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40. STRESS HISTORY AND GEOTECHNICAL PROPERTIES OF SEDIMENT FROM THE CAPE FEAR DIAPIR, BLAKE RIDGE DIAPIR, AND BLAKE RIDGE[1]

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ABSTRACT

Geotechnical properties of sediment from Ocean Drilling Program Leg 164 are presented as: (1) normalized shipboard strength ratios from the Cape Fear Diapir, the Blake Ridge Diapir, and the Blake Ridge; and (2) Atterberg limit, vane shear strength, pocket-penetrometer strength, and constant-rate-of-strain consolidation results from Hole 995A, located on the Blake Ridge. This study was conducted to understand the stress history in a region characterized by high sedimentation rates and the presence of gas hydrates. Collectively, the results indicate that sediment from the Blake Ridge exhibits significant underconsolidated behavior, except near the seafloor. At least 10 m of additional overburden was removed by erosion or mass wasting at Hole 993A on the Cape Fear Diapir, compared to nearby sites.

INTRODUCTION AND GEOLOGIC SETTING

Ocean Drilling Program (ODP) Leg 164 obtained core samples at three different regions off the southeast coast of the United States: Sites 991, 992, and 993 on or near the Cape Fear Diapir, Site 996 on the Blake Ridge Diapir, and Sites 994, 995, and 997 on the eastern edge of the Blake Ridge (Fig. 1; Paull, Matsumoto, Wallace, et al., 1996). Holes drilled at Sites 991–993 and Site 996 were relatively shallow, with penetrations of 50–60 m. Sites 994, 995 and 997 had much deeper penetrations of more than 700 m.

The geologic setting of the region is fairly complex. The Carolina Trough and the Blake Plateau Basin, both located west of the Blake Ridge, were formed and filled to a thickness of 12–13 km, as part of a five-stage continental margin-building process that also created the Blake Plateau (Dillon and Popenoe, 1988). The Cape Fear and Blake Ridge Diapirs (Paull, Matsumoto, Wallace, et al., 1996) are part of a linear set of diapirs that occurs along the seaward side of the Carolina Trough, apparently the result of the flow of evaporites that accumulated in the trough during its early development (Dillon et al., 1983). The Blake Ridge is characterized as a sediment drift deposit formed by contour currents, and consists of hemipelagic mud deposited at relatively rapid rates (Heezen et al., 1966; Shipboard Scientific Party, 1983; Dillon and Popenoe, 1988).

Normalized shipboard vane shear and pocket-penetrometer shear strength ratios are presented for all sites; however, Atterberg limit, vane shear strength, pocket-penetrometer strength, and constant-rate-of-strain consolidation results are presented only from Hole 995A, located on the Blake Ridge in the middle of a sequence of three sites. Site 994 is 3.0 km to the southwest of Site 995, and Site 997 is slightly further to the northeast (Fig. 1). Results of shipboard physical property measurements, typically performed at 3-m intervals, were very consistent among the different sites on the Blake Ridge (Paull, Matsumoto, Wallace, et al., 1996). The implication is that the results from Hole 995A, presented here, may also be applicable to the two adjacent sites. The similarity in physical properties is important because it enables analyses to be inferred over a larger region.

This study analyses the stress history of the Blake Ridge to determine if the high sedimentation rates, in conjunction with the presence of gas hydrates, which could cement the grains together, have influenced the normal compaction process. Hyndman and Davis (1992) have suggested that underconsolidation could be present in the Blake-Bahama outer ridge region.

METHODS

Eight 10-cm-long whole-round samples, earmarked for consolidation testing, were subsampled from cores during Leg 164. They were preserved in the original liner, capped, completely covered in wax, and subsequently stored in a refrigerator at a temperature of ~4°C. Two different studies utilized the samples. A 3-cm-long whole-round subsample was removed to check the influence of drying temperature on water content and to perform mineralogic and grain-size analyses (Winters, Chap. 41, this volume). The remaining material was used for index properties (Atterberg limits), vane shear and pocket-penetrometer strength tests, and constant-rate-of-strain consolidation tests. The sediment was described at sea as nannofossil- and diatom-bearing and nannofossil- and diatom-rich clay to claystone in Hole 995A (Shipboard Scientific Party, 1996). Shore-based grain-size analyses graded the sediment as clayey silt size (Winters, Chap. 41, this volume).

