CHALLENGES & OPPORTUNITIES FOR RESEARCH IN TECTONICS:

Understanding deformation & the processes that link Earth systems, from geologic time to human time

A Community Vision Document Submitted to the National Science Foundation

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WRITING COMMITTEE CO-CHAIRS

Katharine W. Huntington Keith A. Klepeis

VISION DOCUMENT CONTRIBUTORS AND REVIEWERS

Richard Allmendinger
Jeffrey Andrews-Hanna
Ramon Arrowsmith
Whitney Behr
Scott Bennett
Steven Bergman
Rachel Bernard
Kimberly Blisniuk
Richard Briggs
Emily Brodsky
Elizabeth Cassel
Marin Clark
Claire Currie
Juliet Crider
Michele Cooke
Eric Cowgill
Peter DeCelles
Roman DiBiase
Becky Dorsey
Alison Duvall
Melodie French
Patrick Fulton
Christopher Gerbi
Joan Gomberg
Laurel Goodwin
William Ashley Griffith
Sarah Harbert
Greg Hirth
Kip Hodges
Maureen Kahn
Katie Keranen
Eric Kirby
Jamie Kirkpatrick
Robert Kirsch
Seth Kruckenberg
Yvette Kuiper
Karl Lang
Stephen Laubach
Chris Marone
Elena Miranda
Kevin Mahan
Laurent Montesi
Julie Newman
Frank Pazzaglia
Cliff Riebe
Emily Roland
Christie Rowe
Heather Savage
Katherine Scharer
Joshua Schwartz
Christine Siddoway
John Suppe
James Spotila
Robert Stern
Barbara Tewksbury
Basil Tikoff
Ben van der Pluijm
Joseph White
Steven Whitmeyer
Donna Whitney
Mike Williams
Randy Williams
Steven Wojtal
Doug Yule
Peter Zeitler

ORGANIZING COMMITTEE

Basil Tikoff Yvette Kuiper Laurel Goodwin

WORKSHOP COMMITTEE

Richard Allmendinger Marin Clark Eric Cowgill Becky Dorsey Kevin Mahan James Spotila

WORKSHOP PARTICIPANTS

Ruth Aronoff
Ramon Arrowsmith
Alexis Ault
Gary Axen
Suzanne Baldwin
Thorsten Becker
Whitney Behr
Scott Bennett
Jeff Benowitz
Marcia Bjornerud
Barbara Carrapa
Gabrielle Casale
Elizabeth Cassel
Alan Chapman
Michelle Cooke
Catherine Cooper
Darrel Cowan
Juliet Crider
George Davis
Peter DeCelles
Roman DiBiase
Alison Duvall
Cynthia Ebinger
Donald Fisher
Lucy Flesch
Kennet Flores
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Stacia Gordon
William Guenthner
George Hilley
Kip Hodges
Gregory Hoke
John Hole
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Barbara John
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Harvey Kelsey
Eric Kirby
Luc Lavier
Ryan Leary
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Andrew Meigs
David Mogk
Laurent Montesi
Matty Mookerjee
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Wayne Thatcher
Sarah Titus
Harold Tobin
Paul Umhoefer
Ben van der Pluijm
Jolante van Wijk
Laura Webb
Steven Whitmeyer
Donna Whitney
Michael Williams
Randy Williams
Brian Yanites
Lucas Zoet

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PRE-WORKSHOP IDEA PAPER CONTRIBUTORS

Aubreya Adams
Colin Amos
Ramon Arrowsmith
Suzanne Baldwin
Whitney Behr
Susan Beck
Thorsten Becker
Sean Bemis
Scott Bennett
Jeff Benowitz
Marcia Bjornerud
Margaret Boettcher
Richard Briggs
Michael Brudzinski Cathy Busby
Mark Caffee
Barbara Carrapa
Michele Cooke
Darrel Cowan
Hugh Daigle
George Davis
Peter DeCelles
Roman DiBiase
Becky Dorsey
Alison Duvall
Cindy Ebinger
Eric Ferré
Don Fisher
Raymond Fletcher
Rebecca Flowers
George Gehrels
Christopher Gerbi
Frédéric Gueydan
Mark Harrison
Peter Haeussler
Nicholas Hayman
Darrell Henry
George Hilley
Kip Hodges
John Hole
Brian Horton
Ben Horton
Michael Hren
Roy Hyndman
Roy Johnson
Scott Johnson
Harvey Kelsey
Peter Koons
Luc Lavier
Stephen Laubach
James Metcalf
Kitty Milliken
David Mogk
Laurent Montési
Matty Mookerjee
Paul Morin
Paul Mueller
Alan Nelson
Julie Newman
Michael Oskin
Terry Pavlis
John Platt
Katerina Petronotis
David Pollard
Maša Prodanović
Jay Quade
Jacqueline Reber
Phillip Resor
Tammy Rittenour
Christie Rowe
Heather Savage Katherine Scharer
Blair Schoene
Brad Singer
John Suppe
Ashley Streig
Barbara Tewksbury
Christian Teyssier
Sarah Titus
Basil Tikoff
Paul Umhoefer
Douglas Walker
Laura Webb
Jolante van Wijk
Donna Whitney
Mike Williams
Mike Willis
Rob Witter
Lucas Zoet

Link to PDF containing the 40 idea papers submitted prior to the May 2016 Workshop:
https://drive.google.com/file/d/0B_YmIWvGcNGESzNoRjRVakxHQzI1WmpFRldrcEZxcXA0WG9R/view

The *Workshop Organizing Committee* obtained funding for the May 2016 workshop, ran community town halls prior to the workshop, and designated the *Writing Committee Co-Chairs*. The *Workshop Planning Committee*, which was composed of volunteers and individuals recruited to represent the diversity of the tectonics community, managed *Workshop Participant* application and selection, and worked with the *Writing Chairs* and *Organizing Committee* to design and lead the workshop. *Idea Papers* were solicited from the workshop participants and presented as brief pop-up presentations at the start of the workshop to help shape the discussions. Over the year and a half following the workshop, *Vision Document Contributors and Reviewers* worked with the writing co-chairs to participate in focus group discussions, writing, and/or reviewing elements of this document.

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EXECUTIVE SUMMARY

Geoscience is an inherently interdisciplinary endeavor, and one of the most interdisciplinary geosciences is tectonics. Embracing experimental, observational, and theoretical perspectives, tectonics focuses on the interactions among various components of Earth and planetary systems as they evolve over many spatial and temporal dimensions. Many of the products of these interactions—from earthquakes, volcanic eruptions, tsunamis, and landslides to water, mineral and energy resources—have important human consequences. Thus, in addition to contributing to a deeper understanding of planetary dynamics, tectonics research routinely addresses issues essential to human societies. The distinctions between "pure science" and "application-inspired" aspects of tectonics are rapidly blurring, and the time is ripe to re-visit our traditional definition of tectonics as a field within the geosciences and re-imagine it for the 21st Century. In doing so, we have an opportunity to identify newly emergent opportunities and the key technological and infrastructure requirements for breakthrough research.

A year and a half of community-wide discussion of future research opportunities resulted in the identification of five "grand challenges" that will inspire tectonics research over the next decade and beyond:

- ✓ Understanding planetary evolution in four dimensions
- ✓ Understanding the dynamic interactions among Earth-surface processes and tectonics
- ✓ Understanding variations in rheology throughout the lithosphere
- ✓ Understanding fault zone behavior from Earth's surface to the base of the lithosphere
- ✓ Meeting societal needs while advancing research in structural geology and tectonics

This community vision extends beyond understanding the processes we can observe at Earth's surface in the present day to explore planetary system evolution in four dimensions: over three spatial dimensions at scales ranging from nano to global, and across the fourth dimension of time over scales of seconds to billions of years.

On Earth, our global tectonics approach treats the core, mantle, asthenosphere, lithosphere, hydrosphere, cryosphere, atmosphere, and biosphere as components of an integrated system, and seeks understanding of how these components interact. Earth's surface connects the solid Earth, atmosphere, and biosphere, and as a consequence studies of tectonics-surface process interactions empower us to address many broad, crosscutting questions in the new tectonics of the 21st Century. Solid-Earth deformation is an important driver of these interactions, making it critical to quantify how the mechanical properties of rocks (e.g., rock rheology) affect Earth's physical and chemical evolution through their influence on deformation processes. Broad-scale deformation patterns are largely defined by fault zones—which are best known as the source of earthquakes, but exhibit a broad spectrum of slip behaviors and also regulate fluid flow in the subsurface. Throughout the lithosphere, new tools are enabling us to quantify interactions and feedbacks among fluids, fault slip behavior, the development of fault structure and crustal strength, with far-reaching implications for human society's access to resources and resilience in the face of tectonic hazards. The urgent need for research at the intersections of tectonics and human society goes well beyond earthquakes and oil. Our quest for fundamental understanding provides the foundation for hazard assessment and the sustainable management of critical energy, water and environmental resources. At the same time, applied research motivated by challenges related to hazards and resources has tremendous potential to drive basic tectonics research forward.

In order to make real progress on addressing these challenges, we feel that the Division of Earth Sciences of the National Science Foundation should explore new avenues for supporting tectonics research and re-examine current funding priorities. In particular, some of the most exciting tectonics research foci over the coming decade will require consortium approaches that involve the collaboration of a broad spectrum of geoscientists from multiple disciplines, not only researchers traditionally funded by the Tectonics Program and not only individual investigators. Success will require tactical investments in the development of new analytical and observational methods and technologies, advanced digital data sharing and archiving strategies, and new infrastructures to support a transformation of the tectonics research enterprise from one supported by individual, short-term research grants to one also supported by sustained funding of multi-investigator consortia.

INTRODUCTION

CHALLENGES & OPPORTUNITIES FOR RESEARCH IN TECTONICS

TECTONICS IN THE 21st CENTURY

The field of tectonics examines the processes that link Earth systems to deformation and life throughout Earth's billion-year history. As an integrative global geoscience, tectonics provides an intellectual framework that connects processes operating in the solid Earth with those at work in the hydrosphere, atmosphere, and biosphere. Tectonic processes impact every person on our planet by shaping Earth's landscapes, atmosphere and climate, and by creating natural resources and hazards. As a discipline, tectonics is remarkably diverse: It brings together scientists that use a broad spectrum of tools and approaches assimilated from the fields of geology, biology, physics, and chemistry as well as engineering, computer modeling, and material science. Through this broad perspective, research in tectonics empowers us to understand planetary evolution across the deep reaches of space and time—to increase our understanding of the natural world and to provide critical benefits to human society.

Over the past few decades, tectonics research has undergone a transformation in its approach to understanding the Earth. Modern tectonics no longer is restricted to classical concepts involving the movements and interactions of thin, rigid tectonic (lithospheric) plates. The combination of observations derived from natural rocks, experiments, and modeling, has enabled us to move beyond simplified kinematic and steady-state descriptions of solid-Earth deformation and Earth-surface processes, to addressing dynamic and transient phenomena. As a result, a new era of multidisciplinary exploration has emerged that allows us to examine dynamic interactions among all the spheres of the Earth, including the core, mantle, asthenosphere, lithosphere, hydrosphere, atmosphere and biosphere.

New frontiers of exploration have also emerged, made possible by recent technological innovations that enable us to observe and model the natural world at increasingly high resolution. Multispectral, high-resolution imaging techniques, for example, now push the limits of observation from nanometer-scale microstructure to global tomography and topography. Combined with the refinement and expansion of geochronologic tools, these and other advances now allow us to study processes occurring across time scales ranging from microseconds to billions of years. Technical advances have brought together researchers from once independent communities, as interdisciplinary collaborations have stimulated the development and application of new technologies. This synergy between interdisciplinary collaboration and innovation is a natural outgrowth of a tectonics research enterprise that unites scientists through their mutual interest in questions that are by nature interdisciplinary.

Many of the most important questions that unite us are of immediate concern to human society. Demands for energy resources, mineral resources, and freshwater to support Earth's burgeoning human population are more urgent than ever, as is the need to reduce vulnerability to geologic hazards and climate change. The tectonics community brings a broad, Earth-systems perspective to tackle these issues, as well as specific expertise that addresses many of the themes they hold in common. These themes include rock fracturing, subsurface fluid circulation, deformation mechanisms in the crust, surface processes, low temperature geochemistry and geochronology, imaging of the surface and subsurface, and many other cornerstones of both curiosity-driven and

application-based research in tectonics. Conceptual advances, new technologies, and new interdisciplinary approaches now set the stage for further major breakthroughs in both research areas.

GRAND CHALLENGES IN TECTONICS: ADVANCING THE SCIENCE & SERVING SOCIETY

This document presents the tectonics community's vision to understand the dynamics of processes operating on our planet, both past and present, and to help society meet the many challenges associated with maintaining its habitability. This vision is the outgrowth of a year and a half of community discussion and data gathering whose primary goal was to identify future research opportunities and to articulate the key requirements and strategies needed to enable major breakthroughs. It has been 14 years since the last community report summarized key research challenges in the disciplines of tectonics and structural geology (Pollard et al., 2003). In the intervening time, many significant changes have occurred in the way we conceptualize Earth-systems questions, use available technology, approach interdisciplinary collaborations, and apply tectonics research to societal issues. These changes underscore the need to re-envision the future of tectonics research and its impact on human society in the decades to come.

The community visioning effort began with a **NSF-sponsored workshop** held at the University of Wisconsin-Madison in May 2016. This workshop assembled a diverse group of ~90 Earth scientists to: (1) identify grand challenges and opportunities for major advances in the field of tectonics; (2) prioritize the resources, partnerships, and infrastructures needed to make progress; and (3) develop a vision to build and strengthen the tectonics community and maximize its educational and societal impacts. The workshop sparked **a year and a half of community-wide discussion** that involved many layers of public inquiry and data gathering. We solicited short "idea" papers, held town hall gatherings at national meetings before and after the workshop, conducted online forums and surveys, and conducted extensive focus-group discussions. To make sure a wide range of voices was heard, we consulted experts from allied fields, persons from underrepresented groups, scientists at various career stages, industry and government workers, and people at institutions that emphasize different combinations of research and teaching. Requests for feedback and reviews of written material at multiple stages helped us identify ideas that resonate broadly across the community. From start to end the process was advertised widely and designed to be as inclusive as possible. ***The result is a community report that incorporates the opinions of hundreds of scientists and includes specific contributions from over 65 experts in the field of tectonics.***

From the large pool of data we collected, five ***Grand Challenge themes*** emerged that will inspire tectonics research over the next decade and beyond. These themes address rich and fundamental questions in Earth and planetary science, and show the integrative, cross-disciplinary nature of tectonics research. The themes are organized into five chapters, each of which presents examples illustrating how novel analytical tools, concepts, and datasets are sparking new understanding of deformation processes and their products through time and space. The examples highlight both new research frontiers and new opportunities to solve longstanding problems. In all cases, examples focus on areas where we are **poised to make major advances in the near future**. Each chapter also articulates strategies to address the key questions we ask today, and that are likely to stimulate future breakthroughs in areas we cannot predict.

Grand Challenge #1: Understanding planetary evolution in four dimensions, begins with a four-dimensional, global perspective that highlights the broad scales of time and space that are fundamental to tectonics research. This chapter summarizes some of the least-explored realms of our

planet—from its deep interior to its earliest beginnings when the atmosphere, cryosphere and hydrosphere were just forming and plate tectonic processes had yet to begin. The examples emphasize how the dimension of time provides an essential framework for understanding all tectonic processes. By refining this temporal framework and exploring new realms, we can better understand how habitable planets emerge and evolve, and how the different spheres of our planet interact with one another through time.

Grand Challenge #2: Understanding variations in rheology throughout the lithosphere, highlights one of the most important, unresolved problem in all of tectonics: developing an accurate, quantitative description of how the solid Earth deforms at all depths within the lithosphere and on time scales ranging from microseconds to billions of years. This problem, which is addressed by the study of rock rheology, permeates virtually every aspect of tectonics research because it is intimately involved in the physical and chemical evolution of the Earth. Chapter 2 introduces some frontier areas of this problem and highlights the importance of investigating the rheology of the deep crust and its dynamic links to other parts of the lithosphere, including the Earth's surface.

Grand Challenge #3: Understanding fault zone behavior from Earth's surface to the base of the lithosphere, builds on the themes discussed in chapter 2 by exploring the broad spectrum of fault slip behaviors and insights into earthquake processes from fault rocks. This chapter emphasizes the connections between faulting, rheology, and surface processes. It also explores new perspectives on fluid-fault interactions that are key to accessing water, energy and economic resources, and to sequestering contaminants and CO_2 underground. The examples in both chapters 2 and 3 highlight the importance of integrating information from the rock record with the results of deformation experiments, geophysical observations, and physical and numerical modeling, to improve our understanding of lithospheric rheology and its relationship to tectonic processes.

Grand Challenge #4: Understanding the dynamic interactions among Earth-surface processes and tectonics, builds on the concepts of Earth system interactions and deformation processes described in chapters 1-3 to address a fundamental theme that has motivated two decades of Earth and atmospheric science research. This chapter focuses on recent conceptual advances and discoveries that have created new opportunities for breakthroughs in our understanding of Earth-surface evolution and its connections to the atmosphere, biosphere and solid Earth. The examples show how these connections are much more diverse and significant than previously thought. They explore tectonics-surface process connections from hillslope to global scales that involve a large range of phenomena—from global mantle dynamics and crustal rheology to rock strength, topographic stresses, biogeochemical cycles, and the co-evolution of landscapes and life.

The capstone chapter of the five grand challenges—***Grand Challenge #5: Meeting societal needs while advancing research in structural geology and tectonics***—demonstrates the immediate impact and urgency of tectonics research. This section emphasizes the deep symbiosis that exists between research on fundamental problems in the fields of tectonics and structural geology and societal needs. Six examples explore in detail the pivotal role our community plays in addressing some profound challenges humankind will face in the coming decades, including climate change, growing energy needs, and demands for fresh water and minerals. This discussion emphasizes how our community brings a rich array of tools and approaches that can be used to both advance our understanding of planet Earth and tackle some of the most important issues facing humanity in the 21st century.

The examples in these five chapters illustrate some of the many opportunities for breakthroughs in our understanding of Earth systems and dynamics. We view them as a point of departure for ongoing science visioning and community building efforts. The grand challenge themes

already have inspired a **Future of Tectonics Initiative** at the Geological Society of America Annual Meeting in 2017, including 13 conference sessions organized by dozens of researchers, and nearly 270 scientific presentations contributed by research teams from the community. Our efforts have catalyzed synergistic activities with other research communities within and beyond the geosciences. There is great optimism that such efforts will lead to the further breakdown of barriers between disciplines, and between pure-science and application-based research—both of which are critical to achieving our vision.

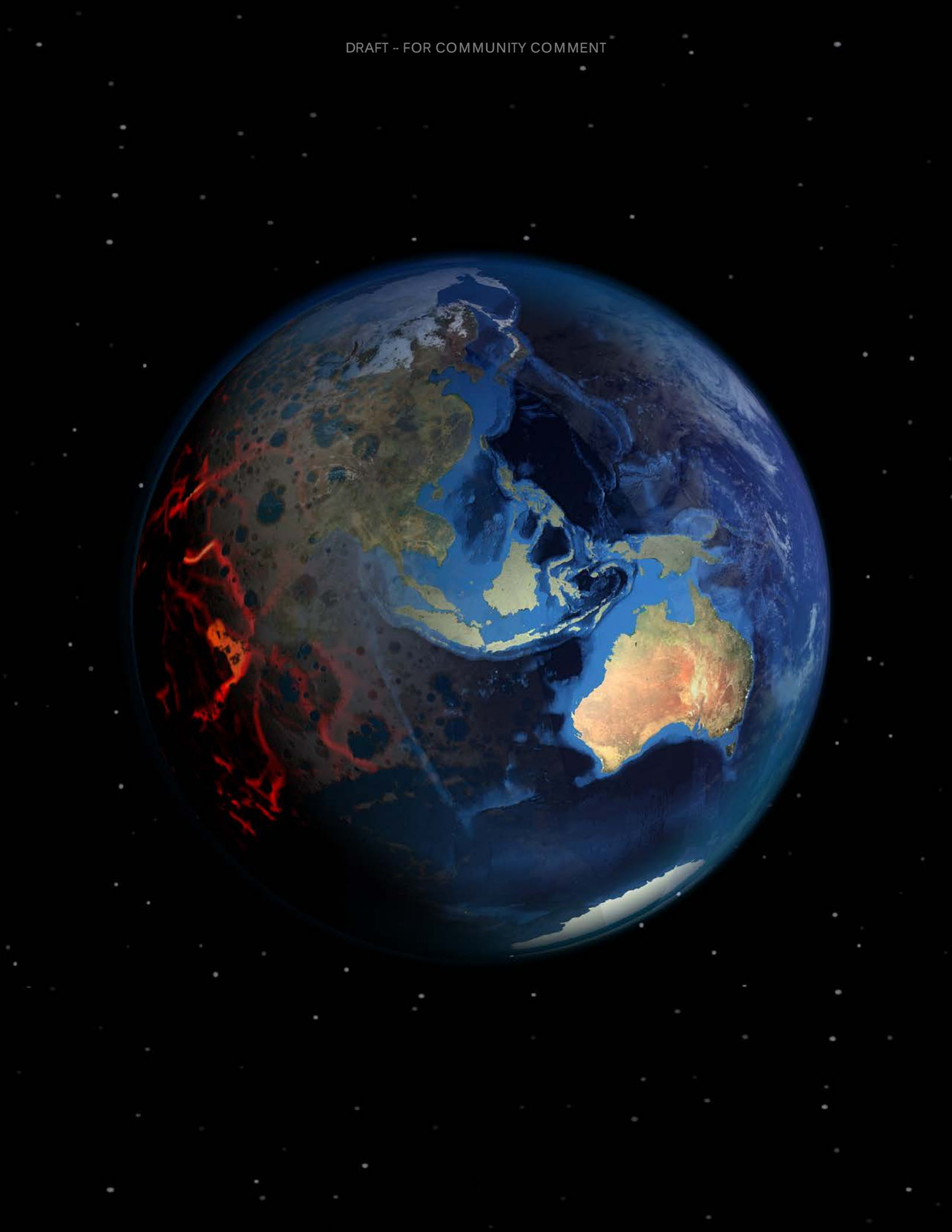
ACHIEVING THE VISION

Far-reaching advances in geoscience research from an Earth-systems perspective have opened new scientific frontiers and position the tectonics community to make major advances in meeting societal challenges. However, key conceptual gaps present barriers to progress. Neither frameworks for collaboration and data sharing, nor resources, have kept pace with the rapid expansion of innovative technologies and interdisciplinary approaches to tectonics research. Community discussions in disciplines that are strongly allied with tectonics, including structural geology, surface processes, geochronology, cyberinfrastructure, and seismology, have highlighted these issues repeatedly. There is an urgent need for—and opportunity to leverage—investments in facilities, infrastructure, and community strategies to integrate fields of research that span the solid-Earth, oceanic, atmospheric, climate, and geospace sciences.

The last chapter (chapter 6) of this report outlines core needs and recommendations for ***Achieving the Vision*** outlined in the five ***Grand Challenge*** chapters. These recommendations include a call to invest in those areas of tectonics research where the ***development and application of new tools and technologies promise sweeping interdisciplinary growth***. Central to this effort are strategies for improving ***cyberinfrastructure, data integration, and data access*** for both existing and new technologies to effectively enable interdisciplinary science. Investment in our intellectual capacity is also critical to success. We therefore propose a strategy to connect more people to practical resources and best practices for ***recruiting, educating, and retaining a diverse and rigorously trained work force***, which could serve as a model for other fields. Finally, to ensure our discoveries will have the maximum societal benefit, we call for support to increase ***engagement with public stakeholders***.

Critical to each of these recommendations is the need for new collaborative partnerships, organizations, and infrastructures that enable tectonics research and amplify its impacts. Building a network of national research and educational facilities linked through a ***community-led consortium for tectonics*** would meet this need. Chapter 6 includes examples of some of the collaborative research strategies that a national tectonics consortium would enable. Consensus on specific strategies, and key ***partnerships with other community-based organizations and facilities***, must be established to further develop this scientific vision. New resources and consideration of new funding strategies within the Division of Earth Sciences of the National Science Foundation—possibly supplemented by external funding—are needed to achieve it.

Capitalizing on the research opportunities set out in this report is likely to lead to major advances in the Earth sciences in the next decade and beyond. Investment in a tectonics initiative will promote research that crosses traditional boundaries among programs and directorates at NSF, among federal agencies, and between fundamental and application-based research. Such investments in tectonics research promise to broaden our understanding of Earth system interactions in the past and their relevance to natural resources and hazards that affect humankind's future.



GRAND CHALLENGE 1

UNDERSTANDING PLANETARY EVOLUTION IN FOUR DIMENSIONS

1.1 OVERVIEW

A surprisingly large fraction of the Earth remains unexplored. Although we walk the Earth on a daily basis, our experience is limited to the surface and the present. Yet the deeper reaches of time and space are being brought into focus as new methods of inquiry enable us to enter a new era of transdisciplinary exploration that treats the core, mantle, asthenosphere, lithosphere, hydrosphere, cryosphere, atmosphere, and biosphere as components of an integrated system. The goal of this exploration is to understand planetary system evolution in four dimensions: over three spatial dimensions at scales ranging from nano to global, and across the fourth dimension—time—over time scales ranging from seconds to billions of years.

We present five examples of unexplored frontiers where the tectonics community is poised to make new advances toward this goal thanks to recent development in community datasets, analytical techniques, and intellectual approaches. Exploration of the deeper interior of our planet is facilitated by advances in seismic tomography, which enable us to link near-surface deformation to the internal dynamics of the mantle and the crust (***Section 1.2***). Exploration of the ocean floor and the structure and tectonics of the oceanic crust and lithosphere reaches beyond classical studies of plate interactions and seafloor volcanism to address mineral resources, natural hazards, and biogeochemical cycles (***Section 1.3***). Exploration of early Earth dynamics takes us back to an era before plate tectonics, when accretionary processes and planetary differentiation were of paramount importance, and enables us to build an understanding of how plate tectonics can arise on rocky planets; the origin of atmospheres, cryospheres, and hydrospheres; and how habitable worlds emerge and maintain their habitability (***Section 1.4***). Studies of these transitions may be informed by exploration of the tectonic evolution of other worlds that seem to have experienced developmental stages similar to that of Earth (e.g., Mars and Venus) but subsequently evolved differently (***Section 1.5***). In all of these endeavors, the fourth dimension of time provides an essential framework for understanding processes, implying a need to explore how accurately and precisely we can establish the tempo of planetary evolution through isotope geochronology and thermochronology (***Section 1.6***).

These examples highlight the interdisciplinary nature of modern tectonics research. They show how many of the recent technological and conceptual advances that make each area of tectonics research possible have originated from outside the traditional disciplinary framework of tectonics and structural geology. A common theme in these and other areas of tectonics research is that future advances will be accelerated by scientists who are brought together by mutual interest in specific problems, not by their individual training or expertise (***Section 1.7***). In the development of these teams—and with more effective funding strategies for such collaborative, interdisciplinary work—tectonics is poised to become the true global geoscience.

1.2 THE UNEXPLORED FRONTIER OF EARTH'S DEEP LITHOSPHERE AND MANTLE

Earth's deep lithosphere and mantle represent a vast, largely unexplored domain of our planet. New tomographic models provide exciting opportunities to integrate geological, geophysical, and geodynamical data sets in efforts to directly link surface geology with deep Earth structure.

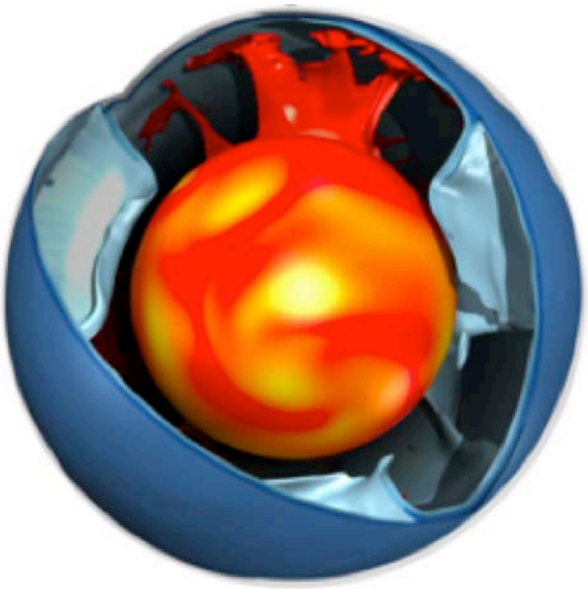


Figure 1

Earth's deep lithosphere and mantle represent a vast, largely unexplored domain of our planet. Access to elements of this domain has been limited to places where they have been exposed at the surface by deep exhumation or imaged by deep crustal and broadband seismology; thus in spite of the great success of the plate tectonic revolution, tectonic reconstructions of Earth's surface lack contributing information from the vast majority of our planet's volume. Recent advances in imaging are opening up these previously hidden realms, with new seismologic methods revealing structural details in the numerous subducted slabs that are present above the core-mantle boundary—just as new tomographic models provide opportunities for the structural geology and tectonics community to engage with geophysicists in efforts to directly link surface tectonic records in orogenic systems worldwide with deep lithosphere and mantle structural seismology. Major discoveries in plate tectonics, regional tectonics on the continents and in the ocean basins, and geodynamics are certain to result from such collaborations. To fully exploit these rich imaging resources requires advances in the ability to map, analyze and manipulate images of geologic structures in 3D tomography, and to integrate these with a variety of other geological and geophysical data and concepts.

Exciting discoveries are being made in both oceanic and continental domains where such datasets exist. A recent seismic tomography catalog of subducted plates in the mantle includes approximately 100 major "slabs" that, together, represent ~200-250 m.y. of subduction history—the time required for slabs to sink to the core-mantle boundary. Many of these slabs can be mapped in three-dimensions and retrodeformed to fit plate reconstructions (e.g., Wu et al., 2016). For example, reconstructions of the Farallon slab, an ancient oceanic plate subducted beneath North America, illuminate how processes deep in the lithosphere affect the surface of the continent—such as driving uplift and development of rugged topography in the Appalachian Mountains more than 200 million years after mountain building ceased (e.g. Gallen et al., 2013). Recent breakthroughs in geodynamic modeling reveal vast domains of potential "discovery space" in the mantle (Crameri et al., 2012), where subducting slabs (**Figure 1**, light blue) have been imaged at progressively increasing resolution, and geodynamic models illustrating slab kinematics anchored to surface datasets provide new opportunities to reconstruct plate tectonic histories of Earth's surface. This work invites further scrutiny of processes that we previously considered to be well understood, such as seafloor spreading, continental rifting, passive margin subsidence/thermal histories, single- vs. double-sided subduction, subduction initiation, interpretation of the seafloor magnetic record, and forearc and backarc

tectonics. There is much to be learned from a combined geological-geophysical-geodynamics approach to global tectonics, in both the oceans and on the continents.

