2017 Crustal Deformation Modeling Workshop Report

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WORKSHOP OVERVIEW

The 2017 Crustal Deformation Modeling Workshop was held June 26–30 at Colorado School of Mines. This continued a series of workshops that Mark Simons and Brad Hager began in 2002; the most recent previous workshop was held in June, 2014. The workshop organizers included Brad Aagaard (USGS), Eric Hetland (University of Michigan), Matthew Knepley (Rice University), Eric Lindsey (Earth Observatory of Singapore and University of California, Berkeley), and Jeanne Sauber (NASA). For this workshop the Computational Infrastructure for Geodynamics at UC Davis provided the majority of the funding with additional funding from the Southern California Earthquake Center to cover travel costs for about one-fourth of the participants. Registration was first-come, first-served with a cap of 60 participants needing lodging 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 64 participants included 40 graduate students, 7 postdocs, 8 faculty, and 9 researchers. Our combination of tutorials and science discussions continues to draw very strong participation from graduate students and postdocs, with over 72% of the participants fitting those categories this year. As in several other vibrant SCEC subdisciplines, we see faculty, who participated as graduate students or postdocs in earlier workshops in this series, sending their own students and postdocs to this workshop. Nearly 80% of the participants had not participated in a previous Crustal Deformation Modeling workshop or PyLith tutorial.

The complete agenda is available on the CIG website at `http://geodynamics.org/cig/events/calendar/2017-cdm-workshop/agenda/`. The agenda includes links to PDF files of the slides from the presentations, and slides and videos for the tutorials.

The consensus of the workshop wrap-up discussion and post-workshop survey (with a response rate of over 45%) was to continue this series of workshops, preferably on a biannual basis. The current group of graduate students and postdocs showed strong interest in numerical modeling with several wanting to contribute to the development of community software, such as PyLith. Participants expressed overwhelming support for the 5-day duration and format of the workshop, with 2-3 days dedicated to tutorials and 2-3 days dedicated to science talks and discussions. On a scale of 1 to 5 with 5 indicating the workshop exceeded expectations, nearly 90% of the post-workshop survey respondents gave a score of 4 or 5. For the tutorial portion, more than 85% of the post-workshop survery respondents gave a score of 4 or 5. They also expressed support for continued use of online tutorials to supplement the training provided during in-person workshops. The respondents to the post-workshop survey were evenly split between favoring a first-come, first-served approach or using an application process. We plan to revisit this issue when organizing the next workshop.

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. We were unable to offer a tutorial on simulating seismicity with RSQSim due to a scheduling conflict on the part of the presenter. A pre-workshop online help session attended by about 20 users facilitated answering initial questions about PyLith features and how to overcome some common installation issues. Most participants made use of the extensive written documentation and on-demand videos from the 2011, 2013, 2015, and 2016 tutorials to get started.

The tutorials were divided into 8 sessions (about 60% of the total time) intermixed with dedicated time for running examples and getting one-on-one help. The tutorial sessions focused on a simplified 3-D version of the Cascadia subduction zone to illustrate a broad range of features of the code, including multiple prescribed slip earthquake ruptures on intersecting faults, inverting for coseismic slip using 3-D static Green's functions, and stresses from gravitational body forces. A 2-D subduction zone example illustrated quasi-static modeling of earthquake cycles using slip-weakening and rate-state friction. The tutorials also included a session dedicated to troubleshooting common problems. While the tutorials focused on a subduction zone, most of the concepts directly apply to modeling strike-slip faults as well. Many of the participants applied the skills they learned in the tutorials to begin working on research problems in a variety of tectonic settings, including strike-slip tectonic environments.

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). In addition to discussions within the organizing committee, we also solicited input on speakers and topics from the leaders and co-leaders of the SCEC Tectonic Geodesy Disciplinary Group, Community Models Focus Group, and Stress and Deformation Over Time Focus Group. The talks spanned a range of topics under the themes of the mechanics of fault slip in subduction zones and crustal faults, constraining geodetic-based slip rates, the effects of fluids on natural and induced earthquakes, viscoelastic and elastoplastic processes throughout the earthquake cycle, and advancing numerical modeling techniques. Elizabeth Hearn was originally scheduled to give a presentation on the SCEC Community Rheology Model, but she was not able to attend, so she provided some slides to foster discussion during one of the breakout sessions.

We used two breakout sessions to inspire discussion on some important topics. For the first breakout session we divided the participants into seven groups based on their interest in discussing three different topics. Three groups discussed imaging fault slip from a variety of perspectives, one group discussed the utility of community rheology models, and three groups discussed identifying new directions in crustal deformation modeling. In the second breakout discussion, we divided the participants into seven different groups, with all of the groups discussing how to reduce the primary obstacles people face in their research.

Breakout 1A: Imaging fault slip

The topic was described as **Imaging fault slip: geodetic vs geologic, elastic vs plastic, etc**. The key points from the three groups discussing this topic include:

- Is there an observable signal associated with shallow plastic deformation? What are its characteristic features, including its temporal and spatial scales?
- Are there significant variations in fault slip over the depth of the seismogeneic zone? How does a single event propagate through a flower structure?
- Imaging fault slip requires more sensors but also better understandings of its physical underpinnings, such as fault constitutive models and physical properties.
- More work is needed to develop a unifying framework for fault slip across disciplines (geodesy, seismology, geology, and rock physics).

