Form A: Natural Sciences
2009-2010 Academic Year

I. ***Cover Sheet*** (See attached)

II. *Title and Abstract*

Temperature Effects on Elasticity of Some Sintered Polycrystalline Minerals

Understanding the features of Earth's interior has long concerned Earth scientists. Specifically, the compositional makeup of the deep Earth is of both academic and practical interest. For example, earthquakes happen because of dynamic processes at great depth. The more we know about Earth's interior, the closer we come to unraveling uncertainties surrounding devastating near surface phenomena such as earthquakes. Estimates of Earth's composition have focused on matching elastic properties of Earth with laboratory data on candidate minerals. Elastic properties indicate how materials strain (deform) in response to applied stresses (forces). Earth's elastic profile is fairly well known from studies of seismic waves (from earthquakes) that travel through Earth's interior before arriving at the surface. Less certain is information on the elastic properties of candidate materials at pressure and temperature conditions of Earth's interior.

Previously, we measured the temperature dependence of elasticity of wadsleyite, an important material believed to be present at depths of 400 km and lower. We observed subtle nonlinear behavior in the elastic properties of wadsleyite over a limited temperature range. However, this nonlinearity drastically affects estimates of the composition of Earth's interior if it is used in extrapolating to temperature at 400-km depth.

Some have claimed the nonlinearity is not due to inherent properties of wadsleyite, but is an artifact of the type of specimen (sintered poly-crystal) that must be used when working with special high-pressure minerals such as wadsleyite. Presumably, nonlinearity would not be observed in single-crystal wadsleyite specimens. To address these uncertainties, we propose high-temperature measurements on sintered poly-crystal specimens for which there are already single-crystal data. Comparing sintered poly-crystals data with those from single-crystals should give some clue whether sintered poly-crystals are appropriate proxies when determining the elasticity of minerals for which single-crystals are not obtainable.

III. *Purpose/Aims*

We intend to investigate nonlinear behavior over temperature of certain physical properties reported in earlier studies of an important mineral called wadsleyite. Interpreting nonlinearity in the elasticity of wadsleyite is problematic. Is it due to actual changes in wadsleyite elasticity as temperature increases? Or, does it that the type of specimen used (sintered poly-crystal) loses integrity as temperature increases? The answers to these questions have important consequences on what compositional model (types and amounts of minerals present) should be favored for Earth's deep interior.

We propose making high-temperature measurements on the elastic properties of two sintered poly-crystal materials (forsterite and garnet) for which secure single-crystal data already exist. By comparing data on sintered poly-crystal specimens with existing single-crystal data, we can test (hopefully verify) the integrity of sintered materials when making elasticity measurements. The results will help interpret data on special high-pressure materials such as wadsleyite which can only be obtain as sintered specimens, and possibly position us to pursue further collaborations with those who fabricate high-pressure materials.

IV. ***Background and Significance of Study***

The elastic properties of solid materials indicate how they strain (deform) in response to applied stresses (forces). For isotropic materials (the material 'looks' the same in all directions), the elastic state is defined by two elastic moduli. The bulk modulus (K) indicates how the material strains in response to a hydrostatic compressive (squeezing) stress, and the shear modulus (G) indicates material strains in response to a shear (sideways) stress.

A first order problem in geophysical studies is determining Earth's composition (what minerals are there) as a function of depth. Earth's center is about 6000 km below the surface, but the deepest drill holes go to only about 12 km depth. So, direct sampling to identify the mineral makeup of Earth only gives information relatively near the surface. Determining the composition of Earth's interior requires additional, indirect methods, and this is why K and G are important geophysical quantities. Studies on the arrival times around the globe of waves from large earthquakes yield a robust picture of Earth's elastic profile. In other words, we have a good idea how K and G vary with depth from Earth's surface to the center. The challenge is to make laboratory measurements of K and G, including their temperature and pressure dependences, of candidate materials in order to determine which materials give a match to the known elastic profile of Earth's interior.