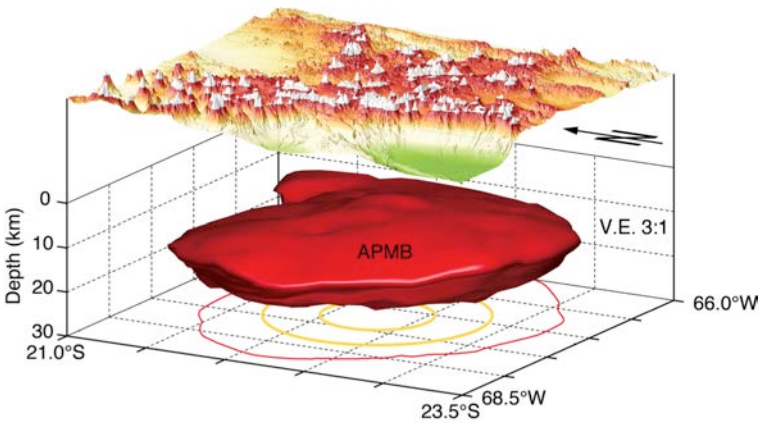


Figure 2

At shallower crustal levels, seismic methods are providing spectacular new observations that have direct tectonic implications. One example of recent discoveries using broadband seismology is the Altiplano-Puna Magma Body (APMB), an approximately 11 km thick low-velocity zone in the middle crust beneath the central Andean magmatic arc (Ward et al., 2014). The APMB is interpreted as a ca. 500,000 km^3 magma mush zone (**Figure 2**) that is spatially correlated with surface calderas, voluminous late Miocene-Pleistocene ignimbrite centers, and a region of ongoing surface inflation (contours in **Figure 2**; Pritchard and Simons, 2004), suggesting that it remains an active component of the magmatic arc. The ability to image features like the Farallon slab and APMB at high resolution presents the opportunity to integrate geological, geophysical, and geodynamical data sets around the world—to directly link surface geology with deep Earth structure in unprecedented detail.

1.3 THE UNEXPLORED FRONTIERS OF THE OCEANIC LITHOSPHERE

Recent exploration of Earth's ocean basins using new marine geological and geophysical tools has led to discoveries that reveal tectonic processes operating at a lithospheric scale. Results have caused us to question many of our past convictions and show the great potential of exploration "beyond the continents" to advance understanding of the tectonic and dynamic behavior of our planet.

Earth's ocean basins cover approximately three-quarters of the surface area of our planet, yet large portions of these regions remain unexplored. Over the last decade, advances in the use of marine geological and geophysical tools have led to discoveries that reveal tectonic processes operating at a lithospheric scale—and caused us to question many of our past convictions. For example, the seismic characterization of a full oceanic plate from ridge to trench has provided new information on the mechanisms of faulting and hydration in oceanic lithosphere (Horning et al., 2016). Data collected from both traditional land-based and new seafloor seismic and geodetic tools also are leading to shifts in our understanding of fault slip behavior (Schurr et al., 2014) and plate unlocking processes across seismogenic zones. These and other data sets provide insight into mantle flow with respect to crustal movement, the rheology of the deep lithosphere, and how hydration influences lithospheric strength and behavior.

Other areas of innovation and discovery have emerged from enhanced sampling technologies and observations from the seafloor. A seafloor network of instruments and fiber-optic cable led to successful real-time observations of a seamount volcanic eruption (Wilcock et al., 2016), including geophysical, geochemical, and geological observations of magma recharge and the eruption process. Sampling and geochemical analyses have shown that mantle rocks are exposed at the seafloor in ancient exhumed settings as well as modern oceanic settings (Reston, 2009)—ranging

from oceanic core complexes (Whitney et al., 2012), to 7-km beneath the ocean surface off Indonesia, where mantle lithosphere is being exhumed by hyperextending crust above one of Earth's largest faults (the Banda detachment, **Figure 3**, Pownall et al., 2016). We now understand that seawater and hydrothermal alteration of exposed mantle influence global geochemical cycles and planetary habitability. This tectonic activity concentrates ore deposits, supports primitive microbial communities, and may represent an analogue to processes operating on the early Earth and on other solar system bodies—suggesting the potential of exploration "beyond the continents" to advance understanding of the tectonic and dynamic behavior, and evolution, of our planet and life.

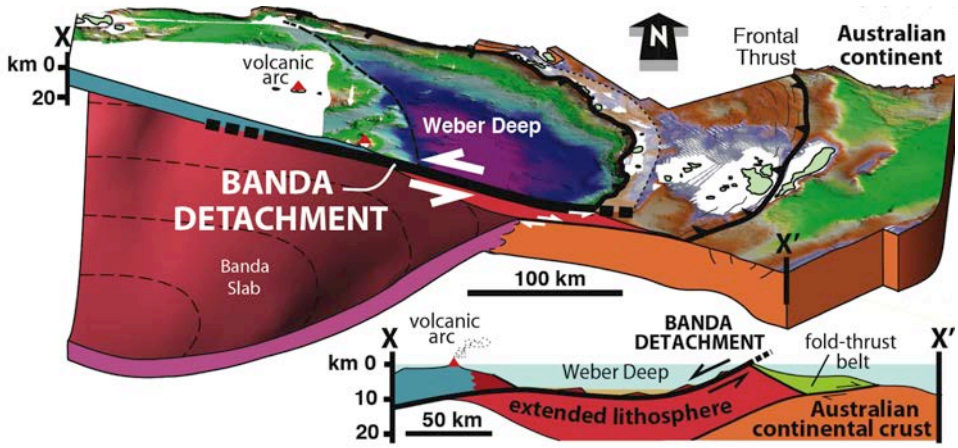


Figure 3

1.4 EXPLORING THE EVOLUTION OF PLATE TECTONICS AND A HABITABLE PLANET

In its earliest stages, Earth was dramatically different than it is now. Exploring Earth's deep past and transition to the world we live in today is a key to understanding how plate tectonics can arise on rocky planets; the origin of atmospheres, cryospheres, and hydrospheres; and how habitable worlds emerge and persist.

Much of our understanding of Earth evolution is framed to varying degrees by our understanding of how plate tectonics operates today. This framework includes the observation that Earth's lithosphere is broken up into a number of rigid plates and microplates whose interactions and movements are due to the sinking of strong, dense oceanic lithosphere in subduction zones, driving mantle convection. However, it is increasingly clear that in our Solar System, only Earth has plate tectonics. We know that early Earth was tectonically and magmatically active, but it is unclear when plate tectonics began, how it began, and what Earth's tectonic style was before plate tectonics. Prior to at least 4 billion years ago, and probably more recently, the tectonics of the Earth were likely driven by vertical heat transfer alone, without the recycling of oceanic lithosphere in subduction zones (Moore and Webb, 2013; Johnson et al., 2017). Remnants of Archean crust over 3 billion years old provide tantalizing evidence of processes that fall outside the realm of modern plate tectonics, including the formation of unique dome-and-keel crustal architectures and stiff, buoyant mantle roots beneath the cratons. These features exhibit distinctive compositional and physical properties that probably resulted from the chemical depletion and extraction of melts from a primitive mantle. In order to understand the evolution of these and many other features of fundamental importance to our planet, we must determine how, why, and when the switch to plate tectonics occurred (Korenaga, 2013; postulated times are indicated by black arrows on the time scale shown in **Figure 4**).

Although few remnants of the Hadean Earth are available to us, studies of these remnants are key to our ability to understand not only the evolution of plate tectonics, but the formation of Earth's atmosphere and the origin of life (Harris and Bédard, 2014). Intriguing geochemical results and models suggest that initiation of plate tectonics and subduction in the Archean, sometime prior to ~2.5 billion years ago, may have caused the first rise of oxygen in Earth's atmosphere—with ongoing tectonic processes and rates driving CO_2 buildup and the second rise of oxygen a billion years later, coinciding with the time complex life evolved in the Phanerozoic (e.g., Lee et al., 2016; **Figure 4**). These results highlight the opportunity to integrate geological and geochemical evidence with models to study atmosphere-tectonic linkages through deep time and better understand the evolution of the habitability of planet Earth.

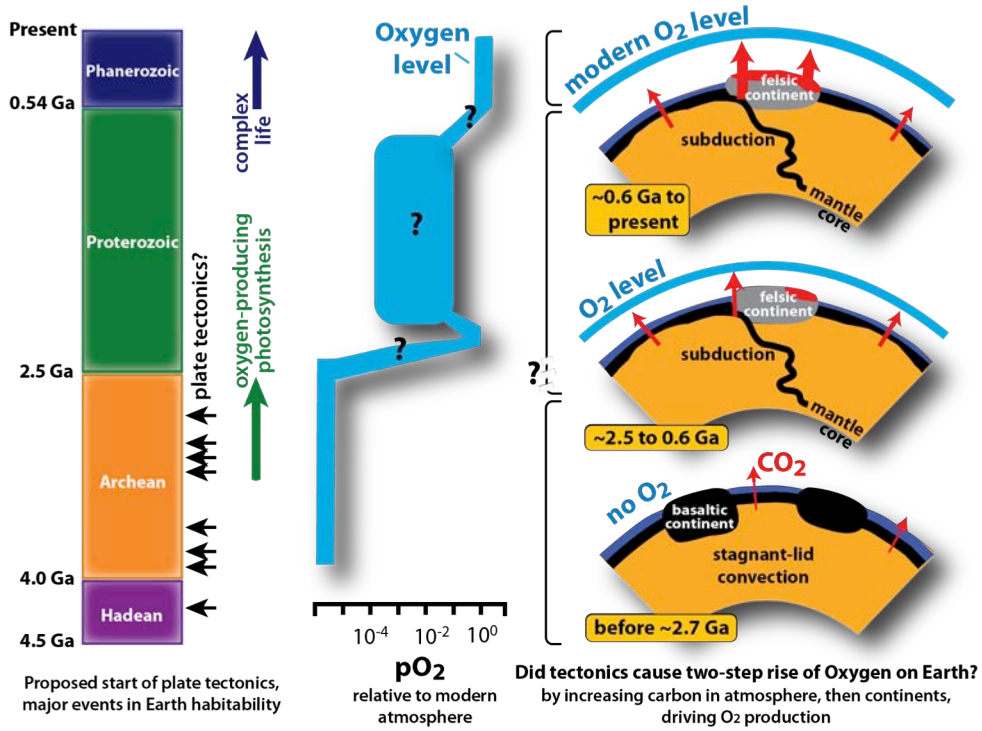


Figure 4

1.5 EXPLORING THE TECTONICS OF OTHER WORLDS

While lithospheric recycling through plate tectonics has limited the available rock record of early Earth, other bodies in our Solar System preserve similar features that can provide insight into our own planet's early history. Exploiting these commonalities to advance understanding of tectonics of both the early Earth and other worlds will require the careful integration of geodynamic modeling, remote sensing, and eventually extraterrestrial field geology.

The diverse zoo of planets and satellites in our Solar System exhibits a striking array of tectonic styles—some resembling Earth in part, but none in whole. While lithospheric recycling through plate tectonics has limited the available rock record of early Earth, these other bodies in our Solar System preserve features that can provide insight into our own planet's early history. For example, our Moon is a witness to how the impacts of asteroids and comets influenced surface processes and the earliest tectonics of the local Solar System, including Earth. Tectonic features visible on Venus also appear strikingly similar to those formed on Earth during Archean times. For example, Tellus Tessera (Venus) and the Pilbara Province (Western Australia), shown in **Figure 5**, both feature an ancient terrain consisting of deformed but coherent blocks separated by shear zones (highlighted by dashed lines). Later units, either volcanic plains on Venus or sedimentary cover on Earth, do not show a similar organization—evidence that both planets underwent changes in tectonic regime.

Tectonic processes on icy worlds, such as Europa and perhaps elsewhere in the outer solar system, may share some of the dynamics and kinematics of plate tectonics on Earth, although the "plates" are the fractured icy crust of these worlds and the driving forces for their interactions may be convection in warm, subsurface ice (Kattenhorn and Prockter, 2014).

A key challenge for Earth and the other terrestrial planets is to understand their early tectonic styles from the first ~1 billion years of their histories—a time in which increased levels of activity are expected, but from which little is preserved on Earth due to plate tectonics and elsewhere due to the high flux of impacts. Geodynamic modeling, remote sensing, and eventually structural field geology performed by robots and/or astronauts must be integrated to explore common features and processes across the Solar System to advance understanding of tectonics of both the early Earth and other worlds.

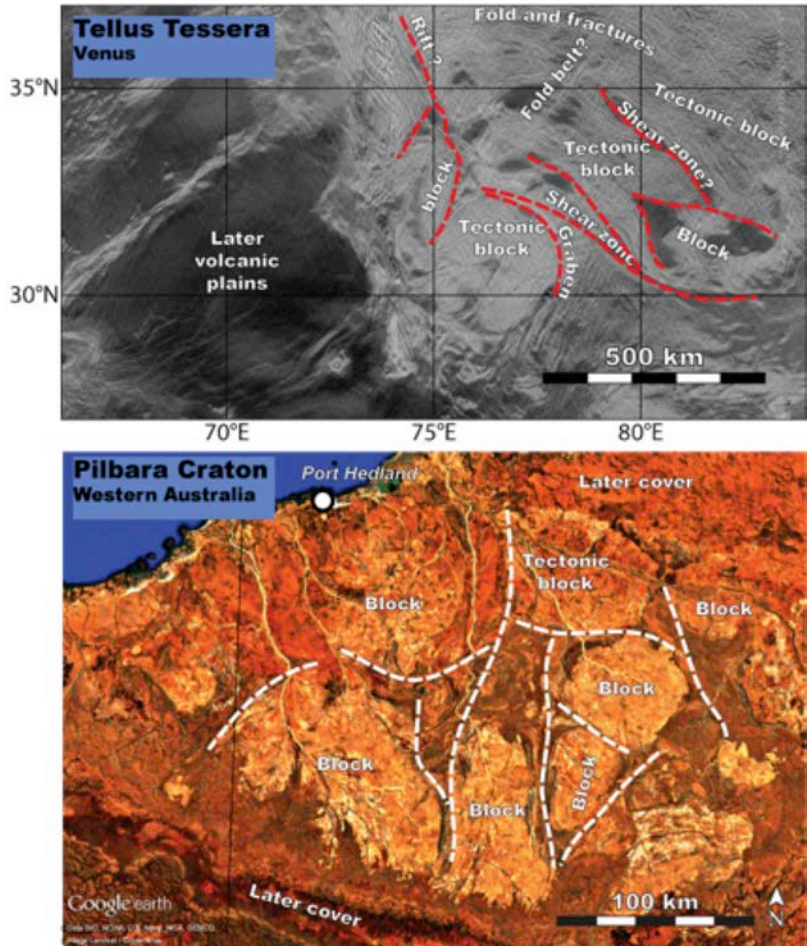


Figure 5

1.6 EXPLORING THE FOURTH DIMENSION OF TIME

Our understanding of virtually all tectonic principles and processes relies on having the ability to accurately determine the timing and tempo of events at scales ranging from billions of years to fractions of a second. New improvements to both established and emergent geochronometers leave the tectonics community poised to make major advances by allowing researchers to directly date a broader range of deformation features and to link processes occurring across different time and length scales in new ways.

Time is one of the great organizing principles in the geosciences, and is of special importance to tectonics in that the quality of our understanding of the interactions among geodynamical processes, the atmosphere, and the biosphere depends on the quality of our constraints on the timing and tempo of those processes. Fortunately, we are conducting research in an era of rapid technological development of instruments and dating techniques. The NSF-sponsored Earthtime initiative, for example, is designed to improve the level of reproducible precision across $^{40}Ar/^{39}Ar$ and U/Pb laboratories to 0.1% or less throughout geologic history, a goal sufficient to inform our understanding of temporal characteristics of most processes and their interactions in the realm of tectonics, from deep time (e.g., Praveen et al., 2016) to human time (e.g., Hutchison et al., 2016).

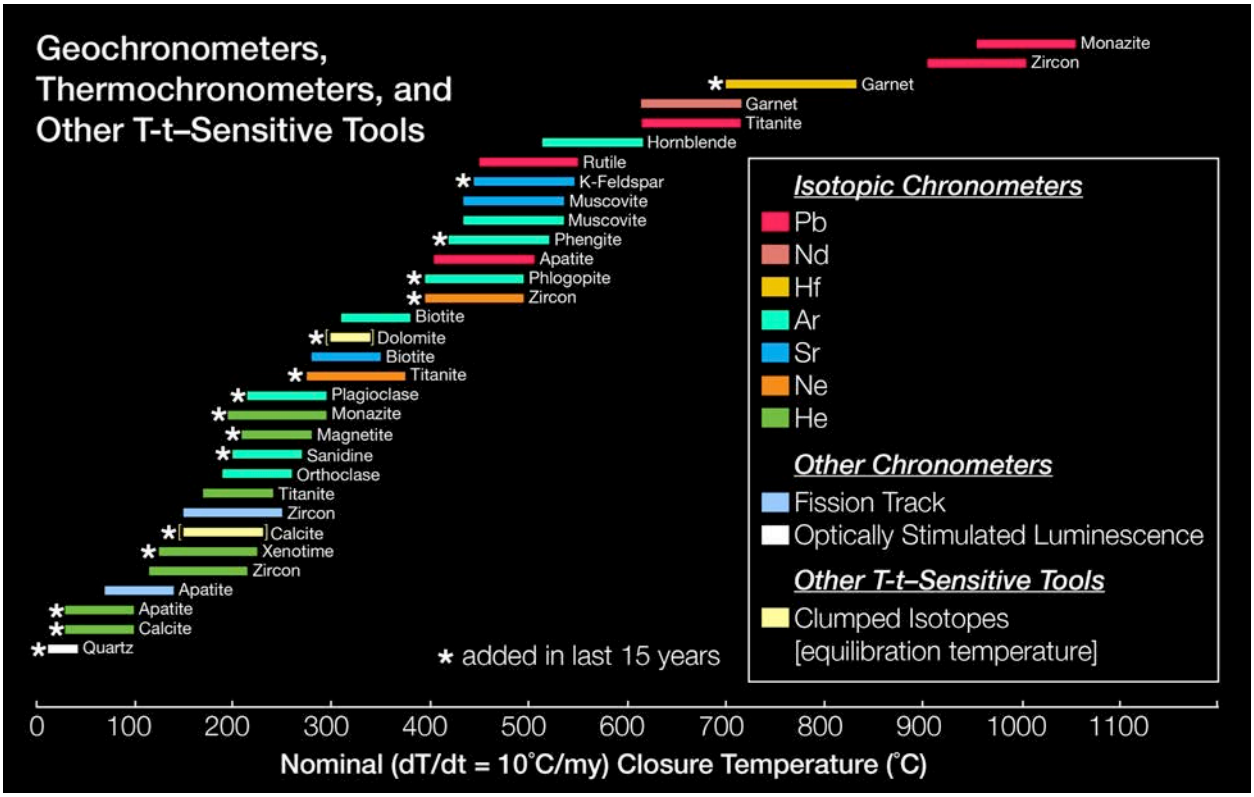


Figure 6

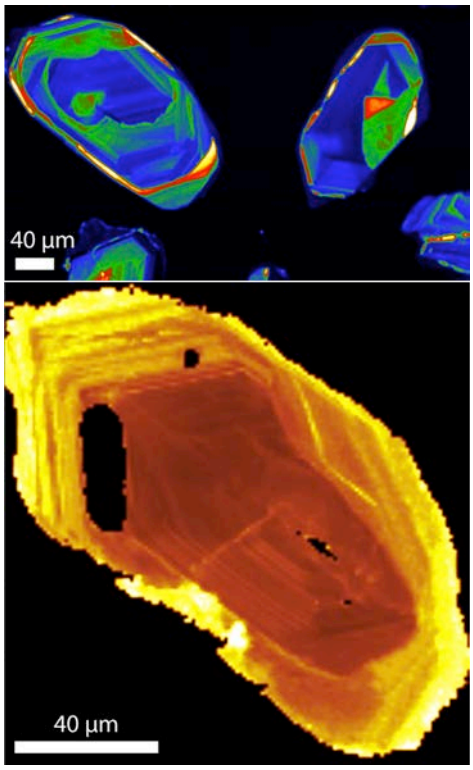


Figure 7

Ever improving accuracy and precision of dates and rates and access to new and increasingly small analytical targets are opening new areas of inquiry and providing insight into many of the questions outlined in this report. Geochronologic constraints on deformation rates are essential to field-based estimates of rheology, one of the properties of Earth materials that controls processes at all scales (***Grand Challenge 2***). Linking surface to deep-Earth processes from the outcrop to the plate scale is made possible by a broad toolkit of geo- and thermochronometers (***Grand Challenges 2, 3, 4***)—many of which have been developed in the last ~15 years (**Figure 6**) and/or enhanced by microanalytical techniques and chemical mapping of mineral heterogeneity (e.g., **Figure 7**, maps of zircon zoning from cathodoluminescence (top) and variations in radiation damage from Raman spectroscopy (bottom). For instance, analytical and conceptual advances enable us to deduce the provenance of sediments in foreland basins and active fluvial and glacial systems—as well as the erosional histories of those source regions, providing opportunities to link mountain building and sediment dispersal in developing orogens (Wang et al., 2014). At the regional scale, the integration of thermochronologic data from multiple chronometers with time-dependent thermal and kinematic models has transformed our ability to reconstruct the structural evolution of orogenic wedges in four dimensions (e.g., McQuarrie and

Ehlers, 2015) and understand the evolution of mountainous landscapes (Fox et al., 2015). New techniques such as K/Ar dating of fault gouge clays (Haines and van der Pluijm, 2008) and U/Pb dating of calcite in mineralized fault zones (Roberts and Walker, 2016) now permit the direct dating of brittle deformation features, just as the geochronology of minerals in petrographic context using advanced microanalytical techniques permit the dating of ductile deformational fabrics (Mottram et al., 2015). Such advances are revolutionizing the study of fault zone behavior (***Grand Challenge 3***) and its impact on human society (***Grand Challenge 5***). These are just some examples of how improvements to both established and emergent geochronometers position the tectonics community to make major advances understanding processes from microscopic to global in physical scale, and from geologic to human in timescale.

1.7 KEY QUESTIONS & REQUIREMENTS TO MAKE PROGRESS

Key questions include:

- How did the continents form and how have they persisted for billions of years to preserve records of tectonic processes and interactions?
- When and how did Earth transition to plate tectonics, and what was the role of tectonic processes in the origin and development of Earth's atmosphere, cryosphere, hydrosphere, and biosphere?
- What role do tectonic processes like spreading at mid-ocean ridges, mountain building and subduction play in changing long-term fluxes of volatiles, carbon and organic matter between surface systems and the Earth's interior?
- What processes and mechanical relations govern plate-like behavior of the lithosphere and the transition to geodynamics of the asthenosphere and deep Earth?
- Why and how do plate interiors deform in both continental and oceanic lithosphere, and how does this behavior relate to plate boundary deformation?
- How are continental and oceanic tectonics linked?
- What processes and mechanical relations govern the tectonics of other terrestrial planets and icy satellites, and how and why are they different from those on Earth?
- How do rates of tectonic processes vary through time and across time scales?

Requirements to make progress include:

- Facilitate collaboration and data integration among different sub-fields of the geological sciences to address global tectonic questions.
- Promote exploration of Earth's distant past, surface, deep interior, ocean and continental lithosphere using a range of geologic, geophysical, and geochemical approaches.
- Increase use of numerical and analog geodynamic models to simulate tectonic conditions that deviate significantly from the modern Earth, e.g., relevant to early Earth and other bodies in our Solar System.
- Facilitate interaction between funding agencies that support space research and funding agencies that traditionally support structural geology and tectonics research to promote geologic-based research on non-Earth worlds.
- Continue advances in, and broader application of, high-precision geochronology, including methods designed to:

- Constrain ages and rates of fault/shear zone movement at a variety of lithospheric levels.
- Quantify the rates of metamorphic reactions during deformation (and vice versa), and accurate P-T-t-d trajectories.
- Quantify the rates of surface exhumation, uplift, and exposure.
- Determine dates and rates over recent/short time scales relevant to studies of biologic change, and to structural geology and tectonics issues of societal importance including tectonic hazards and resources.

DRAFT FOR COMMUNITY COMMENT

GRAND CHALLENGE 2

UNDERSTANDING VARIATIONS IN RHEOLOGY THROUGHOUT THE LITHOSPHERE

2.1 OVERVIEW

One of the most important, long-term goals in tectonics is to develop a conceptual framework and quantitative description of how the solid Earth deforms. An improved understanding of this deformation is crucial, not only because it shapes the evolution of our planet across time scales ranging from microseconds to billions of years, but also because it directly impacts society through countless processes, including earthquakes, volcanic eruptions, changing landscapes, and the formation of natural resources. Our challenge is to quantify the mechanical properties of rocks (i.e., rock rheology) and to understand how rheology controls both the physical and chemical evolution of the solid Earth through deformation processes. All aspects of this deformation—regardless of whether it involves mountain-building caused by the slow motion of tectonic plates, surface rebound following the melting of ice sheets, the rise of magma to feed volcanoes, or the near-instantaneous movements on faults during earthquakes—is governed by the rheology of deforming rocks.

Despite decades of research, we are still only in the initial stages of understanding the interactions that occur among the different layers of deforming lithosphere. Part of the challenge is that rock rheology is influenced by so many variables, including both intrinsic rock properties (mineralogy, grain size, fluid chemistry and content) and external factors (temperature, depth, stress, strain rate). **Figure 1** illustrates how the results of physical experiments constrain the mechanisms by which common minerals, in this case olivine, deform as a function of these variables (e.g., Warren and Hirth, 2006). Such data are used to formulate flow laws that can be tested in the natural world and refined through further experiments. Yet the intricacy of the diagram also highlights the challenge we face in trying to apply the results of laboratory experiments to the lithosphere where the full range of stress, strain rate, rock composition, crustal architecture, temperature, and other factors typically is not well defined and can vary over the course of a single

Deformation mechanisms for olivine in dry, melt-free peridotite at 700°C-1100°C

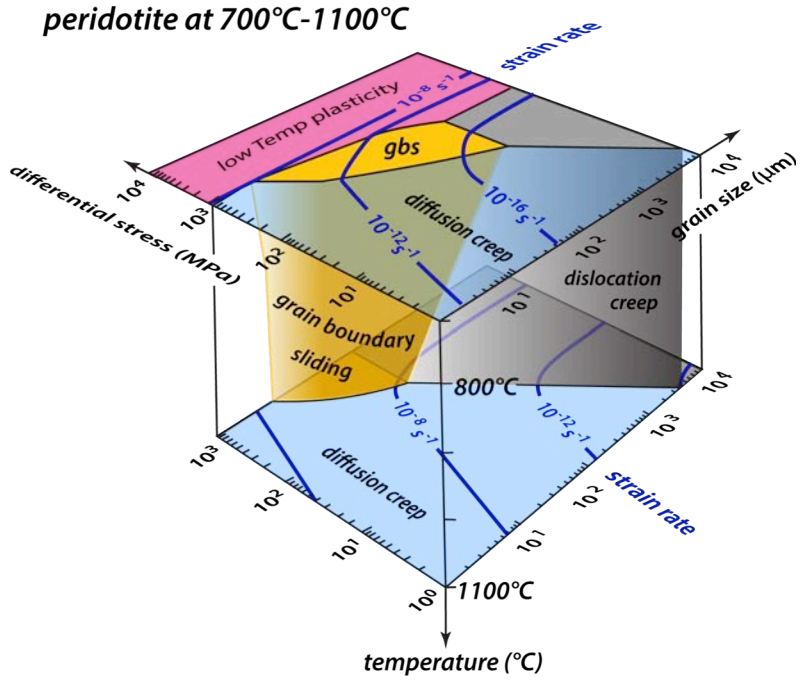


Figure 1

deformation event. One of our primary goals as a community is to reduce these uncertainties so we can make more accurate and precise predictions about tectonic processes.

In the last few years, we have become poised for breakthroughs, in part because of recent improvements in instrumentation and computing, and also because researchers from once separate communities (e.g., Talbot, 1999) have begun to work together and share data in new ways. Many new tools and approaches to studying rock rheology have been developed in the last 15 years, including experimental apparatuses (**Figure 2**) that simulate shear on fault surfaces at seismic slip rates and other improvements highlighted in the examples below. These advances, together with an enhanced capacity to combine experimental data with field-based observations and the results of numerical models, place us on the threshold of better understanding, explaining, and predicting the internal movements of the solid Earth.

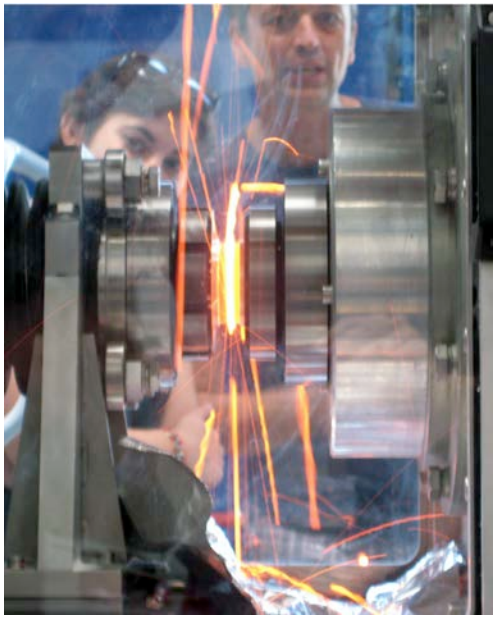


Figure 2

Here, we explore four examples of research where we are making progress toward this goal. For decades, we relied on simple, steady-state descriptions of stress-strain relationships, despite being conceptually aware that both deformation and the mechanical properties of rocks can be highly transient. We are now in a position to combine observations derived from the rock record, experiments, and modeling to move beyond this simplifying assumption of steady state, with an achievable goal of quantifying the behavior of the solid Earth during transient, short-term deformation (***Section 2.2***). This achievement will help us understand phenomena as diverse as slow earthquakes and the deformation-induced flow of both hydrothermal and magmatic fluids. New approaches to measuring strain rate are helping us quantify how lithospheric rheology controls tectonic movements, including where and how deformation localizes (***Section 2.3***). ***Section 2.4*** explains why the deep crust is as a critical target for future rheological studies, made possible by advances in our understanding of how metamorphism and deformation interact. The final example (***Section 2.5***) highlights the importance of exploring the vertical linkages among processes operating at different lithospheric depths to understand the evolution of plate boundaries, orogens, and other tectonic systems. In all of these examples, the ability to integrate information derived from the rock record, geophysical observations, microstructural analyses, deformation experiments, and both analog and numerical modeling provides a promising framework for investigating how rheology varies through both continental and oceanic lithosphere (***Section 2.6***).

2.2 BEYOND STEADY STATE: TRANSIENT DEFORMATION AND THE RHEOLOGY OF THE LITHOSPHERE

Deformation that occurs on short time scales within a longer deformation event characterizes a wide range of Earth processes, including post-seismic stress decay in the crust and mantle, deformation-induced magmatic and hydrothermal fluid flow, and seismic triggering. The path to understanding these and other

examples of "transient" deformation and their relationship to rock rheology lies in integrating information from deformation experiments, numerical models, and the rock record.

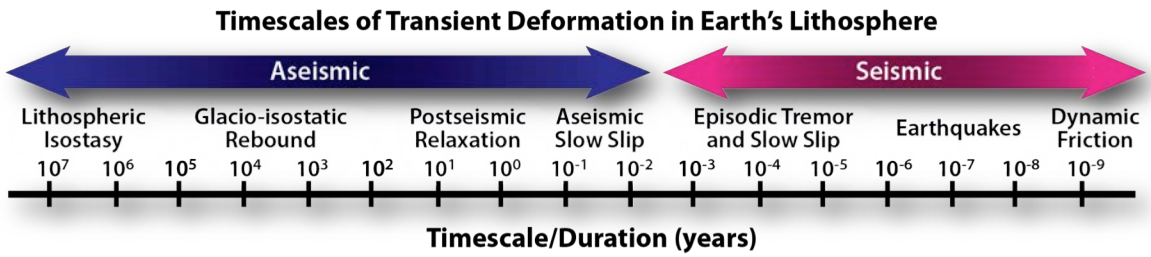


Figure 3

The rheology of Earth's lithosphere is highly sensitive to the rates and timescales of deformation. A wide range of Earth processes are transient, or relatively short-lived, though they respond to longer-lived tectonic or climatic forcing. Transient processes include post-seismic stress decay, deformation-induced magmatic and hydrothermal fluid flow, seismic triggering, and the drivers of earthquake supercycles. Glacier retreat has long been known to induce viscoelastic responses within the upper mantle over thousands of years. Similar effects on decadal to hundred-year timescales have been documented more recently in the lower crust and upper mantle following large-magnitude earthquakes (e.g., Freed et al., 2012). On shorter timescales, annual monitoring of subduction zones and strike-slip faults reveals the existence of slow earthquakes that propagate at rupture speeds of km/day, commonly accompanied by the quiet chatter of low frequency earthquakes and non-volcanic tremor. Even within the timespan of a millisecond during an earthquake, transient deformation is the rule, revealing that the coefficient of friction is dynamic and highly sensitive to sliding velocity. Observations like these highlight a fascinating spectrum of non-steady-state deformation phenomena that have long-term consequences for lithospheric evolution (**Figure 3**; Thatcher and Pollitz, 2008).