See Appendix 1A for notes from the breakout discussion groups.

Breakout 1B: Community Rheology Model

The topic was described as **What is a community rheology model to you and how would you use it?**. The key points from the discussion included:

- There should be a community repository with a user-friendly interface (e.g., `http://www.sentinel-hub.com`) in which one can download models in a standard format. The repository should also allow people to upload their own models. There should be a review process associated to submitting data and maintenance of the repository.
- The model repository should include the raw data used to obtain the model, in order to provide an opportunity for cross-validation / improvement by the community.
- Efforts to build community rheology models should obtain input from the community, define clear goals, and identify and publicize funding opportunities.

See Appendix 1B for notes from the breakout discussion groups.

Breakout 1C: New directions in crustal deformation modeling

This topic was intentionally open ended to allow groups to examine a broad range of topics. As a result, the key points span a wide range of ideas for advancing crustal deformation modeling:

- Use numerical models to determine what observations are most important to make, i.e., where is the best place for a GPS station to constrain slip rate on a given set of faults?
- Encourage the community to apply multiphysics models (e.g., (poroelasticity and thermoelasticity) and obtain the data necessary to validate them.
- Determine invariants (e.g., energy quantities) for connecting scales in multiscale formulations of crustal deformation, such as the earthquake cycle.
- Are there suitable workflow tools for addressing the increased complexity in workflow associated with an increase in the quantity and breadth of observations and use of multiphysics models?
- Develop tools to provide some formalism and guidance for new researchers to see trade-offs in models and parameters.
- SCEC benchmarking has tended to focus on showing people can reach the same plateau; more effort is need to develop a set of benchmarks to highlight differences in methods.

See Appendix 1C for notes from the breakout discussion groups.

Breakout 2: Research Obstacles

Each group focused on identifying the primary obstacles they face in their research and how they can be lowered. The context for this discussion was identifying those things for which researchers think "there must be a better way". Several of the seven groups identified the same key issues and some of the groups developed important, unique ideas. The key points include:

- The community needs to create an environment that openly encourages sharing of methods, codes, data, etc.
- Funding agencies should require data to be published in a database when studies conclude and the uncertainty of the observations should be quantified.
- The community should promote the availability of existing resources (data, software, documentation, etc) and comparison of their features as well as events (conferences, workshops, hackathons, etc) oriented towards computational issues.
- The community needs to adopt tools, such as `https://zenodo.org`, for sharing details of the models and facilitating reproducibility of modeling results.
- Encourage researchers to participate in open forums for discussion of common problems and troubleshooting.
- Develop new techniques for assessing model nonuniqueness.
- Increase the career value of researchers contributing towards community infrastructure, such as software and community models.

See Appendix 2 for detailed notes for each of the breakout groups.

Appendix 1A: Imaging fault slip: geodetic vs geologic, elastic vs plastic, etc.

Group 1

Spend 10 min brainstorming issues related to your topic

Challenges-- sparse data
Type of data
Campaign data is sometimes a struggle
InSAR- good temporal resolution but is sensitive to e-w n-s
Processing data can sometimes be difficult
Ground truthing
Environmental factors
Does what is happening at the surface actually represent what is happening at the subsurface

Pros
- Open access data
- Easy data acquisition
- Remote studying- you don't always have to be there

Geology
- Problem- does not always agree with geodetic measurements
- More costly sometimes

Plastic- elastic
    Weak material at the surface, so the change might appear to be amplified at the surface
    Slip might appear to be plastic? What are you imaging?

Spend 5 min narrowing the scope of your topic to 3-4 main ideas

Geodesy- for future we can have easier processing and accessibility. Better resolution
    Can't be independent from geology
Geology- they see different things within the earthquake cycle
Plastic-elastic-- There may not be an accurate surface expression of the behavior

Spend 10 min discussing each main idea (30-40 min total)

Idea 1: Geodetic data

- Results are model dependent
- Since models can be manipulated, sometimes it is hard to tell where you model is no longer realistic.
- We need more data. We also need to cross check with other forms of data. I.e. one form is not enough.

Idea 2: Geologic rate

- Data from geologic processes is sometimes too localized to constrain large-scale processes.
- You can cross check your model
- Important to integrate them together
- The deformation can be preserved in the correct environment
- You can not always find good places for dating

Idea 3: Plastic/elastic

- Using different plasticity will change the slip estimate which can give inaccurate representation
- Stresses might diffuse out if the material is elastic…?
- You can have high stresses but have no slip
- Is there is signal of plasticity at the surface?

Spend 5-10 min digesting the ideas discussed into 4-6 summary statements (objectives, new directions to pursue, resources needed, etc.)

- Increase integration of many aspects of geology/geodesy into our model.
- Better the accessibility to geodetic measurements/data
- Geodesy is great and can tell us a lot, but with more model refinement and adding more data, models will become more accurate.
- Broaden beyond California. It cannot be an analog for everything.
- Variability of different plastic behavior. Are you repeatable on the same fault that slipped at different times?

