Experimental Studies of Subduction Zone Processes:

A Vision for Community-Driven Infrastructure to Support Experimental Earth Science

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Executive Summary

Subduction zones are among the most dynamic environments on Earth, where the convergence of tectonic plates leads to earthquakes, volcanoes, tsunami, and other natural hazards. Subduction zones are studied using a variety of methods, including seismic, geodetic and satellite observation, numerical modeling, and laboratory experimentation. Laboratory-based experimental science directly informs diverse research into earthquake timing and location, magma transport, and volcanic eruptions, through the study of material properties: viscosity, friction, dynamic rupture, poroelasticity, electrical conductivity, phase equilibria, melting, geothermobarometry, permeability, reaction kinetics, and diffusion. The establishment of major new initiatives such as SZ4D (Subduction Zones in 4 Dimensions), the Modelling Collaboratory for Subduction Zone Science, and the Community Network for Volcanic Eruption Response, highlight the importance of subduction zone science to society, and the essential contributions that experimental research will make in the future.

The experimental study of geologic processes, including those relevant to subduction zones, requires engagement of scientists from the rock physics, experimental petrology and geochemistry, and mineral physics communities. However, these disciplines are small in comparison to other branches of Earth science, with limited opportunities for cross-fertilization of ideas and few resources to support infrastructural development. Progress in critical scientific areas requires new structures and mechanisms to coordinate efforts among experimental labs, develop new equipment and facilities, and provide resources for early career scientists.

This report highlights several key opportunities for scientific progress, describes current technical and infrastructural limitations, and presents a community-defined vision for infrastructure to support experimental Earth Science. In the final section we list three critical 'next steps':

1. Participation of experimental scientists and explicit inclusion of experimental research in the planning and formulation of new interdisciplinary science programs.

2. Establishment of an organizational body that can amplify the impact of individual experimental communities by facilitating connections with other scientific initiatives, sponsoring interdisciplinary technical and scientific workshops, and coordinating proposals for digital and physical infrastructure.

3. Identification of new funding mechanisms, which can support long-term technical projects that are not directly linked to a specific scientific goal.

1. Introduction and Report on Conference Outcomes

On June 4-6th, 2018, scientists from the rock deformation and experimental petrology communities met at Washington University in St Louis, Missouri, for an NSF-funded conference (Award # EAR-1757791) titled "Experimental Studies of Subduction Zone Processes" (EssZP). The rock deformation and experimental petrology communities are united by a common scientific mission, which is to characterize the physical and chemical properties of Earth materials at high pressure and/or temperature. These communities also share common technical approaches to reproduce the pressures, temperatures, stresses, and chemical environments within Earth. The application of laboratory experiments to study the properties of Earth materials is the foundation for diverse research in geology, geophysics, geochemistry, and planetary science. The objective of this conference was to identify scientific goals and shared infrastructural needs of these communities, with specific regard to subduction science.

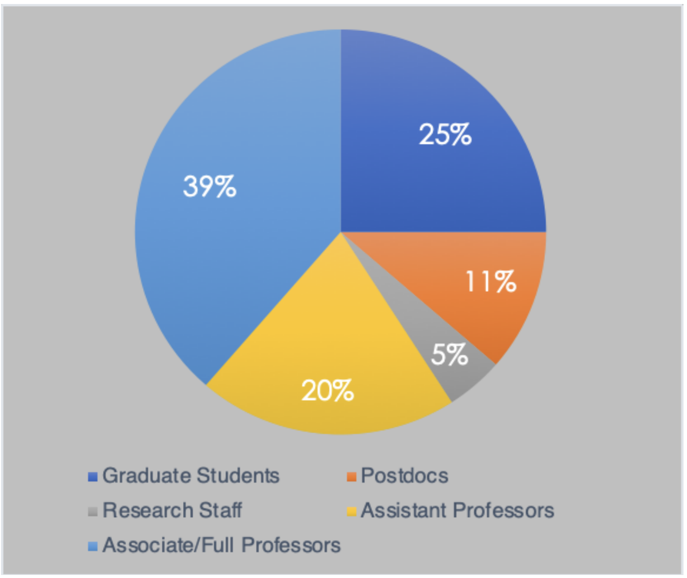

Figure 1 – Career stages of participants (n = 45) who attended the EssZP conference.

