

Technical Note

Physical and Elastic Properties of Marine Sediments off Bombay, India

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Abstract Keeping in view the paucity of information as to the nature of the marine sediments from the continental shelf adjoining the Indian subcontinent, a number of shallow seismic surveys were carried out, nearshore and offshore Bombay between 18°45'N and 21°00'N. Representative core samples preserving their natural state were also retrieved from the region in the water depths ranging from 5 to 70 m for the determination of physical properties in the laboratory. Data on the physical, acoustic, and elastic properties of the sediment cores are reported for the first time. Useful individual least-squares relations are presented for acoustic impedance, reflection coefficient, and bulk modulus against density; for the dependence of rigidity and bulk moduli on the constrained modulus; for the association between impedance and field sediment velocity against P-velocity; and for

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rigidity against Poisson's ratio. Results indicate that the bulk modulus and Young's modulus are higher for silty clay and clayey silt samples than for the clay samples. Similarly, the acoustic impedance, reflection coefficient, and constrained modulus of silty clay and clayey silt are also higher than clay. The results are found to be comparable to the North Atlantic and Bay of Bengal sediments.

Introduction

In recent years, there has been an increasing interest in the physical properties of marine sediments. The sound-velocity profiles and gradients in the upper oceanic sediments are important in underwater acoustics and marine geophysics. When sound velocity can be measured or accurately predicted for the sediment surface, then it is possible to compute a reasonable velocity profile for the upper part of the first layer (Hamilton and Bachman, 1977). Systematic evaluation of drill-hole samples for their physical properties reveals the nature of the soils and sediments. In addition, a study of the elastic properties of the sediments is of interest for drilling. Basic information of this kind can help in estimating site parameters useful for the location of offshore platforms and drilling rigs, laying pipelines, and so on. The works of Smith (1974, 1975), Davis, Horn, and Smith (1974), McCann and Smith (1974), and Hamilton (1971) are a reflection of the importance of the studies on marine sediments.

The absence of information on the physical properties of the sediments from the offshore shelf regions of the Indian coastline prompted the present work. In this study, shallow seismic surveys off Bombay (Figure 1) are carried out in order to achieve an understanding of the nature of the marine sediments. For this purpose, the velocity of sound in seawater is assumed to be 1,500 m/s. In the absence of the true field velocity, the depths obtained from the reflection records denote the apparent thickness only. A number of sediment cores are also retrieved along the survey routes, taking appropriate precautions for their preservation and subsequent use for laboratory measurements.

Experimental Techniques

Field Instrumentation

The shallow seismic profiling surveys off Bombay were carried out by the National Institute of Oceanography, both nearshore and offshore, with a Huntec Hydrosonde 2A system. It consists of an energy source (sparker/boomer), a transmitter (energy storage unit), the hydrophone array, and the receiver. The receiver unit comprises a signal recorder, a graphic recorder (19 cm wide—wet paper type), and a keying programmer. For these surveys, a boomer was used as the energy source, and the predominant frequency of the main pulse was 5 kHz. The 5 kHz frequency was preferred in order to have deeper penetration than the other frequency that was available (10 kHz).

The boomer was normally mounted on a catamaran and the recorder fixed in any given range of 31.25–8,000 ms/sweep. In practice, in the case of nearshore areas 62.5 ms/sweep and in the offshore areas 500 ms/sweep were operated, choosing proper filter setting to obtain the maximum information on the stratification. In general, the subbottom profiles showed sediments of varying thickness (from <1 m to >20 m), deposited over the hard bottom (sand/rock). However, in some favorable locations, when the sediments were sufficiently thick, a maximum penetration of more than 25 m was also recorded.

Core Samples

Alongside the shallow seismic profiles, a number of core samples (maximum length of 5 m) were collected (Figure 1) from the different survey routes followed. The locations for core collection were selected after careful examination of the shallow seismic records. The shallow seismic records helped the site selection because they indicated the nature, thickness, and distribution of the stratified sediments, thus enabling the coring to cover a complete cross-section of the available strata. All the samples were visually examined before they were subjected to smear studies.

It may be noted that in order to preserve the *in situ* conditions of the marine sediments, the retrieved cores were immediately encased in transparent Perspex tubes and capped at both ends in

their wet state, thus preventing any leakage of the sample fluids by sealing the ends. Out of such long cores, smaller lengths of core samples were taken and capped similarly for the various laboratory tests.