A strong candidate as a major mineral in the region from 400 km depth, and below, is wadsleyite, a high-pressure phase of a common mineral, olivine, found at shallower depths. It is widely believed olivine changes to wadsleyite due to pressure at 400-km depth. Accurately determining the elasticity of wadsleyite at pressure and temperature conditions appropriate to 400-km depth is critically important to unraveling questions about the mineral composition of Earth's deep interior at 400 km depth and below. Accordingly, the elastic and thermal properties of wadsleyite have been subjected to much study in recent years (Isaak et al. 2007, Katsura et al. 2001, Li et al. 2001, Lui et al. 2005, Mayama et al. 2001). Our unique contribution is measuring the temperature dependence of K and G.

Small samples of wadsleyite can be 'made' at some research centers by applying large compressive forces on olivine in special apparatus. The high-pressure machinery pulverizes the olivine into small pieces which are then sintered together forming a coherent wadsleyite specimen. When making sintered polycrystalline specimens, the grains of small individual pieces are randomly oriented and essentially welded together through the combined effect of temperature and pressure.

A few years ago, we acquired sintered polycrystalline wadsleyite specimens from colleagues at Delaware State University. The specimens had small differences in their elemental composition; the first was Mg_2SiO_4, and the second $Mg_{1.8}Fe_{0.2}SiO_4$. We completed elasticity measurements from room temperature (295 K) to 640 or 660 K on both. The results for the first specimen have been published (Isaak et al. 2007), and a manuscript presenting data for the second is nearly ready for submission.

Results from the second specimen for G are displayed in Figure 1 below. These are wonderful, repeatable data over the temperature range we were able to use. But, in making application to Earth's composition at 400 km, we must extrapolate beyond the range of measurements, out to 1800 K, the approximate temperature at that depth. Here is where things get especially interesting. One could just linearly extrapolate to 1800 K the data seen in Figure 1 using the solid line. However, there is subtle, but observable and persistent, curvature in the G data (the same occurs for K); the data tend to bend down as temperature increases (dashed line in Figure 1). When extrapolating to 1800 K, we will have significantly different estimates for *K* and *G* of wadsleyite, and consequently on the amount of wadsleyite present around 400 km depth, depending on whether we use the solid or dashed lines.

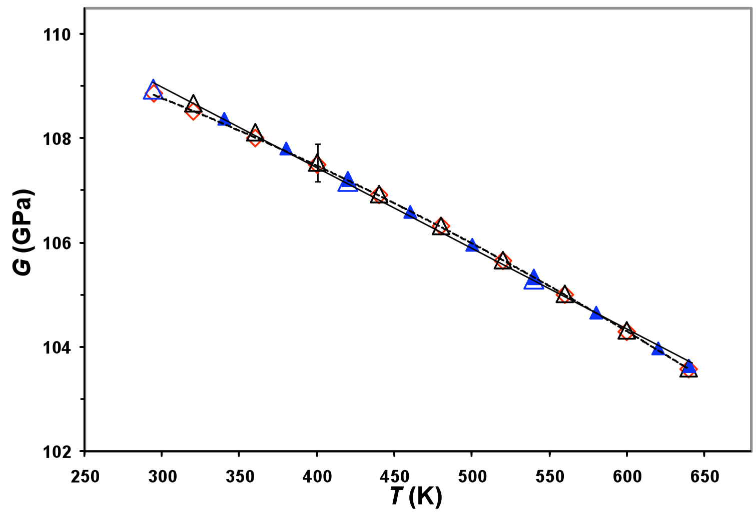

Figure 1 The temperature dependence of the shear modulus for sintered $Mg_{1.8}Fe_{0.2}SiO_4$ wadsleyite (data to be published). Different symbols and colors show different temperature excursions. Solid line is linear fit to data. Dashed line is second order polynomial fit to data.

