Elastic wave velocity in rocks from Dabieshan and its constraints for lithospheric composition and crust-mantle recycling*

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Abstract P- and S-wave velocities in eclogites and granulites from the Dabie ultrahigh pressures (UHP) metamorphic belt, China, were measured at room temperature under the hydrostatic pressures up to 1.0 GPa. The ultrahigh pressure eclogites had the highest densities ($3.3 \sim 3.6\ g\cdot cm^{-3}$), high velocities and the lowest anisotropy (1.4% ~ 2.6%). The lowest densities ($2.8 \sim 3.1\ g\cdot cm^{-3}$) and the highest Poisson's ratios (0.28 ~ 0.29) were found in granulites, whereas the strongest anisotropies (6.1% ~ 8.4%) were found in the high-pressure (HP) eclogites. Comparison of the velocities in rocks with that observed in the deep seismic sounding profile crossing Dabieshan suggests that eclogites might exist in the lower crust of Dabieshan, but the quantity might be small. The upper mantle has very similar velocities as the UHP eclogites and serpentinizated/water-bearing dunite. The formation of eclogite represents the crust-mantle recycling processes. Crustal material is delaminated and sinks into the mantle by way of eclogite, whereas only a small part of the eclogite could return to the crust.

Keywords: Dabieshan, eclogite, elastic wave velocity, anisotropy, Poisson's ratios.

The method of comparing the physical properties of rocks and minerals at high pressure and temperature with the data obtained by deep geophysical survey has been regarded as one of the most important tools in studying the composition and state of the deep lithosphere. With high density, eclogite has suffered high and ultrahigh pressure metamorphism. Seismic velocity in eclogite will be helpful in discovering the structure and constitution of the lithosphere, in explaining the process and genesis of ultrahigh pressure (UHP) and high pressure (HP) rocks, and in evaluating the role of eclogite in crust-mantle recycling. The elastic data of eclogite is still few, although some results have been reported recently. Fountain et al. measured the P-wave velocity (V_P) in 13 eclogite samples from Bergen Arcs, Norway, at pressures up to 0.6 GPa[1]. Gao et al.[2] and Kern et al.[3] studied the V_P and S-wave velocities (V_S) in 7 eclogites and related rocks (a total of 30 samples) of Dabieshan at pressures up to 0.6 GPa and temperatures up to 600℃. Zhao et al. made their measurements of V_P in 10 eclogites of Dabieshan at high pressures up to 5.0 GPa[4]. In this study, we present our new results of V_P and V_S of Dabieshan eclogites and granulites at room temperature and hydrostatic pressures up to 1.0 GPa. The elastic features of eclogite and granulite are well used in estimating the compositions of lower crust and upper mantle in

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Dabieshan and crust-mantle recycling.

1 Sample and experiment

1.1 Sample

Many results of metamorphism, petrology, mineralogy and chronology have been obtained recently on the Dabie ultrahigh pressure metamorphic belt (see the review by Cong and Zhai[5]). The Dabie ultrahigh pressure metamorphic belt is divided into at least three sub-units, ultrahigh pressure belt, high pressure belt and granulite region[6]. We sampled in the key outcrops of the units in Dabie region in Hubei, Anhui and Henan provinces. The specimens used in this work were parts of the samples collected from UHP, HP and granulite facies metamorphic belts (Table 1). The UHP rock samples were coesite-bearing eclogites, with SiO_2 contents ranging from 41.27% to 50.21%. The HP rocks were eclogites and garnet-amphibolite, with SiO_2 in the range of 43.38% ~ 47.78%, except for LW965, which was a serpentinizated dunite. The two granulite samples (biotite-bearing and horblende-bearing granulites) were from Huilanshan, with the SiO_2 contents of 50.13% and 43.46%, respectively.

Table 1 Locations and modal compositions of the experimental samples.

