e.g., cementation) processes (e.g., Marsaglia et al., 2017). Consolidation is a term that is used in contrasting ways by different communities, synonymous with compaction in some usages and with more general terms such as lithification and induration in others.

The best place to determine lithification state may be at the sampling table as various tools are applied there to extract samples.

Methods for distinguishing the lithification state of mud include the following:

- **Sediment dispersion in smear slide preparation**: does the sediment readily disperse into its natural particles in smear slurry?
- **Smear slide petrography**: does the material contain authigenic crystals that are not detrital grains (e.g., carbonate, zeolite, or clay minerals that take the form of intergranular cement)?
- **Response of core to sampling tools**: for example, whether p-mag cube samplers are inserted by pounding, spatula insertion, or cutting with the rock saw.
- **Indentation test via finger, fingernail, or metal probe**: can the surface of the core be readily deformed by manual compression? Warning: fingerprints are forever—carefully perform this test at the sampling table on the working half of the core under the supervision of the Curator at the edge of the core or even on an already extracted sample, preferably while wearing a nitrile glove.
- **Physical properties**: for example, *P*-wave velocity, density, and shear strength measurements of the working half of the core, usually soon after the core is cut.

Unfortunately, materials considered lithified or indurated by one criterion may not be qualify as such by another. For example, sediments may still disperse readily for smear slide production while having physical properties that indicate a substantial increase in density or velocity in comparison with the soupy sediments at the mudline.

In general, lithification state of sediments encountered in drilling increases with depth. Dramatic local variations in lithification may relate to diagenetic features such as concretions (localized cementation) or deformation structures (shear bands). Despite the impact on sediment/rock naming (e.g., mud vs. mudstone), it is important to remember that lithification state may correlate most strongly to depth or diagenetic processes rather than compositional lithology or lithostratigraphy. A transition in lithification state may be used as a subunit boundary because of its importance as an indicator of mechanical properties of interest to several science groups (e.g., petrophysics).

3.4. Classification based on lithology and relevant background

3.4.1. Siliciclastic sediment/rock

3.4.1.1. Terrigenous sediment/rock

Terrigenous sediments are concentrated along the continental margins of oceans but can be transported via ice, wind (loess), submarine canyons, and various currents into deep ocean basins. The MGK Appendix terrigenous classification (Figures **F3.2**, **F3.3**: Wentworth and Shepard) was designed as a nongenetic descriptive scheme; nonetheless, there are those who have integrated interpretation and depositional processes into core description in past volumes.

3.4.1.1.1. Typical terrigenous sediment types

Common practice since the MG Handbook was published has been to use grain size classification as the sole means of describing terrigenous sediments. In many respects this is a practical and efficient choice given the time constraints that often apply to shipboard description. This focus on grain size for terrigenous sediments appears to have led to an unfortunate deemphasis of grain size for nonterrigenous sediments. As stated above, grain size determination is performed on all sediments regardless of grain composition or origin.

A classification of detrital terrigenous sediments based on grain composition has not been routinely applied on IODP expeditions. The Folk sandstone classification (Folk, 1980) is a well-established option that can be applied based on visual estimates of quartz, feldspar, and rock fragment grain percentages (Figure **F3.7**) during both macroscopic and microscopic description of sandstone. In the case of unconsolidated sand, modifiers based on the major grain type may suffice (e.g., glauconitic sand, bioclast-bearing sand, quartzose sand, felspathic sand, or lithic sand). Other published classification schemes may be used but must be clearly defined in the lithostratigraphic methods.

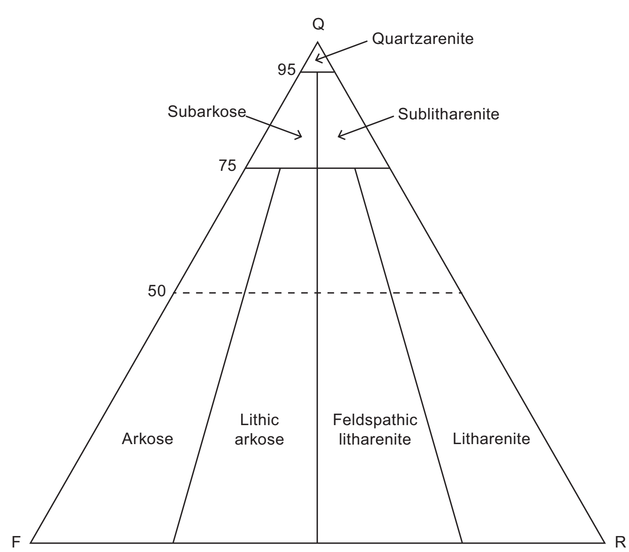


Figure F3.7. Folk (1980) sandstone classification ternary plot.

To our knowledge, an analogous petrography-based compositional classification for terrigenous mudstones has never been developed for use in IODP core description. The mineralogical makeup of silt-size grains can be determined from smear slides, and if abundant, can be used in naming the sediment (e.g., quartzose silt, feldspathic silty clay). Because clay minerals are dominantly of clay size, optical identification of these minerals is of limited use. If XRD data are available, the textural name for terrigenous sands and muds can be modified with the name of the dominant clay mineral (e.g., chloritic silty clay; smectitic clay, etc.). If applied, this should be explained in the methods section.

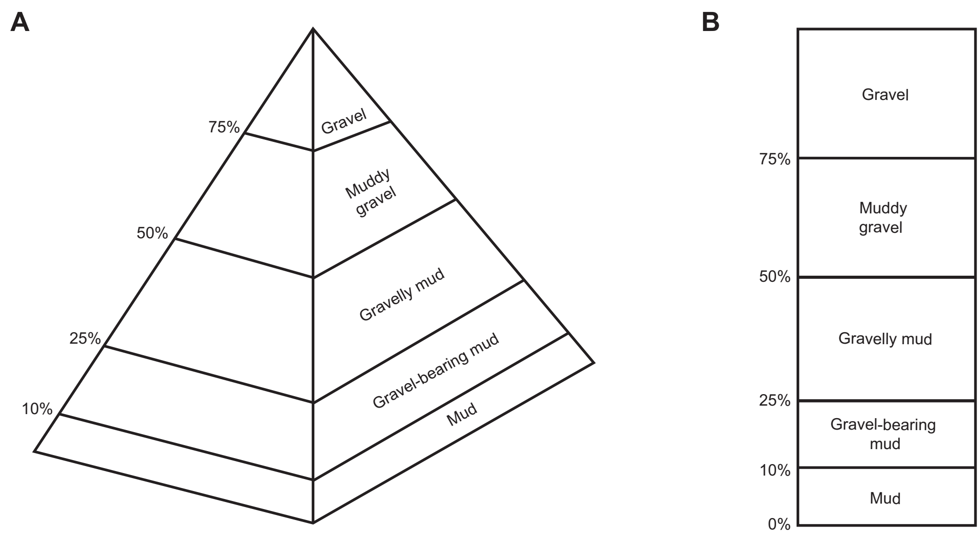
3.4.1.1.2. Glacially influenced terrigenous sediments

Compared to other regions, there have been fewer scientific expeditions to higher latitudes during ODP and early IODP drilling phases. At high latitudes, sediments may be products of direct glacial deposition or affected by glacial-marine processes, and shipboard scientists have often felt a need to modify the MGK Appendix scheme and/or to use other classification schemes specific to glacially influenced sediments during core description. One motivation has been to accommodate the large range of grain sizes and presence of gravel clasts. Note that there are other compositional aspects of glacial sediments that can make them unique such as the potential for high detrital carbonate content and sediment densities (silt-size rock flour vs. clay-size clay mineral content in the mud fraction).

The Leg 119 shipboard scientists (Barron, Larsen, et al., 1989) were the first to use the MGK Appendix classification scheme and the first to point out that this "new" classification scheme did "not adequately address nonsorted or poorly sorted siliciclastic sediments, such as those characterized by tills or debris flows." As noted by the Leg 152 sedimentologists (Larsen, Saunders, Clift, et al., 1994), these sediments had been rarely drilled by DSDP or ODP. Both groups of scientists applied the nongenetic terms diamicton (unlithified) or diamictite (lithified) as defined by Flint et al. (1960). Overall, the use of nongenetic classification for description purposes is preferred with the addition of gravel and the term diamict(on) to the classification scheme.

Descriptions from Leg 151 (Myhre, Thiede, Firth, et al., 1995) and Expedition 302 (Backman, Moran, McInroy, Mayer, et al., 2006) are more nongenetic, based on methods developed for Leg 105 (Srivastava, Arthur, Clement, et al., 1987). Specifically, the scheme is applied to samples containing >10% gravel. Two diagrams summarize these schemes: a classification for siliciclastic sediments (Figure **F3.8A**) and a tetrahedron with increasing gravel (Figure **F3.8B**) where the base of the tetrahedron is the grain-size classification for siliciclastic sediments. Leg 188 scientists (O'Brien, Cooper, Richter, et al., 2001) offer yet another classification scheme for poorly sorted sediments containing gravel (diamict) after Moncrieff (1989) (Figure **F3.8C**). It distinguishes clast-poor and clast-rich facies with different sand contents. The term "clast" can refer to either sand or gravel-sized components. The term "lonestone" is reserved for a gravel-sized (>2 mm) clast floating in fine matrix, where the matrix should be described using schemes depicted in Figure **F3.3** or **F3.4** in lieu of their suggested modified Shepard (1954) plot. A visual percentage estimate of 10% determines the boundary between clast-poor and clast-rich lithologies; the percentage is estimated using a comparator chart in the MG Handbook (their figure 16).

Genetic terminology should be limited to the discussion or interpretation section of the site report and should not appear in the VCDs or descriptions. Leg 177 shipboard sedimentologists (Gersonde, Hodell, Blum, et al., 1999) visually distinguished glaciogenic sediment components using genetic terms like ice-rafted sand debris or angular to subangular dropstones. Various genetic schemes have been applied to these sediments, starting with Leg 119 (Barron, Larsen, et al., 1989), where lodgment, melt-out, basal, and waterlaid tills were differentiated from proximal to distal glaciomarine sediment. Subsequently, Leg 152 sedimentologists (Larsen, Saunders, Clift, et al., 1994) discussed four general types of glacial sediments: distal ice-rafted debris, glacial marine drift, subglacial till, and other ice-contact sediments including outwash, subglacial stream deposits, flow-till, glacially tectonized sediments, and so forth. Leg 178 sedimentologists (Barker, Camerlenghi, Acton, et al., 1999) went on to describe glacial processes in greater detail with a mixture of genetic and nongenetic (facies) classification schemes, also used more recently by Expedition 341 scientists (Jaeger, Gulick, LeVay, et al., 2014). They use the term "diamict" (synonymous with diamicton) as a nongenetic term for unconsolidated sediment consisting of admixtures of clasts (defined here as fragments >2 mm in diameter), sand, and mud, where the sediment is matrix supported as opposed to clast supported (Flint et al., 1960). Diamictite refers to lithified diamict/diamicton. Their descriptive scheme for diamict(ite) is independent of depositional environment or setting but emphasizes the presence or absence of internal structure and organization. Diamict facies are either massive or stratified with variable internal distribution of clasts (normal vs. inverse grading), clast abundances (using a 20% cut-off between clast poor and clast rich), degree of stratification (well developed to chaotic to deformed), and degree of bioturbation. They provide a nice description of the glacial facies relating them, when possible, to glacial depositional environments and provide a detailed section on till that expands on information from Leg 119 presented above (see Barron, Larsen, et al., 1989, for more detail).



C

Percent gravel (>2 mm) in whole rock estimated from core

Percent sand in matrix		Trace <5%	5%-10%	10%-30%	30%-80%	>80%
0–25	FINE-GRAINED SEDIMENTS	CLAY/SILT with dispersed clasts	CLAY/SILT with common clasts	CLAY/SILT with abundant clasts	Clayey/silty GRAVEL/CONGLOMERATE BRECCIA	GRAVEL/ CONGLOMERATE/ BRECCIA
25–50		CLAY/SILT with dispersed clasts	Clast-poor DIAMICT	Clast-rich DIAMICT	GRAVEL/ CONGLOMERATE/ BRECCIA	
50–75		SAND with dispersed clasts	Clast-poor DIAMICT	Clast-rich DIAMICT	GRAVEL/ CONGLOMERATE/ BRECCIA	
75–100		SAND with dispersed clasts	SAND with dispersed clasts	SAND with abundant clasts	Sandy GRAVEL/ CONGLOMERATE/ BRECCIA	

Figure F3.8. Various classification schemes, largely nongenetic, for gravel-bearing high-latitude sediments. A. For Leg 151 and Exp. 302 the scheme for samples containing >10% gravel was a tetrahedron with increasing gravel content at the apex. The base is the classification for siliciclastic sediments modified from Shepard (Figures 3.3 and 3.4 are our preferred versions of the Shepard ternary plots to use here). B. The tetrahedron from (A) depicted in ribbon format with a Shepard plot. C. Leg 188 classification scheme for poorly sorted sediments containing gravel (diamict) after Moncrieff (1989), which distinguishes clast-poor and clast-rich facies with different sand contents. The term "clast" can refer to either sand- or gravel-sized components. The term "lonestone" is reserved for gravel-sized (>2 mm) clasts floating in a fine matrix, where the matrix should be described using schemes depicted in Figure F3.3 or F3.4 in lieu of their suggested modified Shepard (1954) plot. A visual percentage estimate of 10% defines the boundary between clast-poor and clast-rich lithologies. References: Leg 151 (Myhre, Thiede, Firth, et al., 1995); Leg 188 (O'Brien, Cooper, Richter, et al., 2001); Exp. 302 (Backman, Moran, McInroy, Mayer, et al., 2006).

As with other sediment types, genetic terminology related to the depositional mechanism of the deposit is best limited to the discussion or interpretation section of the site report and should not appear in the VCDs or descriptions.

3.4.1.2. Serpentine-rich (serpenticlastic) sediment

Serpentine sediments are another rare but distinctive lithology type encountered by ocean drilling (Legs 125 [Fryer, Pearce, Stokking, et al., 1990]; 149 [Sawyer, Whitmarsh, Klaus, et al., 1994]; 195 [Salisbury, Shinohara, Richter, et al., 2002]; and Expedition 366 [Fryer, Wheat, Williams, et al., 2018]) on both active and passive margins but were not considered in the MGK Appendix scheme. We place them with terrigenous sediments because of their siliciclastic composition, while recognizing that many of these are derived directly from submarine outcrops rather than land-derived materials. Where present, this lithology can dominate major portions of the stratigraphy.

In the case of serpentine muds (including silty or sandy muds), the standard MGK Appendix scheme works well with the addition of compositional modifiers. Gravel and larger particles in serpentine conglomerates and breccias have motivated the use of additional methods from published literature such as Moncrieff (1989). Interestingly, despite the large effort applied to description of serpentine sediments during Leg 149 (Sawyer, Whitmarsh, Klaus, et al., 1994) these materials are not addressed in their Explanatory Notes chapter (today called Methods). Diverse hard rock lithologies in large clasts and complex diagenetic/structural features (e.g., crack/seal veins crosscutting sedimentary fabrics as in Leg 149) that are a common feature of serpentine sediments attract the attention of shipboard science groups beyond the sedimentology group. A plan to involve multiple groups in description of serpentine-bearing materials should be organized immediately if these materials are expected or encountered. One option is for different groups to make separate descriptions of the same intervals (i.e., Leg 195; Salisbury, Shinohara, Richter, et al., 2002); another is to have a collaborative description effort using either sedimentary, structure, or hard rock description forms as seems appropriate.

3.4.1.3. Volcaniclastic sediment/rock

There are several options for pyroclastic/volcaniclastic classification schemes. Approaches differ depending on (1) tectonic setting (e.g., proximity of the drill sites to volcanic sources, compositional range and type(s) of volcanism, and proportion of volcaniclastic sediment encountered); (2) expertise of shipboard scientists (volcanologists vs. nonvolcanologists and their experience with marine depositional systems); and (3) consensus on ability to interpret the generation, transport, and depositional processes of the deposits. Excellent descriptions are key, and nongenetic descriptions are favored in depositional settings wherein origin is often ambiguous.

One option is the standard MGK Appendix classification (Figure **F3.1**), based on the volcaniclastic scheme of Fisher and Schmincke (1984). It is simplified and does not discriminate among the epiclastic, pyroclastic, or hydroclastic interpretive origins of the deposits. Grain size is used as a means of applying terms such as breccia, lapilli, or ash/tuff, whereas tuff is the equivalent to compacted and lithified sediments (see table 5.1 in Fischer and Schmincke, 1984). This simple scheme can be used for description of sections with mainly airfall ash/tuff beds or to separately describe intercalated volcaniclastic beds within a predominant nonvolcanoclastic sediment facies. It can be modified by dividing the ash/tuff into coarse material (1⁄16 inch to 2 mm; sand-size) and fine (<1⁄16 inch: silt- and clay-size) fractions as well as the lapilli into fine (2–8 mm), medium (8–32 mm), and coarse (32–64 mm) subdivisions. Additional description can include types of tephra (e.g., vitric, pumice, scoria) as well as differentiation by glass type and glass morphology and presence of mineral (crystal) and rock fragments.

Other core describers opted to eschew Fisher and Schminke's (1984) classification, considering it to be genetic in nature, and embraced, either partly or completely, more descriptive classifications. Leg 126 shipboard sedimentologists (Taylor, Fujioka, et al., 1990) "…made a special effort to avoid genetic terminology in the naming of volcaniclastic sediments and pyroclastic materials." They did "not use terms otherwise employed by volcanologists, such as ash/tuff, lapilli tephra/tuff, and breccia," instead using "the size terms of Wentworth…" indicating composition with a modifier. "The sediments may consist entirely of volcanic ejecta, but their genesis does not play a part in

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description and is instead discussed only in the interpretative sections of this volume." This leg recovered kilometers of volcaniclastic sediment described in this manner. The one exception (perhaps a compromise among the core describers) was that Pliocene–Quaternary intervals interpreted as ash beds were deemed significant and indicated by "A" in the sedimentary structures columns of the sedimentary description forms.

On other cruises the scientists were more certain of their ability to distinguish pyroclastic (direct products of magma degassing, primary deposits) from epiclastic (detritus derived from erosion of volcanic rocks by wind, water, or ice) origins using Udden-Wentworth scale with the modifier volcaniclastic (e.g., volcaniclastic conglomerate, breccia, sand, or silt) and a modified Fischer and Schminke scheme to describe the former. We do not advocate using a ratio cut-off (e.g., 1:1) of pyroclasts (ash) to epiclasts (terrigenous; sand/silt/gravel) as used by some because that would result in arbitrarily using one scheme vs. the other.

With the advent of the International Ocean Discovery Program, several cruises focused on Izu-Bonin-Mariana magmatic arc initiation and evolution as recorded in volcaniclastic and volcanic units. A comprehensive volcaniclastic classification scheme was developed during Expedition 350 (Tamura, Busby, Blum, et al., 2015), which was then modified for use during Expeditions 351 (Arculus, Ishizuka, Bogus, et al., 2015) and 352 (Reagan, Pearce, Petronotis, et al., 2015). The Expedition 351 scheme was then used for Expedition 376, Brothers Arc Flux (de Ronde, Humphris, Höfig, et al., 2019). The Expedition 350 scheme was in turn modified for use during Expedition 398 in the Hellenic Volcanic Arc field (Druitt, Kutterolf, Ronge, et al., 2024). Examples of these schema (Expeditions 351, 398) are reproduced in Appendix **A3.3**, along with two other representative mixed classifications. These contrast with the original, more simplistic MGK Appendix scheme.

3.4.2. Biogenic sediment/rock

3.4.2.1. Pelagic sediment/rock

The two main groups of pelagic sediments, calcareous and biosiliceous, reflect the composition of the major pelagic organisms (carbonate and opaline silica). It is common to encounter a mixture of sediment produced by both groups of organisms, with one dominant. Additionally, terrigenous material may form an important component where there is eolian, riverine, or ocean-current input, thus creating hemipelagic sediments. It is important to evaluate these description schemes in the context of the hand-specimen and light microscope methodologies for which these classifications were intended.

In the MGK Appendix classification scheme (Figure **F3.1**), terms for pelagic sediments are based on a combination of the "predominant" grain type together with an assessment of the degree of lithification. Preceding modifiers are applied to major components (>25%) and trailing modifiers ("with") to minor components (10%–25%). Other than the requirement that there be <40% of siliciclastic components, no explicit mention is made of either the proportions of clay minerals and other silicates or the particle size distribution (clay-size vs. silt-size).

Pelagic components in these sediments are mainly definable in smear slide because of their fine grain size, as illustrated and discussed in Marsaglia et al. (2013, 2015a) and accompanied by minor amounts of clay minerals and other fines. Exceptions are large sand-sized foraminifers or radiolarians that can be identified macroscopically in cores. Often, core color can be linked to the proportions of pelagic and nonpelagic components in the sediment after enough smear slides are examined to calibrate colors. Once established, this correspondence can be used as a tool for rapid core lithology designations during high-recovery expeditions. If used as such, it should be tabulated and noted in the site reports. See drilling results from Leg 198 (Bralower, Premoli Silva, Malone, et al., 2002), Leg 149 (Site 897; Shipboard Scientific Party, 1994), and 161 (Site 974; Shipboard Scientific Party, 1996) for examples. Color changes noted shipboard in certain sedimentary rock types (e.g., chert) can be also significant (Fontilea et al., 2006).

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3.4.2.1.1. Calcareous pelagic sediment/rock

Calcareous pelagic materials are widespread in the world ocean and have been described in numerous DSDP, ODP, and IODP cores. A modern understanding based on high-resolution petrographic methods has refined concepts of grain alteration and cementation that are not well represented in the MGK Appendix classifications, an approach intended for hand-specimen and light microscope scales.

The MGK Appendix scheme describes calcareous pelagic sediments (Figure **F3.1**) with classification terms as indicated in **Section 3.4.2.1** above. The main components of unconsolidated calcareous ooze are nannofossils and foraminifers, which can be major modifiers. The percent pelagic biogenic debris used to define sediment as "ooze" is 50% in some reports and 60% in others. The former arises from a common modification of the MGK Appendix classification whereby the "mixed sediment" category is removed and the boundary between pelagic and siliciclastic content is assigned at 50% rather than the 40%/60% cut-off. Another common approach is to use the mixed category but assign to it the term "marl."

Frequently, the small size of Pleistocene calcareous nannofossils results in underestimation of their abundance in smear slides (see Marsaglia et al., 2015a), a realization made with the arrival of bulk carbonate data from the geochemists. This is a reason to pair smear and carbonate analysis intervals whenever possible. Be aware that it may take a few days to generate carbonate data. In any event, there is often a revision made midway or after the first site report to remove or add the lithology "ooze" as needed based on calibration from measured bulk carbonate values.

Upon burial, calcareous ooze lithifies into chalk (described as "firm") or may crystallize further into limestone, which is described as "hard" (see **Section 3.3**). The MGK Appendix scheme describes pelagic carbonate lithologies as being composed entirely of granular material, not acknowledging the important role of cementation and other diagenetic processes in lithification. The MGK Appendix scheme also includes "calcite" as a type of chemical sediment, but does not specify how granular and chemical carbonate rocks are differentiated, nor does it recognize the common admixture of granular and diagenetic components. The presence of important cement volumes within carbonate rocks that also contain identifiable granular materials (including fine-grained ones) is, of course, acknowledged by numerous reports and, where very fine-grained (micritic), can lead to the use of the term marlstone (e.g., Exp 317; Fulthorpe, Hoyanagi, Blum, et al., 2011).

As with the biosiliceous counterparts, in classification of carbonate-pelagic materials the focus should remain on the grain assemblage. In postcruise studies using higher magnifications, chalk and limestone may be designated more specifically as "carbonate-cemented" varieties of different lithologies. In oozes, 60% pelagic material tends to be associated with a strong color transition (notably whiter), and this is proposed as the compositional cutoff to be used in defining these sediments. See color discussion in **Section 3.4.2.1** above.

3.4.2.1.2. Biosiliceous pelagic sediment/rock

Although grains composed of biogenic opal, dominantly radiolarians, diatoms, and sponge spicules, are widely present in marine sediments, they are rarely dominant except locally at low and high latitudes, as seen in the smear slide atlases (IODP Technical Notes 1 and 2; Marsaglia et al., 2013, 2015a; **Appendix B**, **Appendix C**).

The complications of naming sediments with abundant biosiliceous debris relates to the prominent diagenetic processes that arise from the high chemical reactivity of these grains. The MGK Appendix scheme describes biosiliceous sediments as a type of pelagic sediment (Figure **F3.1**) with classification terms as indicated in **Section 3.4.2.1**. Oozes (radiolarian, diatom, and spicule) are unconsolidated (unlithified). Radiolarite, diatomite, and spiculite are described as "firm" (see discussion of lithification state in **Section 3.3**). Chert is described as "hard," yet it, along with all of the above, are still described as lithologies composed entirely of granular material. The MG Handbook also includes chert as a type of chemical sediment, but does not specify how granular and chemical cherts are different. Cherts (and also dolomite) are removed from chemical sediments in this Guide. See discussion of diagenesis in **Section 3.5** for further guidance. Note that the opal-A to opal-CT to quartz transition (Isaacs, 1981) in the diagenesis of siliceous sediments correlates strongly with progressive lithification and pore loss but is best determined by XRD and to some degree by SEM rather than by visual core analysis.

