BNL High Pressure Program including NSLS II at XPD and 'dark period' APS program at 6BM: 2016 COMPRES Annual Report

November 2015 – October 2016

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Overview

This has been a busy year. We are in the first full year of operation at beamline 6BM at APS and are full into installation at beamline XPD at the NSLS II. 6BM is a white beamline on a bending magnet. This beamline is unique in the world in terms of how it is set up to measure stress and strain on samples at high pressure. The uniqueness is afforded by the detector geometry in conjunction with the white radiation to limit the x-ray scattering volume along the beam. Experiments such as that of the Karato group, with the RDA require this capability. XPD is a monochromatic beam. It will provide a world class level high energy mono beam to the sample. This facility is unique in that it is the only system in the world designed with a DT25 guideblock. The target of this guideblock is to provide differential stress on samples at 25 GPa, thus enabling rheology studies of lower mantle systems.

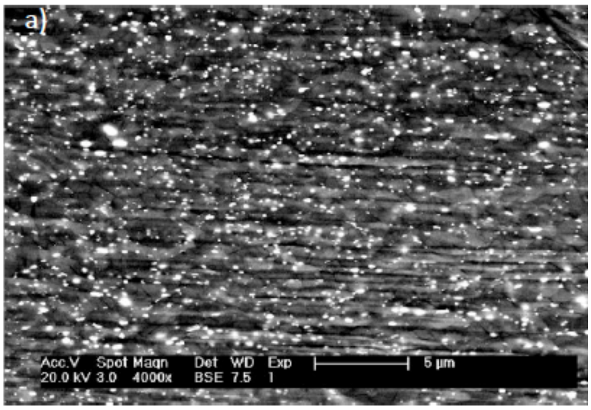
Scientific Highlights

These come from previous experiments at the old NSLS and from 6BMB.

Studies by the Yale program at NSLS (Karato)

We use RDA (rotational Drickamer apparatus) combined with the synchrotron x-ray facility at X17B2 at NSLS to study the plastic flow behavior of materials under high-pressure and temperature conditions. We have conducted quantitative deformation experiments on two important minerals in Earth's transition zone (410 to 660 km depth). The flow laws (stress-strain rate relationship) of these minerals were investigated using the *in-situ* X-ray diffraction and x-ray radiography. These studies have provided constraints on the resistance of these minerals for plastic flow under a broad range of conditions.

In addition, we have pushed the pressure limit of quantitative studies on plastic flow in order to understand the plastic properties of minerals in the lower mantle (660-2890 km). This is the largest portion of the rocky part of this planet. By analyzing the diffracted x-ray from various portions of the sample, we realized that a substantial pressure gradient is present in the sample assembly of RDA. Consequently, we reduced the sample size to conduct deformation experiments at pressures of ~27 GPa and temperature of ~2100 K (both P and T were determined by the equations of state of two materials). Under these conditions, dominant minerals are (Mg,Fe)SiO_3 bridgmanite and (Mg,Fe)O. We found that bridgmanite has substantially higher resistance to deformation than (Mg,Fe)O.



SEM micrograph of a deformed bridgmanite + (Mg,Fe)O aggregate. Dark regions are bridgmanite and light grey regions are (Mg,Fe)O. Bright spots are metallic Fe. Conditions of deformation are P=27 GPa, T=2130 K, strain-rate ~10^{-5} s^{-1}.

Girard, J., G. Amulele, R. Farla, A. Mohiuddin, and S. I. Karato (2016), Shear deformation of bridgmanite and magnesiowustite aggregates at lower mantle conditions, *Science*, *351*(6269), 144-147, doi:10.1126/science.aad3113.

Rheological properties of the lower mantle have strong influence on the dynamics and evolution of Earth. By using the improved methods of quantitative deformation experiments at high pressures and temperatures, we deformed a mixture of bridgmanite and magnesiowustite under the shallow lower mantle conditions. We conducted experiments up to about 100% strain at a strain rate of about 3 x 10(-5) second(-1). We found that bridgmanite is substantially stronger than magnesiowustite and that magnesiowustite largely accommodates the strain. Our results suggest that strain weakening and resultant shear localization likely occur in the lower mantle. This would explain the preservation of long-lived geochemical reservoirs and the lack of seismic anisotropy in the majority of the lower mantle except the boundary layers.

