

Sound Velocity, Density, and Related Properties along a Transect across the Bay of Bengal

K. S. Krishna,¹ D. Gopala Rao,¹ G. Prabhakar S Murty,¹ and Y. V. Ramana²

¹National Institute of Oceanography, Dona-Paula, Goa 403004, India, and ²National Geophysical Research Institute, Hyderabad 500007, India

Abstract

Physical properties, sound velocity and density of 95 core samples from ten locations along a transect (parallel to 15°N latitude) across the Bay of Bengal were measured. Results indicate that sound velocities range from 1,482 to 1,679 m/s (av: 1,583 m/s) and densities from 1,338 to 1,757 kg/m³ (av: 1,527 kg/m³). It has been observed that dark colored clays and sandy clays show higher values of sound velocity and density than the average values. A comparative study of the same with that of the sediment cores collected from the Norwegian basin, Mediterranean Sea, and Hatteras, Nares Abyssal plains, western North Atlantic Ocean was done.

Introduction

The presence of the world's largest sedimentary fan in the Bay of Bengal, northeastern Indian Ocean, invoked varied interest in studying the regional sediments. Our transect runs across the middle fan (Fig. 1). Physical measurements were made to reveal the nature of the sediments and to produce a geo-acoustic model of elastic behavior of the sea bed which are of interest to offshore engineering activities, such as construction and placement of offshore platforms, laying of pipelines, etc. The data are also important for computing velocity profile of the upper sediment layer and its thickness, and for a better understanding of the sound propagation in the sea floor sediments of the region.

These measurements along a transect (parallel to 15°N latitude) across the middle fan are new and have not been reported on. A total of 95 sediment samples were collected from ten different sediment cores (Fig.

1). Necessary precautions were taken to maintain the field in situ conditions while collecting, preserving, and transporting the cores to the laboratory for carrying out measurements in ambient state. A sound velocity of 1,500 m/s in sea water was considered for computation of the velocity ratio and other related properties of the sediments.

This article presents, (1) the general results of laboratory measurements of the sound velocity and density of the sediments from the transect and their computed properties,¹ and (2) the empirical relations and correlation coefficients based on statistical analysis of the measured properties and discussions in the light of the published works of Hamilton and others (1974) in that area.

Sample Collection

During the ORV Sagar Kanya cruise 31 in the Bay of Bengal, as part of the project on Bay of Bengal Fan studies, gravity cores were collected (Fig. 1) at 1° interval along a transect parallel to the 15°N latitude across the mid-fan. No sediment samples were recovered in between stations 4 and 5, and 6 and 7. The sample stations are located in water depths ranging from 2,515 m to 3,162 m, the maximum core length was 7.5 m. The cores were immediately subsampled at varied intervals for laboratory measurements. The

¹The data are presented in graphical form. Readers interested in the real values can obtain a copy of the tables from the senior author.