Sample	Locality	Lithology	Modal composition[a)]
UHP belt			
SH967	Shuanghe, Qianshan	Eclogite	40grt, 25hbl, 10cpx, 10ep, 10ms, 5(rt, zo, ap)
SM961	Shima, Taihu	Coe-eclogite	40grt, 55omp, 5(rt, mgs, hbl, qtz)
WM962	Wumiao, Qianshan	Coe-eclogite	45grt, 45cpx, 10(hbl, ms, mgs, ep, rt, qtz)
BM961	Bamaojie, Yingshan	Coe-eclogite	35grt, 25cpx, 15hbl, 10pl, 5ms, 5qtz, 5(ap, rt)
HP belt			
GQ961	Gaoqiao, Huangpi	Eclogite(retrogressed)	35grt, 40hbl, 10gln, 10cc, 5(ms, qtz, mt)
XD962	Xiongdian, Dawu	Eclogite	45grt, 35cpx, 10hbl, 5ep, 3qtz, 2(rt, ms, ap, spn)
XD966	Xiongdian, Dawu	Eclogite	38grt, 30cpx, 20hbl, 7ep, 3qtz, 2(rt, ap, cc)
XH961	Xuanhuadian, Dawu	Eclogite	25grt, 35tr, 20zo, 10cpx, 5ms, 5(rt, mt)
QJ961	Qianjinhepeng, Xinxian	Eclogite(retrogressed)	35grt, 45hbl, 10qtz, 3pl, 5spn, 1mt, 1ep
LW965	Luwang, Dawu	Serpentinizated dunite	93sep, 5mt, 2ol
Granulite region			
HL963	Huilanshan, Luotian	Bi-two pyroxene granulite	55pl, 20bi, 10cpx, 5opx, 5hbl, 5(mt, ap, qtz)
HL969	Huilanshan, Luotian	Hbl-two pyroxene granulite	45pl, 40cpx, 5opx, 5hbl, 3bi, 2(mt, qtz)

a) Abbreviations: ap, apatite; bi, biotite; cc, calcite; cpx, clinopyroxene; ep, epidote; gln, glaucophane; grt, garnet; hbl, hornblende; mgs, magnesite; ms, muscovite; mt, magnetite; ol, olivine; omp, omphacite; opx, orthopyroxene; pl, plagioclase, qtz, quartz; rt, rutile; sep, serpentinite; spn, sphene; tr, tremolite; zo, zoisite.

1.2 Experiment

The specimens selected for the experiments were fresh samples devoid of cracks and veins by visual inspection, and without secondary alteration. The modal composition (Table 1) and major chemical compositions were determined before the experiments. The density and elastic wave velocity measurements were all performed at Department of Geology and Geophysics, University of Wisconsin at Madison. Three mutually perpendicular cores (for banded and foliated rocks, ***X*** parallel to lineation, ***Y*** perpendicular to lineation and ***Z*** normal to foliation) were taken from each sample using a diamond-coring bit with 2.54 cm diameter. Each core averaged approximately 5 cm in length. The core ends were trimmed and ground flat. The density of each core was calculated from their weights and dimensions. Each core was fitted with a soldered copper jacket to prevent penetration of high-pressure oil into the rock samples. To make velocity measurements, 1 MHz transducers were affixed to both core ends. Gum rubber tubing was placed over the sample assembly as a further prevention of oil leakage. Velocities were measured at room temperature under hydrostatic pressures up to 1.0 GPa (equivalent to about 35 km depth) using the pulse transmission technique described by Christensen[7]. The cumulative error limits for V_P and V_S were estimated to be less than 1 %. Readings were taken at intervals of 0.02 GPa in the range of 0 ~ 0.1 GPa, and intervals of 0.2 GPa in the range of 0.2 ~ 1.0 GPa. Therefore 10 V_P and 10 V_S were obtained for each core, and 30 V_P and 30 V_S for a sample.

2 Results

The relationship between V_P or V_S and the pressure in sample XH961 is plotted in Fig. 1, which is the representative of the 12 samples. V_P and V_S increase quickly with increasing pressure up to 0.2 GPa, slightly increase with increasing pressure in the range of 0.2 ~ 1.0 GPa, showing a linear profile. The quick increase indicates the closure of microcracks in the samples, and the linear relationship represents the intrinsic quality of various types of rocks. We calculated the pressure derivatives of V_P and V_S ($\frac{\partial V_P}{\partial P}$ and $\frac{\partial V_s}{\partial P}$) by a linear regression, and obtained the velocity at 0 GPa. The mean density, average velocity at 1.0 GPa, and Poisson's ratios and anisotropies in the range of 0.2 ~ 1.0 GPa were also calculated. The results are tabulated in Table 2.