Index Properties

Index properties provide information on general engineering behavior. Water content, corrected for salinity, were determined according to American Society for Testing and Materials (ASTM, 1997a, 1997b) Standard D 2216-92, except that the drying temperature was 90°C rather than the specified 110°C to reduce mineralogical changes that can be produced at the higher temperature. Plastic limits were performed according to ASTM (1997a, 1997b) Standard D 4318-95a. However, the fall cone method was used to perform liquid limit tests according to procedures outlined in Head (1980) and Winters (1988).

The relative value of the natural water content in relation to the Atterberg limits (liquid limit, w_L, and plastic limit, w_P) indicates whether the remolded sediment behaves like a liquid, plastic, or semi-solid. That relationship is expressed by the liquidity index, $I_L = (w_c - w_P)/(w_L - w_P)$. A I_L larger than 1.0 indicates that the natural water content is greater than the liquid limit and that the behavior of the sediment would approximate that of a liquid upon remolding. The plasticity index, $I_P = w_L - w_P$, provides a quantification of the range of water content over which the material exhibits plastic behavior.

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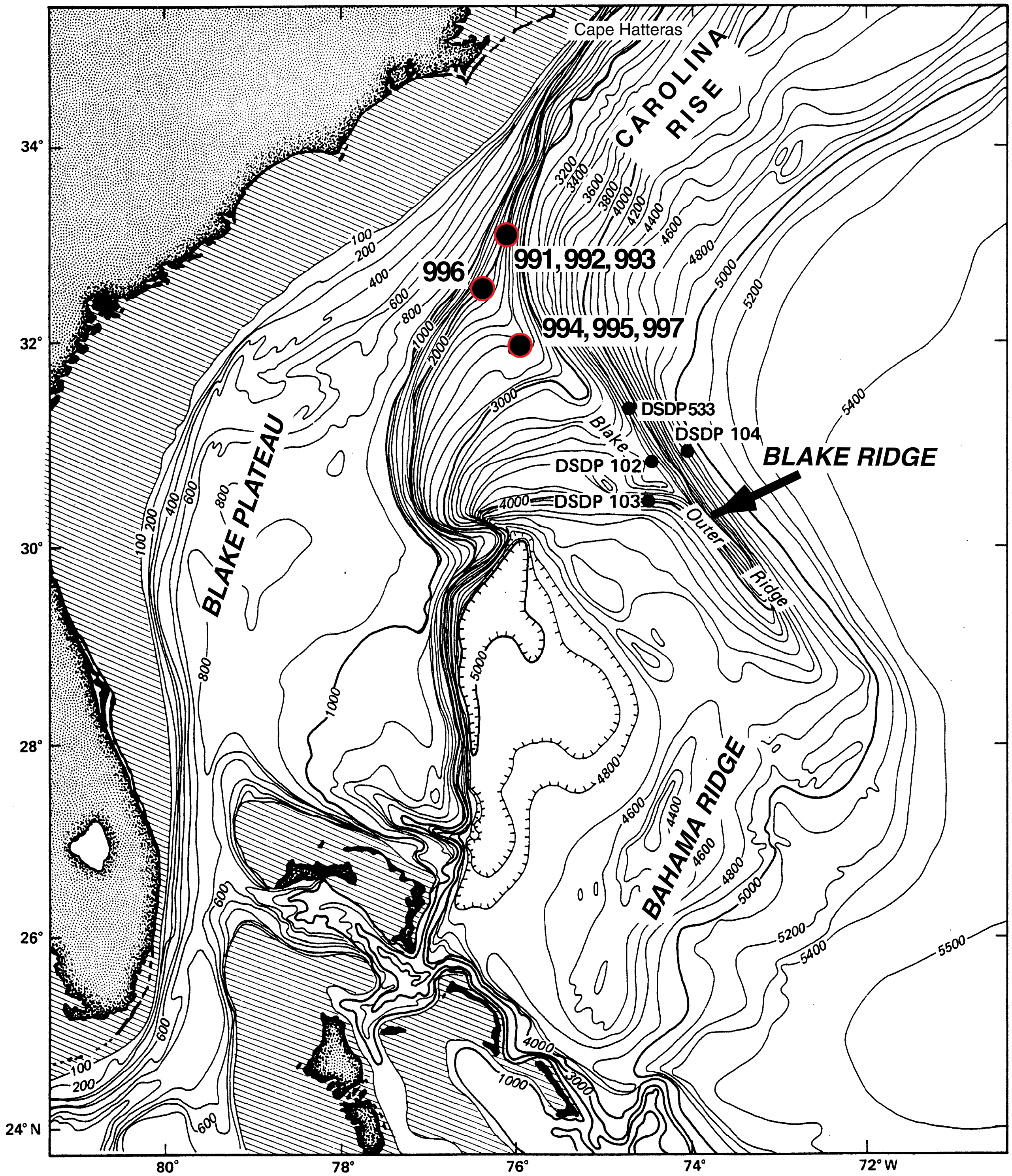

Figure 1. Site location map for ODP Leg 164 and nearby Deep Sea Drilling Project (DSDP) sites (modified from Gradstein and Sheridan, 1983). Bathymetry in meters.

