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Compressional elastic wave velocities of serpentinized olivine-bearing pyroxenite up to 960 °C at 1.0 GPa

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Abstract

Compressional wave velocities (V_p) were measured *in situ* in serpentinized olivine-bearing pyroxenite at 1.0 GPa from room temperature to 960 °C in a multi-anvil pressure apparatus. The velocity showed a remarkable decrease from temperature more than 500 °C which was from 6.2 to 5.0 km s^{-1}. The decline in velocity is attributed to the changes of rock fabric, including the following aspects: composition, size and shape of grain, crack, grain boundary and dislocation changes resulting from dehydration at high temperature. The fine-granular aggregates of minerals formed through dehydration were chemically analysed, and they were found to be composed of forsterite and enstatite. Dehydration of serpentine has a significant effect on the low-velocity zone and earthquake generation.

1. Introduction

Elastic wave velocity measurements on rocks at high temperature and high pressure play a key role in researching the state, properties and movement of the Earth's interior materials. Fluids deep in the Earth may significantly affect rock's physical properties. One of the main sources of these fluids is from the dehydration of hydrous minerals such as micas, amphiboles and serpentine.

Although a few papers focusing on the fact that the dehydration reaction of hydrous minerals may have effects on elastic wave velocities (V_p) at high pressure and high temperature were published [1–5], as regards the aspect of rock fabric change, investigations of the effect of the specific process of serpentine dehydration on seismic wave propagation in rocks are scarce. Importantly, the fine-granulated matrix generated in the dehydration of serpentine needs further research.

In this paper we present experimental data on V_p in rock mainly containing serpentine at the constant pressure 1.0 GPa from room temperature to 960 °C. It is emphasized that the serpentine temperature-induced dehydration process may have a great effect on seismic velocities and the Earth's interior material movement through changing the rock structure.

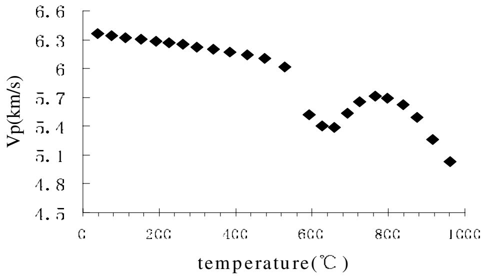

Figure 1. P-wave velocities versus temperature at 1.0 GPa.

Table 1. Chemical composition of samples (wt%).

Oxide	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	Ka_2O	MnO	Loss	Total
Content	41.6	0.11	1.88	9.56	31.25	3.99	0.48	0.16	0.09	10.44	98.56

2. Experimental method

The sample is serpentinized olivine-bearing pyroxenite, and its mineral composition includes serpentine (80%), orthopyroxene and olivine (15%), Ti–Fe oxides (2–3%) and dolomite (2%), with a density of 2.60 kg m^{-3}. The chemical compositions and CIPW results of this specimen are shown in table 1.

2.1. Method of measurement

Compressional wave velocity was measured in a multi-anvil pressure apparatus, the YJ-3000t press at the Institute of Geochemistry, Chinese Academy of Science [6], using the ultrasonic pulse transmission method in combination with the echo–impulse method, with an accuracy of 1.2% [7].

3. Experimental results

Figure 1 shows the various changes of V_p with temperature at 1.0 GPa for the sample. An almost linear decrease in P-wave velocity was observed with increasing temperature from room temperature to about 500 °C, followed by a nonlinear and remarkable drop from 6.2 to 5.4 km s^{-1}: a decrease of 15%. It is interesting to note that the abrupt increase in V_p with increasing temperature from 640 to 780 °C is in sharp contrast to the ‘classical’ velocity–temperature relationship found in plutonic and metamorphic rocks [1, 8]. Secondly, above 780 °C, the velocity decreased rapidly with increasing temperature. At the end of the run (at 960 °C), V_p dropped to 5.0 km s^{-1}.

Four experimental products were obtained respectively at 540, 720, 910 and 960 ° C. The quenched products were polished to thin sections for observation under a microscope and with an electron microprobe analyser. Results of the analysis are summarized in table 2. Optical studies on the quenched products showed a lot of clear fabric changes in the rock at different temperatures. 30% serpentine in the product (540 °C) dehydrated and 80% dehydrated at 720 °C and became fine-granular aggregates filling up inter-grain spaces or micro-fissures of the remaining olivine and pyroxene, with the size of 0.08–0.4 nm. The old sheet-like, fibrous aggregates were greatly changed, and so was all of the serpentine in the products at 910 and 960 °C. In the products at 910 and 960 °C, in which some local variations in optical scattering occurred along the relict olivine and pyroxene grain boundaries, which were curved. Fissures and cracks due to the high pressure and temperature were present in all of the four thin sections.

Table 2. Chemical compositions of the experiment product (1.0 GPa, 960 °C) and mineral analytical results. Analyst: Zhou Jianxiong, Chinese Academy of Geological Sciences. c: centre, m: middle, r: rim, (*n*): *n*: times, Fo: forsterite, Fa: fayalite, Chr: chrysolite, En: enstatite, Br: bronzite, DST: density.

