Highly Accurate Sound Velocity Measurement in Liquid Fe-S System under High Pressure

Accurate sound velocities in liquid Fe-S are required to constrain the composition and structure of the Moon's core. However, two recent studies reported considerably different results, even though they used a similar method. To identify the causes of the discrepancy, we have conducted experiments with a newly developed system at PF and evaluated possible error sources. We have also conducted additional experiments at SPring-8 and reanalyzed previous data. Now we can accurately determine the sound velocities in liquid Fe-S. The proposed seismic velocity of the Moon's liquid outer core is 4.0 ± 0.1 km/s, given a chemical composition of $Fe_{83}S_{17}$.

To constrain the structure and composition of the deep interior of the Earth and the Moon, it is important to accurately determine the sound velocity of candidate materials that can be directly compared with seismological observations. Liquid Fe–S is thought to be a candidate material for the liquid core of the Moon because its eutectic temperature is much lower than that of other Fe alloys, and FeS is a component of chondritic meteorites. However, the sound velocity in liquid Fe–S reported by Jing et al. [1] differs considerably (>10% at 5 GPa) from that of our previous study [2], even though both studies used a similar method. These results lead to significantly different compositions of the Moon's liquid core because a 10% difference in velocity corresponds to a 20 wt.% difference in sulfur content. In this study, we reanalyzed previous data and conducted additional sound velocity measurements for liquid Fe–S at 2–7 GPa, and evaluated the potential error sources to identify the causes of the discrepancies [3].

We conducted high-pressure and high-temperature experiments at AR-NE7A of KEK PF and BL04B1 of SPring-8 using Kawai-type multi-anvil apparatus. We set up a new X-ray radiography system and a sound velocity measuring system at AR-NE7A. **Figure 1** shows a typical X-ray radiographic image and ultrasonic echo signals at AR-NE7A. The main error source of the sound velocity was uncertainty of the sample length caused by imperfect parallelism between the front and back reflecting surfaces of the sample. The sound velocity can be determined within an error of 1% in the best condition. In our previous study [2], pressure was determined from the temperature measured by thermocouple, the unit-cell volume of MgO, and its equation of state (EOS) [4]. However, detailed observations of texture of the recovered samples revealed that the temperatures had been underestimated because the junctions of thermocouples were not located close enough to the sample and pressure markers although the MgO pressure marker is sensitive to temperature. We therefore determined pressure and temperature simultaneously from the unit-cell volumes of both h-BN and MgO by using their EOS [5, 6] without a thermocouple because the pressure was determined mainly from the unit-cell volume of h-BN, which is less sensitive to temperature. According to the error in the unit-cell volume and that of the EOS itself, the pressure and temperature errors were estimated to be ±0.5 GPa and ±100–200 K, respectively.

Figure 2 shows the experimental results for the sound velocity in liquid Fe–S. The results of SPring-8 and PF-AR were consistent with each other, suggesting there were no systematic errors of equipment. The reanalyzed sound velocity values show little change from those of [2]. In contrast, the pressure values of the reanalyzed dataset shift markedly towards higher pressures. The present sound velocities of $Fe_{57}S_{43}$ agree with those reported by [1] in the low-pressure region (P < 3.5 GPa) but still show a large discrepancy in the high-pressure region (P > 5 GPa). Our sound velocity of $Fe_{80}S_{20}$ is also much larger than that of $Fe_{84}S_{16}$ reported by [1]. The most likely reason for this discrepancy is a systematic error in estimating the pressures of [1] which were determined using an MgO pressure marker with the temperature estimated from the power–temperature relationship. We are concerned that this estimation may have a large uncertainty. The pressure difference (~1.2 GPa) between the results of [1] and those of the present study can be explained by an overestimation of 200 K at the pressure marker location, which is a conceivable error.

Although Apollo seismic experiments were performed on the Moon, the accurate seismic velocity of the core is not yet determined. Here we propose a mineral physical seismic velocity model of the Moon's core. Assuming a bulk composition of the Moon's core of $Fe_{90}S_{10}$ [7], the composition of the outer core is estimated to be $Fe_{83}S_{17}$ by mass balance calculations. The best estimate for the seismic velocity of the Moon's liquid outer core is 4.0 ± 0.1 km/s. The bulk core composition is left for future discussion. To obtain a clearer picture of the composition and structure of the Moon's core, more accurate seismic data are required.

