COMPUTATIONAL INFRASTRUCTURE FOR GEODYNAMICS

2018-2019 Annual Report

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COMPUTATIONAL INFRASTRUCTURE for GEODYNAMICS
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Executive Summary

The Computational Infrastructure for Geodynamics (CIG) is funded by the National Science Foundation (NSF) to support and promote development, dissemination, and use of high-quality software for modeling geodynamical and seismological processes. During the current reporting period, we have focused on making progress on all aspects of software development, improving CIG's practices and governance, strengthening partnerships, continuing education and training, and building community.

We held regular meetings and workshops for software development projects, developed and offered tutorials for active codes, including an ASPECT tutorial at CIDER, the first Rayleigh Tutorial and Hackathon, the Crustal Deformation Modeling Workshop, and a hackathon for the mantle convection code ASPECT. CIG continued to advance software development in mantle convection, crustal dynamics, dynamo, long-term tectonics, seismology, and evaluated future directions for these codes. CIG supported community development and knowledge transfer through workshops, webinars, newsletters, tutorials, e-mail distribution lists, and a new discussion forum. Our webinar series focused on open source codes in geodynamics including perspectives on the next generation community codes. We continued work with the CIG community and other relevant communities to improve best practices in software development focusing this year on the role of scientific communities in developing sustainable software.

We tracked various metrics aimed at measuring the impact of CIG's activities, including participation in events, downloads of software (Figure 1), and (when available) presentations and publications that use CIG software. The geodynamics.org website contains a searchable database of CIG associated publications. We partnered with other organizations, including CIDER, EGU, ELSI (U. Tokyo), GEOMOD, IRIS, DCO, CSDMS, CGU, and SCEC.

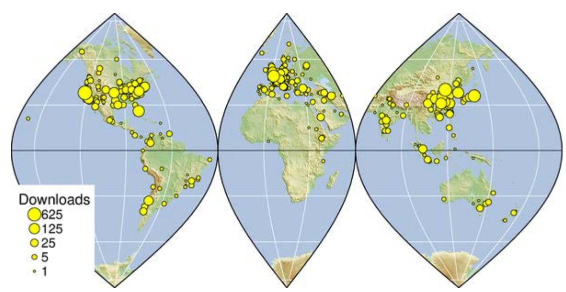

Figure 1. Download map of codes from CIG's software repositories 2018.

Our plans for the coming year include continued development of codes across the scientific domains represented by geodynamics, including release of new codes and new versions of established codes. CIG staff continue to work with the Long-Term Tectonics working group to develop software to meet this communities scientific goals and to support donations of codes as code-donation requests arise through the year through our established approval process. A new Education Working Group was initiated by the community to develop open source materials to teach geophysics using computation. We will support a delegation of early-career US scientists to the biannual EGU mantle and lithospheric dynamics workshop, now called the Ada Lovelace Workshop in Mantle and Lithosphere Dynamics. We will hold a CIG all-hands meeting focused on the scientific questions driving development of next generation geodynamics software: this meeting will launch the community planning effort for CIG IV. We will continue community activities and development (especially for early-career scientists) through planned workshops, tutorials, hackathons, and webinars. We plan to continue the newly established CIG Distinguished Speaker program, which brings CIG-supported science to colleges and universities that are underrepresented in computational geophysics. We continue to develop partnerships with national computing facilities and other partner organizations. These include managing and renewing CIG's allocation on XSEDE. A CIG team was part of a successful NSF proposal for early access to Frontera, the latest XSEDE supercomputer for applications in global mantle flow, lithospheric deformation, and global core flow.

CIG was a partner in a large INCITE allocation on Mira, now the 7th fastest computer in the world, operated by the Argonne Leadership Computing Facility (ALCF). This year a sub grid-scale model was implemented in the geodynamo code Calypso and models were run using INCITE data to explore the role of turbulence. New visualization methods for this data were also developed by a CIG-supported graduate student at UC Davis. Results and future plans for this high-visibility project are discussed later in this report.

CIG Director Louise Kellogg and Associate Director Lorraine Hwang continued to represent the CIG community at a variety of meetings and workshops. CIG held its annual business meeting at the Fall American Geophysical Union annual meeting, December 2018.

In April 2019, CIG Director Louise Kellogg passed away. In accordance with the by-laws of the organization, the Executive committee (EC) elected Prof. Magali Billen, UC Davis, as PI and named her as Interim Director. The EC met in mid-June to establish a transition plan and to discuss strategic planning for the next phase of CIG, including future leadership of CIG. The EC is working closely with the Interim Director to complete this transition period and strategic planning by October 2019.

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1. CIG Overview

The Computational Infrastructure for Geodynamics (CIG) supports computation and research in geodynamics. CIG achieves this by developing, supporting, and disseminating high-quality software for the geoscience community and enabling better access to and use of cyberinfrastructure including high-performance computing. This cyber-enabled geoscience community is maintained and grows through workshops, training, outreach, and partnerships with other organizations. The software maintained and developed by CIG addresses research problems that range widely through the earth sciences and includes mantle convection; the geodynamo; magma, crustal and earthquake dynamics; and seismology. With 85 member institutions including 19 international affiliates, CIG is a member-governed organization with a high level of community participation.

This document updates CIG operational status and covers the period from August 1, 2018 through July 31, 2019 unless otherwise noted.

Prior reports and documents can be found at geodynamics.org.

2. CIG Management and Governance

To remain a nimble and relevant organization, CIG relies on the expertise, vision, and guidance of the community. Its community-centric management structure draws upon features of other successful NSF-supported community infrastructure projects in the Earth sciences. Goals and directions are determined through community input from topical Working Groups and suggestions coming from the scientific community. A Science Steering Committee (SSC) considers and recommends CIG activities, which are then considered and approved by an Executive Committee (EC). The collective charge of the SSC and EC is to identify and balance common needs across disciplines, balancing activities between ongoing support and development of established codes and infrastructure, responding to community needs for new codes and infrastructure, and supporting community development of the CIG community. The management plan, outlined here, has been codified in a set of by-laws updated in 2018 and available on our web site: https://geodynamics.org/cig/files/3415/3057/0459/2018_Bylaws_FINAL.pdf

In early 2019, the Principal Investigator of this NSF Grant that funds CIG, Louise H. Kellogg passed away. In accordance with the by-laws of the organization, the EC elected Prof. Magali Billen, UC Davis, as PI and named her as Interim Director. The EC met in mid-June to discuss transition plans and strategic planning for the next phase of CIG, including future leadership of CIG. The EC is working closely with the Interim Director to complete this transition period and begin strategic planning by October 2019.

2.1 Membership

CIG is an institutionally-based organization governed by an Executive Committee. CIG recognizes educational and not-for-profit member institutions with a sustained commitment to CIG objectives in geodynamics and computational science. International affiliate members are accepted, but only United States members have voting rights. Each member institution selects one member-representative to the electorate. The number of member institutions continues to increase and currently stands at 85 member institutions including 19 international affiliates. Of these, 5 are inactive as member representatives have moved to new institutions. In 2018, CIG welcomed University of Utah and University of Leeds. See Appendix A.

2.2 Executive Committee

The Executive Committee (EC) is the primary decision-making body of CIG. The EC meets regularly to discuss administration and organizational activities. In conjunction with the Director, the EC oversees day-to-day operations through its regular meetings, tele/video conferences, and electronic mail. The EC approves the annual science plan, management plan, and budget; reviews priorities for software development with input from the electorate and the Science Steering Committee, and creates and appoints committees, such as the Nominating Committee, as needed. The EC has the authority to approve proposal submissions and contractual arrangements for CIG.

The EC has 7 members, of which 5 are voting members: Chairman, Vice Chairman, and three members at-large. Members are elected by representatives of member institutions for staggered three-year terms. The two *ex officio* members are the Director, and the Chair of the Science Steering Committee.

Current members of the EC and the term end dates are:

- *Chair,* Louis Moresi (2021), University of Melbourne
- *Vice Chair,* Carl Tape (2020), University of Alaska, Fairbanks
- Katie Cooper (2021), Washington State University
- Claire Currie (2019), University of Alberta
- Frederik Simons (2019), Princeton University
- *Ex officio*, Brad Aagard (2019), United States Geological Survey
- *Ex officio,* Magali Billen, Interim Director CIG

2.3 Science Steering Committee

The Science Steering Committee (SSC) prioritizes CIG software development from the perspective of the earth science and computational science discipline. The SSC assesses the competing objectives and needs of all the sub-disciplines covered by CIG, provides initial assessment of proposals submitted to CIG, and provides recommendations on the allocation of development resources. The SSC evaluates proposed CIG activities at least once a year formulating a prioritized list of tasks and developing a yearly strategic plan for CIG. Recommendations from the SSC are forwarded to the EC and are part of the planning process.

The SSC works in consultation with the software development team and the Director to assess how tasks are inter-related and related to the broader needs of the community. To make this process as productive as possible, the Director and SSC look out for opportunities and new activities and work with those who are in the process of proposing a new effort to ensure that it is within the scope of CIG's mission.

The SSC consists of 8 elected members including a chairperson and 2 *ex officio* members - the CIG Director and the Chair of the EC. The committee includes expertise in both the geosciences and computational sciences and provides guidance within all of the sub-disciplines of computational geodynamics.

Current members of the SSC and the term end dates are:

- *Chair,* Brad Aagaard (2019), United States Geological Survey
- Ebru Bozdag (2021), Colorado School of Mines
- David Ham (2020), Imperial College
- Jessica Irving (2020), Princeton University
- Gabriele Morra (2020), University of Louisiana, Lafayette
- John Rudge (2019), Cambridge University
- Cian Wilson (2021), Carnegie, DTM
- Krista Soderlund (2021), University of Texas, Austin
- *Ex officio,* Louis Moresi (2021), University of Melbourne
- *Ex officio,* Magali Billen, Interim Director CIG

2.4 Working Groups

Working groups (WG) provide the EC and SSC with domain expertise. WG's, formed by the EC, provide input on science drivers, technical challenges and resources necessary for research in their domain. Working groups provide advice to the SSC and EC and form goals and actions for the upcoming year.

CIG's eight working groups represent the main scientific domains and special interests in the CIG community:

Computational Science

This working group informally advises CIG leadership and the other working groups on best practices and identifies opportunities for new partnerships and activities within CIG.

Seismology

The main priority for the Seismology Working Group is the continued advancement in capabilities for high performance computing and to broaden its code and user base.

Dynamo

The long-term goal of the Dynamo Working Group is to produce a series of ever more efficient, massively parallelized, well-documented community dynamo models for broad usage by the dynamo community. With these HPC models, the goal is to significantly decrease the fluid viscosity in such dynamo models by at least two orders of magnitude. This will enable transformative studies of fully developed turbulent dynamo action as it occurs in the Earth's core.

Education Working Group (NEW)

The Education Working Group is interested in developing open source materials for teaching geophysics using computation with an emphasis on computational geophysics. The goal is to develop modules that could be used in a classroom or self-learning setting targeted at undergraduate through early graduate training.

Long-Term Tectonics

The Long-Term Tectonics Working Group's primary goal is to converge towards a community-initiated and maintained 2D and 3D lithospheric deformation computational code (or codes) with flexibility, modularity, and the ability to model a range of geologic processes.

Magma Migration

The Magma Migration Working group's long-term goal is to provide flexible multi-physics modeling capability and training for the exploration of coupled fluid-solid mechanics with an emphasis on the dynamics of magmatic plate-boundaries.

Mantle Convection

The Mantle Convection Working Group activity focuses on developing, supporting and maintaining ASPECT, CitcomS and CitcomCU.

Short-Term Crustal Dynamics

The Short-Term Crustal Dynamics Working Group goals are to create numerical models for observationally constrained and internally consistent physics for the 1) entire seismic cycle, 2) tectonics of magmatic systems, geothermal systems, and the cryosphere; and 3) crustal deformation associated with surface loads.

Approximately 5% of the community (as determined from mailing list subscriptions) is actively involved in governing CIG through the EC, SSC, and WGs, drawing from more than 3/5 of the member institutions. Appendix B provides a list of working groups and the 54 working group members who are engaged with the CIG community.

CIG staff and the SSC and EC make an effort to identify overlapping needs in both scientific and computational functionality from the different domains, in order to support infrastructure for flexible, reusable and interoperable software. This includes a role as a clearinghouse for best practices in computational solid-Earth Science including benchmarking, regression testing and education/training that are consistent across disciplines.

2.5 CIG Operations and Administration

CIG is headquartered at the University of California, Davis (UCD). UCD houses CIG in the Earth and Physical Sciences building and in the adjacent Mathematical Sciences Building (MSB). These locations provide easy accessibility to expertise in numerical methods, gridding, high-performance computing, networking, scientific visualization, geophysics, and tectonics, as well as access to administrative support staff in the Earth and Planetary Sciences Department. MSB houses CIG servers and UCD supported HPC resources that are available to local CIG developers. CIG has access to high-speed networking and state-of-the art scientific visualization facilities through KeckCAVES, a visualization facility dedicated to the geosciences.

