11. SEDIMENT DISTURBANCE AND CORRELATION OF OFFSET HOLES DRILLED WITH THE HYDRAULIC PISTON CORER: LEG 94[1]

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ABSTRACT

At Sites 607 through 611, drilling on Leg 94 with the Hydraulic Piston Corer retrieved cores in upper sediment layers with large-scale $CaCO_3$ variations related to Pleistocene and late Pliocene glaciations over the last 2.5 m.y. The visually striking color-layering caused by these variations permitted detailed correlations between holes on a scale not possible with shipboard paleomagnetics and biostratigraphy. These correlations indicate that demonstrably continuous sections extending back to at least 2 Ma were retrieved at Sites 607 to 610. There appears to be a gap in record continuity at Site 611 in the upper Pleistocene. Making these correlations on site during Leg 94 enabled us to recore intervals where loss of continuity was known or suspected.

INTRODUCTION

Color variations caused by large-scale variations in percent $CaCO_3$ provide an unusual opportunity for defining correlations between offset holes in upper Pliocene and Pleistocene sediments at five North Atlantic Hydraulic Piston Core (HPC) sites on DSDP Leg 94. Correlations were made during the cruise, using photographs obtained just after the cores were split (Fig.1). The primary goal of this effort was to monitor relative stratigraphic offsets between holes at each site in order to check whether material lost across core breaks at any one hole was fully recovered at the others. In many cases, it proved possible to detect breaks in record continuity while still on site and to take additional HPC spot cores across known or suspected gaps.

Full recovery of the available section (which could still contain hiatuses because of sedimentological factors) is assured only if it is possible to span core breaks and disturbed zones in one hole with undisturbed recovery in a nearby hole. Figure 2 shows the ideal use of two-hole HPC coring to collect a continuous record. In this example, Core 9 at Hole B demonstrates continuity across the gap between Cores 8 and 9 in Hole A; it provides a link across both the unrecovered sediment at the bottom of Core 8 and the disturbed sediment at the top of Core 9 in Hole A.

In theory, it should be fairly simple to use the technique shown in Figure 2 to insure continuity of section. On Leg 94, sub-bottom depths (depths below the sediment/water interface) were assigned by first establishing the "mudline" (sediment/water interface) position relative to the length of drill string out, and then using the length of drill string as the standard of reference, with successive cores taken one full joint length (9.6 m) below the previous level. By convention, the top of each recovered core was positioned at the top of the cored interval, and thus by definition the unrecovered interval occurred at the bottom of each core (Fig. 2). To insure overlap of section between holes, therefore, it should only be necessary to use the water depth to the mudline, as determined from the first hole at the site, to fix the length of the initial core taken at the second hole in such a way that its core break aligns with the middle of the first core retrieved at the first hole. This would then position all successive core breaks at each hole midway between the core breaks at the other. Monitoring continuity across these successive offsets then would only require ascertaining that recovery for each core is complete enough to maintain sufficient overlap.

In practice, however, HPC coring involves many complexities, some only vaguely understood at present. The detailed visual correlations between multiple holes on Leg 94 graphically revealed a number of problems. For example, visually correlative lithologic contacts between holes were rarely horizontal as shown in Figure 2, but were commonly offset by 4 m or more, thus defeating the strategy of using only the measure of drill string length for relative positioning of cores between the holes. In addition, on the basis of correlations between multiple holes over intervals in which substantial fractions of the sediment were unrecovered or disturbed, the position of the top of each successive core is not well fixed relative to drill string length. In fact, cores collected during high sea-state conditions that lead to these disturbances appear to float within an uncertain range of sub-

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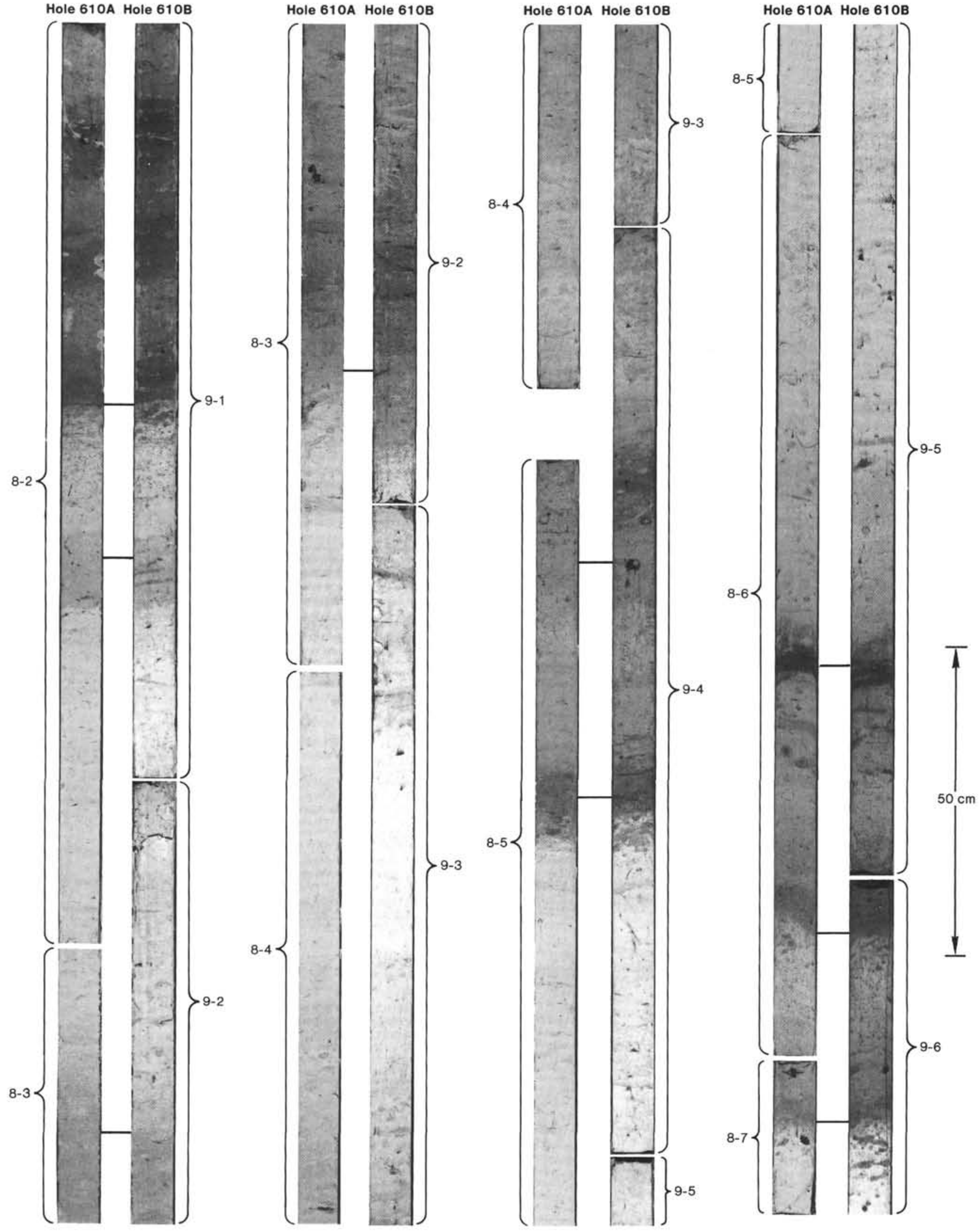

Figure 1. Example of visual similarity between several sections from Cores 610A-8 and 610A-9 and correlative sections from Cores 610B-8 and 610B-9. Correlation lines were picked at prominent contacts between layers of different color/lithology or in the middle of thin distinctive layers. Where color layering was obvious, correlations were made every few tens of centimeters. The gap at the bottom of Section 610A-8-4 is due to chemical sampling before the core was photographed.

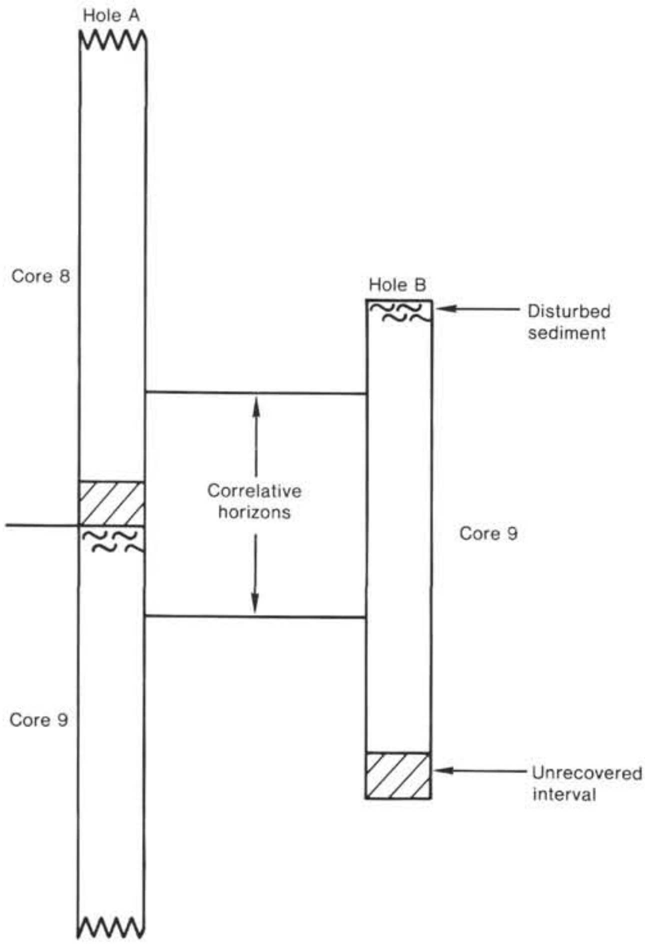

Figure 2. Schematic use of two HPC holes to achieve a complete composite section by overlapping the midsection of the core at Hole B against the core break between the two cores at Hole A. Unrecovered and disturbed sediments at core break in Hole A are retrieved intact at Hole B.

bottom depths, and cannot be precisely assigned to any one depth. The extent of this "floating" is determined largely by the amount of unrecovered and disturbed sediment.

Several disturbances related to the coring process can greatly complicate the goal of collecting a continuous sediment section. The extent to which these problems have appeared in other HPC cores is not well known, because no previous study has directly addressed this subject.

This chapter, then, has two purposes:

1. To indicate the completeness of recovery at Sites 607 through 611, using between-hole correlations. Possible gaps in the record are noted, and estimates are made of their duration. This information (see next section) will be of use mostly to scientists interested in relatively detailed analyses of upper Pliocene and Pleistocene portions of Sites 607 through 611. In addition to the visual correlation of color layering, the levels of polarity boundaries, determined from shipboard paleomagnetic measurements (Clement and Robinson, this volume), provided independent identification of isochronic horizons in adjacent holes. Paleomagnetic samples were taken at an interval of at least one per section and are therefore accurate to within 1.5 m or better.

2. To give an indication of the degree of coring disturbance at each site, and the causes of the disturbances. The disturbances are described site by site in the second (next) section, categorized by type in the third section, and analyzed quantitatively (for selected cases) in the fourth section.

SITE-BY-SITE DESCRIPTION OF CORRELATIONS AND PROBLEMS

Figure 3 provides a key to the symbols used in the diagrams that show correlations and disturbances at Leg 94 Sites 607 through 611. Site 606 lacked color layering, so no detailed correlations were attempted for the Pliocene–Pleistocene sections.

