Earthquake Physics in Beamline Deformation Experiments

1. Introduction

Despite centuries of research, the most fundamental aspects of earthquakes remain unknown including the conditions under which they start, how they propagate, and how they arrest. Because of these holes in the general knowledge of earthquake physics, earthquake prediction remains elusive. The roadblock in making progress revolves around the fact that earthquakes occur at depth, where we cannot observe the micromechanics that are undoubtedly important parts of the failure process. Although rock mechanics experiments have been vital in making progress in understanding earthquake micromechanics, there remain limitations to this approach because deformation at the asperity scale can be difficult to capture. Conducting rock deformation experiments within synchrotrons will help us elucidate this scale.

Beamlines are high energy sources of synchrotron x-ray and neutron radiation. These can be used to illuminate lattice orientation and material contrast, allowing characterization of microstructures, internal stress, and internal strain on the sub-grain scale [Bernier et al., 2011; Robinson and Harder, 2009; Suter et al., 2008; Wang et al., 2005; Weidner et al., 2010]. With specially constructed experimental apparatuses that are radiation-transparent or -translucent [Wang et al., 2003; Voltolini, et al., 2019; Fusseis et al., 2013; Renard et al., 2016; Butler et al., 2020], these techniques can be used in near real time during deformation experiments.

Much if not most of the beamline experimental work in the US to date has focused on conditions within the deep crust, mantle and core of the earth, as an extension of the NSF/DOE CHiPR and COMPRESS, high temperature, high pressure mineral physics initiatives, including the study of deep earthquakes (e.g. Schubnel et al., 2013) or the creep of serpentine under upper mantle conditions (Hilairet et al., 2007). In these deep environments deformation is predominately non-dilatant. Such mechanisms are well suited to be imaged and analyzed during beamline experiments where observable material contrasts are diagnostic of elemental and phase differences. Moreover inelastic strain is largely viscous or plastic and in the ductile field the pattern of crystal preferred orientation developed by deformation is a primary diagnostic tool for determining rheology.
In contrast to deep deformation processes, in the shallow brittle regime where earthquakes nucleate and propagate, the dominant pressure dependence of material strength that controls faulting and earthquakes, originates from or involves dilatancy [Brace et al., 1966]. Propitiously, high X-ray adsorption contrasts among fractures, crystalline and sedimentary rock, interstitial porosity, and dilatant granular shear zones are easily distinguished in beamlines. Work to date primarily images dilatancy during intact failure [e.g., McBeck et al., 2018; Cartwright-Taylor et al., 2020; Renard et al., 2017] and slip on saw-cut rock samples (McBeck, 2019; Renard et al., 2020), although much wider applications are possible. In addition to dilatancy, the onset of earthquake faulting hinges on effective pressure, i.e. the difference between solid (grain framework) stress and pore fluid pressure. Thus imaging of fluid and its pressure distribution are key targets of beamline experiments in earthquake

physics. Additional pressure (and strain rate) dependencies are thought to control the mechanics of earthquake instability (earthquake nucleation) [Ruina, 1980; 1983]. These pressure and strain rate dependences are widely hypothesized to involve true ductile or exotic distributed deformation at isolated highly stressed points of contact [Dieterich and Kilgore, 1994], or surface adhesion or chemical effects on asperity contacts [Li et al., 2011] within the shear zone or on fault surfaces. Beamlines with their attendant sub-micrometer deformation and phase resolution are well-suited for such studies of contact scale friction, granular mechanics and a variety of other topics important to brittle deformation detailed later in this report.

