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Key Points:

- Most piston coring disturbances occur in granular, sandy units
- Disturbed textures chiefly linked to partial strokes and core recovery
- Piston coring disturbance can produce facies similar to density current deposits

Correspondence to:
M. Jutzeler,
jutzeler@gmail.com

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Coring disturbances in IODP piston cores with implications for offshore record of volcanic events and the Missoula megafloods

Martin Jutzeler[1,2], James D. L. White[1], Peter J. Talling[2], Molly McCanta[3], Sally Morgan[4], Anne Le Friant[5], and Osamu Ishizuka[6]

[1]Department of Geology, University of Otago, Dunedin, New Zealand, [2]National Oceanography Centre, Southampton, UK, [3]Department of Earth and Ocean Sciences, Tufts University, Medford, Massachusetts, USA, [4]Borehole Research Group, Lamont-Doherty Earth Observatory, Palisades, New York, USA, [5]Institut de Physique du Globe de Paris, UMR 7154, Sorbonne Paris Cité, Paris, France, [6]Geological Survey of Japan/AIST, Ibaraki, Japan

Abstract Piston cores collected from IODP drilling platforms (and its predecessors) provide the best long-term geological and climatic record of marine sediments worldwide. Coring disturbances affecting the original sediment texture have been recognized since the early days of coring and include deformation resulting from shear of sediment against the core barrel, basal flow-in due to partial stroke, loss of stratigraphy, fall-in, sediment loss through core catchers, and structures formed during core recovery and on-deck transport. The most severe disturbances occur in noncohesive (sandy) facies, which are particularly common in volcanogenic environments and submarine fans. Although all of these types of coring disturbances have been recognized previously, our contribution is novel because it provides an easily accessible summary of methods for their identification. This contribution gives two specific examples on the importance of these coring disturbances. We show how suck-in of sediments during coring artificially created very thick volcaniclastic sand layers in cores offshore Montserrat and Martinique (Lesser Antilles). We then analyze very thick, structureless sand layers from the Escanaba Trough inferred to be a record of the Missoula megafloods. These sand layers tend to coincide with the base of core sections, and their facies suggest coring disturbance by basal flow-in, destroying the original structure and texture of the beds. We conclude by outlining and supporting IODP-led initiatives to further reduce and identify coring disturbances and acknowledge their recent successes in drilling challenging sand-rich settings, such as during IODP Expedition 340.

1. Introduction

Piston coring involves hydraulically shooting a tube that is several meters long and a few centimeters in diameter into unconsolidated, water-saturated sediments. Advanced Piston Coring (APC) is currently the best technique for retrieving large thicknesses of unconsolidated sediments while preserving their stratigraphy and is used extensively by the International Ocean Discovery Program (IODP) and preceding Integrated Ocean Drilling Program (IODP) and Ocean Drilling Program (ODP; Table 1). In most cases, APC retrieves up to 9.5 m long, nondisturbed or weakly disturbed cores in which bed forms, stratification, and bed contacts can be studied and sampled [*Storms*, 1990; *Huey*, 2009]. This technology allows acquisition of contiguous cores by successive shootings to depths that can reach 458 m below seafloor (mbsf).

Coring disturbances have been recognized since the early days of piston coring, including situations where piston cores are single barrels and where multiple consecutive advance piston cores are taken [e.g., *Kullenberg*, 1947, 1955; *Ross and Riedel*, 1967; *Bouma and Boerma*, 1968; *Stow and Aksu*, 1978; *Blomqvist*, 1985; *McCoy*, 1985; *Ruddiman et al.*, 1987; *Buckley et al.*, 1994; *Lisiecki and Herbert*, 2008]. Despite technological advances, some disturbances due to piston coring still occur [*Huey*, 2009] and can be difficult to recognize during core description. This study focuses on IODP (and ODP) technology, which includes piston coring using successive core barrels. Disturbed intervals can show shearing along the core margins, destruction of stratification and homogenization, increase or decrease in apparent bed thickness, unrecovered sediments, vertical and lateral density sorting, and creation of artificial units. We pay particular attention to situations where the core barrel failed to penetrate to its full length in the stratigraphy, producing a partial stroke of the hydraulic piston. Such "partial strokes" are important because they can result in the addition of several

Table 1. Description of Acronyms

Acronym	Name	Description
International Drilling Programs		
DSDP	Deep-Sea Drilling Project	From 1966 to 1983, using the D/V *Glomar Challenger*; Legs 1–96
ODP	Ocean Drilling Program	From 1983 to 2003, using the R/V *JOIDES Resolution*; Legs 100–210
IODP	Integrated Ocean Drilling Program	From 2003 to 2013, using the R/V *JOIDES Resolution*, D/V *Chikyu* and specialized Mission Specific Platforms; Expeditions 301 to 348
IODP	International Ocean Discovery Program	From 2013 to 2023, using the R/V *JOIDES Resolution*, D/V *Chikyu* and specialized Mission Specific Platforms
Drilling Tools		
BHA	Bottomhole Assembly	30 to 150 m long assembly of heavy drill pipes; includes the drill collars
APC	Advanced Piston Core	Hydraulic piston core system currently in use on the R/V *JOIDES Resolution* (*first successful use in 1987–DSDP Leg 94; record coring depth to 458.4 mbsf during IODP 323, Hole U1341B*)
APCT-3	Advanced Piston Core-Thermoprobe	Hydraulic piston core system currently in use on the R/V *JOIDES Resolution*, equipped with a thermoprobe for in situ measurements
HPC	Hydraulic Piston Core	Former hydraulic piston core system (*first successful use in 1982-DSDP Leg 64*)
HPCS	Hydraulic Piston Core System	Hydraulic piston core system currently in use on the D/V *Chikyu* (*first successful use in 2005*)
XCB	Extended Core Barrel	Rotating cutting shoe used to drill soft to medium-hard rocks (*first successful use in 1982-DSDP Leg 90*). Compatible with the BHA used for APC
RCB	Rotary Core Barrel	Drilling tool used on medium-hard to hard rocks (*first successful use in 1971; DSDP Leg 1*)
Physical Properties Presented in This Study (Available Since Start of ODP in 1983)		
MS	Magnetic Susceptibility	Dimensionless quantity relative to the degree of magnetization of a material in response to a magnetic field; taken on both whole round and split core
GRA	Gamma ray Attenuation	Gives the bulk density of a material (g/cm^3); taken on whole core
NGR	Natural Gamma Radiation	Gives the natural radioactivity of the sediment (counts per second); taken on whole core
P wave	Compressional wave velocity	Velocity (m/s) of first arrival of the compressional wave. Gives estimate of compaction in nongranular sediments
Others		
mbsl	Meters below sea level	Dimension used for water depth
mbsf	Meters below seafloor	Dimension used for core depth

meters of fully disturbed sediments to the cores that may show similar textures to natural beds (e.g., density current deposits). Similarly, lengths of unrecovered sediments can be destroyed in the borehole, leading to substantial artificial stratigraphic gaps between the cores.

Coring disturbances occur mostly in noncohesive sediments, from very fine sands to pebbles, rather than cohesive clays, though we also discuss deformation in hemipelagic mud. The best quality cores of IODP Expedition 340 are those with numerous beds of firm mud distributed through the cored intervals, which prevent the noncohesive sands and gravels from being dramatically extended. In addition, the presence of firm mud at the bottom of certain cores acted like a plug in the core catchers, preventing unconsolidated sand from escaping. This study does not discuss disturbances during XCB (Extended Core Barrel) and RCB (Rotary Core Barrel) drilling [e.g., *Piper*, 1975; *Kidd et al*., 1978; *Francis et al*., 1982; *Flood et al*., 1995; *Huey*, 2009].

Investigations of near-source volcanic sediments from IODP Expedition 340 reveal facies that are commonly coarser grained and thicker than in bioclastic and typical siliciclastic realms; they are thus more prone to coring disturbances. The Expedition 340 retrieved 266 APC cores in total and partial strokes were common (52%), whereas 14% of core barrels got stuck. These statistics are similar to those for ODP Leg 126, which drilled similar volcaniclastic sediments in the Izu Bonin arc [*Taylor et al*., 1990a; *Nishimura*, 1991; *Jutzeler and White*, 2013]. Regarding the observable disturbances of Leg 340, similar ones occurred in cores from other ODP Legs, for instance basal flow-in disturbances in Holes 788C, 790A, 790B, and 790C of Leg 126 in the Izu-Bonin arc [*Taylor et al*., 1990b, 1990c; *Nishimura*, 1991; *Jutzeler and White*, 2013], Hole 827A of Leg 134 in the Vanuatu [*Collot et al*., 1992], Hole 840C of Leg 135 in the Lau Basin [*Parson et al*., 1992a], Hole 954A of Leg 157 offshore Gran Canaria [*Schmincke et al*., 1995], Hole 1037B of Leg 169 in the Escanaba trough, offshore California [*Fouquet et al*., 1998], Hole 1224A of Leg 200 offshore Hawaii [*Stephen et al*., 2003; *Garcia et al*., 2006], and Holes 1436A, 1436B, 1436C, and 1437B of IODP Expedition 350 in the Izu rear arc [*Tamura et al*., in press]. Given the extreme technical challenge of recovering such sandy sediment, the levels of core recovery were a major success for IODP and its drilling team and are a testament to the skill of the technical coring team, extending IODP scope to new types of sand-rich sequences.