Site 607

At Site 607, two holes (607 and 607A) were drilled at a nominal offset distance. The color layering was dis-

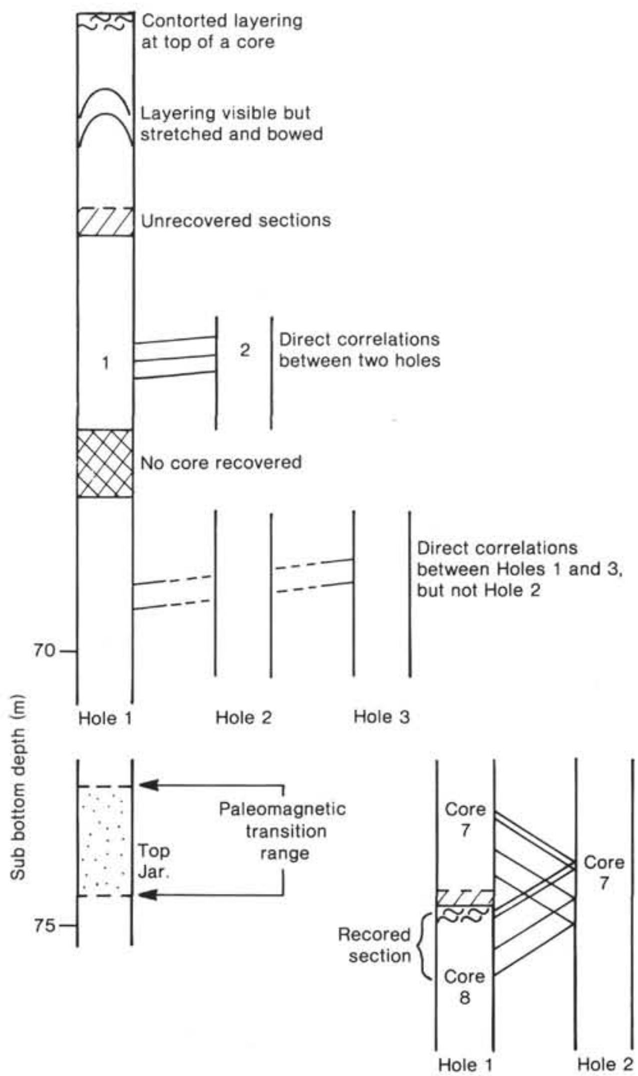

Figure 3. Key to subsequent correlation diagrams (Figs. 4–8) for multiple holes at Sites 607 through 611.

tinct enough to provide numerous visual correlations (Fig. 4). The weather and sea state were generally good, but worsened at times during the drilling of Hole 607A. Table 1 contains core-by-core listings of the pitch of the *Glomar Challenger* at Site 607, based on records kept by the duty officer on the bridge. Also listed are the amount of underrecovery and disturbed sediment for each core.

Overview of Coring Problems

In general, an offset between the two holes appears high in the sediment column and is maintained with little change through the rest of the depth range cored by the HPC (Fig. 4). Although this offset could in theory be due to different sedimentation rates at the two locations, despite the minimal horizontal offset between the holes, there is no direct sign in the between-hole correlations of a higher deposition rate at Hole 607A. Using only those correlations within continuous sections of the cores (i.e., sections with no intervening core breaks), the deposition rates at the two holes appear to have been equal. This suggests that the deepening of correlative horizons in the upper parts of Hole 607A relative to Hole 607 is an artifact of the coring process.

Much of the between-hole offset is introduced abruptly between the second and fourth cores of the two holes, and probably results from the poor seating of the bottom-hole assembly in the soft watery sediments in the upper part of the column. (See "Water Content of the Sediments" in this chapter.)

For reasons that are not clear, there is an abrupt offset introduced at the level of Core 3 in each hole, but this large offset abruptly reverses at the depth of Core 4 in the two holes, with Hole 607A showing correlative horizons at greater depths. This relative offset of about 1 to 2 m is then maintained for much of the rest of the hole. Because the offset remains for successive cores, it cannot be attributed to a one-time shifting and reseating of the bottom-hole assembly in the upper sediments.

One possible explanation of a permanent offset is that it was induced by drift of the ship relative to the positioning beacon during the coring (see "Site 609: Overview of Coring Problems"). Such a drift could induce false depth readings as large as several meters (too shallow if the drift is toward the beacon, too deep if the drift is away from it). Slow drift will gradually induce false depth-offsets; fast drift will create them abruptly. In this instance at Site 607, the abrupt change in sub-bottom depths at Core 607-4 requires a rapid drift, whereas the minimal changes afterward imply little subsequent change in position relative to the beacon. The sense of this drift could have been either toward the beacon at Hole 607 or away from the beacon at Hole 607A.

A very subtle coring problem occurs below Core 4 in both holes. At every core break between Cores 4 and 11 in both holes, the correlation lines require that more sediment be missing from the break than the amount entered in the core logs and indicated on the figures by the diagonally hatched symbol for underrecovery. At the reproduced scale of Figure 4, this trend is not obvious at all core breaks, but it is evident in large-scale plots. Because of the problem, mentioned in the Introduction, of

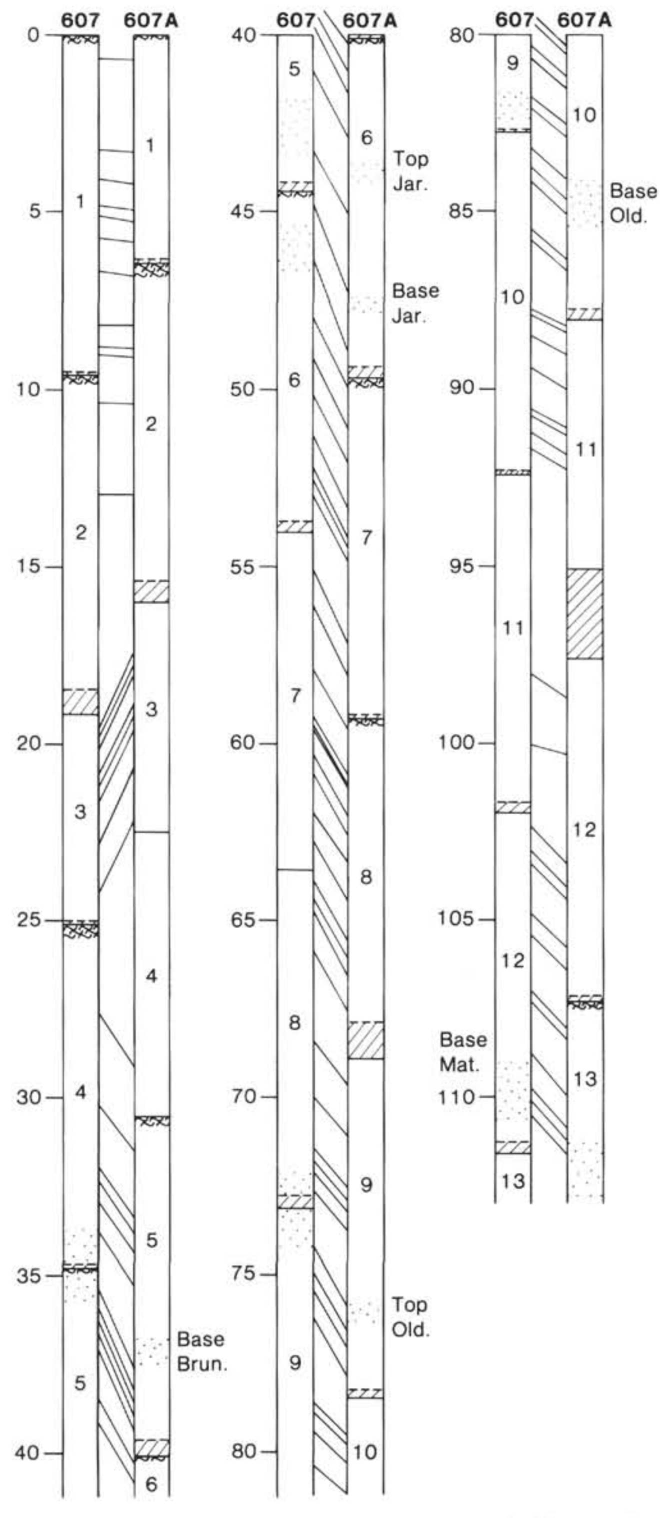

Figure 4. Correlation diagram for upper Pliocene and Pleistocene intervals of two holes at Site 607. Correlations based on visual comparison of color layering. For the paleomagnetic transitions in Figures 4-8, Top and Base indicate the top and bottom of the named magnetic chron. The chron names are abbreviated as follows: Brun. = Brunhes, Mat. = Matuyama, Cobb Mtn. = Cobb Mountain, Old. = Olduvai, Reun. = Reunion.

Table 1. Amount of disturbed core, underrecovery, and pitch of ship, Site 607.

Core	Hole 607			Hole 607A		
	Length of disturbed core (cm)	Length of unrecovered core (cm)	Pitch of vessel (°)	Length of disturbed core (cm)	Length of unrecovered core (cm)[a]	Pitch of vessel (°)
1	25		1	10		1
2	28	7		35	63	2
3	0	20		196	−7	
4	25	13		75	58	↓
5	10	30		23	47	3
6	8	35		10	36	↓
7	2	6		18	20	1
8	0	43		17	97	
9	2	9		0	22	
10	2	10		0	28	
11	0	31		0	260	↓
12	0	32		0	15	2
13	0	10	↓	13	42	↓

[a] Negative "unrecovered" sediment means that more sediment than the nominal 9.6-m joint length was recovered. This is possible because of variations in actual joint lengths; sediment retrieval in the cutting zone just below the piston head; and possibly minor swelling of sediment at the lower atmospheric pressures of the sea surface.

each core "floating" in an imprecise depth range, an occasional occurrence of this kind could be accomodated within the uncertain depth placement of any given pair of cores. At Holes 607 and 607A, however, this trend is maintained for six consecutive core breaks at each hole, and there is not a sufficient amount of sediment underrecovered or disturbed at the breaks to take up the slack. This indicates a persistent and overriding problem in the coring process. The most likely explanation is a slow drift of the ship toward the positioning beacon. This could result in larger gaps in the sediment column than those indicated by the DSDP core-logging procedures (see "Loss of Fine Structure").

Finally, contorted layering was a minor problem in the upper 0.5 m or less of cores from the upper 80 m of the sediment column, but was less common below.

Continuity of Recovered Section

The recovery appears to be complete, with two possible exceptions. There is no proven link of Core 607-3 with Core 607A-4. But the correlations in Figure 4 indicate that Core 607-3 extends roughly 0.75 m deeper in the sediment column than Core 607A-3. This appears to be enough to bridge the very small permissible gap between Cores 607-3 and 607A-4.

There is also no proven link between Cores 607-11 and 607A-11. But correlations between Cores 607-10 and 607A-11 and between Core 607-11 and 607A-12 do not indicate that any gap is likely, despite the absence of clear visual correlations.

Site 608

At Site 608, two holes (608 and 608A) were cored at a nominal offset distance. In general, the color contrasts due to $CaCO_3$ layering were subdued at this site. This, combined with the complexity of the disturbances, made visual correlations far more difficult (and the results presented in Fig. 5 far more tentative) than at the preceding

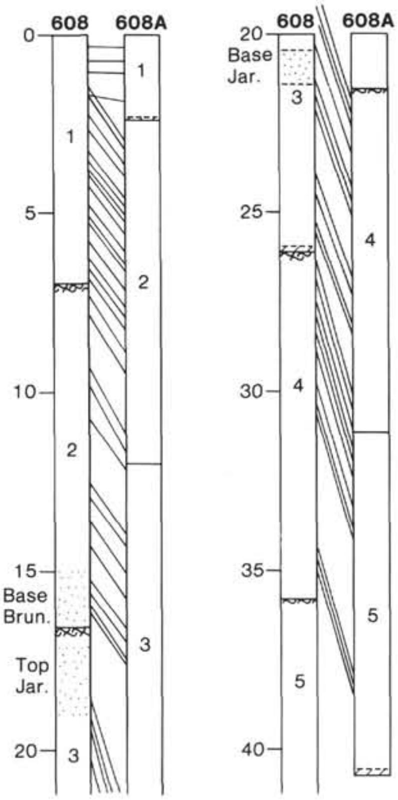

Figure 5. Correlation diagram for upper Pliocene and Pleistocene intervals of two holes at Site 608. Correlations based on visual comparison of color layering. Paleomagnetic transitions as in Figure 4 caption.

site or at several of the succeeding sites. The weather and sea state at Site 608 were slightly rougher than at the previous sites, with swell as great as 5 to 6 feet and the pitch averaging 2 to 3 degrees (Table 2).

Overview of Coring Problems

At Site 608, more complications arose. One instance of double-coring occurred, this time in the spud-in core,

Table 2. Amount of disturbed core, underrecovery, and pitch of ship, Site 608.

