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VELOCITIES, ELASTIC MODULI AND WEATHERING-AGE RELATIONS FOR PACIFIC LAYER 2 BASALTS

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Compressional (V_p) and shear (V_s) wave velocities have been measured to 10 kb in 32 cores of basalt from 14 Pacific sites of the Deep Sea Drilling Project. Both V_p and V_s show wide ranges (3.70 to 6.38 km/sec for V_p and 1.77 to 3.40 km/sec for V_s at 0.5 kb) which are linearly related to density and sea floor age, confirming earlier findings by Christensen and Salisbury of decreasing velocity with progressive submarine weathering based on studies of basalts from five sites in the Atlantic. Combined Pacific and Atlantic data give rates of decreasing velocity of −1.89 and −1.35 km/sec per 100 my for V_p and V_s respectively. New analyses of oceanic seismic refraction data indicate a decrease in layer 2 velocities with age similar to that observed in the laboratory, suggesting that weathering penetrates to several hundred meters in many regions and is largely responsible for the extreme range and variability of layer 2 refraction velocities.

1. Introduction

Recent laboratory studies by Christensen and Salisbury [1] have shown that compressional and shear wave velocities through basalts recovered from the uppermost few meters of layer 2 at six Atlantic sites of the Deep Sea Drilling Project vary linearly with density and that variations in density, in turn, are related to alteration resulting primarily from submarine weathering. Of particular significance, both density and velocity were found to decrease with age from the ridge crest to the abyssal plain. It was thus suggested that layer 2 velocities obtained from careful refraction surveys might possibly be used to determine submarine weathering rates and approximate ages of the sea floor. It was further suggested, since the range of compressional wave velocities measured in the laboratory was found to be similar to that observed for layer 2 from refraction surveys, that weathering might be responsible for the extreme variability [2] long noted in layer 2 refraction velocities.

These early conclusions were regarded as only tentative due to the limited number of sites studied and the uncertainty in the reported intrusive-extrusive relations at these sites. Due to the importance of these findings in the interpretation of marine refraction results and the theory of sea floor spreading, it was felt necessary to expand this study to include basalts from other ocean basins for comparison with the Atlantic data. In this paper we present seismic velocities, elastic moduli, and densities for cores of basalt from 14 new sites drilled during Legs 5, 6, 7, and 9 in the Pacific Ocean and compare these findings with our earlier results. In addition, we present an analysis of reported layer 2 refraction velocities which indicates that the effects of submarine weathering observed in the laboratory can be clearly discerned in refraction data as well.

2. Experimental procedure and data

Samples were selected for velocity measurements from sites in which sufficient quantities of basalt were recovered to obtain cores 1.28 cm in diameter and 2.5 to 3.5 cm in length. A summary of the sites from which samples were available is given in table 1 and their locations indicated in fig. 1. More detailed descriptions of these sites and the basalts recovered can be found in volumes V, VI, VII, and IX of the Deep Sea Drilling Project [3–6].

Velocities given in table 2 were obtained by the pulse transmission technique [7,8] through samples of know length under conditions of confining pressure and water saturation identical to those described by Christensen and Salisbury [1]. Sample identification numbers refer to the leg, hole, and core numbers and indicate whether the cores were cut parallel (||) or perpendicular (⊥) to the site drill hole. In table 3 the ratio of compressional to shear wave velocity (V_p/V_s), Poisson's ratio (σ), the seismic parameter (ϕ), bulk modulus (K), compressibility (β), shear modulus (μ), Young's modulus (E), and Lamé's constant (λ) are calculated at selected pressures from mean velocities and density for each basalt.

3. Velocity-density relations

As in our previous study of Atlantic basalts [1] we find an excellent correlation of seismic wave velocity with density. Compressional wave velocities at 0.5 kb (an approximate pressure for layer 2) vary from 3.70 km/sec for the lowest density sample (2.09 g/cm^3) to 6.38 km/sec for the highest density basalt (3.00 g/cm^3). Shear velocities range similarly from 1.77 to 3.40 km/sec. The velocity-density relations for the Pacific basalts agree well with our findings for the Atlantic basalts, as are illustrated in figs. 2 and 3. It should be noted that wider ranges of velocities and densities were found for the Pacific basalts because several of the Pacific samples are older than the oldest Atlantic basalts.

Least-square regression line parameters of velocity on density and density on velocity for the Pacific basalts are given in table 4 at selected pressures. These agree well with similar data for Atlantic basalts [1]. It appears that layer 2 basalt velocities can be estimated from bulk densities to better than 0.2 km/sec.

