48. LABORATORY-DETERMINED SOUND VELOCITY, POROSITY, WET-BULK DENSITY, ACOUSTIC IMPEDANCE, ACOUSTIC ANISOTROPY, AND REFLECTION COEFFICIENTS FOR CRETACEOUS–JURASSIC TURBIDITE SEQUENCES AT DEEP SEA DRILLING PROJECT SITES 370 AND 416 OFF THE COAST OF MOROCCO[1]

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ABSTRACT

From 661 to 880 m beneath the seafloor at DSDP Sites 370 and 416 are Albian to Barremian claystone with some limestone, sandstone, and siltstone. Compressional-wave velocities ranged from 1.70 to 4.37 km/s, with an average *in situ* vertical velocity of 1.93 km/s.

From 880 to 1430 m are Hauterivian to Valanginian turbidites of alternating graded calcareous and quartzose cycles from siltstone or fine sandstone to mudstone. Compressional-wave velocities range from 1.80 to 4.96 km/s with an average *in situ* velocity of 2.61 km/s.

From 1430 to 1624 m are early Valanginian to Tithonian (Kimmeridgian?) turbidites, with alternating quartzose siltstone grading to mudstone cycles with hard micritic limestone and calcarenite (calciturbidites). Compressional-wave velocities range from 2.26 to 5.7 km/s, with an average *in situ* vertical velocity of 3.25 km/s.

Acoustic anisotropy is 0 to 30% faster parallel to bedding in Cretaceous to Tithonian sandstone–siltstone turbidites in mudstone and minor limestone from 661 to 1624 m below the seafloor. Between 2.0(?) km/s and 4.2(?) km/s, anisotropy becomes particularly significant (below 1178 m), where the anisotropy is about +0.4 km/s or greater. The mudstone, softer sandstone, and softer siltstone tend to have velocities around 2.0 to 2.5 km/s; the cemented sandstone and limestone cluster around 2.5 km/s to 4.2 km/s; thus the relative percentage anisotropy is greater for lower-velocity lithologies. Above 4.2(?) km/s, the well-cemented sandstone and limestone tend to have a smaller (less than +0.4 km/s) absolute anisotropy, and many samples are nearly isotropic.

These physical property data are separated into depth plots for (1) mudstone, (2) siltstone (3) sandstone, (4) marlstone, and (5) limestone. The mudstone's porosity and wet-bulk density curves versus depth are slightly higher and lower, respectively, than similar porosity and wet-bulk density curves summarized in Hamilton (1976). These differences could be some combination of (1) differences in laboratory methods; (2) age, lithologic, and cementation differences; or (3) overconsolidation created by a geological sequence which has been eroded away.

If the average *in situ* vertical velocities calculated by Boyce (1980b) for Hole 416A are correct, then the 1.43-s (round-trip) reflector (blue) discussed by Lancelot and Winterer (1980) and Lancelot, Winterer et al. (1980b), would correlate to about 1500 m in Hole 416A, and not below 1624 m as suggested by Lancelot and Winterer. There appears to be a significant change in the acoustic character at or around that depth (1500 m) to a more lithified, calcareous, and cemented lithology. This does not prove Lancelot and Winterer (1980) and Lancelot, Winterer et al. (1980b) to be incorrect, but only suggests another possible interpretation.

INTRODUCTION

This chapter is concerned with the physical property relationships enumerated below, using data measured on cores recovered from Sites 370 and 416, in the Atlantic Ocean off the coast of Morocco (Fig. 1) for the Cretaceous–Tithonian sandstone, siltstone, mudstone, and minor micritic limestone and calcarenite from 661 to 1624 m below the seafloor. The objectives of the chapter are as follows:

1) At Site 416, to study physical properties versus depth for different lithologic types: (a) mudstone, (b) siltstone, (c) sandstone, (d) marlstone, and (e) limestone. This is important for characterizing the lithology and physical properties of this area and for making comparisons to other areas.

2) At Sites 370 and 416, to undertake additional systematic studies of the horizontal and vertical velocity, acoustic anisotropy, porosity, and wet-bulk density of the geologic sequence. This information is valuable for correctly interpreting gravity data, seismic reflection data, seismic refraction data, and sonobuoy data.

3) At Sites 370 and 416, to attempt to calculate reflection coefficients; and by using *in situ* interval velocities calculated by Boyce (1980b) for the geologic section penetrated at Site 416, to attempt to correlate the acoustic character of the data obtained from Sites 370 and 416 with the 1.43-s (round-trip) reflector (blue) in seismic profiles discussed by Lancelot, Winterer, et al. (1980b) and Lancelot and Winterer (1980).

DATA, DEFINITIONS, AND METHODS

For Site 416 data, the sediment classification is discussed in Lancelot, Winterer, et al. (1980a), and detailed age-dates and lithologies are discussed in Lancelot, Winterer, et al. (1980b). Wet-bulk density is defined as the ratio of weight of water-saturated sediment or rock sample to its volume, expressed as g/cm^3. Wet-water content is the ratio of the weight of seawater in the sample to the weight of the saturated sample, and is expressed as a percentage. Porosity is the ratio of the pore volume in a sample to the volume of the saturated sam-

[1] Hay, W. W., Sibuet, J.-C., et al., *Init. Repts. DSDP*, 75: Washington (U.S. Govt. Printing Office).

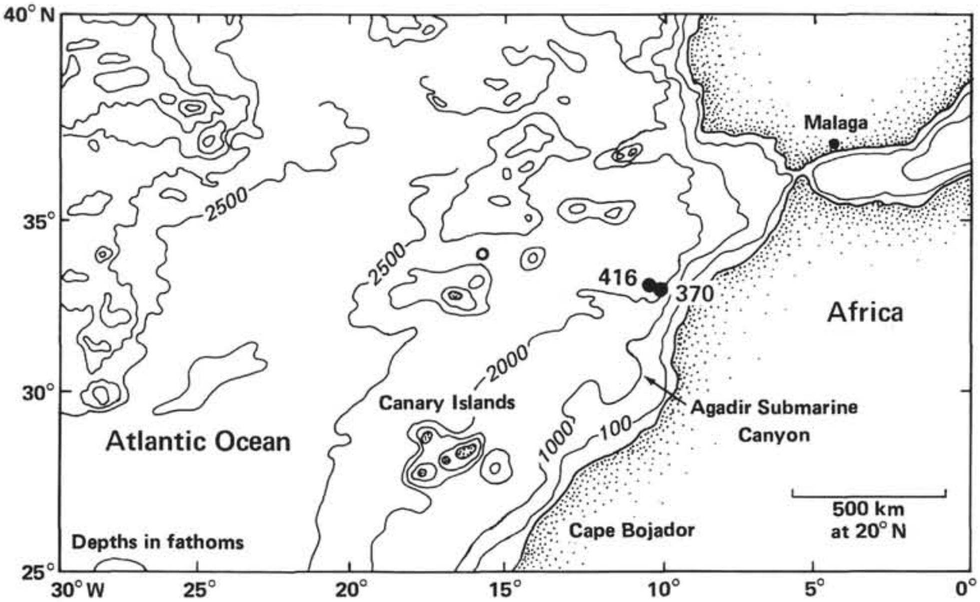

Figure 1. Index map showing locations of DSDP Sites 370 and 416.

ple and is also expressed as a percentage. Acoustic impedance is defined as the product of the velocity and wet-bulk density, and is expressed as $(g \cdot 10^5)/(cm^2 \cdot s)$. All the equations, derivations, and techniques are discussed in detail in Boyce (1980a).

With respect to sampling at Site 416, we generally waited at least 4 hr. after the core had been brought on deck to allow it to reach room temperature. We then cut and removed an undisturbed (visible, undistorted bedding), water-saturated, compressional-sound-velocity sample, about 2.5 cm thick. The sample was carefully smoothed with a sharp knife or file. Velocities were measured to within ±2% accuracy with the Hamilton Frame velocimeter (Boyce, 1980a), perpendicular and parallel to bedding. Immediately afterward, its wet-bulk density was measured to within ±2 or 3% precision with the Gamma Ray Attenuation Porosity Evaluator (GRAPE) (Evans, 1965) as modified in Boyce (1980a), using special 2-minute gamma-ray counts. Then, the wet-water content of a subsample was determined by weighing the sample both wet and after drying 24 hr. at 110°C. The weight of evaporated water was corrected for salt (45‰) to give the weight of seawater (Boyce, 1980a; Hamilton, 1971b). The estimated precision is ±2.5% (absolute). Porosity (precision of ±6%) is determined from the product of the wet-water content and wet-bulk density, divided by the density of the interstitial water (1.032 g/cm³). The acoustic impedance is obtained from the product of the vertical velocity and the wet-bulk density. The laboratory results of Site 416 Cretaceous–Tithonian sedimentary rocks have been tabulated in Table 1.

All data for Site 370 are from Table 1 in Trabant (1978) and will not be tabulated here. Trabant (1978) and Lancelot et al. (1978) discuss their methods and the sediment classification used at Site 370. Detailed lithologies and age-dates for Site 370 data are discussed in detail in Lancelot, Seibold, et al. (1978).

Compressional-wave (sound) velocity in isotropic material has been defined (Wood, 1941; Bullen, 1947; Birch, 1961; Hamilton, 1971a, b) as

$$V = \left(\frac{\varkappa + 4\mu/3}{\varrho_b}\right)^{1/2} \tag{1}$$

where V is the compressional-wave velocity; ϱ_b is the wet-bulk density in g/cm³ and $\varrho_b = \varrho_w\phi + (1 - \phi)\varrho_g$ (here ϕ is the fractional porosity of the sediment or rock, and the subscripts b, g, and w represent the wet-bulk density, grain density, and water density, respectively); $\varkappa$ is the incompressibility or bulk modulus; and μ is the shear (rigidity) modulus

Where samples are anisotropic, $\varkappa$ and μ may have various unique values for the corresponding vertical and horizontal directions. See Laughton (1957), Carlson and Christensen (1977), Gregory (1977), and Bachman (1979) for a discussion of anisotropy.

Compressional-wave (sound) velocity of sediments and rocks has been related to sediment components by Wood (1941), Wyllie et al. (1956), Nafe and Drake (1957) and others. Relationships of the Site 416 data to these equations are discussed in Boyce (1980b). Velocity is related to mineralogical composition, fluid content, water saturation of pores, temperature, pressure, grain size, texture, cementation, direction with respect to bedding or foliation, and alteration, as summarized by Press (1966). Recently, Hamilton (1976, 1978, 1980) has summarized the velocity-density relationships of sediment and rock of the seafloor for oceanic sediments and sedimentary rock.

Acoustic impedance is the product of the vertical velocity and wet-bulk density. Reflection coefficients

Table 1. Data on physical properties, Hole 416A.

