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Physical, Acoustic and Elastic Properties of Submarine Basalts from Bombay Harbour Area, West Coast of India

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ABSTRACT

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Physical, acoustic and elastic properties were determined for submarine basalts from the Elephanta islands, Bombay harbour area. Sample densities ranged from 2.39 to 2.98 Mg·m^{-3}, while sound wave velocities showed a scatter of 3.39 to 6.80 km·sec^{-1} and 1.74 to 4.42 km·sec^{-1}, for longitudinal and transverse waves, respectively. These properties are broadly compatible with the continental basalts of India as well as other parts of the world. Evaluation of analytical results, based on individual least squares solutions amongst various properties and observed property variations, indicates differences in porosity, seawater alteration, and lithological and compositional changes. The significance of the curvilinear relationship between the number of cracks and the longitudinal wave velocity in the specimens is related to coastal and harbour developmental activities.

ADDITIONAL INDEX WORDS: Submarine basalts, Bombay harbour, physical, acoustic and elastic properties, cracks, coastal activities.

INTRODUCTION

A large extent of the Indian peninsula, in western and central India, is carpeted by the Deccan Traps (Figure 1). The basalts attain a maximum thickness of 2 km near the Bombay coast. They are submerged along the continental margin of western India to a maximum depth of 1.5–2.0 km, below the Tertiary sediments. The surface and subsurface geology of the basalts in the Bombay region have been studied by various workers (*e.g.* SUKHESWALA and POLDERVAART, 1958; SETHNA, 1981; DESHMUKH, 1984; KARISIDDAIAH, 1988). Extensive laboratory studies of basalt physical properties were conducted by BALAKRISHNA (1970), RAMANA and GOGTE (1974), KAILASAM *et al.* (1976), and RAMANA *et al.* (1976), and RAMANA (1978) for samples collected from the thin eastern Deccan Traps to the west where their maximum thickness is pronounced. Shallow and deep seismic surveys were carried out by ATHAVALE and INDRA MOHAN (1976), BOSE and ARORA (1969), KAILASAM *et al.* (1976), KAILA *et al.* (1981, 1981a, b), RAVENDRA NATH *et al.* (1987) and KAILA (1988). Sample locations and field survey areas are shown in Figure 1.

The above studies showed that the compact, massive, hard traps exhibit higher densities and velocities whereas the vesicular, porous ones tend towards lower values. These properties help differentiate the flows and identify trap varieties. The traps generally exhibit, over a greater part of the area, a uniform density of 2.9 Mg·m^{-3}; more acid types tend to show minimum values around 2.58 Mg·m^{-3} while ultrabasics may have higher values up to 3.03 Mg·m^{-3} (KRISHNAN, 1968).

More recently, geological and geophysical surveys have attempted to confirm the presence of Deccan Traps in the shallow waters of Bombay harbour, and the surrounding areas, by deploying shallow seismic surveys (BHATTACHARYA *et al.*, 1987; ALMEIDA *et al.*, 1989; RAVENDRA NATH *et al.*, 1989, 1989a).

Although the physical and elastic properties of Bombay basalts that are subaerially exposed have been reported previously, similar information is lacking for basalts lying under shallow waters around Bombay harbour. The physical and elastic properties of submarine sediments and basalts are useful to site characterizations for erection of nearshore structures, laying offshore pipelines, and

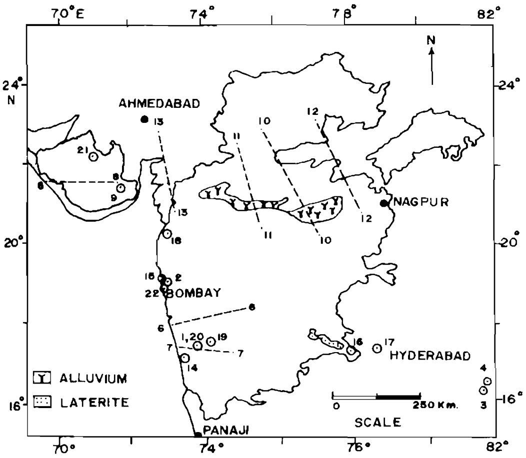

Figure 1. Extent of Deccan Trap exposures on land and some traverses and sample locations. Numbers with dots and circles indicate sample locations while numbers with dashed lines refer to the detailed traverses given in Table 5.

for the location of harbours, wharfs *etc*. The need for geophysical information has been indicated by different agencies for numerous applications. Acoustic and elastic properties of submarine basalts are thus investigated and reported here.

