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Compressional and Shear Wave Velocities of Rock Glasses up to 2.0 GPa and 1 000 ℃ *

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Abstract: Measurements of compressional and shear wave velocities (v_p and v_s) under pressure from 0.4 to 2.0 GPa were performed on seven types of synthetic glasses, including basalt, andesite, dacite, amphibolite, pyroxenite, rhyolite and gneiss. At confining pressure of 2.0 GPa, the wave velocities were also measured as functions of temperature up to 1 000 ℃ for compressional wave velocity (v_p) and up to 730 ℃ for shear wave velocity (v_s). At room temperature, the wave velocities of the glasses decrease anomalously with pressure, as a result of the open structure of SiO_2 in silica-rich glasses. With varying SiO_2 mass fraction in the glasses from 87% to 52%, $\partial v_p/\partial p$ increases from −0.159 to 0.050 μm/(s · Pa), and $\partial v_s/\partial p$ increases from −0.114 to −0.001 μm/(s · Pa). At 2.0 GPa, v_p and v_s of the glasses decrease slowly first up to 600-700 ℃, indicating the glass transition temperatures (T_g), and then decrease rapidly. Based on the elastic properties of basalt glass and mantle rocks, it is concluded that the basalt glass with volume fraction of about 20% in matrix can cause the low velocity zone in upper mantle.

Key words: high temperature and high pressure; rock glass; compressional wave velocity; shear wave velocity; low velocity zone

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1 Introduction

In the past decades, ultrasonic measurements had been performed to aim at the especial elastic properties of glass at different conditions. In previous studies, elastic wave velocities of glasses had been measured at high temperature and ambient pressure[1-3], high pressure and room temperature[4-6] and high temperature and high pressure[7-8]. However, only several types of glass were focused in these studies, such as water-white glass and window glass[1-2,8], basalt glass and obsidian[5-7]. On the other hand, it had been proved that the quenched glass has similar structure with chemically comparable magma[9-10], so measuring elastic properties of quenched glasses under high temperature and high pressure is a good way for investigating structure and composition of melt. Meister *et al*. measured the compressional wave velocity (v_p) and shear wave velocity (v_s) of six types of glass with SiO_2 content from 49% to 100%[6], but their measurements were performed only under high pressure (0-0.8 GPa),

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and only the pressure dependences of wave velocities were discussed. We report here a study of ultrasonic velocity measurements on seven types of synthetic glass with SiO_2 mass fraction from 52% to 87% up to 2.0 GPa and 1 000 ℃. According to the measurements, the wave velocities of glasses are investigated as functions of pressure, temperature and composition. On the basis of our study on the elastic properties of glasses, we discuss the effect of vitreous content on wave velocities of rocks in upper mantle.

2 Sample and Experiment

Rock glasses were synthesized by quenching basalt, andesite, dacite, amphibolite, pyroxenite, rhyolite and gneiss melt. These preparations were performed on YJ-3000t multi-anvil pressure apparatus at Institute of Geochemistry, Chinese Academy of Science. The powders of rocks were heated up to 1 400-1 550 ℃ and then cooled down quickly. The experiments and samples had been described in detail in another article[11]. Chemical compositions of the glasses and main minerals are listed in Table 1 and Table 2, where w is mass fraction.

Table 1 Chemical compositions of the glasses (%)

