Computational Infrastructure for Geodynamics

2019-2020

Annual Report

NSF Award Number EAR-1550901

July 2020

COMPUTATIONAL INFRASTRUCTURE for GEODYNAMICS

2219 EPS, One Shields Avenue
University of California
530.752.2889
Davis, CA 95616
geodynamics.org

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.

CIG supported community development and knowledge transfer through regular meetings, workshops, webinars, newsletters, tutorials, e-mail distribution list, and our discussion forum. We held regular users' meetings and workshops for software development projects Rayleigh and ASPECT. We partnered in 2019 with EGU to send early-career US scientists to the biannual EGU mantle and lithospheric dynamics workshop, now called the Ada Lovelace Workshop in Mantle and Lithosphere Dynamics. Our first virtual user's meeting was held in January 2020 for the code ASPECT - before the full force of the global pandemic hit.

The pandemic subsequently forced us to rethink the remainder of our outreach efforts. We successfully transition to a virtual platform offering a 5-day virtual tutorial on tectonic modeling using the code ASPECT and a follow-on 4-day, virtual workshop brought together members of the observational, experimental, and modeling communities in presentations and discussions focused around ductile shear zones and localization processes. Our very first ASPECT virtual hackathon will be held in August 2020. All events had significant international participation. Our webinar series focused on the intersection of data and geodynamic modeling. The CIG Distinguished Speaker program continues its focus in bringing CIG-supported science to colleges and universities that are underrepresented in the geosciences. Other events planned for 2020 including several webinars and Distinguished Speaker visits were postponed to 2021.

CIG continued to advance software development in mantle convection, crustal dynamics, dynamo, long-term tectonics, seismology, and evaluated future directions for these codes. The community made great progress in adding new features to codes expanding its application to a wide range of scientific problems, which include implementing new physics and improvements to model problems applying multiphysics and viscoelastic and viscoelastoplastic rheologies. Workflow improvements for seismic data continue to benefit a larger community and will improve seismic imaging capabilities. 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 support code contributions as requests arise through the year through our established approval process. We will continue community activities and development (especially for early-career scientists) through planned workshops, tutorials, hackathons, and webinars. We continue to develop partnerships with national computing facilities and other partner organizations. These include managing and renewing CIG's allocation on XSEDE and utilizing a new allocation on Frontera, the latest XSEDE supercomputer, to continue to optimize community codes for applications in global mantle flow, lithospheric deformation, and global core flow.

We continued to 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 added a software checklist and template repository to our best practices to aid code contribution. A Privacy Policy was also added to our website to clarify the data we collect.

The community continues to plan to for the next phase of CIG. Planning activities kicked off late Summer 2019 with a community-wide survey. Elected governance, EC and SSC, met jointly in Spring 2020 to review the state of CIG and discuss next steps. These include a virtual community-wide meeting in October 2020 that will give the community the chance to discuss the infrastructure to advance our understanding of Earth dynamics in the next 5 years.

In Fall 2019, Prof. Magali Billen, UC Davis stepped down as Director/PI. In accordance with the by-laws of the organization, the Executive Committee elected Dr. Lorraine Hwang as Director/PI. She continues her role representing the CIG community participating on international committees and contributing to meetings and workshops.

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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 86 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, 2019 through July 31, 2020 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 [pdf].

In Fall 2019, Prof. Billen stepped down as Director/PI. The EC subsequently elected Dr. Lorraine J. Hwang as Director/PI who will continue her role in management and providing leadership to CIG through the end of the grant.

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 86 member institutions including 19 international affiliates. Of these, 6 are inactive as member representatives have moved to new institutions. In 2019, CIG welcomed University of Florida. 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
- Bruce Buffett (2022), University of California, Berkeley
- Katie Cooper (2021), Washington State University

- Claire Currie (2022), University of Alberta
- *Ex officio*, Scott King (2022), Virginia Tech
- *Ex officio,* Lorraine Hwang, 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,* Scott King (2022), Virginia Tech
- *Vice Chair,* Cian Wilson (2021), Carnegie, DTM
- Ebru Bozdag (2021), Colorado School of Mines
- Juliane Dannberg (2022), University of Florida
- David Ham (2020), Imperial College
- Jessica Irving (2020), Princeton University
- Gabriele Morra (2020), University of Louisiana, Lafayette

- Krista Soderlund (2021), University of Texas, Austin
- *Ex officio,* Louis Moresi (2021), University of Melbourne
- *Ex officio,* Lorraine Hwang, 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

The Education Working Group is interested in developing open source materials for teaching geophysics using computation with an emphasis on computational geophysics. Their 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.

Changes in composition of the Dynamo, Long-Term Tectonics, and Seismology Working Groups reflect the new initiatives these groups are tackling in the upcoming year.

Appendix B provides a list of working groups and the 59 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. CIG compute nodes are pooled with others in the Division of Math and Physical Sciences making up to 2018 CPUs 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. Due to the global pandemic, CIG Staff transitioned to working remotely in March 2020 in accordance with University of California, Davis guidelines

CIG Headquarters is led by the CIG Director. A team of four support CIG – a Project Scientist, 2 Research Scientist, and a System Administrator. Support for system administration and research staff members may come from 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.

CIG's team of computational and research science professionals maintains 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 staff helps to 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:

- *Director,* Dr. Lorraine Hwang*[1]
- *Research Scientist,* Dr. Hiroaki Matsui
- *Assistant Research Scientist,* Dr. John Naliboff
- *Assistant Project Scientist,* Dr. Rene Gassmöller*
- *HPC/Sys Admin Support,* Bill Broadley*
- *HPC/Sys Admin Support,* Terry Knight*

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, dynamo, short-term crustal dynamics, and seismology. The working groups may provide feedback to each project that are part of an overall work plans which may include software development plans, benchmarks, tutorials, and a schedule for working meetings appropriate to each project.

[1] Replaces Professor Magali Billen in October 2019.
**part time effort for CIG*

Strategic Planning

Community Survey

As part of the strategic planning effort leading to the preparation of the next proposal for CIG in 2021, the EC solicited feedback from the community in the Summer of 2019 through a community-wide survey. The community provided feedback on current and possible new directions and were given the opportunity to state their interest in participating in current and upcoming activities.

In total 52 people completed the survey with 11 international respondents. Respondents were primarily faculty from doctoral offering universities with good representation from the breadth of CIG domains. The group was eager to engage with CIG through workshops both as an attendee or leader. In general, respondents were supportive of activities across the categories surveyed – software, science, and outreach, with an emphasis on continuing current infrastructure practices in software and computing and training. Respondents expressed strong interest in community building activities and furthering scientific integrity and reproducibility. Respondents were less interested in supporting a model repository and pursuing community grand challenge science.

See Appendix C for survey results. Names and comments have not been included.

Joint EC-SSC Meeting

Strategic planning was furthered during a two-day virtual meeting May 12-13, 2020 held jointly between the two-elected governance committees. Committee members had the opportunity to exchange ideas while looking in retrospect and to the future to identify current needs in our community. Discussions initiated included topics in governance, subawards, and leadership as well as the identification of trends and opportunities across the sciences and in geophysics. The need for more training and increasing diversity in the codes supported, domains represented, computational resources, communities, and people were amongst recurring themes. Trends in open science and data driven science are opportunities for the community to advance. The need to understand how complex systems interact will increase code complexity. Virtual meetings were looked at not only as a time and cost saver but a way our community can increase its reach while reducing our carbon footprint.

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.

In the past year, the team was part of the successful proposal to NSF for a new petascale computing system, *Frontera* (5th 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 was awarded 0.27 million node hours to participate in Frontera's early testing phase from May 2019 to April 2020. The award has been used to benchmark the performance of existing CIG software and further its scalability using new numerical methods in preparation for wider community use.

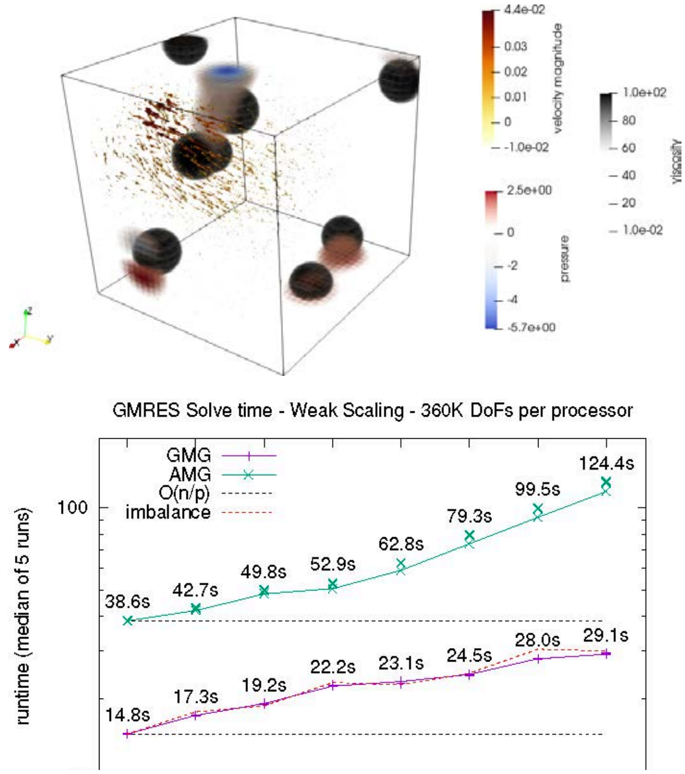

Figure 1. Top. Solution of the Nsinker benchmark in ASPECT. Bottom: GMRES solve time to reduce the residual by 1e6 for the 3D Stokes equations of the Nsinker benchmark in ASPECT for a matrix-based solve with an AMG preconditioner and the new matrix-free solve with a GMG preconditioner. The red dashed line represents the ideal scaling of the Geometric Multigrid method based on the imbalance of the parallel partition of cells due to adaptivity

The team of Timo Heister and Thomas Clevenger (Clemson University) worked on matrix-free, multigrid methods in ASPECT (Figure 1). Matrix-vector products tend to dominate the total amount of work required for the average finite element program, and, as these matrices can be quite large and do not fit into the cache of a modern machine, accessing the data from RAM has become a major bottleneck in finite element computations. These methods show significant gains in the time of a matrix-vector product as compared to traditional matrix-based methods when using degree 2 and higher finite element. This new method also allows for larger computations as storing the matrix has dominated the memory consumption of the matrix-based method. See 4.1 ASPECT for more details.

