2014 Crustal Deformation Modeling Workshop Report

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WORKSHOP OVERVIEW

The 2014 Crustal Deformation Modeling Workshop was held June 23–27 at Stanford University. Registration was first-come, first served with a cap of 80 participants and open to anyone in the community with an interest in crustal deformation modeling. We sent email announcements to CIG, SCEC, UNAVCO, EarthScope, and IRIS email lists. The 77 participants (we had a few last minute cancellations) included 31 graduate students, 17 postdocs, 14 faculty, and 15 researchers. This distribution is similar to our previous crustal deformation modeling workshops. We have found that the combination of tutorials and science talks and discussions results in strong participation by students and early career scientists.

The complete agenda is available on the CIG website at `http://geodynamics.org/cig/events/calendar/2014-cdm-workshop/meeting-info/agenda/`. The agenda includes links to PDF files of the slides from the presentation, and slides and videos for the tutorials.

The consensus of the workshop wrap-up discussion was to continue this series of biannual workshops. This most recent workshop, in particular, suggested a growing interest in sophisticated modeling of the earthquake cycle and incorporating more complex physics. People voiced support for the 5-day duration and general format of the workshop and holding it in late June. Some of the organizing committee did not attend the workshop, so we intend to refresh the organizing committee for future workshops with those more actively involved in the SCEC or CIG communities. Additionally, we will consider registration via an application with a set deadline to facilitate participation from the most relevant members of the community rather than using a first-come, first-served procedure.

Tutorials

The first two days of the workshop were dedicated to tutorials related to the use of PyLith, an open-source code for 2-D and 3-D simulations of quasi-static and dynamic crustal deformation associated with earthquake faulting. A pre-workshop online help session via Adobe Connect attended by 30 users facilitated getting people up to speed in using PyLith, CUBIT/Trelis (finite-element mesh generation software), and ParaView (3-D visualization software). This augmented the extensive written documentation and on-demand videos from the 2011 and 2013 online tutorials to allow the in-person tutorials to start at an intermediate level.

The two days of tutorials included 7 tutorial sessions and 4 tinker time sessions (dedicated time for running examples and getting one-on-one help). The tutorial sessions covered an overview of the software tools, a 2-D subduction zone end-to-end example, mesh generation of a 3-D subduction zone focusing on nonplanar geometry, mesh generation using complex cell sizing functions, use of fault friction in quasi-static and dynamic simulations, generating 3-D static Green's functions, solver options, and debugging simulation errors.

Science Talks and Discussions

The final two and one half days of the workshop focused on science talks and discussions and informal poster sessions (the posters were posted for the duration of the workshop). The talks spanned a range of topics under the umbrellas of 2.5-D and 3-D effects of post-seismic deformation, stress in the lithosphere over the earthquake cycle, and strain localization. One of the goals of the workshop was to inspire an increase in modeling efforts contributing to the Community Stress Model. To this end, Yuri Fialko and Elizabeth Hearn presented talks on the stress field around strike-slip faults over the earthquake cycle. Bridget Smith-Konter, Bill Holt, and Charles Williams presented talks on various aspects of loading from gravitational and basal tractions.

We used a breakout session (see Appendix A) to solicit input from the community on the scientific questions important to modeling crustal deformation and modeling related obstacles to answering those questions. Additionally, we held a group discussion on development of a SCEC Community Rheology Model (see next section). These discussion sessions will hopefully facilitate development of the SCEC-5 and CIG-3 proposals to NSF.

COMMUNITY RHEOLOGY MODEL

The final day of the workshop included a group discussion focused on defining what a SCEC Community Rheology Model might describe and the feasibility of constructing such a model. A Community Rheology Model would serve as a link between the Community Velocity Models, which describe the elastic properties, and the Community Stress Model. Additionally, the rheology model could provide a physical framework for descriptions of attenuation and anisotropy. Constructing a rheology model would require require 3-D descriptions of temperature, composition, and water content along with laboratory flow laws to define the constitutive behavior. Thus, significant resources and strong collaborations across the SCEC community would need to be targeted at this effort.

Much like the Community Stress Model, given limited observations and the inferences necessary to build a 3-D rheology model, multiple rheologies will likely be able to explain the same set of observational constraints. In other words, constructing the model would be a highly non-unique exercise. Furthermore, most of the inputs are not direct observations but are inferred from other observations and have significant uncertainties, thereby compounding the uncertainties in the rheology.