CIG Headquarters is led by the CIG Director. Four full time employees support CIG – an Associate Director, a Project Scientist, a Research Scientist, and a Software Engineer; as well as a Research Scientist, Project Scientist and staff members shared with other projects. The Director is the Chief Executive Officer of the organization and Principal Investigator on the CIG Cooperative Agreement; she bears ultimate responsibility for its programs and budget. The Director's responsibilities include: (a) leading strategic planning for CIG's mission and goals and acting as the primary representative of CIG to the scientific community (b) devising a fair and effective process for implementation of CIG's activities based on proposals or work plans such as those submitted to the Executive Committee by the Science Steering Committee, and overseeing CIG's activities, (c) acting as the Principal Investigator on proposals submitted by the core CIG facility, retaining final authority to make and implement decisions on grants awarded to the core facility and contracts, (d) ensuring that funds are properly allocated to various CIG activities, and (e) overseeing the preparation of technical reports.

The Associate Director supports day-to-day operations and coordination of CIG's activities. The Associate Director leads and supports strategic initiatives and all aspects of contract management, day-to-day operations including personnel and administrative tasks. The Associate Director may act on the behalf of the Director when designated.

CIG's team of computational and research science professionals includes four user-developers (two *Research Scientists* and two *Project Scientists)* with expertise in geodynamics, software development, computing, and numerical methods. They work closely with the Working Groups and sub awardees under direction of the Director and as guided by scientific objectives formulated by the geodynamics community. CIG's software engineering team (*HPC Support)* and staff maintain the infrastructure for the community including: the repository, build and test system, website, email, backend servers, HPC allocations, and related systems and services. The development and technical teams provide software services to the community in the form of programming, documentation, training, and support.

CIG Staff are:

- *Interim Director,* Professor Magali Billen*[1]
- *Associate Director,* Dr. Lorraine Hwang*
- *Research Scientist,* Dr. Hiroaki Matsui*
- *Assistant Research Scientist,* Dr. John Naliboff

[1] Replaces Professor Louise H. Kellogg in May 2019.

- *Assistant Project Scientist,* Dr. Rene Gassmöller
- *Assistant Project Scientist,* Dr. Juliane Dannberg*
- *Software Engineer,* Tyler Esser[2]
- *HPC Support,* Bill Broadley*
- *HPC Support,* Terri Knight*

**part time effort for CIG*

2.6 The Planning Process

Concepts and ideas for CIG activities come directly from the community, member institutions, working groups and their elected committees. As members of the scientific community, WG and SSC members, and the Director are conduits for formal and informal dialog among the CIG community. Formally, users from Member Institutions can submit brief proposals to suggest new CIG software development tasks, workshops, tutorials, and projects. These proposals can be submitted at any time and are provided to the SSC and EC to read and evaluate.

In practice, new CIG activities are developed iteratively; CIG typically works closely with community members, so that proposed activities are relevant to and appropriate for CIG. In turn, the SSC and EC review proposed activities as they come in, provide feedback, and ask questions, again to ensure that proposed activities are aligned with CIG's mission and goals.

CIG is engaged in several multi-year development projects, including state-of-the-art codes for mantle convection, lithospheric dynamics, geodynamo, short-term crustal dynamics, and seismology. The working groups establish annual goals (work plans) for each project, which are discussed, revised as needed, and approved by the SSC and EC. These work plans may include software development plans, benchmarks, tutorials, and a schedule for working meetings appropriate to each project.

2.7 Augmented Funding

CIG, upon approval by the EC, can agree to develop additional software or adopt additional tasks upon receipt of augmented funding. The EC will determine whether the activity is within scope of the CIG mission and whether adequate resources are available that would not jeopardize current CIG priorities. Activities can be in the form of new software development using only CIG resources or in collaboration with other organizations. Activities may also support program outreach efforts.

[2] Position vacant as of May 2019

This year the team was part of the successful proposal to NSF for a new petascale computing system, *Frontera* (5^{th} fastest worldwide), led by and deployed at the Texas Advanced Computing Center (TACC). Proposed CIG applications in computational dynamics include computational models of global mantle flow, lithospheric deformation, and global core flow.

In preparation for these studies, the team has also been awarded 0.27 million node hours to participate in Frontera's early testing phase from May 2019 to January 2020. The award will be used to benchmark the performance of existing CIG software and further its scalability using new numerical methods in preparation for wider community use. Specifically, the team will focus on testing and developing the CIG codes ASPECT and Calypso for mantle and core dynamics, respectively. In addition to research on numerical methods to reduce scalability bottlenecks applicable to a range of CIG codes, the team will also conduct "proof-of-concept" simulations that target outstanding geophysical questions that were intractable with the current generation of HPC systems.

Total value of the award is estimated at $5,107,298.

2.8 Communications

CIG employs a variety of methods to keep its own and other communities informed.

geodynamics.org

The website is the home of CIG as seen by most of the community, and serves to:

- Provide access and visibility to CIG software including most recent releases and documentation;
- Provide committees and working groups a centralized site for organization of community activities;
- Announce CIG events, including workshops and meetings and to support functions such as workshop registration;
- Disseminate and archive CIG documents including annual reports, strategic plans, by-laws, policies, manuals, tutorials etc.;
- Educate the community on software and computational methods;
- Highlight research being accomplished by scientists using CIG codes and collaborative projects;
- Provide a portal to XSEDE resources allowing the community access to preinstalled software on HPC resources;
- Provide easy access to citation and attribution information for software packages,
- Disseminate news of activities of interest and promote discussion, and

- Promote discussion through its forums. **NEW**

E-mail & Forum

CIG maintained a number of electronic mailing lists through the end of 2018. E-mail lists for general information (CIG-ALL) and domain-specific information and discussion are open and accessible through the CIG website and forum. Currently, any member of the public may subscribe to CIG-ALL and the new forum (more information below). These are used to distribute information about software releases, bug fixes, workshops and tutorials, and other general news about activities and programs relevant to the CIG community.

For the period of January 1, 2018 through December 31, 2018, CIG's open e-mail lists distributed information to 1195 unique individuals. Figure 2 displays activity by scientific domain, showing the

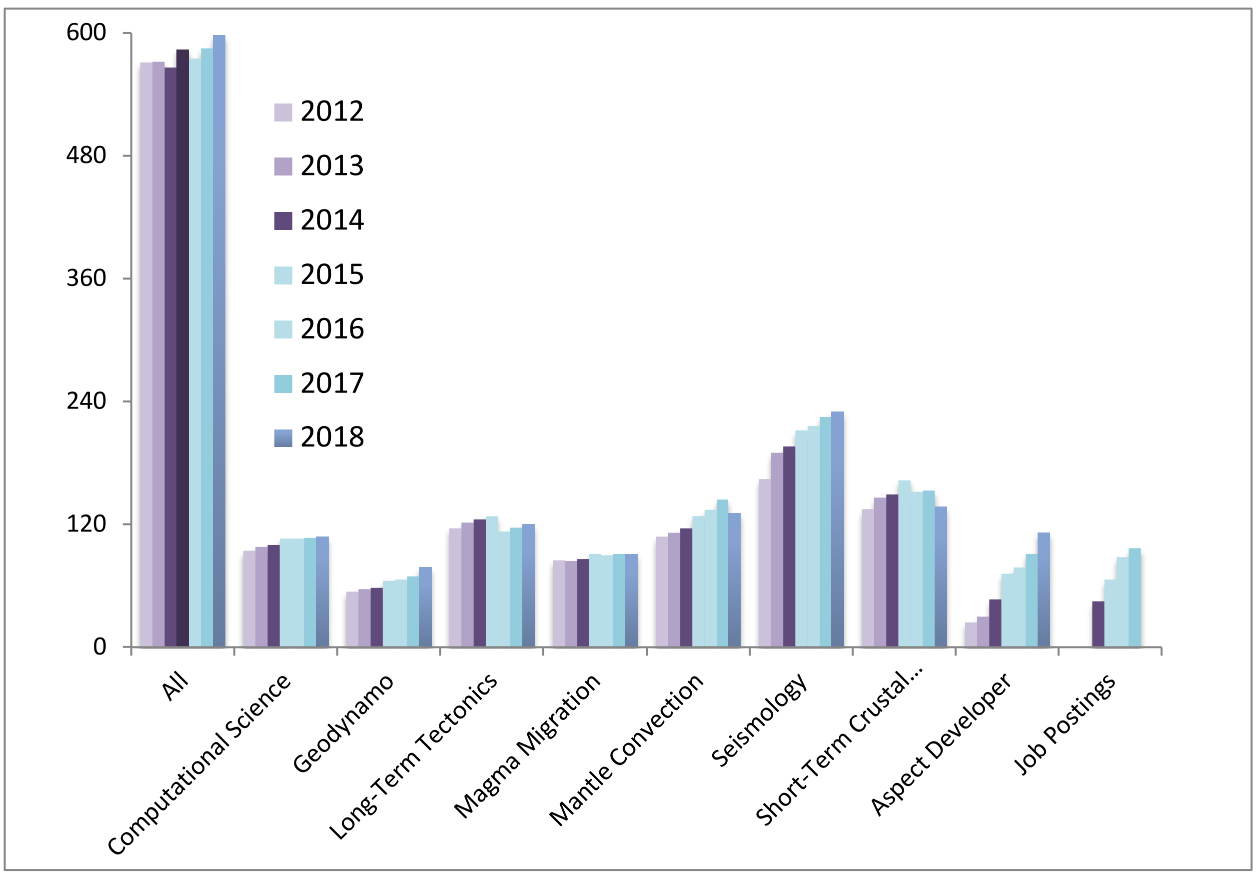


Figure 2a. CIG mailing list served 1195 unique individuals in 2018.

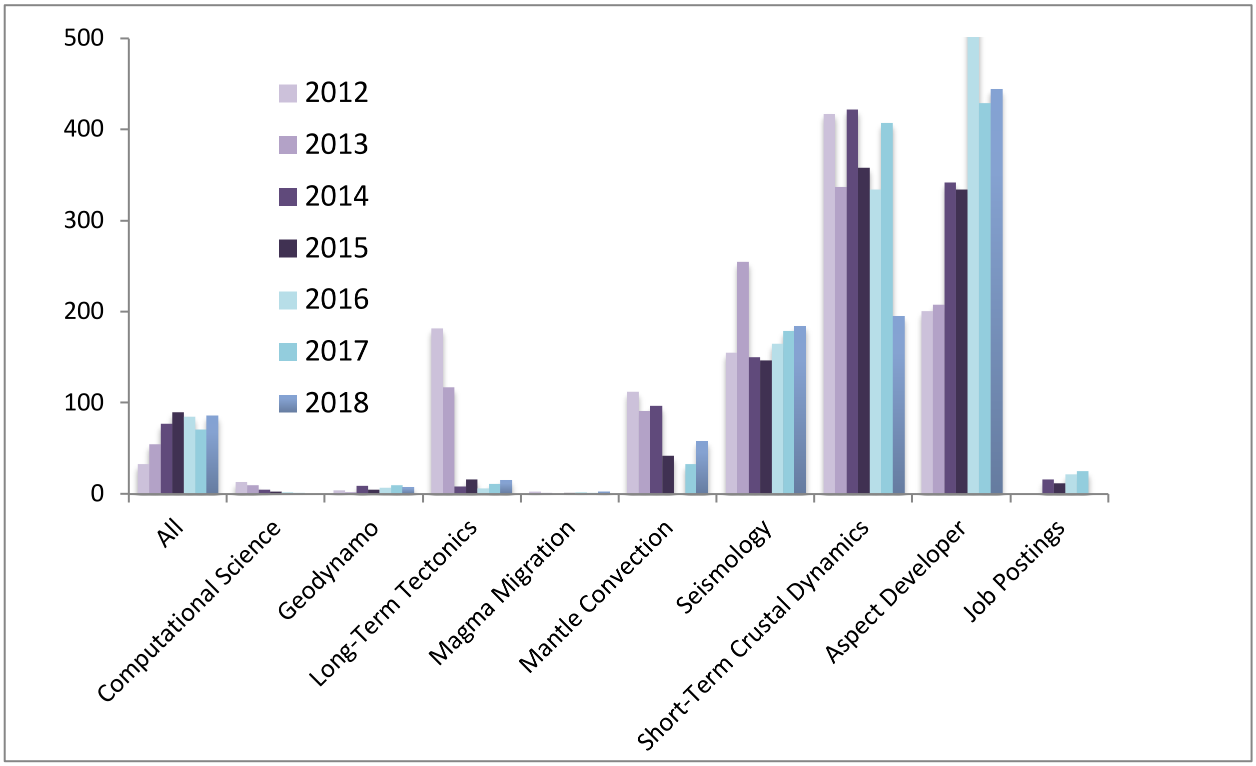


Figure 2b. CIG mailing list sent 1110 messages in 2018.

number of members for each list and number of messages sent. The domain-specific lists for groups that have released codes are used frequently for community support. Anyone may post a question or request for help; questions are wide-ranging from scientific application of a particular code to a problem, scientific methodology, to interpretation of error messages at compile or run time. Anyone may also respond. For active codes, developers and active users usually respond within a short time. CIG staff monitor the lists and will answer or redirect emails that remain unanswered. E-mail traffic for the year totaled approximately 1110 messages, with the most active domain-specific list, ASPECT, accounting for about 44% of the traffic, Short-Term Crustal Dynamics 19%, and Seismology 18%.