With access to a large number of cores, Hiro Matsui, CIG-UC Davis has been able to further development of real time parallel volume rendering and line integration convolution modules for visualization using Calypso. Calypso and the visualization modules are parallelized using MPI and OpenMP. In scaling tests of up to 28,672 cores, elapsed time for both the forward simulation and volume rendering is approximately 10-20% slower in comparison to the Skylake nodes on Stampede2. This is due to the increased needed for data communication in the spherical harmonic transform which will require further optimization on Frontera. See also 4.2 Calypso for future plans.

CIG has successful applied for a Frontera Pathways grant giving us access to 182,400 SUs through June 2021 for further development efforts.

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 and virtual posters;
- 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 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.

Forum

Except for the private governance and the general community-wide (CIG-ALL) mailings lists, all other 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. Currently, any member of the public may subscribe to CIG-ALL and register to participate in the new forum. 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.

As of December 31, 2019, the forum has grown to 368 members, up from 170 from 2018. New users and contributors continue to join at a steady rate since the forum's inception with an average of 215 visits per month in 2019 (Figure 2). The CIG-ALL mailing list (583 members) forwards to the Announcements forum category and remains an option for community members to receive general announcements. Hence, the total number of participants reached are a mix of the two communication methods.

The domain-specific lists for groups that have released codes are used frequently for community support. Anyone register user 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. Any registered user 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.

The ASPECT and PyLith continue to be the most active subject matter categories (Figure 3). However, some of our communities prefer to use github for similar functions, e.g. SPECFEM and hence, forum traffic does not reflect the community's activities.

Past email lists are accessible through the CIG website: (https://geodynamics.org/cig/about/mailing-lists/).

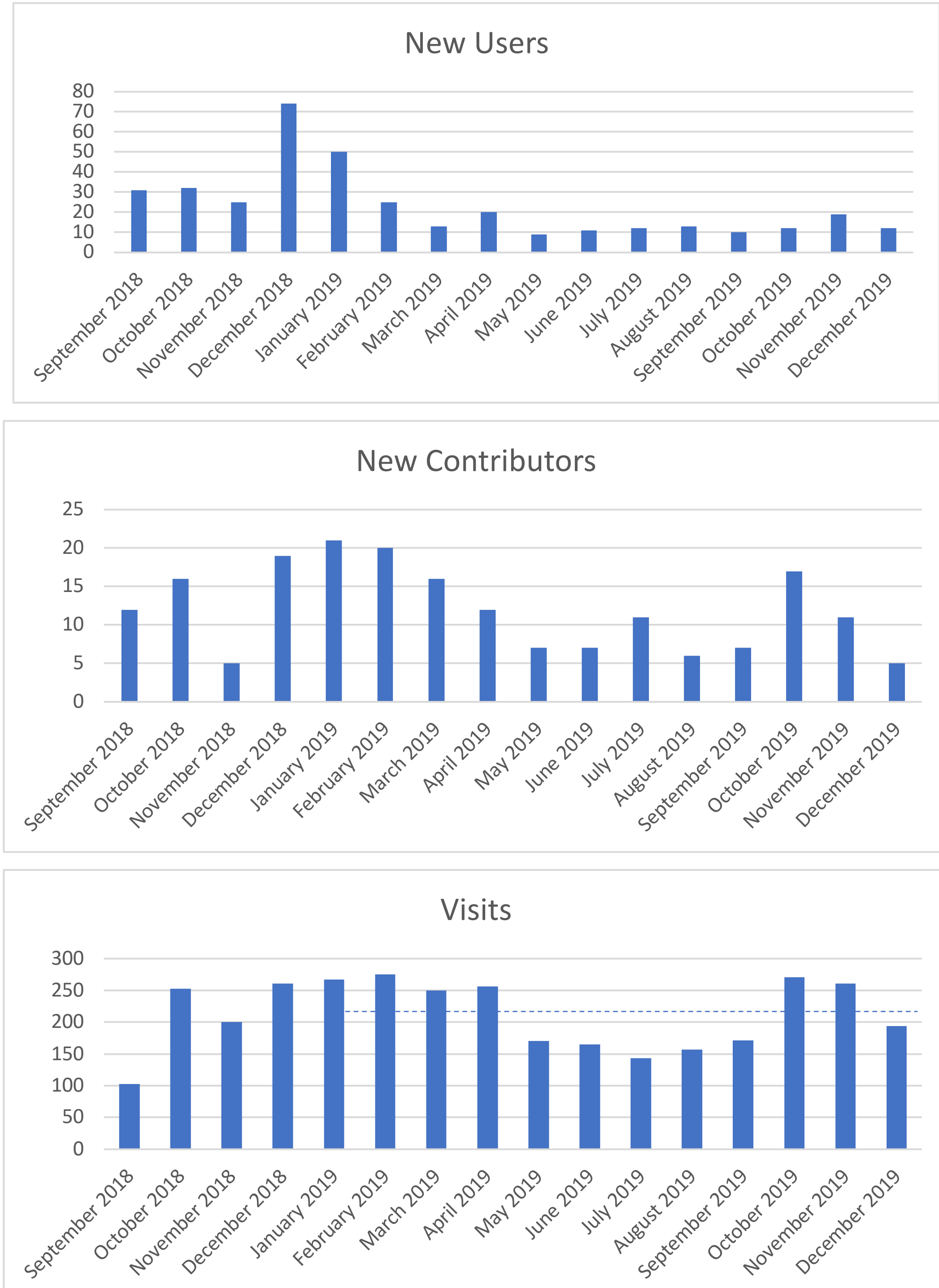

Figure 2. CIG Forum activity since inception (community.geodynamics.org). Shown by month are the (top) number of new users, (middle) new contributors, and (bottom) contributors to the forum. Dashed line in marks the average monthly visits, 215 for 2019.

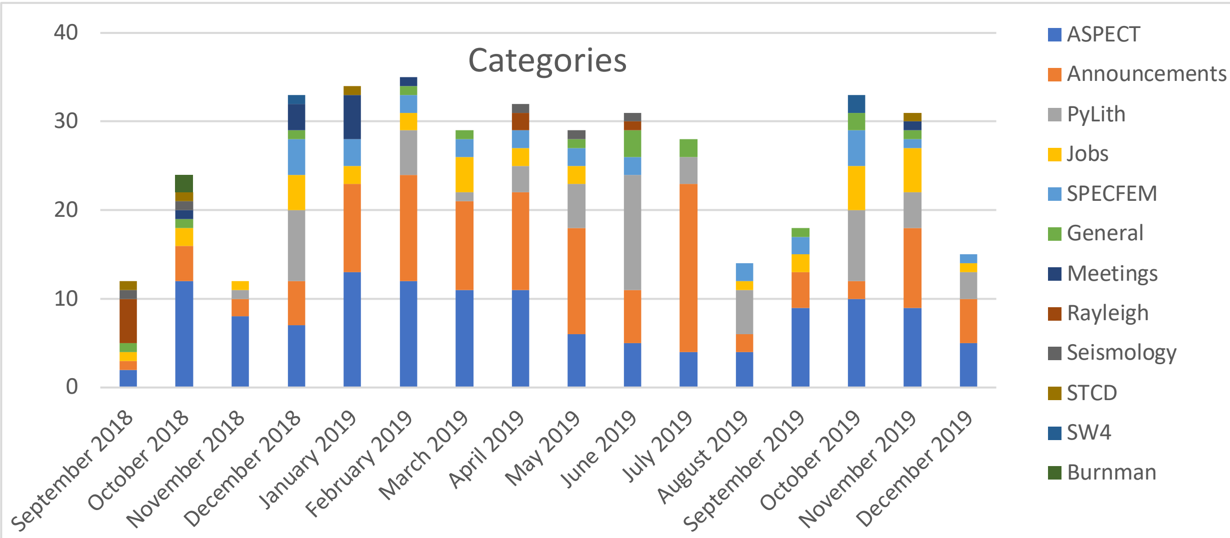

Figure 3. Number of messages posted to the forum my category. Legend is ranked ordered with the users of the ASPECT forum posting the most messages.

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 email 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.

Webinars

Since 2012, 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,
- forum and 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.