Group 2

Spend 10 min brainstorming issues related to your topic

GPS time series for inversions of interseismic strain accumulation, geodetic > geologic rates
Focal mech inversions, uncertainty estimates … what goes into forward models
Aseismic events … geodetic vs seismic discrepancy
Source parameters at subduction zone, stress orientations
Geodetic strain rate > geologic rates for active faults in Japan
Slow earthquakes… more integrated approach incorporating multiple data sets
Modeling fault slip with assimilation framework … comparison of forward models with data and tailoring of model parameters

Uncertainty in geologic vs geodetic measurements … difference in time scales of geologic and geodetic approaches
Geologic: dating technique, picking tie points at the surface
Geodetic: fault geometry, rheology, where we are in the earthquake cycle

Focal mechanisms can help with uncertainty of slip estimates at depth

Machine learning, clustering focal mechanisms

What is fault slip? Difference in scale between geodesists and geologists. Measuring across discrete planes vs zones.

Fault maturity, changes in structure and localization throughout lifespan of fault
Effect of damage zone on permeability, fluid flow during earthquake

Spend 5 min narrowing the scope of your topic to 3-4 main ideas

What is fault slip (distinguished by scale of observation and rate of slip off-fault)?
How do we measure fault slip and are the different techniques consistent? What causes uncertainty?
Fault maturity (strengthening/weakening, changes in structure)
Connecting shallow deformation to deeper deformation (how does rheology change, reconciling different observational data)

Spend 10 min discussing each main idea (30-40 min total)

Idea 1: WHAT IS FAULT SLIP?

Plane or zone across which there is displacement. Scale depends on observation (e.g., space geodesy vs outcrop measurements).

What is the difference between fault slip and plastic deformation? Is fault slip a form of plastic deformation? By the same logic, can we consider frictional faulting at the grain scale faulting?

What's the important part of fault slip? Co-seismic slip, post-seismic slip, interseismic slip

Idea 2: HOW DO WE CONSTRAIN FAULT SLIP FROM MEASUREMENTS/MODELS?

How can we reconcile different sets up deformation to reduce uncertainty?
Bayesian analysis

How to weigh one dataset against another? Machine learning/Bayesian

How in a model can we incorporate both geologic and geodetic time scales?

Can we get direct measurement of fault slip at depth? Drill borehole across creeping fault and monitor deformation.

Better constraints from denser networks higher resolution imaging
Geodetic data will become more valuable as they stay active longer and increase time scale or measurements

What can we do in the lab to improve our constraints of fault slip? Or is it more important for the model techniques to catch up?

Idea 3: HOW DOES FAULT MATURITY AFFECT SLIP/DEFORMATION?

How do we think about “off-fault deformation”?

Optional: Idea 4: RECONCILING SHALLOW AND DEEP DEFORMATION

Spend 5-10 min digesting the ideas discussed into 4-6 summary statements (objectives, new directions to pursue, resources needed, etc.)

- Understanding of fault slip depends on scale of observation. Fault slip has clear theoretical definition, but more ambiguous in practice.
- Unifying framework of fault slip across disciplines (geodesy, seismology, geology, rock physics) still needs work.
- Future of imaging slip requires more sensors but also better understanding of physical underpinnings (constitutive equations and properties)
- Computational and statistical ability to account for uncertainty and implement more realistic constitutive behavior and geometric complexities.

Group 3

Spend 10 min brainstorming issues related to your topic

Automate all coseismic slip distributions? Depends what you want it for (e.g. ARIA InSAR products) Integration of geologic data and geodetic data - sparse geologic data (slip rates, recurrence intervals, style and distribution of faulting), high data uncertainty, geodetic data lower data uncertainty but higher model uncertainty) geodesy ~20 year window, geology integrating over long timescale

Elastic vs. plastic? “Tough one” - is there a way to predict fault slip from loading? - plasticity often used as a ‘catch all’ for things we don’t understand. Plasticity is hard to work with in conjunction with elasticity, too many parameters.

Postseismic relaxation - viscoelastic material can do a LOT of things. If the stresses are really large, it can flow really quickly, then decays quickly.

Fault geometry biggest issue in Eileen’s models

Direction of rupture can play a big role and we don’t really consider that - rupture direction may dictate active fault strands - why does one strand rupture in a given earthquake and not another?

Yann Klinger turns fault strands into straight lines, when you model faults you make straight lines - do we have the tools that we need to investigate the complexity? Also we know the complexity at the surface but how does that correspond to complexity at depth!

Seismic imaging too!

Interpretation part of this is the really difficult thing. Might want to have everyone do his/her own uncertainties

Another thought on imaging fault slip - joint inversions including gravity? What is the influence of gravity? Is it important to turn on gravity? Or should we ignore it?

Maybe we should be talking about reproducibility

All comes down to the same problem of "I don't know" - how much don't we know And $$$

In general we want to be more explicit about uncertainty and reproducibility
What is the end goal of it? To compare to other things.

End goal of slip distributions?