The discussion also generated the idea that it would be important to extend the rheology model to include fault rheology in addition to the bulk rheology. This aspect would strengthen the ties to the Community Stress Model and have broad implications for spontaneous rupture models, deformation models (e.g., block models), and models of seismicity (i.e., earthquake simulators).

Use Cases

Our discussion identified the following use cases, which could easily be expanded:

- forward prediction of postseismic deformation (loading of other faults) and time-dependent stress changes,
- more realistic loading of faults in earthquake simulators,
- prediction of geologic structure in southern California, and
- coupling between the Community Stress Model and the Community Geodetic Model.

Model Construction

A reasonable approach to constructing a Community Rheology Model would likely include two main stages:

1. Collection of input data and assembling reasonable flow laws

   Input data might include composition, water content, surface heat flow (to constrain the temperature field), and resistivity models. The North American Volcanic and Intrusive Rock Database (NAVDAT) could prove valuable in this regard.

2. Preliminary model developed by a PI or group of PIs

   Following the approach used in the Community Velocity Models, the preliminary model would serve as a starting point with the community providing additional resources to further improve the model.

Successfully developing a Community Rheology Model will require a champion to lead the community development effort. Finding an appropriate leader who can assemble a wide spectrum of scientists and direct the effort to synthesize a broad range of scientific knowledge into a model describing the rheology of the crust and upper mantle.

APPENDIX A: BREAKOUT SESSION - RESEARCH OBSTACLES AND MODELING CODES

In order to gather information from the community on issues related to SCEC and CIG, the workshop included a breakout session focused on describing the important scientific questions and tools needed to answer them. The participants were divided into 10 groups of 4-5 people with instructions to compile a list of important scientific questions in short-term crustal dynamics and then pick 1–2 questions and discuss them in more detail, including:

- What physics (governing equations, rheologies, BC, etc) would you model to answer this scientific question?

- Describe the scientific workflow you think is necessary to answer this scientific question, including inputs, outputs, constraints/observations, optimizations, etc.
- What pieces of the workflow dont currently exist or need further development? Please rank these from highest priority to lowest priority.

Group 1

Discussion leader: Eric Lindsey
Scribes: Noel Bartlow, Eric Lindsey
Group members: Eric Lindsey, Mong-Han Huang, Noel Bartlow, Lian Xue, Brent Delbridge

What are the important scientific questions in short-term crustal dynamics?

- Slow slip, models of conditional stability, tremor
- earthquake cycles
- coseismic rupture complexity - near field measurements, ocean bottom data and models
- asperity models, existence of asperities, can coseismic and postseismic slip overlap?
- depth dependence of friction, constitutive laws
- postseismic deformation
- testable predictions of absolute stress
- fluid pressures, poroelastic models, thermomechanical coupling, finite width fault zones
- finite strains (no small strain approximation for large strains, could accumulate over multiple earthquake cycles or near the trench of tsunami earthquakes, etc)

Scientific Question 1: What is the right constitutive model for friction and how does it vary with depth, fault type, etc?

What physics (governing equations, rheologies, BC, etc) would you model to answer this scientific question?

- Model earthquake cycles in a self-consistent way – from dynamic rupture to the interseismic period
- Include custom friction laws, effect of pore fluids, etc.
- Other effects – fault roughness, geometry, etc. constrained by field observations

Describe the scientific workflow you think is necessary to answer this scientific question, including inputs, outputs, constraints/observations, optimizations, etc.

- Inputs: field or lab observations of friction, slip rate (tremor/seismic), pore fluids, temperature, etc.
- Outputs: self-consistent earthquake cycles including slip history, stresses, surface velocities, catalog of event sizes and recurrence times for different constitutive laws
- could use either a grid search or a nonlinear inversion method to compare to observations

What pieces of the workflow dont currently exist or need further development? Please rank these from highest priority to lowest priority.

- additional built-in friction models for PyLith (eg. strong dynamic weakening, pore fluid pressurization, ?)
- easier way to specify constitutive laws through user written scripts or input files

Scientific Question 2: Development of low-viscosity shear zones and/or fault propagation

What physics (governing equations, rheologies, BC, etc) would you model to answer this scientific question?

- thermomechanical coupling / heat flow during simulations
- fracture energy, fracture criteria

Describe the scientific workflow you think is necessary to answer this scientific question, including inputs, outputs, constraints/observations, optimizations, etc.