There were 45 individual scientists representing 20 universities and government institutions who participated in the conference (see Appendix 1). International participation was encouraged, but was not realized due to travel complications and a competing European meeting on related topics (the Sixteenth International Symposium on Experimental Mineralogy, Petrology and Geochemistry). There was reasonable balance between the rock deformation and petrology communities (61% and 39% respectively), and the diversity of gender (41% female / 59% male) and career stages represented (Figure 1). A session that encouraged participants to describe their laboratory capabilities was used to generate a preliminary map of experimental labs in the United

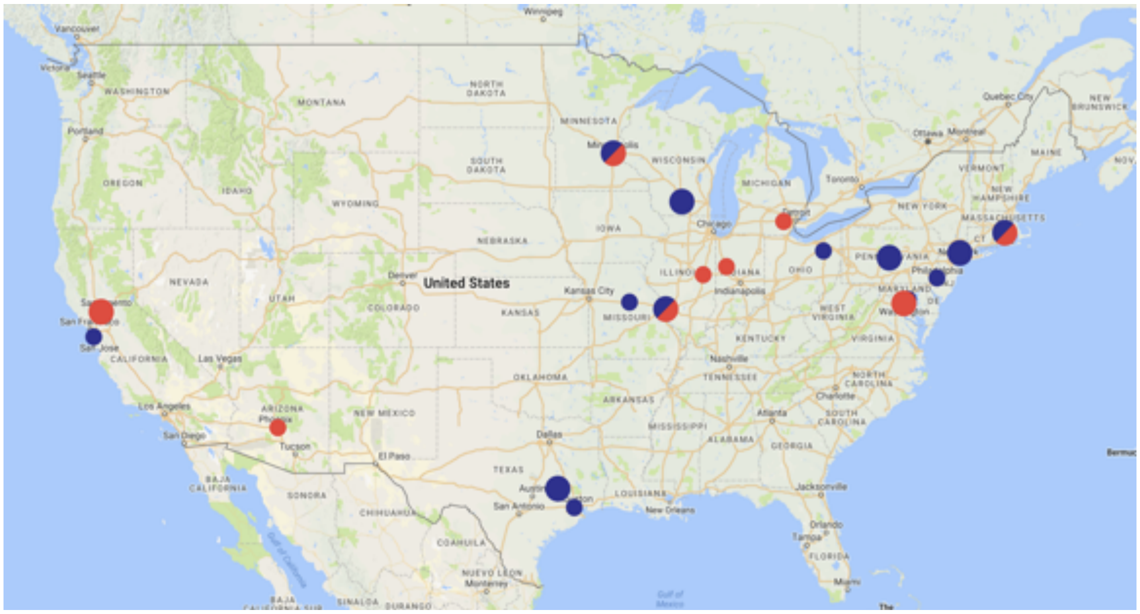

Figure 2 – Locations of experimental rock deformation and petrology labs in the United States whose members participated in the EssZP conference (Appendix 1). Blue data are rock mechanics labs; red data are experimental petrology labs. Small data points indicate single PI labs; large data points indicate multi-PI labs. The underlying Google map will be updated with additional labs at future conferences and using online submissions. Additional information about the capabilities of each lab are included as metadata associated with each map location.

States. This map will be updated at future meetings or via submissions of data to serve as a resource for experimentalists and other interested communities. (Figure 2).

The EssZP conference was motivated by the recent establishment of the Subduction Zones in Four Dimensions (SZ4D) initiative, a multi-disciplinary effort linking observation, modeling, experiments, and theory, to better understand the time and spatially-dependent evolution of subduction zones (McGuire, Plank, et al., 2017). The EssZP conference was organized around a series of thematic discussions in which participants identified gaps in scientific and technical knowledge; considered issues associated with data management, sample archiving, standardized materials and practices; and discussed topics that affect predominantly early career scientists. Through these discussions, several proposals emerged for technical, infrastructural, and community-building activities that will benefit subduction science, sustain growth of experimental labs, and increase scientific output over the next decade. In this document, we highlight opportunities for continued input of experimental data into subduction science (Section 2); describe gaps in current technical capabilities that inhibit progress (Section 3); and discuss infrastructural obstacles to experimental science (Section 4). In Section 5, we identify several paths forward for the experimental communities, both in support of their common infrastructural needs and in support of the mission of SZ4D and related interdisciplinary science programs.

2. Opportunities for experimental contributions to subduction science

2.1 Guidance from SZ4D community vision document

The EssZP conference grew out of discussions that began in October 2016, at the Subduction Zone Observatory (SZO) Workshop, Boise, ID, a meeting that also led to the establishment of the Subduction Zones in Four Dimensions (SZ4D) initiative. At the SZO workshop and articulated in the SZ4D vision document (McGuire, Plank, et al., 2017), four driving science questions were identified. These are:

1. When and where do large earthquakes happen?
2. How is mantle magma production connected through the crust to volcanoes?
3. How do spatial variations in subduction zone inputs affect seismicity and magmatism?
4. How do surface processes link to subduction?