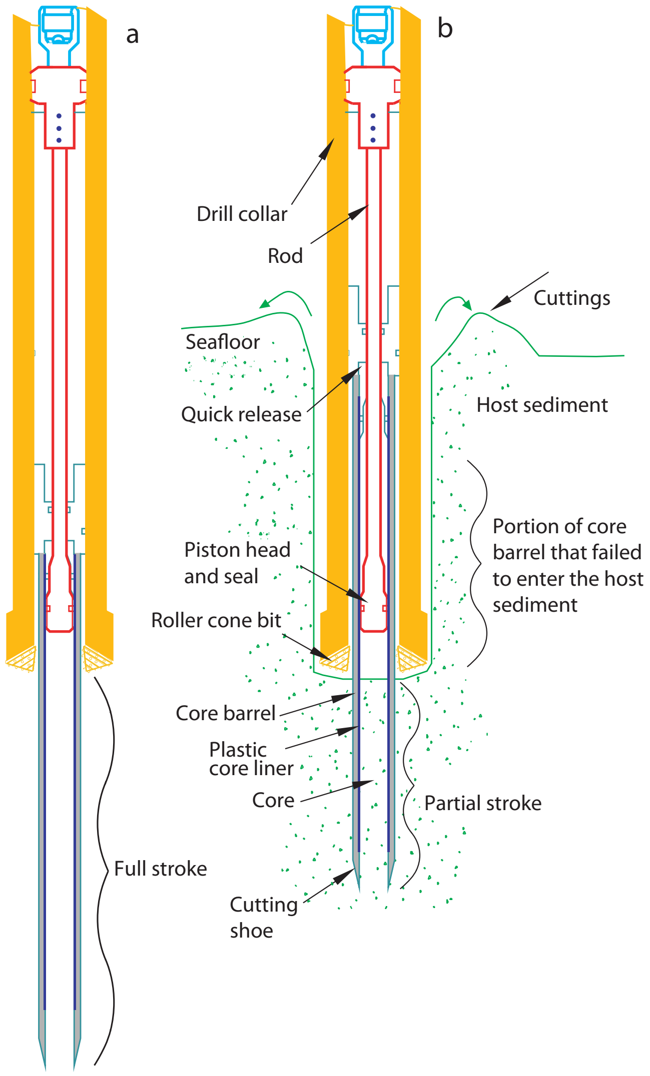

Figure 1. Schematic of the Advanced Piston Corer (APC) after stroking out of the inner core barrel, in a (a) full stroke (b) and partial stroke scenarios. Only the lowest part of the Bottom Hole Assembly (BHA), which is >100 m long, is shown here. Both core liner and cutting shoe are retrieved for each core. Full stroke is 9.5 or 5 m, depending on the apparatus. The cutting shoe contains the core catchers.

In this study, we discuss how to distinguish coring disturbances from natural facies, using core photographs and physical properties data taken onboard the R/V *JOIDES Resolution*. This study identifies the causes, effects, and extent of coring disturbances, therefore giving the opportunity to confidently conduct detailed facies analysis in the undisturbed parts of the cores. This contribution starts by outlining the process of APC (section 2). We aim to provide a comprehensive description of the types of core disturbances that can result from APC, and outline the technical causes of these disturbances (section 3). Examples of each type of coring disturbance are given from APC cores collected offshore Montserrat and Martinique during IODP Expedition 340 [*Expedition 340 Scientists*, 2012; *Le Friant et al*., 2013]. Following this, we outline methods and guidelines for identifying types of core deformation based on characteristic sediment textures, geophysical data, and drilling summaries. In particular, we focus on coring disturbances due to basal flow-in of sand during partial strokes, and settling of sand within individual core sections during transport on deck (sections 3 and 4). Finally in section 5, we illustrate the scientific importance of identifying coring disturbances using the record of (i) volcanic mass flow events offshore Montserrat and Martinique (Lesser Antilles) from IODP Expedition 340 and (ii) the offshore continuation of the Missoula megafloods [*Fouquet et al*., 1998; *Zuffa et al*., 2000] in the Escanaba Trough from ODP Leg 169 at Site 1037. In addition, section 6 outlines and supports initiatives by IODP to minimize APC coring disturbances.

2. APC Coring Technique

Recovery of seafloor sediments by drilling for research purposes started with the Mohole project and was followed by the DSDP, ODP, and current IODP programs [*Storms*, 1990; *Huey*, 2009]. Advanced Piston Coring (APC) under the IODP was developed through improvements to earlier versions of piston coring, first tested during the Swedish Deep Sea Expedition [e.g., *Kullenberg*, 1947; *Weaver and Schultheiss*, 1990]. New technology in the early 1980s provided the Hydraulic Piston Corer (HPC), which was attached to the drilling equipment of the D/V *Glomar Challenger* [*Walton et al*., 1983; *Ruddiman et al*., 1987] and applied by pumping pressure to the drill pipe rather than operating as a stand-alone piston corer. Currently, the R/V *JOIDES Resolution* drilling vessel uses an improved version of the HPC, the Advanced Piston Corer (APC) [*Huey*, 2009].

The D/V *Chikyu*, the latest generation scientific drilling vessel, uses a similar model, with the Hydraulic Piston Coring System (HPCS) [*Huey*, 2009; *Yonebayashi et al*., 2009]. The IODP Mission Specific Platform (MSP) expeditions utilize the wireline coring system of the British Geological Survey (BGS). The APC (and HPCS) allows successive coring of unconsolidated and semiconsolidated sediments down to hundreds of mbsf (Figure 1), whereas drilling with XCB and RCB are mostly performed in consolidated sediments and rocks. Additional drilling tools are used aboard the D/V *Chikyu*, but they are chiefly used for rocks with higher strength and are not part of this study. Here, we describe riserless operations, available on the R/V *JOIDES Resolution*, D/V *Chikyu*, and on the IODP MSPs, where only the core is brought to the surface, the cuttings remaining on the seafloor. As APC and HPCS are almost identical, we refer to both techniques as APC, for simplicity. Summary of the coring techniques and common IODP acronyms are listed in Table 1.

2.1. APC Operations

The methodology of APC operations are summarized here [*Storms*, 1990; *Huey*, 2009]. For the first core, the Bottom Hole Assembly (BHA) that contains the drill collar and core barrel (Figure 1) is lowered to just above the seafloor. Note that this is a wireline coring system whereby the core barrel is deployed and retrieved via a wireline cable through the BHA. A defined hydraulic pressure is released by a piston that shoots the core barrel at 6–12 m/s from the drill collar down into the undisturbed sediments. The core liner cannot rotate during shooting. A full stroke is defined as when full core penetration of 9.5 m (or $\sim$5 m in the recently operational half-piston core) is achieved (Figure 1), which typically takes $<$2 s. In contrast, partial penetration of the host sediments is called a partial stroke. For technical reasons, a heave compensator, commonly used to attenuate the vertical movements of the ship from the heave during the drilling operations, has to be momentarily shut down during the APC shooting. The short coring time reduces most heave effects [*Huey*, 2009; *Iturrino et al*., 2013], but may still affect the core integrity. The core barrel and its acquired sample are then retrieved using the wireline cable back to the vessel, where it is transferred with a high-speed winch onto the ship's deck for processing. A key feature of the APC is that after piston coring, rotary drilling then opens the hole down to the level previously piston cored, after which a new piston core barrel is deployed. A new piston core can then be shot into the next section of stratigraphy. In ideal conditions, 1–4 cores can be taken per hour on the R/V *JOIDES Resolution*. These operations are commonly continued to refusal, which is until the piston core has little or no penetration into stiff sediments or consolidated basement.

2.2. Core Recovery on Deck and Splitting

Once on deck, the core is transferred to a platform (cat walk) adjacent to the rig-floor, where it is cut into individual core sections that are $\sim$1.5 m in length. Each full core produces up to seven such 1.5 m long core sections. In addition, sediment trapped in the core catcher is recovered. The core catcher consists of one to several fingered plates placed just above the cutting shoe (at the bottom of the core barrel, Figure 1) and is designed to prevent loss of sediments by restricting the diameter of the open core barrel. In soft sediments, a "flapper" catcher is added to the core catcher, which closes the entire diameter of the core barrel. On the R/V *JOIDES Resolution*, the core sections are allowed to equilibrate to ambient ship temperature for approximately 3 h, whereas on the D/V *Chikyu*, X-ray tomography is immediately undertaken once the core reaches the deck [*Yonebayashi et al*., 2009]; multiple physical properties are then analyzed before the core is split lengthways, into working and archive halves. Further physical properties analyses, paleomagnetic measurements, paleontology, and biostratigraphy, core description and photographs are taken on the split cores. In addition, discrete samples are taken for analyses. In APC sediment cores, the working-half corresponds to the top-half of the core section during preliminary storage; thus, it commonly contains more pore fluids and may be more disturbed, especially where units of sand and gravel occur.

3. Types of Coring Disturbances and Their Recognition

A primary task of core description teams aboard IODP vessels is to identify bed boundaries and to describe stratifications and lithologies of each bed in a timely manner. Obvious coring disturbances, such as coarse fall-in and soupy textures, are easily recognized by the core description team. However, the extent of some of these disturbances can be more difficult to recognize. Downhole logging is a powerful tool for stratigraphic correlations and can help identify coring disturbances where logging data are available (typically below $\sim$80 mbsf). Hole comparison can be very useful at sites with multiple holes to help identifying