2. Existing approaches and applications

Standard beamline analytical techniques are near-field high-energy diffraction microscopy (HEDM) which is capable of reconstructing 3-dimensional (3D) grain orientation fields; far-field HEDM for determining the average orientation and elastic strain states of thousands of individual grains simultaneously [Bernier et al. 2011]; transmission orientation and strain measurements that probe the orientation dependence of lattice strain in grain ensembles [Bernier et al 2011; Robinson and Harder 2009]; absorption-based X-ray and neutron tomography for imaging mineral distributions, porosity and fractures in rocks [e.g. Cnudde and Boone, 2013; Lindquist et al., 2000; Tengattini et al., 2020; Winkler et al., 2002]; and energy-dispersive X-ray diffraction mapping used to determine 3D elastic fields in large specimens [e.g. Steuwer et al., 2004; Henningson et al., 2020].

An additional advantage to X-ray techniques is that the implied stress from lattice spacing strain can be inferred on a grain scale [Weidner et al., 2010]. When combined with micro-tomographic imaging [Boulard et al., 2018; Wang et al., 2011] (3 dimensional measurements of x-ray attenuation, depending on the composition and microstructure) 3D maps of density, composition, orientation, elastic strain, inelastic strain and stress may be constructed. These techniques allow the evolution of microstructures to be tracked during deformation [Suter et al., 2008].

In the brittle field microtomography has been used primarily to map the onset of fracture induced failure in crystalline rock [McBeck et al., 2021; Renard et al., 2018], marble [Kandula et al 2019; Renard et al. 2020], limestone [Huang et al., 2019], and sandstone [Tudisco et al., 2015; Renard et al., 2019]. Many of these studies focus on the coalescence of fracture populations into system (sample) scale failure or other localization kinematics that are important for earthquake occurrence. Additionally there are isolated preliminary studies of induced fracturing [Zheng et al., 2018], deformation of granular material [Hall et al., 2010], fluid flow in fractures [Polsky et al., 2013] and friction [Zhao et al., 2017; Renard et al., 2020] that have profound promise and important implications for studying earthquake physics in beamlines
Additional potential but nascent techniques are to combine micro-tomography with digital image correlation, allowing the construction of full strain tensors for subvolumes during deformation [Hall et al., 2010; Tudisco et al., 2017]. The presence or absence of pore fluids within the pore space can be investigated by tagging water with high atomic number elements, e.g., iodine, cesium, so that fluid distribution is tomographically visible [Polsky et al., 2013]. Imaging

dynamic pore pressure heterogeneity can potentially be accomplished by leveraging the pressure dependent X-ray attenuation of heavy gasses such as Xenon and Krypton [Aljamaan et al., 2017]. Finally, time independent studies of microstructure of natural shear zones are an important application of micro-tomography to improve interpretation of deformation and rheology [Kirilova et al., 2020]

3. Earthquake physics science priorities

At the February 2021 ISRD Beamline meeting hosted by Advanced Photon Source at Argonne National Lab, we discussed as a group what the top science priorities are for advancing our understanding of earthquake physics. We enumerate them here, but emphasize that this list is not exhaustive. In the following section, we suggest possible beamline experiments that would address some of these questions.

1. What physical processes control fault slip speeds throughout the earthquake cycle?
2. Are there measurable reliable precursors to earthquakes and what process do they represent? Alternatively, is earthquake nucleation a cascade of failures?
3. What are the physics of friction (at room temperature and at elevated temperature in the Earth) and how can it be adequately represented with constitutive relations? how does friction generate on- and off-fault rock damage?
4. How do pore fluids influence the stress and strength in fault zones?
5. What are the source physics of high frequency ground motion (e.g. fault roughness, strength heterogeneity, radiation sources with a wide range of scales, complex motion of fault slip due to fault rheology)?
6. For megathrust earthquakes in subduction zones, how does the updip fault rheology affect coseismic fault slip/slip rate, shear localization, ground motion and tsunami-genesis?
7. How deep do earthquake ruptures propagate below the interseismic brittle-ductile transition?
8. What are the physics of deep slow slip and of non-volcanic tremor?
9. What is a low frequency earthquake? Is it a regular earthquake with a very small stress drop? What controls their spatial location/extent in the deep crust?
10. Can deep slow slip events trigger great subduction earthquakes (is there a gap between the locked and tremor zones and what is its rheology)?
11. Does the final earthquake size scale with earthquake initiation size?
12. Why are earthquake stress drops (on average) small, largely independent of scale, depth, temperature, faulting environment, amount of shear generated heat etc? Why do ruptures propagate at near critical energy release levels?