Core-Section (interval in cm)	Depth in hole (m)	Compressional-sound velocity ∥ Beds (km/s)	Compressional-sound velocity ⊥ Beds (km/s)	Anisotropy ∥-⊥ (km/s)	Anisotropy (∥-⊥)/⊥ (%)	Temp. (°C)	GRAPE "special" wet-bulk density[a] 2-min. count (g/cm^3)[b] ∥ Beds	GRAPE ⊥ Beds	Wet water content Salt corr. (%)	Porosity[c] (%)	Acoustic impedance (g·10^5/cm^2·s)	Lithology[d]
5-1, 30-32	754.30		1.717			25		1.801			3.09	Laminated siltstone
1, 56-58	754.56	3.861	3.466	0.395	11.40	26		2.102	8.25	16.80	7.29	Porcellanite
6-1, 23-25	891.23	1.886	1.767	0.119	6.73	25		2.052	20.58	40.92	3.63	Laminated mudstone
2, 18-20	892.68	1.897	1.767	0.130	7.36	26		2.024	20.89	40.97	3.58	Mudstone (dk. grn.)
2, 140-150	893.95								19.25			I.W.
3, 16-18	894.16	1.868	1.805	0.063	3.49	26	2.100		21.24	43.22	3.79[e]	Laminated siltstone
7-1, 33-35	991.83	4.666	4.451	0.215	4.83	25		2.576	3.34	8.34	11.47	Calcite cemented sandstone
2, 12-14	993.12	1.988	1.836	0.152	8.28	26	2.269		17.88	39.31	4.16[e]	Marlstone (gyish. grn.)
2, 140-150	994.45								16.26			I.W.
3, 2-4	994.52	2.003	1.801	0.202	11.22	25	2.152		16.10	33.57	3.88[e]	Mudstone (brn.)
CC, 14-15							2.600					Calcite cemented sandstone
8-7, 9-11	1102.09	2.588	2.631	−0.043	−1.63	26		2.393	7.77	18.02	6.30	Laminated siltstone
9-1, 146-148	1178.36	2.421	1.858	0.563	30.30	27		2.370	11.06	25.40	4.40	Mudstone (olv. grn.)
2, 58-60	1178.98	4.325	3.887	0.438	11.27	27		2.612	4.48	11.34	10.15	Calcite cemented sandstone
3, 145-147	1181.35	2.489	2.398	0.091	3.79	27		2.332	11.18	25.26	5.59	Siltstone
4, 125-127	1182.65	2.330	2.176	0.154	7.08	27		2.284	10.83	23.97	4.97	Mudstone (gyish. grn.)
4, 140-150	1182.85								10.94			I.W.
6, 11-13	1184.51	4.536	4.526	0.010	2.21	27		2.635	1.95	4.98	11.93	Calcite cemented sandstone
10-1, 13-16	1185.53	4.553	4.602	−0.049	−1.06	27		2.601	1.96	4.94	11.97	Calcite cemented sandstone
2, 6-8	1186.96	2.623	2.133	0.490	22.97	27		2.263	10.87	23.84	4.82	Mudstone (grnish. gy.)
2, 30-32	1187.20	3.014	2.591	0.423	16.33	27		2.469	7.38	17.66	6.40	Laminated siltstone-sandstone
11-1, 2-4	1194.82	4.947	4.422	0.525	11.87	26		2.653	3.71	9.54	11.73	Calcite cemented sandstone
1, 9-11	1194.89	2.607	2.162	0.445	20.58	26.5		2.167	10.76	22.59	4.69	Calcareous mudstone (gy. olv. grn.)
2, 89-91	1197.19	2.497	2.207	0.290	13.14	26		2.281	11.97	26.46	5.03	Mudstone (brn. gy.)
4, 140-150	1200.75								12.77			I.W.
5, 135-137	1202.15	2.502	2.085	0.417	20.00	26		2.265	11.74	25.77	4.72	Calcareous mudstone (gyish. grn.)
6, 77-79	1203.07	2.357	2.130	0.227	10.66	26		2.318	11.94	26.82	4.94	Mudstone (brn. gy.)
12-1, 10-12	1204.40	4.836	4.686	0.150	3.20	25		2.615	2.52	6.39	12.25	Calcite cemented sandstone
2, 42-44	1206.22	2.602	2.175	0.427	19.63	25		2.321	8.42	18.94	5.05	Calcareous mudstone (gyish. grn.)
3, 29-31	1207.59	3.083	2.489	0.594	23.87	25		2.191	14.37	30.51	5.45	Mudstone (dsky. y. brn.)
3, 86-87	1208.17								12.76			I.W.
4, 42-44	1209.22	2.738	2.287	0.451	19.72	25		2.371	10.33	23.73	5.42	Calcareous mudstone (gyish. grn.)
13-1, 7-9	1213.87	2.386	2.019	0.367	18.17	26			12.75			Calcareous mudstone (gyish. grn.)
2, 42-44	1215.72	4.432	4.545	−0.113	−2.49	26			2.36			Calcite cemented sandstone
3, 28-30	1217.08	2.274	2.076	0.198	9.54	25		2.314			4.80	Mudstone (dsky. y. brn.)
14-1, 5-7	1223.45	2.460	2.065	0.395	19.13	26		2.398	13.49	31.35	4.95	Marlstone (gyish. grn.)
2, 49-51	1225.39	2.604	2.216	0.388	17.51	26		2.345	10.59	24.06	5.20	Mudstone (dsky. y. brn.)
3, 96-98	1227.36	3.883	4.069	−0.186	−4.57	25		2.376	3.42	7.87	9.67	Calcite cemented sandstone
4, 62-64	1228.52	4.322	3.545	0.777	21.92	25		2.469	3.43	8.21	8.75	Calcite cemented sandstone
5, 69-70	1230.09	2.376	2.240	0.136	6.07	25		2.206	10.26	21.93	4.94	Soft sandstone-siltstone
15-1, 2-4	1232.92	2.316	2.083	0.233	11.19	25		2.207	13.17	28.16	4.60	Siltstone
2, 11-13	1234.51	2.454	2.011	0.443	22.03	25		2.279			4.58	Mudstone (gy. olv.)
3, 0-2	1235.90	4.585	3.848	0.737	19.15	25		2.520	8.57	20.93	9.70	Calcite cemented sandstone
4, 7-8	1237.47	2.421	2.291	0.130	5.67	25		2.319	3.59	8.07	5.31	Fine-grained sandstone
5, 133-135	1240.23	2.721	2.341	0.380	16.23	25		2.318			5.43	Marlstone (gy. olv.)
6, 55-57	1240.95	2.128	2.006	0.122	6.08	25		2.295	13.47	29.96	4.60	Laminated sandstone (gy. olv.)
16-1, 2-4	1242.52	4.532	4.432	0.100	2.26	25		2.524	2.14	5.28	11.28	Calcite cemented sandstone
2, 6-8	1244.06	2.175	2.001	0.174	8.70	25		2.214	12.11	25.98	4.43	Mudstone (dsky. brn.)
3, 95-97	1246.45	2.698	2.191	0.507	23.14	25		2.342	12.88	29.23	5.13	Mudstone (gy. olv. grn.)
4, 7-8	1247.07	2.434	2.174	0.260	11.96	25		2.287	11.02	24.42	4.97	Mudstone (dsky. y. brn.)
17-1, 33-35	1252.33	2.416	2.019	0.397	19.66	24		2.262	13.61	29.83	4.57	Nannofossil mudstone (dsky. y. grn.)
1, 86-88	1252.86	2.039	1.989	0.050	2.51	25		2.281	13.76	30.41	4.54	Laminated siltstone (dsky. y. brn.)
1, 98-100	1252.98	2.592	2.136	0.456	21.35	25		2.278	10.51	23.20	4.87	Nannofossil marlstone (pale grn.)
2, 52-54	1254.02	2.335	2.075	0.260	12.53	25		2.198	13.61	28.99	4.56	Mudstone (dsky. y. brn.)
4, 28-30	1256.78	3.688	3.249	0.439	13.51	25		2.548	8.70	21.48	8.27	Calcite cemented sandstone
18-1, 49-50	1261.99	2.140	2.044	0.096	4.70	25		2.318	13.93	32.29	4.74	Laminated mudstone (gy. brn.)
2, 25-27	1263.25	4.613	3.855	0.758	19.66	27			1.01			Calcite cemented sandstone
3, 3-5	1264.53	2.493	2.083	0.410	19.68	27			11.73			Mudstone (gyish. brn.)
4, 2-4	1266.02	2.711	2.295	0.416	18.13	27			10.79			Mudstone (dk. grnish. gy.)
4, 66-68	1266.66	2.539	2.177	0.362	16.63	25			10.38			Marlstone (gyish. grn.)
19-1, 15-17	1271.15	2.509	2.082	0.427	20.51	25		2.333	11.10	25.09	4.86	Calcareous mudstone (gyish. olv.)
2, 31-33	1272.81	2.081	2.004	0.077	3.84	25		2.242	17.08	37.11	4.49	Laminated mudstone (brn.)
3, 11-13	1274.11	4.090	3.531	0.559	15.83	25		2.396	1.36	3.16	8.46	Sandstone
3, 36-38	1274.36	2.307	2.111	0.196	9.28	25		2.392	14.15	32.80	5.05	Mudstone (gy. brn.)
CC, 18-20	1278.24	4.181	3.734	0.447	11.97	25			6.28			Calcite cemented sandstone
20-1, 6-8	1277.56	2.649	2.233	0.416	18.63	25		2.166	11.03	23.15	4.83	Mudstone (dk. grn. gy.)
1, 40-43	1277.90	3.267	3.259	0.008	0.25	25	2.439		5.92	13.99	7.95[e]	Calcite cemented sandstone
2, 59-61	1279.59	2.351	2.160	0.191	8.84	25		2.327			5.03	Laminated siltstone
2, 70-72	1279.70	2.483	2.109	0.374	17.73	25		2.322	11.86	26.69	4.90	Mudstone (brn.)
2, 95-97	1279.95	2.947	2.540	0.407	16.02	25		2.368	9.07	20.81	6.01	Calcareous mudstone (dsky. y. grn.)
21-1, 57-59	1290.27	4.289	3.880	0.409	10.54	25		2.481	5.04	12.12	9.63	Calcite cemented sandstone
2, 103-105	1292.53	2.599	2.249	0.350	15.56	25	2.341		10.30	23.36	5.26[e]	Calcareous mudstone (grn.)
3, 88-90	1293.88	2.813	2.360	0.453	19.19	25		2.346	9.20	20.91	5.54	Calcareous mudstone (gyish. grn.)
4, 46-48	1294.96	3.412	3.136	0.276	8.80	25		2.326	7.41	16.70	7.29	Sandstone
5, 4-6	1296.04	2.660	1.819	0.841	46.23?	25		2.509	10.72	26.06	4.56	Mudstone (brn.)
22-1, 0-2	1299.50	2.473	2.051	0.422	20.58	25		2.333	11.33	25.61	4.78	Mudstone (brn.)
2, 22-24	1301.22	2.774	2.358	0.416	17.64	25		2.368	10.47	24.02	5.58	Calcareous mudstone (pale grn.)
3, 8-10	1302.58	3.709	3.036	0.673	22.17	26		2.537	7.35	18.07	7.70	Laminated sandstone (brn.)
4, 52-54	1304.52	2.278				26		2.295	12.05	26.80	5.22	Laminated siltstone
4, 57-59	1304.57	4.446	4.044	0.402	9.94	26		2.559	2.06	5.11	10.34	Calcite cemented sandstone
23-1, 2-4	1309.12	2.555	2.121	0.434	20.46	26		2.331	10.23	23.11	4.94	Mudstone (dk. gyish. grn.)
2, 5-7	1310.65	2.473	2.053	0.420	20.46	26	2.320		11.82	26.57	4.76[e]	Mudstone (dk. brn.)
3, 54-55	1312.64	2.699	2.305	0.394	17.09	26		2.274	10.27	22.63	5.24	Laminated siltstone
4, 13-15	1313.73	2.791	2.380	0.411	17.27	26		2.322	9.81	22.07	5.53	Calcareous mudstone (gy. grn.)
5, 22-24	1315.32	3.612	3.010	0.602	20.00	26		2.483	8.14	19.58	7.47	Laminated calcite cemented sandstone
24-1, 3-5	1318.63	2.336	2.036	0.300	14.73	25		2.247	11.58	25.21	4.57	Mudstone (dk. brn.)
1, 95-97	1319.55	2.730	2.375	0.355	14.95	25		2.375	10.13	23.31	5.64	Calcareous mudstone (gy. grn.)
2, 0-2	1320.10	2.224	2.049	0.175	8.54	25		2.164	10.71	22.46	4.43	Laminated siltstone

Table 1. (Continued).