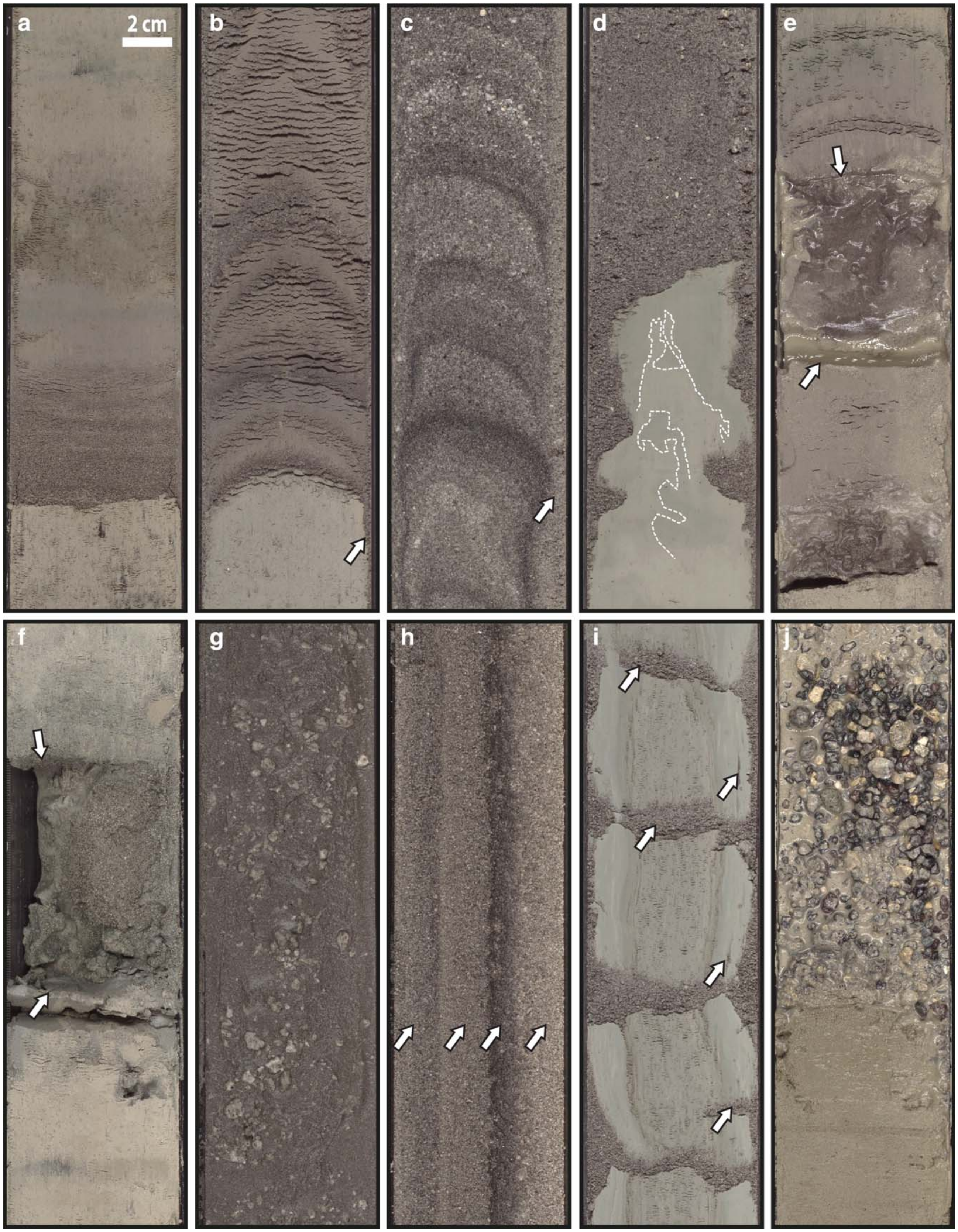

Figure 2.

variations in the initial shooting depth (the water depth where the BHA starts shooting, a few meter above the mudline) and any associated coring disturbances. In addition, core extension can be calibrated [*Lisiecki and Herbert*, 2008].

Here we present a list of the most common causes of coring disturbances in IODP cores, described in order of core flow, from APC shooting to core handling aboard ship. The term "bed" describes a stratigraphic entity deposited from a single natural event, whereas "unit" describes an interval which seems continuous, but may include several beds or entities formed either naturally or by coring disturbances.

3.1. Shearing of Sediment, Sediment Flowage, and Mid-Core Flow-In

Many cores show upward-arching bed contacts at their margins (Figure 2), which result from weak to moderate coring-induced shear between the sediment and core liner [*Skinner and McCave*, 2003]. These disturbances are easily recognized because bedding is uniformly bent upward along the core margins (Figures 2b and 2c). Downward-arching structures can also occasionally occur (e.g., Core 834A-6H from ODP Leg 135) [*Parson et al*., 1992b]. Shearing structures likely affect physical properties data taken along the core length, recording gradual physical changes across the bed boundary zone instead of step-like variations (Figure 3).

In some cases, high shearing rates between cored sediments and core liner can cause sediment flowage, leaving a smear of exotic sediment along the inside of the core barrel (Figure 2c). In cases of sediment shearing, contamination by flowage along the core liner is likely over long sections of the core, and this should be taken into account for analysis of the physical properties data and during any subsequent sampling. The outside rim ($\sim$0.5 cm) of the core should ideally not be sampled.

Mid-core flow-in is the combination of high coring-induced shearing and sediment flowage, which may occur where there is a high rheology contrast between intercalated lithologies. Coring-induced shearing can fracture cohesive beds (typically, clay-rich intervals), allowing injection of flowed sediments (typically sand-rich sediments) in the cracks, thus creating false stratigraphy (Figure 2i).

3.2. Flow-In and Partial Stroke

A key issue for piston coring is when the piston does not penetrate to its full length, resulting in a partial stroke (Figures 1 and 4). A partial stroke commonly occurs when sediments become too stiff, the cutting shoe hits a solid surface (boulder or basement), or where high shear-strength sand is encountered. With the current technology, partial strokes are identified by the coring crew and logged in the drilling summaries, although the actual length of core barrel that penetrated the seafloor remains unknown. A partial stroke has two serious consequences for the integrity of the core.

First, a partial stroke signifies that the core barrel did not deploy to its maximum extent (target depth) of 9.5 m for a full-length APC core barrel. The cored sediments fill an unknown thickness in the basal part of the core liner, with seawater occupying the portion of core liner that remained within the BHA (Figure 1). When the core barrel is recovered with the wireline, the top part of the piston is lifted up and freely operates. It thus continues its stroke backward (without entering more sediments), until it reaches its full mechanical extent (Figure 1). This makes the piston act like a syringe, sucking the cored sediments upward into the core liner, and sucking in granular host (uncored) sediments adjacent to the cutting shoe as well (Figure 4). This process can cause basal flow-in textures of several meters at the bottom of the core and may also strongly disturb the uppermost part of the uncored underlying host sediment (which will be penetrated with the next core). This sucking action may be jerky, involving a range of acceleration rates,

Figure 2. Example of deformations and disturbances in cores from IODP Expedition 340, with pale gray hemipelagic mud and darker volcanic sand; core liner internal diameter is 6.6 cm; top of page is uphole. (a) Undeformed core, with planar bed contacts; U1395B-8H-3; (b) mild deformation with typical uparching beds contacts; beds remain separate and vertical flowage of sediment along the core liner is minor (arrow); U1397B-6H-4; (c) moderate deformation of sandy beds that can still be distinguished from each other; vertical flowage of sediments along the core liner is significant (arrow); U1397B-2H-4; (d) strong deformation, with mingling and distortion of different beds of hemipelagic mud (dashed lines) at contact with overlying volcanic sand; U1398A-13H-3; (e and f) disturbed sandy units (between arrows) amongst much less deformed finer grained units representing initiation of mid-core flow-in. The middle sandy unit is soupy (Figure 2e) or partially empty (Figure 2f), which is distinctive of localized vertical extension that favored liquefaction in this particular layer, destroying all internal structures; U1395A-2H-2 and U1394B-14H-3, respectively; (g) strongly deformed, soupy sandy unit (>8 m in thickness) with few pumice granules in which all structures have been destroyed by liquefaction and/or vertical settling through seawater. Partial stroke occurred and the working-half-core is almost empty; U1394B-19H-4; (h) rare occurrence of pseudohorizontal density grading in several units (arrows), due to 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; U1394B-13H-2. (i) Exceptional deformation in hemipelagic mud that got sheared then truncated by vertical stress during retrieval of the core from the host sediments and aggravated by mid-core flow-in of allochthonous, dark sandy sediment injected between the segmented mud units; U1398B-11H-7; (j) coarse, polymictic clasts in the uppermost part of a core (U1394B-9H-1), representing fall-in from cuttings that were not washed during the drilling of the previous core, which was a partial stroke.

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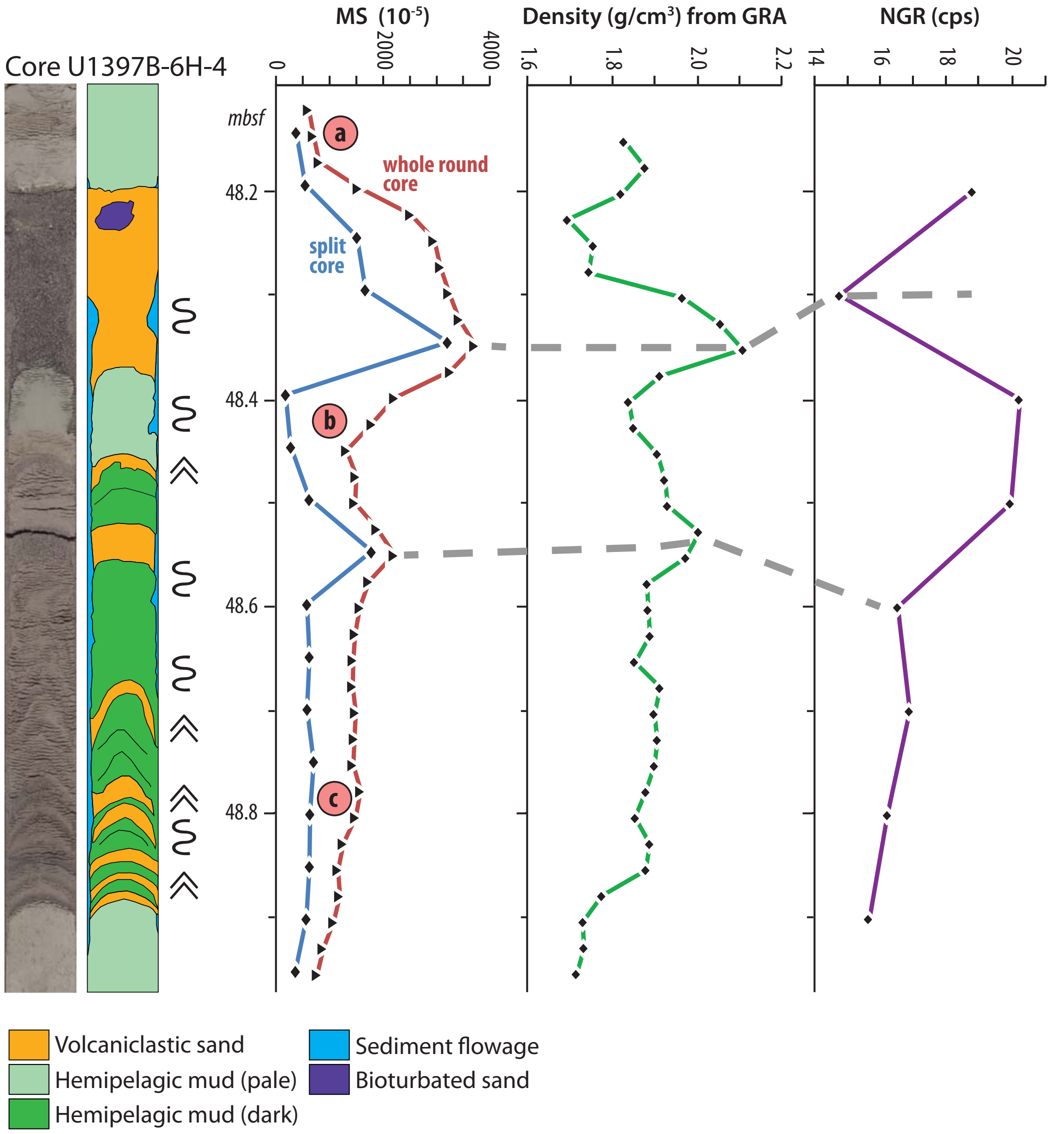