E-mail lists for elected or appointed committees, member representatives, and working groups are closed; only members of each group may subscribe or post. These lists support the specific governance-related responsibilities of these smaller groups (for example, voting by the member representatives).

Except for governance mailings lists, all mailings lists have transitioned to the new CIG forum beginning in late 2018. The forum allows easier searching and tagging of discussion threads as well as many modern features such that users can customize how they follow categories and issues, and trusted users can moderate their communities. At this time the forum has 277 members with strong adoption by the

ASPECT and PyLith communities. The email list CIG-ALL remains an option for community members to receive general announcements hence, we do not expect the forum to have as many users. In addition, some of our communities prefer to use github for similar functions.

Annual CIG Business Meeting

The CIG Annual Business meeting is open to the entire geodynamics community, including scientists from non-member institutions. The meeting reports on CIG activities of the past year and is a forum for open discussions of past and future CIG activities including strategic planning. This meeting is held in conjunction with the AGU Fall meeting in December, when many members of the community are gathered in one place.

CIG Quarterly Newsletter

Launched in August 2012, the CIG Quarterly Newsletter provides information on community and headquarters' activities and news, computational resources, upcoming meetings, current initiatives, and research highlights, along with news of activities from related organizations. The newsletter is available online and distributed to CIG's CIG-ALL general e-mail list.

GitHub

CIG software is developed using GitHub (see github.com/geodynamics) to support version control, community contributions, and CIG best practices for scientific software development. The platform provides continuous transparency about software development directions and offers a mechanism for contributors to introduce new topics and possible development directions for discussion. CIG provides tutorials and guidance for its software projects to leverage the potential of GitHub as the de-facto standard of software development for open-source projects. In 2018-2019 tutorials were held at the CIDER summer program, and Rayleigh and ASPECT hackathons. The next tutorial is scheduled for the 2019 Fall AGU Meeting.

Webinars

CIG's webinars are described below and are used to for more in-depth communication about software projects, research applications, best practices, and governance matters.

2.9 Metrics for Success

Activities to fulfill CIG's mission fall into three broad categories: software, people, and research impacts. We use a variety of metrics to monitor activity in each of these areas throughout this annual report.

These metrics do not encompass the impacts and improvements in computational capabilities in geodynamics that result from CIG's activities. Those are covered in the later sections of this report.

Software

CIG is a community open source software repository and development community. As such its impact to the community is largely measured by usage. Activity can be measured by the number of:

- code releases,
- code downloads,
- donated codes,
- HPC cycles used,
- repository commits, and
- lines of code.

People

CIG is community organization that must be responsive to its users. As such, its impact is largely measured by community involvement and outreach. This can be measured by the number of:

- governance participants,
- mailing list membership,
- workshop participants,
- webinar and online tutorial participants,
- YouTube views,
- education products developed,
- website traffic,
- users of CIG HPC allocations, and
- engagement with other communities

Research

CIG resources are used to advance research. As such, its impact is largely measured by its ability to enable research and research outcomes. These can be measured by the number and impact of:

- publications (abstracts, thesis, papers) and readership,
- acknowledgements and citations of CIG codes in publications and reports,
- proposals by researchers that draw on or use CIG resources,

- partnerships with other organizations,
- diversity of funding sources,
- invited presentations, and
- special sessions of national meetings organized around CIG resources or codes.

3. Facility Status

CIG's primary focus is the creation, training and distribution of open-source software via its website geodynamics.org. CIG is now regularly cited in the data management plan of scientists writing proposals to NSF, with PIs citing CIG's software donation policies. CIG's own data management plan focuses on:

- preservation and availability of software and algorithms,
- incorporation of current technology in the dissemination and distribution of code,
- documentation of code, workshops, meetings, and technical reports; and
- ongoing evaluation and assessment of workshops, training sessions, and other program elements.

CIG utilizes modern software tools to continue to harden its software engineering practice and maintains a robust repository to facilitate sharing of validated open source software. CIG's servers are continuously backed up to protect information in the case of catastrophic loss. All software is maintained with full version control and complete revision history in a Git open source repository. Doxygen routinely updates documentation as extracted from the source files. The build and test framework uses Jenkins. Jenkins test the build on 4 different machine configurations on a daily basis and as changes are committed to the repository. Build status is reflected on each software page.

Facility statistics below cover the periods January 1 – December 31, 2018.

3.1 CIG Code Repository

CIG encourages members to donate codes that have scientific value for the geosciences community. Codes come to CIG from two sources:

- Third-party codes –independently developed codes from small research groups or individuals, and
- Community Codes – codes developed via collaborations with CIG staff.

CIG has established a baseline of required elements for the acceptance of third-party code contributions. These requirements and process of accepting our code can be found at:

http://geodynamics.org/cig/dev/code-donation/

CIG's support categories reflect code development activity and from where primary support is received:

Developed	Actively adding features to support improved science or performance by CIG (D_CIG) or by community contributors (D_CONTRIB).
Supported	Actively supported, maintained and upgraded by CIG (S_CIG) or by community contributors (S_CONTRIB).
Archived	No development activity; not supported. No commitment to updates. (A)

Developed Codes have been validated, passed benchmarks established by the appropriate community, and are leading edge codes in geodynamics. Developed codes may either be donated or developed by CIG Staff or the community. These codes are under active development with a software development plan and are actively supported by CIG or the community through maintenance, technical assistance, training and documentation.

Supported Codes are mature codes that meet community standards but are no longer undergoing active development. Codes have been benchmarked and documented with examples and references such that they remain useful research tools. Supported codes include codes donated to CIG from members of our community. Minor changes such as bug fixes and binary upgrades are supported.

Archived Codes are included in the CIG GitHub code repository. This allows bug reports to be submitted and accessible to the community although little or no resources are applied for further development, maintenance, or support.

CIG formally collaborates with individual and groups of researchers, often as part of their proposal submissions to U.S. and international funding organizations, either in an advisory capacity or as a code repository.

Table 1 lists current repository holdings including software version, number of unique IP addresses that has downloaded the software in 2018, total lines of code, % change in number of lines of code from the previous year, number of commits in the repository, number of lifetime developers and current level of

Table 1. Repository Statistics

	Version	# unique IPs	Lines of Code	% Change	Commits	# developers	Support Level
Short-Term Crustal Dynamics							
Pylith	2.2.1	754	443,091	0%	32	9	D_CIG
Relax	1.0.7	231	1,418,794	0%	18	9	D_CONTRIB
VirtualQuake	3.1.1	132	49,056	1	9	16	D_CONTRIB
SELEN	*2.9.13	117	69483	0	1	3	S_CONTRIB
LithoMop	0.7.2	36	495,786	-	-	5	A
Long-Term Tectonics							
Gale	1.6.1/2.0.1	171	6,680,841	-	-	62	A
Plasti	1.0.0	28	10,967	-	-	1	A
SNAC	1.2.0	17	549,498	-	-	3	A
Mantle Convection							
ASPECT	*2.1.0	185	1,682,498	13%	1480	85	D_CIG
CitcomCU	1.03	52	70,167	0%	2	5	D_CONTRIB
CitcomS	3.3.1	147	239,468	0%	3	21	D_CONTRIB
ConMan	2.0.0	38	360,453	-	-	6	S_CONTRIB
Ellipsis3d	1.0.2	73	51,602	-	-	2	A
HC	1.0.7	56	491,145	0%	4	7	A
Seismology							
Axisem	1.3	90	110,419	-1%	30	12	D_CONTRIB
Burnman	0.9	42	70,342	28%	87	15	D_CONTRIB
Mineos	1.0.2	244	331,364	-	-	7	A
Flexwin	1.0.1	53	95,412	-	-	8	A
Seismic CPML		0	37,820	56%	59	6	S_CONTRIB
Specfem3D		85	10,541,775	7	190	51	D_CIG
Specfem3D Globe	7.0.0	204	2,181,266	0	7	53	D_CIG
Specfem3D Geotech	1.1	55	2,038,521	-	-	4	D_CONTRIB
Specfem2D		50	1,871,169	32%	195	33	D_CONTRIB
Specfem1D		35	5,367	-	-	9	S_CONTRIB
SW4	2.01	178	267,537	0%	3	18	D_CONTRIB
Geodynamo							
Rayleigh	*0.9.1	57	104,969	90%	217	12	D_CIG
Calypso	1.2.0	45	214,963	-	-	7	D_CIG
MAG	1.0.2	37	134,906	-	-	5	A
Computational Science							
Cigma	1.0.0	12	356,371	-	-	7	A
Exchanger	1.0.1	23	5,654	-	-	7	A
Nemesis	1.1.0	12	193	-	-	2	S_CONTRIB
Pythia	0.8.1.18	27	33,078	-	-	4	S_CONTRIB

*new releases in 2018

support. Statistics are as reported by gitinspector[3] which does not discriminate between line types e.g. comments versus code. CIG codes span 6 scientific domains and most use multiple programming languages. The majority of the executable code in the library use shell and scripting languages, C, C++, and Fortran77/90, or Python. Codes that have substantial active development, e.g. addition of new features (net increase) or code rewriting and cleanup (net decrease) are predominantly those that are actively supported by CIG staff, subawardees, or are cooperative efforts with other agencies and research groups.

Download statistics report the number of IP addresses that downloaded a code a single time to avoid bots; however, some bots are most likely still present in these statistics. The CIG Git repositories logged 2337 software commits during 2018. Over the repository lifetime, nearly 494 developers have contributed to code development.

3.2 Web Portal Statistics

The web tool used to report web traffic statistics is annually updated to remove bots. Hence, changes in activity in comparison to prior years may be due to better filtering for bots, worms, or replies with special HTTP status codes.

Website:	www.geodynamics.org
Unique visitors:	10,544
Visits:	18,455
Hits:	5,181,666 hits
Downloads	1164 files
Page Views:	43,779

3.3 High Performance Computing Statistics

CIG continues to provide opportunities to train scientists on HPC by maintaining allocations of HPC resources on community machines. For 2018, CIG applied for 64,160 SUs on Stampede2, 1,000,000 SUs on Comet, and 15,000 Comet GPU nodes but did not receive its full request. These allocations have been extended through September 30, 2019. CIG was awarded:

- Comet (Haswell): 500,000 GPUs
- Comet GPU: 15,000 GPU Hours
- Stampede2 (Skylake): 85,608 Node Hours
- Data Oasis: 10,000 GB
- Ranch: 10,000 GB

[3] https://github.com/ejwa/gitinspector

Stampede and Comet have been heavily used for development of ASPECT. CIG codes ASPECT, Calypso, Citcom, and SPECFEM scale well to hundreds or thousands of cores increasing the demand both for testing and from scientists whose problem size exceeds their available resources.

CIG also houses UC Davis' XSEDE Campus Champion. Campus Champions represent projects with XSEDE allocations, receive training, participate in monthly conference calls to learn methods for improving performance on XSEDE resources, and form a cohort of experts who can consult with one another. The Campus Champion in turn is expected to disseminate information to local users of XSEDE resources. As the name implies, XSEDE bases this program on the campus model; we continue to explore ways to expand this model in improving outreach to the entire CIG community.

3.4 Knowledge Transfer and Capacity Building

CIG builds and sustains its community through both virtual and in-person events. The Director, Associate Director, Staff, and Committee members represent the organization at numerous meetings, conferences and invited talks throughout the year. In addition, CIG actively sponsors outreach through workshops, training, and webinars.

Workshops, Training, and Engagement with Other Communities

CIG has a long tradition of leveraging its resources and community connections with other organizations for educational and strategic planning efforts. Workshops are community driven and organized. Special workshops for community planning reach across government agencies including national labs, other NSF branches, and the U.S. Geological Survey. CIG-sponsored workshops are typically held biannually for each domain. Joint workshops and tutorial sessions have been held historically in conjunction with annual meetings of the Southern California Earthquake Center (SCEC), Incorporated Research Institutions for Seismology (IRIS), Geological Society of America (GSA), EarthScope, Cooperative Institute for Dynamic Earth Research (CIDER), Canadian Geophysical Union (CGU), Earth-Life Science Institute (ELSI), Quantitative Estimation of Earth's Seismic Sources and Structure (QUEST), and Ada Lovelace Workshops (EGU).