Five reports created modifications to the MGK Appendix classification of biosiliceous sediments. The most common modification is the addition of "porcellanite" as an intermediate lithification level between "radiolarite-diatomite-spiculite" and chert. This addition provides greater consistency with respect to the ooze-chalk-limestone variations that are applied to calcareous pelagic sediments. Although never openly discussed in reports, it seems clear that features such as luster, hardness, or porosity are more important determinants for porcellanite and chert than for the radiolarite-diatomite-spiculite, wherein the fossil components are more important. The inclusion of benthic sponge spicules as a component of pelagic sediments is also not explicitly mentioned as an inconsistency in the MGK Appendix classification; however, the Leg 167 volume (Lyle, Koizumi, Richter, et al., 1997) mentions "Pelagic grains are the skeletal remains of open marine siliceous and calcareous microbiota (e.g., radiolarians, diatoms, planktonic foraminifers, nannofossils) and associated organisms." The Leg 138 report (Mayer, Pisias, Janecek, et al., 1992) explicitly excludes spicules from the list of potential pelagic grains. Although siliceous benthic sponge spicules can be locally significant sediment components in modern sediments (Hüneke and Henrich, 2011), spiculitic cherts are most likely to be found in Paleozoic rocks (e.g., Chang et al., 2019; Gates et al., 2004; Ritterbush, 2019) and are seldom encountered in ocean drilling. The MGK Appendix scheme for biosiliceous sediments preceded the recent work on intergranular microquartz cementation in siliceous mudrocks afforded by high-magnification SEM petrography relevant to unconventional resource evaluation (e.g., Milliken and Olson, 2016). Nongranular authigenic minerals or components are essential to lithification of biosiliceous sediments and are important components in radiolarite-diatomite-spiculite, porcellanite, and chert. Diagenetic siliceous rocks may also be created by emplacement of authigenic quartz in nonpelagic sediments as well, producing nonpelagic chert (e.g., Leg 167; Lyle, Koizumi, Richter, et al., 1997).

Figure **F3.1** presents viable alternate classification schemes, largely retaining the MGK Appendix approach to biosiliceous pelagic sediments with the option for a more detailed system of modifiers if the objectives of the cruise justify such an approach. The terms radiolarite, diatomite, and spiculite can be removed from use without loss of detail from descriptions, keeping in mind that terms such as porcellanite and chert are hand-specimen-level terms. Where appropriate, in the case of lithified sediments these allochem types can be used as modifiers for porcellanite and chert. Authigenic quartz in these rocks may occur as cement or replacement of biogenic debris. Cherts representing lithified mixed (carbonate and terrigenous) rocks can be similarly designated using modifiers (e.g., argillaceous chert; calcareous chert). To the degree possible, the focus in classifying biosiliceous pelagic materials should remain on the grain assemblage. In postcruise studies using higher magnifications, many cherts and porcellanites will be designated more specifically as "microquartz-cemented" varieties of different mudrock lithologies, a determination that cannot be made confidently without SEM observations.

3.4.2.2. Neritic carbonate sediment/rock

Common carbonate classification schemes were developed to describe lithified sedimentary rocks in the field (Dunham, 1962) or in thin section (Folk, 1959, 1962). The MGK Appendix's use of the Dunham classification for sediments and rocks dominated by neritic (nonpelagic, shallow water) carbonate grains (>60%), as modified by Embry and Klovan (1971), is preferred by most ODP/IODP scientists (Figure **F3.9**). Embry and Klovan (1971) divided boundstone into bafflestone, bindstone, and framestone and added terms for rocks with grains >2 mm, floatstone and rudstone. Note that this modified Dunham classification does not adapt well to unconsolidated sediments ("-stone" being part of every term).

One term that is often adopted from the Folk (1959, 1962) classification, micrite, was also created solely for lithified materials but can be used for components in smear slide descriptions of semilithified sediments (see discussion in Marsaglia et al., 2015a). There are also issues when neritic carbonate debris is displaced downslope as mass or gravity flows, producing gradations (e.g., Austin, Schlanger, et al., 1986) between neritic and pelagic-dominated end-members. The Dunham classification can be applied across the neritic–pelagic continuum, although further compositional classification is typically applied to pelagic materials (see next section).

3.4.3. Mixed sediment/rock

3.4.3.1. General comments on mixed sediment/rock

Sediments with mixed grain assemblages have been discussed with respect to neritic, pelagic (including hemipelagic), and terrigenous sediments. In the years since the MG Handbook was published, drilling has perhaps encountered more sediments of this type than originally expected, with the result being that this is perhaps the aspect of the MGK Appendix classification scheme that has proven the most controversial. The most common modification of relevance to the mixed category is to remove it entirely, placing the boundary between the major siliciclastic and neritic/pelagic classes at 50%. Another strategy, though less common, is to substitute the mixed category with the term “marl” or “marlstone,” to which a range of modifiers can be applied. This topic is also raised in the discussion of other specific classification schemes. The use of “mixed sediments” within a classification scheme can be problematic.

3.4.3.2. Organic-bearing and organic-rich sediment/rock

Sediments with more than a few percent organic components (e.g., sapropels, black shales) have rarely been reported in ocean drilling, and thus, most such sediments are best described as “mixed” with a notable content of organic matter. Terms for truly organic-dominated sediment can be described using terms such as lignite and the more general term coal. Coal, lignite, sapropel, and organic-rich (black) shale, as well as compositional modifiers related to organic content (coaly, sapropelic, carbonaceous, kerogenous, organic), should be defined in the lithostratigraphy methods section. Note that some muds are black because of sulfidic components. Organic components

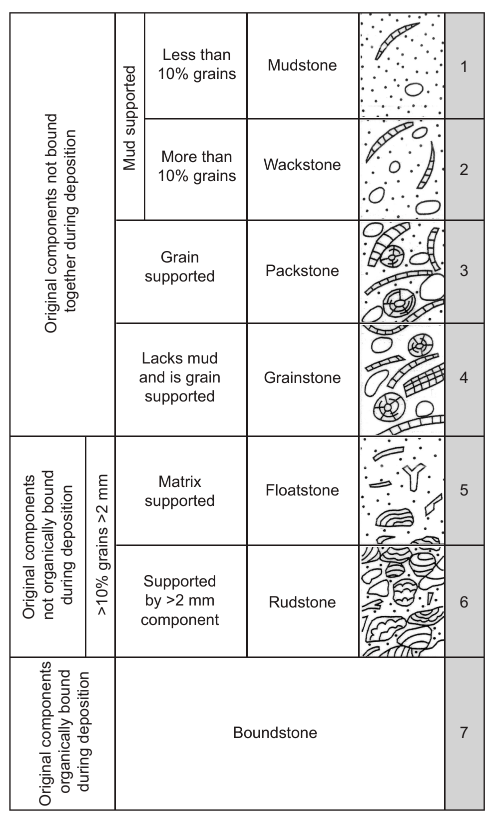

Figure F3.9. Carbonate classification scheme based on depositional texture from Exp. 356 (Gallagher, Fulthorpe, Bogus, et al., 2017), after Dunham (1962) as modified by Embry and Klovan (1971) and Stow (2005). Numbers are the texture “rank” used to plot texture variations downcore.

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may be identified and semiquantified from smear slide analyses with the help of paired TOC (total organic carbon) values measured by the geochemists (see examples of organic smear slide components in Marsaglia et al. (2015b; **Appendix C**).

For definition of organic matter components and description of sapropels, Leg 160 (Emeis, Robertson, Richter, et al., 1996) and 161 (Comas, Zahn, Klaus, et al., 1996) shipboard sedimentologists chose broad definitions (Hilgen, 1991) that encompass all the organic-rich sediments that they encountered based on their appearance in the core: Leg 160 referred to all as sapropels, whereas Leg 161 referred to all as organic-rich sediments. Leg 160 created a custom sapropel description sheet that includes structure, color, bioturbation, and microfossil content (see Emeis et al., 1996).

The relatively lower organic matter content of most sapropels is such that standard descriptions using methods for granular sediments can be readily accomplished with the use of modifiers (e.g., organic-rich or organic-bearing). This also holds for older organic-rich black shales associated with oceanic anoxic events (OAEs), examples of which are included in Technical Note 2, **Appendix C** (Marsaglia et al., 2015a).

3.4.4. Chemical sediment/rock

The MG Handbook lists carbonaceous sediments, evaporites, silicates (cherts), carbonates, and metalliferous sediments as representing "chemical sediments." The term diagenesis does not appear in the MG Handbook text, though today we recognize many of the lithologies they include under the rubric of chemical sediments as ones that have strong diagenetic overprints related to processes such as cementation, organic maturation, and grain alteration through dissolution and reprecipitation (see **Section 3.5** below). The appearance of chert as both a pelagic and a chemical sediment denotes some of the uncertainty that existed at the time the MG Handbook was written (1988). Later. chemical sediments were equated with diagenetic features such as nodules or concretions (chert, carbonate, zeolite), which were mentioned in the MG Handbook as sedimentary structures but not a sediment type/lithology.

Today, organic-rich sediments and the "chemical" silicates and carbonates of the MG Handbook are discussed most logically under granular sediments (see above). The sediment types still recognized as "chemical," notably halite, gypsum, and other evaporites, and also (perhaps?) metalliferous sediments, are described below. All of these latter chemical sediments have significant addition of chemical precipitates essentially synchronous with deposition at the seafloor.

3.4.4.1. Evaporitic sediment/rock

Evaporite sediments and sedimentary rocks, rarely encountered during DSDP and ODP drilling, have been described in the Mediterranean Sea during Legs 13 (Ryan, Hsu, et al., 1973), 42A (Hsu, Montadert, et al., 1978; Garrison et al., 1978), 161 (Comas, Zahn, Klaus, et al., 1996), and in the Red Sea, Leg 23B (Whitmarsh, Weser, Ross, et al., 1974). For the Leg 161 cores, Marsaglia and Tribble (1999) used Carozzi (1993) as a guide to description. The cored Mediterranean facies and details of their composition, textures, structures, and interpretation have been recently reviewed as a whole and summarized in Lugli et al. (2015). When contacted, these authors recommended using the classification by Ciarapica et al. (1985), which at the time was unknown to Marsaglia and Tribble (1999) because it was published in an Italian regional journal. Nevertheless, this is an excellent scheme and is included here as Appendix **A3.4**. Another useful resource on evaporite description is the short course volume edited by Dean and Schreiber (1978).

3.4.4.2. Metalliferous sediment/rock

Given the relative rarity of metalliferous sediments in recovered cores and the tendency for these materials to be handled by specialists in hard rock or ore petrology, no specific recommendations are offered. We note that a relatively recent review of deep-sea sediments (Hüneke and Mulder, 2011) did not include metalliferous sediments, only hydrothermal alteration. The strong association with hydrothermal activity is also noted in the general review by Gurvich (2006). The global classification by Shiga (1996) is made according to tectonic setting, mineralogy, and the nature of the ore body. The treatment of metalliferous sediments in the MGK Appendix classification is brief. They are described as nongranular and nonbiogenic sediments encompassing a broad range of mineralogy including "…pyrite, goethite, manganese, glauconite, and other metal-bearing minerals."

In the few ODP/IODP reports describing metalliferous sediments (e.g., Leg 139 [Davis, Mottl, Fisher, et al., 1992], Expedition 329 [D'Hondt, Inagaki, Alvarez Zarikian, et al., 2011]) it is clear that at least some of these are granular in nature (e.g., Legs 158 [Humphris, Herzig, Miller, et al., 1996] and 169 [Fouquet, Zierenberg, Miller, et al., 1998] and Expedition 331 [Takai, Mottl, Nielsen, et al., 2011). The strong mixing of granular (e.g., particulate sulfides) and authigenic (e.g., sulfide cements) components in metals-bearing rock types are widely recognized features. In the specific case of sulfide-rich sediments, the volume of sulfide has been used (Leg 139; Davis, Mottl, Fisher, et al., 1992) to separate massive (>75%), semimassive (50%–75%), and sulfide-rich (<60%) sediment types, any of these potentially containing resedimented sulfides (i.e., authigenic sulfides reworked as particles at the sediment/water interface). In general, the presence of other metal-bearing lithologies has been treated on a case-by-case basis using references to the metalliferous content as modifiers (e.g., baritic silty mudstone). A key focus in any sedimentological description of these materials should be on identification of granular (resedimented) metals-bearing minerals versus pore-filling (cement) and replacement phases.

3.5. Diagenetic impacts on lithology in marine cores

Diagenesis is broadly defined as encompassing all the chemical and mechanical processes that affect sediments following deposition (e.g., Milliken, 2003). Diagenesis takes place in the presence of a reactive fluid phase and broadly overlaps both weathering (including submarine weathering) and low-grade metamorphism (~250°–300°C). Many processes that might be described as "alteration" or "hydrothermal" are encompassed by diagenesis. Preservation of a clearly discernible grain/intergrain fabric is a hallmark of diagenesis. The transition into metamorphism entails the destruction of such sedimentary fabrics and represents a signal that core description might best be turned over to the hard rock description team. Sediment with strong and higher-temperature diagenetic overprints may present a case where collaborative efforts between sedimentology, hard rock, and structure description teams will be beneficial.

Because diagenesis impacts all sediment types, the presence of diagenetic features is typically treated as a modifier in conjunction with one of the lithology classifications described in **Section 3.4** (e.g., calcite-cemented sandstone, dolomite-cemented foraminiferal chalk, zeolite-cemented tuff). It is only in the case of fine-grained sediment for which the pore-filling nature of the cement cannot be discerned that certain lithology terms may be applied as a primary macroscale description (e.g., chert, dolomite).

A key aspect of mechanical diagenesis is compaction, the movement of particles into a tighter packing in response to overburden loading. Compaction can be described as a 1-D contractional strain perpendicular to the bedding. In the absence of cementation, the compactional state of sediments is measured by a parameter known as intergranular volume (IGV, the sum of intergranular porosity + the volume of intergranular cement) (Paxton et al., 2002). IGV is represented fairly accurately by the moisture and density (MAD) measurements produced by the physical properties team.

In addition to simple grain rearrangement, compaction may also entail components of grain deformation, both brittle and ductile. Fracturing (either intra-, circum-, or trans-granular) is another aspect of mechanical diagenesis, though one typically described by the structural geology team. At the depths of current ocean drilling, brittle behavior in sediments is rarely encountered near faults and in sedimentary rocks within well-cemented basement successions (e.g., Karner and Shillington, 2005).

The principal chemical aspects of diagenesis are cementation, grain dissolution, and grain replacement. "Authigenic" refers to minerals precipitated from aqueous solution. Cementation is the precipitation of authigenic minerals in the pore spaces between or within porous sedimentary particles and can occur in any of the sediment types described above, of any grain size or grain composition. In marine muds at temperatures below about 80°C, cementation is typically highly localized, taking the form of concretions. Common cements in marine sediments include calcite, dolomite, microquartz (in cherts), pyrite (and other sulfides), zeolites, clay minerals, and rarely, sulfate minerals. Mineral precipitates within fractures can also be called cements and may correspond to similar and synchronous precipitates between grains in the host rock.

Secondary pores that mark grain dissolution may be difficult to discern in unconsolidated (unlithified) sediments, although the distinctive cleavage-controlled dissolution in some feldspars or dense mineral grains (e.g., pyroxene or amphibole) of silt and sand size may be seen in smear slides. Near the sediment/water interface in high-porosity sediments that have not yet undergone substantial burial compaction, it is possible that substantial grain dissolution may occur without leaving textural evidence of grain dissolution (e.g., in deep-marine red clays); this may also occur at depth, transforming diatomaceous clay to siliceous claystone [Teske, Lizarralde, Höfig, et al., 2021]).

Grain replacement is not a direct solid-state phenomenon but represents precipitation of an authigenic mineral within spaces left by the dissolution of unstable grains. Common examples encountered in ocean drilling include microquartz or calcite replacing siliceous fossils and zeolites or clay minerals infilling pores within dissolved volcanic glass or phenocrysts.

In situations involving circulation of hot fluids through sediments (e.g., at deep-sea vents or in proximity to some faults or intrusions), a wide array of higher-temperature minerals can form as pore-filling cements and grain replacements, for example, albite, titanite, epidote, amphiboles, and various sulfides. As long as the formation of these minerals does not destroy the basic grain/intergrain fabric, the rock may justifiably be described as sedimentary, but the hard rock team may still play a valuable role in describing those aspects of the core.

4. Visual description of sedimentary cores

4.1. Elements of core description

This chapter describes the methods and terminology for detailed core description. The basic elements of macroscopic core description have not changed much since the Mazzullo and Graham (1988) (MG) Handbook, except for the addition of track core logging data, imaging capabilities, and a searchable core description database. This chapter contains elements derived from the MG Handbook; however the text has been reorganized and updated. Each of these elements is described below (disturbance, lithology, color, bedding/structures/bioturbation), in the order that they are presented in the sedimentary core description form (**Section 4.3**), an important tool in documenting core description elements. This form is the equivalent of a field notebook in outcrop description and section measurement and records observations in the full context of surrounding core-scale observations and property trends. When introduced in the MG Handbook, these forms were routinely used but later transitioned into optional description tools in a green effort to minimize paper usage and to encourage preservation of a digital record when IODP first developed a core description database entry application (DESClogik). This resulted in the loss of basic data and sedimentologic context for hundreds of kilometers of core but with the gain of description data in a searchable, sortable database format that can be readily integrated with other types of digital data. Both systems have value. This form is resuscitated herein and is a highly recommended option (mission-specific platform [MSP] use of this form is described in **Chapter 8**; also see **https://www.marum.de/en/Research/Visual-Core-Description.html**). So valuable is the information collected on this form that many sedimentologists, including the authors, view it as a core description requirement. Ideally, these forms should be scanned and included in the report as primary data (primary = data directly collected by researchers from the core) and at a minimum shared with the shipboard sedimentology team as a postcruise reference. Data tabulated from these forms can then be entered into a core description database. Relatively uniform lithologies, simple lithology sequences, repeated stratigraphy in multiple holes at a given site, staff limitations, and/or high core recovery rates favor direct entry of sedimentological data into a core database (e.g., such as GEODESC or DESClogik).

As stated in the MG Handbook, in the routine description of a section the sedimentologist first defines bedding on the basis of variations in sediment lithology, color, sedimentary structures, or other pertinent characteristics and then proceeds to describe the four major characteristics of each bed:

1. Thickness and attitude,
2. Sedimentary structures and bedding planes,
3. Lithology and color, and
4. Degree of disturbance by the drilling process.

Series of beds that together constitute a systematic pattern (e.g., fining-upward or coarsening-upward series) should be captured in the description as well. In practice, in a section composed of repeated interbeds/interlaminae of multiple lithologies, the description rarely goes bed-by-bed (or lamina-by-lamina). Instead, the existence of this lithologic package and component lithologies are indicated and the estimated proportions for these packages are summarized for the section or core (e.g., the percentage of the total interval formed by each lithology, the number of packages, and average/maximum/minimum thickness of stratification for each package).

4.1.1. Drilling and core-handling disturbance

Perfect cores representing 100% recovery without drilling disturbance are highly desired for core description, but unfortunately, on average, they are not the norm. Such "perfect" cores are more likely products of hydraulic piston coring but are known from rotary-drilled, well-lithified units (e.g., Figure **F4.1**). These are a driller's pride and a joy to describe. Looks may be deceiving, however, as more detailed analyses has shown when "completeness" of sections among holes became

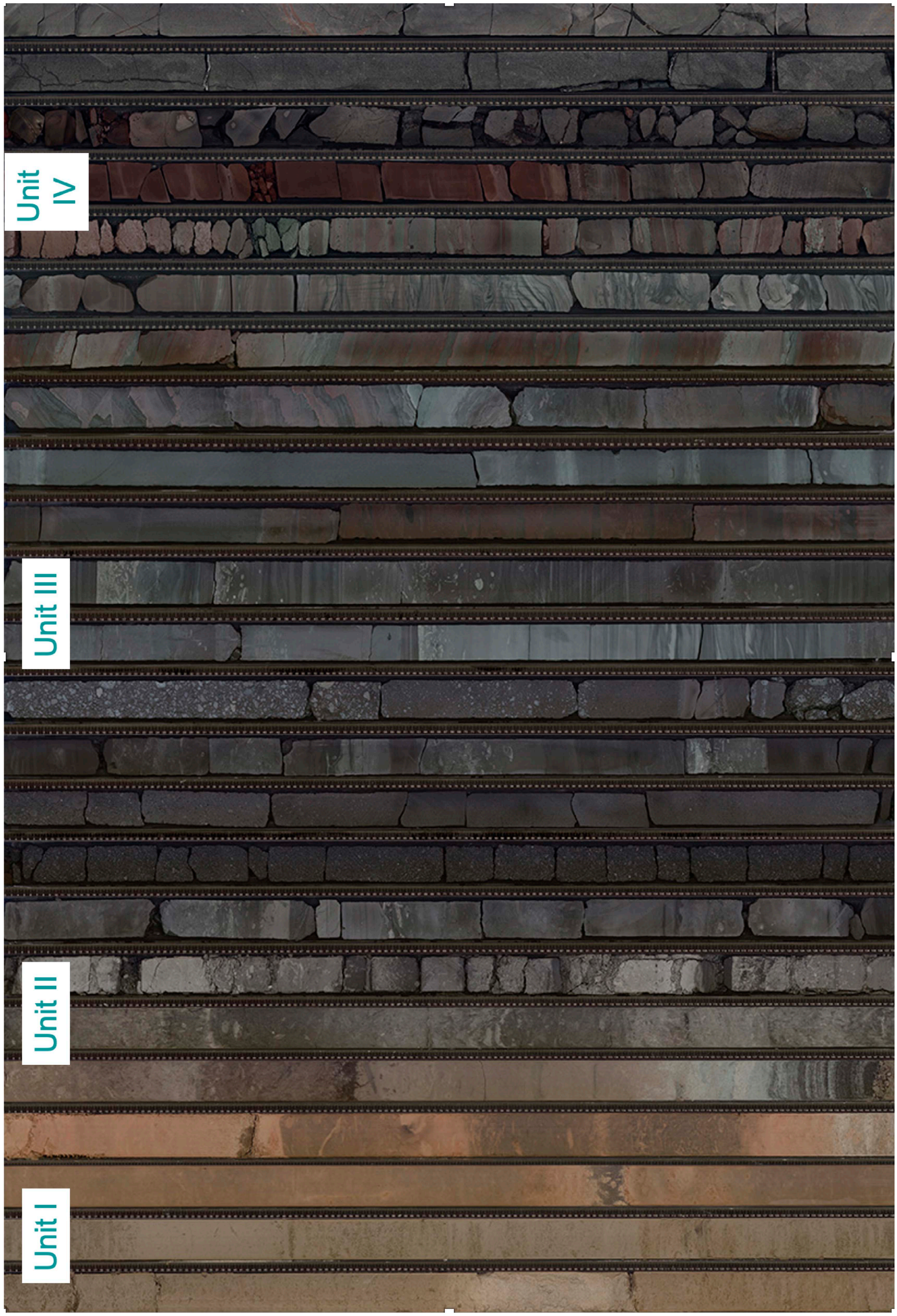

Figure F4.1. Core section montage from Expedition 351 (Arculus, Ishizuka, Bogus, et al., 2015) showing the sedimentary and volcanic record of the birth, life, and demise of a magmatic arc with excellent core quality and recovery. Sediment lithologies are as follows: Quaternary to Miocene calcareous hemipelagic sediments (Unit I) overlying Miocene (Unit II) to Oligocene/Eocene (Unit III) redeposited and progressively more altered (with depth) marine volcaniclastics with red radiolarian-bearing mudstones and fine less altered volcaniclastics at base (Unit IV). Note that dark, underlying basalt is designated as a separate Unit 1. See Arculus et al. (2014) for more information.

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important for paleoceanographic records as described in **Chapter 7**. Incomplete or missing sections may be coring artifacts or local nuance of erosion/deposition.

Modern deep ocean drilling uses mainly advanced piston coring (APC), half-length advanced piston coring (HLAPC), extended core barrel (XCB), and rotary core barrel (RCB) techniques as illustrated in Sylvan et al. (2021; their figure 1). These coring methods are progressively employed with depth and increased lithification in sedimentary sections. Each coring method can disturb sedimentary formations in different ways, as a function of rheology and brittle behavior, in turn a function of sedimentary lithology and degree of induration (for more information on coring techniques, see **http://www.iodp.tamu.edu/tools/index.html**). Figure **F4.2** shows an RCB example of how different formations may be more or less prone to recovery and how gap zones might be distributed within a recovered section, indicating poor-recovery zones. Many such poor-recovery zones are puzzles that need to be "imagined" and, potentially, solved using borehole logging.

Well-indurated sedimentary rocks drilled using the rotary coring technique are prone to break or fracture along bedding planes or in orientations reflecting in situ structural stresses. Fractures can be natural or induced by the drilling process. Detailed analysis of these features is often the purview of the structural geologists or physical properties specialists, especially where fault zones are encountered. Sedimentologists simply note this as drilling disturbance. Extreme fracturing during drilling can produce drilling breccia. In contrast, beds of soft sediment can be flexed and bowed downward by the weight of the drill string or can be flexed and bowed upward as the core barrel is pulled from the hole.

Drilling disturbance issues should be brought to the attention of the Operations Superintendent because it can sometimes be lessened or prevented by changing drilling or coring techniques. Disturbance can be caused also by the tools used for splitting cores, and the marine technicians may be able to minimize core disturbance from this source.