- constraints: geologic observations, heat flow, seismic tomography, Magnetotelluric obs.
- inputs: stress perturbations, background velocity field, initial viscosity/fault geometry, initial inclusion or small fracture
- outputs: models of shear localization or propagating faults in various stress/geologic conditions

What pieces of the workflow dont currently exist or need further development? Please rank these from highest priority to lowest priority.

- thermomechanical coupling
- non-predefined faults, fracture criterion
- keeping track of energy
- adaptive mesh refinement (!)
- finite width shear zones

Group 2

Discussion Leader: Yuri Fialko
Scribe: John Elliott
Group members: Yuri Fialko, John Elliott, Robert Herrendoerfer, Arjun Aryal, Esteban Chaves

What are the important scientific questions in short-term crustal dynamics?

Eq cycle, subduction - stress conditions on fault. Pore pressures. Slow slip, tremor, large eqs, how to incorporate all phenomena in one model/physical approach. Friction formulation - currently use rate-state or use a more physical basis. Rate state good for nucleation, but not when in the seismic ranges that change the friction. Rapid restrengthening.

Thermal pressurisation not observed in lab, but expected theoretically and from geological rock record. Models should look to incorporate laboratory expts that indicate constitutive laws into framework. Dynamic weakening, fault roughness, fault damage zones, in a volume, distributed. Coseismic damage on eq timescale, or long-term fault slip. Properties of damage zones, and ductile shear zones so they are self-consistent in long term simulations.

Whole system - brittle faulting and lower ductile. Long term strain. Track in simulation and fed back into mechanics. Permanent mechanical weakness.

How major faults are loaded - basal tractions versus on the boundaries.

Models with vertical displacement fields incorporating vertical motion as well as the horizontal velocity field.

Models of eq deformation on timescales from seismic ruptures to million of years, incorporating long term slip history and system of faults, accounting for realistic stress, heterogeneity, relevant physics. Fault plasticity, rate state, strong dynamic weakening in high speed friction, expt, thermal pressurisation.

Control of lithology and fault segmentation on the distribution of fault slip and extents of fault rupture. Evolution of fault models in the long-term to take account of changes in fault geometries, history of fault slip introduces stress anisotropy. Localised versus non localised damage, i.e. faults versus off fault deformation.

Scientific Question 1: What are the effects of long-term fault slip and development of weakness structures such as ductile shear zones and damage plastic zones around major faults? How does it affect behaviour from the individual earthquake to geological timescales? How deep does the effect of the fault manifest itself?

What physics (governing equations, rheologies, BC, etc) would you model to answer this scientific question?

- Brittle regime - mohr-coulomb plus plasticity. Rate and slip dependent friction during rapid slip, as well as postseismic transient slip. Visco-elastoplastic in lower crust and upper mantle. Stress controlled basal tractions, velocities at the side of the domain. Gravity important for absolute stress.
- Heterogeneous properties as constrained by geophysical and geological observations. Converting seismic velocities and temperatures into rheological flow laws. Distribution of brittle strength above the brittle-ductile transition. How important are the dynamic rupture (the inertial terms) how is coseismic damage preserved and accumulated over time?

Describe the scientific workflow you think is necessary to answer this scientific question, including inputs, outputs, constraints/observations, optimizations, etc.

- Inputs: Seismic tomography models, geodetically constrained velocity fields, topography, boundaries and interfaces at depth, lithologies, fault geometry, heat flow for temperature, distribution in seismicity at depth to constrain geotherms. Pore fluid pressures.
- Outputs: Stress-rates, strain-rates and velocity fields everywhere. Histories of strains. Present-day slip rates. Slip histories. Earthquake recurrence intervals - magnitude-size distribution, spatial distribution.
- Constraints: Principal directions of stress from boreholes as well as from focal mechanisms.

What pieces of the workflow dont currently exist or need further development? Please rank these from highest priority to lowest priority.

- Account for large strains (if you want to couple long-term with short term).
- Temperature-dependent rheologies (heat flow)
- Feedbacks between strain softening mechanisms - e.g. viscous heating, grain size reduction, fabric development.
- Mineral alterations - Mica transformation from feldspar, smectite.
- Multiphysics - all length-scales and timescales. How the dynamic rupture affects the accumulation of damage. Evolution of pore fluid pressure.
- Would like a theory of everything and a model to match.