CORE SAMPLES

All the rock cores were collected in shallow water depths of nearly 5 m (Figure 2). Out of the several cores collected, twenty-nine specimens were selected for measuring the petro-physical properties. Sample locations are listed in Table 1. Laboratory studies of these core specimens were conducted at the National Geophysical Research Institute. The geographic distribution of bottom and subbottom basalts which underlie a soft surface clay is shown in Figures 2 and 3. A layer of stratified sediments is sometimes sandwiched between the basalts.

LABORATORY ANALYSES

The densities of the rock specimens were determined by employing Walker's steelyard (READ, 1970), and calculating b/b − a, where 'a' is the

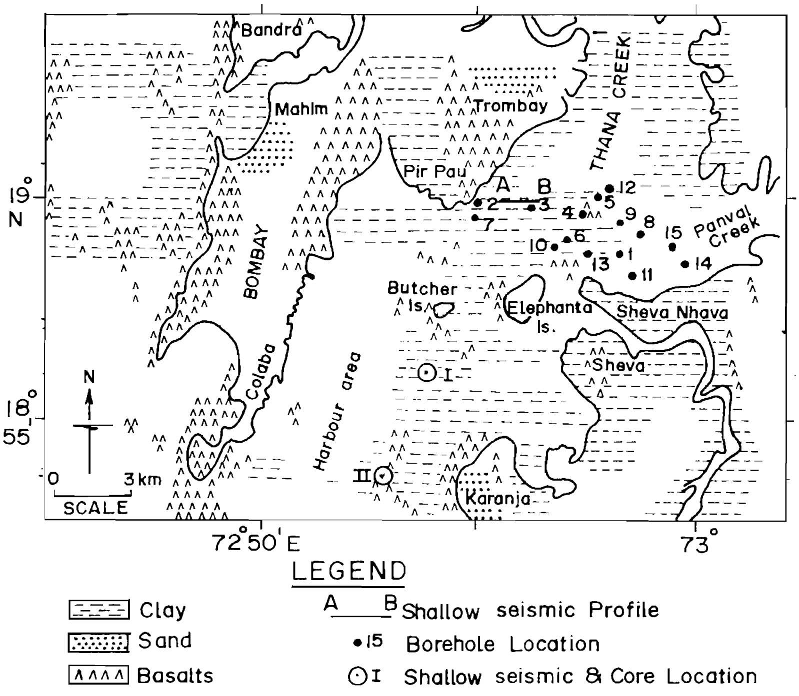

Figure 2. Occurrence of Deccan Traps on land and in the Bombay harbour area (modified after Almeida *et al.*, 1989). Solid circles with numbers inset indicate where the borehole samples were collected. Profile AB and locations I & II are as referred in Figure 3.

Table 1. *Details of field investigations.*

Specimen No.	Site Shown in Figure 2	Sample Interval in the Core from the Top (m)
A/1	1	7.7–9.1
Ba	2	13.6–15.1
Bb		15.1–16.2
B22/1	3	10.5–14.5
B22/2		14.5–18.8
B22/3		18.8–19.8
B22/4		19.8–20.8
C/1	4	24.5–26.5
C/2		29.0–31.0
C/3		31.0–33.0
C/4		33.0–34.0
C/5		34.0–35.0
D1	5	20.3–21.0
E/1	6	15.5–17.1
E/2		17.1–18.1
E/3		18.4–20.5
M3	7	0.0–7.1
M7	8	0.0–10.0
M11	9	11.0–12.5
M13	10	0.0–15.0
M14	11	0.0–5.5
M19/1	12	6.2–10.0
M19/2		10.4–20.0
M19/3		20.0–21.0
M22	13	0.0–10.0
M23	14	7.5–8.5
M25/1	15	0.0–3.0
M25/2		3.0–6.0
M25/3		6.0–7.5

reading obtained with the specimen in the air, and 'b', the reading in water. This method is preferred for the study of large specimens. The laboratory measurements of P- and S-wave velocities (V_P and V_S) in the specimens were determined by the modified pulse transmission technique, using compensating principles introduced by RAMANA and SARMA (1984).