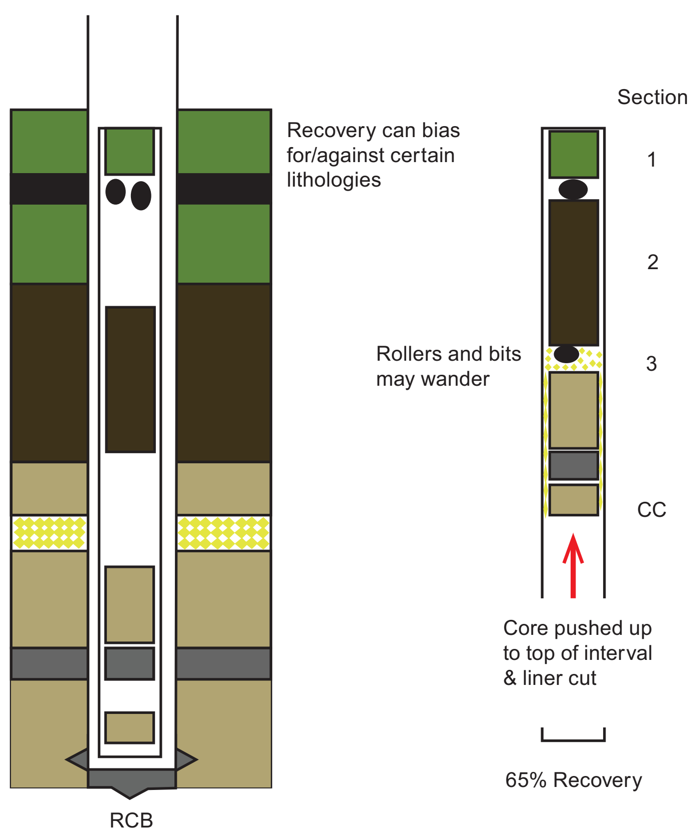

Figure F4.2. Schematic of rotary-drilled core recovery considerations and formation. RCB = rotary core bit.

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Note that some deformation/disturbance may be produced during extraction and processing of the core in the core liner as well as during cutting of the core (see discussion of cutting surface issues above). These are grouped here with drilling deformation to contrast with natural deformation features (folds, fault breccia) or alteration during core transport and storage (e.g., **https://wiki.aapg.org/Core_alteration_and_preservation**). Care must be taken to differentiate natural deformation features (folds, faults) from induced ones (see discussion and images in McNeill, Dugan, Petronotis, et al., 2017, and Marsaglia et al., 2015b [**Appendix D**]). McNeill, Dugan, Petronotis, et al. (2017) conducted an excellent analysis of the relationships among drilling style, drilling rate, lithology, recovery, and drilling deformation. Ductile, brittle, and other disturbance features are outlined below based on the MG Handbook and shown in Figure **F4.3**.

4.1.1.1. Disturbance terms for soft to semi-indurated formations

The following terms are used to describe disturbance in soft to semi-indurated sediments:

- **Slightly deformed**: beds are flexed only along core edges.
- **Moderately deformed**: beds are entirely flexed across the width of the core.
- **Very deformed**: beds are completely disturbed or exhibit diapir-like structures.
- **Flow-in:** lithologies are vertically streaked where sediment sucked into the core barrel.
- **Soupy**: very common in unconsolidated sand (terrigenous, calcareous, and tuffaceous) and ooze and frequently observed in the first core that penetrates the poorly consolidated sediment on the surface of the seabed (mudline) wherein situ porosities can exceed 70%. Soupy textures may be produced where water-saturated or underconsolidated soft sediment flows upward through a core barrel under the weight of the drill string, losing all traces of original bedding. Soupy texture can also be produced by sloshing of water and sediment in partly filled core liners extracted from the core barrel and laid horizontal on the catwalk (see Figure **F4.4**, from Jutzeler et al., 2014, for these and additional terms).

4.1.1.2. Disturbance terms for indurated formations

The following terms are used to describe disturbance in indurated sediments:

- **Biscuited:** beds of semiconsolidated, stiffer sediments drilled by XCB and RCB methods may be split along bedding planes (less consolidated silt/sand) by rotation of the core barrel, producing disc-shaped drilling biscuits of coherent formation that are surrounded by a matrix of soupy disaggregated sediment (a.k.a., gravy). This soupy sediment may also be drilling mud used during coring.
- **Slightly fractured**: rock broken into a few large, stratigraphically intact pieces by a small number of well-defined fractures.
- **Moderately fractured**: core pieces are in place or partly displaced, but original stratigraphic orientation is maintained.
- **Highly fractured**: pieces are probably in correct stratigraphic sequence (although they may not represent the entire sequence), but original orientation is lost.
- **Drilling breccia**: rock crushed and broken into many small and angular fragments, with original orientation and stratigraphic position lost; often drilling breccia is completely mixed within drilling slurry.

4.1.1.3. Other types of core disturbance

The following terms are used to describe other types of core disturbance:

- **Cave-in:** (also called fall-in) occurs at top of cores when during core retrieval material caves from the wall of the borehole, falling to the bottom of the hole, where it is sampled by the subsequent core; some uphole lithologies (e.g., concretions, cemented sandstone, sand, and gravel-size material such as dropstones) may be more prone to caving.
- **Gas expansion cracks:** can form as a result of core degassing and dissociation of gas hydrates on catwalk and in core racks.
- **Puncture:** gas sampling directly through core liner on catwalk may leave distinct features in the core.

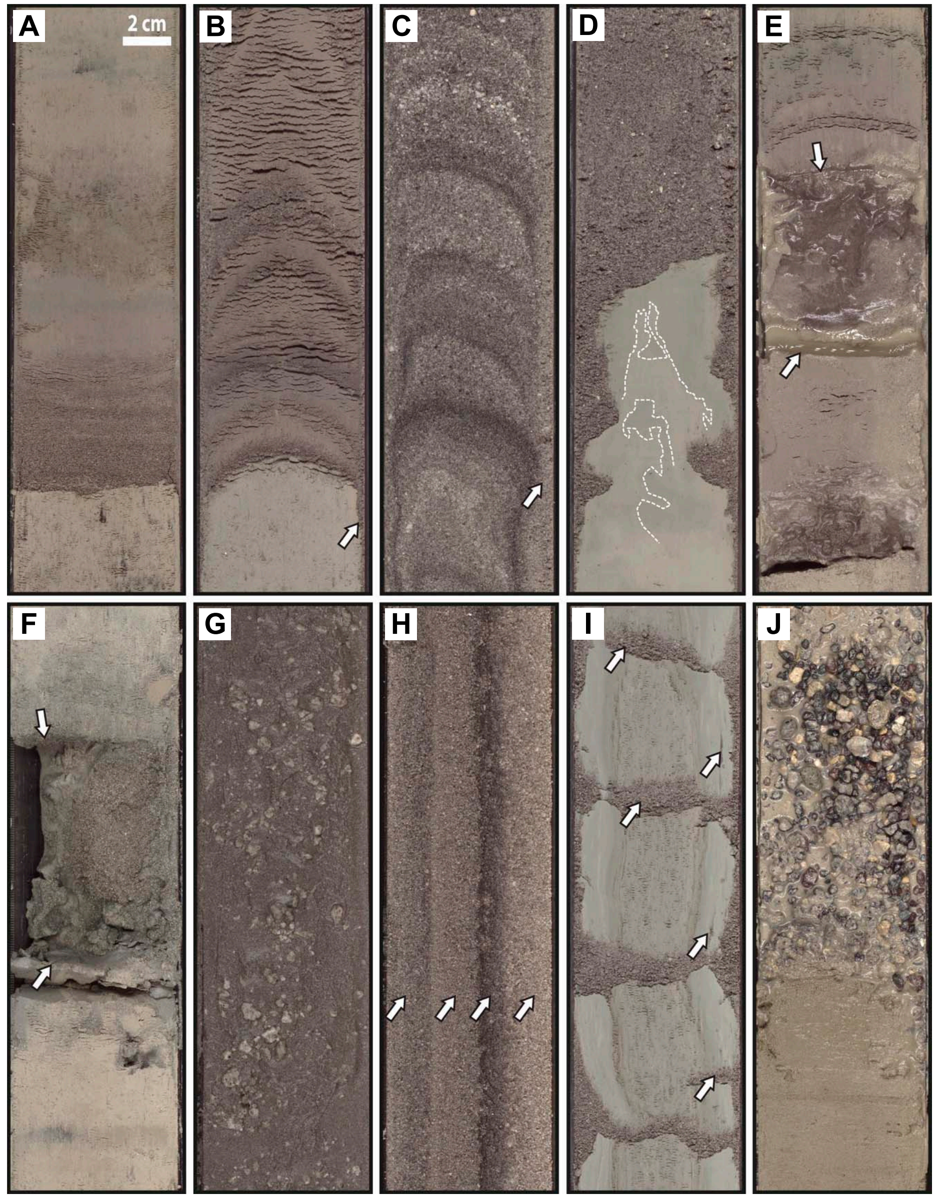

Figure F4.3. Ductile, brittle, and other disturbance features (slightly modified from Jutzeler et al., 2014). A. Undeformed core with planar bed contacts. B. Mild deformation with up-arching bed contacts; beds remain separate and vertical; sediment flowage along the core liner is minor (arrow). C. Moderate deformation of sandy beds that can still be distinguished from each other; vertical sediment flowage along the core liner is significant (arrow). D. Strong deformation with mingling and distortion of beds of hemipelagic mud (dashed lines) at contact with overlying volcanic sand. E. Disturbed sandy units (between arrows) among much less deformed finer grained units representing initiation of midcore flow-in. The middle sandy unit is soupy, which is distinctive of localized vertical extension that favored liquefaction in this particular layer, destroying all internal structures. F. Same as E: the middle sandy unit is partially empty. G. Strongly deformed, soupy sandy unit (>8 m thick) with few pumice granules in which all structures have been destroyed by liquefaction and/or vertical settling through seawater. Partial stroke occurred during coring, and the working-half core is almost empty. H. Rare pseudo-horizontal density grading in several units (arrows) from vertical settling of grains in liquefied sediments when core was lying flat on deck. The core was a partial stroke and suffered basal flow-in. Dense clasts are dark gray; pumice clasts are pale gray. I. Exceptional deformation in hemipelagic mud, sheared, then truncated by vertical stress during retrieval of core from the host sediments and aggravated by midcore flow-in of allochthonous, dark sandy sediment injected between the segmented mud units. J. Coarse polymictic clasts in the uppermost part of Section 340-U1394B-9H-1 representing fall-in from cuttings that were not washed out during drilling of the previous core, which was a partial stroke.

4.1.1.4. Core surface disturbance during cutting

Sedimentary structures in soft sediments may be better recognized if the core surfaces are first scraped using a large glass slide or metal scraper; the tool should be moved from side to side so as not to move material (such as biostratigraphically useful calcareous nannofossils) up- or downcore. Scraping itself may induce surface artifacts and must be used with caution and permission from the Curator. Saw marks visible in indurated rocks cut with a saw can resemble cross-beds in photographs. It is often useful to mention these phenomena and any use of scraping techniques in VCD descriptions and methods sections.

4.1.2. Lithology

Classifying and naming sediment based on macroscopic and microscopic examinations of the core is one of the most important jobs of a shipboard sedimentologist. Here we briefly touch on this topic and refer the reader to **Chapter 3**, which includes a detailed discussion of classification schemes to be used for various lithologies. Printed figures with visualizations of the classification scheme(s) are helpful during macroscopic and microscopic description as proportions of components are estimated or measured that, in turn, are used to determine the sediment/rock name. These include a chart with the Udden-Wentworth scale (Udden, 1898; Wentworth, 1922; Figure **F4.5**), figures with comparators for determining sediment sorting (Figure **F4.6**) and grain rounding (Figure **F4.7**).

Some aspects of lithology may be readily apparent as soon as the archive half of the core is delivered to the description table (e.g., conglomerate), whereas other aspects may only become known after additional analyses that may take minutes (smear slide) to days (thin section, carbonate analysis, X-ray diffraction) to realize. The lithology of the sediment in a bed is determined by analysis of its texture and composition by visual study, petrographic study of smear slides and thin sections, X-ray diffraction analysis, and geochemical analysis. The description usually includes a principal lithology name that defines its sediment type and class, along with major and minor modifiers that describe its texture and composition (see **Chapter 3** for further details).

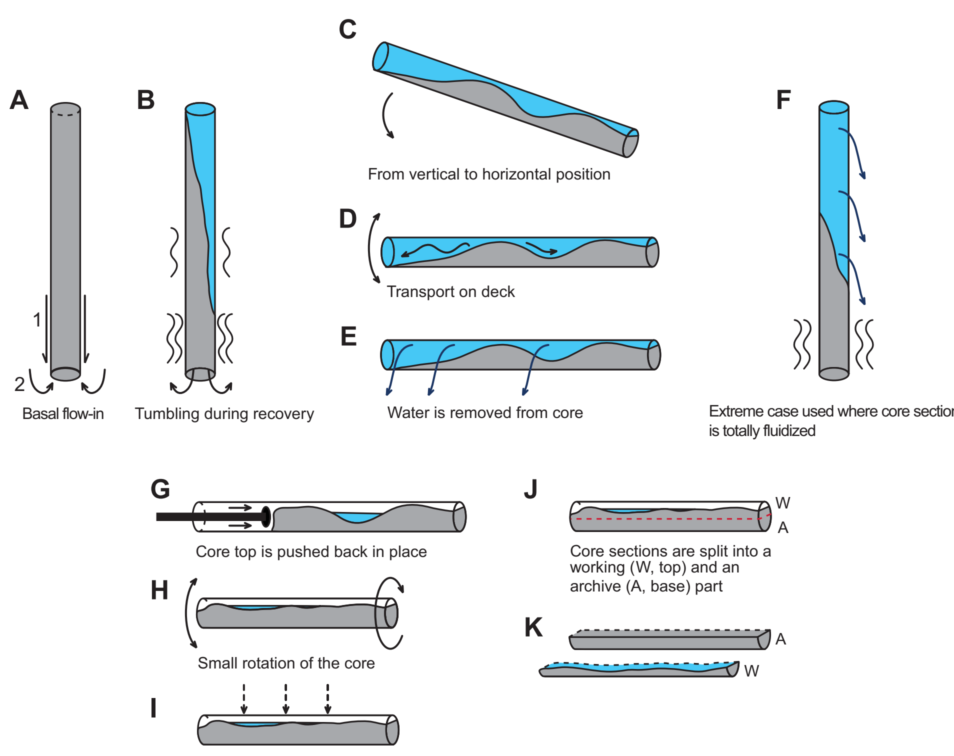

Figure F4.4. Diagram showing how "soupy" texture can also be produced by sloshing of water and sediment in partly filled core liners extracted from the core barrel and laid horizontal on the catwalk (from Jutzeler et al., 2014).

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4.1.3. Color

Lithology color is determined by visual comparison with the Munsell Geological Rock-Color Book (2009) or more detailed Munsell Soil Color Charts (Munsell Color Company, Inc., 2000) available aboard ship. The Munsell Geological Rock-Color Book (2009) is a new binder edition of the earlier flipchart edition: Geological Society of America (GSA) Rock-Color Chart prepared by The Rock-Color Chart Committee (1991). Because these geological charts are limited to 115 color chips, they simplify core description by making color determination more uniform from sedimentologist to sedimentologist, facilitate data input into the database on the ship (fewer entries in pull-down menu), and make summarizing color trends with lithology more straightforward.

		Millimeters	Phi units	Wentworth size class
GRAVEL		4096	-12	Boulder
		1024	-10	
		256	-8	Cobble
		64	-6	Pebble
		16	-4	
		4	-2	Granule
		3.36	-1.75	
		2.83	-1.5	
		2.36	-1.25	
SAND		2.00	-1.0	Very coarse sand
		1.68	-0.75	
		1.41	-0.5	
		1.19	-0.25	
		1.00	0	Coarse sand
		0.84	0.25	
		0.71	0.5	
		0.59	0.75	
		0.50	1.0	Medium sand
		0.42	1.25	
		0.35	1.5	
		0.30	1.75	
		0.25	2.0	Fine sand
		0.210	2.25	
		0.177	2.5	
		0.149	2.75	
		0.125	3.0	Very fine sand
		0.105	3.25	
		0.088	3.5	
		0.074	3.75	
MUD	SILT	0.0625	4.0	Coarse silt
		0.053	4.25	
		0.044	4.5	
		0.037	4.75	
		0.031	5.0	Medium silt
		0.0156	6.0	Fine silt
		0.0078	7.0	Very fine silt
	CLAY	0.0039	8.0	Clay
		0.0020	9.0	
		0.00098	10.0	
		0.00049	11.0	
		0.00024	12.0	
		0.00012	13.0	
		0.00006	14.0	

Figure F4.5. Udden-Wentworth grain-size scale and sediment classes (Udden, 1898; Wentworth, 1922).

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Bed color may be ephemeral and should be described as soon as the core has been split and while the sediment is still wet. Drying and oxidation of exposed sediment can have drastic effects on its original color. For example, diagenetically altered volcaniclastics in Leg 126 cores changed from greenish blue to rusty brown in color (Taylor, Fujioka, et al., 1990), and oxidation has been directly measured after core storage (e.g., see König et al., 2000).

Although color is typically related to minor or trace variations in elemental composition and the redox state of minor components, it is, in fact, an immensely sensitive proxy for depositional and early diagenetic features that are otherwise difficult to discern from bulk properties. Recording of Munsell color and color by reflectance spectroscopy are tremendously valuable adjuncts to core description. Munsell color determination is valuable as readily communicated designations that can be linked to particular lithologies and interpreted facies. Spectroscopy data are more quantitative and readily plotted against other measured properties to look for lithology-specific indicators and cyclical patterns (see **Chapter 6**).

4.1.4. Bedding and sedimentary structures

Representative symbols used to denote bedding and sedimentary structures are provided in Figure **F4.8**. Examples of these features are illustrated in ODP core images in Technical Note 3 by Marsaglia et al. (2015b; **Appendix D**). This document provides site and sample information that can be useful in the interpretation of similar features found while describing cores. Appendix **A4.1** presents material from the MG Handbook on description of internal sedimentary structures and bedding planes.

4.1.4.1. Bed thickness and attitude

The thickness of a stratified unit (bed/lamina) is measured using a metric scale and described by the following terms and ranges in thickness according to Ingram (1954):

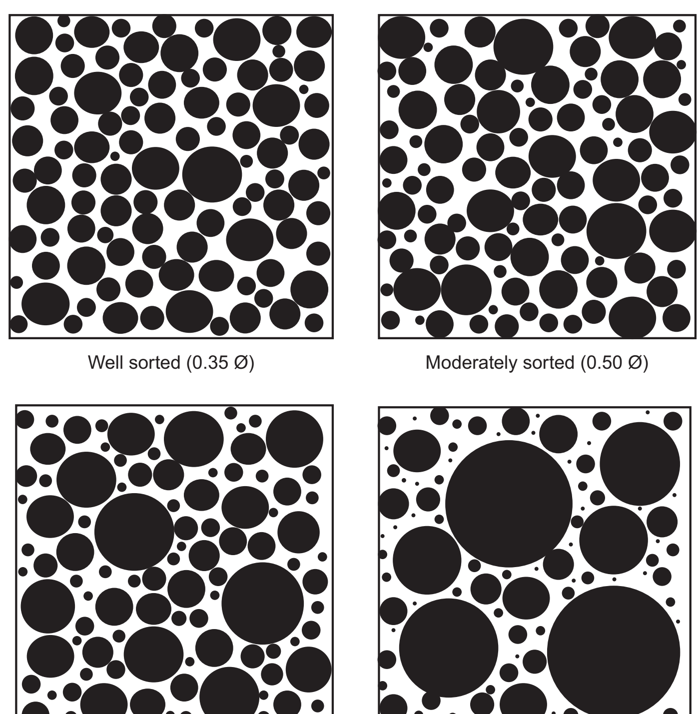

Figure F4.6. Visual images from Harrell (1984) as depicted in Boggs (2011) for estimating grain size and sorting; verbal terms for sorting description (e.g., poorly sorted) are as defined by Folk for different phi (standard deviation) values.

- Very thick bedded (>100 cm);
- Thick bedded (30–100 cm);
- Medium bedded (10–30 cm),
- Thin bedded (3–10 cm),
- Very thin bedded (1–3 cm), and
- Laminated (<1 cm).

We should mention that a similar thickness hierarchy (very thick to very thin) can be used to denote color banding where lithological changes are gradual and not marked by distinct bedding planes.

The attitude (apparent) of a bed within a core may be horizontal or inclined and may be the product of natural sedimentary or tectonic forces or an artificial product of drilling disturbance. The apparent attitude of a bed should be noted if it is not horizontal and should be measured with a protractor (apparent dip) if the inclination is natural (that is, not the product of drilling disturbance). In a succession of variably inclined beds, the range of attitude can be noted. More detailed analysis may be the purview of the structural geology team. If no structural geologists are designated shipboard, then refer to previous expeditions' structural core description methods (e.g., Expedition 362; McNeill, Dugan, Petronotis, et al., 2017).

4.1.4.2. Nonbiogenic sedimentary structures and bedding planes

Sediments and sedimentary rocks can contain one or more types of sedimentary structures. The origin of sedimentary structures can be mechanical (formed during or shortly after the deposition of the sediment), biogenic (formed by reworking of sediment by biota), or chemical (formed by chemical processes after deposition). For example, the lower contacts of stratification features (bedding planes) can be described based on their geometry (irregular, planar, curviplanar, and wavy), appearance (sharp, gradational), origin (hardground), modification (bioturbated), and orientation (horizontal, subhorizontal, inclined, subvertical, and vertical). Sediment in a bed can be ungraded (massive), normally graded (fining upward), or inversely graded (coarsening upward). Lamination within a bed can be parallel to cross-laminated. Some of the structures more commonly observed in ODP and IODP cores are further described by Mazzullo and Graham (1988) in **Appendix A** and pictured in Marsaglia et al. (2015b; **Appendix D**). Very low angle cross-lamination can be difficult to document in core as opposed to outcrops, especially in mud and mudstone where they may appear as parallel lamination at the core scale. Complete descriptions and illustrated examples of sedimentary structures are available in a number of references and sedimentology textbooks in the shipboard library.

4.1.4.3. Biogenic sedimentary structures (bioturbation)

Since the advent of the MG Handbook, there have been significant advancements in the study of sediment modification by burrowing organisms (ichnology). One advance has been the recognition of very intense bioturbation that may either completely homogenize the sediment or, ironically, allow fairly detailed preservation of primary structures through the pervasive action of

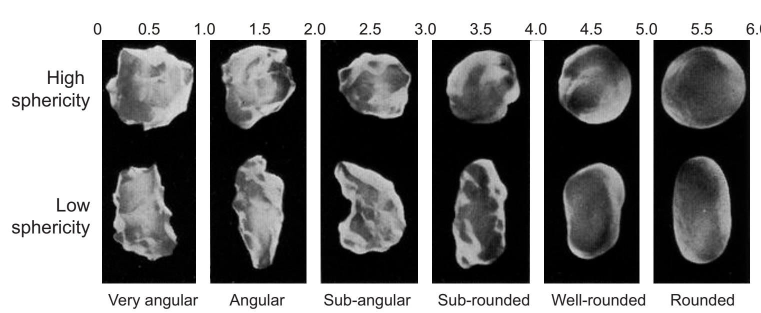

Figure F4.7. Grain rounding scale modified from Powers (1953) with the numerical rounding scale (rho values) of Folk (1955). Grain views provide perspectives on sphericity.

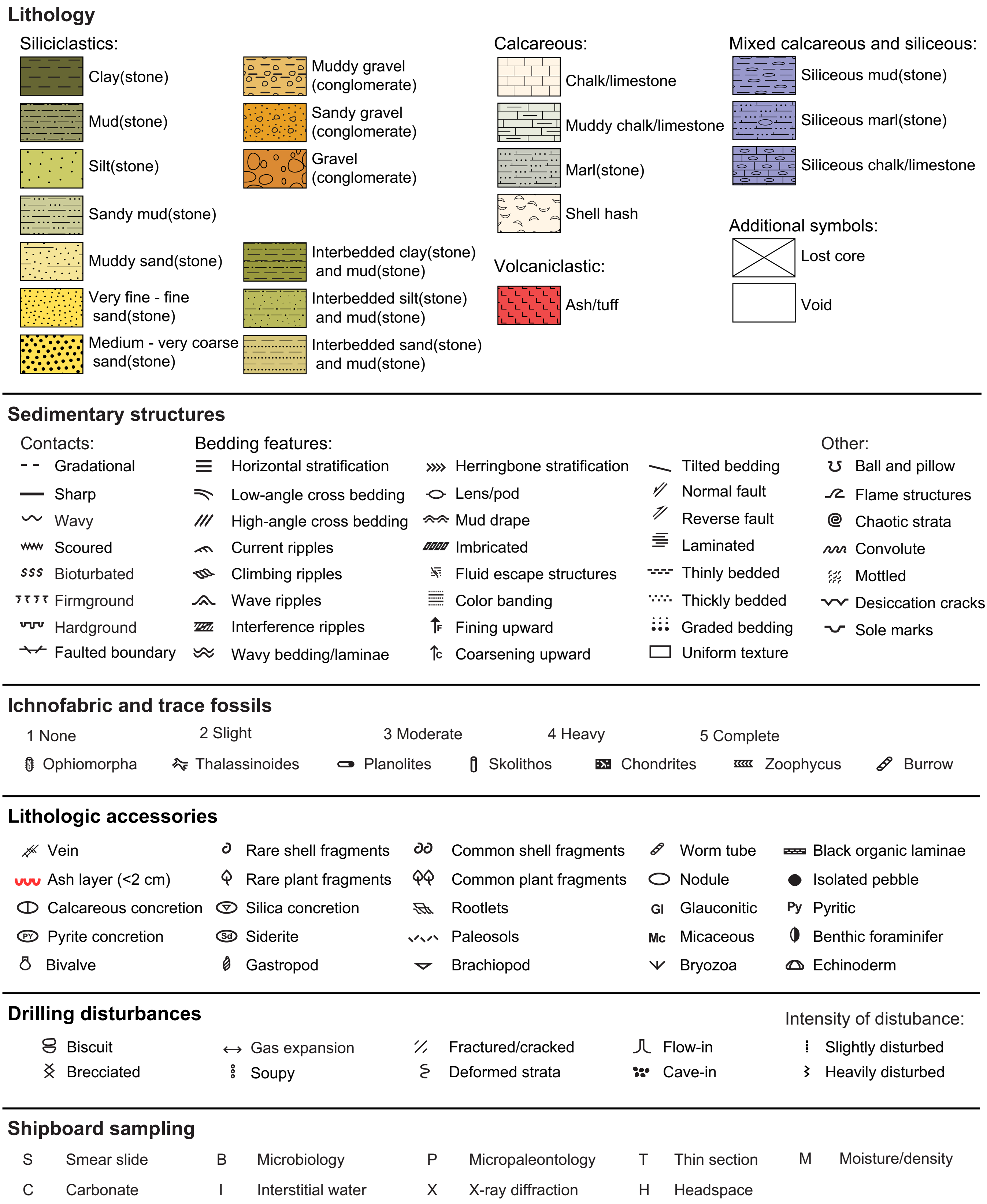

Figure F4.8. Examples of symbols used to denote lithology, sedimentary structures, trace fossils, accessories, drilling disturbance, and samples on VCDs from Expedition 317 (Fulthorpe, Hoyanagi, Blum, et al., 2011). Note that this listing is not complete; see other Expedition *Proceedings* volumes for additional symbols.