Group 3

Discussion Leader: Bill Holt
Scribe: Andrew Bradley
Group members: Andrew Bradley, Bill Holt, Alastair Sloan, Heresh Fattahi, Casper Pranger, Julia Morgan

What are the important scientific questions in short-term crustal dynamics?

- What are the mechanisms of slip on nonplanar faults? Is nonplanarity important?
- How do the wall rocks of faults respond? Elastic? Inelastic? Time scales (seismic waves (seconds: e.g., melt) to long term)?
- Localization of slip below the lowest brittle depth? (Rheology, grain size, spatial distribution of shear zones beneath faults, lower crust and upper mantle, postseismic response) What accommodates deformation below the lowest brittle depth?

- Observations to be explained: slow slip, tremor patterns, deep San Andreas tremor (why different than in subduction zones (large SSE displacements in cascadia vs no discernible displacements in deep SAF)?)
- Fluids as a mechanism in ETS?
- Nature of locked to unlocked transition in subduction zone?
- Do we see transient crustal strain associated with mantle flow? Coupling of lithosphere with mantle flow. Ex: Mantle flow field coupled with crust: detachment at some depth due to forces in conflict?
- Laboratory derived parameter values vs field-inferred?
- Can creeping section of SAF accommodate coseismic slip? What about ETS zone in Cascadia? Slip deficit in creeping/ETS zones?
- Off-known-fault seismicity. Whats the right way of thinking about continental tectonics? Big faults in CA accommodate 70% of the strain. What about the other 30%? How accommodated? Seismic or aseismic? On faults or distributed?
- Techniques (not science):
  - InSAR with 7-day spacing.
  - Convergent DDM for nonplanar faults.

Scientific Question 1: What are the implications of nonplanarity for fault slip behavior and off-fault deformation? (Sources: fault roughness, eg, sea mounts and ridges; long-wavelength changes in strike and dip; fault geometry.)

What physics (governing equations, rheologies, BC, etc) would you model to answer this scientific question?.

- Elastic strain release is dominant. But plastic deformation is important in the wall rock.
- Stress heterogeneity coupled with rheological variations influences how slip is accommodated. As stress builds up in off-fault region, new faults are created or slip is accommodated on previously unknown faults.
- Evolution of fault shape over long-term EQ cycle.
- In terms of rupture dynamics, breaking through the tip of one fault and reaching the tip of the adjacent fault is an example of fault shape effect. How are the stress being transferred from one fault to the next?
- Governing equations: (1) Purely elastic, rate-state friction, quasi-dynamic equations for cycle-level simulations. (2) Elastodynamic. (3) On top of the previous: plasticity, poroelasticity, viscoelasticity.
- Boundary conditions: Surface topography (normal stresses on fault). Velocity BC, traction BC, remote stressing. (Are spontaneous corner and edge nucleations realistic?) Mantle flow coupled to lithosphere as BC, possibly in a multiscale way: far-field mantle flow induces fault BC.
- Geologic structure. Allow for whats known about compositional layering and pre-existing fault geometry, etc. Vp and Vs fields, density, viscosity, water content.

Describe the scientific workflow you think is necessary to answer this scientific question, including inputs, outputs, constraints/observations, optimizations, etc.

- Computational math: Methods to solve PDE. E.g.: Advancing state of the art of displacement discontinuity method: triangular elements that give a convergent method. High-order FD with absorbing BC. Methods that handle fault junctions accurately.
- Data sets and initial conditions: GPS, InSAR, geological observations, strong ground motion data, inversions of seismic data, tomographic images of subsurface structure. Defined rheologies. Prestress.
- Outputs and observational comparisons: goodness of fit, metric for a successful model.

- Observability and sensitivity: Uncertainty quantification.
- Human implications: hazard maps.

What pieces of the workflow dont currently exist or need further development? Please rank these from highest priority to lowest priority.

- InSAR: tropospheric delay problems, good repeat intervals.
- Computational math: new methods for quasi-to-dynamic cycle simulations. Higher-order methods.
- Rheological constraints.
- Fault shape at small scale.

Group 4

Discussion Leader: Michelle Cook
Scribe: Chris Johnson
Group members: Rowena Lohman, Chris Johnson, Jiyang Yi, Will Levandowski, Xiaohua Xu, Michelle Cook

What are the important scientific questions in short-term crustal dynamics?