Strength Properties

A laboratory miniature-vane-shear apparatus and a pocket penetrometer, similar to those used at sea during Leg 164, were also used for this study. The vane-shear test was performed according to ASTM (1997a, 1997b) Standard D 4648 using a 12.7-mm high × 12.7-mm diameter vane at a rotation rate of about 90°/min. Torque was applied through a spring system. The pocket penetrometer was quickly pushed into fine-grained sediment so that drainage would not occur and the measured unconfined compressive strength was converted to shear strength.

Consolidation Properties

Back-pressured constant-rate-of-strain consolidation (CRSC) tests were performed using a unique triaxial test system called

GHASTLI (Gas Hydrate And Sediment Test Laboratory Instrument; Booth et al., 1994; Winters et al., 1994) on 63.5-mm-diameter by 18.9-mm-high specimens, according to ASTM (1997a, 1997b) D 4186. This test system has a high loading capacity and was therefore well suited for performing tests on deep borehole sediment.

RESULTS

Index Properties

Water content and Atterberg limits data are listed in Table 1. A more complete treatment of the water content results is presented in Winters (Chap. 41, this volume).

As expected, water content, w_c, typically decrease with depth in Hole 995A, however, there are two exceptions. The Atterberg limits vary downhole also. The measured liquidity indices vary from 0.89 near the seafloor to 0.19 at 350.8 mbsf, and the plasticity indices range from 64 to 42.

General inferences about behavior can be made if values of plasticity index are plotted against the liquid limit on a plasticity chart (Fig. 2). Most of the sediment is expected to behave like an inorganic clay of high plasticity (above the A-line with a liquid limit greater than 50; Casagrande, 1947). One data point, which plots below the A-line, is indicative of inorganic silt with high compressibility. Data that defines a straight line that is parallel to the A-line is typical for sediment of similar geologic origin (Terzaghi and Peck, 1967). However, the data for this study is too limited to draw conclusions. The major clay mineral grouping can also be estimated from the plasticity chart (Holtz and Kovacs, 1981). Although most of the samples plot slightly further along the A-line than from previously published sources because of higher liquid limit and plasticity index values, the Atterberg limit results indicate that illite and kaolinite are the dominant clay mineral groups, not montmorillonite, which agrees with the mineralogical analyses performed on these samples (Winters, Chap. 41, this volume). However, the presence of high concentrations of biogenic material may cause this sediment to correlate poorly with standard empirical relationships.

The water contents of the entire consolidation test specimens typically were greater than shipboard values at the same sub-bottom depth. This may be the result of coring disturbance around the perimeter of the sample. At-sea water contents were obtained only from the center of the cores.

Strength Properties

The shipboard vane-shear and pocket-penetrometer strengths, S_u, were divided by the cumulative product of submerged unit weight, W_s, and sub-bottom depth, d, at most of the holes occupied during Leg 164 (Fig. 3) to produce a $S_u/(W_s d)$ ratio that can be used to qualitatively interpret stress history. The submerged unit weights were estimated from the shipboard grain density and water content data. Without exception, the $S_u/(W_s d)$ values are higher near the seafloor than at depth. Values range from a high of 46 in Hole 993A to a low of 0.02 in Hole 994C.

The adjacent vane-shear and pocket-penetrometer strengths that were performed at the same depth on the whole-round core sections near the consolidation samples from Hole 995A agreed remarkably well with each other (Table 1). The sensitivity, S_t = intact vane shear strength/remolded vane shear strength, values indicate that the sediment classifies as "sensitive" (Bowles, 1979). Because the same magnitude of sensitivity was present both in sediment obtained with the APC (Advanced Piston Core) and the XCB (rotary Extended Core Barrel), it appears that rotary coring did not appreciably disturb the uppermost sample in Hole 995A obtained with that device.