RESULTS AND DISCUSSION

Investigations to assess the suitability of sediments as foundation materials are by no means new and have been reported for the North Sea sediments by TAYLOR SMITH (1974) and DAVIES *et al.* (1977). Similar studies of Indian continental shelf sediments, *e.g.* physical and elastic properties, were conducted by SUBBA RAJU and RAMANA (1986). Results of the present investigation of submarine basalts are tabulated in Table 2.

Acoustic impedance and constrained modulus were computed from the rock density and velocity, while the reflection coefficient was derived by taking into account the densities and P-wave velocities of unconsolidated sediments (SUBBA RAJU and RAMANA, 1986), and the underlying rock formations, using the relation $(\rho V_p - \rho_1 V_{p1})/(\rho V_p + \rho_1 V_{p1})$, where ρ and $V\rho$ are respectively the density and P-wave velocity of the rock specimens studied, while ρ_1 and V_{p1} are those of the unconsolidated sediments lying above them. Densities and P- and S-wave velocities of some of the specimens were as low as 2.39 Mg·m^{-3}, 3.39 km·sec^{-1} and

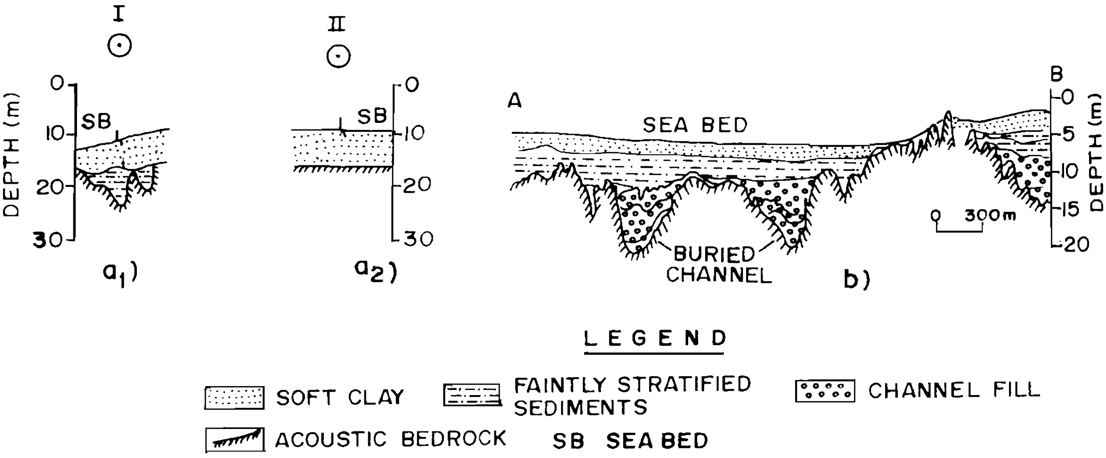

Figure 3. Subsurface formations derived from shallow seismics (a1) and (a2) represent locations I and II, (b) represents the profile AB as shown in Figure 2.

Table 2. *Density and acoustic properties of submarine basalts from Bombay harbour area.*