Figure 3. Variations of physical properties with coring disturbances, Core U1397B-6H4, offshore Martinique. (left) Photo of the core and type of sediments and disturbances. Volcaniclastic sediments are more magnetically susceptible (MS) and denser (GRA), but less naturally radioactive (NGR) than hemipelagic mud. Overall, the properties correctly identify the type of sediment along the core; gray dashed lines for matching peaks. Here we compare the MS measurements taken on whole and split cores. Note that the whole core measurement is a noncontact, loop measurement which will measure the entire core volume at a given depth. The split core measurement is a point sensor, contact measurement which takes a discrete measurement at the center of the split core (less affected by shear effects along the core-liner interface). (a) the core is undisturbed and the MS on both split (blue) and whole core (red) decreases abruptly. In contrast, in (b), MS values on whole core are not low enough to characterize a bed of hemipelagic mud, because flowage of volcaniclastic grains along the core liner and bed uparching blur the bed boundary along the margins of the core liner. Ash beds in (c) cannot be identified by physical properties, due to uparching of sediments that average all quantities in the whole core measurement. In the split core data set, ash layers may not be identified due the resolution of the measurement. See Figure 9 for symbol key.

triggering segmentation and liquefaction of poorly cohesive units (such as sands) throughout the core (Figures 2e and 2f). Sediment flowage can fill open space within the core liner in certain cases [*Stow and Aksu*, 1978; *McCoy*, 1985] and may create an artificial unit between undisturbed beds.

Second, the length of recovered sediments in a core section is used as reference for the distance to drill and lower the BHA before the next APC shooting (Figure 4). The actual length of undisturbed sequence can only be estimated once the split core is evaluated by the science party. In the case of the R/V *JOIDES Resolution*, this timeframe (hours) conflicts with the requirements for continuous drilling, which would need such information within minutes of the core being sectioned. This is an extremely important point, because sediment sucked-in by basal flow-in can significantly increase the core length and hence the perceived recovery of in

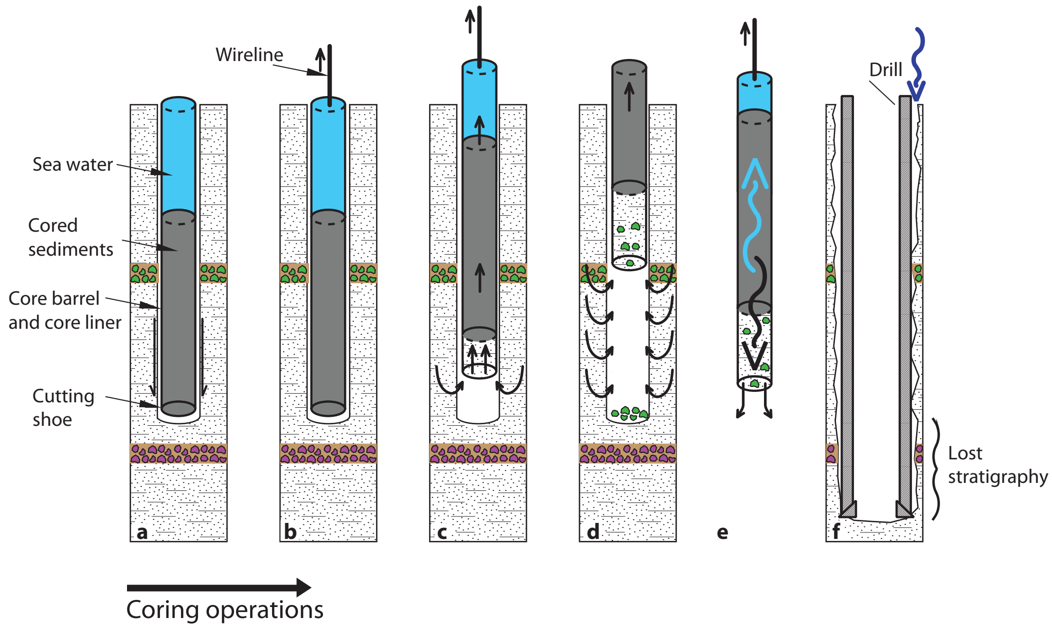

Figure 4. Schematic of the main technical cause of basal flow-in in unconsolidated, sandy to gravelly sediments, creating false basal cores with soupy facies (not to scale). Basal flow-in mostly occurs following a partial stroke of the piston core. (a) Shooting of the piston core in unconsolidated sediments, partial stroke leaves large volume of water at the top of the core barrel; (b) the core barrel is released by pull of the wireline; (c) pull continues the stroke of the piston core, which sucks the core higher in the core liner. Unconsolidated host sediments are sucked-in in the core barrel, such as in an syringe, creating basal flow-in; (d) continuous suction of host sediments into the core barrel and partial collapse of dense clasts into the hole, which may be sampled as the top part of the next core (fall-in, see text); (e) sudden release of the vertical stress when the core is set free from the host sediments. Pressure differential is released, and gravity and high-speed winching induces sediments to fall back down (black arrow), whereas seawater tends to be buoyant (blue arrow), favoring sediment liquefaction and vertical extension of weakly cohesive (sandy) units in the core; (f) after recovery of the core on deck, the rotary drilling operations to deepen the hole resume. The length of recovered core is used to determine the distance to drill (advance by recovery); the additional length of core from basal flow-in is included in the drilling length, implying drilling and total loss of up to several m of sediments.

situ stratigraphy. This means that the next APC will be initiated at a distance corresponding to the length artificially added to core length by flow-in, below the end of the previously cored section, thus producing an artificial stratigraphic hiatus between consecutive APC cores (Figure 5). The strata in this interval will not be recovered (Figure 4), because sediments will be drilled and expelled as "cuttings" onto the seafloor during riserless operations. Unsampled strata from such an interval may be cored in an adjacent hole; however, stratigraphic correlation across holes can be extremely difficult where there are very thick sandy units.

Basal flow-in may be pervasive over several meters at the base of the core (Figures 5 and 6). Basal flow-in sucks in the host sediments mostly at the base of the hole (Figure 4), but also possibly from the entire thickness of strata traversed by the core, during progressive retrieval of the cutting shoe from the host sediments. The sucked-in mixture should therefore be polymict, and more homogeneous and thus not representative of the in situ stratigraphy. Basal flow-in units may be underlain by units that experienced mild to strong sediment liquefaction and mixing. Unconsolidated, massive, soupy, ungraded to complexly graded, sandy to pebbly units that are not underlain by cohesive mud (which would act as a seal between the cored sediments and the open-ended cutting shoe) are prone to contain a significant amount of basal flow-in sediment [e.g., *Stow and Aksu*, 1978; *Walton et al.*, 1983; *Blomqvist*, 1985]. The original stratigraphy in sandy and pebbly beds can be preserved where sandwiched between undeformed beds of cohesive mud. However, core elongation is likely to occur in cores that experienced partial stroke and basal flow-in, which may extend and liquefy sandy beds.

Most basal flow-in textures can be identified from the drilling summaries which record partial strokes, and by the low recovery rate of the core. Composite high-resolution images of the core sections in parallel are very useful for the identification of basal flow-in disturbances (Figure 7). The cores that experienced basal flow-in can be identified by a number of segments of sediments separated by core voids (Figure 7). All partially filled core sections are likely to be made of fluidized basal flow-in sediments, although the boundary