Grain-boundary Plasticity in Olivine (P. Raterron, C. Bollinger*, N. Hilairet, S. Merkel)

The rheology of the Earth upper mantle is controlled by the plasticity of olivine-rich rocks. Olivine single crystal plasticity is understood and quantified to mantle pressures and temperatures (e.g., Bai et al., 1991, JGR, 96, 2441-2463; Raterron et al., 2012, PEPI, 200-201, 105-112). The plasticity of aggregates involves complex mechanisms, and the fundamental question of the amount of strain accommodated at grain boundaries remains unanswered.

Using reported experimental data on San Carlos olivine deformation at mantle conditions - mostly obtained in the D-DIA that equipped the NSLS X17B2 beamline (e.g., Durham et al., 2009, PEPI, 172, 67-73; Bollinger et al., 2014, PEPI, 228, 211-219) - we compared the plasticity of olivine aggregates to that of single crystals and demonstrated that strain at grain boundaries can be orders of magnitude larger than intracrystalline strain. We further showed that the proportion of grain-boundary strain decreases with increasing temperature and stress. Applied along mantle geotherms (Figure), our results shows that grain boundary plasticity is dominant in the shallow mantle. In the deep upper mantle, grain boundary plasticity vanishes and strain is accommodated within the grains.

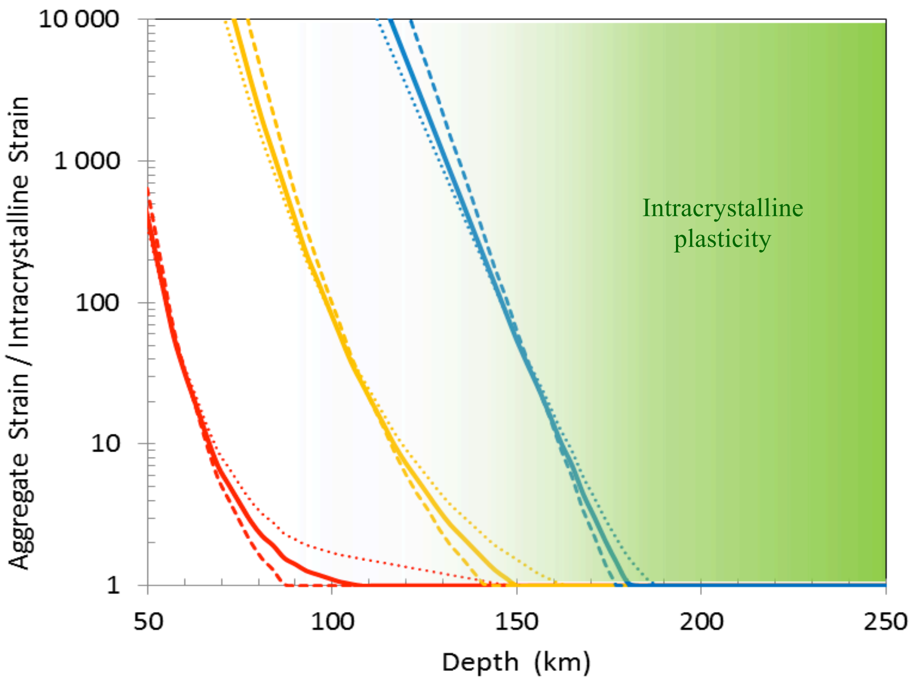


Figure: Aggregate strain / Intracrystalline strain in olivine versus depth, along a 20-Ma (red) and an 80-Ma (yellow) ocean geotherm, and a continental geotherm (blue). The lines correspond to different oxygen fugacities (dotted IW, plain FQM-2, dashed FQM).

Deformation T-Cup: a new controlled strain-rate high-pressure deformation apparatus (Simon Hunt, Richard McCormack, Edward Bailey, Matthew Whittaker, David Dobson, Don Weidner, Li Li; Published as: Hunt et al., 2014, Rev. Sci. Inst., 85, 085103)

The X17B2 side-station beam-line has been host to a new style multi-anvil deformation apparatus, based on the widely used 6-8 split-cylinder geometry. This new apparatus has been used in deformation experiments at pressures in excess of 18 GPa at room temperature and 10 GPa at high temperatures.