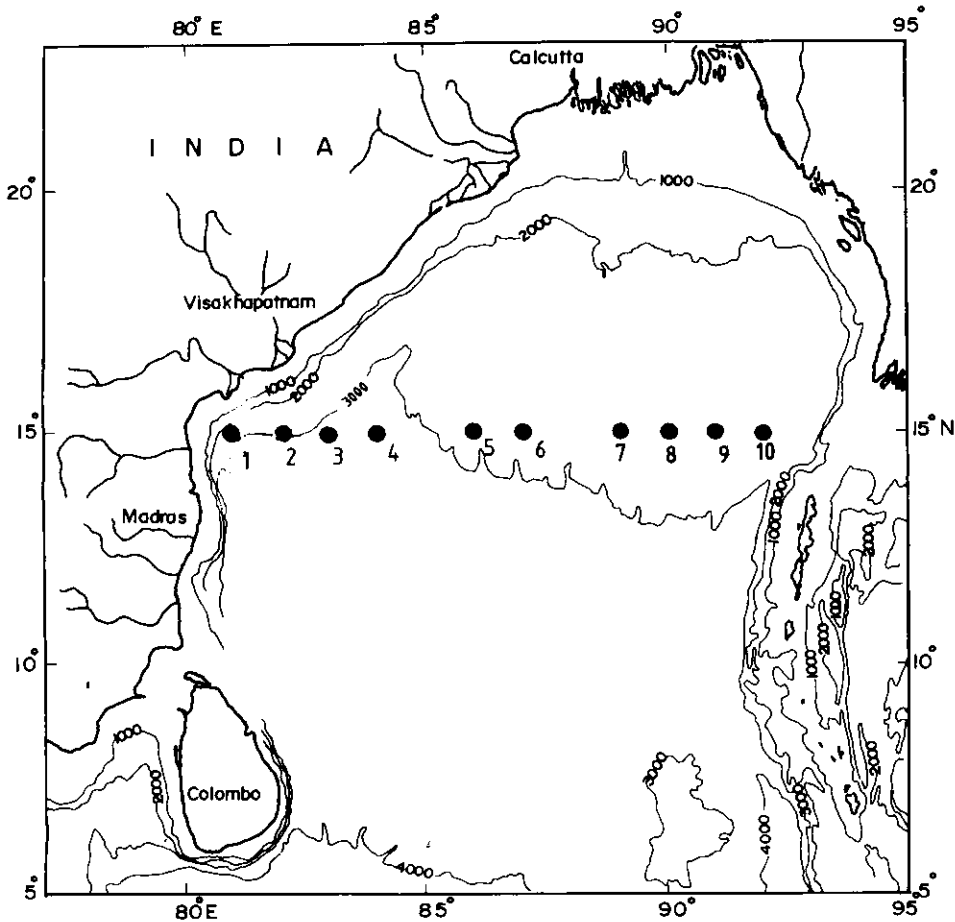


Figure 1. Core locations in the Bay of Bengal and adjacent areas.

subsamples were encased in transparent perspex tubes and capped on both ends, preventing possible leakage of sample fluids.

Laboratory Analysis

Densities (ρ) of the sediment samples were determined by the displacement method using a Walker's steelyard (Read 1970), since it allows the testing of even larger cores. It essentially has a long graduated beam pivoted near one end and counter balanced by a sliding weight on the shorter arm. The test sample is suspended and moved along the beam until it counter balances the constant weight (reading a). The sample is then immersed in water and moved along the beam until the constant weight is again balanced and a second reading b is obtained. The readings a and b being inversely proportional to the weights of the sample in air and in water, respectively.

$$\text{Density of the sample } (\rho) = \frac{1/a}{1/a - 1/b} = b/(b - a)$$

The elastic wave velocities (V_p) were determined by the Compensated Ultrasonic Timer Technique

(CUTT) introduced by Ramana and Sarma (1984) (Indian Patent No. 159375 by Ramana and Sarma 1983, 1988). The experimental arrangement of CUTT is shown in Figure 2. It utilizes a direct pulse (generated by one pair of acoustic transducers) for opening an electronic gate, and another similar (sample delayed) pulse for closing it. A digital display of the difference in the transit times through the test sample and the compensated set of transducers is given by a counter/timer. The experimental setup is sensitive to read time intervals of 0.1 to 0.001 μ s, depending upon the counter/timer working configuration. The travel time for a known length gives the velocity of sound of the sediment sample. We used matched pairs of acoustic transducers of 1 MHz frequency.

The shear wave velocity (V_s) was calculated from the empirical relation $V_s = 2.924 V_p - 4,170.9$ where V_p and V_s are in m/s. It is based on Hamilton and others (1970) and Hamilton (1971). The other parameters—acoustic impedance (Z), constrained modulus (D), velocity ratio (ψ), field sediment surface velocity (VFS), reflection coefficient (R), Young's modulus (E), rigidity modulus (μ), bulk modulus (K) and Poisson's ratio (σ)—were computed from the sediment velocities and densities.

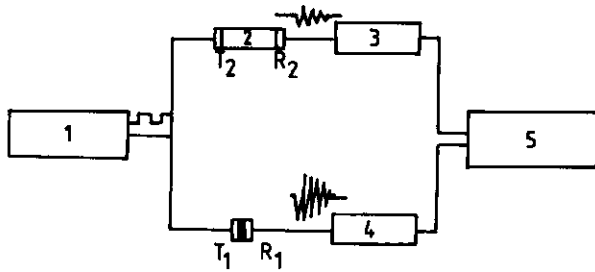


Figure 2. Compensated Ultrasonic Timer Technique (CUTT): 1. Single shot mode pulse generator (50 Ω, 50V, 50W); 2. Sample; 3., 4. Preamplifiers (0–40dB); 5. Digital universal counter/timer ($\pm 0.001\mu\text{sec}$).