2.10 Privacy Policy

CIG adopted a Privacy Policy this year to clarify what data is collected through its website. We collect information to analyze the development and usage of community software, event offerings, outreach efforts, and other services to evaluate their effectiveness in better serving our community. When visiting our website, we automatically store and collect users' internet domain; the type of browser and operating system used; the date and time of access, pages visited, and if any, IP of the referring website. This information is aggregated and anonymized. We do not track or record information about individuals and their visits. We do use a minimal number of cookies to optimize the user's experience.

We collect personal information when you register for events that includes name, affiliation, contact, and other information. We may also collect other optional personal information such as research interests, dietary restriction and other background information.

See Appendix D for our full Privacy Policy.

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, availability, and credit for 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. Where deployed, 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, 2019.

3.1 CIG Code Repository

CIG encourages members to donate codes that have scientific value for the geoscience 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 communities

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 or other communities. 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, total lines of code, % change in number of lines of code from the previous year, number of commits in the repository, number of

Table 1. Repository Statistics

	Version	Lines of Code	% Change	Commits	# developers	Support Level
Short-Term Crustal Dynamics						
Pylith	*2.2.2	443,173	0%	12	9	D_CIG
Relax	1.0.7	1,418,920	0%	5	10	D_CONTRIB
VirtualQuake	3.1.1	49,222	0%	5	17	D_CONTRIB
SELEN	2.9.13	20,844	-233%	30	5	S_CONTRIB
LithoMop	0.7.2	495,786	-	-	5	A
Long-Term Tectonics						
Gale	1.6.1/2.0.1	6,680,841	-	-	62	A
Plasti	1.0.0	10,967	-	-	1	A
SNAC	1.2.0	549,498	-	-	3	A
Mantle Convection						
ASPECT	*2.1.0	1,871,648	11%	1518	102	D_CIG
CitcomCU	1.03	70,288	0%	3	5	D_CONTRIB
CitcomS	3.3.1	239,468	0%	1	21	D_CONTRIB
ConMan	2.0.0	360489	0	17	10	S_CONTRIB
Ellipsis3d	1.0.2	51,602	-	-	2	A
HC	1.0.7	491,187	0%	9	7	A
Seismology						
Axisem	1.3	110,419	-	-	12	D_CONTRIB
Burnman	0.9	97,418	28%	67	17	D_CONTRIB
Mineos	1.0.2	331,364	-	-	7	A
Flexwin	1.0.1	95,412	-	-	8	A
Seismic CPML		37,820	-	-	6	S_CONTRIB
Specfem3D		10,541,775	-	-	51	D_CIG
Specfem3D Globe	7.0.0	2,141,321	0%	4	54	D_CIG
Specfem3D Geotech	1.1	2,038,521	-	-	4	D_CONTRIB
Specfem2D		1,871,169	-	-	33	D_CONTRIB
Specfem1D		5,367	-	-	9	S_CONTRIB
SW4	2.01	267,625	0%	8	19	D_CONTRIB
Geodynamo						
Rayleigh	0.9.1	71,365	-47%	647	25	D_CIG
Calypso	1.2.0	215,017	0%	-	7	D_CIG
MAG	1.0.2	134,906	-	-	5	A
Computational Science						
Cigma	1.0.0	356,371	-	-	7	A
Exchanger	1.0.1	5,654	-	-	7	A
Nemesis	1.1.0	193	-	-	2	S_CONTRIB
Pythia	*0.8.1.19	33,081	0%	-	4	S_CONTRIB

*new releases in 2019, $^{+}$also being used for long-term tectonics lifetime developers and current level of support. Statistics are as reported by gitinspector[2] 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.

The CIG Git repositories logged 2351 software commits during 2019. Over the repository lifetime, nearly 536 developers have contributed to code development.

CIG continues to provide guidance to its community on contributing software for community use. Additional guidelines have been developed in the form of a software checklist and an example github software repository (template). Both follow CIG established software best practices and establishes expectations of what information is needed and how to structure a repository when contributing software. Both are accessible through our website and our GitHub repository (https://github.com/geodynamics/best_practices).

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:	12,887
Visits:	52,042
Hits:	4,882,396 hits
Downloads	816 files
Page Views:	3,591,723

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

3.3 High Performance Computing

CIG continues to provide opportunities to train scientists on HPC by maintaining allocations of HPC resources on community machines. For 2019, CIG applied for and was awarded 73,657 out of 86,600 SUs requested and an additional 10,000 GB of long-term archival storage on Ranch. Allocation was primarily used for development and research runs for the code ASPECT and Calypso.

CIG also received an early access allocation of 270,001 SUs to the NSF leadership-class computing system Frontera to produce scaling results and example production runs for ASPECT and Calypso which continue until April 14, 2020. See sections 2.7, 4.1, and 4. 2 for tasks performed under this allocation.

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, 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). CIG partners with these and other organizations to expand its impact on the geodynamics community.

Upcoming workshops and training are posted online and advertised through CIG email lists and forum and those of our partner organizations. Due to the global pandemic, three CIG workshops were cancelled, and the remaining CIG workshops have been or will be offered virtually. Cancelled in 2020 were the joint CGU meeting, the 2nd PyLith Hackathon, and the first SPECFEM Developers meeting. Virtual workshops offered in 2020 are listed in Table 2. All events build upon CIG's experience using technology to collaborate with our communities worldwide - PyLith has been offering virtual tutorials since 2015 and our very first entirely virtual workshop was held by the ASPECT community in January 2020. By offering our workshops virtually this year, we have been able to further our reach to new communities including meeting the international demand from emerging economies for access to training on state-of-the-art modeling software.

Table 2. January-July 2020 Workshops and Tutorials

Date	Title	Participants
January 21-23	ASPECT User Workshop	35
July 20-24	Tectonics Modeling Tutorial	74
July 27-31	Tectonics Community Science Workshop	166

2020 ASPECT User Workshop

The first virtual ASPECT user meeting that took place January 21-23, 2020. A total of 35 participants (Figure 4) mostly early career researchers joined during the three, 5 ½ hour per day, event which included presentations, Q&A, and discussions. Sixteen of the participants had never attended one of ASPECT's in person hackathons before. Participants learned about ASPECT's features, recent developments, and its community members. The event sparked some discussions that lead to new features in the following days. The optional practical sessions on Day 3 saw less participation.

The event received very positive feedback. Events in the future may be shorter but include an introductory session for beginners and some scheduled time for one-on-one discussions. A big part of the success of the meeting were our 11 community members, who gave excellent presentations and were not afraid of bringing their scientific and software development work to a new presentation format.

Figure 4. A total of 35 participants from 7 countries attended the event. Approximately 31% of the attendees were women.

Meeting Report [pdf]

2020 Tectonics Modeling Tutorial

The 2020 CIG Tectonics Modeling Tutorial provided an opportunity for both new and experienced modelers to receive hands-on training on the fundamentals of long-term tectonic modeling (Figure 5).

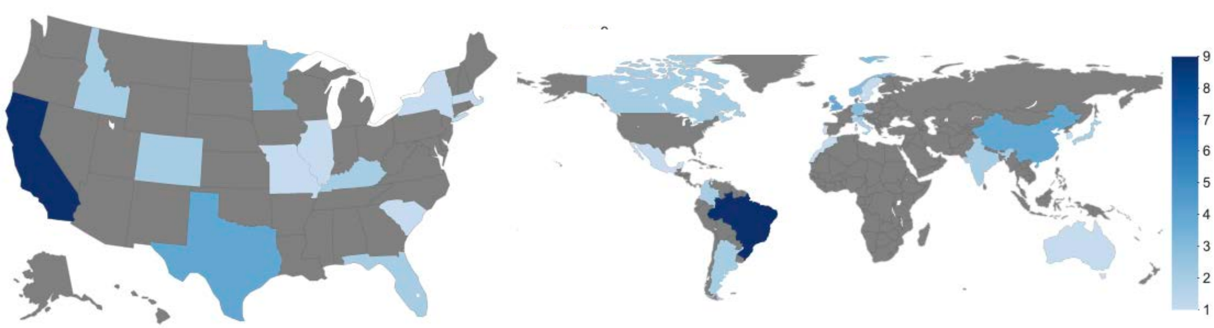

Figure 5. A minimum of 74 researchers participated in the Tectonics Modeling Tutorial – 29 from the United States, 44 from other countries, and 1 unidentified. Attendees were predominantly graduate students

The training modules covered a range of topics, including basic examples of mantle convection and lithospheric deformation, viscoelastic-plastic deformation, two-phase flow, and complex model design. Tutorials were taught using the CIG-supported code ASPECT and Geodynamic World Builder (Menno Fraters, *Developer*). The workshop provided an opportunity for new users to become familiar with the code and its community. Given the virtual nature of the meeting and the wide range of time zones for the participants, formal daily sessions were limited to 3 hours each day with additional sessions available before and afterwards for discussion of tutorial materials and one-on-one virtual assistance with individual participant projects.

The meeting received positive feedback from the participants in its quality and content. Participants spanned 6 continents.

Meeting Report [pdf].

2020 Tectonics Community Science Workshop

The 2020 CIG Tectonics Community Science Workshop brought together the international observational, experimental, and computational lithospheric dynamics community to virtually engage in focused cross-disciplinary discussion and long-term strategic planning (Figure 6).