In 6-8 (Kawai-type) devices the sample assembly is compressed by eight cubic anvils which in turn are confined by 6 outer wedges. In the new apparatus the two cubes which sit along the split-cylinder axis have been replaced by hexagonal cross section anvils (figure 1). Combining these hexagonal-anvils with secondary differential actuators incorporated into the load frame (figure 2), for the first time, enables the 6-8 multi-anvil apparatus to be used for controlled strain-rate deformation experiments to high strains. Testing of the design, both with and without synchrotron-X-rays, has demonstrated the Deformation T-Cup (DT-Cup) is capable of deforming 1–2 mm long samples to over 55% strain at high temperatures and pressures. To date the apparatus has been calibrated to, and deformed at, 18.8 GPa and deformation experiments performed in conjunction with synchrotron X-rays at confining pressures up to 10 GPa at 800 °C.

Post-commissioning, controlled strain-rate experiments, at pressures up to 10 GPa have been performed investigating the relative strength of the SiO_2 polymorphs. In these experiments, each of the SiO_2 polymorphs was deformed with olivine and the strains measured by X-radiography. The strength of the polymorph can then by normalised to that of olivine. These experiments show that the viscosity of stishovite is greater than that of coesite which is greater than that of quartz. The strength of the minerals therefore increases with the stabilisation pressure.

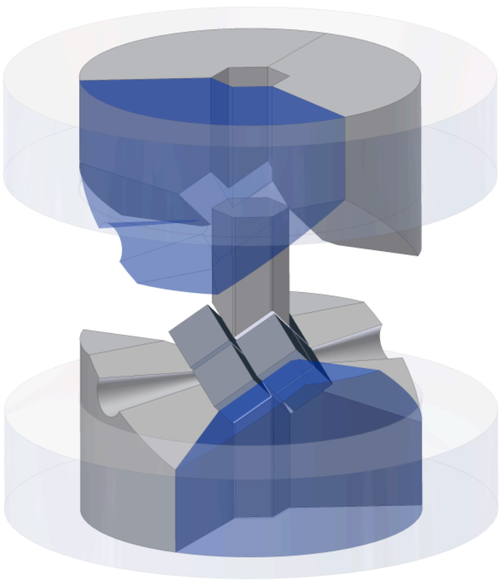


Figure 1: Illustration of the DT-Cup tooling.

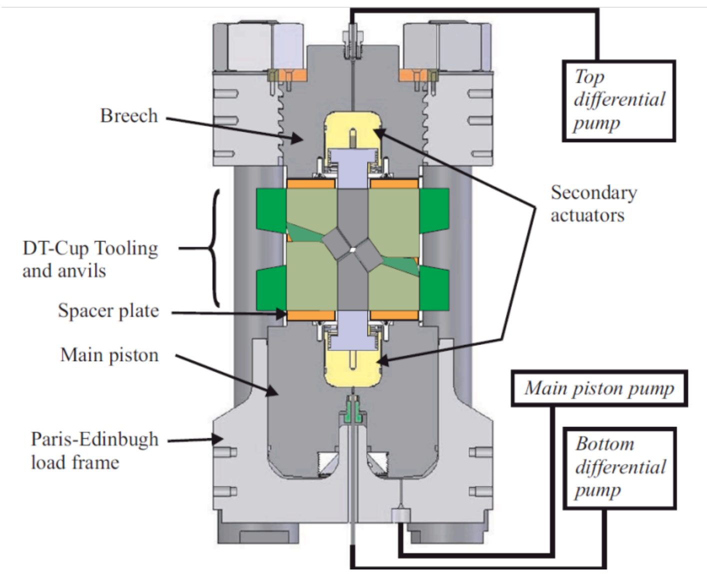
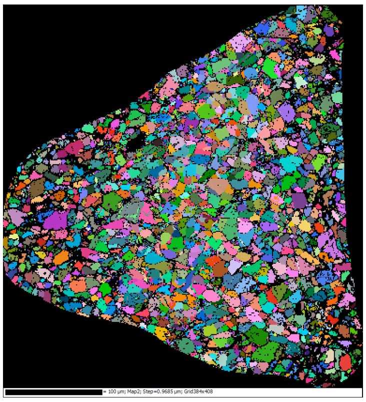


Figure 2: Illustration of Dt-Cup press and tooling.

