Compressional Wave Velocities in Eclogites of the Dabieshan, Central China to 5.0 GPa: A Preliminary Result

Zhidan Zhao, Hongsen Xie, Wenge Zhou, Zeming Zhang*, Jie Guo, Yueming Zhang, Zuming Xu, and Ji-an Xu**

Institute of Geochemistry, Chinese Academy of Sciences, Guiyang 550002, China

** Faculty of Earth Sciences, China University of Geosciences, Wuhan 430074, China*

*** Institute of Earth Sciences, Academia Sinica, Taipei, China*

The Dabie high- and ultrahigh-pressure metamorphic belt is a collisional orogen where coesite and microdiamond inclusions were found. Ten eclogite samples, five from the high-pressure (HP) belt and five from the ultrahigh-pressure (UHP) belt, were selected and measured the compressional wave velocities (V_p) in three mutually orthogonal directions. The UHP eclogites seem to have higher V_p than the HP samples at the identical pressures. The anisotropy in samples from UHP belt (4.16 %) is less than that from HP belt (6.37 %). Eclogite, with a possible content from 7.8 to 16.5 % is distributed in the crust beneath the central Dabieshan.

[compressional wave velocity, anisotropy, high pressure, eclogite, Dabieshan]

1. Introduction

The elastic wave velocities in various minerals and rocks have been measured by many scientists and applied in estimating the composition and state of the earth's interior. Eclogites, being the representative highest grade metamorphic rocks exposed in the crust which have subducted to deeper lithosphere, have gained widely interests of geoscientists. A few data of physical properties of eclogite could be found in papers. Some data of elastic wave velocities were measured at pressure up to 0.6 [1,2], 1.0 [3-6] or 3.0 GPa [7]. We finished the measurement of Dabie eclogites up to 5.0 GPa recently. Some experimental results are reported in this paper.

2. Geological setting, sample and experiment

The Dabie-Sulu ultrahigh-pressure (UHP) metamorphic belt of east-central China is the largest among seven recognized UHP belts in the world [8]. The Dabie HP and UHP belt, being the joint of the North China and Yangtze cratons, includes five units. They are, from south to north, (1) epidote blueschist belt; (2) high P low T belt; (3) UHP belt; (4) high P medium T belt and (5) bare of eclogite belt [9].

We selected 10 eclogite samples, 5 from the HP belt and 5 from UHP belt, and measured the compressional wave velocities

(V_p) in the rocks. A brief description of the samples is as Table 1. The major oxide compositions are listed in Table 2.

The experiments were performed in a high pressure cell in YJ-3000 tons press. Three mutually orthogonal rock cores (X, parallel to lineation; Y, perpendicular to lineation and Z, normal to foliation), each one 12 mm in diameter and 33 mm in length, were cut from one sample in order to measure the V_p in three directions. V_p in the samples at high pressure was calculated from the numerical signals of the length and travel time in the sample on the sound wave detective system (see [11] for details).

V_p in each core was measured with increasing pressures with an interval of 0.1 GPa in the range of 0.1-1.0 GPa, and of 0.5 GPa in the range of 1.0-5.0 GPa. Some results for the eclogites are reported in Table 3. V_p versus pressure in two eclogites, XD966 and WM962, is plotted in Fig. 1.

3. Result and discussion

V_p variation with pressure

In our experiments, V_p increased rapidly with increasing pressure from 0.1 to 1.0 GPa, representing the closure of microcracks in the sample. V_p slowly increased in the range of 1.0-5.0 GPa and exhibits a good V_p -pressure linear relationship. This is much different with the results reported by Kern and his

Table 1. Description of eclogites.