For several sites (5-34-18, 6-54-9, 7-61.1-2 and 7-63.0-11) there are small, but significant variations of velocity with propagation direction. This "apparent anisotropy" is clearly not a consequence of preferred mineral orientation, since the bulk densities of the cores from each of these sites vary systematically with the velocities. Petrographic examination of thin sections cut from the cores used for the velocity measurements show that the variations in density and

TABLE 1
Site summary

Leg	Site	Latitude	Longitude	Water depth (m)	Sediment thickness (m)	Amount of basalt recovered (m)	Age of oldest sediment (my)
5	32	37°07.6'N	127°33.4'W	4758	214	0.5	32 (38*)
5	34	39°28.2'N	127°16.5'W	4322	383	0.9	30 (31*)
5	36	40°59.1'N	130°06.6'W	3273	115	0.3	13 (8*)
6	54.0	15°36.6'N	140°18.1'E	4990	292	1.5	20
6	57.0	08°40.9'N	143°32.0'E	3300	330	3.0	27
7	61.0	12°05.0'N	147°03.7'E	5570	93	2.1	80
7	61.1	12°05.0'N	147°03.7'E	5570	89	0.6	80
7	63.0	00°50.1'N	147°53.4'E	4486	561	3.6	33
7	66.0	02°23.6'N	166°07.3'W	5310	192	0.2	97
9	77B	00°28.9'N	133°13.7'W	4291	470	0.3	36
9	79	02°33.0'N	121°34.0'W	4574	411	0.5	21
9	82	02°35.5'N	106°56.5'W	3707	214	0.3	9
9	83	04°02.8'N	95°44.3'W	3646	241	0.3	11
9	84	05°44.9'N	82°53.3'W	3096	252	0.3	8

* Anomaly age determination.

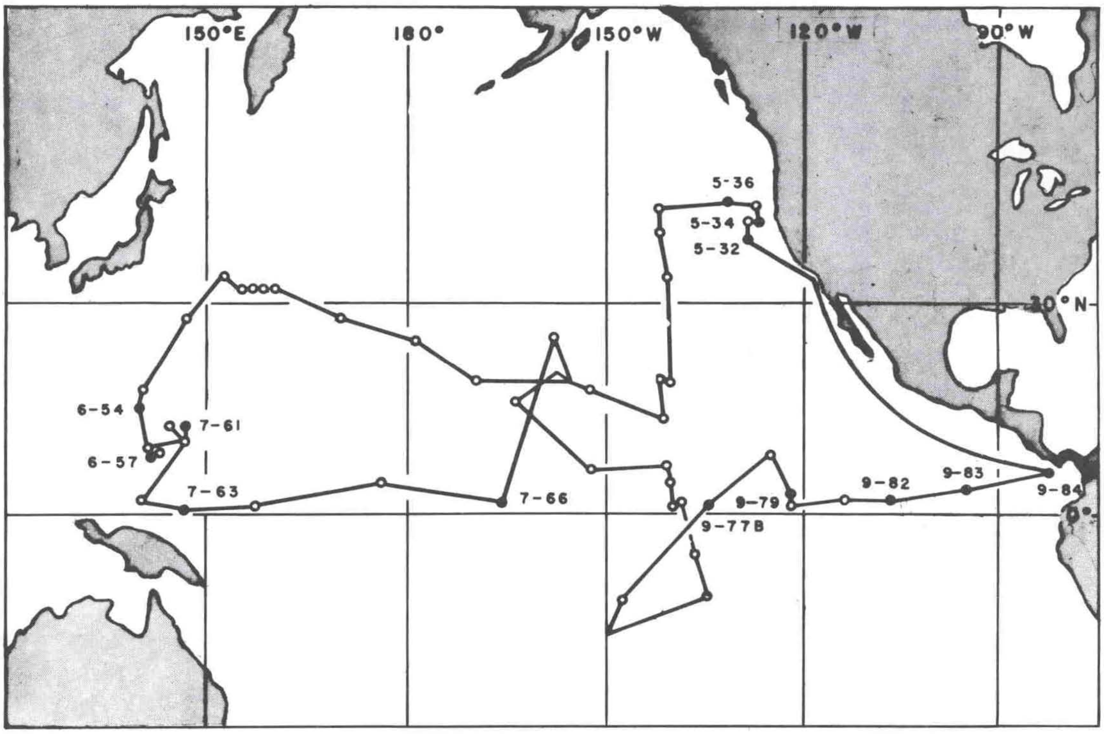

Fig. 1. Legs 5, 6, 7, 8 and 9 site locations. Filled circles indicate sites examined in this study.

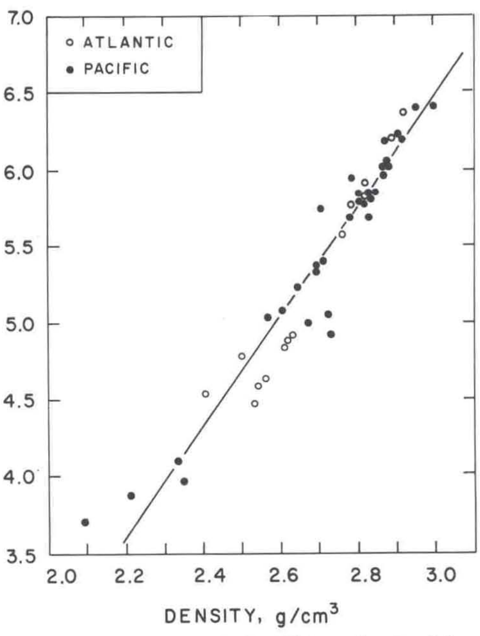

Fig. 2. Compressional wave velocity (V_p) vs. density (ρ) at 0.5 kb for layer 2 basalts.