Within this spectrum, geodetic, seismological, and geological observations are revealing new examples of deformation behaviors that deviate substantially from steady-state conceptions. GPS observations during the seven years following the 1999 Hector Mine, California, earthquake show fast, early post-seismic displacement rates that are poorly fit by steady-state mantle flow laws (e.g., Freed et al., 2010). Evidence of transient deformation also is visible in the rock

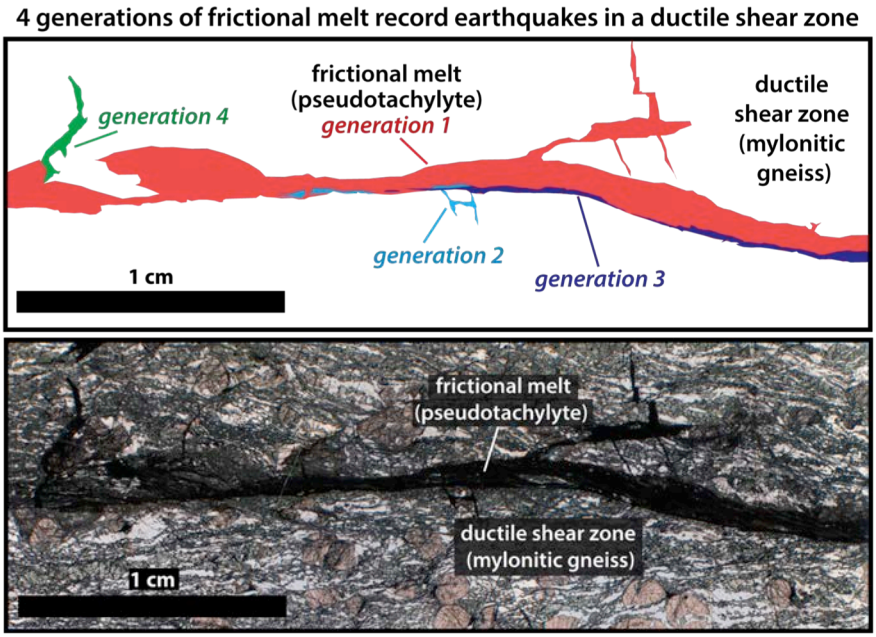


Figure 4

record, from near-surface environments to deep regions well outside the classically defined seismogenic zone—e.g., melts (pseudotachylyte) generated by high-velocity slip at depths (e.g., 20-40 km) where ductile flow typically dominates (White, 2012; Regan et al., 2014; **Figure 4**). These and other recent discoveries compel the tectonics community to go 'beyond steady state' when it comes to deciphering the rheology of the Earth's lithosphere. Key unanswered questions include: what are the types of tectonic environments and conditions under which transient rheologies deviate from steady-state formulations? How can we quantify these behaviors? How do we recognize the signatures of transient processes in the rock record?

Other recent work suggests that the path to understanding transient deformation and its relationship to rock rheology lies in integrating information from deformation experiments, numerical modeling, and the rock record. Deformation experiments provide quantitative information on the mechanical properties of Earth materials and unique insights into the microphysical mechanisms by which strain is accommodated. However, to fully capture the complexity of natural deformation we also must utilize the rock record, which provides our only direct means of determining the long-term rheology of the lithosphere in a tectonic context. The interdependence between experimental and field-based approaches is illustrated by a recent comparison of microstructures in peridotites deformed naturally versus experimentally at upper mantle conditions (Druiventak et al., 2012). The comparison shows that peridotite microstructures commonly interpreted to indicate steady-state dislocation creep in naturally deformed rocks (e.g., recrystallized grains along intragranular microfaults in **Figure 5**) can form by a sequence of transient high-stress deformations that simulate coseismic deformation and post-seismic creep. Numerical modeling provides the context for interpreting observations of experimentally and naturally deformed rocks—for example, by providing insight into how chemical reactions and the evolution of grain size during deformation and metamorphism result in time-dependent rheological behaviors (e.g., Gardner et al., 2017).

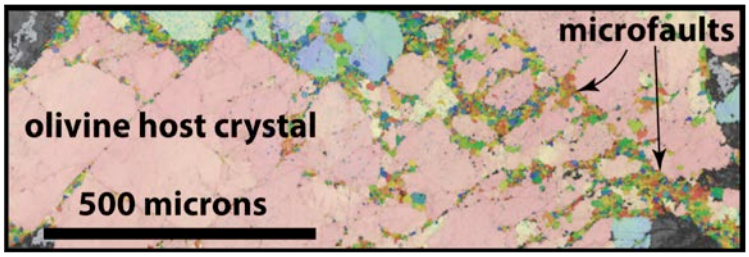


Figure 5

Groundbreaking insights like these show the utility of combining approaches that have traditionally been undertaken separately. Through this integration, capitalizing on technological advances, and expanding our ability to identify and interpret meso- and microstructures, the tectonics community is advancing our understanding of transient and non-steady-state rheologies.

2.3 MEASURING STRAIN RATES IN THE DUCTILE CRUST: A KEY TO QUANTIFYING LITHOSPHERIC RHEOLOGY

Measuring strain rate and determining its relationship to ambient stress and strain is essential to understanding the rheology of naturally deformed rocks. New analytical tools and experimental approaches promise to improve our ability to quantify natural strain rates in the ductile crust and determine how rheology varies through the lithosphere.

One of the most difficult parameters to determine in tectonic systems is the rate at which deformation occurs in the deeper parts of the lithosphere. Nevertheless, obtaining these strain rates, and determining their relationships to ambient stresses and strains, is essential to understanding the extent to which strain localizes in the crust and upper mantle. Strain rates in the ductile lithosphere

sometimes can be inferred using geophysical data, but the most promising, direct methods are rooted in field observations and involve the application of sophisticated analytical and geochronologic tools. In an example from the Ailao Shan-Red River shear zone, China, Sassier et al. (2009) obtained ductile strain rates from a single outcrop of mylonitic crust using high-precision ion probe dating techniques and measures of shear strain from deformed dikes (**Figure 6,** top panel). Boutonnet et al. (2013) then used measures of differential stress (σ) from recrystallized quartz grain sizes (D), and calculations of deformation temperatures (T) from titanium contents in quartz, to find the best rheological flow law that yielded strain rates identical to those measured by Sassier et al. (2009) (**Figure 6**, bottom panel). The application of this method to other parts of the shear zone (**Figure 6**, right panel) showed how strain rate varied across the structure and related to areas of diffuse versus localized strain. Studies like this highlight the utility of combining field-based measurements, high-precision geochronology, single mineral thermometry, and laboratory-derived flow laws to investigate strain rate variations over both space and time in the deep parts of deforming systems.

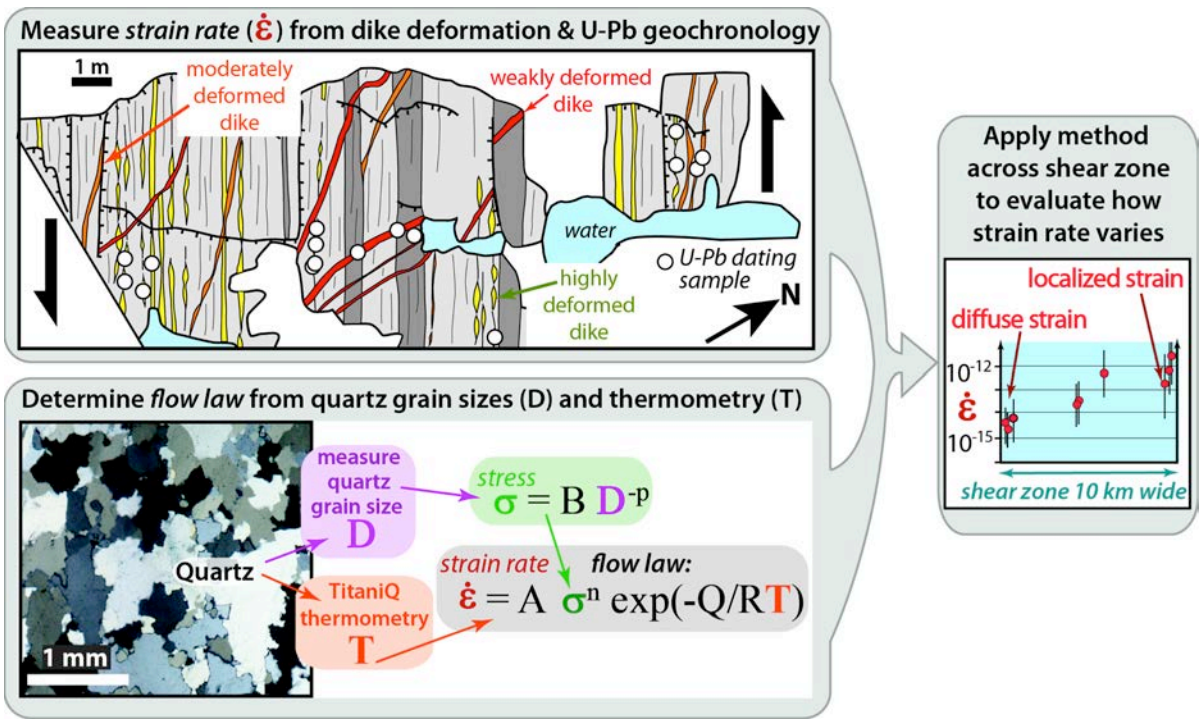


Figure 6

Another key challenge in determining natural strain rates from exhumed ductile crust is that rocks are inherently heterogeneous and anisotropic over virtually every spatial scale, which commonly results in the partitioning of strain (and strain rate) on multiple scales. This characteristic may be one reason why rheological estimates for polyphase materials, despite being of long-standing interest, have proven elusive. More studies aimed at determining how stress, strain, and strain rate vary across compositionally heterogeneous regions are needed to solve this problem. New techniques, including both statistical approaches and numerical modeling, hold great promise for characterizing natural deformation and recasting these kinematic variables in terms of their relationships to rheology. For example, we have long known that the simple shear component of general shear can be accommodated by the weakest phase(s) in a polyphase system. By combining novel statistical and numerical approaches, we can explore such key problems as the magnitude of rheologic contrast required for kinematic partitioning in shear zones.

The novel use of technology and instrumentation also is allowing us to address both new and long-standing problems. Electron backscatter diffraction (EBSD) techniques, for example, have revolutionized microstructural analyses, not only by making it possible to determine the crystallographic preferred orientations (CPO) of minerals across entire thin sections quickly and easily, but also by allowing researchers to explore the character and mechanical significance of grain boundaries, and quantify important parameters such as recrystallized grain size. By integrating these and other data obtained common "workhorse" instruments (e.g., electron microprobes, SEM/EBSD/CL systems, LA-ICP-MS and ion probe instruments) with information obtained through less commonly available instruments and technology (e.g., neutron diffraction, atomic force microscopy, X-ray computed tomography), we can ask higher order questions and better explore physical and chemical processes operating in the deep, ductile parts of the lithosphere.

2.4 THE DEEP CRUST AS A 'CRITICAL' REGION FOR RHEOLOGICAL STUDIES

The deep part of the Earth's crust is as a 'critical' region for rheological studies because it is a physical and chemical link between processes operating in the mantle and those occurring in the region between the middle crust and the surface. Advances in our understanding of how metamorphism and deformation interact in the lower crust, combined with improvements in our ability to image and probe natural materials at the meso- and microscales, are building our knowledge of this important region.

The deep part of the Earth's crust acts as a 'critical' region within the lithosphere because it connects physical and chemical processes operating in the mantle to tectonic activity occurring in the middle and upper crust and at the surface. Metamorphic, magmatic, and deformation events within this region ultimately drive the transfer of mass and heat through continental and oceanic lithosphere. Our challenge in trying to understand the deep crust is to determine how all of these processes, and

Melt flows through rock at a wide range of scales

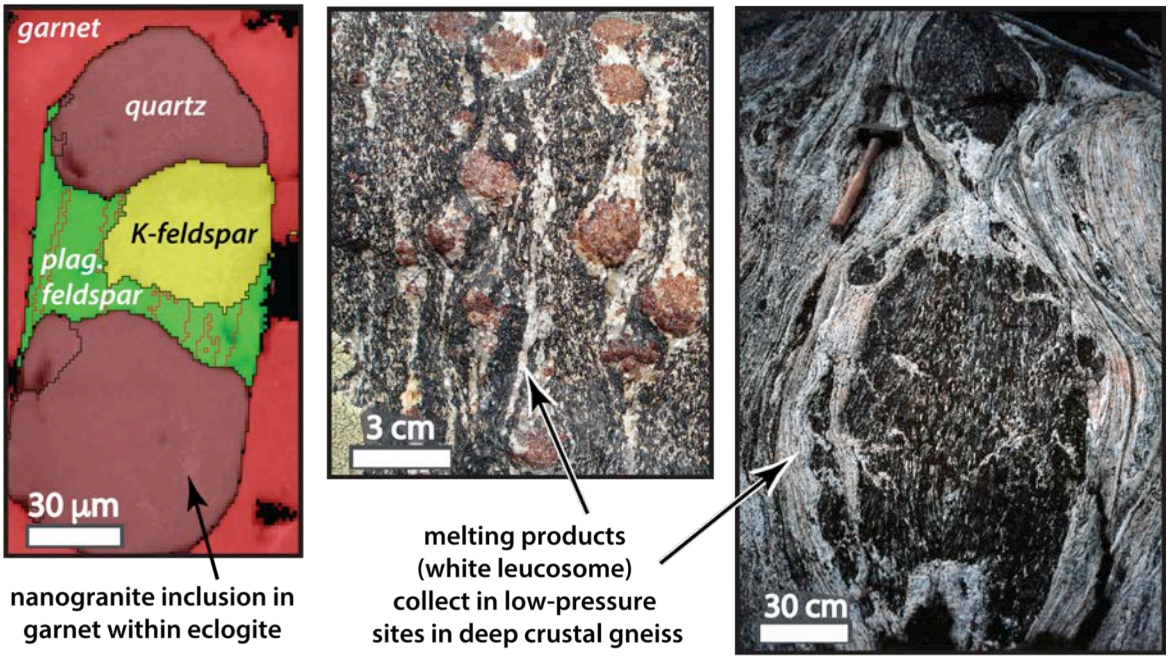


Figure 7

rock rheology, interact with one another to influence the mechanics of deforming lithosphere. Many recent advances obtained through experimental, field-based, and modeling work, show that compositional and mechanical contrasts in the deep crust impact stress and strain-rate fields, which can then influence whether metamorphic and melting reactions occur and go to completion. Melts move through rocks at all scales, and once present profoundly influence crustal strength and deformation partitioning in space and time; **Figure 7**, for example, shows how the products of crustal melting form inclusions inside refractory minerals such as garnet and segregate into low-pressure sites that result from mechanical processes such as boudinage (Flowers et al., 2006; Miranda and Klepeis, 2016). A key focus of current work is to develop new approaches for obtaining quantitative information on how chemical reactions, thermal conditions, the presence or absence of fluids and melt, and the mineralogical states that exist in the deep crust are linked to its rheology.

Exposures of crust and mantle exhumed from ancient and modern plate margins provide an important, and otherwise inaccessible, record of the compositional variations, chemical reactions, and deformation mechanisms that occur deep within the lithosphere. The high degree of compositional heterogeneity revealed by recent compilations of lower crustal records (Hacker et al., 2015) emphasizes the need to determine how different types of heterogeneities impact deformation, metamorphism, and rheology. Yet most of what we know about interactions between deformation and metamorphism is based on a range of mineral assemblages and lithologies that is far too narrow to represent the bulk rheological properties of the deep crust in all settings. Another impediment is that experimental studies relevant to the deep crust, especially those that incorporate melting, are extremely challenging and still in their infancy. This problem persists because most deformation experiments must be performed at exaggerated temperatures in order to allow ductile deformation and observe reactions at accessible timescales.

To solve these problems, the tectonics community is building on recent technological advancements and innovative experimental designs, as well as a more robust understanding of the links between chemical and physical processes. Higher accuracy and precision are now possible in a wide range of measurements on both naturally and experimentally deformed rocks. A variety of new approaches are helping us circumvent the trade-offs between temperature and time/strain rate in experiments; improving our ability to quantify the rates of metamorphic and deformational processes; relate age to depth (barochronometry); and construct more accurate pressure-temperature-time-deformation (P-T-t-d) paths for deep crustal materials (e.g., ***Section 2.3, 2.5***). The latter has been a mainstay of petrologic and tectonic research for decades, and it remains a keystone of future work. The continued exploration of exhumed materials, combined with our improved ability to conduct experiments and to study how deformation and metamorphism interact at the meso- and microscales, will further our understanding of deep crustal rheology.

2.5 LINKING THE RHEOLOGY OF DEEP THROUGH SHALLOW PARTS OF TECTONIC SYSTEMS

Connecting the rheological elements of deep through shallow parts of tectonic systems requires studies at a wide range of scales, from microns to mountain ranges. New advances in both our understanding of processes of metamorphism and deformation, and the composition and microstructure of rocks and minerals, are helping us better explore dynamic linkages among the processes that effect these links at different depths within the lithosphere.

The vertical connections that develop among different layers of deforming lithosphere affect the evolution of virtually every tectonic system on Earth, from subduction zones and orogens (e.g., ***Grand Challenges #1, 4, 5)*** to zones of rifting and large continental faults (e.g., ***Grand Challenge #1, 3***). Determining how these connections develop and evolve through time requires an advanced understanding of the rheology of deforming rocks from the upper crust to the mantle. Over the past few years, our community has improved its ability to integrate information derived from deformation experiments, geophysical investigations, and field-based studies using sophisticated numerical models. These models allow us to investigate quantitatively how physical and chemical processes operating at different depths interact with one another. Most models rely on rheological formulations derived from physical experiments along with assumptions about geotherms, material properties and other factors to describe the magnitudes, trajectories, and timescales of heat and mass transfer through the lithosphere. Consequently, future studies aimed at improving these framework variables will advance our knowledge of the links that develop between the deep and shallow parts of tectonic systems.

The study of regions where the deep crust has experienced partial melting (e.g., ***Section 2.2***) illustrates that the rheologies of lithospheric layers and their vertical connections change over time. In such settings, the superposition of tectonic stress related to the displacement of neighboring plates or crustal blocks, and stress generated by lateral variations in gravitational potential energy, lead to a strong vertical partitioning of strain. **Figure 8** shows examples of two crustal columns undergoing extension and partial melting in which brittle thinning of the upper crust forces ductile flow in the deep (lower) crust, leading to the formation and exhumation of migmatitic (partially molten) gneiss domes. The upper panel is from a computer simulation (Rey et al., 2017) that shows how flow patterns within deep, partially molten layers both depend upon, and affect, the degree of mechanical coupling between strong mantle and upper crustal layers. The lower panel shows a field example from the northwestern United States where a migmatitic gneiss dome formed and was exhumed beneath an extending brittle upper crust (Kruckenberg et al., 2008). Used together, field and numerical studies are

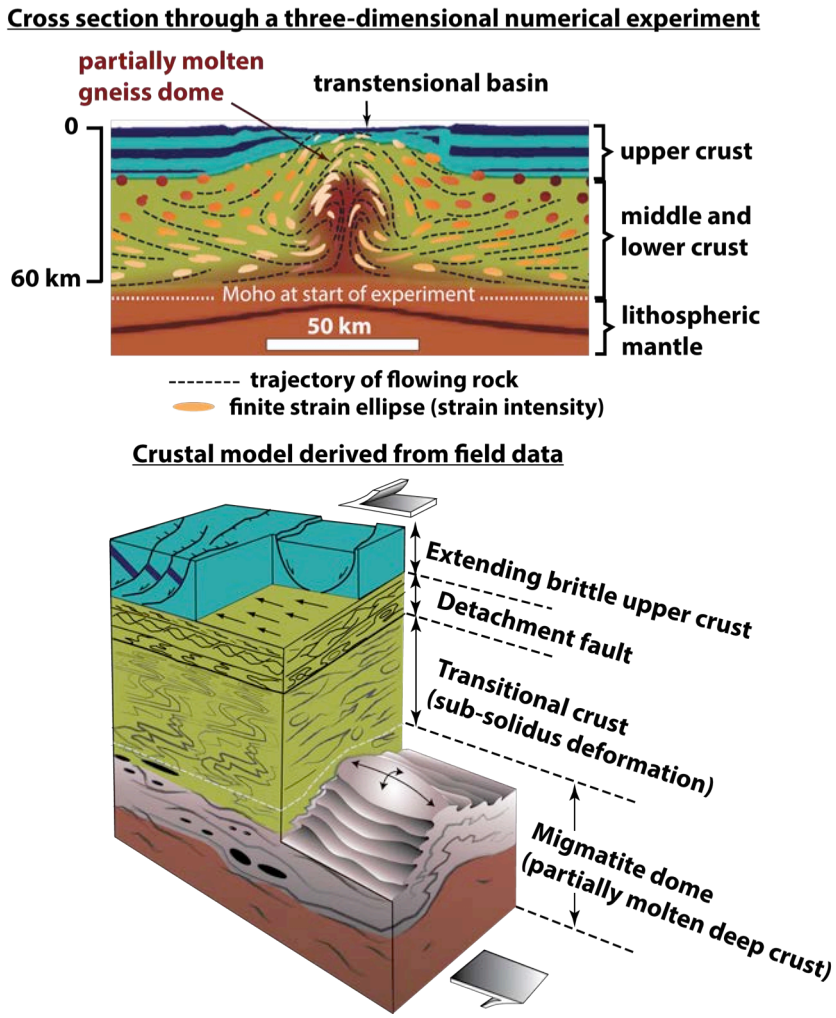


Figure 8

especially powerful for studying the vertical links that develop among processes operating at different depths within the lithosphere.

To fully understand these dynamic links, we must integrate both the physical and chemical properties of materials that react and deform over a range of pressure-temperature conditions. Over long spatial and temporal scales, mass and heat transport occur throughout the lithosphere, creating and modifying minerals, fluids, and melt, and ultimately driving interactions among the solid Earth, landscape, atmosphere, hydrosphere, and biosphere (e.g. ***Grand Challenge #4***). Although conceptual models exist for particular geological settings, better records of contemporaneous stress, strain, strain rate, and viscosity profiles through the crust are needed to quantify the mechanical connections between the deep and shallow parts of tectonic systems. To achieve this, future investigations will benefit from the discovery and use of exhumed cross sections (e.g., **Figure 7)** and other forms of deep sampling (e.g., xenoliths, magmatic records, geophysics) where combinations of field- and lab-based tools can be used to study the relationships among the layers of continental and oceanic lithosphere.

2.6 KEY QUESTIONS & REQUIREMENTS TO MAKE PROGRESS

Key questions include:

- How do deformation processes and mechanical flow laws vary with volatile abundance, metamorphic reactions, partial melting, and microstructural evolution?
- To what degree and on what timescales are rock rheologies transient?
- What physical experiments provide the most insight into the effects of mineral properties and distributions on steady-state and transient rock rheology?
- How well do microstructures and textures observed in physical experiments represent the same formative processes as those observed in nature?
- What are the kinematic and dynamic roles of the deep crust in connecting the mantle and upper crustal realms?

Requirements to make progress include:

- Facilitate collaboration and data integration among scientists who develop models, conduct rock deformation experiments, remotely sense, and observe naturally deformed rocks at all scales.
- Develop new deformation apparatus to expand the rates and conditions of frictional sliding, fracture, and flow experiments.
- Facilitate multi-perspective studies in exemplar, compositionally heterogeneous field areas to derive rheological properties from natural observations.
- Improve the use of high-precision geochronologic tools to quantify strain rate fields.
- Promote computationally based 3D/4D, micro- to macroscale derivation of physical and chemical properties of heterogeneous materials in deforming systems.

DRAFT – FOR COMMUNITY COMMENT

GRAND CHALLENGE 3

UNDERSTANDING FAULT ZONE BEHAVIOR FROM EARTH'S SURFACE TO THE BASE OF THE LITHOSPHERE

3.1 OVERVIEW

Faults and shear zones are the fundamental structures that accommodate large displacements within Earth's lithosphere. These phenomena in turn govern the broad-scale patterns of Earth deformation, the formation of tectonic plate boundaries and the subsequent evolution of plate tectonics. Faults and shear zones act as the plumbing system of the lithosphere, substantially influencing heat and mass transfer through Earth's crust. Although faults are best known as the source of fast slip during earthquakes, they also exhibit important episodes of slow slip and aseismic creep that release energy over a period of hours to years—in what we now recognize is a broad spectrum of behavior accommodated by processes ranging from cataclasis to dislocation creep.

Traditionally, "faults" are defined as the near-surface expressions of localized deformation, while "shear zones" are the deeper, higher temperature expression of localized strain. This convention is useful for dividing the lithosphere into seismic (brittle) and aseismic (ductile) regimes. However, it is now well established that both "brittle" and "ductile" features occur throughout the full extent of fault/shear zone systems that span the lithosphere. This important conceptual advance is enabling us to reintegrate the study of faults and shear zones in a comprehensive model of fault zone evolution that links to surficial processes and the seismogenic cycle (**Figure 1**), with far-reaching implications for human society's access to resources and resilience in the face of tectonic hazards (***Grand Challenge #5***).

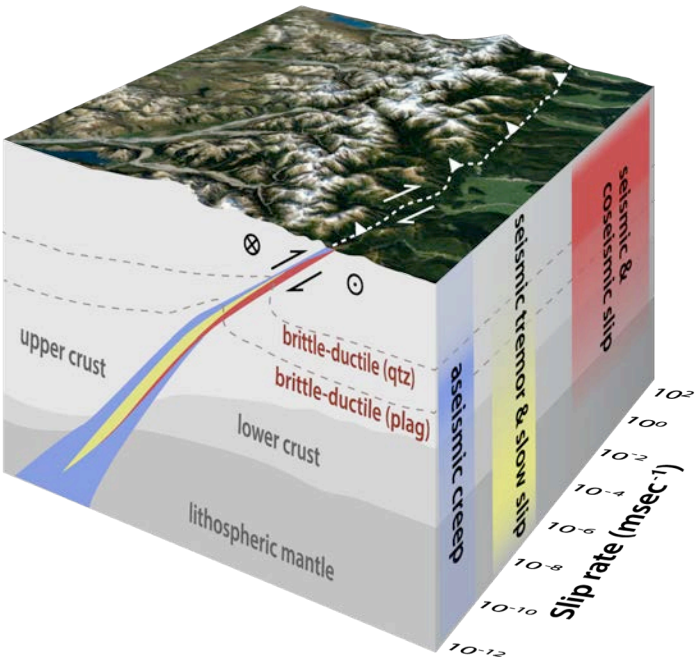


Figure 1

Uncovering the connections among fault slip behavior, heat and mass transfer, and the development of deformation structures that traverse the lithosphere requires a full arsenal of research tools. These include field and petrographic observations, rock deformation experiments, geochemistry and geochronology, and physical and numerical models—each of which contributes quantitative constraints on fault zone processes. Together these approaches are enabling us to connect the spectrum of fault slip behaviors revealed by geophysical observations to the geologic structures preserved in fault rocks. New discoveries in these areas are driving re-examination of long-held hypotheses regarding the rates and conditions of faulting, from Earth's surface to the base of the lithosphere.

These problems demand interdisciplinary approaches. Here we highlight examples of how the tectonics community is bridging disciplinary boundaries to advance our understanding of fault zones. Developments in topographic imaging, geochronology, and surface process modeling continue to provide insights into the Earth-surface record of fault zone evolution, from earthquake cycle deformation to the cumulative effects of faulting on landscapes over millions of years (***Section 3.2***). Progress in understanding the spectrum of fault behavior, combined with advances in fault rock studies, shows that rocks preserve a much richer record of earthquake rupture and other slip behaviors than previously thought, opening up new areas of inquiry into fault zone complexity using earthquake science (***Section 3.3***). Throughout the lithosphere, we are quantifying interactions and feedbacks between fluids, slip behavior, and the development of fault structure and crustal strength. This work is being advanced by combining structural geology, geochemistry and geochronology in ways that cross customary "brittle-ductile" disciplinary divisions (***Section 3.4***). Analog/physical and numerical models bridge the gap between theory and observations of natural rocks in the field and lab to help us understand fault zone changes through time (***Section 3.5***). Our ultimate goal is a comprehensive understanding of fault zone evolution through time and in three spatial dimensions. To reach this goal, we must understand how deformation is linked vertically through the full thickness of the lithosphere. Advances will come through the careful integration of the rock record with experimental data and numerical models that incorporate the composition, microstructure, fluid content, and rates of processes in natural fault zones (***Section 3.6***). In all areas, new and expanded collaborative research tools, digital databases, and instrumentation facilities can accelerate research progress (***Section 3.7***).

3.2 THE EARTH-SURFACE RECORD OF FAULT ZONE EVOLUTION FROM RUPTURE TO MOUNTAIN BUILDING

The Earth-surface record of fault zone evolution allows us to examine processes over timescales from a single earthquake rupture to the integrated effects of faulting over millions of years. New and expanded collaborative research tools, digital databases, and facilities will drive research progress.

Availability of topographic and geodetic information at fine spatial and temporal scales enabled a new generation of research on active faults in recent decades, and these data continue to fuel discoveries. Beyond simply documenting earthquake rupture, Earth-surface changes recorded by InSAR and GPS can document aseismic "afterslip" in the ensuing days to months. Such "real time" tectonics studies following the 2014 South Napa California earthquake showed tens of centimeters of aseismic slip at the surface that was maintained to several km depth (Floyd et al., 2016). GPS observations show continued post-seismic motion a quarter century after the 1989 Loma Prieta California earthquake, permitting estimates of viscoelastic relaxation (and thus the rheology) of the lower crust and deeper fault zone behavior (Huang et al., 2016; see also ***Grand Challenge #2***). Quaternary active faults relevant to earthquake hazard (***Grand Challenge #5***) continue to be discovered and mapped with airborne LiDAR, including Holocene scarps in British Columbia, Canada, where young faults trace but do not completely reactivate a major crustal fault (Morell et al., 2017). In addition to fault zone mapping, analyses of high-resolution topography allow us to reconstruct surface deformation including offset, measure co-seismic deformation both on and off fault using differencing of repeat surveys (e.g., Milliner et al., 2015), and investigate geomorphic responses to active deformation. Topographic data acquired by space- or ground-based surveys and photogrammetry also are essential tools for documenting geomorphic features that capture the longer-term evolution of fault systems (e.g., Zielke et al., 2015).

Numerical models combined with constraints on the rate and timing of surface change are advancing our ability to interpret topographic data by clarifying the interplay between tectonic and geomorphic processes. Such effects have been demonstrated through low-temperature thermochronology studies that reveal the role of the Denali Fault system and lithologic contrasts across it in producing the highest mountains in North America (Benowitz et al., 2013; Fitzgerald et al., 2014). When combined with landscape evolution models, similar thermochronologic studies in New Zealand reveal the surprising role of Pliocene strike-slip faulting in rejuvenating relief in the rugged Inland Kaikoura Mountains, and in producing landforms previously attributed to vertical faulting (**Figure 2** middle and right panels; Duvall and Tucker, 2015). In the same fault system, the Earth-surface record of the 2016 magnitude 7.8 Kaikoura earthquake (e.g., scarp in **Figure 2** left panel) unexpectedly shows that rupture occurred along at least a dozen separate fault segments (Hamling et al. 2017)—challenging assumptions about how faults segments interact. This earthquake also triggered landslides and altered river courses, leaving a landscape record beyond the fault scarps themselves.