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minute fauna (meiofauna) (Pemberton et al., 2008). Other detailed works have further explored the significance of bioturbation features, for example Knaust and Bromley's (2012) edited volume on bioturbation distribution and characterization in various sedimentary environments.

Discrete burrow types can be identified in the core (see Knaust, 2017, and Marsaglia et al., 2015b; **Appendix D**, for examples) and ichnofabric evaluated in terms of the extent of bioturbation within a given core interval. The degree of bioturbation can be assessed semiquantitatively using visual comparator charts. One option employed by Expedition 317 sedimentologists (Fulthorpe, Hoyanagi, Blum, et al., 2011) was a version of the ichnofabric index (1–5) simplified from Droser and Bottjer (1986), Droser and O'Connell (1992), and Savrda et al. (2001) by eliminating "sparse." In this numbered scheme 1 = no apparent bioturbation; 2 = slight bioturbation; 3 = moderate bioturbation; 4 = heavy bioturbation; and 5 = complete bioturbation (no depositional structure remaining) (Figure **F4.9A**). These indexes are illustrated using the numerical scale in the ichnofabric column of the standard graphic reports. Sediments without recognizable depositional or biogenic structures are recorded as Level 1 on this scale but may be extreme versions of Level 5, where proof of bioturbative homogenization may lie in X-ray radiographic imaging of core segments (see **Section 6.4**, XMSL). Alternatively, degree of bioturbation can be indicated symbolically by 1 squiggle (rare or sparse), 2 squiggles (moderate), or 3 squiggles (strong or common to abundant), as pictured by the Expedition 305 scientists (Blackman, Ildefonse, John, Ohara, Miller, MacLeod, et al., 2006) in Figure **F4.9B**. No symbols were used for areas without burrows, including intact and homogeneous sections that could result from complete bioturbative mixing.

4.1.4.4. Complex beds and depositional units

Individual bedding or depositional units may combine a variety of sedimentary structures and lithologies. A classic example is a fining-upward Bouma sequence. We note that such features rep-

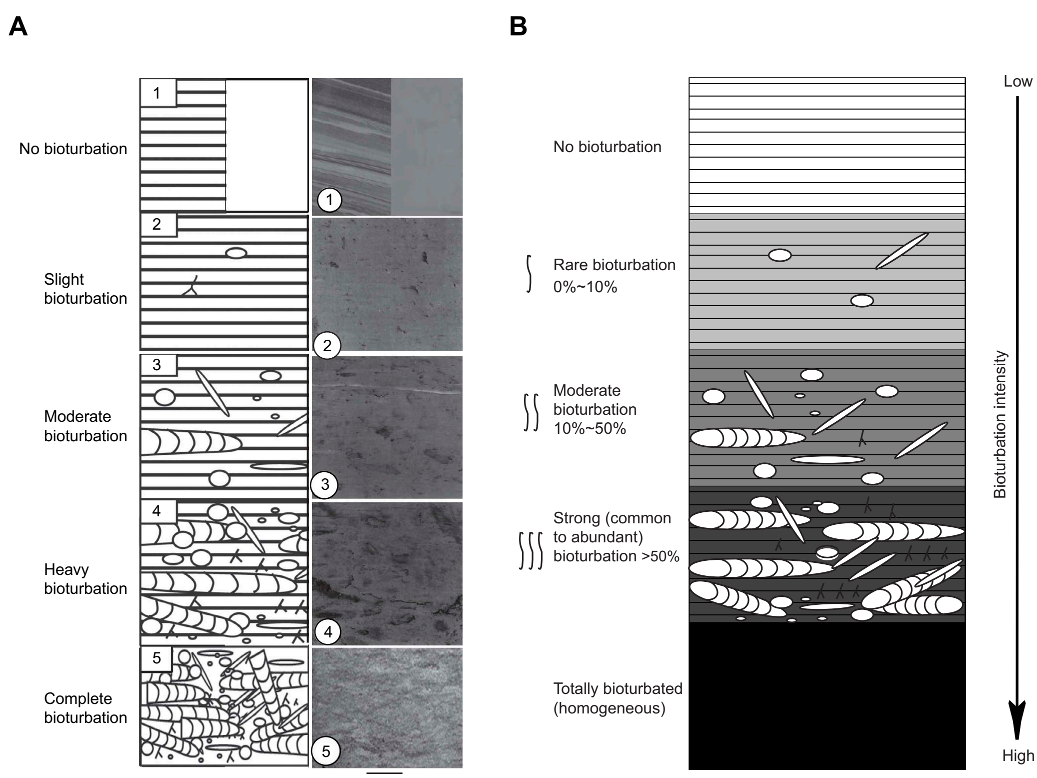

Figure F4.9. A. Schematic and core examples of bioturbation indices used during Expedition 317 (Fulthorpe, Hoyanagi, Blum, et al., 2011, as modified from Droser and Bottjer, 1986, and Savrda et al., 2001). B. Bioturbation indices used during Expedition 306 (Channell, Kanamatsu, Sato, Stein, Alvarez Zarikian, Malone, et al., 2006, as modified from Droser and Bottjer, 1991). Note the "squiggle" symbols on left increase in number with bioturbation intensity.

resenting event bed sedimentation are readily visible in core but must be deconstructed into intervals by sediment type and sedimentary structure for inclusion in a shipboard database such as GEODESC or DESClogik. Note parsing this descriptive information into intervals, some overlapping, may render these features unrecognizable in a database format where it is hard to "see" combinations of lithologies, structures, and bedding planes simultaneously. Successions with such complex beds benefit from description using sedimentary core description forms described in the next section.

4.2. Shipboard database and construction of visual core description (VCD) sheets

Lithologic data and core attributes from the core archive half are digitally entered into a customized template in a description application such as GEODESC or DESClogik on the JR or on shore. The template is constructed prior to drilling and core description (see **Chapter 2**) in collaboration with the onboard Publications Specialist.

On the JR, the number of core describers active at the core description table can range to as many as four or more, with one describer likely focused on smear slide analysis. If description data are entered into the database directly on the core-table computer console, the team dynamic will influence the exact method used. The simplest scenario is one describer per core. This can be a lonely task, with the format of entry a function of the individual's preferences. The most efficient scenario that we have used is to work in teams of two per core, with core describers generally focused on observations of one element (a sheet in database) at a time. One team member pronounces interval information (section number, interval top and bottom in centimeters), and the other types the information into the database. An example workflow for a team would be to describe drilling disturbance first, then color, and then intervals exhibiting sedimentary structures and bioturbation (type by type), bedding planes, tectonic structures, and other features. The last element described is often the names of fine-grained lithologies, as they are based on smear slide analysis that takes some time to process. This element-by-element analysis is a simple routine that can be taught to nonsedimentologist core describers (e.g., Expedition 351 [Arculus, Ishizuka, Bogus, et al., 2015]) and is useful in high-core recovery situations or when cores are rather featureless.

Data collected are used to generate summaries of the core called *visual core descriptions* (VCDs). VCDs are equivalent to the barrel sheets used during the Deep Sea Drilling Project (DSDP), Ocean Drilling Program (ODP), and into the Integrated Ocean Drilling Program. Strater, a commercial plotting software, is currently used to compile the digital VCD plots for each core using the data retrieved from the description database. VCDs provide a summary of the lithologic composition and age (based on biostratigraphy and magnetostratigraphy) and can be combined with downhole data obtained from other shipboard analyses (see example in Figure **F4.10**). A variety of information can be displayed including core depth below seafloor, core length (in centimeters), digital color image of the core, graphic lithology column, section breaks, lithostratigraphic unit, age, locations of shipboard samples taken from the core, drilling disturbance, bioturbation, lithologic accessories, sedimentary structures, and petrophysical data (e.g., from the logging tracks: Whole-Round Multisensor Logger [WRMSL], Section-Half Multisensor Logger [SHMSL], Section-Half Imaging Logger [SHIL], X-ray scanner [XMAN/XSCAN], and/or Natural Gamma Radiation Logger [NGRL]), such as NGR, GRA porosity, MS, lightness, and color reflectance.

The format of the VCD is tailored to the expected needs of the expedition sedimentologists based on their understanding of the likely stratigraphy to be encountered. The VCD template is customized to include description form categories (e.g., lithology, drilling disturbance, and bioturbation). See the core description software manuals for detailed description of the potential elements and construction of the spreadsheets. The template may be modified during the cruise as needed to reflect changes in the core or unexpected attributes, but it is critical that the Publications Specialist be constantly apprised of any needed modifications. The sedimentology group takes the lead on

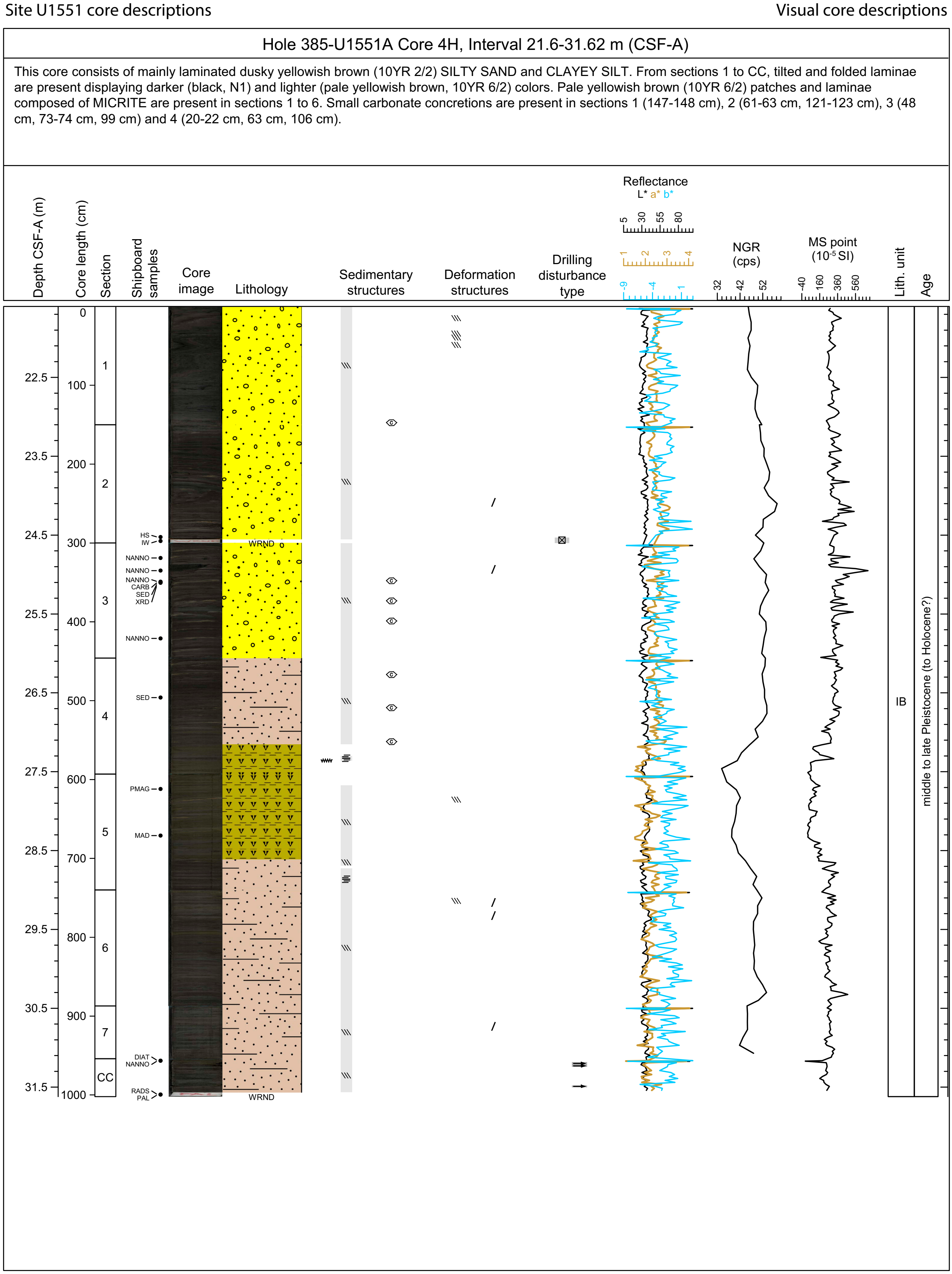

Figure F4.10. Example VCD sheet for Core 385-U551A-4H, 2.6–31.62 m (Teske, Lizarralde, Höfig, et al., 2021).

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the organization and elements of the VCDs in collaboration with other groups, who add physical properties, structural descriptions, and biostratigraphic data.

An important aspect is the lithostratigraphic summary or "Lithologic Description" written by the core describer and uploaded into the database. These summaries contain a succinct overview naming the major and minor lithologies in the core, their Munsell color (using both descriptive terms and hue-chroma-value alphanumeric data), and notable features such as sedimentary structures, bedding, contacts, diagenetic features (e.g., authigenic precipitates), extent of lithification, and major disturbances resulting from the coring process. See **Chapter 7** for further important information on writing the lithostratigraphic summaries. The data and lithostratigraphic summaries for a given core should be entered while the core is being described, or as soon as possible after the core has been described.

The VCD template is described in the Methods chapter. Usually, a preliminary format is modified as results come in from the first holes, with the ultimate goal of a uniform format that will be applied to all site results. Modifications typically include graphic lithologic patterns, structure and drilling disturbance symbols (e.g., Figure **F4.8** an example from Expedition 317 [Fulthorpe, Hoyanagi, Blum, et al., 2011] showing a variety of lithologies and sedimentary structures). VCDs are published in the *IODP Proceedings* volume for the expedition and provide the only complete core-scale summary of the drilling site stratigraphy seen by the general scientific community.

4.3. Construction and use of sedimentary core description forms (CDF)

As mentioned above, core description data for IODP expeditions are entered in the database (e.g., DESClogik, GEODESC). For sedimentological analysis, it is a recommended option that the data be first summarized on sedimentary core description forms. If the handwritten form is used, *a written sedimentary core description form (CDF) is completed for each section of each core (including the core catcher).* The CDF is the most detailed summary of the stratigraphy, bed thickness, lithology, and structures of the sediments or sedimentary rocks at the drilling site and should be completed with careful attention. These forms are effectively field notes that can be scanned and archived with the other site data (also see MSPs, **Chapter 8**). During the cruise, they are an invaluable resource for maintaining consistency of description between shifts and summarizing information for the site chapters, and they also are important reference materials for postcruise studies. Sedimentary core description forms, when utilized, retain a truer holistic core description for sedimentological purposes and show all of these data in an integrated visual format which can then be easily deconstructed to enter into the database. It is understandable that high core recovery and other situations listed in **Section 4.1** may not be compatible with full use of the CDF, but every effort should be made to apply this approach, if not at the scale of sections at least at the scale of a core as explained below.

A blank CDF form for sediments and sedimentary rocks is shown in Figure **F4.11**, as a series of columns bordered by a linear scale in centimeters. This can be linked to section scan imagery to integrate a core image (discuss with shipboard technicians or Publications Specialist, as unprocessed images may be too dark to discern details). Examples of completed forms are provided in Figures **F4.12** and **F4.13**. Text on the CDF must be written legibly (dark #2 pencil or black ink scans best) and in English. Note that for monotonous, relatively featureless stratigraphic sections, a full-core version of this form can be used by expanding to a legal page size (8.5 inches × 14 inches; Figure **F4.14**). To facilitate entry into the shipboard description software, centimeter intervals of all features should be provided, as shown in the example images in Figures **F4.12** and **F4.13**.

The elements of the CDF form are listed below (refer to Figures **F4.12** and **F4.13**):

1. Title boxes (upper right corner): identify the core section being described (expedition, site number, hole letter, core number and type, section number, and the initials of the observer).
2. Indicate voids in the core section by a broad "X" that crosses all six columns. List centimeter intervals for each gap in the core and indicate the origin of the gap: unknown origin (VOID:

some due to gas expansion), intervals where whole-rounds were removed for interstitial water (IW), physical properties (PP), organic geochemistry (O), and other analyses (label as such).

3. Indicate base of section by marking a line at end of section (interval in centimeters). If the section is not a full 1.5 m length, provide centimeter length and check against curated length in

A

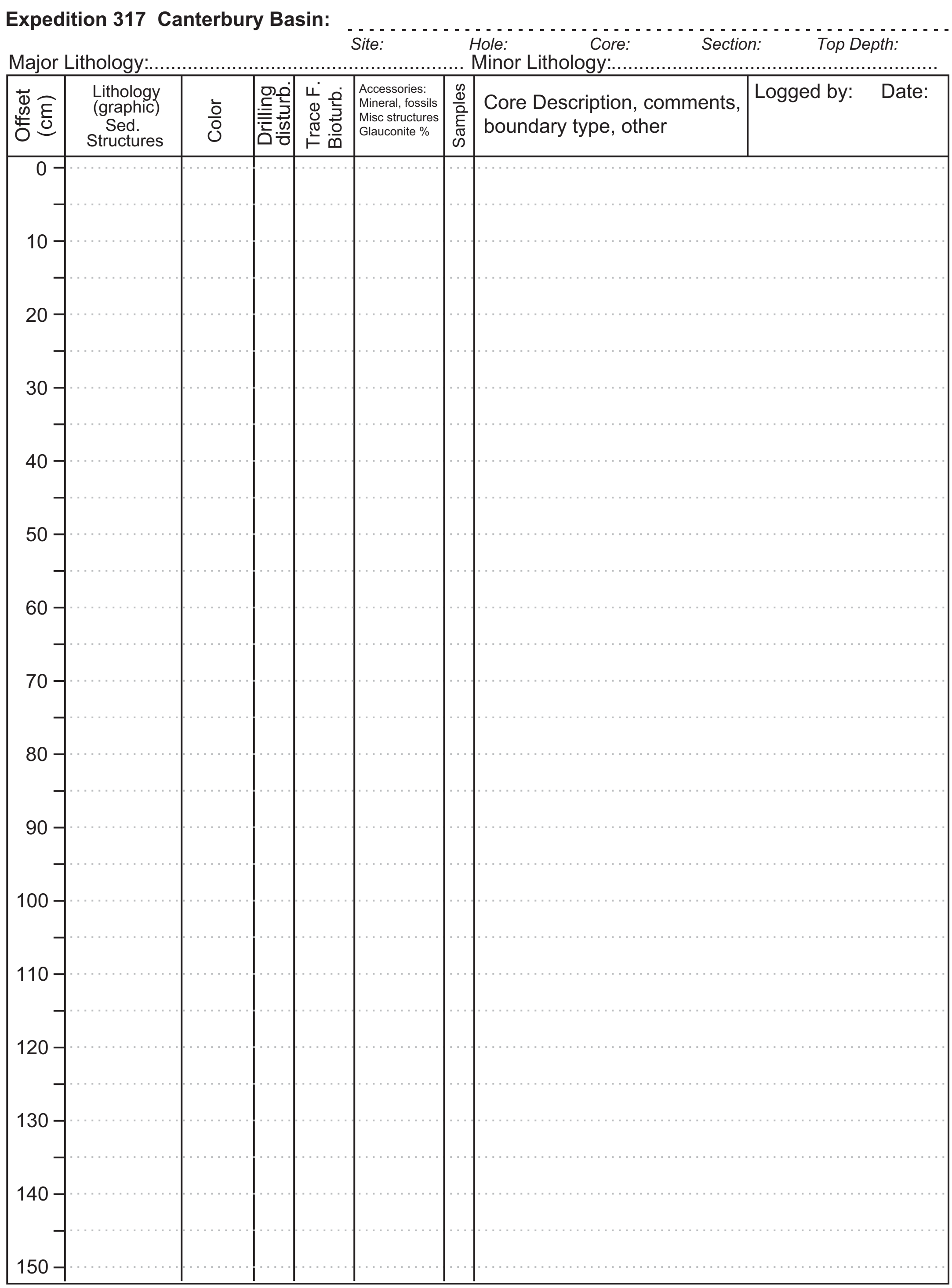

Figure F4.11. A. Blank CDF form for sediments and sedimentary rocks from Expedition 317 (Fulthorpe, Hoyanagi, Blum, et al., 2011). B. Figure continued on next page.

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B

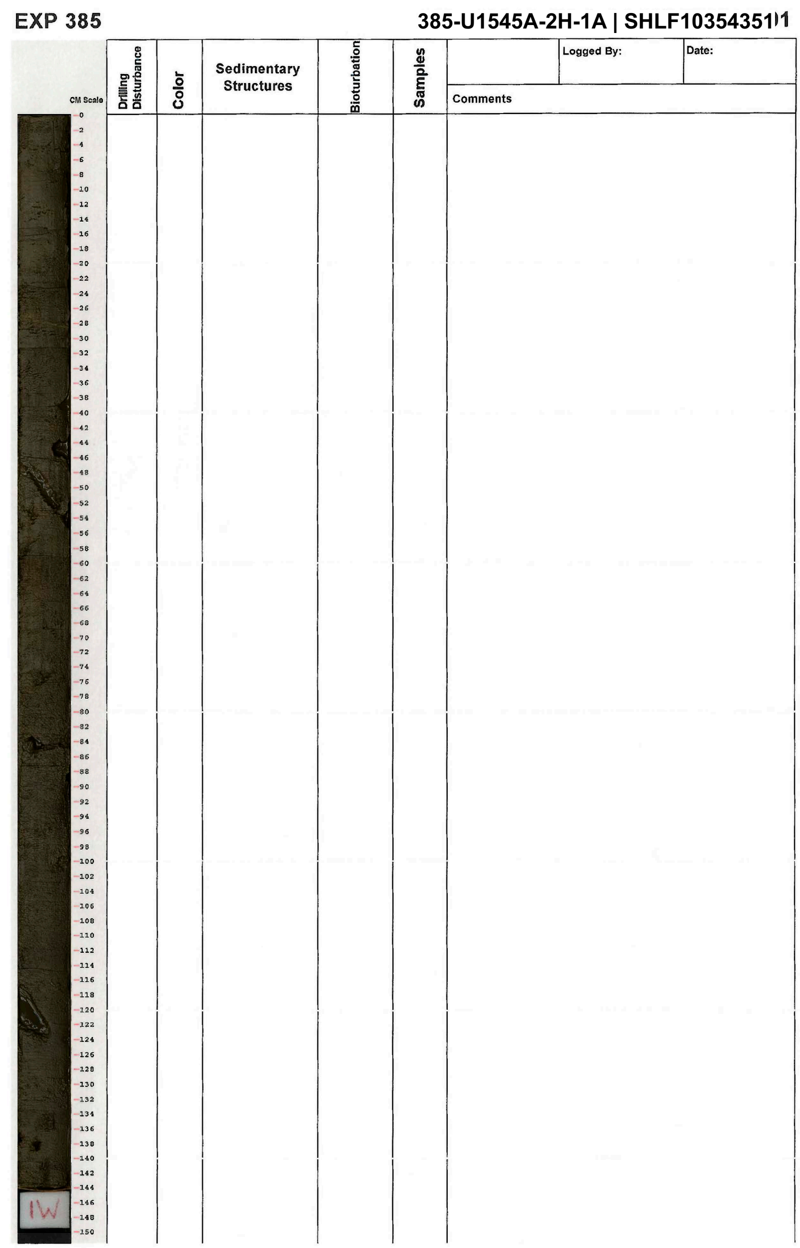

Figure F4.11 (continued). B. Section image has been inserted into far left column of Expedition 385 CDF form (Teske, Lizarralde, Höfig, et al., 2021).

the database, as that length is used to create VCDs (see next section) from core description software entries.