A unifying theme of the SZ4D initiative is the integration of observational data sets and models across three spatial dimensions and time. Experimental work is essential to these efforts. Experiments provide critical data on rates of the relevant geologic processes and the fluxes of minerals, magma, and volatiles by developing quantitative relationships among material properties

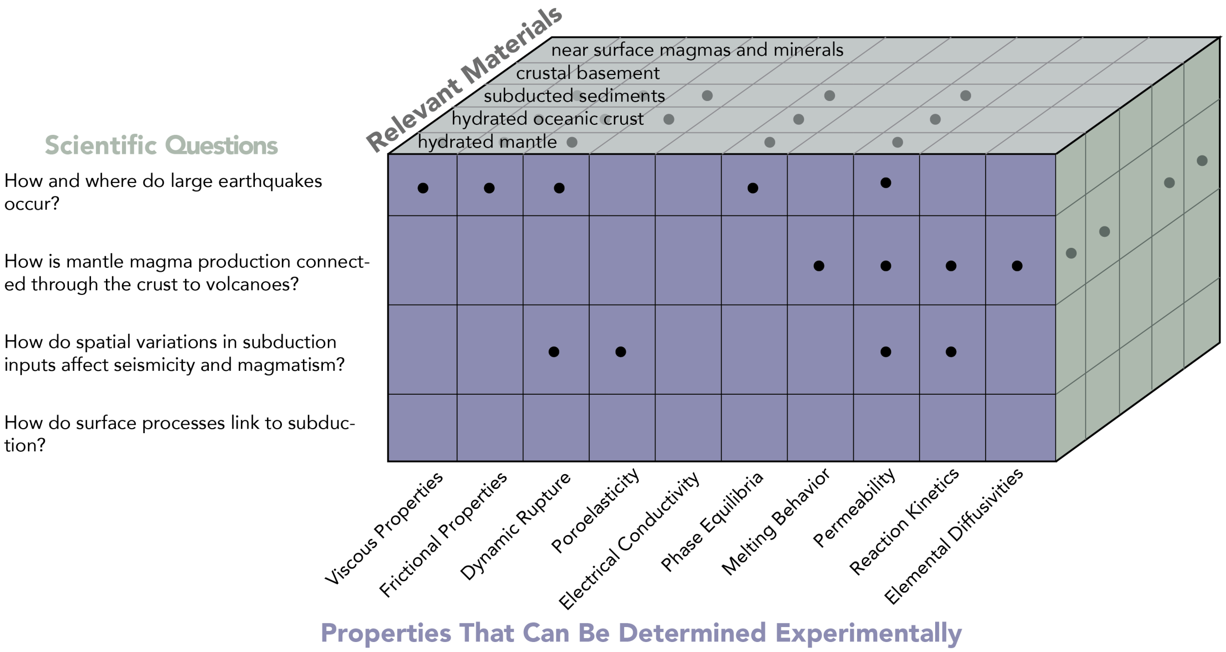

Figure 3 – Efforts to address scientific questions put forth in the SZ4D vision document (McGuire, Plank, et al., 2017) require, in part, the application of experimental techniques to quantify the properties of relevant geologic materials. Each node in this diagram represents the intersection between a scientific question, a material property, and a set of geologic materials.

and pressure, temperature, composition, and time (Figure 3). As such, these community-generated science questions provide a template for some future directions in experimental rock deformation, geochemistry, petrology, and mineral physics.

2.2 Gaps in understanding that can be filled with rock deformation experiments

The results of deformation experiments have been essential to the understanding of subduction zone processes, on topics ranging from the frictional stability of subduction zone materials, the role of deformation on the formation and evolution of crystallographic preferred orientations and attendant seismic anisotropy, and the processes involved with the migration of fluids and melts from the subducting slab, through the mantle wedge to the crust (Hirth and Kohlstedt, 2003; Karato et al., 2008; Kohlstedt et al., 1995). However, our current understanding of major science questions like ‘When and where large earthquakes happen’ (McGuire, Plank, et al., 2017, p. 8) is limited by incomplete knowledge of the physical properties of the relevant rocks at the relevant conditions. At this time, there have been relatively few studies on deformation processes at the pressures and temperatures relevant to subduction zones, on realistic polymineralic lithologies.

Nearly all experimental results with the highest stress resolution are acquired at pressures of < 300 MPa (e.g. Mei and Kohlstedt, 2000) – significantly below the relevant conditions for most parts of a subduction zone. Yet, pressure plays a key role in a variety of deformation processes, through its effect on phase stability, reaction kinetics, solubility, and dissolution rates. In addition, quantifying the activation volume (or pressure dependence) of crystal-plastic deformation remains a persistent challenge (e.g. Karato and Jung, 2003). New advances in high pressure deformation techniques will provide further opportunities to study these processes, which will improve our understanding of the grain scale mechanisms that control the different modes of frictional and viscoplastic behavior and the feedbacks between deformation and fluid topology/fluid flow under hydrothermal conditions.