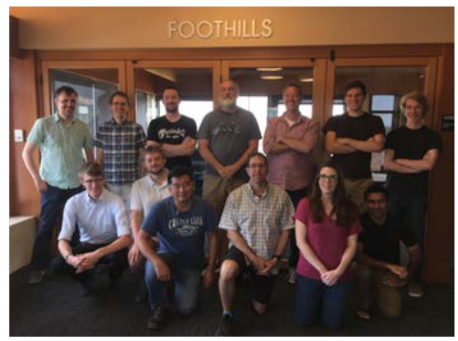
Upcoming workshops and training are posted online and advertised through CIG e-mail lists and those of our partner organizations. In 2018-2019, CIG will have offered 5 workshops and tutorials (Table 2) involving 125 predominantly early career participants from educational institutions, U.S. agencies, companies, and international partners. CIG partners with other organizations to expand its impact on the geodynamics community.

Table 2. 2018-2019 Workshops and Tutorials

Date	Title	Participants
July 8 – August 3	2018 CIDER summer program: ASPECT Tutorial & Scientific Software Development	(76)
September 15-19	Rayleigh Tutorial and Workshop	21 tutorial 17 hackathon
May 22 -June 1	2019 ASPECT Hackathon	24
June 10-14	2019 Crustal Deformation Modeling Workshop	51
July 22-26	Rayleigh Hackathon	16

2018 Rayleigh Tutorial and Workshop

17 user-developers gathered in Boulder, Colorado 16-19 September 2018 for the first Rayleigh Hackathon. Many thanks to Nick Featherstone and Jon Aurnou for leading this project and event.



The 2019 Rayleigh Hackathon will be held July 22-26 in Boulder, Colorado. This workshop will be reported on in 2020.

2019 Crustal Deformation Modeling Workshop

58 researchers gathered in Golden, Colorado June 10-14, 2019 for advanced training on the crustal deformation code PyLith. Instructors Brad Aagaard, Matt Williams, and Matt Knepley worked closely with participants to introduce new features of the code and help participants implement their research problems. The workshop included talks from invited early career and senior researchers on wide-range of topics in crustal deformation and rheology and community projects.

2019 ASPECT Hackathon

24 user-developers gathered in Heber, Utah May 21 – June 1, 2019 for the ASPECT Hackathon. A significant number (10) were first time participants. Code developers – Wolfgang Bangerth,

Juliane Dannberg, Anne Glerum, Menno Fraters, Rene Gasmöller, Timo Heister, and John Naliboff worked side-by-side with participants helping them make progress towards their research projects. The team made significant progress on outstanding and new issues and contributed 29 projects to the workshop report (in preparation). The group's productivity surpassed last year's hackathon as measured by the number of source files, lines of codes, pull requests, commits and tests.

Future Workshops

CIG plans to organize the following community workshops in 2019-2020:

Table 4. 2019-2020 Workshops and Tutorials

Date	Title
August 25-30, 2019	2019 Ada Lovelace Workshop - *Sponsored by EGU*
December 2019	2019 AGU Fall Meeting: Best Practices for Developing and Sustaining Your Open-Source Research Software
Spring 2020	CIG All Hands Meeting
May 3-6, 2020	2020 CGU Meeting Joint with CIG
May 2020	ASPECT Hackathon
June 2020	Lithospheric Modeling Tutorial and Workshop
TBD	Rayleigh Hackathon
TBD	PyLith Hackathon

New next year is the newly proposed Lithospheric Modeling Tutorial and Workshop. This is an outgrowth of the highly successful ASPECT Hackathons. Driving the demand for this workshop are the number of hackathon applicants who indicate interest in developing models using ASPECT (vs. developing code) specifically for lithospheric-scale research problems. The proposed workshop will be built on the Crustal Deformation Modeling Workshop model combining tutorials and tinker time with a science program. The workshop component will address the communities long standing desire for regular lithospheric deformation meetings in the U.S. The workshop will be part of a broader effort by the Long-Term Tectonics Working Group to develop a white paper (led by Jolante van WIjk, John

Naliboff, and Susanne Buiter) outlining a broader vision for the future direction of code development, research, and integration with the broader Earth Sciences community.

Promoting Community

CIG continues its dialogue with NSF and partner organizations SCEC, IRIS, and LLNL in designing a long-term strategy to meet the computing needs for geodynamics and seismology.

Webinars

The CIG Webinar Series draws from a pool of experts including applied mathematicians, computer scientists, and geoscientists, to both inform and disseminate knowledge on the tools and methodologies employed to further the study of problems in geodynamics. In 2018-19, the series focused on open source codes in geodynamics including perspectives on the next generation of community codes and open source codes and tools that are available to the community. The one-hour webinars are recorded for later viewing on the CIG YouTube channel and linked to CIG website. A full listing is given in Table 3.

Table 3. 2018- 2019 Webinar Schedule

Date	Presenters	Title
November 8	Louis Moresi and Romain Beucher, University of Melbourne	Introduction to thermal-mechanical lithosphere models with surface processes
January 31	Louis Moresi, University of Melbourne; and Ben Mather, University of Sydney	Introduction to Quagmire - a parallel python module for numerical landscape modeling
February 14	Tanu Malik, DePaul University; and Eunseo Choi, University of Memphis,	Conducting Reproducible Science with Sciunits
March 8	Eric Mittelstaedt, *University of Idaho*	Where have all the dimensions gone? Hands on methods for introducing students to non-dimensional numbers in laboratory and numerical modeling
April 11	Cian Wilson, Carnegie Science, DTM	TerraFERMA: a framework for rapidly building finite element models in geodynamics.
May 9	Carolina Lithgow-Bertelloni, UCLA	HeFESTO: A tool for exploring Earth's physical properties and their effects on mantle dynamics
May 16	Mark Ghiorso, OFM Research	Thermodynamic calculations and model generation using ENKI

YouTube

CIG's YouTube channel, *CIG Geodynamics*, hosts 217 videos of simulations contributed by the community, and recordings of past webinars and tutorials. The channel links to playlists of other community members (such as recorded lectures). Visitors are directed to the site mainly as a referral through YouTube and through geodynamics.org. Visitors come from an international community with the top viewers from the North America, Europe, India, Asia, and South America. The page has 399 subscribers and approximately 45,107 lifetime views (since 2008). The most popular videos are CIG webinars and tutorials.

AGU Presence

We hold the annual CIG Business Meeting in conjunction with the American Geophysical Union (AGU) Fall Meeting each year, taking advantage of the presence of more than 28,000 geophysicists in one place. The meeting provides a forum for information exchange and discussion about CIG operations.

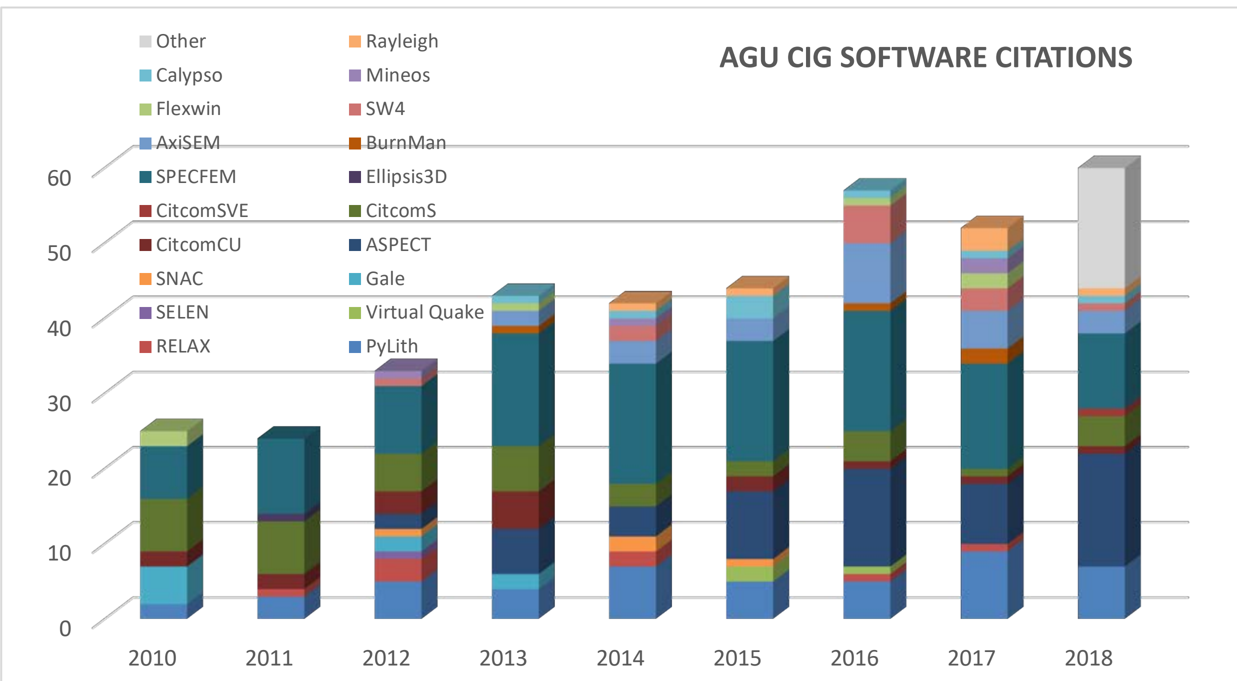


Figure 6. Number of CIG software mentions in an AGU abstract.

This year we scraped the data provided through AGU's open API to search for software mentions using natural language processing. The search returned 44 abstracts that mention CIG software. An additional 16 abstracts were self-reported by the community (other). These 60 abstracts (Figure 6) accepted for the 2018 Fall Meeting spanned 8 disciplines: Study of Earth's Deep Interior, Education, Geodesy, Nonlinear Geophysics, Seismology, Planetary Sciences, Tectonophysics, and Volcanology.

See Appendix C.

Distinguished Speaker Series

The CIG Distinguished Speaker Series continues into its 2nd year. The CIG Speakers Series seeks to promote computational modeling in geodynamics and related earth science disciplines. Speakers are drawn from a diverse pool of experts with exceptional capability to communicate the power of computation for understanding the dynamic forces that shape the surface and operate in the interior of our planet. Lectures are aimed at a broad scientific audience suitable for departmental or university colloquia series, and similar venues. Institutions with strong math and computational science departments or with diverse populations that are underrepresented in STEM are encouraged to apply.

The 2019-2020 Distinguished Speakers are Professor Sylvain Barbot (University of Southern California), *From grains to tectonic plate boundaries* and Professor Jolante Van Wijk (New Mexico Institute of Mining and Technology*), What creates the unique topography of East Africa?* Early requests show strong demand both nationally and internationally for both speakers.

4. Software Development

4.1 ASPECT

ASPECT is a finite element code to model problems in thermo-chemical convection in both 2D and 3D models and supports large-scale parallel computations. Its primary focus is the simulation of processes in the Earth's mantle and it is being extended to studies of lithospheric deformation and magma/mantle dynamics.

ASPECT is being developed by a large, collaborative, and inclusive community. 8 Principal Developers maintain the openly accessible repository on github and provide feedback to those 31 user-developers who have made 1557 commits to the repository in 2018, as well as the broader user community. These commits have added major new features to the code and were incorporated into a new releases of the software in June 2018, ASPECT 2.0.1 (doi: 10.5281/zenodo.1297145)) and 2.1.0 April 2019 (doi: 10.5281/zenodo.2653531). See https://github.com/geodynamics/aspect/releases/tag/v2.1.0 for a list of all changes.

Significant accomplishments of the past year

Major new features in ASPECT 2.1.0 release are:

- Major new melt transport related features: advecting fields with melt velocity, postprocessors to visualize compaction length, and characteristic length scales.
- Various improvements to the advection stabilization scheme that reduces unphysical diffusion, which leads to large improvements to the accuracy, especially for under resolved models.
- Coupling with the Geodynamic World Builder for initial conditions.
- A new example that looks up material properties from PerpleX.
- Dynamically generated citation information with each run.
- Various improvements for initial and boundary conditions supplied in ASCII tables.
- The heat flux through boundary cells is now computed using the consistent boundary flux method as described in Gresho and Sani (1987)[4], which is much more accurate than the previously used method.
- Added basic support for a volume-of-fluid interface tracking advection method in 2D incompressible box models.
- Various new benchmarks, tests, fixes, and smaller features.

And many other fixes and smaller improvements.

In addition, various other features have been worked on since the release:

- ASPECT and the testing infrastructure was switched to a new deal.II release.
- An alternative advection scheme (SUPG method) was implemented.