Interpreting the Earth-surface record of fault zone evolution from earthquake to mountain building

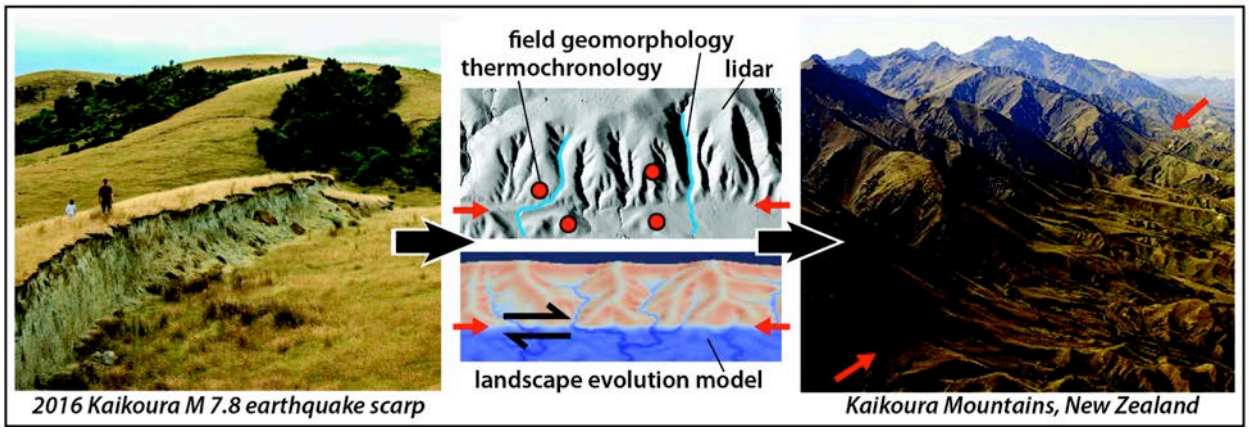


Figure 2

Earth-surface records of fault zone evolution enable us to examine tectonic processes over timescales from a single earthquake rupture to the cumulative effects of displacement over millions of years along mature, highly evolved fault zones (e.g. **Figure 2**). To maintain momentum and accelerate advances in these areas, we need broader access to high-resolution topographic and geodetic data and imagery, expansion of and support for geochronologic facilities, and investment in community modeling tools for tectonic and surface processes.

3.3 THE ROCK RECORD OF EARTHQUAKES AND SLOW SLIP

Understanding the full spectrum of active fault behavior requires integrating geophysical observations with the geologic record of those behaviors. Fault rocks preserve a much richer record of fault behavior than we once thought possible, and recent discoveries provide a template for integrating field, laboratory, and theoretical approaches to advance understanding of fault zone behavior and complexity.

Understanding the full spectrum of active fault behavior—from earthquakes to aseismic creep—requires integrating geophysical observations with the record of those behaviors preserved in fault rocks. Rocks preserve a much richer record of seismic slip than we once thought possible, and a variety of recently developed field and laboratory methods have expanded the tool-kit of earthquake

signatures. Many of these signatures are based on dynamic fracturing driven by fast-propagating and fast-slipping faults during earthquakes, and the related heat production (reviewed in Rowe and Griffith, 2015). Subtle fault heating in sedimentary rocks can now be identified using geochemical or spectral proxies for the thermal maturity of organic matter (Savage et al., 2014; Hirono et al., 2014), and it is possible to date hematite fault rocks that record seismicity up to millions of years in the past (Ault et al., 2015). Such innovative techniques provide direct evidence of seismic slip in the rock record—and on particular structures within a fault zone that can be dated—opening up new areas of inquiry for earthquake science.

Evidence in the rock record of newly discovered slip behaviors like slow earthquakes and aseismic creep is more difficult to identify, as we lack constraints on the structures that form during these events. Identifying the signatures of these slip modes is necessary for a complete description of fault behavior and to constrain the mechanical conditions necessary to cause fault slip and generate earthquakes. Encouragingly, recent work is pushing this frontier with observations of natural exhumed fault rocks that may record signatures of slow slip, aseismic creep or transient shearing (e.g., Angboust et al., 2015; see also ***Grand Challenge #2***).

The integrated effects of varied fault slip behavior and total displacement over time result in complex faults and fault zones. An outcrop map from the Mugi Mélange, Japan (**Figure 3**, Kimura et

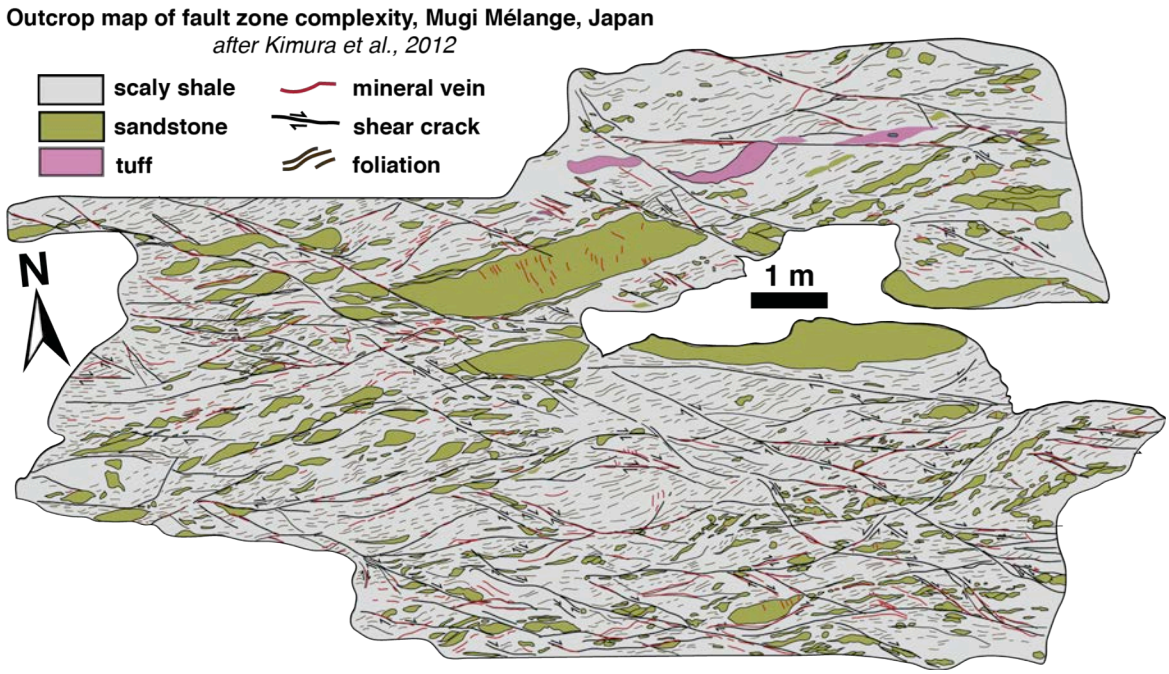


Figure 3

al., 2012) shows one type of fault zone where multiple structures formed during deformation in a shallow subduction zone plate boundary. The fault rock consists of a mechanically heterogeneous assemblage of lithologies in which different volumes have deformed variously by fracture or by viscous flow accommodated by diffusive mass transfer, producing deformation structures that are mutually crosscutting. Coupled field and microstructural observations of exhumed fault rocks such as these, as well as detailed analyses of controlled experiments in the lab (e.g., Leeman et al., 2016; Pec et al., 2016) and in simulations (e.g., Lyakhovsky et al., 2014), emphasize the importance of progressive deformation incorporating multiple mechanisms over the lifetime of a fault.

Recent discoveries regarding the signature of fault slip in rocks provide a template for integrating field, laboratory, and theoretical approaches to advance understanding of the full spectrum of fault zone behavior and complexity. Key advances will come with quantitative measures of the internal 3D/4D architecture of fault zones, along with better correlation of exhumed fault structures with active systems through precise depth, temperature, and strain-rate controls. The identification and study of structures formed at specific strain rates, temperatures, and effective stresses, both in rock mechanics experiments and in correlative field observations from natural faults, can provide some of these constraints. New methods for assessing the relative importance of cooperating and competing deformation mechanisms, and laws for sliding friction, solution creep and flow of polymineralic aggregates at high strain (***Grand Challenge #2***) will be central to progress.

3.4 THE STRUCTURAL, GEOCHEMICAL AND GEOCHRONOLOGICAL RECORD OF FLUID-FAULT ZONE INTERACTIONS

Fluid-fault zone interactions involve mechanical and chemical processes that govern mass and heat transfer, fault slip behavior, and fault zone evolution throughout the lithosphere. Novel approaches integrating geochemistry and geochronology with structural analysis are helping us use the rock record to better understand fluid pathways to, from, and within fault zones and to explore the full spectrum of fault behavior and its variation in space and time.

Fluid-fault zone interactions involve mechanical and chemical processes that govern mass and heat transfer, fault slip behavior, and fault zone evolution throughout the lithosphere. Vertical connections among the different elements of fault zones that traverse the lithosphere are recorded by stable isotope data that show meteoric fluids reaching the ductile crust in shear zones (e.g., Haines et al., 2016), and mantle, metamorphic, and igneous fluids leaking out along surface fault traces (e.g., Boles et al., 2015). However, transitions between different crustal levels, the impact of fault structure and behavior on fluid flow, and the impact of fluids on the full spectrum of fault slip behavior remain incompletely understood. These missing links are key to accessing water, energy and economic resources, and to predicting the path of contaminants or CO_2 injected underground (***Grand Challenge #5***). The potential importance of fluid-fault interactions is also illustrated by the recent hypothesis that many tiny, fluid-overpressure-driven faulting events may produce the low frequency rumble of slow-slip seismicity in the vicinity of the brittle-ductile transition of quartz (Fagereng et al., 2011).

Novel approaches integrating geochemistry with structural analysis are helping us use the rock record to better understand fluid pathways to, from, and within fault zones, and to evaluate their mechanical impacts. Thermometry of vein-fill cements that record the passage of ancient fluids can document fluid sources and pathways during the structural development of shallow crustal faults (e.g., Hodson et al., 2016). In crustal and mantle shear zones, thermobarometry and microstructural analyses can be used to constrain profiles of lithospheric strength in specific regions (Behr and Platt, 2011). An example by Selverstone et al. (2013) integrated structural, geochemical, and mineralogical analyses, calculation of pseudosections, and fluid inclusion analysis to explore the impact of reactive fluids on fault localization in a mid-crustal shear zone, documenting changes in the 'brittle-ductile transition' and crustal strength maximum in space and time. These studies illustrate that fluid- and reaction-driven mineralogical changes within fault zones modify the mechanical properties and permeability of the faults themselves.

Figure 4 shows another approach that combines structural geology, geochemistry and U-Th dating of co-seismic calcite veins (Williams et al., 2017) to evaluate the hypothesis that the veins record fault-valve behavior (cf. Sibson, 1992). The data show that the periodic failure exhibited by

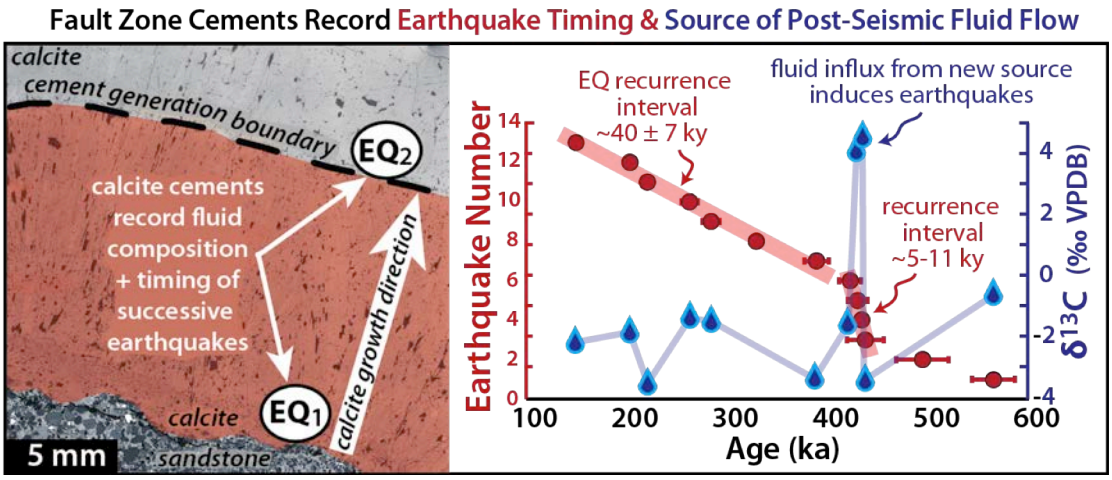


Figure 4

most of the documented earthquakes records a stress renewal process (e.g., Cox and Munroe, 2016), with fractures leaking deep basinal brines following failure. However, a subset of veins records a dramatic decline in earthquake recurrence interval coincident with the influx of fluid from a deeper magmatic source—demonstrating that this influx elevated fluid pressure and changed the seismic cycle. This example of naturally induced seismicity reminds us that fault systems are not closed systems, and must be considered in their entirety to be fully understood. To this end, the integration of structural, geochemical, geochronological, and other approaches to better understand flow pathways to and through lithospheric fault zones is needed to explore the full spectrum of fault slip behavior and its variation in space and time.

3.5 MODELING FAULT SYSTEM EVOLUTION THROUGH TIME

Numerical models and physical experiments explore fault system evolution through time and space to bridge the gaps between observations of active faulting, records of past faulting, and physics of deformation. Developments in high-speed computing, image processing and in situ instrumentation are revolutionizing experimental protocols and making it possible to tackle the complexities of fault network evolution and interactions between deep and shallow crustal processes.

Numerical models and physical experiments explore fault system evolution through time and space to bridge the gaps between observations of active faulting, records of past faulting, and physics of deformation. Simulations of fault evolution can track spatial partitioning of deformation within the crust and provide spatially continuous time-series of information. Such information is key to testing our understanding of fault propagation, linkage, reactivation and abandonment—processes that govern the evolution of fault systems at all crustal levels, but that operate at very different time and length scales than those in rock mechanics experiments, and are difficult to observe in the field due to the discontinuous nature of finite deformation recorded at specific sites.

Developments in image processing and *in situ* instrumentation are revolutionizing protocols for physical experiments, which use analog materials to scale crustal processes down to lengths and times that can be observed directly in the laboratory. For example, digital image correlation (DIC) and new strain and rheology measurements (e.g., Souloumiac et al., 2012; Reber et al., 2015; Dotare, 2016) are illuminating classic physical experiments in transformative ways—as shown in **Figure 5**, where angular strain maps produced from DIC of a wet-kaolin experiment of a strike-slip fault reveal the system's development. Distributed shear evolves to en echelon faulting with associated off-fault

deformation, to localized slip along through-going fault surfaces as overall kinematic efficiency of the fault system increases (Hatem et al., in review). Such results can inform our interpretations of off-fault deformation and relative maturity of crustal strike-slip faults.

Numerical models complement physical experiments by expanding the range of material rheology and boundary conditions that can be investigated. Furthermore, stresses and strains can be queried within numerical models as fault systems evolve, yielding clues about the processes that drive fault evolution at all crustal levels (e.g., Brune, 2014; van Wijk et al. 2017). Improvements in computing are allowing us to tackle complex problems that were cost- and time-prohibitive a decade ago, such as 3D evolution and interactions between deep and shallow crustal processes. When validated with direct field observations and/or physical experimental data, numerical models can help us understand how fault networks evolve via propagation, linkage between segments, reactivation of old segments and abandonment of fault segments that no longer effectively contribute to the system's deformation. In this manner, numerical models help us integrate disparate observations to better understand how fault networks develop through time and predict future evolution of active fault systems.

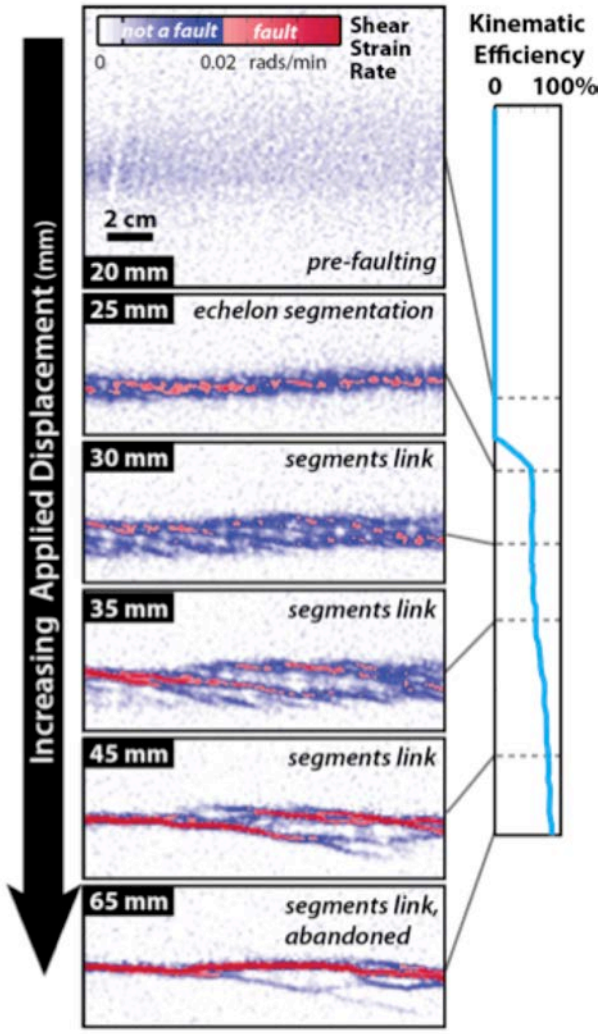


Figure 5

3.6 INTEGRATING FAULT ZONE BEHAVIOR THROUGH THE FULL THICKNESS OF THE LITHOSPHERE

We must address fault zones as vertically integrated, lithospheric-scale systems if we are to fully understand their evolution and role in tectonic deformation, including earthquakes. New perspectives on how flow in the deep lithosphere and frictional processes in the seismogenic zone affect one another will come from the integration of quantitative constraints on material properties and conditions of deformation from natural fault zones with experimental data and numerical models.

We must address fault zones as vertically integrated, lithospheric-scale systems if we are to fully understand their evolution and role in tectonic deformation, including earthquakes. However, determining how near-surface deformation in fault zones links through to the deep crust and upper mantle poses a major challenge. We must resolve the mechanisms that localize displacements and strain at each depth and determine how they change as a fault zone evolves. In the seismogenic shallow crust (upper ~15 km), many fault zone behaviors, including slow slip and low-frequency earthquakes, may be attributed to specific material properties and conditions (Ikari, 2012; Reber et al., 2015; Leeman, 2016). But we lack a complete quantitative understanding of the deformation

mechanisms that dominate in this realm, including cataclasis, frictional sliding, and dissolution-precipitation creep (Rowe and Griffith, 2015). In the deep lithosphere, our quantitative understanding of the interactions among deformation processes, rates, and rheology also remains incomplete.

Recent discoveries are addressing these gaps as researchers develop new approaches to study large fault zones as systems that are vertically integrated through the full thickness of the lithosphere. A focus of this work is to assess the role of deformation in the deep crust and upper mantle during the seismic cycle. For example, the observation that crustal deformation in the San Andreas fault system continues into the lithospheric mantle (Titus et al., 2007), and possibly into the asthenosphere (Ford et al., 2014), challenges the idea that the different layers of the lithosphere deform independently of one another during the seismic cycle. Evidence of rapid slip events in the lower crust and reports of frictional melts (pseudotachylyte) from locations deeper and hotter than the typical seismogenic zone (***Section 3.2, Grand Challenge #2***) challenge the assumption that deformation in deep, viscous shear zones occurs at constant strain rates.

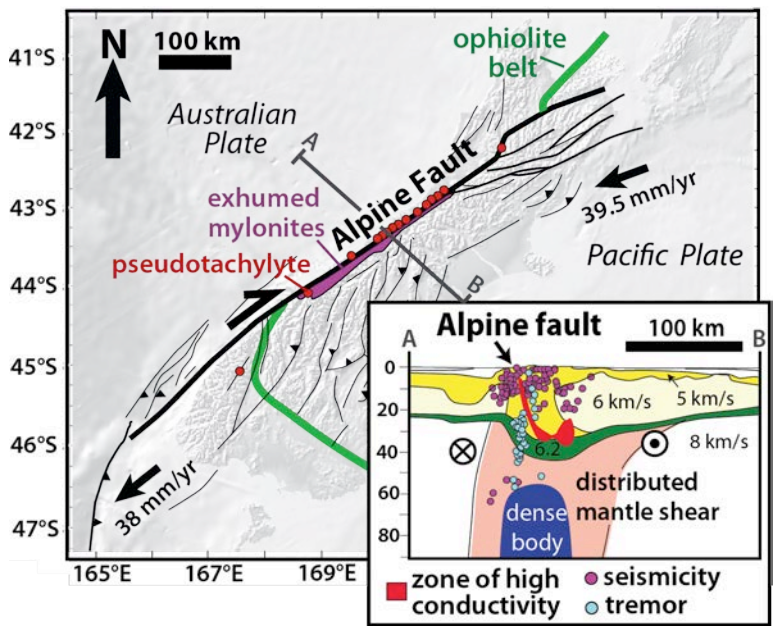


Figure 6

Understanding how flow in the deep lithosphere and frictional processes in the seismogenic zone affect one another requires quantitative information on the material properties and deformation conditions within and below the seismogenic zone of large faults. Geological and geophysical studies of major continental faults can provide these constraints, including composition, temperature, pressure, fluid content, microstructure, viscosity, and rates of processes. In New Zealand, shortening over the past 4 million years has exhumed a mylonitic shear zone that formed by ductile creep ~35 km down dip of the seismogenic Alpine Fault (Toy et al., 2012), exposing the deep root of a large transpressive fault (**Figure 6**, map adapted from Norris and Toy, 2014). Beneath this exposure sits a zone of high electrical conductivity, enhanced fluid flow, and seismic activity in a thick, structurally complex lower crustal root, which overlies a 200 km-wide zone of seismic anisotropy and high-velocity that may reflect distributed shear in the mantle lithosphere (Savage et al., 2007; Houlié and Stern, 2012; **Figure 6**). In an example from California, investigations of rare mantle xenoliths quantitatively constrain the strength, hydration and stress state of the upper mantle below the San Andreas fault system during shearing (Chatzaras et al., 2015). These data—combined with experimental results that suggest transient high-stress deformations in the upper mantle produce structures typically associated with coseismic deformation and post-seismic creep (***Section 3.2, Grand Challenge #2***)—bring new perspectives to the interactions between mantle flow and frictional processes in the seismogenic zone.

Studies like these highlight the opportunity for geological and geophysical observations of the deep lithosphere to link deformation processes and material properties from the upper mantle to the surface. Advances will come through the integration of such observations from natural fault zones with experimental data and numerical models.

3.7 KEY QUESTIONS & REQUIREMENTS TO MAKE PROGRESS

Key questions include:

- How do fault networks at all crustal levels evolve via propagation, linkage, abandonment and reactivation of segments across a range of spatial and temporal scales?
- How do the strengths and other mechanical properties of fault zone materials evolve over the duration of an earthquake cycle at different depths, and over the lifetime of a fault in both the brittle and ductile domains?
- How do specific landforms at Earth's surface and structures within exhumed fault zones result from and record the processes observed in active fault systems?
- How do fault system evolution and vertical linkages among faults and shear zones that traverse the lithosphere influence fluid flow, and how do fluids and chemical reactions affect fault zone evolution and fault slip behavior?
- How do distributed and localized deformation interact and vary in space and time, from the surface to the upper mantle?
- How do flow in the deep lithosphere and frictional processes in the seismogenic zone affect one another?
- What processes cause and regulate the interplay between fast and slow strain behavior on faults?
- What geologic processes and mechanical behaviors govern variations in earthquake frequency, location, and moment release, and what are their implications for hazard?

Requirements to make progress include:

- Facilitate multi-disciplinary studies of fault behavior at different crustal and lithospheric mantle levels, including within and below the seismogenic zone of large faults.
- Broaden access to new technologies for imaging, monitoring and data analysis from microstructural to map scale—including high-resolution topographic and geodetic data and imagery, real-time monitoring of transient deformation, direct measurements of fault and fluid properties, and microanalytical techniques.
- Develop quantitative measures for fault and shear zone geometry, distribution and localization of deformation elements, all with statistical robustness.
- Support interdisciplinary study of exemplar exhumed fault systems that record depth, temperature, timing, and strain rate of fault and shear zone elements at different depths and stages of development.
- Develop laboratory instrumentation to facilitate simultaneous in-situ textural and mechanical measurements under experimental conditions.
- Broaden the range of analog materials and numerical simulations available to study fault zone processes at all scales, including for large displacements.
- Expand computational tools and facilities for integrating observations from active faulting and the rock record with data from deformation experiments.

GRAND CHALLENGE 4

UNDERSTANDING THE DYNAMIC INTERACTIONS AMONG EARTH-SURFACE PROCESSES AND TECTONICS

4.1 OVERVIEW

The idea that atmospheric, surficial and deep Earth processes may be coupled in complex feedback relationships is one of the most fascinating contemporary developments in Earth science. Such feedbacks would have broad implications for understanding links between rheology, deformation and erodibility; the evolution of landscapes and sedimentary basins; and tectonic controls on weathering, the carbon cycle and Earth's habitability. Two decades of study have revealed tantalizing examples of the products of surficial process-tectonic interactions and shifted our understanding of how tectonically active plate boundaries evolve. Still, many challenges remain.

Recent advances in disciplines ranging from geodynamic modeling to geochronology are helping to bring the nature of these interactions into focus—and suggest that strong couplings between the solid earth and various portions of the earth system are more diverse and significant than previously thought. Such interactions occur at a range of scales from a single outcrop to an entire continent, and at these multiple scales involve consideration of such diverse phenomena as crustal rheology and heat transfer, fracture mechanics, landscape evolution, atmospheric circulation patterns, and ecological diversity.

Landscapes serve as a nexus between the solid Earth and atmosphere, and at many spatial and temporal scales landscape morphology and topography are a crucial and accessible constraint on the state of the deeper earth and processes active within it. A growing body of work in the geomorphic community is leading to more sophisticated understanding of how tectonic and other external processes are reflected in topography, erosion and deposition, both in today's landscapes and in the geologic record. Internal "autogenic" processes and self-organization in sedimentary systems, as well as dynamic instabilities in geomorphic systems (such as drainage divides) can affect topography, erosion and stratigraphy independently of or in spite of tectonic forcing—making it critical to consider the internal complexity of these systems as we interpret deep-Earth dynamics from Earth-surface process records.

Such conceptual advances and the development and refinement of new analytical tools and modeling techniques now set the stage for breakthroughs in our understanding of Earth-surface evolution and its connections to the atmosphere, biosphere and solid Earth. At the broadest scales, geophysical observations and modeling of mantle dynamics show that dynamic topography on the continents can offer rich insight into these interactions at the broadest time and spatial scales (***Section 4.2***). Rapid increases in the quality and resolution of paleoelevation reconstructions and geochronologic datasets are enabling geodynamic models and emerging ideas about the coevolution of landscapes and life to be tested (***Section 4.3***). Within mountain ranges, advanced thermo-kinematic and dynamical models are being tested using observations from diverse fields including petrology, thermochronology, geophysics, and geomorphology—particularly in areas of extreme relief and erosion where hypothesized feedbacks are expected to be most pronounced (***Section 4.4***). At finer spatial scales, there is renewed interest in characterizing the influence of rock strength on landscape evolution, which traditionally has been a major limitation to quantitative interpretation of tectonics from topography. New imaging tools including LiDAR and Structure-from-Motion photogrammetry

are revolutionizing our ability to quantify landscape form at high resolution and over the large areas necessary for developing and testing mechanistic surface process models (***Section 4.5***). Finally, at the hillslope scale, new constraints on processes that control near surface rock strength have inspired the idea that topographic and regional tectonic stresses lead to distinctive patterns of subsurface damage, with implications for potential feedbacks among climate, erosion, rock strength, and tectonics (***Section 4.6***). The coupling between subsurface fracturing, flow pathways, and chemical weathering also may impact landscape form and biogeochemical cycles, thus linking these elements back to processes operating at regional and global scales (e.g., ***Grand Challenge #1***).

These examples illustrate some of the ways the tectonics community is currently exploring tectonics-surface process connections from outcrop to global scales, and show that great opportunity to make fundamental advances lies in the true integration of modeling and observational experiments. Infrastructure to support multidisciplinary collaborations among expert users—and developers—of advanced modeling, observational and theoretical approaches are needed to address the many broad, cross-cutting questions that explore the dynamics of tectonic-surface process interactions (***Section 4.7***).

4.2 LINKING GLOBAL MANTLE DYNAMICS TO SURFACE TECTONICS AND TOPOGRAPHY

Dynamic processes occurring in Earth's convecting mantle can deflect the Earth's surface by 100's of meters, affecting sedimentation and erosion patterns, drainage systems and coastline geometry. New observations of Earth structure and quantitative constraints on rock rheology and paleotopography, combined with high-resolution computer models of mantle dynamics and landscape evolution, offer opportunities to investigate the feedback between the Earth's interior and its surface through time.

Dynamic processes occurring in Earth's convecting mantle can deflect the Earth's surface by 100's of meters over wavelengths of 100's to 1000's of kilometers. Such dynamic topography—which is distinct from isostatic topography (e.g., crustal thickness changes) and flexural loading—arises from viscous coupling between the rigid tectonic plates and the more mobile underlying mantle. Despite its low amplitude, dynamic topography can affect sea level and coastline geometry (Flament, 2014). In addition, dynamic topography may explain anomalous elevation changes in the interior of continental plates, far from active plate margins. For instance, the present-day high elevation of southern Africa and low elevation of northern Australia appear to be related to large-scale regions of mantle upwelling and downwelling, respectively (e.g., Braun, 2010). Anomalous elevation changes also may occur on a more local scale, as shown by recent studies of complex mantle flow around subducted slabs in the Mediterranean (Faccenna and Becker, 2010) and delamination of continental lithosphere below the central Andes (e.g., Krystopowicz and Currie, 2013).

These relationships offer exciting possibilities for using paleoelevation constraints and model simulations to reconstruct past mantle dynamics. In an example from North America, mantle convection models predict dynamic subsidence above the subducting Farallon Plate in the Late Cretaceous, consistent with sedimentary records that document the development of the Western Interior Seaway as a region of subsidence that expanded east over time (e.g., Heller and Liu, 2016). In particular, the models show that a shallowing of the subduction trajectory over time induced surface subsidence of up to ~1000 m that migrated eastward over ~30 Ma (**Figure 1**, top row). Shallowing subduction is also correlated with surface tectonic events, such as an eastward migration of arc volcanism and the initiation of Laramide deformation in the continental interior.

