Elastic properties of granulite facies rocks of Mahabalipuram, Tamil Nadu, India

M V M S Rao*, K J Prasanna Lakshmi, L P Sarma and K B Chary

National Geophysical Research Institute, Hyderabad 500 007, India.
**e-mail: mvmsraodr@yahoo.com*

Compressional and shear wave velocities and attenuation measurements have been carried out in some of the borehole samples of acidic, basic and intermediate granulites of Mahabalipuram, Tamil Nadu, India. The results have been obtained at ambient conditions using 'time-of-flight' pulse transmission technique at 1.0 MHz frequency. The results show linear relationships between velocity and density, and velocity and attenuation properties of the rocks. The acidic granulites show lower velocities and higher attenuation than the intermediate and basic granulites. The average values of the Poisson's ratio of acidic, intermediate and basic granulites have been found to be 0.210, 0.241 and 0.279 respectively. The variations in velocities and attenuation in these low porosity crystalline rocks are found to be strongly influenced by their mineral composition. The laboratory velocity data (extrapolated to high pressure) of the present study and the published field velocity data from deep seismic sounding studies indicate that these granulite facies rocks may belong to mid-crustal depths only.

1. Introduction

In recent years, numerous researchers have proposed specific granulite terrains as plausible deep-crustal models of the Earth (Dawson *et al* 1986; Bohlen and Mezger 1989; Newton and Hansen 1986), following which the Southern-Granulite Terrain (SGT) of south India has been studied quite extensively. Detailed geological, geophysical and geochemical studies have provided many interesting and revealing information about the crustal structure, tectonic emplacement and metamorphic evolution of the SGT (for details see Ramakrishnan 2003). The salient observations and results of some of those studies are as follows: the two prominent E–W trending shear zones, namely the Moyar–Bhavani Shear Zone (MBSZ) and Palghat–Cauvery Shear Zone (PCSZ) forming a wide deformation zone have been studied extensively with special emphasis on their evolution, geometry, nature and kinematics. The geophysical studies (seismic, magneto-telluric, electrical and gravity surveys) undertaken by the National Geophysical Research Institute (NGRI), Hyderabad, India along a N–S transect cutting across the abovementioned shear zones have contributed vastly to the formulation of velocity-depth models, location of low velocity layer (LVL), and understanding of the crustal upliftment and Moho up-warp at the shear zone region of the southern granulite terrain. Also, the petrology and geochemical studies of the granulite facies rocks have helped us to understand the metamorphic evolution and fluid regime in the deep continental crust that have bearing on regional tectonics (Santosh 1988; Bhaskar Rao *et al* 1996).

It has also been realized in recent years that inferences about crustal composition using seismic P-wave velocity data alone can be erroneous and incomplete due to the inescapable overlap of the P-wave velocities of diverse rock types. This ambiguity can be reduced significantly if S-wave velocity data (and hence Poisson's ratio) of the corresponding rock formations is also available

Keywords. Velocities; Poisson's ratio; attenuation; granulite facies rocks.

