Sound absorption based on ocean measurements. Part II: Boric acid contribution and equation for total absorption

R.E. Francois and G.R. Garrison

Applied Physics Laboratory, University of Washington, 1013 N. E. 40th Street, Seattle, Washington 98105

(Received 15 June 1982; accepted for publication 18 August 1982)

The absorption of sound in seawater is considered as the sum of three contributions: those from pure water, magnesium sulfate, and boric acid. Contributions from other reactions are small and are not included. The pure water and magnesium sulfate contributions obtained from analyses of extensive oceanic measurements, including many in the Arctic, were discussed in Part I. In Part II, an analysis is made of all reported measurements in the low-frequency region (0.2-10 kHz) to evaluate the contributions determined in Part I from the total absorption to give a more accurate estimate of the boric acid contribution than previously obtained. The three contributions are then combined to form an equation with both a theoretical basis and a satisfactory empirical fit that will be useful to researchers and engineers in the field of underwater sound. The equation applies to all oceanic conditions and frequencies from 200 Hz to 1 MHz.

PACS numbers: 43.30.Bp, 92.10.Vz, 43.35.Bf, 43.35.Fj

INTRODUCTION

The general equation for the absorption of sound in seawater gives the absorption as the sum of contributions from boric acid, magnesium sulfate, and pure water:

$$\alpha = \frac{A_1 P_1 f_1 f^2}{f_1^2 + f^2} + \frac{A_2 P_2 f_2 f^2}{f_1^2 + f^2} + A_3 P_3 f^2, \tag{1}$$

where f is the frequency of the sound, f_1 and f_2 are the relaxation frequencies of boric acid and magnesium sulfate, and P_1 , P_2 , and P_3 are nondimensional pressure correction factors.

The measurements and analyses reported earlier in Part I^1 resulted in more accurate equations for the pure water and magnesium sulfate contributions. Part II treats the boric acid contribution, which is important at frequencies below about 10 kHz.

Numerous low-frequency measurements of absorption have been made in various oceans using sound produced by explosives and transmitted along a sound channel. In analyzing these measurements, other investigators have generally treated the boric acid contribution as a relaxation process, but have usually accepted 1 kHz as the relaxation frequency regardless of the water properties. Our approach was to subtract the two components that were delineated in Part I from the total absorption to obtain a better measure of the boric acid portion. With three adjustable parameters available-the boric acid relaxation frequency, the absorption at that frequency, and a frequency-independent bias in α (such as a spreading loss error)—we made a three-variable least-squares fit to each set of data and obtained a relaxation frequency that varies with temperature and a proportionality factor that varies with pH.

In this paper, we first summarize the measurements reported by others for which the acoustic and environmental data were sufficiently documented to use in our analysis. We then analyze five selected sets whose frequencies bracketed the relaxation frequency to determine equations for the relaxation frequency and the absorption, and compare the boric acid equation thus derived with the remaining absorption measurements.

The paper concludes by combining the three contributions into a single equation and comparing it with the equations of other investigators. A one-page table of absorption versus frequency and temperature is included for the reader's convenience.

I. LOW-FREQUENCY MEASUREMENTS

A. Absorption anomaly

Measurements of low-frequency absorption in the 1950's showed higher values than expected from pure water and magnesium sulfate. Schulkin² proposed a nonchemical relaxation mechanism. A summary by Thorp³ showed a preponderance of data that indicated an anomaly below 10 kHz.

In 1972 this anomaly was shown by Yeager *et al.*⁴ to be caused mainly by a chemical relaxation of boric acid. Simmons,⁵ using laboratory measurements, verified this and noted a variation between the Atlantic and Pacific Oceans. Mellen and Browning⁶ reported that boron-induced absorption in the Pacific Ocean was about half that in the Atlantic. Further comparisons by Mellen and Browning⁷ of the absorption and water properties in several widely spread locations showed that the absorption varied with *p*H.

At about the same time, Schulkin and Marsh⁸ also examined the ocean variations reported by Simmons. They estimated the pH at the sound channel axis for each area, and also found a strong correlation between absorption and pH. Following Glotov's theory, they related the relaxation frequency of the boron absorption to the viscosity of the seawater as well as to the temperature and salinity, and published an equation for the boric acid contribution to absorption. Lovett,⁹ using a Russian oceanographic atlas¹⁰ to obtain pH values for the Atlantic, Indian, and Pacific Oceans, published a world contour map for predicting low-frequency absorption at the sound channel axis but gave no specific temperature or salinity dependence.

The frequency range of the boric acid absorption and that of the MgSO₄ absorption overlap appreciably. At a temperature of 5 °C and a frequency of 3 kHz, for example, the effects are about equal; near the boric acid relaxation frequency of about 1 kHz, the MgSO₄ component is about 20% of the boric acid term. In this region, the study of the boric acid effect requires that the MgSO₄ component be accurately known. Contributions from other relaxations are small and have not been included in the analysis considering the accuracy of the available low-frequency data. Numerous measurements of low-frequency absorption in all oceans during the past decade have provided field data for the studies just mentioned. Most of those measurements involved explosive sources and long-range transmission in a sound channel where cylindrical spreading could be assumed.

B. Review of ocean measurements

A review of the literature provided us with several absorption measurements that were performed in waters of known oceanographic properties. Five of these investiga-

TABLE I. Low-frequency absorption measurements used to derive equations.