Sample	Locality	Lithology	Density (g/cm ³)	Modal mineralogy, (vol. %)	Peak metamorphic PT conditons ⁽¹⁾
UHP belt					
SH967	Shuanghe, Qianshan	eclogite	3.455	40grt, 25hbl, 10cpx, 10ep, 10ms, 5(rt, zo, ap)	550-680 °C, 3.0 GPa
SM961	Shima, Taihu	coe-eclogite	3.575	40grt, 55omp, 5(rt, mgs, hbl, qtz)	639-696°C, >2.7-2.9 GPa
SM962	Shima, Taihu	coe-eclogite	3.198	40grt, 30cpx, 12zo, 10hbl, 5qtz, 3(rt, ap)	639-696°C, >2.7-2.9 GPa
WM962	Wumiao, Qianshan	coe-eclogite	3.460	45grt, 45cpx, 10(hbl, ms, mgs, ep, rt, qtz)	744-778°C, >3.5-3.9 GPa
BX961	Bixiling, Qianshan	eclogite	3.561	50grt, 45omp, 5(rt, zrn, hbl)	600-700 °C, 3.0 GPa
HP belt					
GQ961	Gaoqiao, Huangpi	Eclogite ⁽²⁾	3.413	35grt, 40hbl, 10gln, 10cc, 5(ms, 1qtz, 1mt)	460-550 °C, 1.2-1.7 GPa
CD962	Chendian, Xinxian	eclogite	3.397	40grt, 30cpx, 10ep, 10hbl, 5qtz, 2pl, 3(gln, rt, ms)	410-470 °C, 1.5 GPa
XD962	Xiongdi, Dawu	eclogite	3.414	45grt, 35cpx, 10hbl, 5ep, 3qtz, 2(rt, ms, ap, sph)	430-630 °C, 1.5 GPa
XD966	Xiongdi, Dawu	eclogite	3.100	38grt, 30cpx, 20hbl, 7ep, 3qtz, 2(rt, ap, cc)	430-630 °C, 1.5 GPa
XH961	Xuanhuadian, Dawu	eclogite	3.208	25grt, 35rt, 20zo, 10cpx, 5ms, 5(rt, mt)	520-550 °C, 1.5 GPa

Abbreviations: ap=apatite; cc=calcite; coe=coesite; cpx=clinopyroxene; ep=epidote; gln=glaucofan; grt=garnet; hbl=hornblende; mgs=magnetite; ms=muscovite; mt=magnetite; omp=omphacite; pl=plagioclase; qtz=quartz; rt=rutile; sph=sphene; tr=tremolite; zo=zoisite; zrn=zircon.

(1) PT conditions for UHP are from [8], for HP are from [9] except for GQ961 from [10]. (2) Retrogressed eclogite.

Table 2. Major element analyses of eclogites (wt. %).

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	H ₂ O ⁺	H ₂ O ⁻	P ₂ O ₅	CO ₂	Sum
UHP belt															
SH967	41.27	0.27	17.09	13.30	5.20	0.29	6.20	11.00	1.98	0.17	0.22	0.03	1.41	1.09	99.52
SM961	42.41	0.35	12.53	15.29	5.01	0.39	5.10	11.20	2.89	0.02	0.49	0.03	1.47	1.92	99.10
SM962	53.93	0.09	14.94	5.81	2.69	0.18	5.70	11.50	1.44	0.05	0.73	0.07	0.13	1.90	99.16
WM962	50.21	0.07	14.21	7.42	2.88	0.20	7.90	10.70	2.90	0.25	0.92	0.09	0.07	1.36	99.18
BX961	44.56	0.51	13.33	15.98	5.02	0.29	6.30	8.90	1.90	0.05	1.07	0.07	0.11	1.03	99.12
HP belt															
GQ961	43.38	0.47	10.60	14.36	6.24	0.28	6.30	8.90	2.10	0.03	2.80	0.13	0.12	3.61	99.32
CD962	50.44	0.31	14.77	12.45	1.75	0.28	3.90	7.60	3.85	0.24	1.73	0.07	0.33	1.49	99.21
XD962	45.03	0.33	16.87	10.06	9.04	0.26	3.90	11.00	1.86	0.09	0.60	0.03	0.11	0.70	99.88
XD966	43.66	0.42	14.21	5.79	4.41	0.25	6.00	16.30	1.11	0.14	3.09	0.30	0.12	3.30	99.10
XH961	47.28	0.25	16.62	7.12	4.98	0.20	7.80	9.10	2.61	0.48	1.32	0.10	0.21	1.06	99.13

Table 3. Compressional wave velocities V_p (km/s) and velocity anisotropy (%) at pressures up to 5.0 GPa (room temperature).