J. Earth Syst. Sci. **115**, No. 6, December 2006, pp. 673–683

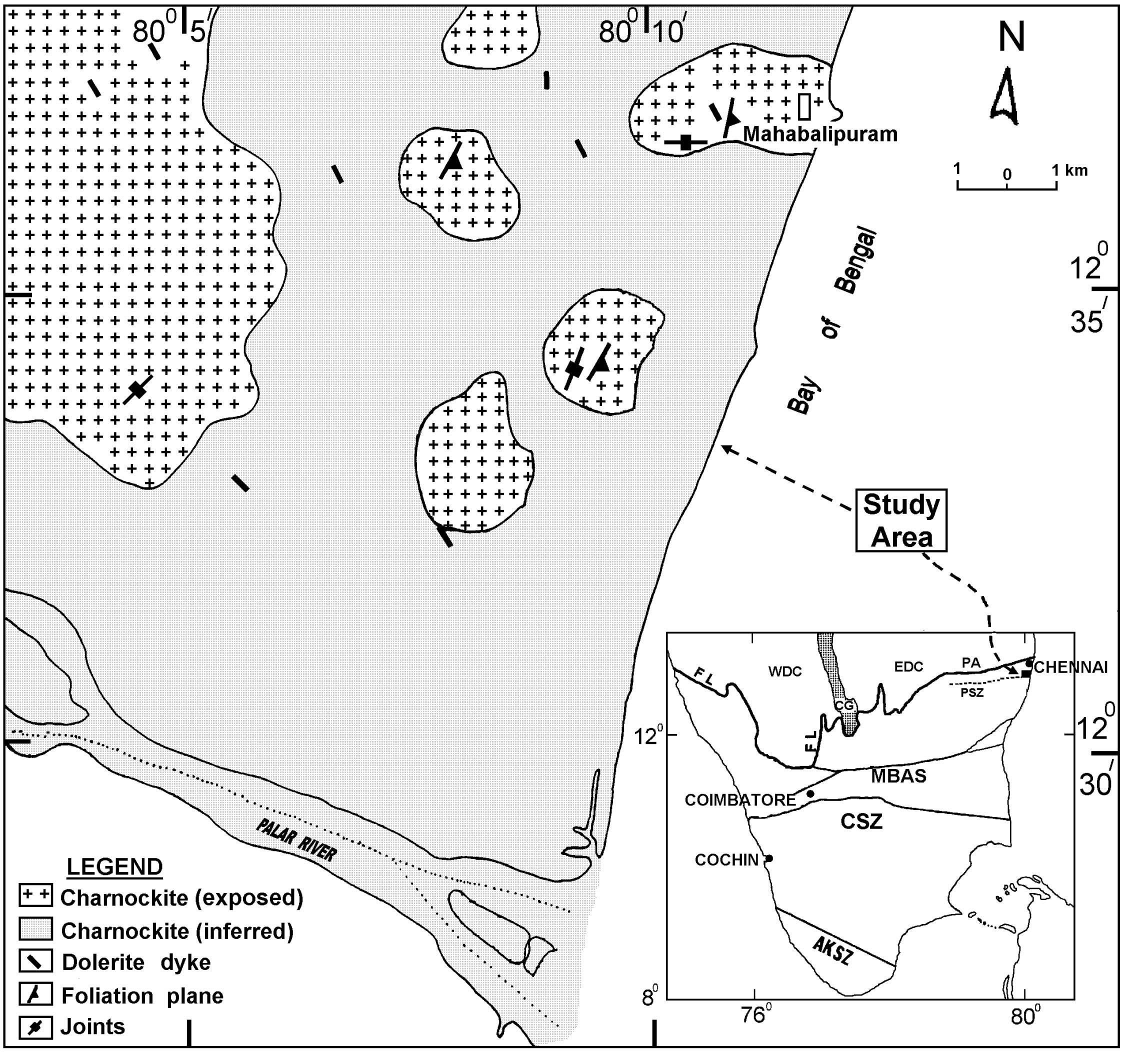

Figure 1. Geological map of the present study area between Mahabalipuram and Palar river. The inset shows some important geological blocks and major tectonic units of the South Indian Peninsular Shield (after Gopalakrishnan 1996). (**WDC:** Western Dharwar Craton; **CG:** Closepet Granite; **EDC:** Eastern Dharwar Craton; **PA:** Palar Lineament; **FL:** Fermor Line; **PSZ:** Palar Suture Zone; **MBAS:** Moyar–Bhavani–Attur Shear Zone; **CSZ:** Cauvery Shear Zone; **AKSZ:** Achankovil Shear Zone).

as evidenced from some of the recent studies (Christensen and Mooney 1995; Christensen 1996; Gaur and Priestly 1997; Rai *et al* 2003). Furthermore, the laboratory studies on physical properties of granulite facies rocks of south India have received special attention in recent years since they are formed in the lower continental crust and the exposed granulite terrains are generally thought to represent the exhumed portions of the lower crust (Newton and Hansen 1986). Among various physical properties, the laboratory data on compressional wave velocity (V_P), shear wave velocity (V_S) and Poisson's ratio of granulite facies rocks have been found to provide broad constraints for the geophysical interpretation of the deeper crustal levels (Christensen and Mooney 1995; Christensen 1996).

In view of the limited data available on V_P of Indian rocks under high pressure conditions (Birch 1960; Ramana and Rao 1974a, 1974b; Rao *et al* 1974; Balakrishna *et al* 1976), there is an imperative need to make new and accurate laboratory measurements of both V_P and V_S (and hence Poisson's ratio) of the exposed rocks of deep crustal origin for supplementing the seismological and other geophysical studies. These elastic properties of rocks are generally influenced by mineral composition, texture and the weathering state. In the light of the above, we have carried out measurements of V_P, V_S and attenuation in some of the borehole granulite facies rock samples obtained from a strategic engineering project site near Mahabalipuram, Tamil Nadu (figure 1). The results obtained at room conditions are

Table 1. *Mineral composition (vol. %) data of some of the granulites of the study area.*

Sl. no.	Sample no.	Plagio-clase	Quartz	K-feldspar	Garnet	Biotite	Opaques	Ortho-pyroxene
1	A-01 (23/1)	10.1	60.7	27.1	–	0.7	0.5	1.2
2	A-02 (37/1)	12.3	51.4	21.0	–	8.3	0.8	6.0
3	A-13 (68/4)	28.4	28.5	21.2	3.1	8.6	4.7	5.5
4	A-16 (60/1)	27.6	51.5	9.7	8.4	5.6	0.6	1.6
5	A-17 (15/1)	71.1	8.7	1.2	–	1.7	0.6	16.6
6	A-21 (30/4)	26.8	26.8	22.1	–	14.3	1.6	17.0
7	B-05 (32/1)	39.0	14.4	–	34.8	5.8	1.5	4.7
8	B-12 (54/2)	28.9	13.7	11.8	17.0	7.1	4.1	17.6
9	B-14 (60/1)	45.1	25.0	–	18.1	13.2	2.3	0.5

presented and discussed in this paper. It may be mentioned here that the first results on V_P of the charnockite rocks (acidic granulites) of Indian origin (Pallavaram which is close to the present study area) under high-pressure conditions up to 10 kb were reported by Birch (1960).

2. Location and petrography of rock samples

The study area ($\sim$250 km^2) lies between 80°03′E and 80°12′E (long.) and 12°27′N and 12°38′N (lat.). It is located near Mahabalipuram $\sim$65 km south of Chennai city (figure 1). It is bound by Bay of Bengal in the east, Tirukkalukkunram hills in the west, Mahabalipuram town in the north and Palar river and the E–W trending narrow Palar Suture Zone (PSZ) in the south (Gopalakrishnan 1996). The study area lies in seismic zone II in the seismic zoning map of India. There are no prominent shear zones and lineaments in the study area and it is considered to be quite stable both seismically and tectonically, which is a prime requirement for the construction and safety of dams, underground tunnels, and other geotechnical engineering projects.

The rocks of the present study area are mainly granulites with associated basic and ultrabasic enclaves of Archaean age and dated as $\sim$2500 Ma (Naqvi and Rogers 1987). The acidic granulites (charnockites) are mostly greyish black in colour. A majority of them are coarse-to-medium grained and show granulitic texture. The microscopic examination, though carried out on a limited number of thin sections ($\sim$10) of selected rock samples using a Leitz optical microscope, shows that the rocks consist of quartz, plagioclase, potash feldspar, garnet, biotite and orthopyroxene. Pyrite is observed in some of the thin sections. Also, the cracks in some of the minerals such as pyroxenes, garnet and biotite contain brownish opaque infillings whereas the microcracks in quartz and feldspars were found to have infillings of secondary minerals. The rocks studied have been categorized as acidic, intermediate and basic granulites according to their modal composition data (table 1). The modal data show that quartz ranges from 8.7 to 60.7% and the plagioclase varies from 10.1 to 71.1% in the rock samples. The quartz and plagioclase together vary from 50 to 80% among the rocks studied (table 1). The volume percentage of garnet is relatively high (34.8%) in one sample [B-5(32/1)], while in others it ranges from 3.1 to 18.1%.