4. Target experiments

The earthquake cycle involves an extremely wide range of slip velocities, at least 11 orders of magnitude from sub nanometer/s up to around 10 meter/s. Because of limits on experiment duration, beamlines are not optimal for studying the low slip speed end of the range. Although imagining is relatively fast, beamline acquisition rates are not fast enough to capture the high end of the range (durations ~ 0.001 to 0.0001 s or shorter). Thus, at present, beamline experiments in earthquake physics might initially focus on important intermediate speeds associated with earthquake nucleation, shear localization/delocalization, afterslip, fault creep and comparative studies of fault zones before and after rapid slip

Studies of contact scale friction – frictional strength is widely thought to result from the product of fractional contacting area and shear strength, with the dominant role being played by contacting area (aka dilatancy; Bowden and Tabor, 1950). Interestingly, recent detailed studies suggest that contact strength is a key (quality over quantity). If we are able to understand frictional processes on the scale of contacts and contact bonding, then we will have made significant advances in understanding the physics of rate and state friction as well as of frictional processes that occur at earthquake slip velocities. Laboratory bare rock surface contact dimensions are micron to sub-micron and contact area is subsequently very poorly resolved using optical techniques (i.e., 450 nm wavelength). Beamline micro-tomography (10s to 100s nm) is ideally suited for contact scale studies of interface friction [e.g., Zhao et al., 2017] and it is now possible, through the use of multi-optics set.u to image both the entire sample and zoom along the sliding interface to image contact at spatial resolution down to 500 nm.

Granular flow – the low strength of plate boundary faults, particularly subduction megathrusts, suggests low effective stresses. Under these conditions grain fracture is less important and faulting is more likely to be dominated by granular shear rather than by slip on fractures or highly localized slip. 3D X-ray and neutron tomography techniques should allow great advances in granular mechanics at intermediate slip rates.

Wear and localization within finite brittle shear zone –There are virtually no useful constraints on wear and shear localization from laboratory faulting experiments due to the difficulties in making in situ observations. The opportunity to use micro-tomography to study the development of shear zones from wear and fracturing, and the subsequent development of localized faults between rough surfaces, are among the most interesting applications of beamline technology in brittle faulting. Processes that result in frictional weakening with increasing slip or slip velocity tend to promote localization, so being able to observe how localization, or delocalization, occurs in samples is helpful for understanding the operational frictional processes behind rate and state friction as well as high-velocity frictional weakening.

Phase changes – Fault healing and aseismic creep may be facilitated by phase transitions within fault gouge materials. At high stress and temperature asperity contacts, minerals might undergo in situ phase changes that could have strong effects of fault strength and stability. Even at low stress and low temperature reaction rates may be high due to large chemical potentials [Moore and Lockner, 2013] and/or small grain sizes [Yund et al., 1990]. Beamline experiments may be a window into the relationship between deformation and reaction within reactive fault zones. In-situ XRD and other measurements could map what might in fact be transient phases for the first time. The other thing with phases is shear zone mixing experiments. doing those blind and interpreting the final microstructures is so time consuming – incredible progress could be made in a few relatively long slip experiments. rotary is the way the way to do those [e.g. a setup like zhao et al 2017 in a ct scanner probably rather than a true beamline?] even if they were done a really low normal stress we'd learn all kinds of stuff

Earthquake nucleation and precursors – Beamline studies would provide the opportunity to study earthquake nucleation and precursors in 3D. Possible novel targets might be imaging fluid injection induced nucleation, and imaging during feedback controlled loading using AE rates (Lockner et al., 1991)

Post seismic fault properties and afterslip - Much of our knowledge of deep fault rheology comes from studies of post–seismic deformation. However, these studies often have difficulty distinguishing deep distributed deformation from true deep fault afterslip (due again to proximity issues between the surface and the deformation). Other issues involve lumping 2 and 3 D depth variation into lower spatial dimension models. Studies of post seismic relaxation at modest temperature are a natural application of beamline technology - to directly determine degree of localization, directly measure the strain rate and time dependent strength and the position of the brittle to ductile transition with strain rate.