Results

Results are presented in diagrams, regression equations, and tables. Table 1 shows the number of samples in each sediment type and range, average, standard deviation, and coefficient variation for density and sound velocity. The algebraic equations utilized to compute the various physical properties are given by Subba Raju and Ramana (1986). Regression equations and coefficients are determined from the computed physical properties and shown in Table 2. Figures 3 and 4 illustrate the depth vs. density and the depth vs. velocity plots respectively. The regression equations are calculated for the plots. Figure 5 illus-

trates the range of the measured density (ρ in kg/m^3) and its interrelationship with V_p and V_s . Figure 6 shows the complete range of values of the various physical properties of the sediments in the area of investigation and their interrelationships.

Discussion

The sediment P -velocities vary between 1,482 and 1,679 m/s, with on average of 1,583 m/s. A great majority of them show velocities in the range of 1,550 to 1,625 m/s. The densities of the sediments range from 1,338 to 1,757 kg/m^3 , with an average value of 1,527 kg/m^3 . After analysis of the data, it is able to say the measured density and velocity are certain extent related to the sediment type. The sediment samples collected from the cores are mainly two types: (1) clays having color range from gray, brown to greenish with various shades, and (2) sandy clays. Most of the dark colored clays and sandy clays are showing higher values of sound velocity and density than the average values. The computed physical properties of these samples are shown in Figure 6. The overall dispersion of the density and velocity are also determined by computing the standard deviation (SD) and coefficient variation. The determined SD and coefficient variation of sound velocity are 42.62 and 2.69 respectively. The SD and coefficient variation for density are 99.35 and 6.51 respectively. From the re-

Table 1. Properties of Sediments from the Bay of Bengal: Average (Avg), Standard Deviation (SD), and Coefficient Variation (CV) of Density and Sound Velocity

Sediment type	No. of samples	Density (Kg/m^3)					Velocity (m/sec)				
		Min	Max	Avg.	SD	CV	Min	Max	Avg.	SD	CV
Clay ^a	76	1338	1649	1491	68.49	04.59	1509	1679	1579	46.80	02.96
Sandy clay	19	1556	1757	1666	56.73	03.41	1482	1658	1590	53.34	03.35

^aranges from light to dark color

Table 2. Regression Equations and their Coefficients between Different Physical Parameters

X-axis	Y-axis	Regression Equation	Regression coefficient
Density	Velocity	$\rho = -0.5V_p + 2320$ (density 1338 to 1529 kg/m^3) $\rho = 0.41V_p + 915$ (density 1529 to 1757 kg/m^3)	
Density	Acoustic impedance	$Z = 1.667\rho - 1.099$	0.89
Density	Reflection coefficient	$R = 0.333\rho - 0.298$	0.92
Density	Bulk modulus	$K = 2.857\rho - 1.054$	0.98
Acoustic impedance	P velocity	$V_p = 0.156Z + 1.197$	0.44
P-velocity	Field sediment surface velocity	$V_{FS} = 2.088V_p - 1.633$	1.00
Rigidity modulus	Poission's ratio	$\sigma = -0.145\mu + 0.500$	-0.99
Constrained modulus	Rigidity modulus	$\mu = 0.370D - 1.094$	0.77
Constrained modulus	Bulk modulus	$K = 0.483D + 1.531$	0.68