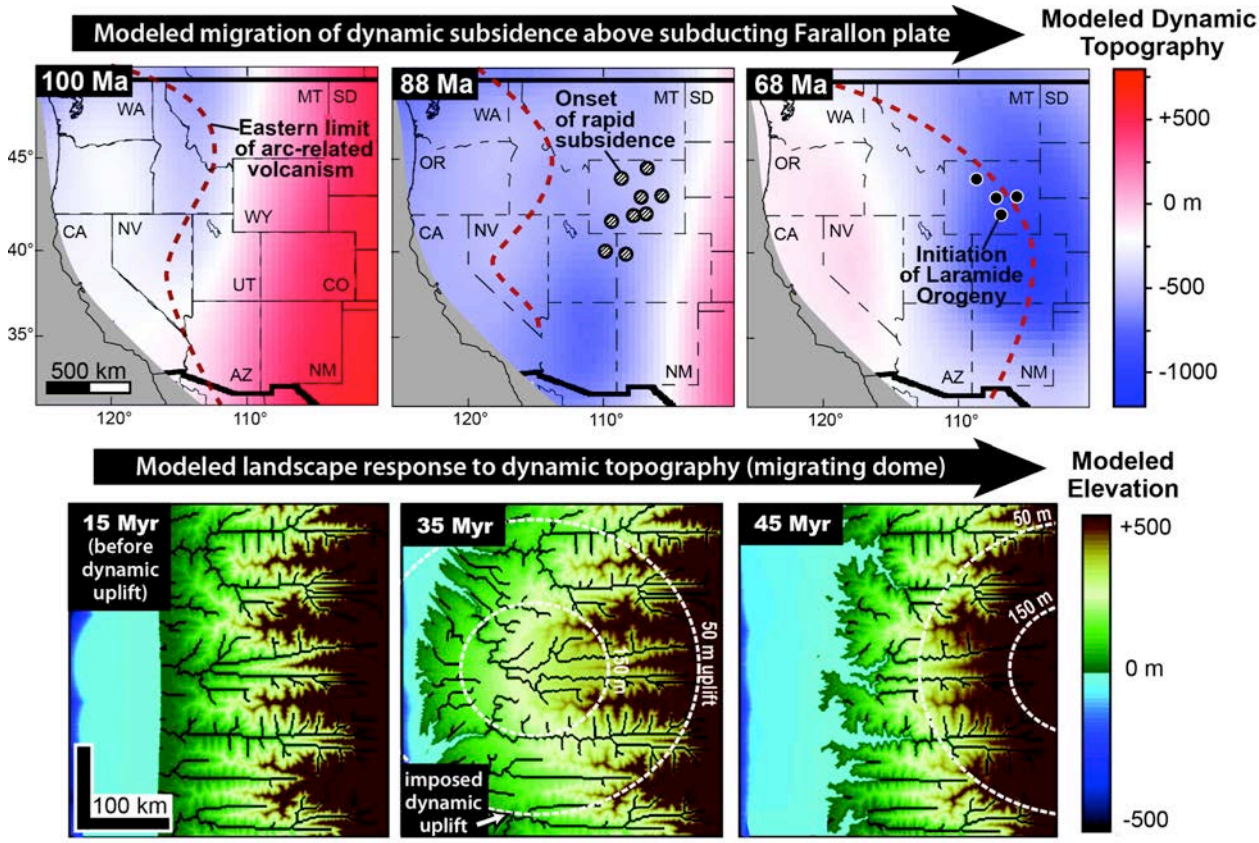


Figure 1

Identifying dynamic topography in surface geological observations is difficult due not only to its low-amplitude, long-wavelength nature, but also to the internal dynamics of geomorphic and sedimentary systems that operate independently of external tectonic forcing (e.g., Willett et al., 2014; Romans et al., 2016; Hajek and Straub, 2017). A detailed understanding of how dynamic topography may be preserved in the rock record depends on the details of how erosion and sedimentation patterns are affected. This is illustrated by the example in **Figure 1** (bottom row), which shows the modeled landscape response to a simplified case in which a 200 m high dome passes below a coastline at 2 cm/yr (Ruetenik et al., 2016). As the initially straight coastline experiences uplift, significant shoreline regression, reorganization of stream channels, enhanced coastal erosion, and increased offshore sediment flux occur and persist long after the topographic changes have ceased. This study also emphasizes the importance of the local topography and near-surface rock properties (i.e., erodibility) in modulating the transient landscape response to regional dynamic topography changes.

Recent computational advances have allowed for increasingly complex models of mantle dynamics, including the development of inverse and adjoint methods in which mantle convection is run backward in time, starting from today's mantle structure as inferred from seismic tomography images. However, coupling large-scale mantle models to detailed landscape models remains a challenge owing to the differing spatial and temporal scales of the models. The path forward is to integrate studies of geomorphic and sedimentary system dynamics with constraints on rock properties (e.g., rheology (***Grand Challenge #2***), erodibility), present-day mantle structure (e.g., from seismic tomography (***Grand Challenge #1***), gravity/geoid observations) and advanced computing resources to develop models that make predictions testable with paleotopographic reconstructions (***Section 4.3***). Innovations in these key areas will improve interpretations of paleotopography data and

global sea level change records, and advance our understanding of the dynamic feedback between the Earth's surface and interior.

4.3 TESTING TECTONIC MODELS USING THE GEOLOGIC RECORD OF SURFACE UPLIFT AND SUBSIDENCE

Constraints on past surface topography can advance our understanding of orogenic and geodynamic processes and the long-term co-evolution of landscapes and life. The potential for breakthroughs lies in the integration of recent paleoelevation proxy and climate modeling advances with high-precision geo- and thermochronology, and sedimentary source-to-sink reconstructions to distinguish between tectonic, climatic, and autogenic controls on the stratigraphic record.

The evolution of Earth's surface topography reflects the competition of surface and deep Earth processes, and influences atmospheric circulation, erosion, and biological habitats. Constraints on paleotopography changes can therefore provide unique insight into orogenic and geodynamic processes that operated in the past. However, reconstructing paleoelevation is challenging and traditionally imprecise, which has limited our ability to test tectonic models and models for the coevolution of landscapes and life (e.g. Mulch, 2016). Recent work is addressing these limitations—with the development of new paleoprecipitation and paleotemperature proxies, advances in understanding climatic and atmospheric controls on those proxies, and their integration with independent stratigraphic and geochronologic constraints—to greatly improve paleoelevation histories of key regions.

In the western US (**Figure 2**), location-specific thermodynamic modeling of past precipitation-elevation relationships (e.g., Cassel et al., 2014; Mix et al., 2015), high-precision chronostratigraphy (Smith et al., 2014; Fan et al., 2014), and independent paleotemperatures from clumped isotopes (Huntington et al. 2010; Snell et al., 2014) enable the comparison of widespread time-correlative and time-transgressive datasets. Combined, these results show that what are now the Sierra Nevada mountains formed the steep western flank of an Eocene-Oligocene orogen that reached elevations of up to 3.5 km prior to Miocene extension (**Figure 2**). In another example from the central Andes, surface uplift reconstructions from stable isotope records and paleoclimate modeling have been integrated with diverse geophysical, geochemical and geological observations to understand the region's tectonic evolution, with implications for the growth of Earth's high-elevation plateaus (Garzione et al., 2017).

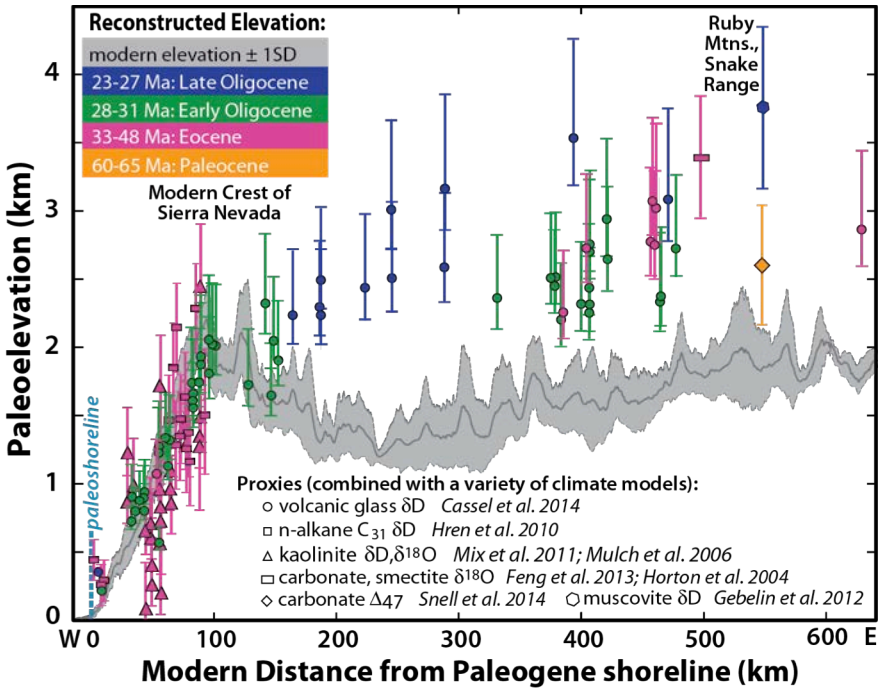


Figure 2

Studies like these highlight how a rich diversity of proxy and modeling approaches is leading to major advances in the ability to reconstruct paleoelevation—a long-standing research question in geoscience. Furthermore, the increasing precision of paleotopographic reconstruction is enabling the biological and geological communities to explore the emerging frontier of biosphere-landscape interactions and the role of topographic complexity in ecology and evolution (e.g., Badgley et al., 2017). The potential for breakthroughs lies in the integration of proxy data with 3D isotope-enabled regional climate models that are calibrated to specific orogens (e.g., Feng et al., 2013, 2016; Sewall and Fricke, 2013); high-precision geo- and thermochronology; geomorphic constraints (e.g., river incision and erosion rates); and sedimentary source-to-sink reconstructions to distinguish between tectonic, climatic, and autogenic controls on the stratigraphic record. This approach must be coupled with simultaneous model refinement—increasing the detail and fidelity of modeled topography, of paleoclimatic constraints on model inputs, and of model and proxy calibration using modern datasets (e.g., Cassel and Breecker, 2017). Continued development in these areas will help us to better understand the linkages among surface and deep-Earth processes and their influence on climatic patterns and plant and animal evolution.

4.4 EVALUATING PREDICTED FEEDBACKS BETWEEN CLIMATE, EROSION AND TECTONICS

The question of whether climate-modulated erosion can drive the location, rate, and style of tectonic deformation remains the focus of vigorous debate, with broad implications for understanding links between rheology, deformation and erodibility; tectonic controls on physical and chemical weathering and the carbon cycle; and the evolution of mountains and the sedimentary record. Opportunities for progress lie in coupling high-resolution field studies and interpretations of the sedimentary record with advances in single-grain detrital geo- and thermochronology, dynamical modeling, and improved constraints on crustal rheology.

Numerical models predict feedbacks between climate, erosion and tectonics—with broad implications for understanding links between rheology, deformation and erodibility; tectonic controls on physical and chemical weathering and the carbon cycle; and the evolution of mountains and sedimentary basins. However, 15 years of study has uncovered the challenges of finding conclusive evidence of feedbacks and revealed that the relationship between climate and erosion is more complicated than anticipated (e.g., Godard et al., 2014; Scherler et al., 2014). Today the question of whether climate-modulated erosion can drive the location, rate, and style of tectonic deformation in nature remains the focus of vigorous debate (e.g., Wang et al., 2014; Whipple, 2014; Zeitler et al., 2015; King et al., 2016).

If strong feedbacks between tectonic driving forces, deformation and erosion exist, they should be most clearly manifest in Earth's most rapidly uplifting and eroding landscapes. Field studies of these areas are unlikely to resolve cause-and-effect relationships from spatial correlations of rapid rock uplift and erosion, rugged topography, and intense precipitation alone, since these factors are expected to covary independent of possible feedbacks due to the physics of weather and erosion. A more fruitful approach is to document the relative timing of tectonic, climatic, and surface-process changes. However, the timing of localized changes in extremely dynamic landscapes can be difficult to pinpoint using geo- and thermochronology of local bedrock samples, which may be inaccessible or too rapidly exhumed to record more than the last few million years of history. Where this is the case, new detrital methods are enabling us to probe the upland landscape with the necessary spatial and temporal resolution to test advanced thermo-mechanical models.

As some of Earth's most dynamic landscapes, the great orogenic bends, or syntaxes, that develop at lithospheric plate corners (e.g. **Figure 3**) (Zeitler, et al. 2014; Gulick, 2015) are "hotspots" of focused rock exhumation. Advances in single-grain detrital geo- and thermochronology now allow us to reconstruct the exhumation history of these areas in detail. For example, detrital (U-Th)/Pb geochronology, $^{40}Ar/^{39}Ar$, and fission track thermochronology show a dramatic increase in exhumation rate occurred in the eastern Himalayan syntaxis 5-7 million years ago (**Figure 3**; Lang et al. 2016). Similarly, multiple geo- and thermochronometers from glacially eroded cobbles reveal the exhumation history of otherwise inaccessible ice-covered parts of the St. Elias syntaxis in southeast Alaska (Falkowski et al., 2016). Such paleo-exhumation rate reconstructions can be compared to model predictions and the timing of climate, tectonic, or drainage pattern change (e.g. **Figure 3**) to test possible feedback relationships.

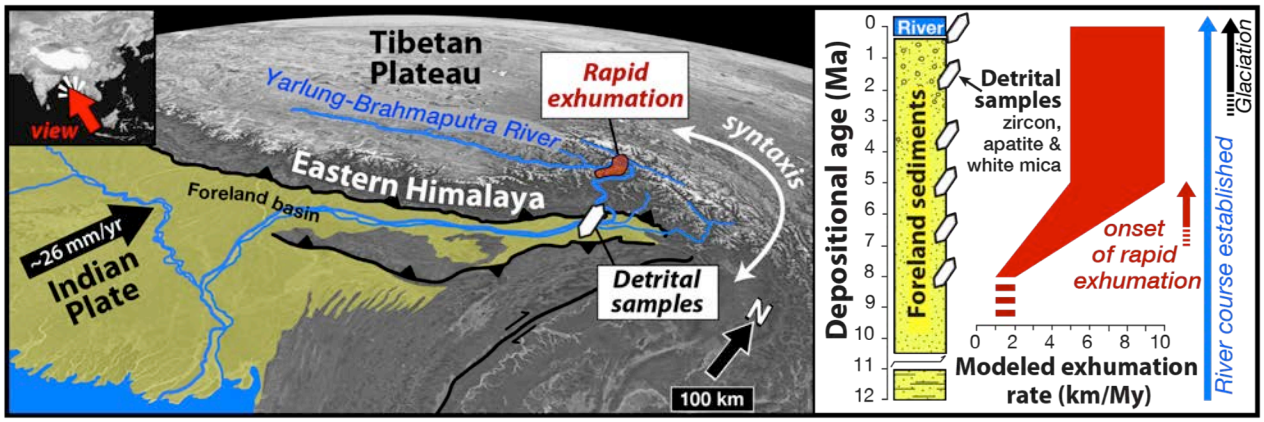


Figure 3

Opportunities for progress lie in coupling high-resolution field studies and interpretations of the sedimentary record with geodynamical modeling (e.g. Koons et al., 2013; Bendick and Ehlers, 2014) and improved constraints on crustal rheology (***Grand Challenge #2***). Such an integrated approach to studying Earth's rapidly deforming landscapes has the potential to illuminate possible tectonics-erosion-climate linkages—and a broad array of related processes from the effects of partial melting on the rheology of crustal rocks, to the coupling of rock strength and strain patterns with river erosion, to the role of tectonics in chemical and physical weathering and global cycles.

4.5 ROCK STRENGTH CONTROLS ON TOPOGRAPHY AND EROSION RATE

The global distribution of erosion rates highlights a large unexplained spread in the topographic relief required to erode at a given rate, and therefore limits our ability to quantitatively interpret tectonics from topography. Although rock strength has long been expected to contribute to this scatter, only recently have new tools and applications such as drones, structure-from-motion photogrammetry, and shallow geophysics transformed our ability to quantify rock material properties at high resolution and large spatial scales. As a result, we are poised to make significant progress on the connections between climate, tectonics, topography, and rock material properties.

As mountain ranges evolve, their topography adjusts towards a balance between erosional fluxes at the surface and the accretion of material from below by tectonics. The relationship between topography and erosion rate thus dictates the height of mountain ranges and controls the sensitivity of potential feedbacks between climate, tectonics, and erosion (Whipple and Meade, 2004). The global

distribution of erosion rates (Portenga and Bierman, 2011), however, highlights a large unexplained spread in the topographic relief required to erode at a given rate, and therefore limits our ability to quantitatively interpret tectonics from topography. This knowledge gap exists primarily due to an incomplete conceptual understanding of the influence of climate and rock strength on erosion rates.

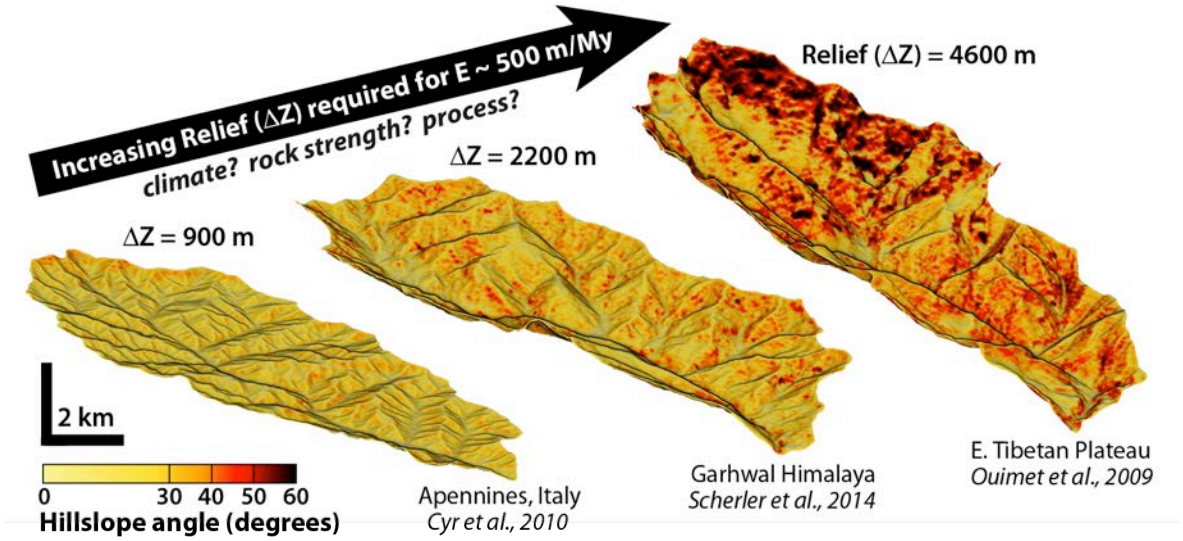


Figure 4

Figure 4 shows three watersheds with similar erosion rate (*E* ~ 500 m/My), but exhibiting a 5-fold variation in topographic relief—analogous to the difference in topography between the Appalachians and the Andes. Although climate differs between the three landscapes, no systematic pattern emerges and the variability shown in **Figure 4** is likely determined in part by differences in rock material properties and their effects on basin-scale erodibility. Despite considerable and long-standing attention, defining and quantifying metrics of near-surface rock strength (e.g., tensile strength, fracturing, sediment grain size) remain challenging. Likewise, theory needs to be developed for links between climate, tectonics, and rock strength. Rock strength may also itself be a function of local climatic (Murphy et al., 2016) or tectonic (Roy et al., 2015) conditions, raising the possibility for intriguing feedbacks between surface and deep earth processes.

Although the approaches typically used to quantify rock material properties are straightforward (e.g., Schmidt hammer measurements, laboratory strength tests, fracture mapping, grain size), heterogeneity at a range of scales make *in situ* field measurements extremely time consuming and difficult to extrapolate over the broader landscape. Now, two approaches are reinvigorating the field. First, the rapid increase in LiDAR datasets (Roering et al., 2013), drones, and structure-from-motion photogrammetry (James and Robson, 2012) is helping to bridge the gap between detailed field observation and the landscape-scale analyses needed to make progress. Second, the use of shallow geophysical surveys and the accompanying parameterization of key metrics of near-surface damage enables the mapping of rock strength in areas without exposed bedrock (see ***Section 4.6***). As a result, it is now feasible, for example, to map at high resolution and vast spatial scales the patterns of surface and subsurface fracturing and the resulting landscape morphology. Coupled with a continued effort to quantify spatial and temporal patterns of erosion and weathering in landscapes, we are poised to make significant progress on the connections between climate, tectonics, topography, and rock material properties.

4.6 DYNAMIC COUPLING OF CRUSTAL STRESSES, FRACTURING, CHEMICAL WEATHERING, AND PHYSICAL EROSION

Compelling new studies suggest that Earth's atmosphere and deep crust are coupled via previously underappreciated linkages between bedrock fracturing, weathering, and erosion at the landscape surface. Striking comparisons between theory and geophysical observations of subsurface weathering demonstrate that the tectonics and surface processes communities are well poised to greatly expand understanding of dynamic couplings between tectonics, fracturing, and erosion through integration of geochemistry, tectonic geomorphology, and near-surface geophysics.

Compelling new studies suggest that Earth's atmosphere and shallow crust are coupled via previously underappreciated linkages between bedrock fracturing, weathering, and erosion at the landscape surface. Geochemists and geomorphologists have long understood that subsurface fracturing promotes rapid flow of reactive meteoric fluids, thus enhancing chemical weathering and ultimately enabling erosion of disaggregated rock fragments at Earth's surface (e.g., Riebe et al., 2017). Recently, the growing field of near-surface geophysics has confirmed that the distribution of bedrock fractures may often be tightly coupled to the subsurface stress field (St. Clair et al., 2015), which varies across landscapes due to interactions between regional plate tectonic forces and local gravitational stresses (Slim et al., 2015). This raises the potential for as yet largely unexplored feedbacks between climate, tectonics, and landscape erosion: Topography, which controls the distribution of gravitational stresses, is shaped by erosion, and erosion is in turn strongly coupled to tectonic exhumation and rock strength, implying that connections between fracturing and erosion provide a crucial link between surface and crustal processes.

Exciting new opportunities to investigate these two-way linkages are now opening up thanks to the surge in near-surface geophysical studies of subsurface weathering (Parsekian et al., 2015). **Figure 5** exemplifies the great potential of this fertile new research area (after St. Clair et al., 2015). Subsurface stress computations predict that open fractures should closely mimic topography, rising in sync with hillslopes away from the channel in landscapes where tectonic stresses are small relative to gravitational stresses

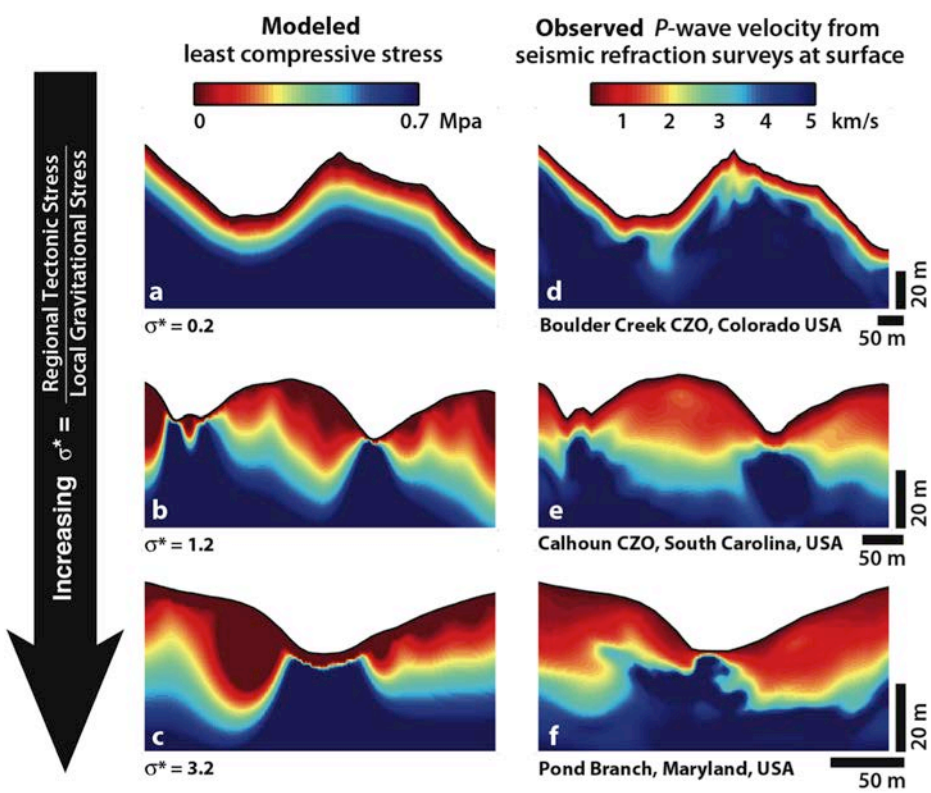


Figure 5

(e.g., **Figure 5a**). However, as compressive tectonic stresses increase relative to gravitational stresses, the base of the densely fractured zone should increasingly mirror the surface topography, diving deeper into the subsurface away from the channel and creating a "bowtie" shape in cross section (**Figure 5b, c**). Observations from seismic refraction surveys of bedrock damage across three sites with differing tectonic stress regimes are consistent with the stress computations (**Figure 5d-f**), corroborating the hypothesis that subsurface fracturing and weathering are strongly influenced by subsurface stress gradients (St. Clair et al., 2015). This striking comparison between theory and observation demonstrates the potential for new data to test this hypothesis and other competing ideas (e.g., Maher and Chamberlain, 2014; Riebe et al., 2017)—and for the tectonics and surface processes communities to greatly expand understanding of dynamic couplings between tectonics, fracturing, weathering and erosion through integration of geochemistry, tectonic geomorphology, and near-surface geophysics.

4.7 KEY QUESTIONS & REQUIREMENTS TO MAKE PROGRESS

Key questions include:

- How does dynamic topography affect continental tectonics and surface processes?
- How are mantle-driven changes in surface topography recorded in the geologic record, including sedimentary, geomorphic, geochronologic, geochemical, and geodetic archives?
- How are the exogenic forcings of tectonics and climate encoded and propagated in sedimentary deposits and stratigraphy?
- How do we compare erosion rates, rock uplift rates, and climate proxy records across various timescales?
- How do rheology, deformation and orogenesis affect surface erosion, and vice versa?
- How do bio-geomorphic feedbacks that link vegetation, slope stability, and weathering operate during orogen evolution?
- How does the interplay of biotic, tectonic, surface and climatic processes affect the global carbon cycle?
- How do topographic and tectonic stresses, hydrology, chemical fluxes and weathering interact to fracture rocks and reduce near-surface strength?
- How do we quantify erodibility and rock-mass strength at scales relevant to landscape evolution models?

Requirements to make progress include:

- Facilitate integration of models and field-based datasets including topography, climatology, geochronology, and geochemistry data through collaborative projects.
- Refine and develop new high-resolution geodetic, geomorphic, stratigraphic, and geochemical techniques to reconstruct paleotopography over a wide range of spatial and temporal scales.
- Broaden access to new techniques for imaging and image analysis at all scales.
- Develop remote sensing (e.g., satellite and airborne) techniques to increase the quantity and resolution of field-based observations.
- Facilitate continued refinement and development of geochronologic and thermochronologic dating and data interpretation techniques, and their application to critical field areas.

- Develop tools for measuring rock mechanical properties relevant to surface-process modeling at outcrop to continent scales.
- Provide continuous monitoring of exemplar field areas to document Earth-surface change due to tectonic and surface processes, and to better understand proxies for reconstructing paleoelevation, paleoclimate, erosion and weathering.
- Expand cyberinfrastructure to support open access to, and rapid processing and analysis of, point cloud data from coordinated mapping and monitoring efforts and from haphazard data sources such as drone data and individual photograph collections.
- Accelerate development of community-based simulation tools for linking crustal and mantle dynamics, land surface evolution, hydrology, and chemical weathering fluxes.

GRAND CHALLENGE 5

MEETING SOCIETAL NEEDS WHILE ADVANCING RESEARCH IN STRUCTURAL GEOLOGY AND TECTONICS

5.1 OVERVIEW

Some of the greatest advances in tectonics and structural geology have resulted from research and development on problems of great societal relevance. Given interdependencies between our increasing human population, technology, and the built environment, society must recognize and address the pressure on Earth's resources and natural systems and the hazards posed by natural and anthropogenic risk factors on these systems. Geoscience plays a pivotal role in tackling these issues; many of the key questions that are of immediate concern to society are addressed within the interdisciplinary fields of structural geology and tectonics, supported by a score of allied fields ranging from geophysics to petrology and stratigraphy. Research that aligns with meeting societal needs can break down unnecessary divisions between theoretical and applied science; fundamental discoveries in structural geology and tectonics research include evidence-based solutions to problems of societal relevance, while research directed toward societal needs further deepens our fundamental understanding of the Earth systems. In addition, observational techniques or technologies that might be impractical in basic research due to cost, scale, or perceived risk may be justified when applied to research problems with more direct relevance to humans—providing new opportunities for discovery.

In the 21st Century, what are the areas of great societal relevance that are likely to yield data, techniques, and technologies that will stimulate fundamental Earth science advances? In the broadest terms, these areas will include natural and anthropogenic hazards, resource demands ranging from freshwater to minerals, growing energy needs and climate change—each of which presents profound challenges for humankind in our lifetimes and those of our children. Several commonalities are shared across these areas, including fluid circulation in the lithosphere, rock fracturing, stress states in the crust, low temperature geochemistry and chronology, surface processes, and high resolution imaging of the surface and subsurface.

Serving society and science at the same time is a key attribute of modern structural geology and tectonics. We present six examples of synergies between theses goals that highlight areas of opportunity to make significant progress. Anthropogenic earthquakes triggered by injection of wastewater into the subsurface pose a human hazard and policy challenge, but also provide opportunity to study faults and tectonics at scales previously eluding academic research (***Section 5.2***). In the wake of natural disasters, like large earthquakes, landslides, volcanic eruptions and tsunamis, both the affected communities and scientific community share a desire to learn as much as possible about the driving processes responsible for devastation, and potential for mitigation. Rapid scientific response to catastrophe complemented by long-term monitoring efforts meets this shared goal, as shown by unique observations made after the 2011 Tohoku-Oki Earthquake and tsunami (***Section 5.3***). Predicting the flow of fluids through faults and fractures is crucial for meeting society's needs for energy, economic and groundwater resources, and for safely sequestering contaminants and potentially greenhouse gases underground. New perspectives and tools for quantifying the interactions between chemical and mechanical processes in fault zones are changing the way we study fault zone permeability through the earthquake cycle and over millions of years (***Section 5.4***)

and enabling breakthroughs in the notoriously difficult problem of characterizing and predicting subsurface fractures (***Section 5.5***). Structural geology and tectonics research also informs natural hazard assessments and risk reduction—for example, study of subduction zones that span continents and ocean basins are helping us understand hazard potential and build resilient societies (***Section 5.6***). A key goal of structural geology and tectonics research is to provide relevant data for hazard and risk models while making fundamental discoveries and observations, that, in turn, provide the foundation for the next generation of improved hazard models (***Section 5.7***). Our community brings to bear an effective combination of field, laboratory, experimental, numerical, and theoretical approaches to tackle these problems. Future progress will require closer collaboration with scientists and engineers from other disciplines if we are to leverage fully the underlying opportunities (***Section 5.8***).

These examples illustrate the opportunity and need for research at the intersection of structural geology and tectonic processes and human society. In each, our quest for fundamental understanding provides the foundation for hazard assessment and the sustainable management of critical energy, water and environmental resources. At the same time, applied research motivated by challenges related to hazards and resources has tremendous potential to push the science forward. The structural geology and tectonics community embraces both perspectives to advance the twin goals of meeting society's challenges and advancing fundamental understanding of our planet.

5.2 LEARNING FROM HUMAN-INDUCED EARTHQUAKES: THE OKLAHOMA FLUID INJECTION "EXPERIMENT"

Anthropogenic earthquakes pose a mitigation challenge for the areas impacted, but also provide an opportunity to study faults and tectonics at scales previously unavailable to academic research. Avenues of research made possible by such large-scale natural experiments include studies of earthquake nucleation, precursor seismicity and rupture processes, earthquake statistics, fault permeability, and studies of the impact of fault healing or cohesion on seismogenesis.