Intermediate product - to be compared to other things! E.g. interseismic coupling, lithology, topography, aftershocks, etc.

Geology, not usually reproducible (with a couple exceptions - California, Himalaya, Japan, Taiwan)

Compliant zones in very mature faults

Simple simulations that we do can be used for education for k-12

Spend 5 min narrowing the scope of your topic to 3-4 main ideas

(every time you see a large earthquake you get 200 slip distributions - either automate or consider ensemble of models)

Spend 10 min discussing each main idea (30-40 min total)

Idea 1: More explicit about uncertainty and reproducibility

Model aggregation with uncertainties? - Challenging because everybody uses different fault geometries fault connectivity - but something like this. With geology - have multiple groups independently log the same trench (in person or photos). Trench the whole compliant zone.

Idea 2: Difference between surface and depth

We don't know what's happening at depth!

Idea 3: End goal of slip distributions?

Intermediate product - to be compared to other things! E.g. interseismic coupling, lithology, topography, aftershocks, etc.

Spend 5-10 min digesting the ideas discussed into 4-6 summary statements (objectives, new directions to pursue, resources needed, etc.)

- *Purpose of imaging fault slip is not an end in and of itself - purpose is for comparison and validation against other observables, e.g., interseismic coupling, lithology, topography, aftershocks*
- *More explicit about uncertainty and reproducibility - For models, some sort of model aggregation, for geology, have multiple groups independently interpret the same trench*
- *Differences between surface and depth, how does a single event propagate through a flower structure? - trench the whole compliant zone!*

Appendix 1B: What is a community rheology model to you and how would you use it?

Spend 10 min brainstorming issues related to your topic

- *Need to get good models of rheology of upper mantle and lower crust (specially for viscoelastic modeling for the different rheologies). Perhaps start with maxwell rheology. Also for elastic parameters (media velocities and density).*
- *Standard exchange format, with utilities to convert to/from txt, pylith spatial databases,*
- *What we understand of community rheology model:*
    - *Some groups can provide rheological parameters based on their inferences*
    - *Some other groups will use and validate/reject such models and report back to improve community model.*
    - *Content of the rheological models: 3D elastic structure, more complex rheological parameters (ex: Maxwell Viscoelastic, Burgers, etc. pick a flavor)*
    - *Models should include:*
        - *actual values and uncertainty quantification.*
        - *Brief explanation of a priori assumptions and references.*
        - *It should be easily accessible for either experts on the topic and researchers that just want to use those models.*

Spend 5 min narrowing the scope of your topic to 3-4 main idea

1) *Integrate/differentiate different models : rheological parameters related to physical model used. (Ex.: time dependence of rheological parameters, spatial complexity, hypothesis behind data generation, analog modeling results).*
2) *Community understanding about what the most relevant open questions are: More experimental data, more estimates of rheological parameters from inversion procedures on the field.*
3) *Classification of data based on the intended use: Ex:, flexural models, post- inter-seismic deformation modeling,*
4) *User improvements/validation of rheological models (including values and uncertainties).*

Spend 10 min discussing each main idea (30-40 min total)

Idea 1/2/3/4:

The classification must include: Place in Earth where the data is valid (ex: where the experiment was done, or "samples" come from), time scale, spatial scale, spatial complexity of the rheological model (1D, 2D, 3D), references. The database must include references to the hypothesis and datasets used to infer such values.

Depending on the physical problem that the database of rheological parameters will be used, there should be something like a graphical database, in which shows a map of the globe indicating the available resources (rheological parameters, thermal models, community velocity models, etc).

There should be a community repository in which one can download databases in a standard format, and also to have people upload their own models (also in a standard format). There should be a review process associated to submitting data and maintenance of the repository.

In order to upload a model to the repository, one should ideally upload the raw data used to obtain the model, in order to provide an opportunity of cross-validation / improvement by the community.

Spend 5-10 min digesting the ideas discussed into 4-6 summary statements (objectives, new directions to pursue, resources needed, etc)

- *There is the need of a global, rheological, standardized, community maintained model for crust and upper mantle. (rheological parameters integrated with thermal models, community velocity models, etc)*
- *Challenges in integrating existing models: classification in terms of hypothesis and intended purposes.*
- *User friendly interface!!!! (ex: Sentinel HUB webpage , or API).*
- *Uploads from community must be accompanied with raw data that allows validation.*
- *Define clear goals and funding possibilities based on community interests.*

Appendix 1C: New directions in crustal deformation modeling

Group 1

Spend 10 min brainstorming issues related to your topic

Eq hazard/safety – we determine avg long-term rates/ periodicity well, need to look at practical valuable info we can provide. Move in eq prediction direction… temporal refinement of long term rates.
But is system just chaotic?

Block models of active faults/determining which faults are active when

State of stress in the Earth

Thermo-hydro-mechanical effects. Expand past just elasticity to model deformation in general

Different geometries of the fault, not just planar- how about when it gets near BDT. State of stress at BDT along a fault

Coupling codes with different time and spatial scales- easy with PETSc solvers from Matt? Coupling is ready, need to implement.