Experiments: "Compressional anelasticity of HCP metals: a key to the dynamics of Earth's core" (Andrew Walker, University of Leeds)

Team: Andrew Walker, Simon Hunt, Ollie Lord, Ed Bailey, Lewis Schardong, Lora Armstrong, Stephen Stackhouse and Matt Whitaker

We undertook two experimental sessions in 2014 with the objective of beginning to constrain the anelasticity of Earth's inner core with a view understanding its microstructure (which would provide information on inner core deformation) and temperature (independently from that available from the melting point iron alloys at extreme pressure). Our proposal included two experimental strands: (a) Measurements of the anelastic response of HPC metal analogues using the D-DIA apparatus installed on the X17B2 beamline. The approach for these experiments follows that described by Li and Weidner (2007; Rev. Sci. Instrum. 78:053902). (b) Direct experiments on HCP iron using the new DTcup installed on the X17B2ss beamline. Although the approach is the same, these experiments would be the first using the new, higher pressure, deformation apparatus.



Data from EBSD analysis of recovered Zn sample showing grain orientation (colours relate to Euler angles of crystallographic orientation) and microstructure.

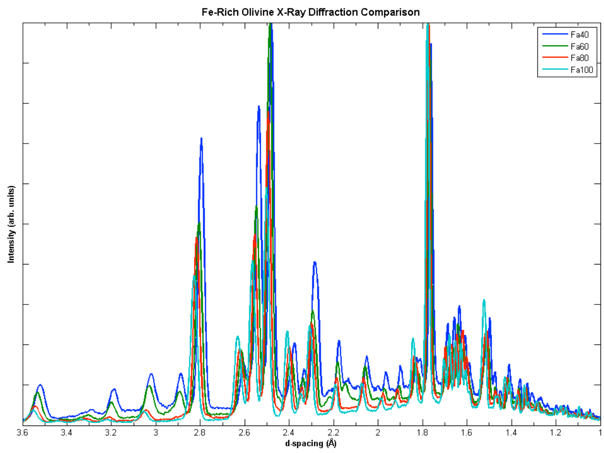
The two experimental sessions were marred by machine problems (specifically, problems with the superconducting wiggler's cryogenic system, leading to the loss of around half of the allocated time) but did yield useful insight. Experiments on a zinc analogue show clear evidence for frequency dependent Young's modulus developing at high temperature. Furthermore, the degree of this frequency dependent softening appears to be strongly correlated with the microstructure of the sample, with samples manufactured from packed powder showing less softening than those manufactured from extruded wire. The experiments on HCP iron were less successful. Although we were able to transform iron powder into the high-pressure HCP structure, the DTcup was unable to generate sufficient differential stress to measurably deform the sample at seismic frequencies. Work to understand the cause of this difficulty (which appears to related to an asymmetry in the behavior of the upper and lower differential anvils) is ongoing.

Introducing DIASCoPE: Directly Integrated Acoustic System Combined with Pressure Experiments: System and Design – Matthew L. Whitaker, Kenneth J. Baldwin, William B. Huebsch, Haiyan Chen, Michael T. Vaughan, Donald J. Weidner

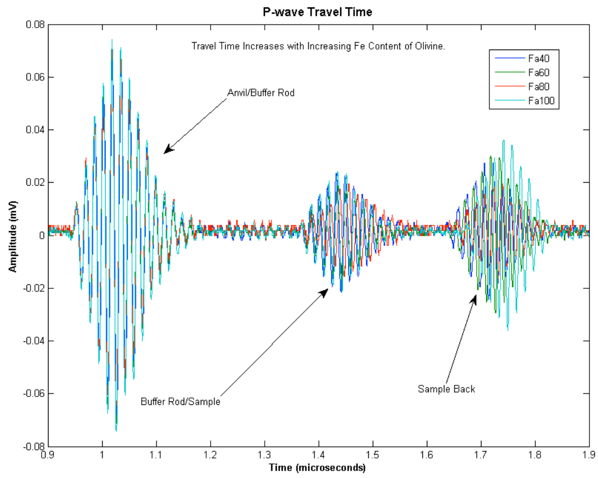
Samples and Science – Matthew L. Whitaker, Frederic Bejina, Misha Bystricky, Nicolas Terce