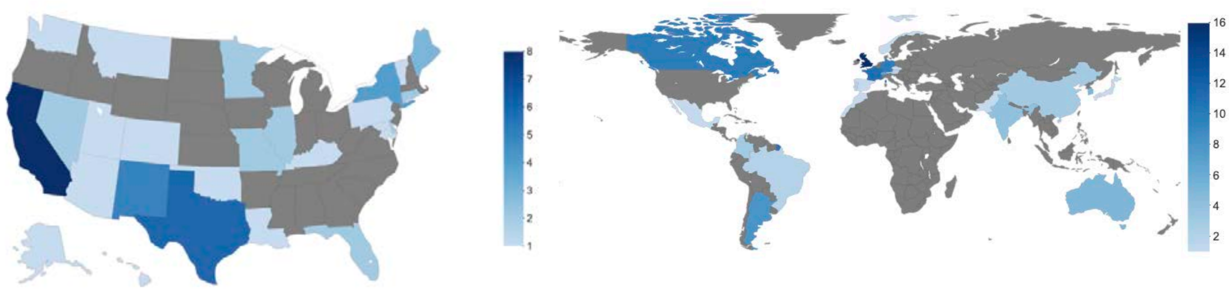

Figure 6. 164 unique participants attended the Tectonics Community Science Workshop with at least 63 from the U.S. and 99 from other countries. Attendance spanned -10 to +12 UTC. Attendees were predominantly early career (graduate students and postdocs.

The meeting introductory session covered current challenges and open questions in distinct domains of the lithosphere, current cross-disciplinary community efforts, and an introduction to the meeting scientific focus on ductile shear zones and localization processes.

Keynote lectures and panel discussions on this topic were divided between three topical sessions, which include *Localization in the lithosphere*, *Evolution and transient behavior of lithospheric shear zone*, and *How to make a plate boundary - from microphysical and chemical processes to geodynamic scenarios*.

The final meeting session focused on summary activities and planning, including future directions in modeling and existing geologic data sets that can be integrated into robust statistical comparisons between modeled and observed data.

Given the virtual nature of the meeting and the wide range of time zones for the participants, formal daily sessions were limited to 3-4 hours each day and held in the morning within the Pacific Time zone.

Early feedback suggests that future events that bring together researchers applying a broad spectrum of methods to study lithospheric deformation would be well received.

Members of the Long-Term Tectonics Working Group plan to develop a white paper based on workshop discussion and organize a special issue of *Geochemistry, Geophysics, Geosystems*. The white paper and the Tectonics Modeling and Science Workshops were major activities for the group.

Future Workshops

CIG plans to organize the following community workshops in 2020-2021:

Table 3. 2020 Workshops and Tutorials

Date	Title
August 3-7 & 10-14,2020	ASPECT Hackathon
Fall 2020	Rayleigh Hackathon
October 13-15, 2020	CIG Community Workshop
May 3-6, 2021	2020 CGU Meeting Joint with CIG
Summer 2021	PyLith Hackathon
Summer 2021	Introduction to Computational Modeling in Geodynamics and HPC
Summer 2021	ASPECT Hackathon
Summer 2021	SPECFEM Developer’s Meeting

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 2019-20, the series focused on the intersection of data and models (Table 4). The one-hour webinars are recorded for later viewing on the CIG YouTube channel and linked to CIG website. The Spring 2020 seminar schedule was impacted by the global pandemic. We hope to reschedule webinars next year for those who had to cancel due to shifting workloads.

Table 4. 2019- 2020 Webinar Schedule

Date	Presenters	Title
November 14	Richard Styron, GEM Foundation	The Release of the GEM Global Active Faults Database and Global Seismic Hazard Map
February 26	Brandon Schmandt, University of New Mexico	Seismic data and data products to motivate, guide, and test geodynamic models of the lithosphere and upper mantle
April 16	Boris Kaus, Tobias Bauman, Georg Reuber,and Anton Popov; Institute of Geosciences, Johannes Gutenberg University, Mainz	Geodynamic inversion: Methods to link models with data & how that helps to obtain insights in the physics and rheology of the lithosphere
May 14	Rene Gassmöller, CIG UC Davis.	Discovering and addressing social challenges during the evolution of scientific software projects

YouTube

CIG's YouTube channel, *CIG Geodynamics*, hosts 204 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 google searches. Viewers can also access webinar videos 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 487 subscribers and approximately 53,210 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 25,000 geophysicists in one place. The meeting provides a forum for information exchange and discussion about CIG operations.

This year we searched the data provided through AGU's open API to search for software mentions and solicited community members for relevant abstracts. The 66 abstracts (Figure 7) accepted for the 2019 Fall Meeting spanned disciplines including Study of Earth's Deep Interior, Education, Geodesy, Nonlinear Geophysics, Seismology, Planetary Sciences, Tectonophysics, and Volcanology.

See Appendix E.

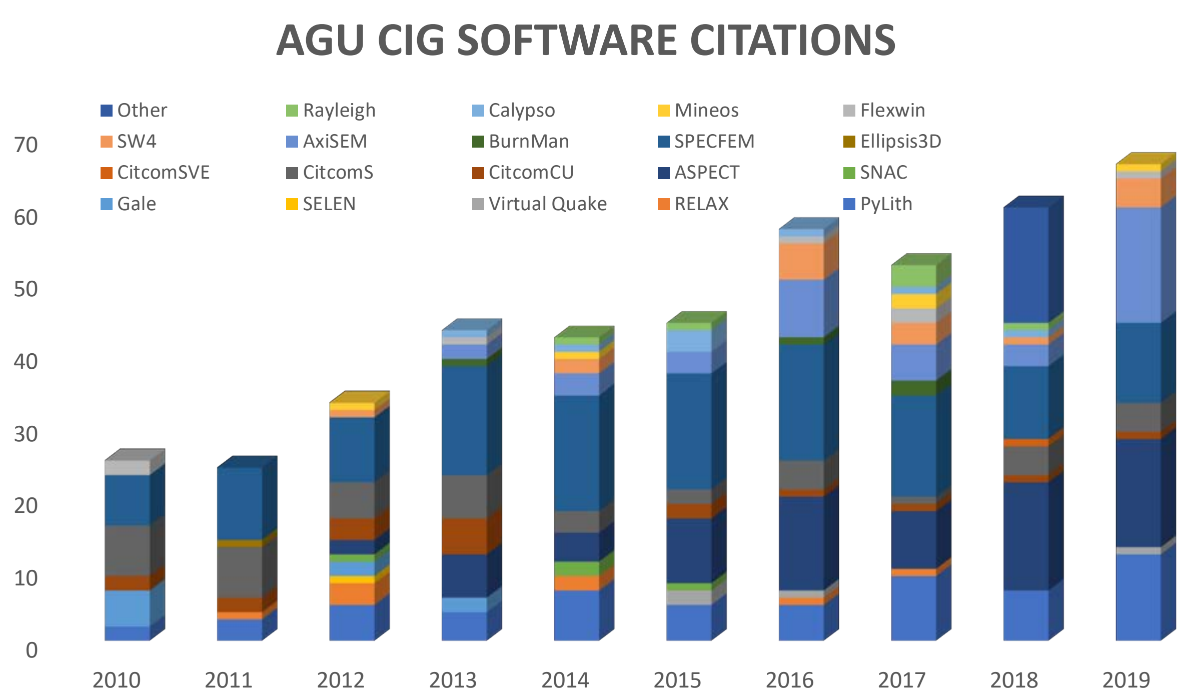

Figure 7. Number of CIG software mentions in an AGU abstract.

Distinguished Speaker Series

The CIG Distinguished Speaker Series continues into its 3rd 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 three 2019-2020 CIG Distinguished Speakers completed 6 visits (Table 5) in which the majority were located in EPSCoR states or at R2 research institutions. One visit was postponed due to travel restrictions implemented due to the global pandemic. The program received positive feedback from

Table 5. CIG Distinguished Speakers and Host Institutions

2019-2020	
From grains to tectonic plate boundaries *Prof. Sylvain Barbot, University of Southern California*	October 2: University of Louisiana, Lafayette October 4: Louisiana State University
Clues About the Break-up of the African Continent *Prof. Sarah Stamps, Virginia Tech*	November 8: Michigan State University November 11: Grand Valley State University Fall 2020: University of Alaska Fairbanks - POSTPONED
What creates the unique topography of East Africa? *Prof. Jolante Van Wijk, New Mexico Institute of Mining and Technology*	January 17: Florida State University February 24: University of Montana February 25: Montana Tech
2020-2021	
How mantle flow changes sea level and ice sheets *Jacqueline Austermann, Columbia University*	TBD: Florida International March 26: University of Alabama TBD: University of Hawaii, Manoa *virtual*
To slide or to flow: Studying extremes in different natural systems sheds light on common physical processes *Jenny Suckale, Stanford University*	TBD: California State University Northridge TBD: Northern Arizona University TBD: Utah State University

both Host Institutions and Speakers. Speakers had opportunities to interact with both students and faculty in formal and informal settings taking advantage of the opportunity to deliver guest lectures and exchange research ideas and perspectives on career paths in geosciences.

The two 2020-2021 CIG Distinguished Speakers are:

- Jacqueline Austermann, Columbia University. *How mantle flow changes sea level and ice sheets*
- Jenny Suckale, Stanford University**.** *To slide or to flow: Studying extremes in different natural systems sheds light on common physical processes*

Speakers are working to schedule in person and/or virtual visits.