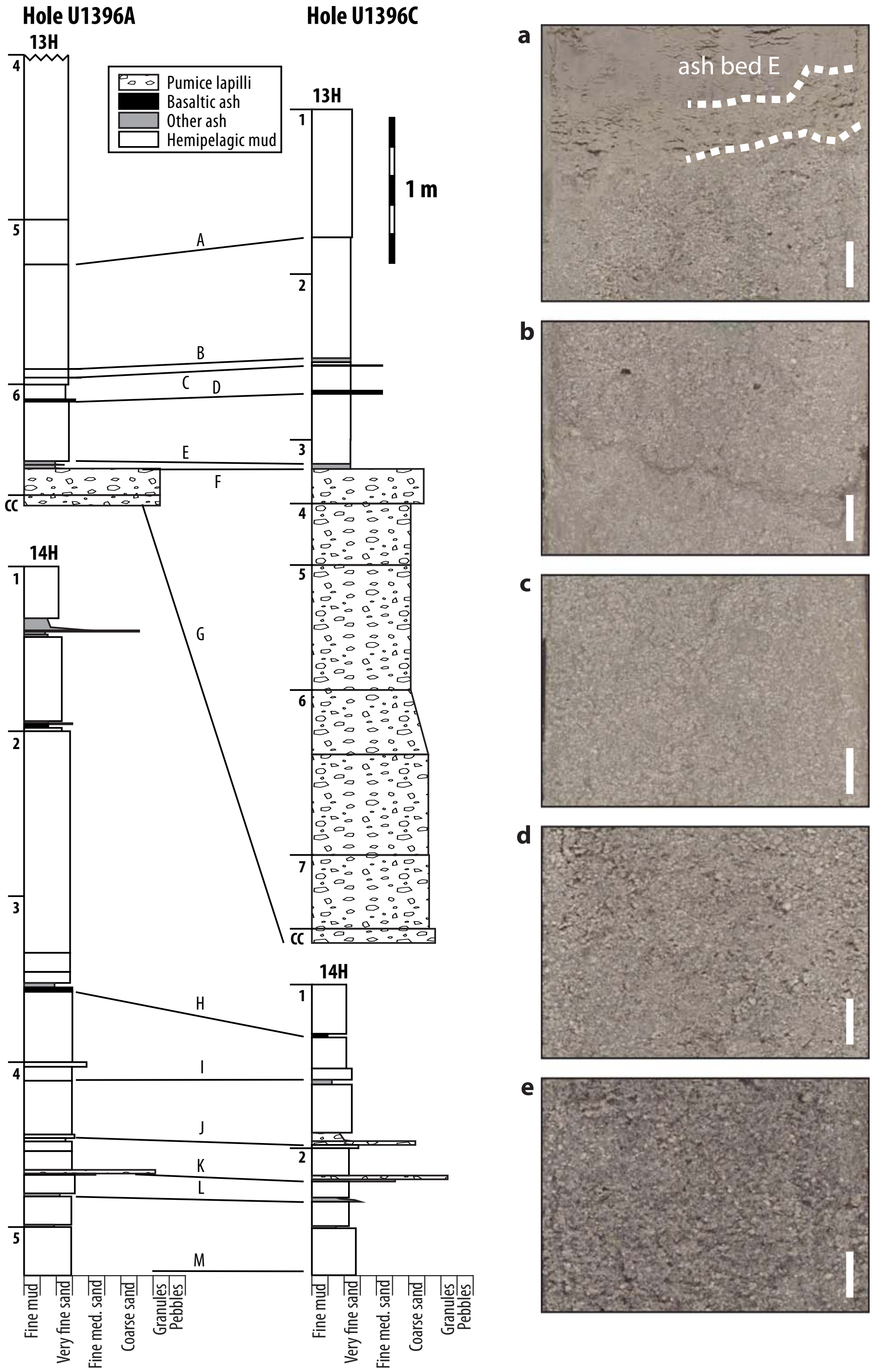

Figure 5. Complex stratigraphic variations due to basal flow-in within Holes U1396A and U1396C, IODP Expedition 340. The two holes were drilled 40 m apart on the summit of a ~800 mbsl ridge offshore Montserrat, where very low accumulation rate produced relatively thin and laterally continuous beds. The pumice lapilli unit between F and G is (a) 35 cm thick at the base of U1396A-13H (full stroke, initiated at 107.3 mbsf), whereas it is (b–e) a 4.4 m thick, homogeneous, soupy, weakly normally and density-graded pumiceous sand at the base of U1396C-13H (partial stroke, initiated at 112.9 mbsf). Basal flow-in of ~4 m of pumiceous sand occurred during recovery of U1396C-13H, which caused large oversampling of the granular unit, and loss of 3.3 m of hemipelagic mud and ash layers, because the drilling length to position the drill collar for the next coring operation is calculated from the recovered length of the previous core, and in this case includes the flow-in sediments. A–M indicates the main stratigraphic units; U1396A-13H-6 (Figure 5a); U1396C-13H-3 (Figure 5b); U1396C-13H-4 (Figure 5c); U1396C-13H-6 (Figure 5d); U1396C-13H-7 (Figure 5e); white scale bars are 1 cm; top of page is uphole.

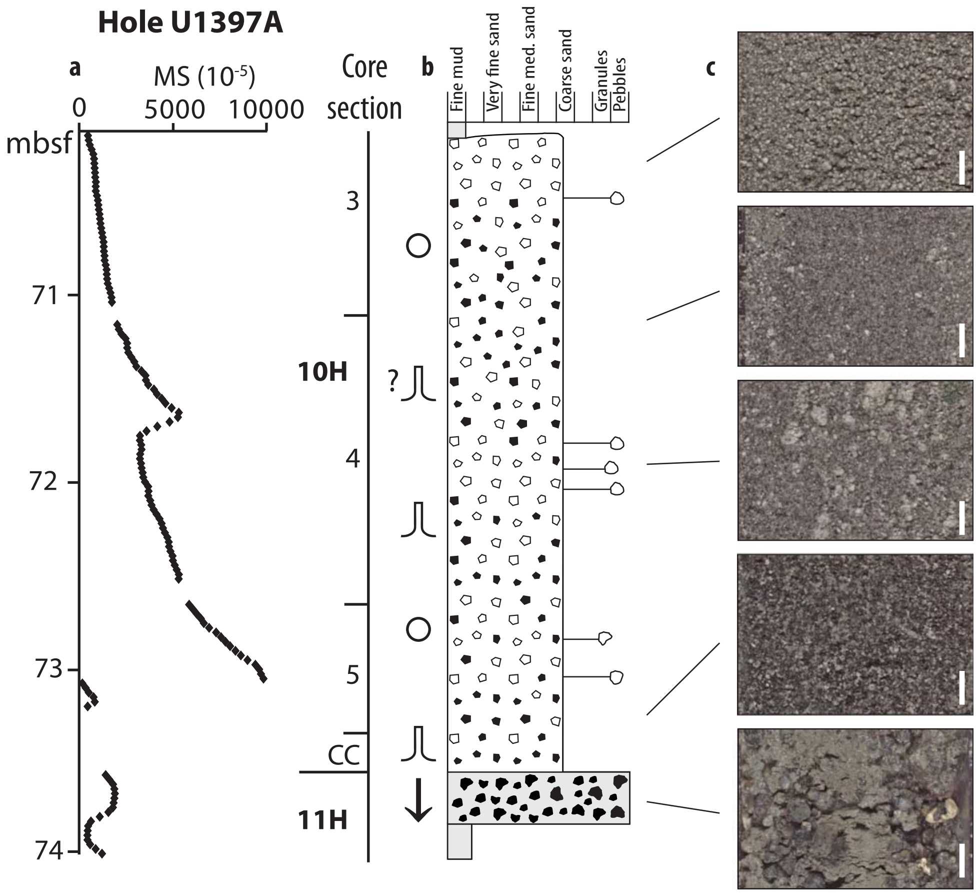

Figure 6. Basal flow-in and fall-in disturbances in Hole U1397A, offshore Martinique, IODP Expedition 340. The bottom part of the Core U1397A-10H (70.2–73.6 mbsf) is generally homogeneous in composition and is complexly graded in clast size and clast types (dense clast versus pumice); the entire core is only 6.9 m in length. (a) Magnetic susceptibility (MS) reflects normal grading in grain size and grain type separated in two intervals. (b and c) Soupy texture occurs between cores U1397A-10H-3 and U1397A-10H-4. Fall-in of polymict coarse dense pebbles mixed with mud occurs at the top of the core U1397A-11H, reflecting hole stability issues in the units above. The shift in MS grading at 71.6 mbsf may reflect the boundary between sediment liquefied in place within the core liner (above) and sediment sucked-in by basal flow-in. Alternatively, the entire core length below the hemipelagic mud at ~70.2 mbsf may be the product of two major pulses of basal flow-in. White scale bars on photos are 1 cm; top of page is uphole. See Figures 7 and 8 for symbol keys.

between undisturbed and disturbed sandy/gravelly sediments is difficult to establish. In addition, fall-in units (see below) are commonly found in the core taken after a partial stroke.

3.3. Core-Barrel Stuck in the Sediment

The core barrel can become stuck in the sediment, making it very difficult to retrieve the core. This happens most commonly when there is a partial stroke resulting from the presence of stiff sediments. If the core barrel does not detach from the host sediments, a drill-over operation is then required to retrieve the BHA and to preserve the hole. Drilling-over involves use of the rotary drill bit to clear sediment around the core barrel; this reduces friction between the core barrel and the host sediments, and the core barrel is generally released. Drilling-over is difficult and endangers the BHA and the core barrel and is accompanied by extensive pumping of seawater (and eventually drilling mud) through the drill string. This pumping should not affect the core unless drilling-over takes place too close to the cutting shoe. However, the initial "overpull" (where elevated wireline tensions are used to try and release the core barrel prior to drilling-over) is likely to vertically extend the core and hence deform it.