One particularly important shortcoming of our current knowledge base is related to the role of pore-fluid pressure at subduction zone conditions. Our understanding of the mechanical effects of pore-fluid pressure is largely limited to experiments conducted at pressure less than 300 MPa. The community has generally accepted this limitation, arguing that the effective pressure (pressure minus fluid pressure) is the relevant variable. However, this approach neglects all of the other roles of pressure noted above, which are likely to have important feedbacks on the mechanical effects of fluid pressure. The experimental community is poised to make new advances on this problem.

Understanding the processes that control the down-dip transition from earthquake slip to aseismic creep along the subduction megathrust poses a unique challenge. While many critical geologic processes may take place over times scales of $10^{12\text{-}15}$ seconds, lab experiments are effectively limited to $\sim 10^{4\text{-}7}$ seconds. The limitations of experimental time-scales make it difficult to investigate deformation processes at conditions near the brittle-plastic transition, or at the seismic/aseismic transition. In many applications, one can trade-off either temperature for time (to enhance the rate of thermally-activated deformation processes) or trade-off stress for time (taking advantage of the stress-dependence of effective viscosity during power law creep). However, for many lithologies relevant to subduction conditions (e.g., clay, amphibole, or serpentine-rich lithologies), the limited thermal stability of the relevant phases limits the approach of increasing temperature (e.g. Chernak and Hirth, 2010). Similarly, when restricted to lower temperature, increasing stress will promote undesired brittle deformation or alter the frictional properties of the material. Some of these limitations can be addressed by conducting experiments on fine-grained synthetic aggregates, or conducting experiments at high pressures (Bollinger et al., 2015; Mei et al., 2010). Additional progress is also being made through the use of nanomechanical testing methods developed in the materials sciences (Idrissi et al., 2016; Kranjc et al., 2016). However significant investment in method development and infrastructure to perform these experiments is still needed.

Theoretical studies have highlighted the importance of dynamic weakening processes in controlling the rupture behavior of faults during earthquakes (Di Toro et al., 2011). Again, experimental studies on these processes have almost all been conducted at very low pressures (indeed, at ambient pressure). However, several laboratories have initiated efforts to extend these measurements to higher pressures and temperatures, and major advances are forthcoming.

New experimental apparatuses have also been developed to conduct high strain experiments at subduction zone conditions (Paterson and Olgaard, 2000; Yamazaki and Karato, 2001). With these advancements, we can begin to explore processes that lead to strain localization at a wide range of conditions on a wide range of lithologies (Cross and Skemer, 2017; Hansen et al., 2012). Prior to these advancements, the interpretation of deformation microstructures in high strain mylonites had limited experimental validation. We are now seeing new experimental results that are challenging our understanding of the role of grain size and highlighting new processes that can dramatically influence mechanical behavior.

Progress in all of these areas is dramatically increasing as a result of new advancement in the imaging, stress measurement, and controlling thermodynamic environment on the high-pressure deformation apparatus that take advantage of the synchrotron beamline facilities (e.g. Bollinger et al., 2015; Zhu et al., 2011). Such studies allow new high-resolution measurement on acoustic velocity at high pressure-temperature conditions relevant to both hydrothermal and melting environments, the feedbacks between the properties and deformation processes, and new constraints on the long-standing "grand challenge" of determining the pressure-dependence of creep processes at mantle conditions.

2.3 Gaps in understanding that can be filled with geochemical / petrological experiments

Experimental methods in geochemistry and petrology facilitate the broader study of subduction processes, in particular mass fluxes between subduction zones, the deep mantle, the mantle wedge, arc crust, and surface.

An overarching question in subduction science, as expressed in the SZ4D vision document, asks how mantle magma production is connected through the crust to volcanoes (McGuire, Plank, et al., 2017, p. 12). Addressing this question necessitates a quantitative chemical and mechanistic understanding of fluid and melt transport in the uppermost mantle through the surface, along with the application of suitable geochronometers. Geochemical characterization of volatile (H,C,N,S,O) and redox fluxes require improved experimental documentation of solubilities, partitioning, and speciation behavior of volatile bearing melts, fluids, and minerals. In particular, the chemistry of materials transitional between solute-loaded hydrous fluids and hydrous silicate melts, remains poorly characterized. The experimental community will continue to play an integral role in the characterization of composition and physical properties of fluids, melts and/or supercritical fluids over the complex P-T space of the mantle (e.g. Grove et al., 2012; Hirschmann, 2006).

New experiments are needed to better understand the conditions of storage, differentiation, and degassing of magmas in the crust, ranging from residence and differentiation in the deep and middle crust, to the short-term processes associated with volcanic eruptions and physiochemical evolution in shallow magma chambers just below the surface and in the eruption column. In the deeper parts of the system, key challenges include interactions between crystallization and oxygen fugacity and constraining the role of complex phases such as amphibole. Tying magmatic petrology to volcanological processes requires calibration of improved geo-forensic tools, including thermometers, barometers, hygrometers, and chronometers/speedometers to better understand the processes and time scales associated with magma chamber evolution and eruption dynamics.