Rock	w_{SiO_2}	$w_{Al_2O_3}$	w_{FeO}	w_{MgO}	w_{CaO}	w_{Na_2O}	w_{K_2O}	w_{MnO}	w_{TiO_2}	$w_{P_2O_5}$
Basalt	52.46±0.46	20.91±0.85	10.06±0.23	5.26±0.21	5.71±0.37	1.51±0.13	1.23±0.27	0.14±0.06	2.44±0.03	0.28±0.10
Andesite	57.00±1.03	18.76±0.80	7.44±1.06	3.18±0.33	5.89±0.10	3.96±0.01	2.37±0.11	0.13±0.04	1.28±0.35	0.03±0.03
Dacite	67.06±0.30	17.37±0.27	4.67±0.33	1.39±0.09	2.62±0.04	3.24±0.07	3.01±0.12	0.06±0.05	0.60±0.06	0.00±0.00
Amphibolite	64.14±0.78	17.98±0.91	7.86±0.83	3.01±0.85	1.44±0.11	1.26±0.22	2.96±0.34	0.19±0.07	1.10±0.21	0.07±0.07
Pyroxenite	52.41±0.32	14.32±0.29	6.78±0.13	6.30±0.09	11.28±0.12	0.58±0.05	6.04±0.10	0.07±0.02	1.31±0.11	0.93±0.10
Rhyolite	79.63±0.58	13.97±0.17	0.84±0.10	0.23±0.04	0.40±0.03	1.33±0.35	3.43±0.18	0.02±0.03	0.12±0.03	0.01±0.02
Gneiss	86.66±0.60	7.73±0.58	1.55±0.33	0.47±0.11	2.57±0.24	0.45±0.11	0.18±0.08	0.09±0.06	0.30±0.04	0.00±0.00

Note: Chemical compositions of the glasses were analyzed by electron-probe (EPMA-1600) in Institute of Geochemistry, Chinese Academy of Sciences; the data are arithmetic averages of 10 points.

Table 2 Main minerals in original rocks

Rock	Main minerals	Rock	Main minerals
Basalt	Plagioclase, clinopyroxene, orthopyroxene	Pyroxenite	Pyroxene, olivine
Andesite	Plagioclase, hornblende, clinopyroxene	Rhyolite	Quartz, K-feldspar, plagioclase
Dacite	Quartz, K-feldspar, plagioclase, hornblende	Gneiss	Quartz, plagioclase, hornblende
Amphibolite	Hornblende, plagioclase		

v_p and v_s of different types of glass were measured on an ultrasonic measurement system equipped in the YJ-3000t multi-anvil pressure apparatus, which was described in detail elsewhere[12]. The sample assembly is shown in Fig. 1. Molybdenum foils (0.1 mm thick) are put on the ends of sample, which can enhance the reflection signal. Pulse-reflection method was used to determine the wave velocities of the glass specimen. When the temperature exceeds about 800 ℃, the signal reflected from lower interface is weak, and

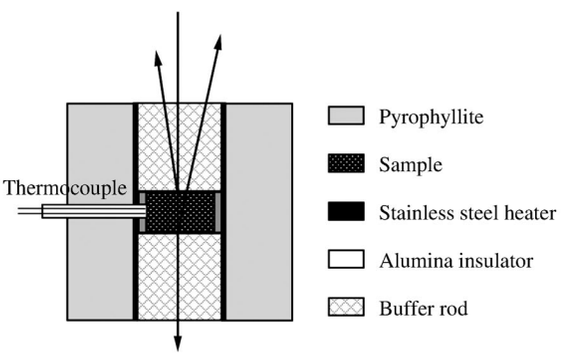


Fig. 1 Schematic representation of sample assembly

the wave velocities are measured by transmission-reflection-combined method[13-14]. Length of specimens under high pressure and room temperature is corrected by using the internally consistent method[15]. The measured relative errors of v_p and v_s are less than 1.2%. Pyrophyllite acts as a buffer rod in v_p measurement, which is substituted by aluminium in v_s measurement. The experimental method was described in detail in Ref. [16].

3 Results and Discussion

3.1 Pressure Effects

The values of v_p and v_s for the glasses up to 2.0 GPa are illustrated as function of pressure in Fig. 2. It is shown that, with increasing pressure, v_p of most of the glasses decreases anomalously except for a little increase in basalt and pyroxenite glass, and v_s of all of the glasses decreases anomalously. For example, as elevating pressure from 0.4 to 2.0 GPa, v_p of basalt glass increases from 5.91 to 5.98 km/s, and v_s decreases slowly from 3.44 to 3.43 km/s. But for gneiss, the wave velocities decrease from 5.71 to 5.45 km/s for v_p and from 3.51 to 3.44 km/s for v_s, respectively.