3.4. Fall-In Textures

Fall-in textures can occur when the hole partially collapses, allowing debris to reach the bottom of the hole. Hole stability is an important issue in drilling operations, owing to differences in the geological formation

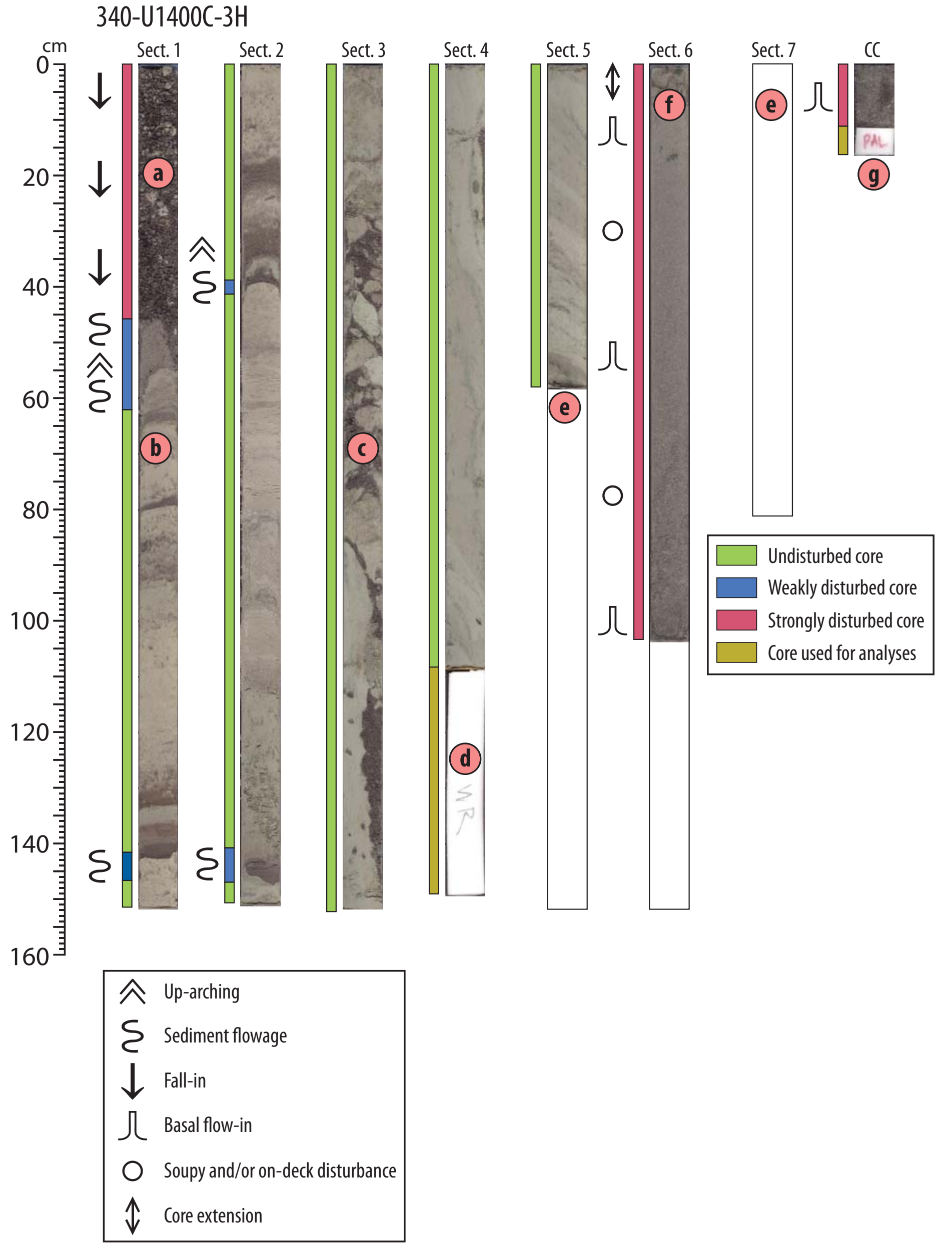

Figure 7. Color and symbol-coded coring disturbances in Core U1400C-3H, offshore Martinique. The core was a partial stroke (only 7.8 m in length). Sections 5 and 6 are incomplete and section 7 is absent. The upper part of the underlying core (U1400C-4H) contains fall-in. (a) Fall-in of coarse volcanic clasts from overlying interval; (b) pristine, undisturbed beds of hemipelagic mud and volcanic origin. Small uparching of beds at 60 cm; (c) deformed clast of hemipelagic mud in volcaniclastic matrix and distorted beds of hemipelagic mud. This facies is common along these cores, and is not related to coring disturbances; (d) whole core sampled for specialized analyses (108–149 cm); (e) last section of firm hemipelagic mud in the core; (f) normally graded volcaniclastic unit interpreted as basal flow-in. The base of the unit is absent (continuing (G) from the core catcher (CC) and from the underlying core); (g) the core catcher is the continuation of section 6. Pristine core is limited to the interval from 55 cm in section 1 down to 58 cm in section 5.

being sampled. Core intervals affected by fall-in characteristically occur at the top of individual cores and are relatively easy to identify (Figures 2J and 6–8) because they contain clasts that were too dense or coarse to be evacuated as cuttings during drilling operations. Intervals of fall-in are commonly a few cm thick but can reach more than a meter and consist of clast-supported, polymictic coarse sand to pebbles, although clayey matrix can also occur. During IODP Expedition 340, the maximum thickness of fall-in was 125 cm (U1394A-5H). Fall-in deposits are commonly associated with basal flow-in deposits in the overlying core; both indicate difficulties during coring operations.

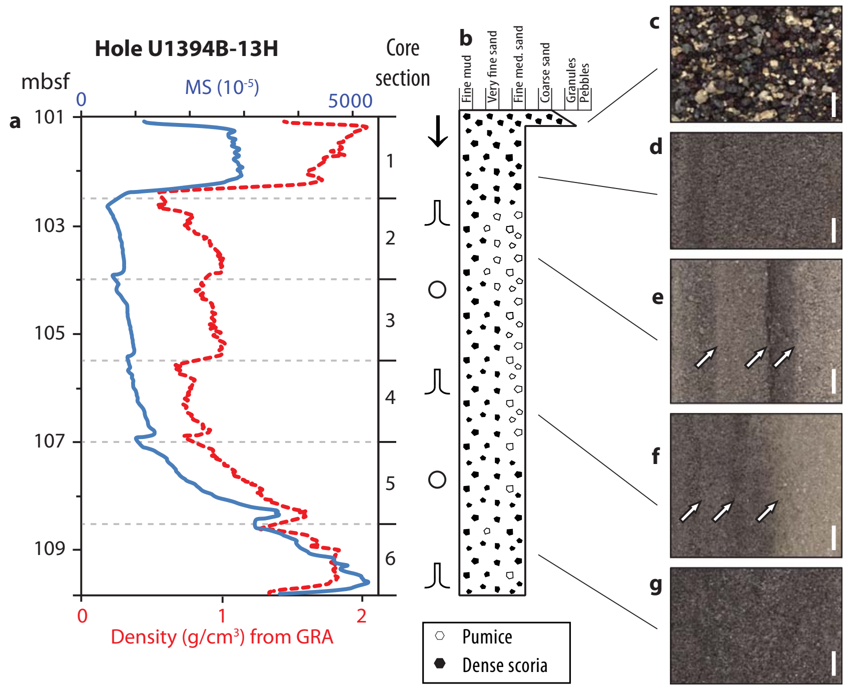

Figure 8. Fall-in, basal flow-in, and on-deck disturbances in Core U1398B-13H offshore Montserrat. Disturbances include: (a) liquefaction, basal flow-in, and vertical sorting during retrieval of the core to the drilling platform (density grading); (c) fall-in (uppermost of core); (e and f) vertical settling on deck (horizontal grading). (a) Magnetic susceptibility (MS, solid blue) and gamma-ray attenuation (GRA, dashed red line) of whole core. Spikes in MS and GRA values at core section boundaries (gray dashed lines) are not representative of the sediments, because plastic core liner and void are also measured. (b) Stratigraphic log showing that most of the core was soupy when split. (e and f) Horizontal grading of dense clasts (left) and pumice (right). White arrows show stratifications formed by density grading in liquefied sediments when core was in a horizontal position (on the cat walk and in the storage racks). White scale bars are 1 cm; top of page is uphole. See Figure 7 for symbol key.

3.5. Sediment Loss Through the Core Catchers

Once decoupled from the host sediments, the core barrel containing the core liner and the cored sediments is returned to the rig-floor with a high-speed winch (Figure 4b). One or several core catchers in the cutting shoe are used to prevent sediments from falling out of the core barrel. Core catchers work efficiently with muds and consolidated sediments, but anything coarser than fine sands in the lowest part of the core may be lost, especially if these are unconsolidated and become liquefied. Such loss of sediment will result in an identifiable absence of sediment from the base of the core section. Loss of sediment through the core catcher will have the opposite effect to a partial stroke. Because the drilled interval is measured from the length of recovered core, the stratigraphic thickness of sediment penetrated by the core barrel will be underestimated, and the drilling operations to lower the BHA will not attain the actual cored depth. The next APC will be deployed from a "too shallow" BHA, "penetrating" an already cored interval filled with seawater and/or or fall-in debris, which will be sampled at the top of the next core.

3.6. Deformation Due to Core Recovery and Transport on Deck

Using a high-speed winch to retrieve the core barrel involves strong accelerations and decelerations that may initiate liquefaction of sands in the core liner or promote the escape of sand through the core catchers. Equally, the generation or continuation of sediment flowage and/or core extension may occur from any resulting sediment liquefaction. Tumbling of the core barrel during recovery from the BHA to the deck may also increase these disturbances (Figure 9b). Despite great care from the highly experienced IODP crew, handling of cores may promote unavoidable disturbances in the structure of the core. Once on deck, the core in its liner is removed from the metal core barrel, passing from a vertical to a horizontal position before being carried onto the cat walk (Figure 9c).