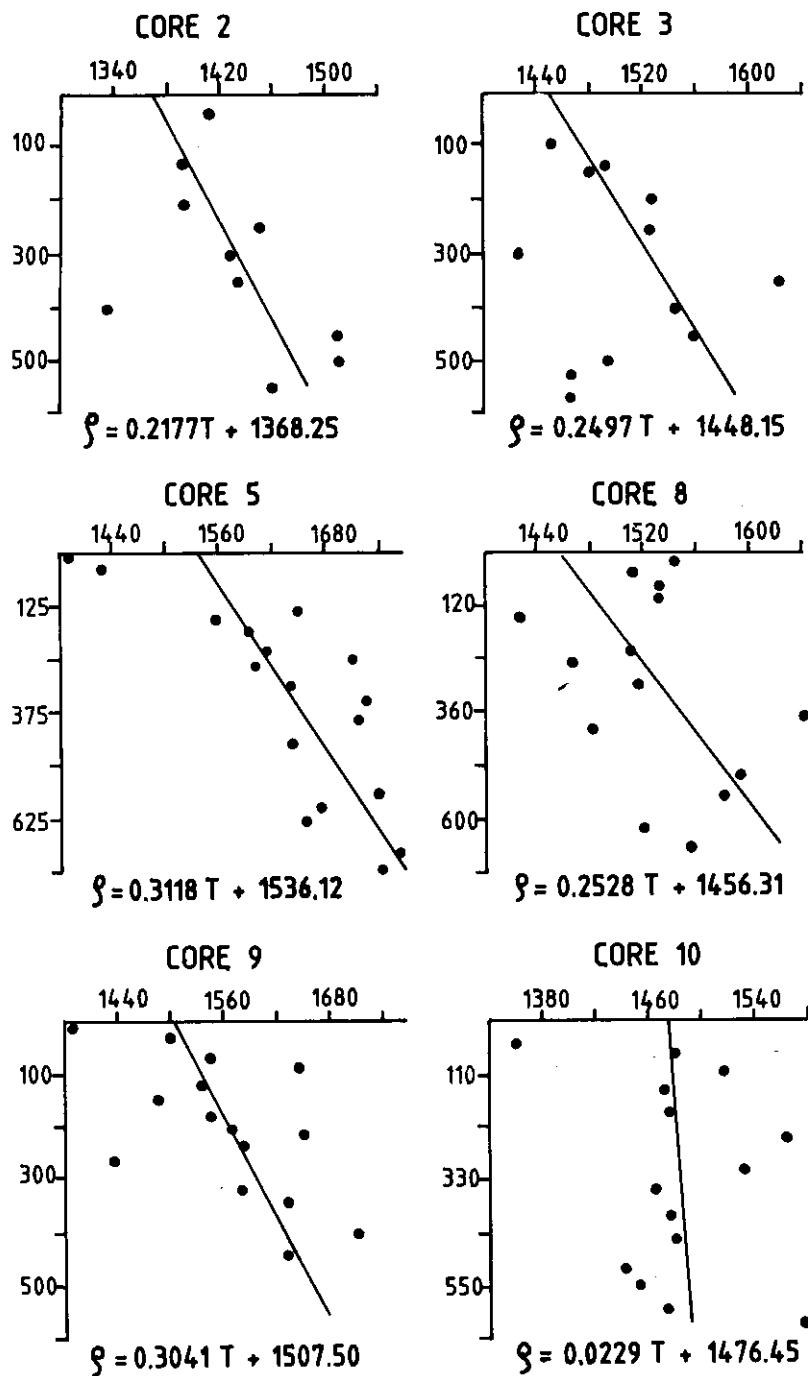


Figure 3. Depth vs. density plots for different cores. Horizontal axis: density (ρ) (kg/m^3). Vertical axis: Depth (T) (cm).

sults, it is evident that the elastic modulus values are low in general and are a reflection of the density and velocity observed. The high Poisson's ratio and the low modulus denote the low strength of the sediments. However, these results are as expected of the oceanic sediments and are comparable with those reported by earlier workers (Bachman and Hamilton 1983, Hamilton and others 1974, 1977).

The plots (Fig. 3) for the depth vs. density of cores

2, 3, 5, 8, 9, and 10 indicate a general increasing trend of density with depth. However, core 10 shows a less of a slope of increasing density with depth than the other cores. The results of cores 8 and 9 show a wide scattering in the density depth results, but exhibit an increasing trend. The plots (Fig. 4) for the depth vs. velocity of the cores 5, 8, 9, and 10 indicate a general increasing trend of velocity with depth. However, cores 2 and 3 show a decrease in velocity