Sample	Pressure (GPa)						Anisotropy	
	0.6	1.0	2.0	3.0	4.0	5.0	range	mean
UHP belt								
SH967	8.29	8.77	9.02	9.28	9.54	9.82	0.69-3.56	2.41
SM961	7.89	8.35	8.68	8.96	9.20	9.44	0.59-4.70	2.03
SM962	7.47	7.90	8.09	8.36	8.64	8.94	3.69-6.31	5.04
WM962	8.71	9.27	9.61	9.97	10.26	10.54	0.37-4.99	2.55
BX961	7.96	8.45	8.76	9.07	9.39	9.68	7.94-13.33	8.79
HP belt								
GQ961	7.98	8.34	8.61	8.89	9.12	9.37	2.08-5.51	3.51
CD962	8.00	8.42	8.75	9.11	9.41	9.71	9.46-11.60	10.28
XD962	7.71	8.05	8.26	8.49	8.76	8.99	1.68-3.94	2.37
XD966	7.59	7.88	8.08	8.32	8.57	8.80	8.49-11.66	10.15
XH961	7.52	7.84	8.14	8.40	8.67	8.93	5.04-6.85	5.55

Notes: 1. V_p in each sample is the average compressional wave velocities in the X, Y and Z directions. 2. Anisotropy (%) = $(V_{p, \max} - V_{p, \min}) \times 100 / V_{p, \text{mean}}$, the anisotropy listed are calculated in the range of 0.1-5.0 GPa.

co-workers (i.e., [2] and other papers), a closure pressure of about 0.2 GPa was obtained in their experiments. Our result is much similar to Matsushima [12]) and Christensen [7]. There appears to be a linear relation in the ranges of 1.0-1.8 GPa [12] and 1.0-3.0 GPa [7], suggesting that some grain boundary porosities are still existing until the pressure approximately 1.0 GPa is reached in some hard rocks, such as dunite or eclogite.

Pressure derivatives of V_p in the eclogites are calculated from the linear trends between 1.0 and 5.0 GPa (Table 4). It lies in the range 0.26-0.32 $\text{kms}^{-1}\text{GPa}^{-1}$ (mean 0.283) for UHP eclogites and 0.23-0.33 $\text{kms}^{-1}\text{GPa}^{-1}$ (mean 0.264) for HP

Table 4. Pressure coefficients of V_p between 1.0 and 5.0 GPa.

Sample	$\partial V_p / \partial P$ ($\text{kms}^{-1}\text{GPa}^{-1}$)			
	X	Y	Z	Mean
UHP belt				
SH967	0.269	0.247	0.269	0.262
SM961	0.222	0.289	0.265	0.259
SM962	0.250	0.276	0.275	0.267
WM962	0.341	0.311	0.301	0.318
BX961	0.312	0.308	0.308	0.310
HP belt				
GQ961	0.266	0.246	0.261	0.257
CD962	0.352	0.338	0.286	0.325
XD962	0.222	0.242	0.231	0.232
XD966	0.223	0.214	0.269	0.235
XH961	0.282	0.260	0.274	0.272

eclogites. These values are comparable with the typically data 0.1-0.3 $\text{kms}^{-1}\text{GPa}^{-1}$ (between 0.4 and 0.6 GPa) for the eclogites from Bergen Arcs of Norway [1].

The V_p appears different between the eclogites from UHP and HP belts. At 1.0 GPa, V_p ranges from 7.90 to 9.27 km/s (mean 8.55) for the samples from UHP belt, and 7.84 to 8.42 km/s (mean 8.11) for HP belt. At 5.0 GPa, an average V_p 9.68 km/s (8.94-10.54) for the UHP eclogites is higher than that of HP eclogites (8.80-9.71, average 9.16 km/s). Generally, the UHP eclogites have much higher V_p than the HP eclogites at the identical confining pressure. This may be explained by the mineral composition preserved after they have suffered UHP or HP metamorphic conditions. Eclogites from UHP belt have much more garnet, clinopyroxene and omphacite, and higher

Fig. 1. V_p as a function of pressure at room temperature for two selected eclogites XD966 and WM962. V_p in X, Y, Z directions are shown.

Fig. 2. V_p vs. density plot for eclogites at pressure of 1 GPa. Other data are from [1,3-7].

densities.