3. Experimental

The core samples were obtained from 12 strategic shallow boreholes (8 to 32 m deep) of the study area. The test samples (30 mm dia and 60 mm long) were prepared from the borehole cores for the measurements of velocity and attenuation. The density (ρ) data were obtained from the measurements of mass (m) and bulk volume (v) of each oven-dried test sample using the formula, $\rho = m/v$. The lithology data were also taken into account and the velocity and attenuation were measured in at least 3 samples of each lithological unit and averaged. The velocity measurements were done at the room conditions using 'time-of-flight ultrasonic pulse transmission technique' as described in detail by Birch (1960); Ramana and Rao (1974a); Rao and Prasanna Lakshmi (2003) in which arrival times of compressional (P) and shear (S) waves are measured accurately (error $\pm$1%) in each test sample at 1.0 MHz frequency. The transmitting and receiving transducers (PZT) are seated in specially made housings with suitable damping material. They are coupled to the test sample on either side using machine oil and honey as acoustic couplants for the transmission and reception of P-waves and S-waves respectively. A high energy pulser on the driving side and a digital storage oscilloscope on the receiving side are used for the measurements of travel time and pulse width of the first received pulse for calculating the velocity and Q as

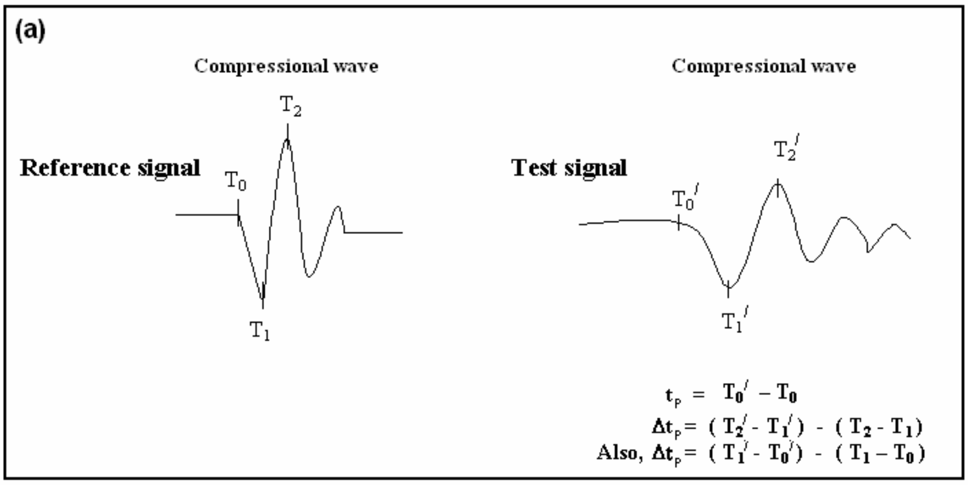

Figure 2. **(a)** Schematic diagram of the waveforms of reference and test signals for the measurement of t_P and Δt_P using ultrasonic P-wave transducers. Notice the increase in half-width (i.e., pulse broadening) and decrease in amplitude of the received signal of P-wave on propagation through the material.

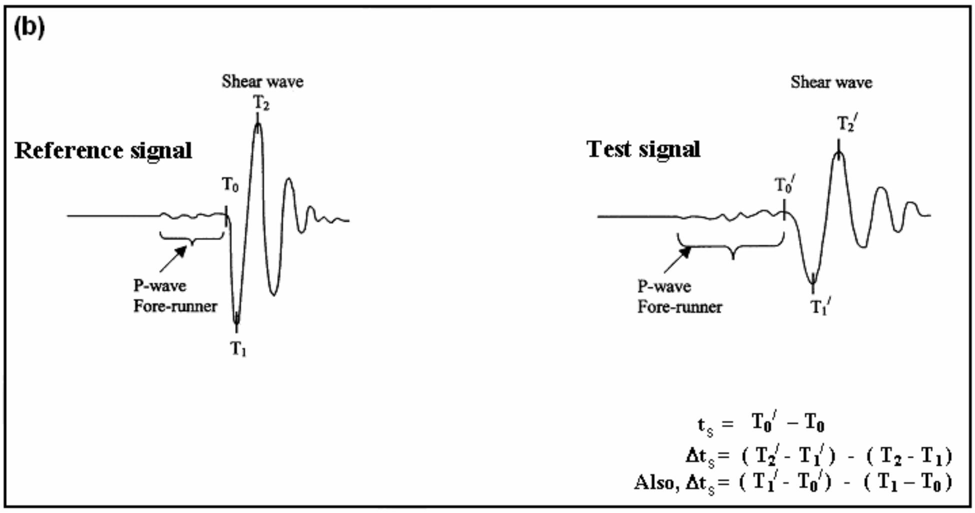

Figure 2. **(b)** Schematic diagram of the waveforms of reference and test signals for the measurement of t_S and Δt_S using ultrasonic shear wave transducers. The P-wave forerunner is very weak and the shear wave is quite prominent. Notice the increase in half-width (i.e., pulse broadening) and decrease in amplitude of the leading signal of shear wave on propagation through the material.

discussed in detail in our earlier paper (Rao and Prasanna Lakshmi 2003). The initial readings of travel time and pulse width are made in the reference signal which is obtained by directly coupling the transmitter and receiver using an acoustic couplant. The transmitter and receiver are then glued to the ends of the test core and the waveform (test signal) obtained is observed on the screen of the oscilloscope. The travel time and pulse width of the first received pulse of the test signal are measured as before in cores of different lengths from the same rock. The values of travel time (tp and ts) and pulse width (Δt_p and Δt_s) as shown in figure 2 are measured using the time cursors of the oscilloscope. The velocities are calculated from sample lengths and travel time measurements. The results of pulse-broadening measurements show that Δt increases proportionately with increasing length presenting the relation, $V(\Delta t)\alpha L$ in which V is the velocity and L is the length of the core. The constant of proportionality is Q^{-1} following the theoretical deductions reported by Knopoff (1956, 1964). Details of the method of determination of Q have been described in our earlier papers (Ramana and Rao 1974b; Rao *et al* 2002; Rao and Prasanna Lakshmi 2003). The attenuation data of P-waves (α_P) and S-waves (α_S) have been obtained from the data of 'Q' using the standard

Table 2. *Velocities, Poisson's ratio (ν), Young's modulus (E) and attenuation (α) data of some of the granulites of the study area.*

