New Directions for Fundamental Earthquake Research

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Executive summary Many discoveries in earthquake science will come from pushing the current limits of tectonophysics, geodesy, and scientific computing. Numerous research opportunities exist to expand the field of earthquake science. Accompanying the development of new theories and methods with targeted laboratory and field observations will be key to enable transformative research. The modeling infrastructure needs to be improved to incorporate all the dominant deformation mechanisms from the crust to the asthenosphere. Fundamental earthquake science will unlock new thematic research at tectonic hotspots and benefit a better understanding of induced seismicity.

Introduction Fundamental research in earthquake science that transcends region-specific targets is necessary to enable new discoveries in a variety of tectonic settings and to better understand induced seismicity. Earthquake physics finds itself at the intersection of geology, geodynamics, geodesy, mineral physics, engineering, scientific computing, and other allied fields. Major progress in our understanding of the earthquake phenomenon, with an eye towards mitigation of seismic hazards, will come from growing this intersect, i.e., by gaining more insights from all of the relevant disciplines. We present some of the challenges ahead towards building a physical representation of seismic processes that is compatible with our understanding of fault physics and mantle dynamics. In addition, we identify specific research opportunities that may be particularly productive, including progress towards a physics-based constitutive law for fault slip, new insights into fault dynamics to better anticipate rupture styles and recurrence patterns, new insights into the rheology of viscoelastic deformation, new appreciation of the importance of folding in the upper crust, and new strategies to improve numerical models of the seismic cycle. We also highlight observational gaps, either in the laboratory or in the field, that must be filled to accomplish important research targets.

Fault constitutive behavior A major roadblock in earthquake physics is a lack of a well established constitutive law for fault slip. In the last decades, friction laws have been developed within the framework of visco-elasto-plasticity, where both the velocity of sliding and the state of the fault contact affect fault strength. In a kinematic friction law, an explicit relationship exists between frictional resistance and the velocity of sliding, modulated by a state variable that represents the real area and quality of contact. The advantage of kinematic friction laws is to allow the analytical or numerical treatment of the entire seismic cycle consistently. The most comprehensive empirical friction law accounts for the effect of sliding velocity, state, and temperature of the fault.

A major goal is to derive a constitutive framework for fault slip that captures the dependence of friction on lithology, sliding velocity, real area of contact, quality of contact, temperature, pore fluid pressure, the presence of a lubricating phase, and possibly other physical parameters found in crustal conditions over the whole range of parameters relevant to the seismic cycle. These theoretical development will help understand natural earthquakes and the implications for faulting of evolving temperature and pore pressure during hydraulic fracturing. This effort must evolve in tandem with new laboratory experiments to test the working hypotheses of micro-physical models, isolate the properties of individual healing mechanisms, and identify the controlling parameters.

New insights on fault dynamics Fault dynamics refers to the spontaneously emerging behavior of a fault resulting from its constitutive behavior under external loading. The enormous variety of observed rupture styles and recurrence patterns observed on faults can be considered the natural response of a complex mechanical system with emergent behavior. The controlling factors that govern the behavior of a fault can be identified through a dimensional analysis of the governing equations for fault slip. A wide range of styles of seismic cycle can be attributed to a coordinate in a two-dimensional phase space associated with two non-dimensional parameters. This pair of numbers largely determines many important aspects of the seismic cycle during the inter-, co-, and post-seismic periods.

The wide range of behaviors predicted by theoretical models must be tested in laboratory experiments and compared to seismo-geodetic observations in natural systems. Dynamic models must be used to predict possible fault behavior with more realistic geometries, constitutive formulations, and parameter ranges to map out the phenomena that can be expected from the physical assumptions. These efforts must be supported by more efficient numerical modeling techniques and a dedicated computing infrastructure, improvements in experimental instrumentation to systematically explore a wider range of hydro-thermal conditions for different rocks, and renewed efforts to reconcile theory and observations.

Coupling the lithosphere and the asthenosphere Faults occupy the brittle layer of the lithosphere and develop above a viscoelastic substrate where deformation is accommodated by plastic, distributed deformation. One of the major targets of earthquake physics is a consistent representation of the lithosphere and the asthenosphere that takes into account the mechanical coupling between brittle and ductile deformation. A theoretical framework to make these simulations more routine is growing. Numerical methods that include fault slip and viscoelastic flow during seismic cycle simulations must be further developed to describe lower-crustal and mantle flow along with faulting in the brittle field in a consistent manner.

Further progress are needed to better explain the physics of viscoelastic deformation. The rheology of plastic flow at steady state is well established, but a remaining unknown is the constitutive framework that describes deformation before steady state, the so-called transient creep. Dedicated efforts should be made to produce quality laboratory data on quartzite, olivine, peridotite, serpentinite, at various confining stress, temperature, water content, and strain rates to unravel the physics of transient creep.

Seismic cycle simulations Our current capacity of modeling the seismic cycle is under-developed compared to the richness of observations, the variety of deformation mechanisms, and the size of the problem. Many opportunities exist to expand our modeling capacity to represent the dynamics of the lithosphere more realistically. Our goals should be to develop thermo-mechanical models of plate boundaries that produces realistic seismic cycle simulations. The model should include multiple faults, the coupling between brittle and ductile deformation modulated by shear heating and heat transfer, realistic constitutive laws for friction and viscoelastic flow, and off-fault deformation by folding in the upper crust.

Folding, a type of distributed deformation in the brittle field that is widespread in thrust-and-fold belts and accretionary prisms, is an important mode of deformation that is largely overlooked in earthquake physics and crustal dynamics. The region around folding where anelastic deformation occurs, called an active axial surface, can readily be incorporated in seismic cycle models for a particular type of fold that grows above fault bends. However, more research is needed to capture the rheology of folding, which is much less understood than distributed deformation in the ductile regime. New laboratory experiments must be designed to control and measure stress and strain-rate during shortening by distributed deformation. Seismic cycle simulations of actively shortening regions must incorporate folding mechanisms to better represent the mechanisms of deformation and stress interaction.

New developments in geodynamics modeling are needed to incorporate realistic fault networks to more directly link tectonic processes to the time scales of the seismic cycle. New theoretical developments are needed to describe the inception of faults from intact media and their evolution towards maturity, compatible with current knowledge of fault friction.

Conclusion This document highlights a range of new research directions that will advance the frontiers of earthquake science. New laboratory experiments are needed to understand the physics of friction, the rheology of transient creep, and that of folding. New theoretical developments must come to play to describe Earth's deformation from the surface to the asthenosphere. New numerical techniques must be introduced to describe the tectonic context surrounding faults more accurately. Empirical formulations of rate- and state-dependent friction should be replaced with physics-based constitutive laws. A research center focused on fundamental earthquake science that transcends regional boundaries will unlock new scientific discoveries across the field and contribute to improving the national welfare.