The locations of the core samples collected for laboratory studies at the National Geophysical Research Institute are given in Figure

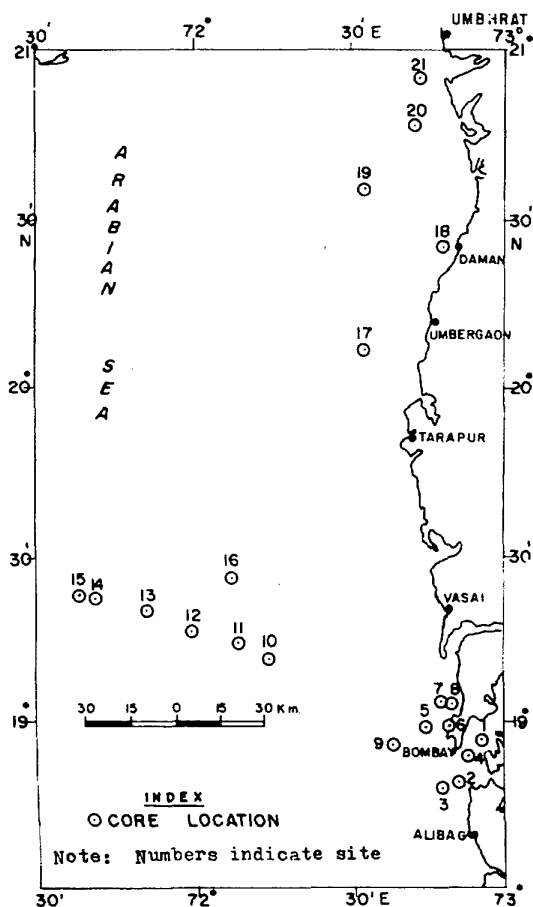


FIGURE 1. Core locations in the Arabian Sea.

1. The nature of the bottom and subbottom stratigraphic formations for the different locations may be seen in Figure 2. The area of Figure 2 abounds in clay, clayey sand, and sandy clay in that order, and at some places alternating sand and clayey sand, above the rocky terrain.

Of the many cores collected, some representative samples were selected for the study of their physical properties, on the basis of visual examination of the sediments through the Perspex walls of the core container, so as to include a cross section of the different types of sediments encountered in the surveys. These include four cores from Bombay harbor, four cores nearshore Bombay, seven cores between Bombay and Bombay High, and six cores between Bassein and Umbhrat. Full details concerning the cores are in Table 1.

Lab Instrumentation

The laboratory measurements of P-wave velocity on the sediment cores are determined by pulse transmission technique (Figure 3). The experimental setup of Ramana, Gogte, and Sarma (1981) consists of a pulse generator and a transmitting transducer on one side of the test sample and a receiving transducer and a preamplifier on the second side of the sample. The amplified signals are fed to an oscilloscope along with a synchronizing signal from the pulse generator to ensure a stable waveform on the screen for visual observations. The transit times are measured with the help of a movable marker and are accurate to 0.01 μ s. Piezoelectric circular plates of lead zirconium titanate vibrating in the compressional mode are suitably housed in the transmitting and receiving transducers. The piezoplates used are of 10 mm diameter and of 1 MHz fundamental frequency. A specially devised jig enables the seating of the test sample and ensures direct acoustic contact with the two transducers. The jig has the provision for flush contact of the front face of the acoustic transducer with that of the sample, and a rubber O-ring on the transducer holds the perspex core container in position, while at the same time preventing the leakage of fluids from the sample. A similar arrangement keeps the second acoustic transducer in position at the second face of the test sample. Owing to