Sl. no.	Sample no.	Density (ρ) (gm/cc)	V_P (m/s)	V_S (m/s)	V_P/V_S	ν	E (GPa)	α_P (dB/cm)	α_S (dB/cm)
Acidic									
1	A-01 (23/1)	2.701	5691	3600	1.581	0.166	81.66	0.361	0.723
2	A-02 (37/1)	2.753	5428	3497	1.552	0.145	77.12	0.806	1.815
3	A-13 (68/4)	2.720	6190	3685	1.680	0.226	90.53	0.179	0.359
4	A-16 (60/1)	2.680	6212	3761	1.652	0.211	91.79	0.325	1.407
5	A-17 (15/1)	2.739	5785	3259	1.775	0.268	73.75	0.942	1.586
6	A-21 (30/4)	2.739	6215	3626	1.714	0.242	89.44	0.090	0.181
Average		**2.722**	**5920**	**3571**	**1.659**	**0.210**	**84.05**	**0.451**	**1.012**
Intermediate									
7	C-03 (1/1)	2.777	6431	3777	1.703	0.237	97.99	0.377	0.651
8	C-05 (2/2)	2.754	6193	3575	1.732	0.250	88.00	0.648	1.828
9	C-06 (3/3)	2.770	6246	3618	1.726	0.248	90.47	0.357	1.892
10	C-10 (41/1)	2.808	6332	3800	1.666	0.219	98.82	0.562	0.843
11	C-11 (26/1)	2.755	6243	3539	1.764	0.263	87.18	0.364	1.636
12	C-11 (46/1)	2.784	6422	3822	1.680	0.226	99.70	0.411	1.688
13	C-13 (85)	2.807	6258	3620	1.729	0.249	91.85	0.447	1.118
Average		**2.779**	**6304**	**3679**	**1.714**	**0.241**	**93.43**	**0.452**	**1.379**
Basic									
14	B-05 (32/1)	3.101	6884	3837	1.794	0.275	116.39	0.258	0.576
15	B-12 (54/2)	2.932	6672	3794	1.759	0.261	106.44	0.181	–
16	B-14 (25/1)	2.902	6588	3516	1.874	0.301	93.34	0.318	0.909
17	B-14 (60/1)	2.946	6645	3685	1.803	0.278	102.25	0.107	0.555
Average		**2.970**	**6697**	**3708**	**1.807**	**0.279**	**104.60**	**0.216**	**0.680**

relationship between velocity, Q and attenuation namely $\alpha = (8.686\pi f)/(VQ)$ (Knopoff 1964) and as discussed in detail by Ramana and Rao (1974b); Rao and Prasanna Lakshmi (2003). In this relationship, f is the frequency (1.00 MHz in the present work), V is the velocity in cm/s and α is attenuation in dB/cm, 8.686 is the conversion factor to convert the units of attenuation from nepers/cm to dB/cm.

4. Results and discussion

4.1 *Velocity-density systematics, Poisson's ratio and attenuation*

The velocity and attenuation data (average values obtained from measurements made on three samples of each lithological unit) are shown in table 2. The data set summarizes velocity and attenuation measurements made on a total number of 51 cores taken from 17 rock samples which consist of acidic (charnockites), intermediate and basic granulites. The values of V_P/V_S, Poisson's ratio (V) and Young's modulus (E) are also computed and presented in table 2. The density (ρ) and velocities of acidic granulites are relatively low (mean $\rho = 2.722$ gm/cc, $V_P = 5920$ m/s and $V_S = 3571$ m/s) compared to those of basic granulites (mean $\rho = 2.970$ gm/cc, $V_P = 6697$ m/s and $V_S = 3708$ m/s) while the intermediate granulites show values lying between those of acidic and basic granulites (table 2) as expected. Consequently, the Poisson's ratio and Young's modulus are relatively low in the acidic granulites (table 2). These observations imply that the acidic granulite rocks of the present study area might have been influenced by either the prograde or retrograde metamorphism of granulite facies rocks. Further, among the acidic granulites, the volume percentage of quartz and the ratio of quartz to plagioclase seem to have a strong influence on V_P, Poisson's ratio and attenuation. The inter-relationships among the measured parameters (density *versus* velocities, and velocity *versus* attenuation) have been examined and the data are plotted in figure 3(a) and 3(b) respectively. The density of these granulites ranges from 2.680 gm/cc to 3.101 gm/cc while the V_P ranges from 5428 m/s to 6884 m/s and V_S ranges from 3259 m/s to 3837 m/s for these rocks (table 2 and figure 3a). The results show that V_P increases more gently with increase of density although showing more scatter of data than V_S (figure 3a). It could perhaps be due to the fact that the high-grade mineral pyroxene/hypersthene in these rocks is seen in a state of alteration to low grade minerals in thin sections and it may have more influence on V_P than on V_S. The Poisson's ratio (ν) and Young's modulus have been obtained from the velocity data of rock samples using the standard relationships, namely:

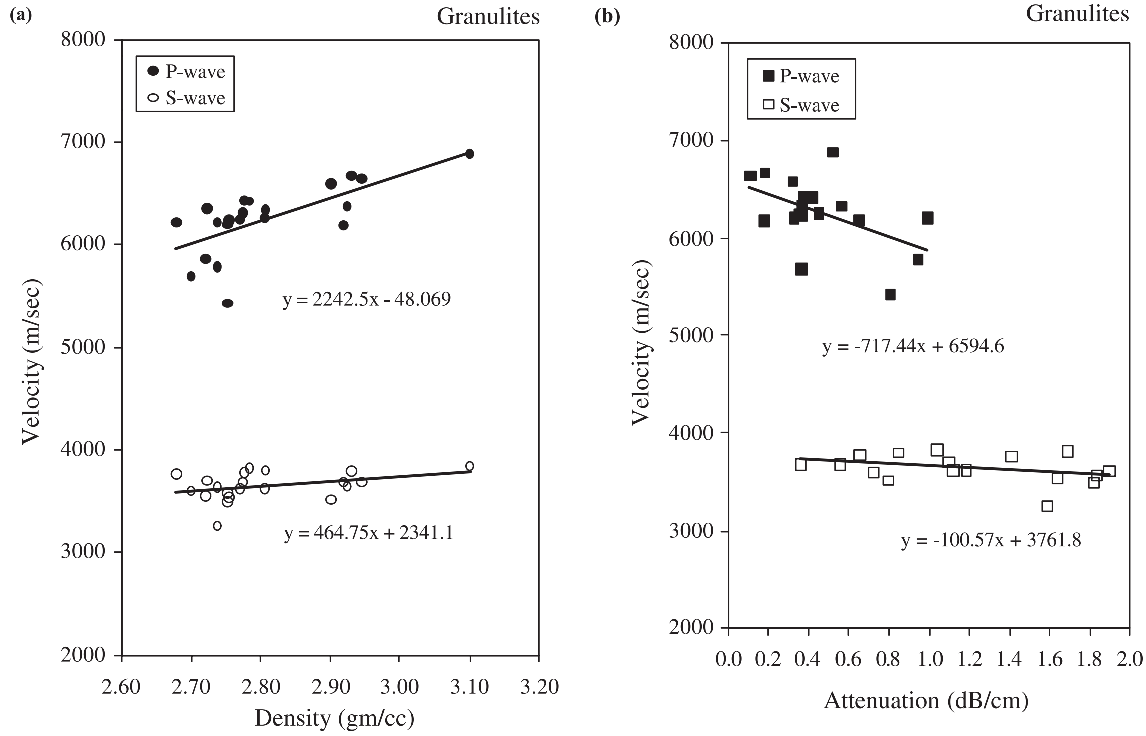

Figure 3. **(a)** Plots showing the relationship between density and velocity data and **(b)** the relationship between velocity and attenuation data of some of the granulites of the study area. The data are in table 2. The best fit line and its equation of each plot are also shown.

$$2\nu = \left[\frac{\{(V_P/V_S)^2 - 2\}}{\{(V_P/V_S)^2 - 1\}}\right]$$

and

$$E = \left[\frac{\{\rho(1+\nu)(1-2\nu)V_P^2\}}{(1-\nu)}\right]$$

respectively.