Multiphysics coupling- fluid flow at depth- do we have sufficient data to constrain this? Many parameters have effects – temps, minerals. How do we tease out effects of each in a given location?

Constraining coupled problem- How well are we constraining our model? Figure out how to get better constraints. We don't know well about spatial variability. We need more observations about things at depth. More expansive.

Scaling issues between lab and nature

EQ prediction difficulties – precursor prediction vs failure forecasting. Are there precursors between interseismic and seismic times?

Spend 5 min narrowing the scope of your topic to 3-4 main ideas

EQ prediction- challenges, precursor prediction, stress prediction
Spatial/temporal coupling between different codes
Can crustal deformation modeling explore precursors to earthquakes?
What are we looking for in a precursor?

Spend 10 min discussing each main idea (30-40 min total)

Idea 1: Need to be able to run models faster to try more things more rapidly

Fluid flow, poro-elastic deformation, adaptive mesh refinement (Code needs to do AMR with full elasticity and plasticity as well)

Idea 2: Can crustal deformation modeling find precursors to earthquakes?

Modeling itself cannot determine a precursor but it can work as validation for a proposed precursor as observed in real data

Idea 3: Is the physical process of a big earthquake the same as for a small earthquake, can crustal modeling address this? – How can we better understand asperities on the fault plain that allow big earthquakes to build

Can DEM help us with this? Incorporate particle breakage, let fault plain asperities develop over time, create laws about how fault plain asperities evolve over single and/or multiple earthquake cycles

Idea 4: Anisotropy in the crust and how it affects elastic response is not well modeled

Can we build models to develop artificial seismograms to see how seismic waves are affected by deformation in the crust? Then use these models to say something about stresses in crust from seismic waves

Spend 5-10 min digesting the ideas discussed into 4-6 summary statements (objectives, new directions to pursue, resources needed, etc)

- *Multiphysics coupling is technically ready but not as popular as it should be, need to encourage that in the community*
- *We need to more intelligently choose using FEM, BEM, DEM, block models, coupled models, etc. depending on the problem being addressed... is the most important question rheology, geometry, present day kinetics, etc.*
- *How can we constrain and validate the coupled problem? Still an issue*
- *How can we better determine the stress field in the earth? Is this even answerable? What tools are needed to do this?*
- *Using modeling to determine what observations are most important to make.. I.e. where is the best place for a GPS station?*

Group 2

Spend 10 min brainstorming issues related to your topic

With availability of data growing, how do we better use that data? Coupled modeling, multiscale, spatial and temporal. Growing interest in community bridging quasi-static to long-term tectonic.

- *What we need is more physics, more numerical solutions and physics and better simulations*
- *More user-friendly interface to couple with the different data types (GPS, InSAR, LIDAR)*
- *Better physics to inform long term tectonics*
- *More interseismic and post-seismic to understand entire EQ cycle*
- *Bring in fluid flows (multiphysics)*
- *Fully dynamic understanding of whole EQ cycle (physics)*

        - *Use information from interseismic to inform coseismic*
- *Go beyond numerical modeling*
    - *Use geodetic data with better resolution*
    - *Different data types included in simulation using GPS*

Spend 5 min narrowing the scope of your topic to 3-4 main ideas

1. Modeling of the full EQ cycle
2. Assimilation of data and stress observations, stress inferences
3. Evolution of the physics-based codes
4. Meta-documentation

Spend 10 min discussing each main idea (30-40 min total)

Idea 1: Meta-documentation

-Workshop focused on benchmarking – throw one problem in multiple codes designed for primarily different things
-Community expertise on what software is good for certain application (beyond broad capabilities)

Idea 2: Data assimilation and management

-Comparison between GPS and InSAR and coming up with one data product or keep it separate?
-Processing of large data sets available: work flow mechanisms put in place

Idea 3: Computation

-Multiscale: Should scale relationships be determined by what data can be collected as input to numerical models?
-Finite-element vs. finite-difference: meshing issues, a lot of knobs to turn (with nonlinear responses), uniqueness of the model, FEM requires calibration and data constraints because models susceptible to failure,

Idea 3: Evolution of physics-based codes

-Are the science objectives dependent on having a bigger and better PyLith?
-Are we limited by the fact that we don't have a numerical tool that incorporates the physics or are we too myopic in the data we are using?
-What can we learn by ignoring the mechanics of the problem?

Spend 5-10 min digesting the ideas discussed into 4-6 summary statements (objectives, new directions to pursue, resources needed, etc)

- *One tool/simulation to solve multi-scale/time? Or use separate tools/simulators to solve different time scales (e.g., earthquake to seismic cycle, seismic cycle to geologic time scale) or spatial scales. What is the feedback between the models, what are the initial conditions to individuals models, can simulations on larger scale be used to provide initial conditions, and vice versa? Is there overlap in simulators designed to solve problems on different scales? If so, would it be a worthwhile effort to simulate similar problems in that overlapping region in the different codes, with goal to better understand each simulation in the extreme.*

- *Lots of data brings up issue of weakness in workflow, is a community workflow worth our time?*
- *Use different data to constrain simulations... requires simulator that predicts observations over a wide-range of data types, which introduces new parameters to control the simulation. What is the trade-off between introducing new parameters vs. new data constraints?*

Group 3

Spend 10 min brainstorming issues related to your topic

What is missing in modeling? Poroelasticity
What is blocking doing earthquake cycles?