Core-Section (interval in cm)	Depth in hole (m)	Compressional-sound velocity: ∥ Beds (km/s)	Compressional-sound velocity: ⊥ Beds (km/s)	Anisotropy: ∥-⊥ (km/s)	Anisotropy: (∥-⊥)/⊥ (%)	Temp. (°C)	GRAPE "special" wet-bulk density[a] 2-min. count (g/cm^3)[b]: ∥ Beds	GRAPE "special" wet-bulk density[a] 2-min. count (g/cm^3)[b]: ⊥ Beds	Wet water content Salt corr. (%)	Porosity[c] (%)	Acoustic impedance $(g \cdot 10^5/cm^2 \cdot s)$	Lithology[d]
2, 123–129	1321.33	4.531	3.373	1.158	34.33	25		2.635	0.86	2.20	8.89	Calcite cemented sandstone
3, 96–98	1322.59	2.402	2.026	0.376	18.56	25			12.82			Mudstone (olv. gy.)
25-1, 94–96	1328.65	4.478	4.091	0.387	9.46	25		2.616	6.59	16.70	10.70	Calcite cemented sandstone
2, 16–18	1329.36	3.459	3.021	0.438	14.50	25		2.240	8.51	18.47	6.77	Sandstone
2, 123–125	1330.43	2.406	2.246	0.160	7.12	25		2.286	10.34	22.90	5.13	Laminated siltstone
3, 20–22	1330.90	2.468	2.460	0.008	0.33	25		2.414	10.09	23.60	5.93	Calcareous mudstone (gy. grn.)
4, 3–5	1332.23	2.317	2.084	0.233	11.18	25		2.254	10.42	22.76	4.70	Mudstone (lt. brn. gy.)
5, 113–115	1334.83	2.515	2.044	0.471	23.04	25			11.55			Mudstone (olv. grn.)
26-1, 72–74								2.379	11.40	26.28		Marlstone (gyish. grn.)
2, 3–4	1338.73	2.362	2.077	0.285	13.72	25		2.220	6.63	14.26	4.61	Mudstone (gyish. red)
3, 34–36	1340.54	2.254	2.209	0.045	2.04	25		2.287	8.73	19.35	5.05	Sandstone
4, 32–34	1342.02	2.097				25	2.228		14.80	31.95	4.67[e]	Calcareous mudstone (dk. y. grn.)
5, 55–57	1343.75	2.809	2.422	0.387	15.98	25		2.382	9.37	21.63	5.77	Sandstone
27-1, 0–2	1346.70	2.657	2.274	0.383	16.84	26		2.519	6.55	15.99	5.73	Calcareous mudstone (gyish. grn.)
2, 39–41	1348.59	4.615	4.362	0.253	5.80	26		2.666	2.44	6.30	11.63	Calcite cemented sandstone
3, 11–13	1349.81	3.856	2.925	0.931	31.83	26		2.419	8.08	18.94	7.08	Sandstone
3, 106–107	1350.76	2.887	2.466	0.421	17.07	26		2.373	5.04	11.59	5.85	Calcareous mudstone (gy. grn.)
28-1, 12–14	1356.32	2.874	2.462	0.412	16.73	25		2.172	7.86	16.54	5.35	Calcareous mudstone (gyish. grn.)
2, 59–61	1358.29	4.376	3.672	0.704	19.17	25		2.529	2.96	7.25	9.29	Calcite cemented sandstone
3, 85–87	1360.05	2.423	2.221	0.202	9.10	25		2.408	10.95	25.55	5.35	Laminated siltstone (pale brn.)
5, 10–12	1362.30	2.493	2.196	0.297	13.52	25		2.361	12.31	28.16	5.18	Mudstone (pale brn.)
6, 2–4	1363.72	2.501	2.256	0.245	10.86	25		2.393	9.10	21.10	5.39	Mudstone (olv. grn.)
29-1, 52–54	1366.22	4.307	3.852	0.455	11.81	25		2.593	4.82	12.11	9.99	Calcite cemented sandstone
2, 2–4	1367.22	2.518	2.088	0.430	20.59	25		2.300	12.37	27.57	4.80	Mudstone (olv. grn.)
3, 97–99	1369.67	2.823	2.384	0.439	18.41	25		2.365	10.61	24.31	5.64	Calcareous mudstone (gy. grn.)
4, 103–105	1371.23	2.433	3.349	−0.916	−27.35	25		2.326	8.97	20.22	7.79	Sandstone
5, 51–53	1372.21	2.193	2.127	0.066	3.10	25		2.299	7.96	17.73	4.89	Laminated siltstone (gyish. brn.)
6, 127–129	1374.47	2.791	2.335	0.456	19.53	25		2.408	10.64	24.83	5.62	Mudstone (brn. gy.)
30-1, 77–79	1375.97	2.715	2.310	0.405	17.53	25		2.277	9.33	20.58	5.25	Mudstone (brn.)
2, 107–109	1377.77	3.239	2.672	0.567	21.22	25			8.20			Calcareous mudstone (gy. grn.)
3, 29–31	1379.49	2.655	2.472	0.183	7.40	25		2.368	9.32	21.39	5.85	Sandstone
4, 147–149	1381.17	2.681	2.259	0.422	18.68	25		2.191	8.21	17.43	4.95	Mudstone (olv. grn.)
5, 104–106	1382.24	2.497	2.240	0.257	11.47	25		2.292	8.63	19.17	5.13	Laminated siltstone (brn.)
31-1, 14–16	1384.74	3.242	2.814	0.428	15.21	25		2.436	6.66	15.72	6.85	Calcareous mudstone (gy. grn.)
2, 81–82	1386.91	2.643	2.269	0.374	16.48	25		2.323	10.72	24.13	5.27	Mudstone (pale grn.)
2, 144–146	1387.54	4.189	4.289	−0.100	−2.33	25		2.574	3.13	7.81	11.04	Calcareous cemented sandstone
3, 35–37	1387.95	2.626	2.358	0.268	11.37	25		2.406	8.48	19.77	5.67	Mudstone (brn.)
3, 95–97	1388.55	3.142	2.513	0.629	25.03	25	2.462	2.361			5.93	Claystone-siltstone-sandstone (graded bed)
32-1, 21–23	1394.31	3.067				25		2.398	7.96	18.50	7.35[e]	Calcareous mudstone (gy. grn.)
1, 131–133	1395.41	2.572	2.112	0.460	21.78	25		2.313	11.85	26.56	4.89	Mudstone (olv. grn.)
2, 0–2	1395.60	2.984	2.490	0.494	19.84	25		2.352	6.70	15.27	5.86	Laminated siltstone (brn.)
2, 100–104	1396.60	3.778	3.438	0.340	9.89	25		2.334	4.67	10.56	8.02	Sandstone
3, 71–74	1397.81	3.053	2.475	0.578	23.35	25		2.386	7.47	17.27	5.91	Marl (gy. grn.)
34-1, 12–14	1406.92	3.144	2.683	0.461	17.18	26		2.410	4.86	11.35	6.47	Calcareous Mudstone (gyish. grn.)
2, 6–8	1408.36	2.724	2.270	0.454	20.00	26		2.364	7.32	16.77	5.37	Mudstone (dsky. y. brn.)
3, 33–35	1410.13	2.766	2.544	0.222	8.73	26		2.406			6.12	Sandstone-siltstone
4, 24–26	1411.54	4.594	4.303	0.291	6.76	26		2.591	8.51	21.37	11.15	Calcite cemented sandstone
35-1, 35–39	1416.75	3.357	2.771	0.586	21.15	26		2.431	10.40	24.50	6.74	Calcareous mudstone (grn. gy.)
1, 58–60	1416.98	2.975	2.262	0.713	31.52	26		2.335	5.70	12.90	5.28	Laminated mudstone (brn.)
2, 82–84	1418.72	2.930	2.440	0.490	20.08	26		2.331	8.01	18.09	5.69	Laminated siltstone (brn.)
3, 0–2	1419.40	5.257	4.293	0.964	22.46	26		2.556	2.54	6.29	10.97	Calcarenite (yish. gy.)
36-1, 16–18	1425.56	3.820	2.994	0.826	27.59	26		2.521	5.61	13.70	7.55	Laminated siltstone (olv. gy.)
1, 130–133	1426.70	3.099	2.458	0.641	26.08	25	2.435		10.01	23.62	5.98[e]	Mudstone (mod. brn.)
2, 68–70	1427.58	3.244	2.766	0.478	17.28	25		2.439	7.77	18.36	6.75	Calcareous mudstone (gy. olv.)
3, 8–10	1428.48	3.428	3.014	0.414	13.74	25		2.514	7.01	17.08	7.58	Marly limestone (lt. olv. gy.)
3, 29–31	1428.69	3.456	3.077	0.379	12.32	25		2.501	4.41	10.69	7.70	Laminated siltstone (olv. gy.)
37-2, 2–4	1436.52	3.204	2.749	0.455	16.55	25		2.491	5.50	13.28	6.84	Laminated siltstone (olv. gy.)
2, 54–57	1437.04	2.761	2.215	0.546	24.65	25		2.336	11.24	25.44	5.17	Mudstone (gy. brn.)
3, 27–29	1438.27	4.326	3.569	0.757	21.21	25		2.550	5.86	14.48	9.10	Calcarenite (grn. gy.); graded bed
4, 17–19	1439.67	2.803	2.332	0.471	20.20	25		2.403	10.81	25.17	5.60	Claystone (med. brn.)
4, 35–37	1439.85	3.785	3.003	0.782	26.04	25		2.509	6.05	14.71	7.53	Cross-laminated sandstone-siltstone (brn. & gy.)
4, 55–57	1440.05	3.882	3.580	0.302	8.44	25		2.483	5.05	12.15	8.89	Limestone (lt. olv. gy.)
4, 70–72	1440.20	3.356	2.976	0.380	12.77	25		2.457	6.53	15.55	7.31	Marlstone (gyish. olv.)
38-1, 10–12	1445.10	3.180	2.113	1.067	50.50	25		2.447	6.73	15.96	5.17	Mudstone (brn. gy.)
1, 44–46	1445.44	3.277	2.754	0.523	18.99	25		2.463	7.03	16.78	6.78	Laminated siltstone (olv. gy.)
1, 135–138	1446.35	2.836	2.368	0.468	19.76	25		2.411	8.98	20.98	5.71	Claystone (mod. brn.)
2, 38–41	1446.88	4.300	3.822	0.478	12.51	25		2.576	4.76	11.88	9.85	Calcite cemented sandstone (dsky. y. brn.)
2, 44–46	1446.94	3.277	2.887	0.390	13.51	25		2.473	3.56	8.53	7.14	Marlstone (pale y. brn.)
40-1, 33–36	1454.83	3.162	2.494	0.668	26.78	24		2.234	5.90	12.77	5.57	Mudstone (mod. brn.)
1, 80–82	1455.30	3.999	3.386	0.613	18.10	24		2.558	4.79	11.87	8.66	Limestone (pale brn.)
2, 127–128	1457.27	3.702	3.291	0.411	12.49	24		2.534	6.72	16.50	8.34	Laminated siltstone (olv. gy.)
3, 23–25	1457.73	3.580	2.699	0.881	32.64	24		2.414	7.71	18.03	6.52	Calcareous mudstone (gy. olv.)
3, 48–50	1457.98	4.705	4.402	0.303	6.88	24		2.650	2.14	5.50	11.67	Calcite cemented sandstone (lt. olv. gy.)
3, 79–81	1458.29	4.460	3.466	0.994	28.68	24		2.548	7.75	19.13	8.83	Laminated calcisiltite (pale brn.)
41-1, 4–5	1463.94	4.532	4.474	0.058	1.30	26		2.643	2.90	7.42	11.82	Limestone (pale y. brn.)
1, 84–87	1464.74	3.205	2.394	0.811	33.88	26		2.264	12.42	27.25	5.42	Mudstone (dsky. y. brn.)
3, 107–109	1467.97	4.692	4.401	0.291	6.61	26		2.586	4.35	10.90	11.38	Calcarenite (pale y. brn.)
4, 110–113	1469.50	3.373	2.909	0.464	15.95	26		2.524	8.62	21.08	7.34	Laminated siltstone (dsky. y. brn.)
5, 8–9	1469.98	4.635	4.038	0.597	14.78	26		2.585	3.20	8.02	10.43	Laminated sandstone (olv. gy.)
42-1, 43–45	1473.73	5.161	5.484	−0.323	−5.89	27		2.692	1.99	5.19	14.76	Calcarenite (lt. olv. gy.)
1, 96–98	1474.26	3.951	2.747	1.204	43.83	26		2.431	9.40	22.14	6.68	Sandstone-siltstone (lt. olv. gy.); laminated
2, 110–113	1475.90	3.882	3.648	0.234	6.41	25		2.709	5.36	14.07	9.88	Limestone (dk. y. brn.)
3, 58–60	1476.88	3.737	3.432	0.305	8.89	26		2.519	4.64	11.33	8.65	Calcareous mudstone (gy. red)
43-1, 35–37	1482.75	3.702	3.338	0.364	10.90	26		2.570	6.21	15.46	8.58	Calcareous mudstone (mod. brn.)
1, 80–82	1483.20	3.021	2.476	0.545	22.01	26	2.386		9.29	21.48	5.91[e]	Mudstone (gy. red)
1, 93–95	1483.33	3.781	3.252	0.529	16.27	26		2.534	4.93	12.11	8.24	Laminated sandstone (olv. gy.)
2, 36–38	1484.26	3.844	3.362	0.482	14.34	26		2.481	1.30	3.13	8.34	Limestone (pale red)
3, 66–68	1486.06	3.597	3.057	0.540	17.66	26		2.398	1.30	3.02	7.33	Laminated siltstone (dsky. brn.)

Table 1. (Continued).

