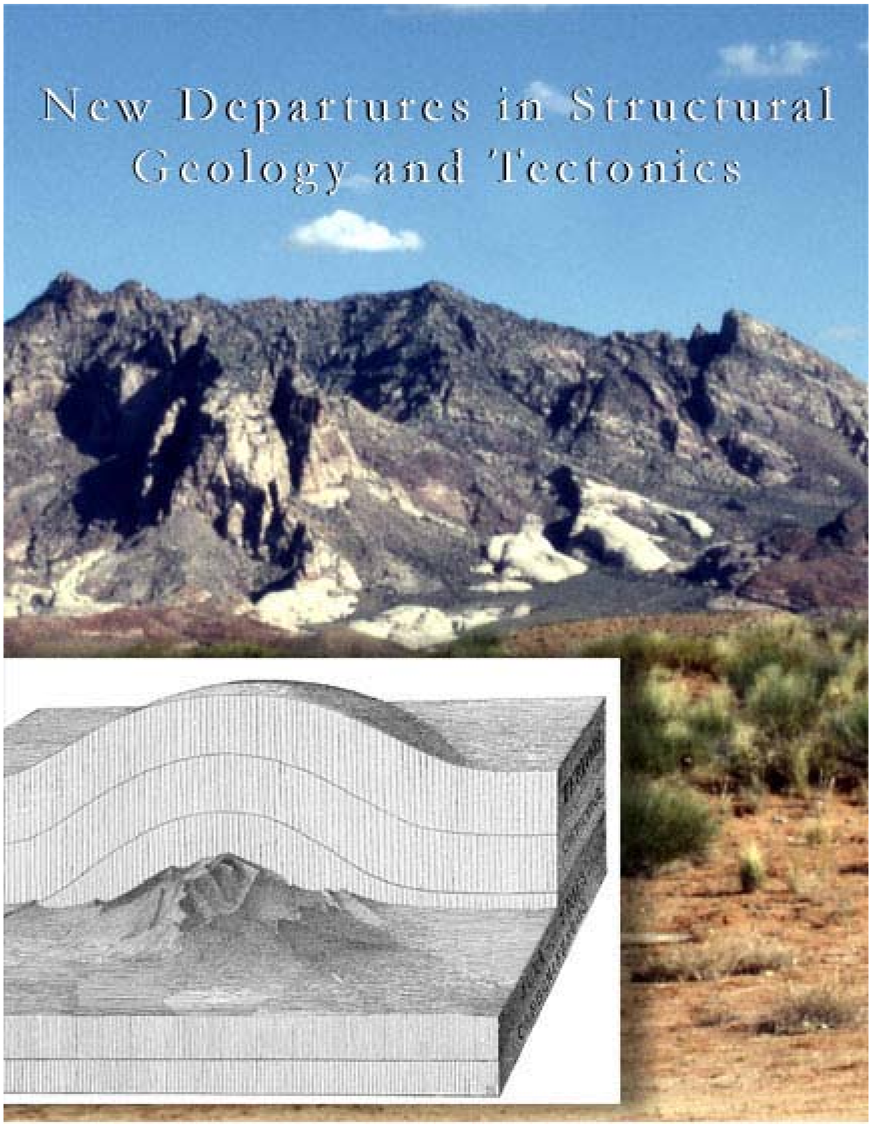
New Departures in Structural Geology and Tectonics



New Departures in Structural Geology and Tectonics

A White Paper resulting from a workshop held at Denver Colorado, September 22nd and 23rd, 2002 sponsored by the Tectonics Program, Earth Sciences Division, and National Science Foundation (GEO/EAR).

April 2003

Website and downloadable pdf file available at:

http://www.pangea.stanford.edu/~dpollard/NSF/

Executive Summary

Recognition of exciting opportunities for research in structural geology and tectonics (SG&T), brought into focus by recent technological developments, new quantitative data sets, and both conceptual and theoretical advances, motivated a workshop to consider the future directions (New Departures) for science in this field over the next ten years. Four topical areas of research were identified at the workshop:

1) Beyond Plate Tectonics: Rheology and Orogenesis of the Continents;
2) The Missing Link: From Earthquakes to Orogenesis;
3) Dynamic Interactions between Tectonics, Climate, and Earth Surface Processes;
4) Co-evolution of Earth and Life.

Descriptions of these research themes along with sections on research facilities and education form the major sections of this white paper. A major theme of this document is the integrated nature of research and teaching in SG&T.

Research funded by the NSF in this area has contributed to our fundamental understanding of how the lithosphere works, helped to build the scientific workforce of the nation, fostered international collaborations, and spun off knowledge that has had a direct economic benefit to the nation. Researchers in structural geology and tectonics have integrated field-based analyses, laboratory work on rock deformation, fluid-rock interactions, metamorphic reactions, continuum and fracture mechanics, geochemistry, geochronology, isotope geochemistry, and a variety of other disciplines, across vast ranges of time and space to develop new ways to examine and understand our planet. However, total funding and the number of awards in SG&T has remained essentially level for the last 17 years while collaborative proposals have increased significantly. The new research opportunities and strong basis for collaborative research on interdisciplinary problems argue for increased levels of support for the SG&T community.

Plate tectonics emerged as a unifying theory of the solid Earth from observations of the ocean floors where deformation, seismicity, and volcanism are localized at boundaries between rigid plates. On the other hand, more pervasive deformation and wide continental mountain belts indicate weak rheological behavior typifies continental orogenesis. Thus we must move ‘beyond plate tectonics’ and seek significant improvement to our understanding of continental tectonics through a detailed and comprehensive study of the rheology of continental crust and mantle rocks. Deformation of the Earth's crust is unevenly distributed in space and time: a single earthquake may produce substantial deformation and damage in just tens of seconds while tectonic events such as mountain building occur over millions to tens of millions of years. Deformation appears very different from these two perspectives, and the temporal and conceptual ‘missing link’ between them is one of the most fertile areas for future research. Topography represents the net product of tectonic and surficial processes, and unraveling the intricacies of this coupled system represents a primary challenge in this field, with the opportunity to gain new insights concerning tectonic processes operating within the Earth. Tectonicists are poised to help usher in new paradigms for understanding the motions and deformation of continents in deep time. This will require forging a new understanding of pre-Pangean supercontinents and the supercontinent “cycle” and will lead to newly realized connections between Earth processes and the evolution of life.

The support for research facilities plays a major role in the path toward scientific discovery outlined about. Cosmogenic isotope studies provide important constraints on tectonic processes that have affected the Earth's surface during the past several hundred thousand years, a time range that has previously been difficult to study. Geochronology and thermochronology provide critical constraints on the ages of geological events and on the rates of geological processes. The fundamental understanding of dynamic processes as diverse as the earthquake cycle, fluid transport through the crust, and sedimentary basin development hinges upon critical input from laboratory measurements of mechanical and transport properties of rocks. There is an urgent need to support the infrastructure that would nurture the necessary technological advances, provide the wider availability of existing experimental and analytical facilities, and encourage synergistic collaborations among researchers in rock mechanics, field geology, numerical simulation and materials science.

The Global Positioning System (GPS) not only provides a vital tool for detailed, precise and quantitative mapping of geological structures, the products of tectonic processes operating in Earth’s crust. Furthermore, geodetic grade GPS permits us to measure the relative velocity of any two points on the earth's surface to within a fraction of a millimeter per year, after just 2 to 3 years of monitoring. Similarly, interferometric synthetic aperture radar (InSAR) allows us to create maps showing the movement of broad areas of Earth’s surface over time (surface velocity fields). Combined, these two methods will yield seamless, high spatial- and temporal-resolution maps of surface movement across plate boundaries and throughout the continental interiors. There is an urgent need to support instrumentation for both structural mapping and geodetic studies of crustal deformation.

Educational priorities in SG&T parallel those of the broader Earth Science community, as articulated in a rich literature of ongoing publications, web sites and workshops. Fundamental scientific literacy, rigorous scientific methodology, and the development of quantitative skills at all levels, from K-12 through undergraduate and graduate education, underlie these priorities. There is a need for integrating quantitative methods into geoscience classes, interactive exercises, involvement of students in research, and computer visualization tools as viable strategies for increasing the effectiveness of earth science education. Geoscience education based on such a foundation will play an important role in preparing the next generation of researchers, teachers, and citizens. We encourage college and university earth science departments to be flexible in defining programs of study that facilitate collaborative and interdisciplinary work. Tuition and credit should be given for course work in mathematics, physics and chemistry, as well as related engineering disciplines. For the development of quantitative skills at the graduate level we point to the role of differential geometry in characterizing geological structures, and cite continuum mechanics as an example of the fundamental scientific literacy necessary for mechanical modeling in structural geology and tectonics.

Table of Contents

Participants

David D. Pollard (Chair), Stanford University
Rick Allmendinger, Cornell University
Mark T. Brandon, Yale University
Roland Bergmann, University of California, Berkeley
Rebecca J. Dorsey, University of Oregon
David A. Evans, Yale University
James P. Evans, Utah State University
Raymond C. Fletcher, University of Colorado
David M. Fountain, National Science Foundation
George E. Gehrels, The University of Arizona
Laurel B. Goodwin, New Mexico Institute of Mining & Technology
Arthur Goldstein, National Science Foundation
Karl Karlstrom, University of New Mexico
Andreas K. Kronenberg, Texas A&M University
Tracy Rushmer, University of Vermont
Jane Selverstone, University of New Mexico
John H. Shaw, Harvard University
Carol Simpson, Boston University
Bruno Vendeville, The University of Texas
Brian P. Wernicke, California Institute of Technology
Kelin Whipple, Massachusetts Institute of Technology
Sean Willett, University of Washington
Martha Withjack, Rutgers University
Teng-fong Wong, State University of New York at Stony Brook
An Yin, University of California, Los Angeles
Herman B. Zimmerman, National Science Foundation

Preface

Over the past 30 years research in structural geology and tectonics (SG&T), supported by the National Science Foundation (NSF), has generated an impressive body of knowledge about the physical and chemical processes that shape the lithosphere of our planet. Work funded by the Tectonics Program has increased our fundamental understanding of how the lithosphere evolves, contributed to building the scientific workforce of the nation, fostered international collaborations, and spun off knowledge that has directly benefited the economy of the nation. Well before other fields discovered the concept of multidisciplinary approaches to science, researchers in structural geology and tectonics have integrated field-based analyses, laboratory work on rock deformation, fluid-rock interactions, metamorphic reactions, continuum and fracture mechanics, geochemistry, geochronology, isotope geochemistry, and a variety of other fields, across vast ranges of time and space to develop new ways of examining and understanding Earth's lithosphere.

In light of recent changes at the NSF, including the signing of the act to double the budget, changes in the managers of the programs that affect the structural geology and tectonics communities, new initiatives in topics such as biocomplexity, information technologies, engineering, earth systems science, and the increased emphasis on large integrative projects such as Earthscope, combined with the need to support single PI projects, it is timely that the structural geology and tectonics community reflect on their recent accomplishments and future prospects, and communicate these to the broader community.

In order for the program managers within NSF to make a case for increased funding, we must provide them with the evidence of past successes and our visions for the future. This document is one effort at providing an overview of some of the recent exciting advances we have made, and an attempt to provide an overview of where some of our discipline is headed in the next 10 years. This document is not intended to tell NSF what to fund, nor is it inclusive of every significant advance made by SG&T researchers. Rather, this white paper is the best effort of a group of researchers from a diverse spectrum of our community to reflect upon some of the recent highlights and suggest where this research might lead.

This white paper is the outgrowth of a workshop organized by David Pollard of Stanford University and held in Denver, in September 2002. During this two-day workshop, twenty members of the SG&T academic community presented brief overviews of topics related to their research specialties, and discussed future objectives and needs. Representing the NSF were David Fountain, Arthur Goldstein, and Herman Zimmerman. From this meeting draft chapters were written by working groups. Edited versions were circulated amongst the whole group, and the final document was collated and edited by David Pollard. In an intellectually diverse community, there will be some who disagree with some of this document. Our intent was to begin to provide some guidelines for our science in the near future. A major theme of this document is the integrated nature of our work, and the implications this has for future funding of the research and teaching we do. We look forward to fostering a stronger structural geology and tectonics program at the NSF, and appreciate the opportunity to craft this document.

Recognition of new opportunities for research in structural geology and tectonics, brought into focus by recent technological developments, new quantitative data sets, and both conceptual and theoretical advances, motivated a workshop to consider the future directions of science in this field. Four broad topical areas of research were identified at the workshop:

1) Beyond Plate Tectonics: Rheology and Orogenesis of the Continents;
2) The Missing Link: From Earthquakes to Orogenesis;
3) Dynamic Interactions between Tectonics, Climate, and Earth Surface Processes;
4) Co-evolution of Earth and Life.

Descriptions of these research themes along with sections on research facilities and education form the major sections of this white paper. These new opportunities also bring into focus long standing questions in this area of research about the relative merits of descriptive versus quantitative methods, case studies of particular regions versus experimental studies of particular mechanisms, kinematic versus mechanical modeling, and historical versus process-oriented objectives.

This White Paper is meant to encourage a broader segment of the Earth Science community to apply for grants from the Tectonics Program based on identification with one of the themes described herein. While an increase in proposals is likely to lead to a decrease in the percentage of proposals that can be funded, it is through this kind of proposal pressure that new funding may be earmarked for the program. In addition members of the community are encouraged to use this White Paper as a calling card when visiting the National Science Foundation or communicating with the program directors.

Priorities in Solid Earth Sciences: A Related Workshop

A broadly based, NSF-sponsored workshop on "Setting Priorities in the Solid Earth Sciences" was conducted by members of the Earth sciences community in Denver on October 26, 2002, immediately prior to the national Geological Society of America meetings. The organizing committee consisted of Mike Brown (University of Maryland), Cathy Manduca (Carleton College), Tracy Rushmer (University of Vermont), Basil Tikoff (University of Wisconsin), and Ben van der Pluijm (University of Michigan). Attendance was open to everyone and approximately 100 geologists from a variety of disciplines attended, including structural geology, petrology, geophysics, geochemistry and sedimentology.

The goals of the workshop were: 1) To foster integration of sub-disciplines within the solid earth sciences; 2) Recognition of important research areas and merging needs; 3) Integration of teaching and research; and 4) Discussion of needs and methods of interaction within the Solid Earth Sciences community. Given the wide range of interests and the limited time (1 day), the discussion focused on general approaches rather than specific research agendas. By the end of the workshop, there was a collective sense that an approach (and perhaps an organization) that represents scientists in a range of fields in Solid Earth Sciences is needed to advance future research goals. Further, there was a clear recognition of the importance to organize in order to contribute to other Earth science initiatives.

Research in Structural Geology and Tectonics at NSF

Mark T. Brandon

The Tectonics Program is commonly identified as the core source of funding for tectonics research in NSF. In actuality, tectonics research is funded by 5 out of the 6 programs in the Earth Science Division at NSF. The Tectonics program largely supports research in structural geology but some of this also spills over into other programs. The remarkable breadth of this research makes it an integral part of the Earth Science Division.

The Tectonics Program provides a useful vantage from which to view proposal activity and funding for research in structural geology and tectonics overall. The plots in Figures 1 through 4 provide an informal summary. They were constructed using web-based archival data from NSF for the Tectonics Program over the period from 1985 to 2002. We did not distinguish between different types of awards, although there were only a minor number that provided support for activities other than research (e.g. conference support, etc.). It is also important to note that some awards were made by shared funds from different programs, so the boundaries between different EAR programs are slightly blurry. Thus, the total amount awarded per year is not necessarily equivalent to the total annual budget for the Tectonics Program. Dollar amounts have been converted to '2002 dollars' using the Federal Consumer Price Index. Awards were recorded as awards to institutions, which obscures the fact that some awards involved more than two PIs at the same institution. We asked the Tectonic Program to make a comparison with their more detailed internal records. They found that the numbers summarized here are reasonably similar, to their records for the last couple of years.

Figure A shows that funding has varied from about 6 to 14 million dollars with no clear trends for the last 17 years with an average of about 10 million per year in 2002 dollars. The average award (Fig. 2) to an institution has remained approximately flat, at about $140,000 per award. The number of awards has (Fig.3) varied from about 50 to 130 with no clear trend and an average of about 78 awards per year. The number of collaborative proposals (Fig. 4) has increased significantly over the past 17 years, from about 15 percent in 1985 to 60 percent in 2002. In this summary, collaborative research was identified by the fact that the grants were part of a larger multi-institutional project. Collaborative research between PIs within an institution is not captured in this statistic. This strong trend towards increasing collaboration reflects, to a large extent, the increasing importance of interdisciplinary research in tectonics.

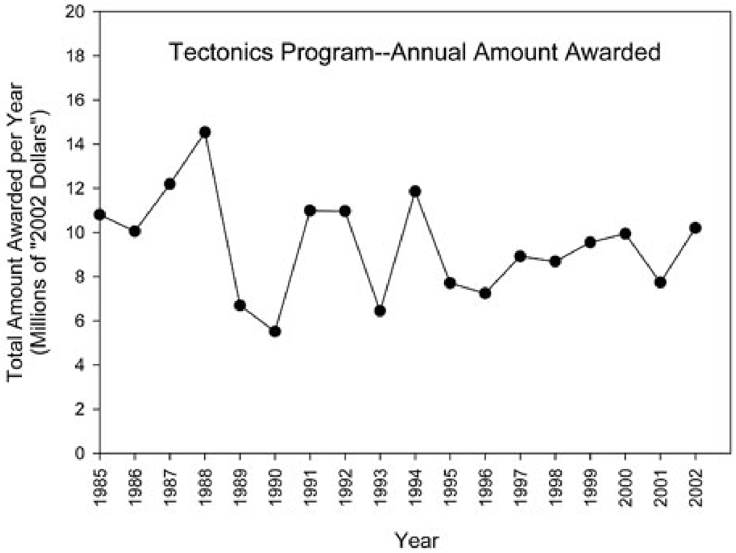


Figure 1. Annual amount of funds awarded in the Tectonics Program from 1985 to 2002.