The velocity variation with pressure (v-p) was reported by Meister *et al.* on synthetic glasses of basalt, andesite, rhyolite, and quartz composition and on natural obsidian[6], and by Pan *et al.* on natural basalt glass[5]. In Meister's study, v_p and v_s of different types of glass were measured as function of pressure up to 0.8 GPa, and it is pretty consistent with those in this work that the wave velocities of most of the glasses decrease anomalously with pressure except for v_p of basalt, as seen in Fig. 2. By correcting the effects of cracks, vesicles and minor crystals on the wave velocities, Pan *et al.* obtained the v-p of natural basalt glass, which showed that both v_p and v_s for the basalt glass increase with elevating pressure. It is obvious that the wave velocities for basalt glass in this work are lower than those reported by Meister *et al.*[6] and by Pan *et al.*[5] We attribute it to a little bleb and microcrack remained in the synthetic sample, since the most compression was measured on basalt glass after experiment run.

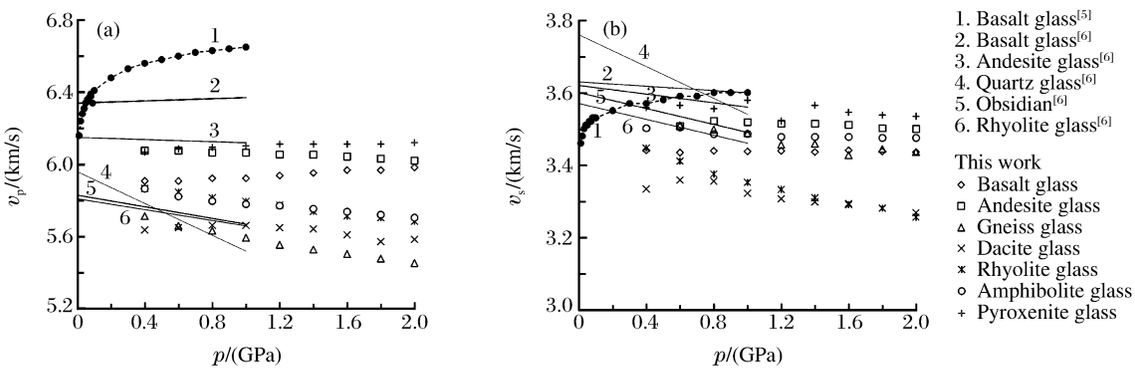


Fig. 2　v_p and v_s of glass under high pressure up to 2.0 GPa

Lots of researches have proved that the wave velocities increase with the increasing of pressure for most of the polycrystalline material. It was reviewed by Christensen and Mooney[17] and by Jackson *et al.*[18] that the pressure derivative of v_p ($\partial v_p/\partial p$) is about 0.1 μm/(s • Pa) for most of rock and mineral. Kern's research showed that the pressure derivative of v_p ($\partial v_p/\partial p$) is generally higher than the pressure derivative of v_s ($\partial v_s/\partial p$) for natural rock and mineral[19]. For example, $\partial v_p/\partial p$ and $\partial v_s/\partial p$ for gneiss, which is used to synthesize gneiss glass in this work, are 0.104 and 0.022 μm/(s • Pa) up to

2.0 GPa, respectively. Therefore we believe that the anomalous pressure effect of wave velocity for glass is correlated with not only the chemical composition but also the structure of vitreous material.

Fig. 3 illustrated the correlations between $\partial v/\partial p$ and main chemical compositions of glasses, in which the data from this work is compared with that from Meister's study[6]. The pressure derivative of velocity ($\partial v/\partial p$) is negatively correlated with SiO_2 content in the glasses, and the pressure effect on v_p is more obvious than which on v_s. The $\partial v/\partial p$ is positively correlated with the content of Al_2O_3, FeO^* ($FeO+Fe_2O_3$), MgO and CaO. And there is little correlation between $\partial v/\partial p$ with Na_2O and K_2O. Generally, the wave velocity of polycrystalline materials is positively correlated with the density. In other words, the wave velocity increases with increasing content of heavy elements such as Fe and Mn. For most of silicate rocks, the content of FeO^*, MgO and CaO is negatively correlated with that of SiO_2, Na_2O and K_2O, so $\partial v/\partial p$ of the glasses has opposite correlation with the contents, which is shown in Fig. 3.