What parameters do you use? Scale dependence of parameters.

How to delineate problems that are good for BEM and those for volumetric FEM?
Where can the two be integrated together?
As a naive user, how do you properly couple codes?

How does someone new to modeling choose which technique to use?
Community benchmarks for different codes - how to design to tell the difference between methods, not just reach benchmark step. Benchmark to highlight differences

Consistent input and output - move from purely forward modeling approach to more inversion
How to determine sensitivity of forward model to input parameters
Adjoint as tools for building inversions.

Spend 5 min narrowing the scope of your topic to 3-4 main ideas

Blockers for earthquake cycles:

Spend 10 min discussing each main idea (30-40 min total)

Idea 1: *Blockers for earthquake cycles:*

Hard part is connecting time scales and spatial scales, use stress field to spin up quasi-static simulation
Notice when something is about to rupture, go back to dynamics
Would like invariants for these scale coupling problems

Mesh for dynamics and mesh for quasi-statics - how do solutions from one convert to the other. Need more physical insight into connecting problems.

Heterogeneous elastic properties - not available in BEM, can do in pylith
Need to understand what projections of solutions mean

Idea 2: Communication for trade-offs to new users

Trade-off in models, algorithms for models, where you can run them (cluster versus local machine)
Trade-off between parameter selection is important to know - need a formalism for choosing parameters
Dependency on decisions compound

Idea 3: What is the usefulness of benchmarking?

SCEC benchmarking is useful in showing people can reach the same plateau
Can we determine benchmarks that highlight the value of different methods

Spend 5-10 min digesting the ideas discussed into 4-6 summary statements (objectives, new directions to pursue, resources needed, etc)

- *Poroelasticity is necessary, we should do it*
- *Thermoelasticity also desired*
- *How to properly incorporate earthquake cycles along with broader scale quasi-static simulations*
- *Provide some formalism and guidance for new users to see trade-offs in models and parameters*
- *Develop a set of benchmarks to highlight differences in methods*

Appendix 2: What are the primary obstacles you face in your research? How can they be lowered?

Group 1

Each group member describes the main obstacles he/she faces in advancing his/her research (15 min total)

Consider both numerical modeling related obstacles and other obstacles

- *Computations are so time consuming, make pylith to run faster*
- *Introducing problems*
- *Not knowledgeable of available codes*
- *Not knowledgeable of other works or problems already solved*
- *How to make sure the problem is set up right*
- *Difficulty using the Aperpro*
- *Using Cubit/Trelis*

Identify 4-5 common obstacles or themes (5 min)

Place greater emphasis on numerical modeling obstacles

- *Computational times*
- *Defining problems and choosing the best codes to solve the problem*
- *Not knowledgeable of available codes and problems they can solve*

How can these 4-5 obstacles be lowered (20 min)

Do you have recommendations on how CIG and/or SCEC could help?

- *More available benchmarks and examples available on the web*
- *More comprehensive list of codes and the problems they can solve*
- *Categorize the studies which has referenced pylith*
- *Using python codes for Cubit/Trelis*
- *Optimized solver setting, run on big computer, more availability of solver settings*

Summarize your ideas (5 min)

Obstacle 1: Not knowledgeable of problems that are solved already, How to make sure the problem is set up right

- Ask people to upload their works using pylith.
- *Categorize the studies which has referenced pylith*

Obstacle 2: Not knowledgeable of available codes

- *Add a comprehensive list of codes and the problems they can solve in the CIG website.*

Obstacle 3: Difficulty using the Aperpro

- *Using python codes for Cubit/Trelis*

Obstacle 4: ***Computations are so time consuming, make pylith to run faster***

- *Optimized solver setting, run on big computer, more availability of solver settings*

Group 2

Each group member describes the main obstacles he/she faces in advancing his/her research (15 min total)

Consider both numerical modeling related obstacles and other obstacles

Complicated slip patterns are hard to interpret over to a model
Different specializations don't agree? Different approaches to problems across disciplines
Language varies-- the way people conceptualize things varies. There are many unstated assumptions that people do not always make clear
Problems related to funding and uncertainty in funding-- long term problems are difficult to anticipate funding for
Logistics and difficulty of getting data sets
Densities of data in more remote regions
The amount of information shared normally does not make a study reproducible.

Identify 4-5 common obstacles or themes (5 min)

Integration of geology and geophysics
Issues with data acquisition, processing, and policy.
Data issues
Open sharing

How can these 4-5 obstacles be lowered (20 min)

Integrated trainings
Better communication-- unifying the way communication happens and the language used
What level do we want to integrate at?

Data issues- Use biology system as an analog to create banks for our data. People like to hold data-- we should make this organized and have open access. EarthScope, IRIS, and UNAVCO are doing an okay job at it. We need more consistent open data policies across the community. Lack of open data creates stagnancy. Troubles with data in general.