Core-Section (interval in cm)	Depth in hole (m)	Compressional-sound velocity ∥ Beds (km/s)	⊥ Beds (km/s)	Anisotropy ∥-⊥ (km/s)	(∥-⊥)/⊥ (%)	Temp. (°C)	GRAPE "special" wet-bulk density[a] 2-min. count (g/cm³)[b] ∥ Beds	⊥ Beds	Wet water content Salt corr. (%)	Porosity[c] (%)	Acoustic impedance (g·10⁵/cm²·s)	Lithology[d]
44-1, 72–74	1492.62	3.660	3.066	0.594	19.37	26		2.475	4.94	11.85	7.59	Laminated sandstone (olv. gy.)
1, 89–91	1492.79	3.188	2.437	0.751	30.82	25		2.378	9.11	20.99	5.80	Mudstone (dsky. y. brn.)
1, 143–145	1493.33	4.095	3.751	0.344	9.17	25		2.671	3.10	8.02	10.02	Limestone (pale y. brn.)
2, 104–106	1494.45	3.146	2.787	0.359	12.88	25		2.416	8.17	19.13	6.73	Laminated siltstone (dsky. y. brn.)
45-1, 13–15	1501.33	5.163	4.730	0.433	9.15	25		2.655	5.11	13.15	12.56	Calcarenite (pale y. brn.)
1, 65–67	1501.85	4.229	4.170	0.059	1.41	25		2.498	3.99	9.66	10.42	Laminated sandstone (gy. red)
1, 68–70	1501.88	3.197	2.429	0.768	31.62	25		2.283	6.30	13.94	5.55	Mudstone (mod. brn.)
2, 72–75	1503.42	5.050	5.165	−0.115	−2.23	25		2.653	1.27	3.26	13.70	Limestone (pale y. brn.)
3, 8–10	1504.28	3.362	1.922?	1.440	74.92	25		2.519	7.94	19.38	4.84	Laminated siltstone (dsky. y. brn.)
46-1, 6–8	1510.66	3.451	2.966	0.485	16.35	26		2.540	5.18	12.75	7.53	Mudstone (mod. brn.)
1, 74–76	1511.34	3.439	2.950	0.489	16.58	25		2.509	2.97	7.22	7.40	Marlstone (dk. y. brn.)
1, 82–84	1511.42	4.434	4.211	0.223	5.30	26		2.617	3.37	8.55	11.02	Limestone (pale y. brn.)
2, 0–2	1512.10	3.765	3.191	0.574	17.99	26		2.437	3.42	8.08	7.78	Laminated sandstone (dk. y. brn.)
2, 20–22	1512.30	4.264	4.095	0.169	4.13	26		2.647	0.63	1.62	10.84	Limestone (gy. olv.)
47-1, 11–13	1520.11	3.705	3.334	0.371	11.12	26		2.545	3.38	8.34	8.49	Laminated sandstone (dk. y. brn.)
1, 36–38	1520.36	3.187	2.443	0.744	30.45	26		2.408	9.17	21.40	5.88	Mudstone (dsky. brn.)
2, 98–100	1522.48	3.343	4.454	−1.111	−24.94	26		2.614	3.48	8.81	11.64	Limestone (pale y. brn.)
48-1, 6–9	1529.56	2.776	2.245	0.531	23.65	25		2.327	7.35	16.57	5.22	Mudstone (mod. brn.)
1, 52–53	1530.02	4.053	3.732	0.321	8.60	26		2.572	2.58	6.43	9.60	Marlstone (dk. y. brn.)
1, 97–100	1530.47	4.605	4.803	−0.198	−4.12	26		2.643	1.75	4.48	12.69	Limestone (pale y. brn.)
1, 107–110	1530.57	4.548	4.332	0.216	4.99	26		2.520	1.12	2.73	10.92	Laminated sandstone (olv. gy.)
2, 0–2	1531.00	3.364	2.997	0.367	12.25	26		2.465	7.17	17.13	7.39	Laminated siltstone (olv. gy.)
49-1, 24–26	1539.34	3.685	2.975	0.710	23.87	25		2.474	5.53	13.26	7.36	Laminated siltstone (dsky. y. brn.)
1, 43–46	1539.53	3.413	2.623	0.790	30.12	25		2.353	7.01	15.98	6.17	Mudstone (gyish. brn.)
2, 18–20	1540.78	4.878	4.545	0.333	7.33	25		2.613	2.51	6.36	11.88	Limestone (pale y. brn.)
2, 55–57	1541.15	4.554	4.413	0.141	3.20	25		2.674	2.31	5.99	11.80	Calcarenite (dk. y. brn.)
2, 133–135	1541.93	4.551	3.733	0.818	21.91	25			2.20			Laminated sandstone (olv. gy.)
50-1, 6–8	1548.66	2.987	2.465	0.522	21.18	26		2.373	8.48	19.50	5.85	Mudstone (gy. olv. grn.)
1, 18–20	1548.78	3.998	3.640	0.358	9.84	26		2.600	2.61	6.58	9.46	Marlstone (mod. brn.)
1, 23–25	1548.83	5.281	5.216	0.065	1.25	26		2.610	2.17	5.49	13.61	Calcarenite (pale y. brn.)
1, 133–135	1549.93	4.623	4.392	0.231	5.26	26		2.575	2.82	7.04	11.31	Limestone (pale y. brn.)
2, 82–83	1550.92	3.120	2.616	0.504	19.27	26		2.282	7.57	16.74	5.97	Laminated siltstone (dsky. y. brn.)
3, 18–20	1551.78	4.441	4.160	0.281	6.75	26		2.600	3.10	7.81	10.82	Laminated sandstone (olv. gy.)
51-1, 24–25	1558.24	3.998	3.643	0.355	9.74	26		2.511	4.07	9.90	9.15	Limestone (pale brn.)
1, 33–34	1558.33	4.742	4.645	0.097	2.09	26		2.629	3.42	8.71	12.21	Laminated sandstone (lt. olv. gy.)
2, 24–25	1559.74	3.136	2.490	0.646	25.94	26		2.338	7.59	17.20	5.82	Laminated mudstone (dsky. y. brn.)
2, 72–74	1560.22	4.746	4.581	0.165	3.60	26		2.613	1.92	4.86	11.97	Calcarenite (gy. olv.)
52-1, 9–10	1567.49	4.430	4.243	0.187	4.41	25		2.630	1.85	4.71	11.16	Limestone (lt. olv. gy.)
1, 31–35	1567.71	3.135	2.357	0.778	33.01	25		2.391	11.09	25.70	5.64	Mudstone (gy. brn.)
1, 79–80	1568.19	4.323	4.184	0.639	3.32	25		2.545	1.64	4.04	10.65	Calcarenite (lt. olv. gy.)
2, 96–98	1569.86	4.809	4.786	0.023	0.48	25			2.39			Laminated sandstone (olv. gy.)
3, 16–18	1570.56	3.882	2.970	0.912	30.71	25		2.478	4.98	11.96	7.36	Laminated siltstone (mod. brn.)
53-1, 0–2	1576.80	4.475	4.480	−0.005	−0.10	26		2.539	0.83	2.04	11.37	Laminated sandstone (gy. olv.)
1, 7–9	1576.87	3.277	2.623	0.654	24.93	26		2.435	5.81	13.71	6.38	Mudstone (gy. brn.)
1, 107–109	1577.87	3.417	3.064	0.353	11.52	26		2.442	5.27	12.47	7.48	Laminated siltstone (dsky. y. brn.)
3, 140–142	1581.20	5.251	4.896	0.355	7.25	26		2.681	2.75	7.14	13.13	Limestone (pale y. brn.)
57-1, 11–13	1614.61	3.307	2.528	0.779	30.81	25		2.429	8.02	18.88	6.14	Mudstone (dsky. brn.)
1, 36–38	1614.86	4.358	3.966	0.392	9.88	26		2.555	2.00	4.95	10.13	Sandstone (lt. olv. gy.)
1, 44–45	1614.94	4.955	4.510	0.445	9.87	26		2.629	1.40	3.57	11.86	Limestone (pale y. brn.)
1, 104–106	1615.54	3.811	3.111	0.700	22.50	25		2.415	3.12	7.30	7.51	Laminated siltstone (dsky. y. brn.)
1, 145–147	1615.95	5.699	5.532	0.167	3.02	25	2.717		0.74	1.94	15.03[e]	Calcarenite (pale y. brn.)

[a] The calculation used the following parametrs: ϱ_g, ϱ_{gc} = 2.7 g/cm³; ϱ_f = 1.025 g/cm³, ϱ_{fc} = 1.128 g/cm³, μ = 0.1028 cm²/g for Cores 1 through 16, and μ = 0.1024 cm²/g for Cores 17 through 57.

[b] S.I. units are m/s = (km/s) × 1000; kg/m³ = (g/cm³)/10³.

[c] Porosity = [salt corrected wet-water content) × (wet-bulk density)]/(density interstitial water); assume salinity = 45‰ and interstitial water density = 1.032 g/cm³.

[d] Gray = gy.; green = grn.; brown = brn.; yellow = y.; olive = olv.; light = lt.; dark = dk.; moderate = mod.; medium = med.; -ish = -ish (e.g., gyish = grayish); I.W. = interstitial water sample.

[e] Horizontal velocity or density used in the calculation.

(R.C.) from 661 to 1624 m are calculated from the impedance data:

$$\text{R.C.} = \frac{I_1 - I_o}{I_1 + I_o} \qquad (2)$$

where I_o is the upper acoustic impedance and I_1 is the lower impedance value. Reflection coefficients are computed very simply by using the upper and lower impedance values as they are listed in their tables, and plotting the reflection coefficient value at the same depth as the lower impedance value. Because of this very simple approach, investigators must be very careful about precisely correlating these reflection coefficients to reflectors in the seismic profiles.

RESULTS

The physical property data discussed in this chapter are for the following Cretaceous–Tithonian geologic sequence at Site 370 and Site 416 (Lancelot, Winterer, et al., 1980b):

1) From 661 to 880 m below the seafloor are Albian to Barremian claystone with some limestone, sandstone, and siltstone.

2) From 880 to 1430 m are Hauterivian to Valanginian turbidites of alternating graded calcareous and quartzose cycles from siltstone or fine sandstone to mudstone.

3) From 1430 to 1624 m are early Valanginian to Tithonian (Kimmeridgian?) turbidites with alternating quartzose siltstone grading to mudstone cycles with hard micritic limestone and calcarenite (calciturbidites).

For the Cretaceous–Tithonian geologic sequence at Sites 416 and 370, as discussed above, horizontal compressional-wave velocity versus depth below the seafloor is plotted in Figure 2, and vertical compressional-wave velocity versus depth are shown in Figure 3. From Figure 3 there is an obvious change in acoustic character at ~1375 and ~1475 m.

From 1475 to 1624 m velocities are widely scattered; this is caused by varying amounts of cementation by calcium carbonate. Even the relatively lower-velocity mudstone, in general, appears to have a slightly higher velocity than similar relative low-velocity mudstone above ~1475 meters. The very high vertical velocities (greater than 5.0 km/s) are the micritic limestone, but particularly the well-cemented calcarenites below ~1473 meters.

The first (going down the hole) high vertical velocity (>5 km/s) layer occurs at ~1474 meters, but this is a relatively thin layer and thus it may not create a significant reflection on the seismic profile. However, it could be possible that an important reflector is created as a result of the overall increase in cementation or lithification of the entire lower geologic sequence from ~1474 meters and downward. If this is assumed to be possible, then the actual reflector in the seismic profiles may be lower, perhaps at approximately 1500 m or more. This would allow for the proper ideal thickness (about a quarter wave length) needed for a significant reflecting horizon.

Figure 4 displays reflection coefficients versus depth. It is not particularly helpful as there is such wide variation in all the data; thus it does not appear to be as useful as Figure 3 in helping to identify potential seismic reflectors. However, at about 1460 to 1500 m there are some variations in velocity which could be a potential reflector.

Acoustic anisotropy is important for estimating vertical velocities (for seismic-reflection profiles) from the horizontal velocities determined by refraction techniques, and the oblique velocities determined by sonobuoy techniques. Acoustic anisotropy in sedimentary rock may be created by some combination of the following variables as summarized in Press (1966): (1) alternating layers with high- or low-velocity materials; (2) tabular minerals that are aligned with bedding, thus creating fewer gaps in a direction parallel to bedding; (3) minerals with acoustic anisotropy, whose high-velocity axis may be

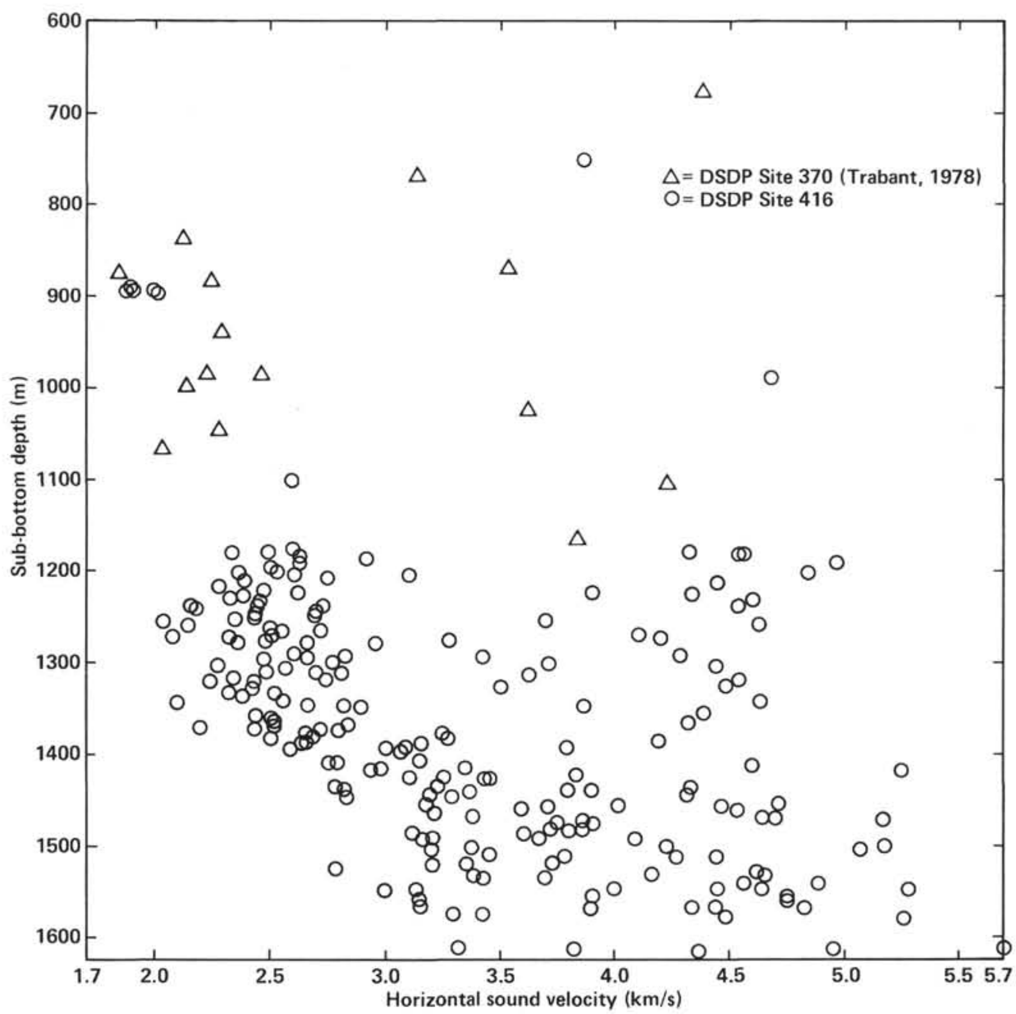

Figure 2. Horizontal velocity versus depth for the Cretaceous–Jurassic geologic section at Sites 416 and 370.