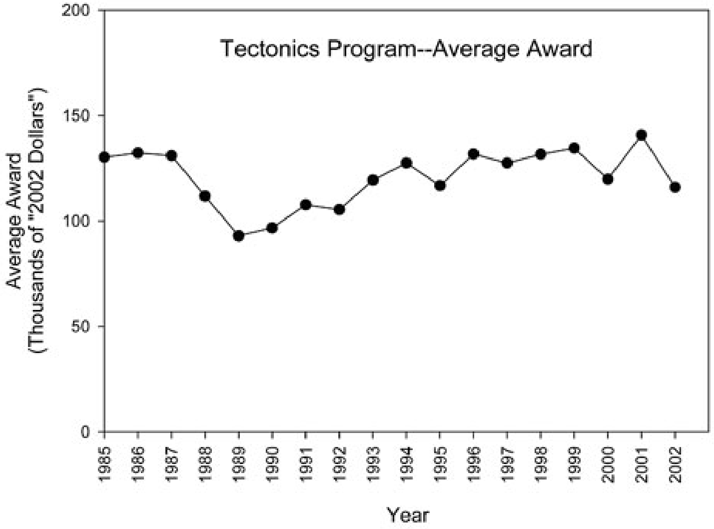


Figure 2. Average award in the Tectonics Program. Awards are enumerated on the basis of awards to institutions. Some awards may fund several PIs at a single institution.

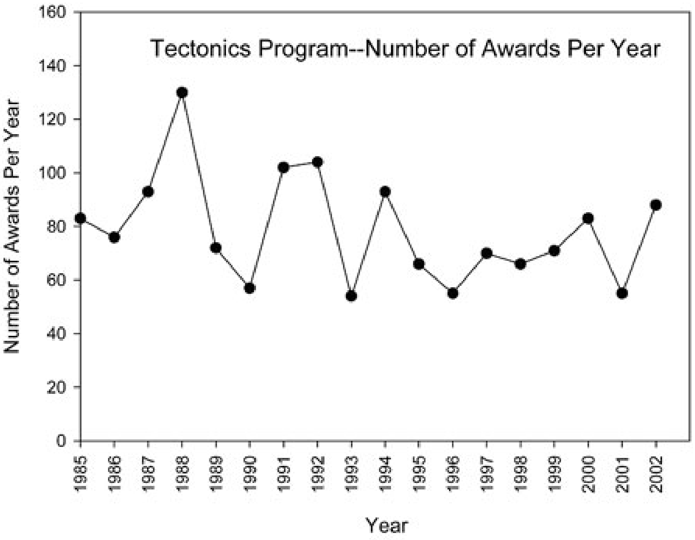


Figure 3. Number of awards per year in the Tectonics Program.

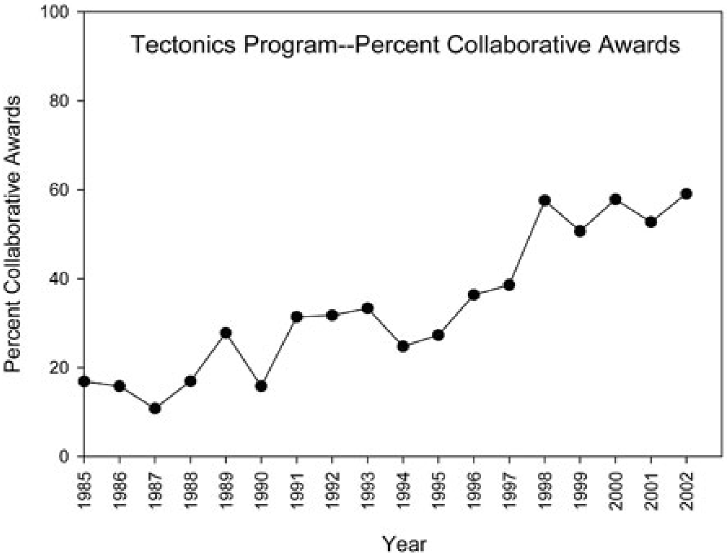
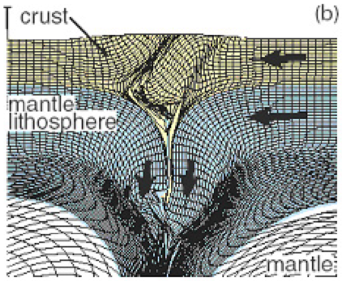


Figure 4. Percentage of awards in Tectonics Program that are part of a larger collaborative project. The designation "Collaborative Research", which NSF requires in the title of the proposal, is used to judge which grants are part a larger multi-institutional collaborative project.

Beyond Plate Tectonics: Rheology and Orogenesis of the Continents



Andy Kronenberg (Coordinator)
Mark T. Brandon
Raymond Fletcher
Karl Karlstrom
Tracy Rushmer
Carol Simpson
An Yin

Introduction

Plate tectonics emerged as a unifying theory of the solid Earth from observations of the ocean floors long after geologists had described the orogenic belts of the continents. Deformation, seismicity, and volcanism in the oceans are localized at boundaries between rigid oceanic plates overlying viscous asthenosphere. Continental geology, on the other hand, does not fit the plate tectonic model as well. The pervasive deformation and internal structure of wide continental mountain belts (Figure 5) indicate non-rigid behavior. Continents appear to be weak relative to oceanic plates, and quantitatively significant deformation within continental lithosphere interiors and margins is documented by GPS, seismic and stratigraphic methods. This weak rheological behavior typifies continental orogenesis, in all of its manifestations, including regions of convergence, divergence, and transform faulting. Significant improvement to our understanding of continental tectonics will require a detailed and comprehensive study of the rheology of continental crust and mantle rocks.

The response of lithosphere and asthenosphere to tectonic, gravitational and thermal loads is strongly dependent on rheological behavior. We know that oceanic plates owe their mechanical character to the friction and flow laws of crust and mantle, and their dependence on lithostatic load and temperature. Oceanic plate thickness and effective rigidity are well explained by the properties of oceanic gabbro and an upper mantle dominated by olivine. Continental lithosphere is much more varied in composition and physical properties. The maximum depth of seismicity in oceanic plates matches the thermally defined transition from brittle dilatant processes to ductile viscous processes. We do not have such a clear correlation in continental lithosphere. Recently, the importance of trace hydrous components of olivine to oceanic lithosphere rheology has been recognized; extraction of water in melts generated at divergent rifts leads to a marked strengthening of oceanic lithosphere. Does water play a similar role in the strength of continental lithosphere?

Figure 5. Field example illustrating structures and fabrics associated with pervasive ductile flow in the lower crust. Photograph shows the north face (2000 meter high) of Dickson Fjord (72o 52'N, 26o 37'W), with large folds exposed in Precambrian gneisses of the Greenland Caledonides (courtesy of Jane Gilotti).

The contrast between oceanic and continental deformation is highlighted by the remarkable range of models currently being considered for mantle return flow associated with convergent deformation of continental lithosphere. At one extreme (Figure 6a), continental mantle lithosphere is relatively strong; thus it is subducted in a plate-like fashion. The weaker, buoyant crust is left behind to form a thickened orogen. At the other extreme (Figure 6b), the mantle lithosphere behaves in a more fluid fashion. Return flow may involve steady down welling in a symmetric or asymmetric fashion (as illustrated by Figure 6b), or it may involve episodic drip-like return flow. Seismic tomography provides tentative evidence for the full range of behavior. Modeling indicates that the mode of the return flow is dependent on convergence rate and the rheologies of the crust and mantle. Mantle return flow causes the crust to thicken, forming a large orogenic wedge, much as observed for the Alps, Himalayas, and Rocky Mountains.

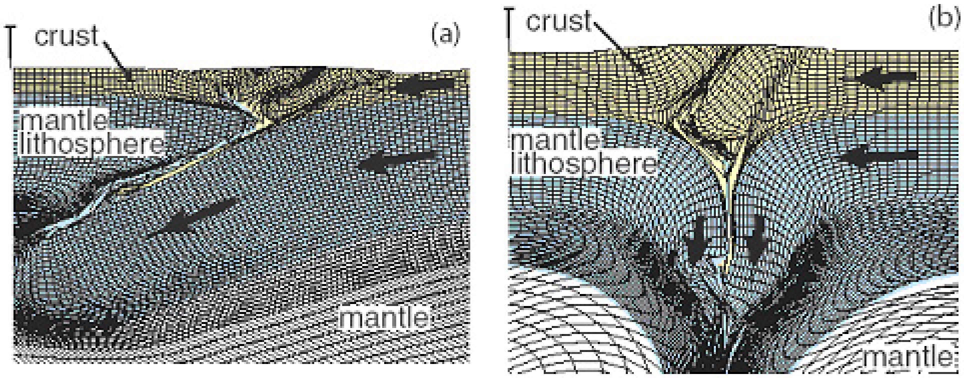


Figure 6. Numerical models illustrating different modes of mantle return flow associated with continent-continent collision. (a) Continental lithospheric mantle subducts in a plate-like fashion. (b) Fluid-like, symmetrical return flow with episodic drip-like pulses. The models use temperature-dependent viscous-plastic rheologies. Deformed tracking mesh shows accumulated strain and arrows are relative velocity vectors (from Pysklywec, R.N., 2001, Evolution of subducting mantle lithosphere at a continental plate boundary, Geophys. Res. Lett., 28, 4399-4402; Pysklywec, R. N., C. Beaumont, and P. Fullsack, 2002, Lithospheric deformation during the early stages of continental collision: Numerical experiments and comparison with South Island, New Zealand, J. Geophys. Res., 107(B7), ETG 3 1-19).

Another exciting problem concerns the relative strengths of the lower crust and mantle. Despite some 40 years of study of rock strength, and the implications for continental tectonics, we are still debating the relative contributions of crust and mantle strength to lithosphere properties (Figure 7). The idea of a weak and highly fluid lower crust dominated tectonics research for the last 15 years. There is now a school of thought that continental lithosphere consists of weak middle crust and a stronger lower crust, which in places may exceed underlying mantle strengths. These arguments are based on inferences from earthquake distributions and estimates of elastic thickness of the lithosphere using topographic loads. These kinds of arguments are indirect and carry with them assumptions that have yet to be corroborated. Nonetheless, they highlight how little we know about the composite rheology of the continents and the presence of weak layers that interrupt stronger load-bearing layers. Resolution of the rheological structure of continental regions will significantly improve our understanding of continental orogenesis in a wide range of tectonic settings.

These diverse conceptual models illustrate the excitement and potential of rheological contibutions to tectonics. We are now able to integrate field-based studies of the structure and evolution of collisional orogens with geophysical studies of the crust and underlying mantle. Numerical models are essential for this work because they allow us to examine the implications of crust and mantle rheology, as extrapolated from laboratory experiments. Field studies of deeply exhumed rocks that have been through the orogenic wedge are vitally important for the validation of predictions from the lab and geodynamic modeling. But most importantly, experimental studies are the underpinning for this area of research. Traditionally, the United States has been the leader in the study of rheology of the crust and mantle. This situation has shifted dramatically over the last 10 years, with the result that labs in Europe are now dominating the field. Experimental rock deformation has flourished in Europe due to better funding, and better institutional support for the facilities that are required for this work.

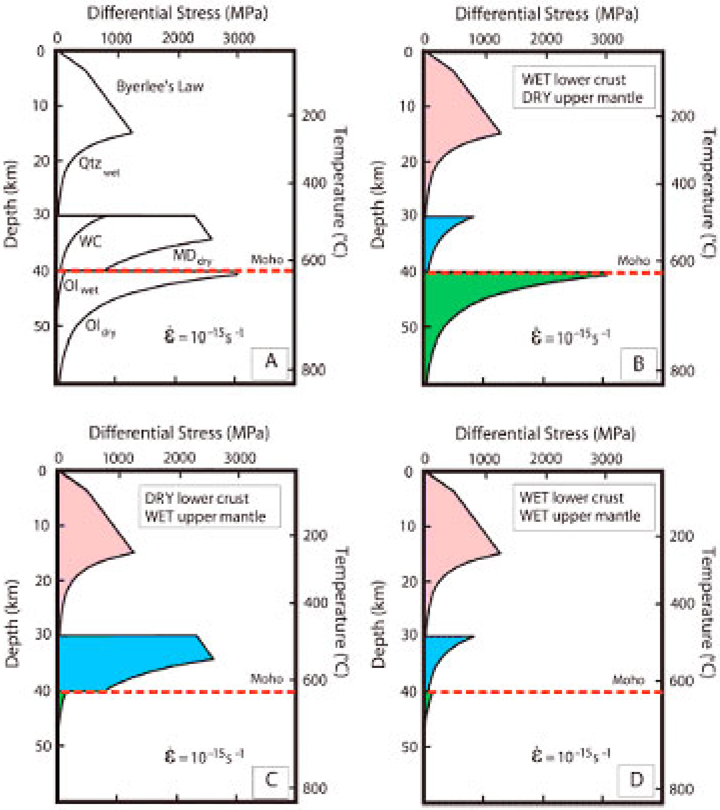


Figure 7. Strength envelopes with depth for continental crust and mantle illustrating competing interpretations for the relative strength of the lower crust and underlying mantle. In all cases, upper crust strengths are represented by Byerlee's frictional strength and a thermally activated flow law for wet quartz. Lower crust strengths are predicted by wet and dry rheologies for diabase (MD) and granulite (WC). Mantle strengths are given by wet and dry olivine rheologies (from Jackson, J., 2002, Strength of the continental lithosphere: Time to abandon the jelly sandwich?, GSA Today, 12, 4-9).

Research Questions and Opportunities

Unlike the behavior of oceanic crust, continental deformation depends markedly on the strengths of both crustal and upper mantle rocks. Continental crust does not have a common mode of origin, and is an assemblage of heterogeneous compositional elements with widely varying tectonic and thermal histories. Also interaction with fluids and melts can greatly modify the rheological structure. Studies of mechanical properties and evaluations of deformation mechanisms of key mineral phases will provide an accurate picture of the dependence of continental strength, faulting, and depth of seismicity on thermal and compositional structure. Outstanding questions that need to be addressed include:

1) How does the rheological structure of the continents lead to non-plate-like behavior?

2) Is the lower crust the strongest element of the lithospheric column? What are the relative strengths of the continental lower crust and mantle?

3) How do mechanical properties change with strain? How do these changing properties influence localization of deformation?

4) How distributed or localized is deformation in shallow, middle and lower crust and mantle?

5) What constitutive relations govern the mechanics of faults and underlying, persistently weak shear zones?

6) What are the feedbacks between dilatant rock deformation, fluid transport, and elevated fluid pressures?

7) How does lithology and fluid chemistry influence continental rheology and how is this related to tectonic setting?

8) What underlying physics and chemistry, from atomic to grain scale mechanisms, govern the macroscopic rock rheology? What is their dependence on temperature, pressure and chemical activities?

9) How do rheologies determined for small, homogeneous specimens at rapid experimental strain rates scale to deformations of composite continental rocks at geologic rates?

10) Does partial melt play a major role in the flow of deep crustal rocks?

11) What are the feedbacks between deformation and reaction during dynamic metamorphism?

12) How do deformation and metamorphism determine rheological anisotropy and fabric?

Rheological behavior can be determined by direct measurement in experiments in which stress, strain, strain rate and relevant thermodynamic variables are controlled. However, two major problems must be solved to apply these results to the study of continental orogenesis. First, a reliable extrapolation must be made to natural strain rates that are five to seven orders of magnitude lower than those of laboratory experiments. Second, reliable methods are required to estimate the bulk rheological behavior of large representative volumes of composite and structured rock from data on its components in small laboratory specimens. Deforming rocks are non-equilibrium systems and the observed flow relationships, microstructures, and textures depend on competing rates of deformation and recovery processes. Studies of the physics and chemistry governing mechanical properties are required if we are to formulate mechanism-based flow laws and to recognize microstructures that result from the same processes in experimental specimens and naturally deformed rocks.

Experimental studies are needed to evaluate the rheologies of a wide range of crustal lithologies, with and without fluids present, and across conditions that favor dilatant brittle failure and frictional sliding, thermally activated plastic and diffusional flow, and transitional brittle-ductile deformation. However, experiments alone cannot answer all questions posed. Physical and chemical processes of rock deformation operate at scales ranging from failure of crystalline bonds at crack tips and motion of lattice defects, to grain-scale deformation in multiphase rocks, to displacement on map-scale faults and shear zones (Figures 5 and 8).

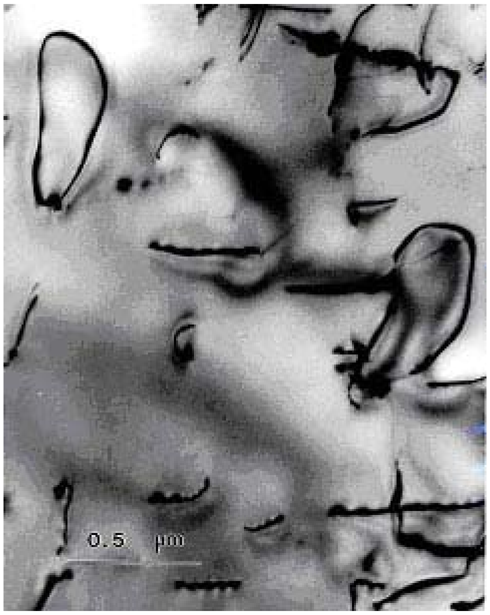


Figure 8. Dislocation loops in feldspar deformed at greenschist conditions, within a granodiorite shear zone, Sierra Nevada near Lake Edison - Mount Abbott quadrangle (from Kronenberg, A.K., P. Segall, and G.H. Wolf, 1990, Hydrolytic weakening and penetrative deformation within a natural shear zone, in Geophysical Monograph 56, AGU, 21-36).

Thus, constraints on rheology are equally needed from careful field and observational studies and mechanical modeling. Integration of detailed field observation and mechanical modeling allow naturally deformed rocks and active tectonic regions to be used as natural laboratories. Estimates of rheological behavior from experimental studies may be tested against field examples selected for the availability of constraints on strain, strain rate, thermodynamic conditions, and tectonic & thermal history.

Field and theoretical studies of small-scale structure and fabric may be used to examine simultaneous deformation and reaction at conditions where fluid-rock interaction, mineral growth and dissolution, and melting are important (Figure 9). Modeling of large-scale active tectonics may be used to examine the sensitivity of rheology to thermal and lithologic structure, and to examine the consequences of gravitational loading, uplift, erosion, and magmatic events. In addition to mechanical constraints and boundary conditions, these models require petrological, geochronological, and stratigraphic constraints on pressure and temperature histories, and information on conductive and advective heat flow, and rates of rock exhumation and burial.