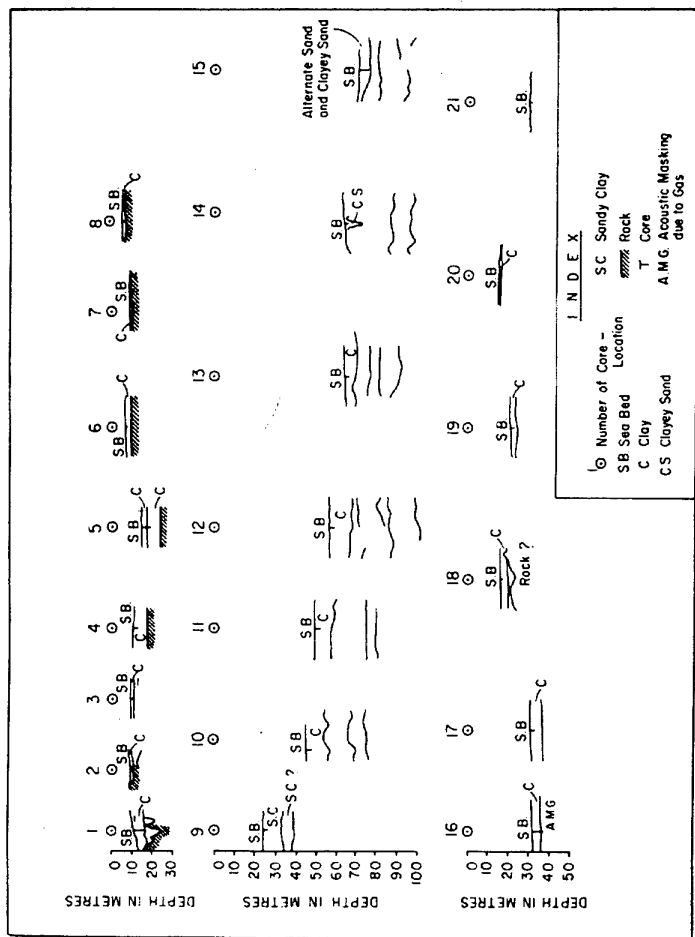


FIGURE 2. Diagram showing the nature of the sediments from seismic profiles at different locations.

Table 1
Summary of Field Investigation

Sample Number	Site Shown in Figure 1	Location	Depth to the Seabed (m)	Sample Interval in Core from Top (m)	Nature of the Sediment
BK 10a	1	18°56'05"N	10.8	0.95-1.13	Olive-gray clay
BK 10b		72°53'48"E		4.21-4.36	
BK 15	2	18°49'10"N	8.4	0.17-0.32	Olive-gray clayey silt
		72°49'50"E			
BK 17	3	18°48'05"N	9.0	1.12-1.28	Olive-gray clayey silt
		72°47'15"E			
BM 1	4	18°53'40"N	8.4	2.34-2.43	Olive-gray clay
		72°52'45"E			
BM 4	5	18°59'00"N	14.6	4.86-4.93	Olive-gray clay
		72°44'10"E			
BM 10	6	18°59'15"N	6.4	0.73-0.80	Silty clay
		72°47'48"E			
BM 12	7	19°02'33"N	8.2	0.58-0.65	Fine sand with shell fragments
		72°46'06"E			
BM 14	8	19°02'31"N	4.8	1.46-1.53	Olive-gray silty clay
		72°48'09"E			

(continued)

Table 1 (continued)

Sample Number	Site Shown in Figure 1	Location	Depth to the Seabed (m)	Sample Interval in Core from Top (m)	Nature of the Sediment
BH 3a	9	18°54'10"N	22.0	0.31-0.41	Olive-gray clay
BH 3b		72°36'50"E		1.60-1.70	Medium dark gray silty clay
BH 8a	10	19°09'50"N	45.0	0.60-0.70	Olive-gray clay
BH 8b		72°12'30"E		2.63-2.73	
BH 9a	11	19°12'40"N	49.0	0.30-0.40	Olive-gray silty clay
BH 9b		72°06'15"E		2.52-2.62	
BH 11a	12	19°15'50"N	57.0	0.20-0.30	Olive-gray silty clay
BH 11b		71°59'15"E		2.30-2.40	
BH 13a	13	19°18'40"N	63.0	0.00-0.10	Light olive-gray silty clay
BH 13b		71°59'15"E		2.30-2.40	
BH 16a	14	19°21'20"N	63.0	0.30-0.40	Medium bluish gray clayey sand
BH 16b		71°38'35"E		1.70-1.80	