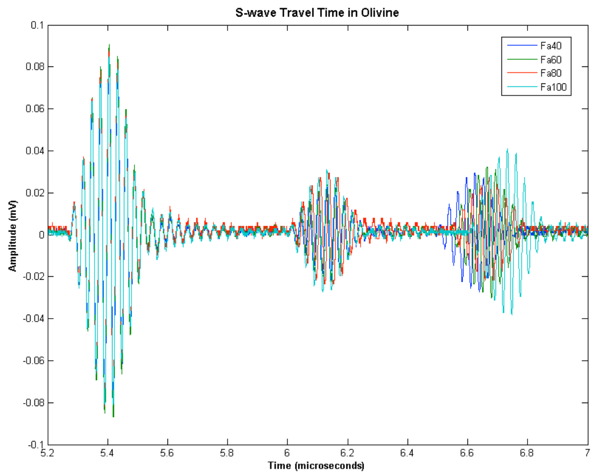
Understanding the properties and behaviors of materials and multi-phase aggregates under conditions of high pressure and temperature is vital to unraveling the mysteries that lie beneath the surface of the planet. Advances in *in situ* experimental techniques using synchrotron radiation at these extreme conditions have helped to provide answers to fundamental questions that were previously unattainable. Synchrotron-based ultrasonic interferometry measurements have proven to be especially important in determining acoustic velocities and thermoelastic properties of materials at high pressures and temperatures. However, due to relatively slow data collection times, it has been difficult to measure the effects of processes as they occur, and instead the measurement is made on the end product of these processes. DIASCoPE is an important step toward addressing this problem.

Over the last three years, we have designed and developed an on-board ultrasonic acoustic velocity measurement system that cuts data collection time down by over an order of magnitude. We can now measure P- and S-wave travel times in samples at extreme conditions in less than one second. Moreover, the system has been fully integrated with the multi-anvil apparatus and the EPICS control system at beamline X17B2 of the National Synchrotron Light Source, allowing for greater ease of control *and* full automation of experimental data collection. The DIASCoPE has completed the testing and commissioning phase, and the first data collected using this powerful new system is presented here.



As a collaboration between Stony Brook and Toulouse, we have begun investigating the effects of iron content on the thermoelastic properties and acoustic velocities of iron-rich olivine. While there have been several studies on the Mg-rich side of this solid solution series, there is virtually none on the Fe-rich side, which is something we hope to rectify in this study. Below are three figures showing a very preliminary comparison of the first four samples studied in this investigation: Fa100, Fa80, Fa60, and Fa40. As these figures clearly show, there is a progressive change in d-spacing, P-, and S-wave velocities with Fe content of the olivine.





Beamline Personnel

Operation is located at two synchrotron sources, the Advanced Photon Source at Argonne National Laboratory and the National Synchrotron Light Source II at Brookhaven National Laboratory.

The project leadership is comprised of Donald Weidner and Michael Vaughan. The operation and the personal support are heavily leveraged by staff of the Mineral Physics Institute at Stony Brook University and Facility Staff at Brookhaven National Laboratory and at Argonne National Laboratory.

The subcontract from COMPRES supported: Matthew Whitaker (LVP XPD-D), Haiyen Chen (LVP 6 BM), and part time:William Huebsch (Electronic Support XPD & 6 BM)

Additionally, the operation is supported by the following staff members of the Mineral Physics Institute at Stony Brook University: Kenneth Baldwin (Software/Controls Specialist), Samantha Lin (Administrative Support); Michael Vaughan; and Donald Weidner

Establishing the high pressure program at XPD-D at the NSLS II is supported by a significant number of NSLS II staff: Eric Dooryhee (XPD Lead Scientist), Sanjit Ghoose (XPD Scientist), Hengzi Wang (XPD Engineer), John Trunk (XPD Technician), Chris Stebbins (Safety Engineer), Wayne Lewis (Controls Group), Lars Ehm (SBU/BNL Joint Appointee)

Beamline Operations

The multi-anvil beamline at APS is the only one of our program currently serving users as the NSLS II beamline is still under construction. At APS our beamline, 6BMB time shares the beam with 6BMA. Our current agreement is that we take 55% of the beam time. This time may vary as the proposal pressure between the beamlines vary.