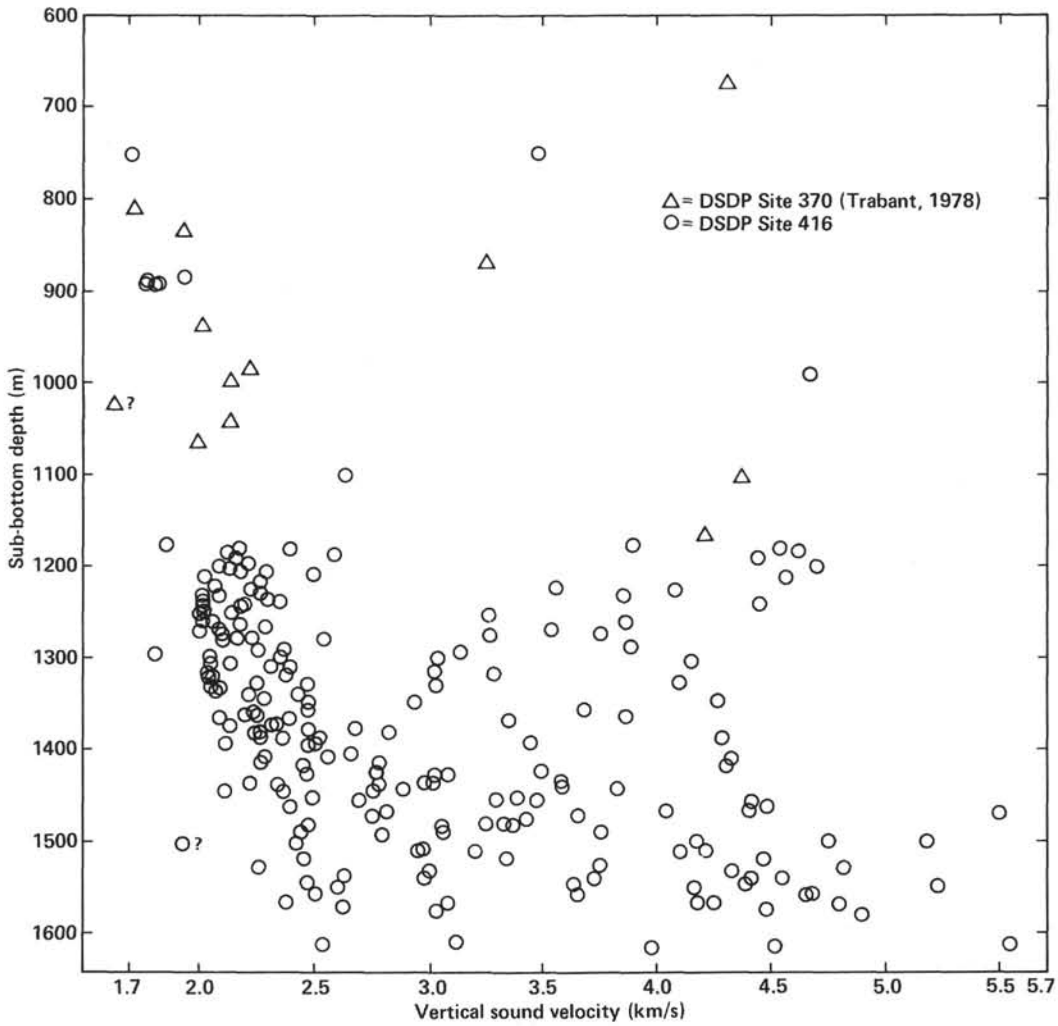

Figure 3. Vertical velocity versus depth for the Cretaceous-Jurassic geologic section at Sites 416 and 370.

aligned with the bedding plane; (4) foliation parallel to bedding, and (5) cementation along certain horizontal layers.

Figure 5 shows acoustic anisotropy for Cretaceous to Tithonian sandstone and siltstone turbidites in mudstone and minor limestone from 661 to 1624 m below the seafloor. In general, acoustic anisotropy of the sedimentary rocks below 1178 m, which have velocities between about 2.0 and 4.2 km/s, is about 0.4 km/s or more, faster in the horizontal than in the vertical plane. Some samples have an absolute anisotropy as great as 1.0 km/s. The relative acoustic anisotropy ranges from 0 to 30%, 5 to 20% being typical. The mudstones which have velocities of 2.0 to 3.0 km/s, tend to have the greatest relative anisotropy, as compared with the higher velocity (3 to 4.2 km/s) sandstones, siltstones, and limestones. Where the sandstone, siltstone, and limestone have velocities greater than about 4.2 km/s, the acoustic anisotropy becomes much less significant, as the sample is more thoroughly cemented, and many samples are isotropic.

Figures 6 through 15 show the following physical properties versus depth for each lithologic type at Hole 416A: (1) vertical velocity and horizontal velocity (both at laboratory temperatures and pressures), (2) acoustic anisotropy, (3) porosity, (4) wet-bulk density, and (5) acoustic impedance. Mudstones are presented in Figures 6 and 7; siltstones, in Figures 8 and 9; sandstones, in Figures 10 and 11; marlstones, in Figures 12 and 13; and limestones, in Figures 14 and 15. Some of the calcarenites in Figures 10 and 11 are equivalent to limestone. Only the Hole 416A data listed in Table 1 are plotted, as the techniques used at Site 370 are not precisely comparable to the Site 416 data.

In Figure 7 the wet-bulk density and porosity of the mudstones are greater and less, respectively, than similar curves summarized in Hamilton (1976) for oceanic terrigenous sedimentary sequences. The fact that Site 416 data are different from Hamilton's could be in part related to differences in: (1) methods; (2) differences in grain-size distribution and mineralogy; (3) differences in the amount of calcium carbonate cement; (4) age of the Site 416 mudstones (being older, they have had more time to recrystallize, lithify, and to consolidate to a greater degree); or (5) overconsolidation of Site 416 mudstones by a theoretical, previously overlying sedimentary sequence which has been eroded away (Hedberg, 1936; Hamilton and Menard, 1956; Hamilton, 1959,

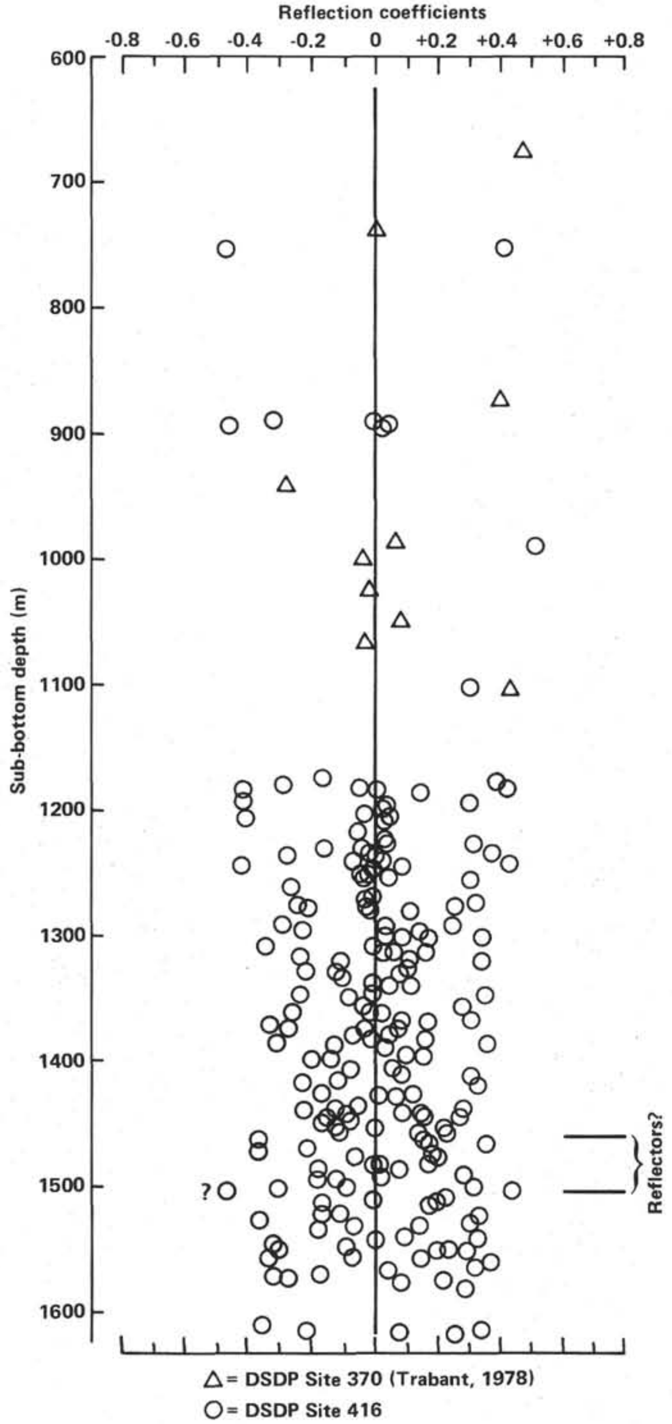

Figure 4. Reflection coefficient versus depth for the Cretaceous–Jurassic geologic section at Sites 416 and 370.

1976, 1980; Margara, 1978). Of these possible causes, 1 through 4 are the most probable.

In Figure 7 there is a definite boundary at 1330 m where calcareous mudstones have a distinctly lower porosity than the overlying unit. Below 1450 m in Figure 6, mudstone acoustic anisotropy is at its greatest, which is what one would expect for mudstone as the clayey minerals become aligned horizontally and samples become more fissile (Press, 1966; Bachman, 1978).

Siltstones in Figures 8 and 9 show a distinct boundary at about 1425 m. The siltstones are relatively uncemented above 1425 m, and abundant calcareous cemented siltstones occur below 1425 m, which have greater velocities and greater acoustic anisotropy. Irregular density-porosity variations are probably created by different grain-size distribution, grain packing, and different degrees of cementation.

Sandstone plots in Figures 10 and 11 show an uncemented sandstone trend and a cemented sandstone trend around 1200 m depth, with semilithified sandstones having a relatively high acoustic anisotropy. From 1200 m down the uncemented sandstone trend becomes more cemented and merges with the cemented sandstone trend (from 1200 to 1600 m). Below 1300 or 1400 m the maximum relative acoustic anisotropy decreases down to 1550 m. Below 1550 m, porosity is typically around 5%, sound velocity is very high, and acoustic anisotropy is relatively small. This is a result of the sandstones becoming so cemented (particularly the calcarenites) that they become more isotropic than the semicemented sandstone above. At 1420 m is the first high-horizontal-velocity-calcarenite (>5.0 km/s). Below 1420 m sandstones appear to be more cemented.

The calcarenites in Figures 10 and 11 are essentially limestones, and they have typically greater velocities than the micritic limestone at the same horizon or depth. This is because they are more recrystallized.

Marlstone velocities in Figure 12 uniformly increase with increasing depth, but with a possible boundary at about 1530 m.

Limestone velocity increases and porosity decreases with increasing depths in Figures 14 and 15. Many of the more cemented and lower porosity limestones have smaller relative acoustic anisotropies. Porosities here range from 4 to 18%, which are lower than porosities of Cretaceous Pacific Ocean pelagic nannofossil-foraminiferal limestones (Schlanger, Jackson et al., 1976), where identical laboratory methods were used. However, Site 416 limestones are micritic, older, and more deeply buried; thus they are more recrystallized and probably should have a smaller porosity than the nannofossil-foraminifer types. Site 416 limestone porosities are also slightly lower than the limestone porosity-depth plot summarized by Scholle (1977).

In Situ Reflection Velocity

In general, from 661 to 880 m, the Albian to Barremian claystone, with some limestone, sandstone, and siltstone, have velocities ranging from 1.70 to 4.37 km/s. According to Boyce (1980b) an *in situ* average vertical velocity is estimated to be 1.93 km/s.

From 880 to 1430 m, the Hauterivian to Valanginian turbidites of alternating graded calcareous and quartzose cycles from siltstone or fine sandstone to mudstone have velocities ranging from 1.80 to 4.96 km/s. Boyce (1980b) estimated an *in situ* average vertical velocity of 2.61 km/s.