Core	Hole 608			Hole 608A		
	Length of disturbed core (cm)	Length of unrecovered core (cm)[a]	Pitch of vessel (°)	Length of disturbed core (cm)	Length of unrecovered core (cm)[a]	Pitch of vessel (°)
1	0		2	0		2
2	15	8		27	−3	
3	14	19	↓	0	−19	
4	10	−3	3	8	−21	
5	10	79		0	20	↓
6	3	29	↓	0	−8	3
7	0	34	1	6	39	↓
8	0	119		3	23	2
9	0	68	↓	12	13	
10				4	−21	↓

[a] Negative "unrecovered" sediment means that more sediment than the nominal 9.6-m joint lengh was recovered. This is possible because of variations in actual joint lengths; sediment retrieval in the cutting zone just below the piston head; and possibly minor swelling of sediment at the lower atmospheric pressures of the sea surface.

and this introduced a large (and probably false) depth-offset between the holes.

Core 608A-2 appears to be a recoring of material in the bottom of Core 608A-1. The recoring in Core 608A-2 suggests that we may have respudded in somewhere slightly offset from the position of Core 608A-1. The sub-bottom depth-offset of lithologic contacts (relative to Hole 608) introduced by Core 608A-2 is then maintained for several cores. This suggests that Core 608A-2 cannot be explained as an accidental coring of the side walls of the hole consequent to heaving of the ship, but must be a core taken at or near the "correct" depth that would be cored in the absence of heaving. This means that Core 608A-1 was the one taken at an "anomalous" depth, probably because of down-heaving of the ship at the instant of coring. (See "Coring Too Low in the Section.")

This interpretation poses an interesting challenge to the DSDP convention for recording the mudline and subsequent sub-bottom depths. It suggests that the normal procedures for logging-in cores may have incorporated a false mudline depth into the Hole 608A log and subsequently maintained that anomaly for the rest of the downcore record-keeping.

Continuity of Recovered Section

Recovery appears to be complete to the bases of Cores 608-4 and 608A-5. Below this level, it was not possible to verify offsets between cores and thus to evaluate continuity of the sediment section by color/$CaCO_3$ layering, because the color contrasts grew too faint. The layering apparent in upper Pliocene and Pleistocene sediments indicated a considerable degree of sediment disturbance. It is not clear whether this represents coring disturbances or slumping.

Site 609

At Site 609, four holes were cored with the HPC. The primary holes were 609 and 609B (Fig. 6). The section recovered from Hole 609A consists of two cores taken in a failed attempt at a mudline core; the failure was caused by an incorrect estimate of pipe stands on the drill string, because of a miscount on the drill-rig floor. The recovery from Hole 609C consists of seven cores taken deeper in the section in an attempt to assure continuity of record across an interval where recovery had been poor in Holes 609 and 609B. The color layering at this site is distinctive, and the correlations shown in Figure 6 are thus quite firm, except where noted in the discussion following. The weather and sea state at Site 609 were in general moderately poor. Pitch varied between 1 and 4° during HPC coring (Table 3). The worst swell occurred during the drilling of the first seven cores of Hole 609B and of all the short offset Hole 609C.

Overview of Coring Problems

Site 609 represents a more complex situation than the two previous sites. The amount of section lost to both disturbed and unrecovered sediment was greater throughout the HPC coring. In general, the between-hole correlation lines oscillate around the horizontal (Fig. 6), rather than maintaining a consistent depth-offset as in the previous holes. This argues against gradual drift of the ship during coring operations, and it suggests that continuous heaving of the ship has introduced small random uncertainties into the DSDP method of positioning the core tops. In addition, the between-hole convergence and divergence of the visual correlation lines within continuous sections of core suggest that differential deposition contributes to some of these oscillations in the correlation lines.

Visual correlation lines near some core breaks indicate that more sediment is missing than the core-log plots directly indicate—as was consistently the case at Sites 607 and 608. At an equal number of core breaks, however, the correlation lines indicate exactly the opposite: the total amount of sediment shown as missing and disturbed in Figure 5 is overestimated (see "Buildup of Depth Offsets"). In these cases, either the amount of missing sediment was smaller than shown, or the sediment shown as disturbed and implied by the logging convention to be *in situ* actually includes extraneous material from elsewhere in the hole. Because no more than two consecutive core breaks in either hole show the same sense of anomaly (i.e., either more or less sediment missing and disturbed than the core logs permit), all these discrepancies can be accommodated within the uncertainty of the sub-bottom depth range which these cores float. For Site 609, the large amounts of disturbed and underrecovered sediment make this depth-range uncertainty very large. In physical terms, these anomalies at the core breaks can be explained by vigorous heaving of the ship during coring, with the seemingly random effects on the cores due to the HPC firing at random phases of the continuous up-heaving and down-heaving.

One possible incidence of recoring is noted: Core 609-15 may repeat material obtained in the bottom of Core 609-14, but the $CaCO_3$ layering is not so instructive as elsewhere in the hole, and this correlation needs verification. It is also difficult to ascertain whether or not the depth-offset induced by the repetition was just temporary or was carried through in the next few cores; without this information, it is hard to choose from among the possible explanations (See "Coring Too High in the Section: Repeated Intervals.") A repeated section would require that Core 609-15 penetrated into the side wall of the hole at a level in the sediment column slightly higher than the section it was supposed to retrieve from the middle of the hole. Although side-wall coring is certainly possible in the watery upper sediments of each hole, where the drill string is poorly seated and subject to movement by heaving of the ship, it is difficult to understand how this could happen at a sub-bottom depth of 130 m.

Also evident at this site are several kinds of deformation less severe than that frequently observed in core tops where the sediment appears soupy. For example, there are intervals (as in Cores 609B-2 and 609-3) where the layering is bowed upward and stretched relative to comparable levels in other holes. This deformation may be caused by premature release of some or all of the shear pins during descent of the coring assembly through the water column. Because it occurs within, rather than

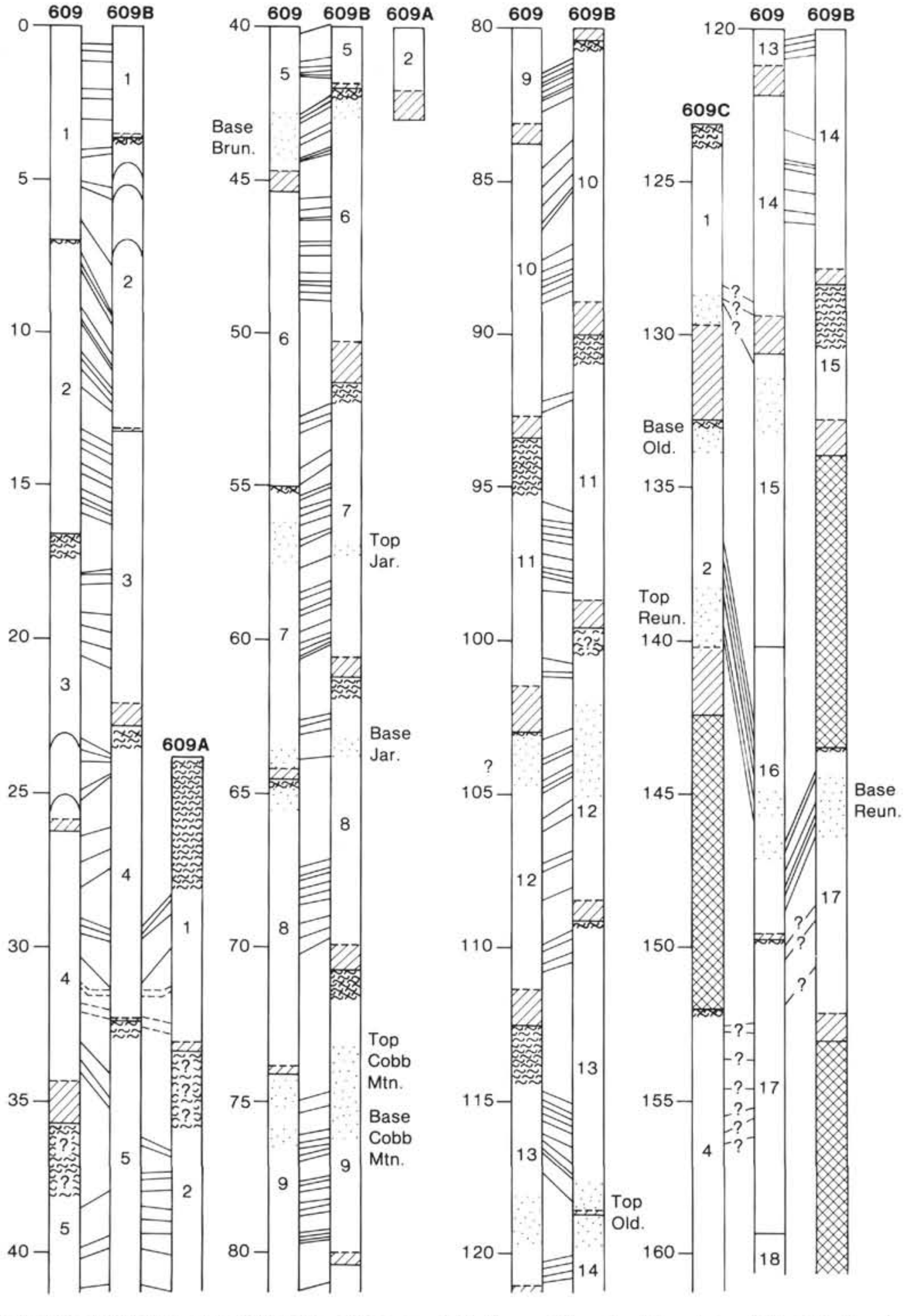

Figure 6. Correlation diagram for upper Pliocene and Pleistocene intervals of four holes at Site 609. Correlations based on visual comparison of color layering. Paleomagnetic transitions as in Figure 4 caption.

at the bottom of, the cores, this deformation is not equivalent to the flow-in observed at the bottom of conventional piston cores. (See "Upbowed/Stretched Sections Within Cores.")

Another kind of disturbance occurs in the top of Core 609-4, where layer boundaries seem artificially sharpened and burrowing and fine structure are reduced or eliminated. Layers of each lithology (carbonate-rich ooze or carbonate-poor glacial marine) are relatively structureless, and the entire interval is somewhat compressed relative to the comparable section in Hole 609B. (See "Compression" and "Loss of Fine Structure.")

An interesting example of problems related to ship's motion is evident in comparing Cores 609C-1 to 609C-4 with Cores 609-15 to 609-17. Core 609C-2 seems too low in the correlation scheme, relative to correlations that

Table 3. Amount of disturbed core, underrecovery, and pitch of ship, Site 609.

	Hole 609			Hole 609B		
Core	Length of disturbed core (cm)	Length of unrecovered core (cm)[a]	Pitch of vessel (°)	Length of disturbed core (cm)	Length of unrecovered core (cm)	Pitch of vessel (°)
1	0		3	0		4
2	10	−11		17	12	
3	80	38		0	67	
4	10	145		94	10	
5	270	68		70	15	
6	0	−6		34	147	
7	17	35		60	68	
8	27	17		85	83	
9	3	65		90	39	
10	7	75		38	110	
11	190	155	2	93	90	
12	11	120		95	62	
13	190	102		24	9	
14	2	118		4	55	
15	0	−8				

[a] Negative "unrecovered" sediment means that more sediment than the nominal 9.6-m joint length was recovered. This is possible because of variations in actual joint lengths; sediment retrieval in the cutting zone just below the piston head; and possibly minor swelling of sediment at the lower atmospheric pressures of the sea surface.

are evident both above and below it. The next core (609C-3) at Hole 609C returned empty, and the following Core 609C-4 reestablished the "normal" correlation. This sequence can best be explained by down-heaving of the ship during the coring of Core 609C-2, with Core 609C-3 then being fired at the anticipated depth but coming up empty because the sediment was already removed in Core 609C-2. (See "Coring Too Low in the Section.") Core 609C-4 was taken at the correct depth and came up nearly full.

Continuity of Recovered Section

It is possible to step down sequentially from the mudline to Core 609-8 without problems. No visual links are obvious between the bottom of Core 609-8 and the top of Core 609B-9, probably because both sections show a similar structureless carbonate ooze. It is very likely, however, that the section is continuous across this interval, because the offset of overlying layers between Cores 609-8 and 609B-8 is nearly identical to that of the underlying layers between Cores 609-9 and 609B-9. This anchors the between-hole correlation well enough to disprove any gaps, except for the extremely remote possibility of very large and coincidentally equal losses of sediment at each core break. The continuity of correlations in cores still higher and lower in the column argues strongly against this possibility.

