EARTH SCIENCE FRONTIERS
Volume 14, Issue 3, May 2007
Online English edition of the Chinese language journal

Available online at www.sciencedirect.com
ScienceDirect

Cite this article as: Earth Science Frontiers, 2007, 14(3): 158–164.

RESEARCH PAPER

Measurement on Wave Velocities of Rock Glasses to 900℃ at 1.0 GPa and Geophysical Implications

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Abstract: At 1.0 GPa, compressional and shear wave velocities (v_p and v_s) of seven types of glass were measured as a function of temperature up to 900℃ and 730℃, respectively. Experimental runs indicated that with elevating temperature under high pressure, the compression of glass is responsible for the decrease in travel time in sample and the glasses show little change in height during cooling process. When the temperatures are lower than the glass transition temperatures (T_g), it is fitted that the temperature derivatives of velocities of the glasses are between -0.2×10^{-3} km • s^{-1} • ℃$^{-1}$ and -0.7×10^{-3} km • s^{-1} • ℃$^{-1}$ for v_p and almost -0.1×10^{-3} km • s^{-1} • ℃$^{-1}$ for v_s, respectively. At higher temperatures ($T > T_g$), v_p of the glasses decrease quickly with temperature derivatives between -0.8×10^{-3} km • s^{-1} • ℃$^{-1}$ and -3.6×10^{-3} km • s^{-1} • ℃$^{-1}$. According to the change in temperature derivatives of v_p, the glass transition temperatures are determined to be between 584℃ and 654℃. Using the Voigt-Reuss-Hill (VRH) average method, it is calculated that the wave velocities of the lower crustal rocks decrease with increasing glass content. Because of this, we suggest that the low velocity layer in lower curst is a function of the glass contents in rocks, which results in a decrease in the wave velocity of rocks in lower crust.

Key Words: high temperature and high pressure; glass; wave velocity; low velocity layer

1 Introduction

The transportation and the crystallization of magmatic melt induce the migration and the differentiation of materials in the interior of earth, which play an important role in keeping the evolution and activity of Earth. Thus, investigating the physical properties of melt can provide basic data for inspecting the structure and the evolvement of lithosphere[1]. An important way for studying melt is to analyze and measure the physical and chemical properties of its quenched glass, because the quenched glass has the similar structure as that of the chemically comparable melt[2,3]. As an important method for investigating elastic properties of material, the ultrasonic measurement had been performed on many glasses under different temperature and pressure. Pan et al. carried out the measurements on the compressional and shear wave velocities (v_p and v_s) of natural basalt glass under pressure from 0.01 to 1.0 GPa at room temperature, and then corrected the effects of cracks, vesicles and minor crystals on the velocities of natural glass[4]. At pressure up to 0.8 GPa and room temperature, Meister et al. measured the velocities of six types of glass, with SiO_2 content from 49% to 100%, and by extrapolating the results to the temperature and pressure in upper mantle, discussed the seismic velocities of upper mantle rocks with different content of basalt glass[5]. Using the Brillouin scattering method, Xu et al. and Askarpour et al. determined the velocities as the functions of temperature for water-white glass[6], $K_2Si_4O_9$ glass[7] and diopside-, anorthite- and grossular-glasses[8] up to above 1000℃ at normal pressure and discussed the changes of the velocities at the critical and soft temperatures. However, only little study on elastic properties

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Received date: 2007-01-05; **Accepted date**: 2007-01-20.

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Foundation item: Supported by the the National Basic Research Program of China (No. 2005CB724400) and partially by the National Natural Science Foundation of China (40574036) and the Knowledge Innovation Program of the Chinese Academy of Sciences (No.KJCX2-SW-N20).

of glass was performed under the condition of high pressure and high temperature. Matsushima reported the measurements on the wave velocities of glass up to 2.0 GPa and 900℃ and it was found that when the temperature is lower than the glass transition temperature (T_g), the velocities of glass increase abnormally with elevating temperature[9]. However, his study was performed for only three types of samples including obsidian, basalt glass and glass-containing sanukite. In our work, the v_p and v_s were measured up to 1000℃ at 1.0 GPa and 2.0 GPa for seven types of glass. In previous paper[10], we presented the effects of temperature on the velocities of the glasses up to 1000℃ at pressure of 2.0 GPa, and it was calculated that above 20 % of basalt glass in lherzolite can result in the seismic low velocity layer in the upper mantle. Here, we report a study on velocities of the rock glasses up to 900℃ at 1.0 GPa and discuss the effects of vitreous content on wave velocities of rocks in the lower crust.