Statistics for this past year, see Appendix A for more detail:

Number of beamtime proposals received: 42

Number of beamtime proposals granted beamtime: 31
Total number of shifts requested: 442
Total number of shifts granted: 303
Total number of shifts available for both beamlines: 625
Oversubscription rate (= shifts requested / shifts available): 1.45
Number of unique users, categorized by affiliation (University, Gov't Lab/agency, Private institution, or Industry) and by origin (USA, Canada, Europe, Asia, Other): 32
Number of undergraduate users 1
Number of graduate student users 10
Number of visits funded by each funding agency (NSF: 32, DOE: 4, NNSA: 6 Foreign/Other: 7)

Performance Metrics

See Appendix A

Beamline Development

The major development effort this last year has been devoted to the installation of the DT25 and 1000 ton press at the NSLS II on beamline XPD. This past year has been both productive and frustrating as it pertains to the XPD-D multi-anvil project. We began the year still in a holding pattern, unable to advance in the installation of the new facility while COMPRES was determining the fate of the diamond anvil cell program at XPD. Once the official word came down that the DAC program would no longer be a part of this facility, we had to go back to the drawing board and rearrange all of the planning for how to proceed with the process of getting the new facility off the ground. Over the last few months, we have been able to generate a path forward and a working relationship with the critical people at Brookhaven National Laboratory whose help is necessary in moving this project forward.

It is important to understand the differences between building the new facility in XPD-D at NSLS-II and the process of building the multi-anvil facility at 6-BM-B of APS. At APS, we were moving into an existing and operational facility. As such, most of our existing controls, electronics, motors, machines, and equipment were compatible with their systems, and we were allowed to move everything in and install them ourselves with relatively little alteration. However, this is not the case at NSLS-II, which is a new facility operating under a new, rigid set of standards. Much of the work that is done during the installation process cannot be done by our team, and must be carried out by the appropriate BNL employees. In addition, we are the first Partner User group attempting to install a facility at a working beamline at NSLS-II, so not all of the rules, protocols, and standards have been established yet.

These restrictions and regulations have led to some setbacks in our projected timeline. For example, all cables used at NSLS-II must be rated as Low Smoke Zero Halogen (LSZH), which means that all of the cabling and connections we already have on hand are no longer usable and new ones must be made. All of the motors that we had in use from X17B2 and elsewhere were 5-phase motors, which had been expressly forbidden from use at NSLS-II. Instead, we had to purchase all new 2-phase motors to install on our systems.

All of our motors were controlled by MaxV carriers in a VME crate, but we are not allowed to have a VME crate at the beamline. We have purchased 3 of the Delta Tau controllers that NSLS-II has standardized on along with a power supply to feed them. We purchased these items, and when they arrived two months later, we found out that the proprietary power cords for them were not included, and were an optional purchase which took another few weeks for delivery.

Once the motors, controllers, and power cables were in hand, it then took over a month to learn how to simply drive a motor using the native Delta Tau control software (which was an additional $1500 purchase). During this time, we were finally able to make contact with a person at the NSLS-II who specializes in the Delta Tau controllers, and he was able to get us much further along in the process of establishing communications between the controller and the associated motors. Now, we are able to drive motors using the native Delta Tau control software, but the transition to the actual EPICS controls is not straightforward. This arduous process has been begun, but will take time to reach a satisfactory completion point. In addition, the LSZH cabling that the NSLS-II requires for motor connections does not have enough conductors to allow for brakes to be implemented on the motors. These brakes are required for several of our motors due to the extreme weight of the equipment, and we have not yet received word from the NSLS-II people how we can go about implementing and controlling these brakes. Once these communications are firmly established and understood, the Delta Taus can be installed in the roof rack above the hutch, and the motors can be installed on the equipment inside the hutch. Once the motors are installed, then breakout boxes for their connections must be made and installed on each of the major pieces of equipment.

Much of what will be done in the hutch relies on having cables to connect the appropriate controllers to their motors, etc. However, we have been told that we are not permitted to run any cables through the labyrinths ourselves, and this must be done by BNL employees. Moreover, they want to do all of the cables at once so they do not have to open the labyrinth multiple times for installation. In order for this to be possible, we needed to have the final placement of all the equipment inside the hutch laid out and approved, along with exactly where each breakout box will be, showing where cable will terminate so they can be made to the appropriate length specifications. This process took several weeks, and we finally got the stamp of approval on the hutch layout needed to move forward with the cable installation in late September, but were then informed that we also needed to determine the exact rack layout before the cables can be run. The rack layout must be done by a BNL employee, and the person who was originally in charge of such things for the XPD complex recently left the NSLS-II and their replacement has not yet been identified.