Specimen No.	Density (Mg·m^{-3})	P-wave Velocity (m·s^{-1})	S-wave Velocity (m·s^{-1})	Acoustic Impedance (10^5 kg·m^{-2}·s^{-1})	Constrained Modulus (MN·m^{-2})	Reflection Coefficient (ratio)
A/1	2.863	5,479	2,986	157	85,937	0.75
Ba	2.599	4,547	2,647	118	53,743	0.68
Bb	2.682	4,603	2,832	124	56,823	0.70
B22/1	2.619	4,328	2,719	113	49,049	0.67
B22/2	2.741	5,096	3,358	140	71,182	0.73
B22/3	2.744	4,920	2,481	135	66,425	0.72
B22/4	2.900	6,803	4,083	197	134,223	0.80
C/1	2.781	5,401	2,906	150	81,127	0.74
C/2	2.749	5,054	2,696	139	70,210	0.72
C/3	2.750	4,375	2,515	120	52,637	0.69
C/4	2.595	4,130	2,287	107	44,261	0.66
C/5	2.719	4,480	2,657	122	54,575	0.69
D/1	2.978	6,606	4,422	197	129,935	0.80
E/1	2.593	4,225	2,468	110	46,288	0.66
E/2	2.748	4,545	2,529	125	56,755	0.70
E/3	2.641	3,857	1,916	102	39,289	0.64
M/3	2.476	3,386	1,992	84	28,392	0.58
M/7	2.392	4,567	2,007	109	49,897	0.66
M/11	2.656	4,655	2,483	124	57,553	0.70
M/13	2.494	3,431	1,739	86	29,354	0.59
M/14	2.661	4,197	2,661	112	46,880	0.67
M19/1	2.628	4,232	2,551	111	47,069	0.67
M19/2	2.811	4,915	2,888	138	67,894	0.72
M19/3	2.772	5,123	3,361	142	72,754	0.73
M22	2.691	4,229	2,741	114	48,127	0.67
M23	2.626	4,839	2,525	127	61,504	0.70
M25/1	2.668	3,919	2,300	105	40,983	0.65
M25/2	2.654	3,887	2,700	103	40,102	0.65
M25/3	2.656	4,094	2,470	109	44,512	0.66

1.74 km·sec^{-1}, respectively. Some specimens having low densities also showed a moderate reflection coefficient (about 0.66) because of the moderate P-wave velocities observed in them.

The elastic properties of the basalts are summarized in Table 3. The interrelationships between the different physical properties are collectively displayed in Figure 4 whereas the corresponding least squares best fit relations, between the different parameters, are displayed in Table 4. The densities of the submarine basalts range from 2.39 and 2.98 Mg·m^{-3} but a great majority of them lie in the narrow range of 2.62 and 2.78 Mg·m^{-3}. The corresponding P- and S-wave velocities lie between 3.38 and 6.8 km·sec^{-1} and 1.74 and 4.42 km·sec^{-1}, but a majority of them fall between 4.09 and 5.48 km·sec^{-1} and 2.01 and 3.36 km·sec^{-1}, respectively. As expected, sound propagation is better in specimens having good compactness, but deteriorates in specimens with vesicles and pores.

The drillhole data near Elephanta, Nhava and Sheva Island suggest the presence of a sequence of three basalt flows with a variable thickness of 10–15 m. Some of these island flows exhibit olivine alteration, either partially or completely (DESHMUKH, 1984). The olivine content of the phenocrysts in these flows ranges from 2.8 to 32%, and that of the groundmass varies from 0.7 to 3.3%. The samples also exhibit deformation and microfaulting, marking a shear zone along which some movements may have taken place (DESHMUKH, 1984). These deformational features acted as a conduit for penetration of seawater which in turn altered the density and acoustic properties of the rock formations.

Some specimens (Table 2) showed an increase in density with increasing depth, revealing the presence of compact samples as either unsaturated or unaltered. The same effect was observed in P- and S-wave velocities. The low velocities are attributed to saturation, composition and lithological variations in the rock. The specimen (D/1) with the highest density, and wave velocity, is