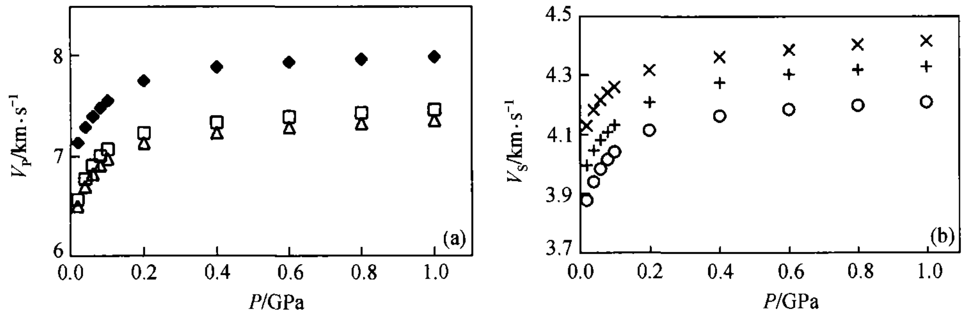

Fig. 1 V_P(a) and V_S(b) as a function of pressure in Dabieshan eclogite (XH961). (a) ◆, *X*; □, *Y*; △, *Z*; (b) ×, *X*; +, *Y*, ○, *Z*.

2.1 Density and velocity

The samples from different metamorphic belts have variable density and velocity. A good linear relationship was found both for V_P and V_S with respect to density in the 12 samples (Fig. 2). Among the samples, the UHP eclogites have the highest density

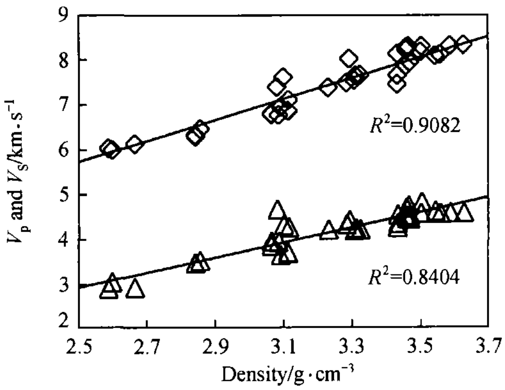

Fig. 2 V_P and V_S versus densities in rocks from Dabieshan. ◇, V_P; △, V_S

Table 2 Elastic wave velocity and related data in the rocks of Dabieshan

Sample	Density/g·cm^{-3}	V_P/km·s^{-1}		$\frac{\partial V_P}{\partial P}$/km·s^{-1}·(GPa)$^{-1}$	V_S/km·s^{-1}		$\frac{\partial V_S}{\partial P}$/km·s^{-1}·(GPa)$^{-1}$	Poisson's ratio[a)]	A-V_P/%[b)]
		P = 0 GPa	P = 1 GPa		P = 0 GPa	P = 1 GPa			
UHP belt									
SH967	3.501	7.796	8.125	0.363	4.433	4.546	0.127	0.268	1.441
SM961	3.591	8.106	8.219	0.123	4.528	4.570	0.046	0.275	2.563
WM962	3.475	8.077	8.256	0.196	4.644	4.739	0.103	0.254	1.759
BM961	3.314	7.177	7.590	0.446	4.139	4.211	0.074	0.271	2.370
HP belt									
GQ961	3.453	7.420	7.726	0.332	4.301	4.428	0.137	0.253	6.272
XD962	3.445	7.583	7.879	0.319	4.391	4.436	0.050	0.261	6.122
XD966	3.101	6.999	7.355	0.393	4.278	4.417	0.155	0.212	6.372
XH961	3.270	7.357	7.606	0.271	4.204	4.315	0.123	0.261	8.415
QJ961	3.073	6.523	6.772	0.256	3.787	3.919	0.146	0.243	7.882
LW965	2.618	5.847	6.058	0.225	2.951	2.978	0.028	0.371	2.410
Granulite region									
HL963	2.848	6.050	6.356	0.334	3.389	3.498	0.118	0.279	3.058
HL969	3.108	6.625	6.878	0.271	3.632	3.689	0.062	0.294	3.077

a) Average Poisson's ratios at pressure of 0.2 ~ 1.0 GPa; b) average anisotropy of V_P at pressure of 0.2 ~ 1.0 GPa.

and velocity, whereas granulites show the lowest density and velocity. Density and velocity of HP eclogites are in the middle of UHP eclogites and granulites (Table 2). Elastic wave velocities in rocks are mostly controlled by the volume percentage of major minerals and their single crystal elastic properties. Comparing with the HP eclogites, the UHP eclogites are abundant in minerals with high density and velocity (garnet, omphacite, and pyroxene). The granulite is constituted by plagioclase and pyroxene. Therefore in the rocks with similar composition (SiO_2 contents of 41% ~ 51%), its density and velocity increase with increasing metamorphic grade. At 1.0 GPa, V_P and V_S(Table 2) in serpentinizated dunite (LW965) are lowered by about 28% ~ 38%, as compared with the fresh dunite (8.4 and 4.8 $km \cdot s^{-1}$)[8]. This shows that serpentinization could lower the velocity of the olivine-abounded mantle. Pressure derivatives of V_P and V_S in the rocks are in the ranges of 0.123 ~ 0.446 and 0.028 ~ 0.155 $km \cdot s^{-1} \cdot (GPa)^{-1}$, respectively. The result in this study agrees very well with the reported experimental data[1~4] and with the compilation[8~10].