In the meantime, we had made plans for the installation of necessary utilities both inside the hutch and outside at the endstation. These include purchase and installation of a 48-port network switch from XPD's operating budget, a powered network line for a telephone, an additional power circuit added to the endstation control area, controls network jacks for computers and equipment to connect with the experimental data network (8 outside, 12 inside), a BNC breakout panel on the rear wall of the hutch, and relocation of the emergency stop on the far wall of the hutch so that it would not be blocked from access by the press. In addition, arrangements were being made to have all of the equipment surveyed in and placed in their final positions, which would allow us to begin to move forward with the installation of the hydraulic lines for the pumps. We have also purchased and received the new camera that will be implemented in our X-radiographic imaging setup. This camera is being set up and tested in our test facility at Stony Brook in the next couple of weeks.

Progress was happening quickly, and we had begun to plan for our first light and first technical commissioning in the D hutch in April for the 2017-1 cycle. However, in mid-October NSLS-II management put a firm halt on any progress toward our installation because the Partner User Agreement with COMPRES was not in place. Our standard biweekly meetings were cancelled, and their people were instructed not to give us any time until this situation was rectified. This persisted for several weeks, effectively putting a stop to the forward momentum we had gained.

Just recently, we were informed that we can continue moving forward with some of the plans while the PUA is still being negotiated between COMPRES and NSLS-II. Now, we are trying to put some of these wheels back in motion with the end goal of keeping that 2017-1 goal for first technical commissioning of XPD-D despite losing several weeks of lead time. However, we are not at present considered a priority until the PUA is finalized, and many of the necessary people involved are now working on other things, so we are back at the end of the queue and waiting until we are at the top of the pile. Hopefully, we will be able to regain the momentum that we lost without too much trouble, and once the PUA is in place, we will be able to march forward full steam ahead toward first light in the D hutch of XPD in the new year.

Off line, at Stony Brook, we have been working to define the optimum design of the anvil assembly for the DT25 that provides the highest pressure, with 25 mm anvils, with total x-ray visibility, and minimum cost. The steel wedges of the DT25 requires 25 mm cubic anvils to minimize the deformation of the wedges. Smaller sintered diamond anvils can be used if they are backed by 'cheater plates' or some method to bring the size up to 25 mm. We have tried several geometries with varied success. We still have a few to try. One option is to use 25 mm sintered diamonds which we can now purchase for a reasonable price ($1200 each). The testing is done with high pressure presses at Stony Brook and are being led by a graduate student, Richard Triplett.

Planned Activities

The planned activities at the NSLS II are as follows:

<u>First Technical Commissioning Beamtime: 2017-1 Cycle</u>

Tasks to be Accomplished During Commissioning Time

- Radiation Survey of XPD Hutch D (BNL Staff)
- Testing and alignment of X-radiographic imaging system
- Testing and alignment of Perkin-Elmer detector for X-ray diffraction
- Collection of standard diffraction patterns both in air and in the cell assembly(ies)
- Refinement of Data Collection Protocols

Tasks to be Accomplished in Preparation for Beamtime

- Hutch layout specified and approved – <u>Complete</u>
- Safety approval for equipment placement – <u>Complete</u>
- Build computer workstations for experimental endstation – <u>4/7 Complete</u>
- Purchasing and/or fabrication of necessary additions and modifications to

equipment
    - 48 port network switch for roof rack
    - Secondary containment for low pressure pump reservoir
    - Steel lift plates to raise the pedestals to allow the press to meet the beam
    - Insulating connection in hydraulic line for differential pump
- Electronic rack layout design – Awaiting BNL liaison appointment
- Installation and testing of new camera system for sample imaging
- Optimization of "hutch swap" capability for P-E detector
- Installation of new motors on all equipment systems
- Installation of Delta Tau controllers and power supply in roof rack (BNL Staff)
- Motor control cables run from roof rack to terminations inside hutch (BNL Staff)
- Make breakout panels on major equipment pieces for cable connections (Bill)
- Installation of controls network ports both inside hutch and at endstation (BNL Staff)
- Powered network line for telephone installation (BNL Staff)
- Utilities design, placement, and installation (BNL Staff)
- Communication between Delta Tau controllers and EPICS (Ken & Matt + BNL Staff)
- Design of experimental motor control schemes (Ken & Matt)
- Final surveying and placement/positioning of equipment (BNL Staff)
- Installation and testing of hydraulic lines
- Installation and implementation of required press safety precautions