Fluid flow – Fluid flow and pore pressure are first order influences on induced seismicity and on failure onset in saturated shear zones in lab studies [French and Zhu, 2017; Proctor et al., 2020]. The ability to track pore fluid movement [e.g., Polsky et al., 2013] in and out of fault zones and simultaneous tomographic inferences of elastic properities/density/wavespeed will likely lead to many breakthroughs in fault mechanics

Fluid pressure – Among the holy grails of experimental brittle rock mechanics is measuring in situ pore pressure. There is mounting evidence that the distribution of pore pressure controls undrained failure and energy release during the onset of failure (French and Zhu, 2017). Possible techniques that would allow measuring the spatial distribution of pore pressure or relative pore pressure are a high long-term priority in brittle rock physics and earthquake fault mechanics.

References.

Aljamaan, Hamza, Cynthia M. Ross, and Anthony R. Kovscek. "Multiscale imaging of gas storage in shales." *SPE Journal* 22.06 (2017): 1-760.

Bernier, J.V., Barton, N.R., Lienert, U. and Miller, M.P. (2011) Far-field high-energy diffraction microscopy: a tool for intergranular orientation and strain analysis, *The Journal of Strain Analysis for Engineering Design*, 46(7), pp.527-547.

Boulard, E., et al. (2018) High-speed tomography under extreme conditions at the PSICHE beamline of the SOLEIL Synchrotron, Journal of Synchrotron Radiation, https://doi.org/10.1107/S160057751800486.

Bowden, F. P., and D. Tabor (1950), *The Friction and Lubrication of Solids*, 374 pp., Oxford Univ. Press, New York.

Brace, W. F., B. W. Paulding, and C. H. Scholz (1966), Dilatancy in the fracture of crystalline rock, J. Geophys. Res., 71, 3939 – 3953.

Butler, I., F. Fusseis, A. Cartwright-Taylor and M. Flynn, (2020), Mjölnir: a miniature triaxial rock deformation apparatus for 4D synchrotron X-ray microtomography J. Synchrotron Rad. 27, 1681-1687, https://doi.org/10.1107/S160057752001173X

Cartwright‐Taylor, A., Main, I. G., Butler, I. B., Fusseis, F., Flynn, M., & King, A. (2020). Catastrophic Failure: How and When? Insights From 4‐D In Situ X‐ray Microtomography. Journal of Geophysical Research: Solid Earth, 125, e2020JB019642. https://doi.org/10.1029/2020JB019642

Dieterich, J. H., and B. D. Kilgore (1994), Direct observation of frictional contacts: New insights for state-dependent properties, *Pure and Applied Geophysics*, *143*, 283–302. doi:10.1007/BF00874332

French, M.E. and W. Zhu (2017), Slow fault propagation in serpentine under conditions of high pore fluid pressure, Earth and Planetary Science Letters, 473, 131-140.

Hall, S. A., Bornert, M., Desrues, J., Pannier, Y., Lenoir, N., Viggiani, G. and Bésuelle, P. (2010) Discrete and continuum analysis of localised deformation in sand using X-ray μCT and volumetric digital image correlation. *Géotechnique*, 60(5), 315-322.