Consolidation Properties

Constant-rate-of-strain consolidation tests were performed to evaluate the stress history of the sediment (Table 2, Fig. 4). The test results are plotted as void ratio, e = volume of voids/volume of solids, vs. the logarithm of the vertical effective stress, σ'_v. Typical e – logσ'_v curves form a straight line, the virgin compression line, at higher stresses. The slope of the virgin line is termed the compression index, C_c, and represents how much one-dimensional compression can be expected from a logarithmic cycle of loading.

The preconsolidation stress, P'_c, can be determined from consolidation test results that have a straight virgin line by the Casagrande (1936) graphical technique and is assumed to equal the in situ maximum past stress, σ'_{vm}. The consolidation results exhibit a wide range of maximum past stresses and compression indices. Maximum past stresses vary from 40 kPa to 2730 kPa at depth. The compression indices change by a magnitude of 2 and are 5% to 43% higher than what would be expected from an empirical relation based on the liquid limit results (Terzaghi and Peck, 1967). However, the high biogenic content of the sediment may affect empirical comparisons.

DISCUSSION

Normalized strength profiles from all sites decreased markedly with sub-bottom depth (Fig. 3) in a manner that indicates the sediment is overconsolidated ($S_u/\sigma'_v > 0.2$; Ladd et al., 1977) near the seafloor, but underconsolidated at depth. This is especially apparent at Sites 994, 995, and 997, because of their greater drilling depth. How-

Table 1. Index properties and shear strengths from Hole 995A.

Core, section, interval (cm)	Depth (mbsf)	Water content (% dry wt)	Porosity (%)	Liquid limit	Plastic limit	Liquidity index	Plasticity index	Vane shear strength (kPa)	Remolded vane shear strength (kPa)	Sensitivity	Pocket-penetr. shear strength (kPa)
164S-995A-											
2H-1, 139-149	3.09	69.3	64.7								
	3.09	63		68	24	0.89	44	25	4	6.2	22
7H-1, 37-47	49.57	87.9	70.0					55	13	4.2	55
19H-2, 140-150	148.48	62.5	62.3								
	148.48	60		99	35	0.39	64	135	34	4.0	120
31X-1, 110-120	253.40	52.4	58.1					130	19	6.8	94
42X-2, 70-80	350.80	44.5	54.1								
	350.80	44		83	35	0.19	48	>145			>230
57X-2, 130-140	467.00	37.5	49.9								
66X-4, 125-135	546.11	50.5	57.2								
	546.11	52		82	40	0.29	42				
80X-1, 75-85	666.85	39.3	51.0								

Note: Two water-content samples in some intervals show intralayer variability. See also Winters, Chap. 41, this volume.

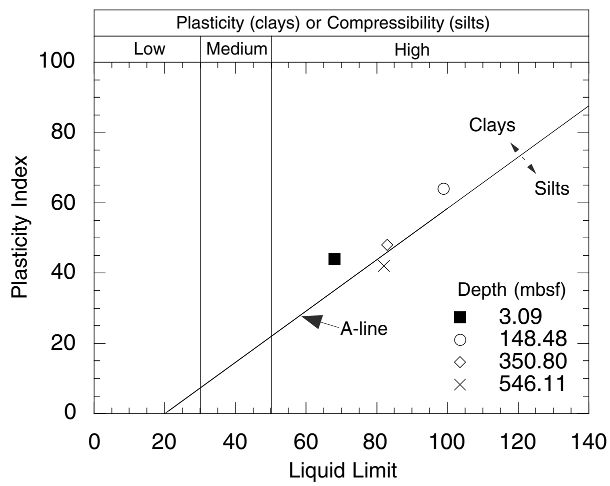

Figure 2. Plasticity chart (modified from Peck et al., 1974) for sediment from Hole 995A.

ever, drilling disturbance, especially in XCB cores, may artificially reduce the strength ratio (Dadey and Silva, 1989).

Sites 991–993

Of the three sites transecting the Cape Fear Diapir, Hole 993A has the largest seafloor-normalized strength values and strength, indicating that the shallow sub-bottom sediment is more overconsolidated at that location than the sediment at the other two nearby sites. This is consistent with the location of Hole 993A, which is on the steep flank of the diapir (Paull, Matsumoto, Wallace, et al., 1996) and is therefore more prone to mass wasting or erosion.

An estimate of the thickness of overburden that could have been removed to produce the near-seafloor shear strength profile observed in Hole 993A can be approximated by comparing the uppermost strength value at Hole 993A with the depth at which that strength is reached in the adjacent two sites. Using this method, it is estimated that 10 to 18 m of overburden were removed.