Distributed off fault deformation, coupling fluid migration and the stress field

Scientific Question 1: Can we resolve the stress influence on a fault due to fluid injection and migration during the seismic cycle?

What physics (governing equations, rheologies, BC, etc) would you model to answer this scientific question?

- Track advection
- Biots equation
- Skempton constant
- porosity
- Poroelastic deformation
- Heat flow

Describe the scientific workflow you think is necessary to answer this scientific question, including inputs, outputs, constraints/observations, optimizations, etc.

- More geodetic data to constrain poroelastic stress.
- Model the effects of fluid injection on induced seismicity.
- Get a time dependent model that tracks fluid flow and observed deformation.

What pieces of the workflow dont currently exist or need further development? Please rank these from highest priority to lowest priority.

- Poroelastic deformation

Scientific Question 2: The rheological evolution of off fault distributed deformation What physics (governing equations, rheologies, BC, etc) would you model to answer this scientific question?

- Evolving rheologies, power law

Describe the scientific workflow you think is necessary to answer this scientific question, including inputs, outputs, constraints/observations, optimizations, etc.

- Model the rupture dynamics in regions of distributed deformation.
- Describe the damaged rheology outside the fault.
- Using multiple passes to determine the change in fault rheology.

What pieces of the workflow dont currently exist or need further development? Please rank these from highest priority to lowest priority.

- Problem is mesh design to allow rheology to evolve with distance and time.
- Implement time dependent fault healing/ weakening

Group 5

Discussion Leader: Charles Williams
Scribe: Jeanne Sauber
Group members: Xiaowei Chen, Kang Wang, Yan Hu, Charles Williams

What are the important scientific questions in short-term crustal dynamics?

1. What controls various physical mechanisms following a large earthquake? How do we model diffusion such fluid flow, heat flow, and the coupling between multiphysics processes?
   - How do stress and frictional properties evolve over time (multiple earthquake cycles)?
   - How does this affect earthquake triggering?
   - How does short-term deformation transform into long-term expression?
2. Pre-earthquake changes in physical properties, such as Vp/Vs anomalies? Non-elastic behavior prior to earthquake?

Scientific Question 1: What controls various physical mechanisms following a large earthquake? How do we model diffusion such fluid flow, heat flow, and the coupling between multiphysics processes?

What physics (governing equations, rheologies, BC, etc) would you model to answer this scientific question?

Darcy flow in porous medium, heat flow through conduction and advection, time-dependent rheology, fault friction, bulk rheologies (e.g., power-law). We also need coupling between all of these different physics (e.g., multiphysics) to allow representation of features such as poroelasticity and fluid and temperature dependent viscoelasticity.

Describe the scientific workflow you think is necessary to answer this scientific question, including inputs, outputs, constraints/observations, optimizations, etc.

- Input: Need high-resolution seismic tomography and then time varying seismic velocities & anisotropy. Standard geodetic product such as surface deformation, gravity changes, heat flow, water level from wells.
- Output: Poissons ratio, shear modulus, order of magnitude estimate of permeability and porosity (output from seismic observations).
- Workflow:
  1. Start in a region with very high data density, including knowledge of structure and fault geometry.

2. We need a good time history of data prior to a seismic event to develop a background model, and to possibly observe pre-seismic changes.
3. We then need a good time history of the coseismic and postseismic periods to record all observed changes in our observations.
4. We need a good geometric/structural representation of the region, which can be represented as a finite element mesh.
5. We need to represent the changes the coseismic event could produce on all of our observations (e.g., geodetic, time-varying seismic properties, heat flow, gravity changes, water well levels, etc.). This will involve a multi-physics simulation.
6. Once the coseismic event has been simulated, we continue the simulation to evaluate the possible contributions to postseismic behavior, including afterslip, poroelasticity, viscoelastic response, etc. The goal is to constrain the contributions of each component.

What pieces of the workflow dont currently exist or need further development? Please rank these from highest priority to lowest priority.

- We dont believe that a region with sufficient data density currently exists, although there are some regions (e.g., Japan, USA) where we may be approaching what is needed.
- Freely-available multi-physics simulation tools. Some commercial tools (e.g., Abaqus) have many of the features that are needed.

Group 6

Discussion Leader: Matthew Knepley
Scribe: Han Yue
Group members: Junle Jiang, Lingling Ye, Matthew Knepley, Han Yue, Nicholas Voss

What are the important scientific questions in short-term crustal dynamics?