Huang, L., Patrick Baud, Benoit Cordonnier, François Renard, Lin Liu, Teng-fong Wong, Synchrotron X-ray imaging in 4D: Multiscale failure and compaction localization in triaxially compressed porous limestone, Earth and Planetary Science Letters,Volume 528, 2019, https://doi.org/10.1016/j.epsl.2019.115831

Kandula, N., Cordonnier, B., Boller, E., Weiss, J., Dysthe, D. K., & Renard, F. (2019). Dynamics of microscale precursors during brittle compressive failure in Carrara marble. Journal of Geophysical Research: Solid Earth, 6121–6139. https://doi.org/10.1029/2019JB017381

Kirilova, M., Toy, V., Sauer, K., Renard, F., Gessner, K., Wirth, R., Xiao, X., and Matsumura, R.: Micro- and nano-porosity of the active Alpine Fault zone, New Zealand, Solid Earth, 11, 2425–2438, https://doi.org/10.5194/se-11-2425-2020, 2020.

Lockner, D., Byerlee, J., Kuksenko, V. et al. (1991), Quasi-static fault growth and shear fracture energy in granite. Nature 350, 39–42. https://doi.org/10.1038/350039a0

Li, Q., Tullis, T. E., Goldsby, D., & Carpick, R. W. (2011). Frictional ageing from interfacial bonding and the origins of rate and state friction. Nature, 480(7376), 233–236. https://doi.org/10.1038/nature10589

McBeck, J., Kobchenko, M., Hall, S. A., Tudisco, E., Cordonnier, B., Meakin, P., & Renard, F. (2018). Investigating the onset of strain localization within anisotropic shale using digital volume correlation of time‐resolved X‐ray microtomography images. Journal of Geophysical Research: Solid Earth, 123, 7509– 7528. https://doi.org/10.1029/2018JB015676

McBeck, Jessica A., Wenlu Zhu , and François Renard, The competition between fracture nucleation, propagation, and coalescence in dry and water-saturated crystalline rock Solid Earth, 12, 375–387, 2021 https://doi.org/10.5194/se-12-375-2021

Moore, Diane E., and David A. Lockner. "Chemical controls on fault behavior: Weakening of serpentinite sheared against quartz-bearing rocks and its significance for fault creep in the San Andreas system." *Journal of Geophysical Research: Solid Earth* 118.5 (2013): 2558-2570

Polsky, Y., Anovitz, L.M., Bingham P., and Carmichael, J. (2013) Application of Neutron Imaging to Investigate Flow through Fractures for EGS," *Proc. 38th Workshop on Geothermal Reservoir Engineering*, Stanford Univ., Stanford, CA.

Proctor, B., D.A. Lockner, B.D. Kilgore, T. Mitchell and N.M. Beeler, (2020), Direct measurement of fault pore pressure during aseismic and seismic slip, *GRL*, https://doi.org/10.1029/2019GL086767

Renard, F., B. Cordonnier, D. K. Dysthe, E. Boller, P. Tafforeau and A. Rack, A deformation rig for synchrotron microtomography studies of geomaterials under conditions down to 10 km depth in the Earth, J. Synchrotron Rad. (2016). 23, 1030-1034, https://doi.org/10.1107/S1600577516008730

Renard, F., Cordonnier, B., Kobchenko, M., Kandula, N., Weiss, J., Zhu, W. (2017) Microscale characterization of rupture nucleation unravels precursors to faulting in rocks, Earth and Planetary Science Letters, 476, 69-78, doi: 10.1016/j.epsl.2017.08.002

Renard, F., Weiss, J., Mathiesen, J., Ben‐Zion, Y., Kandula, N., & Cordonnier, B. (2018). Critical evolution of damage toward system‐size failure in crystalline rock. Journal of Geophysical Research: Solid Earth, 123, 1969– 1986. https://doi.org/10.1002/2017JB014964

Renard, F., McBeck, J., Cordonnier, B. et al. Dynamic In Situ Three-Dimensional Imaging and Digital Volume Correlation Analysis to Quantify Strain Localization and Fracture Coalescence in Sandstone. Pure Appl. Geophys. 176, 1083–1115 (2019). https://doi.org/10.1007/s00024-018-2003-x

Renard, F., Kandula, N., McBeck, J., & Cordonnier, B. (2020). Creep burst coincident with faulting in marble observed in 4D synchrotron Xray imaging triaxial compression experiments. Journal of Geophysical Research: Solid Earth, 125, e2020JB020354. https://doi.or10.1029/2020JB020354

Robinson, I. and Harder, R. (2009) Coherent x-ray diffraction imaging of strain at the nanoscale. *Nat Mater* 8, 291–298, https://doi.org/10.1038/nmat2400.