A different technique to estimate the amount of removal can be made from the S_u/σ'_v ratio. Assuming that S_u/σ'_v equals 0.2 for normally consolidated sediment, ~60–70 m of overburden is required to develop the shear strength observed at the seafloor at Site 993. This, however, is probably a gross exaggeration because many deep-sea sediments, including these from Leg 164, show an apparent overconsolidated layer near the seafloor (Richards and Hamilton, 1967; Silva and Jordan, 1984). In fact, different sediments may have different normally consolidated S_u/σ'_v values (Richards and Hamilton, 1967). Furthermore, disturbance induced by XCB drilling may also influence the normalized strength values (Dadey and Silva, 1989). Care was used to perform the tests only within the more intact biscuits from XCB cores, rather than in the disturbed infilling material both at sea and in the laboratory.

Site 995

Based on the overconsolidation ratios, OCR = $P'_c/(W_s d)$, derived from the consolidation tests, all sediment is underconsolidated, OCR < 1.0, except for the sample at 3 mbsf (Table 2; Fig. 4). High overconsolidation ratios have been observed at numerous seafloor locations (Zizza and Silva, 1988) and especially in areas of high organic-rich sediment (Lee et al., 1990). The underconsolidated behavior at Site 995 may have been caused by the high sedimentation rate (up to 400 m/m.y.; Shipboard Scientific Party, 1996) or the presence of gas hydrate, which may have cemented the grains together or filled the voids so that normal compaction processes could not take place in situ. The hydrate in such a sediment would dissociate upon sampling and could produce an underconsolidated sediment. Arguing against hydrate-induced underconsolidation, none of the tested samples showed any signs of having degassed. This undercompaction is also indicated by the relatively constant porosity profiles in the deeper holes (Sites 994, 995, and 997) (Paull, Matsumoto, Wallace, et al., 1996).

Maximum past stresses, from consolidation tests performed on Hole 995A sediment, typically increase with sub-bottom depth (Fig. 5). The excess effective stress, $\sigma'_e = P'_c - (W_s d)$, is a measure of the amount of under- or overconsolidation present in the sediment. It is sometimes beneficial to use the excess effective stress instead of OCR because σ'_e is not affected by small values of vertical effective stress near the seafloor. The σ'_e values decrease with sub-bottom depth in Hole 995A and may be related to the amount of excess pore pressure (above hydrostatic) present (Moran et al., 1995). It is uncertain which of the possible factors contributes the most to the large degree of underconsolidation at depth. However, sedimentation rate may play a significant role since the lowest excess effective stress occurs at the same depth, ~550 mbsf, as the highest sedimentation rate (Shipboard Scientific Party, 1996).

CONCLUSIONS

Three different regions were drilled during Leg 164: the Blake Ridge, the Cape Fear Diapir, and the Blake Ridge Diapir. The Blake Ridge is a drift deposit that contains a large quantity of gas hydrate. Physical properties tests indicate that sediment has been removed from the flank of the Cape Fear Diapir, and the shallow sub-bottom sediment from all three regions exhibits overconsolidation or apparent overconsolidation. The sediment from Hole 995A, located in the middle of a three-site transect on the Blake Ridge, exhibits overconsolidated behavior near the seafloor and significant underconsolidation at depth. The underconsolidation may be a result of the high sedimentation rates present in the area, presence of free gas, or of gas hydrate cementation that prevents the normal compaction process from occurring. Coincidentally, the smallest excess effective stress value, indicative of the presence of in situ excess pore pressure, occurs at the location of the maximum sedimentation rate.