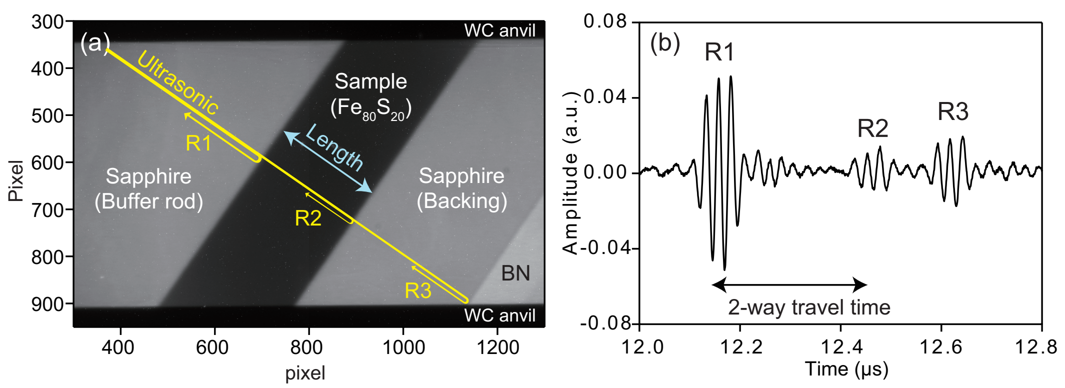

Figure 1: (a) Typical X-ray radiographic image of the molten sample acquired at 3.9 GPa and 1720 K. The sample length was determined by image analysis assuming that the right and left boundaries are parallel. **(b)** Compressional wave echoes from buffer rod/sample (R1), sample/backing (R2) (inverted), and backing/BN (R3) at 3.9 GPa and 1720 K. These echoes correspond to the yellow reflected arrows in **(a)**. The two-way travel time was determined by the cross-correlation function between R1 and inverted R2 echoes.

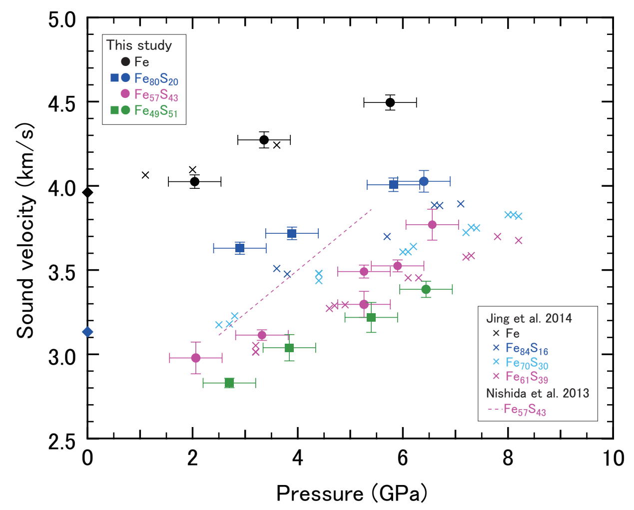

Figure 2: Effect of pressure and composition on sound velocity in the liquid Fe–S system. Filled circles and squares denote data obtained at the SPring-8 and KEK PF-AR facilities, respectively. The dataset of $Fe_{57}S_{43}$ is mainly composed of reanalyzed data of [2]. The dashed line denotes the linear regression line for original (i.e., pre-reanalysis) data of [2]. Crosses denote the data from [1]. Filled black and blue diamonds denote the sound velocity in liquid Fe [8] and in liquid $Fe_{79.3}Ni_{4.4}S_{16.3}$ [9].

REFERENCES

[1] Z. Jing, Y. Wang, Y. Kono, T, Yu, T. Sakamaki, C. Park, M. L. Rivers, S. R. Sutton and G. Shen, *Earth Planet. Sci. Lett.* **396**, 78 (2014).
[2] K. Nishida, Y. Kono, H. Terasaki, S. Takahashi, M. Ishii, Y. Shimoyama, Y. Higo, K. Funakoshi, T. Irifune and E. Ohtani, *Earth Planet. Sci. Lett.* **362**, 182 (2013).
[3] K. Nishida, A. Suzuki, H. Terasaki, Y. Shibazaki, Y. Higo, S. Kuwabara, Y. Shimoyama, M. Sakurai, M. Ushioda, *E. Takahashi*, T. Kikegawa, D. Wakabayashi and N. Funamori, *Phys. Earth Planet. Inter.* **257**, 230 (2016).
[4] Y. Kono, T. Irifune, Y. Higo, T. Inoue and A. Barnhoorn, *Phys. Earth Planet. Inter.* **183**, 196 (2010).
[5] Y. Tange, Y. Nishihara and T. Tsuchiya, *J. Geophys. Res.* **114**, B03208 (2009).
[6] D. Wakabayashi and N. Funamori, *High Press. Res.* **35**, 123 (2015).
[7] N. Rai and W. van Westrenen, *Earth Planet. Sci. Lett.* **388**, 343 (2014).
[8] P. M. Nasch and M. H. Manghnani, Molar Volume, Thermal Expansion, and Bulk Modulus in Liquid Fe-Ni Alloys at 1 Bar: Evidence for Magnetic Anomalies? in *Properties of Earth and planetary materials at high pressure and temperature*, eds. M. H. Manghnani and T. Yagi, 307-317. AGU pubulishing, (1998).
[9] P. M. Nasch, M. H. Manghnani and R. A. Secco, *Science* **277**, 219 (1997).

BEAMLINE

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