The continuity of record can then be traced without problems to the bottom of Core 609-14. A somewhat tenuous visual correlation indicates that the top of Core 609-15 repeats the bottom of Core 609-14, with both sections correlating into the lower portion of Core 609C-1. If this is correct, continuity is assured to the bottom of Core 609-15, where another potential problem occurs. There is at this point no provable link across the break between Cores 609-15 and 609-16. Even though the DSDP core-positioning convention indicates that no sediment is missing between Cores 609-15 and 609-16, the problem of "floating" cores, mentioned earlier, leaves open the possibility that some is in fact missing. But if Core 609C-2 is translated down into place on the rationale discussed earlier, then the extra 0.3 to 0.4 m of section lying above proven tie-lines in Core 609C-2 can be used to bridge any gap between Cores 609-15 and 609-16. Unless the actual gap between these two cores exceeds 0.4 m, there is no loss of continuity in the composite section.

The correlation may then be extended through the bottom of Core 609-17 at 159.4 m, although the visual correlations forming the basis of the link between Cores 609-17 and 609B-17 are somewhat tenuous and need verification. This would extend the continuity to 2.2 Ma.

Below this level, visual correlations become problematical owing to the paler hues of the glacial layers and to the roughened surfaces on the split faces of the cores (apparently caused by the stiffer lithologies at this depth). It seems likely that the lower part of Core 609-17 correlates with the upper part of Core 609C-4, and that the lower part of Core 609C-4 in turn correlates with the upper part of Core 609-18. This would carry the continuity to an age of about 2.3 Ma. The section may be complete to the top of the Gauss at 2.47 Ma (roughly 172 m), but it seems more likely that gaps of up to 1.0 m (15,000 yr.) are present. This may be verifiable by $CaCO_3$ analyses.

Site 610

Five holes were attempted in the upper sediment column at Site 610. The first (Hole 610) was abandoned after five HPC cores because of very poor recovery and rough weather. The largest number of HPC cores was taken at Holes 610A and 610B. Coring in the last two holes (610C and 610D) was in short intervals where recovery had been very poor, to fill in gaps in the record. Hole 610D was significantly offset from the previous four holes; it lies in the trough of a sedimentary mud wave rather than on the adjoining crest where the previous holes were located. The color layering at this site is very distinct, and the correlations indicated in Figure 7 are thus quite firm, except where noted in the following discussion. The weather and sea state at Site 610 were highly variable (Table 4). In general, there was a marked improvement in conditions between the early holes (610 and 610A) and the later ones (610B, 610C, and 610D).

Overview of Coring Problems

As at the previous site, it proved very difficult to obtain full recovery of undisturbed sediments. Again, the complexity of the results limits the following comments to an overview of the most striking problems. A potential additional complication to correlating between holes was introduced by the choice of a major offset distance for Hole 610D, although the sedimentation rate at this hole does not appear to have differed significantly from the rates at other holes (Kidd and Hill, this volume).

The general trend in Figure 7 is of major depth-offsets between holes, particularly between Holes 610B and

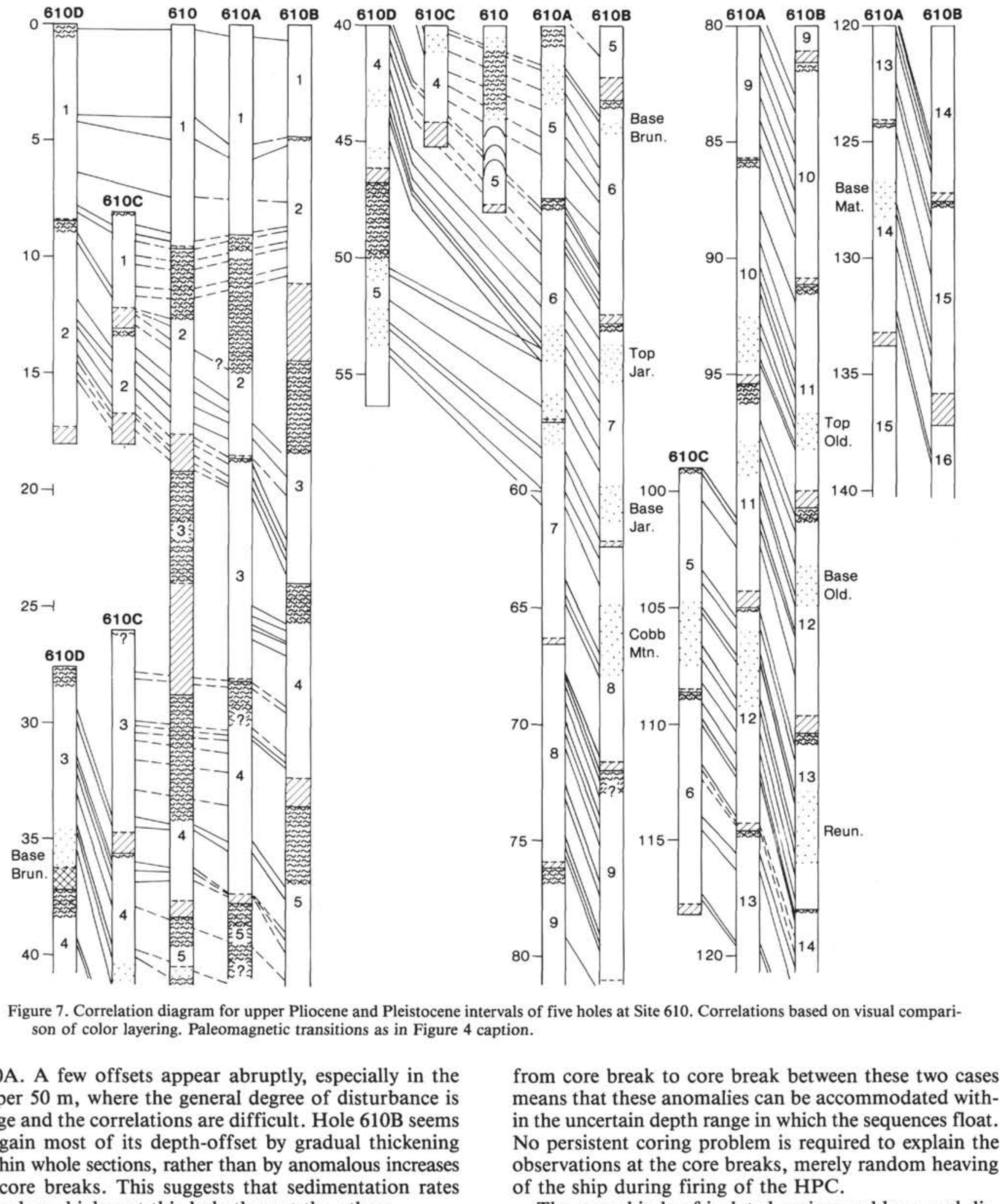

Figure 7. Correlation diagram for upper Pliocene and Pleistocene intervals of five holes at Site 610. Correlations based on visual comparison of color layering. Paleomagnetic transitions as in Figure 4 caption.

610A. A few offsets appear abruptly, especially in the upper 50 m, where the general degree of disturbance is large and the correlations are difficult. Hole 610B seems to gain most of its depth-offset by gradual thickening within whole sections, rather than by anomalous increases at core breaks. This suggests that sedimentation rates have been higher at this hole than at the others.

At the core breaks, there are alternating occurrences of the two opposed cases also noted at Site 609: (1) more sediment missing than is shown by the logs plotted in Figure 7, and (2) less sediment missing (or disturbed) than is indicated. And again, the frequent alternations from core break to core break between these two cases means that these anomalies can be accommodated within the uncertain depth range in which the sequences float. No persistent coring problem is required to explain the observations at the core breaks, merely random heaving of the ship during firing of the HPC.

The same kinds of isolated coring problems and disturbances occurred at Site 610 as at previous sites. For example, Core 610D-5 repeats an interval already cored in 610D-4. It is not possible to choose from among the possible explanations of this repeat coring by checking whether the induced offset of correlative horizons is per-

Table 4. Amount of disturbed core, underrecovery, and pitch of ship, Site 610.

	Hole 610			Hole 610A			Hole 610B			Hole 610C			Hole 610D		
Core	Length of disturbed core (cm)	Length of unrecovered core (cm)	Pitch of vessel (°)	Length of disturbed core (cm)	Length of unrecovered core (cm)	Pitch of vessel (°)	Length of disturbed core (cm)	Length of unrecovered core (cm)	Pitch of vessel (°)	Length of disturbed core (cm)	Length of unrecovered core (cm)	Pitch of vessel (°)	Length of disturbed core (cm)	Length of unrecovered core (cm)	Pitch of vessel (°)
1	0		4	0		4	10		2	50[a]	83[a]	3	50		2
2	300	163	↓	575	4	↓	12	326	↓	27[a]	131[a]	↓	45	65	↓
3	960	483	↓	7	8	↓	400	0	↓	4[a]	83[a]	↓	85[a]	100[a]	↓
4	545	69	↓	185	38	↓	170	122	↓	8[a]	94[a]	↓	130[a]	61[a]	↓
5	120	25	↓	320	3	↓	338	87	3	20[a]	10[a]	↓	345[a]	85[a]	↓
6				32	15	↓	32	42	↓	36[a]	48[a]	↓			
7				40	25	↓	33	19	↓						
8				32	26	3	24	34	4						
9				105	16	↓	0	48	↓						
10				30	42	↓	32	36	↓						
11				141	70	↓	30	114	↓						
12				10	32	↓	48	68	↓						
13				13	17	↓	50	133	3						
14				8	56	↓	7	35	↓						
15							10	133	↓						
16							30	50	↓						

[a] Deeper cores taken after a wash-down interval.

manent; Core 610D-5 was the last core taken in that hole. (See "Coring Too High in the Section: Repeated Intervals.")

In general, however, two problems proved especially disruptive at several of the holes at this site: excessive amounts of contorted sediment and large unrecovered intervals. Contorted sediments were a major problem in the upper 50 m of the sediment column, so we took numerous cores at the various holes in an attempt to obtain a complete record. At first, the contorted sediment in the upper 50 m was attributed to the weather, which was very poor at the early holes; but efforts at later holes during better weather were only marginally more successful. This suggests that the physical state of the sediments may account for the poor results. (See "Quantitative Analysis...")

Continuity of Recovered Section

The first major problem occurs at a sub-bottom depth of roughly 8 to 12 m (Fig. 7). The only link across a possible gap in the record is the correlation of Core 610C-1 with Core 610D-2. This correlation is tenuous, however, because of the short length of overlap between the two sections; it requires confirmation by laboratory analyses.

The second problem occurs at the base of Core 2 in several holes, at roughly 20 m sub-bottom depth. The only correlation across this possible gap is between the bottom of Core 610A-2 and the top of Core 610B-3. This correlation is visually convincing, but still should be checked.

The continuity can then be traced downward without major problems through the rest of the interval of generally poor recovery between 20 and 50 m sub-bottom, even though in several intervals only two of the five cores provide the linkages and continuity.

The next problem is the lack of a provable link between Cores 610A-9 and 610B-9. The problem arises because the depth-offset of datum levels between holes is almost identical to the 4-m offset of the core breaks, thus nearly aligning the ages of the sediments at the core breaks. There are firm visual correlations between Cores 610A-8 and 610B-9 and between Cores 610A-9 and 610B-10. If the cores are brought into rough realignment at this interval, it appears that there is an overlap of about 0.2 m between the uppermost uncontorted part of Core 610A-9 and the lowermost recovered portion of Core 610B-9. There are, however, uncertainties as to the exact gaps associated with core breaks, as noted several times previously. The change in relative alignment of the tie-lines above and below the core breaks in this instance suggests that there is either 0.5 m more sediment missing from the break between Cores 610B-9 and 610B-10 or 0.5 m less sediment missing from the break between Cores 610A-8 and 610A-9. In the latter case, there would be no loss in continuity of the combined record across this interval. In the former case, there could be as much as a 0.3-m gap, or about 7000 yr. at the mean sedimentation rate for the site. Also, as at some previous sites, both holes may have larger (coincidentally equal) gaps than those indicated by the unrecovered lengths in Figure 7. But the relatively small gaps in adjoining cores in Hole 610A leave little room for such a missing section.