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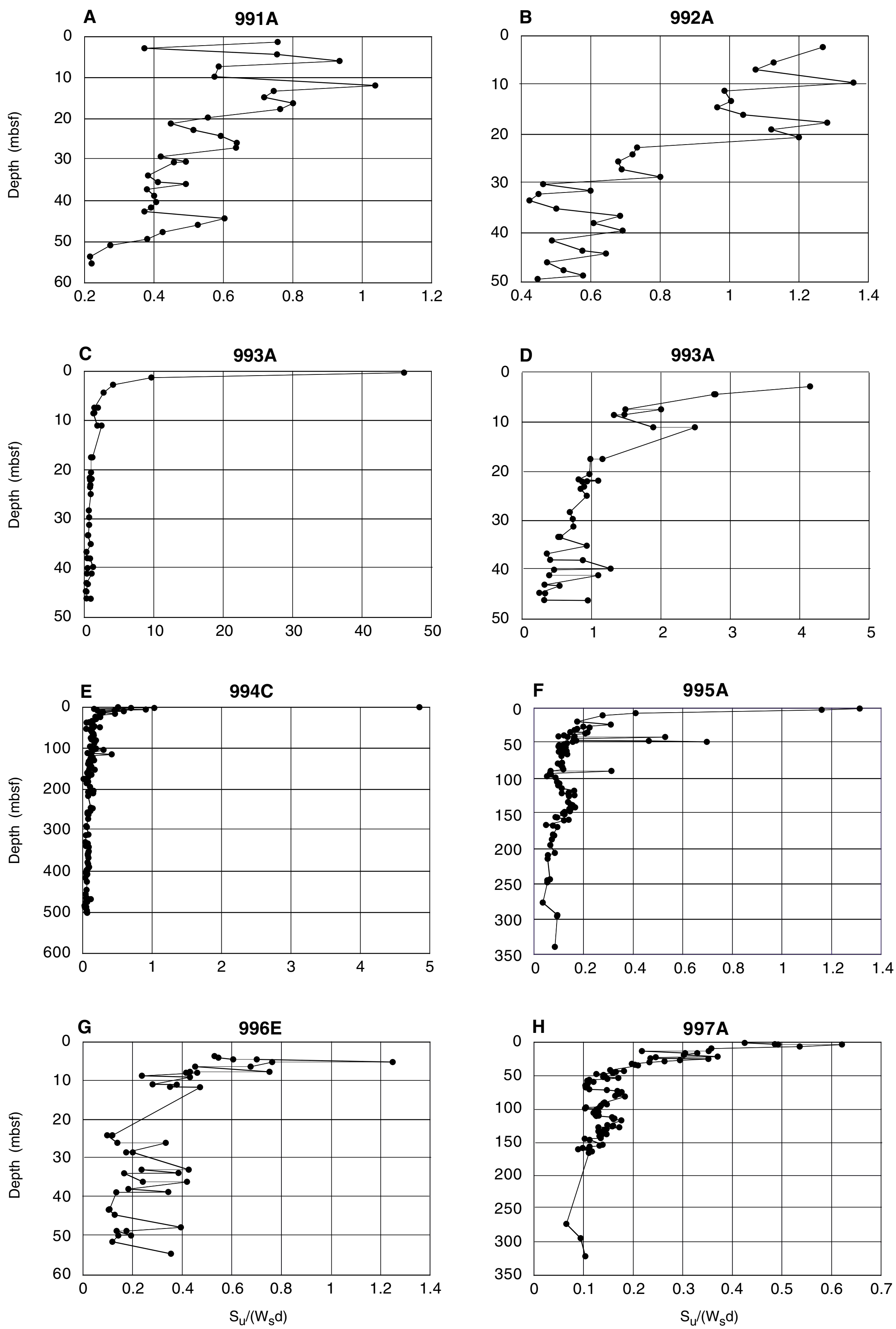

Figure 3. **A–H.** Normalized shear strengths vs. depths.

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Table 2. Consolidation test results from Hole 995A.

Hole, core, section	Depth (mbsf)	Test number	Water content (initial; dry%)	Void ratio (initial)	$W_s d$ (kPa)	P'_c (kPa)	OCR	σ'_e (kPa)	C_c
164S-995A-									
2H-1	3.09	GC012	76.0	2.01	14	40	2.9	26	0.67
7H-1	49.57	GC011	95.4	2.53	270	205	0.76	–65	1.38
19H-2	148.48	GC009	64.9	1.72	885	430	0.49	–455	0.94
31X-1	253.40	GC008	54.2	1.44	1610	400	0.25	–1210	0.68
42X-2	350.80	GC007	54.2	1.44	2350	780	0.33	–1570	0.69
57X-2	467.00	GC010	49.9	1.36	3290	1770	0.54	–1520	0.93
66X-4	546.11	GC006	65.3	1.73	3940	1330	0.34	–2610	0.97
80X-1	666.85	GC005	57.3	1.52	4970	2730	0.55	–2240	0.93