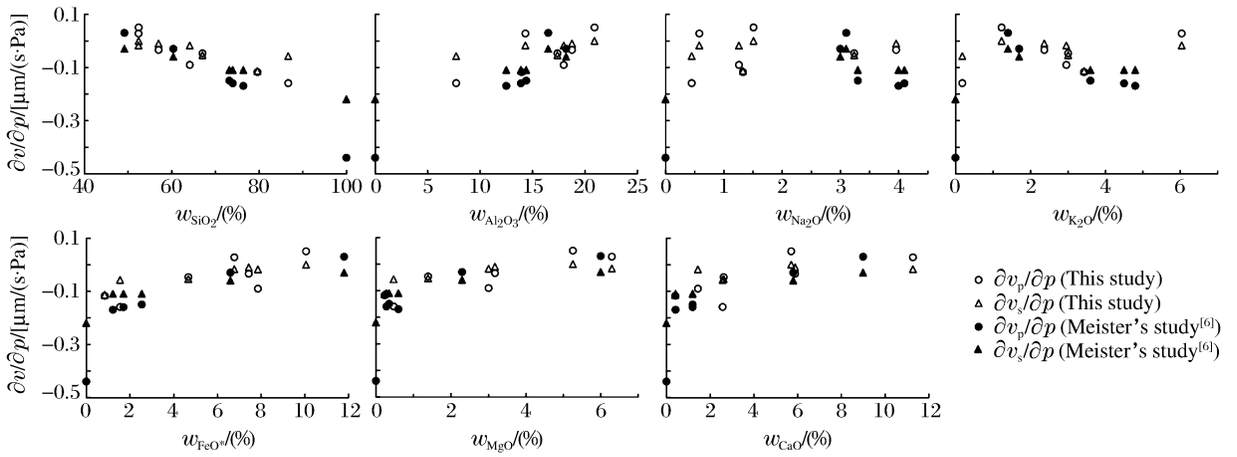


Fig. 3 Variations of pressure derivatives of v_p and v_s with chemical compositions in the glasses

However, we consider that the structure of glass is main reason for the anomalous pressure effect of velocity, which had been explained in previous works[4,6]. For most of solid, ionic distances are reduced under high pressure, which results in that the structure is more condensed than that before compression. Therefore the rigidity and the elastic wave velocities will increase with elevating pressure for polycrystalline materials. But in the silica-rich glasses, the SiO_4 tetrahedron retains the open structure. In the structure, ions will rotate as elevating pressure if there are external forces on the materials. This means that the pressure produces bending rather than shortening of Si—O—Si bonds. The bending of Si—O—Si bonds will expend energy and cause the decrease in rigidity of the structure, as it is represented by the equation of elastic modulus[4], namely

$$E = \frac{\sigma}{\varepsilon} \tag{1}$$

where E, σ and ε are the Young's modulus, stress and strain, respectively. The rotational motion of ions results in higher value of ε in the open SiO_4 tetrahedral structure, which produces the decrease in E, and then v of the glasses decrease with pressure as well. The basic structure of vitreous materials is long-range disorder (LRD), but the SiO_2 in glass retains short-range order (SRO). Because of the special open structure, SiO_2 content in the glasses is the most important for explaining the anomalous $\partial v/\partial p$ of the silica-rich glasses. It is found both in our work and in Meister's study that the less SiO_2 content in glass, the more normal pressure behavior of wave velocities. In this work, with varying SiO_2

mass fraction in the glasses from 87% to 52%, $\partial v_p/\partial p$ increases from −0.159 to 0.050 μm/(s • Pa) and $\partial v_s/\partial p$ increases from −0.114 to −0.001 μm/(s • Pa), respectively.