		Sound Channe 1		Measurement			Adjuste Give Eq.	d to (7) f ₁	Calculated From Our Final Equation	
Location and Investigator	Year	Axis Depth (m)	Max. Range (km)	f (kHz)	Total a (dB/km)	Boric Acid Excess a ^b (dB/km)	(αλ) _m (10 ⁻⁵ Np)	Total α (dB/km)	Total α (dB/km)	Adjusted α - Calculated α (dB/km)
NE Pacific ⁶ Chow and Turner ¹¹	1973	505	1400	0.160	0.0046 ± 0.0009 0.0077 ± 0.0012	0.0044 0.0071	0.42 ± 0.28 0.54 ± 0.16	0.0016 0.0047	0.0019 0.0044	-0.0003 0.0003
(T=4.6°C, S=34.05‰, pH=7.69 ^a , c=1476 m/s)				0.400 0.630 0.800	$\begin{array}{r} 0.0131 \pm 0.0016 \\ 0.0264 \pm 0.0027 \\ 0.0328 \pm 0.0033 \end{array}$	0.0116 0.0226 0.0266	0.49 ± 0.09 0.56 ± 0.08 0.51 ± 0.07	0.0101 0.0234 0.0298	0.0104 0.0215 0.0299	-0.0003 0.0019 -0.0001
Atlantic Thorp ³	1962	1200	1800	0.354 0.446	0.0161 ± 0.0010 0.0229 ± 0.0010	0.0150 0.0211	0.90 ± 0.07 0.92 ± 0.05	0.0135 0.0203	0.0139 0.0207	-0.0004 -0.0004
(T=5.0°C, S=35.0‰, pH=8.03, c=1490 m/s)				0.562 0.707 0.891 1.120 1.410 1.780 2.240 2.820 3.540	$\begin{array}{c} 0.0292 \pm 0.0010 \\ 0.0398 \pm 0.0010 \\ 0.0550 \pm 0.0010 \\ 0.0638 \pm 0.0025 \\ 0.789 \pm 0.0037 \\ 0.1129 \pm 0.0120 \\ 0.1511 \pm 0.0170 \\ 0.1826 \pm 0.0220 \\ 0.1931 \pm 0.0250 \end{array}$	0.0264 0.0354 0.0480 0.0528 0.0614 0.0850 0.1070 0.1128 0.0832	$\begin{array}{c} 0.82 \pm 0.03 \\ 0.83 \pm 0.03 \\ 0.78 \pm 0.02 \\ 0.78 \pm 0.04 \\ 0.78 \pm 0.05 \\ 0.97 \pm 0.14 \\ 1.13 \pm 0.18 \\ 1.13 \pm 0.20 \\ 0.79 \pm 0.25 \end{array}$	0.0266 0.0372 0.0524 0.0612 0.0763 0.1103 0.1485 0.1800 0.1905	0.0299 0.0415 0.0555 0.0711 0.0882 0.1076 0.1307 0.1614 0.2048	$\begin{array}{c} -0.0033\\ -0.0043\\ -0.0031\\ -0.0099\\ -0.0119\\ 0.0027\\ 0.0178\\ 0.0186\\ -0.0143\end{array}$
Mediterranean Sea Skretting and Leroy ¹²	1966	800	32	0.500 0.600 0.800	$\begin{array}{rrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrr$	0.0111 0.0143 0.0313	$\begin{array}{rrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrr$	0.0350 0.0390 0.0580	0.0243 0.0332 0.0524	0.0107 0.0058 0.0056
(T=13°C, S=38.0‰, ph=8.15, c=1517 m/s)			·	$\begin{array}{c} 1.000\\ 1.500\\ 2.000\\ 2.500\\ 3.000\\ 3.500\\ 4.000\\ 4.500\\ 5.000\\ 5.500\\ 6.000\\ 8.000\end{array}$	$\begin{array}{rrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrr$	0.0496 0.0983 0.1304 0.1488 0.1335 0.1695 0.1818 0.1905 0.2155 0.1969 0.1847 0.1099	$\begin{array}{c} 1.29 \pm 0.29 \\ 1.41 \pm 0.23 \\ 1.45 \pm 0.29 \\ 1.46 \pm 0.26 \\ 1.24 \pm 0.24 \\ 1.46 \pm 0.23 \\ 1.51 \pm 0.30 \\ 1.55 \pm 0.29 \\ 1.71 \pm 0.29 \\ 1.75 \pm 0.21 \\ 1.46 \pm 0.21 \\ 0.91 \pm 0.28 \end{array}$	0.0790 0.1370 0.1820 0.2170 0.2220 0.2820 0.3220 0.3620 0.4220 0.4420 0.4720 0.6020	0.0719 0.1155 0.1512 0.1822 0.2119 0.2423 0.2743 0.3088 0.3461 0.3865 0.4301 0.6382	0.0071 0.0215 0.0308 0.0348 0.0101 0.0397 0.0477 0.0532 0.0759 0.0555 0.0419 -0.0362
Red Sca Browning ¹³	1971	200	280	0.570	0.0360 ± 0.0022 0.0440 ± 0.0044	0.0340 0.0408	1.32 ± 0.12 1.12 ± 0.16	0.0264	0.0246	0.0018
(T=22°C, S=40.5‰, pH=8.18, c=1536 m/s)	·			1.150 1.400 1.800 2.280 2.850 3.500 5.600 8.900	$\begin{array}{rrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrr$	0.0562 0.0840 0.1111 0.1333 0.1594 0.1846 0.2156 0.2686 0.3621	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	0.0514 0.0824 0.1134 0.1434 0.1814 0.2244 0.2804 0.4494 0.8324	0.0536 0.0802 0.1058 0.1445 0.1856 0.2284 0.2727 0.4180 0.7214	-0.0022 0.0022 0.0076 -0.0011 -0.0042 -0.0040 0.0077 0.0314 0.1110
Gulf of Aden Browning ¹⁴ (T=14.31°C, S=35.8‰, pH=7.72, c=1510 m/s)	1973	300	500	0.400 0.500 0.630 0.790 1.000 1.300 1.650 2.000 2.500 3.200 4.000 5.000 6.000	$\begin{array}{l} 0.0350 \pm 0.0040 \\ 0.0400 \pm 0.0040 \\ 0.0460 \pm 0.0040 \\ 0.0550 \pm 0.0050 \\ 0.0650 \pm 0.0050 \\ 0.0820 \pm 0.0050 \\ 0.0980 \pm 0.0060 \\ 0.1200 \pm 0.0060 \\ 0.1530 \pm 0.0060 \\ 0.1530 \pm 0.0070 \\ 0.1700 \pm 0.0100 \\ 0.2950 \pm 0.0300 \\ 0.3720 \pm 0.1000 \end{array}$	0.0339 0.0382 0.0432 0.0506 0.0619 0.0700 0.0786 0.0915 0.1085 0.0972 0.0673 0.1175 0.1167	$\begin{array}{ccccc} 0.47 & \pm & 0.31 \\ 0.54 & \pm & 0.21 \\ 0.54 & \pm & 0.14 \\ 0.57 & \pm & 0.17 \\ 0.56 & \pm & 0.07 \\ 0.55 & \pm & 0.06 \\ 0.60 & \pm & 0.06 \\ 0.68 & \pm & 0.06 \\ 0.53 & \pm & 0.08 \\ 0.29 & \pm & 0.07 \\ 0.63 & \pm & 0.21 \\ 0.61 & \pm & 0.69 \end{array}$	0.0072 0.0122 0.0182 0.0272 0.0412 0.0542 0.0702 0.0922 0.1252 0.1252 0.1532 0.2672 0.3442	0.0080 0.0121 0.0180 0.0260 0.0369 0.0522 0.0691 0.0852 0.1081 0.1870 0.2535 0.3329	-0.0008 0.0001 0.0012 0.0043 0.0020 0.0011 0.0070 0.0171 -0.0001 -0.0338 0.0137 0.0113

^aAll pH values have been corrected for temperature and pressure. ^bMeasured absorption less pure water and MgSO₄ contributions.