2 Samples and experiment

2.1 Samples

The glasses were synthesized by quenching melted rocks, which range from acidic to basic in chemical compositions and are listed in Table 1. The preparations of glass were carried out in the YJ-3000 ton multi-anvil pressure apparatus at Institute of Geochemistry, Chinese Academy of Science, Guiyang, China. The powder of rocks in graphite tube was heated up to high temperature (1400–1550℃) at 1.0 GPa and then quenched. The samples are vitreous, except a little of remnant quartz (<3%) in which rich in SiO_2 content such as Ly974, Q96-7. The experiment and samples were described in detail in another article[11].

Table 1 Main chemical composition of rocks for synthesizing glasses

Rock	Sample	w_B/%													
		SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	MnO	TiO_2	P_2O_5	CO_2	H_2O+	Total
Basalt	10082	48.36	14.47	6.63	4.51	6.58	8.59	3.28	1.48	0.16	2.35	0.78	0.15	2.57	99.58
Andesite	10017	56.00	15.98	4.49	3.60	3.38	5.89	4.38	2.58	0.17	1.69	0.54	0.02	1.27	99.99
Gneiss	Ly974	79.35	9.00	2.29	1.30	0.56	3.93	0.33	0.17	0.03	0.74	0.30	-	1.56	99.56
Dacite	Q96-4	63.86	15.90	3.77	0.97	1.47	2.82	3.32	2.81	0.06	0.62	0.21	1.74	1.93	99.48
Rhyolite	Q96-7	76.96	12.93	0.67	0.25	0.36	0.45	2.30	3.78	0.06	0.17	0.01	0.36	1.19	99.49
Amphibolite	T95-19	61.99	17.82	5.46	3.54	2.70	1.90	1.32	2.49	0.19	0.84	0.26	-	0.69	99.20
Pyroxenite	Zp978	47.70	12.53	4.83	2.67	6.83	12.54	0.94	6.12	0.16	0.75	1.17	2.52	0.45	99.21

Note: Chemical composition was analyzed with wet method, which were performed in the Analysis Center of Hubei Institute of Geology and Mineral Resources, except that sample of Ly974 was performed in the Key Laboratory of Ore Deposit Geochemistry, Chinese Academy of Sciences.

2.2 Sample assembly and experimental process

Ultrasonic measurements under high pressure and high temperature were performed in the YJ-3000 ton multi-anvil pressure apparatus at Institute of Geochemistry, Chinese Academy of Science, Guiyang, China. The details of the apparatus were described elsewhere[12]. In the experimental process, pressure was first increased up to 2.0 GPa at a rate of 0.01 GPa/min at room temperature. The sample was then heated to aim temperature at a rate about 5℃/min. We kept the temperature 10 minutes and then decreased it at same rate. During the course of decreasing temperature, the travel time of ultrasonic wave was measured after every temperature point was kept 15 minutes until room temperature. Then, we put down the pressure to 1.0 GPa at a rate of 0.01 GPa/min and repeated the steps above until the experiment were finished. The pulse reflection and the transmission-reflection combined method were used to measure the wave velocities in the rock glasses. As shown in Fig. 1, when the temperature is lower than about 800℃, according to the travel time of reflected signals from upper and lower interfaces (T_1 and T_2) and the height of sample (H), the wave velocity in sample can be calculated by using the expression of $v=2H/(T_2-T_1)$. When the temperature is higher than about 800℃, the reflected signal from lower interface is so weak that the travel time T_2 cannot be determined, and then the transmission- reflection combined method[13] is used to determine the wave velocities of sample by measuring the travel time of transmitted signal. In this experiment, the travel time was determined with a TDS784A digital oscilloscope (Tektronix Corporation, USA),

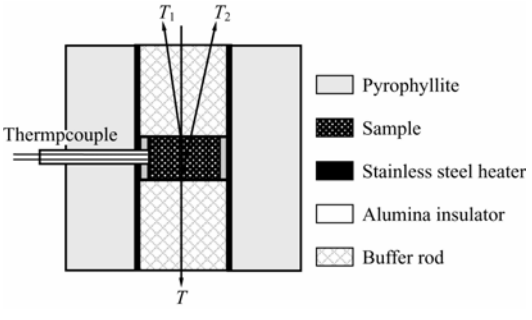

Fig. 1 Schematic representation of sample assembly and velocity measurement

which can reach a very high precision less than 2 ns. Because the waves are subjected to a reflection in the sample, the travel times of compressional and shear wave are about 2 μs and 3.5 μs, respectively. Considering the height of sample changing little with temperature and pressure, we estimate that the errors of measurements are 1.5% and 1.0% for v_p and v_s, respectively. For enhancing the reflecting signal, we put molybdenum foils (0.1 mm) on the ends of the sample. The buffer rods for measurement on v_p were made from pyrophyllite, which had been baked under high temperature of 800℃. And those for measurement on v_s were made from aluminium, which were separated from the anvils with pieces of pyrophyllite of 1 mm thickness.