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. Eight (8) Principal Developers maintain the openly accessible repository on github and provide feedback to 36 user-developers who have made 1518 commits to the repository in 2019, as well as to the broader user community. Many of these commits have added major new features to the code and were incorporated into a new release of the software in June 2020, ASPECT 2.2.0 (doi: 10.5281/zenodo.3924604). See https://github.com/geodynamics/aspect/releases/tag/v2.2.0 for a list of all changes.

Significant accomplishments of the past year

ASPECT version 2.2.0 (10.5281/zenodo.3924604) added the following noteworthy features:

- Improvements to the multigrid solver (details below).
- A rewrite of substantial parts of the viscoelastic and viscoelastoplastic material model infrastructure. Initial work to output information only on the surface of the model, rather than the entire volume.

- A new “projected density field” compressible formulation (details below).
- Performance improvements.
- New benchmarks, tests, fixes, and smaller features.

For all significant changes and their contributors (CIG staff, CIG subawardees, and community contributors) see the release notes: https://github.com/geodynamics/aspect/releases/tag/v2.2.0

Other work performed as part of this award not part of the ASPECT release 2.2 mentioned above:

- Research and benchmarks in the development of new formulations for the continuity equation that includes dynamic density variations due to temperature, pressure and composition without using a reference profile for density. The resulting publication[3] quantifies the improvement in accuracy relative to existing formulations in a number of benchmark models and evaluates the practical applications effects that these effects are important (Figure 8).

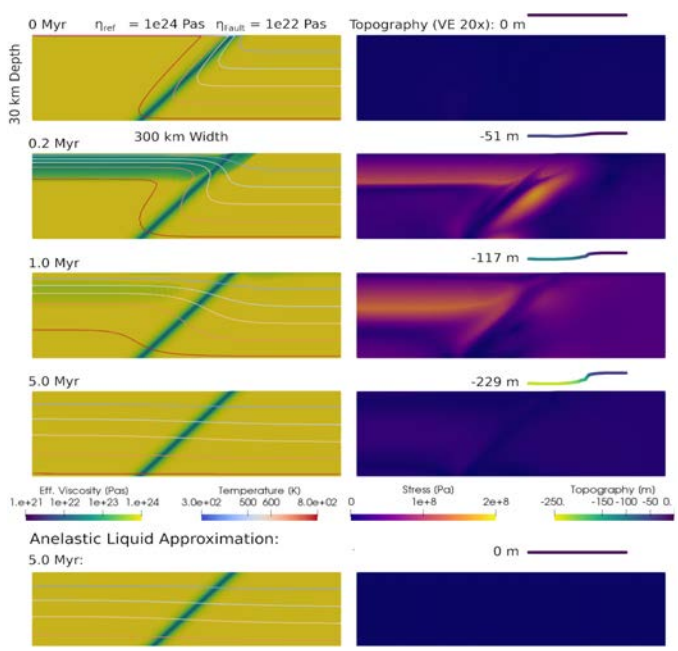

Figure 8. Top rows: idealized model of a cooling crust using the projected density approximation from model start to 5 Myr. Left: effective viscosity after plasticity (background colours) and temperature (isocontours) of the model evolution. Right: deviatoric stress (background colours) and topography (upper inlet, vertical exaggeration 20 ×). Bottom row: final state of an identical model setup using the anelastic liquid approximation. While the temperature evolves identically, no stress or topography is created over time in previous simplified models illustrating the benefits of our new approximation for modeling thermal stresses and deformations.[3]

[3] Rene Gassmöller, Juliane Dannberg, Wolfgang Bangerth, Timo Heister, Robert Myhill, On formulations of compressible mantle convection, *Geophysical Journal International*, Volume 221, Issue 2, May 2020, Pages 1264-1280, https://doi.org/10.1093/gji/ggaa078

- Research into the numerical accuracy of particle-in-cell (PIC) methods showing that existing PIC methods limit the convergence order of the higher-order methods that are used in ASPECT and preliminary measures to circumvent this limitation.[4]
- Performance improvements, bug fixes, feature development in deal.II to allow for very large computations.[5]
- Replacement of the multithreading framework TBB in deal.II by TaskFlow (ongoing effort) promising better node performance.
- Initial implementation of plasticity-based adaptive refinement.

Timo Heister with his postdoc Thomas Clevenger continued the work to improve scalability and performance of ASPECT. An initial version of the geometric multigrid solver with limited features was merged into ASPECT in May 2019. Since then, the following work happened:

- Benchmarks on TACC Frontera with up to 112k MPI ranks and 10^11 unknowns (this is 100x larger than what was possible in ASPECT 2 years ago).[6]
- Implementation, testing, benchmarking of IDR(s) Krylov solvers for better performance and lower memory requirements.
- Extension of the solver in ASPECT to support compressible computations, nonlinear problems, spherical geometries, and more.
- Support for different averaging schemes for viscosity. This is an important generalization of the initial version implemented last year that required harmonic averaging of viscosities, forcing usage of a constant value per cell (and as such reducing accuracy for some computations).

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[4] Rene Gassmöller, Harsha Lokavarapu, Wolfgang Bangerth, Gerr Puckett, Evaluating the accuracy of hybrid finite element/particle-in-cell methods for modelling incompressible Stokes flow. *Geophysical Journal International*, Volume *219*, Issue 3, 1915-1938, https://doi.org/10.1093/gji/ggz405

[5] Daniel Arndt, Wolfgang Bangerth, Bruno Blais, Thomas C. Clevenger, Marc Fehling, Alexander V. Grayver, Timo Heister, Luca Heltai, Martin Kronbichler, Matthias Maier, Peter Munch, Jean-Paul Pelteret, Reza Rastak, Ignacio Thomas, Bruno Turcksin, Zhuoran Wang, David Wells: The deal.II Library, Version 9.2 submitted, 2020

[6] Thomas C. Clevenger, Timo Heister: Comparison Between Algebraic and Matrix-free Geometric Multigrid for a Stokes Problem on an Adaptive Mesh with Variable Viscosity, submitted, 2019.

Project goals for the upcoming year

Development goals for the next year:

- Continue the implementation and testing of gradient plasticity methods, making the width of shear bands caused by plastic yielding independent of the cell size.
- Incorporate a rheology that realistically describes fluid-rock interactions during brittle deformation, such as hydro-fracturing.
- Continue the development of viscoelastic material behavior towards a fully compressible formulation.
- Continue the development of interfaces for prescribing phase changes to thermodynamic and rheological properties.
- Develop a fully compressible viscoelastic-plastic formulation for lithospheric deformation and mantle convection, which self-consistently incorporates existing (phase changes, two-phase flow) and in-development (fluid-rock interaction) functionality.
- Improve visualization features in ASPECT especially for large-scale simulations.
- Improve ASPECT's performance and scaling by improving the geometric multigrid solver.
- Continue the push for more thermodynamically consistent models by adding the option to solve the energy equation in terms of entropy, instead of temperature.
- Provide a basic interface for bulk-surface coupling that allows for solving equations on the surface of the earth.
- Continue developing 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.
- Benchmark viscoelastic deformation and apply it to glacial isostatic adjustment models.
- Continue developing rate-dependent plasticity formulations, towards the aim of modeling the earthquake cycle and additional short-term tectonic processes.
- Prepare ASPECT for solving the adjoint equations to allow it to address inverse problems.
- Substantially extend the documentation of new features that have been added.

In addition, the first ASPECT Virtual Hackathon will be held August 3-7 and 10-14, 2020.

Outreach and Broader Impacts

The community has been active in community building through the following support and outreach activities:

- Development follow-ups from 2019 hackathon
- Organization of the ASPECT Virtual User Meeting
- Bi-weekly online community meetings
- Organization of the Tectonics Modeling Tutorial
- Organization of the Tectonics Science Workshop
- Planning of the 2020 ASPECT Virtual Hackathon
- Presentations at:
    - Poster at NSF CSSI meeting, Seattle, Washington (T. Heister and W. Bangerth)
    - Posters at AGU conference, San Francisco (See Appendix E.)
    - Invited talk, University of Goettingen, Germany (T. Heister)
    - Seminar/colloquium talks (3) that provided overviews of ASPECT (W. Bangerth)

ASPECT and deal.II continue to benefit from each other's development efforts. For instance, the particle infrastructure that was created for ASPECT as part of this award was transferred to the deal.II project and is now used for applications outside of its original scope, such as several example cookbooks in deal.II, e.g. electrons travelling through an electric field in a cathode ray, and chemical anomalies stirred in a chemical reactor. Additionally, the framework is used for chemical engineering models of mixing in the code Lethe-cfd (https://github.com/lethe-cfd/lethe/wiki), thus illustrating how software in one field can be transferred to other disciplines (Figure 9).

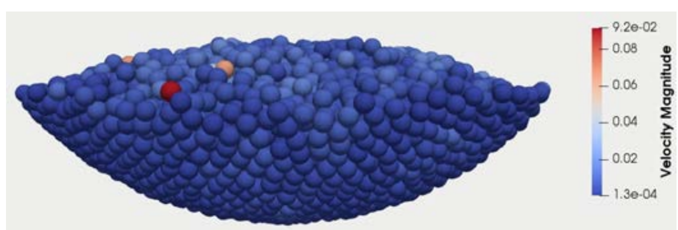

Figure 9. Example of discrete particles packed into a spherical domain in the software lethe-cfd, build on the particle framework originally developed for ASPECT and now widely available through deal.II. Image from: https://github.com/lethe-cfd/lethe/wiki/Example-6-:-Particle-Packing-in-Ball-(Three-dimensional).