Location and Investigator		Sound Channel Axis Depth (m)		Т (°С)	S (‰)	рН			Calculated From Our Final Equation		
			Max.				Measured			Measured α -	
	Year		Range (km)				f (kHz)	lotal α (dB/km)	lotal α (dB/km)	Calculated α (dB/km)	
NE Pacific Thorp ⁶ c=1479 m/s	1975	753	3000	4.25	34.1	7.67	0.120 0.150 0.200 0.250 0.300 0.400	0.0011 0.0018 0.0026 0.0035 0.0062 0.0094	0.0010 0.0016 0.0028 0.0043 0.0061 0.0101	0.0001 0.0002 -0.0002 -0.0008 0.0001 -0.0007	
Pacific Lovett ¹⁵ (ISAR) c=1481 m/s	1969	700	245	5.0	34.4	7.67	0.750 1.500 3.000	0.0221 0.0547 0.1470	0.0263 0.0594 0.1321	-0.0042 -0.0047 0.0149	
Gulf.of Alaska Lovett ¹⁵ c=1465 m/s	1971	75	270	4.0	33.1	7.72	1.500 2.500	0.0744 0.1290	0.0644 0.1132	0.0100 0.0158	
NE Pacific Morris ¹⁶ c=1476 m/s	1975	505	2900	4.60	34.1	7.69	0.050 0.080 0.100 0.125 0.160 0.200 0.250 0.310 0.400	0.0002 0.0004 0.0007 0.0012 0.0018 0.0028 0.0042 0.0068 0.0092	0.0002 0.0005 0.0007 0.0012 0.0019 0.0029 0.0044 0.0066 0.0104	0.0000 -0.0001 -0.0000 0.0000 -0.0001 -0.0001 -0.0002 0.0002 -0.0012	
S. Pacific Kibblewhite and Denham ¹⁷ (Line PA) c=1488 m/s	1971	1250	1150	4.31	35.0	7.96	0.106 0.212 0.424	0.0007 0.0030 0.0083	0.0013 0.0049 0.0173	-0.0006 -0.0019 -0.0090	
(Line PB1) c=1487 m/s	1971	1250	1700	4.07	35.0	7.90	0.106 0.212 0.424	0.0002 0.0032 0.0084	0.0012 0.0045 0.0158	-0.0010 -0.0013 -0.0074	
(KIWI WEST) ⁶ c=1488 m/s	1974	1250	3000	4.31	35.0	7.96	0.029 0.060 0.120 0.250 0.424	0.0015 0.0012 0.0021 0.0034 0.0079	0.0001 0.0004 0.0016 0.0067 0.0173	0.0014 0.0008 0.0005 -C.0033 -0.0094	
(TAS 1) ¹⁸ c=1489 m/s	1963	1300	900	4.35	35.0	7.87	0.450 0.900	0.0203 0.0246	0.0165 0.0440	0.0038 -0.0194	
S. Pacific Bannister et al. ¹⁹ (TAS 2, Northwest) c=1488 m/s	1975	1350	1800	3.92	35.0	7.87	0.125 0.250 0.500	0.0016 0.0063 0.0167	0.0015 0.0059 0.0197	0.0001 0.0004 -0.0030	
(TAS 2, West) c=1484 m/s	1975	1100	2800 1600	3.94	35.0	7.87	0.125 0.250 0.500	0.0012 0.0055 0.0189	0.0016 0.0059 0.0198	-0.0004 -0.0004 -0.0009	
Baffin Bay ^a Mellen et al. ²⁰ c=1442 m/s	1972	100	400	-1.50	33.7	8.01	0.320 0.410 0.500 0.640 1.000	0.0170 0.0198 0.0246 0.0393 0.0683	0.0143 0.0214 0.0288 0.0399 0.0643	0.0027 -0.0016 -0.0042 -0.0006 0.0040	
Bismarck Sea Mellen and Browning ²¹ c = 1546 m/s	1974	45	?	30	36	8.20	0.560 1.200 2.300 4.500	0.0700 0.1000 0.1900 0.3600	0.0203 0.0776 0.1854 0.3367	0.0497 0.0224 0.0046 0.0233	

TABLE II. Other absorption measurements compared with our final equation.

 $^{a}\ensuremath{\mathsf{Measured}}$ values have been adjusted by -0.02 dB/km.

.

. .

,

tions, each in a different ocean or sea, had a sufficient frequency spread to determine the relaxation frequency and were analyzed to develop an absorption equation. These measurements are summarized in Table I and described briefly in the following paragraphs. Other investigations



FIG. 1. Determination of the boric acid relaxation frequency for five water types. Each set of absorption measurements has been adjusted by $\Delta \alpha$ (in decibels/kilometer) to give the best fit to relaxation theory.

1882 J. Acoust. Soc. Am., Vol. 72, No. 6, December 1982

with limited frequency coverage are listed in Table II. In selecting these data, we avoided measurements that crossed ocean fronts and may have involved waters of different pH. The pH at the sound channel axis for each set of measurements was estimated from Lovett's contour diagram.⁹ All the measurements reported involved explosive sources except for the cw transmissions of Lovett.¹⁵

1. Northeast Pacific Ocean

These measurements were made by the Canadian Defence Research Establishment Pacific (DREP) in 1973 during a joint project with U.S. laboratories. The data were presented by Mellen and Browning⁶ and are especially valuable for studying *p*H dependence because of the low *p*H in the northeast Pacific. A scattering loss of 0.0033 dB/km was apparently present. Sufficient data were available to determine the relaxation frequency. More recently, another version of the data¹¹ became available which, when analyzed, gave similar results.

2. Atlantic Ocean

Thorp³ reported measurements made in 1962 for which explosives were dropped from a ship and detonated every 9 km along a 900-km track extending southwest from Bermuda. Receivers were at the axis of the sound channel. In determining the absorption coefficient, Thorp assumed that cylindrical spreading started at about 40 km. The maximum range of useful measurements was 900 km for the lower frequencies, but dropped to 110 km for the highest frequency. However, Thorp disregarded the five highest frequencies and, instead, included a second set of lower-frequency measurements made the following year (1963). We found the higher frequencies to be helpful in determining the relaxation frequency. For the second set, at the lower frequencies, good documentation is not available. Although Thorp does not report the standard deviation of his absorption coeffi-



FIG. 2. Boric acid relaxation frequency f_1 determined from measurements in various oceans. θ is the absolute temperature (T + 273). The best-fit line corresponds to Eq. (7).

TABLE III. Analysis of low-frequency absorption measurements.

	Ad	justed For Bes	Adjusted to Give Same f1 as Eq. (7)			Weighted Average ^a	Final Par	Final Equation Parameters	
Location	Δα (dB/km)	f ₁ (kHz)	(αλ) _m (10 ⁻⁵ Np)	Δα (dB/km)	f ₁ (kHz)	(αλ) _m (10 ⁻⁵ Np)	(αλ) _m (10 ⁻⁵ Np)	f ₁ (kHz)	(αλ) _m (10 ⁻⁵ Np)
NE Pacific	-0.0026	0.83 ± 0.08	0.52	-0.0030	0.90	0.52	0.52 ± 0.04	0.90	0.51
Atlantic	-0.0065	1.12 ± 0.22	0.78	-0.0026	0.93	0.85	0.86 ± 0.03	0.93	0.94
Mediterranean Sea	+0.0150	1.41 ± 0.20	1.25	+0.0215	1.29	1.36	1.31 ± 0.12	1.29	1.16
Red Sea	-0.0091	1.81 ± 0.22	1.24	-0.0096	1.81	1.24	1.24 ± 0.05	1.81	1.22
Gulf of Aden	-0.0258	1.23 ± 0.18	0.61	-0.0278	1.31	0.58	0.55 ± 0.04	1.31	0.54

^aAverage of the sets in Table I using a weighting of $1/\sigma$.

cient determinations, his plots of loss-versus-range gave us a good basis for estimation. The shortened range at the higher frequencies causes a considerable increase in the standard deviation of the calculated coefficient. Thorp presents results for both "refracted only data" and "all-path data." We have used only the refracted data, expecting a better fit to theory.

