Measuring the effect of water on the seismic wave and its application to the lithosphere and asthenosphere boundary

The weakened asthenosphere below rigid lithosphere is a critical research target for understanding the mechanisms of plate tectonics on Earth. Traditionally, the asthenosphere was defined as a region softened primarily due to thermal activation. However, with advancements in seismological techniques, a more complex understanding has emerged [1]. New mechanisms are required to explain the sharp seismic anomalies observed at the lithosphere-asthenosphere boundary (LAB), which cannot be entirely accounted for by thermal processes alone.

Several mechanisms have been proposed to explain these seismic observations [2,3]. One prominent hypothesis involves the effect of water on the rheology of upper mantle minerals, suggesting that variations in water content between the lithosphere and asthenosphere might play a significant role. This hypothesis is particularly compelling in regions where seismic anomalies occur at relatively low-temperature boundary areas. To explore this possibility, our research focuses on studying the influence of water on seismic wave properties within the mantle [4].

Olivine, the dominant mineral in the upper mantle, was selected as the starting material for our study due to its significance in controlling mantle rheology and seismic properties. To eliminate potential interference from oxygen fugacity, we used iron-free olivine in our experiments. The olivine samples with varying water contents were synthesized at the Institute for Planetary Materials, ensuring precise control over their composition and hydration levels.

The core of our experimental work involved measuring anelasticity using a developed *in situ* short-period cyclic loading system integrated into a multianvil press [5]. This setup was located at SPring-8 **BL04B1** beamline, enabling measurements under simulated upper mantle conditions. The experiments were conducted at pressures of approximately 3 GPa and temperatures ranging from 1173 to 1373 K, conditions representative of the LAB. These parameters allowed us to closely replicate the physical environment of the upper mantle and investigate how water influences seismic wave behavior.

Our results demonstrated a clear relationship between water content and seismic properties.

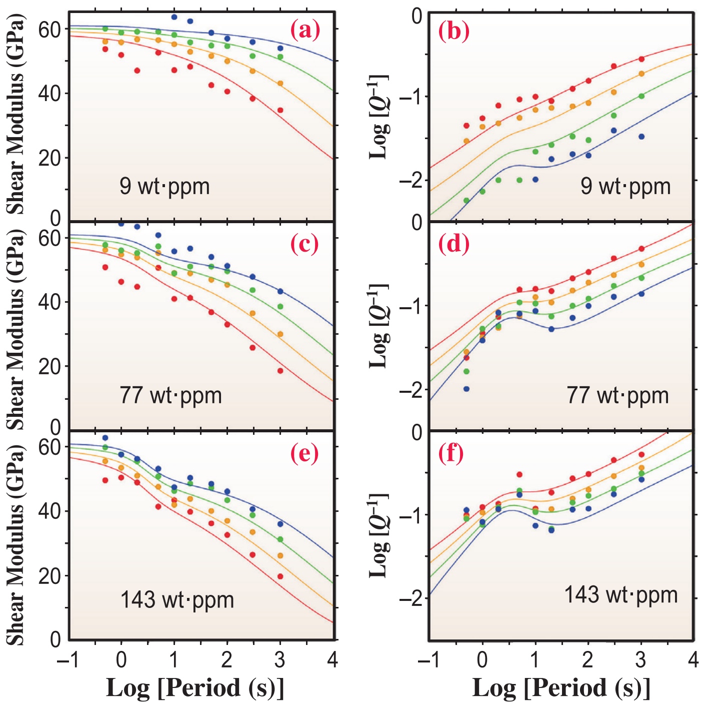

Fig. 1. The anelastic experimental results. The **(a)**, **(c)**, and **(e)** are the shear modulus and **(b)**, **(d)**, and **(f)** are the attenuation of samples at various water contents at different temperature.

As water content increased, the Young's modulus of the olivine samples decreased, while attenuation—a measure of energy dissipation in seismic waves—increased. Notably, we observed attenuation peaks directly associated with water content, a phenomenon identified for the first time in our study (Fig. 1). These peaks indicate that water significantly enhances anelastic behavior, providing a potential explanation for the seismic anomalies observed at the LAB.