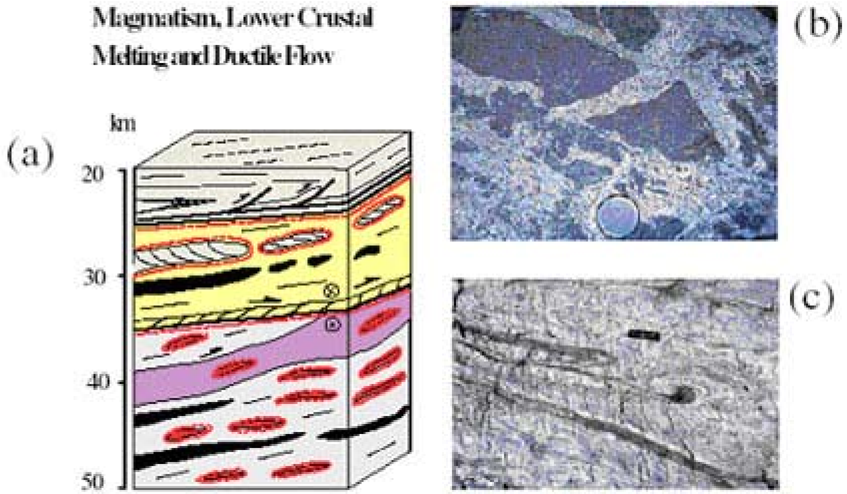


Figure 9. Synchronous deformational and magmatic processes operating in the lower part of the continental crust. The example shown here, from exposures in Fiordland, New Zealand, highlights what can be learned from direct study of deeply exhumed continental crust. (a) The section shows a vertically stratified crust consisting of a meta-sedimentary middle crust (green), a late-stage ten km thick mafic to intermediate batholith (yellow, Western Fiordland Orthogneiss) that was emplaced into the crustal section at 126-119 Ma), and a mafic lower crust (purple) with lenses of dioritic partial melt (red). Outcrop photographs show (b) the dioritic partial melts in an older gabbroic unit (mafic lower crust), and (c) melt-enhanced deformation in a shear zone developed at the base of the batholith (courtesy of Keith Klepeis).

Studies of Transitional Brittle-Ductile Deformation and Strain Localization

Yield envelopes based on purely brittle processes of friction and failure at shallow crustal depths and purely ductile processes of plasticity and creep at deeper levels grossly over-estimate strengths at intermediate crustal depths. Geophysical measures of shear stress on the San Andreas and other crustal-scale faults indicate that experimentally derived yield envelopes may be inappropriate for analysis of faulting and seismicity. Close inspection of laboratory results for mechanical behavior and mechanisms of deformation indicates that complex combinations of brittle and ductile mechanisms operate over a wide range of conditions.

Application of the observed transitional behavior to deformation in the crust has been hindered by a lack of quantitative formulation, especially that bearing on its extrapolation to natural conditions. Better models are needed that incorporate interaction between dilatant brittle mechanisms, crystal plasticity, diffusion, and solution transport. These must be guided by key microstructural observations that clarify the physics and chemistry involved. Such relations will yield lower integrated strengths for the crust than are predicted by simple end-member friction and flow laws.

Coupled Mechanical-Hydrologic Systems

Transitional brittle-ductile deformation appears closely linked to the role of fluids during faulting through mechanisms affecting positive and negative dilatation of fault and host rocks. Grain size reduction and lithologic mixing within fault gouge alter permeability in the fault-host system. Fluid flow affects dissolution at grain contacts, transport, and precipitation of cements. Field observations indicate that many processes that affect fault mechanics have not been replicated or quantified in laboratory experiments.

Integrated Studies of Material-Specific, Mechanism-based Rheologies

Improvements in experimental methods have led to better data quality. These include closer control on thermodynamic conditions, refined measurement of stress, and digital data acquisition. However, with few exceptions, creep data have been fit to theoretical flow laws, borrowed from materials science, that were developed to model metals and simple oxides. These relations only approximate the behavior of more complex silicates and carbonates. Material-specific flow laws are needed that fully incorporate the dependencies of defect populations, deformation mechanisms and recovery processes on temperature, stress, and chemical activity. In turn, these relations form the basis for realistic tectonic models of continental deformation.

Formulation and Evaluation of Rate and State Constitutive Relations that Describe Transient and Steady-State Behavior

Formulation of improved crustal flow laws can also come from studies of transient creep through load relaxation experiments and high strain torsion experiments and the development of rate and state constitutive relations. Steady-state flow laws have been obtained for many important silicates of the continental crust. Few studies have addressed the transient creep with strain-hardening that precedes a steady state, or with strain softening that results in strain localization and development of shear zones. Recent experiments using torsion apparatus have shown that relations that appear to represent steady-state creep over small strain increments change significantly with increasing shear strain. These longer, more gradual transients correspond to changes in microstructure and texture. Quantitative determinations of transient creep require new types of creep laws and new types of experiments. These creep laws have important implications for the evolution of intracontinental fault systems and continued displacement on mature faults.

Fabric Development and Anisotropy at Large Shear Strains

Deformation of upper mantle rocks by dislocation creep gives rise to strong foliation and lattice preferred orientations that result in the seismic anisotropy of oceanic plates. Equally strong fabric and lattice preferred orientation are seen in rocks exhumed from the middle to lower continental crust. However, owing to longer and varied deformation histories, fabrics and anisotropy of the middle and lower continental crust are more varied and complex.

Recent technical advances improve our ability to study lattice preferred orientations in deformed rocks in the field and the laboratory, and to interpret the patterns on the basis of crystal plastic slip systems. New scanning electron microscope methods based on electron backscattered diffraction allow measurements of lattice preferred orientation on large populations of grains in fine-grained and heterogeneous rocks. Together with torsion apparatus experiments, they allow comparison of naturally deformed rocks and experimentally deformed specimens at equivalent strains. Self-consistent theoretical models of texture development contribute to our understanding of lattice preferred orientations and predict anisotropy in rheology that develops with strain.

Chemical Weakening and Hardening

Mechanical properties of rocks are strongly influenced by chemistry. In well-studied minerals such as olivine, quartz and halite, trace element chemistry critically affects the structural defect populations and deformation mechanisms. In particular, trace levels of hydrous defects within these nominally anhydrous minerals and hydrous complexes at their surfaces greatly weaken them. We have much more to learn about deformation of minerals in the presence of reactive fluids, as well as the effects of major component variation in minerals. Flow laws have generally only been determined for end-member compositions and little is known about the effects on strength of solid solution, cation ordering, or exsolved phases within minerals.

Additional chemistry and physics must be introduced to rheological laws to describe the bulk rheology of reacting multiphase systems. Discontinuous reactions alter the modal compositions of rocks and contribute to volumetric strains, dissolution and growth. Continuous reactions may contribute to driving forces for recrystallization. Recent experiments involving partial melts have been successful in describing processes of flow, melt segregation, and transport. Reactions that evolve or consume fluids may affect local effective pressures, facilitating dilatant brittle processes at nominally high pressure and temperature as well as diffusional solution transfer creep. Much more work is needed to understand how changes in mineral chemistry affect the strength of the lithosphere.

The Missing Link: From Earthquakes to Orogenesis

Laurel Goodwin (Coordinator)
Rick Allmendinger
Roland Burgmann
Jim Evans
David Pollard
John Shaw
Bruno Vendeville
Martha Withjack
Teng-fong Wong

Introduction

Deformation of the Earth's crust is unevenly distributed in space and time and thus its study has become partitioned into disciplines with tools of markedly different precision populated by practitioners with markedly different perspectives (Fig. 10). A single earthquake may produce substantial deformation and significant damage of relevance to society in just tens of seconds (10^{-6} years). Seismologists and geodesists have developed highly accurate methods and tools (seismometers, strong motion instruments, creep meters, GPS, InSAR, etc.) to measure deformation during and between major earthquakes (up to 10^{2} years if we also utilize historic leveling and triangulation data). The majority of the signal captured by GPS, InSAR, and similar instrumentation may be modeled as linear elastic deformation. However, the time span of decades is too short to capture more than a few major earthquakes on the important seismogenic faults in an actively deforming volume of the Earth's crust and may miss much of the associated inelastic deformation.

Tectonic events such as mountain building, development of major transform systems, and rifting occur over millions to tens of millions of years. The structures produced on these longer time scales also directly affect society. For example, faults provide both conduits and barriers to fluid flow, and thereby influence the distribution and production of water and hydrocarbons as well as contaminant transport; mountain belts affect global atmospheric circulation patterns, thereby impacting climate. Field relations seldom allow age constraints tighter than ± 1 m.y. (10^{6} yr) to be placed on individual structures, though growth strata imaged by seismic reflection permit some additional resolution. Deformation at these time scales is decidedly permanent; the transient elastic strain measured at 10^{1} yrs and less is an insignificant fraction of the total finite strain recorded in a mountain belt.

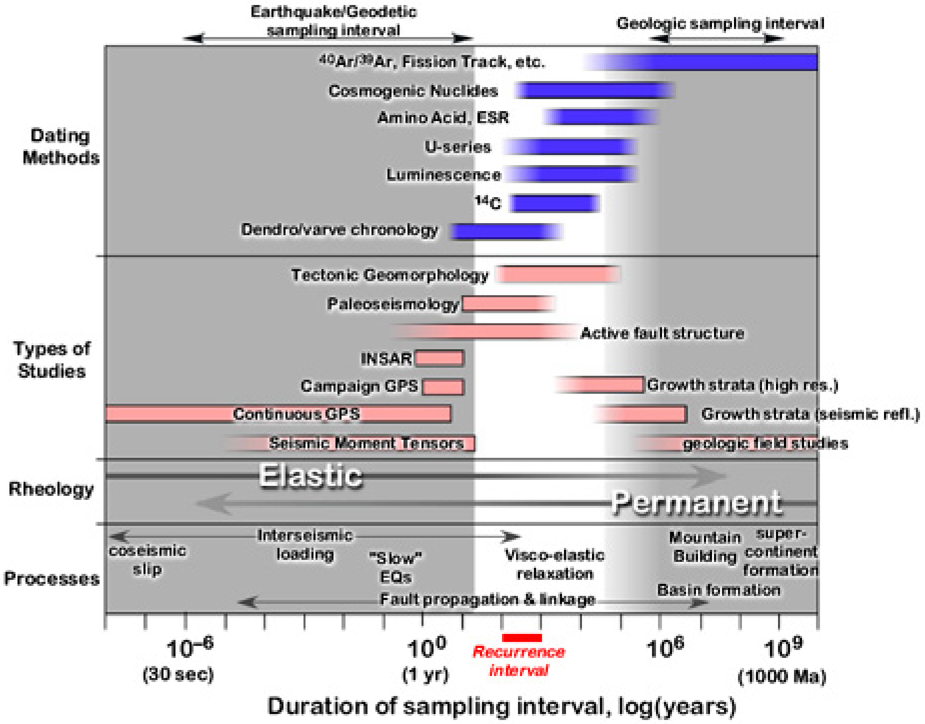


Figure 10. Earth scientists study deformation across more than 15 orders of magnitude of temporal sampling windows. Processes, rheologies, types of studies, and methods used vary enormously across this range. The white band, corresponding to times from decades to a million years, is the least understood part of the range and thus the missing link in relating earthquakes to orogenesis.

Deformation appears very different from these two perspectives. The temporal and conceptual gap between them is one of the most fertile areas for future research: How does deformation at the time scale of decades and less which includes elastic strain as well as permanent deformation accomplished by seismic and aseismic fault movement, integrate over hundreds to millions of years to form a major tectonic province? The time range from 10^2 to 10^6 years is the missing link. Without studies at these time scales, we are unlikely to understand the spatial and temporal distribution of earthquakes, which is fundamental for evaluating seismic hazards. The life cycle of faults is initiated and their mechanical character set over this time range. If we wish to use map- to micro-scale observations to read the rock record of earthquakes we must understand this missing link. Finally, to understand fully the rheological character of the upper crust we must bridge this conceptual gap between elastic and inelastic deformation.

We expect that tangible results from this line of research will include: 1) a much clearer understanding of rates, durations, and the episodic nature of deformation in the crust, as well as the mechanisms controlling these factors; 2) physically based and mechanically plausible models for earthquake sources and the complex process of rupture propagation, along with an understanding of the driving forces and energy balance of earthquakes and the earthquake cycle; 3) a better understanding of the role of chemical and hydrologic processes in rock deformation; 4) characterization of material properties of rocks in the seismogenic zone and the architecture of faults in different lithologies and tectonic settings; and 5) characterization of structures in the upper few kilometers of the crust and a better understanding of their relationship to such factors as topography and tectonic geomorphology.

Research Questions

1) How do the elastic strains measured by techniques such as GPS and InSAR bear on earthquake distribution and how does this elastic signal relate to permanent deformation at the scale of millions of years?

2) Are the repeat times for earthquakes quasi-periodic or more complex?

3) How and why does deformation localize into faults?

4) What role do fluids play in these phenomena?

5) What is the structural/microstructural record of fault-zone processs and how does this record reflect the mechanical behavior of fault-zone materials?

Relating Elastic and Permanent Deformation

Geodetic data such as GPS and InSAR record predominantly an elastic signal that can yield non-intuitive results, such as evidence of crustal shortening in domains enclosed within the regionally extending Basin and Range Province. In other areas, GPS velocity vectors in active zones of continental deformation display rates startlingly similar to geologically measured shortening rates (Fig. 11), even though the GPS signal is ephemeral and may be related in part to distant processes such as subduction-zone locking. Because we don't have a 10^2 to 10^3 year record of GPS observations to cover a more complete seismic cycle along an entire major fault zone, we do not know how the short-term elastic deformation is converted into long-term permanent strain. This conceptual gap can be filled by studies focused on the 10^2 to 10^6 year time interval.

Study of this temporal window will be facilitated by a variety of geochronometers that have been / are being developed to constrain the timing and duration of events in this interval (Fig. 10) and the growing number of GPS networks and availability of InSAR data around the world (Fig. 11). These data alone will not be sufficient to determine how short-term elastic deformation is integrated into long-term inelastic strain; that requires examination of the geologic record of deformation, particularly that which has accrued over 10^2 to 10^6 years. In addition to paleoseismological and tectonic geomorphology studies to address recurrence intervals, studies of the structures and microstructures associated with young faults in poorly lithified sediment can illuminate deformation processes and strain rates at these time intervals.

Structures in sediments may provide the sole record of recent slip sense (and perhaps slip style, i.e., stick-slip versus creep) where seismologic data are not available. For example, rotation and cataclasis of elongate pebbles, cobbles, and sand grains during faulting of poorly lithified sand and gravel produces lineations that record slip in normal faults of the Rio Grande rift (Fig. 12). Such observational and descriptive studies can not alone answer the questions posed. Integration of these studies with mechanical modeling will permit regions of active tectonics to be utilized as crustal-scale laboratories within which conceptual models can be tested and refined.

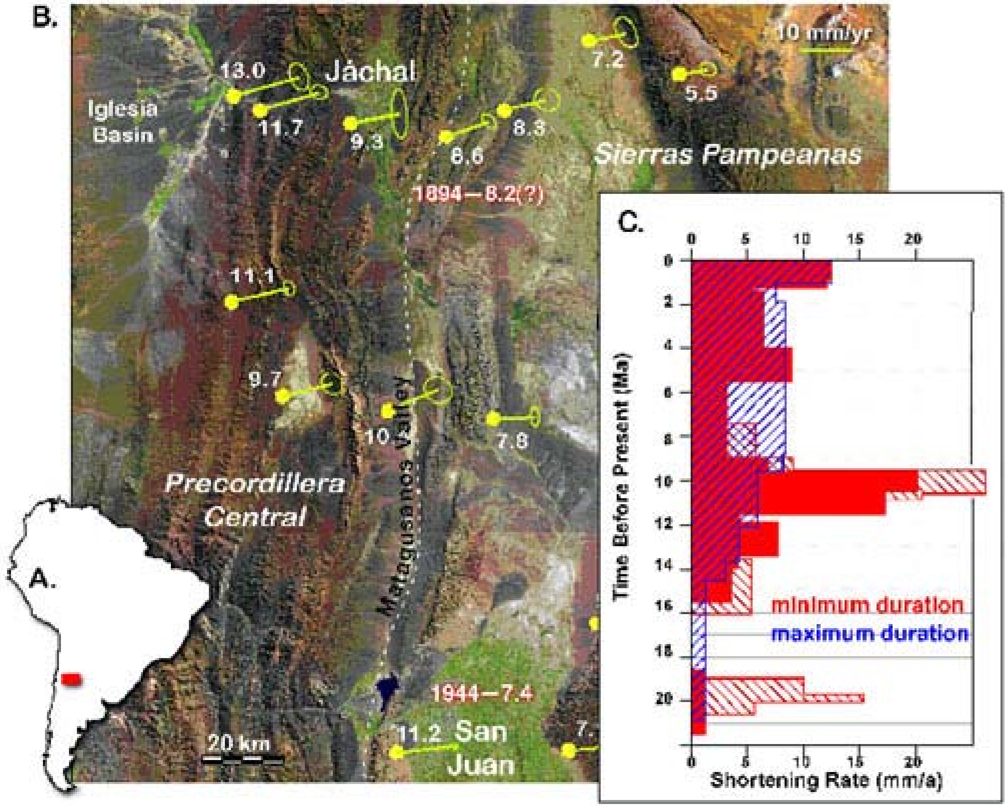


Figure 11. An example from active foreland thrust belt in western Argentina of studying deformation at several time scales. (A) Location of study area in western South America, shown with red box. (B) Landsat Thematic Mapper base showing active thin-skinned Precordillera thrust belt and active thick-skinned Sierras Pampeanas. Dashed white line marks reversal of structural vergence; the thick-skinned structures to the east verge west whereas the thin-skinned structures to the west verge east. White letters highlighted with red show the approximate locations of two large historic earthquakes and their magnitudes; another M 7.4 earthquake occurred just east of San Juan in 1977. Yellow lines and ellipses: velocity vectors (relative to a fixed South America) and uncertainties from the MATE GPS network (data courtesy of B. Brooks, R. Smalley, M. Bevis, & E. Kendrick). (C) Shortening rate history of the Precordillera and western Sierras Pampeanas for the last 20 Ma from Jordan et al. (1993) and Zapata & Allmendinger (1996). Red curves show rates based on minimum permissible duration of motion for each thrust plate; blue curves show rates based on maximum permissible duration. Note the striking similarity of million year rates to GPS velocities, even though the latter are dominated by an elastic signal from a locked plate boundary.

