Elastic properties of charnockites and associated granitoid gneisses of Kudankulam, Tamil Nadu, India

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Laboratory data of velocity ($V_p$ and $V_s$) and quality factor ($Q_p$ and $Q_s$) of a large number of charnockites and associated granitoid gneisses of Kudankulam are reported in this article. The results show linear relationships between density and velocity, and density and $Q$ values of both the rocks. Charnockites show higher velocities and a wide range of Poisson’s ratio and $Q$ values compared to granitoid gneisses. The laboratory velocity data when extrapolated to high-pressure conditions are comparable to the published field velocity data from deep seismic sounding studies, which were carried out in the southern part of the Southern Granulite Terrain.

Keywords: Charnockites, granitoid gneisses, Poisson’s ratio, $Q$ values, velocity.

Charnockitic rocks and other high-grade granulites of deep crustal origin are well exposed in the southern parts of the well-known Southern Granulite Terrain (SGT) of South India. Several geological, geochemical and geochronological studies of charnockites and associated rocks of the SGT have contributed in understanding the evolution of early continental crust, regional tectonics and the granulite grade metamorphism. Integrated geophysical surveys carried out along some of the geotransects running across the prominent shear zones of the SGT have yielded valuable data on crustal-velocity structure, electrical-conductivity structure and heat-flow estimates. All these integrated studies have revealed that the SGT has a complex and long-lived tectonic history from Palaeoarchean to Neoproterozoic (3000 to 550 Ma), and the present-day exposed granulite terrains represent the exhumed portions of the middle and lower continental crust of the earth. Further, charnockites of more than one generation are recognized in the SGT. Although progressive formation of charnockites from gneisses was observed in many parts of Tamil Nadu and Kerala, reports of arrested partial conversion of gneiss to charnockite have also appeared. In some places it is not clearly known whether the gneiss–charnockite relation is prograde or retrograde. The estimated pressure and temperature conditions for the formation of charnockites and other granulite facies rocks of the SGT are also reported to vary widely. The sources for the influx of CO$_2$ for charnockitization are also found to be different in different parts of the SGT. All these factors have a strong bearing on rock properties, and also influence the geophysical field data and its interpretation for understanding and deciphering the crustal structure and tectonic evolution of the SGT.

Laboratory data on physical properties, especially elastic wave velocities ($V_p$ and $V_s$), of the exposed granulite rocks of deep crustal origin can provide broad constraints for the interpretation of seismic data of deeper crustal levels. But there has not been any systematic study or data of $V_p$, $V_s$ and Poisson’s ratio ($\nu$) of charnockites and other granulite facies rocks of the SGT to enable a comparison with the properties of deeper crustal levels. Only limited data of $V_p$ under high-pressure conditions are available for Pallavaram charnockites and ultramafic rocks of Peninsular India. We have recently taken up the study of physical properties of charnockites and other granulite facies rocks of all the important crustal blocks of the SGT. The results obtained on velocities, Poisson’s ratio and attenuation ($Q^{-1}$) measurements of some of the granulite facies rocks from Mahabalipuram in the Madras Block have been reported recently. In this article, the results of elastic wave velocities ($V_p$, $V_s$), Poisson’s ratio ($\nu$) and quality factor ($Q$) of some borehole samples of charnockites and associated granitoid gneisses of Kudankulam which is close to Kanyakumari and belongs to the Nagercoil Granulite Block (NGB) of the southernmost part of the SGT, are presented and discussed.

Geologic setting and description of rocks

Rock samples in the present study are from a project site for rock-engineering applications at Kudankulam (Figure 1). Several geological and geophysical studies are being conducted there for site characterization and site-response studies. Deep seismic sounding (DSS) studies along a 220 km long N–S geotransect from Vattalkundu to Kanyakumari (Figure 1) cutting across the Achankovil Shear Zone (ACSZ), is the latest geophysical study. The char-
nokites and associated granitoid gneisses of Kudankulam belong to the Nagercoil Granulite Block (NGB). The NGB is one of the three important crustal blocks of the southern part of the SGT. The NGB that is at the south of the ACSZ is bounded by the Trivandrum Block (TGB) in the north and extends into the tip of the peninsula in the south (Figure 1). The NGB is also adjacent to the Kerala Khondalite Belt (KKB). The NGB comprises mostly massive charnockites and pyroxene granulites.

