The Influence of Water on Seismic Wave Attenuation in the Earth's Upper Mantle: An Exploratory Experimental Study

Yoshitaka Aizawa[a,b,c], Auke Barnhoorn[a], Ulrich H. Faul[a,d], John D. Fitz Gerald[a]
and Ian Jackson[a]

[a] *Research School of Earth Sciences, Australian National University, Canberra, Australia*
[b] *Institute for Study of the Earth's Interior, Okayama University, Misasa, Japan*

Established methods for the study of viscoelastic behaviour at simultaneously high temperature and pressure have been extended to allow the maintenance of a high pore fluid pressure during prolonged annealing and micro-strain mechanical testing. A natural olivine-rich rock, initially containing water in accessory hydrous phases subjected to in situ dehydration within a welded Pt capsule, was tested with low-frequency forced-oscillation methods. The observed viscoelastic relaxation was significantly enhanced by the presence of the pressurised aqueous pore fluid.

1. Introduction

The viscoelasticity of the Earth's mantle, manifest in the dispersion and attenuation of seismic waves, is potentially strongly influenced by the presence of water – either as a free fluid phase or associated with defects in nominally anhydrous silicate minerals like olivine [1]. Here we demonstrate a new procedure for the encapsulation of rock specimens that allows high-temperature mechanical testing under water-saturated conditions.

2. Experimental method

2.1 Mechanical testing

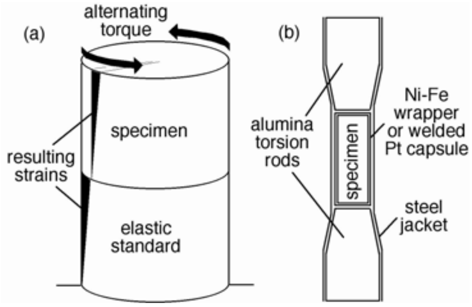

Fig. 1. (a) The principle underpinning studies of viscoelastic behaviour through observation of torsional forced oscillations. (b) Detail of the specimen assembly showing alternative arrangements in which the specimen is either wrapped in Ni-Fe foil or sealed within a welded Pt capsule.

In our laboratory, torsional forced-oscillation tests (Fig. 1a) are performed on cylindrical rock specimens under conditions of simultaneously high temperature and pressure [2]. The cylindrical rock specimen is mounted between alumina torsion rods within the hot-zone of a furnace operated within a gas-charged pressure vessel. The specimen and alumina torsion rods are housed within a thin-walled steel jacket sealed at both ends onto hollow steel

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[c] *Present address: Research Center for Seismology, Volcanology and Disaster Mitigation, Nagoya University, Nagoya, Japan*
[d] *Present address: Department of Earth Sciences, Boston University, Boston, USA*

torsion members in order to exclude the argon pressure medium (Fig. 1b). Venting of the hollow interior of the steel assembly ensures that a normal stress equal to the confining pressure acts across each interface within the system, thereby providing the necessary mechanical coupling.

The specimen assembly is first subjected to a prolonged period (~100 h) of annealing at the highest working temperature T (typically 1300°C) and a confining pressure P_c of 200 MPa, during which any evolution of the mechanical behaviour associated with microstructural changes is monitored. Mechanical testing involves the conduct of forced-oscillation tests at selected oscillation periods T_o between 1 and 1000 s at maximum strain amplitudes of order 10^{-5} and complementary torsional microcreep tests of duration <10000 s. Once the mechanical behaviour has stabilized, testing is done during slow staged cooling.

2.2 Specimen preparation and characterisation

For this study we chose a fine-grained natural rock from Anita Bay, New Zealand, composed mainly of the upper-mantle mineral olivine along with ~0.3 wt % H_2O mainly in accessory hydrous silicate phases. In order to prevent chemical alteration of the ferromagnesian silicate minerals, such a specimen is normally wrapped in Ni-Fe foil (Fig. 1b) that serves to maintain an appropriate oxygen fugacity. Gravimetric analysis and Fourier-transform infrared spectroscopy were used to measure the water concentration in specimens recovered following prolonged annealing and mechanical testing. The microstructures of the starting material and recovered specimens were examined by light microscopy and SEM.

2.3 Data analysis

Analysis of the forced-oscillation experiments provides determinations of the shear modulus G and strain energy dissipation Q^{-1} for the rock specimen. These data were fitted to a model based on a Burgers creep function $J(t) = J_U + \delta J\,[1 - \exp(-t/\tau)] + t/\eta$ modified to incorporate a suitable distribution $D(\tau)$ of anelastic relaxation times τ. J_U is the unrelaxed compliance, δJ the recoverable anelastic contribution, and η the steady-state viscosity.