The V_p in the 10 eclogites covers the range of 7.47-8.71 km/s (average 7.91) at 0.6 GPa, which is close to the compilation 7.714-8.582 km/s (mean 8.095 ± 0.226) of Rudnick et al., [13]. In order to compare our results with others, some V_p (at 1.0 GPa) and density data are plotted altogether in Fig. 2. V_p at pressure of 1.0 GPa for Dabie eclogites ranges from 7.84 to 9.27 km/s (mean 8.33), which is similar to that of Fountain et al. (8.2-8.9)[4], Christensen (7.6-8.5) [5,7], Manghnani et al. (7.9-8.7) [3], Kumazawa et al. (7.6-8.7) [4], Birch (7.6-8.1) [6] and the compiled of Christensen (8.198 km/s) [14]. The densities of all the eclogites in Fig. 2 are in the range of 3.2-3.6 g/cm³, which is close to that of 3.235-3.585 g/cm³ [13] and 3.485-3.503 g/cm³ [14, 15]. The V_p in two eclogite samples given by Christensen [7], 8.39 and 8.57 km/s at 2.0 GPa, 8.51 and 8.69 km/s at 3.0 GPa, fall into our range (8.06-9.97 km/s).

Few experimental data of V_p in eclogite could be found at the pressures above 3.0 GPa, as we know. At 5.0 GPa, V_p ranges from 8.94 to 10.54 km/s and 8.80-9.71 km/s for UHP and HP belts, respectively. These data agree with those observed in the mantle rock-forming minerals α - and β -Mg₂SiO₄ [16,17].

Anisotropy

Variable anisotropy is observed in the eclogites. It varied from 2.60 to 11.06 % with a mean of 5.72 % at 1.0 GPa, exhibiting a wide range and higher mean values than those of Christensen et al. (1.9 ± 0.8 %) [15], Holbrook et al. (2.4 ± 0.9 %) [18] and Fountain et al (1-6.5, mean 3.0 %) [1]. At pressures between 0.1 and 5.0 GPa, the HP eclogites seem to have much stronger anisotropy (2.37-10.28, mean 6.37 %) than the samples from UHP belt (2.03-8.79, mean 4.16 %) (Table 3). There is not any consistent tendency of anisotropy with increasing pressure in the eclogites, some decreases with increasing pressure, while the others do not. Otherwise the anisotropy decreases with increasing pressure in the rocks of Kern et al. [i.e. 19], showing a good trend.

Eclogites and the deep crust

A recently finished deep seismic sounding profile and the crustal structure of P-wave velocity exactly across the eastern Dabieshan show, some high-velocity anomaly zones are existing in the deep crust from 3 to 38 km beneath the central part of Dabieshan [20]. The scattering eclogites or other type of UHP and HP rocks with high V_p are possibly responsible for the zones. We assume the high- V_p zones are the mixture of two end members, one is the rocks with normal V_p beneath Dabieshan, one is the eclogites with high V_p as we got in the present study. The available parameters used in the calculation are listed in Tab. 5. The V_p of eclogite in different depth is the average of the Dabie samples at corresponding pressures (assume 1.0 GPa correspond to about 35 km depth [15]) and being corrected of temperature. The geotherm of high heat flow and temperature coefficients are applied in the temperature correction [15].

The contents of eclogite in various depth ranges in the high- V_p zones are shown in Table 5. About 16.5 % eclogite is contained in the high- V_p zone between 3 and 8 km depth. There is about 7.8-12.1 % eclogite in the lower part of the upper crust and the middle crust. A possible content of 11.6 % of eclogite is existing in the lower crust beneath the central Dabieshan. We need emphasize here that, (1) the calculated values above are the

Table 5. Contents of eclogite in the high- V_p zones in Dabieshan*.

Depth (km)	V_p (km/s)			Content (%)
	Normal	High- V_p zones	Eclogite	
3-8, upper crust	6.0	6.2	7.21	16.5
8-18, upper crust	6.2	6.3	7.48	7.8
18-28, middle crust	6.45	6.6	7.69	12.1
28-38, lower crust	6.9	7.0	7.76	11.6

* V_p in eclogites and content are calculated, other data after [20].

contents of eclogite in the high- V_p zones, instead of the whole Dabieshan region. The contents of eclogite in the whole Dabie Orogen will be far less than the values we obtained here; (2) the high V_p is not only in eclogite, but also in other type of rocks found in the HP and UHP belts in the region actually.