2.3 Measurement on wave velocity

Matsushima's study presented that under high pressure, the velocities of glass increase with increase in temperature until about 600℃, indicating the glass transition temperature (T_g), and then decrease[9]. Xu et al. found at normal pressure, there is a little increase in both v_p and v_s of $K_2Si_4O_9$ glass with increase in temperature before T_g, but which is far less than those shown in Matsushima's study. Moreover, in the studies of water-white glass[6], diopside-, anorthiteand grossular-glasses[8], it was found that the velocities of the glasses decrease monotonously with increase in temperature at normal pressure. Therefore, we believe it is connected with the experimental pressure that the velocities of glass increase abnormally with the increase of temperature in Matsushima's work.

It is illustrated in Fig. 2 that in this experiment, with elevating temperature at 2.0 GPa, the travel time of the wave in sample decreases with temperature until about 600℃ and then increases. This indicates that the velocity of glass increases with temperature on the assumption that the height of the sample did not change with pressure and temperature, which is consistent with Matsushima's work. However, it is found during cooling the sample that the velocity increases monotonously with decrease of temperature. When the experimental pressure is reduced from 2.0 GPa to 1.0 GPa, the travel time in sample is almost consistent between heating course and cooling course. We investigated the samples after experiments and found they were shortened about 3%–5% because of the compression under high pressure and high temperature, which indicate that the samples had been squeezed irreversibly at 2.0 GPa and high temperature and there was little change in height of samples between heating course and cooling course at 1.0 GPa. Therefore, we hold that the compression of sample is responsible for the decrease in travel time with elevating temperature at 2.0 GPa and there is little change in the height of sample during cooling course. Therefore, the wave velocity of glass is determined with the travel time measured during cooling course and the height of the sample was measured after the experiment.

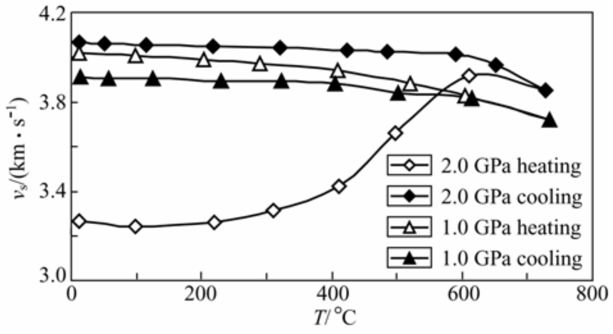

Fig. 2 Temperature effect on v_s of Q96-4 at 1.0 and 2.0 GPa on the assumption that the length of sample is invariable with temperature and pressure

3 Results

Figure 3 shows v_p and v_s of the glasses as functions of temperature at 1.0 GPa. At room temperature, it is obvious that with the increase in SiO_2 content, the compressional wave velocities of the glasses decrease from 6.95 km • s^{-1} for basalt glass to 5.65 km • s^{-1} for gneiss glass. The shear wave velocities of the glasses, which range from 3.74 km • s^{-1} for gneiss glass to 3.59 km • s^{-1} for dacite glass, have little connection with the chemical compositions of original rocks. With the increase in temperature at 1.0 GPa, v_p and v_s of the glasses decrease slowly until about 600℃ and then decrease quickly. As shown in Fig. 4, the glass transition temperature (T_g) is determined with the change in the temperature derivatives of v_p. Table 2 lists the glass transition temperatures and the temperature derivatives of wave velocities.