Core samples from 15 closely-spaced, shallow boreholes drilled down to a depth of 20 m at the project site have been used for the present study. A large number of them are fresh, garnet-free, massive charnockites and granitoid gneisses. The charnockites are medium-to-coarse grained and occur at depths ranging from 1.5 to 15.0 m in nine boreholes. The rock samples of the other six boreholes are medium-grained granitoid gneisses at shallow depths (<15 m). In some boreholes, both gneisses and charnockites occur at different depths. The modal composition data (vol. %) for some of the samples are presented in Table 1. The charnockites contain less quartz (22.63%), more plagioclase (50.53%) and are totally free from garnet compared to those of Mahabalipuram charnockites of the Madras Block. These charnockites contain small amounts of clinopyroxene (4.64%), orthopyroxene (1.66%) and haematite (2.9%), whereas the associated granitoid gneisses contain more quartz (28.72%), less plagioclase (45.77%) and smaller quantities of pyroxene. These variations in mineral composition can influence the data on velocities and Poisson’s ratio of the rocks studied, as discussed later.

**Experimental**

The test samples (30 mm dia and ~60–70 mm long) were prepared from NX size cores (54 mm dia). Measurements of $V_p$, $V_s$, $Q_p$ and $Q_s$ were carried out under room conditions on at least three samples of each lithological unit, following our earlier published methods. While velocities are based on travel-time measurements, $Q$ is obtained from pulse-width measurements in rocks, as discussed elsewhere. Prior to the measurement of velocity and $Q$, all the test samples were oven-dried and cooled to room temperature for the removal of moisture. The density data ($\rho$) 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 time-of-flight (or travel time) measurements were made in the test samples at 1.0 MHz frequency using time-of-flight ultrasonic pulse transmission technique, in which arrival times of compressional ($t_p$) and shear ($t_s$) waves are measured accurately (error ±1%) in each test sample. A high-energy pulser on the driving side and a digital storage oscilloscope on the receiving side were used for the measurements of travel time and pulse width of the first received
Results and discussion

Velocity–density systematics, Poisson’s ratio and Q values

The density, velocity and Q data (all average values) obtained from measurements made under room conditions on three specimens of each lithological unit are shown in Table 2 for the charnockites and granitoid gneisses. The data were obtained from measurements carried out on nearly 60 core samples of charnockites and granitoid gneisses. Poisson’s ratio (ν) and Young’s modulus (E) were also computed using the standard relationships between velocities and elastic moduli (Table 2). The density (ρ) of charnockites range from 2.689 to 2.784 m/s (ave 2.735 m/s) and V_p range from 5998 to 6289 m/s (ave 6134 m/s)
Figure 2. Plots showing the relationship between density ($\rho$) and P-wave velocity ($V_p$) (a) and density ($\rho$) and S-wave velocity ($V_s$) (b) of charnockites and granitoid gneisses.

(Table 2 and Figure 2). Poisson’s ratio ranged between 0.225 and 0.306 (ave 0.279), and Young’s modulus vary from 73.44 to 88.64 GPa (ave 80.15 GPa) for the charnockites (Table 2). The $Q$ data of rock samples showed a wider range than velocities, since attenuation ($Q^{-1}$) is a more sensitive parameter (Table 2). The granitoid gneisses show lower values of density, velocity, Young’s modulus and $Q$ compared to the charnockites (Table 2), whereas the values of Poisson’s ratio charnockites and gneisses are comparable. The density–velocity and density–$Q$ relationships for the rocks are shown in Figures 2 and 3 respectively. The large variations in velocities and $Q$ values of charnockites and gneisses are due to the differences in their mineralogical composition and metamorphic histories. The granitoid gneisses show large variation in velocities and $Q$ (Figures 2 and 3) compared to charnockites, which indicates significant changes in their mineralogical composition caused perhaps due to the retrograde metamorphism of charnockites. The results show the expected increasing trend in velocities and $Q$ with increase in density, although the scatter is more in the $V_s$–$\rho$ and $Q$–$\rho$ relationship, especially for the granitoid gneisses (Figures 2 b and 3 b). The granitoid gneisses used for the present study are not oriented samples, and the direction of gneissosity with respect to the direction of propagation of the elastic wave also has a significant influence on velocity and $Q$. Another reason for the large scatter is due to the fact that these results have been obtained under room conditions and not under hydrostatic pressure. Linear regression analysis confirms once again that velocities and $Q$ increase with the increase in density of the rocks (Figures 2 and 3).