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

The dynamic subgrid-scale (SGS) model is undergoing testing on the development version of Calypso. This model is being used to investigate the effects of the small-scale fields on large-scale fields using the dynamical SGS model from hi-resolution simulation results obtained using the Rayleigh code under the INCITE project. Investigations found that the SGS heat flux term effects all length scales but has the largest effects on the large-scale field. These results suggest that the hyper diffusivities, which work only on the small-length scale component, cannot model the effects of the unresolved scale on the large-scale field.

Under development is a feature to connect Calypso to the Line Integral Convolution (LIC) visualization module developed by Dr. Yangguang Liao in 2019. More optimization is required for LIC to run effectively with the simulation model.

Graduate student, Yuki Nishida (Tohoku University) is collaborating on investigations of dynamo processes in the past Earth. For this purpose, Nishida performs dynamo simulations in a spherical shell with solid inner core smaller than the present Earth's inner core. Comparing simulation results under the fixed temperature and heat flux conditions, Nishida concludes that these conditions require a smaller Rayleigh number range to sustain the dipole field.

Project goals for the upcoming year

The next release (v2.0) is currently in testing and is planned for release in September 2020. This version will have a large number of updates to use modern Fortran 90 and 2003 features. In v2.0, MPI-IO and data compression modules using zlib are introduced. This significantly reduces the number of data files and hence, data size. After release of v2.0, the parallel volume rendering (PVR) module will be migrated. This will also include a data viewer for cross section and isosurface data. This is necessary to easily modify the parameters for PVR.

To further SGS modeling using Calypso, dynamo simulations will be performed by applying nonlinear terms obtained by the large- scale fields results from the INCITE project. Because these simulations require the same spatial resolution as the original simulation by INCITE project, the simulations will be performed on TACC Frontera. This will allow a deeper quantitative investigation of the importance of the turbulent process in the geodynamo.

A new collaboration with Graduate student, Takumi Kera (Tohoku University) was started in April 2020. Kera investigates processes of the dipole reversal of the geomagnetic field through numerical modeling. Kera focuses on the contributions of symmetric and anti-symmetric flow and magnetic fields on the energy transfer between the kinetic and magnetic energies. For this data analysis, Kera will develop a module to evaluate energy fluxes by the symmetric/anti-symmetric fields.

Graduate student Nishida will perform additional dynamo simulations to discover more suitable thermal condition to sustain axial dipole magnetic field under the condition of a small inner core.

Outreach and Broader Impacts

Hiro Matsui, lead developer, is collaborating with 2 graduate students at Tohoku University.

Presentations include:

Kera, T., Katoh, Y., Nishida, Y., and Matsui, H., Matsushima, M., Kumamoto, A., Investigation of symmetry of the flow and magnetic field with respect to the equator in numerical dynamo with dipole reversal, JpGU-AGU Joint meeting 2020, Virtual, July, 2020. (in Japanese)

Nishida, Y., Matsui, H., Matsushima, M., Kumamoto, A., Katoh, Y., Effects of thermal boundary conditions on geodynamo with various Rayleigh numbers and inner core radii, JpGU-AGU Joint meeting 2020, Virtual, July, 2020.

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 volcano magma chambers.

Significant accomplishments of the past year

Development has continued to focus on completing the multiphysics formulation and its implementation with support for higher order discretizations. PyLith v3.0 (late summer 2020 release) will have the PetscFE class to discretize the continuum equations. In addition to the linear Lagrange elements currently in use, PetscFE provides high-order Lagrange elements and a host of finite element support operations, such as interpolation and L2 projection.

With the new release, PyLith will now be able to model faults with prescribed slip. The reformulated fault model now uses the total stress, making the problem much better conditioned and allowing rapid solution of through-going faults. In addition, the new formulation will enable coupling to other subsurface stresses, such as the pore pressure originating from saturating fluid. Currently under development are models of fault interaction with surrounding fluid and its application to investigation of hypothesized effects on slow slip and earthquake swarms (see Figure 10).

The substantial progress on poroelasticity has been made by Matt Knepley and Robert Walker (Postdoctoral Scholar, University at Buffalo). This is the most complete demonstration of the new multiphysics capability in PyLith. Nonlinear poroelastic models can easily be accommodated. The multiphysics implementation provides a flexible interface for implementing different governing equations. As a first test, PyLith now have a fully functional incompressible elasticity examples, allowing much easier setup (prestress) of models using gravity. This will give users the ability to add in thermal and fluid effects to their previous elastic models greatly expanding the range of physical models that can be simulated.

The team has made several minor improvements to the user interface through the introduction of application-wide defaults and better trapping of runtime errors associated with configuration/build errors. Some performance bottlenecks associated with recent changes have also been removed.

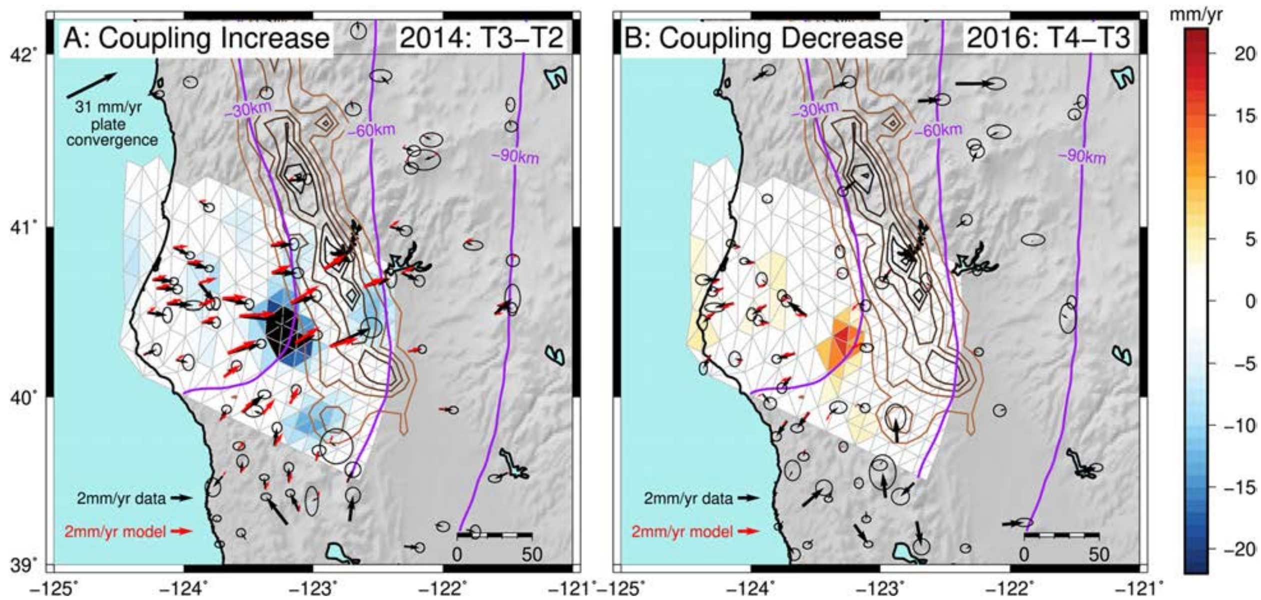

Figure 10. Velocity changes observed inn 2014 and 2016 in Cascadia were modeled using heterogeneous elastic Green's functions calculated using PyLith. The brown contours represent tremor density from the modified PNSN catalog, ranging from 0 to 2,000 tremor epicenters per 10 × 10 km grid cell. The purple lines show the depth contours of the interface geometry. The most prominent feature is a localized coupling change on the interface around 40.3°N in both inversions. Transient coupling changes have important implications for earthquake processes on faults.[7]

More tests using the Method of Manufactured Solutions (MMS) including those for linear poroelasticity as well as full-scale tests have been added. The test suite has already been extended to high-order Lagrange discretizations.

Brad Aagaard updated the continuous integration testing to use Docker containers. This simplifies the build procedure and caching of dependencies; currently the continuous integration tests run on 11 different flavors of Linux. The continuous integration also reports code coverage for the C++ and Python unit tests, MMS tests, and full-scale tests.

[7] Materna, K., Bartlow, N., Wech, A., Williams, C., & Bürgmann, R. (2019). Dynamically triggered changes of plate interface coupling in Southern Cascadia. *Geophysical Research Letters*, 46, 12890– 12899. https://doi.org/10.1029/2019GL084395

Brad Aagaard completed a major update of the spatial database library used by PyLith. It now uses the Proj v6 API, which provides a more flexible interface for specifying georeferenced coordinate systems. The updates also included simplifying the unit test code, which significantly improves maintainability.

Project goals for the upcoming year

Version v3.0 is anticipated for release in late summer 2020. The release will include the multiphysics implementation with support for quasi-static and dynamic simulations and spatial discretizations up to 4th order, time-dependent Dirichlet and Neumann boundary conditions, absorbing boundaries, and faults with prescribed slip.

The global pandemic derailed plans to hire a student to update Pythia/Pyre from Python 2 to Python 3; Brad Aagaard is working on this, which also includes adding tests to Pythia/Pyre, as time permits.