The Poisson's ratio of the granulite facies rocks of the present study ranges between 0.145 and 0.301, and the Young's modulus varies from 73.75 GPa to 116.39 GPa (table 2). The mean V_S of all these granulites is 3648 m/s and it is higher than the mean V_S of Pallavaram charnockites (mean $V_S = 3300$ m/s reported by Balakrishna and Subrahmanyam 1962), while there is close agreement among the V_P data reported by them ($V_P = 6269$ m/s) and our present work (mean $V_P = 6261$ m/s). The Poisson's ratio (ν) of 'acidic charnockites' of Pallavaram was reported to be $\sim$0.335 by Balakrishna and Subrahmanyam (1962), while the present work shows only 0.210 for the acidic granulites. They also reported Poisson's ratio of 'basic granulites' as $\sim$0.325 compared to 0.279 of the basic granulites of the present study (table 2). It could be due to the 'wedge method' used by them, which is less accurate especially for the measurements of V_S than the 'digital technique' and 'through transmission technique' with direct S-wave transducers which we have used for the present study. The linear regression analysis further confirms that velocities increase with the increase of density and attenuation decreases with the increase of velocity (figure 3a and 3b). The variations in density among these granulites are strongly related to the variations in mineral composition, especially quartz, plagioclase and mafic minerals such as garnet and clinopyroxene.

The P-wave attenuation (α_P) of acidic granulites ranges between 0.090 dB/cm and 0.942 dB/cm and the S-wave attenuation (α_S) ranges between 0.181 dB/cm and 1.815 dB/cm, whereas the intermediate and basic granulites show a relatively narrow range in attenuation (table 2). The velocity-attenuation relationship shows a decreasing linear trend with $V_P - \alpha_P$ plot showing more scatter than $V_S - \alpha_S$ plot (figure 3b). This needs a detailed study of the microstructure and its influence on scattering attenuation in these rocks.

4.2 *Dependence of velocities on mineral composition*

Though the data are limited, the dependence of velocities on mineral composition are plotted in figure 4. The variations in quartz and other minerals do not seem to have any significant influence on the V_S of these granulites. On the other

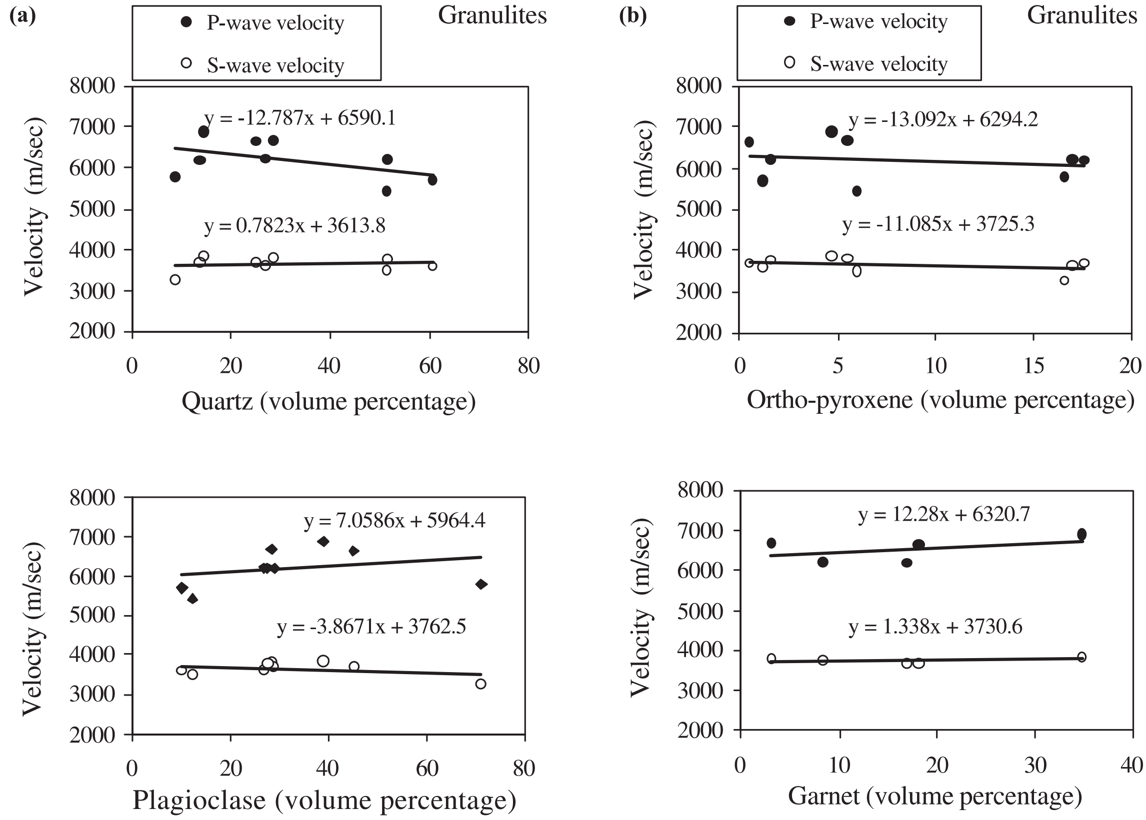

Figure 4. Plots showing the relationships between velocities and modal data of some of the granulites of the study area. The data are in tables 1 and 2. The best-fit line and its equation of each plot are also shown.

hand, a marginal increase in V_P and a nearly constant V_S is observed with the increase of plagiocalse and garnet in these granulites (figure 4). The V_P has decreased with the increase of quartz. However the values of V_P/V_S, Poisson's ratio (ν) and Young's modulus (E) show appreciable changes with variations observed in the mineral composition data of these rocks (table 2). For example, the influence of quartz/plagioclase on velocities and Poisson's ratio of these rocks is illustrated in figure 5(a) and 5(b) respectively. With the increase of quartz/plagioclase in these rocks, the V_P decreases more prominently than V_S and therefore the Poisson's ratio follows the same trend. This is understandable because quartz has a lower density, velocity and Poisson's ratio than plagioclase (Christensen 1996). The velocity (V_P) values of acidic and intermediate granulites of present study (mean $V_P = 6127\,\mathrm{m/s}$) at room conditions are fairly close to the results reported on Pallavaram charnockites (table 3) by Birch (1960) at 0.001 kb confining pressure ($V_P = 6019\,\mathrm{m/s}$).