3. Mediterranean Sea

Skretting and Leroy¹² made transmission measurements in the western Mediterranean using explosive sources in June 1966 (trial 1). Similar measurements had been made in 1964 and 1965 and some were made later (trial 2) but we have sufficient information only on trial 1. Of all the lowfrequency measurements examined, these are unique in that refraction upward from the deep was so uniform that spherical spreading was a close approximation. The shock wave data and the bubble pulse data gave nearly the same results. indicating that finite amplitude effects were negligible. We used the shock wave data which were scaled from Fig. 3 of Ref. 12. The frequencies bracketed the relaxation frequency, and the data were analyzed to determine a best fit to the relaxation equation. Our analysis required a correction of + 0.015 dB/km, which is in fair agreement with the correction of $+ 0.02 \, dB/km$ made by Skretting and Leroy to eliminate the negative attenuation at the lowest frequencies.

4. Red Sea

Mellen *et al.*¹³ summarized the results of absorption measurements in the Red Sea with a reference to a technical report for the details. The data were very valuable for this study because of the high temperature (22 °C).

5. Gulf of Aden

Mellen et al.¹⁴ reported measurements of sound transmission using explosive sources over a 500-km track in the Gulf of Aden. The frequency range of 0.25 to 6.0 kHz was suitable for determining the relaxation frequency. During this process, we found that a correction of -0.021 dB/km was required, which is in close agreement with the 0.02 dB/ kyd given by the investigators as the loss caused by scattering due to inhomogeneities in the sound speed.

II. BORIC ACID CONTRIBUTION

A. Equation for excess absorption due to boric acid

The excess sound absorption caused by boric acid is calculated from the first term of the absorption equation (1) and is referred to here as α_1 .

$$\alpha_1 = A_1 P_1 f_1 f^2 / (f_1^2 + f^2), \qquad (2)$$

where, as stated in Part I, $P_1 = 1$. The maximum product of the boric acid absorption and the wavelength $(\alpha \lambda)_m$, which occurs at $f = f_1$, appears to be a more fundamental constant than A_1 , and is related to A_1 by the sound speed c. With conversion of units, the relation is given by

$$(\alpha\lambda)_m = cA_1/2(8686)10^3$$
 Np. (3)

By replacing A_1 in Eq. (2) and multiplying by λ ($\lambda = c/f$), the absorption per wavelength can be expressed as

$$\alpha_1 \lambda = 2(\alpha \lambda)_m f_1 f / (f_1^2 + f^2) \text{ Np.}$$
(4)



FIG. 3. Boric acid excess absorption per wavelength $(\alpha \lambda)_m$ for waters with diverse *p*H. The best-fit line shown is given by Eq. (9).



FIG. 4. Comparison of our boric acid absorption equation with measured data that have been adjusted to give relaxation frequencies in agreement with Eq. (7). $\Delta \alpha$ is the adjustment in decibels/kilometer.

In most measurements reported in the literature, the investigator has calculated absorption assuming cylindrical spreading. In our analysis, we have included an adjustment $\Delta \alpha$ as described in Part I,¹ Sec. IV, to provide a better fit to the theoretical excess absorption equation. In essence, this corrects for any frequency-independent error such as a small deviation from the assumed spreading loss.

B. Theory of boric acid absorption

Glotov^{22,23} examined the excess absorption due to the small concentrations of boric acid and its derivatives in ocean water, and related the relaxation frequency of the process to the association energy Δh by

$$f_1 = (F\theta / \eta)e^{-\Delta h/R\theta},\tag{5}$$

where θ is the absolute temperature (T + 273), where $T \leq 20$ °C), η is the viscosity, R is the gas constant, and F is a constant.

Following the procedure of Schulkin and Marsh,⁸ we combined Eq. (5) with Eq. (13) given for viscosity in Part I to obtain

$$f_1 = F/Ee^{-(\Delta h + \Delta u)/R\theta},\tag{6}$$

where $\Delta h + \Delta u$ is the activation energy of the process. Their plot of $\ln f_1$ vs $1/\theta$ for the ocean data summarized by Simmons showed that the slope of the line giving the best (leastsquares) fit required a negative Δh . Schulkin and Marsh pointed out that Δh could not be negative and set $\Delta h = 0$, which gave about as good a fit to the data.

The laboratory measurements of both $Glotov^{23}$ and Simmons⁵ indicate that the boric acid relaxation frequency varies as the square root of the concentration. Considering that seawater has a very constant relative composition, the salinity S should be proportional to the boron concentration. A concentration dependence of $S^{0.5}$ is therefore assumed.

C. Analysis of low-frequency measurements

When analyzing low-frequency ocean measurements, the excess absorption due to boric acid is obtained by subtracting the values calculated for the MgSO₄ and pure water components from the measured absorption. If our results in Part I for the absorption due to MgSO₄ are correct, analyses in the past would be subject to error. The absorption calculated for MgSO₄ would be 5%-10% low if the Schulkin-Marsh equation²⁴ reported in 1962 was used and 20%-30%low if the Fisher–Simmons equation²⁵ was used. The use of our new equation for the MgSO₄ absorption should improve the accuracy of the remaining absorption allocated to boric acid.

We proceed in the next paragraphs to examine all suitable low-frequency data that we found in the literature, subtract the MgSO₄ and pure-water components calculated from our new equation, and examine the dependence of the remaining boric acid component on temperature and pH.

The five investigations listed in Table I permitted a reasonably accurate calculation of the relaxation frequency. Plots of the absorption per wavelength determined from the measured absorption are shown in Fig. 1 for the five sets. Values for f_1 , for $(\alpha \lambda)_m$, and for the adjustment $\Delta \alpha$, which was applied equally to all values, have been selected to give the best fit of $\alpha_1 \lambda$ to the theoretical curve, Eq. (4).

The five relaxation frequencies determined in this manner have been plotted against temperature in Fig. 2, where logarithmic scales result in a straight line for Eq. (6). The line for Eq. (6) is the best fit to the five points, using a weighting of $1/\sigma$. This line corresponds to the equation

 $f_1 = 2.8(S/35)^{1/2}10^{(4-1245/\theta)}$ kHz.

and its slope is a measure of the activation energy for the process; i.e.,

$$\Delta h + \Delta u = 1245R \ln 10 = 5.7 \text{ kcal/mole},$$
 (8)

where R is the general gas constant, 1.987 cal mole⁻¹ deg⁻¹.

Since Δu , the activation energy of seawater viscosity, has been shown in Part I, Sec. V, to be 4.8 kcal/mole, we subtract this amount and obtain for the association energy

 $\Delta h = 0.9$ kcal/mole,



(7)

FIG. 5. Comparison of our boric acid absorption equation with reported measurements of absorption that have an insufficient frequency spread for determining the relaxation frequency. The pH values given are our best estimate for the location and depth.