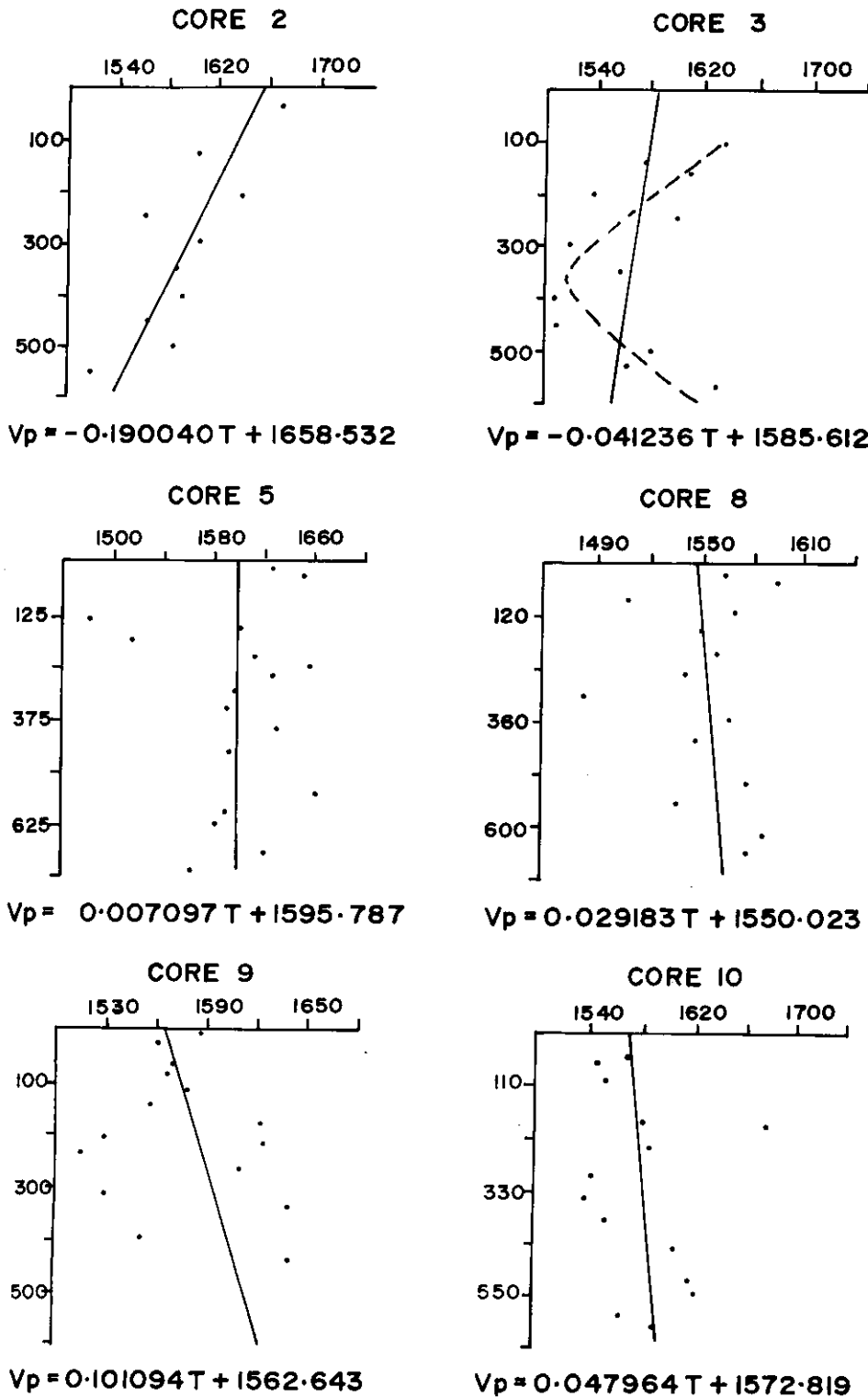


Figure 4. Depth versus sound velocity plots for different cores. Horizontal axis: velocity (V_p) (m/sec). Vertical axis: Depth (T) (cm).

with depth, though the least square fit of velocities vs. depth in core 3 shows a decrease in trend with depth (continuous plot) which appears to be in agreement with results from cores 2 and 9. An overview of the plot for core 3 resembles a decrease in velocity

with depth in the top 3.5 m length and then an increase (dashed line) (Fig. 4). This is indicative of the presence of fine grained sediments concealed by the coarse grained sediments, contributing to an increase in porosity. The coarse nature of the alluvium near