Version 3.1 planned for release in the next year will include a much-improved implementation for spontaneous earthquake rupture (i.e., fault friction) and parallel mesh loading. Additional development planned for next year will increase capabilities to:

- examine the impact of sub-surface fluids on fault triggering and rupture dynamics,
- model the full seismic cycle,
- study the interaction of waves in the solid and fluid e.g. incorporation of dynamic bore pressure measurements, and
- incorporate AMR using Pragmatic and exploit the PETSC TS class for adjoints and time-dependent optimization.

Current development plans for PyLith are maintained on github: https://github.com/geodynamics/pylith/wiki

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.

The PyLith Hackathon scheduled for June 2020 was postponed to June 2021 due to the global pandemic.

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 (Figure 11 and 12). In addition, this project benefits a broader scientific community, with specialists in stellar and planetary convection/dynamos now using the software as well.

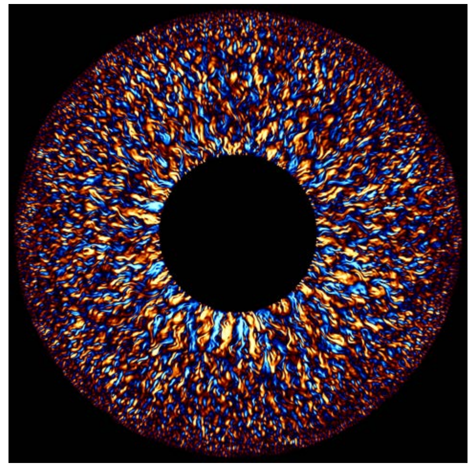

Figure 11. Image of the radial convective velocity field in the equatorial plane of an INCITE geodynamo simulation. Radially outward (inward) flows are shown in red (blue). The rotation period is one ten-millionth of a viscous diffusion time (Ekman E = 1e-7), the thermal and viscous diffusion times are equivalent (Prandtl Pr = 1), the magnetic diffusion time is one twentieth of the viscous diffusion time (magnetic Prandtl Pm = 0.05), the buoyancy forcing is about ten times supercritical (Rayleigh Ra = 1.5e11), and the spherical shell geometry is Earth-like (radius ratio r_i/r_o = 0.35). *Image courtesy of R. Yadav (Harvard University).*

Significant accomplishments of the past year

Development focused on the revision of the output quantity codes and output modules. These revisions will enable use of the model data and development of post processing tools by the community. The addition of command-line arguments will facilitate the scripting of large-scale parameter-space studies.

The Dynamo Working Group held a Writeathon at the University of Texas, Austin, from July 28 - August 1st, 2019. Five members of the INCITE Frontiers in Planetary and Stellar Magnetism Through High Performance Computing met to make progress on project-based publications. The participants presented their results from the DWG INCITE Rayleigh dynamo simulations and then proceeded to outline and prepare three manuscripts, all of which are still in process. Hiro Matsui is lead author on an analysis of sub-grid scale parameterizations using the INCITE run dynamo simulation results. Krista Soderlund is lead author on an analysis of electrical conductivity effects in INCITE models of the Ice Giant dynamos. Moritz Heimpel is lead author on a study of zonal jet flows and vortex properties in INCITE models of the Jovian deep atmosphere.

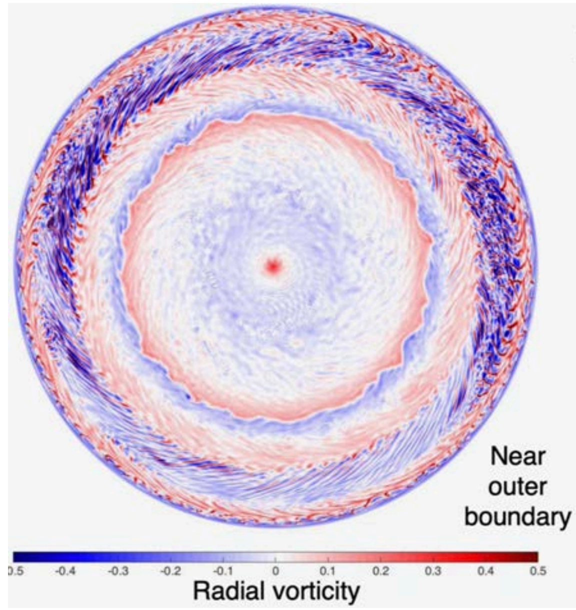

Figure 12. Near surface radial vorticity field in an INCITE model of Jovian deep convection. This extreme simulation generates features similar to those observed on Jupiter: Multiple strong zonal (east-west) jets form between the equator and pole. In addition, a strong cyclonic polar vortex forms here at the north pole. This simulation was made with the *Rayleigh* code, using up to 512,000 cores on Argonne's Mira device. *Image courtesy of M. Heimpel (University of Alberta).*

Project goals for the upcoming year

The DWG plans to develop an open online repository for numerical simulations of rotating convection and dynamos based on simulation runs from Rayleigh. The repository would allow users to download input and restart files to reproduce or continue existing models, and also visualize output data using python and possibly a 3D renderer like Vapor or Paraview. A repository will enable sharing of super high resolution (low Ekman number) and computationally expensive models so that new simulations can be extended. Data in the repository could also be useful for systematic studies and scaling analysis of a large number of models. Inclusion of onset solutions for various spherical shell systems and look-up tables will allow users to compare results between different systems.

Outreach and Broader Impacts

The Raleigh User Group held a series of virtual meetings this Spring to introduce upcoming changes in Rayleigh, discuss development objections and the organization and development of documentation going forward. A demonstration/mini-tutorial in April demonstrated how to turn Rayleigh's 3D output into Vapor-compatible datasets.

The group is planning a virtual hackathon for Fall 2020.

4.5 SPECFEM

SPECFEM3D_GLOBE simulates global and regional (continental-scale) seismic wave propagation (Figure 13[8]). 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.

Core Spectral-Element Code Developments

The team is developing and enhancing the SPECFEM3D and SPECFEM3D_GLOBE software suite on three main fronts.

A new SPECFEM3D–based quasi-static solver simulating post-seismic rebound is basically ready and will be released this spring. Leah Langer (Graduate Student) and Dr. Hom Nath Gharti (Research Scientist) are the main developers of this package. The team is currently investigating the effects of topography and bathymetry, 3D heterogeneity, and rheology on calculations of post-seismic relaxation.

A second development involves a SPECFEM3D_GLOBE-based quasi-static infinite-spectral-element method for simulations of post-glacial relaxation with full gravity. This

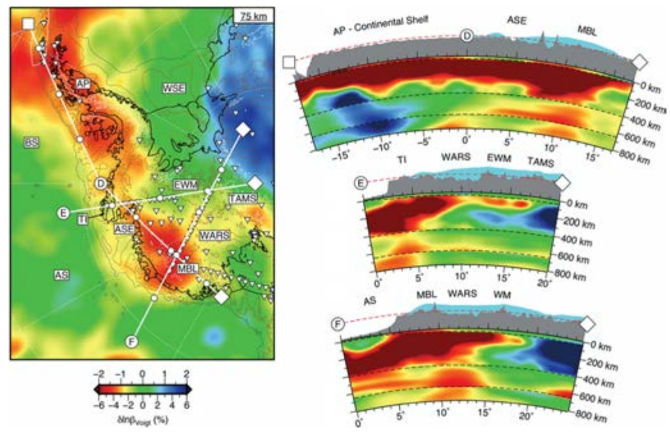

Figure 13. Tomographic imaging using SPECFEM3D_GLOBE combined with data from earthquakes recorded at broadband stations are used to produce regional-scale resolution models of the upper mantle and transition zone beneath Antarctica. Shown is the Voigt average shear-wave speed structure beneath West Antarctica at 75-km depth and along profiles D, E, and F. The horizontal slice depicts the locations of the profiles, shear-wave speeds, bedrock topography, bathymetry, plate boundaries, and lines of latitude and longitude. Abbreviations: AS—Amundsen Sea, ASE—Amundsen Sea Embayment, AP—Antarctic Peninsula, BS—Bellingshausen Sea, EWM—Ellsworth-Whitmore Mountains, MBL—Marie Byrd Land, TAMS—Transantarctic Mountains, TI—Thurston Island, WARS—West Antarctic Rift System, WSE—Weddell Sea Embayment, WM—Whitmore Mountain.[8]

[8] Lloyd, A. J., Wiens, D. A., Zhu, H., Tromp, J., Nyblade, A. A., Aster, R. C., et al (2020). Seismic structure of the antarctic upper mantle imaged with adjoint tomography. *Journal of Geophysical Research: Solid Earth*, 125. https://doi.org/10.1029/2019JB017823

solver is also being developed by Langer and Gharti. Uno Vaaland (Graduate Student) 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, Gharti's current main area of research. This has turned out to be much more challenging than originally anticipated because one can no longer use Gauss-Lobatto-Legendre quadrature 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 Oak Ridge National Laboratory (Norbert Podhorszky) and the ObsPy (www.obspy.org) group (Dr. Lion Krischer, Munich University), the team continues to make progress 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. The ADIOS file format is also used for other I/O functionalities such as kernels and check pointing. NVIDIA and IBM are teaming up to optimize ASDF and ADIOS I/O in the context of the Center for Advanced Application Readiness program.