A similar problem occurs across the subsequent pair of core breaks in Holes 610A and 610B, again because the 4-m offset in the correlative horizons causes the ages of sediments in the core breaks to come nearly into alignment. In this case, however, the indicated overlap of the bottom of Core 610B-10 with the top of Core 610A-10 is 0.8 m. The correlations above and below the two core breaks indicate that no more than an extra 0.1 m of sediment should be missing from the break between Cores 610B-10 and 610B-11. This still would leave a 0.7-m overlap across this interval. Once again, coincidentally larger gaps in the breaks in both sections are technically possible, but unlikely.

The problem recurs at the subsequent pair of core breaks, with the added complications of a large underrecovery in Core 610B-11 and a large contorted interval at the top of Core 610A-11. With the core breaks roughly aligned, there is a 0.2-m overlap between the bottom of Core 610B-11 and the top of Core 610A-11. In addition, however, there is a 0.75-m change in offset of correlative horizons across the pair of breaks. The change of the offset between holes is opposite to the last two cases; it indicates either a 0.75-m smaller loss than indicated across the Core 11/12 break in Hole 610B or a 0.75-m larger loss than indicated across the Core 10/11 break in Hole 610A. In the latter instance, there would be no loss of continuity, and a small overlapped interval would exist. In the former instance, this could indicate a net loss of about 0.55 m of continuity of record, equivalent to about 11,000 yr. and occurring at a level of about 1.7 Ma. Again, minor but equal losses of sediment in each core break could also go undetected.

The problem of overlapping core-break gaps at Holes 610A and 610B then was overcome because we recored the next five core breaks at Hole 610C. The next two overlapped core breaks thus recored at Hole 610C are instructive because neither shows any equal (and coincidentally compensating) additional gaps across the core breaks. This suggests that some of our worst-case scenarios in the three previous examples do not apply, although firm proof is still lacking.

Below the 1.7-Ma level, the record is then demonstrably complete down through the end of the glacial $CaCO_3$ cycles at roughly 2.4 Ma—at 132 m in Hole 610A and at 138 m in Hole 610B.

Site 611

Six holes were attempted at Site 611. Coring in Holes 611 and 611A recovered long sections from the crest of a sedimentary mud wave. Hole 611B was a one-core attempt in the adjoining trough of the same sediment wave, but it was abandoned because of partial loss of the coring tool. Coring in Hole 611C subsequently recovered a long section from the same trough of the sediment wave. Holes 611D and 611E were spot-coring attempts to fill in possible record gaps back at the wave crest. As at the two previous sites, it proved very difficult to obtain complete, undisturbed cores. An additional complication arose from the very subdued color and value contrasts in many of these cores, compared with the dramatic contrasts evident in the equivalent portions of Sites 607 to 610. Thus the visual tie-lines indicated in Figure 8 are in general tenuous, and should be taken only as rough guidelines to actual correlations, the verification of which should be pursued in later studies. The wide differences of sedimentation rates between holes (differences both between crest and trough holes and within the group of crest holes) also complicated both the correlations and their depiction in Figure 8. All these difficulties limit the degree of detail with which we can discuss the correlations and problems indicated in Figure 8.

The weather and sea state at Site 611 were poor at the beginning, but improved to fairly good and then to very good midway through operations (Table 5). Swells of 4 to 5 ft. during coring at Holes 611 and 611A subsided to 1 to 3 ft. during coring at Holes 611C, 611D, and 611E. Pitching of 4° at Holes 611 and 611A subsided to 2° at Holes 611C, 611D, and 611E.

Overview of Coring Problems

In general, problems of underrecovery and contorted sediment occur throughout the range of HPC-cored sediments, with less concentration in the upper 50 m than at previous sites. Between-hole correlations in Figure 8 generally show increasing offsets with depth, and the question again is whether this is due to real differences in sedimentation rate or to artifacts induced by coring.

Comparisons of continuous core sections from Holes 611 and 611A show roughly equal numbers of instances of relative thinning and thickening, indicating that there is no mean difference in sedimentation rates between these two adjacent holes. The explanation for the offsets of most correlative horizons must therefore lie in coring problems. The offset between the two holes is abruptly introduced in the upper two cores, and then remains at a more or less constant value through the rest of the column. As at several previous sites, this suggests that the basic 1- to 2-m offset carried throughout these two holes is an artifact caused by taking a mudline core too deep at one hole of too shallow at the other (as a result of heaving of the ship at the instant of coring).

The depth-offsets of correlation lines for Hole 611A relative to other holes also tend to increase across core breaks, indicating smaller amounts of missing/disturbed sediment than shown by the logs (Fig. 8). This is consistent with slow drifting of the ship away from the positioning beacon at this hole (see "Buildup at Depth-Offsets"). Hole 611 shows no consistent trend in the change of correlation lines across core breaks, compared with Hole 611A.

Correlative levels in Hole 611C (the offset hole in the mud-wave trough) are offset to much greater depths than at any of the other holes. The fanning-out of the correlation lines linking continuous sections of this hole with the others indicates that sedimentation rates in the mud-wave trough at Hole 611C were higher than those at the mud-wave crest (Kidd and Hill, this volume). This suggests differing deposition rates as the primary cause of the gradual increase of depth-offsets between this and the other holes. Coring-induced problems are, at most, secondary factors. It is possible that part of the abrupt 12-m offset introduced in the upper three or four cores of Hole 611C is a consequence of a false mudline depth, caused by heaving of the ship. (See "Coring Too High in Sections: Repeated Intervals.") Comparisons across core breaks at Hole 611C indicate, however, no consistent trend in the correlations toward either increased or decreased offsets relative to other holes.

In several intervals in the downcore record, abrupt excesses or deficits of sediment appear randomly in one hole relative to the others. In contrast with previous sites, several instances of this at Site 611 are not associated with core breaks, but occur within apparently correlative sequences between complete cores.

For example, the top of Core 611C-10 appears to contain extra sediment relative to comparable sections in Cores 611-7, 611-8, and 611A-7. Alternatively, Core

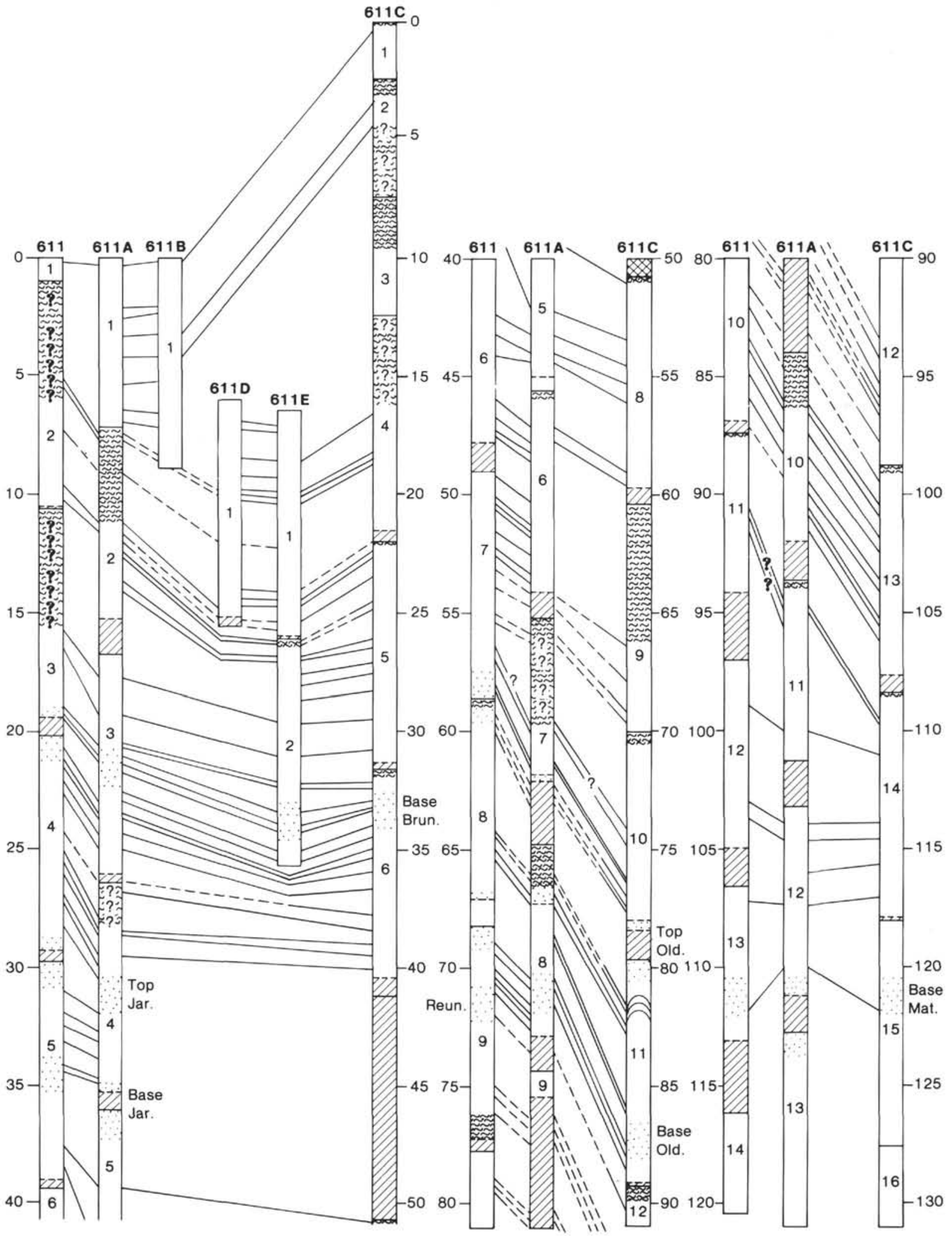

Figure 8. Correlation diagram for upper Pliocene and Pleistocene intervals of six holes at Site 611. Correlation based on visual comparison of color layering. Paleomagnetic transitions as in Figure 4 caption.

Table 5. Amount of disturbed core, underrecovery, and pitch of ship, Site 611.

	Hole 611			Hole 611A			Hole 611C			Hole 611D			Hole 611E		
Core	Length of disturbed core (cm)	Length of unrecovered core (cm)	Pitch of vessel (°)	Length of disturbed core (cm)	Length of unrecovered core (cm)	Pitch of vessel (°)	Length of disturbed core (cm)	Length of unrecovered core (cm)[a]	Pitch of vessel (°)	Length of disturbed core (cm)	Length of unrecovered core (cm)[a]	Pitch of vessel (°)	Length of disturbed core (cm)	Length of unrecovered core (cm)[a]	Pitch of vessel (°)
1	10		4	7		4	7		3	15	35	2	55		2
2	450	8		398	146		70	9		9[b]	−23[b]		13	−5	
3	490	73		65	29		224	−7		5[b]	−3[b]				
4	6	46		4	75		310	49		3[b]	−28[b]				
5	73	39		47	55		13	22		7[b]	−1[b]				
6	192	116		45	105		30	74		8[b]	−20[b]				
7	21	18		50	270										
8	0	105		187	150		15	67							
9	27	52		?	853		585	1							
10	35	49		240	159		53	140							
11	10	280		37	188		10	9							
12	160	161		15	61		72	−6							
13	38	308		65	107		69	69							
14	24	86					22	11							
							12	−11							

[a] Negative "unrecovered" sediment means that more sediment than the nominal 9.6-m joint length was recovered. This is possible because of variations in actual joint lengths; sediment retrieval in the cutting zone just below the piston head; and possibly minor welling of sediment at the lower atmospheric pressures of the sea surface.
[b] Deeper cores taken after a wash-down interval.

611C-10 may repeat sediment already retrieved in the bottom of Core 611C-9. The uncertainties in visual correlations at this level preclude choosing from among these possibilities. Core 611A-11 also appears to contain extra material relative to the suggested correlation with Core 611C-14. Again, these conclusions are tentative and would have to be confirmed by $CaCO_3$ analyses. These intervals could reflect actual hole-to-hole differences in sedimentation rate in the relatively high-energy bottom environment of the eastern Reykjanes Ridge. Or they could be caused by compressive stresses induced by coring (see "Compression").