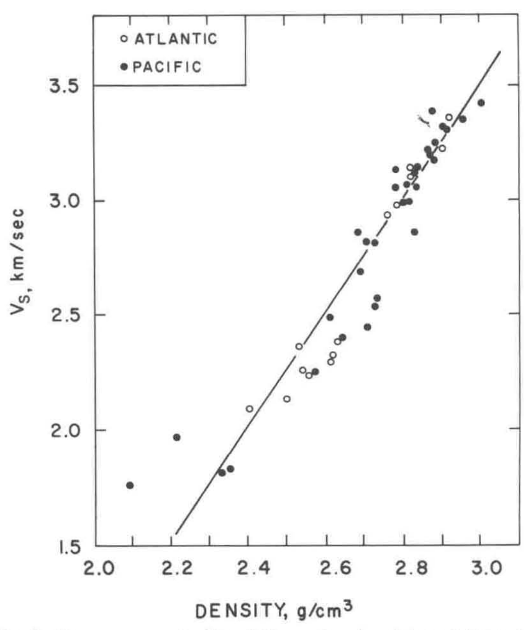

Fig. 3. Shear wave velocity (V_S) vs. density (ρ) at 0.5 kb for layer 2 basalts.

TABLE 2
Compressional (P) and shear (S) wave velocities in km/sec

Identification number	Bulk density	Mode	p = 0.2 kb	p = 0.4 kb	p = 0.6 kb	p = 0.8 kb	p = 1.0 kb	p = 2.0 kb	p = 4.0 kb	p = 6.0 kb	p = 8.0 kb	p = 10.0 kb
5-34-18A ⊥	2.088	P	3.66	3.68	3.71	3.73	3.741	3.804	3.922	4.043	4.142	4.250
B ∥	2.211	P	3.83	3.86	3.88	3.90	3.914	3.978	4.101	4.223	4.332	4.436
Mean	2.150	P	3.75	3.77	3.80	3.82	3.828	3.891	4.012	4.133	4.237	4.343
A ⊥	2.088	S	1.72	1.75	1.78	1.80	1.828	1.933	2.077	2.145	2.189	2.220
B ∥	2.211	S	1.94	1.97	2.00	2.02	2.048	2.156	2.293	2.396	2.479	2.543
Mean	2.150	S	1.83	1.86	1.89	1.91	1.938	2.045	2.185	2.271	2.334	2.382
5-32-13A	2.829	P	5.64	5.66	5.67	5.68	5.685	5.716	5.766	5.806	5.842	5.862
A	2.829	S	2.83	2.85	2.86	2.88	2.890	2.950	3.023	3.059	3.077	3.080
5-36-14A ⊥	2.909	P	6.15	6.18	6.20	6.23	6.243	6.300	6.370	6.404	6.439	6.466
B ∥	2.900	P	6.19	6.22	6.24	6.26	6.282	6.372	6.395	6.433	6.465	6.490
Mean	2.905	P	6.17	6.20	6.22	6.25	6.263	6.336	6.383	6.419	6.452	6.478
A ⊥	2.909	S	3.29	3.30	3.31	3.32	3.334	3.369	3.400	3.410	3.415	3.415
B ∥	2.900	S	3.30	3.32	3.33	3.34	3.350	3.383	3.414	3.430	3.443	3.450
Mean	2.905	S	3.30	3.31	3.32	3.33	3.342	3.376	3.407	3.420	3.429	3.433
6-54-9A ⊥	2.867	P	5.89	5.94	5.97	5.99	6.011	6.081	6.162	6.217	6.270	6.311
B ∥	2.873	P	6.16	6.19	6.21	6.22	6.238	6.293	6.361	6.408	6.443	6.470
Mean	2.870	P	6.03	6.07	6.09	6.11	6.125	6.187	6.262	6.313	6.357	6.391
A ⊥	2.867	S	3.17	3.19	3.20	3.21	3.218	3.244	3.277	3.292	3.301	3.306
B ∥	2.873	S	3.38	3.39	3.40	3.40	3.398	3.401	3.408	3.416	3.422	3.430
Mean	2.870	S	3.28	3.29	3.30	3.31	3.308	3.323	3.343	3.354	3.362	3.368
6-54-8A ∥	2.869	P	5.97	6.00	6.03	6.05	6.064	6.125	6.203	6.271	6.330	6.380
B ∥	2.877	P	5.97	6.01	6.04	6.06	6.076	6.124	6.188	6.248	6.302	6.349
Mean	2.873	P	5.97	6.01	6.04	6.06	6.070	6.125	6.196	6.260	6.316	6.365
A ∥	2.869	S	3.17	3.19	3.20	3.21	3.222	3.259	3.299	3.326	3.343	3.348
B ∥	2.877	S	3.14	3.16	3.17	3.18	3.185	3.217	3.248	3.262	3.270	3.273
Mean	2.873	S	3.16	3.18	3.19	3.20	3.204	3.238	3.274	3.294	3.307	3.311
6-57-3A ⊥	3.004	P	6.35	6.37	6.39	6.40	6.406	6.468	6.530	6.568	6.602	6.631
B ∥	2.955	P	6.35	6.37	6.38	6.39	6.405	6.443	6.493	6.530	6.562	6.588
Mean	2.980	P	6.35	6.37	6.39	6.40	6.406	6.456	6.512	6.549	6.582	6.610
A ⊥	3.004	S	3.38	3.39	3.40	3.41	3.422	3.463	3.514	3.534	3.544	3.550
B ∥	2.955	S	3.34	3.34	3.35	3.36	3.363	3.389	3.418	3.433	3.446	3.452
Mean	2.980	S	3.36	3.37	3.38	3.39	3.393	3.426	3.466	3.484	3.495	3.501
7-66.0-11A	2.348	P	3.91	3.95	3.98	4.01	4.027	4.108	4.235	4.349	4.450	4.545
B	2.336	P	4.06	4.08	4.10	4.12	4.140	4.216	4.353	4.485	4.602	4.693
Mean	2.342	P	3.99	4.02	4.04	4.07	4.084	4.162	4.293	4.417	4.526	4.619
A	2.348	S	1.73	1.80	1.86	1.90	1.935	2.067	2.215	2.301	2.347	2.370
B	2.336	S	1.73	1.78	1.85	1.90	1.932	2.076	2.229	2.303	2.346	2.373
Mean	2.342	S	1.73	1.79	1.86	1.90	1.934	2.072	2.222	2.302	2.347	2.372
7-61.1-2A ⊥	2.641	P	5.21	5.23	5.24	5.25	5.263	5.320	5.422	5.509	5.585	5.653
B ∥	2.562	P	4.98	5.02	5.05	5.07	5.091	5.149	5.205	5.243	5.272	5.292
C ⊥	2.605	P	5.01	5.05	5.07	5.10	5.115	5.189	5.294	5.380	5.458	5.531
Mean	2.603	P	5.07	5.10	5.12	5.14	5.156	5.219	5.307	5.377	5.438	5.492
A ⊥	2.641	S	2.30	2.37	2.42	2.46	2.488	2.580	2.655	2.688	2.707	2.720
B ∥	2.562	S	2.15	2.23	2.29	2.33	2.368	2.477	2.597	2.677	2.698	2.711
C ⊥	2.605	S	2.46	2.48	2.50	2.52	2.536	2.594	2.645	2.650	2.683	2.689
Mean	2.603	S	2.30	2.36	2.40	2.44	2.464	2.550	2.632	2.672	2.696	2.707
7-61.0-2A ⊥	2.726	P	4.95	5.01	5.05	5.08	5.100	5.194	5.314	5.397	5.454	5.496
B ∥	2.734	P	4.78	4.88	4.94	4.99	5.038	5.209	5.403	5.507	5.566	5.600