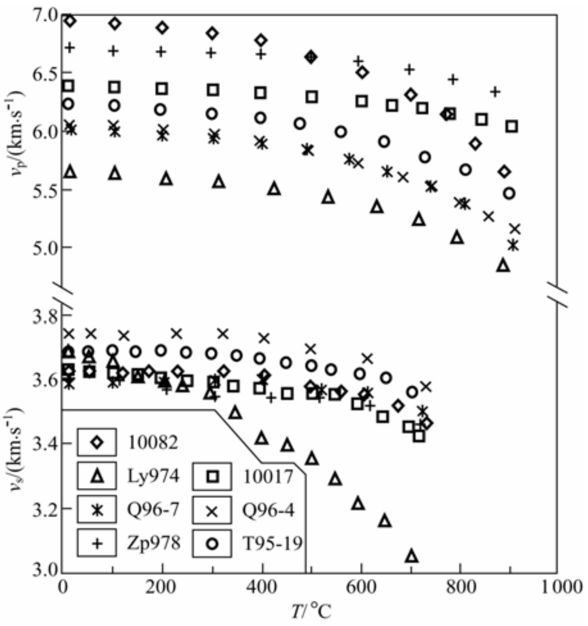

Fig. 3 Temperature effects on wave velocities of rock glasses at 1.0 GPa

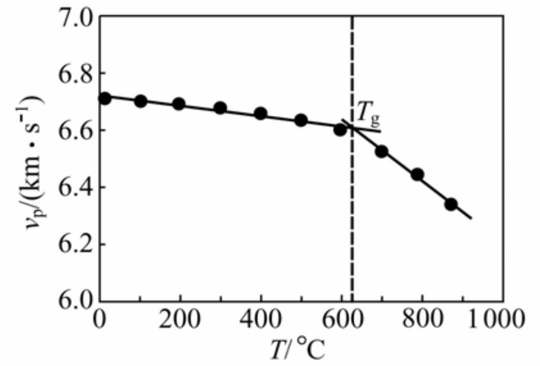

Fig. 4 Measurement on the glass transition temperature (T_g) for sample of Zp978 according to the variation of v_p with temperature

Table 2 Transition temperature and temperature derivative of velocities of rock glasses at 1.0 GPa

Sample	Glass transition temperature T_g (℃)	$\partial v/\partial T$ (10^{-3}km • s^{-1} • ℃$^{-1}$)		
		v_p		v_s
		$T < T_g$	$T > T_g$	$T < T_g$
10082	654	–0.7	–3.6	–0.1
10017	619	–0.2	–0.8	–0.2
Ly974	612	–0.4	–2.0	–0.8
Q96-4	593	–0.5	–2.1	–0.1
Q96-7	584	–0.4	–1.8	–0.1
T95-19	599	–0.4	–1.7	–0.1
Zp978	626	–0.2	–1.1	–0.1

From Table 2 the temperature derivatives of v_p of the glasses range from $–0.2\times10^{-3}$ km • s^{-1} • ℃$^{-1}$ to $–0.7\times10^{-3}$ km • s^{-1} • ℃$^{-1}$ at $T < T_g$ and from $–0.8\times10^{-3}$ km • s^{-1} • ℃$^{-1}$ to $–3.6\times10^{-3}$ km • s^{-1} • ℃$^{-1}$, when the temperature is higher than the glass transition temperature. The decrease of v_p with temperature is the most for basalt glass, from 6.95 km • s^{-1} at 15℃ to 5.65 km • s^{-1} at 892℃, and the least for andesite glass, from 6.38 km • s^{-1} at 13℃ to 6.03 km • s^{-1} at 906℃. The temperature derivatives of the velocities are little correlative with the chemical compositions of the original rocks. Because the temperatures for measurements on v_s are low as about 730℃, only the data of v_s at $T < T_g$ are used to fit the temperature derivatives of the velocities. Except that of gneiss glass, the temperature derivatives of v_s of the glasses are almost $–0.1\times10^{-3}$ km • s^{-1} • ℃$^{-1}$, which change little with the chemical compositions. The temperature derivative of v_s of gneiss glass is high as $–0.8\times10^{-3}$ km • s^{-1} • ℃$^{-1}$ and the v_s decrease from 3.69 km • s^{-1} to 3.05 km • s^{-1} with increase of temperature from 14℃ to 705℃. We attribute the high temperature derivative of v_s of gneiss glass to the high SiO_2 content and the remnant quartz in the glass, because the shear modulus of SiO_2 is so high that the shear wave in the glass is more sensitive to temperature and pressure.

4 Geophysical implications

From this work, the compressional velocities of rock glasses are correlative with the chemical compositions and are lower than those of crystal rocks. It was understood that the glass above the glass transition temperature transforms to supercooled liquid (SCL)[9]. Matsushima[14] and Meister et al[5] proposed that the SCL in upper mantle rocks could decrease the seismic velocities of the rocks and then results in quasi-dry low velocity layer in upper mantle. Therefore, if the glass was contained in lower crustal rocks, it must decrease the wave velocities of the rocks. Based on the investigation on the rock glasses we can discuss the effect of glass on the velocities of rock. For example, in the lower crust of north China the temperature ranges from 450℃ to 750℃[15] and the rock contains mainly amphibolite and mafic granulite[16]. By using the Voigt-Reuss-Hill (VRH) average method[17], we calculated the velocities of the lower crustal rocks at 1.0 GPa and 550℃ with different content of glass. The results are listed in Table 3. It is obvious that the more glass in the rocks, the more decrease in velocities of the rocks, and glass has more effect on v_p than on v_s. The velocities were averaged for five types of acidic and intermediate glass except basalt and pyroxenite glass. With the average velocities, it is calculated that 10% (vol) of acidic and intermediate glass can induce a decrease of 1.4% in v_p for both amphibolite and mafic granulite and if 40% (vol) of the glass are contained in the rocks, the v_p will decrease 5.5% for amphibolite and 5.7% for mafic granulite, respectively.