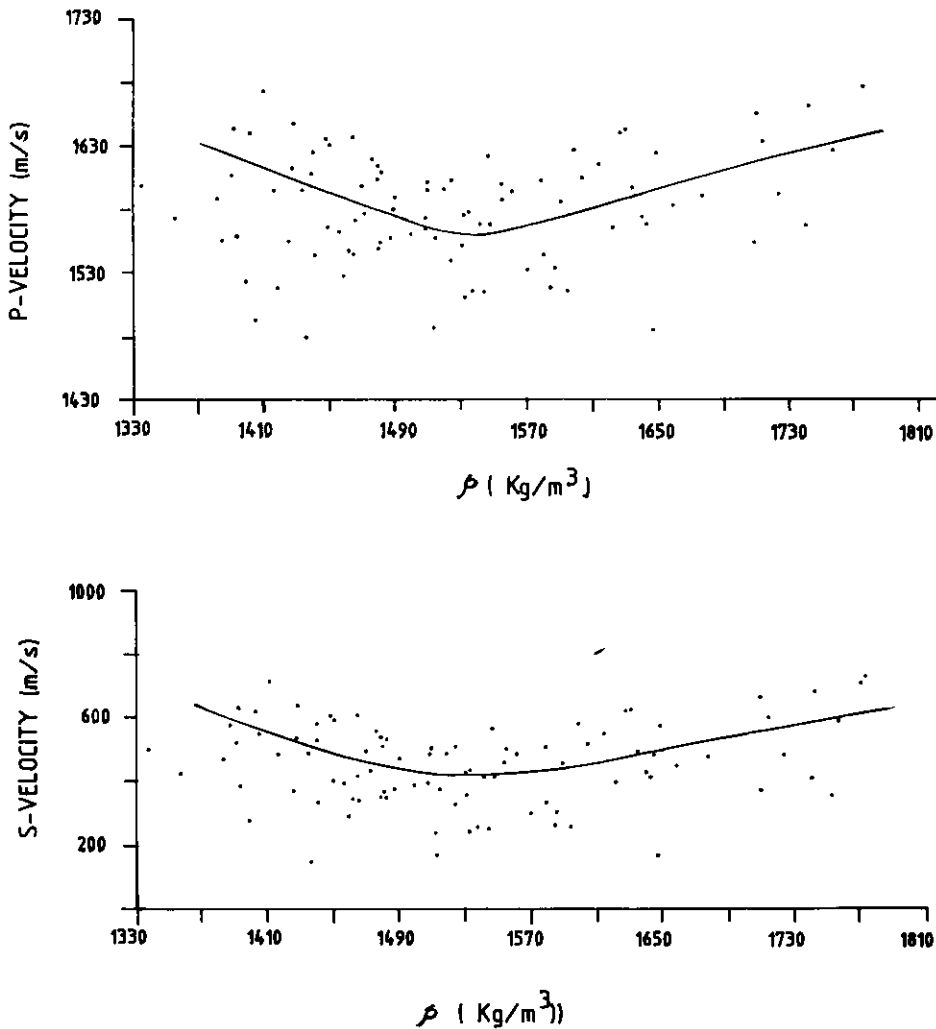


Figure 5. Compressional wave (sound) velocity and shear wave velocity vs. density plots.

the coast, due to active deposition caused by the fast flowing discharge from the East Coast rivers (Fig. 1), accounts for the decreasing trend (Fig. 4) (anomalous relationship) shown by core 2, whereas the results of density–depth plot (Fig. 3) for core 2 are showing an increasing trend. It appears that this particular core is very much influenced by porosity. The results of core 9 show a wide scattering of velocity depth results, but exhibit an increasing trend. The velocity vs. density plots (Fig. 5) also indicate an initial decrease followed by an increase in velocities. But the generally expected relation of increase in velocity with density is not explicit in the sediments, particularly with those samples whose densities range from 1,338 to 1,500 kg/m^3 . It appears that these arcuate trend variations in sound velocity of the sediments are considerably influenced by porosity. The trend of an initial decrease, and thereafter an increase, in wave velocities (both compressional and shear) with density is because of the coarse fractions at shallow depths and

the finer fractions below them all along this transect. The scatter distribution of sample points in the velocity–density plot of Figure 5 may be the reason that our data are collected from different morphologic provinces. However, density is the most important physical property because of its direct use in gravity and seismic studies. Consequently, the velocity–density relationships are more useful. The plots of the computed properties (Fig. 6) show linear best fit lines, although some scatter in the points is evident.