BH 17a	15	19°21'50"N	70.0	0.45-0.55	Olive-gray sand
BH 17b		71°36'40"E		1.75-1.85	Dusky yellow-green clayey sand
G 37	16	19°24'48"N 72°06'05"E	32.0	1.80-1.90	Olive-gray clay
G 29a	17	20°06'15"N	31.0	0.70-0.80	Grayish olive-green clay
G 29b		72°31'15"E		1.50-1.60	Light olive-gray sand
G 31a	18	20°24'12"N	16.0	0.95-1.10	Olive sandy clay
G 31b		72°43'45"E		1.20-1.30	Olive sandy clay
G 34a	19	20°32'40"N	21.0	0.00-0.11	Dark yellowish brown sandy clay
G 34b		72°31'15"E		0.90-1.01	Dark yellowish clayey sand with shells
G 32a	20	20°46'30"N	15.0	0.00-0.10	Dark yellowish brown sand
G 32b		72°38'45"E		0.60-0.70	Olive-gray clay
				1.24-1.34	Pale red clay
G 33	21	20°55'10"N 72°39'35"E	29.0	0.38-0.49	Olive-gray clay with shells

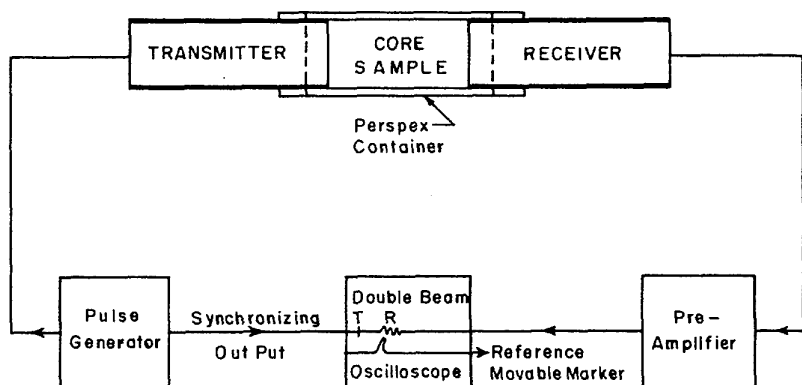


FIGURE 3. Schematic diagram for laboratory P-velocity measurements.

the wet state of the samples studied, no extraneous pressure on the sample was necessary to obtain good contact conditions. In fact, the arrangement of Figure 3 incorporated measures to ensure the natural state of the samples, arresting the leakage of the fluid media present in the cores.

Results and Discussion

The physical parameters of the marine sediments studied and the relevant relations that enable their determination are presented in Table 2. The density and P-wave velocity of the different sediment cores are in Table 3. Published data on the P- and S-velocity from the works of Hamilton et al. (1970) and Hamilton (1971) are used to derive the empirical relation $V_s = 2.924V_p - 4170.75$, where V_p and V_s are in m/s. The acoustic parameters—the acoustic impedance, constrained modulus, velocity ratio, field sediment surface velocity, and reflection coefficient—are evaluated, and the results so obtained are tabulated in Table 3. Acoustic impedance and constrained modulus were computed from the data on sediment velocity and density. It is appropriate to point out that although the surficial sediment velocities were lower than the overlying bottom water values, some good reflections were recorded because of the higher sediment densities and the impedance differences. The elastic properties (Table 4) of the respective sediment samples, such as Young's

Table 2
Physical Parameters Studied*

Physical Parameter	Relation	Legend	Units
Density (ρ)	$\rho = m/v$	mass/volume	kg/m ³
P-wave velocity (V_p)	$V_p = s/t$	distance/time	m/s
Acoustic impedance (Z)	$Z = \rho \cdot V_p$	density \times P-wave velocity	10 ⁵ kg/m ² ·s
Constrained modulus (D)	$D = \rho \cdot V_p^2$	density \times P-wave velocity ²	MN/m ²
Sediment velocity ratio (ψ)	$\psi = V_p/V_w$	P-wave velocity/P-wave velocity in seawater	ratio
Field sediment surface velocity (V_{fs})	$V_{fs} = V_p^2/V_w$	P-wave velocity ² /P-wave velocity in seawater	m/s
Reflection coefficient (R)	$R = (\rho V_p - \rho_w V_w) /$ $(\rho V_p + \rho_w V_w)$	(Density \times P-wave velocity - density in seawater \times P-wave velocity in seawater)/(density \times P-wave velocity + density in seawater \times P-wave velocity in seawater)	ratio
Rigidity modulus (μ)	$\mu = \rho V_s^2$	mass density \times S-wave velocity ²	MN/m ²
Bulk modulus (K)	$K = \rho(V_p^2 - \frac{4}{3}V_s^2)$		MN/m ²
Poisson's ratio (σ)	$\sigma = \frac{[(V_p/V_s)^2 - 2]}{2[(V_p/V_s)^2 - 1]}$	derived from V_p and V_s	ratio
Young's modulus (E)	$E = \rho V_p^2(1 - \sigma^2)$	derived from ρ , V_p , and σ	MN/m ²

* Where it is not mentioned, density and velocity refer to the sediments.