4.3 *Comparison of estimated and measured values of velocities in rocks*

The velocities were estimated using the modal composition data of all the minerals present in the rock samples of the present study and the appropriate elastic moduli of the published data of individual minerals (Bass 1995) to obtain the Voigt and Reuss bounds of the velocities (c.f., Sidney and Carel 1977). The formulae for Voigt and Reuss bounds of velocities are calculated from the square root of the calculated elastic modulus-density ratio for the particular volume fraction of the rock composite. The upper bound (Voigt) for the longitudinal modulus (K_V) is obtained from $K_V = v_1k_1+v_2k_2+\cdots$ and the lower bound (Reuss) for the longitudinal modulus (K_R) is obtained from $1/K_R = v_1/k_1 + v_2/k_2 + \cdots$ where k_1, k_2, etc. are the Young's modulus of individual minerals and v_1, v_2, etc. are the fractional volume of individual minerals. Similarly, the upper and lower bounds for the shear modulus are obtained using the rigidity modulus (G) data of individual minerals using the above equation. The estimated values of velocities have been compared with the measured values of the rock samples and the results are shown in figure 6. The difference between the upper and lower bounds of velocities is not much for the acidic granulite rocks whereas the basic granulites show some spread between them. The measured values of velocities are found to occupy an intermediate position for the basic granulites while the acidic granulites show some scatter. The scatter

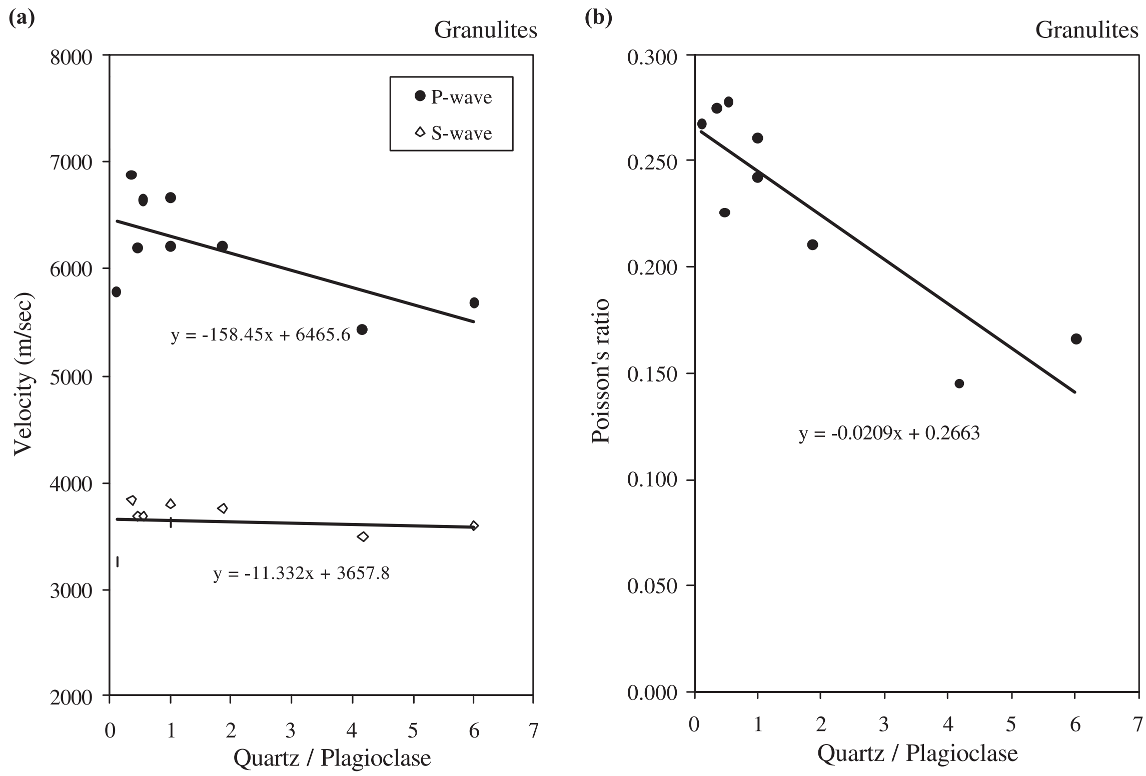

Figure 5. **(a)** Plots showing velocity *versus* quartz/plagioclase data and **(b)** Poisson's ratio *versus* quartz/plagioclase data of some of the granulites of the study area. The data are in tables 1 and 2. The best-fit line and its equation of each plot are also shown.

Table 3. *Comparison of V_P data of some granulites at 8 kb and 10 kb confining pressure.*

Rock type	Density (gm/cc)	V_P (m/s) Confining pressure (kb) 0.001	8	10	Source
Charnockite (Pallavaram)	2.740	6019	6455	6460	Birch (1960)
Felsic granulite	2.755	6355	6755	6775	Christensen and Mooney (1995)
Felsic granulite	2.758	5707	6545	6571	Christensen (1996)
Acidic granulite (Mahabalipuram)	2.722	5920	(6299)	(6308)	Present work
Intermediate granulite (Mahabalipuram)	2.779	6304	(6707)	(6718)	Present work
Acidic + Intermediate granulite (Mahabalipuram)	2.753	6127	(6519)	(6529)	Present work
Mafic granulite	2.977	6789	7223	7234	Christensen and Mooney (1995)
Mafic granulite	2.971	6128	6973	7000	Christensen (1996)
Basic granulite (Mahabalipuram)	2.970	6697	(7125)	(7136)	Present work

in velocities of acidic granulites may be influenced by the variations in mineral composition, porosity, connectivity of micro-cracks of the individual minerals and their velocity anisotropy. It requires a detailed study of all these aspects to analyse and give a better explanation for the observed scatter.