2.2 Anisotropy

The anisotropy of elastic wave velocities in rocks is defined as:

$$A(\%) = [(V_{Max} - V_{Min})/V_{Mean}] \times 100\%,$$

which reflects the velocity difference caused by lattice preferred orientations. The V_P anisotropy ($A - V_P$) of UHP eclogites ranges from 1.441% to 2.563%, which agrees very well with the measurements of 3%[1], 1.95% ~ 2.07%[2], and compiled results of 0.9% ~ 2.7%[9]. The $A - V_P$ in UHP eclogites is very low and reaches the lowest value in metamorphic rocks. The major minerals in UHP eclogites are garnet (35% ~ 45%) and omphacite (10% ~ 55%). Garnet is cubic in symmetry without anisotropy. Thus, the anisotropy of omphacite crystal is responsible for that of the UHP eclogites. $A - V_P$ of HP eclogites is much higher than that of UHP eclogites and similar to that of amphibolite[9]. This mostly arose from their higher contents of horblende, and most of the HP eclogites have retrograded to garnet-amphibolite.

2.3 Poisson's ratio

Poisson's ratio, calculated from both V_P and V_S, is one of the most important parameters in distinguishing rock types[8]. For example, in the progressive metamorphism of mafic rocks, V_P and V_S increase gradually, but the variation of Poisson's ratios is different. Poisson's ratios change from green-schist- and amphibolite-facies (0.26) and granulite-facies (0.28) to eclogite-facies (0.27)[8]. In this study, Poisson's ratios in all samples increase with increasing pressure, and reach the constant values in the range of 0.2 ~ 1.0 GPa. The values are 0.279 ~ 0.294 for granulites, 0.254 ~ 0.275 for UHP eclogites, and the lowest 0.212 ~ 0.261 for HP eclogites. The highest value is found in serpentinizated dunite (0.371), suggesting that Poisson's ratios in dunite can be increased greatly by serpentinization. The Poisson's ratios in UHP eclogites are similar to the compiled data[8]. The lowest values found in HP eclogites are close to that of granite gneiss[8], which needs a further study.

3 Discussion

The crustal structures of P-, S-wave velocity, Poisson's ratios and density in the deep seismic sounding profile across the Dabie ultrahigh pressure metamorphic belt and adjacent regions were established by Wang et al.[11, 12]. It supplied the fundamental data in studying the lower crust and upper mantle composition of Dabieshan, by means of seismic velocity in rocks.

3.1 Constitution of the lower crust

High-velocity zone deeper than 3 km beneath Dabieshan was found. V_P and Poisson's ratios of the lower crust are 6.9 ~ 7.0 km·s^{-1} and 0.272 ~ 0.282 respectively, which are higher than those of the adjacent Yangtze block (6.8 km·s^{-1} and 0.265) in the south and the North China block (6.7 km·s^{-1} and 0.265) in the north. The high-velocity zone is considered to be related with UHP rocks[11] and a content of 11.6% of eclogite calculated by Zhao et al.[4] results from the high-velocity zone. The lower crust is commonly accepted to be granulite-facies. We calculated the velocity and Poisson's ratios of the eclogites and granulites at the depth of 35 km using the temperature derivatives of Gao et al.[2]. The average heat flow of Christensen[9] was assumed in Dabieshan, with the temperature of 550 ℃ at the depth of 35 km. Our calculations of Dabieshan eclogites and granulite, together with the data of the lower crust of Dabieshan, North China block, and Yangtze block[11,12] are all plotted in Fig. 3. The data of mafic granulites of Gao et al.[2] and Christensen[9] are also included using the same method. Fig. 3 shows that the data of the lower crust beneath Dabieshan does not agree with that of the granulites and eclogites of our work. The granulites have higher Poisson's ratio and lower V_P, whereas eclogites have higher V_P and lower Poisson's ratio than the Dabieshan lower crust. Therefore, the lower crust seems to include two endmembers, the biotite (horblende) granulites and the eclogites of this work. It means some eclogites might still exist in the lower crust beneath Dabieshan, which is consistent with the other results[4, 12]. On the other hand, we note that the Huilanshan mafic granulite of Gao et al.[2] and the mafic granulite complied by Christensen[8] agree very well with Dabieshan lower crust (Fig. 3). This suggests that the lower crust is possibly composed of only mafic granulites, there are no or only a small number of eclogites in the lower crust.