3.2 Temperature Effects

Matsushima[7] found that both v_p and v_s of obsidian and glassy andesite increase with temperature up to 600 ℃, indicating the glass transition temperature (T_g). In this work, the transition temperatures are determined by the temperature derivatives of v_p to be 600-700 ℃, which are negatively correlated with SiO_2 content in the glasses. It is also found in our experiments that, at 2.0 GPa, the travel time decreases with temperature up to T_g. There are two reasons for explaining it. One is that heating specimen cause increase in the wave velocities of the glasses, as found in Matsushima's study. The other is that the specimen continually shortens with increasing temperature under high pressure of 2.0 GPa. By measuring the length of the specimens after experiments, we found the specimens were indeed shortened about 3%-5% after high temperature and high pressure processing. Comparing with heating process, more normal temperature behavior of travel time was observed during cooling process[16]. So v_p and v_s of the glasses were measured during cooling process, while there is little change in length of sample.

The temperature effects on v_p and v_s of the glasses at 2.0 GPa are shown in Fig. 4. At confining pressure of 2.0 GPa, v_p and v_s of the glasses decrease slowly with temperature up to 600-700 ℃, which are considered to be the glass transition temperatures, and then decrease rapidly. For example, from room temperature to 627 ℃ v_p of amphibolite glass decreases softly (3%) from 6.48 to 6.31 km/s, and then decreases quickly (6%) to 5.88 km/s as increasing temperature from 627 to 955 ℃.

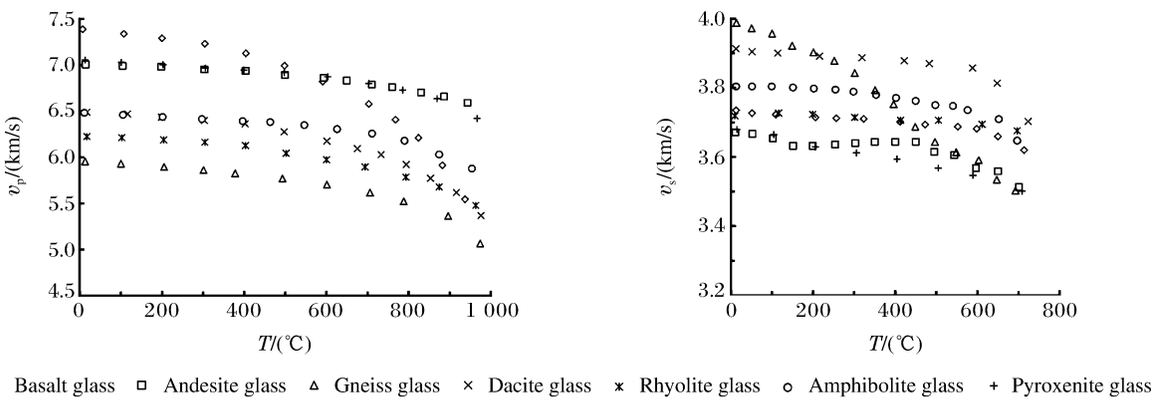


Fig. 4　Temperature effects on v_p and v_s of the glasses at 2.0 GPa

When $T < T_g$, $\partial v_p/\partial T$ and $\partial v_s/\partial T$ for most of the glasses are ranged from −0.237 to −0.517 m/(s • ℃) and from −0.062 to −0.171 m/(s • ℃), respectively, except low $\partial v_p/\partial T$ of −0.755 m/(s • ℃) for basalt glass and $\partial v_s/\partial T$ of −0.745 m/(s • ℃) for gneiss glass. The temperature effects on wave velocities of glasses obtained by this work are compared with those in previous literature[3], in which v_p and v_s were measured up to 1 400 K at ambient pressure for diopside ($CaMgSi_2O_6$), anorthite ($CaAl_2Si_2O_8$) and grossular ($Ca_3Al_2Si_3O_{12}$) glasses. The temperature derivatives of wave velocities have little correlation with the chemical compositions of the glasses in this work. Generally, $\partial v_p/\partial T$ of the glasses is lower than $\partial v_s/\partial T$, which is consistent with that of polycrystalline rock. For example, $\partial v_p/\partial T$ and $\partial v_s/\partial T$ for the gneiss, which is used to synthetize gneiss glass in this work, are −0.289 and −0.133 m/(s • ℃) up to 712 ℃ at 2.0 GPa, respectively.