The rate of induced seismicity in the US has soared in recent years (Ellsworth, 2013; e.g., **Figure 1**), causing public concern and a regulation conundrum. However, human-induced earthquakes also provide an opportunity to study faults and tectonic processes at scales previously unavailable to academic research.

For example, a plethora of observations made possible by the unintended experiment of large-scale fluid injection in Oklahoma is providing unique insights into faulting and earthquake processes. Broadly, some faults are easily triggered by minute fluid pressure changes, supporting the conceptual framework that some faults exist near a critical failure state (Keranen et al., 2014). However, other regions of equivalent fluid injection volumes show little to no response to the injection. One possibility is that faults misoriented in the present day stress field are nearly impossible to trigger (Walsh and Zoback, 2016). Another is that we do not fully understand the complex nature of subsurface permeability in the fault zones or along the pathways of injected fluids. One promising observation for earthquake forecasting is that remote earthquakes appear to cause areas with induced seismicity to shake more than usual in the months before a large induced event (van der Elst et al., 2013)—implying that shaking levels from distant earthquakes can help test the stress levels of local faults and assess their likelihood of failure. Furthermore, detailed aftershock studies are illuminating subsurface fault networks in fine resolution, showing multiple subparallel, active fault strands within tens to hundreds of meters of one another. It remains unclear whether these adjacent faults are rupturing simultaneously during the main-shock or immediately become active in the aftershock

sequence. Observations from one earthquake sequence in Oklahoma show that at least one fault became active with weak (M<0) seismicity in the hours prior to hosting a moderate earthquake, and that these precursory earthquakes migrated with time to the eventual nucleation point (Savage et al., 2017). Further observations are needed to evaluate the ubiquity of such precursory activity.

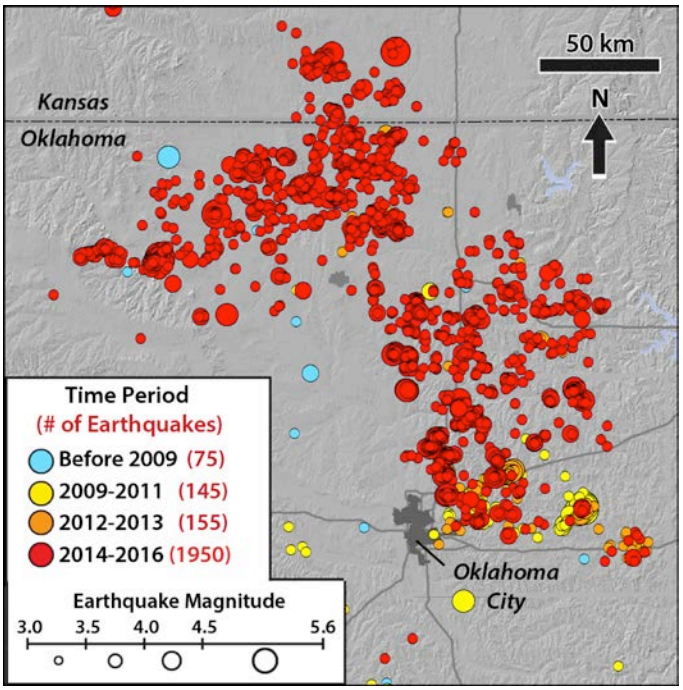


Figure 1

Some of the major knowledge gaps that persist for both natural and induced seismicity include: 1) How do earthquakes nucleate and is there an observable precursory signal? And 2) What fault processes, structures, or stress and fluid-pressure conditions control rupture propagation and arrest? Direct observations of the basic processes that link key parameters such as stress, pore fluid pressure, and slip are impossible without *in situ* measurements along faults, such as those produced by the San Andreas Fault Observatory at Depth (SAFOD) project (e.g., Zoback et al., 2011). An earthquake induced through fluid injection on a known fault, similar to the Rangely experiment of the 1970s (Raleigh et al., 1976), would allow us to obtain near-field information with a network of instruments. Observatory boreholes constructed in advance of the experiment would collect real-time data close to the source from initiation to arrest. An experiment like this would be unprecedented in terms of near-field observations and advance our understanding of the stress states and the role of fluids in seismogenesis, as well as earthquakes more generally.

5.3 LEARNING FROM NATURAL DISASTER THROUGH RAPID SCIENTIFIC RESPONSE: AN EXAMPLE FROM DRILLING THE JAPAN TRENCH

In the aftermath of large earthquakes, tsunamis, landslides and volcanic eruptions, there is great opportunity to gain scientific good from what may otherwise be a devastating disaster. Preparing in advance for rapid scientific response to such events, combined with complementary long-term observation efforts, make the most of this opportunity to advance fundamental research and provide the foundation for risk mitigation.

In the aftermath of large earthquakes, tsunamis, landslides and volcanic eruptions, there is great opportunity to gain scientific good from what may otherwise be a devastating disaster. For instance, many major tectonic questions about the strength of faults and mechanics of deformation are best addressed in the immediate aftermath of an earthquake. How strong are faults? Are there specific geological fingerprints of sudden slip? What is the residual stress state? What roles do fluids play in influencing the fault stresses? Answers to these questions gleaned from the geological record can be tested and pushed forward by careful observations after a major earthquake. Preparing in advance for rapid scientific response to such events, combined with complementary long-term

observation efforts, make the most of the opportunity to advance fundamental research and provide the foundation for risk mitigation.

The Japan Trench Fast Drilling Project (JFAST) is one example of a successful post-earthquake rapid response project involving a large-scale and technically complex international collaboration. The JFAST science team set sail on the deep sea drilling vessel Chikyu for an IODP expedition less than one year after the March 2011 magnitude 9.0 Tohoku-Oki Earthquake struck off the coast of Japan (**Figure 2**). Their goal: to drill through the plate boundary fault zone where it had slipped a full 50 m, crossing the fault 820 m below the sea floor and in an extreme water depth of ~7 km. The team successfully 1) conducted downhole geophysical logging that identified the fault zone and constrained the stress state after the earthquake (Lin et al., 2013), 2) collected core sections of fault and surroundings which provide insight into the geologic controls contributing to large slip magnitudes and devastating tsunami (Chester et al., 2013; Ujiie et al., 2013), and 3) installed and recovered data from a borehole temperature observatory that recorded the frictional heat signal from the earthquake—a key to measuring co-seismic frictional strength of the fault (Fulton et al., 2013). The observatory data also recorded evidence of transient damage, fluid flow and healing behavior associated with subsequent aftershocks (Fulton and Brodsky, 2016). Long-term data collection from the observatory continues to shed light on slow-slip earthquakes, with implications for understanding large earthquakes and tsunamis (Araki et al., 2017).

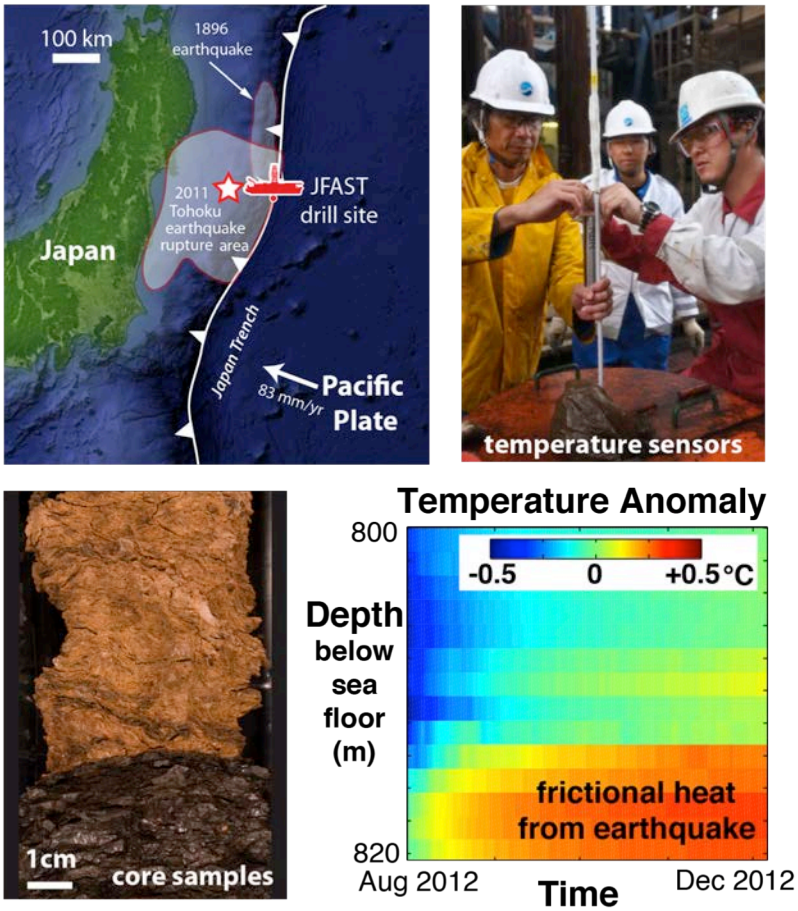


Figure 2

The results of the project already are helping us reach a greater understanding of earthquake mechanics, fluid flow and fault zone structure, showing the value of planning ambitious projects guided by key science questions *before* a natural disaster occurs. Considerable forethought had been given towards how to potentially drill into a fault after a large earthquake. These efforts were guided foremost by outstanding science questions, particular experiments to be conducted, and the technical and environmental considerations necessary to ensure success. The ideas were conveyed directly to science agencies in key countries at that time so that decision makers could digest the scientific need prior to the chaotic conditions that exist in the aftermath of a major earthquake. Advance planning also enabled the JFAST project to capitalize on strong international collaboration, existing infrastructure and project management structures, and lessons learned from previous successful long-term fault monitoring efforts (SAFOD).

In addition to advancing fundamental research that provides the foundation for risk mitigation (e.g., ***Sections 5.6 & 5.7***), we, as a tectonics community, should be ambitious and prepare to maximize potential knowledge gains when disaster strikes—both for fundamental science and in service to society.

5.4 FAULT ZONE PERMEABILITY: UNDERSTANDING STRUCTURE-FLUID EVOLUTION AND NATURAL RESOURCES

Structures of varying permeability within fault zones can produce a barrier, conduit, or barrier-conduit system with respect to fluid flow, with important implications for a wide range of societally relevant processes. New perspectives on the interactions between chemical and mechanical processes in fault-zone development combined with new geochemical approaches are changing the way we study fault-zone processes and the evolution of permeability structure through the earthquake cycle and over millions of years.

The movement of fluids in fault zones has implications for a wide range of societally relevant issues, including finding fluids (like hydrocarbons and clean water) or retaining fluids (like CO_2 sequestered from the atmosphere or nuclear waste) in the subsurface. Fault zones can produce a barrier, conduit, or barrier-conduit system with respect to fluid flow depending on the nature of the geological structures within the fault zone (e.g., Caine et al., 1996); the resulting fault zone permeability structure influences whether, where, and when faults trap—or leak—fluids. If faults are seals over long time scales, they can produce overpressured compartments like the one that led to the Deepwater Horizon tragedy and oil spill (**Figure 3**). Even short-term seals can slow the passage of wastewater injected into the subsurface, allowing pore fluid pressure to build sufficiently to cause fault slip and earthquakes (***Section 5.2***). At deeper crustal levels, fault slip and fracturing can provide high permeability zones for ore deposition. Thus, understanding the development of fault zone permeability over time is critical to meeting societal needs for both resources and a habitable environment.

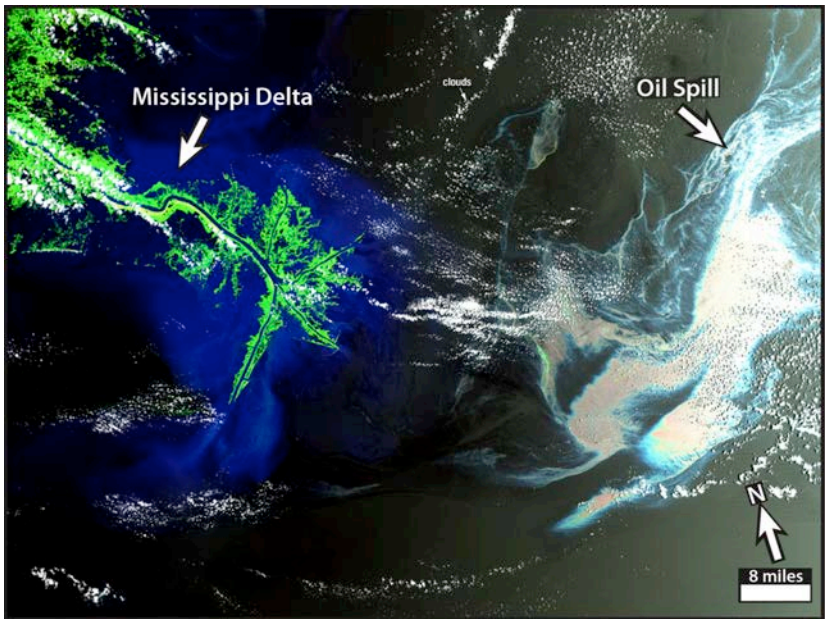


Figure 3

Innovative approaches to quantifying the time-space development of minerals that grow in fault zones are fundamentally changing the way structural geologists study the evolution of fault permeability from individual earthquake cycles to millions of years. Explicit consideration of the timescales of permeability changes is one facet of a growing understanding of critical feedbacks between structural/mechanical and geochemical processes (e.g., Laubach et al., 2010). In an example from the Moab fault in Utah, integrated $^{40}Ar/^{39}Ar$ dating and mineralogical analyses document >50% syntectonic enrichment of

clay (illite) in the fault core, recording fluid-rock interaction ca. 60-62 million years ago (Solum et al., 2005). Illite growth in fault cores occurs in distinct pulses through time, likely reflecting the role of fault slip, both in fluid migration (Boles et al., 2015) and in frictional heating that drives endothermic, clay-producing reactions (Jacobs et al., 2006). These results challenge the common assumption that low permeability fault gouge is a persistent barrier to fluid flow, and may explain the otherwise enigmatic observation that hydrocarbons locally leak along the surface traces of clay-rich faults (cf. Boles et al., 2005; **Figure 4**, left). The role of clays in fault mechanics—not only in reducing permeability in interseismic periods but also in changing the frictional and strength characteristics of fault cores—highlights the significance of these developments for basic as well as applied research.

Fault-zone permeability structure can also vary over short timescales. Fractures formed in damage zones during earthquakes produce transient increases in permeability with a lifespan that depends on both opening and sealing processes. For instance, modeling of seismic slip on a fault jog demonstrates that the quartz veins that host ~30% of the world's gold deposits (e.g., **Figure 4**, right)

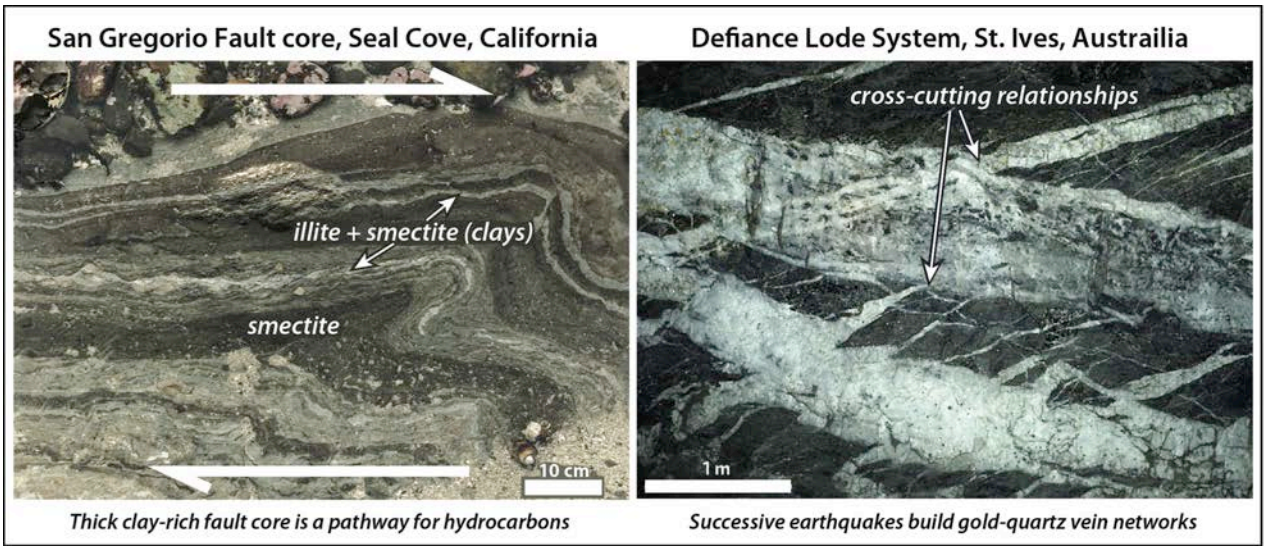


Figure 4

might record not only fracture opening during an earthquake, but also seismically-induced, near-instantaneous fluid decompression and flash vaporization that drives rapid precipitation of vein-filling minerals (Weatherly and Henley, 2013). The 4D evolution of fault systems is characterized by long periods of low permeability punctuated by transient episodes of high permeability. Constraints on the longevity of the latter may come from recent advances in dating syntectonic veins (e.g., Roberts and Walker, 2016). These examples illustrate some of the ways that the mineralogical archive of fluid-fault interactions can be exploited to evaluate the longevity of flow pathways and to track the evolution of fault-zone permeability over time, foreshadowing major changes in our understanding of these dynamic processes.

5.5 THE AGE AND ORIGIN OF NATURAL FRACTURES: LEARNING FROM NEW DISCOVERIES AND TECHNOLOGICAL ADVANCES

Subsurface fractures influence the engineering and seismic properties of rock and govern the movement of economically important fluids and contaminants, yet characterizing and predicting natural fracture systems at depth has long been one of the structural geology and tectonics community's most intractable problems. Breakthroughs are now possible due to recent microanalytical advances and new approaches

integrating theoretical and experimental work with petrological, geomechanical and geochemical tools commonly used to study metamorphic mineral assemblages and ore deposits in the deep subsurface.

Opening-mode (extensional) fractures and faults in the subsurface govern the movement of economically important fluids and contaminants. They influence the strength and seismic properties of rock and interfere with engineering operations, including hydraulic fracturing (e.g., ***Section 5.2***). Fractures also form key elements of unconventional shale reservoirs and are becoming increasingly central to energy development worldwide (Evans et al., 2014; Gale et al., 2014). As a result, understanding fractures is important in many industries and fields of study, from hydrogeology and waste disposal to seismology, construction, mining, and oil and gas production (**Figure 5**).

Figure 5

However, characterizing and predicting natural fracture systems at depth has long been one of the structure and tectonics community's most intractable problems. One challenge is that regional opening-mode fracture arrays can form from multiple causes and may exhibit no clear relationship to structural or stratigraphic fabric, regional faulting, folding, or orogenic events. Moreover, conventional observations from surface outcrops can be misleading, and constraints from costly subsurface samples are inherently incomplete. The lack of true ages and opening rates of fracture arrays impedes our ability to create accurate and testable geomechanical models, and limits our understanding of the mechanical and hydrogeologic evolution of sedimentary basins (e.g., Engelder and Whitaker, 2006; Becker et al., 2010; English, 2012). These problems lead to unacceptable uncertainties in many practical applications, including in seismic risk assessment, contaminant disposal, groundwater recovery, and the mineral and energy industries.

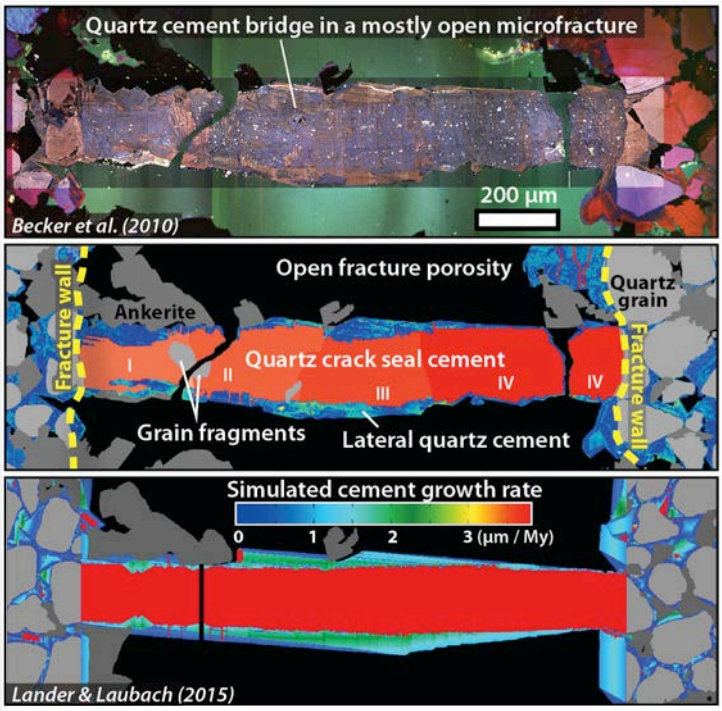


Figure 6

New discoveries and technologies are changing the way researchers tackle these challenges. A key recent development is the recognition that many fractures, including ones that are mostly open, contain a rich array of mineral deposits, textural complexity, and fluid inclusion evidence (e.g., Hanks et al., 2006; Fall et al., 2016). The quartz bridge imaged in the microfracture in **Figure 6** (upper panel), for instance, shows multiple generations of crack-seal cementation revealed by high-resolution cathodoluminescence mapping. These intricate, microscopic features reflect the presence of hot, chemically reactive fluids in subsurface fractures. Their discovery means that all of the petrological and

geochemical tools commonly used to study the formation and evolution of diagenetic and metamorphic mineral assemblages and ore deposits in the deep subsurface can be brought to bear on issues that previously were addressed mainly from fracture mechanics perspectives. We now can use the diagenetic and geochemical aspects of fracture systems to interpret field observations, quantify fracture age, and build better geomechanical models and numerical simulations (Ankit et al., 2015; Lander and Laubach, 2015)—like simulation of the fracture opening history and mineral precipitation rates **Figure 6** (lower panel) needed to build the quartz bridge (see the animation here: http://www.geosociety.org/datarepository/2014/, item 2014339). Innovations in microscopy (SEM-CL, TEM, EBSD) also are fueling advances in the study and interpretation of fluid inclusions in fracture-filling cements using microthermometry and geochemical data (e.g., Anders et al., 2014). Breakthroughs in understanding the origin, timing and growth rates of fracture systems are now possible through the integration of these new approaches with theoretical and experimental work—both to benefit applications in engineering, contaminant disposal and energy production, and to advance fundamental understandings of regional stress field evolution, fold and fault zone development, rheology and the earthquake cycle (e.g., ***Grand Challenges #2, 3, 4***).

5.6 SUBDUCTION ZONE SCIENCE FOR RESILIENT SOCIETIES

Advancing tectonics research to inform natural hazard assessments and risk reduction is important in subduction zones, where earthquakes, tsunamis, volcanic eruptions, and landslides are uniquely large, inevitable, and coupled. To build resilience to these tectonic hazards, we need improved understanding of tectonic processes at subduction zones and the development of new observationally verified, integrative models derived from field and laboratory studies, with data collection and monitoring efforts that cross the coastline.

The importance of advancing tectonics research to inform natural hazard assessments and risk reduction is well illustrated in subduction zones, where earthquakes, tsunamis, volcanic eruptions, and landslides are uniquely large, inevitable, and coupled.

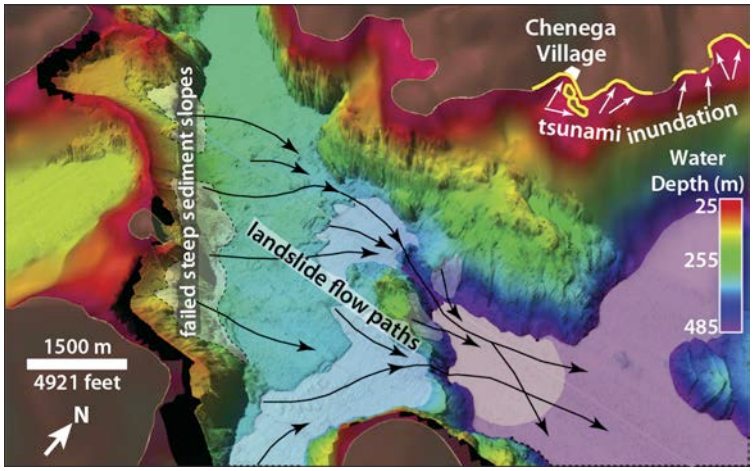


Figure 7

As populations increasingly concentrate in coastal regions—many of which lie along subduction zones—there is a pressing need to reduce risks from subduction-related hazards. Tectonic studies focused on understanding offshore and coastal processes are the foundation of any effective, efficient risk-reduction strategy. For instance, a study of recently acquired high-resolution, shaded-relief bathymetric and topographic images (**Figure 7**) showed that the 1964 magnitude 9.2 Alaska earthquake likely triggered a submarine landslide, which in turn generated a damaging tsunami that killed 23 people (Brothers et al., 2016). Many of the other destructive tsunamis that followed this earthquake were likely caused by similar submarine landslides. Understanding of these coupled, shoreline-crossing tectonic processes, along with state-of-the-art topographic data and mapping, will help identify the likely sources of local tsunamis so that the impacts of future tectonic events may be mitigated. This example highlights the potential for analogous studies of other

localized hazardous phenomena to underpin new maps, scenarios, and forecasts on time-scales and in locations not previously possible, particularly in coastal regions.

In all regions with significant population or infrastructure, engineers, planners, emergency managers and policy-makers now request information about neighborhood-scale variations in earthquake shaking, ground-failure, tsunamis, landslides, volcanic eruptions and their impacts. Local tectonic features have profound effects on these phenomena including earthquake ground shaking, which must be simulated in detail for engineering design of new structures and to prioritize retrofitting of existing ones. In Seattle, Washington, retrofitting of vulnerable unreinforced masonry buildings is guided by the new USGS urban hazard map, which shows spatial variations in expected earthquake shaking city block by city block (**Figure 8**; Gomberg et al., 2017). More broadly, research on fault zone evolution (***Grand Challenge #3***) and the ability to characterize tectonic events at high-resolution translate directly into cost and life-saving mitigation activities, urban planning, and emergency preparedness.

Building resilience to geologic hazards requires understanding of how the tectonic processes that lead to hazardous events evolve temporally and spatially and how one event affects another. Understanding these relationships in four-dimensions will enable early warnings of strong earthquake shaking, volcanic eruptions and landslides, delivered in time to implement life- and property-saving measures. Multi-disciplinary monitoring (e.g., employing geophysical sensor networks, or tectonic geomorphology studies of satellite imagery) is key to developing these capabilities, and also to understanding the tectonic framework of hazardous subduction zone events—such as monitoring of slow earthquakes in Alaska that contradict prevailing models of Pacific-North American Plate boundary activity and delineate the edges of a region that slipped in a great earthquake (Wech et al., 2016).

To move forward, we need improved understanding of tectonic processes at plate boundaries. This can be achieved through the development of new observationally verified, integrative models derived from geologic field and laboratory studies, new seafloor measurements (e.g., cores, subsurface images), multi-disciplinary monitoring, and coast-crossing seamless topographic data.

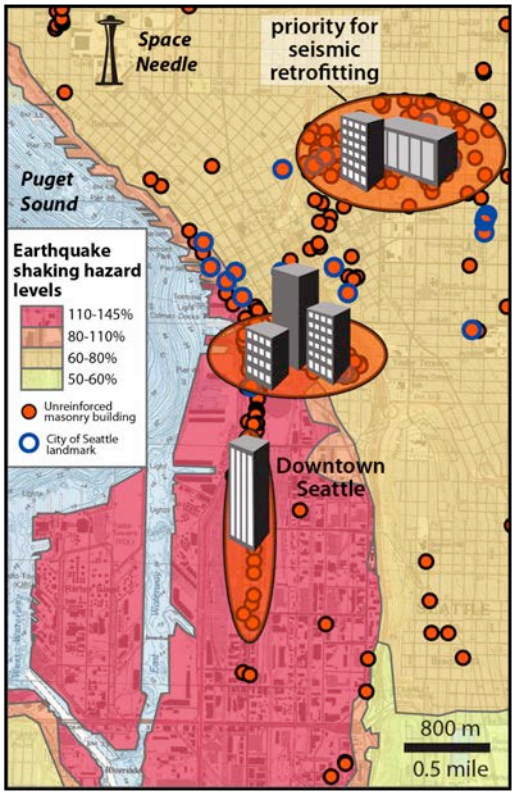


Figure 8

5.7 FROM RESEARCH TO RISK REDUCTION

Structural geology and tectonics research provides foundational data for earthquake, landslide, tsunami and volcanic hazard models and risk mitigation practices. A key goal is to use fundamental research and observations to determine where hazard models succeed or fall short, and foresee what inputs will be needed to improve future models of impacts.

A primary goal of the structure and tectonics community is to advance research that meets societal needs and challenges. Research in this domain benefits society by guiding building codes, mitigation practices for major lifelines, and the safe siting of critical facilities; it also provides the foundation for securing vital freshwater, mineral and energy resources, and for understanding how tectonic hazards like tsunamis and landslides may be exacerbated as sea level and precipitation patterns adjust to climate change. However, the path from hypothesis-driven science to supporting policy and decision-making is not always clear. What are concrete ways that fundamental research can help quantify and minimize risk? And, how can societal needs drive great science?

It is critical to understand the essence of hazard and risk models—and to think beyond current practices. Hazard models attempt to capture the location, frequency, and intensity of natural phenomena. Risk models build on hazard to calculate losses in terms of lives, injuries, infrastructure and economic impacts. Central to both is this challenge for the tectonics community: What processes matter at societally relevant time scales of years to centuries?

Structural geology and tectonics research provides foundational data for earthquake, landslide, tsunami and volcanic hazard models. Seismic hazard models, for example, require fault geometry and slip sense (where is the fault? what is its orientation? what are the rock properties? how does the fault slip?), recurrence interval (how often does the fault rupture?), and estimates of earthquake magnitude distributions, among other parameters. Future seismic hazard models will incorporate earthquake histories and realistic fault networks with physics-based rupturing, coupled with a three-dimensional, broadband record of ground shaking. Considerable fundamental science is needed to parameterize these components and integrate long-term tectonic problems with shorter-term societal concerns to realize the goal of a realistic, global earthquake engine (**Figure 9**).