Other problems encountered at previous sites and pertinent to individual cores occur here. For example, Core 611-11 appears to have been taken somewhat too deep in the section, probably because of down-heaving of the ship (see "Coring Too Low in the Section"). Core 611C-11 shows upbowed layering at the top of an interval that abruptly thickens relative to comparable sections in Holes 611 and 611A. This suggests that the coring process has stretched the section (see "Compression"). The bottom of Core 611-9 has structures that resemble flow-in in conventional piston cores.

Continuity of Recovered Section

Because of difficulties already noted, the following compilation covers only the major problems obvious from the correlations shown in Figure 8. There appears to be a major gap (loss of continuity) in the upper part of the record in the sub-bottom depth range of 5 to 8 m. Core 611B-1 penetrates what appears to be the bottom of oxygen isotopic stage 7 (determined using $CaCO_3$-induced color changes to identify major glacial/interglacial cycles). Presumably it just misses the *Emiliania huxleyii* dominance change at the top of stage 8 (Ruddiman and McIntyre, 1976), dated at 263,000 Ma (Thierstein et al., 1977). Below this section, there appears to be a gap spanned by none of the five holes. The youngest level cored below this gap seems to be the upper part of Holes 611D and 611E, both roughly equivalent to the partly jumbled upper part of Core 611-2. Because Core 611C-3 did not obviously correlate with any other core, it is remotely possible that it might bridge the gap, as might the upper part of Core 611C-4. The best estimate at this time is that there are one or more gaps in this interval, conceivably with several tens of thousands of years of record missing.

Below this major problem area, it is possible to trace a continuous record well down the section. There is a problem associated with Cores 7 and 8 in Holes 611 and 611A and Cores 10 and 11 in Hole 611C. The visual tie-lines suggest that continuity is maintained through the following pathway: from Core 611-7 to 611C-10 and back to 611-8. This link needs further verification.

The next problem is the lack of a proven link across the three core breaks separating Cores 10 and 11 at Holes 611 and 611A and Cores 13 and 14 at Hole 611C. These three core breaks are roughly aligned at correlative horizons, even though they fall across a 20-m range of sub-bottom depths. On the basis of good correlations above and below these core breaks, however, it appears that there is an adequate thickness of sediment at the top of Core 611-11 to span the gap. The links shown in Figure 8 suggest that this core overlaps more than a meter with the bottom of Core 611C-13. Again, this conclusion assumes that there are no larger, and coincidentally equal, gaps in all three core breaks.

Correlations become particularly difficult below this level, owing to the weaker color changes in the glacial carbonate cycles. The few tie-lines shown imply major relative gains and losses of sediment between holes. It is probable that the record is continuous in this deeper interval, but the simple visual correlation methods used here cannot prove it.

CATEGORIZING TYPES OF CORING PROBLEMS

Problems related to the coring process fall into three broad categories: (1) those resulting in underrecovery of sediment, (2) those in which sediment is recovered but deformed, and (3) those detectable by abrupt depth-offsets of correlative horizons. As a starting point for the following discussion, the reader is referred to the introductory chapter of this volume for information on the normal operation of the Hydraulic Piston Corer.

Underrecovery of Sediment

The most common flaw in HPC coring is the recovery of a length of section shorter than the core barrel that was sent down the wireline. The most likely way for this to occur is by transmission of ship motion through the drill string to the coring assembly. Shortly before the core is taken, the coring assembly is lowered to the desired depth (as determined on the drill-rig floor by the length of pipe out) and the pump is pressured up. If, just before shooting of the core, the ship heaves upward, the core assembly will also be pulled upward to the level above its intended depth of firing. The core will then fire partly through a column of water and thus into a shorter length of sediment than was intended (Fig. 9). This oversimplifies; actually, heaving is likely at the same time to cause deformation of sediments at the core tops. Underrecovery could also occur by loss of sediment out of the core catcher because of physical jarring during recovery. Small amounts of underrecovery (a few tens of centimeters at most) could occur if the actual joint length is less than the nominal 9.6 m assumed as an average.

Deformation of Recovered Sediment

The second category involves retrieved sediment which is disturbed. Cores retrieved on Leg 94 indicate three general types of disturbances.

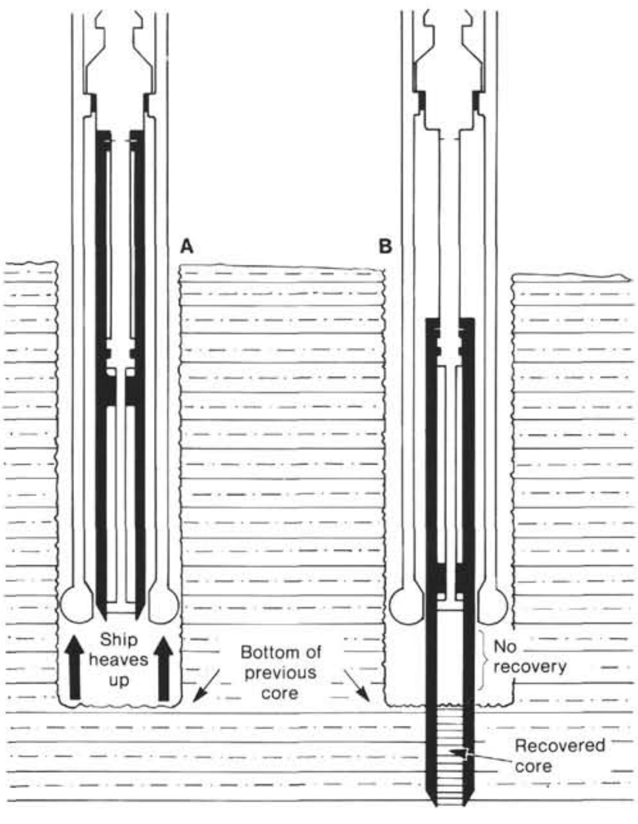

Figure 9. Schematic illustration of underrecovery of sediment during HPC coring attempt, caused by up-heaving of ship at time of core firing. A. Initial upheaving of ship and drill string. B. Firing of core.

Contorted Sediment at Core Tops

This is the most obvious kind of disturbance in HPC coring, and shows clearly even in sediments without strong color/lithologic layering. In most HPC cores, the upper portions (ranging from a few centimeters to over a meter) are recovered contorted. This could be ascribed to any of several causes.

First, the core assembly may heave up just before shooting of the HPC (as already described). This would retrieve a short core with a column of water left at the top. The agitation of the water may then disturb the upper sediment column during retrieval of the core.

Second, the contorted sediments may be cuttings made by the bit as the hole was reamed down to the depth of the next core. Because very little circulation is used at this stage of the coring process, the cuttings may not be carried away up the hole annulus as they would be during a stronger "wash-down." This would leave cuttings at the top of the hole before HPC coring. Any heaving up of the ship just before the corer is shot could result in retrieval of the jumbled cuttings as the "top" of the HPC core.

Third, sediment can fall down the sides of the hole on the outside of the drill string, because motion of the drill string enlarges the diameter of the hole around it. Direct evidence of this effect is available from Site 608, where we repeatedly retrieved up to 50 cm of glacial marine sediments at the tops of Miocene to Eocene cores taken from sub-bottom depths well below the upper 2.4-Ma Pliocene–Pleistocene interval of North Atlantic ice-rafting. The glacial marine debris was mainly sand and gravel, with fine sediment washed away. The intact lower portions of the cores were all Neogene and Paleogene calcareous oozes and marls. Sediment from the upper (Pliocene–Pleistocene) part of the hole must have repeatedly fallen down the outside of the drill string between successive cores, then been washed by the drill-bit circulation, and finally cored by the HPC.

Fourth, the uppermost layers of sediment may have been deformed by the core bit itself. This could occur after washing down to the desired interval but before HPC coring. In general, several minutes elapse between arrival of the drill string and corer at the bottom and buildup of enough pump pressure to fire against the shear-pin resistance; this is enough time for deformation of the top of the sediment column.

Fifth, uppermost layers that were intact when penetrated by the HPC may have lost their integrity due to subsequent motion of the piston within the top of the HPC core. This explanation assumes that motion from the ship can be transmitted through the wireline independently of the drill string. The newly taken HPC core is vulnerable to this kind of effect only after coring but before the time when tension is put on the wireline to retrieve the core. During this short time, the piston at the top of the HPC core is free to move around. After tension is taken up, the piston is locked against the upper part of the assembly and cannot move relative to the sediment in the core.

Relative motion of the piston can be further subdivided into two kinds: that caused by up-heave and that caused by down-heave. If the HPC achieves full stroke, the piston will lie at the top of the barrel (Fig. 9B), and no relative motion should occur between the piston and the barrel during up-heaving of the bottom-hole assembly. If only a partial stroke were achieved, an upward heave would pull the piston to the top of the barrel, possibly stretching the upper part of the core (in addition to drawing extra sediment in at the bottom).

In down-heaving, the results may depend on the degree of consolidation of the sediment. If the sediments are sufficiently consolidated to support the weight of the HPC core barrel, the bit will plunge down on heaves while the barrel stays in place because of sediment resistance. With the piston rod no longer supported on the inner shoulder of the drill string, the combined weight of the rod and the slack wireline could create a compressive load of 4000 to 6000 pounds on the cored sediments at the top of the barrel. If the sediments are unconsolidated, there is likely to be no decoupling of drill string and core barrel, and thus no deformation of the already-taken core. But both the bit and the barrel will disturb the top of the underlying (uncored) sediments during down-heaving. And in conjunction with the up-heaving case already noted, partial stroke (incomplete penetration) of the corer will particularly enhance the likelihood of deformation of the sediment within the core barrel by the piston, which is left free to move around.

We do not attempt in this study to discriminate quantitatively among the five possible ways of contorting the tops of cores. Close examination of the physical form of the disturbances and the composition of the disturbed sediment (*in situ* vs. displaced) might well yield this kind of information.

Upbowed/Stretched Sections within Cores

A few cores at Sites 609 and 611 show a more subtle type of deformation in which layers are bowed upward, sometimes to the point of looking as if they have flowed within the core (Fig. 10). When correlated with sections in other holes, these intervals often span a larger range of core depth, as if they were stretched.

Visually, some of this deformation resembles flow-in observed in conventional piston coring. In conventional piston coring, flow-in occurs during retrieval of the coring apparatus: the piston is pulled to the top of the core barrel, the cored sediment is pulled upward because of the partial vacuum created by the moving piston, and disturbed sediment is pulled into the vacuum created at the bottom of the barrel. In the Leg 94 HPC cores, however, the bowed layers occur both in the middle portions and at the tops of cores, rather than in the lowermost parts. Therefore, this cannot be flow-in of the kind observed at the bottom of conventional piston cores.