In general stiff clays and dark colored clays occurring at greater depths showed high velocities, with the exception of core 2 which is located close to the continental slope of India, in contrast to gray clays with low velocities. The low velocities of the stiff clays and the sandy clays of the continental slope are, perhaps, due to the high porosity of the increased sediment input from the coastal rivers, i.e., the Krishna and Godavari Rivers, and local slumping.

The sound velocities and densities of sediment from

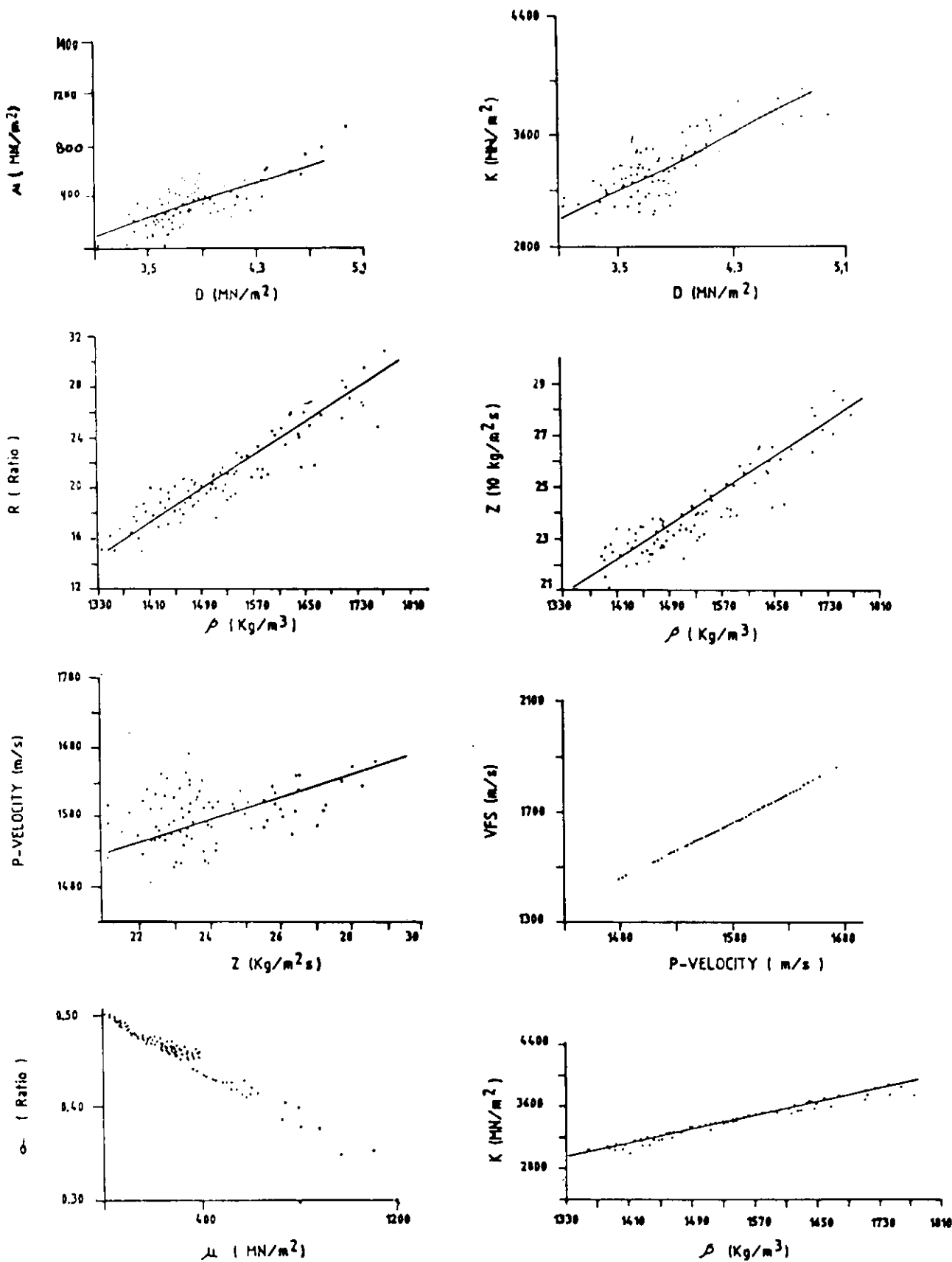


Figure 6. Interrelationships between the different physical properties.

the Bay of Bengal are comparable to the results by Hamilton and others (1974) from the Bay of Bengal, Hamilton and Bachman (1977) in the sediments off the Andaman coast in the Bay of Bengal, and Bachman and Hamilton (1983) in the Bay of Bengal and adjacent areas.