Geometric complexity complicates everything. We have fixed ideas about how things should be, but that is not how things occur in the real world. Scientific advancement comes when people consider previously ignored years.

The amount of information shared normally does not make studies reproducible. We need more methods and more openness of coding. We need more transparency.

Summarize your ideas (5 min)

Obstacle 1

We need integration of training and language to foster clarity and scientific advancement.

Obstacle 2

Keeping data private stagnates science and harms us all. Funding agencies should require data to be published in a database when studies conclude.

Obstacle 3

Sometimes our fixed ideas limit our ability to accurately model.

Obstacle 4

We need to create an environment that openly encourages sharing of methods and code, etc.

Group 3

Each group member describes the main obstacles he/she faces in advancing his/her research (15 min total)

Consider both numerical modeling related obstacles and other obstacles
a) Installation (difficult before the workshop) meshing is difficult.
b) Starting with geology background, it is difficult to code or to do numerical modeling- steep curve
c) Boundary element and collaboration with finite element, mesh is different for different group. No consensus on which mesh is right. Not sure which software to use for the problem.
d) Long term and strong term. Higher learning curve with learning.
e) Less constraints , reproducibility.
f) Codes are changing, keeping up with the pace, revert to earlier codes can be more efficient sometimes. Changing landscapes, meshing for complex geometries.

Identify 4-5 common obstacles or themes (5 min)

Place greater emphasis on numerical modeling obstacles
a) Identify the simulation code – choosing the right code for the problem, choosing from different codes solving similar problem.
b) Meshing.

c) Being a geologist, difficulties in using a code.
d) Reproducibility and uniqueness.

How can these 4-5 obstacles be lowered (20 min)

Do you have recommendations on how CIG and/or SCEC could help?
a) Contributing to the repository, sometimes can find similar problems solved before, make a community tutorial wiki. Reproducibility can be tackled if everyone share their parameter files.
b) People with non-computation background will be helped with more of such workshops and webinars and video lectures.
c) Meshing can be addressed by having standalone software with meshing incorporated.
d) Identifying what is the method (FEM, BEM etc) or code (pylith, relax etc) to use for your model can come with experience. Having a more active user interface for all the codes which can give idea about all the codes and what problems they solve better in one.

Summarize your ideas (5 min)

Obstacle 1: Spending time again on similar problems

Groups across different universities may spend time for a problem tackled before. A community wiki or repository could be set up where everyone can make tutorials for their problem and share their parameter files.

Obstacle 2: Education on codes

A clear progression on video tutorials for students without computational background so that they can have a good learning curve

Obstacle 3: Meshing

Commercial software not available everywhere, standalone software with meshing incorporated would be very helpful.

Obstacle 4: Identifying the code

Identifying what is the method (FEM, BEM etc) or code (pylith, relax etc) to use for your model can come with experience. Having a more active user interface for all the codes which can give idea about all the codes and what problems they solve better in one.

Group 4

Identify 4-5 common obstacles or themes (5 min)

Place greater emphasis on numerical modeling obstacles

- *More people at conferences*
- *More documentation, tutorials for modeling tools*
- *Tools we don't know exist, hard to choose which software is best suited for our particular problems, what the limitations of different software packages are*
- *Youtube videos are helpful, forums are helpful, these workshops are helpful*
- *Data: we don't have enough...how to find data that is available, know that data that you have to request exists*
- *Sharing codes is helpful: writing your own can be computationally inefficient, having access and documentation to scripts that more experienced programmers wrote is an excellent resource*
- *Better advertising for updated programs, scripts. More communication through the community*

How can these 4-5 obstacles be lowered (20 min)

Do you have recommendations on how CIG and/or SCEC could help?

-CIG can make an email list: authors of packages can update users on developments
-more YouTube videos giving tutorials on how to run a simulation
- a forum for troubleshooting
-things change so fast: maybe a blog that serves as sort of a "Textbook" for us, a standard baseline for all of us to operate on
-communication is a big barrier: writing papers that are digestible to a larger group outside of your niche group so the data can be incorporated
-webinars: based on region of study//topic, people give talks on preliminary updates so
- try to standardize the models we use in regions: make sure people are using similar models are aware to better compare results

Summarize your ideas (5 min)

Obstacle 1: Communication

Better communication between disciplines...reproducibility, comparison, synthesizing and incorporating information from other groups
Talk to people outside your lab/institution about how you are doing your work, get feedback (e.g. nobody in the community uses that model anymore, etc…), find alternatives

Obstacle 2: Data access

Sharing data, making it accessible. Quantifying the uncertainty of the data being shared.