Understanding magma transport, as well as the physical processes that drive pre-eruptive phenomena (McGuire, Plank et al., 2017, p. 13), requires the continued development and improvement of suitable geochronometers. Experiments provide the fundamental data used for constraining diffusivities of elements at relevant P-T-X for diffusion chronometry (Cherniak et al., 2018; Song et al., 2018; Turner and Costa, 2007; Watson and Dohmen, 2010; Zhang and Cherniak, 2010) and have provided a number of breakthroughs in constraining kinetic behavior that can be interpreted in the natural crystal record (e.g. Cooper and Kent, 2014; Costa and Dungan, 2005). This field remains in its infancy however, and significant future work is required to develop into its full potential of building databases to inform hazard and eruption forecasting models. In addition to fundamental diffusion and partitioning data, experiments are critical for understanding the mechanisms for volatile and elemental fractionation. For example, the magmatic processes that produce changes in CO_2/SO_2 emissions now documented in the months leading to a number of volcanic eruptions (McGuire, Plank et al., Box 2.3) is not clear (e.g. de Moor et al., 2017, 2016; Edmonds and Mather, 2017). Experiments on relative CO_2 and SO_2 solubility over a range of pressures, magma compositions and oxygen fugacities is an important hurdle that will be overcome experimentally in the coming decade. These experiments will help to determine what produces this volcanological signature, and better understand the mechanisms leading to eruption. Similarly, interpretation of the detailed crystal record requires an in-depth understanding of crystal growth rates, which is a field of study in urgent need of experimental calibration. Crystal-chemical processes have rates that vary over several orders of magnitude, and can cause dramatically different interpretations of the timescales over which a given change of magmatic intensive variables took place.

2.4 Gaps in understanding that require progress in both experimental rock deformation and petrology

Processes at the intersection of petrology, geochemistry, and rock deformation, represent an exciting opportunity for synergism within the experimental communities. For example, petrologic and geochemical mass transfer caused by subduction modifies the mantle wedge and the growing subcontinental lithosphere, and influences formation of arc crust and the growth of continental crust. These mass transfer processes also influence geodynamic characteristics of the slab/wedge/crust system, by altering the composition of the deforming material, the fluid or volatile content, and the conditions under which deformation takes place. Improved understanding of these feedbacks requires experimental studies of the nature of fluids and melts released from the subduction zones, and of the dynamic interactions between these fluids and overriding mantle. Associated questions include the P-T-X transition from hydrous fluids to silicate melts, as well as petrologic constraints the ability of such melts and fluids to transfer volatiles and the redox-sensitive elements (Fe, S, C, H) into the mantle wedge.

Subduction inputs, another key scientific target for the subduction science community (McGuire, Plank, et al., 2017, p. 15), represents another important intersection of the experimental sciences. Petrologic and deformation processes define the chemical and physical state of the subducting lithosphere, which sets up the cascade of processes that ultimately (1) promote or inhibit seismicity and (2) produce what is erupted at the surface. For example, the extent of hydration of the incoming plate may be controlled by deformation-induced hydration of the outer rise (Peacock, 2001), and likely affects both the flux of volatiles to the mantle as well as fault slip behavior (e.g. Shillington et al., 2015). The nature of the flux of volatiles from the crust into the mantle wedge and magmatic system depends on precisely determined phase equilibria and the permeability of rocks with small melt fractions. Moreover, seismological detection of hydrated ocean lithosphere relies on experimentally determined phase equilibria and petrophysical properties, which can be used to interpret seismic wave speeds within the incoming plate and in the mantle wedge. The feedbacks among experimental constrained processes—deformation, phase equilibria, reaction kinetics, and fluid flow—represent the fundamental bases of subduction zone inputs and spatial variations thereof.