Table 3
Density and Acoustic Properties of Sediments

Sample Number	Density (kg/m ³)	Measured		Calculated		Acoustic Impedance (10 ⁵ kg/m ² ·s)	Constrained Modulus (MN/m ²)	Sediment Velocity (ratio)	Field Sediment Surface Velocity (m/s)	Reflection Coefficient (ratio)
		P-wave Velocity (m/s)	S-wave Velocity (m/s)	S-wave Velocity (m/s)	Sediment Velocity (ratio)					
BK 10a	1,440	1,530	303	22.0	3.37	1.020	1,561	0.166		
BK 10b	1,440	1,544	344	22.2	3.43	1.029	1,589	0.171		
BK 15	1,560	1,518	268	23.7	3.59	1.012	1,536	0.201		
BK 17	1,480	1,535	318	22.7	3.49	1.023	1,570	0.181		
BH 3a	1,470	1,511	247	22.2	3.36	1.007	1,522	0.170		
BH 3b	1,470	1,515	259	22.3	3.37	1.010	1,530	0.171		
BH 8a	1,470	1,533	312	22.5	3.45	1.022	1,567	0.178		
BH 8b	1,470	1,549	358	22.7	3.52	1.033	1,600	0.182		
BH 9a	1,470	1,505	230	22.0	3.31	1.003	1,510	0.165		
BH 9b	1,460	1,574	432	23.0	3.62	1.049	1,652	0.187		
BH 11a	1,460	1,523	282	22.7	3.46	1.015	1,546	0.181		
BH 11b	1,490	1,559	388	23.2	3.62	1.039	1,620	0.192		
BH 13a	1,490	1,487	177	22.0	3.27	0.991	1,474	0.166		
BH 13b	1,480	1,498	209	22.2	3.32	0.999	1,496	0.169		
G 29a	1,470	1,531	306	22.5	3.45	1.021	1,563	0.177		
G 37	1,390	1,537	323	21.4	3.28	1.025	1,575	0.151		

Table 4
Elastic Properties of Offshore Sediments

Sample Number	Young's Modulus (MN/m ²)	Rigidity Modulus (MN/m ²)	Bulk Modulus (MN/m ²)	Poisson's Ratio
BK 10a	2,592	132	3,190	0.479
BK 10b	2,658	170	3,201	0.473
BK 15	2,753	112	3,446	0.483
BK 17	2,585	149	3,287	0.477
BH 3a	2,563	90	3,236	0.486
BH 3b	2,581	99	3,242	0.484
BH 8a	2,659	143	3,256	0.478
BH 8b	2,737	189	3,268	0.471
BH 9a	2,520	77	3,204	0.488
BH 9b	2,854	272	3,254	0.459
BH 11a	2,653	119	3,297	0.482
BH 11b	2,831	224	3,322	0.467
BH 13a	2,516	46	3,212	0.493
BH 13b	2,561	65	3,234	0.490
G 29a	2,675	138	3,262	0.479
G 37	2,511	145	3,091	0.476