1885 J. Acoust. Soc. Am., Vol. 72, No. 6, December 1982



FIG. 6. Comparison of low-frequency absorption equations (for S = 35%) and two pH values).

which is nicely above 0 rather than negative as indicated by Mellen *et al.*¹³

The steepness of the line in Fig. 2 is determined primarily by the data point for the Red Sea. We calculated a higher relaxation frequency, 1.72 kHz compared with 1.50 kHz, for the Red Sea data than that presented by Mellen *et al.* using a three-relaxation model.¹³ When we adjusted the same data by -0.0026 dB/km to get the best fit to the relaxation equation, we obtained an even higher relaxation frequency, 1.81 kHz.

After selecting Eq. (7) as the equation for the relaxation frequency, we readjusted each set of data to the relaxation frequency calculated by this equation. The corresponding $(\alpha \lambda)_m$, which also varies with the adjustment, was then determined for each of the five locations. These manipulations are summarized in Table III. Using Eqs. (1)–(3) and the relaxation frequency obtained from Eq. (7), we calculated $(\alpha \lambda)_m$ in terms of the measured and adjusted absorption. After determining a value for $(\alpha \lambda)_m$ from each absorption measurement, we found the average and standard deviation for each set of data. These averages are shown in Table III and plotted in Fig. 3 against *p*H. The least-squares fit of an equation of the form given by Schulkin and Marsh⁸ is

$$(\alpha \lambda)_m = 5.1 \times 10^{(0.78 \, pH - 12)}$$
 Np. (9)

 A_1 can be expressed in more practical units as

$$A_{1} = [2(8686)(10^{3})/c](\alpha\lambda)_{m}$$

= (8.86/c)×10^(0.78 pH-5) dB km⁻¹ kHz⁻¹. (10)

With
$$f_1$$
 and $(\alpha \lambda)_m$ given by Eqs. (7) and (9), the boric

TOTAL SOUND ABSORPTION IN SEAWATER

$$\alpha = \frac{A_1 P_1 f_1 f^2}{f^2 + f_1^2} + \frac{A_2 P_2 f_2 f^2}{f^2 + f_2^2} + A_3 P_3 f^2 \quad dB \ km^{-1}$$

for frequency f in kilohertz.

Boric Acid Contribution

A

$$A_{1} = \frac{8.86}{c} \times 10^{(0.78 \text{ pH} - 5)} \qquad \text{dB km}^{-1} \text{ kHz}^{-1}$$

$$P_{1} = 1$$

$$f_{1} = 2.8 (S/35)^{0.5} 10^{(4 - 1245/\theta)} \qquad \text{kHz},$$

where c is the sound speed (m/s), given approximately by

c = 1412 + 3.21 T + 1.19 S + 0.0167 D,

T is the temperature (°C), θ = 273 + T, S is the salinity (‰), and D is the depth (m).

MgSO₄ Contribution

$$A_{2} = 21.44 \frac{s}{c} (1 + 0.025 T) \qquad dB \ km^{-1} \ kHz^{-1}$$

$$P_{2} = 1 - 1.37 \times 10^{-4} D + 6.2 \times 10^{-9} D^{2}$$

$$f_{2} = \frac{8.17 \times 10^{(8 - 1990/\theta)}}{1 + 0.0018 \ (s - 35)} \qquad kHz$$

Pure Water Contribution

For
$$T \le 20^{\circ}$$
C,
 $A_3 = 4.937 \times 10^{-4} - 2.59 \times 10^{-5} T$
 $+ 9.11 \times 10^{-7} T^2 - 1.50 \times 10^{-8} T^3$ dB km⁻¹ kHz⁻².
For T > 20°C,
 $A_3 = 3.964 \times 10^{-4} - 1.146 \times 10^{-5} T$
 $+ 1.45 \times 10^{-7} T^2 - 6.5 \times 10^{-10} T^3$ dB km⁻¹ kHz⁻².
 $P_3 = 1 - 3.83 \times 10^{-5} D + 4.9 \times 10^{-10} D^2$.

FIG. 7. Francois-Garrison equation for sound absorption in seawater.

acid absorption can be computed using Eq. (4) for the conditions of the five sets of data in Table I. The values of f_1 and $(\alpha \lambda)_m$ for each set are tabulated in the final columns of Table III. Figure 4 shows the fit of our boric acid equation to the five sets of data. The $\Delta \alpha$ adjustment originally applied has been slightly altered so that the data are well fitted by the $\alpha_1 \lambda$ curve corresponding to the relaxation frequency given by Eq. (7). In all five comparisons, our equation is a good representation of the data.

A similar comparison with the data listed in Table II, which had an insufficient frequency spread to determine the relaxation frequency, is presented in Fig. 5. No adjustments

TABLE IV. Absorption in seawater according to the Francois–Garrison equation (dB/km). The upper value for each frequency is for S = 30% and the lower for S = 35%. Depth = 0 and pH = 8.