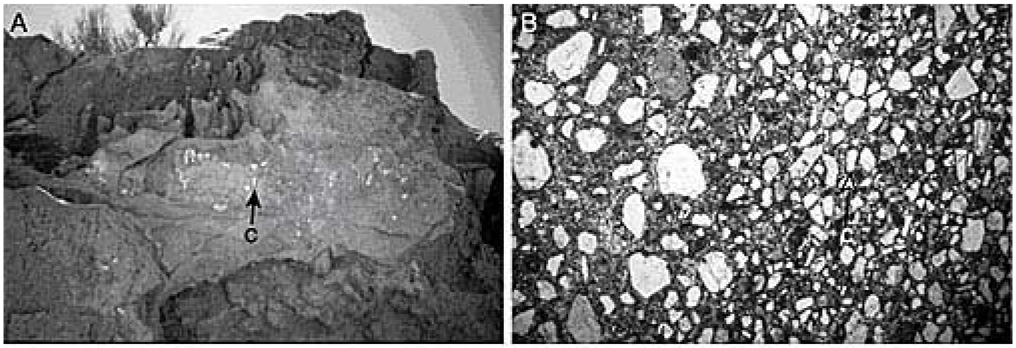


Figure 12. Clast lineations recording slip direction in the Sand Hill fault, Rio Grande rift, New Mexico. Images show deformed sediments in the hanging wall mixed zone that were subsequently cemented with calcite (Heynekamp et al., 1999). A. View looking east at fault core bounding surface. Elongate clasts ('c') are parrallel to subsequently formed slickenside striaw. Shrubs are roughly 1 m high. B. Photomicrograph taken in the plane light, ~6 mm wide in longest dimension. Fragmented sand grains ('c') in zone of deformation bands are demonstrably aligned parallel to macroscopically visible lineations in 3-d (Goodwin and Tikoff, 2002). This zone of deformation bands os juxtaposed against colluvial wedge sediments, preserved in the hanging wall, that record paleo ground rupture.

Spatial and Temporal Distributions of Earthquakes

The spatial and temporal distribution of earthquakes reflects the distribution and transfer of stress within the crust as well as local source mechanics. The frequent occurrence of major earthquakes in clusters or sequences (e.g., 1954 Fairview Peak-Dixie Valley, 1987 Superstition Hills, and 1992 Landers earthquake sequences in the western U.S.; the 1944 San Juan and 1977 Caucete earthquakes in western Argentina; or 1999 Izmit, Duzce and earlier earthquakes in Turkey) suggests that earlier events may trigger later ones. When and how this occurs are two of the most promising avenues to understanding (and possibly predicting) earthquakes. Recent studies suggest that the conceptual model of foreshocks, mainshock, aftershocks may be inadequate to explain the triggering phenomenon.

Localization of Deformation

Deformation can be distributed throughout a region of interest or localized within discrete zones. Many mature, major faults, like the San Andreas, appear to be weaker than rock mechanics experiments would predict. Processes of nucleation and growth and the mechanical behavior of faults - which bear on localization and fault reactivation - are poorly understood. These processes can be best investigated by the integration of experimental deformation studies, analytical and numerical modeling, and structural and microstructural analyses of faults and fault-zone materials in the field and laboratory. Investigation of how fault segments become linked in space and time, for example, will help us to understand the significance of the geometric complexity of fault systems. Understanding the spectrum of failure and localization modes recorded by fault-zone structures (e.g., opening and shear fractures, shear and compactive deformation bands, foliations and lineations) would further elucidate the faulting process.

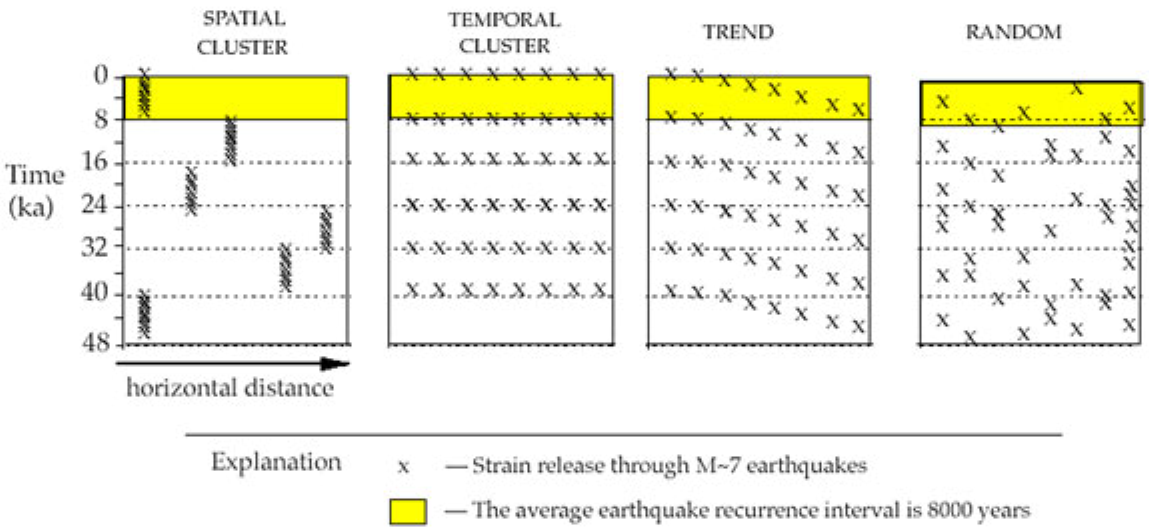


Figure 13. Space-time patterns of strain release in a hypothetical plate boundary fault system with total horizontal displacement rate of 2 mm/yr, 2 m of horizontal slip per event, and a long-term average of 0.25 mm/yr displacement on each fault. Courtesy of B. Wernicke and colleagues.

The Role of Fluids

Research into fluid-fault interactions generally falls into two categories: 1) the impact of faults on fluid flow (typically based on static conceptual models of fault-zone architecture) and 2) the impact of fluids on fault-zone mechanics (in which dynamic mechanical processes are considered in detail but the hydrology of the fault-protolith system is not considered). Bridging the gap between these approaches requires consideration of three-dimensional spatial and temporal variations in fault-zone character, and their resulting impact on both the hydrology and mechanics of fault-protolith systems.

The fact that faults span different crustal levels also needs to be fully considered. This emphasizes the importance of integrating structural investigations with hydrologic, petrologic, and geochemical studies of fault systems. For example, variations in flow pathways over time leave a geochemical signature (e.g., stable isotope, fluid inclusion) that can help us understand how fluids evolved and how their changing compositions affect the rheology of fault systems. In addition, fluid-fault interactions can cause significant chemical changes within and adjacent to fault zones; these chemical changes can in turn affect the mechanical behavior of the fault zone rocks.

Fault Zone Processes and Materials

Faults can rupture dynamically, produce slow earthquakes, and/or creep aseismically. Studies of fault-zone architecture and microstructures that might provide evidence of different modes of failure/ strain rates have been handicapped by the nature of the geologic record, which integrates the signal of different events over time, producing a composite fault rock that records every event of its history. In addition, field and laboratory data demonstrate that fault rock strength and rheology evolve with both rock microstructure and mineralogy, emphasizing the fact that the mechanical response of an individual fault can change over time.

Recent developments suggest ways to exploit new and old technologies to better understand the geologic record of fault-zone processes. Combined geodetic and seismologic data offer the opportunity to target faults that record different deformation histories, including different strain rates. New experimental approaches should allow structures formed in the lab to be compared with those developed in the field and suggest new research directions. For example, during dynamic rupture and coseismic slip, dramatic changes in frictional strength may arise from frictional melting and thermal pressurization. Recent lab measurements argue for the coefficient of friction attaining values as low as 0.1 at slip velocities ~0.1 m/s, possibly due to the generation of a ¦gel-like² microstructure. Field observations indicate that seismic slip may be highly localized; theoretical models would then imply that the microstructure associated with partial melting, ¦flash heating² and thermal transients can be resolved only at a very fine scale.

Research Opportunities

Answering the questions we pose will require investigation in a variety of tectonic environments. We therefore recommend taking advantage of, but not restricting research to, the focused initiatives mentioned herein. Activities such as EarthScope leverage, but do not replace, research into these fundamental questions. The integration of field, geophysical, laboratory, and theoretical studies when feasible and appropriate will facilitate the proposed work. We therefore support efforts to remove artificial boundaries between disciplines, to which deformation processes do not adhere. This recognition that other disciplines may contribute to research in structural geology and tectonics is intended to encourage collaborations with geophysicists, hydrologists, geochemists, and petrologists.

- GPS and InSAR (addressing questions 1-3) Continued GPS monitoring and development of new techniques such as InSAR will assist in understanding the nature and spatial distribution of surface movements on the time scale of years. Present GPS arrays in large diffuse plate boundary zones (Tibet, Andes, and western U.S.) are, however, too sparse - we get an averaged, continuous velocity field but miss important information on the motion and deformation near individual faults. Geodesy becomes particularly useful when integrated with seismic paleoseismic, and structural geologic constraints. For example, we can consider a large earthquake as the beginning of a lithosphere-scale rock mechanics experiment. The boundary conditions imposed by the coseismic rupture on the surrounding crust and upper mantle can be defined. It is possible to constrain the geometry of the experimental 'apparatus' - fault geometry, crustal layering or heterogeneity, topography - and gauge the response of the system using surface displacement data and the results of a mechanical model of elastic strain associated with fault slip (Fig. 14).

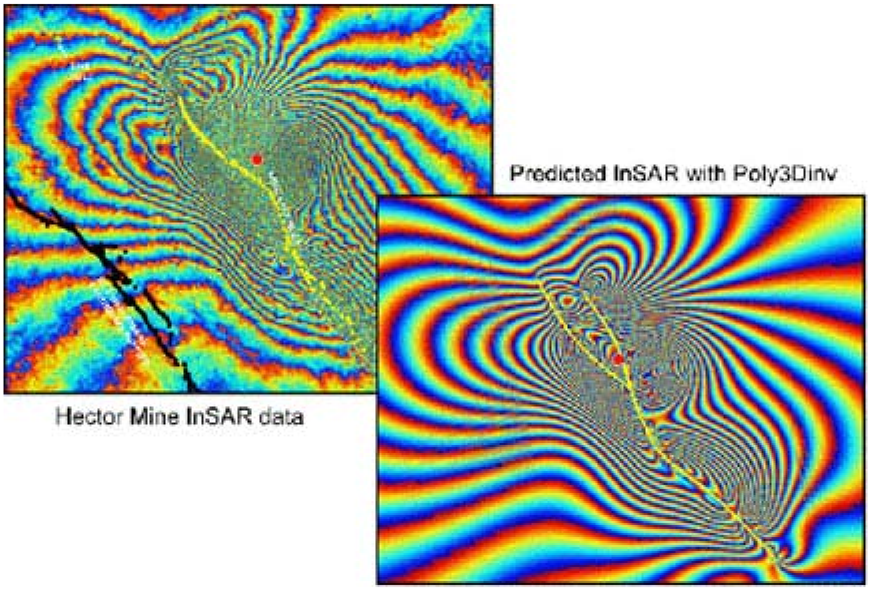


Figure 14. InSAR and model interferograms from the 1999 Mw 7.1 Hector Mine earthquake, CA. One fringe cycle = 28.3 mm displacement in the look direction of the satellite. Model developed by Laurent Maerten using the Poly3Dinv code utilizes the boundary element method solution for elastic deformation associated with fault slip.

The elastic models reproduce the pattern of deformation recorded by the InSAR data, demonstrating a powerful tool for investigating such phenomena as triggered earthquakes. Geodetic monitoring on scales from major plate boundaries to individual faults is therefore an important goal. Finally, models can be constructed to help interpret the processes and their rates, and ultimately to constrain rheologic parameters of fault zones and lithospheric rocks at different depths.

- Reflection Seismic Characterization of 3-D Structures (addressing questions 1-3). Research into the areas discussed above requires the understanding that deformation is typically three-dimensional. The longer-term geologic record (e.g., as interpreted in 3-D seismic data from the Gulf of Mexico) shows us that faults that appear as independent segments at one structural level may be linked at another or may be linked laterally. We therefore support efforts to collect, analyze, and model data in three dimensions to characterize structurally complex areas, and would like to see more efforts on the part of individuals and the federal government and industry to transfer data from industry to academia. The Flexible Array associated with U.S. Array also offers potential for extending seismic coverage of key areas and better understanding of 3-D fault geometries.

- Geophysical and Geological Characterization of Active Faults (addressing questions 1-5). SAFOD will allow sampling and instrumentation of the seismogenic zone of an active strike-slip fault. NanTroSEIZE (the Nankai Trough Seismogenic Zone experiment), designed to take advantage of a new Japanese drill ship to sample and instrument a major subduction-zone fault and splay fault at a variety of depths. In-situ measurements can be used to constrain hydrologic and petrophysical characteristics of fault-zone rocks. A particularly appealing aspect of NanTroSEIZE is that it will allow a comparison of these parameters both up dip from and within the seismogenic zone, which will allow investigators to evaluate which parameters control seismic behavior.

- Mapping and Field Structural Analysis (addressing questions 1-5). Mapping and field structural analysis of both outcrops and core from the active faults mentioned above are critical to this effort. Identification and quantitative characterization of 3-D patterns of deformation, observations pertaining to strain localization, and structural analysis of young faults that extends beyond paleoseismic investigations are particularly important to answering the questions detailed earlier. This research must include observations made from regional to hand-sample scales, where fabrics that may record strain localization or strain rate, or impact fault strength, are visible.

- Microstructural Analysis (addressing questions 1-5). Microstructural analysis (the characterization of structures at the scale at which processes controlling frictional failure operate) must be done in the context of mapping at a larger scale, and should be integrated with geochemical and geochronologic / thermochronologic studies to constrain interpretations of the data collected. The goal of microstructural analyses in the research proposed here is a better understanding of the geologic record of fault-zone mechanics. Microstructural evidence of strain rate (e.g., seismic rupture versus creep) and documentation of features that might affect the dynamic coefficient of friction of fault rock are examples of particular focus areas. Microstructural analysis will benefit from the continued development of image analysis tools; notable among these is NIH Image freeware. Improved electron imaging capabilities have resulted in better electron microprobe, SEM, and TEM resources (for example, EBSD) for microstructural analysis.

- Geochemical and Mineralogical Analyses (addressing questions 3-5). Fluid inclusion, stable isotope, and major, minor, trace and REE analyses coupled with mineralogical and microstructural analyses of fault rocks can, when compared with protolith materials, provide a record of fluid-fault interactions. This is a record not only of flow pathways, and thus paleohydrology, but also of reactions resulting in changes in fault-zone porosity, permeability, and strength, therefore effecting fault-zone weakening or strengthening over time. Chemical processes operating in fault zones are commonly not well characterized, but may critically affect such factors as rate-and-state constitutive relationships and pore fluid pressure.

- Hydrologic Analyses (addressing questions 2-5). Although pore fluid pressure variations have been intimately linked to the seismic cycle, our understanding of faults as part of a larger hydrologic system is surprisingly limited. Analyses of fault-zone permeability and permeability variations at a variety of scales, cross-fault flow tests, and flow models involving dynamic fault systems, would all contribute to the proposed efforts.

- Geochronology / Thermochronology (addressing questions1-3). The exploitation and development of geochronometers that can help constrain both the ages and durations of deformational events in the time window from 10^2 to 10^6 years are clearly critical to this effort (Fig. 2).

- Experimental Deformation (addressing questions 1-5). Experiments have the potential to contribute substantially to our understanding of the rheology of the upper crust, where frictional processes dominate. The successful application of experimental results to understanding large-scale processes, however, demands: 1) an understanding of the fundamental physics and chemistry underlying processes of interest; and 2) that experiments are designed with materials, boundary conditions, and extrinsic parameters that adequately represent natural systems. The scaling issue is highlighted, for example, by the large gap between stresses predicted by laboratory experiments and stresses now inferred on the San Andreas fault. A major obstacle to fully utilizing experimental approaches to understanding shallow crustal deformation is the dearth of experimental labs in the U.S. and the limited number of people with appropriate expertise to use these labs. One solution might be an STC devoted to these processes, designed to bring together field structural geologists, experimentalists, and theoreticians to conduct experiments of mutual interest successful examples of this approach include Institutes in Potsdam and Bayreuth, Germany.

- Analytical and Numerical Modeling (addressing questions 1-5). Participants in this workshop recognize the value of using analytical and numerical models to test conceptual models generated through field and laboratory research, and to suggest new directions for data gathering and for studying natural and experimental deformation. Of potential value to answering the questions outlined above would be the formulation of numerical models that capture the continuum and discrete attributes of natural deformation. Lattice Boltzmann and percolation network models are examples of approaches that offer promise for coupling hydrologic and mechanical models of fault development. Fracture mechanics models are examples that capture the continuous and discontinuous nature of a faulted rock mass. Development of graphical user interfaces that facilitate the construction of geometrically complex models and the visualization of model results are a priority.

Dynamic Interactions Between Tectonics, Climate and Earth Surface Processes

Sean Willett (Coordinator)
Mark T. Brandon
Rebecca Dorsey
Bruno Vendeville
Kelin Whipple

Introduction

The Earth's surface represents an important and underexploited source of information regarding tectonic processes operating within the Earth. The ready availability of digital topographic data and new data obtained by emerging technologies (STRM, ASTER, Lidar, GPS Total Station, reflectorless laser rangefinders, etc) thus represent new opportunities to study structures and tectonic processes within the lithosphere. However, our ability to infer tectonic information from surface observations is hampered by a lack of quantification of the causal links between tectonic activity and topography. Topography represents the net product of tectonic and surficial processes and unraveling the intricacies of this highly coupled system represents a primary challenge in this field.

We recognize that the geosphere, atmosphere, hydrosphere and biosphere interact in diverse ways at a variety of spatial and temporal scales. The principal interface between these spheres is the Earth's surface. Tectonic activity creates the surface relief that amplifies these interactions. Surface processes destroy relief by redistributing mass. These processes are coupled insofar as there is a deformational response to surface change and the resultant gravitational forces. Rates of surface processes are modulated by climatic factors, primarily precipitation rate and distribution which determines discharge levels in rivers. Interactions between tectonic and surficial processes are complex and involve coupling with feedback through diverse mechanisms (Fig. 15). For example, fluvial incision rates increase in response to a tectonically-driven increase in channel slope, but may also increase or decrease in response to changes in drainage area as water divides are moved or created by tectonic activity. Climatic response to increased elevation includes orographically-enhanced precipitation, but it also includes lower surface temperatures as mountains rise through the atmospheric lapse rate; lower temperatures result in periglacial erosion processes and eventually the creation and growth of alpine glaciers (Fig. 15).

The dynamic system of the Earth's near surface has implications for natural hazards and the environment in which we live. Floods, landslides, debris flows and even earthquakes are a consequence of the processes creating dynamic landscapes in tectonically-active areas. Understanding the rates and variability of mass transport systems on the earth's surface will lead to better hazard forecasting. There are also implications for climate change; a better understanding of how the Earth's surface has responded to climate change over geologic time will lead to a better understanding of how climate change will affect the Earth's surface environment over human timescales.