Some critics of our earlier work suggest the subtle curvature in the wadsleyite *K* and *G* data occurs because sintered poly-crystals, rather than single-crystal, specimens were used in the measurements. In other words, curvature in the data is not from changes in material properties, but from problems with sintered poly-crystals specimens when heated. We do not believe this is correct, but are unable, to date, to irrefutably rebut it. Given that wadsleyite is a high-pressure phase of olivine and unattainable as a single-crystal specimen, we cannot directly test the criticism's accuracy.

However, we have obtained sintered specimens of other minerals, forsterite and garnet, which have previously been thoroughly studied as single-crystal specimens. Our plan is to make multiple high temperature measurements for *K* and *G* of sintered forsterite and garnet, and then compare with previous data from single-crystals. To be sure, these new measurements are not needed to understand the elasticity of forsterite and garnet. The single-crystal data are secure. But, new measurements will help verify the integrity of sintered specimens when make high-temperature elasticity measurements. The results will apply to the wadsleyite data, whether curvature in the data is 'real' or not, and to other high-pressure phases of the deep Earth we hope to study but can acquire only as sintered materials.

Bibliography

Isaak, D.G., Gwanmesia, G.D., Falde, D., Davis, M.G., Triplett, R.S., and Wang, L., The elastic properties of β-Mg_2SiO_4 from 295 to 660 K and implications on the composition of Earth's upper mantle. Phys. Earth Planet. Int., 162: 22-31 (2007)

Katsura, T., Mayama, N., Shouno, K., Sakai, M., Yoneda, A., and Suzuki, I., Temperature derivatives of elastic moduli of $(Mg_{0.91}Fe_{0.09})_2SiO_4$ modified spinel. Phys. Earth Planet. Int., 124: 163-166 (2001)

Li, B., Liebermann R.C., and Weidner, D.J., P-V-V_P-V_S-T measurements on wadsleyite to 7 GPa and 873 K: Implications for the 410-km seismic discontinuity. J. Geophys. Res., 106: 30575-30591 (2001)

Liu, W., Kung, J., and Li, B., Elasticity of San Carlos olivine to 8 GPa and 1073 K. Geophys. Res. Lett., 32: L16301 (2005)

Mayama, N., Suzuki, I., and Saito, T., Temperature dependence of elastic moduli of β-$(Mg,Fe)_2SiO_4$. Geophys. Res. Lett., 31: L019247 (2004)

V. *Methods*

The elastic moduli, K and G, will be determined for two sintered poly-crystals using the right-rectangular parallelepiped resonance (RPR) version of resonant ultrasound spectroscopy (RUS). In RPR, the elastic properties of a right-rectangular parallelepiped specimen are determined from measurements of its mechanical resonance spectrum, edge lengths, and density. The specimen is placed between a pair of transducers (small pieces of ceramic material that strain in response to applied electric fields and visa versa). One transducer receives an oscillating electric signal from a frequency synthesizer and provides the mechanical vibrations to the specimen; the other transducer monitors the vibration of the specimen and provides a discernable increase in electric output when the vibration amplitude increases due to frequency being at a resonance value. By scanning a range of frequencies (using a DRS Modulus II apparatus brought to APU this past summer from the UCLA Mineral Physics Lab) the spectra of the resonant frequencies can be obtained. Spectral data at different temperatures are obtained by surrounding the specimen and transducers with a cylindrical heating coil. Temperature in the furnace is measured with two Pt-Pt13%Rh thermocouples placed on opposing sides of the specimen. The data reduction by which spectral data are converted into the desired K and G elastic moduli is done via an inversion technique. The inversion processes is usually straightforward, even though it is intensely computational. To be sure, we have on hand all the major hardware and software required to make the measurements and the data reduction.