Where this deformation occurs within otherwise normal layer in the middle of a core, the disturbance probably took place episodically during coring. One possible explanation is the premature failure of the shear pins during the wireline trip down. This explanation was used by scientists on Leg 86 to explain similar deformation structures within the middle sections of cores from Site 576 (Heath, Burckle, et al., 1985). In this scenario, the

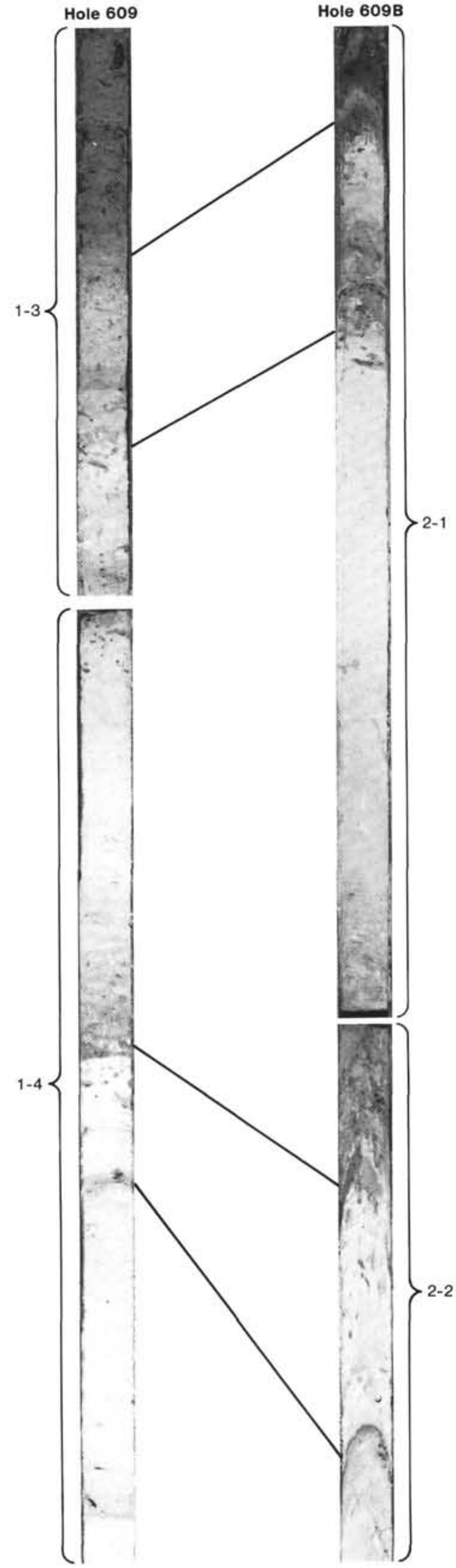

Figure 10. Example of upbowed and stretched section of Hole 609B relative to same interval retrieved undisturbed in Hole 609.

corer may fall open during descent through the water column, but then close again when it contacts the sediment. When pressured up for coring, the HPC will be injected into the sediments more slowly than normally, and with the sudden overcoming of shear-pin resistance will be abruptly fired into the sediments. The HPC may also be injected in discrete pulses as the pump strokes. If, at the same time, there is considerable heave of the ship, each upward heave of the drill string may result in localized deformation of the layers being cored at that instant.

McCoy (in press) has found examples of a somewhat analogous type of sediment deformation within piston cores. He attributes this to two heave-related complications: (1) anomalously accelerated upward motion of the piston head during the coring process, or (2) anomalously retarded upward motion of the piston head during pullout.

The Advanced Piston Corer (APC), which has ¼-in.-diameter shear pins and much less mass than the Variable Length HPC, is virtually immune to premature shear-pin failure. Yet some APC cores from Leg 96 have shown the same type of intermittent disturbance as that already described. This suggests that the injection rates may be slower in some types of sediments than has been assumed, thus permitting interference from bit movement and circulation-pump pulses. Very little is known about sediment resistance to corer penetration, and a study of the relevant sediment properties (shear strength, adhesion, propensity for liquefaction) would be useful.

Compression

Weaver and Schultheiss (1983) show how compression of layers (glacial marls) more plastic than the stiffer sediments (interglacial oozes) occurred during gravity coring of North Atlantic sediments in a region very near Site 608. The compression and thinning of the layers took place out in front of the coring apparatus. Although their results were based on a study of gravity cores, it is possible that such an effect could occur in the lower sections of piston cores if injection rate of the HPC varies. This would show up as a relative thickening and thinning of individual layers between different holes at the same site, with thinning of the more plastic layers greatest near the bottoms of individual cores. Some differences in layer thickness are evident at Site 611 and sporadically at other sites, but it is not clear whether they are caused by this kind of compressive effect or by differential deposition.

Loss of Fine Structure

A few cores show a still more subtle kind of disturbance in which fine structures, such as burrows or the details of layer contacts, are blurred or otherwise suppressed. Again, these disturbances are most common within the middle portions of cores, rather than in the bottom sections. They may be related to early firing of shear pins, but could also conceivably result from severe physical jarring of the core during some portion of retrieval.

Other Problems

The third category of disturbances consists of those which can be detected only by detailed correlations between offset holes. The critical evidence that a problem has occurred is deduced from anomalous between-hole offsets in the sub-bottom depths of correlative horizons.

Buildup of Depth-Offsets

At all sites examined here, holes positioned at nominal lateral separations developed vertical offsets between correlative horizons. These offsets sometimes developed gradually and sometimes abruptly. They may or may not indicate disturbances in the coring process. They could be explained by changes in sedimentation rate over very small lateral distances. Little is known about such changes in most areas of deep-sea pelagic sedimentation, because of the lack of coverage by deep-towed vehicles capable of distinguishing such changes over small distances.

Two problems related to coring could also contribute to some of these depth-offsets. One is that all joint lengths are assumed to be 9.6 m, when in fact they might vary by ±30 cm around that average. Thus, underrecovery or overrecovery of this amount of sediment might occur for any one core, and by random chance might occur for several cores in succession. These offsets should be no larger than a few tens of centimeters per core, and should tend to cancel out after a few cores.

The second problem is positioning of the ship. The system used to position the *Glomar Challenger* over each hole tolerates lateral displacements of up to 200 m from the positioning beacon. In calm weather with weak currents, the positioning can be held to within just a few meters of the desired location. In rougher weather and/or in strong currents (and especially for undesirable combinations of winds, seas, and currents), the larger lateral displacements may occur.

The relative degree of positioning accuracy could translate into depth-offsets of correlative horizons between holes by requiring different lengths of drill string to maintain coring operations in the various holes. For example (Fig. 11), consider the case in which all cores at Hole A are taken without complications from weather or currents. Then, after Hole B is spudded in during relatively calm weather and precise ship's positioning, the weather deteriorates (or currents increase), gradually offsetting the ship's position from the beacon. At Hole B, the lateral offset of the ship at the surface will have to be compensated for by additional drill string to maintain operations within the hole. Relative to the configuration at Hole A, the 200-m lateral ship's offset at Hole B could translate into an extra length of drill string of several meters for water depths of 3000 to 5000 m. The extra length required to maintain operations depends on the water depth at which the drill string returns to a vertical orientation, as suggested in Figure 11.

Because drill-string length is the means used to keep track of sub-bottom depth, any extra drill string needed to compensate for the lateral offset from a hole will be recorded as a greater sub-bottom depth to a given sedi-

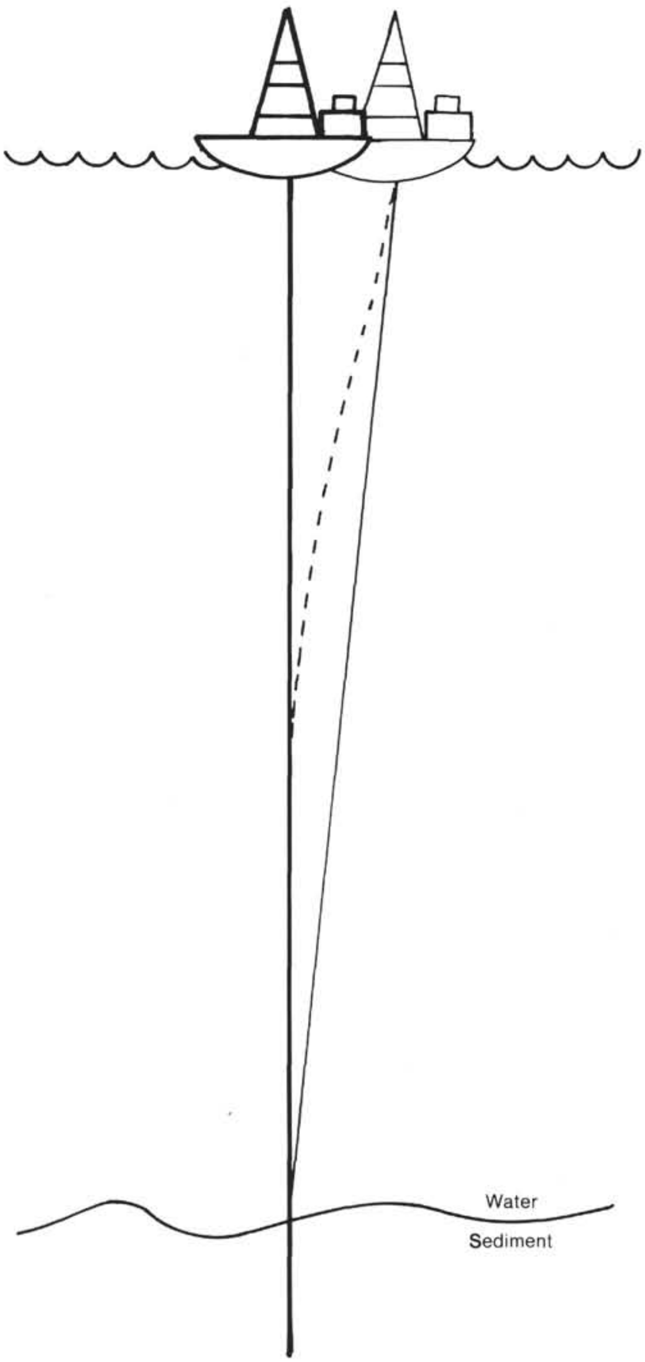

Figure 11. Schematic illustration of lateral drift of ship off positioning beacon, resulting in apparent vertical offset of correlative horizons as a consequence of greater length of drill string used to compensate for drift.

ment horizon. This will cause apparent vertical offsets of equivalent horizons of several meters between Holes A and B, where in fact none exist. In effect, the ship's real horizontal offset at the surface translates into a false vertical offset of sub-bottom depth at Hole B. If the ship drifted back toward the beacon during coring, the reverse sense of apparent offset of correlative horizons (toward depths that appear too shallow) could also occur.

The changing configurations of correlative horizons across core breaks may also provide clues about the occurrence of this kind of drift. To simplify the following analysis, it is assumed that no other problems related to heaving of the ship intervene. Actually, the ship will tend to drift during the poor weather that triggers these other problems.

When the ship is slowly drifting away from the positioning beacon, each successive core will be taken shallower than the depths intended. From this vertical increment through which the drill string has (unknowingly) been raised, the next core will retrieve either nothing (because the sediment was removed in the previous core) or contorted sediment that has fallen down the hole from higher levels. Under the simplified conditions assumed in the preceding paragraph, none of the actual sediment column will be missing at holes where the ship is drifting away from the beacon. The intervals indicated as unrecovered will actually be artifacts of the drift, as will some of the disturbances at the tops of the cores.

In contrast, if the ship is drifting toward the beacon, each successive core will be taken deeper than the intended level. This vertical increment through which the drill string has unknowingly been lowered between successive cores will be washed away during the final lowering of the drill string, and the actual core will penetrate an equal increment deeper into the sediment column. In this case, an increment of the sediment column is actually lost between each pair of cores, but no underrecovery is indicated in the core-logging procedures.

Whether drift is away from or toward the beacon, detailed between-core comparisons of correlative tie-lines provide evidence that can, in concert with observed trends toward shallowing or deepening of the correlative horizons, suggest drift of the ship. For drift away from a beacon, the evidence will be measurements showing that less sediment is missing from the core breaks than the core-logging procedures indicate. For drift toward a beacon, the evidence will be measurements showing that more sediment is missing than indicated by the core-logging procedures.

In actual conditions at rough-weather holes where the ship is most likely to drift, however, other more serious coring disturbances will intervene and mask these lines of evidence. Because of these other disturbances, the range of uncertain sub-bottom depths within which all cores float will make it difficult to prove by correlations between holes that the ship has drifted. In a case such as that discussed earlier for Site 607, however, where other disturbances are relatively small, and where the anomalous change persists across many consecutive cores, the evidence for drift can be strong.

Finally, the drift of the ship relative to the beacon can either be slow, causing gradual apparent depth-offsets, or rapid, causing abrupt apparent depth-offsets. Rapid drift will tend to occur when a ship changes heading while on station. For example, a heading change in response to an altered direction of incoming swell may put the ship in a less favorable position relative to prevailing winds and/or strong subsurface currents, leaving it unable to maintain close positioning over the beacon. This was a common problem in rough weather aboard *Glomar Challenger*.

Coring Too High in the Section: Repeated Intervals

Several sites discussed here showed evidence of repeated coring of certain intervals, with the top of one core repeating the bottom of the one previously obtained. There are several ways to double-core part of a section. One is when sediment deformation (faulting or small-scale slumping) unrelated to the coring process has already created a repeated section that the HPC then recovers intact. A second is when the HPC fires into the side wall of the hole at a level slightly higher than anticipated. This could occur because the ship heaved up at the time of coring and the ship's motion was transmitted through the drill string with sufficient force to move the end of the drill string around in the soft and watery sediments. This will be most likely if the drill string is buried only a few meters or tens of meters in the sediment.