Geophysical exploration has discovered that there are many seismic low velocity layers to different depths of global continental crust. For example, beneath the Wuqing of north China there is a low velocity layer with v_p of 6.3 km/s to the depth of 28 km in lower crust[18]. Along the crustal profiles of Yadong-Yangzhuoyong lake and Shamada-Namu lake in Tibet Plateau, a low velocity layer with v_p of 5.7 km/s is found to the depth between 20 km and 30 km, which is interlaid by upper layer with v_p of 6.1 km/s and lower one with v_p of 6.3 km/s. In previous studies, some tectonic and material interpretations had been suggested for the formation of the crustal low velocity layer, such as weak layer caused by ductile shearing and fluid activity[19,20], the quartz-rich rocks[21], dehydrating and partial melting[22–24] and so on. The rock in low crust consist mainly of amphibolite, gabbro and granulite, which are high in compressional wave velocity (>6.6 km/s)[25]. According to the calculation above, if there was enough glass in the rocks it may form a low velocity layer in lower crust. Ever since early the last century, scientists have found lots of vitreous rocks in the ductile shear belts and called them as pseudotachylite, but which are acidic or intermediate in chemical composition[26]. It is reported recently that a new

Table 3 Variations of velocities in amphibolite and mafic granulite with different glass content at 1.0 GPa and 550℃

Sample	Glass content velocity (km·s^{-1})	Glass 100%	Amphibolite					Mafic granulite				
			0	10%	20%	30%	40%	0	10%	20%	30%	40%
10082	v_p	6.61	6.78	6.76	6.75	6.73	6.71	6.80	6.78	6.76	6.74	6.72
	v_s	3.59	3.76	3.74	3.73	3.71	3.69	3.79	3.77	3.75	3.73	3.71
10017	v_p	6.28	6.78	6.73	6.68	6.63	6.58	6.80	6.75	6.69	6.64	6.59
	v_s	3.53	3.76	3.74	3.71	3.69	3.67	3.79	3.76	3.74	3.71	3.68
Ly974	v_p	5.45	6.78	6.63	6.49	6.35	6.21	6.80	6.65	6.50	6.36	6.22
	v_s	3.30	3.76	3.71	3.66	3.62	3.57	3.79	3.74	3.69	3.64	3.59
Q96-4	v_p	5.84	6.78	6.68	6.58	6.48	6.39	6.80	6.70	6.60	6.50	6.40
	v_s	3.71	3.76	3.75	3.75	3.74	3.74	3.79	3.78	3.77	3.77	3.76
Q96-7	v_p	5.81	6.78	6.68	6.57	6.47	6.37	6.80	6.69	6.59	6.49	6.39
	v_s	3.58	3.76	3.74	3.72	3.71	3.69	3.79	3.77	3.75	3.73	3.70
T95-19	v_p	6.02	6.78	6.70	6.62	6.54	6.47	6.80	6.72	6.64	6.56	6.48
	v_s	3.65	3.76	3.75	3.74	3.73	3.72	3.79	3.78	3.76	3.75	3.73
Zp978	v_p	6.62	6.78	6.76	6.75	6.73	6.72	6.80	6.78	6.76	6.75	6.73
	v_s	3.55	3.76	3.74	3.72	3.70	3.67	3.79	3.77	3.74	3.72	3.69

Note: The glass content is a volume percent (vol%) of glass in rocks. The VRH method is used to calculate the velocities of mixture. Both v_p and v_s of amphibolite and mafic granulite are calculated with velocities under ambient condition and their derivatives of pressure and temperature listed in literature [16].

natural vitreous rock was found in east of Jiangxi province China, which is acidic in chemical composition and may be magmatogenic rock[27]. It is accepted that during the geologic evolution, the time is so lengthy that the magma can crystallize completely[28], but we hold that it cannot be excluded that some vitreous content may be contained in the rocks at special time and region. Therefore, a new possible explanation can be used to interpret the seismic low velocity layer in lower curst that the vitreous content in the rocks decreases the wave velocity of the rocks.

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