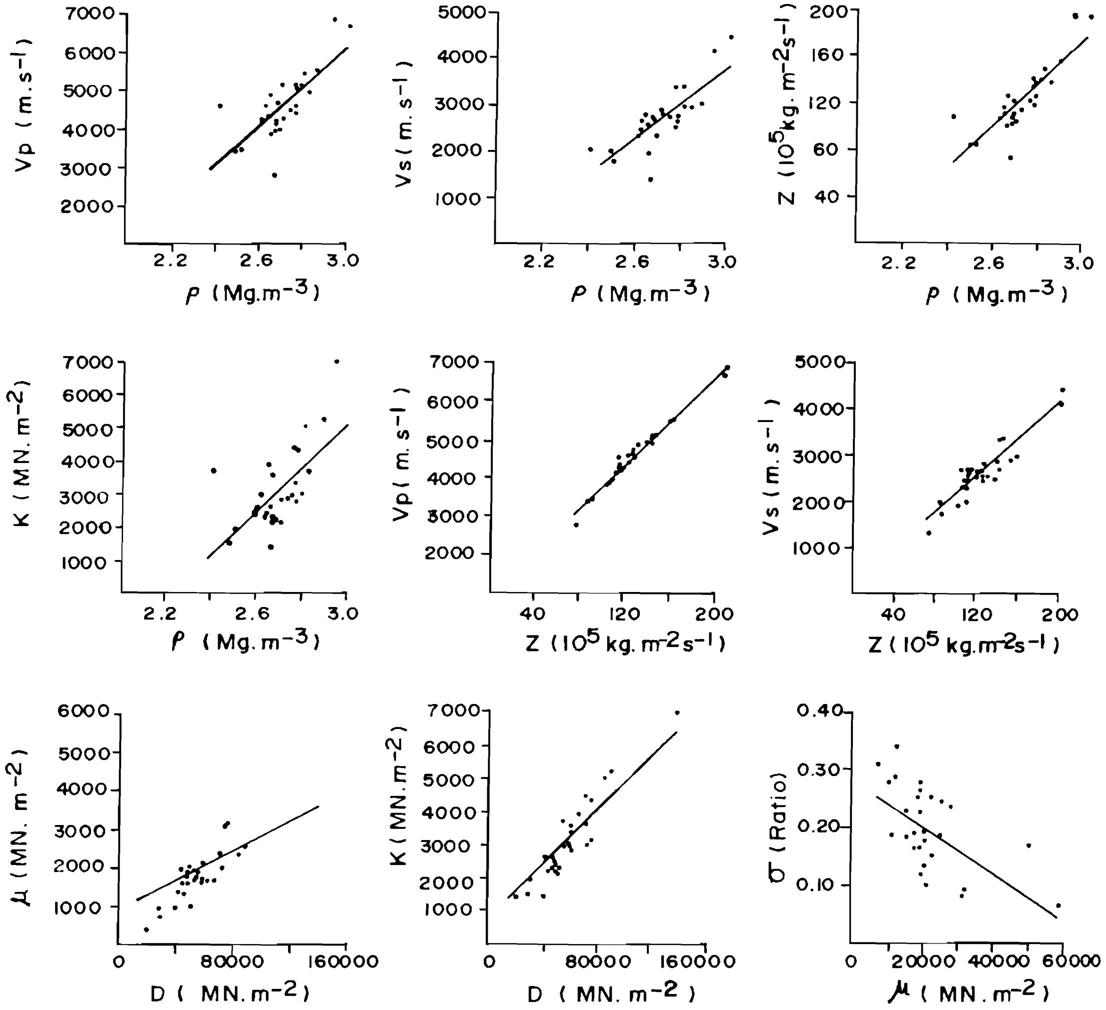

Figure 4. Interdependence of different physical parameters.

recognised as a dolerite (from petrological examinations). Its olivine content (between 25 and 33%) denotes a picritic/oceanitic composition.

In general, the density and wave velocities of Bombay harbour basalts are comparable (see Table 5) to those reported from other parts of India, particularly those from Koyna and Mahim bay (Bombay) regions. The physical, acoustic and elastic properties of Bombay harbour basalts are also comparable to those reported by PRESS (1966) (German basalts) and BIRCH (1966) (Russian and American basalts). They are also comparable with the properties of basalt glass (DALY, 1966). The scatter in the density and wave velocities of Bombay harbour basalts, which is relatively low compared to those from Hawaii (WOOLLARD and MANGHNANI, 1964), may be due to their relatively low porosity and mineralogical changes.

APPLICATIONS

The theoretical curve shown in Figure 5 depicts the relationship between the number of cracks and P-wave velocities reported earlier for a variety of specimens (SJOGREN *et al.*, 1979). With these experimental results in mind, the curve was extended up to 7.0 km·sec^{-1} by using the empirical relation