Double-coring can also occur if the ship swings around abruptly to a new position farther from the beacon because of a change in weather or currents. The abrupt drift of the ship off the hole will result in the next core being taken higher in the hole than anticipated. Again, side-wall coring is suggested.

These possible mechanisms can be partially distinguished from one another by examination of the resulting offset of correlative horizons. If the offset induced by coring too high in the section disappears abruptly in the next core, then the cause is probably that the core misfired into the side wall of the hole as a result of the ship's heaving. If the offset persists (e.g., Core 608A-2 and below), then either prior sediment deformation or abrupt ship drift (see "Buildup of Depth-Offsets") is the more likely explanation. It will be impossible to distinguish between these two possibilities for the initial (mudline) core.

Coring Too Low in the Section

When coring occurs too deep in the section, no repeated section is available as evidence. Instead, detection is by correlation lines that are misaligned only for one core out of a total sequence. The possible explanations are similar: (1) prior sediment deformation, (2) large-scale down-heaving of the ship at the instant of coring, and (3) abrupt drift of the ship back toward the hole because of changes in weather or currents (see "Buildup of Depth-Offsets"). Again, the second explanation can be inferred if the abruptly induced offset of correlative horizons disappears with the next core, and the third explanation if the offset persists.

One of the best examples of the consequence of apparent down-heaving is Core 609C-2, which, by correlation with the sequence at Hole 609B, was taken roughly one full core too deep in the section, relative to Core 609C-1. Subsequently, Core 609C-3 came up empty because those sediments had already been retrieved in Core 609C-2. Finally, Core 609C-4 returned to the same relative offset as Core 609C-1, thus reestablishing the "normal" correlation. A similar occurrence was noted at the bottom of Site 576 during Leg 86 (Heath, Burckle, et al., in press).

A special case of coring too deep in the section occurs for mudline cores, and has important ramifications for the convention of recording sub-bottom depths. If the first core were taken during a down-heave of the ship, then the mudline measured by the drill-string convention would be recorded at too shallow a level. If for the next core the HPC then fired at the correct level, that core would have significant underrecovery (or an excess of disturbed "false core" at the top). As a result, all sub-bottom depths below the mudline core would be logged in at too great a depth, and the error would be propagated throughout the record for the entire hole. This appears to have occurred at Hole 608A, as noted earlier.

QUANTITATIVE ANALYSIS OF CAUSES OF CORING PROBLEMS

Several of the coring problems noted in this chapter occurred relatively rarely on Leg 94, so that it is difficult to link them quantitatively to specific causes. But two kinds of data collected on a core-by-core basis can be used for quantitative analysis of casual mechanisms: (1) the amount of sediment retrieved in a disturbed state and (2) the amount of sediment underrecovered (lost or never obtained) at each cored interval (Tables 1-5). In all analyses that follow, we based the calculations only on HPC cores and omitted consideration of cores collected by the Extended Core Barrel (XCB). We consider here two possible causes of these coring disturbances: (1) motion of the ship (also listed in Tables 1-5), and (2) water content of the sediment (site reports, this volume). The pitching of the ship is the best quantitative proxy available for the midship heave that actually causes motion on the drill string. The water content is the best proxy indicator of the degree of lithification/cohesiveness of the sediments.

Motion of the Ship

As was evident in the preceding section, most of the coring problems appear to be ultimately related to drill-bit motion caused by motion of the ship. According to a recent study of the effect of sea state, the motion of the drill bit may actually be amplified relative to the motion at the top of the drill string (Cameron, in press). This study was based primarily on computer modeling simulations, and the results were supported by shipboard deployments of the Drill Bit Motion Indicator (DBMI) and the Instrumented Drill String Sub (IDSS). The simulations (Fig. 12) indicate that motion at the top of the drill string is affected only by the direct heave of the ship in response to wave height; the negligible mass of the drill string relative to the ship's mass causes no additional effect. At the bottom of the drill string, however, the predicted bit motion at each given wave height increases measurably with the increased weight caused by the added pipe length.

In a broad way, it is clear that ship motion was indeed an important factor on Leg 94. Few badly disturbed cores and relatively little underrecovery occurred during the very calm weather at the three southernmost sites (606–

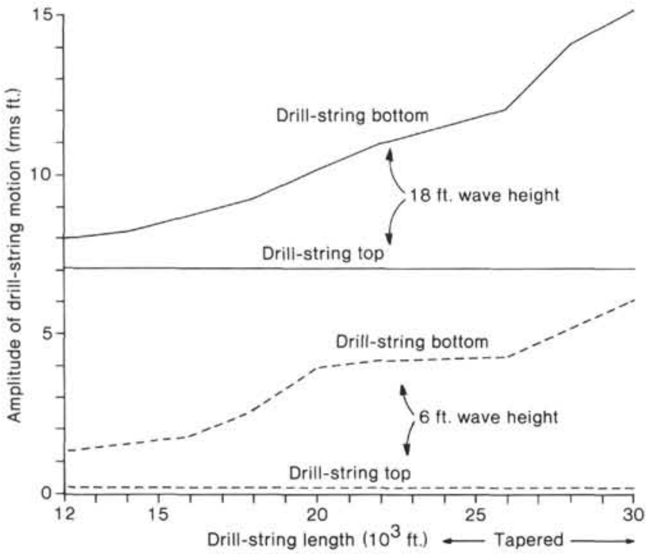

Figure 12. Comparison of amplitude of motion of top and bottom of drill string as a function of drill-string length and of wave height.

608; Tables 1 and 2). Most of the problems were concentrated at the three northernmost sites (609–611), where the weather was rougher (Tables 3–5). Weather was clearly not the only factor, however.

Because the recording of the ship's pitch varies over only four increments, we did not run a correlation coefficient on these data core by core. Instead, we calculated average values of disturbance and underrecovery for each of the four values of pitch. The average amount of disturbed sediment at the tops of the cores shows some relationship to pitch (Table 6), with only 6.7 cm of disturbance for a pitch of 1°, increasing to 116 cm for a pitch of 4°. With this increase in the average amount of disturbed sediment, there is a corresponding increase in the standard deviation, reflecting the tendency for the disturbance to be heavily concentrated in a few cores and to leave others unaffected. The link is much weaker for underrecovery versus pitch: only the 4° pitch shows higher underrecovery than the other categories. This suggests a threshold value above which recovery deteriorates markedly.

Water Content of the Sediments

The second factor that may be important in coring problems is the physical state of the sediment. The incidences of disturbed sediment were disproportionately concentrated in the upper 50 m of the sediment column at Sites 607, 608, and 610, at levels where the water content of the sediments was markedly higher (site reports, this volume). At Sites 609 and 611, the disturbances were more evenly spread across the range of HPC coring, and the water content at these sites remained high throughout the upper 150 m.

We calculated average amounts of disturbed and unrecovered sediment per core for five classes of water content: ≤35, >35 ≥ 40, >40 ≤ 45, >45 ≤ 50, and >50%. The amount of disturbance shows an erratic tendency to increase with water content (Table 6). A point of inflection (indicated by the bracketed entries on Table 6) appears to occur at a water content of about 40%: the average amount of disturbed sediment for water contents above 40% was 87 cm; the average value for water contents below 40% was 39 cm. The amount of unrecovered sediment also tends to increase for higher values of water content (Table 6). We conclude that both the amount of contorted sediment at the tops of HPC cores and the underrecovery of HPC cores are related to the water content of the sediments.

Another comparison strongly supports this conclusion. Our continuing problems with recovery at shallow sub-bottom depths in the high latitudes of the North Atlantic contrasted strikingly with the success of Leg 81 in obtaining a largely undisturbed record in a single HPC sequence at Hole 552A (Roberts, Schnitker, et al., 1984). Except for Core 552A-6, which was brought back totally disturbed, most of the Hole 552A cores were nearly complete and undisturbed, save for a short length (5–30 cm) of disturbance at each core top. The explanation for this difference cannot be weather; coring in Hole 552A began immediately after passage of a major storm and continued through conditions of large storm-related swell throughout. This contrasts with the lack of storms and the modest swell during Leg 94. Another potential variable is the choice of corer: Leg 81 used the 5-m HPC in Hole 552A, whereas we used mostly the 9.6-m version. On several occasions, however, we also tested the 5-m HPC, and the problems persisted.

This appears to leave only one explanation of the different results on these two legs: the physical state of the sediments. The lithology at Hole 552A was generally very similar to lithologies at Sites 609 and 610, with interglacial nannofossil oozes interbedded with glacial marine silty clays. But at Hole 552A, the deposition rate averaged about 15 m/m.y., whereas at Sites 609 and 610

Table 6. Statistics on amount of disturbed and urecovered sediment (cm) at Sites 606 through 611, Leg 94.

		Pitch (°)				Water content (%)						
Sediment		1	2	3	4	≤35	>35 ≤ 40	≤40	>40	>40 ≤ 45	>45 ≤ 50	>50
Disturbed:	Mean	6.7	56.8	58.1	116.1	3.2	43.3	39.1	87.0	133.4	42.7	83.7
	Standard deviation	9.6	95.5	107.3	182.5	4.7	81.0	77.5	153.2	229.2	54.1	131.3
	N	22	38	51	57	6	51	57	111	28	25	58
Unrecovered:	Mean	44.7	42.2	46.5	102.6	35.3	45.9			74.0	67.0	80.5
	Standard deviation	58.7	71.9	42.2	137.6	50.1	46.0			114.2	47.9	132.7
	N	20	33	49	53	6	51			24	21	53

Note: *N* = number of cores used to calculate statistics.

the rates were 70 and 50 m/m.y. Ruddiman and McIntyre (1976) showed that local redistribution of sediment occurs in this area of the North Atlantic, such that cores with high deposition rates have higher percentages of redeposited silt and clay, whereas those with low deposition rates have higher contents of residual sand. In general, the water content of the (finer) sediments deposited at high sedimentation rates should be higher.

Physical properties measurements indicate generally higher water contents at Leg 94 Sites 607 to 611 (site reports, this volume) than at comparable sub-bottom depths in Hole 552A (Roberts, Schnitker, et al., 1984). The water contents even at the top of Hole 522A were just slightly over 40%, and they decreased to the 35 to 40% range at depths of 5 to 60 m and then to the 30 to 35% range from 60 to 160 m. Water contents at Hole 552A are thus in the range for which Leg 94 sediments were relatively undisturbed (Table 6). The water-content differences between Hole 552A and Sites 609 and 611 were especially large; at comparable sub-bottom depths, there was an average of 48% more water at Site 611 and 37% more water at Site 609 than at Hole 552A.

We conclude that the significant differences in physical properties between sediments cored at Leg 81 Hole 552A and at Leg 94 Sites 607 to 611 account for the differences in amount of core disturbance and recovery. Sediments at most Leg 94 sites were more watery, less dense, and presumably more susceptible to coring disturbances, especially at Sites 609 and 611.

Recommendations for Future HPC Coring

Future drilling legs, in which the basic strategy is to HPC-core sediments deposited at locally enhanced deposition rates to recover detailed paleoclimatic signals, will presumably be subject in some degree to the same retrieval problems evident on Leg 94, particularly in moderate to high sea states. We recommend that such legs utilize any prominent lithologic variations present to monitor continuity of section. This could be done much more efficiently than on Leg 94 by making use of hard paper copy of some continuously measured parameter that varies with lithology. The two best techniques currently planned to be made available on ODP legs are bulk density records from the GRAPE and susceptibility records from the cryogenic magnetometer.

It may also be advisable for the co-chiefs on such legs to avoid trying to core where the sedimentation rates were highest in a given region, because the sediments may be significantly more watery and susceptible to disturbance. Instead, it may be advisable to enhance core recovery by coring firmer sediments deposited at more moderate sedimentation rates.

Finally, we recommend that ODP not use the "advance-by-recovery" method of HPC coring that has been used on some DSDP/IPOD legs (but not on Leg 94). Our findings show that the amount of intact core actually recovered may result from any number of factors other than the incomplete stroking-out of the core barrel inferred by those advocating the "advance-by-recovery" method.

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