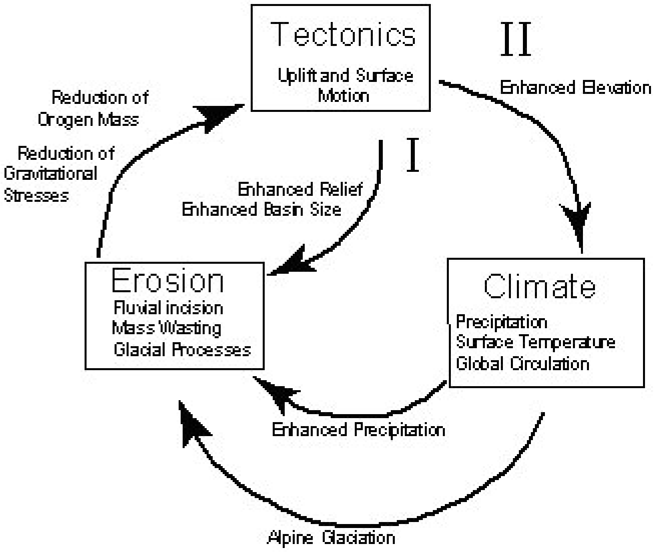


Figure 15. Feedback loops within the dynamic system defined by tectonics, climate and erosional surface processes. There are two feedback loops; a direct path (I) whereby tectonics increases erosion rates by increasing elevation, relief and drainage basin areas and an indirect loop (II), whereby increased elevation induces increased erosion rates through changes in climate. Climate change is in the form of enhanced precipitation or lower temperatures, which lead to glaciation. In each case, there is feedback in the tectonic response to surface mass redistribution. More complex processes and pathways are likely to exist.

Research Questions and Opportunities

The last decade has seen considerable growth of interest in the coupled tectonic-surface-climate system. We anticipate that this interest will continue or even accelerate as new technologies and new theories lead to further progress. We identify here a number of research questions that exemplify this interest, and are likely to motivate research in fruitful areas of future study. The list below is not exhaustive, but rather is intended as an illustrative set of examples.

1) What are the mechanisms and magnitudes of feedbacks among tectonic activity, structural style, strain partitioning, erosion and sediment deposition at the earths surface?

2) What are the nature and strength of the climatic feedback?

3) How do rates and patterns of erosion influence growth of individual structures, orogen kinematics, metamorphism and exhumation?

4) How do mechanical, climatic, or geomorphic thresholds influence the evolution of the coupled system?

5) How can we extract quantitative information about climatic and tectonic processes and histories from the topography of the Earth's surface and the sedimentary record?

6) What is the nature of the coupling between erosional and depositional systems?

7) What is the timescale of response for the coupled system to climatic or tectonic perturbation?

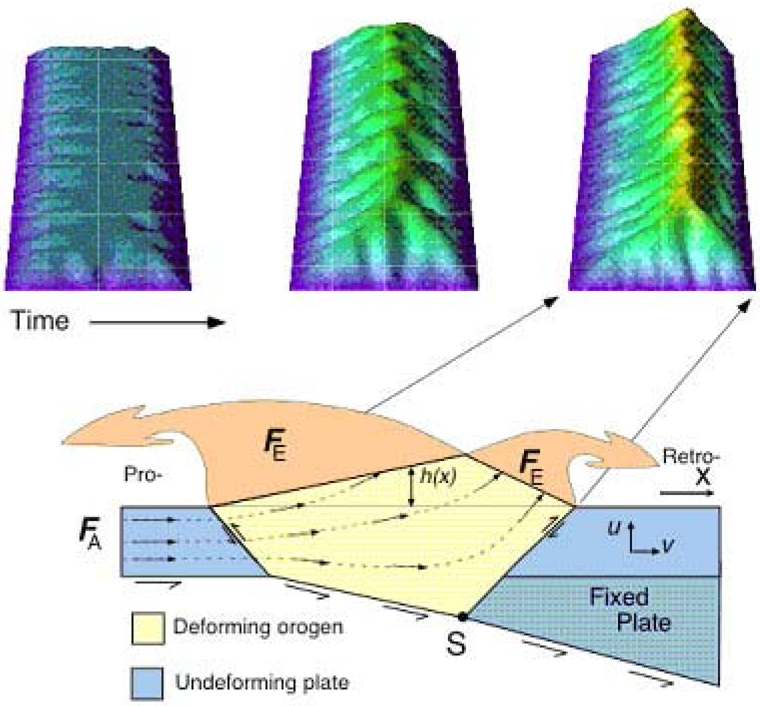
8) How do we determine the elevation history of a mountain belt?

In the following sections, we highlight some fields of research that present opportunity to directly address one or more of the questions above.

Coupled Surface Process and Tectonic Models

The quantitative study of large-scale landscape evolution has blossomed over the last decade, driven by the widespread inter-disciplinary interest in discovering the nature of potential global-scale interactions among climate, surface processes, and tectonics, and fueled by the advent of high-speed desktop computers and the availability of new data resources (digital topography, remote sensing imagery, new isotopic chronometers). The complexity inherent to dynamic systems with non-linear processes and multiple feedback mechanisms as described by Fig. 15 has led to extensive development of numerical models to couple tectonic, climatic and surface processes. Most research has been focused on surface processes, given our lack of understanding of the physics of geomorphic processes such as fluvial incision into bedrock, but as the confidence in surface process models increase, attention will shift towards tectonic and climatic processes. Tectonic models to date have been applied at an orogen scale (tens to hundreds of km) where sensitivity to specific geomorphic processes is less (Figure 16). Applications to individual structures (1 to 10 km in size) are increasingly common and will become more so as this scale provides the best possibility of constraining the kinematics of tectonic motions and the causative tectonic stresses.

Figure 16: Model for topographic evolution of a convergent orogen, driven by plate subduction and accretion (From Willett and Brandon, 2002). Accretionary flux, FA, and erosional flux, FE, determine material transport (dashed lines), with vertical and horizontal components u and v, respectively. Upper illustrations show topography predicted from a surface-process model driven by constant tectonic uplift and constant horizontal shortening rate. Surface process model includes uniform precipitation collected into a river network that incises proportional to stream power and diffusion of hillslopes.



Study of the Mechanics of Erosion

As noted above, the field of tectonic geomorphology has been in a productive phase of initial discovery and exploration; many important new insights have been derived from first-generation landscape evolution models erected on essentially "generic" process rule sets. Major advances in the study of long-term landscape evolution in the coming decade will depend on: (1) the development and testing of refined process laws that more fully capture the richness of fluvial and hillslope erosion, and (2) initial exploration of the different dynamics of glacial landscapes. For instance, work is underway to replace the stream-power erosion model (a widely used "generic" model for river incision) with more sophisticated treatments that incorporate the effects of sediment flux, threshold shear stresses, and a probabilistic representation of flood discharges and sediment influxes from hillslopes.

First-generation generic process models have enjoyed some measure of success, partly because of their generality. However, these models have so many parameters that competing theories often can not be discriminated on the basis of available data. Refined mechanical understanding of erosion processes through a combination of field and laboratory study will permit independent determination of physical processes and parameters, thereby reducing the number or range of parameter values. Numerical experiments with coupled landscape evolution models incorporating these new rule sets should guide data collection and model testing strategies.

A fuller representation of climate (e.g. representation of the stochastic distribution of floods via measurable climate variables) in landscape evolution models is a pre-requisite to a quantitative exploration of the linkages between climate and tectonics, including feedback loops such as the orographic enhancement of precipitation. Coupling with the vast range of climate and meso-scale meteorogical models is likely to lead to important new insights.

Studies of Fluvial Terrace Systems

Mapping deformation of fluvial and marine terraces has long been a tool for neotectonic studies, particularly those that aim to discover the rates and patterns of deformation and rock uplift associated with active faulting processes. In recent years this has become a useful tool for older systems as new cosmogenic dating methods have been applied to terrace straths and treads. Dating based on Be^{10} and $A1^{26}$ have pushed back the datable age of fluvial terraces from the 50ky limit of C^{14} to several hundred thousand years as well as permitting age control on terraces with no carbon-bearing material. This has increased the utility of terraces as tools for characterizing tectonic activity.

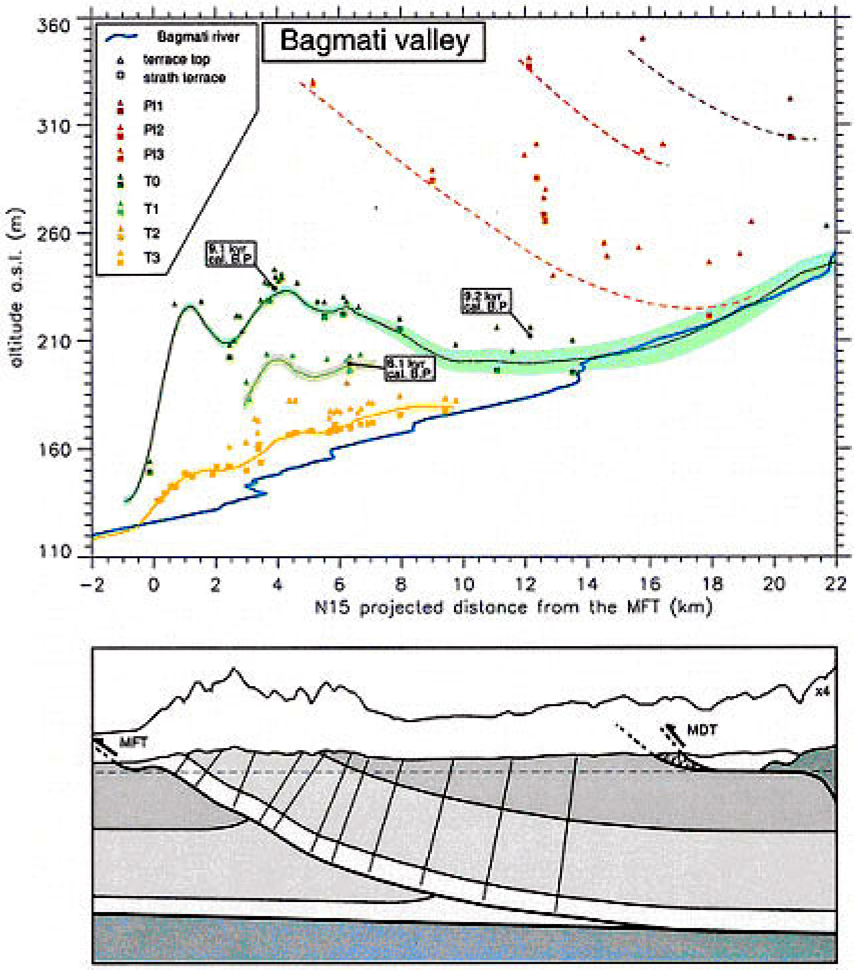


Figure 17: Elevation of strath terraces along the Bagmati River (From Lave and Avouac, 1999). The elevation of the strath levels computed from all DEM and field measurements are indicated by solid thin lines and dashed lines. Solid thick lines correspond to Holocene terraces, and dashed lines correspond to hypothetical levels between late Pleistocene terraces correlated by similar color and depth of weathering. The structural cross section, with the same horizontal scale is shown for

comparison. The terraces attest to sustained Holocene and late Pleistocene activity of the MFT fold. In contrast, they did not record significant offset across the MDT and suggest little deformation linked to this thrust.

The height of a dated terrace above the modern river channel provides a rate of incision or, with an assumption of steady channel elevation, provides a rock uplift rate. For example, Lave and Avouac mapped and dated Holocene and Pleistocene terraces (Fig. 17) across the Siwaliks along the Himalayan front, noting their relationship with mapped structures. They were able to infer and quantify motion on the Main Frontal Thrust of the Himalaya.

Terrace incision rates in space and time will provide important constraints on the structural style of deformation, geometry of sub-surface structures, and time-averaged deformation rates at multiple space and time scales. Such information can greatly aid studies of regional strain partitioning, the interaction and evolution of individual structures, and can provide a linkage between geologic and geodetic measures of deformation rates.

Low Temperature Thermochronometry and Cosmogenic Dating

New methods in low-temperature thermochronometry and cosmogenic dating are providing powerful new constraints on erosion rates, patterns and rates of exhumation and models of geomorphic evolution. The development of U-Th/He dating of apatite with its closure temperature of 70°C provides a new tool for assessing rock cooling in the near-surface environment where the thermal regime is dominated by erosion and motion towards the earth's surface. The low closure temperature of this system implies sensitivity, not only to erosion rate, but also to the form of the earth's surface, thus providing the potential for measuring topographic relief at the time of closure. For example, House et al. found variation in U-Th/He ages that correlated with existing topography in the Sierra Nevada (Fig. 18), implying that the present relief of the Sierras has existed since the late Mesozoic. U-Th/He dating of apatite also provides another constraint on cooling histories of rocks exhumed in orogenic belts, complementing fission-track dating of apatite and zircon and Ar^{40}/Ar^{39} dating of micas and feldspars, which have higher closure temperatures. U-Th/He dating of other minerals including zircon and sphene will further constrain cooling histories as the kinetics of these systems are confirmed.

Surface dating by cosmogenic isotope production provides a technique to investigate rates of processes such as fluvial incision by dating of straths or terrace fill at a timescale that has been historically problematic (ka to Ma). Another innovative technique that provides more complete spatial and temporal coverage in sampling for exhumation rate is based on analysis of the distribution of individual grain ages in a sample of modern or ancient sediment. Modern sediment provides a sample of an entire drainage basin and the grain exposure ages thus provide an integrated measure of the time spent in the cosmic ray exposure zone. This technique has also been applied using thermochronometric ages such as zircon fission track ages. This is particularly useful in estimating the history of exhumation rate by using well-dated stratigraphic sections.

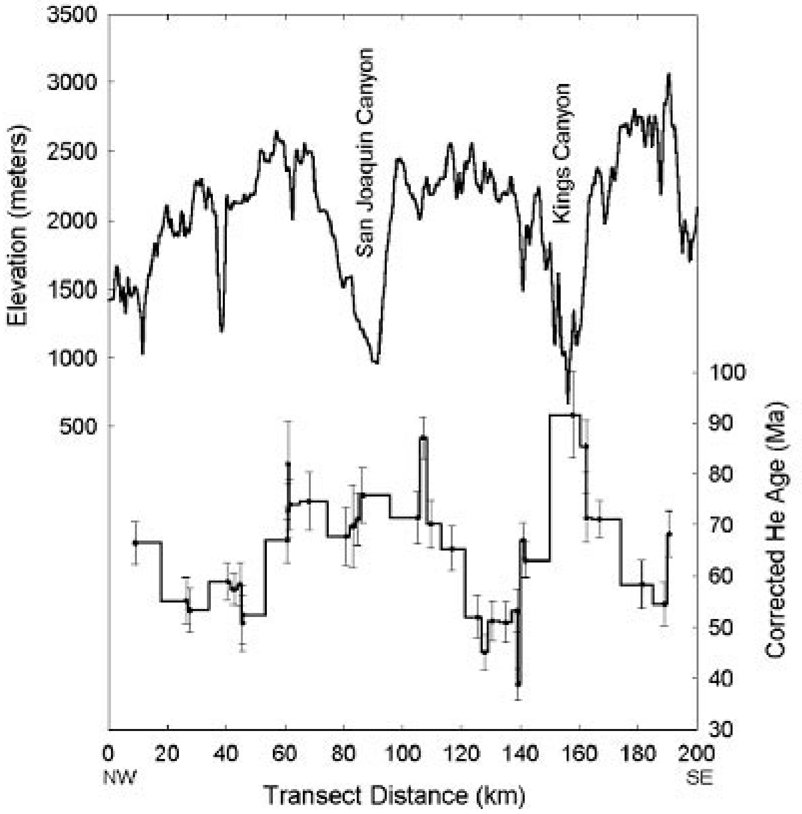


Figure 18: Apatite U-Th/He ages on an orogen-parallel, 2000 m elevation transect in the Sierra Nevada, compared with the modern elevation profile, after House et al. (1998). The correspondence between the location of deep and wide valleys and higher He ages suggests that He ages were influenced by perturbations in isotherms associated with paleocanyons located approximately where they are today, suggesting relief of ~ 3 km at ~ 75 Ma, i.e., the Sierra Nevada were a large mountain range by Late Cretaceous time.

Analysis of Digital Elevation Models

Where the distribution and nature of active structures are not well known, analysis of topography, using digital elevation models (DEMs), can provide important first-order information about the rates and spatial distribution of displacements. Even where structures are well known, knowledge of lateral variations in slip along faults is commonly sparse. Approaches to landform analysis include using abandoned geomorphic surfaces (river terraces, alluvial fans, moraines, etc) as passive strain markers and using river profiles as dynamic recorders of tectonic activity. As described in the section on studies of fluvial terraces, the topography of offset geomorphic surfaces can often be used to define displacement gradients with high precision. These studies traditionally require time-consuming field surveys of landform morphology. However, in the coming decade, high-resolution digital topographic data, such as that attainable with airborne laser swath mapping (ALSM), will provide an invaluable, and highly efficient, tool for quantifying these deformational patterns with high precision.

A less common, but promising, approach is to attempt to extract quantitative information about deformational patterns in space and time from analysis of landforms as a dynamic recorder of tectonic activity. Hillslope gradients record information about the nature of active transport processes and the rate of erosion. However, once erosion rates exceed the rate of soil production, hillslope gradients reach a maximum set by the landsliding stability threshold and no longer record information about the erosion rate. Accordingly, analyses of river profiles are often most promising. Recent examples ranging from continental scale (Fig. 19) to the scale of a single anticline have demonstrated the potential of this approach, although quantitative estimates of erosion rate await refinement and testing of river incision models. With progress in the quantification of erosional processes, DEM analyses of dynamic landforms will allow a rapid, inexpensive assessment of active deformational patterns at an unprecedented and unmatched spatial resolution. Digital analysis also provides opportunity to tap the rich resource of surface and remotely-sensed climate data important to surficial processes (Fig. 19).

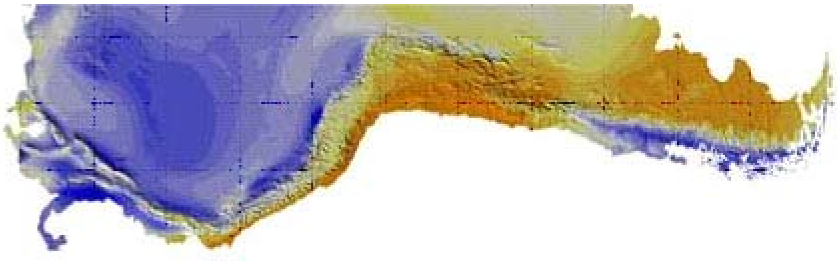


Figure 19: Shaded relief and precipitation (color scale) of the Andes. Topography is from the global 30 s GTOPO30 digital elevation model. Precipitation is from Hoffman (1975). Orography and global climate zonation are clearly visible with wet (blue) and dry (brown) zones reversing east-west polarity from north to south. Figure from Montgomery et al. (2001)

Sedimentary Basin Architecture and Facies

Just as topography contains the record of tectonic activity in a mountain belt, sedimentary basins contain the record of orogenic denudation. As the precision of estimates of exhumation, cooling and erosion increase, comparison with the sedimentary record will become increasingly important. In addition, the structure of sedimentary basins is itself a measure of the accommodation space created by tectonic processes and vertical loading. Innovative methods of relating sediment to its source have been and will continue to be critical tools in the evaluation of coupled tectonic and surface processes. Isotopic and thermochronometric fingerprinting to establish provenance is one example of a powerful technique. More sophisticated techniques for deriving additional source information from foreland basin sediments include the calculation of basin-wide denudation rates as described above.