TABLE 2 (continued)

Identification number	Bulk density	Mode	$p =$ 0.2 kb	$p =$ 0.4 kb	$p =$ 0.6 kb	$p =$ 0.8 kb	$p =$ 1.0 kb	$p =$ 2.0 kb	$p =$ 4.0 kb	$p =$ 6.0 kb	$p =$ 8.0 kb	$p =$ 10.0 kb
7-61.0-2C ⊥	2.676	P	4.89	4.96	5.02	5.06	5.090	5.194	5.313	5.388	5.442	5.480
Mean	2.712	P	4.87	4.95	5.00	5.04	5.076	5.199	5.343	5.431	5.487	5.525
A ⊥	2.726	S	2.49	2.51	2.54	2.56	2.574	2.621	2.683	2.720	2.740	2.753
B ‖	2.734	S	2.51	2.54	2.56	2.58	2.592	2.650	2.705	2.725	2.734	2.740
C ⊥	2.676	S	2.40	2.42	2.44	2.46	2.472	2.525	2.583	2.614	2.632	2.643
Mean	2.712	S	2.47	2.49	2.51	2.53	2.546	2.599	2.657	2.686	2.702	2.712
7-63.0-11A ⊥	2.780	P	5.59	5.67	5.69	5.71	5.722	5.753	5.790	5.824	5.853	5.882
B ‖	2.697	P	5.30	5.33	5.36	5.37	5.382	5.417	5.463	5.508	5.549	5.590
C ⊥	2.881	P	5.98	6.02	6.04	6.06	6.074	6.113	6.155	6.192	6.225	6.256
Mean	2.786	P	5.62	5.67	5.70	5.71	5.726	5.761	5.803	5.841	5.876	5.909
A ⊥	2.780	S	3.04	3.06	3.07	3.08	3.085	3.102	3.117	3.127	3.133	3.141
B ‖	2.697	S	2.78	2.81	2.83	2.84	2.857	2.908	2.958	2.982	3.000	3.012
C ⊥	2.881	S	3.24	3.25	3.25	3.26	3.265	3.290	3.326	3.348	3.359	3.364
Mean	2.786	S	3.02	3.04	3.05	3.06	3.069	3.100	3.134	3.152	3.164	3.172
7-63.0-10A ⊥	2.826	P	5.79	5.82	5.83	5.85	5.861	5.903	5.943	5.968	5.989	6.009
B ⊥	2.836	P	5.79	5.81	5.82	5.84	5.846	5.883	5.925	5.957	5.987	6.015
Mean	2.831	P	5.79	5.82	5.83	5.85	5.854	5.893	5.934	5.963	5.988	6.012
A ⊥	2.826	S	3.11	3.12	3.13	3.14	3.144	3.168	3.192	3.202	3.206	3.208
B ⊥	2.836	S	3.13	3.14	3.15	3.15	3.159	3.178	3.200	3.212	3.217	3.221
Mean	2.831	S	3.12	3.13	3.14	3.15	3.152	3.173	3.196	3.207	3.212	3.215
9-77B-54A ‖	2.716	P	5.37	5.38	5.40	5.41	5.424	5.482	5.555	5.602	5.632	5.651
B ⊥	2.693	P	5.32	5.34	5.36	5.37	5.380	5.422	5.493	5.554	5.600	5.639
Mean	2.705	P	5.35	5.36	5.38	5.39	5.402	5.452	5.524	5.578	5.616	5.645
A ‖	2.716	S	2.80	2.81	2.82	2.83	2.836	2.855	2.882	2.894	2.899	2.899
B ⊥	2.693	S	2.66	2.68	2.70	2.71	2.722	2.763	2.814	2.838	2.847	2.849
Mean	2.705	S	2.73	2.75	2.76	2.77	2.779	2.809	2.848	2.866	2.873	2.874
9-79-17A ⊥	2.781	P	5.97	5.98	5.99	6.00	6.014	6.057	6.116	6.152	6.179	6.201
B ⊥	2.686	P	5.74	5.76	5.78	5.80	5.816	5.862	5.926	5.977	6.026	6.074
Mean	2.734	P	5.86	5.87	5.89	5.90	5.915	5.960	6.021	6.065	6.103	6.138
A ⊥	2.781	S	3.13	3.16	3.17	3.19	3.195	3.222	3.250	3.264	3.270	3.271
B ⊥	2.686	S	2.81	2.86	2.90	2.91	2.926	2.960	2.998	3.017	3.027	3.029
Mean	2.734	S	2.97	3.01	3.04	3.05	3.061	3.091	3.124	3.141	3.149	3.150
9-82-7A	2.801	P	5.67	5.75	5.81	5.87	5.910	6.050	6.198	6.286	6.343	6.369
B	2.801	S	2.84	2.94	3.00	3.05	3.096	3.227	3.350	3.403	3.430	3.440
9-84-30A ⊥	2.809	P	5.76	5.80	5.82	5.83	5.848	5.882	5.921	5.979	6.041	6.071
B ‖	2.812	P	5.84	5.86	5.88	5.89	5.899	5.931	5.986	6.042	6.084	6.114
Mean	2.811	P	5.80	5.83	5.85	5.86	5.874	5.907	5.954	6.011	6.063	6.093
A ⊥	2.809	S	2.98	2.99	2.99	3.00	3.006	3.025	3.047	3.061	3.066	3.070
B ‖	2.812	S	3.07	3.07	3.08	3.08	3.087	3.100	3.117	3.128	3.135	3.139
Mean	2.811	S	3.03	3.03	3.04	3.04	3.047	3.063	3.082	3.095	3.101	3.105
9-83-9A ⊥	2.833	P	5.77	5.80	5.82	5.84	5.853	5.929	6.019	6.076	6.111	6.145
A ⊥	2.833	S	3.04	3.06	3.07	3.08	3.087	3.116	3.158	3.181	3.190	3.192