Num.	C (c)	C (m)	C (r)	E (1)	E (2)	G (c)	G (r)	Num.	F (r)	F (c)	D (1)	D (2)
Na_2O	0	0	0	0	0	0	0	Na_2O	0	0.13	0.15	0.11
MgO	47.54	50.46	51.01	50.19	49.2	46.91	46.00	MgO	34.68	32.01	35.34	35.06
Al_2O_3	0.08	0	0	0	0	0	1.16	Al_2O_3	2.68	1.84	0.51	1.07
SiO_2	39.86	40.19	40.54	41.07	40.84	39.87	40.57	SiO_2	56.44	55.49	56.67	56.79
K_2O	0	0	0	0.08	0	0	0.04	K_2O	0	0	0	0
CaO	0.12	0.07	0.11	0.13	0.1	0.05	1.38	CaO	1.02	0.26	0.85	0.66
TiO_2	0	0	0	0.04	0.01	0.03	0.05	TiO_2	0.1	0.04	0.09	0
Cr_2O_3	0	0	0	0	0.02	0.1	0.03	Cr_2O_3	0.33	0.21	0.04	0.03
MnO	0.2	0.02	0.12	0.09	0.1	0.15	0.04	MnO	0.1	0.07	0.03	0.06
FeO	11.69	8.43	7.86	7.62	8.53	12.18	9.46	FeO	3.9	8.75	5.27	5.26
Total	99.49	99.17	99.64	99.22	98.8	99.29	98.73	Total	99.25	98.8	98.95	99.04
Fo	0.879	0.914	0.92	0.922	0.911	0.873	0.897	En	0.922	0.868	0.938	0.928
Fa	0.121	0.086	0.08	0.078	0.089	0.127	0.103	Fs	0.058	0.127	0.045	0.059
Mg	0.876	0.913	0.918	0.919	0.909	0.871	0.879	DST	3.251	3.303	3.254	3.256
Fe	0.121	0.086	0.079	0.078	0.088	0.127	0.101					
Phase	Chr	Fo	Fo	Fo	Fo	Chr	Fo	Phase	En	Br	En	En

Observed by an electron microprobe analyser, the fine-granular aggregates were forsterite and enstatite (see the D and E columns in table 2). In the remaining olivine and pyroxene grains, the contents of Fe clearly became lower from the central area to the rim (see the C, F and G columns in table 2).

4. Discussion

The measured velocity versus temperature characteristics reported in this study demonstrate that the thermally induced fabric changes in the rock play a key role in wave propagation in rocks. The rock fabric has aspects such as mineral composition, size and shape of grain, crack, grain boundary and dislocation changes.

The linear part of the temperature–velocity relationship between room temperature and 500 °C reflects intrinsic behaviour that can be interpreted in terms of a decrease in matrix velocities due to thermal expansion of minerals. Though there may be some cracks, they cannot open for the high pressure of 1.0 GPa. In contrast, at temperature above 500 °C the discontinuous velocity drop indicates the onset of dehydration.

80% serpentine was resolved in the thin section of the product at 720 °C, and no serpentine was found at 910 °C. It is also reported that serpentine dehydrates in a wide temperature range of 500–800 °C at about 1.0 GPa [9–12]. In addition, the dolomite decomposes into (Mg, Ca)O and CO_2 at 600–960 °C [13]. The fluids would be in the supercritical state at the conditions of experiment temperature and pressure. Supercritical fluids (SCF) have many special features [14, 15], such as higher conductivity and chemical activity and low viscosity with the exception of lower wave velocity, so they are easy to make flow, and act with mineral grains and decrease wave velocity. With the temperature increasing, a consequence of thermal stress induced by fluid expanding results in a widening of old cracks and the formation of new cracks. The fine-granular aggregates of fosterite and pyroxene formed and the abrupt increase in pore space and reconstitution of the pore geometry would predominantly be the causes of the observed sharp velocity decrease. Furthermore, the alternation of fabric and composition of the rock might be contributing to the wave velocity decrease at higher temperature.

There was an abrupt increase in wave velocity that seemed abnormal at temperatures of 640–780 °C (figure 1), and similar phenomena were reported in [1, 16]; but the reasons for the wave increase remain a puzzle, even though some explanations were proposed. For example, the SCF expulsion from the sample cell might cause the fluid volume decrease and the cracks to close with the result that V_p increases. In addition, the new minerals formed in the higher temperature range, which have high wave velocities, are also regarded as another reason. Undoubtedly, there is still a lot of further research needed.

The hydrous minerals play an important role in tectonic movement, earthquake generation and lithosphere evolution. In this experiment the wave velocity change of the serpentinized olivine–pyroxene ranges between 6.4 and 5.0 km s^{-1} (the decrease rate of about 22%) at 1.0 GPa from room temperature to 960 °C, which is concordant with those in the low-velocity zones in the lithosphere [17, 18]. What is more, the fluids released by dehydration of hydrous mineral are good for the fault slipping. The changes of volume and energy in rocks during the dehydration process have an important effect on earthquake generation. Acoustic emission was registered as serpentine dehydrated between 2.0 and 9.0 GPa [19], and most of the earthquake focus distributes near to or along the low-velocity layers [20, 21].

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