Pore Pressure Effects on Fault Slip and Earthquake Triggering

Jha and Juanes (2014) present a new computational model to simulate the coupling between multiphase flow and poromechanics of faults and developed a two-way coupled simulator that interfaces with geomechanics simulator, CIG’s open source code PyLith, with a multiphase flow simulator, Stanford’s General Purpose Research Simulator (GPRS).

The coupling between subsurface flow and geomechanical deformation is critical in the assessment of the environmental impacts of groundwater use, underground liquid waste disposal, geologic storage of carbon dioxide, and exploitation of shale gas reserves. In particular, seismicity induced by fluid subsurface technologies that tap into water and energy resources. Faults are represented as surfaces embedded in a three-dimensional medium by using zero-thickness interface elements to accurately model fault slip under dynamically evolving fluid pressure and fault strength. The effect of fluid pressures are incorporated from multiphase flow in the mechanical stability of faults and employ a rigorous formulation of nonlinear multiphase geomechanics that is capable of handling strong capillary effects. The numerical simulation tool couples the two codes using the unconditionally stable fixed-stress scheme for the sequential solution of two-way coupling between flow and geomechanics. It is unconditionally stable, due to the use of the fixed-stress sequential split between multiphase flow and deformation. The model accounts rigorously for multiphase flow effects through a fully nonlinear poromechanics formulation. The modeling approach is validated through comparison with analytical solutions of the Terzaghi and Mandel Problem as well as test cases that illustrate the onset and evolution of earthquakes from fluid injection and withdrawal.

Contributed by Birendra Jha.


Please send us your recent publications as well as research highlights so we may continue to keep the geosciences community informed of all the current research being conducted in geodynamics with CIG codes. Submit publications at: http://geodynamics.org/cig/news/publications/submit/
**Code Corner**

### NEW RELEASES

- ASPECT 1.1 2014-06-01
- AxiSEM 1.0 2013-012-20
- Pylith 2.0.2 2014-07-02
- SPECSEM ongoing via git
- Virtual California 1.0.0 2014-7-11

### ALLOCATIONS

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<th>Location</th>
<th>Stampede</th>
<th>Yellowstone</th>
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<td></td>
<td>159,638 / 1,079,619</td>
<td>467,102 / 490,000</td>
</tr>
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### RESPOSITORY STATUS

**AxiSEM**

- Current Version: 1.0.0 2013-2-20
- Status: D_CONTRIB
- Mailing List: cig-seismo@geodynamics.org
- Bug Reports: Github Issue Tracker
- License: GNU Public License

**Virtual California**

- Current Version: 1.0.0 2014-7-11
- Status: D_CONTRIB
- Mailing List: cig-short@geodynamics.org
- Bug Reports: Github Issue Tracker
- License: MIT License

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**User Meetings**

**Citcom** User Meetings are held every other Wednesdays from 1-2pm PT. Contact Rajesh Kommu: rkkommu@geodynamics.org

**ASPECT** User Meetings are held once a month on Thursdays from 10-11am. Contact Eric Heien: emheien@geodynamics.org

Dates and time and connection information can be found on the Event calendar: [http://geodynamics.org/cig/events/calendar/](http://geodynamics.org/cig/events/calendar/)

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**AxiSEM**

NEW @CIG! AxiSEM is a parallel spectral-element method to solve 3D wave propagation in a sphere with axisymmetric or spherically symmetric visco-elastic, acoustic, anisotropic structures allowing the computational domain to be collapsed to a 2D disk. This leads to extreme speedup and enables a full coverage of the seismic body- and surface wave frequency spectrum between 0.001-1Hz. The time-domain code delivers full spatio-temporal wavefields that can be stored on disk and transformed to frequency domain. Due to the dimensional reduction, global wave propagation at typical seismic of periods down to 5 seconds can be tackled on laptops, and at 1Hz on moderate clusters.

The Fortran 90 code is divided into a Mesher, a Solver utilizing the message-passing interface (MPI) for communication between separate domains, and comprehensive post processing for ease of visualization. This method allows the efficient calculation of seismograms, wavefield movies, and those wavefields that underly sensitivity kernels to allow for tomographic inversions of any portion of a seismogram. The code scales very well on supercomputers and is available from the CIG Git repository under the GPL license.

**Virtual California**

NEW@CIG! Virtual California, a boundary element code designed to investigate long term fault system behavior and interactions between faults through stress transfer.

Virtual California is a boundary element code that performs simulations of fault systems based on stress interactions between fault elements to understand long-term statistical behavior. It uses a model of faults embedded in a homogeneous elastic half space with arbitrary dips and rakes. The code performs calculation assuming linear stress increase in the long term based on element-element interaction calculations governed by Okada’s implementation of Green’s functions. During the rupture phase elements may fail and release stress based on a combination of static and dynamic stress thresholds. The behavior of the system is determined by interactions between elements from the Green’s function and the stress release from elements during events.

Virtual California also includes QuakeLib, a C++ library and Python wrappers containing key mathematics, geophysics and I/O functionality related to earthquake simulation and result analysis.

The code is available from the CIG Git repository under the MIT license.