Obstacle 3: Scripts and Package knowledge

Sharing scripts, how to use them: wiki page, YouTube channels, updates from developers.
Hackathons: community working together to fix bugs in widely used code

Obstacle 4: Standardized information and updates

More textbooks/ updated sources of information: rapid, inexpensive...maybe Webinars so people are aware on what's going on in the community

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Group 5

Each group member describes the main obstacles he/she faces in advancing his/her research (15 min total)

Consider both numerical modeling related obstacles and other obstacles

- *EQ cycle modeling. Easier access to others' modeling results (slip inversion), i.e., I use SCEC's CVM, but there is not a comprehensive portal. Benchmarks needed. Better advertising of computation-oriented conferences and workshops.*
- *Long-term & short-term. AMR + (compressible) elasto-viscoplastic rheology + good parallel scaling.*
- *Starting graduate student. Steep learning curve in numerical methods, numerical tools (poor documentation), work procedure, data processing.*
- *Numerical simulation of tsunami, data base (open access geographical, geophysical, etc.), need high-res (desirable/open access) bathymetry around Circumpacific belt. Existing data are low-res for global tsunami modeling.*

Identify 4-5 common obstacles or themes (5 min)

Place greater emphasis on numerical modeling obstacles

Benchmarks, meshing (AMR), high-res data, more accessible documentation and tutorials.

How can these 4-5 obstacles be lowered (20 min)

Do you have recommendations on how CIG and/or SCEC could help?

- *SCEC can lead benchmark efforts. Maybe need a dedicated channel for benchmark proposal.*
- *CIG long-term tectonic modeling community can help but needs revival.*
- *If SCEC improves its numerical modeling to include higher-resolution bathymetry (and similar data in other areas?), that could help other countries/areas to do the same.*
- *Tutorials are helpful but are there alternatives to Trelis that do not require a license?*

Summarize your ideas (5 min)

Obstacle 1: Benchmarks

SCEC can lead benchmark efforts. Maybe need a dedicated channel for benchmark proposal.

Obstacle 2: Meshing

Maybe CIG can develop (or isolate from existing software) a meshing library that can do AMR? Alternatives to Trelis that do not require a license?

Obstacle 3: More accessible documentation and tutorials

Better promotion of existing resources (available software, documentation, tutorial models and videos) as well as events (conferences, workshops, hackathons etc) oriented towards computational issues.

Group 6

Each group member describes the main obstacles he/she faces in advancing his/her research (15 min total)

Consider both numerical modeling related obstacles and other obstacles

Connecting short term geological observations to numerical models
Find useful collaborators
Understanding capabilities of different numerical models in a faster way
Single document oriented to earth scientists
Maintaining up to date database
Extrapolating lab data and field work
Data accessibility
Non uniqueness of model results

Identify 4-5 common obstacles or themes (5 min)

Place greater emphasis on numerical modeling obstacles

1- Extrapolating lab data and field work
2- Understanding capabilities of different numerical models in a faster way
3- Data accessibility
4- Non uniqueness of model results
5- Increase career value of software developers

How can these 4-5 obstacles be lowered (20 min)

Do you have recommendations on how CIG and/or SCEC could help?

1- Sensitivity test of parameters on both large scale models and lab experiments
2- Single document oriented to earth scientists, users experience, maintaining up to date database
3- Form cooperative agreements to facilitate sharing of data without releasing important data information
4- Doing site specific studies to groundtruth models
5- Fund more grants, hiring and tenure decisions, host software developers

Summarize your ideas (5 min)

Obstacle 1: *Extrapolating lab data and field work*

Sensitivity test of parameters on both large scale models and lab experiments

Obstacle 2: *Understanding capabilities of different numerical models in a faster way*

Single document oriented to earth scientists, users experience, maintaining up to date database

Obstacle 3: *Data accessibility*

Form cooperative agreements to facilitate sharing of data without releasing important data information

Obstacle 4: *Non uniqueness of model results*

Doing site specific studies to groundtruth models

Obstacle 5: *Increase career value of software developers*
Fund more grants, hiring and tenure decisions, host software developers

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Group 7

Each group member describes the main obstacles he/she faces in advancing his/her research (15 min total)

Every software has its limitations, difficult to know what those are beforehand and how other codes perform in comparison

Meta-documentation that outlines what available codes are for crustal deformation modeling and what they are particularly useful for Wiki and talk page, people can give reviews and commentary

More user examples
Best and worst practices in numerical modeling, meshing
Collect standards in one place or build a standard repository for parameters
Parameter guidelines - physical parameters, numerical parameters

Technical support - commercial code often has support

Code benchmarking examples showing how different codes do for different standard programs

How to build simple models from scratch
Better documentation for different codes

Identify 4-5 common obstacles or themes (5 min)

Difficult for new users to know where to start, what code to use, the trade-offs

How can these 4-5 obstacles be lowered (20 min)

Community wiki
Organize codes in one place and have a site for online discussion
Docker - keep track of what input parameters and versions you used to produce individual models

Summarize your ideas (5 min)

Idea 1: Community Wiki or repository

Include different pages for various scientific fields
Standards for input parameters in different fields
Best practices for numerical modeling
List of PETSc settings

General comparison of different methods (BEM, FEM, DEM, etc.)
As well as comparison of different codes within these methods

Developers for different codes can create their own pages with information about their code
Have benchmark examples to compare strengths of different codes for different problems

Open forums for discussions for common problems, debugging
Repository of scripts and published models

Expand SCECpedia

Idea 2: Local User groups

Directory of people using different codes, who to ask for help

Idea 3: More workshops, diversity of workshops

Nice to meet people with different backgrounds and from different fields
Can also have specialized workshops for new users or code developers