(kHz) -1.8 -1.5 -1 0 2 4 6 8 10 12 14 16 18 20 0.4 0.021 0.021 0.020 0.020 0.019 0.018 0.017 0.016 0.015 0.014 0.013 0.013 0.012 0.01 0.01 0.01 0.015 0.014 0.013 0.012 0.01	25 11 0.010 0 11 0.009 0 23 0.020 0 22 0.019 0 38 0.033 0 36 0.032 0 52 0.048 0 52 0.047 0	30 0.008 0.008 0.018 0.017
0.4 0.021 0.020 0.020 0.019 0.018 0.017 0.016 0.015 0.014 0.013 0.013 0.012 0.012 0.012 0.012 0.012 0.012 0.012 0.012 0.012 0.011 0.012 0.011 0.012 0.011 0.012 0.011 0.012 0.011 0.012 0.011 0.012 0.011 0.012 0.011 0.012 0.011 0.012 0.011 0.012 0.011 0.012 0.011 0.012 0.011 0.012 0.011 0.012 0.012 0.012 0.012 0.012 0.011 0.012 0.011 0.011 0.011 0.011 0.011 0.011 0.011 0.011 0.011 0.011 0.011 0.012 0.012 0.012 0.012 0.012 0.012 0.012 0.011 0.012 0.011 0.012 0.011 0.012 0.012 0.012 0.012 0.012 0.012 0.012 0.012 0.025 0.026 0	11 0.010 0 11 0.009 0 23 0.020 0 22 0.019 0 38 0.033 0 36 0.032 0 52 0.048 0 52 0.047 0	0.008 0.008 0.018 0.017
0.6 0.036 0.036 0.035 0.034 0.033 0.032 0.031 0.030 0.028 0.027 0.026 0.025 0.0 0.6 0.036 0.036 0.035 0.034 0.033 0.032 0.031 0.030 0.028 0.027 0.026 0.025 0.02 0.6 0.036 0.036 0.035 0.034 0.033 0.032 0.030 0.029 0.028 0.026 0.025 0.024 0.0 0.8 0.050 0.050 0.049 0.049 0.048 0.047 0.045 0	23 0.020 0 22 0.019 0 38 0.033 0 36 0.032 0 52 0.048 0 52 0.047 0	0.018 0.017
0.8 0.050 0.050 0.049 0.049 0.049 0.048 0.047 0.046 0.045 0.044 0.042 0.041 0.040 0.0	38 0.033 0 36 0.032 0 52 0.048 0 52 0.047 0	0 030
0.8 0.051 0.051 0.051 0.051 0.050 0.049 0.048 0.046 0.045 0.043 0.042 0.040 0.038 0.0	52 0.048 0 52 0.047 0	0.028
1 0.061 0.061 0.061 0.061 0.061 0.061 0.061 0.060 0.059 0.058 0.057 0.056 0.054 0.0 1 0.064 0.064 0.064 0.064 0.064 0.063 0.062 0.061 0.060 0.059 0.057 0.055 0.054 0.0		0.043 0.042
2 0.111 0.111 0.111 0.111 0.112 0.112 0.113 0.114 0.114 0.115 0.116 0.117 0.117 0.1 2 0.122 0.122 0.122 0.122 0.122 0.122 0.122 0.122 0.122 0.123 0.12	17 0.116 0 22 0.119 0	0.113 0.115
4 0.256 0.254 0.252 0.248 0.240 0.233 0.227 0.223 0.219 0.216 0.214 0.212 0.212 0.2 4 0.291 0.290 0.287 0.282 0.272 0.264 0.256 0.250 0.245 0.241 0.237 0.235 0.233 0.2	11 0.213 0 32 0.231 0	0.215 0.231
6 0.485 0.481 0.475 0.463 0.440 0.420 0.401 0.384 0.369 0.356 0.345 0.335 0.327 0.3. 6 0.558 0.553 0.546 0.532 0.505 0.481 0.459 0.438 0.420 0.405 0.391 0.379 0.368 0.3	21 0.309 0 50 0.344 0	0.304 0.335
8 0.794 0.788 0.777 0.755 0.714 0.675 0.638 0.605 0.575 0.547 0.522 0.500 0.481 0.44 8 0.918 0.910 0.897 0.872 0.824 0.778 0.735 0.696 0.660 0.627 0.597 0.571 0.547 0.5	54 0.430 0 26 0.485 0	D.409 D.457
10 1.18 1.17 1.15 1.12 1.06 0.995 0.938 0.884 0.835 0.789 0.747 0.709 0.675 0.6 10 1.36 1.35 1.33 1.29 1.22 1.15 1.08 1.02 0.963 0.909 0.859 0.815 0.774 0.7	4 0.581 0 57 0.661 0	D.536 D.606
12 1.62 1.61 1.59 1.55 1.46 1.38 1.30 1.22 1.15 1.08 1.02 0.962 0.910 0.80 12 1.88 1.86 1.84 1.79 1.69 1.59 1.50 1.41 1.33 1.25 1.18 1.11 1.05 0.9	0.764 0 02 0.874 0	D.689 D.784
14 2.12 2.10 2.08 2.03 1.92 1.82 1.71 1.61 1.51 1.42 1.34 1.26 1.19 1.1 14 2.45 2.43 2.41 2.35 2.23 2.10 1.98 1.86 1.75 1.65 1.55 1.45 1.37 1.2	2 0.978 0 9 1.12 0	D.867 D.992
16 2.65 2.64 2.61 2.55 2.43 2.30 2.17 2.05 1.93 1.81 1.70 1.60 1.50 1.44 16 3.07 3.05 3.02 2.96 2.82 2.67 2.52 2.37 2.23 2.10 1.97 1.85 1.74 1.6	1.22 1	L.07 L.23
18 3.22 3.20 3.18 3.12 2.98 2.84 2.69 2.53 2.39 2.24 2.11 1.98 1.86 1.7 ^{,7} 18 3.73 3.71 3.68 3.61 3.46 3.29 3.11 2.94 2.77 2.60 2.44 2.29 2.15 2.0	1.50 1 1.73 1	1.30
20 3.81 3.79 3.76 3.70 3.57 3.41 3.24 3.06 2.89 2.72 2.55 2.40 2.25 2.1 20 4.40 4.39 4.36 4.29 4.13 3.95 3.75 3.55 3.35 3.15 2.96 2.78 2.61 2.4	1.81 1 2.09 1	L.56 L.80
30 6.78 6.79 6.80 6.81 6.75 6.62 6.43 6.19 5.92 5.63 5.33 5.03 4.74 4.4 30 7.81 7.82 7.84 7.85 7.80 7.66 7.45 7.18 6.87 6.53 6.19 5.84 5.50 5.1	3.80 3 4.40 3	3.24 3.75
40 9.45 9.50 9.59 9.74 9.94 10.0 9.95 9.78 9.52 9.19 8.81 8.40 7.97 7.53 40 10.8 10.9 11.0 11.2 11.4 11.5 11.5 11.3 11.0 10.7 10.2 9.75 9.25 8.7	6.48 5 7.52 6	5.53
50 11.7 11.8 12.0 12.3 12.8 13.2 13.4 13.4 13.3 13.1 12.7 12.3 11.8 11., 50 13.3 13.4 13.6 14.0 14.7 15.1 15.4 15.5 15.4 15.1 14.7 14.2 13.6 13.1	9.77 8 11.3 9	8.39 9.74
60 13.6 13.7 13.9 14.4 15.3 16.0 16.5 16.9 17.1 17.0 16.8 16.4 15.9 15 60 15.4 15.6 15.8 16.4 17.4 18.3 19.0 19.5 19.7 19.6 19.4 19.0 18.4 17.	13.6 1 15.7 1	11.8 13.7
70 15.2 15.4 15.7 16.3 17.4 18.5 19.4 20.1 20.6 20.8 20.8 20.6 20.2 19. 70 17.2 17.4 17.7 18.4 19.8 21.1 22.2 23.1 23.7 24.0 24.0 23.8 23.4 22.	0 17.7 1 20.6 1	15.6 18.1
80 16.7 16.9 17.3 17.9 19.3 20.6 21.9 23.0 23.8 24.4 24.7 24.8 24.5 24. 80 18.8 19.0 19.4 20.2 21.9 23.5 25.0 26.3 27.3 28.1 28.5 28.6 28.4 27.1	22.2 1	19.8 23.0
90 18.2 18.4 18.7 19.5 21.0 22.6 24.1 25.5 26.8 27.7 28.4 28.8 28.8 28. 90 20.3 20.6 21.0 21.9 23.7 25.6 27.4 29.2 30.6 31.8 32.7 33.2 33.3 33.1	26.9 2 31.2 2	24.3
100 19.6 19.8 20.2 21.0 22.6 24.4 26.1 27.9 29.4 30.8 31.9 32.6 33.0 33.1 100 21.8 22.1 22.5 23.4 27.5 29.7 31.7 33.6 35.3 36.6 37.5 38.0 38.	31.7 2 36.7 3	29.1 [°] 33.7
120 22.6 22.8 23.1 23.9 25.7 27.6 29.8 32.0 34.2 36.2 38.0 39.6 40.7 41. 120 24.8 25.1 25.5 26.5 28.6 31.0 33.6 36.2 38.8 41.3 43.5 45.3 46.7 47.4	41.3 3	59.1 15.2
140 25.8 25.9 26.3 27.0 28.7 30.8 33.1 35.6 38.2 40.9 43.4 45.6 47.6 49. 140 28.1 28.3 28.7 29.6 31.8 34.3 37.1 40.1 43.2 46.4 49.4 52.1 54.5 56.	50.7 4 58.4 5	19.4 57.1
160 29.3 29.4 29.7 30.3 31.9 33.9 36.3 39.0 41.9 45.0 48.1 51.0 53.7 56. 160 31.6 31.8 32.2 33.0 35.0 37.5 40.4 43.7 47.2 50.9 54.5 58.0 61.3 64.4	59.6 S 68.5 6	59.7 58.8
180 33.1 33.2 33.4 33.9 35.3 37.2 39.5 42.3 45.4 48.8 52.3 55.8 59.2 62.3 180 35.5 35.6 35.9 36.6 38.4 40.8 43.7 47.1 50.9 54.9 59.1 63.3 67.3 70.9	67.9 6 77.8 8	59.7 30.2
200 37.4 37.5 37.8 38.9 40.6 42.9 45.6 48.8 52.4 56.3 60.2 64.1 67.1 200 39.8 39.9 40.1 40.6 42.1 44.3 47.2 50.6 54.4 58.7 63.3 68.0 72.7 77.1	75.5 7 86.4 9	79.3 91.1
250 49.8 49.7 49.5 49.2 49.4 50.3 52.0 54.5 57.6 61.3 65.6 70.2 75.1 80.1 250 52.2 52.1 52.0 52.6 54.1 56.4 59.6 63.4 68.0 73.1 78.7 84.5 90.4	92.1 1 105 1	01 16
300 64.9 64.5 63.0 63.0 61.8 61.7 62.6 64.4 67.2 70.7 75.0 79.8 85.2 90.5 300 67.3 67.0 66.5 65.8 65.1 65.6 67.1 69.6 73.1 77.5 82.7 88.6 95.1 102	106 13 120 13	20
350 82.6 81.9 80.9 79.1 76.5 75.1 74.9 75.9 77.9 81.0 85.0 89.8 95.3 101 350 85.0 84.4 83.5 81.9 79.8 79.0 79.4 81.1 84.0 87.9 92.9 98.8 105 113	119 13 133 19	36 54
400 103 102 100 97.7 93.3 90.4 88.9 88.8 90.0 92.4 95.9 100 106 112 400 105 105 103 100 96.6 94.3 93.4 94.1 96.1 99.4 104 110 116 124	130 19 146 13	51
450 126 125 123 119 112 108 105 103 104 105 108 112 117 123 450 129 127 125 122 116 112 109 109 110 112 116 121 128 135	142 10 158 14	.64 .85
500 152 150 147 142 133 127 122 119 118 119 121 124 129 135 500 154 153 150 145 137 131 127 125 125 126 129 134 140 147	154 1 170 1	77
600 212 209 205 197 183 171 163 157 153 151 151 153 156 160 600 214 212 207 199 186 175 167 162 159 158 160 162 167 173	178 20	203
700 282 279 272 261 240 224 211 201 194 189 187 186 187 190 700 285 281 275 264 244 228 215 206 200 196 195 196 197 190	205 22 222 2	29
800 366 359 350 335 307 284 266 251 240 232 227 224 223 224 800 366 361 353 338 311 288 271 257 247 240 235 740 740 746	235 25	57 80
900 456 450 439 419 383 353 329 309 293 281 273 267 263 262 900 459 452 442 442 386 357 333 314 299 280 281 277 275 274	269 20 286 3	88
1000 562 554 540 515 471 434 403 378 359 344 332 376 319 314	306 32 323 34	21 144