In previous studies, researchers found that the wave velocities of glass increase anomalously with

temperature up to T_g, and the positive temperature derivatives of velocities are attributed to a so-called skeleton structure in glass[7]. It was presented that the weak thermal vibration of atoms means that there are some larger vacant spaces in this structure at low temperature. Heating can induce more severe thermal vibration of atoms, which make the structure of the glass appear more tightly compacted than that before heating. So wave velocities of the glasses increase with temperature up to T_g. However, in this work, the framework of the specimen has been squeezed irreversibly during heating course under 2.0 GPa, and we carried out measurements on wave velocities of the glasses during cooling process. So both v_p and v_s decrease monotonically with temperature at confining pressure of 2.0 GPa, as the normal behavior of solid material. It is obvious that, as shown in Fig. 4, the wave velocities of compressed sample are higher than those of original glass.

4 Geophysical Significance

A prevailing interpretation for low velocity zone (LVZ) in upper mantle is partial melting of basalt in mantle rock. But some researchers concluded that, taking the reasonably low viscosity and the deformation of matrix into consideration, the melt fraction is unlikely to exceed a few percent anywhere for a long geologic time within the mantle[20-21]. Consequently, the scientists proposed a new interpretation that vitreous amorphization can decrease the velocities of rock and then form LVZ in upper mantle, because of the low velocities and the special pressure derivatives of velocities of glass[6-7]. By extrapolating the elastic moduli of basalt glass to 3 GPa and 1 200 ℃, Meister *et al*. calculated that 10%-30% volume fraction of felsic basalt glass in rock can cause LVZ in mantle[6]. From this work, we found that after compressing under high pressure and high temperature, the density and wave velocities of glass are much higher than those of sample under high pressure and room temperature. Some errors can occur when extrapolating room temperature experimental data to high temperature and high pressure conditions. For this reason, Meister's result is revised here.

It is generally accepted that the material in mantle is lherzolite, which consists mainly of olivine, orthopyroxene, clinopyroxene and garnet. According to volume fraction (φ) and elastic parameters of the minerals, presented in Table 3[22-23], the elastic properties of the lherzolite are calculated with Voigt-Reuss-Hill (VRH) model[24]. ρ, K, G listed in Table 3 are density, bulk modulus and shear modulus, respectively. Average values of elastic moduli and velocities for composites of basalt glass in lherzolite at 800 ℃ and 2.0 GPa were calculated and presented in Table 4 by means of Hashin-Shtrikman (HS) bounds[24]. The calculations presented here indicate that basalt glass with volume fraction of about 20% in lherzolite can produce a reduction of 5% in seismic velocities. Therefore, it is possible that dry low velocity zone will present in the upper mantle with a low heat flow, if there are sufficient vitreous content in rock.

Table 3 Volume fraction and elastic parameters of minerals in the mantle rock

Mineral	φ/(%)[22]	ρ/(g/cm^3)[23]	K/(GPa)[23]	G/(GPa)[23]
Olivine	45	3.32	130	80
Orthopyroxene	32	3.35	104	75
Clinopyroxene	13	3.31	114	65
Garnet	10	3.74	170	102

Table 4　Elastic properties of mantle rock with different basalt glass content at 800 ℃ and 2.0 GPa

Material	φ/(%)	ρ/(g/cm^3)	v_p/(km/s)	v_s/(km/s)	K/(GPa)	G/(GPa)
Basalt glass(1)	100	3.07	6.32	3.59	69.87	39.57
Lherzolite(2)	0	3.37	8.20	4.82	122.28	78.17
	10	3.34	7.98	4.67	115.38	72.98
	20	3.31	7.77	4.54	108.96	68.18
	30	3.28	7.57	4.41	102.95	63.72

Note: (1) The density of glass was measured after the experimental cycle;
(2) The calculations were performed with the elastic properties of lherzolite under ambient condition, considering the multiple effects of temperature and pressure.