4. Image file: a section image can be placed in the first column (see **Chapter 6**).
5. Piece #: insert piece number, if applicable, for broken indurated core (determined by curator).
6. Graphic representation: sketch the arrangement, size, and shape of indurated core pieces and drilling disturbance effects (e.g., brecciation, biscuiting, flow-in, or other unique core features) to allow easier correlation with core images.
7. Drilling disturbance: record drilling effects on internal stratification and coherence of sediments and sedimentary rocks using graphic symbols shown in Figure **F4.8**. Drilling disturbance examples are shown in Marsaglia et al. (2017) and Jutzeler et al. (2014). Figure **F4.3**

shows a generic figure compiled from these sources. An expedition-specific figure can be compiled for the methods chapter with examples of the different deformation styles in expedition cores.

8. Color: use Munsell soil color charts (Munsell Color Company, Inc., 2000) to qualitatively describe the hue, value, and chroma (e.g., 10YR 8/2, very pale orange; including both alphanumeric and color name is important) of the sediment(s) in each bed in the core section. Do not lay the color page directly on the core face; instead, compare a small sample (tip of toothpick or small fragment held by tweezers) from the core edge (be careful to select from coherent core)

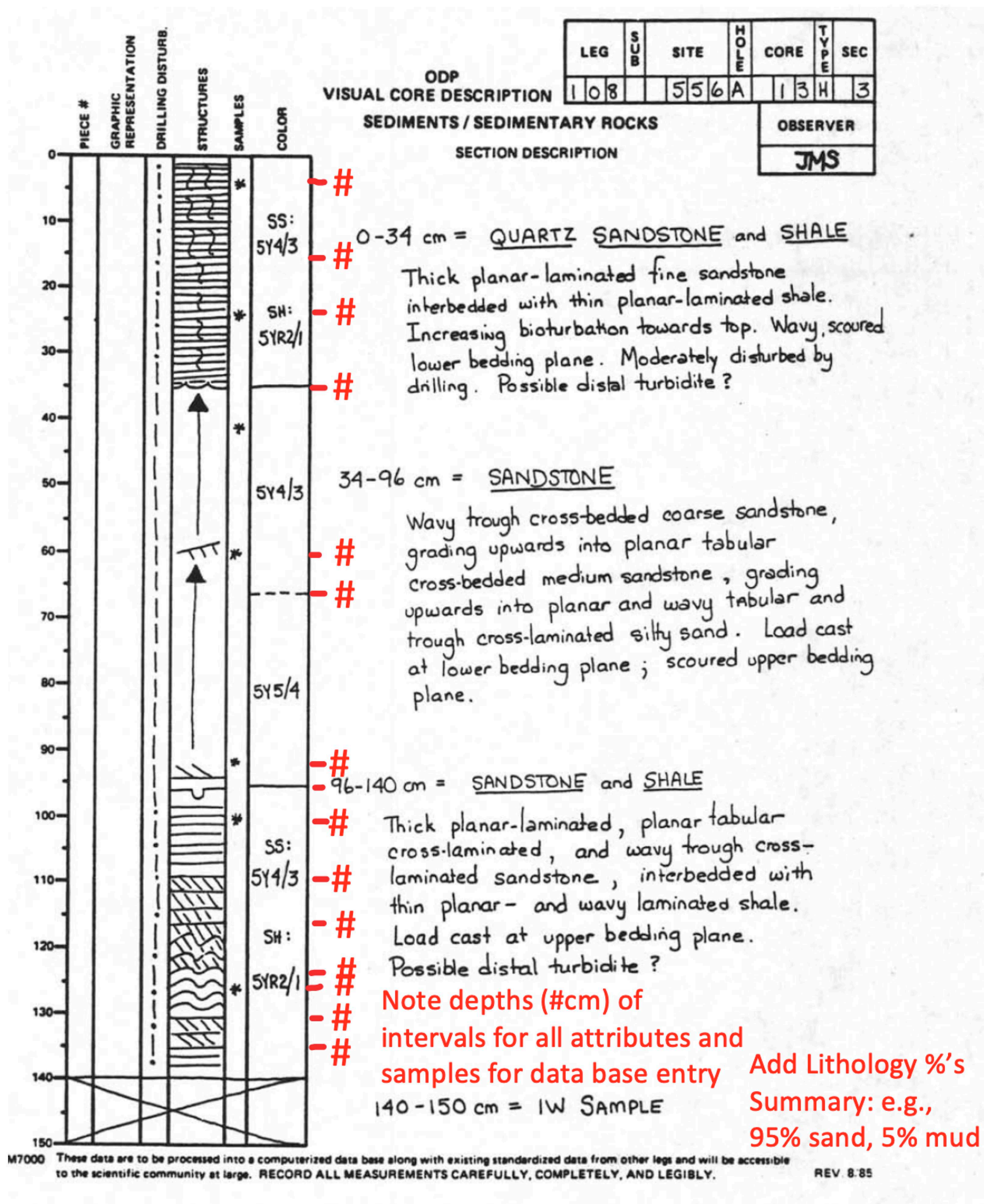

Figure F4.12. Example of a completed CDF form for a siliciclastic section from Mazzullo and Graham (1988) modified to show additional interval depths (#) needed to enter descriptive information into database (e.g., GEODESC or DESClogik). Also suggested is the addition of a core summary with information on the percentages of lithologies (can be added for each section or as a summary on the last section sheet).

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to Munsell color chips. Try to be uniform in color options across describers and shifts (to prevent patterns in data associated with shift changes). If a bed contains two or more sediment types, clearly indicate the color of each type. If a bed grades upward from one color to another, indicate the colors at the extreme upper and lower parts of the bed separated by a dashed line. Color mottling may be linked to bioturbation or diagenesis; mottled color end-members may be indicated over an interval.

9. Structures and notable features: illustrate bedding planes (horizontal, heavier lines), thickness, and sedimentary structures (thinner lines) of each bed in the core section. Bedding planes are

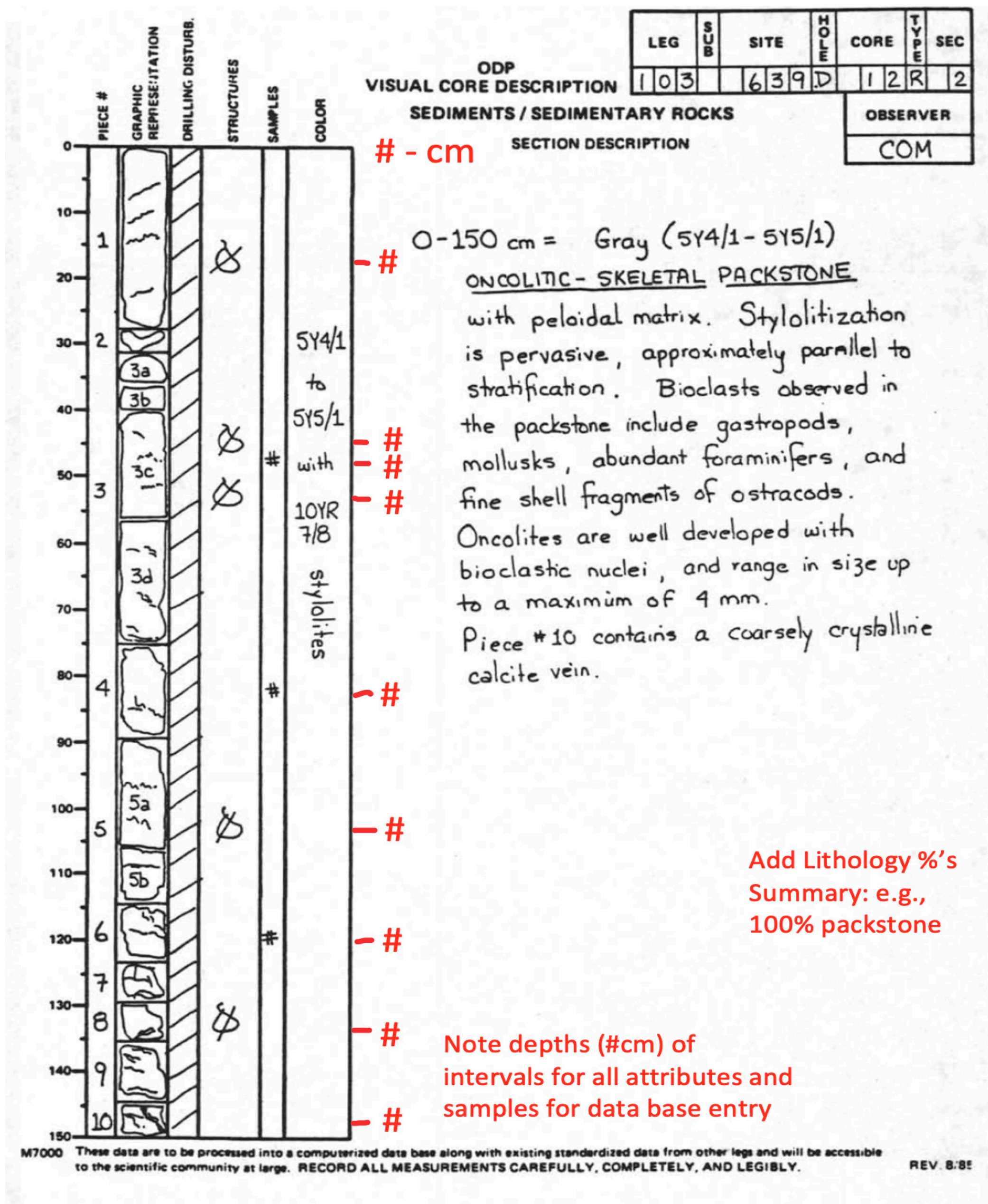

Figure F4.13. Example of a completed CDF form for a carbonate section from Mazzullo and Graham (1988) modified to show additional interval depths (#) needed to enter descriptive information into database (e.g., DESClogik). Also suggested is the addition of a core summary with information on the percentages of lithologies (can be added for each section or as a summary on the last section sheet).

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generally illustrated by solid or dashed lines (for abrupt and gradational contacts, respectively) that are planar or wavy (and inclined when the bedding is inclined); use additional symbols for erosive lower bedding planes and bedding planes with distinctive surface and sole marks (Figure **F4.8**). The types of internal sedimentary structures and their vertical sequences within a bed are also graphically represented in this column (Figure **F4.13**). Massive bedding, repeated patterns of interbedding of two or more lithologies, or color banding (rhythmic bedding) are other options indicated using symbols, as well as bioturbation (degree and discrete burrow

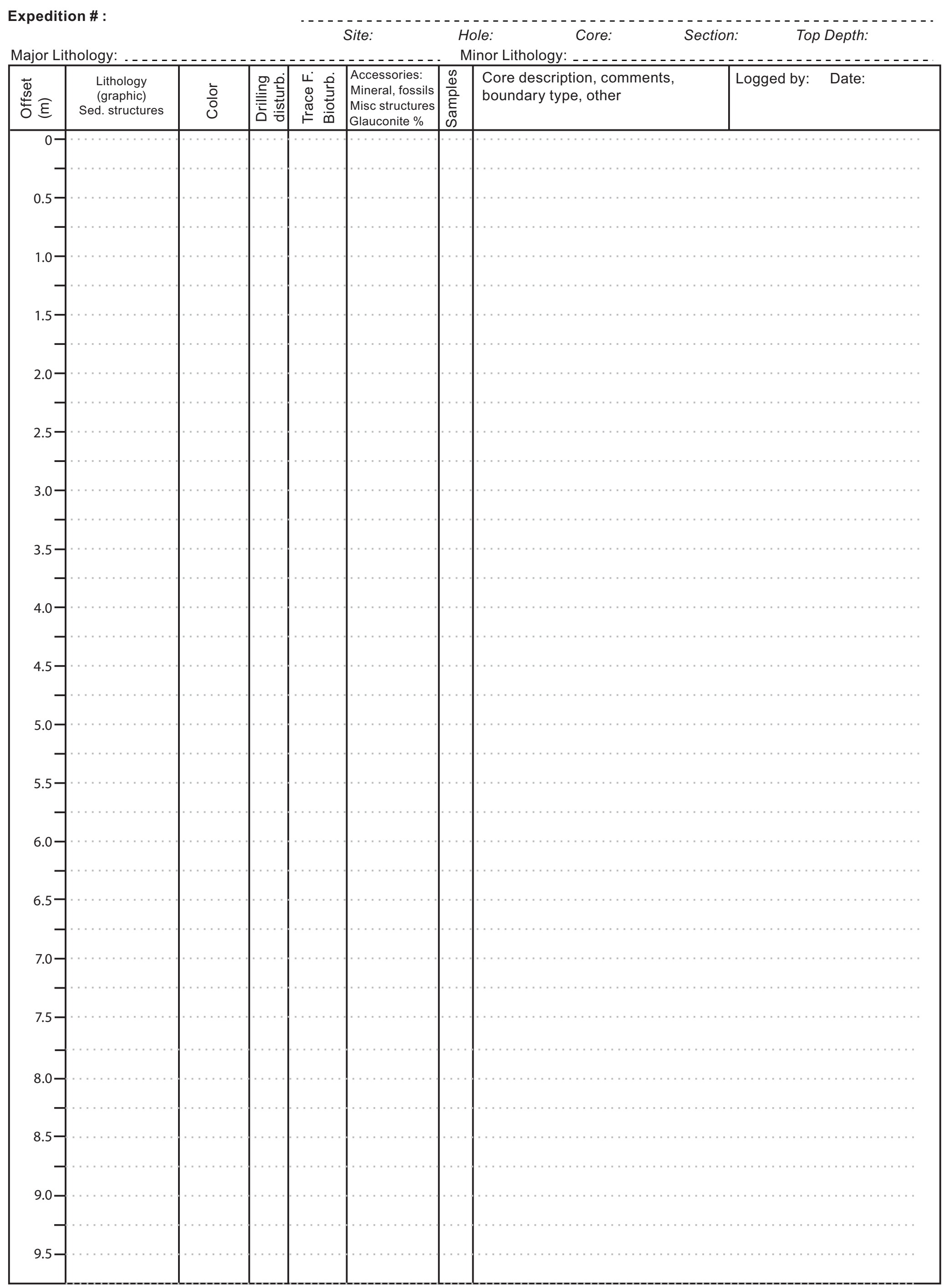

Figure F4.14. Full-core (9.5 m) version of a blank CDF form for monotonous successions.

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types). Minor but notable features include macrofossils, lenses, nodules of different sediment types, and other diagenetic features (see features and symbols in Figure **F4.8**).

10. Samples: mark the locations of all relevant samples collected from the core, archive (smear) or working (thin section, carbonate/TOC, XRD) halves of the section for routine shipboard analyses (as listed below): required (a, b), strongly suggested (c, d, e), optional (f, g). Complete a record of the results of the lithologic analyses for all smear slides or thin sections noted.
    a. Smear slides: asterisk (*) and interval in centimeters
    b. Thin sections: pound sign (#) and interval in centimeters
    c. X-ray diffraction: XRD and interval in centimeters
    d. Total organic carbon: TOC and interval in centimeters
    e. Total carbonate: CARB and interval in centimeters
    f. Moisture and density: MAD
    g. Paleomagnetics: PMAG
11. Detailed description and other information (determination of lithology by visual inspection): at the right side of the CDF form include a detailed written lithology description of each bed or core interval of interest. For each bed (or interval or depositional unit), the following data should be routinely reported:
    a. lnterval (in centimeters) that is occupied by the bed (e.g., “10–45 cm”)
    b. Indication of major vs. minor lithologies
    c. Lithology of the sediment(s) in the bed determined according to **Chapter 4** (use capital letters and underline)
    d. Internal sedimentary structures including bioturbation; types of bedding contacts (sharp, gradational, planar, or wavy) and surface and sole marks
    e. Preliminary interpretation of the genesis of the bed (e.g., “Note: may be contourite?”), if desired. However, the CDF form is intended to contain description rather than interpretation of the cores, so any interpretations or genetic descriptors such as “turbidite” or “debris flow” should be kept out of the main body of the description.
    f. As in sedimentological field work, it is useful to sketch relationships for future reference and highlight specific structures or features that may be used in the site report. This can be done in this area of the form as well.
    g. Note that care must be taken to link a section description with that of the previous and next section, especially where thick beds may straddle core boundaries or where recovery rates dramatically change from section to section. Similarly, linkages from core to core, Section 1 vs. Section CC in previous core, and so on.
    h. Normally the CC section is short. This is a perfect point in the core description to write the core summary for use in the VCD (see next section).
    i. Note that it is also important to note intervals of interest where close-up photographs have been requested or images might be used in the site report.

To aid in core description, core data can be displayed graphically in the LIMS Information Viewer (LIVE, version 4.0), a separate browser-based application that displays core images alongside physical properties, section photos, and geochemical data. These can be projected on screens associated with the core description table.

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5. Petrologic sample description procedures

The basic procedures for petrologic description of marine sediments and sedimentary rocks have changed little since Mazzullo and Graham (1988) (MG Handbook). Details of smear slide production and description are given in Technical Notes 1 and 2 (**Appendix B**; **Appendix C**). The following general guidance quotes extensively from the MG Handbook with many minor edits.

Analyses of smear slides and thin sections are conducted in close concert with analyses of bulk carbonate, organic matter, and XRD mineralogy. Thus, submission of samples for these analyses and receipt of these data types must be carefully coordinated with the geochemistry and XRD labs to ensure timely integration. Smear slide and thin section locations are entered into the curatorial application SampleMaster, marked on the visual core description forms, and ultimately appear on VCDs.

5.1. Smear slides and thin sections

5.1.1. Sample selection

Smear slides of unconsolidated sediment and thin sections of lithified materials are prepared aboard ship to document the lithology of recovered material and to aid in core description. Primarily, these preparations are made from all representative lithologies along with special or unique layers of particular interest. Thus, the number of smear slides (or thin sections) produced is a function of the homogeneity of the sedimentary section.

There are two other things to note about the sampling procedures when combined with other shipboard analyses. First, whenever there are two or more analyses to be conducted on the sediment, it is preferred that they be conducted on a split of the same sample. Second, the archive half of the core that is being described by the shipboard sedimentologists is not to be sampled for any routine lithologic analysis, with the exception that the archive half may be scraped for a smear slide to determine the general lithology of the sediment. However, once this determination is made, a larger sample (same horizon, lithology, sediment color) must be collected from the working half of the core for the full complement of petrographic, geochemical, and/or XRD analyses. In rare instances, typically in cases of shore-based sampling, the archive half may be sampled with special permission of the Curator.

Locations of smear slides and thin sections are entered into the database system after which labels are created. Guidance on this process can be obtained from the Curator or science technicians at the beginning of the cruise.

5.1.2. Thin section requests

JR thin section user guides: **https://wiki.iodp.tamu.edu/display/LMUG/Thin+Sections**.

The smear slide technique is best used on unconsolidated sediments but, as described in Marsaglia et al. (2013, 2015a), it can also provide useful and rapid information from scrapings of recovered rocks.

Lithologies of lithified rocks in most cases are better determined using thin section petrography. This requires designating samples to be taken from the working half of the core. These are labeled TSB (thin section billet) samples. First and foremost, sedimentologists must follow instructions from the Curator on sample selection and volume allowed. Thin sections are normally requested as part of the shipboard sampling routine. Requests for thin sections should be limited to certain critical samples, as the capacity for shipboard thin section production is limited (see **Section 5.1.3**). Residues from thin section production are considered core material and may be requested for additional analyses.

The scientists responsible for petrographic data should visit the thin section lab early in the cruise to meet the technician and to learn about the status of the lab's thin sectioning capabilities and expected production times.

5.1.3. Fabrication of smear slides and thin sections

Smear slides are produced by the sedimentology team (see IODP Technical Notes 1 and 2 [**Appendix B** and **Appendix C**]), but thin sections are produced shipboard by a designated technician using cutoff saws and grinding equipment housed in a designated laboratory. Smear slides are produced within minutes, but thin sections may take days; note that silt-sized rock scrapings from a consolidated core may provide some quick useful information on components and their mineralogy and help target the best horizon for thin sectioning in a core. Success with thin section production, especially in the case of semilithified materials, depends on the skill of the thin section technician. Sections are generally polished and left uncovered and placed in a designated thin section box by the technician. Coverslips should be applied with index oil before microscopic study.

5.1.3.1. Staining thin sections

The thin section lab may have limited capability for staining thin sections, although it is generally discouraged because of safety concerns. Check with the technician if staining might be needed. Elemental analysis by energy dispersive spectroscopy (EDS) analysis on thin sections in the SEM may be a favorable alternative for determining specific component mineralogy.

5.1.4. Description of smear slides and thin sections

IODP Technical Notes 1 and 2 (Marsaglia et al., 2013, 2015a; **Appendix B**, **Appendix C**) provide a detailed guide to selection, production, description, and interpretation of smear slides. Information in these atlases is only very generally repeated here. Knowledge represented in Technical Notes 1 and 2 should be within the scope of expertise of sedimentology team members responsible for collection of smear slide data. Much of the information presented for smear slides can be also applied to thin sections, along with guidance from other description resources listed in Table **T5.1**.

Paper smear slide and thin section description forms (Figures **F5.1**, **F5.2**) are used for data entry at the microscope and should be preserved as a backup in case of computer system failure or inadvertent data erasure. See information on these forms in **Chapter 2**. It is useful to note on these forms a variety of observations that may be used in the site reports or in postcruise studies.

Table T5.1. Resources for microscopic identification of sedimentary rock components.

Adams, A.E., and MacKenzie, W.S., 1998. A Colour Atlas of Carbonate Sediments and Rocks Under the Microscope. London: Manson Publ. Ltd.
Adams, A.E., MacKenzie, W.S., and Guilford, C., 1984. Atlas of Sedimentary Rocks under the Microscope. New York: Wiley.
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Flügel, E., 2004. Microfacies of Carbonate Rocks. Berlin: Springer.
Folk, R.L., 1980. Petrology of Sedimentary Rocks. Austin: Hemphill Publ. Co.
Haq, B.U., and Boersma, A. (Eds.), 1978. Introduction to Marine Micropaleontology. New York: Elsevier North-Holland.
Horowitz, A.S., and Potter, P.E., 1971. Introductory Petrography of Fossils. Berlin: Springer-Verlag.
Lazar, O.R., Bohacs, K.M., Schieber, J., Macquaker, J.H.S., and Demko, T.M., 2015. Mudstone Primer: Lithofacies variations, diagnostic criteria, and sedimentologic/stratigraphic implications at lamina to bedset scale. Society for Sedimentary Geology: Concepts in Sedimentology and Paleontology, 85.
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Marsaglia, K.M., Milliken, K.L., Leckie, M., Tentori, D., and Doran, L., 2015. IODP smear slide digital reference for sediment analysis of marine mud. Part 2: Methodology and atlas of biogenic components. IODP Technical Note 2.
Milliken, K.L., and Choh, S.-J., 2011. Carbonate Petrology: An Interactive Petrography Tutorial, v. 1.0. Tulsa: AAPG Discovery Series 15.
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Nesse, W.D., 2013. Introduction to Optical Mineralogy. New York: Oxford Univ. Press.
O'Brien, N.R., and Slatt, R.M., 1990. Argillaceous Rock Atlas. New York: Springer-Verlag.
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Scholle, P.A., 1979. A Color Illustrated Guide to Constituents, Textures, Cements, and Porosities of Sandstones and Associated Rocks. Tulsa: AAPG Memoir 28.
Scholle, P.A., and Ulmer-Scholle, D.S., 2003. A Color Guide to the Petrography of Carbonate Rocks: Grains, Textures, Porosity, Diagenesis. Tulsa: AAPG Memoir 77.
Ulmer-Scholle, D., Scholle, P. A., Schieber, J., and Raine, R. J., 2014. A Color Guide to the Petrography of Sandstones, Siltstones, Shales, and Associated Rocks. AAPG Memoir 109.
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5.1.4.1. Description aids

Charts for the sediment classifications selected for the methods section and for percentage estimation are normally posted in the microscope area early in the cruise. Various references are available for identification of sedimentary rock components, textures, porosity, and authigenic phases (listed in Table **T5.1**). Estimating percentages of components requires a good set of comparison charts. See discussion in Marsaglia et al. (2013, 2015a).

IODP Expedition 317

SEDIMENT SMEAR SLIDE & THIN SECTION WORKSHEET

Leg	Site	Hole	Core	Type	Sec	Interval (cm) Top	Interval (cm) Bottom
317							

Sediment/Rock Name		Observer	

SMEAR	Thin Sect

Dominant	Minor

Percent Texture		
Sand	Silt	Clay

Percent	Component
	SILICICLASTIC GRAINS/MINERAL
	Framework minerals
	Quartz
	Feldspar (undifferentiated)
	K-feldspar (Orthoclase, Microcline...)
	Plagioclase
	Rock fragments
	Volcanic glass
	Accessory/trace minerals
	Micas
	Biotite
	Muscovite
	Chlorite
	Clay Minerals
	Glauconite
	Ferromagnesian minerals
	Authigenic minerals
	Zeolite
	Pyrite
	Opaque minerals (undifferentiated)
	Fe-oxide
	Carbonate
	Micrite
	Others

Percent	Component
	BIOGENIC GRAINS
	Calcareous
	Foraminifera
	Nannofossils
	Pteropods
	Ostracodes
	Bioclast (undiferentiated)
	Siliceous
	Radiolarians
	Diatoms
	Silicoflagellates
	Sponge spicules
	Siliceous debris (undifferentiated)
	Others
	Dinoflagellates
	Pollen
	Organic debris
	Plant debris
	Bryozoans
	Echinoderm
	Fish remains (teeth, bones, scales)
	Bivalves
	Others

Comments:

Figure F5.1. Smear slide description template from Expedition 317 (Fulthorpe, Hoyanagi, Blum, et al., 2011). Also see example of smear data sheet in Appendix B (Marsaglia et al., 2015a).