3. Experimental barriers to scientific progress

3.1 Gaps in parameter space

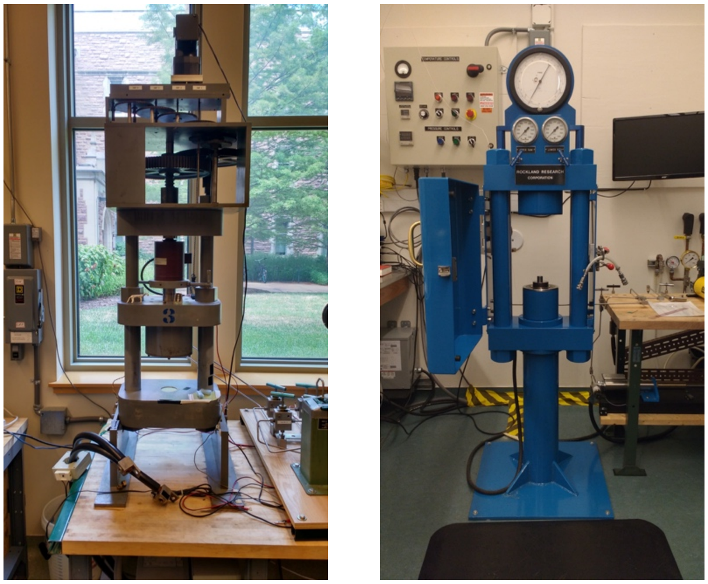

Figure 4 – Two experimental apparatus that are used for the study of subduction zone and related processes. (*Left*) A Griggs apparatus used by rock deformation experimentalists for deforming large samples at high pressure and temperature. (*Right*) A piston cylinder apparatus used by experimental petrologists to generate high pressure and temperature to study melting or phase equilibria. Both of these apparatus are designed to achieve a specific set of experimental conditions. Many different types of experimental apparatus, including some yet to be designed or built, are needed to test geologic materials over the full range of pressure, temperature, stress, and fluid or chemical environments, that are required for subduction science.

Experimental studies of geologic materials require the simultaneous generation of pressure and temperature, with specific chemical or volatile-rich environments, and stresses imposed in different geometries and at different rates. This imposes a vast parameter space that must be reproduced in order to provide suitable data on the physiochemical properties of complex, multi-phase assemblages. Different experimental apparatus are configured or optimized for different purposes (Figure 4). Some apparatus are best-suited for precise deformation experiments at low stresses, while others may be optimized for high strain deformation at high pressure and temperature. Some experiments may be completed in a matter of seconds, while others, due to kinetic limitations, may take weeks. Some apparatus are designed to retain volatiles or fluid phases, while others cannot. Most apparatus used in experimental labs are custom-built for a relatively limited and specific purpose. These apparatus may be unique or modeled after other designs, but typically require long (>3 year) periods to design, build, commission, and benchmark.

Because of the multi-dimensional nature of experimental work there are numerous gaps in parameter space that cannot be achieved by existing apparatus. Some notable needs, as described in subsequent sections, are experimental apparatus that can measure stress precisely at high confining pressure (P > 1 GPa) and temperature; apparatus that can control fluid pressure at high confining pressure, and apparatus that are x-ray transparent for *in situ* imaging.

3.2 Measurements at high confining pressure

External measurements of stress in conventional high-pressure solid-media apparatus are not generally accurate due to friction within the pressure medium (e.g. Borch and Green, 1989). Careful technical improvements, validated though comparison with data from the more precise (lower-pressure) gas-medium Paterson apparatus, have led to significant improvements for the Griggs solid-medium apparatus (Holyoke and Kronenberg, 2010). New technological investment using x-ray diffraction and synchrotron radiation is required to improve stress measurements at higher pressure (Burnley and Zhang, 2008). In addition, pore fluid chemistry/pressure is neither controlled nor measured in conventional solid-media apparatus due the challenge of transmitting the fluids through a solid pressure medium. It is critical in the coming decade to develop novel *in situ* techniques to measure stresses, pore fluid pressure, and chemistry.

3.3 Time limitations

Few experiments are conducted over long (>10^6 s) time-scales. A typical lab, with several students, cannot afford to restrict access to a single instrument for months at a time. Similarly, experiments that require a synchrotron x-ray source are normally limited to a few days. Long-term experiments are inherently risky, especially for early career scientists. Historically, this was not the case. David Griggs, in his lab at UCLA, maintained a large number of deformation apparatus that could be run simultaneously over weeks to months (Getting and Christie, 1994). Changes in the way science is conducted, including the relatively short funding cycle for extramural grants, have made these types of experiments nearly impossible. Nonetheless, many kinetically limited processes, including viscous deformation, diffusion, grain-growth, and fluid-rock reactions, would benefit from data conducted over relatively long time scales. Kinetically limited and low strain-rate experiments may be facilitated by development of a community facility.

3.4 Spatial dimensions of experimental samples

Another important issue concerns the size of samples. High precision analysis of experimental material post-experiment is becoming the new normal for experimental work. Small sample sizes can limit the use of certain analytical techniques. As an example in the petrology community, more accurate data on element and isotope partitioning needs to be obtained using techniques such as laser-ablation ICPMS and SIMS analysis, but these techniques provide more precise results when analyzing larger sample sizes and/or larger crystals. Large volume apparatus would facilitate these studies, however they are expensive and require a lot of physical space, and are typically beyond the means of an individual PI.

3.5 Composition of fluids and control of fluid pressure

An important facet of subduction science is the role of fluids. Fluids influence nearly every material parameter, including viscosity, friction, melting curves, the brittle/ductile transition, density and eruptability of magmas, and volcanic degassing. It is challenging to measure pore fluid pressure and chemistry in-situ during an experiment within sealed sample capsules because fluid samples must be extracted for analysis outside the experimental apparatus.