TABLE 3
Effective elastic constants calculated from V_p, V_s, and ρ

Identification number	Pressure [kb]	V_p/V_s	σ	ϕ [km sec^{-1}]^2	K [Mb]	β [Mb^{-1}]	μ [Mb]	E [Mb]	λ [Mb]
5-34-18	0.4	2.02	0.34	9.6	0.21	4.83	0.07	0.20	0.16
	1.0	1.98	0.33	9.6	0.21	4.81	0.08	0.21	0.15
	2.0	1.90	0.31	9.5	0.21	4.85	0.09	0.24	0.15
	6.0	1.82	0.28	10.0	0.22	4.52	0.11	0.29	0.15
	10.0	1.82	0.28	11.0	0.25	4.06	0.12	0.32	0.16
5-32-13	0.4	1.99	0.33	21.2	0.60	1.67	0.23	0.61	0.45
	1.0	1.97	0.33	21.2	0.60	1.67	0.24	0.63	0.44
	2.0	1.94	0.32	21.0	0.60	1.68	0.25	0.65	0.43
	6.0	1.90	0.31	21.1	0.60	1.66	0.27	0.69	0.43
	10.0	1.90	0.31	21.5	0.62	1.62	0.27	0.71	0.44
5-36-14	0.4	1.87	0.30	23.8	0.69	1.44	0.31	0.83	0.48
	1.0	1.87	0.30	24.3	0.71	1.42	0.32	0.84	0.49
	2.0	1.88	0.30	24.9	0.73	1.38	0.33	0.86	0.50
	6.0	1.88	0.30	25.5	0.75	1.34	0.34	0.89	0.52
	10.0	1.89	0.30	26.0	0.77	1.31	0.34	0.90	0.54
6-54-9	0.4	1.84	0.29	22.3	0.64	1.56	0.31	0.80	0.43
	1.0	1.85	0.29	22.9	0.66	1.52	0.31	0.81	0.45
	2.0	1.86	0.30	23.5	0.68	1.48	0.32	0.82	0.47
	6.0	1.88	0.30	24.7	0.72	1.40	0.32	0.84	0.50
	10.0	1.90	0.31	25.5	0.74	1.35	0.33	0.86	0.52
6-54-8	0.4	1.89	0.31	22.6	0.65	1.54	0.29	0.76	0.46
	1.0	1.89	0.31	23.1	0.67	1.50	0.30	0.77	0.47
	2.0	1.89	0.31	23.5	0.68	1.48	0.30	0.79	0.48
	6.0	1.90	0.31	24.6	0.71	1.40	0.31	0.82	0.50
	10.0	1.92	0.31	25.7	0.75	1.34	0.32	0.83	0.54
6-57-3	0.4	1.89	0.31	25.4	0.76	1.32	0.34	0.88	0.53
	1.0	1.89	0.30	25.7	0.77	1.31	0.34	0.90	0.54
	2.0	1.88	0.30	26.0	0.78	1.29	0.35	0.91	0.54
	6.0	1.88	0.30	26.6	0.80	1.25	0.36	0.94	0.56
	10.0	1.89	0.30	27.1	0.82	1.22	0.37	0.96	0.57
7-66.0-11	0.4	2.24	0.38	11.8	0.28	3.60	0.08	0.21	0.23
	1.0	2.11	0.36	11.7	0.27	3.65	0.09	0.24	0.22
	2.0	2.01	0.34	11.5	0.27	3.67	0.10	0.27	0.21
	6.0	1.92	0.31	12.3	0.29	3.41	0.12	0.33	0.21
	10.0	1.95	0.32	13.6	0.33	3.05	0.13	0.35	0.24
7-61.1-2	0.4	2.16	0.36	18.5	0.48	2.07	0.15	0.40	0.39
	1.0	2.09	0.35	18.5	0.48	2.08	0.16	0.43	0.38
	2.0	2.05	0.34	18.5	0.48	2.07	0.17	0.46	0.37
	6.0	2.01	0.34	19.2	0.51	1.97	0.19	0.50	0.38
	10.0	2.03	0.34	20.1	0.53	1.87	0.19	0.51	0.41