Sediments also provide one of the few direct measures of paleo-climate. Traditional means of interpreting facies and depositional environment are now supplemented by isotopic analyses of stable isotopes such as carbon to determine plant metabolic pathways and oxygen to determine paleo-temperature and, more recently, paleo-altitude through fractionation of precipitation.

Remote Sensing / Neotectonics

The quantitative characterization of active structures depends primarily on high-precision images of the earth, especially topographic data with cm- to m-scale vertical resolution. Despite a long history of investigation, a significant fraction of active structures within active tectonic zones have not yet been identified or precisely located. Even for those structures that have been identified, little systematic effort has been invested in quantitative analysis of offset features (e.g., fan surfaces, river terraces) in order to deduce slip rates. The advent of multispectral airborne and spaceborne cameras have made available a number of image types, such as Landsat, SPOT, and ASTER that cover large areas at relatively fine horizontal resolution (10 m to 30 m horizontal posting) and that have been extremely useful in identifying active structures. In addition, Light Detection and Ranging (LIDAR) techniques, also known as Airborne Laser Swath Mapping (ALSM), have recently become commercially available.

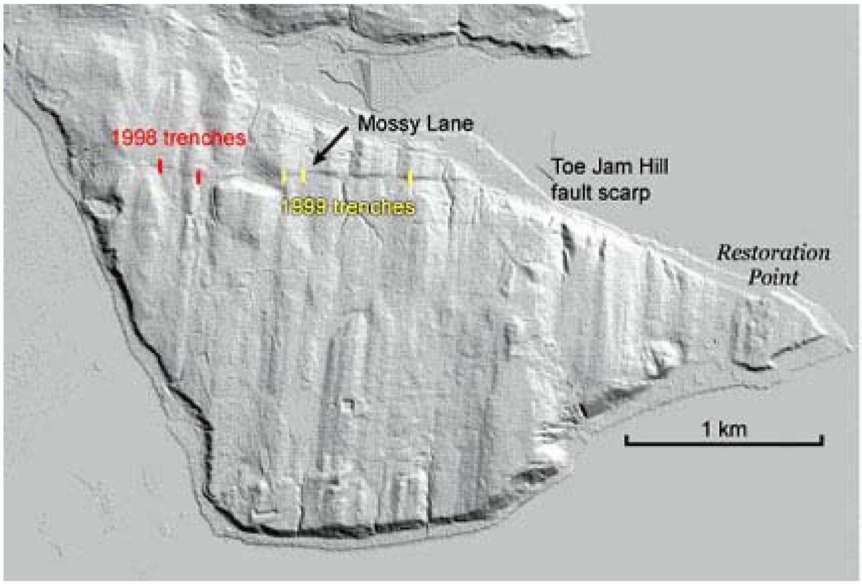


Figure 20. LIDAR image of SE Bainbridge island, near Seattle, showing the Toe Jam Hill scarp of the Seattle fault. Fault was trenched by the USGS in 1998 and 1999.

LIDAR/ALSM is the first practical system for producing high-resolution images of the earthÃs surface in areas covered by a thick canopy of vegetation. Because the relief created by the latest movements on active structures is only a small fraction of the thickness of a forest canopy (of order meters versus tens of meters, respectively), it can be very difficult to detect by conventional methods. For example, the Seattle fault in the Puget Sound lowlands, is difficult to detect in the field and completely obscured in aerial photography. However, LIDAR imagery clearly reveals this structure (Figure 20), indicating its recent activity and current threat to the Puget Sound population centers. In addition to this capability, LIDAR/ALSM may also be used to produce high-resolution

(25 cm) digital topographic data, which are essential for quantitative analysis of active structures.

Co-evolution of Earth and Life

David Evans (Coordinator)
George Gehrels
Karl Karlstrom
Brian Wernicke

Introduction

This section summarizes the need for the Earth Sciences community, and tectonicists in particular, to study the evolution of Earth in 'deep time.' As presently understood, geological processes of billion-year antiquity appear at once rather similar to those observed today (the principle of uniformitarianism) and also divulge some important secular changes in planetary (and biological) evolution. The study of Earth's multi-billion-year geological record allows us to assess these factors with numerous 'natural laboratories' of ancient processes. About 85% of Earth history passed prior to the Cambrian appearance of skeletal animals, whose rich fossil record in the succeeding 550 million years has permitted precise timekeeping of natural events. Without such a complete fossil record, Earth scientists who delve into the Precambrian eras must rely on diverse datasets for even a basic understanding of stratigraphic correlations, let alone complex and interwoven Earth-system processes. Reconstruction of Archean (older than 2.5 billion years, still nearly half of Earth history) surface environments, home to the earliest forms of life on this planet, is especially difficult due to a limited number of well preserved sedimentary successions of that age.

Processes operating on the longest temporal scales can be related to those associated with the largest spatial scales, and some of the broadest scales of scientific thought. For example, one of the grandest tectonic problems on Earth concerns the episodic assembly and fragmentation of supercontinents. The supercontinent of Pangea, which was assembled about 300 million years ago, during a time of spectacular diversification of animal and plant life, is now well accepted and its shape and evolution are increasingly well understood. However, it is instructive to realize that the acceptance that the Pangean supercontinent existed was directly linked to the acceptance of the Plate Tectonic paradigm. This paradigm, that lithospheric plates move at rates of cm per year and that tectonic processes are concentrated at plate margins, developed in the late 1960s and became accepted in the 1970s, and may mark science's most important advance in understanding our dynamic planet.

As Earth science matures, tectonicists are poised to help usher in new paradigms for understanding continents in deep time. This will require forging an international understanding of pre-Pangean supercontinents and the supercontinent cycle[2] and will lead to newly realized connections between Earth processes and their affects on life that will be vitally important for humans. Problems of continental evolution bring together and unify diverse issues such as mantle dynamics, economic geology, paleoclimate, and surface geochemical cycles; and they also provide important paleogeographic constraints on significant events in biological evolution. Methods of solving these ancient continental puzzles involve diverse tools: field observations at the outcrop scale and laboratory analyses at the microscopic scale. Tectonics, the study of the achitecture, evolution, and dynamics of the lithosphere, is well suited to address questions of early Earth history, for it is a discipline that uses every tool available to understand the geological record, over the broadest ranges of spatial and temporal scales. Tectonicists, trained to assimilate diverse data sets and integrate diverse analytical methods, will play a key role in continued efforts to study the co-evolution of our planet and its life.

Research Questions and Opportunities

There are numerous areas for promising research on Earth systems in deep time, where tectonicists will make important contributions as integrators of diverse data sets. Several examples are:

1) Mass extinctions and biologial radiations.

2) Evolution of the carbon-cycle.

3) Tectonic and climatic influences on Phanerozoic diversification of life.

4) Lithosphere-asthenosphere interactions and understanding the difference between continental and oceanic tectonics.

5) Core dynamics and influences on mantle plumes or the geomagnetic field.

6) Changes in thermal evolution through time and possible difference between Archean Proterozoic, and Phanerozoic tectonic processes.

7) Evolution of the atmosphere and hydrosphere in the context of shifting plate configurations.

The Neoproterozoic Era (1000 - 543 Ma) is one example of the way that any of these major issues has potential to blossom onto new paradigms. The Neoproterozoic was different than any time before or since. It encompassed: (a) Final assembly of Rodinia and its subsequent breakup, and rearrangement of fragments to form Gondwanaland. (b) Extremely rapid continental motions (as speedy as 30 cm/yr or faster) attributed either to favorable combinations of plate-driving forces or true polar wander; (c) Low-latitude glacial deposits and cap carbonates perhaps indicative of several ~10-Myr "Snowball Earth" events followed by extreme greenhouse conditions; (d) A bolide impact leaving a crater (at Lake Acraman in South Australia) over half the diameter of the K-T impact scar at Chicxulub; and amid this tumult; (e) Evolution and rapid diversification of of fungi, plants, and animals whose genetic diversity already existed, but which had not been able to express this diversity in terms of different species and different life niches. The 1990s was a decade of initial discovery and great speculation on many of these features in the Neoproterozoic record. Students of the Neoproterozoic world now stand poised to make great strides toward their understanding through theoretical development of the proposed models, and detailed hypothesis-testing in the field and laboratory. The following paragraphs illustrate several examples of how tectonics may contribute to solving important enigmas of the Neoproterozoic interval.

Rodinia

Since the initial conception of a late Precambrian supercontinent in the early 1970s, serious consideration of Rodinia's paleogeography began only about ten years ago. The last decade has witnessed many refinements of RodiniaÃs configuration, and some refutations of long-held tectonic assumptions. Reconstructing Rodinia, and any other supercontinent from the pre-Pangean era which lacks the high precision afforded by seafloor magnetic anomalies, involves two fundamental datasets: comparisons of ancient tectonostratigraphic links among presently fragmented continental terrains, and paleomagnetic reconstructions in a fixed external reference frame. The former dataset is generated by detailed field mapping, stratigraphic reconstruction, structural analysis, and high-precision geochronology, and will increasingly rely on projects of international cooperation and integration. The latter dataset also requires excellent field geology combined with precise geochronology and improving paleomagnetic techniques.

Modern conceptions of Rodinia were born of qualitative tectonostratigraphic comparisons between western North America (at the margin of the Proterozoic craton Laurentia) and Australia-East Antarctica, combined with a very sparse paleomagnetic data set. The SWEAT reconstruction initially found some paleomagnetic support, although it was recognized that reliable data were few in number. Alternative reconstructions have since arisen, emphasizing different qualitative aspects of Laurentian geology as compared with the Trans-Antarctic Mountains, central Australia, South China, and Siberia. Recent high-quality paleomagnetic results from Western Australia continue to confound the 'classic' reconstructions of Laurentia with Australia and East Antarctica, leaving substantial freedom for new models. Our present understanding of Rodinian paleogeography is the subject of healthy and vigorous debate at nearly every geological and geophysical meeting (Fig. 21).

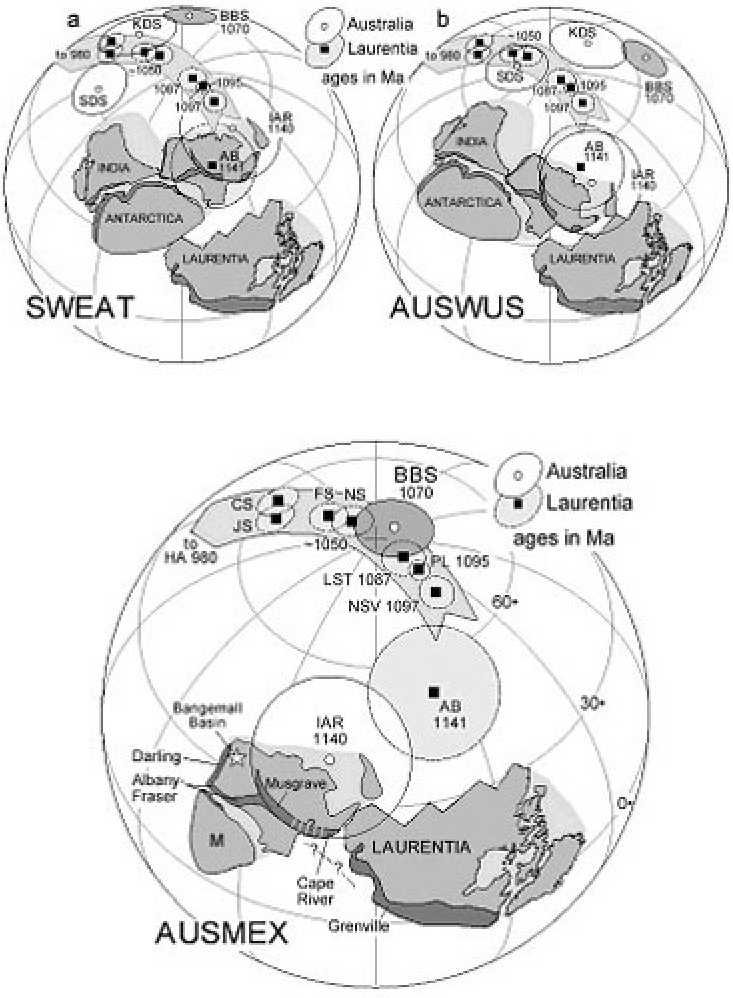


Figure 21. SWEAT, AUSWUS, AUSMEX, or other? Increasing tectonostratigraphic, geochronological, and paleomagnetic data acquired over the next ten years are expected to produce a lasting, first-order picture of Rodinian paleogeography. [After Wingate et al., 2002, Terra Nova, v.14, p.121-128.]

The Rodinian controversies have persisted primarily due to a lack of high-precision geochronological and high-quality paleomagnetic data among Neoproterozoic and older rocks. During the past decade of intense scrutiny, many precise U-Pb ages from these rocks have been obtained, yet many more successions remain essentially undated. The last decade of Rodinia hypothesis-testing has gained only a handful of reliable paleomagnetic poles. Better dating of Neoproterozoic rocks, in the context of detailed field and other supporting studies has provided and will continue to generate many new opportunities for quantitative paleomagnetic constraints on Rodinia's paleogeography. In the next decade, the international tectonics community is likely to produce a lasting first-order map and animated reconstruction of the evolution of Rodinia.

Rapid Continental Motions

Velocities of between-plate motions presently attain 18 cm/yr, and although continent-bearing plates tend to have slower speeds, India nearly achieved that rate during its northward flight toward Asia in the early Cenozoic. In contrast, rapid motions of large continents relative to the paleomagnetic reference frame appear commonplace in Paleozoic and late Precambrian times (Fig. 22). Does this indicate constructive combinations of plate-driving forces at those times, superimposed on a greater velocity of mantle convection corresponding with generally higher geothermal heat fluxes in the earlier parts of Earth history? Alternatively, a greater proportion of true polar wander, as a component of all continental motions, has been proposed to explain the measured velocities. If true polar wander was more prevalent in the past, why has it been of minimal magnitude during Mesozoic-Cenozoic times yet presently responding to deglaciation at rates of ~10cm/yr? Rapid continental motions, regardless of mechanism, set the stage for increased marine biological speciation through abrupt changes in oceanic circulation as well as regional changes in flooding of continental shelves, creating and eliminating paleogeographic barriers. Better resolution of the Neoproterozoic paleomagnetic record in the next decade could determine whether the presently inferred rapid continental motions are real, and what geodynamic processes they represent.

Figure 22. The gently folded sedimentary succession contained within this photograph, of the Flinders Ranges in South Australia, span two ~45° rotations of the Australian continent (and any formerly contiguous neighbors) in latest Precambrian time. Well preserved Neoproterozoic sedimentary-volcanic successions such as this are found throughout the world, with rapidly increasing precision on numerical age constraints. Detailed studies of these successions during the next decade will help answer many of today's enigmas of the Neoproterozoic world. [Photo: David Evans]

Low-latitude Glaciations

The essence of the Neoproterozoic climatic paradox is the widespread abundance of glacial deposits intimately associated with warm-climate indicators such as marine carbonates. Unusual isotopic signatures, including shifts in ^{13}C as great as 15%, characterize those carbonate successions, and paleomagnetic results from several glacial deposits and bounding units indicate near-equatorial depositional latitudes. Much recent attention and controversy has surrounded the Snowball Earth hypothesis, a suggestion that the planet's oceans may have iced over completely for as long as 10 Myr, as many as five times in the Neoproterozoic Era. Appearance of the enigmatic Ediacaran megascopic fauna and earliest evidence of animal embryos follow soon in the geological record after the last of these glaciations, and it has been proposed that enduring global ice cover could have caused evolutionary 'bottlenecks' that cleared the way for biological advent of multicellularity (Fig. 23). The Snowball Earth hypothesis, and any competing models for explaining Neoproterozoic low-latitude glaciations, will be tested through detailed field mapping (including stratigraphy and structural analysis) and multidisciplinary combinations of laboratory techniques (including isotopic and paleomagnetic studies) and forward modeling. The problem is inherently broad in scope, and tectonic studies will play an important part in defining spatial and temporal boundary conditions at the regional at local, regional, and global scales.

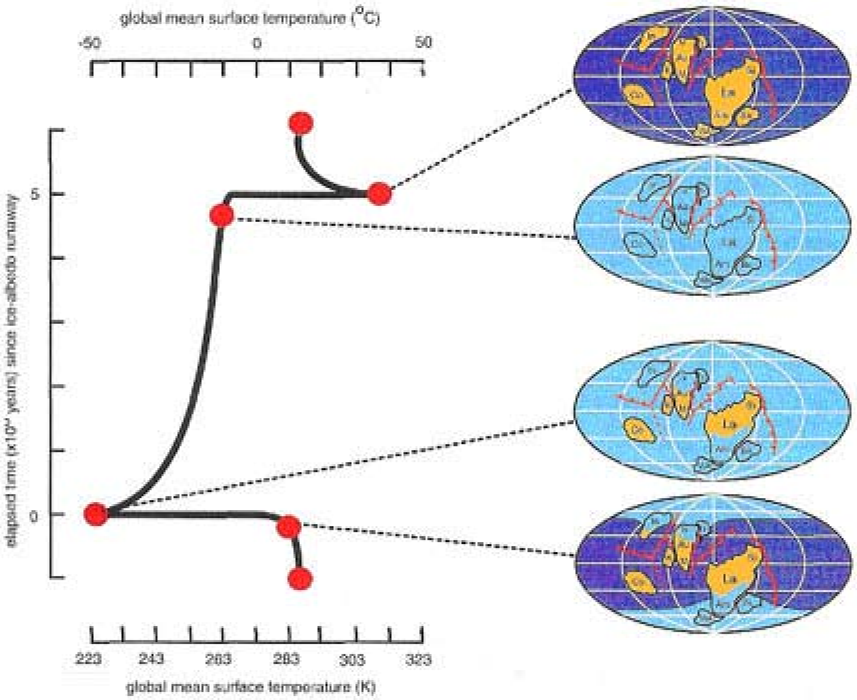


Figure 23. Could 'freeze-fry' extreme and sudden shifts in paleoclimate have paved the way for the evolution and rapid diversification of animals? The Snowball Earth hypothesis invokes global sea ice cover for as long as 5-10 million years, occurring as many as five times in Neoproterozoic history. [From Hoffman and Schrag, 2002, Terra Nova, v.14, p.129-155.]