Only a small fraction of experiments are conducted with controlled fluid pressures, and few chemical measurements have been made of equilibrium fluid compositions. Understanding supercritical fluids and their transport properties, reactive porous flow and non-equilibrium transport in the mantle wedge, and the influence of fluid pressure on deformation, will be a primary consideration for experimental work in the next decade.

3.6 New material standards for experiments and interlaboratory comparison

Experimental rock deformation and petrology has progressed not through the efforts of individual research groups, but through the collective activity of many labs applying complementary approaches to the study of standard materials. There are numerous standard rock samples that have been used historically by the rock deformation and experimental petrology communities (e.g. Westerly granite, Carrara marble, Berrea sandstone, San Carlos olivine, KLB-1 peridotite). However, these materials, while well-studied, do not encompass the lithological diversity found in subduction zones, and thus cannot adequately explain the full spectrum of geophysical and geochemical observations. One example of this are slow earthquakes (e.g. Schwartz and Rokosky, 2007), the mechanics of which are challenging to interpret given the limitations of existing data . Further progress requires the community to work collaboratively to identify appropriate compositions, sample preparation methods, and benchmarking procedures, for next-generation standards.

Of utmost importance to subduction science are standardized and benchmarked experimental starting materials that include hydrous phases, like serpentinite or hydrated mantle compositions and on materials that are neither homogeneous nor isotropic. In addition, experiments on intracrystalline diffusion processes will require the synthesis of novel materials including large single crystals, which may require a shared infrastructure for crystal growing.

While these materials are likely critical to advances in the study of numerous phenomena, their complexity makes the establishment of new standards inherently challenging. The lack of available raw materials, the huge sample-to-sample variations, and the practical difficulties related to sample preparation seriously impede our ability to establish standards for such research activities. Collective efforts of the experimental communities are needed to establish new standards and new methods of mass production, to facilitate interlaboratory comparison and improve the efficiency of laboratory studies.

4. Infrastructural obstacles that reduce scientific productivity

4.1 Lack of critical mass as a discipline in geosciences

Laboratory measurements provide critical constraints for understanding a wide range of fundamental scientific topics, from mantle convection and earthquake cycles, to energy explorations and geologic carbon sequestration. However, compared to many other disciplines in geosciences (e.g., seismology, tectonophysics, analytical geochemistry), the fields of experimental rock deformation and experimental petrology are extremely small, both in terms of infrastructure and human resources. The limited numbers and geographic dispersal of experimental facilities (Figure 2) makes it difficult to develop laboratory-based multi-disciplinary projects. One consequence of this lack of critical mass is that most of the geoscience departments do not teach rock mechanics, experimental petrology, or mineral physics at the undergraduate level; thus few students in geology are exposed to experimental branches of Earth and planetary science. This directly impacts recruiting the next generation of talented scientists to these fields. Another negative impact is that very few manufacturers make commercially-available testing machines appropriate for experiments with geological applications. With no equipment available off-the-shelf, building a career in experimental rock deformation or petrology often requires significant time and effort to develop instrumentation, which hinders the research productivity and the accumulation of traditional metrics of research productivity. For early career researchers, this poses a real threat to career advancement, or may steer talented graduate students towards other fields. Without some fundamental improvements to the current infrastructure, it will be hard to break this negative feedback.

4.2 Lack of opportunities for cross-disciplinary training

There is an overwhelming consensus that multi-physical and multi-dimensional understanding of Earth's dynamic processes requires multi-disciplinary collaborations among researchers with different backgrounds, areas of expertise, and perspective. Current model of spontaneous collaborations between non-experimentalists and deformation labs, while effective for individual researchers involved, cannot meet the growing science demands. We need to build new digital and physical infrastructure that allow non-experimentalists to gain systematic (not *ad hoc*) access to a wide-range of experimental data and facilities. This will enhance our ability to launch truly innovative research and greatly benefit the developing careers of junior researchers. Cross-disciplinary training is the first step towards the success of such collaborations. However, the hands-on nature of the experimental work has its unique challenges. Under the current mode of operation, the vast majority of the deformation laboratories lacks personnel and funding to provide training and technical support to guest investigators. Furthermore, the time required to gain competencies in experimental methods are long, and users without experimental training cannot achieve scientifically meaningful goals during brief lab visits.

4.3 Need for appropriate funding mechanisms to take on new challenges

Most natural phenomena involve concurrent operation of several interconnected processes. Accurate assessment of the properties of geologic materials requires quantitative knowledge of the rate of change of properties under various conditions of effective stress, temperature, and chemistry. Extrapolation across geologic time scales requires knowledge of the kinetics or time dependence of these processes. To date, the scope of experimental studies are limited by instrumentation that operates at a rather narrow range of pressure, temperature and chemical conditions. To answer the grand challenges that we are facing in geological and energy sciences, laboratory measurements have to be made at much higher pressures and temperatures, and in the presence of chemically active fluids. After the paradigm shifting discoveries of earthquakes as stick-slip phenomena (Brace and Byerlee, 1966) and quantitative upper mantle rheology (Hirth and Kohlstedt, 2003; Karato and Wu, 1993), we are now facing fundamental questions about deep earthquakes, rheology of lower mantle, unconventional energy exploration, among others. Adequately addressing these questions requires development and implementation of a new generation of experimental apparatus that are able to achieve new and broader ranges of conditions. These will require is an infrastructure scale investment that is often beyond the scope of typical short-term funding mechanisms for an individual or a small groups of PIs.