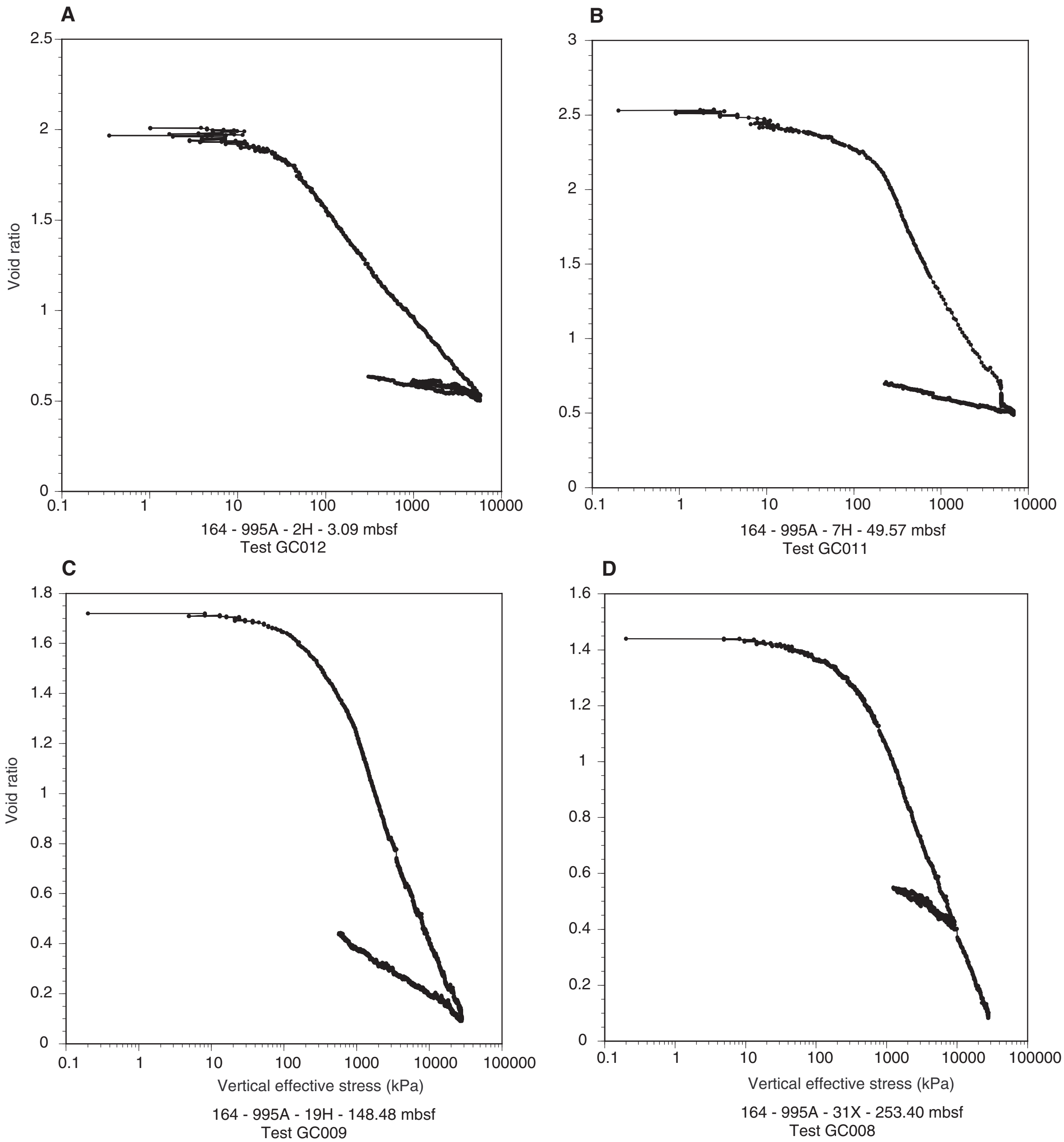

Figure 4. **A–H.** Consolidation test results from Hole 995A. (Continued next page.)