.

have been applied. Some of the data at frequencies below 200 Hz have been omitted because the attenuation was excessively high. Mellen and Browning⁶ relate this phenomenon to an oceanic scattering process which sometimes becomes evident when the boric acid absorption is very low. Measurements at frequencies below 200 Hz have been summarized by Kibblewhite and Hampton²⁶ in an effort to show a regional dependence for the excess attenuation at low frequencies. They state that this anomalous contribution, which they also attribute to various scattering processes, is constant with frequency and varies with latitude, from 0.004 dB/km in polar waters to as low as 0.0002 dB/km in the tropics.

The South Pacific data (lines PA, PB, and KIWI in Fig. 5) would fit our equation if pH = 7.6, which is about minimum for the Pacific Ocean, instead of nearly 7.9 as shown. This would require that low pH values extend 20° farther south than outlined by Lovett⁹ and would be in appreciable disagreement with his information¹⁰ about pH in the Pacific.

A visual comparison between the values given by our equation, by the Schulkin-Marsh equation,⁸ and by the Fisher-Simmons equation,²⁵ is presented in Fig. 6, which shows the variation of absorption with temperature and pH. The values given by our equation tend to fall between the others. The need for an equation with temperature and pH dependence is clear.



FIG. 8. Seawater absorption at three temperatures (°C) for frequencies of 100 Hz to 1 MHz as given by our absorption equation (for S = 35% and pH = 8). Lines for pure water absorption have been added.

1888 J. Acoust. Soc. Am., Vol. 72, No. 6, December 1982

III. RECOMMENDED ABSORPTION EQUATION

In summary of both Part I and this paper, we present the equations shown in Fig. 7 for predicting the absorption of sound in seawater.

The boric acid contribution has been determined from measurements in waters with salinities of 34%-41%, temperatures of -2° to 22 °C, and depths to 1500 m. The equation may not hold below 200 Hz, where the boric acid contribution may be exceeded by a scattering loss.

Table IV presents our results for ocean temperatures of -1.8° to 30 °C, frequencies of 0.4 to 1000 kHz, and salinities of 30% and 35%. The values are estimated to be accurate to within 5% in the range of parameters covered by the APL-UW measurements and to within about 10% outside our frequency range.

The absorption equation is plotted for three temperatures in Fig. 8, which shows the effect of the two relaxation phenomena. A three-dimensional plot for a family of absorption curves is shown in Fig. 9 to illustrate the changes in the relaxation phenomena with temperature.

Comparisons of our absorption equation with the 1962 Schulkin–Marsh equation (which has been augmented by the low-frequency boric acid equation prepared by Schulkin and Marsh in 1977) and with the Fisher–Simmons equation are given in Fig. 10. Above 10 kHz the agreement with the Fisher–Simmons equation is much better than with the Schulkin–Marsh equation, with a maximum difference of about 20%. Below 1 kHz, in warm waters, the agreement with the Schulkin–Marsh equation is the better.

Considering that our absorption equation is probably accurate to within 5%, we note large areas in the frequencytemperature domain where the disagreement with the other equations is significant. Our equations represent an improvement of 10%-20% in absorption prediction over most



FIG. 9. Three-dimensional diagram of seawater absorption versus frequency and temperature. The effect of the boric acid and magnesium sulfate relaxation frequencies is apparent.





ocean conditions and over the acoustic frequencies of interest.