<u>Approximate Work Schedule</u>

January 2010	Orient/train student assistant in experimental technique.
February 2010 – May 2010	Acquire spectral data on two sintered specimens from 295 – 640 K. (Do multiple runs. Collect data during heating and cooling phases)
June 2010 – August 2010	Analyze spectral data. Identify resonant peaks. Complete data reduction by which spectra at temperature are converted to K and G.
Fall 2010	Analyze results. Compare with single-crystal data. Prepare for conference presentations (SCCUR, AGU).

VI. *Human Subjects Review* (Not applicable)

VII. *Animal Subjects Review* (Not applicable)

VIII. *Budget* (See attached)

IX. *Brief statement regarding applicant's long range program of research and plans to apply for external funding.*

As explained in the *Background and Significance of Study* section, this project derives directly from earlier work on special high-pressure mineral phases. We expect to show the integrity of polycrystalline sintered specimens remains intact when they are heated during elasticity experiments. If our expectation bears out, there is the real prospect of collaborating with those who fabricate sintered specimens in order to make measurements of additional high-pressure phases of mantle materials. This includes the prospect of a collaborative NSF proposal with contacts at Delaware State University or the Geophysical Laboratory (Washington DC). There is strong interest in the geophysical community to reliably determine the temperature dependence of elasticity for several other high-pressure phase materials.

Immediate plans for dissemination include presentations at the next Southern California Conference on Undergraduate Research (SCCUR), November 20, 2011, Pepperdine University, and the Fall 2011 American Geophysical Union Fall 2010 Meeting, December 13-17, 2011, San Francisco. Please note that APU students I mentored in research have made presentations at SCCUR meetings on four prior occasions.

X. *Biographical Sketches of Research Team* (See attached)

XI. *Appendices* (Not applicable)

Application for an Internship/Research Assistant Grant

Name: _

Phone Number(s):

Department/School: CLAS

E-mail address:

1. **Student's Name (if known):** XXX

2. **Student's Major:** Physics

3. ☒ **Full Time Student** ☐ **Part Time Student** ☐ **Graduate Student** ☐**Undergraduate**

4. **Intern/Research Assistant Estimated Total Working Hours:** 180

5. **Amount of Internship Money Requested: (**Calculate by using the hourly wages for either graduate or undergraduate students which can be found in the current student handbook)

   $1656 (180 hours @ $9.20/hour)

6. **Explain briefly but specifically what this intern/research assistant will do.**

   Prepare specimens (grind, polish, ensure right rectangular corners).

   Take spectral data while heating and cooling on multiple temperature excursions.

   Identify values of resonant frequencies.

   Run data reduction code so as to determine elastic moduli at each temperature.

   Make posters for meetings (SCCUR, AGU).

7. **How will this particular internship enhance the intern/research assistant's university education?**

   XXX will gain experience in all aspects of a science research project – specimen preparation, data acquisition, data reduction, interpretation of results, and presentation of new results. The presentation of results will be at a regional undergraduate conference (SCCUR) and at a national research conference (American Geophysical Union). At the AGU meeting, XXX will be able to meet leading researchers in geophysics and mineral physics, many of whom are seeking to recruit new graduate students to their labs.

Proposal Budget Form

Maximum total award is $3,000.

Name(s):

Proposal Title: <u>**Temperature Effects on Elasticity of Some Sintered Polycrystalline Minerals**</u>

Proposal Budget with Brief Justifications		
	Projected Cost	**Hours Requested**
Personnel		
Investigator:	**$**	
Consultant:	**$**	
Intern(s)/ Research Assistant(s):	**$ 1656**	**180**
Clerical Assistance:	**$**	
Other (please specify):	**$**	
Equipment (please specify; include only if not provided by APU) Miscellaneous glues, epoxy, tape, foils, wires, and clips to configure specimen/transducer holding apparatus at high temperature.	**$ 200**	
Books, Software, and Other Computer Costs (please specify; include only if not provided by APU): Adobe Illustrator CS4	**$ 275**	
Other Related Expenses:		
Travel for data collection:	**$**	
Other (please specify):	**$**	
Total of Research or Scholarly Project Proposal Request	**$ 2131**	