To bridge the gap between our laboratory findings and Earth's seismic observations, we utilized the generalized Burger's model [6]. This physical model allowed us to extrapolate our experimental results to geophysical scales and predict the effect of anelasticity on seismic wave propagation in the upper mantle (Fig. 2). Our analysis revealed that as water content increases, the strength of anelasticity also increases. This finding aligns with the hypothesis that water plays a crucial role in modifying the seismic properties of the mantle.

Further, by considering plausible grain sizes in the upper mantle, we extrapolated our results to seismic observations in regions such as the western North Pacific. The comparison revealed that differences in water content between the lithosphere and asthenosphere could account for the observed seismic anomalies in low-temperature boundary areas (Fig. 3). These results support the notion that water content variations at the LAB are a key factor in understanding the transition between the lithosphere and asthenosphere.

This study provides significant insights into the role of water in influencing seismic properties and the mechanical behavior of the upper mantle. By demonstrating the impact of water on anelasticity and seismic wave attenuation, we offer a plausible explanation for the sharp seismic contrasts at the LAB. Our findings also highlight the importance of integrating experimental, theoretical, and observational approaches to advance our understanding of mantle dynamics.

Future research could build on our results by exploring additional factors that may influence seismic properties at the LAB, such as the presence of iron or variations in mineral composition and oxygen fugacity.

In conclusion, this research underscores the critical role of water in shaping the seismic and rheological properties of the upper mantle. By linking experimental observations with geophysical models, we provide a robust framework for interpreting seismic anomalies at the lithosphere-asthenosphere boundary.

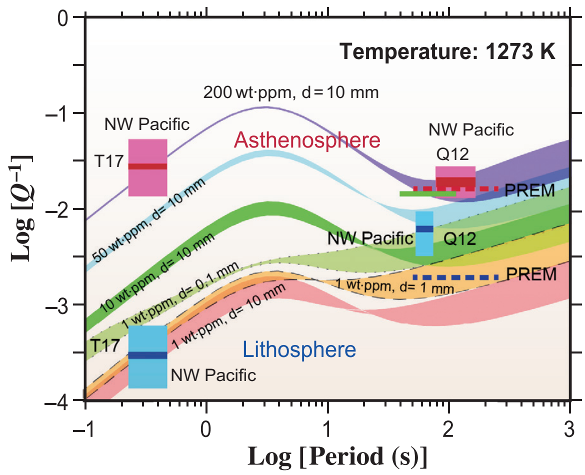

Fig. 3. The effect of water on seismic wave attenuation at different periods at 1273 K.

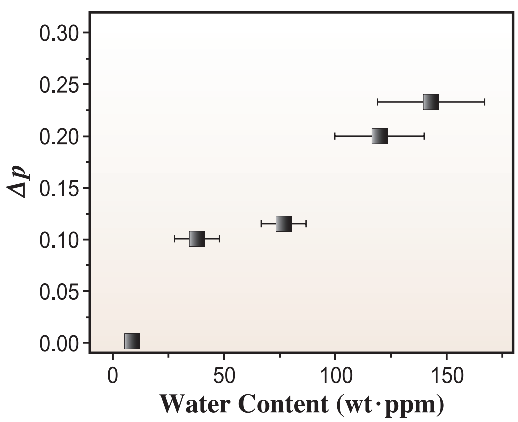

Fig. 2. The effect of water content on the strength of anelasticity.

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References

[1] C. A. Rychert *et al.*: Nature **436** (2005) 542.
[2] S. Karato: Earth Planet. Sci. Lett. **321-322** (2012) 95.
[3] C. A. Rychert *et al.*: J. Geophys. Res.: Solid Earth **125** (2020) e2018JB016463.
[4] *C. Liu, T. Yoshino, D. Yamazaki, N. Tsujino, H. Gomi, M. Sakurai, Y. Zhang, R. Wang, L. Guan, K. Lau, Y. Tange and Y. Higo: Proc. Natl. Acad. Sci. USA* ***120*** *(2023) e2221770120.*
[5] T. Yoshino *et al.*: Rev. Sci. Instrum. **87** (2016) 105106.
[6] U. Faul and I. Jackson: Annu. Rev. Earth Planet. Sci. **43** (2015) 541.