7-61.0-2	0.4	1.99	0.33	16.3	0.44	2.26	0.17	0.44	0.33
	1.0	1.99	0.33	17.1	0.46	2.15	0.18	0.47	0.35
	2.0	2.00	0.33	18.0	0.49	2.04	0.18	0.49	0.37
	6.0	2.02	0.34	19.7	0.54	1.85	0.20	0.53	0.41
	10.0	2.04	0.34	20.5	0.57	1.77	0.20	0.54	0.43

TABLE 3 (continued)

Identification number	Pressure [kb]	V_p/V_s	σ	ϕ [km sec^{-1}]^2	K [Mb]	β [Mb^{-1}]	μ [Mb]	E [Mb]	λ [Mb]
7-63.0-11	0.4	1.87	0.30	19.9	0.55	1.80	0.26	0.67	0.38
	1.0	1.87	0.30	20.2	0.56	1.77	0.26	0.68	0.39
	2.0	1.86	0.30	20.3	0.57	1.76	0.27	0.69	0.39
	6.0	1.85	0.29	20.7	0.58	1.71	0.28	0.72	0.40
	10.0	1.86	0.30	21.3	0.60	1.66	0.28	0.73	0.41
7-63.0-10	0.4	1.85	0.30	20.7	0.59	1.71	0.28	0.72	0.40
	1.0	1.86	0.30	21.0	0.60	1.68	0.28	0.73	0.41
	2.0	1.86	0.30	21.3	0.60	1.66	0.29	0.74	0.41
	6.0	1.86	0.30	21.7	0.62	1.61	0.29	0.76	0.43
	10.0	1.87	0.30	22.1	0.64	1.57	0.29	0.76	0.44
9-77B-54	0.4	1.95	0.32	18.6	0.50	1.98	0.20	0.54	0.37
	1.0	1.94	0.32	18.9	0.51	1.96	0.21	0.55	0.37
	2.0	1.94	0.32	19.2	0.52	1.92	0.21	0.56	0.38
	6.0	1.95	0.32	20.0	0.55	1.83	0.22	0.59	0.40
	10.0	1.96	0.33	20.6	0.57	1.76	0.22	0.60	0.42
9-79-17	0.4	1.95	0.32	22.4	0.61	1.63	0.25	0.65	0.45
	1.0	1.93	0.32	22.5	0.62	1.63	0.26	0.68	0.44
	2.0	1.93	0.32	22.7	0.62	1.60	0.26	0.69	0.45
	6.0	1.93	0.32	23.5	0.65	1.54	0.27	0.71	0.47
	10.0	1.95	0.32	24.2	0.67	1.49	0.27	0.72	0.49
9-82-7	0.4	1.96	0.32	21.5	0.60	1.66	0.24	0.64	0.44
	1.0	1.91	0.31	22.1	0.62	1.61	0.27	0.70	0.44
	2.0	1.87	0.30	22.7	0.64	1.57	0.29	0.76	0.44
	6.0	1.85	0.29	23.9	0.68	1.48	0.33	0.84	0.46
	10.0	1.85	0.29	24.6	0.70	1.43	0.33	0.86	0.48
9-84-30	0.4	1.92	0.31	21.7	0.61	1.64	0.26	0.68	0.44
	1.0	1.93	0.32	22.1	0.62	1.61	0.26	0.69	0.45
	2.0	1.93	0.32	22.3	0.63	1.59	0.26	0.69	0.45
	6.0	1.94	0.32	23.2	0.66	1.52	0.27	0.71	0.48
	10.0	1.96	0.32	24.0	0.69	1.46	0.27	0.72	0.50
9-83-9	0.4	1.90	0.31	21.1	0.60	1.67	0.27	0.69	0.42
	1.0	1.90	0.31	21.5	0.61	1.64	0.27	0.71	0.43
	2.0	1.90	0.31	22.2	0.63	1.59	0.28	0.72	0.45
	6.0	1.91	0.31	23.3	0.67	1.50	0.29	0.75	0.47
	10.0	1.93	0.32	23.9	0.69	1.45	0.29	0.76	0.49