The LVZ in upper mantle are found usually in depth of between 50 and 200 km. It was estimated that, based on the heat flow data, the temperature of upper mantle could be as low as 800 ℃, which is far from the melting temperature of basalt rock[17]. For example, along the lithospheric profile of Yuanshi-Jinan of north China, there is a LVZ with v_p of 7.6-7.8 km/s in depth between 43 and 63 km, which is sandwiched by the layers with v_p of 8.1-8.3 km/s, as shown in Fig. 5[25]. It had been calculated that the temperature of Moho-discontinuity is lower than 750 ℃ in the lithosphere of north China[26], which is difficult to cause partial melt of mantle rock. According to the calculation above, such a basalt glass with volume fraction of 18.5%-28.5% in the matrix would account for the observed velocity lowering in the LVZ (Fig. 5). So it is a possible explanation for the LVZ that some vitreous content in the rocks cause the decrease in velocity of rock in upper mantle.

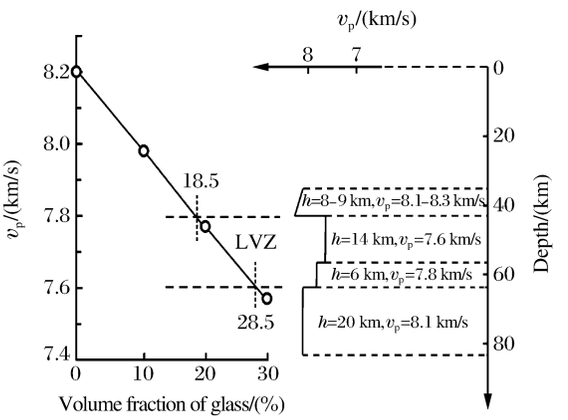


Fig. 5　Change of v_p of mantle rock with increasing content of glass in upper mantle (The profile of velocity versus depth is cited and modified from Ref. [25])

5　Conclusions

v_p and v_s of most of the synthetic glasses decrease anomalously with increasing pressure at room temperature, which is different from the crystal rocks. We hold that the anomalous pressure effect of wave velocity for glass is determined by both the chemical composition and the structure of vitreous material. v_p and v_s of the synthetic glasses decrease monotonically with temperature at confining pressure. According to the measurements, we conclude that vitreous content in the rocks can cause the seismic low-velocity zone in upper mantle.

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高温高压下几种岩石熔融玻璃的弹性波速

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摘要:利用超声波脉冲反射法和透射-反射联合法,测量了压力在 0.4～2.0 GPa 条件下 7 种岩石熔融玻璃的纵波波速(v_p)和横波波速(v_s),并在恒压 2.0 GPa 下,在 0～1 000 ℃和 0～730 ℃温度范围内,分别测量了纵波波速和横波波速随温度的变化。结果显示,室温下随着压力的升高,大多数玻璃的 v_p 和全部玻璃的 v_s 异常地降低。异常的波速-压力关系与玻璃中 SiO_2 的含量密切相关,随着 SiO_2 的质量分数从 87%降低到 52%,玻璃的纵波波速和横波波速对于压力的导数($\partial v_p/\partial p$ 和 $\partial v_s/\partial p$)分别从 −0.159 和 −0.114 μm/(s·Pa)升高到 0.050 和 −0.001 μm/(s·Pa)。分析认为,玻璃的波速随压力升高而降低的原因主要与玻璃中 SiO_2 所具有的敞型结构有关。在 2.0 GPa 压力下,玻璃的波速首先随温度升高而缓慢降低,当达到 600～700 ℃后,开始快速下降,设此温度为玻璃的转变温度 T_g。根据实验测得的玄武岩玻璃波速,结合上地幔二辉橄榄岩的弹性性质,推测若在上地幔岩石中存在体积分数大于 20%的玄武岩质非晶质体,上地幔便可能形成地震波低速层。

关键词:高温高压;岩石玻璃;纵波波速;横波波速;低速层

中图分类号:O521.2　　**文献标识码**:A