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Thin section data are compiled into a report that shows scans of the entire thin section in plane light and under crossed-polars (see JR user guides: Thin Section Report Builder: **https://wiki.iodp.tamu.edu/display/LMUG/Thin+Section+Report+Builder** and Petrographic Image Capture and Archiving Tool [PICAT]: **https://wiki.iodp.tamu.edu/display/LMUG/PICAT+User+Guide**). These images are taken by a technician using equipment in the microscopy area.

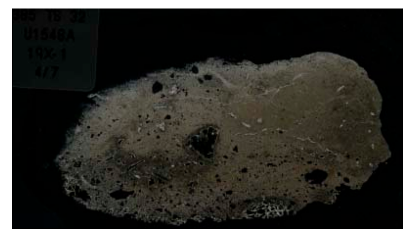
All smear slides and thin sections created shipboard must be described and the data entered into the shipboard core description program (preferably during each shift). The results of petrographic analysis of a sediment or sedimentary rock are best tallied using paper forms (effectively field notes), examples of which are provided in Figures **F5.1** and **F5.2**. The form is created and may be

Site U1548 core descriptions Thin sections

THIN SECTION LABEL ID: **385-U1548A-19X-1-W 4/7-TSB-TS 32** Thin section no.: 32

Observer: KM

Plane-polarized: 54903711 Cross-polarized: 54903731



Sediments and Sedimentary Rock

Lithology: micrite

TEXTURE	Percent	CONSTITUENT	Percent
Sand		Siliciclastic Grains/Mineral	5
Silt		Authigenic Minerals	65
Clay		Biogenic Grains	5
Total Texture		Total Constituent	90

Framework grain abundance

Component	%	Component	%	Component	%
Quartz		Ferromagnesium minerals		Vitric Grains	15
Feldspar		Opaque Minerals		Foraminifera	
Plagioclase		Zeolite		Radiolarians	
Rock Fragments		Pyrite	10	Diatoms	15
Igneous Volcanic Fragments		Quartz (Authigenic)		Organic Debris	
Sedimentary Fragments		Calcite	40	Plant Debris	
Matrix (Silt and Clay)		Dolomite		Fish Remains	
Biotite		Porosity		Other	15
Clay Minerals	5				

Figure F5.2. Thin section description template for soft rock thin section: display mode for Expedition 385 (data and image) Sample 385-U1548A-19X-1-W 4/7-TSB-TS 32 (385-U1548A-19X-1, 4–7 cm) (Teske, Lizarralde, Höfig, et al., 2021).

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modified after the first site, once components are better defined. It is best if elements on the thin section or smear slide description forms correspond in naming and order with the shipboard core description template, as this will facilitate data entry. See the GEODESC user guides (**https://wiki.iodp.tamu.edu/display/LMUG/GEODESC+overview**); further assistance is available aboard ship from the Core Lab technicians and/or the Marine Computer Specialists and Applications Developers.

5.1.5. Photomicrographs to document smear slides and thin sections

JR microscopy user guides at **https://wiki.iodp.tamu.edu/display/LMUG/Microscopy**.

Microscopes are set up onboard to take digital photomicrographs. Pixel resolutions of photographs should be set to produce published photos at around 300 dpi.

In addition to digital entry of image data, it may be useful to keep a notebook listing sample, magnification (i.e., objective used), image type (plane-, cross-polar, or both), and the intended purpose for each photomicrograph. This list contains important information for figure captions and is a valuable resource when selecting photomicrographs for reports and presentations.

5.1.6. Archiving

Thin section and smear slide intervals are marked on VCDs along with other samples (Figure **F4.14**). It is the responsibility of the shipboard sedimentologists to make certain that these intervals are correctly added to the VCDs and ultimately correctly listed in the tables of thin section and smear slide data that are included in the expedition *Proceedings* volume.

Please note that all smear slides, grain mounts, and thin sections are the property of the International Ocean Discovery Program and are collected by the Curator at the end of drilling at each site for archival at the appropriate core repository. However, any of these petrographic slides can be requested from the Curator and checked out for further shore-based analysis. Thin section billet residues are considered to be core material and may also be requested for additional postcruise analyses. Such sample requests are routed through the Curatorial Advisory Board (including the Curator, Co-Chiefs, and EPM) during the data and publications moratorium period.

5.2. Scanning electron microscopy (SEM)

JR SEM user guides: **https://wiki.iodp.tamu.edu/display/LMUG/Hitachi+SEM+User+Guide**.

Although time for this type of study is typically limited, SEM imaging and EDS elemental analysis are possible on the JR. Permission for SEM use and training on the instrument can be requested from EPMs when the need for these analyses can be justified. Data from any SEM study must be included in the ensuing site chapter either as images or elemental spectra, complete with figure captions.

The SEM is housed in the micropaleontology laboratory, and use of the instrument is shared between the micropaleontologists, sedimentologists, and structural geologists. The equipment is available to answer pressing questions about the form and composition of sediment components that cannot be resolved with light microscopy. Common uses of the SEM by the sedimentology group include the following:

- Determination of unusual but abundant minerals or grain types.
- Discrimination between authigenic and detrital components in cases of ambiguity.
- Recognition of small or opaque authigenic minerals.
- Examination of pores in lithified materials.
- Clarification of relationships between components (e.g., for example, authigenic minerals nucleated on specific fossils or other grain types).
- Identification of biogenic components to help define major and minor lithologies.

Sample preparation for SEM study of bulk samples entails attaching a small piece of sample to a mounting stub with an adhesive and then applying a conductive coating. A conductive coating may not be absolutely needed but is generally preferred if observation will be at any but the very lowest magnifications. Samples should be as small as possible (<1 cm or smaller), consistent with making the needed observation. Bulk samples should be mounted with surfaces intended for observation as horizontal as possible. Loose grains may be thinly distributed onto double-sided sticky carbon dots placed on the mounting stub. Thin sections can be attached to stubs for SEM observation. Conductive coatings, applied properly, do not pose a serious impediment to later transmitted light microscopy.

5.3. X-ray diffraction (XRD)

JR XRD user guides: **https://wiki.iodp.tamu.edu/pages/viewpage.action?pageId=129204495**.

Samples for XRD are chosen by the sedimentology team from the sampled half of the core during sampling shifts. XRD is of critical importance for clarification of bulk mineralogical trends and for identification of the minerals in the clay-size fraction, which typically is dominated by clay minerals or carbonates. A few representative samples of major lithologies should be selected from each core, depending on heterogeneity. In general, XRD data are used in a qualitative way to indicate presence/absence of major minerals.

Processing of XRD data from powders mounted in highly random particle orientations (as opposed to oriented mounts of clay-size separates) to generate semiquantitative mineralogy is sometimes carried out by specialists on the sedimentology team (Underwood et al., 2020). Appropriate mineral mixtures that represent expected lithologies may be brought on board to establish calibrations at the beginning of the cruise. Plotting of XRD data should separate samples by lithology (sands, muds, etc). Processing and tabulating semiquantitative XRD data is a somewhat time-consuming task that typically requires dedication of a significant portion of time from one or more members of the sedimentology team. In the case of unusual mineral components, plots of XRD peaks, without quantification, are useful documentation.

5.4. Carbonate and organic matter (geochemistry)

Samples for bulk carbonate and organic matter are routinely designated by the sedimentology team for calibration of smear slide analysis (1–2 per core), and additional such samples are chosen by the geochemistry team. The bulk analytical samples are especially important for calibration purposes early in a cruise as the initial smear slide work is being done. For this reason, it is very useful to coordinate CARB samples with smear slide samples so that smear slide analysis can be calibrated to known %$CaCO_3$.

6. Core-logging (track) systems

6.1. General considerations

Split-core tracks including the Section-Half Multisensor Logger (SHMSL: point MS, color reflectance), Section Half Imaging Logger (SHIL: linescan section images, RGB color), and X-Ray Imaging Logger (XMSL) are run by the sedimentology team or members of other teams who step in to assist when needed. They collect continuous and/or spot data of particular utility for integration with the visual core description. Track data are collected section by section from archive-half cores that have arrived at the core description table.

Quick attention to scanning allows the track data to be created on the freshest core, with fewer effects from drying and oxidation. Description activities may continue on most sections simultaneously with collection of the track data, depending on the preferences of the team. Visual description processes are briefly interrupted for the section that is being scanned. Coordination among description team members is essential during this elaborate dance of scanning and visual description processes. Care is needed in moving the sections between description table and tracks, making sure to keep all in the correct order and orientation.

Generally, scanning begins soon after a core becomes available to the description team and is completed well before the visual description is finished, allowing team members who run the tracks to also contribute to aspects of the visual description and for the scans to be available for integration. Core flow demands may be such that track operations are turned over to operators entirely outside the sedimentology team. All scans of all sections for a core must be complete before the core is moved from the description area; it is best to keep a written chart for each track to document as section scans are completed to ensure sections are not inadvertently skipped before core is moved into cold storage. This is especially important during high-recovery expeditions.

Quick-start guides and detailed manuals are available for track operations. Early in the cruise, sedimentology team members will receive tutorials from a technician on the essentials of track operations and image retrieval and adjustments. Descriptions of X-ray computed tomography (XCT) and X-ray fluorescence (XRF) core scanning systems that may be available at various shore-based core facilities are not described here. These particular methods may, however, contribute in major ways to core description if completed in a shore-based facility. User manuals for each of these techniques are available at **https://wiki.iodp.tamu.edu/display/LMUG/Physical+Properties**.

6.2. Section-Half Imaging Logger (SHIL): image scanning

JR user guide: **https://wiki.iodp.tamu.edu/display/LMUG/SHIL+User+Guide**

The SHIL creates a high-resolution image of a core section using a line scanning digital camera (20 lines/mm or 50 µm/line) that moves along the core on a motorized gantry. The lines, each a single row of pixels, are captured individually and compiled to make the image. The image is produced in visible light using a red-green-blue (RGB) color model. Illumination of the core surface from multiple angles, together with the very limited spatial reach of each separate line, minimizes shadowing effects from surface irregularities. If the surface of the cut core has been damaged, for example, by a shell or coarse debris pulled along with the wire), the surface may be repaired by scraping, with caution to not add further surface artifacts in the process. Before "correcting" a damaged core surface in this manner, the Curator must give permission for the procedure. Care must be taken to ensure that the core surface is uniformly wet or dry. Standing water on the core surface can produce unwanted reflections. Gaps in the core from removal of whole-round pieces must be filled with Styrofoam inserts labeled as to the nature of the whole-round sample (e.g., IW for interstitial water; MB for microbiology).

Core section images can be readily retrieved for use at the core description table (inserted into core description sheets or displayed on monitors) and for creating figures from complete or cropped areas of section images for reports and presentations. Some adjustment of the images using Photoshop is typically required to lighten and optimize the image for viewing.

6.3. Section-Half Multisensor Logger (SHMSL)

JR user guide: **https://wiki.iodp.tamu.edu/display/LMUG/SHMSL+Quick+Start+Guide**

On the SHMSL, color reflectance spectroscopy and magnetic susceptibility are collected simultaneously. Measurement begins as a laser locates the base of the section. The track detectors then pull back so that the operator can cover the core section with plastic wrap to protect instrument contact sensors. When signaled, the platform progresses to the top of the core section, recording data at user-specified intervals (generally 2–10 cm). This equipment can be very temperamental, so it is best to closely follow user guide instructions.

6.3.1. Color reflectance spectroscopy

Measurements of color reflectance are made through the range 380–900 nm (visible spectrum and slightly into the infrared) at 2 nm intervals. Combined LED and halogen light sources are used.

Reflectance data are collected using a CIELAB L*a*b* color model for which:

- L* represents lightness, where 0 is black and 100 indicates diffuse white,
- a* represents magenta–green tinting
  - negative numbers indicate red/magenta shading
  - positive numbers indicate green shading
- b* represents yellow–blue tinting
  - negative numbers indicate yellow shading
  - positive numbers indicate blue shading

Data are stored and converted to RGB values to facilitate comparison with the imaging logger RGB values. Color reflectance provides a more quantitative measure of color that supports and extends the Munsell color data collected for individual lithologies at the description table. Note that color reflectance data cannot be translated into Munsell color terms, so the latter are needed for core description.

6.3.2. Point-source magnetic susceptibility

Magnetic susceptibility (MS) can be used to confirm whole-round core section MS measurements. The SHMSL can measure magnetic susceptibility at a similar sampling point spacing to the whole-round measurements, or the user can select a different frequency of analysis. MS data are used for correlation with other age-depth proxy measurements and may be used to track certain components in sediments (e.g., dense minerals in volcanogenic and terrigenous intervals) or to pinpoint changes in redox conditions at deposition or early diagenesis.

6.4. X-ray Image Logger

JR user guides: **https://wiki.iodp.tamu.edu/display/LMUG/X-ray+Image+Logger**.

Two-dimensional X-ray radiography can be performed on both whole and split cores. Images produced highlight variations in X-ray transmissivity (transparency) that reveal a wide variety of sediment and rock features that may be invisible or poorly discernible from examination of the core surface including core disturbance, larger particles such as dropstones and shells, trace fossils (bioturbation), and void spaces, as well as structural and soft-sediment deformation features (inclined and folded bedding planes). X-ray imaging may be performed prior to cutting the core to avoid or minimize damage to important structures.

At this writing, X-ray imaging is a recent addition to the JR (first the XMAN logger and currently the XSCAN logger) analytical suite with potential use by several groups. Standard practices for its use are in development. Because this instrument is located outside of the core description area, sedimentologists should coordinate with EPM, Co-Chiefs, and technicians early in the cruise if X-ray imaging is anticipated as a part of the core description routine. Core recovery rate may dictate the degree to which this analytical technique is used: every core section or selected intervals of interest. X-ray imagery may have particular use in guiding preliminary interpretations that are based on the core description.

6.5. Other online resources

JRSO shipboard laboratory manuals and user guides:
https://wiki.iodp.tamu.edu/display/LMUG/

JOIDES Resolution Core description overview:
https://wiki.iodp.tamu.edu/display/LMUG/Core+Description#CoreDescription-Overview

7. Site lithostratigraphy and other expedition reports

Several written documents are produced by the sedimentologists (lithostratigraphy group). The three main types of documents are listed below, and the most extensive one (lithostratigraphy chapter sections for the *Proceedings* volume) is detailed in subsequent sections. These products are specific to IODP JRSO expeditions but can be modified as needed for MSP and repository work. The *IODP Shipboard Writing Guide* is an important resource for all documents (**http://iodp.tamu.edu/publications/resources/IODP_shipboard_writing_guide.pdf**).

1. **Daily and Weekly Reports** must be contributed by the lithostratigraphy group while at sea. Sedimentologists contribute a short paragraph to daily reports and multiple paragraphs to weekly reports. These daily summaries may be routinely the responsibility of one shift because of the time they are due (e.g., 6 am, the middle of night shift), and so the alternate shift may take on responsibility for creating the weekly reports to balance effort. The daily reports may not be reviewed by the entire group of sedimentologists, but the weekly reports should be read and signed off by the entire contingent of sedimentologists before they are transferred by the sedimentological team lead. The EPM and Co-Chiefs will provide guidance as to what information these reports should contain.
2. **Lithostratigraphy sections for site chapters in the *Proceedings* volume** are the most detailed written shipboard product. They are detailed below in **Section 7.1** and **Section 7.2**. Site chapters and results are legacy items, intended to help future workers, as few scientists will likely see the cores in the same detail as the shipboard sedimentologists. Cores described shipboard or immediately upon return to a shore-based facility are also at their freshest state—not masked by secondary microbiology or mineral growth from storage, often manifested by a color change (e.g., Milliken and Olson, 2017). The sedimentology team has a responsibility to provide as much pertinent information as possible, as organized as possible, including preliminary interpretation backed up by reference citations. The latter are important and should not be waived.
3. **Lithostratigraphic site summaries for the *Expedition summary*/*Preliminary report*** range from ~300–600 words depending on depth of penetration at a site and unit complexity. They may include one or two key figures. They are usually written as summaries of the lithostratigraphy sections in the site chapters of the *Proceedings* volume during the latter half of the cruise.

7.1. Establishing lithostratigraphic units and writing site chapters

Procedures for composing site summaries and establishing lithostratigraphic units and subunits are practiced today in essentially the same manner as described by Mazzullo and Graham (1988) (quoted extensively and with only slight modification below). "When drilling at a site is finished, the shipboard scientists compile a site summary that contains a series of short chapters by each working group as well as the barrel sheets [today's VCDs] for all cores." In truth, a site summary is compiled incrementally during the process of core description and finalized into a draft for the *Proceedings* volume once drilling at a site is completed.

"The shipboard sedimentologists provide a chapter on "Lithostratigraphy" for each site in the expedition *Proceedings* volume summarizing the general lithology, stratigraphy, and inferred depositional history of the stratigraphic section at each site. For this purpose, the shipboard sedimentologists divide the stratigraphic section into discrete lithostratigraphic units (numbered from the top as I, II, III, etc.) and subunits (A, B, C, etc.) on the basis of variations in its lithology. There are no hard-and-fast rules for the definition of units and subunits in a stratigraphic section, but some obvious breaks between them are defined by (1) significant changes in sediment lithology, (2) significant changes in sedimentation rates at the site, (3) significant changes in geophysical properties of the sediments (especially their geophysical log characteristics), and (4) unconformities." A very handy, some would say essential, method to help define units as drilling progresses at a site is to keep track of the relative percentages of lithologies that constitute each core (% of recovered lithology, recalculated total to 100%) during core description. These can be tabulated and plotted in histogram fashion next to a core recovery plot for discerning downhole trends (see **Section 7.3.5**). Other descriptive properties may also be tabulated with depth alongside this plot to potentially display significant downhole changes (e.g., maximum clast size per core, proportions of sedimentary structures per core, percent carbonate data, etc.). The lead sedimentologist for a site should coordinate the gathering of data for these efforts.

Integration of the large quantity of data coming from whole-core petrophysical and split core tracks (**Chapter 6**) with core description is a daunting but essential task. Major shifts in physical and chemical properties that correlate with trends noted in visual core description can be added to the list of characteristics that define unit and subunit boundaries. The lithostratigraphic units established by the sedimentology team become the framework against which all the other science groups present their results. The critical nature of this collaborative process cannot be overemphasized. Lithostratigraphic boundaries should be ratified by all the groups, particularly the biostratigraphers, EPM, and Co-Chiefs before use in site reports.

Finally, considering that the Lithostratigraphic Units and Subunits are roughly the equivalents of Formations and Members, respectively, as defined in onshore stratigraphies, the North American Stratigraphic Code may be a useful guide for their definition (included as Appendix **A7.1**).

7.2. Outline of a chapter lithostratigraphy section

There are five major elements of a chapter lithostratigraphy section, defined, in order, as follows.

7.2.1. Introduction

The introduction contains a brief summary of the overall lithology and age of the stratigraphic section; the number of units and subunits; the general age, lithology, thickness, and distinctive characteristics of each unit and subunit; and other appropriate information. The information is best summarized in table format (see Table **T7.1**).

7.2.2. Unit descriptions

This section contains a series of subsections for each unit and subunit. Note that description generally proceeds from the top to downhole, working from younger to older sediments.

7.2.2.1. Unit header

Each unit section begins with a title that includes the unit number followed by the interval (core interval, from top to base, including core numbers and types, section numbers, and centimeter interval in each hole that contains that unit), the age of the unit, and the depth of each unit (in meters below seafloor or other depth scale). Below is an example of a unit description header.

Unit I (Holes U1438A and U1438B)

Intervals: 351-U1438A-1H-1, 0 cm, to 3H-CC, 60 cm (all of Hole U1438A); 351-U1438B-1H-1, 0 cm, to 18H-1, 109 cm
Thickness: 160.3 m
Depths: Hole U1438A = 0–24.9 mbsf; Hole U1438B = 0–160.3 mbsf
Age: recent to latest Oligocene (Pleistocene in Hole U1438A)
Lithology: tuffaceous mud, mud with ash, mud, clay with some discrete ash beds

If the unit is not divided into subunits, the header is followed by a description of the lithostratigraphy that summarizes all the visual core descriptions and petrographic analyses as well as reference to pertinent geochemical, geophysical, and/or paleontological data.

7.2.2.2. Subunit descriptions

If the unit is divided into subunits, the header for the unit is followed by a brief and general description of the unit's lithology and stratigraphy, the definition of the number of subunits within it, and a brief and general description of the lithostratigraphy of each subunit. Following this, each subunit is introduced with its own header (similar to the header for the unit) and is a detailed description of its lithostratigraphy and other pertinent characteristics.

7.2.2.3. Photographic documentation

Units and subunits should be appropriately documented with photographs and photomicrographs of lithologies, sedimentary structures, grain assemblages, and diagenetic features. These features should be also selected to support preliminary interpretations. These images should have scales, detailed sample information, and markers (arrows, circles, outlines, etc.) indicating critical features.

7.2.2.4. Hole correlation

This optional section contains a detailed discussion of correlation among holes at a site. In many cases a correlation figure is helpful.

7.2.2.5. Interpretation

The interpretation section is an opportunity for shipboard sedimentologists to interpret the origins of the stratigraphic section. This part should begin with a broad interpretation of the entire stratigraphic section and then proceed to a detailed interpretation of the sedimentation history, depositional environments, and/or diagenetic history of each unit and subunit. The content of this part varies from cruise to cruise. The Co-Chief Scientists may want most interpretation in the overall Summary and conclusions section for the site because interpretation usually involves information from other shipboard studies as well. Citations relevant to the interpretation must be included.

Interpretations typically include an element of geohistory narrative, proceeding from oldest at the base to youngest at the top of a cored interval, describing the sequence of depositional events responsible for the cored succession. Thus, the core interpretation is presented from bottom-to-top, as opposed to the downhole progression in which the core is described. When writing this narrative, it is important to remember that descriptions are referred to in the present tense (e.g., a sediment described as laminated is still laminated a week or a month later) whereas historical

Table T7.1. Example unit description table (adapted from Sawyer, Whitmarsh, Klaus, et al., 1994).

Unit	Age	Lithology	Fraction (%)	Color	Facies	Environment	Thickness (m)	Core, section, interval (cm) Top	Core, section, interval (cm) Base	Depth (mbsf) Top	Depth (mbsf) Base
								149-	149-		
I	Pleistocene to early Pliocene	Nannofossil ooze	3	Gray/green	Terrigenous turbidites and hemipelagites/pelagites	Abyssal plain	55.2	897A-1R-1, 0	897A-6R-CC	0	55.2
		Nannofossil clay	27				292	897C-1R-1, 0	897C-26R-1, 50	49.9	292
		Silty clay to clayey silt	60								
		Silt and fine sand	10								
IIA	early Pliocene to late Miocene	Nannofossil claystone	60	Gray/green/ brown	Terrigenous turbidites and hemipelagites/pelagites	Abyssal plain	9.2	897C-26R-1, 50	897C-27R-1, 0	292	301.2
		Claystone	20								
		Nannofossil silty claystone	15								
		Siltstone and sandstone	5								
IIB	late Miocene to early Miocene	Nannofossil chalk	1	Brown	Calcareous turbidites/contourites	Abyssal plain; below CCD?	58.6	897C-27R-1, 0	897C-33R-1, 65	301.2	359.8
		Calcareous claystone	45								
		Claystone	37								
		Silty claystone to clayey siltstone	14								
		Siltstone and sandstone	1								
IIC	early Miocene to middle Eocene	Nannofossil chalk	<1	Gray/brown	Calcareous turbidites/contourites	Abyssal plain; below CCD?	259.9	897C-33R-1, 65	897C-60R-1, 0	359.8	619.7
		Claystone	3				30.2	897D-1R-1, 0	897D-3R-5, 38	596	622.9
		Silty claystone to clayey siltstone	68								
		Siltstone and sandstone	3								
IIIA	Uncertain	Claystone	100	Brown	Pelagite/hemipelagite	Abyssal plain; below CCD?	19.7	897C-60R-1, 0	897C-62R-1, 30	619.7	639.4
							19	897D-3R-5, 38	897D-6R-1, 0	622.9	645.2
IIIB	Uncertain	Clayey conglomerate	40	Variegated	High-density turbidite and debris flow		9.3	897C-62R-1, 30	897C-63R-1, 0	639.4	648.7
		Clayey sandstone	20				10	897D-6R-1, 0	897D-7R-1, 0	645.2	655.2
		Sandy silty claystone	40								
IV	late Aptian to Hauterivian	Basement lithologies - 63%; sedimentary - 37%	—	Variegated	Mass flow		28.8	897C-63R-1, 0	897C-66R-1, 18	648.7	677.5
		Sandstone, dolomite, limestone	37				38.6	897D-7R-1, 0	897D-11R-1, 0	655.2	693.8
		Calcareous claystone									

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events (e.g., sediment deformation by a dropstone) are described in the past tense. Correlations between lithostratigraphic units and those at other deep-sea drilling sites (from the current expedition or previous expeditions) are useful to include in interpretations.

7.2.2.6. References

The reference section lists (in alphabetical order and complete IODP format) all publications cited within the chapter.

7.2.2.7. Tables and figures

There are a wide range of other figures and tables that could be included in the site lithostratigraphy section depending on the goals of the expedition. Browsing previous expedition reports for examples is encouraged. Each table and figure must be numbered in the order they appear in the text and include a caption. The figure captions and figure numbers should follow IODP formats.