The following processes can occur in very thick sand deposits that are commonly cored in volcanic aprons. Liquefaction of sands during transport can allow fluid (interstitial pore fluids and/or seawater) to escape

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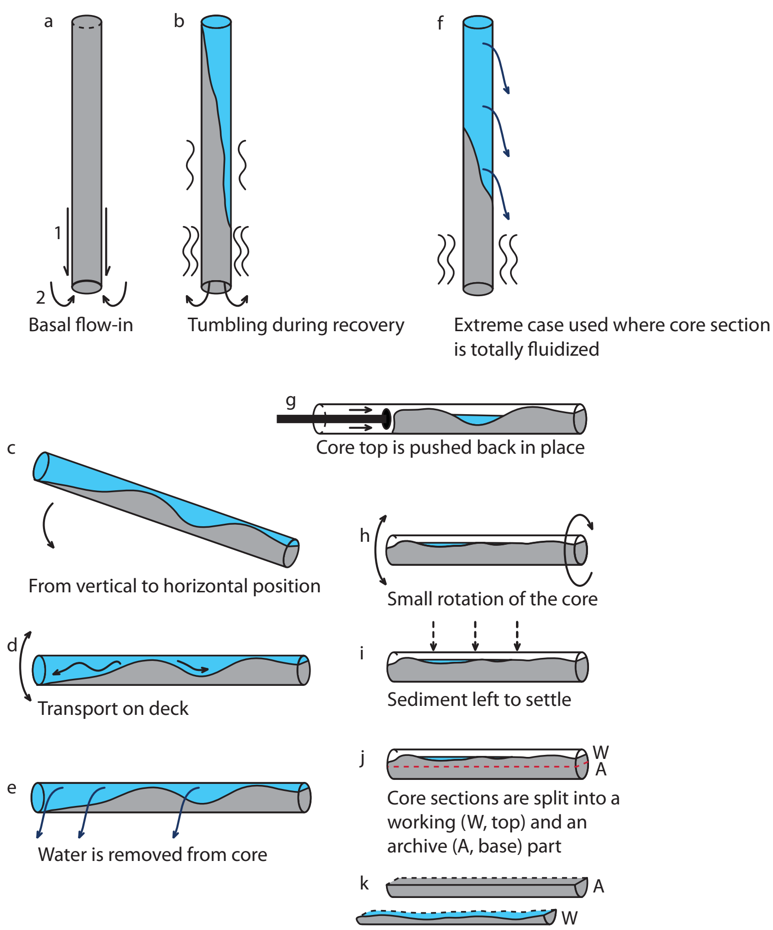

Figure 9. Possible disturbances in sandy to gravelly cores retrieved by APC. (a) Sudden release of the core liner into the sediment (1); sucking in of loose clasts at the bottom of the core liner during retrieval, creating basal flow-in (2; see Figure 4); (b) tumbling on the core barrel and vertical accelerations during recovery; release of small amount of loose sediments through the core catcher; (c) transfer of the core liner to a horizontal position on deck; (d) loose clasts flush back and forth during transport and lying down on deck (cat walk); (e) the core liner is drilled at many places to release excessive pore pressure. Small volumes of fines are lost; (f) rare case when abundant water is in the core. The core liner has to be put in vertical position to release exceeding seawater; (g) loose patches of sediments at the top of the core liner are pushed together to make a coherent core volume, any voids are therefore lost; (h) the core liner is cut in ~1.50 m long sections, which are eventually rotated to put the archive-half on the lower part of the cylinder; (i) sediment settles for 3 h to reach ambient ship temperature; occasional shaking and tumbling when analyzed as whole core on two track systems; (j) the core liner is split lengthways, from base to top; (k) the working-half (W) is commonly much less voluminous than the archive-half (A), corresponding to fluid loss.

from the sediment, or more specifically, for sand to settle through the fluid. Initial liquefaction may occur during transport of the core to the ship, in which case initial fluid-sediment segregation is vertical. Alternatively, it may occur when the core is rotated to horizontal on deck or afterward. In either case, the flowable sand and water will ultimately stabilize with sand overlain by water. During horizontal transport to the cat walk, the top portion of sandy cores can be devoid of sediments. Instead, sloshing of slurries (that can include isolated pebbles; Figure 9d) can contaminate or otherwise modify the sand, which no longer retains its depositional fabric. In long intervals where firm mud units are absent, waves of slurry can commonly be seen in motion through the transparent core liner (Figure 9d).

Fines-rich fluid removed from the sand is typically lost during sectioning of the core, or intentionally removed prior to sectioning by drilling discrete holes along the core liner to lower the pore pressure (Figure 9e). Examination under the microscope of the fluid collected from loose volcaniclastic sand deposits during IODP Expedition 340 revealed a broad range of grain sizes and grain types up to fine sands, including crystals. The mass of fines removed from the core is relatively low in comparison to the mass of the core and should not affect the bulk grain size distribution for thick units. Sectioning of the cores into core sections

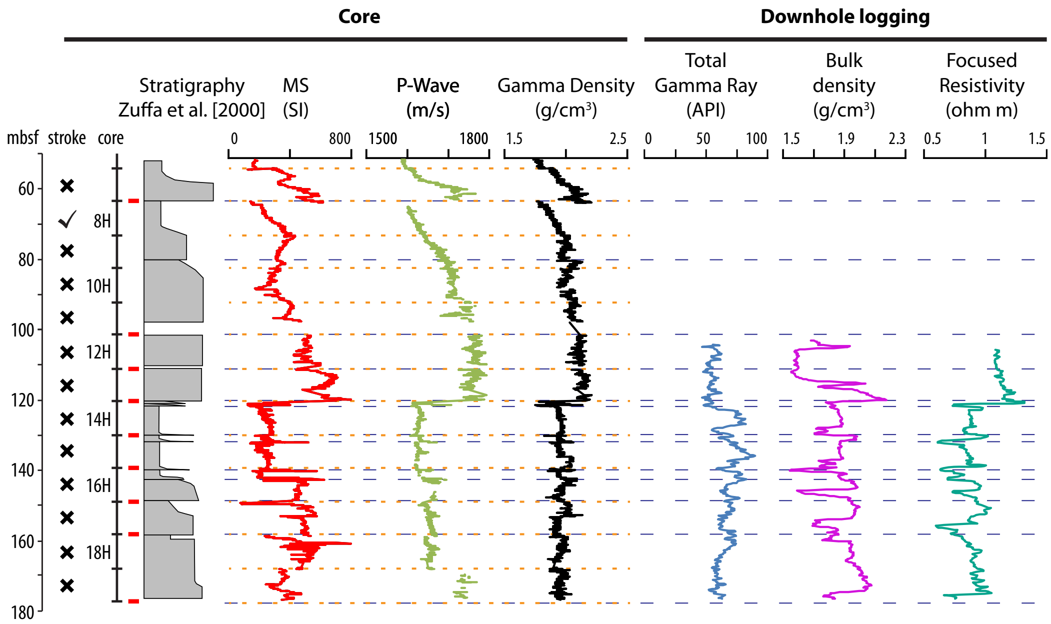

Figure 10. Physical properties and downhole logging data from the Escanaba trough (IODP 169, East Pacific). Tick mark for full stroke, cross for partial strokes (left). The ~65–120 mbsf unit shows overall regular grading in physical properties, interpreted here as chiefly resulting from intensely disturbed sands during core recovery, resulting in destruction of most stratifications. Dashed amber lines for stratigraphic boundaries in *Zuffa et al.* [2000]; dashed gray lines for core boundaries. Thick red tick (left) shows where interpreted stratigraphic boundaries in *Zuffa et al.* [2000] match core boundaries.

induces liquefaction and fines removal, thus creating spikes in physical properties over a few centimeters at the end of core sections. However, it is IODP practice to discard physical properties data from the top and bottom of core sections to avoid such end effects. In addition, drill holes through the core liner can affect the core itself, by forming small indents and more pervasive deformation of the sediments, and locally depleting the sediments from very fine grains [*Flood et al.*, 1995]. In very rare and extreme cases, for instance where fully liquefied sands are present in the lower part of a core that experienced partial stroke, the core sections have to be stood vertically to separate sediments from water by gravity (Figure 9f) before sectioning can be undertaken.

The uppermost sediments of each retrieved core are in direct contact with seawater, favoring their partial collapse once put into a horizontal position during transport to the cat walk. These sediments are gently pushed back using a plastic tool, to recreate a coherent core (Figure 9g). Unavoidable rotation and motion of the core sections during transport to the first storage racks may promote further mixing of the sediments (Figure 9d).

Sediment liquefaction can be distinguished through the transparent core liner, and split cores will show very thick, soupy texture and/or excess free water, ungraded or complexly graded units in which original bed boundaries have been completely destroyed (Figures 2g, 5, 6, and 8). The effects of strong sediment liquefaction may be recorded by sediment segregation in the cores during two stages of core recovery. First, magnetic susceptibility and bulk density show very consistent decreases through single or multiple meter long intervals upcore (Figure 8a), from density segregation of dense magnetic minerals during the high-speed winching of the core through the drill string. In general, magnetic susceptibility is proportional to the concentration and/or size of specific dense oxide crystals. A perfect density gradient approaches results from vertical settling experiments. Second, sediments are generally still liquefied once put horizontally on the cat walk, and grain settling by density will continue, forming density-stratified layers parallel to the length of the core (Figure 2h). Such textures are rarely documented because cores are split lengthways and parallel to their orientation at rest since on the cat walk (Figures 9i and 9j), thus cutting through a single layer of density-segregated sediment. The core U1394B-13H, acquired at the foot of Montserrat, was slightly rotated before splitting, and reveals 5.5 m of continuous density grading from side to side of the core length (Figures 8e and 8f).

3.7. Other Disturbances

Depressurization of core, with expansion and escape of gas (particularly methane in continental settings) from muddy sediments, can occur for hours after the core arrives on deck [*Flood et al*., 1995]. Striking examples occurred when sectioning cores on the cat walk during Expedition 340. In several instances, hemipelagic mud expanded beyond the ends of freshly cut core liners, increasing total core length by up to 20 cm (>2%). Consequently sediment flowage and bed thickness overestimation are very likely to have occurred in these cores. Very rarely, and for unidentified reasons [*Huey*, 2009], the core liner may break or shatter during APC shooting, affecting the consistency of the core; such occurrences are duly mentioned in the drilling summaries.

Heave is ship motion induced by waves. Its effects on the boat and attached drill string were a very important problem during early drilling operations [*Ruddiman et al*., 1987; *Goldberg et al*., 2000; *Guerin and Goldberg*, 2002; *Huey*, 2009], and the common use of passive heave compensators in combination with GPS positioning aboard the R/V *JOIDES Resolution* reduce the heave effects to <50 cm during drilling under normal weather conditions [*Iturrino et al*., 2013]. For technical reasons, the heave compensators have to be stopped during the few seconds of shooting during APC operations. This very brief break in operation of the heave compensators could still produce as much as a few meters of vertical displacement of the core barrel during APC. A positive heave (boat and drilling platform go up) would result in sampling of water at the top of the core, whereas negative heave would crush the sediments with the cutting shoe. Sediment damage from such heave is rarely identified in IODP cores. None could be positively identified in the cores of Expedition 340, but heave may be responsible for some episodes of sediment fall-in.