IV. SUMMARY

Low-frequency measurements of absorption reported in the literature that were conducted at widespread locations and over long ranges were reviewed. The $MgSO_4$ and pure water components, now given more accurately by the equations we developed in Part I, were subtracted to obtain a better estimate of the excess absorption due to boric acid. The dependence of the boric acid relaxation frequency on temperature and the change in the absorption from ocean to ocean as a result of *p*H differences were determined.

Combining our results for boric acid with the results for pure water and $MgSO_4$ developed in Part I, we have compiled an equation to predict absorption in natural seawater in the frequency range of 200 Hz to 1 MHz and to depths of 5000 m. In general, our predicted absorption lies near or between the Schulkin–Marsh and the Fisher–Simmons predictions, which differ by 30%–50% in some areas. Our equation, the result of an extensive review of field measurements and fitting of data to relaxation theories, is sufficiently accurate to improve absorption prediction in these areas.

Future absorption measurements would be more valuable if investigators obtained a better record of the environment along the transmission path. The sound intensity measurements and the environmental properties should be reported in detail so that others can analyze the data using their preferred methods. One problem at low frequencies is that properties along the axis of the sound channel are often used in the calculations, even though the nonsymmetry of the channel results in much of the transmission being off axis. The pH measurement is very important and should always be included in the environmental data set. Ideally, measurements of absorption should be performed over a frequency range that brackets one of the relaxation frequencies so that, when the data are fitted to relaxation theory, errors in the assumed spreading loss will become evident. Such refinements may lead to more accurate results and a better fit to theory. Some of the large discrepancies we observed, however, indicate that absorption may be affected by some seawater property or component that has not been included in the analysis.

ACKNOWLEDGMENTS

The authors are grateful to Dr. M. Schulkin for his thoughtful criticism of this paper and to Dr. F. H. Fisher for rewarding discussions. The assistance of our colleague J. T. Shaw, in the analysis of the data, is appreciated. This study was supported by the Arctic Submarine Laboratory, Naval Ocean Systems Center, San Diego, and the Naval Surface Weapons Center, Silver Spring, Maryland.

³W. H. Thorp, "Deep-ocean sound attenuation in the sub- and low-kilocycle-per-second range," J. Acoust. Soc. Am. **38**, 648–654 (1965).

¹R. E. Francois and G. R. Garrison, "Sound absorption based on ocean measurements. Part I: Pure water and magnesium sulfate contributions," J. Acoust. Soc. Am. 72, 896–907 (1982).

²M. Schulkin, "Eddy viscosity as a possible acoustic absorption mechanism in the ocean," J. Acoust. Soc. Am. **35**, 253 (1963).

- ⁴E. Yeager, F. H. Fisher, J. Miceli, and R. Bressel, "Origin of the low-frequency sound absorption in sea water," J. Acoust. Soc. Am. 53, 1705–1707 (1973).
- ⁵V. P. Simmons, "Investigation of the 1-kHz sound absorption in sea water," Ph.D. thesis, Univ. California, San Diego, 1975.
- ⁶R. H. Mellen and D. G. Browning, "Low-frequency attenuation in the Pacific Ocean," J. Acoust. Soc. Am. **59**, 700-702 (1976).
- ⁷R. H. Mellen and D. G. Browning, "Variability of low-frequency sound absorption in the ocean: *p*H dependence," J. Acoust. Soc. Am. **61**, 704–706 (1977).
- ⁸M. Schulkin and H. W. Marsh, "Low-frequency sound absorption in the ocean," J. Acoust. Soc. Am. **63**, 43–48 (1978).
- ⁹J. R. Lovett, "Geographic variation of low-frequency sound absorption in the Atlantic, Indian and Pacific Oceans," J. Acoust. Soc. Am. **67**, 338–340 (1980).
- ¹⁰World Ocean Atlas, Atlantic and Indian Oceans, Vol. 2, pp. 234–235 and World Ocean Atlas, Pacific Ocean, Vol. 1, pp. 234–235, edited by S. G. Gorshkov (Pergamon, New York, 1974).
- ¹¹R. K. Chow and R. G. Turner, "Attenuation of low-frequency sound in the northeast Pacific Ocean," J. Acoust. Soc. Am. 72, 888–891 (1982).
- ¹²A. Skretting and C. C. Leroy, "Sound attenuation between 200 Hz and 10 kHz," J. Acoust. Soc. Am. 49, 276–282 (1971).
- ¹³R. H. Mellen, D. G. Browning, and V. P. Simmons, "Investigation of chemical sound absorption in seawater by the resonator method: Part I," J. Acoust. Soc. Am. 68, 248–257 (1980).
- ¹⁴R. H. Mellen, D. G. Browning, and J. M. Ross, "Attenuation in randomly inhomogeneous sound channels," J. Acoust. Soc. Am. 56, 80–82 (1974).
- ¹⁵J. R. Lovett, "Northeastern Pacific sound attenuation using low-frequen-

cy CW sources," J. Acoust. Soc. Am. 58, 620-625 (1975).

- ¹⁶G. B. Morris, "Low-frequency sound attenuation in the Northeastern Pacific Ocean," J. Acoust. Soc. Am. Suppl. 1 59, S44 (1976).
- ¹⁷A. C. Kibblewhite and R. N. Denham, "Low-frequency acoustic attenuation in the South Pacific Ocean," J. Acoust. Soc. Am. 49, 810–815 (1971).
- ¹⁸A. C. Kibblewhite and R. N. Denham, "Long-range sound propagation in the South Tasman Sea," J. Acoust. Soc. Am. 41, 401–411 (1967).
- ¹⁹R. W. Bannister, R. N. Denham, K. M. Guthrie, and D. G. Browning, "Project TASMAN TWO: Low-frequency propagation measurements in the South Tasman Sea," J. Acoust. Soc. Am. 62, 847–859 (1977).
- ²⁰R. H. Mellen, D. G. Browning, J. M. Ross, and H. M. Merklinger, "Lowfrequency sound attenuation in Baffin Bay," J. Acoust. Soc. Am. 57, 1201–1202 (1975).
- ²¹R. H. Mellen and D. G. Browning, "Attenuation in surface ducts," J. Acoust. Soc. Am. 63, 1624–1626 (1978).
- ²²V. P. Glotov, "Calculation of the relaxation time for the degree of dissociation of magnesium sulfate in fresh and sea water as a function of temperature," Sov. Phys.-Acoust. **10**, 33–38 (1964).
- ²³V. P. Glotov, "Influence of minute quantities of beryllium and boron on the bulk viscosity of water and on the low-frequency attenuation of sound in the ocean," Sov. Phys.-Acoust. 22, 67–68 (1976).
- ²⁴M. Schulkin and H. W. Marsh, "Sound absorption in sea water," J. Acoust. Soc. Am. 34, 864–865 (1962).
- ²⁵F. H. Fisher and V. P. Simmons, "Sound absorption in sea water," J. Acoust. Soc. Am. 62, 558-564 (1977).
- ²⁶A. C. Kibblewhite and L. D. Hampton, "A review of deep ocean sound attenuation data at very low frequencies," J. Acoust. Soc. Am. 67, 147– 157 (1980).