From 1430 to 1624 m, the early Valanginian to Tithonian (Kimmeridgian) turbidites with alternating quartzose siltstone grading to mudstone cycles with hard mi-

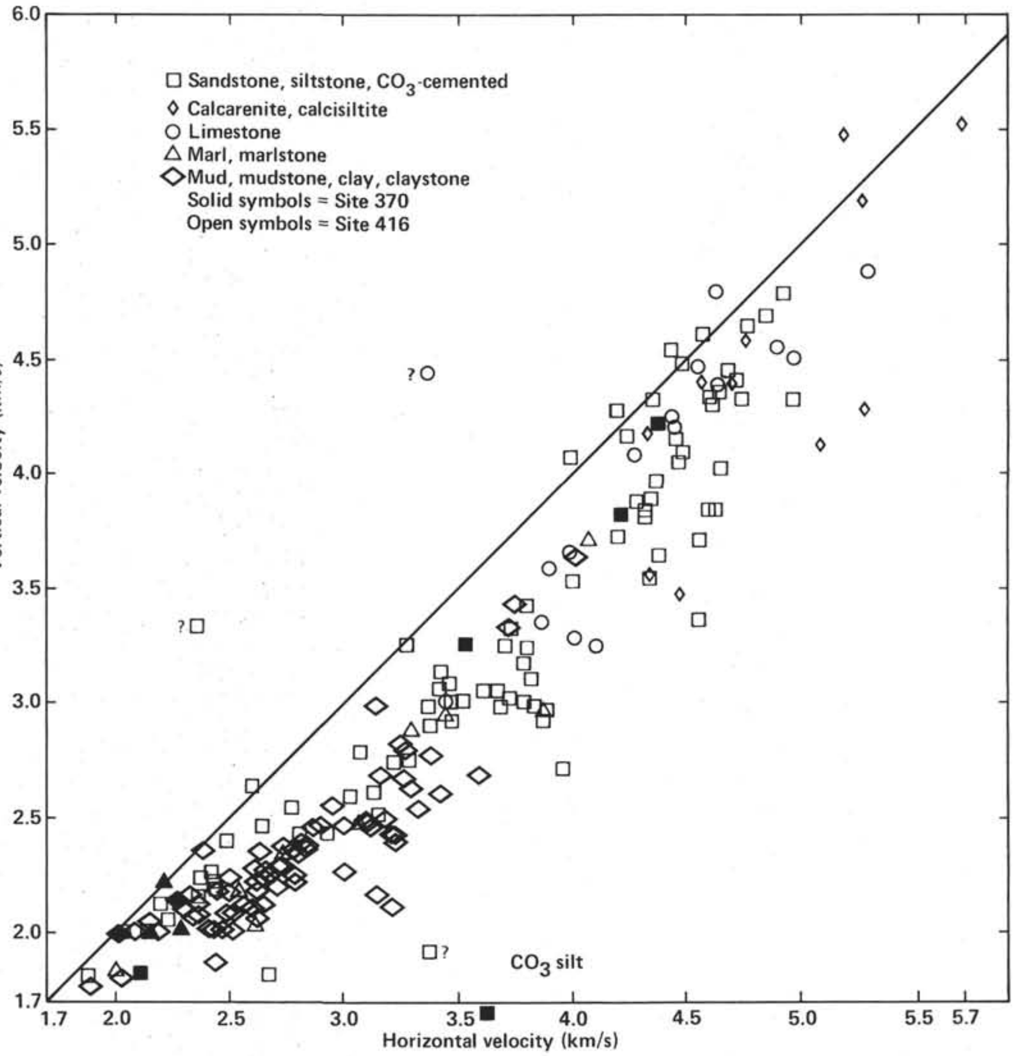

Figure 5. Vertical velocity versus horizontal velocity for the Cretaceous-Jurassic geologic section at Sites 416 and 370.

critic limestone and calcarenite (calciturbidites) have velocities from 2.26 to 5.7 km/s. According to Boyce (1980b) the unit has an *in situ* average vertical velocity of 3.25 km/s (see footnote 2). These *in situ* velocities are based on logging velocities and laboratory velocities. The results are very subjective, for: (1) the percentages of each rock type must be known, (2) he (Boyce) must fill in data where coring data are sparse, (3) log velocities tend to be biased too low, and (4) there is no caliper data to judge the variability of the sonic log.

If we assume that Boyce's (1980b, Table 6) estimated *in situ* velocities and reflection time (round-trip) from 0 to 1616 m of 1.50 s are correct,[3] then the 1.43-s-reflector discussed by Lancelot, Winterer et al. (1980b) would correlate at about 1500 m in the geologic section at Hole 416A, where there is a major change in the acoustical character of the sequence at about a quarter wavelength above 1500 m (Fig. 3).

Lancelot, Winterer (1980b) believe this 1.43-s reflector is actually below 1624 m at Site 416, based on stacking velocities and general geologic knowledge of the area. They may be correct, for the data here are also highly subjective. While these results do not disprove the conclusions reached by Lancelot, Winterer et al. (1980b), they do offer another possible interpretation to add to those already discussed in Lancelot, Winterer et al. (1980b) and Lancelot and Winterer (1980) and point to the difficulty of correlating seismic reflection data to drill hole data. Lancelot and Winterer (1980) interpreted the 1.43-s reflector (blue reflector) to represent a Callovian-Oxfordian transgressive phase of more pelagic sediment character. If the blue reflector actually correlates to 1500 m in Hole 416A, then the Callovian-Oxfordian transgressive sedimentary sequence is not represented by this blue reflector, but may occur as a "deeper" reflector in the seismic section.

[2] The text of Boyce (1980b), p. 316, incorrectly lists "3.75 km/s" for the velocity of the Tithonian to Valanginian sandstone, siltstone, marlstone, and limestone from 1430 to 1624 m; it should be 3.25 km/s as in Table 6. This also applies to p. 150 in Lancelot, Winterer et al., 1980b.

[3] Hole 516 penetrated to 1624 m; however, because of less than 100% recovery and DSDP depth conventions, the deepest velocity measurement is at 1616 m.

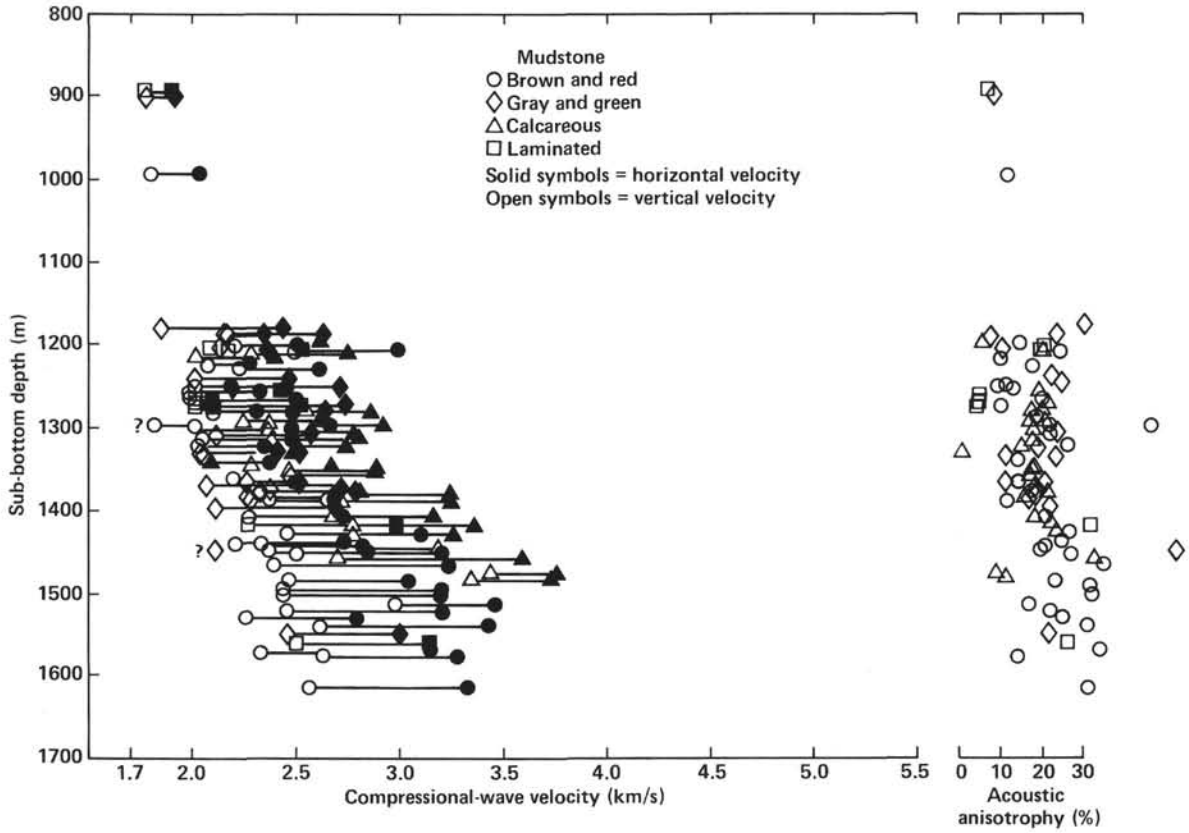

Figure 6. Mudstone velocities and acoustic anisotropy versus depth for the Cretaceous-Jurassic geologic section at Site 416.

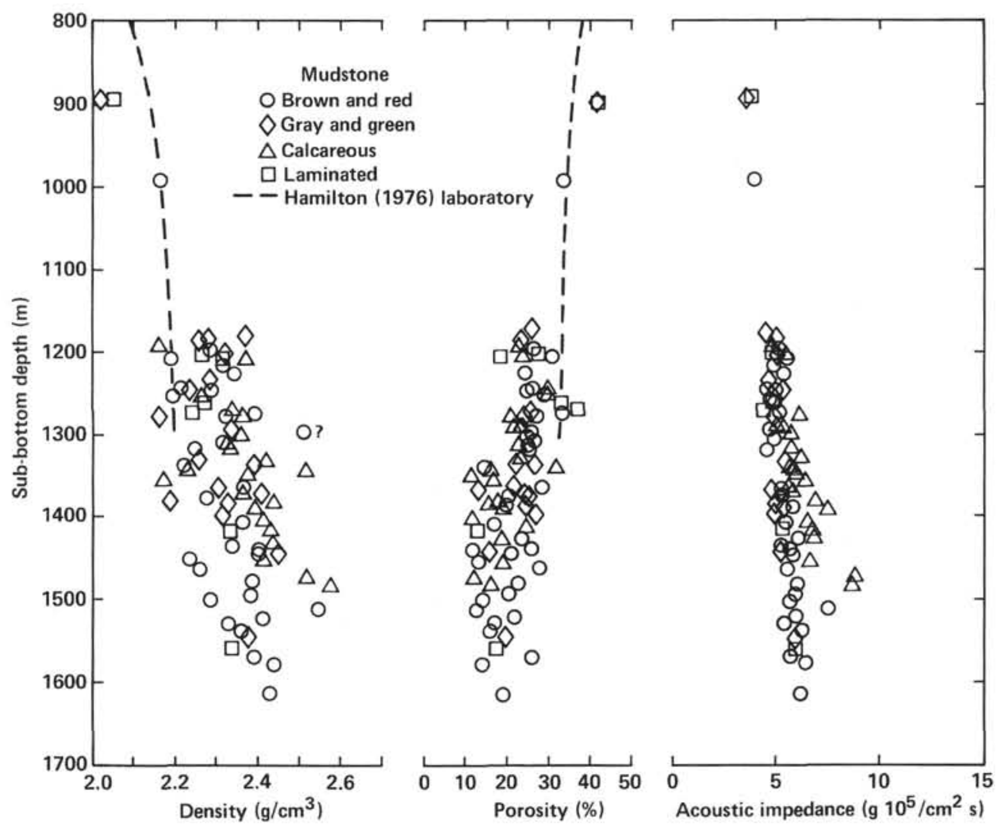

Figure 7. Mudstone density, porosity, and acoustic impedance versus depth for the Cretaceous-Jurassic geologic section at Site 416.