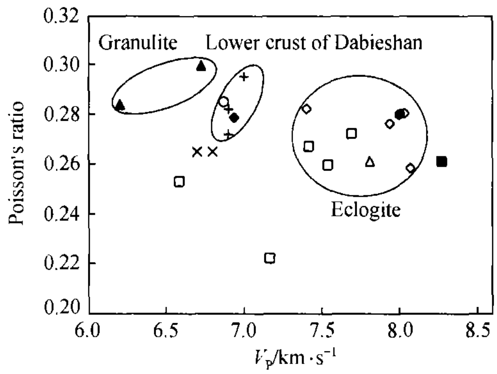

Fig. 3 Poisson's ratios ~ V_P plot of the lower crust and upper mantle of Dabieshan and in rocks (calculated to 35 km depth). Data sources: ◇, UHP eclogites, this work; □, HP eclogites, this work; ▲, granulites, this work; ○, mafic granulite[8]; ◆, mafic granulite[2]; ×, lower crust of North China and Yangtze blocks[12]; +, lower crust of Dabieshan[12]; ●, upper mantle of Dabieshan[12]; ■, dunite[8]; △, pyroxenite[8].

3.2 Eclogite and the upper mantle

The deep seismic sounding profile shows that the Moho beneath Dabieshan is the seismic boundary of crust and upper mantle. The seismic parameters of the upper mantle are V_P = 7.9 ~ 8.1 km·s^{-1} with a mean of 8.0, and V_S = 4.42 km·s^{-1} with the Poisson's ratios greater than 0.28[11, 12]. We calculated the velocity of dunite and pyroxenite[8] for the pressure and temperature at the depth of 35 km (corresponding to the shallowest depth of the upper mantle), and added it into Fig. 3 together with that of the upper mantle of Dabieshan. It is not expected to see that the data of the upper mantle is very close to that of UHP eclogites, whereas dunite is high in V_P and is lower in Poisson's ratio (0.261). The results from olivine- and pyroxene-dominated upper mantle models (with lower Poisson's ratios) differ from that obtained from Dabieshan upper mantle (> 0.280). Thus, eclogite maybe dominate in composition of Dabieshan upper mantle, estimating only from the seismic properties. Serpentinization could increase the Poisson's ratio of dunite, as mentioned above. Another research showed that the presence of fluids at high pressures could also increase the Poisson's ratio apparently[13]. Hence, the fluid bearing or partly serpentinizated dunite will have the same characteristics with the upper mantle of Dabieshan. We should emphasize that these models need more evidence.

3.3 Eclogite and crust-mantle recycling

Are eclogites crustal materials that have been recycled by delamination? Is the UHP metamorphism one of the processes of crust-mantle exchange? Elastic wave velocity and density of UHP eclogite provide some evidence for us to answer these questions.

Eclogite can be generated in the lower part of the crust or upper mantle of thickened area caused by subduction and collision at a depth up to 120 km. In the formation of eclogite facies metamorphism, the rock will become eclogite with the increased P-wave velocity and density. The density of fresh eclogites ranges from 3.4 to 3.6 $g \cdot cm^{-3}$, which is significantly denser than the candidates for mantle mineral (3.4 $g \cdot cm^{-3}$ of garnet-dunite, 3.3 $g \cdot cm^{-3}$ of pyroxenite and dunite)[9] and than the upper mantle beneath Dabieshan (3.38 $g \cdot cm^{-3}$)[12]. The density of the mantle at 6 GPa (equivalent to > 180 km) is 3.38 $g \cdot cm^{-3}$, as calculated by Saxena[14]. The density difference between UHP eclogite and the upper mantle (> 0.2 ~ 0.3 $g \cdot cm^{-3}$) is very important. A definite volume of UHP eclogite will detach from the upper part of the subducted slab of less dense continental crust and sink into the deeper mantle, under the conditions that their weight are higher than the critical buoyancy of the underlying mantle rocks. This is a widely accepted model called delamination that has been supported by geochemical evidence[15, 16]. It is the process that the crustal material recycles into the mantle by way of high-density eclogites. The less densely subducted upper continental slab separated from the delaminated eclogites will come back quickly to the crust because of buoyancy, forming some eclogites in the lower part. Some of the eclogites will be exposed on the Earth's surface through other process. Two interacted processes are included in the formation of eclogite. Some eclogite are delaminated into the deeper mantle, whereas some exhume to the crust. The formation of eclogite stands for the crust-mantle recycling process and the UHP rocks may be a breakthrough point in explaining some geodynamic problems.

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