Timo Heister with his student Thomas Clevenger began work on efficient linear solvers. A first prototype of the new matrix-free geometric multigrid solver is implemented in ASPECT and has been benchmarked on Stampede2 in Austin, TX. They achieved weak and strong scaling up to 24,576 cores and more than 2 billion degrees of freedom. Compared to the current solver, they achieved about 3x faster computations, better strong scalability with about one fifth of the memory consumption. This allows computations of much larger problems with the same compute resources. The initial version was merged during the hackathon in May.

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[4] Gresho, P. M. and Sani, R. L. (1987), On pressure boundary conditions for the incompressible Navier-Stokes equations. Int. J. Numer. Meth. Fluids, 7: 1111-1145. doi:10.1002/fld.1650071008

On behalf of the LTT working group, John Naliboff, Juliane Dannberg and Rene Gassmöller expanded and tested the CIG code ASPECT to address problems related to long-term and short-term tectonics. These additions to ASPECT include:

- Viscoelastic deformation (publicly available)
- Viscoelastic-Plastic deformation (publicly available)
- Simplification and re-organization of key source code sections
- Visco-Plastic deformation with compressibility and phase changes (in development)
- Two-phase transport through brittle shear bands (in development)
- Normalization of brittle shear band characteristics (in development)
- New methods for processing and analyzing simulation data (in development)
- Testing new techniques for running computationally massive LTT-type simulations on HPC resources.

Project goals for the upcoming year

The developers have the following goals for ASPECT's development in the next year:

- Implementing and testing gradient plasticity methods, making the width of shear bands caused by plastic yielding independent of the cell size.
- Incorporating a rheology that realistically describes fluid-rock interactions during brittle deformation, such as hydro-fracturing.
- Improving ASPECT's performance and scaling by improving a geometric multigrid solver.
- Adding a basic interface for coupling ASPECT to surface evolution models.
- Find self-consistent formulations and, possibly, implement self-gravitation to more accurately compute the gravity vector and the geoid.
- Benchmarking viscoelastic deformation and applying it to glacial isostatic adjustment models.
- Prepare ASPECT for solving the adjoint equations to allow it to address inverse problems.
- Substantially extending the documentation of new features that have been added.
- Developing solver strategies that use entropy instead of temperature as primary variable, allowing for a more consistent handling of sharp phase transitions.

Additional LTT-related development of ASPECT through 2019 and 2020 includes the following topics:

- Compressible elastic deformation.
- Rate-state friction.

- Grain-size evolution within the lithosphere.
- Thermo-mechanical feedbacks between solid deformation, fluid migration and phase changes.

Outreach and Broader Impacts

Over the last year, CIG and the principal developers of ASPECT conducted community building, community support, and outreach activities. These include:

Proposals

- Successful proposal for early access to Frontera, the latest XSEDE supercomputer.
- ASPECT developers submitted a successful collaborative proposal "Collaborative Research: Development and Application of a Framework for Integrated Geodynamic Earth Models".

Tutorials/Workshops/Hackathons:

- July 2018, ASPECT tutorial, CIDER summer program, University of California, Santa Barbara
- September 2018, ASPECT tutorial, Durham University
- November 2018, ASPECT tutorial, The Centre for Earth Evolution and Dynamics at University of Oslo.
- April 2019, Geodynamics 101A: Numerical methods at the EGU General Assembly (I. van Zelst, J. Dannberg, A. Glerum, A. Rozel)
- 2019 Hackathon. May 21 - June 1, 2019, Heber City, Utah.

Presentations: *see also Appendix C for AGU presentations*

J. Dannberg, R. Gassmöller, T. Heister, W. Bangerth (2018), Advances in the geodynamic modelling code ASPECT. Keynote: German-Swiss Geodynamics Workshop in Noer, Germany.

J. Dannberg, R. Gassmöller, T. Heister (2018), Modeling the transport of melt and volatiles by integrating thermodynamic models in geodynamic simulations using the community code ASPECT. Janet Watson Meeting 2019: From core to atmosphere: Deep carbon.

J. Dannberg, J. Rudge (2019), Reconciling the formation of shear-induced melt bands in numerical and laboratory experiments: The effects of surface tension and a porosity-weakening bulk viscosity. 2019 EGU General Assembly.

J. Dannberg, R. Gassmöller (2019), Linking chemical trends in ocean islands to the complex interaction between starting plumes and the core-mantle boundary. 2019 EGU General Assembly.

R. Gassmöller, Scientific Software Development 101 (2018), Fundamentals. CIDER Summer Program.

R. Gassmöller, H. Lokavarapu, E. Heien, E.G. Puckett, W. Bangerth (2019), Accurately utilizing particle-in-cell methods for adaptively refined finite-element models. SIAM Geosciences.

Timo Heister. Seminar talks: University of Trieste, Italy; University of Utah, Guy F. Atkinson Distinguished Lecture; Goettingen, Germany, Zurich Switzerland.

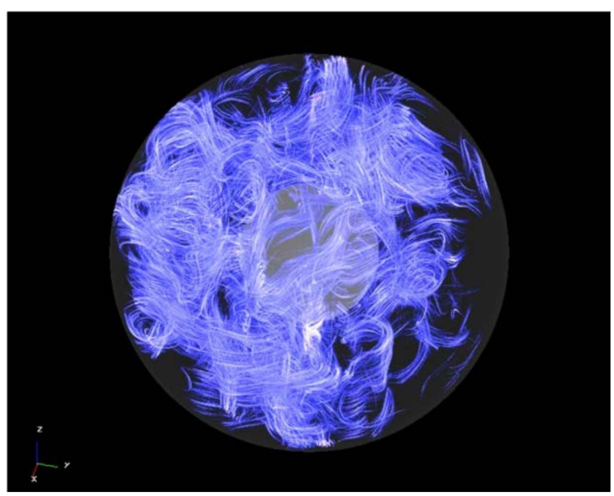
Wolfgang Bangerth. Seminar talks: University of Trieste, Italy. Conference presentations: Washington, DC; Lubbock, TX; Spokane, WA; Collegeville, MN.

4.2 Calypso

Calypso is a set of codes for magneto-hydro-dynamics (MHD) dynamo simulation in a rotating spherical shell using spherical harmonics expansion methods.

Significant accomplishments of the past year

A dynamic sub grid-scale (SGS) model has been implemented into the development version based on Calypso V1.2. The evaluated SGS terms are compared with results by Matsui and Buffett (2013)[5] which were obtained by finite element methods. To investigate roles of the turbulence in the small Ekman and magnetic Prandtl number condition, SGS terms from simulation results obtained by the INCITE project were investigated. The results are reported by Dr. Matsui in an invited talk of Japan Geoscience Union meeting on May 26th, 2019 in Chiba, Japan.



To improve the visualization of vector fields, line integral convolution (LIC) modules (right) were developed by Graduate Student Yangguang Liao (UC Davis). The LIC module works in a massively parallel environment in order to visualize during simulations. While the LIC module works successfully in a parallel environment, results suggest that data re-partitioning from simulation is required to obtain maximum performance. The paper reporting this study was presented at

[5] Matsui, H. and Buffett, B. A. (2013), Characterization of subgrid-scale terms in a numerical geodynamo simulation, Physics of the Earth and Planetary Interiors, 223, 77-85.

theEuroGraphics Symposium on Parallel Graphics and Visualization (EGPGV 2019), held on June 3, 2019 in Porto, Portugal.

Project goals for the upcoming year

In the coming year, Calypso v2.0 will be released. Calypso v2.0 will implement more sophisticated data IO (binary and compressed data). A dynamic sub-grid scale model is under verification. In addition, a whole sphere dynamo model to solve the Earth's dynamo more than a billion years ago will continue to undergo testing in collaboration with a graduate student in Tohoku University, Japan. For visualization, a parallel-volume rendering module is also implemented to the v2.0.

4.3 PyLith

PyLith is portable, scalable software for simulation of crustal deformation across spatial scales ranging from meters to hundreds of kilometers and temporal scales ranging from milliseconds to thousands of years. Its primary applications are quasi-static and dynamic modeling of earthquake faulting. Other applications include modeling crustal deformation from dike intrusions and inflation/deflation of magma chambers.

Significant accomplishments of the past year

Development has focused exclusively on completing a multiphysics formulation and its implementation with support for higher order discretizations. The multiphysics implementation provides a flexible interface for implementing different governing equations, such as coupling elasticity and fluid flow (poroelasticity). We added incompressible elasticity with displacement and pressure solution fields to demonstrate the capabilities of the multiphysics approach, and we are working with members of the community to implement poroelasticity.

We have added additional new features in addition to reimplementing much of the functionality in PyLith v2.2 using the new multiphysics formulation. PyLith now uses the PETSc time-stepping implementations and allows for specification of initial conditions. We completely reorganized the code and refactored several objects to increase modularity. This has led to more flexible output for boundary conditions and materials.

A beta version of the software was used in tutorials at the 2019 Crustal Deformation Modeling workshop, held June 10-14, 2019, in Golden, Colorado. We reorganized and revised the suite of examples to provide a more continuous spectrum of complexity from toy problems to simplified research-type problems. We expect to release v3.0.0 in August 2019, which will include most of the functionality of v2.2 for quasi-static problems. Version 3.1 will include reimplementation of the dynamic simulation and spontaneous rupture capabilities.

Development plans can be viewed in the projects repository on github:
https://github.com/geodynamics/pylith/wiki/Development-Plans

Project goals for the upcoming year

PyLith development in the upcoming year will focus on reimplementing the dynamic simulation and spontaneous rupture capabilities using the new multiphysics formulation and integrating the poroelasticity implementation being developed by members of the community (graduate students Josimar da Silva and Robert Walker). As part of the dynamic simulation capabilities, we will add parallel mesh loading, which will significantly increase the scalability of the code. We are also working with Jed Brown to leverage his work on libCEED for fast high order residual evaluation in dynamic simulations.

Outreach and Broader Impacts

PyLith development continues to drive development of the DMPlex finite-element data structures and operations in PETSc. PyLith also serves as an important test bed for new DMPlex features. As a result, new features are added to DMPlex that facilitates its use in numerical modeling in other scientific disciplines.

4.4 Rayleigh

Rayleigh has been developed under the guidance of the Geodynamo Working group. Its development has been led by working-group member Nick Featherstone. Rayleigh is a 3-D convection code designed for the study of dynamo behavior in spherical shell geometry. It evolves the incompressible and anelastic MHD equations in spherical geometry using a pseudo-spectral approach. Rayleigh employs spherical harmonics in the horizontal direction and Chebyshev polynomials in the radial direction. The code has undergone extensive accuracy testing. It demonstrates excellent parallel performance on national level supercomputers, including the Mira supercomputer at Argonne Leadership Computing Facility. In addition, this project benefits a broader scientific community, with specialists in stellar and planetary convection/dynamos now using the software as well.

Significant accomplishments of the past year

Development and optimization of Rayleigh has continued throughout the past year. These efforts include:

- Revision of the output quantity codes and output modules.

- Applying critical bug fixes (e.g., angular momentum conservation fix).
- Reviewing pull requests from other users.
- Adding additional command-line arguments to Rayleigh that facilitate the scripting of large-scale parameter-space studies.

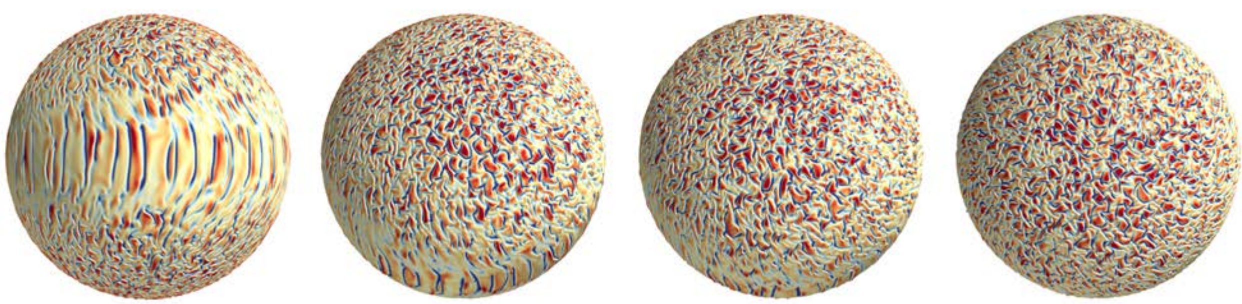
Project goals for the upcoming year

In the upcoming year, development efforts will be focused on:

- Implementing a sparse linear solve, based on the quasi-inverse method, for the time-stepping scheme.
- Exploring the potential for GPU-enabled spectral transforms to enable enhanced performance on GPU-capable HPC resources.
- Continued maintenance - applying critical bug fixes to the Rayleigh code and in reviewing pull requests from other users.