3. Results: mechanical testing and microstructural characterisation

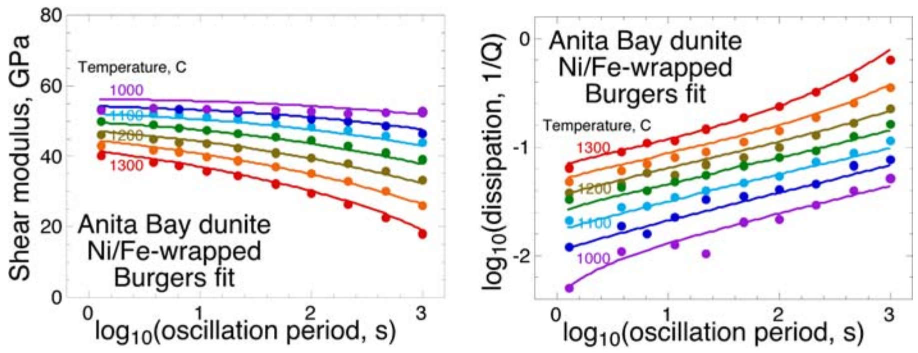

Fig. 2. The variation of shear modulus and dissipation with oscillation period and temperature for the specimen tested 'dry' within an Ni-Fe wrapper. The curves represent the Burgers model fit to the data.

The specimen tested in the Ni-Fe foil wrapper was recovered essentially dry (~40 wt ppm water) proving that this arrangement is incapable of retaining the water released by in situ dehydration for the extended duration of these experiments. The forced-oscillation tests for this specimen (Fig. 2) reveal a broad viscoelastic absorption band without any evidence of a superimposed dissipation peak.

Examination of another specimen recovered following testing within a welded Pt capsule provided clear evidence of the retention of essentially the entire inventory of water as a pressurised pore fluid occupying ~2% of newly created porosity (Fig. 3).

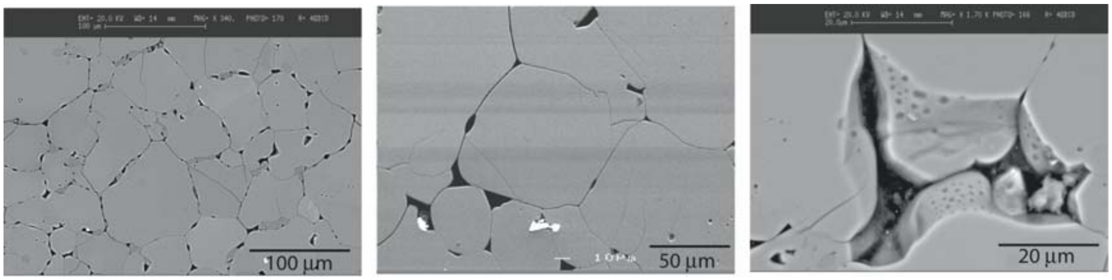

Fig. 3. SEM micrographs highlighting the porosity created in the Pt-encapsulated specimen of Anita Bay dunite during dehydration and subsequently maintained by high pore-fluid pressure.

For this specimen, tested to a maximum temperature of 1150°C, qualitatively similar absorption-band behaviour was observed but with systematically lower shear modulus and higher dissipation (Fig. 4).

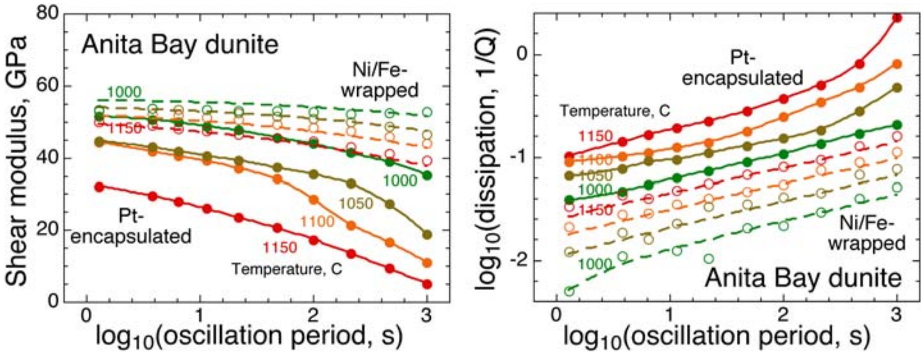

Fig. 4. A comparison of the forced-oscillation data for the essentially dry (Ni-Fe-wrapped) and water-saturated (Pt-encapsulated) specimens of Anita Bay dunite for a representative common temperature range 1000-1150°C.

4. Discussion and conclusions

This exploratory study clearly demonstrates the utility of Pt-encapsulation for essentially quantitative retention of water during prolonged periods of annealing and mechanical testing to temperatures of 1150°C at a confining pressure of 200 MPa. The overall textural maturity of the specimens is attributed to the role of water in enhancing grain growth. The very marked reduction in shear modulus for temperatures >1000°C is attributed to the widespread wetting of grain boundaries resulting from hydrofracturing and the maintenance of conditions of low differential pressure $P_d = P_c - P_f$, where P_f is the pore pressure. During staged cooling, accompanied by decreasing P_f and increasing P_d, a different microstructural regime is encountered in which the fluid is increasingly accommodated in arrays of partly-isolated grain-boundary pores. The more pronounced viscoelastic behaviour observed within this regime for the Pt-encapsulated specimen than for the dry specimen is tentatively attributed to enhanced grain-boundary sliding facilitated by the presence of interconnected pore fluid & lower grain-boundary viscosity. Future work will focus on the role of trace amounts of water associated with defects within the crystal structure of synthetic olivine.

References

[1] S. Karato, Mapping water content in the Earth's upper mantle, *The Subduction Factory*, AGU Monograph, 135, (2003).

[2] I. Jackson and M. S. Paterson, *Pure Appl. Geophys*. **141**, 445 (1993).