4. Conclusions

V_p in the eclogites of Dabieshan, five from the HP belt and five from the UHP belt, in three mutually orthogonal directions at pressure up to 5.0 GPa is measured. Higher V_p is observed in the eclogites from UHP belt than that from HP belt. The pressure derivative of V_p between 1.0 and 5.0 GPa ranges from 0.23 to 0.33 km s⁻¹GPa⁻¹ for the eclogites. The HP eclogites seem to have stronger anisotropy comparing to the UHP samples. A simple calculation shows that there may be 7.8-16.5 % eclogites in the upper and 11.6-12.1 % in the middle- and lower crust, beneath the central part of the Dabieshan. Far less than these contents are expected in the deep crust of the whole Dabieshan.

Acknowledgements: We thank the comments on the manuscript by reviewer T. Irifune and the help by M. Nakahara. This project is supported by the National Natural Science Foundation of China (NSFC), grant No. 49672142.

References

- [1] D. M. Fountain, T. M. Boundy, H. Austrheim, and P. Rey, *Tectonophysics*, **232**, 411-424 (1994).
- [2] H. Kern, *High-Pressure Researches in Geoscience* (eds. W. Schreyer), E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, 15-45, 1982.
- [3] M. H. Manghnani, R. Ramanananantoandro and S. P. Clark, *J. Geophys. Res.*, **79**, 5427 (1974).
- [4] M. H. Kumazawa, H. Helmstaedt, and K. Masaki, *J. Geophys. Res.*, **76**, 1231 (1971).
- [5] N. I. Christensen, and M. H. Salisbury, *Earth Planet. Sci. Lett.*, **15**, 367 (1972).
- [6] F. Birch, *J. Geophys. Res.*, **65**, 1098 (1960).
- [7] N. I. Christensen, *J. Geophys. Res.*, **79**, 407 (1974).
- [8] J. G. Liou, Q. Wang, M. Zhai, R. Y. Zhang, and B. Cong, *Chinese Science Bulletin*, **40** (Supplement), 1-40 (1995).
- [9] Z. You, Y. Han, W. Yang, Z. Zhang, B. Wei, and R. Liu, *The High-pressure and Ultra-high-pressure Metamorphic Belt in the East Qinling and Dabie Mountains, China*, China Univ. Geosci. Press, Wuhan, 1996.
- [10] G. Z. Zhou, J. G. Liou and Y. J. Liu, *High-pressure and Ultrahigh-pressure Metamorphic Belts in Northern Hubei Province, China*, China Univ. Geosci. Press, Wuhan, 1996 (in Chinese, with English abstract).
- [11] H. Xie, Y. Zhang, H. Xu, W. Hou, J. Guo, and H. Zhao, *Science in China (B)*, **36**, 1276-1280 (1993).
- [12] S. Matsushima, *J. Phys. Earth*, **20**, 187-195 (1972).
- [13] R. L. Rudnick and D. M. Fountain, *Rev. Geophys.*, **33**, 286 (1995).
- [14] N. I. Christensen, *J. Geophys. Res.*, **101**, 3144 (1996).
- [15] N. I. Christensen and W. D. Mooney, *J. Geophys. Res.*, **100**, 9761-9788 (1995).
- [16] T. S. Duffy, C. Cha, R. T. Downs, H. Mao, and R. J. Hemley, *Nature*, **378**, 170-173 (1995).
- [17] B. Li, G. D. Gwanmesia, and R. C. Liebermann, *Geophys. Res. Lett.*, **23**, 2259-2262 (1996).
- [18] W. S. Holbrook, W. D. Mooney, and N. I. Christensen, *Continental Lower Crust* (eds. D. M. Fountain, R. Arculus, and R. W. Kay), Elsevier Science Press, New York, 14, 1992.
- [19] H. Kern, S. Gao, and Q. Liu, *Earth Planet. Sci. Lett.*, **139**, 445 (1996).
- [20] C. Y. Wang, X. K. Zhang, B. Y. Chen, X. B. Chen, S. Y. Song, J. H. Zheng, H. X. Hu, and H. Lou, *Science in China (D)*, **27**, 221-226 (1997).