Ruina, A.L. (1980) Friction Laws and Instabilities, a Quasistatic Analysis of some Dry Frictional Behavior, PhD Thesis, Brown University, 99 pp.

Ruina, A. (1983) Slip instability and state variable friction laws, *J. Geophys. Res.*, 88(B12), 10359–10370, doi:10.1029/JB088iB12p10359.

Suter, R. M., et al. (2008) Probing microstructure dynamics with x-ray diffraction microscopy. *Journal of Engineering Materials and Technology* 130,021007-0210075, https://doi.org/10.1115/1.2840965.

Tudisco, E., Hall, S. A., Charalampidou, E. M., Kardjilov, N., Hilger, A., and Sone, H. (2015) Full-field measurements of strain localisation in sandstone by neutron tomography and 3D-volumetric digital image correlation. *Physics Procedia,* 69, 509 – 515.

Tudisco, E., Andò, E., Cailletaud, R., and Hall, S. A. (2017) TomoWarp2: a local digital volume correlation code. *SoftwareX*, 6, 267-270.

Voltolini, M., Barnard, H., Creux, P. and Ajo-Franklin, J. (2019) A new mini-triaxial cell for combined high-pressure and high-temperature *in situ* synchrotron X-ray microtomography experiments up to 400°C and 24 MPa, J. Synchrotron Rad. 26, 238-243.

Wang, Y., Durham, W.B., Getting, I.C., and Weidner, D.J. (2003) The deformation-DIA: a new apparatus for high temperature triaxial deformation to pressures up to 15 GPa, *Review of Scientific Instruments*, 74, 3002-3011, doi: 10.1063/1.1570948.

Wang, Y., et al. (2005) High-pressure x-ray tomography microscope: Synchrotron computed microtomography at high pressure and temperature, *Review of Scientific Instruments*, 76(7), 073709. https://doi.org/10.1063/1.1979477

Wang, Y., et al. (2011) In situ high-pressure and high-temperature X-ray microtomographic imaging during large deformation: A new technique for studying mechanical behavior of multiphase composites, *Geosphere* 7 (1), 40-53.

Weidner, D.J., Vaughan, M.T., Wang, L., Long, H., Li, L., Dixon, N.A., and Durham, W.B. (2010) Precise stress measurements with white synchrotron x rays, *Review Scientific Instruments*, 81, 013903, doi: 10.1063/1.3263760

Yund, R. A., Blanpied, M. L., Tullis, T. E., & Weeks, J. D. (1990). Amorphous material in high strain experimental fault gouges. *Journal of Geophysical Research: Solid Earth*, *95*(B10), 15589-15602.

Zhao, Q., N. Tisato, G. Grasselli, (2017) Rotary shear experiment under x-ray micro-computed tomograpohy, Rev. Sci. Instrum. 88, 015110 (2017); https://doi.org/10.1063/1.4974149

Zheng, X., Cordonnier, B., Zhu, W., Renard, F., and Jamtveit, B. (2018) Effects of confinement on reaction-induced fracturing during hydration of periclase, G3, doi.org/:10.1029/2017GC007322

Zhu, W., Fusseis, F., Lisabeth, H., Xing, T., Xiao, X., De Andrade, V., Karato, S. (2016) Experimental evidence of reaction-induced fracturing during olivine carbonation*, Geophysical Research Letters,* doi: 10.1002/2016GL070834.