Table 3. *Elastic properties of submarine basalts.*

Specimen No.	Rigidity Modulus (MN·m ^{2})	Youngs's Modulus (MN·m ^{2})	Bulk Modulus (MN·m ^{2})	Poisson's Ratio
A/1	25,524	81,053	51,904	0.24
Ba	18,213	51,721	29,459	0.19
Bb	21,509	55,548	28,144	0.15
B22/1	19,358	48,204	23,237	0.13
B22/2	30,908	70,679	29,971	0.08
B22/3	16,891	61,161	43,904	0.28
B22/4	48,349	130,331	69,758	0.17
C/1	23,486	76,212	49,812	0.25
C/2	19,979	65,780	43,572	0.25
C/3	17,394	50,466	29,444	0.20
C/4	13,572	41,953	26,165	0.23
C/5	19,197	52,809	28,980	0.18
D/1	58,222	129,354	52,306	0.07
E/1	15,795	44,592	25,229	0.19
E/2	17,573	53,876	33,325	0.23
E/3	9,695	36,010	26,362	0.29
M/3	9,827	27,409	15,290	0.19
M/7	9,636	44,140	37,049	0.34
M/11	16,375	53,921	35,720	0.25
M/13	7,541	27,070	19,299	0.28
M/14	18,845	46,175	21,753	0.12
M19/1	17,103	45,756	24,265	0.17
M19/2	23,441	65,519	36,639	0.19
M19/3	31,315	72,182	31,001	0.09
M22	20,218	47,635	21,170	0.10
M23	16,746	57,230	39,176	0.26
M25/1	14,116	39,535	22,162	0.19
M25/2	19,349	40,080	14,303	0.02
M25/3	16,202	43,281	22,909	0.17

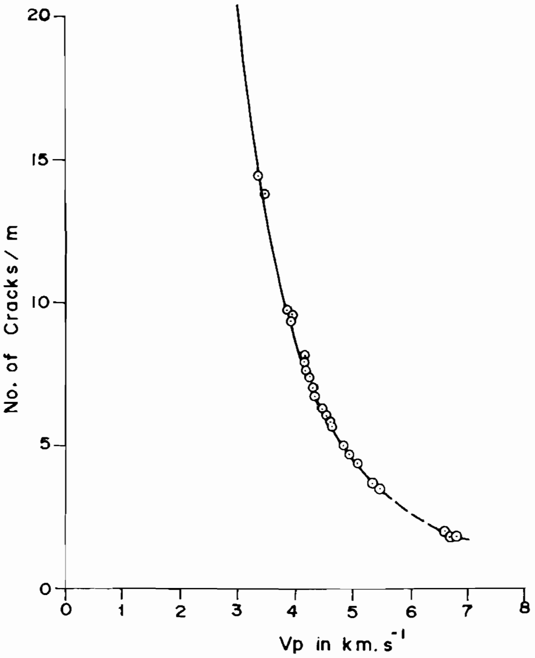

Figure 5. Number of cracks plotted against the P- wave velocity. The solid curve represents the values reported by Sjogren *et al.* (1979) while the dashed line is an extrapolation. Dot with circle shows the relationship between number of cracks and P- wave velocities from the present study.

$$Y = (X^{2.945}) \times (3.535 \times 10^{11})$$

where X is the number of cracks/m and Y is the value of P-wave velocity in the rock specimen.

It is thus possible, with the above equation, to evaluate the fracturisation of the subsurface layers (SJOGREN *et al.*, 1979; DUTTA, 1984). Deviations in the experimental points reflect the non-uniformity in the fracturisation of the terrain. Inspection of the results suggests that sites (Table 1) having a large number of cracks should be regarded as unsuitable for coastal operations.

In addition, laboratory sound wave velocities support underwater acoustics and marine geophysics because such data is useful to computation of velocity-depth profiles of the upper sediment layers in sea floor sediments. Likewise, the physical and elastic properties of offshore and nearshore rock specimens provide essential knowledge on site parameters and evaluation. This

Table 4. *Least-squares best-fit relations between different physical parameters.*