1. Evaluate the effect of complex fault geometry and on rupture evolution and seismic wave propagation in a 3D media with velocity and viscosity heterogeneities. Trying to compute Greens functions with a more realistic source and media and evaluate its improvements to finite fault model inversion, especially fitting to higher frequency seismic records. How could that help to locate exact location of slow-slip events.
2. Behavior of asperities of different scales in earthquake faulting. On laboratory scale, realistic physical models are needed to reproduce and validate phenomenological rate-and-state friction laws; On earthquake scales, asperity of different scales and/or scale-dependent physics should be incorporated in numerical models to be compared against observations of co-seismic rupture of earthquakes, slow-slip/tremor seismicity, and other related phenomenon.

Scientific Question 1: Evaluate the effect of complex fault geometry and on rupture evolution and seismic wave propagation in a 3D media with velocity and viscosity heterogeneities

What physics (governing equations, rheologies, BC, etc) would you model to answer this scientific question?

For both problems:

- Multi-grid is an optimal way to solve globally coupled elliptic problem. It need accurate projection of solution and good local solvers. It also need an understanding of material property change at multi scale dimensions.
- Elastic wave propagation in heterogeneous media with intrinsic attenuation will be needed.

Describe the scientific workflow you think is necessary to answer this scientific question, including inputs, outputs, constraints/observations, optimizations, etc.

- For wave propagations in regional distances, GFs created by a single dislocation source and recorded at any location are needed.
- For teleseismic GFs, seismic waves need to be gathered at some depth or surface and integrated with representation theory to propagate with 1D layered model to teleseismic stations.

What pieces of the workflow dont currently exist or need further development? Please rank these from highest priority to lowest priority.

PyLith could handle this problem currently. However to calculate GFs with realistic time cost, multi-grid may be necessary to be adopted.

Scientific Question 2: Behavior of asperities of different scales in earthquake faulting

What physics (governing equations, rheologies, BC, etc) would you model to answer this scientific question?

For multi-scale modelling of laboratory asperity problem, not only we need numerical models that can simulate complex topography on the scale of fault samples, but also methods that study micromechanical models from the material science point of view , such as discrete element method. With such hybrid approach, we can study the realistic collective behavior based on reasonable micromechanical models.

For modelling realistic earthquakes on various scales, numerical methods in valuable for testing hypothesis on different physical models. For example, to represent realistic heterogeneity on seismogenic faults, how kind of spatial distribution of asperity, how size/density, what kind of fault property variation are needed? Alternatively, is scale-dependent physics required in the problem? Or is it sufficient that such complexity could be formulated into a unified constitutive law? These physical hypothesis need to be tested by numerical methods capable of simulated multiple time scales and spatial scales. These methods should also be able to directly gauge model observables with real-world observations such as seismic radiation, source spectrum of major earthquake rupture, seismicity distribution of small events and relations between earthquakes and ETS, etc.

Group 7

Discussion Leader: Richard Styron
Scribe: Richard Styron
Group members: Richard Styron, Achraf Koulili, Akram Mostafanejad, Michal Dichter, Lei Wang

What are the important scientific questions in short-term crustal dynamics?

1. Absolute stress magnitudes, values for fault friction and fluid pressure
    - including stress/friction/etc. before, during and after EQs
2. Rheology of the lithosphere
    - transients
    - how does rheology affect this?
    - no inversion/optimization methodologies implemented
    - poroelastic effects
3. EQ recurrence
    - regular/periodic vs. stochastic, etc.
    - partial vs. complete or patchy stress drop
4. continental/global scale effects
    - stress, deformation, etc. over a large region
    - effects on self-gravitating spheroid

- stress, deformation, etc. across plate boundaries
- long-distance EQ triggering

5. EQ source effects
   - new constitutive fault models
   - thermal effects
6. Dealing with multi-scale problems in space and time
   - (sub)seconds to thousands of years timescales
   - 10^-3 m to 10^6 m spatial scales
   - how to deal within a computer simulation
   - many EQ cycles

Scientific Question 1: Absolute stress magnitudes, and temporal changes in stress, and how those relate to strain

- What are absolute stresses in the crust, and values for static and dynamic fault friction?
- Is stress drop complete or not on faults, and to what extent does seismic-cycle stress change change regional stresses?
- How does this affect earthquake magnitude, recurrence and triggering?

What physics (governing equations, rheologies, BC, etc) would you model to answer this scientific question?