5. Next Steps

5.1 Experimental community contributions to large interdisciplinary programs

Experimental science and its practitioners have made essential contributions to many large interdisciplinary programs supported by NSF, including most recently GeoPRISMS, Earthscope, and SAFOD. However due to the small size of experimental research communities in comparison to other Earth science disciplines, efforts must be made to ensure that these contributions and future efforts are not marginalized. As new initiatives are established experimental science must continue to be a priority. Experimental scientists should be included on planning committees and writing teams. Science plans should include detailed experimental needs, and strategies for incorporating the latest data on material properties into broader analytical and modeling efforts. New integrated science programs should explicitly invite proposals for experimental and laboratory-based research.

5.2 Establishment of coordinating body

This document highlights myriad infrastructural obstacles that must be overcome to achieve major advances in experimental rock deformation and petrology. While progress is possible, and indeed expected, greater coordination among the experimental labs is needed to expedite paths forward. Establishment of a steering committee would help to coordinate activities, promote growth and facilitate future interaction among experimental sub-disciplines, and provide a resource for other interdisciplinary science programs. An established organization could help to organize conferences on technical topics, especially those that are not explicitly linked to a single scientific objective. This group could also help coordinate scientists or provide resources to seed multi-institution infrastructure projects. As a first step, the experimental communities urgently need a basic website, which could serve as an archive for data on labs, engineering drawings of equipment, and standard operating procedures. Though simple, these steps would be of enormous value to experimental communities, and especially early career scientists.

5.3 Establishment of new funding mechanism to support long term infrastructure projects

A new funding mechanism is needed to support long term investment in community infrastructure. Core science programs at NSF and other federal agencies typically support projects that can be achieved by a small group of PIs in a few years. Major infrastructure programs are normally intended to support efforts for which there is a clear and urgent scientific need, or to acquire equipment that is available commercially. There are no well-established mechanisms to provide long term (5-10 year) support for projects that require extensive development, and cannot be completed during a typical 2-3 year grant. Similarly, there are no mechanisms to support infrastructure projects that cannot be explicitly linked to a single scientific objective. Critical long-term needs for the experimental community, such as the development of new apparatuses, centralized facilities for long duration experiments, or development of next-generation rock standards, will require coordinated planning on the part of both scientists and funding agencies.

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Appendix 1 – EssZP Workshop Participants

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Nick	Beeler	USGS
Yuval	Boneh	Brown University
Fred	Chester	Texas A&M University
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Helene	Couvy	Washington University in St. Louis
Andy	Cross	Washington University in St. Louis
Melodie	French	Rice University
Maxim	Gavrilenko	University of Nevada, Reno
David	Goldsby	University of Pennsylvania
Andrea	Goltz	Washington University in St. Louis
Thomas	Herbst	University of Missouri
Marc	Hirschmann	University of Minnesota
Greg	Hirth	Brown University
Megan	Holycross	Smithsonian Institution
Caleb	Holyoke	University of Akron
Charis	Horn	Washington University in St. Louis
Tamara	Jeppson	Texas A&M University
Taka	Kanaya	University of Maryland
Hiroko	Kitajima	Texas A&M
David	Kohlstedt	University of Minnesota
Mike	Krawczynski	Washington University in St. Louis
Andreas	Kronenberg	Texas A&M University
Becky	Lange	University of Michigan
David	Lockner	USGS
Craig	Lundstrom	Univ of Illinois
Catherine	Macris	IUPUI
Ananya	Mallik	Brown University

Gordon	Moore	University of California, Davis
Liz	Olree	Washington University in St. Louis
Kelsey	Prissel	Washington University in St. Louis
Xiaofei	Pu	University of Michigan
Hannah	Rabinowitz	Brown University
Demian	Saffer	The Pennsylvania State University
Phil	Skemer	Washington University in St. Louis
Mike	Sly	Washington University in St. Louis
Hiroki	Sone	University of Wisconsin - Madison
Christopher	Thom	University of Pennsylvania
Basil	Tikoff	University of Wisconsin - Madison
Christy	Till	Arizona State University
Harold	Tobin	University of Wisconsin - Madison
Jack	Touran	Washington University in St. Louis
Terry	Tullis	Brown University
Paola	Vannucchi	Royal Holloway
Wenlu	Zhu	University of Maryland