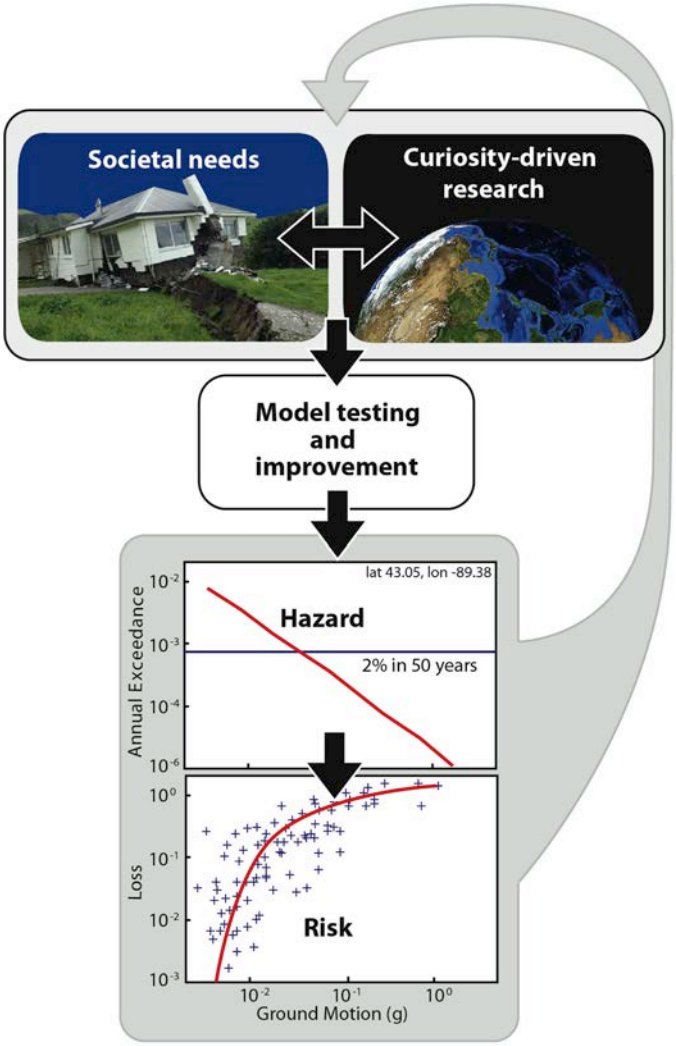


Figure 9

Curiosity-driven research and use-inspired research converge in hazard assessment. Decades ago, discoveries of subduction zones and blind faults expanded seismic hazard models in fundamental ways, and forced new approaches to data collection and interpretation. It is easy to overlook the importance of exploratory, observational studies, but devastating earthquakes and landslides in unforeseen locations make it clear that we simply have not seen enough to confidently

model Earth deformation. In fact, crucial behaviors for fault systems commonly assumed to be well characterized—such as the San Andreas, Wasatch, and Cascadia systems—are still being discovered. Great promise is shown by recent approaches that bridge curiosity-driven research and hazard assessment, such as low-temperature thermochronology that ties exhumation histories to earthquake histories and fault slip rates (e.g. Enkelmann et al., 2015); reconstruction of the full seismic cycle from fault rock microstructures and geochemistry (e.g. ***sections 3.3 and 3.4***); new methods for establishing regional landslide chronologies using surface roughness from LiDAR (e.g., LaHusen et al., 2016); and studies of the role of rheology in controlling ground shaking (e.g. Roten et al., 2014; ***Grand Challenge #2***). A central challenge for tectonics and structural geology research in the future will be to provide relevant data for existing hazard and risk models even while making fundamental discoveries that guide the next generation of hazard and risk assessment.

Progress will require collaboration between tectonic and structural geologists and hazard modelers to address issues such as: What data do hazard models need? How well do tectonics studies address hazards problems at spatial and temporal scales that matter to society? How can we quantify uncertainty? And where do hazard models fail and require fundamentally new approaches? A community mindset that embraces hazards-related research will push science forward while also saving lives and reducing financial impacts.

5.8 KEY QUESTIONS & REQUIREMENTS TO MAKE PROGRESS

Key questions include:

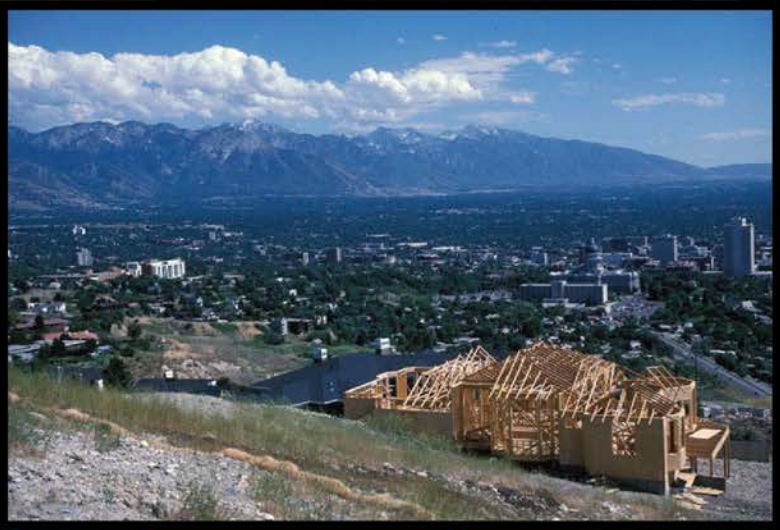
- What processes and physical relationships are most important for developing quantitative models of tectonic hazards, including subduction-zone earthquakes, volcanic eruptions, landslides and tsunamis, at spatial and temporal scales that matter to society?
- How can we anticipate extreme tectonic events and both natural and anthropogenic geohazards that fall outside the predictive power of current models?
- How can we collaborate with stakeholders to develop resilience and mitigation strategies?
- How do we create early warning systems for hazardous tectonic events, assess their fundamental limitations, and communicate their effectiveness to stakeholders?
- How do human activities modulate natural systems at time scales relevant to geologic hazards, such as seismicity induced by subsurface fluid injection for oil and natural gas extraction?
- How do the physical and chemical changes that result from fluid-rock interactions affect fault-zone mechanics, structure, and permeability over timescales of seconds to millions of years?
- How do fluid-structure-tectonic interactions impact freshwater resources, the containment of contaminants, the stability of buildings and other infrastructure, and geothermal energy potential?
- What are the physical controls on the integrity and long-term seismic stability of sites selected for CO_2 sequestration?

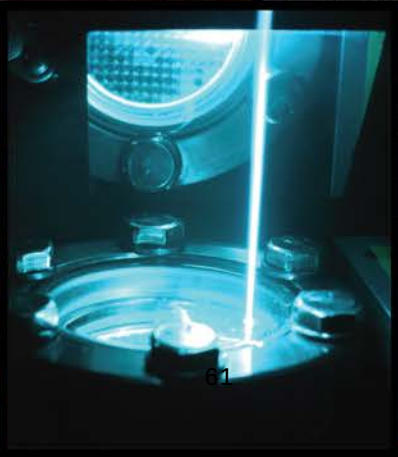
Requirements to make progress include:

- Increase collaboration and engagement among scientists who study fundamental tectonic and structural processes, those who work on applied problems and risk management, and industry geoscientists.

- Develop a community-based resource network to aid in translating disciplinary research into loss reduction, and to aid in coordinating experimental design, hazard and risk assessment, and policymaking activities.
- Support the use of community-based study sites that take advantage of active processes and crosscutting problems to better understand hazards, such as subduction zones, or fault systems where fluid pressure, ground motions, and building response are measured before, during, and after earthquakes.
- Extend the integration of field-based, historical, and interdisciplinary approaches to hazard assessment pioneered by the Southern California Earthquake Center (SCEC) to a broader range of tectonic settings.
- Increase feedback between modelers of hazardous tectonic events and researchers conducting observational studies so that models can inform data collection and data can inform model refinement.
- Refine and develop techniques to date geological events over timescales and at resolutions that provide predictive power for hazard models.
- Prepare to rapidly deploy scientists and observatories following significant natural hazard events, to advance fundamental research and provide the foundation for improved risk mitigation.
- Fund interdisciplinary collaborations that include structural geologists, hydrologists, geophysicists and geochemists on projects addressing fault zone permeability.
- Increase open data sharing agreements with industries, such as those engaged in mineral and petroleum exploration and extraction.

DRAFT FOR COMMUNITY COMMENT





ACHIEVING THE VISION

STRATEGIES FOR ENABLING DISCOVERY, ENGAGEMENT & IMPACT

6.1 OVERVIEW

Achieving the tectonics community's ambitious vision to understand planetary evolution and meet societal challenges (***Grand Challenges #1-5***) will require investment in several key areas. Profound advances in geoscience research over the past decade and a half—particularly in interdisciplinary approaches and in the ability to make high-resolution observations at both micro and global scales—have opened new scientific frontiers and opportunities to make major breakthroughs. Yet structural barriers, knowledge gaps, and resource needs present obstacles to building on this momentum. In order to catalyze new discoveries, first we must invest in the continued development of key approaches and technologies that have the potential to impact many areas of research in unexpected ways (***Section 6.2***). Second, we must address needs in the areas of cyberinfrastructure, data integration, and data access for both existing and new technologies to effectively enable interdisciplinary science (***Section 6.3***). Third, we must invest in our community's intellectual capacity by recruiting and retaining a diverse and rigorously trained workforce (***Section 6.4***). Finally, for our discoveries to have the maximum societal benefit, we must increase engagement between the geosciences community and public stakeholders (***Section 6.5***).

Common to each of these areas is the pressing need for new collaborative partnerships, organizations and infrastructure to facilitate the science and amplify its impacts (***Sections 6.6***). In particular, enabling major progress toward our vision in the coming decade will require consortium approaches that involve the collaboration of a broad spectrum of geoscientists from multiple disciplines, not just individual researchers traditionally funded by the National Science Foundation Division of Earth Sciences Tectonics Program. The following sections highlight three ***priority strategies for investment for a tectonics initiative*** to meet these needs and solve future challenges, including those we cannot yet foresee:

(1) **Invest in research approaches and tools** in key areas that promise broad, interdisciplinary change, including observational and experimental technologies, and strategies that promote the sharing of digital data and numerical models ***(Sections 6.2, 6.3)***

(2) **Invest in organizations** that connect more people to practical resources and best practices for recruiting, educating, and retaining a diverse and rigorously trained workforce, and for engaging with public stakeholders ***(Sections 6.4, 6.5)***

(3) **Invest in infrastructure** that facilitates interdisciplinary collaboration, model-data comparison, and technical innovation ***(Sections 6.6)***

6.2 CATALYSTS FOR DISCOVERY: INVESTING IN TRANSFORMATIVE INTERDISCIPLINARY RESEARCH APPROACHES AND TOOLS

The development of new tools and technologies has sparked major advances in our understanding of the structure and dynamic behavior of the Earth. Here, we highlight areas of tectonics research where the continued development and application of these innovations promises broad interdisciplinary growth.

RECOMMENDATION #1: FACILITATE RESEARCH IN AREAS THAT PROMISE SWEEPING INTERDISCIPLINARY ADVANCEMENT

The following are examples of research areas and approaches that have high potential to stimulate major advances in many disciplines. Areas such as these appear especially promising because they challenge common assumptions used to study and model tectonic processes, chart unexplored realms of our planet, and bridge the broad range of temporal and spatial scales needed to understand Earth evolution.

- ***Exploring Earth's deep interior from a geological perspective.*** The explosion of geophysical data exploring Earth's deep lithosphere and mantle (e.g., **Figure 1**) has created enormous and largely untapped opportunity for progress in tectonics research (e.g., ***Grand Challenges #1-5, Sections 1.2, 2.5, 3.6, 4.2, 5.3***). A **common assumption** in the study of these realms is that geophysical observations relate directly to some key property, such as density, strain, fluid, or some other depth- or temperature-dependent characteristic. Geological observations are needed to test these assumptions. **Surface geology and direct observations of exhumed rocks**, including the use of new geochronologic, geochemical, and microstructural tools on xenoliths and exposed sections (e.g., ***Grand Challenges #3 and 2, Sections 2.4, 2.5, 3.4, 3.6***), are a critical complement to geophysical exploration of the deep interior of our planet and a key to major advances in understanding of Earth structure and dynamics.

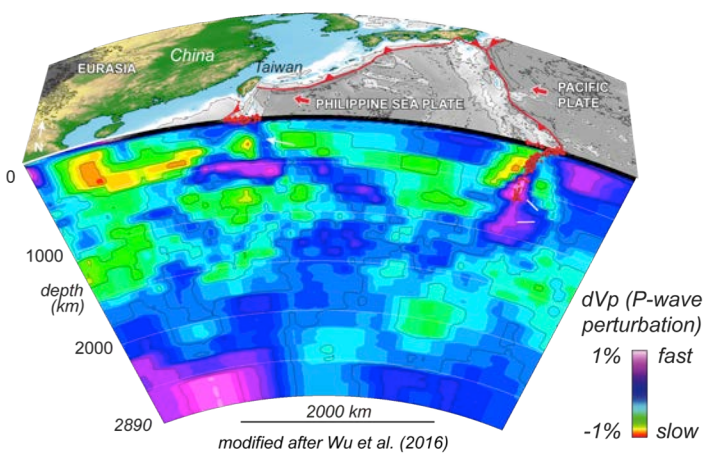


Figure 1

- ***Exploring Earth surface change, today and through deep time.*** Topographic form and change measured over all timescales—from seconds to millions and billions of years—provides first-order constraints on tectonic and geodynamic processes and represents a key link between the atmosphere and deep Earth. The availability of topographic and geodetic data and imagery at increasingly fine spatial and temporal scales has been transformational to tectonics research in virtually all areas, from traditional geologic mapping and structural geology to tectonic geomorphology and hazard assessment (e.g., ***Grand Challenges #1-5***). **Global coverage and repeat surveys** of such datasets would vastly expand the tectonics community's capacity for discovery and process-based understanding. Enhancing the resolution of **topographic reconstructions through deep time** promises to be similarly transformative for our understanding of both: 1) tectonic processes; and 2) the connections between Earth-surface evolution and the atmosphere, biosphere and solid Earth.

- ***Integrating the rock record with experiments and modeling.*** The development of better empirical laws for relating stress and strain in natural, polymineralic materials can be achieved by

integrating information from the rock record with experimental data and numerical and analogue models (e.g., ***Grand Challenges #2 and 3, Sections 2.2, 3.5***). This approach has great potential to reveal how the strength and rheology of faults and many other geological and tectonic features vary with depth in the lithosphere (e.g., ***Grand Challenge #5, Section 5.3***).

- ***Addressing problems of spatial and temporal scaling***. To develop realistic models of natural physical and chemical processes, all researchers eventually must address the question: Over what spatial and temporal scales does heterogeneity matter? Breakthroughs in our ability to properly scale dynamic processes and material properties will be enabled by enhancing the accuracy and range of geochronologic methods (e.g., ***Grand Challenge #1, Section 1.6***), applying new high-resolution geophysical tools (e.g., ***Grand Challenges #1, 3 and 4, Sections 1.2, 3.2, 4.5***), and increasing our understanding of rock strength and rheology (e.g., ***Sections 2.1-2.3, 4.4, 4.5***).

- ***Exploring the oceanic lithosphere***. Continued exploration of the oceanic lithosphere promises expansive interdisciplinary change both on scientific frontiers and on problems of great societal relevance, like subduction zone earthquakes and tsunamis (e.g., ***Grand Challenges #1 and 5, Sections 1.3, 5.6***). Many new discoveries in this realm are leading us to question past assumptions, from the mechanisms of faulting (e.g., ***Grand Challenge #4, Section 4.2***), to the relationships between mantle flow and crustal movements, to how hydration influences lithospheric strength (e.g., ***Grand Challenge #5, Section 5.3***).

RECOMMENDATION #2: BUILD ON RECENT ADVANCES IN TECHNOLOGY & INSTRUMENTATION THAT ARE CENTRAL TO MANY FIELDS

Technological advances in the following areas have stimulated breakthroughs to long-standing questions and opened up new areas of inquiry, including those related to the scientific themes listed in ***Grand Challenges #1-5*** and ***Recommendation #1***. This track record and their centrality to so many facets of tectonics and geoscience research ensure that continued investment in these areas can transform the science in unexpected ways.

- ***Technologies for mapping the Earth in three dimensions.*** New instrumentation and observing platforms now permit unprecedented spatial resolution of the topology of landscapes, providing foundational data for a wide array of tectonics studies (e.g., ***Grand Challenges #1, 3, 4, 5***). In addition to both airborne and field LiDAR systems (**Figure 2**), new procedures developed for the derivation of digital surface maps from satellite imagery enable the production

Figure 2

of **high (2 to 0.5 m) resolution terrain data for large regions of the planet**. Moreover, the frequency of satellite imaging is such that terrain data can be generated repeatedly on short timeframes, permitting researchers to literally **monitor landscape evolution in near real-time**. A pilot program using these technologies—involving NSF's Office of Polar Programs, the National Geospatial-Intelligence Agency and the Polar Geospatial Center at the University of Minnesota—has revolutionized many aspects of polar science in just a few years. *We strongly endorse an on-going geoscience community initiative to expand this effort globally*. This effort, combined with broader access to new techniques for **3D sub-surface imaging and data visualization & analysis**, is certain to fuel major advances.

- ***Analog/physical and numerical modeling capabilities.*** Models bridge the gap between theory and observations and enable us to link processes that operate on widely different timescales (e.g., ***Grand Challenge #2 and 4, Sections 2.2, 2.5, 4.2***). Investing in high performance computing, new observational tools for physical experiments, and community networks for numerical modeling (e.g., ***Section 6.3***) will enable us to more effectively model the complex interactions, heterogeneities, and non-linear behaviors of many tectonic processes.

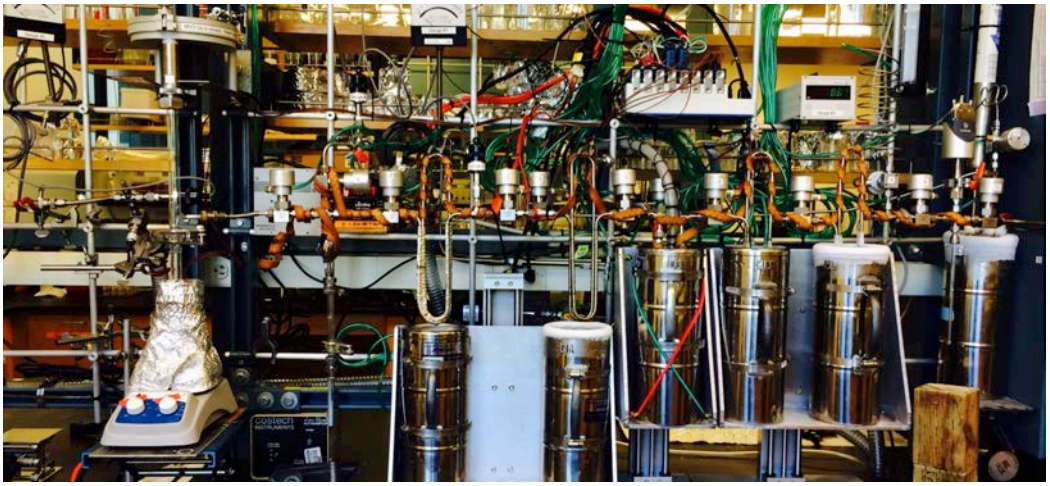


Figure 3

- ***Geochemical & isotopic proxies.*** Proxy data from the rock record quantitatively constrain Earth-system interactions and tectonic processes operating at microscopic to global scales, over timeframes of a fraction of a second to billions of years. Such data yield insights into topics ranging from the role of tectonics in Earth's habitability to the effects of fluid-fault interactions on seismic hazard, water and energy resources (e.g., ***Grand Challenges #1-5, Sections 1.4, 2.3, 3.4, 4.3, 4.4, 4.6, 5.2, 5.3, 5.4, 5.5***). The development of new proxies and microanalytical techniques (e.g., **Figure 3**)—and integration of these tools with high-precision geo- and thermochronology and models that explore tectonic linkages—promise to enable major advances in understanding of the formation and evolution of the Earth's lithosphere, atmosphere, biosphere and hydrosphere.

- ***Observational and experimental technologies for quantifying Earth-material properties.*** New observational technologies, including EBSD and CT imaging, and neutron diffraction, Raman and FTIR spectroscopy are transforming our ability to quantify Earth-material properties (e.g., ***Grand Challenges #1-5, Sections 1.6, 2.3, 2.4, 3.3, 3.5, 4.6, 5.4, 5.5***). Continued developments in techniques like these, combined with the results of rock mechanics and deformation experiments,

will enable us to push the frontiers of understanding the coupling of mechanical and chemical processes, rheology and metamorphic reactions, fracture evolution, and the rock record.

- ***Geochronology.*** Improvements in spatial resolution, precision and accuracy, throughput, and training have enhanced our ability to date geological materials and determine the rates of processes (e.g., ***Grand Challenges #1-4, Sections 1.6, 2.3, 3.4, 4.4***). Acquiring higher resolution thermo- and geochronology, developing better in-situ dating methods, and expanding techniques that are sensitive to a wide range of temperatures and time scales (*c.f.*, Harrison et al., 2015) is the lynchpin for linking processes operating on every spatial scale and over timescales of seconds to billions of years.

6.3 ENABLING THE SCIENCE: CYBERINFRASTRUCTURE NEEDS FOR INTEGRATING HETEROGENEOUS DATA & MODELS

Many efforts are underway to promote effective data sharing in the geosciences. The following recommendations explore ways to align cyberinfrastructure and data access practices across the heterogeneous field, analytical, micro-imaging, remote sensing, and model datasets that must be integrated to promote innovation and make major advances in tectonics and structural geology research.

RECOMMENDATION #1: STANDARDIZE DATA MANAGEMENT & REPORTING PRACTICES FOR HETEROGENEOUS DATASETS AND MODELS

The shear breadth of approaches needed to address tectonic problems presents a challenge for integrating datasets and models. For instance, assessing seismic hazard along a single fault can require the assimilation of heterogeneous geological observations (e.g., geological maps and structural, microstructural, stratigraphic and geomorphologic data); geochronologic and geochemical data (e.g., radiocarbon dating, thermochronology, fault cement stable isotopes); remote sensing data (e.g., LiDAR, LANDSAT, INSAR, SFM); and geophysical observations (e.g., seismic event catalogs, electrical conductivity) into landscape evolution, geophysical and geomechanical models. Data management practices vary widely among sub-fields of the tectonics community that produce these varied datasets and models, owing to both historical and structural reasons. Many efforts are underway to align practices and promote **effective sharing of standardized, open-access digital data and models across the spectrum of tectonics fields**. In particular, we emphasize the need to better **standardize and communicate the rigor, reproducibility and statistical robustness of field-based and other datasets** to facilitate their use by non-experts and integration into quantitative models.

Support for new ***collaborative strategies*** (e.g., ***Section 6.6***) and expanded use of ***cyberinfrastructure*** (**Figure 4**) designed to ***assimilate heterogeneous datasets*** and effectively ***communicate uncertainties*** to both

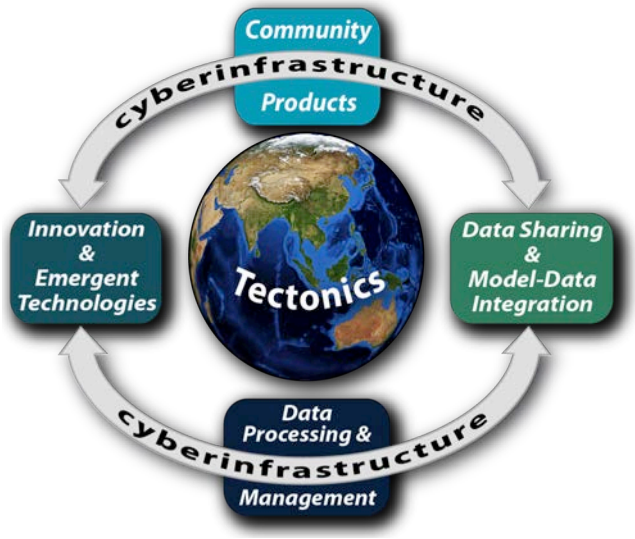


Figure 4

expert and non-expert users in allied fields will help us achieve this goal and foster innovation across the scientific ***Grand Challenges***. Specific recommendations include:

- Promote use of open-access archives in order to standardize and integrate heterogeneous geological, geochemical, and geophysical sample and analytical data sets, including those typically collected in ***traditional field-based*** structural geology, petrology, sedimentary geology, and subsurface coring endeavors. ***Community-driven programs*** such as ***CINERGI, EarthCube, EarthChem*** and the ***StraboSpot*** data system (**Figure 5**)—which include open source data, sample archives, digital geologic maps, and other products—can be adapted to accommodate the heterogeneity of datasets and use.
- Improve access to, and promote the compilation and sharing of, data sets and numerical tools. This can be aided by using community web portals or networks (e.g., ***CSDMS***), and tools like ***GitHub*** and ***Jupyter notebooks***, which help developers work together to host and review code, build new software, and train users.
- Democratize, codify, and fortify all data treatments and reporting, including making ***community standards for data/model reproducibility and quantitative analyses*** (e.g., statistical tools), to enable advanced data-model comparisons that are shaped by all sub-disciplines of the tectonics community.
- Work with third party developers to enhance free and open access to data and models such as ***SRTM***, ***Google Earth***, ***TRMM***, and ***declassified military data***.
- Promote the use of a systematic sample catalog linked to existing datasets. This effort includes both surface and subsurface core samples that have been acquired at great expense by governments, industry and academics, and possess immense value for research. Several repositories and registries (e.g., ***Texas A&M ODP***, the University of Texas at Austin's ***Bureau of Economic Geology***, ***SESAR***) provide models.

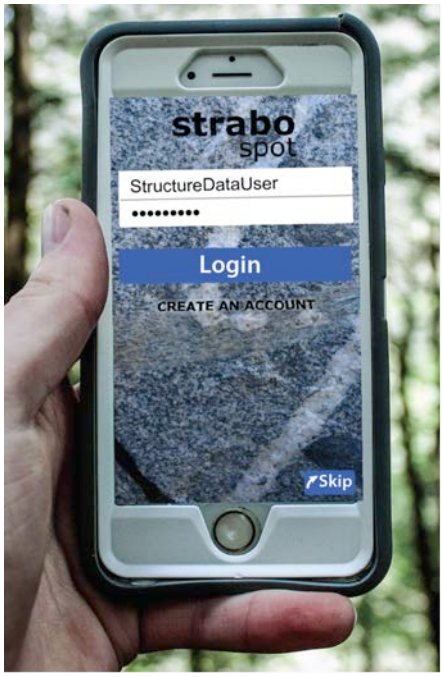


Figure 5

RECOMMENDATION #2: INCREASE ACCESS TO DATA FROM INDUSTRY & GOVERNMENT PARTNERS

Marine seismic reflection data originally acquired for the purposes of oil and gas exploration within the U.S. Economic Exclusive Zone represent a valuable national scientific resource. The National Archive of Marine Seismic Surveys, which is organized and maintained by the U.S.G.S., provides free and open access to data acquired by or contributed to U.S. Department of the Interior agencies. The tectonics community could expand this effort to include other data types, including core and cuttings samples, well logs, subsurface temperature/pressure data, potential fields data, data related to induced seismicity, and high-resolution military satellite data from all parts of the globe. Data collected from outside the U.S. can strengthen international partnerships and promote cross-disciplinary collaborations.

RECOMMENDATION #3: INVEST IN INTEGRATIVE DATA PRODUCTS, SIMULATION & VISUALIZATION TOOLS

It is not enough for diverse data types to be accessible and quantitatively rigorous. Rather, to maximize their impact, high-level data products and software that require advanced data processing, synthesis, and interpretation to produce are also needed. Examples include ***repositories of Earth models,*** (e.g., **Figure 6**), ***visualization software,*** and ***mapping and multiprocess simulation tools*****.** These kinds of resources allow researchers to build three-dimensional models of the subsurface (e.g., Midland Valley's ***MOVE*** software suite, Maptek's ***Vulcan*** 3D mining software, Intrepid Geophysics' ***GeoModeller***, the IRIS ***Earth Model Collaboration***), construct high-resolution maps of strain fields and ground motions (e.g., the ***Earth Imaging Group***), and make paleogeographic reconstructions (e.g., ***G-Plates, PaleoGIS***). These types of integrative data products and software are a recipe for major advances because they enable researchers, students, and public policy professionals to build intuition, integrate observations and models, and forecast future changes.

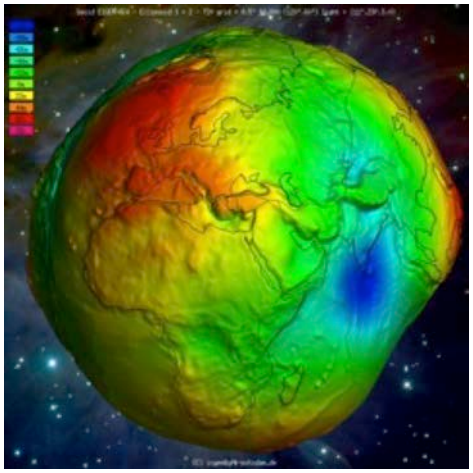


Figure 6

6.4 BREADTH IS OUR STRENGTH: RECRUITING, EDUCATING AND RETAINING A DIVERSE & RIGOROUSLY TRAINED WORKFORCE

Effectively recruiting, educating, and retaining a diverse and rigorously trained workforce is a grand challenge, not only for the tectonics community, but for the geosciences, STEM fields, and our nation in general. We seek to transform the face of tectonics in the 21st Century by facilitating the practical application of research-based best practices and efficient strategies for institutional change—supported by centralized, community-based infrastructure tailored to tectonics.

RECOMMENDATION #1: FACILITATE PRACTICAL IMPLEMENTATION OF BEST PRACTICES IN GEOSCIENCE EDUCATION

The content and methods of geoscience education have undergone major changes in recent decades and years, including the proliferation of hands-on, inquiry-based teaching (e.g., Macdonald et al., 2005; Thomas and Roberts, 2009; Tewksbury et al., 2013) and development of community educational centers and programs that disseminate knowledge and support educators from college and pre-college settings (e.g., ***SERC***, Manduca et al., 2017). The tectonics community faces two main challenges associated with capitalizing fully on these developments. First, from the perspective of many **disciplinary researchers**, digesting the geoscience education literature, adapting best practices to the specific needs of their students, and implementing them effectively is a daunting challenge. Second, **geoscience education researchers** generally see the increased need for: 1) communication of their findings with disciplinary researchers and educators; and 2) collaboration with the disciplinary research community to develop high-quality instructional material on quantitative reasoning. While neither of these challenges is new, there is increased urgency for both of them in the face of society's tectonics-related challenges (e.g., ***Grand Challenges #4, #5***).

A third aspect of education is the need to better prepare students for **career opportunities that extend beyond purely academic research**. The need for energy, environmental protection, and responsible land and resource management is projected to increase demand for geoscientists over the next decade and a half (Bureau of Labor Statistics, 2017). Tectonics students are well prepared to meet this demand, as they develop a broad background in the sciences and enter the job market with high-demand skills in areas including integrative thinking, quantitative reasoning, computer modeling, data analysis, and digital mapping. Educating educators about these opportunities, and incorporating materials into curricula that help students develop strong communication skills and engage in community issues (e.g., ***Grand Challenge #5***), can help attract and retain students from the K-12 to the Ph.D. level. This approach will greatly enhance the intellectual capacity and societal impact of the tectonics community.

The persistent barriers to progress in these areas are time-commitment issues, information overload, and the difficulty of connecting people with key resources that are tailored to their specific needs. We recommend development of a new **tectonics community organization** (***Section 6.6***) as the cornerstone of an efficient strategy to overcome these barriers. Such an organization could efficiently ***connect more people to practical educational resources and best practices that are likely to contribute to immediate, lasting institutional change***, and ***facilitate collaboration*** between educational and disciplinary specialists in tectonics. An organization that acted as an **"onramp" to education** could tailor, organize, and scaffold educational resources for the tectonics community, e.g., providing one-pager "cheat sheets" on efficient ways to implement best practices on key topics with links that branch out to additional resources and forums for connecting with experts (**Figure 7**).