*Eric Heien, Michael Sachs, Kasey Schultz, and John Rundle*
Code Corner cont.

ASPECT
We are pleased to announce the release of ASPECT 1.1. ASPECT is the Advanced Solver for Problems in Earth Convection. It uses modern numerical methods such as adaptive mesh refinement, multigrid, and a modular software design to provide a fast, flexible and extensible mantle convection solver.

This release combines the incredible number of changes made during the ASPECT hackathon in May 2014, as well as other changes made since the last release. In particular, it includes the following changes:
- Fixes to Stokes solver tolerance
- Free surface computations
- Optional direct solver support
- New material models
- Finer mesh refinement control
- Updates to dynamic topography postprocessors
- Updates to qplates boundary conditions
- Compositional fields can now react with each other
- New cookbooks: reaction between fields, free surfaces
- Improved PETSc support
- Time dependent boundary conditions
- Support for radiogenic heating models

Subsequent releases, 2.0.1 & 2.0.1, fix compatibility issues with example journal files, memory allocation issues, and Python netCDF4 import error.

Brad Aagaard

Governance

Letter from the Director
Dear Colleagues,
I recently returned from the CIDER program on "Dynamics of Planetary Interiors", where more than 80 graduate students, postdocs, and senior participants participated in tutorials and research projects, many using CIG codes. This spring and summer, CIG has engaged with other organizations to offer tutorials and workshops, including a joint meeting with the Canadian Geophysical Union and tutorials at the Earth – Life Science Institute at Tokyo Tech. It’s exciting to see these partnerships flourish and to see how others are using the codes. These events also provide CIG staff with an opportunity to meet and work with researchers from around the world.

New modeling codes lead directly to a greater demand for intermediate-scale and large-scale computing capability. Most CIG scientists have access to some parallel computing at their own institution or through programs like XSEDE, but many are starting to bump up against the limits and need more resources for large, high-resolution models. CIG, with IRIS and SCEC, is discussing this emerging need with NSF and national labs, and we’ve produced a white paper on high performance computing needs for the geodynamics community. We welcome feedback and ideas on this topic.

New modeling codes – and a culture of increasing openness – also raises a question: how do we provide adequate credit to scientists for the open source code they develop? A new CIG pilot project on software citation will be starting in the fall; we’ll be working with experts on digital data curation and asking for your ideas and perspective. Keep an eye out for additional information.

I hope everyone has an enjoyable and productive remaining weeks of summer.

Best wishes,
Louise Kellogg

XSEDE
CIG has applied for a renewal of the XSEDE allocation on Stampede and Maverick. If you are interested in using either of these systems for small-scale research through the CIG allocation, or if you need your own larger allocation on an XSEDE system, please contact Eric Heien for assistance: emheien@geodynamics.org

Plyth
I am pleased to announce the release of PyLith 2.0.0, a finite-element code designed to solve dynamic elastic problems and quasi-static viscoelastic problems in tectonic deformation.

This release fixes several bugs in PyLith v1.9.0 and contains major under-the-hood improvements. We strongly recommend all users of previous PyLith releases switch to this latest release. A few small changes are needed in .cfg files to switch from v1.9.0 to v2.0.0. Please consult the migration instructions. Names changes have been made to various C++ objects.

This release includes the following changes:
- Replaced C++ Sieve implementation of finite-element data structures with CDMplex implementation.
- Improved treatment of buried fault edges, so that the slip naturally tapers to zero along the buried edges.
- Switched from using Subversion to Git for version control.
- Added ability to recursively refine a mesh.
- Directories for output are created as necessary.
- Improved error messages.
- Improved CUBIT example for mesh sizing functions.
- Manual improvements based on feedback and questions from users.
- Bug fixes

Subsequent releases, 2.0.1 & 2.0.1, fix compatibility issues with example journal files, memory allocation issues, and Python netCDF4 import error.

Wolfgang Bangerth, Timo Heister, and many other contributors.

HPC White Paper
The solid earth science community has identified their needs for high performance computing (HPC) for the immediate and long term. Initiating with the 2012 CIG LLNL workshop on HPC and continuing discussion with the community, this white paper discusses the science drivers and both hardware, software and human capacity needs that limit and will be needed to push forward solid earth system science research. To meet these needs to address both fundamental science problems and societal needs will require deep collaboration and leveraging resources among communities. The paper can be downloaded at: http://geodynamics.org/cig/files/512/3458/2014_CIG_SP_FINAL.pdf

2014 Strategic Plan
Now available for download, CIG’s 2014-15 Strategic Plan and Annual Report reviews last year’s operations and next year’s community plans: http://geodynamics.org/cig/files/4014/0522/2014_CIG_SP_FINAL.pdf
Events

CIG Webinars
CIG webinars draw from a pool of experts from mathematicians, to computer scientists, and to geoscientists, among others to bring together a cross-cutting community of faculty, students and researchers to both inform and disseminate knowledge on the tools and methodologies employed to further the study of problems in geodynamics.

The one hour webinars will be held the 2nd Thursday of each month October through May (no webinar in December due to AGU) at 2pm PT unless otherwise noted. Webinars will be recorded for later viewing. Reminders and details are sent through the cig-all mailing list.