X-axis	Y-axis	Relation
Density (ρ)	P-wave velocity (V_p)	$V_p = 5.107\rho - 9{,}154.930$
Density (ρ)	S-wave velocity (V_s)	$V_s = 3.921\rho - 7{,}887.581$
Density (ρ)	Acoustic impedance (Z)	$Z = 0.188\rho - 382.816$
Density (ρ)	Bulk modulus (K)	$K = 68.864\rho - 153{,}335.551$
Acoustic impedance (Z)	P-wave velocity (V_p)	$V_p = 29.912\ Z + 877.660$
Acoustic impedance (Z)	S-wave velocity (V_s)	$V_s = 20.361\ Z + 137.033$
Constrained modulus (D)	Rigidity modulus (μ)	$\mu = 0.187\ D + 9{,}328.355$
Constrained modulus (D)	Bulk modulus (K)	$K = 0.406\ D + 9{,}476.092$
Rigidity modulus (μ)	Poisson's ratio (σ)	$\sigma = -3.885 \times 10^{6}\mu + 0.271$

Table 5. *Comparative results of density and acoustic properties of basalts from various part of India.*

S. No. (1)	Rock Type (2)	Region (3)	Density in Mg·m^{-3} (4)	Velocity in km·s^{-1} P-wave (5)	Velocity in km·s^{-1} S-wave (6)	No. of Samples Studied (7)	Exp. Technique and Condition of Work (8)	Reference (9)
I. Field studies								
1.	Basalts	Koyna region		2.50–4.50			Seismic refraction	Athavale and Indra Mohan (1976)
2.	Basalts	Bombay Deccan Traps	2.90	4.20			Shallow seismic refraction	Bose and Arora (1969)
3.	Basalts	West Godavari Dt. (A.P.)	2.90	4.50			Shallow seismic refraction	Bose and Arora (1969)
4.	Basalts	East Godavari Dt. (A.P.)	2.90	4.20			Shallow seismic refraction	Bose and Arora (1969)
5.	Basalts	Deccan	3.00	4.80–6.30			Field seismic	Kailasam *et al.* (1976)
6.	Trap rock	Kelsi-Loni profile		4.80–5.00			DSS field	Kaila *et al.* (1981)
7.	Trap rock	Guhagarh-Chorochi profile		4.70–5.00			DSS field	Kaila *et al.* (1981a)
8.	Trap rock	Navibandar-Amreli profile		4.90–5.15			DSS field	Kaila *et al.* (1981b)
9.	Basalt	Kakrapar (Gujarat)	2.80	3.50–6.00	2.10 (Ave)		Shallow seismic	Ravendra Nath *et al.* (1987)
10	Trap rock	Ujjain-Mahan profile		4.70–5.10			DSS field	Kaila (1988)
11.	Trap rock	Thaudara-Sindad profile		4.70–5.00			DSS field	Kaila (1988)
12.	Trap rock	Khajuriakalan-Pulgaon profile		4.70–5.10			DSS field	Kaila (1988)
13.	Trap rock	Mehmadabad-Billimoria profile		4.80–5.07			DSS field	Kaila (1988)
14.	Basalts	Ratnagiri port		4.00–5.90			Seismic refraction	Ravendra Nath *et al.* (1989)
15.	Basalts	Mahim Bay (Bombay)		2.70–5.50			Seismic refraction	Ravendra Nath *et al.* (1989a)
II. Laboratory studies								
16.	Basalts	Vikarabad (A.P.)	3.02	5.97	3.13		Pulse ambient	Balakrishna (1970)
17.	Dolerite	Hyderabad	3.05	6.59	3.39		Pulse ambient	Balakrishna (1970)
18.	Trap rock	Dadra and Nagar Haveli	2.50–2.90	4.50–6.10	2.30–3.20	10	Pulse ambient	Ramana and Gogte (1974)
19.	Trap rock	Alore (Maharashtra)	3.00	6.30			Ambient	Kailasam *et al.* (1976)
20.	Trap rock	Koyna region	2.50–3.00	3.00–6.30	1.80–3.60	82	Ambient	Ramana *et al.* (1976)
21.	Trap rock	Rajkot	2.90–3.10	4.90–6.30		50	Ambient	Ramana (1978)
22.	*Trap rock*	*Bombay harbour region*	*2.39–2.98*	*3.39–6.80*	*1.74–4.42*	*29*	*Pulse transmission*	*Present study*

kind of information was, for example, needed by oil exploration agencies, for laying the Bombay High offshore to nearshore pipelines (to transport crude oil or natural gas), because the pipeline corridor transgressed sedimentary and basaltic sections. Civil construction activities, crude oil storage facilities, and preparation of berths for wet and dry docks at ports require similar information dealing with physical and elastic rock properties.