Members of the INCITE team *Frontiers in Planetary and Stellar Magnetism through High Performance Computing* will meet in Austin, Texas July 29 - August 2, 2019 to advance publication of results and plan for the next grand challenge INCITE proposal.

Outreach and Broader Impacts



Models computed by *Rayleigh* are informing a polar mission to the Sun. The proposed SOLARIS mission would study the 3D structure of the solar magnetic and velocity field, the variation of total solar irradiance with latitude, and the structure of the corona. Above images are snapshots of radial velocity computed from *Rayleigh* for the "Sun" taken from (left to right) the equator, lat=60, lat =70, and the pole. Red tones indicate upflows/positive vorticity. Blue tones indicate downflows/negative vorticity. Rotation is opposite solar rotation -- downflows have positive vorticity due to angular momentum conservation.

The *Rayleigh* team held a tutorial on September 15, 2018 and the follow-on development workshop and hackathon on September 16–19, 2018 in Boulder, Colorado. The 2nd development workshop and hackathon will be held July 22–26, 2019 in Boulder, Colorado with approximately 16 participants.

4.5 SPECFEM

SPECFEM3D_GLOBE simulates global and regional (continental-scale) seismic wave propagation. Effects due to lateral variations in compressional-wave speed, shear-wave speed, density, a 3D crustal model, ellipticity, topography and bathymetry, the oceans, rotation, and self-gravitation are all included.

The main focus is the continued development of the spectral-element seismic wave propagation solvers SPECFEM3D and SPECFEM3D_GLOBE for exascale simulations, which are estimated to become feasible in the 2020–2022 timeframe. The project is a collaboration with NVIDIA and Intel's Exascale Lab to optimize the code for their processors. These exascale efforts will focus on the following aspects of code development and optimization: 1) GPU/Phi/ARM computing, 2) OpenMP, 3) MPI optimization, 4) I/O, and 5) fault tolerance. To achieve these goals, this project is one of eight partnerships selected for ORNL's Center for Accelerated Application Readiness program to prepare computational science and engineering applications for highly effective use on the OLCF system Summit.

Core Spectral-Element Code Developments

Development and enhancement of SPECFEM3D and SPECFEM3D_GLOBE software suite continue on three main fronts.

- A new SPECFEM3D–based quasi-static solver simulating post-seismic rebound is basically ready and will be released this spring. Graduate student Leah Langer and Research Scientist Hom Nath Gharti are the main developers of this package. The effects of topography and bathymetry, 3D heterogeneity, and rheology on calculations of post-seismic relaxation are currently being investigated.
- A second development involves a SPECFEM3D_GLOBE-based quasi-static infinite-spectral-element method for simulations of post-glacial relaxation with full gravity. This solver is also being developed by Leah Langer and Hom Nath Gharti, and graduate student Uno Vaaland is using it as a basis for fully 3D simulations of sea level change.
- The third development focuses on a full gravity version of SPECFEM3D_GLOBE for simulations of the Earth's free oscillations. This is Hom Nath Gharti's current main area of research. This has turned out to be much more challenging than originally anticipated since Gauss-Lobatto-

Legendre quadrature cannot be used for the mass matrix. Basically, the assumption of a diagonal mass matrix is no longer invalid, and one has to resort to Gauss quadrature. With this crucial insight, the team is optimistic that they can finally make a full-gravity version work.

Peripheral Software Developments

In collaboration with ORNL (Norbert Podhorszky) and the ObsPy group (Lion Krischer), excellent progress continues on further developing the Adaptable Seismic Data Format (ASDF). All provenance related to earthquakes, stations, and processing is stored in an HDF5 container to ensure complete reproducibility. SPECFEM3D and SPECFEM3D_GLOBE have been adapted to read and write the new data format. ADIOS file format is used for other I/O, e.g., kernels and check pointing. The team is working with NVIDIA and IBM to optimize ASDF and ADIOS I/O in the context of the CAAR program.

The seismic imaging and inversion toolkit SeisFlows continues to be very actively developed, with lots of new (international) users trying it out, giving feedback, and making useful contributions. It is not only used for seismic imaging and inversion, but it has also attracted interest from users in medical imaging and nondestructive testing. A first paper documenting the software package has been submitted for publication.

Collaborations continue with Shantenu Jha at Rutgers University to develop an *Ensemble Toolkit for Earth Sciences* so as to move towards fully automated imaging and inversion workflows. This workflow management tool will stabilize and expedite seismic imaging and inversion, e.g., by providing recovery mechanisms for simulation failures. Adjoint tomography involves thousands of forward and adjoint simulations, and a robust workflow management system is badly needed for practical applications and productivity.

Software Testing & Documentation

For both core SPECFEM3D and SPECFEM3D_GLOBE development and peripheral software development the team has increased their software testing and documentation efforts. In addition to BuildBot, Jenkins and Travis are now used for unit testing.

4.6 SW4

SW4 implements substantial capabilities for 3-D seismic modeling, with a free surface condition on the top boundary, absorbing super-grid conditions on the far-field boundaries, and an arbitrary number of point force and/or point moment tensor source terms. Each source time function can have one of many predefined analytical time dependencies, or interpolate a user defined discrete time series.

Significant accomplishments of the past year

Released this year, Version 2.0 (doi: 10.5281/zenodo.1063644) of SW4 implements mesh refinement with hanging nodes. Mesh refinement is currently supported in the Cartesian portion of the mesh but can be used together with realistic topography and heterogeneous isotropic viscoelastic material models.

Outreach and Broader Impacts

SW4's development is based at Lawrence Livermore National Laboratory where it is applied in studies of earthquakes and man-made explosions. SW4Lite was one of the applications used in testing the performance of the National Nuclear Security Administration's (NNSA) *Trinity* platform installed at Los Alamos National Laboratory[6]. Advanced Technology Systems are part of the NNSA's Computing Strategy which underpins the complex qualification workload for the United States nuclear security program.

4.7 Virtual Quake

Virtual Quake is a boundary element code that performs simulations of fault systems based on stress interactions between fault elements to understand long term statistical behavior. Earth's crust is modeled as a homogenous elastic half-space, with faults being represented as dislocations within this medium. Each fault is made up of many interacting square elements. Each element accumulates stress at a user-defined rate and uses coulomb friction laws to determine the failure threshold. Upon failure, elements slip back to equilibrium, transferring stress through the fault system via Okada Green's functions. Cascades of element failures are recorded as earthquakes.

Virtual Quake is optimized for fast computation of large ensemble simulations. The fault model remains static, allowing for the precomputation of all stress interactions prior to long-term slip simulation. Each interseismic period is then a simple update of all element stresses to the time of next element failure. Virtual Quake can also be run on multiple processors, allowing many hundreds of thousands of years of seismicity on a large fault model to be simulated on common desktop hardware in the time frame of a few hours.

Virtual Quake is developed primarily by researchers at University of California, Davis, but has contributions by researchers around the world. Current research projects that have made use of Virtual Quake include modelling seismicity in California, Iran, and China, as well as theoretical investigations into the effects of fractal fault traces on known seismic scaling laws.

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[6] https://cfwebprod.sandia.gov/cfdocs/CompResearch/docs/bench2018.pdf

Significant accomplishments of the past year

Tsunamis are one of the most damaging natural disasters. They are often caused by seafloor displacement due to large subduction zone earthquakes. In a recent study[7], initial seafloor uplift simulated by Virtual Quake was used as input to the Tsunami Squares method to simulate coastal run-up and wave heights from the 2011 Great East Japan Earthquake. These large events are rare and understanding the limited observation data from this event is important in understanding risk from tsunamigenic events. An upcoming Asian Pacific Rim Universities (APRU) workshop will touch on the topic of earthquakes and tsunami simulations.

The team is currently developing “simple VQ” which is a stripped-down version of VQ that is more appropriate for local simulations and continues to interact with the SCEC community that is developing simulations on an alternative platform (“RSQSim”).

4.8 Software Pipeline

FDPS-SPH

CIG is actively working with Prof. Miki Nakajima (University of Rochester) and lead developer Dr. Natsuki Hosono (JAMSTEC) on developing their open source impact code, FDPS-SPH, for release and hosting by CIG. The code is based on the Framework for Developing Particle Simulator (FDPS) an application-development framework which helps application programmers and researchers to develop mesh-less, particle-based simulation codes. FDPS-SPH implements the smoothed particle hydrodynamics (SPH) methods for the study of impacts of planetary-type bodies. Compared to existing impact codes FDPS-SPH is completely open-source, makes use of modern development methods and builds on existing libraries. CIG personnel are providing support and guidance on best practices, in particular developing a user manual, creating an architecture-independent build system, a system for user input files, and a unit test system. Additionally, support is provided for the interface between FDPS-SPH and the ANEOS software for the computation of equation of states for materials undergoing shocks. The software is already available and actively used for research, and an official release is planned within the next year when the code reaches CIG's minimum best practices.

[7] Wilson, J. M., Schultz, K. W., Rundle, J. B., Ward, S. N., Grzan, D., Saeed, O. and Kausahl, H. (2019), Tsunami Squares simulation of megathrust generated waves: application to the 2011 Tohoku Tsunami, submitted.

ConMan2

At present, a new version (3.0) of ConMan is being prepared for public release and is expected to be available by the end of summer 2019. The updates to ConMan began in 2018 after CIG staff and the principal ConMan developer (Prof. Scott King) recognized that the current version of ConMan no longer compiles successfully on a wide range of platforms. To address this issue, Scott King provided a significantly revised version of ConMan, which compiles on nearly all operating systems and also contains a number of key feature improvements. To date, the new version has been tested on a wide range of operating systems by CIG staff. Final revisions to documentation and test suites are being conducted by CIG and Scott King.

CitcomSVE

Prof. Shijie Zhong (University of Colorado) has expressed interest in CIG hosting a viscoelastic loading modeling package CitcomSVE, where “VE” stands for viscoelastic. This code has a lot of similarity to CitcomS in code structure, except that it uses viscoelastic rheology on a deformable (small-deformation) lagrangian grid. Applications include problems in post-glacial rebound, tidal loading and volcanic loading. The project has been under development with NASA support with a goal to make it publicly available to the community. CIG will evaluate the package when it becomes publicly available for conformance to software standards and help the developers prepare it for broader release.

5. Scientific and Broader Impacts

5.1 Science Highlights

SW4: Modeling High frequency 3D Ground Motion Simulations

Rodgers et al. (2019)[8] investigate the effects of fault geometry on 3D ground-motion for a M_w 6.5 earthquake on the Hayward fault (HF) using SW4, a 4th order seismic wave propagation code. Their simulations of large earthquakes on the northeast-dipping HF using the U.S. Geological Survey 3D seismic model have shown intensity asymmetry with stronger shaking for the Great Valley Sequence to the east relative to the Franciscan Complex to the west. For frequencies up to 5 Hz, peak ground velocities to the west of the HF show much higher amplification than to the east. They conclude that

[8] Rodgers, A. J., Pitarka, A., and McCallen, D. B. (2019), The Effect of Fault Geometry and Minimum Shear Wavespeed on 3D Ground-Motion Simulations for an MwM 6.5 Hayward Fault Scenario Earthquake, San Francisco Bay Area, Northern California. Bulletin of the Seismological Society of America doi: https://doi.org/10.1785/0120180290

shaking intensity to the west depends on the minimum shear wave speed value 250 m/s versus 500 m/s, which could underestimate intensities for frequencies above 0.5 Hz. Higher intensities to the west can be attributed to low upper crustal shear wave speeds.

SPECFEM: Probing Mars interior with 3D seismic wave simulations

Contributed by Ebru Bozdağ and Daniel Peter

InSight launched on May 5, 2018 from Vandenberg Air Force Base on the coast of California, and successfully landed in the Elysium Planitia, the second largest volcanic region on Mars surface, on November 2, 2018 after a 300-million-mile journey. The mission is the first to gather geophysical measurements from surface-installed instruments to explore the internal structure and dynamics of a solar system object other than the Earth or Moon. Understanding Mars' interior and its dynamics will also help us understand the formation of the Earth and how our planet, together with our solar system, has evolved over time.

The lander's geophysical payload includes a very broad band seismometer to listen to the seismic activity on Mars. To better characterize and interpret seismic signals recorded by the single broad-band seismometer deployed to Mars, we run numerical seismic wave simulations using a global 3D wave propagation solver, SPECFEM3D_GLOBE (Komatitsch & Tromp 2002)[9]. The simulations have been initiated by implementing a 1D reference model for Mars, followed by superimposing topography and crustal thickness variations to analyze the distinct crustal dichotomy between the southern and northern hemispheres specifically on surface waves. Following Earth simulations, attenuation, Mars ellipticity, rotation and gravity (Cowling approximation) are all taken into account during simulations. All Mars models will be soon integrated into the SPECFEM3D_GLOBE package available through CIG.