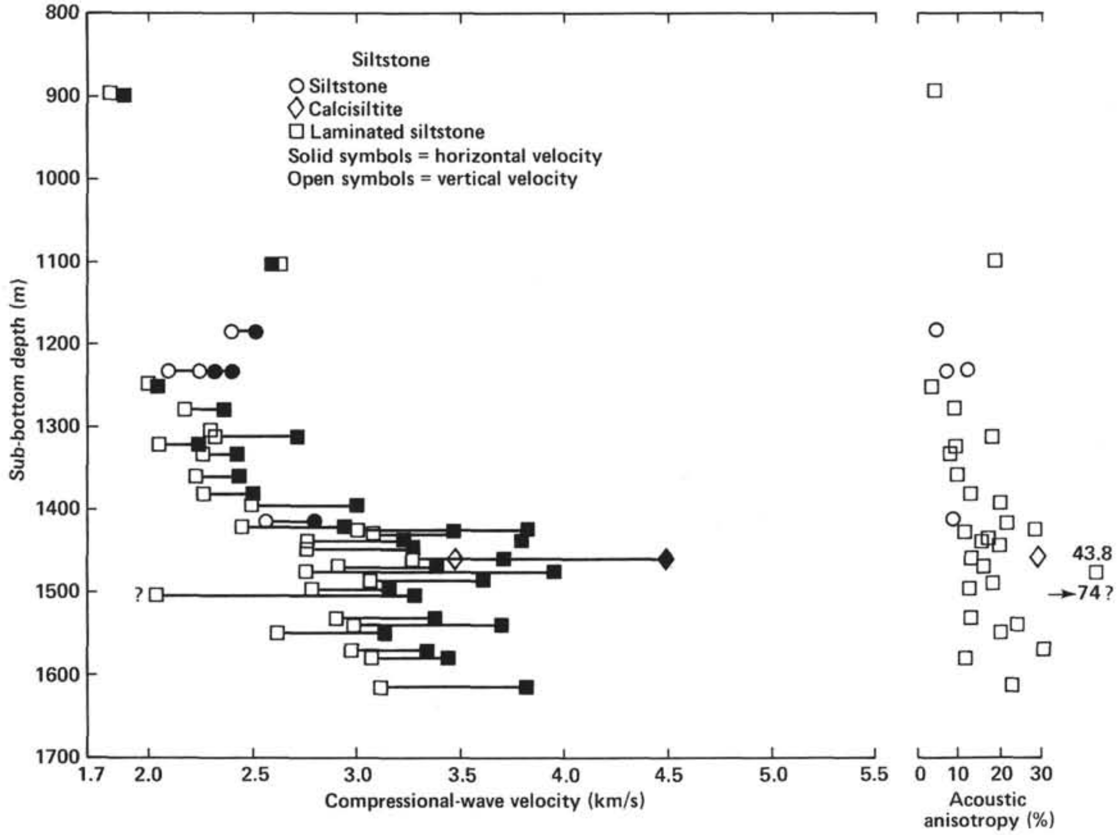

Figure 8. Siltstone velocities and acoustic anisotropy versus depth for the Cretaceous–Jurassic geologic section at Site 416.

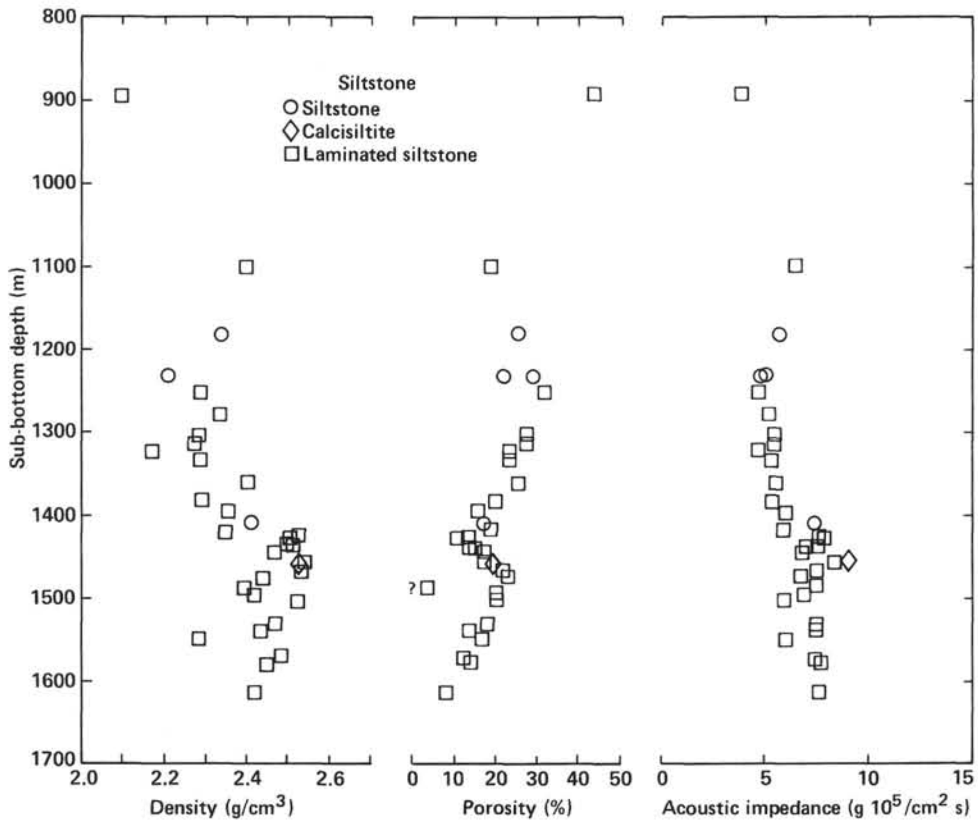

Figure 9. Siltstone density, porosity, and acoustic impedance versus depth for the Cretaceous–Jurassic geologic section at Site 416.

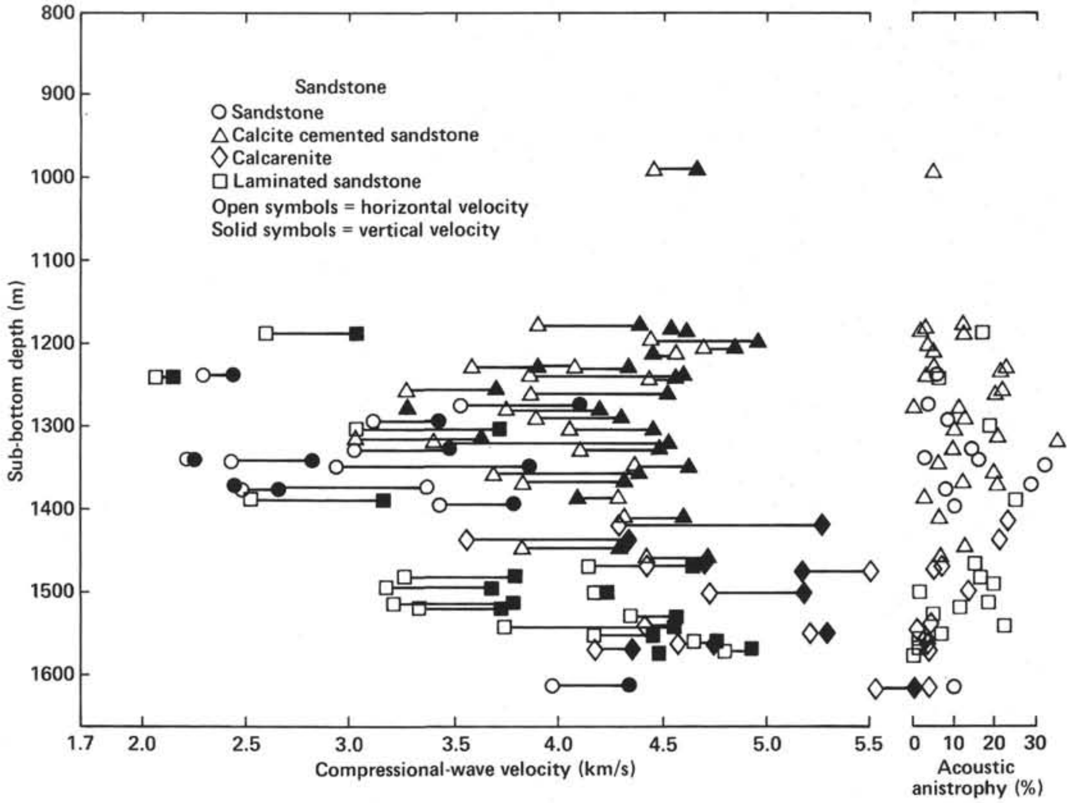

Figure 10. Sandstone velocities and acoustic anisotropy versus depth for the Cretaceous-Jurassic geologic section at Site 416.

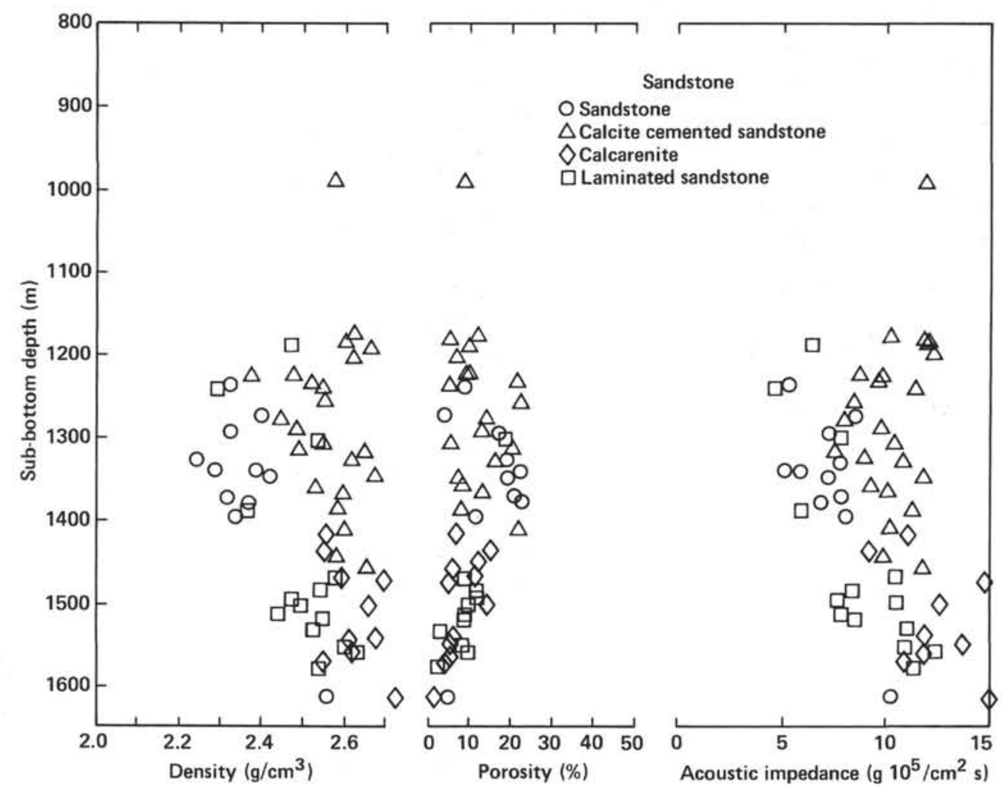

Figure 11. Sandstone density, porosity, and acoustic impedance versus depth for the Cretaceous-Jurassic geologic section at Site 416.

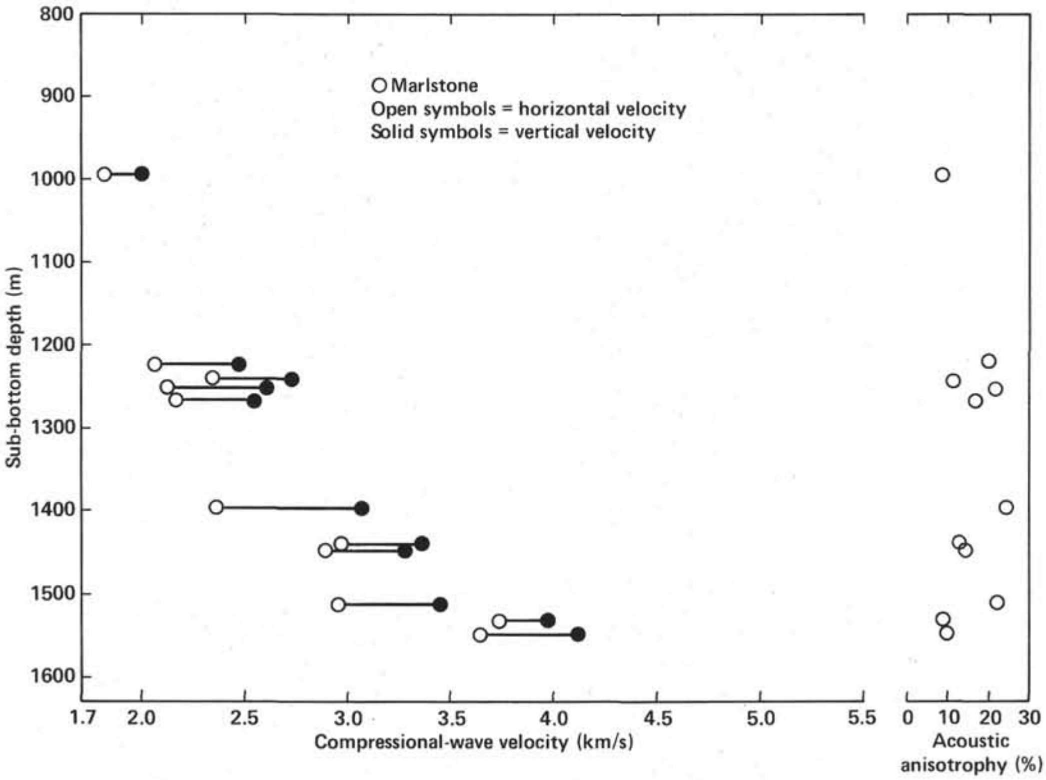

Figure 12. Marlstone velocities and acoustic anisotropy versus depth for the Cretaceous–Jurassic geologic section at Site 416.