This year’s series features topics in software infrastructure and development that enables our science. Webinars focus on bridging communities, laying foundations for robust and usable software that address active areas of geodynamic research and HPC for big data.

Webinar Schedule
October 9 - Anna Kelbert, OSU
November 13 – Jed Brown, ANL
January 8 – Louise Kellogg & Pierre Arrial, UC Davis
February 12 – Eric Heien & Hiro Matsui, UC Davis
March 12 – Cedric Thieulot, U. Utrecht
April 9 – Lucy Flesch, Purdue
May 14 - Arben Pitarka, Stanley Ruppert, & Douglas Dodge, LLNL

Next Webinar
Thursday, October 9, 2014 @ 2pm PT
Earth System Bridge: NSF’s EarthCube entry point for solid Earth geosciences
Anna Kelbert
Oregon State University

NSF’s EarthCube is a relatively new Earth science knowledge integration initiative. It has a grand ambition to develop a common cyber infrastructure for all of the environmental sciences in the United States. The Earth System Bridge currently under development intends to provide pathways for communication between existing modeling frameworks. These initial efforts are possible entry point into the cyber infrastructure initiative for the CIG community and an opportunity to help shape the outcome of the EarthCube effort.

For more details on this and all CIG webinars see:
http://www.geodynamics.org/cig/community/Webinar

ASPECT Hackathon
The first ASPECT “hackathon” was held May 14-23, 2014 in College Station, TX bringing together 14 US and international participants (13 early career). Participants were all ASPECT users about which half had previously contributed code. The hackathon’s main objective was to jointly work on code and create! Participants worked on a variety of projects to support their scientific needs which included: nonlinear and direct solvers, radiogenic heating, material models, time dependent temperature boundary conditions. In addition, the group has begun a benchmarking paper to be completed this summer.

During the hackathon, the participants committed some 400 patches to the ASPECT repository adding to the 2000 prior commits. These patches increased the number of lines of code in ASPECT from around 45,000 to around 52,000. Patchsets increased the number of test cases in ASPECT from 33 to 102. Look for the full meeting report on the ASPECT wiki.

http://wiki.geodynamics.org/software:aspect:start

CDM Workshop
The biannual Crustal Deformation Modeling Workshop was held June 23-27, 2014 at Stanford University. The Workshop combined tutorials and science presentations and brought together 74 participants including 46 early career and 9 international researchers. Prior to the workshop, organizers offered an online introduction and help session which was well attended. Advanced tutorials during the week covered Pylith, Cubit/Trelis and ParaView. Science talks focused on post-seismic deformation and stress and strain in the lithosphere over the earthquake cycle. More information can be found under the conference website.

2014 CIG Annual Business Meeting
The CIG community will gather at the Parc55 on Tuesday December 16 for our annual business meeting. Planning for the next phase of CIG will be one of the many important topics discussed. See our website for more information as AGU approaches.
**Upcoming Meetings**

**August 2-3, 2014. ELSI Summer School, Tokyo, Japan.**
The inaugural ELSI Summer School will be held August 2nd and 3rd in the ELSI building on the Tokyo Tech campus and will provide hands-on tutorials of computational tools related to planetary formation and Early Earth evolution. [http://old.elsi.jp/en/activity/elsi-summer-school/](http://old.elsi.jp/en/activity/elsi-summer-school/)

**September 4, 2014. GEOMOD Short Course, Potsdam, Germany.**

**November 6-7, 2014. Geodynamo Benchmarking Workshop, Boulder, Colorado**
Please check the website for workshop details.

**December 15-19, 2014 Fall AGU, San Francisco, California**
Network with more than 22,000 Earth and space scientists, educators, students and other leaders at the Moscone Center in San Francisco for 5 days of presentations, workshops, and town hall meetings.

**December 16, 2014. CIG Annual Business meeting**
The CIG Annual Business Meeting will be held on Tuesday, December 16 during Fall AGU. Please join us for light hors d'oeuvres beginning at 6pm followed by the Business Meeting at 6:30pm at the Parc 55.

*For more information on CIG hosted events, please go to geodynamics.org*

**Recently Published**


Lee, Shian-Jong and Liu, Qinya and Tromp, Jeroen and Komatitsch, Dimitri and Liang, Wen-Tzong and Huang, Bor-Shouh (2014) "Toward real-time regional earthquake simulation II: Real-time Online earthquake Simulation (ROS) of Taiwan earthquakes", *Journal Of Asian Earth Sciences* Volume 87 DOI: 10.1016/j.jseaes.2014.02.009


Zheng, Lin and Zhao, Qi and Milkereit, Bernd and Grasselli, Giovanni and Liu, Qinya (2014) "Spectral-element simulations of elastic wave propagation in exploration and geotechnical applications", *Earthquake Science* Volume 27 (2) DOI: 10.1007/s11589-014-0069-9

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**Computational Infrastructure for Geodynamics (CIG)** is a membership-governed organization that reports and promotes Earth science by developing and maintaining software for computational geophysics and related fields.

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