First Science Commissioning Beamtime: 2017-2 Cycle
Experiment Performed TBD
Tasks to be Accomplished in Preparation for Beamtime
- Final load testing of hydraulic systems – main ram and differential pumps
- Testing heater power supply and electrical insulation of pressure toolings
- Temperature measurement system designed and installed
- Allen Bradley logic controller deployed
- Development of data collection and experiment control protocols
- Testing and optimization of anvils and sample cell assembly(ies)
- Development of on the fly preliminary data analysis tools
- Installation of any necessary shielding to minimize background scatter
- Installation and integration of acoustic velocity measurement system
  We will continue anvil development during the coming year.

Appendices

A. Beamline statistics see attached excel file

B. List of Publications

2014

Bollinger, C., Raterron, P., Cordier, P., Merkel, S. (2014) Polycrystalline olivine rheology in dislocation creep: revisiting experimental data to 8.1 GPa, Phys. Earth Planet. Int., 228, 211-219. http://dx.doi.org/10.1016/j.pepi.2013.12.001.

Chen, J.C., T Yu, S Huang, J Girard, X Liu (2014) Compressibility of Liquid FeS Measured Using X-ray Radiograph Imaging, . Phys. Earth Planet. Interiors, 228, 294-299

Dixon, N.A. (2014) Experimental Constraints on the Rheological Behavior of Olivine at Upper Mantle Conditions, Ph.D., p. 125. Massachusetts Institute of Technology.

Du, W., Li, L., and Weidner, D.J. (2014) Experimental observation on grain boundaries affected by partial melting and garnet forming phase transition in KLB1 peridotite. Physics of the Earth and Planetary Interior(228), 287-293.

Gwanmesia, GD; Wang LP; Heady, A; Liebermann, RC (2014) Elasticity and sound velocities of polycrystalline grossular garnet (Ca3Al2Si3O12) at simultaneous high pressures and high temperatures. Physics of the Earth and Planetary Interiors, 228, 80-87, SI; DOI: 10.1016/j.pepi.2013.09.010

Hunt, S.A. Dobson, D.P. Li, L. McCormack, R.J. Vaughan, M.T. Weidner, D.J. & Whitaker, M. Deformation T-Cup: A new apparatus for high temperature controlled strain-rate deformation experiments at pressures in excess of 18 GPa. Rev. Sci. Instr. 85, 085103, 2014.

Karato, S., 2014. Does partial melting explain geophysical anomalies?, Phys. Earth Planet. Inter., 228: 300-306.

Karato, S., 2014. Some remarks on the models of plate tectonics on terrestrial planets: From the view-point of mineral physics, Tectonophysics, 631: 4-13.

Kung, J., B Li. . (2014) Lattice Dynamic Behavior of Orthoferrosilite (FeSiO3) toward Phase Transition under Compression, . J. Phys. Chem. C 118(23), , 12410-12419

Li, B., R Liebermann. (2014) Study of the Earth's Interior Using Measurements of Sound Velocities in Minerals by Ultrasonic Interferometry. Phys. Earth Planet. Interiors, 233, 135-153

Li, L., and Weidner, D. (2014) Detection of melting by X-ray imaging at high pressure. Review of Scientific Instruments, doi:10.1063/1.4880730(85), 4.

C. Liu, R. Röder, L. Zhang, Z. Ren, H. Chen, Z. Zhang, C. Ronning, and P. Gao, "Highly efficient visible-light driven photocatalysts: a case of zinc stannate based nanocrystal assemblies", Journal of Materials Chemistry A, 2 (2014) 4157

C. Liu, H. Chen, Z. Ren, C. S. Dardona, M. Piech, and P. Gao, "Controlled synthesis and structure tunability of photcatalytically active mesoporous metal-based stannate nanostructures ", Applied Surface Science, 296 (2014) 53

Lord, O.T., E. Wan, S. A. Hunt, A. M. Walker, J. Santangeli, M. J. Walter, D. P. Dobson, I. G. Wood, L. Vočadlo, G. Morard and M. Mezouar. (2014) The NiSi melting curve to 70 GPa. Physics of the Earth and Planetary Interiors, 233, 13-23.

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