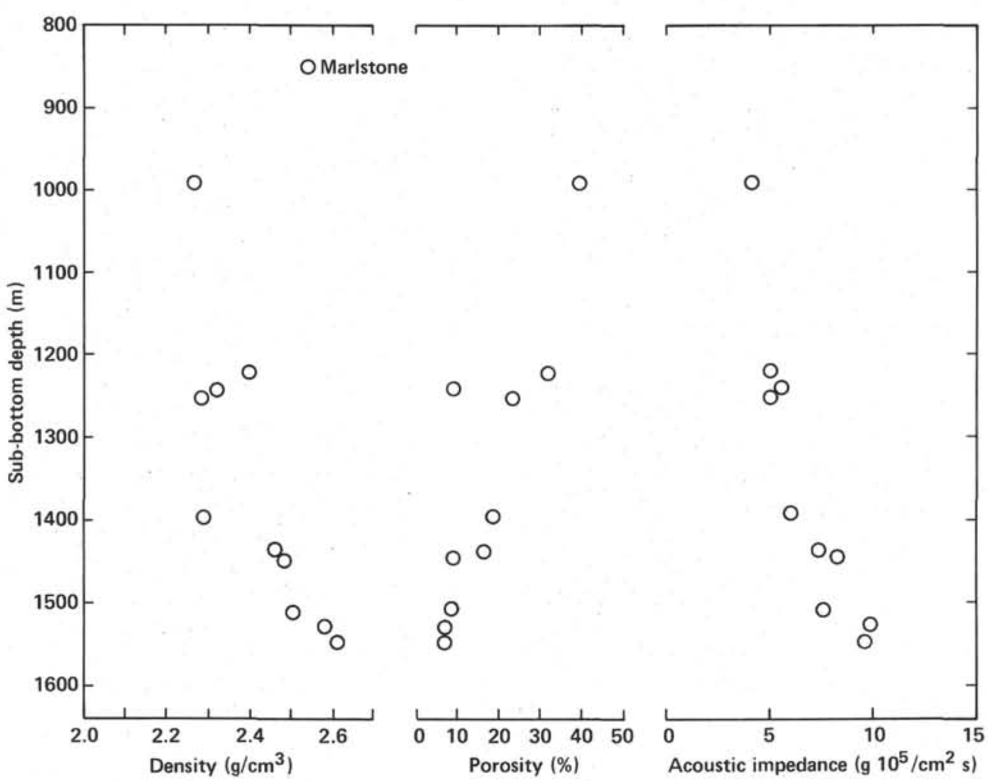

Figure 13. Marlstone density, porosity, and acoustic impedance versus depth for the Cretaceous–Jurassic geologic section at Site 416.

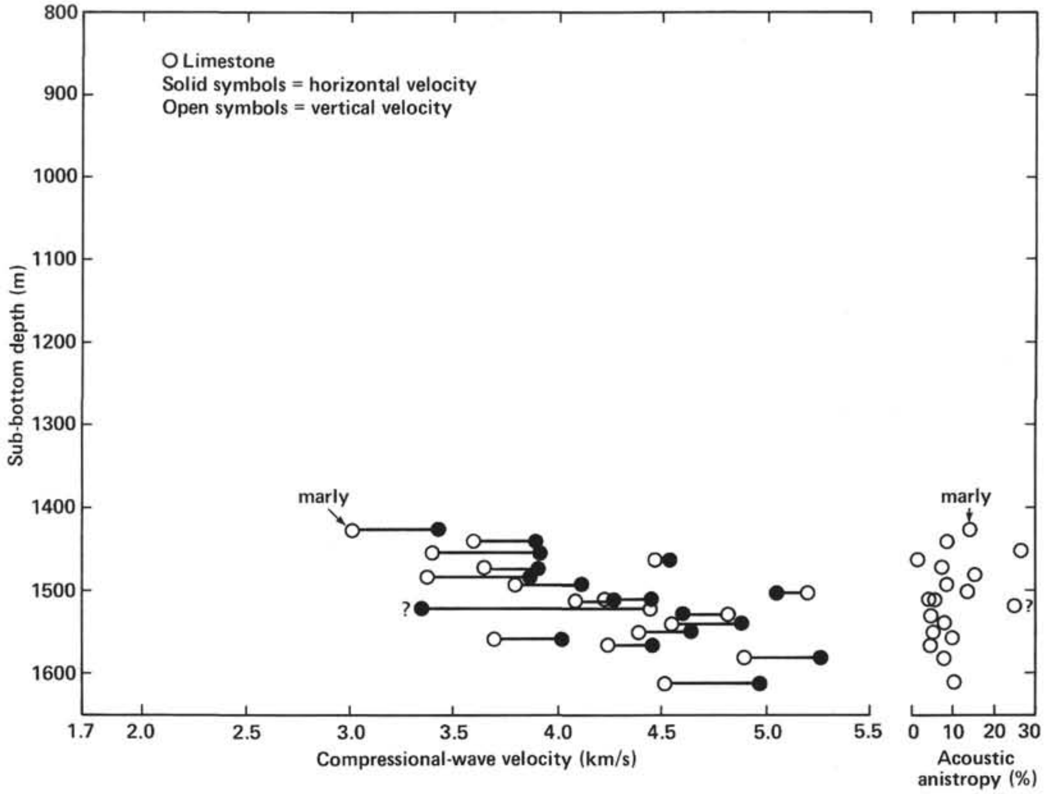

Figure 14. Limestone velocities and acoustic anisotropy versus depth for the Cretaceous–Jurassic geologic section at Site 416.

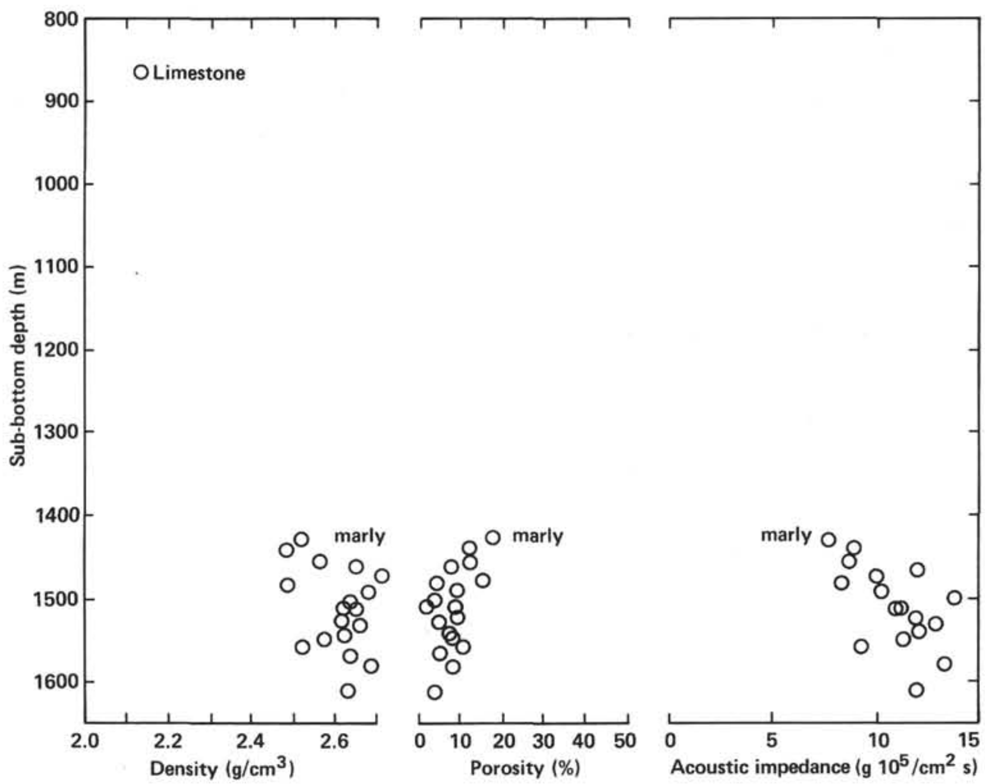

Figure 15. Limestone densities, porosity, and acoustic impedance versus depth for the Cretaceous–Jurassic geologic section at Site 416.

Comparison to Site 530 Cretaceous Rocks

The oldest sediment recovered at Site 530 is Cenomanian. These are younger than any of the Cretaceous–Jurassic (Albian to Tithonian) sediments recovered at Sites 370 and 416. In addition, data from Sites 370 and 416 extend to a much greater depth below the seafloor (1624 m vs. 1103 m). Therefore, one would expect these to be more lithified than sediments at Site 530.

The greater degree of lithification at Sites 370 and 416 compared to Site 530 is suggested by comparing mudstone–porosity versus depth curves from each area (Boyce, this volume). At Site 530, Hamilton's (1976) summary curve matches the data very well, while at Sites 370 and 416 Hamilton's (1976) mudstone-porosity curve versus depth does not match. Mudstone porosities at Sites 370 and 416 are less than Hamilton's curve, suggesting either (1) different methods; (2) different mineralogy, grain-size, packing and cementation; (3) or overconsolidation at Sites 370 and 416 by a geologic section which has now been eroded away. This does not appear to be the case at Site 530, which appears to be normally consolidated, and mudstone lithologies and grain size may be more similar to those mudstones discussed in Hamilton (1976). Velocities of mudstone are generally higher at Sites 416 and 370.

Limestone porosities at Site 530 are about 15%, which compares well with limestones at Sites 370 and 416. In addition, at Site 530, limestone velocities are within the limestone-velocity range at Sites 416 and 370.

Porosities of carbonate-cemented siliclastic sandstones compare well at both Site 530 and Sites 370/416. Porosities are ~10 to ~12%. Velocities of carbonate-cemented sandstone of both areas are also similar.

The acoustic anisotropy of the two areas is, however, quite different. The anisotropy at Site 530 is relatively low compared with all of the data from Sites 370 and 416. At Site 530, anisotropy is typically about 0.2 km/s, which is generally similar to anisotropy at other DSDP sites (Bachman, 1978), and it even compares well to Sites 370 and 416 above 1178 m. However, below 1178 m at Sites 416 and 370, anisotropy is very large (about 0.4 km/s or more) where velocities are between 2.2 and 4.2 km/s. In part this could be related to a more calcareous cementation or to greater lithification at Sites 370 and 416. However, the calcareous-cement concept also explains the calcareous mudstones at Site 530, which had significantly higher (37%) anisotropies than uncemented mudstone.

SUMMARY AND CONCLUSIONS

From 661 to 880 m are Albian to Barremian claystone with some limestone, sandstone, and siltstone. Compressional-wave velocities ranged from 1.70 to 4.37 km/s, with an average *in situ* vertical velocity of 1.93 km/s.

From 880 to 1430 m are Hauterivian to Valanginian turbidites of alternating graded calcareous and quartzose cycles from siltstone or fine sandstone to mudstone. Compressional-wave velocities range from 1.80 to 4.96 km/s, with an average *in situ* velocity of 2.61 km/s.

From 1430 to 1624 m are early Valanginian to Tithonian (Kimmeridgian?) turbidites with alternating quartzose siltstone grading to mudstone cycles with hard micrite and calcarenite (calciturbidites). Compressional-wave velocities range from 2.26 to 5.7 km/s, with an average *in situ* vertical velocity of 3.25 km/s

Acoustic anisotropy is 0 to 30% in the Cretaceous to Tithonian sandstone–siltstone turbidites in mudstone and minor limestone from 661 to 1624 m below the seafloor. Between 2.0(?) km/s and 4.2(?) km/s, anisotropy becomes particularly significant (below 1178 m), where the anisotropy is about +0.4 km/s or greater. The mudstone, softer sandstone, and softer siltstone tend to have velocities around 2.0 to 2.5 km/s; the cemented sandstone and limestone cluster about 2.5 km/s to 4.2 km/s; thus the relative percentage anisotropy is greater for the lower-velocity lithologies. Above 4.2(?) km/s, the well-cemented sandstone and limestone tend to have a smaller (less than 0.4 km/s) absolute anisotropy, and many samples are nearly isotropic. The anisotropy can be related to some combination of the following: (1) elongated or platy grains, which provide a faster path horizontally as a result of there being fewer gaps between minerals, (2) preferred orientation of minerals which have an acoustic anisotropy, (3) cementation along certain horizontal layers, (4) alternating high- and low-velocity layers, and (5) a larger number of horizontal cracks or foliation.

The mudstone's porosity and wet-bulk density curves versus depth are slightly higher and lower, respectively, for similar porosity and density curves in Hamilton (1976). This could be the result of some combination of methods, age, and lithology differences, or overconsolidation by an overlying geologic section which has been eroded away.

Limestone porosities are typically less than Cretaceous limestones from the Pacific Ocean (Schlanger, Jackson et al., 1976), where identical methods were used. These Pacific limestones are the nannofossil foraminifer type, and the limestone from Site 416 is micritic; thus the micritic limestone is probably more recrystallized and thus could perhaps be expected to have a smaller porosity.

If the average *in situ* vertical velocities calculated by Boyce (1980b) for Hole 416A are correct, then the 1.43-s (round-trip) reflector (blue) discussed by Lancelot and Winterer (1980) and Lancelot, Winterer et al. (1980b) would correlate to about 1500 m in Hole 416A, and not below 1624 m as discussed by Lancelot and Winterer (1980c). There does appear to be a significant change in the acoustic character at or around 1500 m (early Valanginian) to a more calcareous and cemented lithology. This investigator only suggests another possible interpretation, since this one is based on many assumptions and is highly subjective.

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