velocity at each site are related to slight differences in weathering.

4. Progressive weathering and associated changes in seismic velocities

It was suggested from the study of cores recovered from Legs 2, 3, and 4 in the Atlantic that the velocities of seismic waves through layer 2 basalts decrease steadily with age due to decreasing density brought about by progressive submarine weathering, mineralogically expressed as a steady increase in phyllosilicates and zeolites at the expense of feldspar, pyroxene and olivine. These early conclusions, though based upon findings at only a small number of sites, have now been confirmed.

In fig. 4, the averages of the compressional and shear wave velocities measured at 0.5 kb for each of the 18 Pacific and Atlantic sites examined to date are

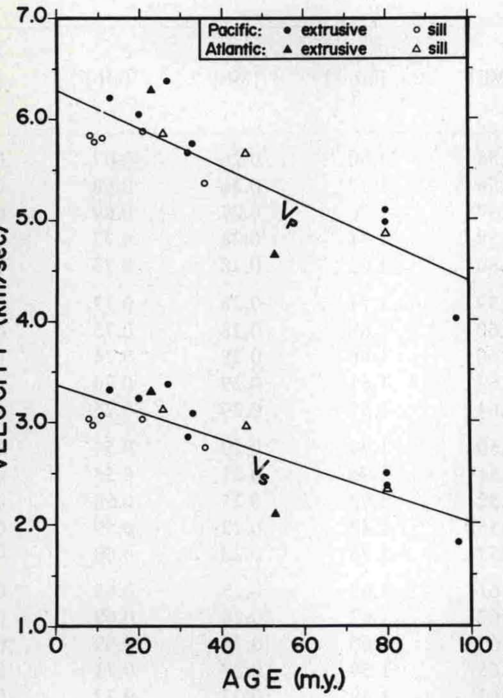

Fig. 4. Compressional (V_p) and shear (V_s) velocities at 0.5 kb vs. age for layer 2 basalts.

seen to decrease markedly with age. The rates of change of V_p and V_s with age have been computed respectively as

$$\Delta V_p/\Delta t = -1.89 \times 10^{-2} \text{ km/sec my}$$

and

$$\Delta V_s/\Delta t = -1.35 \times 10^{-2} \text{ km/sec my}$$

by the method of least squares, and the solutions plotted in fig. 4. The effect of submarine weathering upon seismic velocities measured in the laboratory is clearly profound; young basalts cored near the ridge crests display compressional wave velocities of nearly 6.5 km/sec, whereas samples cored in 100 my old sea floor average only 4.5 km/sec.

It should be noted that no clear distinction can be made in fig. 4 between intrusive and extrusive trends of velocity on age, suggesting that the intrusion of sills at the sites examined has been nearly contemporaneous with the formation of the underlying sea floor and that submarine weathering continues beneath the accumulating sediment pile.

Should weathering penetrate to depths of several hundred meters, equivalent to the wavelengths monitored in refraction surveys, its effects should be noted in refraction results as a pronounced decrease in layer 2 refraction velocities with age. As was noted by Christensen and Salisbury [1], this proposition can be readily tested from published refraction data. In fig. 5a layer 2 refraction velocities from the literature are presented in histogram form. All incorporated velocity measurements are from sites in the main ocean basins which can be dated and which are structurally uncomplicated (thus velocities from behind-arc basins, trenches, island chains and fracture zones are omitted).