Coastal land reclamation in the Bombay region and remedial measures to arrest land subsidence find physical and elastic data useful. The Bombay Municipal Corporation, for example, sought such assistance from the National Institute of Oceanography and the National Geophysical Research Institute.

CONCLUSIONS

(1) Laboratory measurements of basalts from the Bombay harbour area showed a wide range in density, P- and S-wave velocities. These variations were attributed to variations in rock structure and composition.

(2) Analyses of physical, acoustic and elastic properties of submarine basalts in the Bombay Harbour area indicate that coastal and harbour operations should be restricted to rock formations that are characterized by high P-wave velocities and few fractures. In other areas, remedial measures must be incorporated in construction and maintenance activities.

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□ RÉSUMÉ □

On a déterminé les propriétés physiques, acoustiques et l'élasticité des basaltes des Iles Elephanta, dans la zone du port de Bombay. La densité des échantillons est comprise entre 2,39 et 2,96 mg/m^3, les vitesses de l'onde sonore s'étalent de 3,39 à 6,80 km/s pour les ondes longitudinales et de 1,74 à 4,42 km/s pour les ondes transverses. De telles propriétés sont comparables à celles des basaltes continentaux de l'Inde ou d'autres parties du monde. Les résultats analytiques basés sur des solutions individuelles parmi de nombreuses propriétés par les moindres carrés et les variations observées des propriétés, indiquent des différences de porosité, une altération de l'eau de mer et des modifications de la lithologie ou de sa composition. La signification de la relation curvilinéaire entre le nombre de ruptures et la vitesse de l'onde longitudinale des spécimens est liée aux activités côtières et au développement portuaire.—*Catherine Bousquet-Bressolier, Géomorphologie, E.P.H.E., Montrouge, France.*

□ RESUMEN □

En los basaltos submarinos de las islas Elefante del área del Puerto de Bombay, se determinaron las propiedades físicas, acústicas y elásticas. Las densidades de las muestras se hallaban comprendidas entre 2.39 a 2.98 mg/m^3, las velocidades de las ondas acústicas mostraron una dispersión de 3.39 a 6.80 km/s, para las ondas longitudinales y 1.74 a 4.42 km/s para las ondas transversales. Estas propiedades son, de manera general, compatibles con los basaltos continentales de la India y con los de otras partes del mundo. La evaluación analítica se basó en soluciones individuales por el método de los mínimos cuadrados, entre las diversas propiedades y las variaciones de las mismas, se encuentran diferencias en la porosidad, alteración en el agua de mar y cambios composicionales y litológicos. El significado de la relación curvilínea se halla relacionado al desarrollo de las actividades costeras y portuarias.—*Néstor W. Lanfredi, CIC-UNLP, La Plata, Argentina.*

□ ZUSAMMENFASSUNG □

An submarinen Basalten der Elephanta Inseln beim Hafengebiet von Bombay wurden physikalische, akustische und elastische Eigenschaften gemessen. Die Dichte der Proben variiert zwischen 2,39 und 2,98 Mg m^{-3}. Die Geschwindigkeiten der Schallwellen zeigten eine Streuung von 3,39 bis 6,80 km s^{-1} für Longitudinalwellen und 1,74 bis 4,42 km s^{-1} für Transversalwellen. Diese Eigenschaften sind voll im Einklang mit den Werten für Basalte des kontinentalen Indien wie für solche aus anderen Teilen der Welt. Gestützt auf den statistisch gesicherten Zusammenhang zwischen den verschiedenen Eigenschaften und den beobachteten Veränderungen zeigen die Untersuchungsergebnisse Unterschiede in der Porosität, Verwitterung durch Meerwassereinfluß sowie lithologische Änderungen. Die Beziehung zwischen der Anzahl der Gesteinsrisse und der Geschwindigkeit der Longitudinalwelle in den Proben wird durch eine krummlinig begrenzte Korrelationskurve beschrieben; sie hängt mit den Aktivitäten bezüglich der Küsten- und Hafenentwicklung zusammen.—*Helmut Brückner, Department of Geography, University of Marburg, Germany.*