7.3. Good practices for core/site summaries

7.3.1. Anticipating unit boundaries

The lead sedimentologist's job begins as drilling commences at the site. The lead should become aware of and review results of previous regional expeditions and ensure continuity and consistency of description processes. This will keep the group in tune with changes that might signify a unit or subunit boundary (see **Section 7.3.2** below). The lead should actively engage in discussions with lead scientists from other labs whose data may have supporting evidence of downhole changes in support of unit boundary designations. For this purpose, short meetings with the Co-Chiefs and other group leaders would be beneficial and should be scheduled by the Co-Chiefs.

It is also important that lithology nomenclature and distribution be continually monitored between shifts to ensure continuity and consistency of description processes and application of methods. Strategies to avoid this include cross-over discussion among scientists at shift changes, where the last described core is left out along with next, freshly cut core for description by the following shift. At that time, smear slide results are also calibrated as well as structure symbology, carryover of thick beds between cores, and so on. Continuous plotting of lithology percentages on a core-by-core summary as described below is a great way to nip any inconsistencies in the bud, saving efforts later in the cruise as chapters are written and revised.

Shift change is also the time for sedimentologists to discuss any potential changes encountered that would signify a unit or subunit boundary. Once decided upon by the sedimentologists, then it is put it forward for discussion to the other groups. If possible it is beneficial to keep key sections to show the lithologic changes to the upcoming shift and/or to discuss on how to proceed.

7.3.2. Designating unit boundaries: consensus and specifics

It is very important to obtain the consensus of every lab group for potential unit boundaries before announcing them (make sure there is an informal consensus, not only on the general location but also on the specifics for each hole at a site): site (hole), core (type), section, depth in section (centimeters) along with also meters depth below seafloor (mbsf) depth or other depth scale. Once solidified by in-person meetings with each group leader for the site, it is best to distribute a dated table with the specifics (see example in Table **T7.1**). Each group will plot their data sets with units/subunits designated according to the data in that table. Mistakes or changes to unit boundaries have far-reaching and time-consuming consequences for every group. It is best to distribute this table only in its final, agreed-upon form. The unit boundaries are often the topics of discussion at cross-over site/hole meetings involving the entire shipboard scientific party. The final version of the table is then added to the site chapter.

7.3.3. Use of previous local leg/expedition format

Previous drilling in the region creates a potential need to correlate among legs/expeditions. Consider adopting uniformity of methods between legs/expeditions or, alternatively, adding a key for translating lithologic determinations when integrating them into the discussion section for a site, as appropriate. In some cases, a separate section may be included in the expedition report covering overall correlations with previous drilling.

7.3.4. Accommodating midstream changes in format/lithology definitions

New lithologies are encountered with drilling, and there are often unexpected surprises or reasons to adjust classification schemes or other established methods. If this happens, it is imperative that previous hole or site results be adjusted, preferably before the end of the expedition, but if not, then before the first postcruise (editorial) meeting. This may require significant editing of text and figures for previous holes. It is common to have some revision because understanding of lithostratigraphy naturally evolves as more information is obtained.

7.3.5. Summarizing and integrating core-level descriptions (holes vs. site)

A downhole representation of the lithology variations at a site is useful for determination of subunit and unit boundaries. Creating a lithostratigraphic column using a core-by-core summary by depth of lithology proportions paired with recovery percentages is an excellent way of showing this variation. See Persad and Marsaglia (2023) and Johnson et al. (2017) for examples of how these columns are constructed using a program like Adobe Illustrator (Figure **F7.1**). It is good practice to record the relative percentages of lithologies for each core during core description to facilitate drafting this series of stacked histograms. As mentioned in **Chapter 4** and above, failure to faithfully record this seemingly minor observation is a loss of one of the most useful property trends for identifying unit and subunit boundaries. Perhaps in the future, this figure may be directly generated as a product of the database.

Finally, for the sake of completeness it may be feasible to integrate some types of early postcruise data into the core/site summaries. For example, XRF scanning may be a useful addition for the determination of key boundaries.

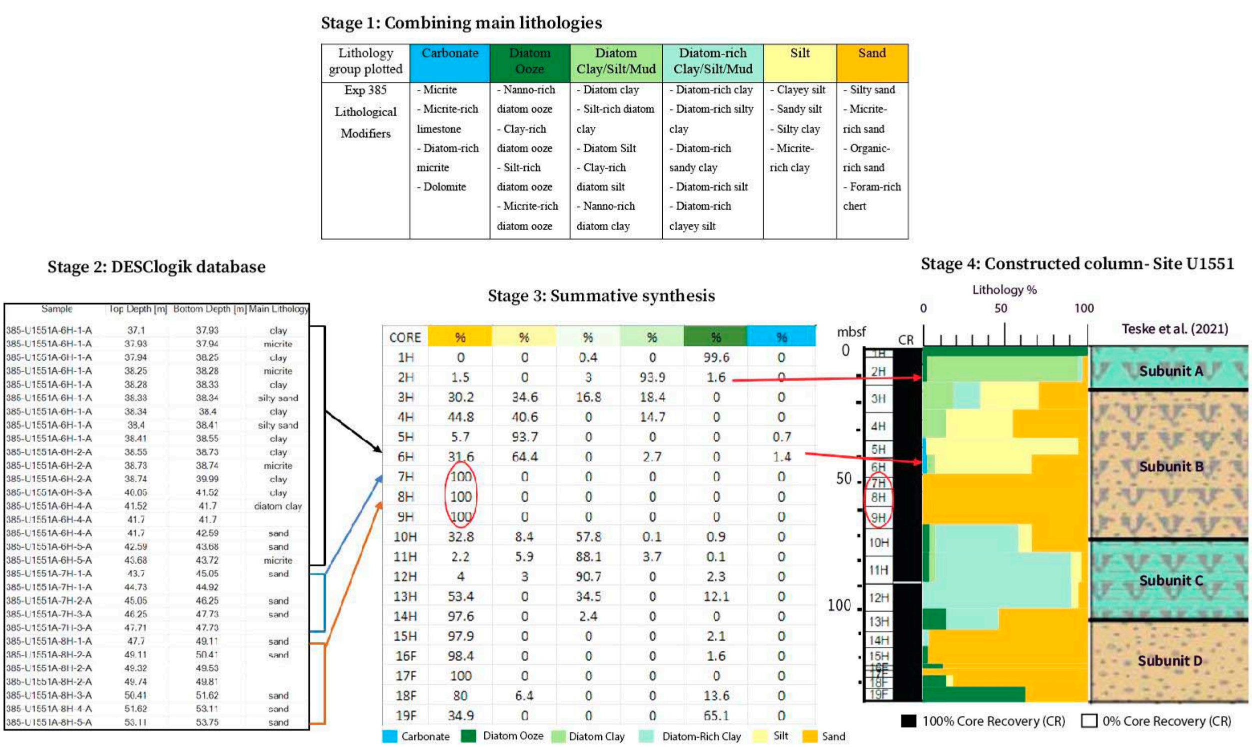

Figure F7.1. Simplification of lithologies into 7 sedimentary and 3 other (igneous/metamorphic) lithologic data sets to produce detailed stratigraphic columns for Expedition 385 sites (Teske, Lizarralde, Höfig, et al., 2021). Stage 1: various lithologies were grouped under parent lithologies for plotting in new columns. Stage 2: DESClogik database was used to classify lithologies and their thickness intervals for each section of core. Stage 3: lithologies were summed on a core by core basis. Stage 4: data calculated for each core was plotted based on recovery to produce new, detailed stratigraphic columns (from Persad and Marsaglia, 2023).

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8. *Chikyu*, MSP, and repository-based core description

The Integrated Ocean Drilling Program (IODP) welcomed the addition of the riser drillship *Chikyu* and alternate drilling platform (mission-specific platform) options. Each of these new systems developed core handling protocols closely affiliated with new core repositories in Kochi, Japan, and Bremen, Germany, respectively. Each of these is briefly addressed below.

IODP MSP expeditions (9 expeditions to date) are conducted by the ECORD Science Operator (ESO). These have expanded IODP drilling techniques and capabilities to shallow water and high latitudes, to overcome other obstacles (e.g., low bridges), and to work in lithologies where alternative coring methods might yield better recovery using various drilling platforms, research vessels, commercial drillships, and ice breakers (see **https://www.ecord.org/expeditions/msp/concept/**). Each expedition is unique but with one commonality: cores taken at sea are then usually transferred to the IODP Bremen Core Repository at MARUM, University of Bremen, for onshore work (Onshore Science Party, OSP) including splitting, detailed description, analysis of standard shipboard measurements, and detailed sampling for postexpedition research projects.

When cores are retrieved on MSP alternate platforms, initial shipboard visual core description in containerized laboratories is limited to looking through the transparent core liner and examining material at the section ends and in the core catcher. Core diameters and lengths may vary due to a wide range of drilling systems, and where drilling mud is used, cuttings may also be available for description and are ultimately curated along with the cores. Processing and description of cuttings has been carried out on the *Chikyu* (Strasser, Dugan, Kanagawa, Moore, Toczko, Maeda, et al., 2014). Preliminary lithologic descriptions and analyses are important for formulating methods or explanatory notes, sample requests, and lithological summaries. These shipboard descriptions are of general lithology and basic drilling disturbance. However, the core catcher sample material and the physical properties data from nondestructive logging of the full core provide decent information for initial sediment and rock characterization and core correlation. Smear slides can be made from core lithologies by shaving or crushing material and creating a slurry (see **Appendix B**).

The offshore description data are augmented by more detailed description by the OSP in the repository after the cores are split and processed. These descriptions may modify the preliminary offshore core description. The onshore phase occurs over a short time period (weeks), which requires significant pre-meeting preparation to coordinate and maximize results. The details of core analysis and description are similar to those used shipboard but with some additions. For example, the Corewall-Corelyzer application can be used for visualization purposes correlating core images with computed tomography (CT) scans or XRF core scanning. For core description, most scientists prefer paper core description sheets (Figure **F8.1**) with a linescan image of the accompanying core section on the left side of the sheet. These handwritten visual section unit description (VSUD) sheets are then entered into the database (currently the ExpeditionDIS) before scanning and archiving as volume supplementary material. The MSP VCD generated from ExpeditionDIS is shown in Figure **F8.2**. VCDs include an overview of major and minor lithologies, color, sedimentary structures, and coring disturbance. In some cases lithologies are emphasized, whereas in others with complex and finely interbedded lithologies, the stratigraphy is described in terms of sedimentary facies associations (e.g., Expedition 381; McNeill, Shillington, Carter, et al., 2019) or at the lamina and thin bed scale (e.g., Expedition 386; Strasser, Ikehara, Everest, et al., 2023).

As part of IODP, the drillship *Chikyu* has focused on drilling offshore Japan. Core and smear slide description procedures are similar to those used on the JR, with the common addition of computed tomography (CT) of whole core prior to splitting. Study of CT scans may reveal details of biogenic structures and deformation features that are difficult to discern or even invisible when examining the cut core face. XRF scanning of split cores has also been utilized as part of sedimentological description on some *Chikyu* expeditions. Riser drilling on the *Chikyu* also enables collection of cuttings in intervals that are not cored. Cuttings are amenable to a wide range of characterization methods and are notably suitable for smear slides, thin sections, and XRD.

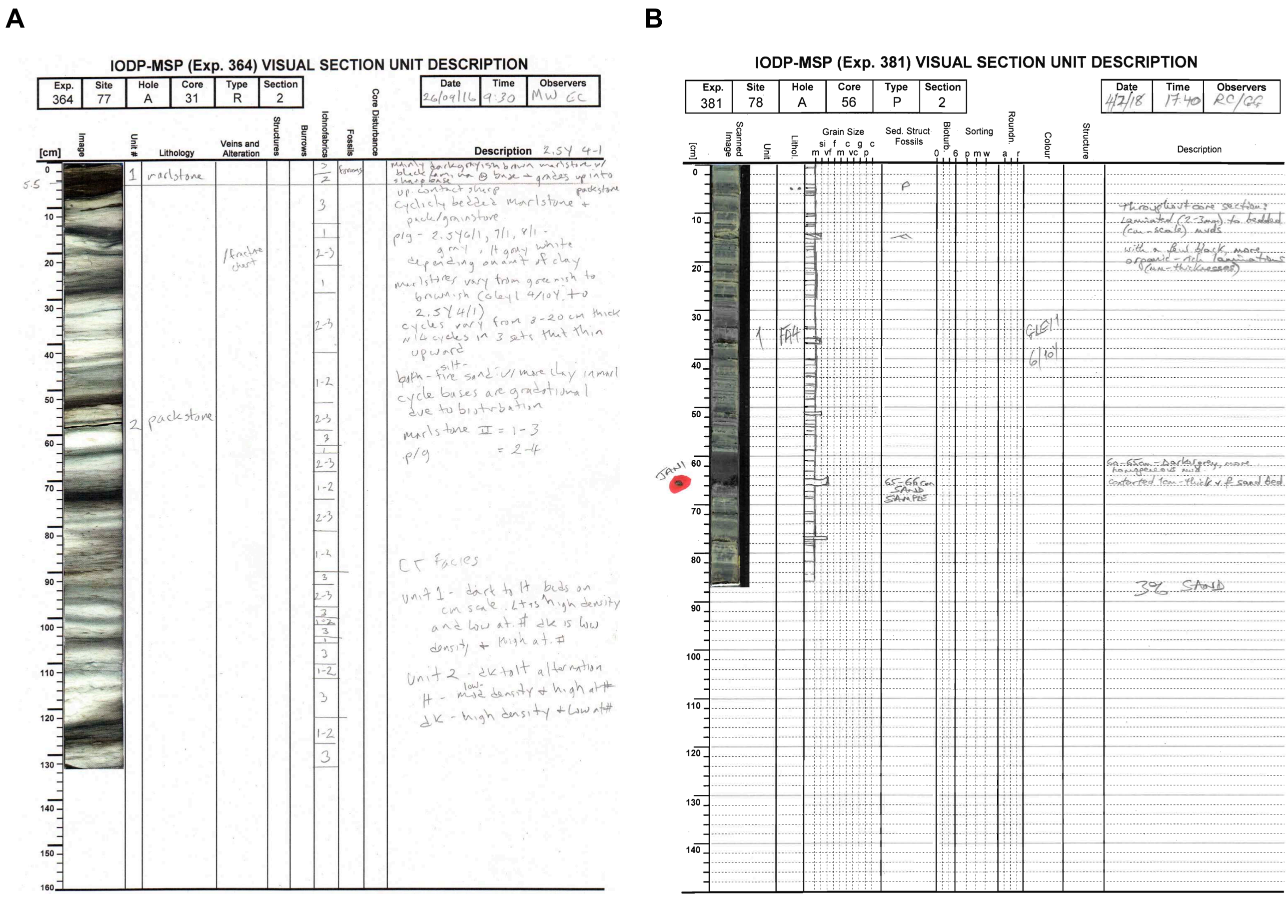

Figure F8.1. Handwritten visual section unit description sheets from MSP Expeditions (A) 364 (Morgan, Gulick, Mellett, Green, et al., 2017) and (B) 381 (McNeill, Shillington, Carter, et al., 2019).

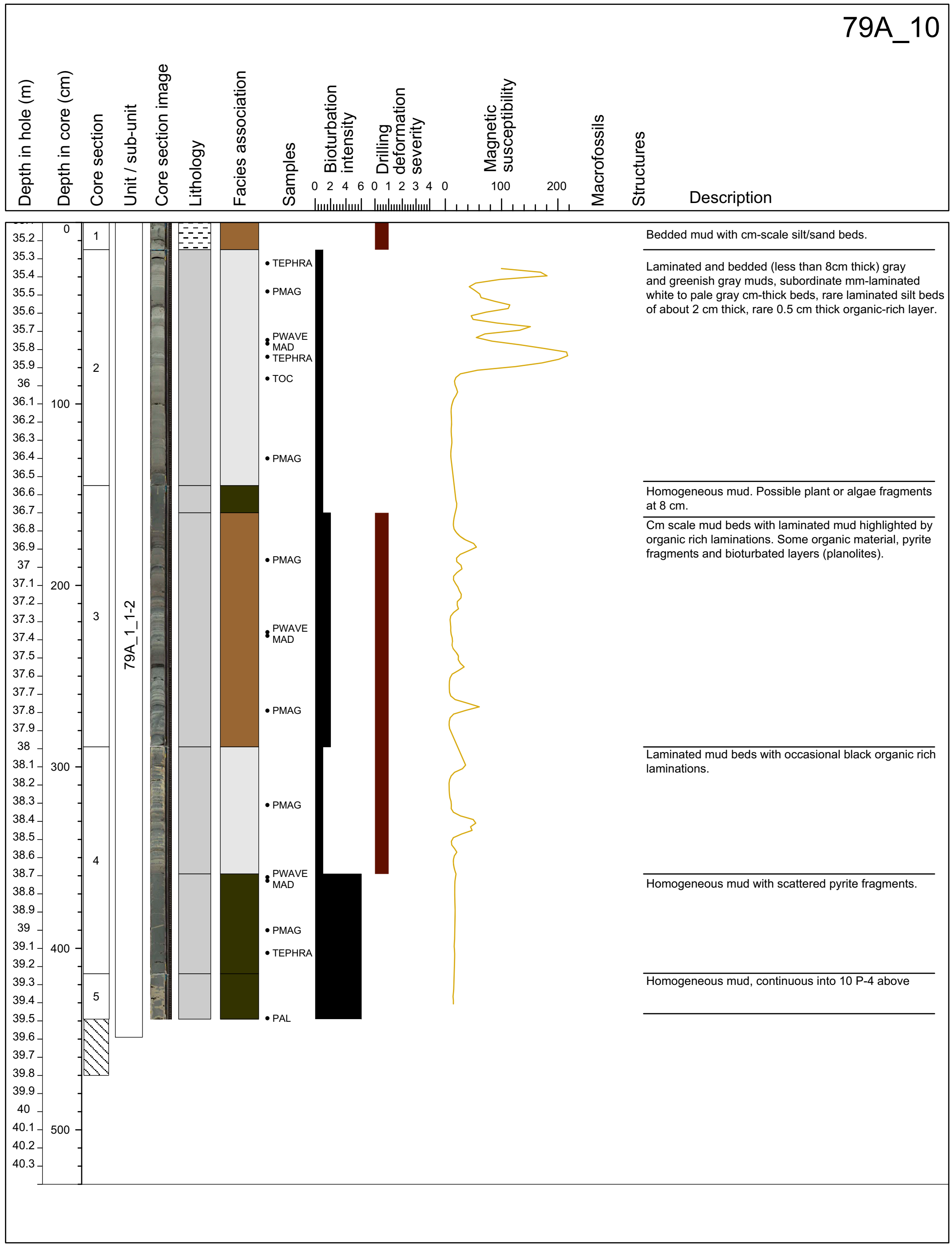

Figure F8.2. VCD for MSP Expedition 381 (Core 79A_10; from McNeill, Shillington, Carter, et al., 2019).

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General appendices

Appendix A: Mazzullo and Graham (1988)

Mazzullo, J., and Graham, A.G., 1988. Handbook for Shipboard Sedimentologists. Ocean Drilling Program Technical Note, 8. **https://doi.org/10.2973/odp.tn.8.1988** (**Updated TechNote 8**)

Appendix B: Smear slide atlas of siliciclastic and volcanogenic grains

Marsaglia, K.M., Milliken, K., and Doran, L., 2013. ODP digital reference for smear slide analysis of marine mud, Part 1: Methodology and atlas of siliciclastic and volcanogenic components. Integrated Ocean Drilling Program Technical Note, 1. **https://doi.org/10.2204/iodp.tn.1.2013**

Appendix C: Smear slide atlas of biogenic grains

Marsaglia, K., Milliken, K., Leckie, R., Tentori, D., and Doran, L., 2015a. IODP smear slide digital reference for sediment analysis of marine mud, Part 2: Methodology and atlas of biogenic components. Integrated Ocean Drilling Program Technical Note, 2. **https://doi.org/10.14379/iodp.tn.2.2015**

Appendix D: Atlas of sedimentary structures

Marsaglia, K., Shapiro, S., Doran, L., and Tentori, D., 2015b. ODP Core Photo Atlas, IODP (International Ocean Discovery Program) Technical Note 3. **https://doi.org/10.14379/iodp.tn.3.2015**

Chapter appendices

Appendix: Chapter 3

Appendix A3.1. Summary of previous methods sections (ODP Leg 119 through IODP Expedition 370). This table is available in an **oversized format**.

IODP Technical Note 5. Shipboard Sedimentologist Handbook.
Appendix 3.1. Compilation of lithostratigraphy methods for previous legs/expeditions.