Dependence of $V_p$ and Poisson’s ratio on mineral composition

Though the data are limited, the dependence of velocities and Poisson’s ratio on mineral composition has been examined. The results show some interesting relationship between the plagioclase content and $V_p$ and $\nu$ of the rocks (Figure 4 a and b). The variations in quartz and pyroxene do not seem to have any significant influence on $V_p$ and $V_s$ in these charnockites. These observations are similar to the results obtained from measurements made on Mahabalipuram charnockites, in which a marginal increase in $V_p$ and a nearly constant $V_s$ were observed with increase of plagioclase in them. This is understandable because quartz has a lower density, velocity and Poisson’s ratio than plagioclase and pyroxene. Data on the velocity and Poisson’s ratio of charnockites in the present study show fairly good agreement with the results reported on $V_p$ for Pallavaram charnockites by Birch and Poisson’s ratio by Christensen for the mid-crustal rocks. The Pallavaram charnockites ($\rho = 2.740$ g/cc) show $V_p$ of 6150 m/s at 10 bar confining pressure and 6460 m/s at 10 kilobar confining pressure. Though the charnockites are low-porosity rocks, application of hydrostatic pressure can certainly reduce the anomalies noticed among the velocities and attenuation in them at NTP conditions.
**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\(^{19-21}\). The $V_p$ in lower continental crust\(^{19}\) ranges mainly from 6500 to 7500 m/s and density from 3.0 to 3.2 g/cc. 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 profile data from Kavalli to Udupi\(^1\). At shallow crustal depths in the SGT, the seismic velocities\(^{8,5,33}\) range from 6000 to 6500 m/s for $V_p$ and from 3000 to 3500 m/s for $V_s$. DSS study of the subsurface velocity structure using $P$- and $S$-wave seismic refraction data and 2D tomographic images along a 220 km long N–S geotransect from Vattalkundu to Kanyakumari (Figure 1) cutting across the ACSZ, is the latest geophysical study\(^9\). The tomographic images show relatively high $V_p$ (6300–6500 m/s) and high $V_s$ (3500–3800 m/s) bodies at very shallow depths (0.5–8.0 km) along that profile across the ACSZ\(^9\). These observations indicate that the rocks present at the shallow depths are high-grade metamorphic charnockites of deeper origin that are exhumed to shallow depths and differ in composition from the rocks of the surrounding gra-
nulite facies. Also, the charnockites present in Madurai and Trivandrum Blocks on either side of the ACSZ contain more garnet, which might have contributed to such high seismic velocities. On the other hand, the NGB charnockites are relatively free from garnet and the estimated pressure ranges from 4.0 to 6.0 kbar (ave 5.0 kbar), and the metamorphic temperature is quite high (up to 934°C) for the formation of NGB charnockites. The corresponding depth for the above-mentioned estimated pressure is ~15 km and the seismic velocities are expected to be around 6500 m/s for Vp and 3600 m/s for Vs at that depth. In the absence of high-pressure laboratory velocity data of the charnockite rocks of Kudankulam, and by applying the velocity-pressure gradient values of Palavaram charnockites (mean ρ = 2.740 g/cc and Vp under room conditions = 6019 m/s) to the present data of Kudankulam charnockites (mean ρ = 2.735 g/cc, mean Vp = 6134 m/s, mean Vs = 3385 m/s under room conditions), we conclude that the charnockites of the present study area would have Vp of the order of 6500 m/s and Vs of the order of 3590 m/s at 5.0 kbar pressure, corresponding to a depth of ~15 km. These pressure-corrected velocity values of Kudankulam charnockites are comparable to the DSS data at such depths. The gneisses which have shown lower wave velocities and moduli in accordance with the changes in mineralogical composition, are perhaps products of the retrograde metamorphism of the charnockites of the SGT and this requires detailed studies.

Conclusion

The observed large variations in the velocities and Q of charnockites and granitoid gneisses are due to the mineralogical differences between the two groups of rocks. The granitoid gneisses, compared to charnockites, show large variation in velocities and Q due to their complex mineralogy. The pressure-corrected velocity data are comparable to the DSS velocity values at depths ~15 km in the southern part of the SGT. This lends support to the field observations that charnockites of the present study belong to the high-grade metamorphic basic granulites which are exhumed to shallow crustal levels. The interrelationships among the measured parameters, and the dependence of velocities on mineral composition are useful for applications in the interpretation of seismic velocity and Q data for site characterization and rock-engineering applications.


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