4.4 *Tectonic implications*

Among various physical properties, the laboratory data of V_P of the granulite facies rocks have been considered by several investigators to interpret the suites of exposed granulites as representatives of lower continental crust (Christensen

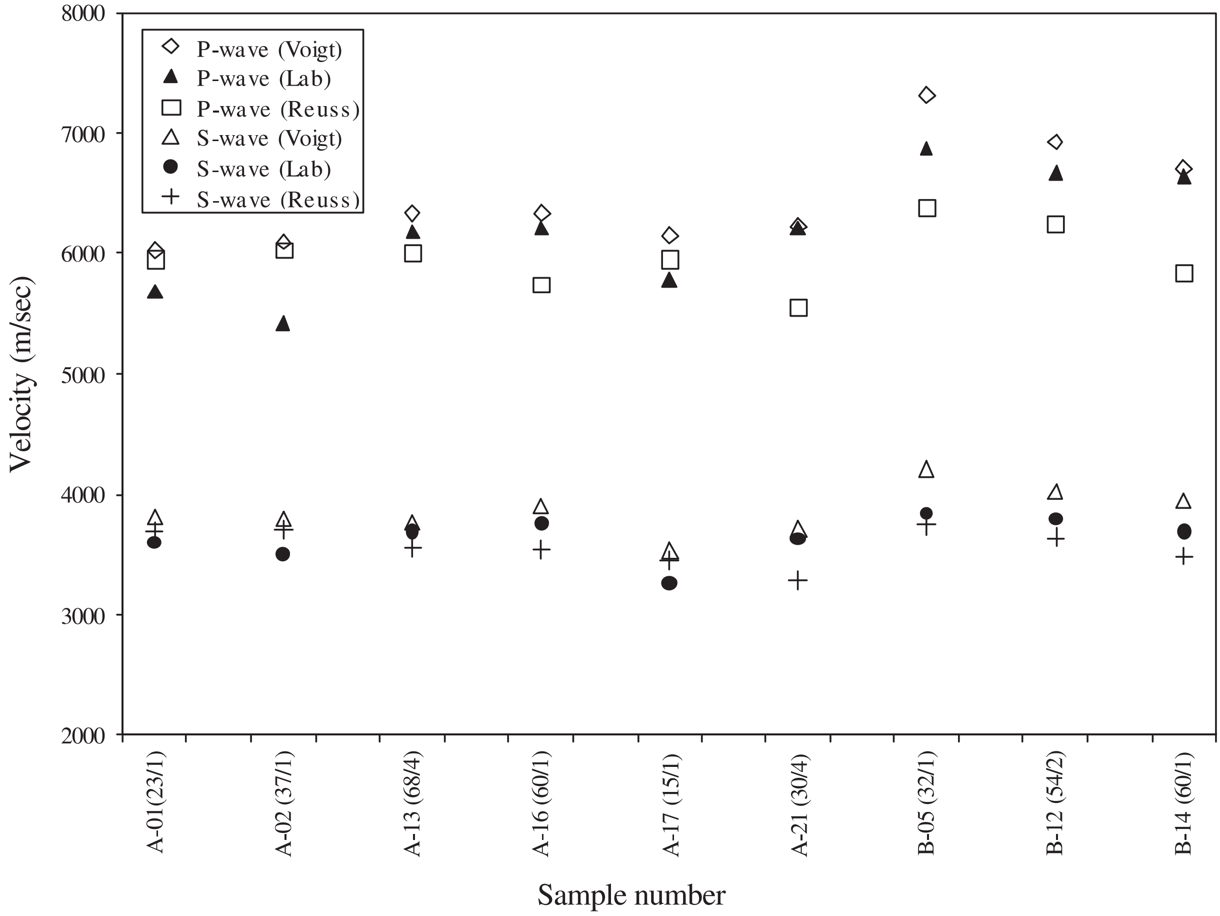

Figure 6. Plot showing the comparison of estimated and measured velocities for the rock samples of the present study. The upper bound is derived from the Voigt model and the lower bound from the Reuss model using the modal composition data (for details, see the text).

and Fountain 1975; Christensen and Mooney 1995; Christensen 1996). The V_P in lower continental crust ranges mainly from 6500 m/s to 7500 m/s and density from 3.0 to 3.2 gm/cc (Christensen and Fountain 1975). In south India, the minimum V_P of the 'lower crust' at 23 km depth is 6600 m/s and it gradually increases to 7200 m/s at 40 km depth as reported from the DSS (Deep seismic sounding) data obtained along the Kavali–Udipi transect (Reddy and Vijaya Rao 2000). The palaeo pressure ranges between 6 kb and 9 kb in the lower crust near Pallavaram (Santosh 1988) which is close to the present study area. The Pallavaram charnockite (mean $\rho = 2.740$ gm/cc, $V_P = 6019$ m/s at the room conditions) shows a V_P of 6455 m/s at 8 kb confining pressure (corresponding to a depth of $\sim$23 km) and 6460 m/s at 10 kb confining pressure (Birch 1960). These values are lower than the minimum V_P of the lower crust at 23 km depth ($V_P = 6600$ m/s). Furthermore, the density and V_P indicate that the Pallavaram samples studied by Birch (1960) may have had mineral composition lying in between the acidic and intermediate varieties of granulites. By applying the velocity-pressure gradient values of Pallavaram charnockites to our data of acidic and intermediate granulites together (mean $\rho = 2.753$ gm/cc, mean $V_P = 6127$ m/s), we find that the rocks of the acidic and intermediate granulites of the present study area would have V_P of the order of 6519 m/s at 8 kb pressure, and it would still fall short of the minimum V_P of the lower crust as obtained from the DSS studies at 23 km depth (table 3). The extrapolated values of V_P at 8 kb and 10 kb confining pressure for the rock samples of the present study are shown in parentheses in table 3. On the other hand, the basic granulites of the present study show an average density of 2.970 gm/cc and V_P of 6697 m/sec at room conditions and they would attain values of $\sim$7100 m/s for V_P at pressures ranging between 8 kb and 10 kb (table 3). These values are comparable to the results reported on mafic granulites by Christensen and Mooney (1995) as can be seen in table 3. The above discussion clearly shows that the density and elastic wave velocities of the 'acidic and intermediate granulite facies rocks' of the present study are less than those of the lower crust. Hence these rocks can be considered to be of midcrustal origin and they are perhaps subjected to either arrested partial conversion of gneiss to charnockite or intense retrograde metamorphism.