						CLASSIFICATION SCHEME(S)															TERRIGENOUS ELEMENTS											
								MG Modification						MG Areas Modified																		
ODP Leg/ IODP Exp	Leg/Exp title	Sites	Region	Setting	Main Sed. Type	1. Unspecified source	2. MG	Unmodified	Modified	Minor	Moderate	Significant	Degree/Area Unspecified	Volcaniclastics	Mixed category	Carbonate	Biosiliceous	Glacial/diamict	Other	3. New	1. Udden-Wentworth	2. Shepard Texture Ternary	Original	Modified w/no sand-silt-clay (spokes)	Modified w/side mixtures combined	Divide sand-silt-clay into muddy sand/sandy mud	Modified in other ways	3. Mazzulo Classification	Original	Modified	Mazzulo-based? Ternary or ribbon	4. New
119	Kerguelen Plateau-Prydz Bay	736-746	Antarctica	Intra-oceanic	Pelagic				1		1			X		X		use diamict/ diamictite	Shephard		1		1						1			
120	Kerguelen Island-Prydz Bay	747-751	Antarctica	Intra-oceanic	Pelagic				1		1					X	Issue w/ mixed sed		Glauconite		1		1						1			
121	Broken-Ninetyeast Ridges	752-758	S.Indian	Intra-oceanic	Pelagic			1													1		1						1			
122	Exmouth-Wombat Plateau	759-764	S.Indian	Passive margin	Mixed S/C			1													1		1						1			
123	Argo Abyssal Plain	765-766	N.Indian	Intra-oceanic	Mixed S/C				1	1									Resediment-ed pelagics, added conglomerate		1		1						1			
124	Celebes abd Sulu Seas	767-771	South China Sea	Magmatic arc	Mixed S/C/V				1		1			X		X					1		1						1			
124E	Phillippine Sea	772-777	Philippine Sea	Mixed	Mixed S/V				1					X		X																
125	Izu-Bonin-Mariana Region	778-786	W.Pacific	Mixed	Mixed S/C/V	1								X							1		1						1			
126	Bonin Arc-Trench System	787-793	W.Pacific	Mixed	Mixed S/C/V				1					X						1	1		1			1				1		
127	Japan Sea	794-797	Japan Sea	Magmatic arc	Mixed S/V				1	1									Compl mods		1		1							1		
128	Japan Sea	794, 798-799	Japan Sea	Magmatic arc	Mixed S/C/V				1	1						X	X				1								1			
129	Old Pacific Crust	800-802	C. Pacific	Intra-oceanic	Mixed S/C/V				1		1						X				1		1							1		
130	Ontong Java Plateau	803-807	S. Pacific	Intra-oceanic	Pelagic			1													1								1			
131	Nankai Trough	808	Philippine Sea	Accretionary prism	Mixed S/C/V			1													1		1						1			
132	Western and Central Pacific	809-810	W./C. Pacific	Intra-oceanic	Pelagic			1													1		1						1			
133	Northeast Australian Margin	811-826	S. Pacific	Passive margin	Carbonate								1								1		1						1			
134	Vanuatu (New Hebrides)	827-833	S. Pacific	Mixed	Pelagic				1	1				X							1		1						1			
135	Lau Basin	834-841	S. Pacific	Magmatic arc	Mixed S/C/V				1	1				X									1						1			
136	Hawaiian Arch	842-843	C. Pacific	Intra-oceanic	Mixed S/C/V				1	1			1								1									no mixed		
138	Eastern Equatorial Pacific	844-854	C. Pacific	Intra-oceanic	Pelagic				1			1					Leg 85				1											
139	Middle Valley, Juan de Fuca Ridge	855-858	C. Pacific	Intra-oceanic	Pelagic/V				1	1			1								1		1						1			
141	Chile Triple Junction	859-863	S. Pacific	Intra-oceanic	Mixed S/C/V				1				1	X							1				1				1			
143	Guyots	865-870	C. Pacific	Intra-oceanic	Mixed S/C/V				1	1					X																	
144	Guyots	871-880	C. Pacific	Intra-oceanic	Mixed S/C/V				1				1																			
145	North Pacific Transect	881-887	N. Pacific	Intra-oceanic	Mixed S/C/V				1				1								1		1						1			
146 pt.1	Cascadia Margin	888-892	N. Pacific	Convergent margin	Siliciclastic				1				1						Leg 124		1				1				1			
146 pt.2	Santa Barbara Basin	893	N. Pacific	Passive margin	Mixed S/C				1				1						Leg 124		1				1				1			
147	Hess Deep Rift Valley	894-895	C. Pacific	Intra-oceanic	Mixed S/C/V				1				1						Leg 124													
149	Iberia Abyssal Plain	897-901	C. Atlantic	Passive margin	Mixed S/C/V				1				1						Leg 124		1				1				1			
150	New Jersey Continental Slope/Rise	902-906	C. Atlantic	Passive margin	Mixed S/C			1													1				1				1			
151	N. Atlantic-Arctic Gateway	907-913	N. Atlantic/Arctic	Passive margin	Mixed S/C/V													X	Leg 105								1					glacial
152	East Greenland Margin	914-919	N. Atlantic/Arctic	Passive margin	Mixed S/C/V				1		1			X				X			1								1			
154	Ceara Rise	925-929	S.Atlantic	Intra-oceanic	Pelagic/V			1																					1			
155	Amazon Fan	930-946	C. Atlantic	Passive margin	Siliciclastic	1															1		1							1		
156	Northern Barbados Ridge	947-949	Caribbean	Accretionary prism	Mixed S/C/V			1													1		1						1			
157	Gran Canaria and Madeira Abyssal Plain	950-956	C. Atlantic	Intra-oceanic	Mixed S/C/V			1													1		1						1			
159	Cote d'Ivoire-Ghana transform margin	959-962	C. Atlantic	Passive margin	Mixed S/C				1				1								1		1						1			
160	Mediterranean Sea I	963-973	Mediterranean	Intra-oceanic	Mixed S/C/V			1																					1			
161	Mediterranean Sea II	974-979	Mediterranean	Passive margin/ Intra-oceanic	Mixed S/C/V				1	1				X		micrite					1				1				1			
162	North Atlantic-Arctic Gateway II	980-987	N. Atlantic/Arctic	Intra-oceanic	Mixed S/C/V			1													1		1						1			
163	Southeast Greenland Margin	988-990	N. Atlantic/Arctic	Volcanic Rifted margin	Mixed S/C/V/I				1		1								Leg 152		1								1			
164	Blake Ridge and Carolina Rise Gas Hydrates	991-997	C. Atlantic	Passive margin	Mixed S/C	1																										
165	Caribbean Ocean History and the K/T Boundary Event	998-1002	Caribbean	Intra-oceanic	Mixed C/V				1	1				X							1		1						1			
166	Great Bahama Bank	1003-1009	Caribbean	Intra-oceanic	Carbonate	1															1		1						1			
167	California Margin	1010-1022	N. Pacific	Passive margin	Mixed S/C/V				1	1							X				1								1			
168	Ridge	1023-1032	N. Pacific	Intra-oceanic	Mixed S/C/V/H/I			1																					1			
169	Sedimented Ridges II	1035-1038	N. Pacific	Intra-oceanic	Mixed S/C/V/H/I														Leg 139													
170	Costa Rica Accretionary Wedge	1039-1043	C. Pacific	Accretionary prism	Mixed S/C/V			1																					1			
171B	Blake Nose Transect	1049-1053	N. Atlantic	Passive margin	Mixed S/C				1	1					X																	
172	NW Atlantic Sediment Drifts	1054-1064	N. Atlantic	Passive margin/ Intra-oceanic	Mixed S/C				1				1								1		1						1			
173	Return to Iberia	1065-1070	N. Pacific	Passive margin/ Intra-oceanic	Mixed S/C/V/I				1				1						Leg 149		1				1				1			
174A/B	New Jersey Coastal Plain	Bass River	N. Atlantic	Passive margin	Siliciclastic				1				1								1					1			1			
175	Benguela Current	1075-1087	S.Atlantic	Passive margin	Mixed S/C				1				1																			
177	Southern Ocean Paleoceanography	1088-1094	S.Atlantic/Antarctic	Intra-oceanic	Pelagic/S			1											Leg 113?											1	genetic	
178	Antarctic Glacial History and Sea-Level Change	1095-1103	Antarctic	Intra-oceanic	Mixed S/C													X	Leg 105								1					1
180	Western Woodlark Basin	1108-1118	S. Pacific	Intra-oceanic	Mixed S/C/V				1	1				X													1					1
181	Southwest Pacific Gateways	1119-1125	S. Pacific	Passive margin/ Intra-oceanic	Pelagic				1	1					X												1			no mixed		
182	Great Australian Bight	1126-1134	S. Pacific	Passive margin	Mixed S/C	1															1		1						1			
183	Kerguelen Plateau-Broken Ridge	1135-1142	Indian Ocean	Intra-oceanic	Mixed S/C/V/I				1		1				X	X										1				1		
184	South China Sea	1143-1148	South China Sea	Intra-oceanic	Pelagic	1															1		1							1		
185	Izu-Mariana Margin	801, 1149	S. Pacific	Convergent margin/ Magmatic arc	Mixed S/C/I															1											1	1
186	W. Pacific Geophys. Observatories	1150, 1151	Japan Sea	Convergent margin	Pelagic/V				1		1				X					?	1		1							1		
188	Prydz Bay-Cooperation Sea	1165-1167	Antarctic	Intra-oceanic	Mixed S/C				1		1				X			X			1			1								1
189	Tasmanian Gateway	1168-1172	S. Pacific	Intra-oceanic	Pelagic	1																		1								1
190	Nankai Trough Accret. prism	1173-1178	Philippine Sea	Accretionary prism	Mixed S/C			1																								
191	NW Pacific Seismic Observatory/ Hammer Drill	1179-1182	N. Pacific	Intra-oceanic	Pelagic/I											X			Leg 185	?										1		
192	Ontong Java Plateau	1183-1187	S. Pacific	Intra-oceanic	Pelagic/ I				1	1					X						1									no mixed		
194	Marion Plateau Sea Level	1192-1199	S. Pacific	Passive margin	Mixed S/C/I	1															1		1									
195	Seafloor Obs./ Kuroshio Current	1200-1202	C. Pacific	Intra-oceanic	Mixed S/C/V/I			1													1		1							add diamict		
197	Hawaiian Hotspot Motion	1203-1206	C. Pacific	Intra-oceanic	Mixed S/C/V			1													1		1						1			
198	Shatsky Rise	1207-1214	C. Pacific	Intra-oceanic	Mixed S/C/V				1	1					X						1									no mixed		
199	Paleogene Equatorial Transect	1215-1222	C. Pacific	Intra-oceanic	Mixed S/C/V/I				1	1					X						1									no mixed	1	
200	Hawaii-2 Observatory (H2O) and Nuaanu Landslide	1223-1224	C. Pacific	Intra-oceanic	Pelagic/ I			1													1								1			
201	Eastern Equatorial Pacific/Peru Margin	1225-1231	C. Pacific	Passive margin/ Intra-oceanic	Mixed S/C/V				1	1					X						1			1						simplified		
202	Southeast Pacific Transects	1232-1242	S./C. Pacific	Convergent margin	Mixed S/C/V				1	1					X						1		1								1	
203	Dynamics of Earth and Ocean Systems	1243	C. Pacific	Intra-oceanic	Mixed C/I														Leg 138											modified		
204	Hydrate Ridge, Cascadia Continental Margin	1244-1252	N. Pacific	Accretionary wedge	Mixed S/V			1													1		1						1			
205	Costa Rica Convergent Margin	1253-1255	C. Pacific	Convergent margin	Mixed S/C/V/I			1													1		1						1			
206	Superfast Seafloor Spreading	1256	C. Pacific	Intra-oceanic	Mixed S/C/V/I				1	1					X						1								1	simplified?		
207	Demerara Rise Transect	1257-1261	C. Atlantic	Intra-oceanic	Pelagic				1	1					X						1								1	simplified?		
208	Walvis Ridge Transect	1262-1267	S. Atlantic	Intra-oceanic	Mixed Pelagic/V	1															1			1						no mixed	1	
210	Newfoundland-Iberia Transect	1276-1277	N. Atlantic	Passive margin	Mixed S/C/I	1															1				1		1				1	
301	Juan de Fuca Hydrogeology	1026, U1301	N. Pacific	Intra-oceanic	Mixed S/I				1	1					X						1								1	no mixed		
302	Arctic Coring Expedition	M0001–M0004	Arctic	Intra-oceanic	Mixed S/C														Leg 151								1				1	glacial
303/306	North Atlantic Climate	–U1308/U1312–	N. Atlantic	Intra-oceanic	Mixed S/C				1	1					X						1		1							1	1	
307	Modern Carbonate Mounds	U1316–U1318	N. Atlantic	Passive margin	Mixed S/C														Dunham+		1		1							1		
308	Gulf of Mexico Hydrogeology	U1319–U1324	C. Atlantic	Passive margin	Mixed S/C/V	1															1						1			1		
310	Tahiti Sea Level	M0005–M0026	S. Pacific	Intra-oceanic	Mixed S/C														Dunham+													1
311	Cascadia Margin Gas Hydrates	U1325–U1329	N. Pacific	Accretionary prism	Mixed S/C				1	1					X						1		1							no mixed		
313	New Jersey Shallow Shelf	M0027–M0029	N. Atlantic	Passive margin	Mixed S/C														Leg 174		1					1			1			
314/315/316	NanTroSEIZE Stage 1: Nankai Trough Seismogenesis	C0001–C0006	N. Pacific	Accretionary wedge	Mixed S/C/V			1																								
317	Canterbury Basin Sea Level	U1351–U1354	S. Pacific	Passive margin	Mixed S/C															1	1						1				1	
318	Wilkes Land Glacial History	U1355–U1361	Antarctica	High Latitude	Mixed S/C														Leg 188		1						1		1			glacial
319	NanTroSEIZE Stage 2: Riser/Riserless Observatory	C0009–C0011	N. Pacific	Accretionary wedge	Mixed S/C/V			1																								
320/321	Pacific Equatorial Age Transect	U1331–U1336	C. Pacific	Intra-oceanic	Mixed P/I														Leg 199		1									1		
322	NanTroSEIZE Stage 2: Subduction Inputs	C0011, C0012	N. Pacific	Accretionary wedge	Mixed S/C/V				1				1						Various		1									1		
323	Bering Sea Paleoceanography	U1339–U1345	Bering Sea	Intra-oceanic	Mixed S/C									X						1	1			1							1	1
324	Shatsky Rise Formation	U1346–U1350	N. Pacific	Intra-oceanic	Mixed S/C/V/I			1													1								1			
325	Great Barrier Reef	M0030–M0058	S. Pacific	Passive margin	Carbonate														Dunham+													
327	Juan de Fuca Ridge-Flank Hydrogeology	U1362, U1301, 1027, U1363	N. Pacific	Intra-oceanic	Mixed S/C/I														Leg 210		1				1		1				1	
329	South Pacific Gyre Microbiology	U1365–U1371	S. Pacific	Intra-oceanic	Pelagic			1													1										1	glacial
330	Louisville Seamount Trail	U1372–U1377	S. Pacific	Intra-oceanic	Mixed S/C/I				1		1			X	X						1									no mixed		
333	NanTroSEIZE Stage 2: Subduction Inputs, Heat Flow	C0011, C0012, C0018	N. Pacific	Accretionary wedge	Mixed S/C			1													1								1			
334	Costa Rica Seismogenesis (A1)	U1378–U1381	C. Pacific	Convergent margin	Mixed S/C	1																										
336	Mid-Atlantic Ridge Microbiology	U1382–U1384	C. Atlantic	Intra-oceanic	Pelagic/ I	1															1											
338	NanTroSEIZE Stage 3: Plate Boundary Deep Riser 2	C0002, 12, 18, 21, C0022	N. Pacific	Accretionary wedge	Mixed S/C /V				1	1				X							1								1			
339	Mediterranean Outflow	U1385–U1391	C. Atlantic	Passive margin	Siliciclastic				1		1				X				?		1						1				1	
340	Lesser Antilles	U1393–U1401	C. Atlantic	Intra-oceanic	Mixed S/C/V/I	1															1										1	glacial
341	Southern Alaska Margin	U1417–U1421	N. Atlantic	Passive margin	Mixed S/C									X					178, 317, 318	?	1						1				1	glacial
342	Newfoundland Sediment Drifts	U1402–U1411	N. Atlantic	Intra-oceanic	Mixed S/C				1	1					X															no mixed		
343/343T	Japan Trench Fast Drilling	C0019	N. Pacific	Convergent margin	Mixed S/C/V														Exp. 308		1						1				1	
344	Costa Rica Seismogenesis (A2)	U1380, U1381, U1412–U1414	C. Pacific	Convergent margin	Mixed S/C/V	1																					1					
346	Asian Monsoon	U1422–U1430	Japan Sea	Intra-oceanic	Mixed S/C/V									X					155, 303, 339	1											1	1
347	Baltic Sea Paleoenvironment	M0059–M0067	Baltic Sea	Passive margin	Mixed S/C	1															1		1									glacial
348	NanTroSEIZE Stage 3: Plate Boundary Deep Riser	C0002	N. Pacific	Accretionary wedge	Mixed S/C/V	1																										
349	South China Sea Tectonics	U1431–U1435	South China Sea	Intra-oceanic	Mixed S/C/V				1	1					X						1			1						no mixed	1	
350	Izu-Bonin-Mariana Rear Arc	U1436, U1437	N. Pacific	Magmatic arc	Mixed S/C/V				1			1		X						1												1
351	Izu-Bonin-Mariana Arc Origins	U1438	N. Pacific	Magmatic arc	Mixed S/C/V														126 + 351	1	1											1
352	Izu-Bonin-Mariana Fore Arc	U1439–U1442	N. Pacific	Mixed Magmatic arc	Mixed S/C/V/I	1															1											1
353	Indian Monsoon Rainfall	U1443–U1448	S. Indian	Mixed passive margin/Intra-oceanic	Mixed S/C/V				1	1					X					?	1			1						1		
354	Bengal Fan	U1449–U1455	S. Indian	Intra-oceanic	Mixed S/C/V														155, 339	1				1							1	
355	Arabian Sea Monsoon	U1456–U1457	S. Indian	Intra-oceanic	Mixed S/C/V														105, 178		1			1							1	
356	Indonesian Throughflow	U1458–U1464	S. Indian	Passive margin	Mixed S/C															1	1			1								1
359	Maldives Monsoon/Sea Level	U1465–U1472	S. Indian	Intra-oceanic	Carbonate														Dunham+													
361	South African Climates (Agulhas)	U1474–U1479	S. Indian	Passive margin	Mixed S/C			1													1										1	
362	Sumatra Subduction Zone	U1480–U1481	S. Indian	Convergent margin	Mixed S/C/V				1				1								1		1							1		
363	Western Pacific Warm Pool	U1482–U1490	S. Indian	Passive margin	Mixed S/C	1															1			1							1	
364	Chicxulub: K-Pg Impact Crater	M0077	C. Atlantic	Passive margin	Mixed S/C/V														Dunham+													
365	NanTroSEIZE Stage 3: Shallow Megasplay LTBM	C0010	N. Pacific	Accretionary wedge	Mixed S/V			1											Exp 352		1		1									
366	Mariana Convergent Margin and South Chamorro Seamount	1200, U1491–U1498	S. Pacific	Convergent margin	Mixed S/C				1		1			X	X				Exp 352		1								1			1
370	Temperature Limit of Deep Biosphere off Muroto	C0023	N. Pacific	Convergent margin	Mixed S/C/V	1																										
					Totals:	20		27	58	28	12	2	17	18	22	7	5	5	34	9	92		40	11	9	4	14		52	16	21	13

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Appendix A3.2. Feedback survey on preferences for sediment classification schemes. This table is available in an **oversized format**.

Handbook Recommendation Evaluation Form Name of reviewer (optional): ____________________

Recommendations	**AGREE**	**NO OPINION**	**DISAGREE**	**Comments**
	(please mark your opinion with **X**) (KMM and KLM recommendations in gray)			If you disagree with KMM and KLM recommendations please explain why.
1. Terrigeous Sediments				
1A - Use Udden-Wentworth Scale				
1B - Clarify use of term clay				
1C - Use of Shepard Diagram				
1C.1 Include unmodified (Fig. 1A)				
1C.2 Include Slightly Modified Options (Figs. 1B,C)				
1C.3 Include Significantly Modfied Options (Figs. 1D, E, F, G)				
2. Volcaniclastic Sediments (marine)				
2.A Use nongenetic terminology for sediment description in VCD and Barrel Sheets				
2. B Use genetic terminology for preliminary interpretation in report if confident on origin and transport mechanism of volcaniclastic intervals				
3. Glacial (high lattitude) sediments				
1. Add descriptive options for poorly sorted sediments				
2.A Use nongenetic terminology for sediment description in VCD and Barrel Sheets				
2. B Use genetic terminology for preliminary interpretation in report if confident on origin and transport mechanism of sediment				
4. Neritic Carbonate Sediments				
1. Continue use of Dunham classifiction with Embry/Kloyan modfication				
5. Biosiliceous Pelagic Sediments				
1. Continue to use MG approach emphasizing grain assemblage				
2. Use terms radiolarite, diatomite, spiculite				
3A. Use hand specimen terms porcellanite and chert for lithified				
3B. Use radiolarian, diatom and spicule as modifiers for chert/porcellanite				
6.Calcareous Pelagic Sediments				
1. Continue to use MG approach emphasizing grain assemblage				
2. Use minimum total carbonate of 50% for ooze(chalk) vs. mud(mudstone) boundary				
2. Use minimum total carbonate of 60% for ooze(chalk) vs. mud(mudstone) boundary				
7. Other Rock Type Comments?				
1. Organic-rich				
2. Serpenticalstic				
3. Evaporitic				
4. Metaliferous				
8. Classification Diagram Options				
1A. Include MG diagram (Fig. 6A)				
1B. Include Modified MG without mixed sediment (Figs. 6B)				
1C. Include Modified MG with Ribbon Format (Figs. 6C)				
1D. Include suggested ternary options (Figs. 6D, 6E)				
GENERAL RECOMMENDATIONS				
1. Identify and provide sources (references) for methods				
2A. Use non-genetic terminology in description				
2B. Reserve genetic terminology for preliminary interpretation in report				
3. Methods should align with Expedition goals				

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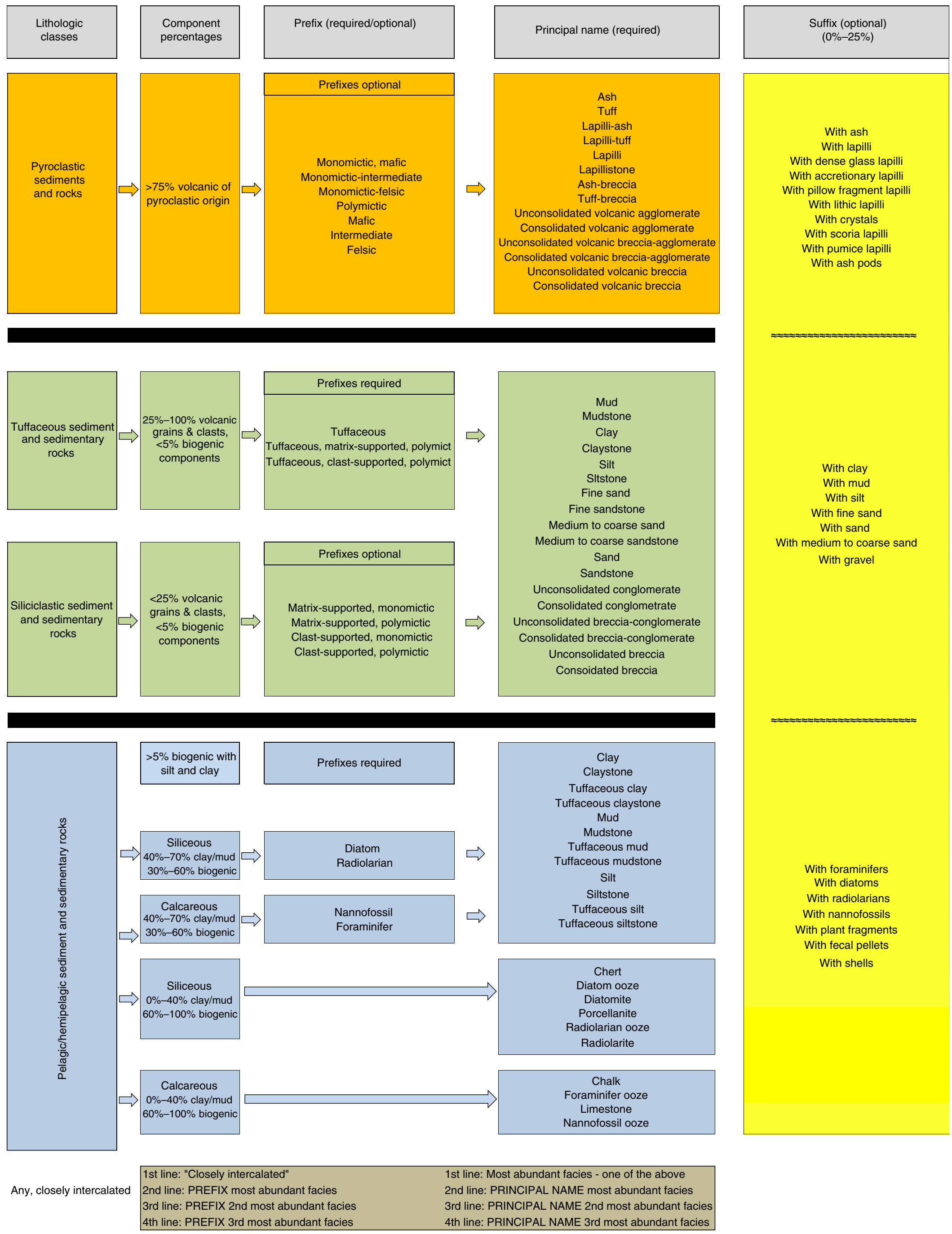
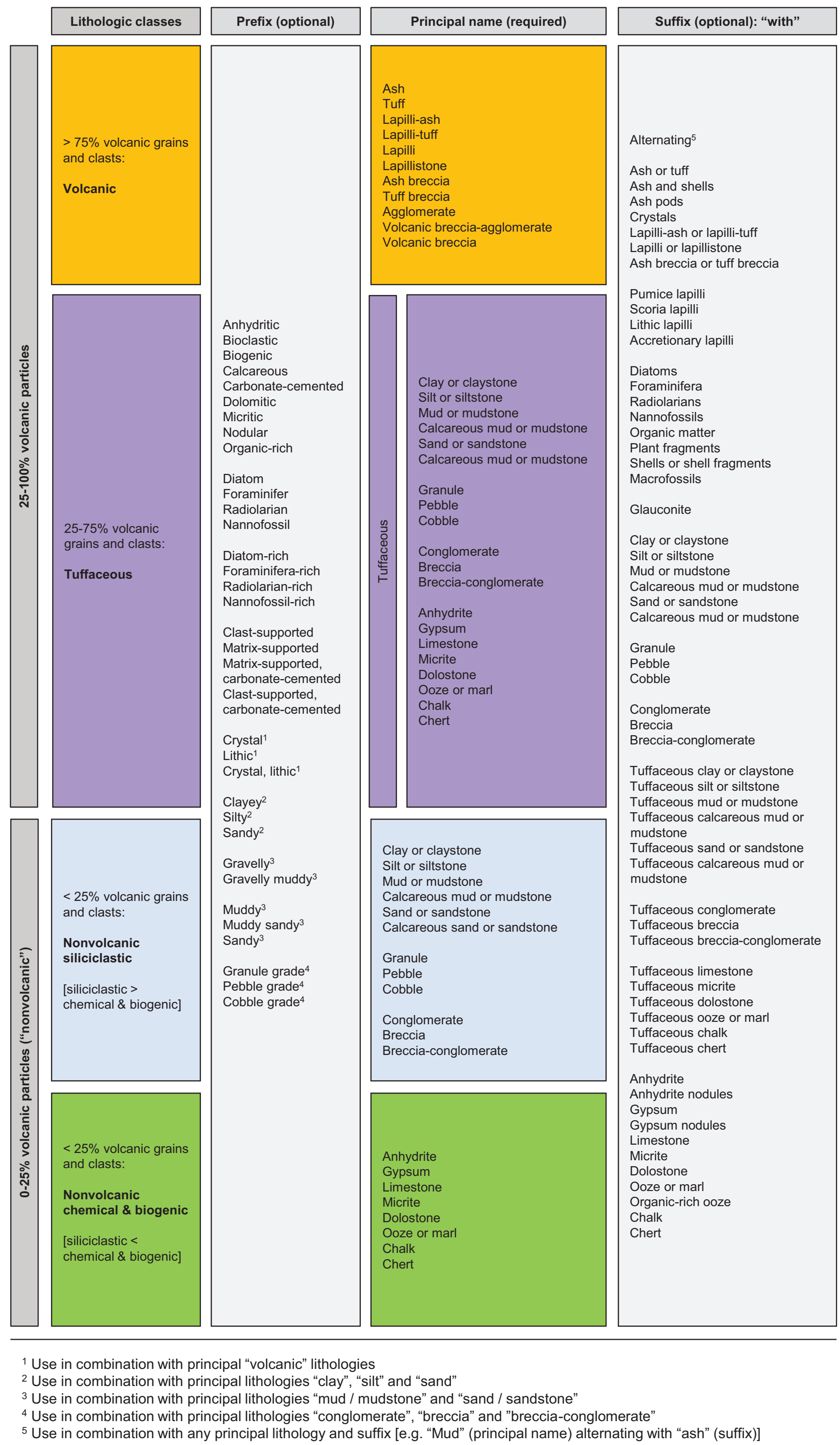
Appendix A3.3. A. Expedition 351 volcaniclastic classification scheme (Arculus, Ishizuka, Bogus, et al., 2015). B. Expedition 398 volcaniclastic classification scheme (Druitt, Kutterolf, Ronge, et al., 2024). (Continued on next page.)



Appendix A3.3 (continued).



Appendix A3.4. Evaporite classification scheme of Ciarapica et al. (1985). View **PDF**.

Appendix: Chapter 4

Appendix A4.1. Sedimentary structures and bedding planes (from Mazzullo and Graham, 1988). View **PDF**.

Appendix: Chapter 7

Appendix A7.1. North American Stratigraphic Code. View **PDF**.