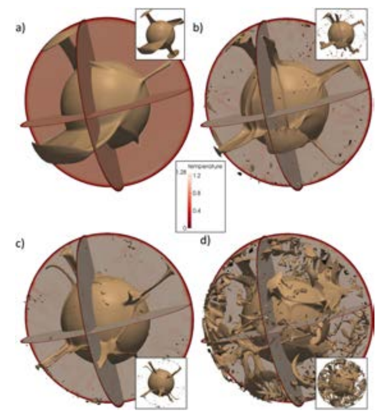
Every wiggle from Mars is invaluable, thus 3D wave simulations, both at regional and global scales, are complementary to other modelling techniques to reveal Mars' mysteries. Future steps consist of implementing a set of crustal models as well as 3D mantle models derived from thermal evolution simulations and Mars' seismic sources – mars quakes, meteorite impacts, etc. Adjusting and refining

[9] Komatitsch, D. and Tromp, J. (2002), Spectral-element simulations of global seismic wave propagation—I. Validation. Geophysical Journal International, 149: 390-412. doi:***10.1046/j.1365-246X.2002.01653.x***

these models based on observed seismic waveforms from InSight will add to our understanding of the Mars interior.

CitcomS: Venus Resurfacing Constrained by Geoid and Topography

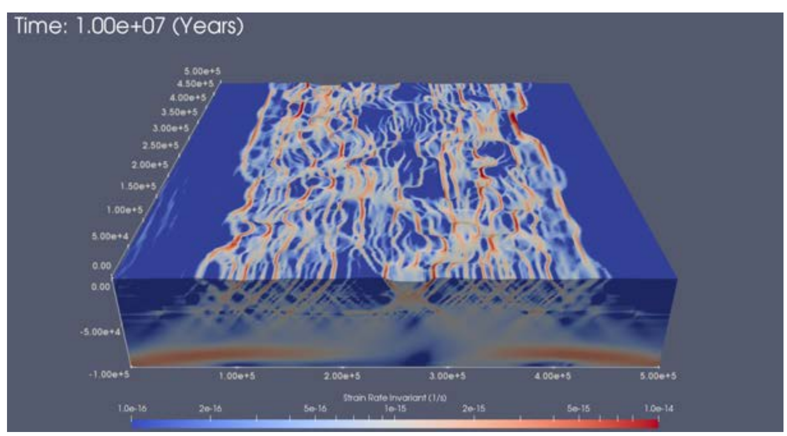
Contributed by Scott King[10]



When compared with Mars or the Moon, Venus has a small number of craters, indicating that the planet has been resurfaced in the last 250–750 Myr. The primary explanations for the young crater age of the surface of Venus are progressive volcanic resurfacing and a period of mobile-lid tectonics. However, model results also must explain the offset in the center of mass (CM) of the planet and its geometrical center (CF) as well as a lack of a geodynamo. King (2018) used CitcomS 3.3.2 to study the role of initial conditions, mantle potential temperature, and core potential temperature on Venus surface mobility. The results show that while mobile lid tectonics produces progressive resurfacing, it overpredicts the CM-CF offset. In addition, the resulting heat flow would also be sufficient to power a core dynamo which Venus lacks. Hence, Venus' youthful surface is inconsistent with catastrophic overturn.

Elucidating the origins of complex lithospheric deformation patterns

Contributed by John Naliboff



High-resolution thermal-mechanical simulation of continental extension using ASPECT. The model spatial extent is 500x500x100 km and the upper free surface boundary allows topography to develop over time in response to continued extension. Deformation is driven by prescribed outflow velocities on the sidewalls (5 mm/yr total), which is combined with initial randomized strength perturbations. These two factors produce normal faulting patterns that vary in orientation along the model length as distinct fault strands deflect around strong crustal domains or transfer deformation to

[10] King, S. D. (2018), Venus resurfacing constrained by geoid and topography. Journal of Geophysical Research: Planets, 123, 1041– 1060. https://doi.org/10.1002/2017JE005475

new fault strands. Faults can be identified as regions of concentrated deformation (e.g., high-strain rate) adjacent large blocks with minimal internal deformation (low-strain rate). This work was done in collaboration between collaborators John Naliboff, UC Davis/CIG, and Sophie Pan, Rebecca Bell, and Chris Jackson all at Imperial College.

5.2 Publications

Publications included in our database include refereed papers submitted by authors as well as those found using google scholar based on keyword search by author, software package name, or DOI. In 2018, the community published 105 journal articles using CIG codes. See Appendix D.

5.3 Cross Cutting Initiatives

CIG is working with the Data Sciences Initiative at UC Davis to understand the impact of outreach efforts on science, communities, and careers. An outgrowth of CIG's involvement in software sustainability and citation, the study looks closely at two CIG communities and how different outreach efforts, workshops and hackathons, have contributed to career growth and science through examination of collaboration networks as represented by peer reviewed publication.[11] Examination of two of our communities at different states of maturity is moving the ASPECT community towards offering user oriented workshops in the model of the successful Crustal Deformation Modeling workshops offered by the short-term tectonics community. ASPECT networks also reveal how important hackathons have been in creating community and collaborations as well as launching its early career scientists.

ASPECT and Rayleigh are currently exploring collaborations with the yt project (https://yt-project.org/). Both communities are looking for alternatives to Vapor and Paraview to visualize data in parallel. yt is an open-source, permissively-licensed python package for analyzing and visualizing volumetric data. yt supports structured, variable-resolution meshes, unstructured meshes, and discrete or sampled data such as particles. The yt-project is looking for ways to expands its functionality to accommodate geodynamic data and simulations. Currently yt is focused on astrophysics data and the team is building new features for weather and neuroimaging.

[11] Hwang, L. J., Pauloo, R. A. and Carlen, J. (2019), Assessing Impact of Outreach through software citation for community software in geodynamics, *submitted to IEEE Transactions CISE.*

5.4 Beyond the Geosciences

CIG participates and contributes to communities outside the geosciences that impact the research it supports including communities in high performance computing and software sustainability through initiatives such as FORCE11, WSSSPE, codemeta, IDEAS_ECP, and URSSI. CIG staff and community members have delivered talks on best practices in software and community building to these and other communities.

Through these activities we have seen an increased interest in CIG best practices in community building and software. Growing open source software user-developer communities through hackathons has garnered much interest from the community and encouraged the team to publish a paper on *The role of scientific communities in creating reusable software: lessons from geophysics* (Kellogg et al., 2019).[12] In addition, CIG has delivered invited talks at the 2019 SIAM Conference on Computational Science and Engineering and will give a on this topic to a wider audience in the Fall. In addition, CIG staff member Rene Gassmöller has been awarded the Better Scientific Software Fellowship of the Department of Energy's IDEAS-ECP project to increase developer productivity and community sustainability of scientific software projects and served as a panel member for 2018 AGU Community Forum: The Role of an Open-Source Software Initiative Within AGU.

[12] Kellogg, L. H. Hwang, L. J., Gassmöller, R., Bangerth, W. and Heister, T. (2019), The Role of Scientific Communities in Creating Reusable Software: Lessons from Geophysics, in *Computing in Science & Engineering*, vol. 21, no. 2, pp. 25-35, 1 March-April 20. doi: 10.1109/MCSE.2018.2883326

6. CIG III 5-Year Budget

A.&B.	**Salaries and Wages**	2,434,254
C.	**Fringe**	1,012,062
D.	**Equipment**	60,000
E.	**Travel**	289,900
F.	**Participant Support**	956,455
G.	**Other Direct Costs**	2,527,492
H.	**Total Direct Costs**	7,280,165
I.	**Indirect Costs**	1,538,829
	Total Costs	$8,818,994

Total 5-year commitment by NSF: $8.82 M

In 2019, $5.1M of in kind support for computational time and a supplement of $7,298 was received to support travel for the Frontera project bringing the total funds for the award to $8.89M.

Appendix A: Institutional Membership

U.S. Academic Institutions

Argonne National Laboratory (MSC)
Arizona State University
Boston University
Brown University
California Institute of Technology
California State University, Northridge
Carnegie Institution of Science, DTM
Clemson University
Colorado School of Mines
Colorado State University
Columbia University
Cornell University
Georgia Institute of Technology
Harvard University
Indiana University
Johns Hopkins University
Lawrence Livermore National Laboratory
Los Alamos National Laboratory (ES)
Massachusetts Institute of Technology
Michigan State University
National Center for Atmospheric Research
New Mexico Institute of Mining and Technology
Northwestern University
Oregon State University
Pennsylvania State University
Portland State University
Princeton University
Purdue University
Rensselaer Polytechnic Institute
Rice University
State University of New York at Buffalo
State University of New York at Stony Brook
Texas A&M University
Tulane University
U.S. Geological Survey (Menlo Park)
University of Alaska, Fairbanks
University of Arizona
University of California San Diego
University of California Santa Cruz
University of California, Berkeley
University of California, Davis
University of California, Los Angeles
University of Colorado
University of Connecticut
University of Hawaii
University of Houston
University of Kentucky
University of Louisiana, Lafayette
University of Maine
University of Maryland
University of Memphis
University of Michigan
University of Minnesota
University of Missouri-Columbia
University of Nevada, Reno
University of New Mexico
University of Oregon
University of Rochester
University of Southern California
University of Texas at Austin
University of Utah*
University of Washington
Virginia Polytechnic Institute and State University
Washington State University
Washington University in St. Louis
Woods Hole Oceanographic Institution

International Affiliates

Australian National University
Cardiff University
Earth Observatory of Singapore
Geological Survey of Norway (NGU)
GNS Science
Johanes Gutenberg University Mainz
Monash University
Munich University LMU
University of Alberta
University College London
University of Bristol, UK
University of Leeds*
University of Melbourne
University of Oslo
University of Science and Technology of China
University of Sydney
University of Toronto
University of Tuebingen, Germany
Victorian Partnership for Advanced Computing

*New Members

Appendix B: CIG Working Group Members

Computational Science (8)

- Brad Aagaard, U.S. Geological Survey
- Wolfgang Bangerth, Colorado State University, Fort Collins
- Jed Brown, Argonne National Laboratory
- Nick Featherstone, University of Colorado, Boulder
- Timo Heister. Clemson University
- Matthew Knepley, Rice University
- Eldridge G. Puckett, University of California, Davis
- Marc Spiegelman, Columbia University

Dynamo (11)

- *Lead,* Jon Aurnou, University of California, Los Angeles
- Bruce Buffett, University of California, Berkeley
- Mike Calkins, University of Colorado, Boulder
- Peter Driscoll, Carnegie DTM
- Nick Featherstone, University of Colorado, Boulder
- Moritz Heimpel, University of Alberta
- Hiroaki Matsui, University of California, Davis
- Peter Olson, Johns Hopkins University
- Krista Soderlund, University of Texas, Austin
- Cian Wilson, Carnegie DTM
- Rakesh Yadav, Harvard University

Education Working Group (9)

- Catherine Cooper, Washington State University
- Frederik J. Simons, Princeton University
- Gabriele Morra, University of Louisiana, Lafayette
- John Louie, University of Nevada, Reno
- John Vidale, University of Southern California
- Louis Moresi, University of Melbourne
- Sanne Cottaar, University of Cambridge
- S.-H. Dan Shim, Arizona State University
- Sarah Stewart, University of California, Davis

Long-Term Tectonics (8)

- *Co-Chair,* Jolante van Wijk, New Mexico Tech
- *Co-Chair,* Cedric Thieulot, Utrecht University
- Mark Behn, Boston College
- Susanne Buiter, Norwegian Geological Survey
- Claire Currie, University of Alberta
- Lijun Liu, University of Illinois, Urbana-Champaign
- Eric Mittelstaedt, University of Idaho
- John Naliboff, University of California, Davis

Magma Migration (8)

- *Lead,* Marc Spiegelman, Columbia University
- Mark Behn, Woods Hole Oceanographic Institution
- Marc Hesse, University of Texas, Austin
- Garrett Ito, University of Hawaii
- Richard Katz, Oxford University
- Matt Knepley, University of Chicago
- Ikuko Wada, Woods Hole Oceanographic Institution
- Cian Wilson, Columbia University

Mantle Convection (8)

- *Lead,* Scott King, Virginia Polytechnic Institute
- *Lead,* Shijie Zhong, University of Colorado, Boulder
- *Lead,* Thorsten Becker, University of Texas, Austin
- Juliane Dannberg, University of California, Davis
- Timo Heister, University of Utah
- Margarete Jadamec, University of Buffalo
- Mark Richards, University of Washington
- Max Rudolph, University of California, Davis

Seismology (7)

- *Lead,* Arthur Rodgers, Lawrence Livermore National Lab
- Tim Ahern, IRIS Data Management System, Seattle
- David Al-Attar, University of Cambridge
- Ebru Bozdag, Colorado School of Mines
- Carene Larmat, Los Alamos National Lab
- Carl Tape, University of Alaska at Fairbanks
- Michael Wysession, Washington University at St. Louis

Short-Term Crustal Dynamics (4)

- *Lead,* Brad Aagaard, U.S. Geological Survey
- Eric Hetland, University of Michigan
- Eric Lindsey, University of California, Davis
- Charles Williams, GNS Science

Appendix C: 2018 Fall AGU Presentations

A mostly self-reporting list of presentations by CIG scientists at the 2018 Fall AGU meeting. List was augmented with key word searches by software name.