- Proper boundary conditions, whatever those are (basal shear on plates?)
- correct rheology
- Unify interseismic stress changes w/ stress drop estimated from strain and from seismic wave propagation
- Integration of topography (surface and moho), mantle stresses, dynamic topography
- Multiple seismic cycle models, including w/ embedded faults and weak zones that may be triggered

Describe the scientific workflow you think is necessary to answer this scientific question, including inputs, outputs, constraints/observations, optimizations, etc.

- match surface deformation over relevant timescales
- produce seismic waves that can be compared to seismic recordings
- model aftershocks

What pieces of the workflow dont currently exist or need further development? Please rank these from highest priority to lowest priority.

- FEMs (or other models) that can produce aftershocks, handle EQ timescales to interseismic timescales

Scientific Question 2: Continental/global scale effects: understanding stress and deformation over a very large region

Understanding feedbacks between events and boundary conditions: for example, at what level do events affect plate kinematics, and are kinematic vs. stress appropriate over large regions

What physics (governing equations, rheologies, BC, etc) would you model to answer this scientific question?

- Self-gravitating spherical (shell) earth
- BCs that can be updated/ affected by events within the model domain and (and maybe outside of it?)
- Highly heterogeneous materials
- Embedded faults on many scales, potential interaction

Describe the scientific workflow you think is necessary to answer this scientific question, including inputs, outputs, constraints/observations, optimizations, etc.

- General workflow similar to current workflow, dependent on individual problem/question
- Use community meshes/databases (large scale w/ good detail)
- Benchmarks
- self-gravitating models

What pieces of the workflow dont currently exist or need further development? Please rank these from highest priority to lowest priority.

- Need community meshes/databases (large scale w/ good detail too much for one-off projects)
- Benchmarks
- self-gravitating models
- big computers

Group 8

Discussion Leader: Eunso Choi
Scribe: Trever Hines
Group members: Eunso Choi, Trever Hines, Nicolas George, Francisco Delgado, Rishabh Dutta

What are the important scientific questions in short-term crustal dynamics?

- what are the dynamics of magma chamber development. What are the condition for eruption? How does this apply to rift dynamics?
- what is the relationship between faulting and magma migration?
- how can long term process influence stress state on a fault. These processes can be tectonic or erosion, sedimentation, etc.
- how could inferred long term and short term rheologic properties be reconciled.
- how uncertainties in slip models propagate to uncertainties in stress change?

Scientific Question 1: how can long term geologic processes influence the state of stress state in the lithosphere. These can be tectonic processes, erosion, sedimentation, etc.

What physics (governing equations, rheologies, BC, etc) would you model to answer this scientific question?

- Multi-phase flow and deformation to include pore fluid and/or magma in crust/lithosphere. Governing equations are mass momentum and energy conservation equation in their proper forms.

- Diffusion is used to model erosion.
- Elasto-visco-plastic rheologies is used to model long term tectonic processes.
- Damage rheology is used for long term and short term processes.
- Coulomb failure can be used to model when and where faulting occurs.
- In order to understand sedimentation and erosion we need to understand lithology of the bedrock, topography, climate. etc.
- We would use Dirichlet velocity boundary conditions for tectonic processes

Describe the scientific workflow you think is necessary to answer this scientific question, including inputs, outputs, constraints/observations, optimizations, etc.

- Workflow: load the system with a tectonic velocity boundary conditions. When a stress threshold is met, invoke a fault rupture which will influence topography. Use the state of the model to determine erosion and sedimentation rates.
- Observables: geologic maps, topography, borehole stress measurements, gravity can be used measure mass movement. Geodetic measurements for rates of deformation.

What pieces of the workflow dont currently exist or need further development? Please rank these from highest priority to lowest priority.

- The capability of modeling on multiple timescales.
- High uncertainty in boundary conditions (and their time dependence) and material properties.

Group 9

Discussion Leader: Emily Montgomery-Brown
Scribe: Jennifer Weston
Group members: Emily Montgomery-Brown, Lucile Bruhat, Chelsea Scott, Jennifer Weston, Qingjun Meng, Maurizio Battaglia

What are the important scientific questions in short-term crustal dynamics?

We started with a few specific example problems as talking points, but ultimately there was a lot of overlap and the details fell into these broad categories.