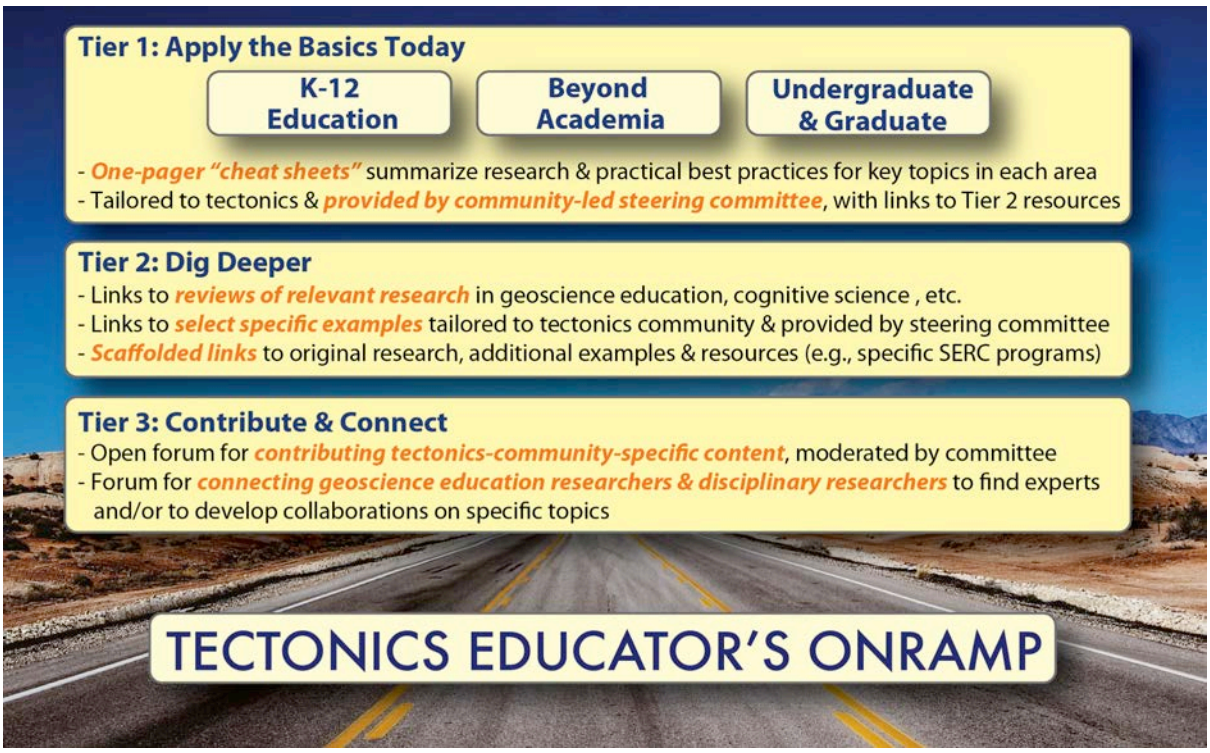


Figure 7

Such an organization could efficiently share and help people plug into existing models that are well suited to educational efforts in tectonics. These efforts could include '***GeoBuses***' (e.g., the

BioBus, http://www.biobus.org) that bring mobile laboratories to students; activities that illustrate the links between geology and areas of traditional knowledge and cultural heritage (e.g., Reano & Ridgeway, 2015); efforts that support trans-disciplinary educational research (e.g., Ormand et al., 2014), get students involved in research at a system level (e.g., ***EarthScope AGeS***, ***REU programs, Keck Consortium projects***), or help graduate students bring their research experience into the K-12 classroom (e.g., NSF's ***GK-12 program***). A dedicated infrastructure—and the institutional memory that it engenders—would significantly facilitate efforts by individual scientists, promote sustainability of high-impact practices, help identify learning gaps, and connect key players to promote innovation.

RECOMMENDATION #2: CREATE INSTITUTIONAL CHANGE VIA BEST PRACTICES FOR INCREASING DIVERSITY OF OUR COMMUNITY & LEADERSHIP

There is great excitement and optimism in the tectonics community around the idea that breadth is our strength. The diversity of viewpoints from the disciplinary perspective (e.g., ***Grand Challenges #1-5***) increases the strength and robustness of our scientific enterprise, by encouraging open-mindedness and allowing distinctly different insights on complex problems. **We can, as a community, benefit equally from thinking broadly about diversity**: from the great value that accrues with the recruitment of more African American, Latino, and Native American scientists to our ranks; to inclusion and equity regardless of socio-economic or cultural background, power status, age, gender, gender identity, disability, and many other areas. These issues are neither new nor unique to the tectonics community. Our key challenge is to implement practical best practices that align with our needs and have high potential to make both immediate and lasting institutional change.

The good news is that research shows what approaches do and do not work. While mandatory diversity training programs actually tend to strengthen bias—the opposite of their intended effect—voluntary training reduces bias, with strikingly positive results (e.g., Dobbin and Kalev, 2016). A culture that not only values diversity, but also embraces equity and inclusion, is needed for all members of the community to thrive and foster innovation (e.g., Sherbin and Rashid, 2017). Isolation of underrepresented minority students in universities is known to reinforce underrepresentation and frustrate recruitment (e.g., Allen-Ramdial and Campbell, 2014). By recruiting, including, and mentoring underrepresented members of the tectonics community at all career stages, we can overcome institutional inertia towards addressing these issues and dismantle implicit biases that limit participation.

Figure 8

One potentially useful approach is to develop a **tectonics community-based organization** (see ***Section 6.6***) that provides practical guidance on ***best practices for recruiting broadly, strengthening the culture of diversity, equity and inclusion, and mentoring and leadership training*** for members of underrepresented groups. A centralized ***Onramp to Diversity & Inclusion*** organization for the tectonics community could adapt, distill and organize key resources similar to the Tectonics Educator's Onramp model described in Recommendation #1. For example, Tier 1 resources under "Recruitment at all levels" (**Figure 8**) could include research-based one-pagers on topics that arise throughout the academic year like avoiding gender bias in letters of reference (www.csw.arizona.edu/LORbias, based Trix and Psenka, 2003; Madera et al, 2009), and best practices for faculty searches (e.g., http://www.washington.edu/diversity/faculty-advancement/handbook/). Tier 2 and 3 resources could include research on issues of diversity, equity and inclusion from the STEM, business, and psychology literature, and key resources adapted for the tectonics community from programs such as ***Sparks for Change***, ***ASPIRE*** and ***FIELD*** (from National Science Foundation's ***GOLD*** Program). Finally, partnerships could be built with professional organizations such as ***ESWN***, ***SACNAS*** and ***NABG***.

6.5 ENGAGEMENT AND IMPACT: FACILITATING COMMUNICATION & COLLABORATION WITH PUBLIC STAKEHOLDERS

Effective communication and collaboration with the broader public and community leaders is critical for the tectonics community to address challenges facing society (e.g. ***Grand Challenge #5****). Similar to the strategy outlined for educational and diversity resources in* ***Section 6.4****, we recommend investment in a tectonics community-based organization to facilitate public outreach and engagement, enhance collaboration with decision makers and risk managers, and expand engagement with the private sector.*

RECOMMENDATION #1: BUILD CENTRALIZED INFRASTRUCTURE TO COMMUNICATE SCIENCE WITH NON-EXPERTS & FACILITATE PUBLIC OUTREACH

The tectonics community engages in extensive public outreach and education activities, and has identified the need for a centralized organization (e.g., ***Section 6.6***) to help maximize the efficiency and effectiveness of these efforts. Such an organization guided by a tectonics community-based steering committee and knowledgeable, dedicated communication and outreach personnel could greatly amplify the impact of tectonics research across society. A limited number of quick-start "how to" guides that are tailored to the tectonics community could be linked to additional resources as a "one-stop-shop" for developing communication skills for non-scientific audiences and efficiently plugging into successful outreach models, technologies, and funding opportunities. Such a model could help promote creativity and serve as a hub for attracting funding streams at the national (e.g., NSF, NASA, DOE, NASA, DOD, FEMA, NOAA) and state levels. It would also synergize with educational efforts (***Section 6.4***) and engagement with community leaders and the private sector (Recommendations #2 and #3).

An ***Onramp to Engagement & Impact*** organization for the tectonics community could adopt a variety of approaches. For instance, for high-profile events such as earthquakes, volcanic eruptions, or a major discovery, this organization could facilitate and train "**Rapid Response**" teams that partner with media experts and university news offices to supply public groups with links and educational materials that illustrate the strong connections between tectonics and society. Non-profit corporations that are run by various academic communities, such as the IRIS "teachable moment" and

UNAVCO's ***RESSESS*** (Research Student Internship) and ***Field Geodesy Education*** and outreach support programs could be tailored to the tectonics community. Centralized **technology resources** could train researchers in social media outreach, and help expand the use of educational, geotagged smart phone software (e.g., the '***ShoMe***' and '***Rockd***' apps). Onramp resources for **interfacing with the arts** could help tectonics researchers and educators convey the beauty and mystery of the natural world through storytelling, dance, music, and the visual media. Building a participatory ethos in communities through these and other means also can help make connections between scientists and other stakeholders self-sustaining (Lybecker et al., 2016).

An ***Onramp*** organization (e.g., **Figure 9**) also could promote **public engagement and participation in tectonics research** in the area of data acquisition, including crowdsourcing and data mining. Recent examples show these approaches already are having a significant impact on long-standing problems in tectonics—e.g., in the case of early warning systems for earthquakes and tsunamis (e.g., ***Grand Challenge #5, Section 5.6***), mapping landslides and earthquake damage (e.g., ***Grand Challenge #3, Section 3.2***), oil and gas exploration, and many others.

Figure 9

RECOMMENDATION #2: BUILD CENTRALIZED INFRASTRUCTURE FOR DEVELOPING DATA PRODUCTS AND MATERIALS WITH AND FOR COMMUNITY LEADERS

A key aspect of enhancing our impact on public policy for the benefit of society is to develop data/research products and educational materials that better serve the needs of our community leaders. Most public officials do not realize thatr knowledge of the geosciences could help them make better decisions (e.g., Leiserowitz et al., 2010). ***Onramp*** resources could facilitate engagement and dialog between community leaders and tectonics researchers. Enhanced collaboration on practical issues, and aid in translating disciplinary research into loss reduction, including coordination of experimental design with hazard and risk modelers and policymakers, would be transformative (e.g., ***Grand Challenge #5, section 5.7***).

A community-based task force that includes policymakers and risk managers is needed to develop the road map and priorities for key ***Onramp*** resources and programs. One point of departure could include quick-start guides that help researchers adapt tools and technologies that have direct practical applications, including remote sensing data sets (e.g., InSAR and LiDAR), 3D and 4D visualization technologies (e.g., paleogeographic reconstructions for the energy and mining industries

including **G-Plates** and **PaleoGIS**, ***Section 6.3, Recommendation #2***), and interpretive data products (e.g., earthquake, landslide and volcanic hazard assessment maps and tsunami animations). These tools can be tailored to provide accurate information on many practical problems that policy makers and risk managers contend with, including those related to natural and induced seismicity, water contamination, CO_2 sequestration and mitigation, waste storage, and a multitude of engineering problems (e.g., ***Grand Challenge #5, Sections 5.2-5.6***). Community centers with dedicated staff, such as at ***SERC***, could provide expertise in tailoring data products and tools that help the tectonics community collaborate with and serve the public sector.

RECOMMENDATION #3: EXPAND ENGAGEMENT WITH THE PRIVATE SECTOR

The perspective and experience of private sector geoscientists in energy, minerals, and environmental-related industries are great assets in our quest to communicate and interact more effectively with policy makers and community leaders. In addition, private foundations and companies, such as the Bill and Melinda Gates Foundation, the MacArthur Foundation, the David and Lucile Packard Foundation, Google and many others, harbor some of the most creative approaches to communicate science to people of all abilities and backgrounds. Expanding our engagement with these organizations can help us more effectively communicate new concepts and applications and how they can serve societal needs. Inviting members of these communities to participate in the development of ***Onramp resources*** and collaborative strategies suggested in ***Section 6.6*** may be an effective means to facilitate this engagement, and enhance ***synergies with outreach, community engagement, and educational and diversity efforts*** (Recommendations #1 and #2 above, and ***Section 6.4***).

6.6 NEW COLLABORATIVE STRATEGIES & FUNDING MODEL FOR A TECTONICS INITIATIVE

The needs outlined in the previous sections compel us to recommend that the Division of Earth Sciences of the National Science Foundation explore new avenues for supporting tectonics research and re-examine current funding priorities. Sustained funding for a multi-investigator consortium would provide the infrastructure needed to support a transformation of the tectonics research, education, and societal engagement enterprise, with far-reaching implications for our understanding of planetary system evolution and for human society's access to resources and resilience in the face of tectonic hazards.

Figure 10

RECOMMENDATION #1: BUILD A NATIONAL CONSORTIUM FOR TECTONICS

Our ambitious vision for tectonics in the 21st Century cannot be achieved with "business as usual" resources and infrastructure. The continued investment in small laboratory facilities at academic and

other institutions remains critical to promote discovery and technological innovation, foster creativity, and facilitate training and education at all levels (National Research Council, 2012). Yet this report makes it clear that new, centralized infrastructure and facilities are needed to make major progress on addressing scientific ***Grand Challenges*** in tectonics to advance fundamental understanding and serve society. To this end, we recommend the creation of a ***network of national research and educational facilities linked through a community-led consortium for tectonics*** (**Figure 10**).

Such a consortium could include programs to support **investigator-led research**, and coordinate an investigator, educator, and public stakeholder community that participates in **science visioning and synthesis, education, and public engagement activities**. The community visioning aspect is particularly important as a means to connect scientists that are brought together by their mutual interest in specific problems rather than by their disciplinary expertise, research tools or geographic area of study—a recipe for accelerating future advances. The consortium would amplify the impact of investments in new analytical and observational technologies by supporting **analytical, computational, and advanced digital data sharing facilities that require stable and dedicated technical staff**. It could also coordinate expansion of and access to **physical sample collections and data sets** (e.g., the searchable ***PetLab*** database and archive system, maintained by GNS Science in New Zealand). In addition to facilitating **collaborative working groups** that focus on scientific grand challenges identified by the community, a consortium would provide the framework and support for development of **education (Figure 7), diversity and inclusion (Figure 8), and public engagement resources (Figure 9) tailored to the tectonics community**. Community-run organizations such as **EarthScope**, **IRIS**, **GeoPRISMS**, **UNAVCO**, **COMPRES**, **STEPPE**, and others are effective at many of these practices. *However, neither these, nor any other existing organization meets the specific needs of the tectonics community because they do not cross enough disciplinary boundaries to address questions in global tectonics.*

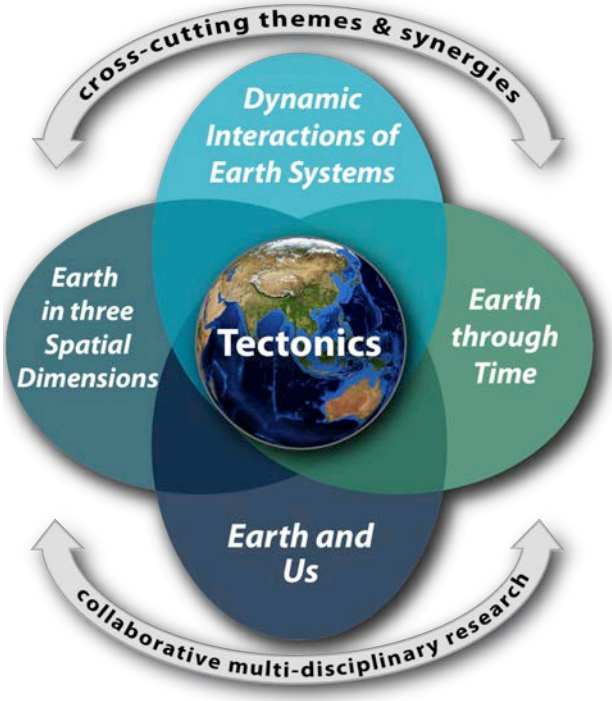


Figure 11

A national tectonics consortium would meet this need by integrating the broad array of approaches that make up tectonics research (**Figure 11**), while enabling new ***strategies for collaborative research*** to address the ***Grand Challenges*** outlined here and those of the future. Consensus on key strategies must be developed by the community in the next phase of our science visioning efforts. The following recommendations are ***examples*** of some of the collaborative research strategies that a national tectonics consortium could enable:

- A new system of ***facility-based tectonics observatories*** that provides access to analytical and computational resources, with support for dedicated technical staff and advanced digital data sharing and archiving, in order to unite researchers in the pursuit of tectonic questions.
- Support for ***exploration-based projects and data acquisition*** that do not necessarily solve a

testable hypothesis; this may include funding for such things as large-scale, long-term monitoring studies, data acquisition enabled by new technologies, annual research themes (e.g., **NCED2**), and/or "new directions" grants to support new collaborations or high-risk areas of research.

- Support for ***interdisciplinary, collaborative partnerships between methods developers and end-users***. A program like **EarthScope AGeS** could be expanded to a range of geochronologic, geochemical, electron backscatter diffraction and other data sets that require specialized facilities and technical support, to (1) ensure interpretation of data benefits from the input of experts who generate the data, (2) fully integrate field observations with laboratory experiments and modeling, and (3) broaden access to *both* the 'tried and true' methods of data acquisition *and* developmental approaches that lead to new methodologies.
- Fostering of ***new links with other research communities***, including industry, AAPG, the military, the U.S.G.S, DoE, NRC, the State Geological Surveys, EarthScope, UNAVCO, IRIS, NASA, NSF GeoPRISMS, COMPRES and many other programs, for example through think-tank workshops. Existing resources like the NSF-sponsored Structural Geology and Tectonics forum could be adapted, and several National Academy programs that include tectonics within their domain may provide an ideal forum to establish new linkages, in synergy with the recommended technical investments (***Sections 6.2, 6.3***) and Onramp to Engagement resources (**Figure 7**) described above.

RECOMMENDATION #2: RE-EXAMINE FUNDING PRIORITIES & EXPLORE NEW AVENUES FOR SUPPORTING TECTONICS RESEARCH

New resources and a re-examination of funding strategies within the Division of Earth Sciences of the National Science Foundation are needed to implement these strategies. ***Major new NSF investments*** in research approaches and technologies that promise sweeping change (***Sections 6.2, 6.3***), organizations that empower us with key practical resources for developing a diverse and rigorously trained workforce and engaging with public stakeholders (***Sections 6.4, 6.5***), and infrastructure to facilitate new kinds of interdisciplinary collaboration (Recommendation #1 above) are critical to achieving our vision. Support for a tectonics consortium that links these investments will maximize their impact and create a whole that greatly exceeds the sum of its parts. Partnering with other community-based organizations and facilities that draw from multiple programs and agencies, such as ***IRIS, UNAVCO, EarthCube*** and ***SERC***, would leverage resources and avoid duplicating efforts. A tectonics initiative could be a means for breaking down barriers among different divisions and programs at NSF to integrate cyberinfrastructure, facilities, and fields of research that span the solid-Earth, oceanic, atmospheric, climate, and geospace sciences.

The tectonics community vision and capabilities are closely aligned with the goals of other potential funding sources. ***NSF support for a tectonics initiative could be leveraged*** to attract support from other federal agencies (DOE, USGS, NASA, DOD, FEMA, NOAA); international partnerships (e.g., GEOSS, IMS); the energy, mining, and technology industries (e.g., Google); and private foundations and non-profit institutes (e.g., the Gordon and Betty Moore Foundation, the Tinker Foundation's field research grants, the AEG Foundation, etc.). There are obvious benefits of diversifying funding beyond traditional NSF sources in terms of resources. However, the greatest benefit of leveraging NSF support to link the tectonics community to these organizations is the significant, untapped potential for creativity and synergy in our efforts to understand planetary evolution and serve society.

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LIST OF ACRONYMS

AAPG (American Association of Petroleum Geologists)
AGI (American Geological Institute)
AGU (American Geophysical Union)
ASPIRE (Active Societal Participation in Research and Education)
CINERGI (Community Inventory of EarthCube Resources for Geoscience Interoperability)
COMPRES (Consortium for Materials Properties Research in Earth Sciences)
CSDMS (Community Surface Dynamics Modeling System)
DOD (U.S. Department of Defense)
DoE (U.S. Department of Energy)
EarthScope AGeS (Awards for Geochronology Student Research program)
EBSD (Electron Backscatter Diffraction)
ESWN (Earth Science Women's Network)
FEMA (U.S. Federal Emergency Management Agency)
FIELD (Fieldwork Inspiring Expanded Leadership for Diversity)
FTIR (Fourier Transform Infrared spectroscopy)
GK-12 (Graduate STEM Fellows in K-12 Education (GK-12) Program)
GOLD (National Science Foundation's Geoscience Opportunities for Leadership in Diversity Program)
GSA (Geological Society of America)
InSAR (Interferometric synthetic aperture radar)
IRIS (Incorporated Research Institutions for Seismology)
LiDAR (Light detection and ranging)
NABG (National Association of Black Geoscientists)
NASA (National Aeronautics and Space Administration)
NCALM (National Center for Airborne Laser Mapping)
NOAA (National Oceanic and Atmospheric Administration)
NRC (The Nuclear Regulatory Commission)
NSF (U.S. National Science Foundation)
NTERC (National Tectonics Research and Educational centers-proposed)
NTO (National Tectonics Office-proposed)
RESSESS (UNAVCO Research Student Internship)
REU (Research Experiences for Undergraduates)
SACNAS (Society for Advancement of Chicanos/Hispanics and Native Americans in Science)
SERC (Science education and resource center at Carleton college)
SESAR (System for Earth Sample Registration)
SFM (Structure from Motion photogrammetry)
SRTM (NASA Shuttle Radar Topography Mission)
STEPPE (a joint venture under the leadership of the Geological Society of America, the Society of Sedimentologists and the Paleontological Society)
Texas A&M ODP (Ocean Drilling Program)
TRMM (NASA Tropical Rainfall Measuring Mission)
UNAVCO (a non-profit university-governed consortium, facilitates geoscience research and education using geodesy)
USGS (United States Geological Survey)

FIGURE CREDITS

Cover

Fold panorama landscape photo by N.D. Perez: Permian carbonates (gray) folded during the late Permian are cut by a normal fault (dipping to the left) produced during Triassic extension. The snow-covered peaks in the left background were carried over rocks in the foreground by a reverse fault during Cenozoic shortening and construction of the Andes. Photograph taken at ~4900 m elevation in the Eastern Cordillera of southern Peru.

Idea Paper Contributor page

Photograph by C.C. Gerbi. A rheological contrast between a fine-grained polymineralic layer and the surrounding coarse calcite resulted in folding during deformation in the Adirondack Mountains, New York.

Grand Challenge #1

Front page – Figure by K.W. Huntington integrates imagery from NASA blue marble, Earth with continents and bathymetry image, and artistic conception by S. Marchi of the early Earth showing a surface pummeled by large impacts, resulting in extrusion of deep-seated magma onto the surface.

Figure 1 – Image modified from F. Crameri's tomographic model of ocean slabs falling to Earth's core (www.fabiocrameri.ch/artwork.php). Version with yellow slabs published in Voosen (2016).

Figure 2 - 3-D surface of 2.9 km/s velocity contour defines the inferred volume of the APMB. Adapted from Ward et al. (2014) by K.M. Ward.

Figure 3 - Top: Block diagram of eastern Banda Arc, with cross section X-X' cut parallel to grooves on fault surfaces and proposed direction of slab rollback. Bottom: Enlargement of Banda detachment (2x vertical exaggeration) with continental allochthons in dark red. Modified after Pownall et al. (2016) by K.W. Huntington.

Figure 4 – Figure by K.W. Huntington; middle and right panels adapted from Lee et al. (2016).

Figure 5 – Figure by L.G.J. Montesi.

Figure 6 – Figure by K.V. Hodges and K.W. Huntington.

Figure 7 – Photomicrographs of cathodoluminescence (top) and radiation damage (bottom) in zircon. Images courtesy of K.V Hodges.

Grand Challenge #2

Front page - Photo by C.C. Gerbi: Mesoscopic structures (moss and lichen for scale) record kinematics in the Parry Sound Domain, Ontario, Canada, where hydration controls the distribution of strain in mafic and felsic orthogneisses.

Figure 1 – Figure by K.A. Klepeis and L.B. Goodwin, constructed with maps produced using J.M. Warren's Matlab code (OlivineDefMaps_v11Public).

Figure 2 – High strain rate, frictional melting experiment conducted using SHIVA apparatus at the National Institute of Geophysics and Volcanology, Rome, under the watchful eyes of G. di Toro (right) and H. Rabinowitz. Photo courtesy of P. Skemer.

Figure 3 – Figure by K.A. Klepeis and K.W. Huntington, adapted after Thatcher and Pollitz (2008).

Figure 4 – Photo courtesy of O. Orlandini; figure modified by K.A. Klepeis and K.W. Huntington.

Figure 5 – Figure of olivine with microfaults adapted from Druiventak et al. (2012) by K.A. Klepeis and K.H. Mahan.

Figure 6 – Figure by K.A. Klepeis, K.W. Huntington, and K.H. Mahan, adapted from Sassier et al. (2009) and Boutonnet et al. (2013).

Figure 7 – Figure by K.A. Klepeis and K.W. Huntington. Photos are from Miranda and Klepeis (2016) (left), K.H. Mahan (middle), and Flowers et al. (2006) (right).

Figure 8 – Figure by K.A. Klepeis, adapted from Rey et al. (2017) (upper panel), and Kruckenberg et al. (2008) (lower panel).

Grand Challenge #3

Front page – Photo by M.B. Miller: calcite fibers record kinematics of an oblique-slip fault in Jura-Cretaceous sandstone near Lillooet, British Columbia.

Figure 1 – Figure by M.J. Kahn, L.B. Goodwin, and K.W. Huntington.

Figure 2 - Figure by K.W. Huntington. Left photo by S. LaHusen, middle panel courtesy of A. Duvall, right photo by D.L. Homer (from Rattenbury et al., 2006).

Figure 3 – Figure after Kimura et al. (2007).

Figure 4 – Figure by R.T. Williams, L.B. Goodwin and K.W. Huntington, adapted from Williams et al. (2017).

Figure 5 – Figure by M.L. Cooke and K.W. Huntington, adapted from Hatem et al. (2017).

Figure 6 – Figure by K.A. Klepeis and K.W. Huntington, adapted from Norris and Toy (2014). Conductivity from magnetotelluric data is from Wannamaker et al. (2001).

Grand Challenge #4

Front Page – Photo by E. Enkelmann: Mount St. Elias and Tyndall Glacier transporting sediment to Icy Bay and the Gulf of Alaska.

Figure 1 – Figure by C.A. Currie and K.W. Huntington. Top panel after Heller and Liu (2016). Bottom panel after Ruetenik et al. (2016).

Figure 2 – Figure by E.J. Cassel, K.W. Huntington, and M.J, Kahn, adapted from Cassel et al. (2017) with additional data from other sources listed on the figure.

Figure 3 – Figure by K.A. Lang and K.W. Huntington.

Figure 4 – Figure by R.A. DiBiase.

Figure 5 – Figure modified after St. Clair et al. (2015) by C.S. Riebe and K.W. Huntington.

Grand Challenge #5

Front Page – Photo by J.L. White, showing the West Salt Creek landslide in Mesa County, Colorado. The landslide was unusually fast-moving (40-85 MPH) and large, (2.8 miles long, covering almost a square mile, with net volume displacement of 38 million cubic yards).

Figure 1 - Figure by K.W. Huntington, adapted from U.S. Geological Survey Earthquake Hazards Program map, "Oklahoma Seismicity Map (M3+) 1973 to June 2016," available at

https://earthquake.usgs.gov/earthquakes/byregion/oklahoma.php.

Figure 2 - Figure by P.M. Fulton, E.E. Brodsky, K.W. Huntington, and M.J. Kahn. Map adapted after Chester et al. (2013). Temperature sensors photo by P.M. Fulton. Core photo courtesy of JAMSTEC/IODP. Frictional heat figure adapted after Fulton et al. (2013).

Figure 3 – False-color Landsat 7 image of Deepwater Horizon oil spill, credit: NASA GSFC Landsat/LDCM EPO Team.

Figure 4 – Figure by L.B. Goodwin, R.T. Williams, K.W. Huntington, and S. Ralser. Left panel photo courtesy of H.J. Tobin, with information re: distribution of clay minerals from Lohr et al. (1999). Right panel photo taken by S.F. Cox, from Weatherly and Henley (2013).

Figure 5 – Photograph by D. McCartney of drilling rig in Pinedale field with the Wind River Mountains, Wyoming, USA, in the background. Photograph appeared in AAPG Memoir 107.

Figure 6 – Top image from Becker et al. (2010). Middle panel interpretation after Becker et al. (2010) and Lander and Laubach (2015). Lower panel after Lander and Laubach (2015). Figure by K.W. Huntington.

Figure 7 – Figure modified after Brothers et al. (2016) by J. Gomberg.

Figure 8 – Figure by A. Franklin, J. Gomberg, K.W. Huntington and M.J. Kahn. Adapted from Gomberg et al. (2017), based on US Geological Survey Seattle Seismic Hazard Maps and Data, available at https://earthquake.usgs.gov/hazards/urban/seattle.php, with data from unreinforced masonry buildings map prepared June 28, 2012, by DPD-GIS, sources: DPD Structural Inspection, Reid Middleton Engineering, 1995 EQE City Landmark, Department of Neighborhoods, Landmark Preservation Board.

Figure 9 – Figure by R. Briggs, K. Scharer, M.J. Kahn and K.W. Huntington. House photo courtesy of New Zealand GNS. Hazard and risk panels adapted from USGS public domain materials (https://earthquake.usgs.gov/hazards/interactive/ courtesy of N. Lugo).

Achieving the Vision

Front Page – Figure by K.W. Huntington. From left to right: (row 1) photo by B. Tikoff of students using iPads to make structural measurements in the field; photo by M.B. Miller of fault scarp on the Owens Valley fault, California, just west of the town of Lone Pine, with Sierra Nevada in background; photo by M.B. Miller of oil pump jacks in oil field, California; (row 2) photo by B. Hallet of glacier in St. Elias Mountains, Alaska; photo by Y.D. Kuiper of folded marble in the Paleoproterozoic Foxe Fold Belt, Melville Peninsula, Nunavut, Canada; photo by A.M. Heimsath of Lodrak river, Tibet; (row 3) photo by M.B. Miller of geologists in crater of Mt. St. Helens volcano, Washington; photo by M.B. Miller of landslide scar, Dawson, Yukon, Canada; photo by M.B. Miller of building construction along an active fault zone (Wasatch fault zone, Salt Lake City, Utah); (row 4) photo courtesy of J. J. Schwartz of students Solishia Andico (left) and Luisa Buritica (right) analyzing isotopic data from zircon; photo courtesy of Berkeley Geochronology Center of a sample chamber of an Ar-ion laser; image by J.R. Arrowsmith showing view to south over Wheeler Ridge active fold including minor and major wind gaps (latter contains the California Aqueduct). High resolution topography (1 m/pix DEM) collected by National Center for Airborne Laser Mapping Student Seed grant to E.J. Kleber. Data processed at OpenTopography.

FIgure 1 – Figure after Wu et al. (2016).

Figure 2 – (top, middle) Photos by K.A. Klepeis of data collection by drone. (bottom) Photo by D. Lilien of students using a terrestrial laser scanner (TLS).

Figure 3 – Photo by K.W. Huntington of automated clumped isotope sample preparation system, University of Washington IsoLab.

Figure 4 – Figure by K.A. Klepeis and K. W. Huntington.

Figure 5 - Figure by K.W. Huntington with Strabo image courtesy of B. Tikoff.

Figure 6 – Three-dimensional model of the Earth's gravity field with colors representing undulations in the geoid (Barthelmes and Köhler, 2016). Geoid undulations (in meters) are exaggerated and projected onto a sphere to make them visible.

Figure 7 – Figure by K.W. Huntington.

Figure 8 – Figure by K.W. Huntington.

Figure 9 – Figure by K.W. Huntington.

Figure 10 – Figure by K.A. Klepeis and K.W. Huntington.

Figure 11 – Figure by K.A. Klepeis, K.W. Huntington and the Future Directions in Tectonics workshop participants.

Back Cover

Photograph by W.D. Mooney, USGS, shows damage to structures in downtown Concepcion, Chile, due to the February 27, 2010 magnitude 8.8 earthquake.