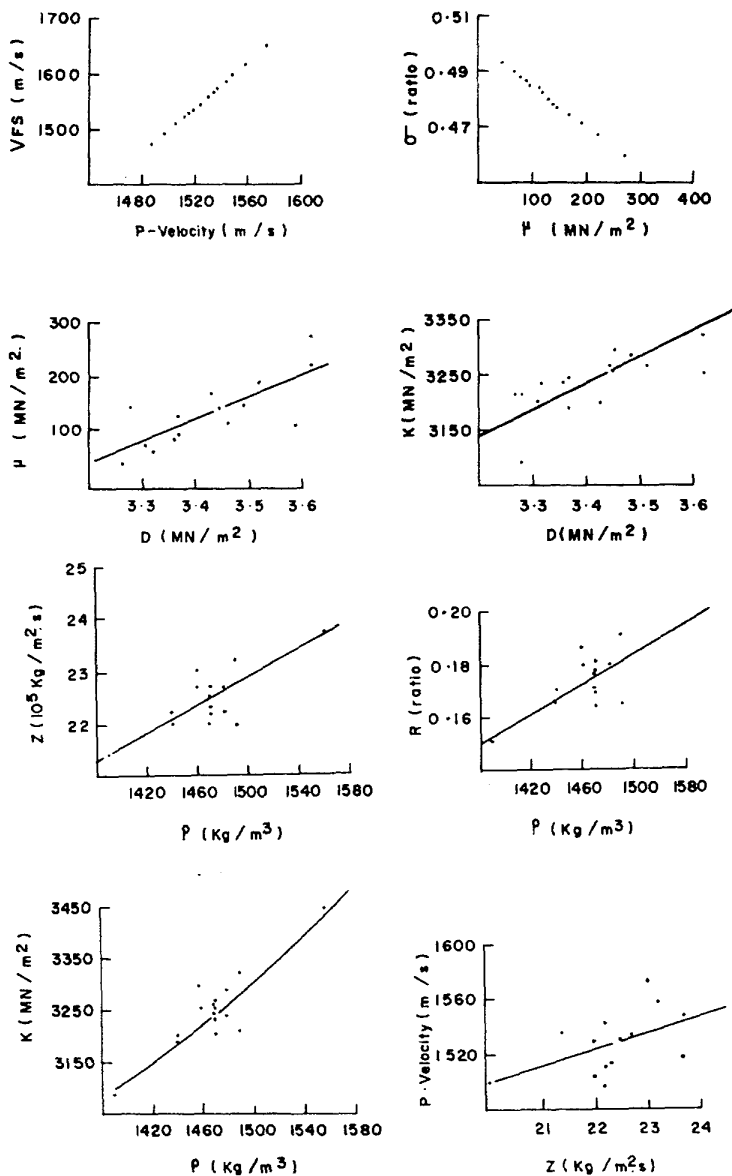


FIGURE 4. Interdependence of physical properties.

Table 5
Least-Squares Best-Fit Relations Between Different Physical Parameters

X-axis	Y-axis	Relation
Density	Acoustic impedance	$Z = 1.336\rho + 0.283$
Density	Reflection coefficient	$R = 0.285\rho - 0.245$
Density	Bulk modulus	$K = 5.091\rho - 4.229$ (linear)
		$K = -0.5851 + 3.2806\rho$ $- 0.4561\rho^2$ (nonlinear)
Acoustic impedance	P-velocity	$V_p = 0.122Z + 1.255$
P-velocity	Field sediment surface velocity	$V_{FS} = 3.757V_p - 4.184$
Rigidity modulus	Poisson's ratio	$\sigma = -0.143\mu + 0.499$
Constrained modulus	Rigidity modulus	$\mu = 0.394D - 1.216$
Constrained modulus	Bulk modulus	$K = 0.468D + 1.644$

modulus, the rigidity modulus, the bulk modulus, and Poisson's ratio, are also calculated. The interrelationships between the different physical properties are shown in Figure 4. The empirical relations derived from such an analysis are summarized in Table 5. It may be seen that, with the exception of the relation between density and bulk modulus, all the relations are linear. Regression analysis for the data of Figure 4 showed a correlation coefficient varying between 0.73 and 0.99 (P-velocity versus acoustic impedance being an exception).

It is evident from Table 3 that the offshore sediment P-velocities lie between 1,480 and 1,570 m/s, but the majority of them have a very narrow range of 1,510–1,550 m/s, giving an average P-velocity of 1,530 m/s, whereas the average velocity of the bottom water samples was 1,500 m/s. The corresponding densities of the same sediments range from 1,390 to 1,560 kg/m³, giving an average value of 1,470 kg/m³. Sound propagation varied from sample to sample, and in general the transmission was better in clayey samples than in sandy sediments. In particular, propagation deteriorated in samples with shells and those whose ends were gritty.

The wave velocities in the marine sediments off Bombay are comparable to those reported by Smith (1974) in Atlantic cores and Hamilton and Bachman (1977) in the sediments off Andaman coast in the Bay of Bengal. In fact, the scatter in the wave velocities off Bombay is relatively low in contrast to the North Atlantic cores, and this pattern is perhaps due to the narrow shelf area covered by the present work. The bulk modulus and rigidity values of the sediments of this work are also comparable to those of McCann and Smith (1974).

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