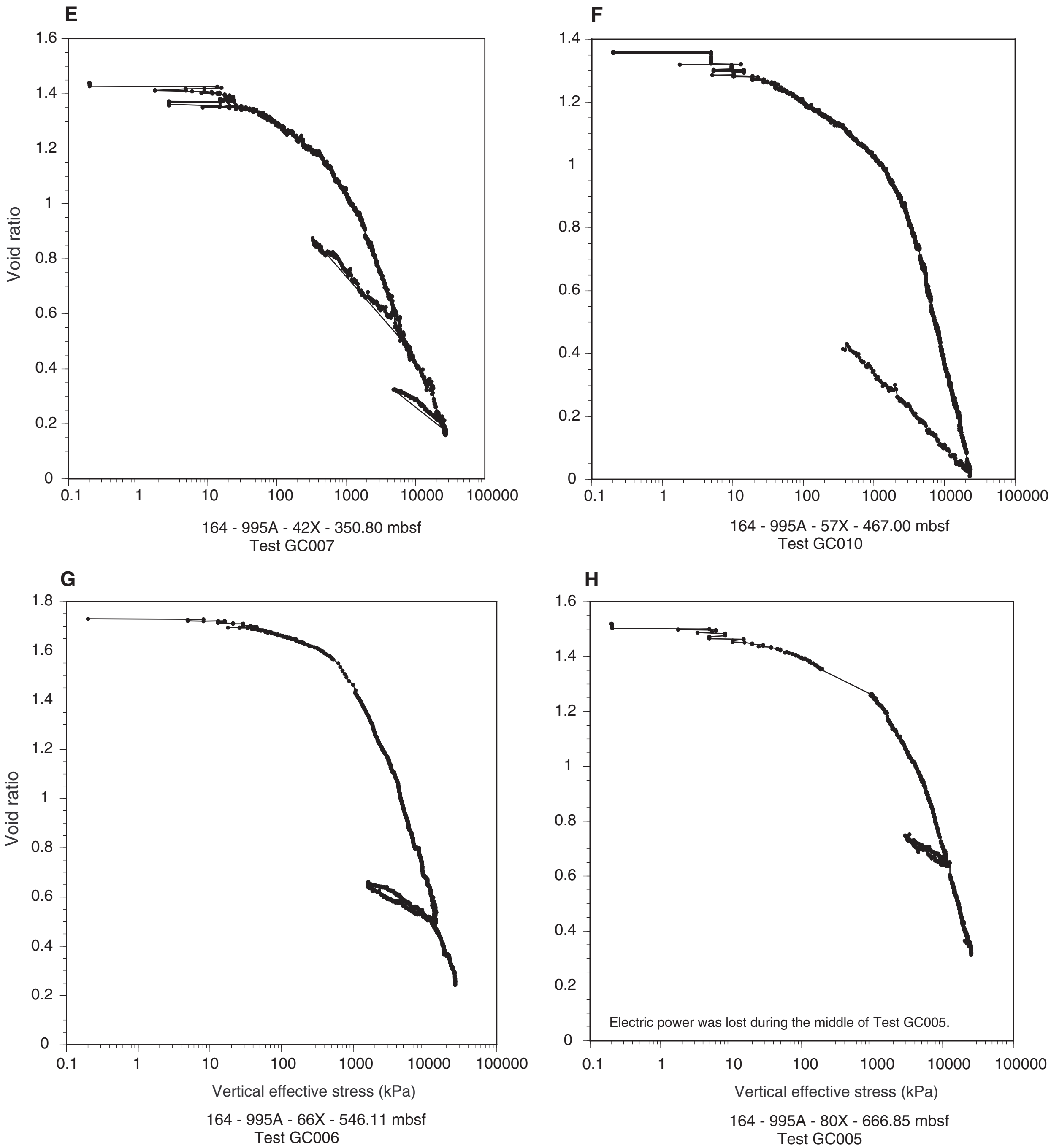

Figure 4 (continued).

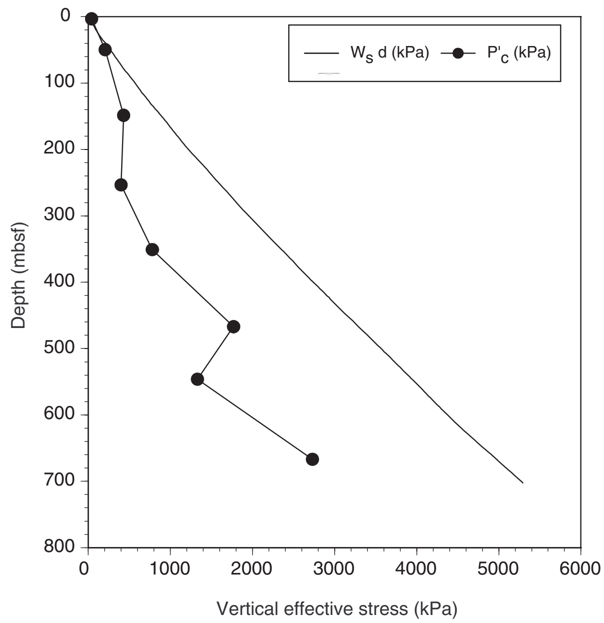

Figure 5. Preconsolidation stress, P'_c, determined from consolidation tests and estimated vertical stress calculated from the cumulative product of the submerged sediment unit weight and depth, $W_s d$, vs. depth for Hole 995A.