Monday, December 10

DI13B-0029 A Comparative Study of Slab-edge Driven Mantle Flow in the Alaska subduction Zone, the Cocos-Nazca Gap, and the Vanuatu-North Fiji system. Margarete Ann Jadamec, Karen M. Fischer, Patricia MJ Durance, and Kirstie LaFon Haynie.

DI13B-0034 Small Scale Flow Induced Azimuthal Seismic Anisotropy beneath Madagascar: Implications for Rheology. Tahiry Andriantsoa Rajaonarison, D. Sarah Stamp, Stewart Fishwick. Sascha Brune. and Anne Glerum.

G13B-0516 Cryospherically Induced Stress Fluctuations in Tectonically Active Southern Alaska. Jeanne M Sauber,, Natalia A Ruppert, and Christopher Rollins.

S13C-0436 Analogue and Numerical Modelling of Elastic Strain Effect on Coda Wave Interferometry. Jérôme Azzola, Jean Schmittbuhl, Dimitri Zigone, Olivier Lengliné,, Vincent Magnenet, and Frederic Masson.

T13A-08 Geodynamic Modeling of Mantle Evolution of the South China Sea and Surrounding Subduction Systems. Zhiyuan Zhou and Jian Lin.

T13F-0295 Quantitative analysis of distributed normal faulting patterns in 3D thermal-mechanical simulations of continental rifting. John Naliboff, Sascha Brune, and Tim Hake.

T13I-0353 Multicycle Simulations of Fault Parameters of Mw6-7 Inland Faults. Anatoly Petukhin, Percy Galvez, Paul Somerville, and Andreas Skarlatoudis.

Tuesday, December 11

DI21B-001 Investigation of dynamic sub-grid scale (SGS) terms in dynamo simulations with small Ekman number. Hiroaki Matsui and Bruce A Buffett.

DI22A-05 Dynamics of Stagnant Slabs in the Mantle Transition Zone. Ying Zhou and Zhen Guo.

DI23A-01 Sensitivity kernels for geodynamic surface observables based on adjoint methods. Jacqueline Austermann, David Al-Attar, Wolfgang Bangerth, and Mark Hoggard.

DI23A-02 CitcomSVE: A massively parallelized finite element software package for modeling elastic and viscoelastic deformation on regional and global scales. Shijie Zhong.

DI23A-04 Nonlinear Constitutive Laws for Fault Dynamics. Matthew Knepley, Brad Aagaard, and Charles A Williams.

DI23A-05 Pythonic Parallel Implementation of 3D Lattice Boltzmann Method for Geophysical and Geological Applications.Gabriele Morra, Peter R Mora, and David A Yuen.

DI24B-01 Adaptive Multigrid Solvers for Stokes flow in ASPECT. Timo Heister and Thomas Clevenger.

DI24B-02 Mantle Convection Beyond the Reference Profile: Accurately Modeling Dynamic Effects of Compressibility. Rene Gassmoeller, Juliane Dannberg, Timo Heister, Wolfgang Bangerth, and Robert Myhill,

DI24B-03 The Impact of Geodynamically Constrained Lateral Viscosity Variations on Convection-Related Surface Observables. Marie Kajan, Alessandro M Forte, and Petar Glisovic.

DI24B-07 Assessing spectral-element seismic wave propagation on current HPC architectures. Daniel B Peter, Vadim Monteiller, Dimitri Komatitsch, Malte Schirwon, Matthieu Philippe Lefebvre, Etienne Bachmann, Youyi Ruan, Jeroen Tromp, Ebru Bozdag, Yangkang Chen, and Jonathan Vincent.

DI24B-14 Spectral-Infinite-Element Simulation of Potential Field. Problems in Geophysics. Hom Nath Gharti, Leah Langer, Jeroen Tromp, Frederik Simons, and Stefano Zampini.

ED21B-13 Why Are the Pieces of Land in the Wide Water that Breath out Fire and Smoke Made of Different Types of Rocks? Juliane Dannberg and Rene Gassmoeller.

NG24A-08 Convection Simulations Explain the Compositional Heterogeneity of Oceanic Island Chains. Juliane Dannberg and Rene Gassmoeller.

P24A-07 What Can Surface Observations Tell Us About Ceres' Interior? Scott D King, Michael T Bland, Julie C Castillo, Anton Ermakov, Roger R Fu, Simone Marchi, Carol A Raymond, Jennifer E. C. Scully, Hanna G Sizemore, and Christopher T Russell.

S21C-0464 Reconstruction of Fault Geometry Through Hypocenter Clustering for Coulomb Stress Analysis During the L'Aquila Earthquake Swarm. Brennan Brunsvik, Gabriele Morra, Gabriele Cambiotti, Lauro Chiaraluce, Raffaele Di Stefano, Maddalena Michele, and David A Yuen.

S21D-0474 Effect of damage and spallation on Rg waves for SPE-5. Zhou Lei, Esteban Rougier, Howard J Patton, Carene S Larmat, and Christopher R Bradley.

S21D-0479 Triggering mechanisms of aftershocks from explosions and earthquakes using physics-based simulations. Kayla Krol, Arben Pitarka, Sean Ricardo Ford, William R Walter, and Keith B Richards-Dinger.

TH25E Community Forum: The Role of an Open-Source Software Initiative Within AGU. Panel participation Rene Gassmoeller.

V23K-0196 Machine Learning on Infrared Images of Strombolian Eruptions atop Mount Erebus, Antarctica. Brian Dye and Gabriele Morra.

Wednesday, December 12

DI31C-0026 Mapping transition zone topography beneath China by migration of ScS reverberations. Samuel McRae Haugland, Jeroen Ritsema, Jeannot Trampert, and Daoyuan Sun.

DI33C-0051 Venusian Impacts: Starting a Mobile Lid. Grant Euen and Scott D King.

S31C-0520 Variation in Interplate Coupling Between Downgoing and Overriding Plates: Implications for Great Earthquakes in Areas of Flat Slab Subduction from 3-D Geodynamic Models of Alaska. Angela Olsen and Margarete Ann Jadamec.

S31D-0538 Born and Rytov Approximations for Forward Modelling of Seismic Waveforms that Sample the Lower Mantle. Harriet Godwin, Tarje Nissen-Meyer, and Karin Sigloch.

S31E-0559 Transdimensional receiver function waveform inversion. Scott Burdick, Makayla Myers, and Sarah J Brownlee.

S31E-1650 Square-root variable-metric (SRVM) based null-space shuttle: a characterization of the non-uniqueness in elastic full-waveform inversion (FWI). Qiancheng Liu and Daniel B Peter.

T33C-0416 Stability of cratons since early Phanerozoic. Jyotirmoy Paul and Attreyee Ghosh.

T33C-0417 Evolution of lithospheric drip and its impact on the seismicity in the Central and Southeastern US. Arushi Saxena, Eunseo Choi, and Christine Ann Powell.

T33C-0418 The numerical simulation for lithospheric mantle delamination triggered by oceanic plate subduction. Miao Chen, Xiaobing Shen, and Wei Leng.

T33D-0443 Fault Slip Rates and Off-fault Deformation Rates in Southern California Examined with Elasto-Plastic Deformation Models. Yi-Rong Yang and Prof. Kaj M Johnson.

V31H-0222 Quantifying state-of-stress and surface deformation in magmatic rift zones:Eastern Rift, Africa. Sarah Jaye C Oliva, Cynthia Ebinger, Eleonora Rivalta, Christelle Wauthier, and Charles A Williams.

Thursday, December 13

DI41B-0006 Effect of viscosity structure on long wavelength convection and comparison with tomographic models. Diogo José Louro Lourenço, Maxwell L Rudolph, and Pritwiraj Moulik.

DI43C-0030 Geodynamics of Martian Volcanism and Mantle Melting: Formation of the Tharsis Rise Due to Small-Scale Convection at the Dichotomy Boundary. Josh Murphy.

IN43C-0909 A Decade+ of Open Software Practice at CIG. Lorraine Hwang and Louise H Kellogg.

P43D-3805 Simulating Atmospheric Features of Jupiter and Saturn With Deep Convection Models. Moritz H Heimpel, Nicholas Andrew Featherstone, and Jonathan M Aurnou.

S43C-0611 Joint theory of friction and fracturing for earthquake rupture modelling. Ekaterina Bolotskaya and Bradford H Hager

T43G-0506 Towards Earthquake System Science: Constraining Basal Mantle Stress Partitioning Within the Lithosphere and Crust. Ravi V S Kanda and Anthony R Lowry

T41H-0393 Assessing the Generation of the 1964 Great Alaska Earthquake in Terms of the Dynamics of a Fore-arc Sliver System. Kirstie LaFon Haynie and Margarete Ann Jadamec.

T43H-0518 Modeling Lithospheric Stress of Continental United States. Zebin Cao, Lijun Liu, and Quan Zhou.

Friday, December 14

DI51B-0003 Role of Strain-Dependent Weakening Memory on the Style of Mantle Convection and Plate Boundary Stability. Lukas Fuchs, Zel Hurewitz, and Thorsten W Becker.

DI51B-0005 The Role of Dynamic Topography on Glacial Inception in North America. Sophie Coulson, Jacqueline Austermann, Mark Hoggard, and Jerry X Mitrovica.

DI51B-0017 Explore the Density Structure of Cratonic Lithosphere Using Global Residual Topography. Yaoyi Wang, Lijun Liu, and Jiashun Hu.

DI51B-0020 The Relation Between Tractions and Strain Rate at the Base of the Lithosphere: Key to Understanding Cratonic Stability. Attreyee Ghosh, Jyotirmoy Paul, and Clinton P Conrad.

S51A-05 The Advantages of Sp Pre-stack Migration Based on Scattering Kernels. Junlin Hua, Karen M. Fischer, and Nicholas J Mancinelli.

S53C-0409 Full Waveform Tomography: A Comparison Between Adjoint-Wavefield and Scattering-Integral Approaches. Changyang Yin, Li Zhao, and Jieyuan Ning.

S53C-0413 Impact of surface topography on full-waveform tomography for Central Mexico. Armando Espindola-Carmona and Daniel B Peter.

S53C-0417 Adjoint Tomography of South America based on 3D Spectral-Element Seismic Wave Simulations. Caio Ciardelli, Ebru Bozdag, and Marcelo Assumpcao.

S53E-0458 Moment tensor estimation and uncertainty quantification using mtuq, instaseis, obspy and pymc. Ryan Modrak, Vipul Silwal, Celso R Alvizuri, and Carl Tape.

S53E-0460 Hybrid waveform modeling for small-scale source complexity at teleseismic distances. Marta Pienkowska-Cote, Stuart E.J. Nippress, David Bowers, and Tarje Nissen-Meyer.

T51G-0255 Numerical simulations of stress variations with depth in a model for the San Jacinto fault zone. Niloufar Abolfathian, Christopher W Johnson, and Yehuda Ben-Zion.

T51I-0279 Understanding subduction dynamics in the Southwest Pacific. Diandian Peng, Lijun Liu, and Jiashun Hu.

T51I-0282	Adjoint Tomography of the Hikurangi Subduction Zone and New Zealand's North Island. Bryant Chow, Yoshihiro Kaneko, Vipul Silwal, Carl Tape, and John Townend.
T52D-05	Transition Zone Structure Beneath the Eastern US. Shangxin Liu, John C. Aragon, Maggie Benoit, Maureen D Long, and Scott D King.
T53C-02	Static and Time-Dependent Inversions of Slow Slip at the Hikurangi Subduction Zone, New Zealand, Using Numerical Green's Functions. Charles A Williams, Laura M Wallace, Noel M Bartlow, and Ryan Michael Yohler.
T54B-08	Imaging the Sharpness of the Lithosphere-Asthenosphere Boundary (LAB). Shuyang Sun and Ying Zhou.
V53A-01	Modeling Melt Generation and Transport by Integrating Thermodynamic Models in Geodynamic Simulations Using the Community Code ASPECT. Juliane Dannberg, Rene Gassmoeller, and Timo Heister.

Appendix D: Publications

Articles in 2018 using CIG codes either reported by authors or discovered using keyword searches on google scholar.

1. Omar Aaziz et al. “A Methodology for Characterizing the Correspondence Between Real and Proxy Applications”. In: 2018 IEEE International Conference on Cluster Computing (2018). issn: 2168-9253. doi: 10.1109/CLUSTER.2018.00037.
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