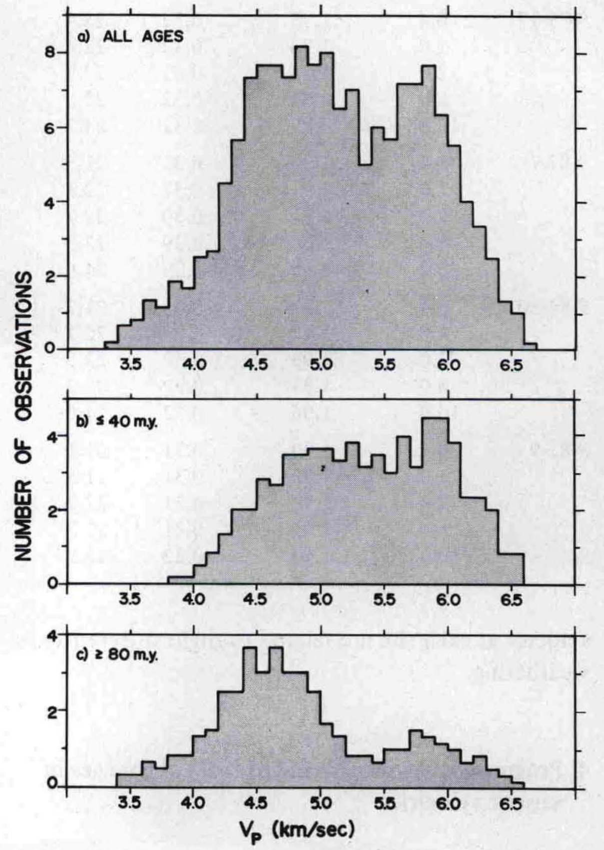

Fig. 5. Compressional wave refraction velocity histograms for layer 2 (data from [9, 10]). Fractional observations arise from digital filtering.

TABLE 4
Regression line parameters

Pressure [kb]	n	a [km sec^{-1}]	b $\frac{\text{km sec}^{-1}}{\text{g cm}^{-3}}$	$S_{(V,\rho)}$ [km sec^{-1}]	r	r^2 [%]
			$V_p = a + b\rho$			
0.5	32	−3.55	3.32	0.20	0.96	92
1.0	32	−3.47	3.31	0.19	0.96	93
2.0	32	−3.35	3.28	0.18	0.97	94
6.0	32	−2.61	3.06	0.17	0.97	94
10.0	32	−2.01	2.88	0.17	0.96	92
			$V_s = a + b\rho$			
0.5	32	−3.04	2.15	0.16	0.94	88
1.0	32	−2.73	2.06	0.15	0.94	89
2.0	32	−2.31	1.92	0.14	0.94	89
6.0	32	−1.53	1.66	0.14	0.92	85
10.0	32	−1.11	1.52	0.15	0.91	83
Pressure [kb]	**n**	**a [g cm^{-3}]**	**b $\frac{\text{g cm}^{-3}}{\text{km sec}^{-1}}$**	**$S_{(V,\rho)}$ [g cm^{-3}]**	**r**	**r^2 [%]**
			$\rho = a + bV_p$			
0.5	32	1.20	0.278	0.06	0.96	92
1.0	32	1.17	0.281	0.06	0.96	93
2.0	32	1.13	0.285	0.05	0.97	94
6.0	32	0.97	0.306	0.05	0.97	94
10.0	32	0.85	0.322	0.06	0.96	92
			$\rho = a + bV_s$			
0.5	32	1.57	0.411	0.07	0.94	88
1.0	32	1.48	0.433	0.07	0.94	89
2.0	32	1.38	0.462	0.07	0.94	89
6.0	32	1.19	0.512	0.08	0.92	85
10.0	32	1.07	0.545	0.09	0.91	83

n = number of data points,
$S_{(V,\rho)}$ = standard error of estimate of V on ρ,
$S_{(\rho,V)}$ = standard error of estimate of ρ on V,
r = correlation coefficient,
r^2 = coefficient of determination.

In addition, the data has been filtered in accordance with the mean standard error of the refraction determinations. The distribution is similar to that found in earlier treatments [2, 9] and is clearly representative of the wide range in velocities observed for layer 2.

If the velocity histogram of fig. 5a is broken down into age groups as in figs. 5b and 5c, strikingly different velocity distributions can be seen for young and old sea floor. Young oceanic crust (fig. 5b) displays generally high layer 2 compressional wave velocities, the commonly observed values ranging from 4.5 to 6.3 km/sec with a mode of nearly 6.0 km/sec; old sea floor velocities (fig. 5c) are characteristically low, with common values ranging from 4.2 to 5.0 km/sec about a mode of 4.6 km/sec. Though it is possible to explain the entire spectrum of layer 2 velocities in terms of submarine weathering, it is evident from the wide range of velocities observed in each group that other processes such as neovolcanism, low grade metamorphism and fracturing are in part responsible for this range. Nonetheless, a pronounced trend of decreasing layer 2 refraction velocities with age similar to that observed in the laboratory is clearly indicated. We conclude that this trend, both in the laboratory and in the field, may be attributed to deep, progressive submarine weathering in oceanic layer 2 and that such weathering is consistent with the theory of sea floor spreading.

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