Questions for the Next Decade

The Neoproterozoic Era serves as a telling example of how multidisciplinary approaches, with tectonics playing a central role, will constrain important events in the long-term history of Earth and life. Substantial advances in our understanding of the Neoproterozoic world during the last decade have thus far produced many provocative hypotheses, which can be seriously addressed during the next ten years. As a guideline toward approaching these issues from the standpoint of tectonics, we focus on the following questions:

1) As a first-order constraint on global climate and evolution, what were the positions of oceans, continents, and major mountain ranges in Deep Time?

2) What are the correlations between extreme tectonic, climatic, and extraterrestrial events and the rapid development of animal life?

3) Were there one or more "Snowball Earth" events in Neoproterozoic time and did the assembly and dispersal of supercontinents play a role in generating those events? Did Snowball events also occur in the Paleoproterozoic Era, and do extreme climatic shifts signify a fundamentally different climatic regime on early Earth?

4) Have rapid Neoproterozoic continental motions and/or true-polar-wandering profoundly affected surface processes? Can detailed paleomagnetic studies address these issues as well as elucidate the long-term behavior of the geomagnetic field?

5) Do the extreme rates and magnitudes of changes possibly recorded in these 'natural laboratories' place limits on the severity of potential global climate change on a human timescale?

Tectonics can contribute directly to answering these questions through:

a) identification and characterization of key stratigraphic successions through field mapping, stratigraphy, and structural analysis; in support of concomitant advances in paleontology, biogeochemistry, and molecular biology;

b) determining the ages and durations of these successions through high-precision geochronology, in order to develop a global temporal reference frame for key tectonic, climatic, and biotic events; and

c) reconstructing continental configurations using quantitative paleomagnetic tests of key tectonic piercing points defined by tectonic syntheses.

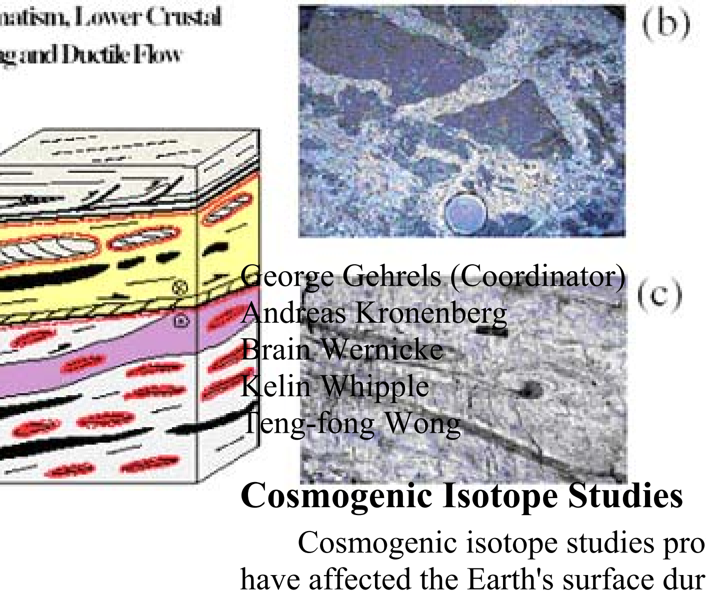
We have emphasized the opportunities offered by integrated tectonic studies of the Neoproterozoic as an example of the key role tectonic studies can play in Earth sciences. As was true for the creation and testing of the plate tectonics paradigm, the tectonics community continues to offer integration of diverse data sets, over the broadest ranges of temporal and spatial scales, toward new paradigms that will span the physical sciences.

New Technological Opportunities

A number of technological or methodological innovations in recent years have created opportunities for significant advances in understanding Neoproterozoic events, with ready application toward older and younger times in the evolution of planet Earth. Recent advances in high-resolution geochronology, including better control of procedural Pb blanks in standard TIMS analysis as well as more routine application of the SHRIMP and Laser-ablation ICP-MS techniques, have been applied to a growing suite of dateable minerals. These include the possibility of dating sedimentary rocks through early diagenetic xenotime overgrowths on detrital zircons and authigenic (diagenetic) monazite. Greater sensitivities afforded by state-of-the-art mass spectrometers extend the study of isotopes to individual phases rather than whole-rock analyses.

New methods of measuring mass-independent isotopic fractionation are providing insights into Precambrian geochemical cycles, and in-situ analyses of stable isotopes point to new dimensions of investigation in the same way that in-situ dating has helped to revolutionize geochronology. Standards of paleomagnetic reliability have increased due to the recognition of widespread partial overprinting, combated by detailed field stability tests on the ages of magnetization. Just as recent geochemical approaches have recognized microscopic heterogeneities in rocks or even single crystals, the newly developed SQuID (magnetometer) Microscope is leading traditional paleomagnetic directional studies toward ever smaller spatial scales.

Facilities



George Gehrels (Coordinator)
Andreas Kronenberg
Brain Wernicke
Kelin Whipple
Teng-fong Wong

Cosmogenic Isotope Studies

Cosmogenic isotope studies provide important constraints on tectonic processes that have affected the Earth's surface during the past several hundred thousand years, a time range that has previously been difficult to study. Dating of geomorphic surfaces has traditionally been accomplished via carbon-14 dating, which requires scarce carbonaceous materials, and is limited to features under about 50,000 years old. Although Ar-Ar dating may be effective down to this age range, it too suffers from difficulty in finding datable materials, such as volcanic ashes, associated with any given surface. Cosmogenic dating can be applied to most common rocks types, is accurate for features ranging in age from a few thousand to a few hundred thousand years, and these methods open up a broad new frontier of investigation of geologic processes at these time scales. Given the impact of earthquakes, volcanic eruptions, and landslides on society, there is an urgent need to increase our understanding of the rates and magnitudes of these processes and their tectonic framework. It is therefore critical that funds are available to develop this technology as rapidly as possible.

At present, most cosmogenic isotope analyses are conducted with accelerator mass spectrometer (AMS) facilities at Purdue University, Lawrence Livermore National Labs, and the University of Arizona. These facilities are able to meet the current demand for analyses, but future demands for higher sample through-put, better precision, and smaller sample size will require both improvements in facilties and a larger number of highly skilled researchers. In particular, sample preparation, which involves routine wet chemical methods and can be done at a separate facility from the actual AMS analyses, is currently a major bottleneck in investigations involving cosmogenic dating. A facility dedicated to both sample preparation and the analysis of ^{26}A1, ^{10}Be and ^{36}C1 would be a tremendous asset for studies of the age of surficial features and for determinations of paleo-elevation. In addition to support for large research centers, there is also a need for refinement of the production rates of cosmogenic nuclides, and for the development and application of new isotope systems.

Geochronology and Thermochronology

Geochronology and thermochronology provide critical constraints on the ages of geological events and on the rates of geological processes. This information is central to many aspects of tectonic analysis, and will become even more so with future attempts to quantify how our planet has evolved through geologic time and how tectonic processes affect life on Earth. It is therefore vital to maintain strong support for the application of existing geochronologic and thermochronologic techniques, and for the development of new chronometers. Figure 24 shows the array of thermochronometers that are in current use, and the approximate temperature range below (or within) which each chronometer begins to record the passage of time.

At present, most geochronologic and thermochronologic information is generated by individual researchers (and their staff) using facilities at academic institutions. Most of these researchers and facilities are supported primarily by EAR at NSF. Development of a national geochronology/thermochronology center may be an effective means of making this essential information more available to tectonics researchers, and of driving the development of new geo- and thermochronometers.

Studies of Rock Deformation

The fundamental understanding of dynamic processes as diverse as the earthquake cycle, fluid transport through the crust, and sedimentary basin development hinges upon critical input from laboratory measurements. Determination of the mechanical and transport properties of rocks is a necessary first step in understanding the tectonic processes and structures at all scales in the Earth. To understand the spatio-temporal complexity of seismicity, it is necessary to investigate the frictional behavior at sliding rates ranging from quasi-static to seismic and to relatively large slip. To elucidate the complex interplay of metamorphic reactions, fluid transport, and mechanical deformation, it is necessary to investigate the rheology and failure mode to relatively large strain under controlled conditions of nonhydrostatic loading, fluid drainage and reaction kinetics. Furthermore it is important to systematically characterize the microstructure of naturally deformed samples, down to TEM-scale, in order to correlate the micromechanical processes before one has confidence in extrapolating the laboratory data to relevant spatial and temporal scales.

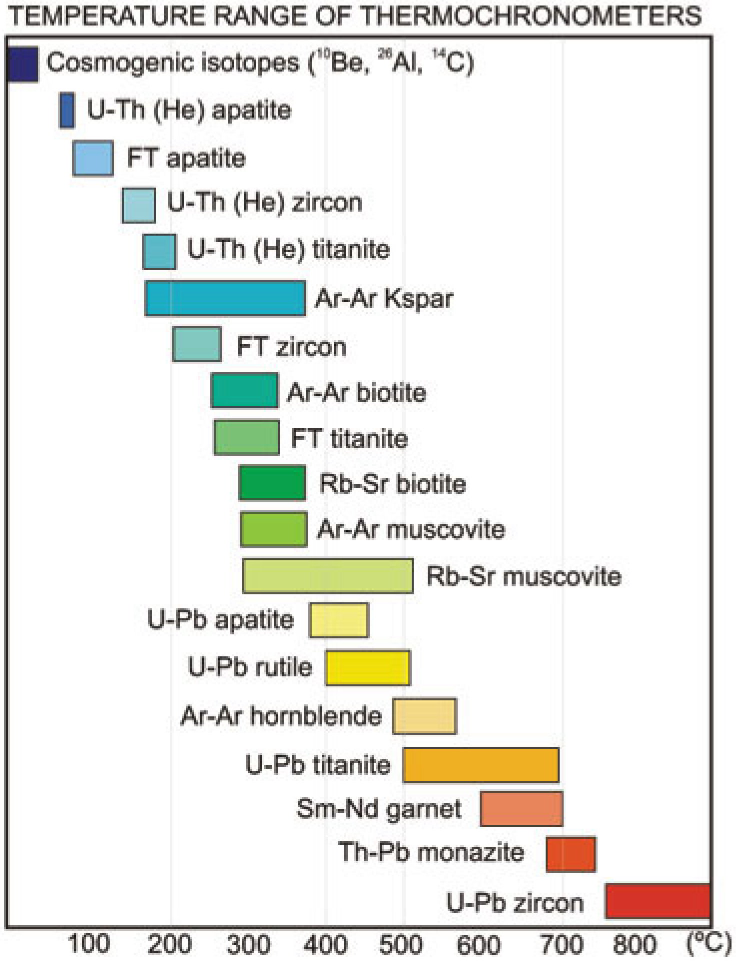


Figure 24. Thermochronometers that are in current use, and their effective closure temperatures (adapted from P. Fitzgerald, S. Baldwin, G. Gehrels, P. Reiners, and M. Ducea).

These questions pose significant technical challenges that necessitate the development of new experimental and analytical facilities. In the past decade significant advances have been made in the use of the gas apparatus for determination of rheology and hydromechanical properties with the advent of the Paterson rig. While there are currently two such rigs in the U.S., eight others are located in Europe, as a result of superior funding and prioritization of this research. With the establishment and growth of rock deformation laboratories and analytic facilities such as new scanning electron microscopes capable of measuring fabrics by EBSD, European countries have taken the lead in studies of crustal and mantle rheology.

Several laboratories in this country have the shear and triaxial compression rigs capable of studying frictional instability and failure mode of crustal rocks. However, there has only been one new rig established in a US academic institution in the past decade, while five new machines have been developed for such endeavors in Tokyo, Kyoto and Tsukuba. There is an urgent need to implement the infrastructure that would nurture the necessary technological advances, provide the wider availability of existing experimental and analytical facilities, and encourage synergistic collaborations among researchers in rock mechanics, field geology, numerical simulation and materials science.

Geodetic Studies

There have been dramatic improvements in our ability to measure the position and relative movement of different regions of the earth's surface. The Global Positioning System (GPS) permits us to determine the location of any point on the earth's surface to within a millimeter or so. As a result, we can measure the relative velocity of any two points on the earth's surface to within a fraction of a millimeter per year, after just 2-3 years of monitoring. Similarly, interferometric synthetic aperture radar (InSAR) allows us to create maps showing the movement of broad areas of the surface over time (surface velocity fields). Combined, these two methods will soon yield seamless, high spatial- and temporal-resolution maps of surface movement across entire plate boundary systems. Because of the power of these techniques to measure short-term tectonic motion, it is important that structural geology and tectonics researchers participate in the design of future experiments to gather and interpret this type of information.

Satellite-based geodesy is one area in which establishment of one or more dedicated research centers in the U.S. would be more effective than individual or small-group research programs. At present, the Earthscope initiative is laying plans for dense geodetic coverage of the western part of the United States. However, a solid geodetic infrastructure, through continued support of the University Navstar Consortium (UNAVCO), will be necessary for projects involving active deformation outside of the western US. This infrastructure should include GPS instrumentation available for campaign-style geodetic surveys, expertise in the development of continuous GPS monitoring, and a readily accessible community database of InSAR imagery that may be processed and analyzed by small teams of investigators.

Educational Departures in Structural Geology and Tectonics

David Pollard (Coordinator)
Rebecca J. Dorsey
James P. Evans
Raymond C. Fletcher
Laurel B. Goodwin
Jane Selverstone

Introduction

Within the context of developments in the fields of structural geology and tectonics (SG&T), we recognize a number of challenges and opportunities in geoscience education that range from K-12 and public outreach through undergraduate and graduate education. While it is beyond the scope of this document to address all of these issues, we have identified some unifying themes that were raised at the workshop and in subsequent discussions, which are summarized below.

Educational priorities in SG&T parallel those of the broader Earth Science community, as articulated in a rich literature of ongoing publications, web sites and workshops. Fundamental scientific literacy, rigorous scientific methodology, and the development of quantitative skills at all levels, from K-12 through undergraduate and graduate education, underlie these priorities. Many scholars have discussed the need for integrating quantitative methods into geoscience classes, interactive exercises, involvement of students in research, and computer visualization tools as viable strategies for increasing the effectiveness of earth science education. Geoscience education based on such a foundation will play an important role in preparing the next generation of researchers, teachers, and citizens for future challenges. Here we focus on a few priorities that are especially relevant for SG&T education.

Research in structural geology and tectonics is becoming increasingly quantitative while retaining its orientation as a field-based, observationally motivated science. The integration, for example, of structural, petrologic, geochemical, stratigraphic, geomorphologic and geochronologic studies permits us to produce conceptual models that can be used as a foundation for analytical and numerical models that test hypotheses generated in the field. This process-based approach has already started to yield exciting new results (for example, the use of low-temperature thermochronology in constraining rates and processes of crustal exhumation in orogenic belts), and will continue to provide significant insights into Earth's deformation and driving forces in the coming decades.

To support movement toward this goal, we encourage education at all levels that will unite structural geology, tectonics, petrology, geochemistry, geochronology, geophysics, and other related disciplines in a broad-based field of inquiry that is motivated by fundamental questions about processes of Earth deformation. This objective can be supported with workshops, short courses, and symposia, and through development of course curricula in the classroom, laboratory, and field settings. Our suggestions for addressing these educational needs are presented in three areas: (1) interdisciplinary, (2) undergraduate, and (3) graduate education.

Interdisciplinary Education

We anticipate that the next generation of students will have unprecedented opportunities and needs to work across disciplinary boundaries. Indeed, many of the research targets that we have identified elsewhere in this document will require input from, and interaction with, geoscientists in the fields of hydrology, petrology, low- and high-temperature geochemistry, stratigraphy, geodesy, seismology, and geomorphology, as well as with experts from other sciences. Many of the research targets also admit input from the engineering disciplines including civil and mechanical engineering, chemical engineering, computer science and materials science. We thus need to ensure that students are given the tools to facilitate this cross-disciplinary research. The necessary tools include: (1) an emphasis in all geoscience courses on cross-disciplinary communication skills, and (2) appropriate course content from both the earth sciences and from allied disciplines (math, physics, chemistry, and biology). In light of this need, we make the following recommendations:

- Not everyone can be an expert in all topics, and thus collaborative efforts will continue to be essential to move our science forward. We recommend placing increased emphasis on collaborative projects, papers, proposals, and presentations in many geoscience courses, at both the undergraduate and graduate levels. Although such work can be difficult to initiate and evaluate, it helps to develop the skills necessary for successful communication with colleagues.
- We encourage college and university earth science departments to be creative and flexible in defining programs of study. Tuition and credit should be given for course work in mathematics, physics and chemistry, as well as related engineering disciplines. We recognize that this may require changes at departmental and higher levels, particularly at state universities, but feel that it is essential for adequate training of the next generation of structural geology and tectonics students.

Undergraduate Education

Here we emphasize the need for improved quantitative skills in mathematics and statistics, information technology, physics, and chemistry in undergraduate curricula. All geoscience students entering graduate school require a strong background in ancillary sciences, mathematics and statistics. Anecdotal evidence suggests that our students' ability to use this background effectively is directly correlated with the degree to which we successfully integrate quantitative methods into geoscience classes. It is also important, however, to teach quantitative skills at an accessible level to non-major undergraduate students, as this contributes to an educated public that can interpret graphs and plots and evaluate the results of scientific research that bear on public policy.

In addition to the above priorities, we must also keep in mind that what sets us apart from some other disciplines is our ability to make observations about the natural world and interpret these observations through critical analysis. It is important that undergraduate students learn to think critically and solve problems in situations that simulate the challenges of field work. For this, we encourage teaching of undergraduate geoscience courses that require students to:

- record and interpret primary observations, and collect original data in the field or lab;
- learn how to handle data (i.e. analysis, interpretation, hypothesis testing, etc.);
- work with complex problems that require integration of different methods and tools;
- predict outcomes and understand dynamic relationships of complex systems; and
- manipulate and interpret statistical uncertainties in data and model calculations.

This approach goes beyond the call for a strengthening of curricula with more mathematics, physics, and chemistry, and stretches into nontraditional settings (field and lab) where students learn to think and engage in science through their own experience of inquiry, hypothesis-testing, analysis, and interpretation. The increasing complexities and uncertainties of a highly technological world require us to synthesize complex and sometimes contradictory information, and compile it into a coherent understanding of dynamic systems. Critical-thinking and problem-solving skills gained in this way will benefit students whether they go on to graduate school, law school, business, teaching, or public policy, and will therefore benefit society as a whole.