5. Conclusions

- The majority of the granulite facies rocks of Mahabalipuram are acidic and intermediate in composition. There were a few basic granulite samples also in the present study. The overall results show that V_P ranges between 5428 m/s and 6884 m/s and V_S ranges from 3259 m/s to 3837 m/s in these rocks. The Poisson's ratio ranges between 0.145 and 0.301. The P-wave attenuation (α_P) ranges between 0.090 dB/cm and 0.942 dB/cm and the S-wave attenuation (α_S) ranges from 0.181 dB/cm and 1.892 dB/cm in these rock samples.
- The acidic granulites show lower velocities and higher attenuation than the intermediate and basic granulites. The velocities, Poisson's ratio and Young's modulus of both intermediate and basic granulites are close to each other. However, the attenuation data, which is perhaps influenced by the microstructure and grain scattering, have shown a strikingly different character. The intermediate granulites show higher α_P and α_S than the basic granulites and it requires a detailed study of the microstructure and attenuation properties of these rocks.
- The mean V_P of acidic and intermediate granulite facies rocks of Mahabalipuram is lower than the minimum DSS velocity of the lower crust. Hence these rocks may belong to mid-crustal levels only and not of lower crust.
- The inter-relationships among the measured parameters, and the dependence of velocities on mineral composition are quite useful for applications in the interpretation of seismic velocity and attenuation data for the purposes of site characterization and rock engineering applications.

Acknowledgements

We thank M/s Larsen & Toubro Ltd., Chennai for the borehole samples and the Department of Science and Technology, New Delhi for the financial support. We thank Dr. V P Dimri, Director, National Geophysical Research Institute, Hyderabad for permission to publish this paper. Our special thanks are due to our colleagues Dr. D S N Murthy for the petrography report, and to Dr. T R K Chetty and Dr. P Senthil Kumar for many helpful discussions. The comments and suggestions received from Prof. Douglas R Schmitt, Professor of Geophysics and Physics, University of Alberta, Canada, and from another anonymous reviewer have vastly improved the manuscript and we are grateful to them.

References

Balakrishna S, Rao M V M S and Ramana Y V 1976 Integrated studies on elastic properties of ultramafic rocks; *Tectonophys.* **35** 229–250.

Balakrishna S and Subrahmanyam Y 1962 Variation of ultrasonic velocities in charnockites; *Curr. Sci.* **31** 62–63.

Bass J D 1995 Mineral Physics and Crystallography; In: *A Handbook of Physical Constants*, Ahrens T J (ed.), AGU Reference Shelf 2, Washington, American Geophysical Union, **2** 45–63.

Bhaskar Rao Y J, Chetty T R K, Janardhan A S and Gopalan K 1996 Sm–Nd and Rb–Sr ages and P–T history of the Archaean Sitampundi and Bhavani layered meta-anorthosite complexes in Cauvery shear zone, South India: Evidence for Neo-Proterozoic reworking of the Archaean crust; *Contributions to Mineralogy and Petrology* **125** 237–250.

Birch F 1960 The velocity of compressional waves in rocks to 10 kilobars. Part – I; *J. Geophys. Res.* **65** 1083–1102.

Bohlen S R and Mezger K 1989 Origin of granulite terrains and formation of lowermost continental crust; *Science* **244** 326–329.

Christensen N I 1996 Poisson's ratio and crustal seismology; *J. Geophys. Res.* **101** 3139–3156.

Christensen N I and Fountain D M 1975 Constitution of lower continental crust based on experimental studies of seismic velocities in granulites; *Geol. Soc. American Bull.* **86** 227–236.

Christensen N I and Mooney W D 1995 Seismic velocity structure and composition of the continental crust: A global view; *J. Geophys. Res.* **100** 9761–9788.

Dawson J B, Carswell D A, Hall J and Wedepohi K H (eds) 1986 The Nature of the Lower Continental Crust; *Geol. Soc. London Spl. Publ.* **24** 297–307.

Gaur V K and Priestley K 1997 Shear wave velocity structure beneath the Archaean granites around Hyderabad inferred from receiver function analysis; *Proc. Indian Acad. Sci. (Earth Planet. Sci.)* **106** 1–8.

Gopalakrishnan K 1996 An overview of Southern Granulite Terrain, India – Constraints in reconstruction of Precambrian assembly of Gondwanaland; *Gondwana Nine* **2** 1003–1026.

Knopoff L 1956 The seismic pulse in materials possessing solid friction, I: Plane waves; *Bull. Seismol. Soc. Am.* **46** 175–183.

Knopoff L 1964 *Q. Rev. Geophys.* **2** 625–660.

Naqvi S M and Rogers J J 1987 Precambrian geology of India; *Oxford Monographs on Geology and Geophysics*, No. **6**, Oxford University Press, 223p.

Newton R C and Hansen H C 1986 South India – Sri Lanka high grade terrain as a possible deep crust section; *Geol. Soc. London Spl. Publ.* **24** 297–307.

Rai S S, Priestley K, Prakasam S S, Srinagesh D, Gaur V K and Du Z 2003 Crustal shear velocity structure of the south Indian Shield; *J. Geophys. Res.* **108** 2088, doi:10.1029/2002JB001776.

Ramakrishnan M (ed.) 2003 Tectonics of Southern Granulite Terrain, Kuppam-Palani Geotransect; *Memoir Geol. Soc. India* **50** 1–434.

Ramana Y V and Rao M V M S 1974a Compressional velocities in ultramafic rocks of India at pressures to five kilobars; *Geophys. J. Roy. Astron. Soc.* **38** 212–217.

Ramana Y V and Rao M V M S 1974b Q by pulse broadening in rocks under pressure; *Phy. Earth and Planet. Inter.* **8** 337–341.

Rao M V M S, Ramana Y V and Gogte B S 1974 Dependence of compressional velocity on the mineral chemistry of eclogites; *Earth Planet. Sci. Lett.* **23** 15–20.

Rao M V M S, Sarma L P and Prasanna Lakshmi K J 2002 Ultrasonic pulse broadening and attenuation in volcanic rock: A case study; *Indian J. Pure and Appl. Phys.* **40** 396–401.

Rao M V M S and Prasanna Lakshmi K J 2003 Shear wave propagation in rocks and other lossy media: An experimental study; *Curr. Sci.* **85** 1221–1225.

Reddy P R and Vijaya Rao V 2000 Structure and tectonics of the Indian peninsular shield – Evidences from seismic velocities; *Curr. Sci.* **78** 899–906.

Santosh M 1988 Fluid inclusion paleopressures and sources of carbonic fluids in the massive charnockites of Kerala, South India; *Geol. Soc. India Memoir* **11** 91–100.

Sidney L and Carel L D 1977 Ultrasonic measurement of some mineral filled plastics; *IEEE Transactions on sonics and ultrasonics* **SU-24** 222–225.

MS received 23 January 2006; revised 30 May 2006; accepted 11 July 2006