4. Guidelines About Coring Disturbances

4.1. Proposed Symbolic

Onboard core describers commonly log core disturbances on the basis of their severity. Here, we propose to chiefly log the core disturbances on the basis of their type, their severity being somewhat subjective. Representative symbols should be consistently used and mentioned in any core log. We propose to mention sediment flowage, fall-in, basal flow-in, and soupy texture and/or on-deck disturbances, and core extension (Figure 7). In addition, core boundaries and partial strokes are extremely important to log. The almost ubiquitous presence of uparching beds makes it irrelevant to be logged for nonspecific studies.

4.2. Use of Composite Images

Core composite images produced by IODP show single cores segmented by core sections put in parallel on a single image (Figure 7). Such representation per core is very useful to evaluate core recovery and identify coring disturbances. Difficulties during coring and/or recovery of the core are revealed with partially filled and/or empty core sections on core composites, and notes in drilling summaries. Core voids are discarded during sectioning of the core liner on the cat walk, and partially vacant core sections indicate the core was segmented. The parts of cores that experienced basal flow-in are commonly segmented into multiple partially filled core sections.

4.3. Sampling Strategy

Sampling should always consider the degree and type of coring disturbances. We recommend extreme caution in using samples and physical properties data where there is any sign of sediment disturbances. When disturbances cannot be avoided, all studies should clearly discuss the limitations implied using such samples.

Whole core physical properties are likely to be strongly affected by all types of coring disturbances, whereas point sensor (Figure 3) data may avoid sediment flowage and bed uparching, although tridimensional complexities in the sediment core are difficult to assess. Physical properties data should clearly mention which intervals are disturbed. Physical properties are not representative in most disturbed units, because of the destruction of bed fabric and boundaries, and vertical settling and density-sorted resedimentation of the liquefied sediments.

Sampling of intervals including uparching and sediment flowage disturbances may lead to mixing of several beds into the same sample, especially if beds are thin. Identified soupy texture and/or on-deck disturbances, fall-in, and basal flow-in units should not be used for stratigraphic or dating purposes. However, they still represent an average composition of the loose sediments from an unknown depth in the overlying stratigraphy (± subjacent strata sucked-in into the core). Despite this, fall-in sediment may include pebbles that are useful for geochemical analyses, if the uncertainty regarding their stratigraphic level of origin is clearly noted. The grading of such units should not be used to infer the original depositional process. More broadly, liquefaction destroys original bedding, so a thick sand unit cannot be directly equated to a thick (depositional) bed. All sandy and pebbly units whose lower boundary coincides with the base of a core should be treated with caution, as they are potentially formed by basal flow-in.

5. Natural Facies Versus Coring Disturbances

We now provide two examples of the scientific importance of core disturbances.

5.1. Understanding Volcanic Events Offshore Montserrat (IODP Expedition 340)

Some of the cores collected offshore Montserrat and Martinique by IODP Expedition 340 contain intervals of ungraded, density-graded, or complexly graded, polymictic volcaniclastic sand to pebble, which can be up to several meters thick (Figures 5 and 6). These intervals are often massive, and lack any planar or cross lamination. In some cases the bases of these massive sand layers coincide with the base of core sections associated with partial strokes (Figures 5 and 6). This suggests that a large part of these specific units may have been sucked in during coring. The partial APC strokes caused basal flow-in by sucking in loose, granular volcaniclastic material in which the core barrel halted (Figures 5 and 6). However, in other cases the massive sand intervals in these IODP Expedition 340 cores occur entirely within core sections and were thus not sucked in during coring. It is obviously important to determine which of these massive sand layers are artifacts of coring and which are intact stratigraphy. For instance, these massive sand layers could be interpreted to be density current deposits that provide a valuable record of associated volcanic eruptions or flank collapse events. We need to know which layers are artifacts or intact stratigraphy in order to reconstruct the history of eruptions and collapses for geohazard analyses. This example demonstrates the need to consider technical core recovery issues as well as sedimentological processes to interpret sand-rich sediment cores. In particular, it demonstrates the importance of marking core section boundaries and occurrence of partial strokes on all core logs, not just those made onboard the vessel.

5.2. Understanding the Record of the Missoula Megaflood (ODP Leg 169)

We now provide a second scientific example of why identification of basal flow-in during APC is important. Hole 1037B in the Escanaba trough contains a >55 m thick sand-rich interval (~65–120 mbsf) [*Fouquet et al*., 1998] that is interpreted to be deposited by a single turbidity current associated with the extremely large Missoula outwash floods [*Zuffa et al*., 2000]. The Missoula floods had prodigious discharges on land (>1 million m^3/s), and occurred when an ice-dammed lake was periodically and abruptly drained in a number of individual megafloods [*Baker*, 2009]. Hole 1037B is important because there are few other records of megafloods that have generated turbidity currents that reached the deep ocean [*Talling et al*., 2013, and references therein]. The internal character of deep-sea turbidites could potentially give important insights into the offshore continuation of such megafloods [*Zuffa et al*., 2000], but only if those turbidites are in situ stratigraphy and not the result of suck-in by basal flow-in during coring.

These APC cores from Hole 1037B are partial strokes and were extensively disturbed by basal flow-in generating soupy, homogeneous sand over the entire length of the interval (Figure 10). Physical properties show continuous upcore decrease in magnetic susceptibility, total gamma ray, and *P* wave velocity [*Fouquet et al*., 1998] suggesting the presence of a single bed; however, these values are subtly stepped at core boundaries, implying destruction of the original bed boundaries (Figure 10). Unfortunately, downhole logging is not available over most of the length of the interval, though it suggests the basal 10 m of the interval consists of sand with homogeneous properties. The extent and intensity of coring disturbances in this interval hinder interpretations of depositional process, and the presence of a single, extremely thick sand-rich bed at this location remains unlikely.

The deeper APC cores (~140–180 mbsf) are all partial strokes, and most of the bed boundaries identified by *Zuffa et al*. [2000] match core boundaries, but do not mirror downhole logging data. This strongly suggests their stratigraphy is based on basal flow-in disturbances. This means that the thickness, bed organization, and number of sandy turbidites within Hole 1037B may be problematic to use as a deep-sea record of Missoula-aged megafloods.

6. Ongoing IODP Initiatives and Propositions to Improve APC Operations

There are several initiatives that may aid improvement of APC operations to reduce the degree of core disturbance. We strongly support these ongoing IODP-led initiatives to mitigate and identify core disturbances caused by the APC process. We propose our own additional ideas as well.

1. To install a breakaway piston head [*Huey*, 2009] would reduce the suction effect during retrieval of the core. This technology strongly reduces the suction effect responsible for basal flow-in by disabling the seals of the piston head (Figure 1) after the stroking action has ended, allowing free flow of seawater on both sides of the piston head. This apparatus was in an advanced stage of preparation, passed laboratory tests, but failed field tests [*Huey*, 2009]. We strongly recommend reassessment of this technique.

2. The use of half-size barrels (4.7 m) in recent IODP Expeditions (341, 346, 349, 350) showed successful results (http://iodp.tamu.edu/scienceops/sitesumm/346) [*Jaeger et al.*, in press] in reducing the extent of basal flow-in; however, this technique reduces the rate of coring in comparison to using full-size barrels and does not entirely eliminate basal flow-in.

3. Use of a drill string acceleration tool. Experiments carried out by *Guerin and Goldberg* [2002] show that variations in core-barrel acceleration during coring can be acquired using a relatively simple apparatus. They proposed the addition of an accelerometer directly in the cutting shoe of the APC (in a similar fashion to the APCT-3 cutting shoe that carries a thermoprobe) to allow a timely assessment of the behavior of the core barrel during shooting. Acceleration data can be rapidly acquired and interpreted and could be used to better quantify the degree of partial stroke. In addition, this instrument can characterize the in situ shear strength of the cored formations, an important quantity that cannot be estimated precisely once the sediments have been retrieved to the surface.

4. To determine basal flow-in textures by visual examination of the core on the cat walk, and/or by X-ray tomography, such as on the D/V *Chikyu*. Where basal flow-in is suspected, the length of section rotary drilled should be reduced. This technique would not avoid basal flow-in, but simply reduce the amount of unsampled stratigraphy when there is overestimation of recovery rate.

5. To install a probe that can measure the amount of pressure left in the piston after the stroke, or otherwise calculate the distance traveled by the piston during its stroke. This could give the length of actual core penetration into the deposit, giving an accurate distance for the hole to be drilled prior to the next core. This would however not reduce the effects of basal flow-in.

6. To test the effects of accelerations and decelerations during winching to better quantify their impact on coring disturbances, as high levels of either are likely to generate sediment flowage and increase sediment liquefaction.

7. Conclusions

Coring disturbances can overprint features of seafloor deposits recovered by piston coring during IODP expeditions. Many siliciclastic environments, especially volcaniclastic aprons, contain thick units of coarse, granular sediments, which are prone to the effects of coring disturbances. This study outlines how coring disturbances result from: (i) shear deformation of sediment against the core barrel; (ii) basal flow-in; (iii) fall-in; (iv) sediment loss through core catchers; and (v) formation of new structures during core recovery and on-deck transport. Shear of sediment against the barrel is readily identified by upwardly bent laminations or beds. Basal flow-in due to partial strokes or stuck BHAs will produce density-graded sand layers that terminate at the base of the cores and which are typically absent at the top of the underlying section. Fall-in features appear at the top of sections and coincide with basal flow-in and hole stability issues during drilling of the overlying cored interval. In case of sediment liquefaction during core recovery, sediment may be remobilized once on deck.

Partial strokes are recorded in the drilling summaries, and such information, as well as core boundaries (where most of the coring disturbances occur), and occurrence and type of any coring disturbances, should be included in all core logs. We wish to support the continued efforts of IODP to address and identify such deformation structures, as part of their remarkably successful efforts to drill and core more sand-rich settings, such as those offshore Montserrat and Martinique during Expedition 340 in 2012.

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