The present results of measured velocity and density ranges are found to be comparable to those reported from the Norwegian basin and the Mediterranean Sea (Horn and others 1968), and from the Hatteras and Nares Abyssal plains, western north Atlantic Ocean (Tucholke 1980). The scatter in the velocity–density plot of present study is relatively high in contrast to the western north Atlantic Ocean cores and more or less same to the Norwegian basin and the Mediterranean sea cores. The reason for the tight distribution of sample points in the velocity–density plot of western north Atlantic Ocean cores is that all the cores were collected from one morphologic province. The general arcuate trend relationship in the velocity–density (Fig. 5) plot is explicitly seen and comparable to the cores from the Norwegian basin and the Mediterranean sea, and in situ velocity–wet bulk density of cores from Hatteras and Nares Abyssal plains, western north Atlantic Ocean.

Conclusions

1. The laboratory studies of the sediment core samples provides a profile of the variations in the compressional and shear wave velocities vs. depth and other physical properties of the top 7.5 m sediment across the Bay of Bengal. A linear relationship of velocity increase with depth has been observed in general even within the shallow zone.

2. The spatial variations in the physical properties will be complimentary to arrive at a reliable velocity–depth profile of the deeper parts and to establish interrelationship models of the properties of the sediments of the margin and the Bay of Bengal.

Acknowledgments

The authors thank the Directors of National Institute of Oceanography, Goa and National Geophysical Research Institute, Hyderabad for permission to carry out these studies and to publish the results. Shri P. S. N. Murthy encouraged us, and Drs. Ch. M. Rao, M. Veerayya and A. L. Paropkari helped in collecting the cores, with sampling, and onboard geological studies.

References

- Bachman RT, Hamilton EL (1983) Sediment sound velocities from sonobuoys: Sunda trench and Forearc basins, Nicobar and central Bengal fans, and Andaman sea basins. *Journal Geophysical Research* 88:9341–9346
- Hamilton EL (1971) Elastic properties of marine sediments. *Journal Geophysical Research* 76:579–604
- Hamilton EL, Bucker HP, Keir DL, Witney JA (1970) Velocities of compressional and shear waves in marine sediments determined in situ from a research submersible. *Journal Geophysical Research* 75:4039–4049
- Hamilton EL, Moore DG, Buffington EC, Sherrer PL (1974) Sediment velocities from sonobuoys: Bay of Bengal, Bering sea, Japan sea, and North Pacific. *Journal Geophysical Research* 79(17):2653–2668
- Hamilton EL, Bachman RT (1977) Sediment velocities from sonobuoys: Bengal fan, Sunda trench, Andaman basin and Nicobar fan. *Journal Geophysical Research* 82:3003–3012
- Horn DR, Horn BM, Delach MN (1968) Correlation between acoustical and other physical properties of Deep sea cores. *Journal Geophysical Research* 73:1939–1957
- Ramana YV, Sarma LP (1984) Compensated ultrasonic timer technique. *Acoustics Letters* 7:177–180
- Ramana YV, Sarma LP (1988) A Compensated Ultrasonic Timer Device to determine mean velocity in solid/liquid/underground strata for use in earth materials and engineering sciences. Indian Patent No. 159375, 1988 (filed 15 June 1983)
- Read HH (1970) *Rutley's elements of mineralogy*. George Allen & Unwin Ltd., London, Edition 26, pp. 65–66
- Subba Raju LV, Ramana YV (1986) Physical and elastic properties of marine sediments off Bombay, India. *Marine Geotechnology* 6:359–375
- Tucholke BE (1980) Acoustic environment of the Hatteras and Nares Abyssal plains, western north Atlantic Ocean, determined from velocities and physical properties of sediment cores. *Journal Acoustical Society America* 68:1376–1390

Manuscript received 27 June 1988; revision received 3 March 1989.