A few examples of related earth-science web resources and recent workshops include:

Digital Library for Earth System Education (http://dlesecommunity.carleton.edu/)

Science Education Resource Center (http://serc.carleton.edu)

NAGT 'On the Cutting Edge' professional development workshop series

Building Quantitative Skills of Students in Geoscience Courses (NAGT, 2000)

Graduate Education

As is evident from the research areas highlighted in this document, there are many paths through which we might train students in more quantitative approaches to structural and tectonic problems. The exact path chosen by a given researcher will depend on the hypotheses to be tested and both individual and institutional goals and resources. Beyond advanced courses in structural geology, tectonics and related geological and geophysical subjects, graduate training might therefore include (but need not be exclusive to) one or more of the following: differential equations and linear algebra, thermodynamics, continuum mechanics, hydrogeology, inverse theory, numerical methods, and/or spatial statistical analysis.

Because it is beyond the scope of this document to address all of the opportunities available to teachers at the graduate level, we identify particular examples of two of the themes introduced above. For the development of quantitative skills we point to the role of differential geometry in characterizing geological structures. We cite continuum mechanics as an example of the fundamental scientific literacy necessary for mechanical modeling in structural geology and tectonics. Finally, the adoption of a rigorous scientific methodology is illustrated with a flow chart applicable to quantitative investigations. It is recommended that graduate-level curricula in structural geology and tectonics include lectures and practical exercises that demonstrate the utility of mathematical concepts (such as differential geometry), and utilize the solutions of relevant problems from related disciplines (such as continuum mechanics) for the analysis of tectonic processes.

Characterization of Geological Structures using Differential Geometry

Geological structures are locally classified as ‘linear’ (e.g. slickenlines, rib marks, metamorphic lineations, and surface intersections) or ‘planar’ (e.g. sedimentary bedding, faults, fractures, metamorphic foliations, and unconformities), but these structures are inherently three-dimensional: they are, in fact, curves and curved surfaces. As such, differential geometry is the appropriate tool for their quantitative description. Differential geometry includes the analytical study of points, curves, and surfaces in three-dimensional space using vectors and the methods of calculus. The elementary concepts of differential geometry enable one to describe the departure of geological lineations from a straight line and the departures of geological surfaces from a plane.

Data on the local orientation of structures are gathered at scattered outcrops as point measurements and the locations of these points are geographic coordinates measured, for example, using the Global Positioning System (GPS). The classical procedure of plotting the attitudes of a set of structures on a stereographic projection enables one to compare their orientations. While serving a useful purpose, stereographic projections provide an inadequate characterization for some applications because they lack spatial information. It may be clear from a structural map that a particular surface has different strikes and dips at different outcrops, but what is the shape of the surface? Differential geometry provides the tools for the quantification and analysis of these shapes.

As an example consider the fact that for over a century structural geologists have worked to elucidate the mechanisms by which sedimentary strata are deformed during folding. Analogue models of folds (Figure 25) have played an important role in these investigations. The results of model experiments, whether physical or numerical, are compared to descriptions of natural folds to test hypotheses about the folding mechanisms. However, the various geometrical measures of folds in common use today are inadequate to describe uniquely the three-dimensional spatial variations in fold shape. Geological surfaces are sufficiently described by the two fundamental forms of differential geometry, and the unit normal vectors and principal normal curvatures, k_{min} and k_{max}, can be calculated from these quantities to characterize folded surfaces (Figure 26).

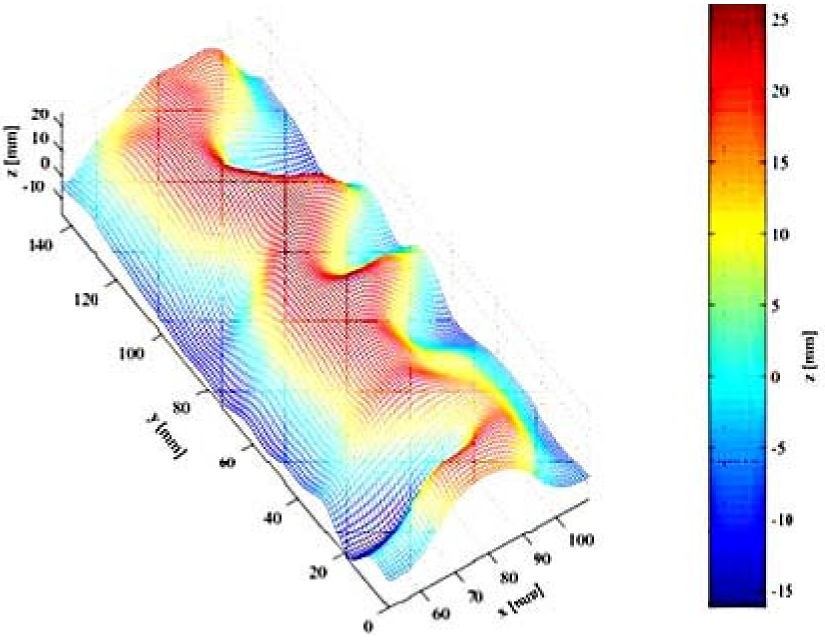


Figure 25: Geometry of a multiply-folded surface obtained by scanning an analogue model. The surface was constructed using 984 data points with 1 mm precision. Data courtesy of D. Grujic (2002)

Modern technological innovations such as GPS, 3-D seismic reflection, and 3-D scanning provide data that allow a more rigorous approach to the description and subsequent analysis of deformed surfaces. Incorporating the elementary concepts and methods of differential geometry in the curriculum of structural geology and tectonics can provide a good starting point for productive discussions of the geometry of geological structures.

Analysis of Tectonic Processes Using a Complete Continuum Mechanics

A complete mechanics, as we understand it, includes a complete sub-set, or 'N equations in N unknowns', of the laws of conservation of mass, momentum and energy, of relations describing the kinematics, and of the constitutive relations describing material behavior. The familiar kinematic quantities of displacement and velocity, and the associated displacement gradient tensors (strain and rotation) and velocity gradient tensors (rate of deformation and vorticity) are found throughout these equations, but are by no means the only physical quantities. In its simplest forms a complete mechanics is represented by linear elastic theory and the dynamics of linear viscous fluids. However, relevant constitutive laws are not limited by linearity and isotropy, but include non-linear material behavior, anisotropic materials, and finite deformation. Also, numerical solutions using the finite element method or boundary element method, coupled with high-speed computing, admit consideration of heterogeneous and discontinuous bodies of complex geometry. Therefore, problems with complex constitutive behavior, boundary conditions, and geometry are tractable.

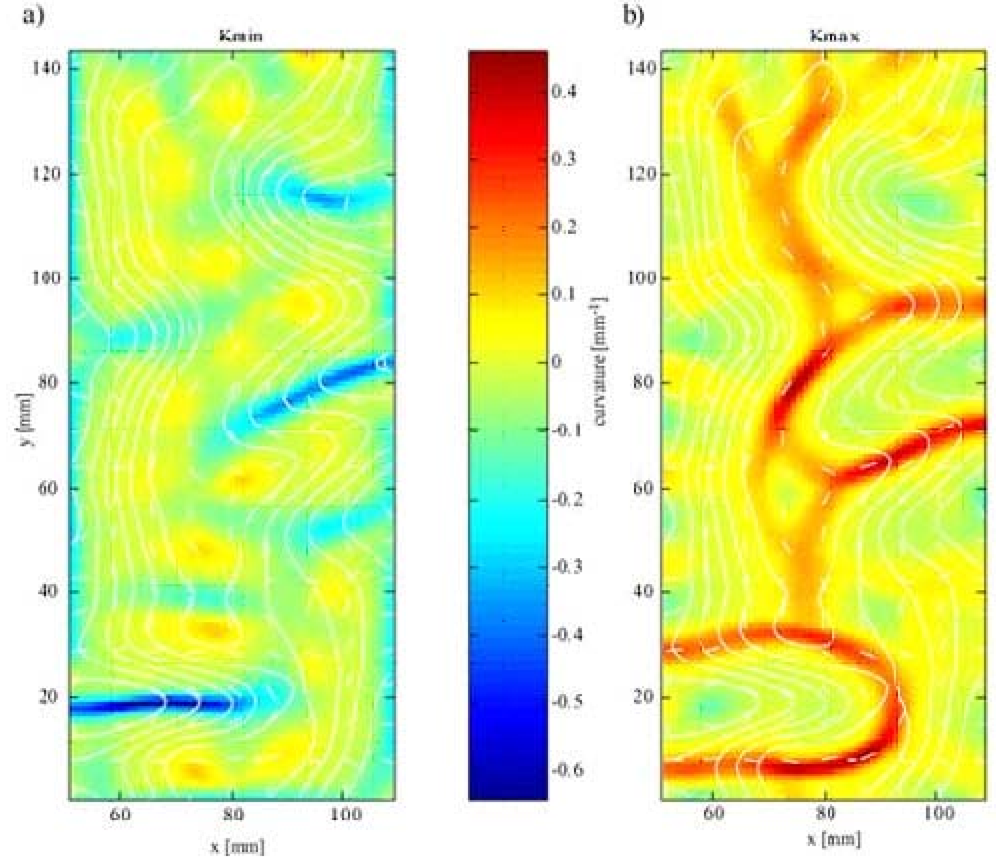


Figure 26: Principal normal curvatures for the multiply folded surface shown in Figure 26. a) Contour plot of k_{min}. b) Contour plot of k_{max}. White tic marks are trajectories of k_{min}. From S. Bergbauer, PhD Thesis, Stanford University, 2002.

Using a complete mechanics does not result in the simulation of all the details in a process leading to a particular structure or structural type. Instead, it requires that explicit choices have been made of constitutive relations, boundary conditions, and initial conditions, which together with the fundamental laws produce a closed set of relations from which all results follow. If the model results do not conform in all aspects with the field data, a more refined model may be formulated by a different choice of these mutable elements. The explanatory power of simpler models is examined first; often providing significant physical insight. Then robustness and more detailed simulation are pursued, thereby providing testable hypotheses and refutable outcomes.

As an example of a scientific methodology that applies the extensive machinery of the physics of the processes involved, most centrally rock deformation, to both suggest observations and to analyze, visualize, and interpret them we offer Figure 27. In this way, a coherent and self-consistent, if idealized, and non-unique, re-construction of the development of a geological structure may be achieved. Tectonic processes and their products will not be completely described by mechanical models; however, for prescribed initial and boundary conditions, forward models are generated that may produce likenesses of some of the observed geological structures and fabrics, to some satisfactory degree of approximation. If the forward model fails to produce satisfactory likenesses we learn that one or more of the postulates is inappropriate and must be excluded or modified (i.e., one may conduct an analysis of the sensitivity of the process of interest to specific intrinsic and extrinsic variables). One cannot, however, exclude or modify the fundamental laws upon which the mechanical model is based. The general approach includes the construction of a sequence of quantitative models, graduated in their degree of detail and successively providing an improved understanding.

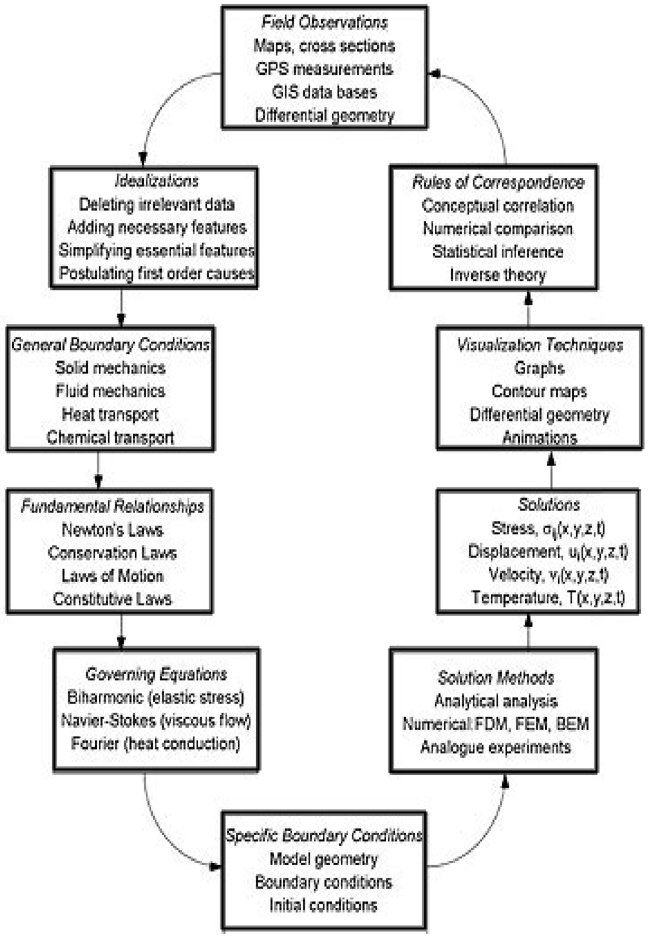


Figure 27: A methodology for designing, implementing, and testing complete mechanical models of rock deformation.

Contact Information

Dr. David D. Pollard (Chair)
Dept. of Geol. and Env. Sciences
Stanford University
Stanford CA 94305-2115
Phone: 415-723-4679
Email: dpollard@pangea.stanford.edu

Dr. Rick Allmendinger
Dept. of Earth & Atm. Sciences
Cornell University
Ithaca, NY 14853-1504
Phone: 607-255-3376
E-mail: rwa1@cornell.edu

Dr. Mark T. Brandon
Dept. of Geology and Geophysics
Yale University
P.O. Box 208109
210 Whitney Avenue
New Haven, CT 06520-8109
Phone: 203-432-3135
Email: mark.brandon@yale.edu

Dr. Roland Burgmann
Dept. of Earth and Planetary Science
University of California, Berkeley
307 McCone Hall
Berkeley, CA 94720-4767
Phone: 510-643-9545
Email: burgmann@seismo.berkeley.edu

Dr. Rebecca J. Dorsey
Department of Geological Sciences
1272 University of Oregon
Eugene, OR, 97403-1272
Phone: 541-346-4431
Email: rdorsey@darkwing.uoregon.edu

Dr. Andreas K. Kronenberg
Dept. of Geology & Geophysics
Texas A&M University
3115 Texas A&M University
College Station, TX 77843-3115
Phone: 979-845-0132
Fax: 979-845-3002
Email: a-kronenberg@tamu.edu

Dr. Tracy Rushmer (Priorities Workshop Rep.)
Dept. of Geology
Perkins Hall
University of Vermont
Burlington, VT 05405-0122
Phone: 802-656-8136
Email: trushmer@zoo.uvm.edu

Dr. Jane Selverstone
Dept. of Earth & Planetary Sciences
Northrop Hall
200 Yale Blvd. NE
University of New Mexico
Albuquerque, NM 87131-1116
Phone: 505-277-6528
Email: selver@unm.edu

Dr. John H. Shaw
Dept. of Earth & Planetary Sciences
Harvard University
20 Oxford St.
Cambridge, MA 02138
Phone: 617-495-8008
Email: shaw@eps.harvard.edu

Dr. David A. Evans
Department of Geology and Geophysics
Yale University
P.O. Box 208109
New Haven, CT 06520-8109
Phone: 203-432-3127
Email: david.a.evans@yale.edu

Dr. James P. Evans
Dept. of Geology
Utah State University
4505 Old Main Hill
Logan, UT 84322-4505
Phone: 435-797-1267
Email: JPEVANS@cc.usu.edu

Dr. Raymond C. Fletcher
Dept. of Geological Sciences, Box 399
University of Colorado
Boulder, CO 80309-0399
Phone: 303-735-4723
Email: fletchr@spot.colorado.edu

Dr. David M. Fountain (Geophys. Program Dir.)
Program Director, Geophysics
National Science Foundation
4201 Wilson Boulevard
Arlington, VA 22230
Phone: (703) 292-8556
Email: dfountai@nsf.gov

Dr. George E. Gehrels
Dept. of Geosciences
The University of Arizona
Gould-Simpson Building, 1040 E. Fourth St.
Tucson, Arizona 85721-0077
Phone: 520-621-6026
Email: ggehrels@geo.arizona.edu

Dr. Carol Simpson Provost's Office
Boston University
143 Bay State Road
Boston MA 02215
Phone: 617-353-6851
Email: csimpson@bu.edu

Dr. Bruno Vendeville
Bureau of Economic Geology
The University of Texas
University Station, Box X
Austin, Texas 78713-7508
Phone: 512-471-8334
Email: bruno.vendeville@beg.utexas.edu

Dr. Brian P. Wernicke
Div. of Geological and Planetary Science
California Institute of Technology, MC 100-23
Pasadena, CA 91125-0001
Phone: 626-395-6192
Email: brian@gps.caltech.edu

Dr. Kelin Whipple
Dept. of Earth, Atm. and Planetary Sciences
Massachusetts Institute of Technology
Cambridge, MA 02139
Phone: 617-253-2578
Email: kxw@mit.edu

Dr. Sean Willett
Dept. of Earth and Space Sciences
University of Washington
Box 351310
Seattle, WA 98195
Phone: 206-543-8653

Dr. Laurel B. Goodwin
Dept. of Earth & Env. Sciences
New Mexico Institute of Mining & Technology
801 Leroy Place
Socorro, NM 87801-4796 USA
Phone: (505) 835-5178
Email: lgoodwin@nmt.edu

Dr. Arthur Goldstein (Tectonics Program Dir.)
Tectonics Program Director
The National Science Foundation
4201 Wilson Boulevard
Arlington, Virginia 22230, USA
Phone: 703-292-8552
Email: agoldste@nsf.gov

Dr. Karl Karlstrom
Dept. of Earth and Planetary Sciences
Northrop Hall
University of New Mexico
Albuquerque NM 87131
Phone: 505-277-4346
Email: kek1@unm.edu

Dr. Martha Withjack
Dept. of Geological Sciences
Rutgers University
610 Taylor Road
Piscataway NJ 08854-8066
Phone: 732-445-6974
Email: drmeow3@rci.rutgers.edu

Dr. Teng-fong Wong
Dept. of Geosciences, ESS Building
State University of New York at Stony Brook
Stony Brook, NY 11794-2100
Phone: 631-632-8212
Email: wong@mantle.geo.sunysb.edu

Dr. An Yin
Dept. of Earth and Space Sciences
University of California, Los Angeles
595 Charles Young Drive East, Box 951567
Los Angeles, CA 90095-1567
Phone: 310-825-8752
Email: yin@ess.ucla.edu

Dr. Herman B. Zimmerman (EAR Div. Dir.)
Director, Division of Earth Sciences
The National Science Foundation
4201 Wilson Boulevard
Arlington, Virginia 22230, USA
Email: hzimmerm@nsf.gov