- Why does a volcanic caldera (e.g., Long Valley, Yellowstone) occur where it does? Tectonic controls?
- Can we use induced seismicity to test/verify physical models that can be upscaled to larger earthquake problems (ie, subduction zone events)?
- What is the largest earthquake that could occur?
- How much variability is there in earthquake cycle models?

How to integrate crustal deformation data effectively with seismic and geologic data?

Scientific Question 1: What causes volcanoes to form and earthquakes to happen where they are? (Possible alternative: interaction between volcanic activity and seismicity)

What physics (governing equations, rheologies, BC, etc) would you model to answer this scientific question?

- Continuum mechanics, Linear and non-linear rheology (elasticity, viscoelasticity, plasticity)
- Constraints on fluid migration

- Small strain vs Large strain
- Fault friction
- Interaction with earthquakes
- Rupture propagation
- Mechanical discontinuities
- Flat earth (fine with local problems) vs. spherical earth model (global problems)

Describe the scientific workflow you think is necessary to answer this scientific question, including inputs, outputs, constraints/observations, optimizations, etc.

- Data collection: Select field area
- Data processing
- Testing and selecting an appropriate model
- Model calibration
- Model verification by testing against future predictions or community examples
- Public release of data, metadata, mesh, model, codes, etc.

What pieces of the workflow dont currently exist or need further development? Please rank these from highest priority to lowest priority.

- Overall theme: we need to collaborate with other communities (seismology, data gathering, geology etc.) and come up with a method to verify models (ie, community standards or test problems for verification)
- How to use small scale, repeatable, experiments to apply to larger scale problems
- Modeling more realistic earth models
- Conceptual models with a realistic constraints
- Realistic, verifiable, subsurface structure
- Realistic fluid flow models
- Appropriate noise characterization
- Mesh repository for sharing (ideally searchable by area or tectonic regime)
- Guidelines for rigorous integration of different data types (seismic, geological, hydrological, etc.)

Scientific Question 2: How to integrate crustal deformation data effectively with seismic data?

What physics (governing equations, rheologies, BC, etc) would you model to answer this scientific question?

- Elasticity equations, stress/strain constitutive equations
- Elastic rheology, linear elasticity, small strain assumption
- Coupled fluid flow / elasticity equations (if appropriate, for example to study volcanic seismicity)

Describe the scientific workflow you think is necessary to answer this scientific question, including inputs, outputs, constraints/observations, optimizations, etc.

- Data: co-located geodetic and seismic observations
- Test possible stress/strain constitutive relations
- Test stress/strain constitutive equations against numerical and/or analog experiments
- Calibrate test models against observed data
- Verify model predictions

What pieces of the workflow dont currently exist or need further development? Please rank these from highest priority to lowest priority.

- Appropriate stress/strain constitutive equations
- Data set to calibrate and verify models

Group 10

Discussion Leader: Betsy Madden
Scribe: Eric Hetland
Group members: Betsy Madden, Eric Hetland, Paul Segall, Andreas Mavrommatis, Mike Floyd

What are the important scientific questions in short-term crustal dynamics?

- friction (empirical law, what are the underlying physics/microstructure; slow slip) localization, evolution of properties as deformation occurs; fluid migration & stimulated seismicity (porous media flow); rheological behavior, heterogeneities, heat flow & viscosity; what about stress? purely descriptive vs. capturing physical process; predictive power; robust earthquake simulator (modeling the entire eq. cycle internally consistently)
- connections between short term and long term deformation - disconnect between elastic view of block models and long term plasticity & building of structure

Scientific Question 1: What are the key physical processes important between linking short and long term deformation?

What physics (governing equations, rheologies, BC, etc) would you model to answer this scientific question?

Material state variables, e.g., finite strain and related anisotropy of material properties. Self-gravity. Plasticity. Finite strain.

Describe the scientific workflow you think is necessary to answer this scientific question, including inputs, outputs, constraints/observations, optimizations, etc.

AMR & adaptive time stepping

What pieces of the workflow dont currently exist or need further development? Please rank these from highest priority to lowest priority.

AMR & adaptive time stepper

Scientific Question 2: Resolve the entire seismic cycle in simulations that capture interseismic deformation, rupture nucleation and propagation, and postseismic deformation with realistic Earth models (geometrical complexity, material heterogeneity, and inelastic rheologies).

What physics (governing equations, rheologies, BC, etc) would you model to answer this scientific question?

couple interseismic viscoelastic deformation (stress reloading of fault) and earthquake physics (short term elasto-dynamics)