The seismic imaging and inversion toolkit SeisFlows continues to be very actively developed, with many new users trying it out, providing 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. See doi: `10.1016/j.cageo.2018.02.004`

To move towards fully automated imaging and inversion workflows, the team is collaborating with Prof. Shantenu Jha (Rutgers University) to develop an *Ensemble Toolkit for Earth Sciences*. This workflow management tool will stabilize and expedite seismic imaging and inversion, for example, 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 software testing and documentation efforts have been increased. In addition to BuildBot, Jenkins and Travis are now used for unit testing, and all Python code use standard software development best practices.

4.6 ConMan

ConMan is a 2-D Cartesian finite element program for the solution of the equations of incompressible, infinite-Prandtl number convection in two dimensions, originally written by Scott King, Arthur Raefsky, and Brad Hager.

Significant accomplishments of the past year

The release of ConMan v3.0.0 (10.5281/zenodo.3633152) overhauled memory allocation using F90 allocate and deallocate functions eliminating many of the compile problems with v2.0.0. As part of the clean-up, a new input subroutine was created and many of the subroutine's names were lengthen and the Picard iteration for the temperature equation is now a runtime option as opposed to a compiler option.

The new version includes the compressible convection formulations commonly used in deep Earth dynamics, EBA, TALA, and ALA formulations[9], as well as examples based a subduction zone benchmark[10] and the compressible convection benchmark paper[3].

4.7 Software Pipeline

REM3D

CIG is actively working with Prof. Ved Lekic and Dr. Pritwiraj Moulik to prepare a release of the NSF supported REM3D/Avni software project within the CIG ecosystem, with a first release planned within

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[9] Scott D. King, Changyeol Lee, Peter E. Van Keken, Wei Leng, Shijie Zhong, Eh Tan, Nicola Tosi, Masanori C. Kameyama, A community benchmark for 2-D Cartesian compressible convection in the Earth's mantle, Geophysical Journal International, Volume 180, Issue 1, January 2010, Pages 73–87, https://doi.org/10.1111/j.1365-246X.2009.04413.x

[10] Peter E. van Keken, Claire Currie, Scott D. King, Mark D. Behn, Amandine Cagnioncle, Jiangheng He, Richard F. Katz, Shu-Chuan Lin, E. Marc Parmentier, Marc Spiegelman, Kelin Wang, A community benchmark for subduction zone modeling, Physics of the Earth and Planetary Interiors, Volume 171, Issues 1–4, 2008, Pages 187-197, ISSN 0031-9201, https://doi.org/10.1016/j.pepi.2008.04.015.

2021. CIG is providing support for improving documentation and testing infrastructure to prepare the software for public distribution.

5. Scientific and Broader Impacts

5.1 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 2019, the community published 101 journal articles using CIG codes. See Appendix F.

5.2 Cross Cutting Initiatives

In the upcoming year, CIG will be the sponsor for the CSDMS Geodynamics Focus Research Group (FRG). The Geodynamics FRG's goals are to provide input to the CSDMS effort on how to best represent geodynamic processes and models within CSDMS. The membership and interests of the Geodynamics FRG overlap with CIG's and will provide a connection for future collaborations.

CIG has been invited to collaborate on a joint webinar series with the Modeling Collaboratory for Subduction RCN. In partnership with SCEC, CSDMS, and EarthCube, the 2020-2021 webinar series will emphasize the role of computational geoscience in the predictive assessment of plate boundary systems and hazards.

5.3 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, RDA, US RSE, 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. CIG staff member Rene Gassmöller with support from Better Scientific Software Fellowship of the Department of Energy's IDEAS-ECP project, lead a workshop at the 2019 AGU Fall

Meeting on Best Practices for Developing and Sustaining Your Open-Source Research Software and participated in a Town Hall Update and Future Directions of the Open-Source Software Initiative.

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.

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
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 Florida*
University of Connecticut
University of Hawaii
University of Houston
University of Kentucky
University of Louisiana at 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

State University of New York at Buffalo
State University of New York at Stony Brook
Texas A&M University
Tulane 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 of Bristol, UK
University College London
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, University of Colorado, Boulder
- Nick Featherstone, University of Colorado, Boulder
- Timo Heister, Clemson University
- Matthew Knepley, University of Buffalo
- Eldridge G. Puckett, University of California, Davis
- Marc Spiegelman, Columbia University

Dynamo (8)

- *Lead,* Peter Driscoll, Carnegie DTM
- John Aurnou, University of California, Los Angeles
- Bruce Buffett, University of California, Berkeley
- Mike Calkins, University of Colorado, Boulder
- Philip Edelmann, LANL
- Hiroaki Matsui, University of California, Davis
- Maria Weber, Delta State University
- Cian Wilson, Carnegie DTM

Education (10)

- Magali Billen, University of California, Davis
- Katie Cooper, Washington State University
- Sanne Cottar, University of Cambridge
- Lorraine Hwang, UC Davis
- John Louie, University of Nevada, Reno
- Louise Moresi, Australian National University
- Gabriele Morra, University of Louisiana

- Federik Simons, Princeton University
- Sarah Stewart, University of California, Davis
- John Vidale, University of Southern California

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, Boston College
- Marc Hesse, University of Texas, Austin
- Garrett Ito, University of Hawaii
- Richard Katz, Oxford University
- Matt Knepley, University of Chicago
- Ikuko Wada, University of Minnesota
- Cian Wilson, Carnegie DTM

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 Florida
- Timo Heister, Clemson University

- Margarete Jadamec, University of Buffalo
- Mark Richards, University of Washington
- Max Rudolph, University of California, Davis

Seismology (5)

- *Lead,* Carl Tape, University of Alaska at Fairbanks
- Ebru Bozdag, Colorado School of Mines
- Carene Larmat, Los Alamos National Lab
- Arthur Rodgers, Lawrence Livermore National Lab
- Andrew Valentine, Australian National University

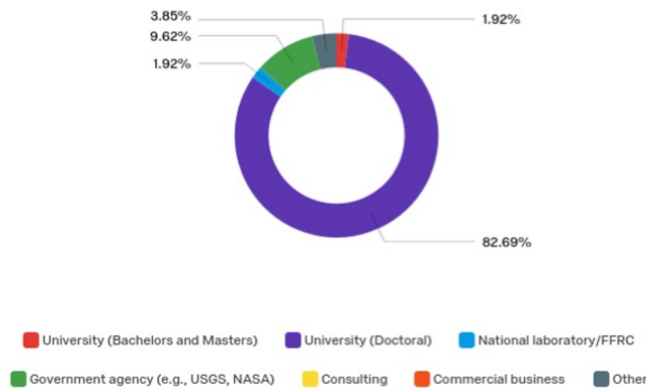
Short-Term Crustal Dynamics (4)

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

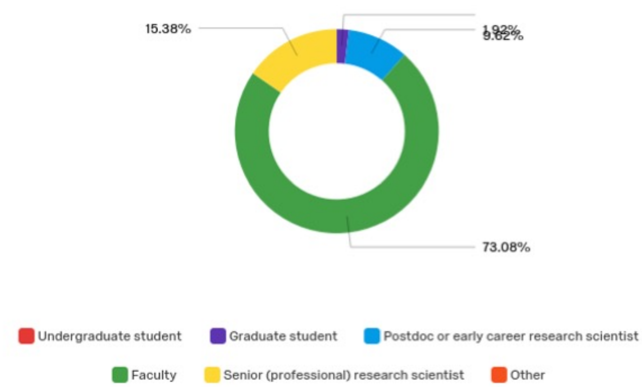
Appendix C: 2019 Community Survey Results

Demographics

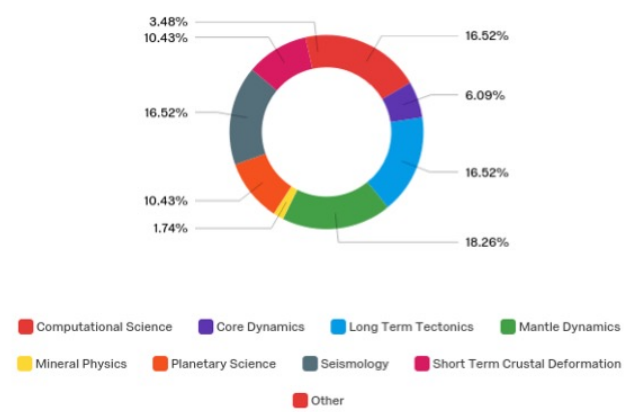
My primary affiliation is with a:



Career level:

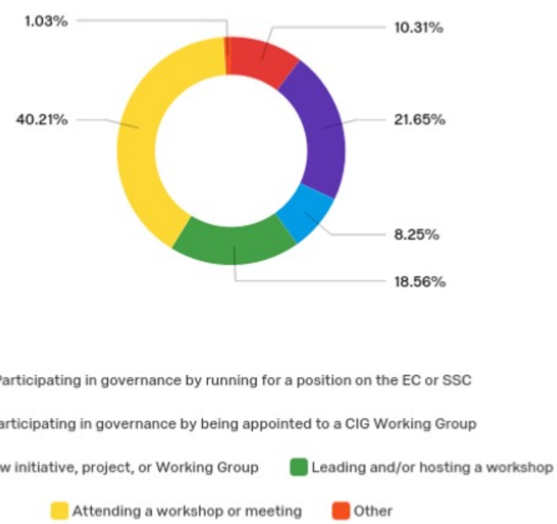


My domain area(s) of expertise are:
choose all that apply



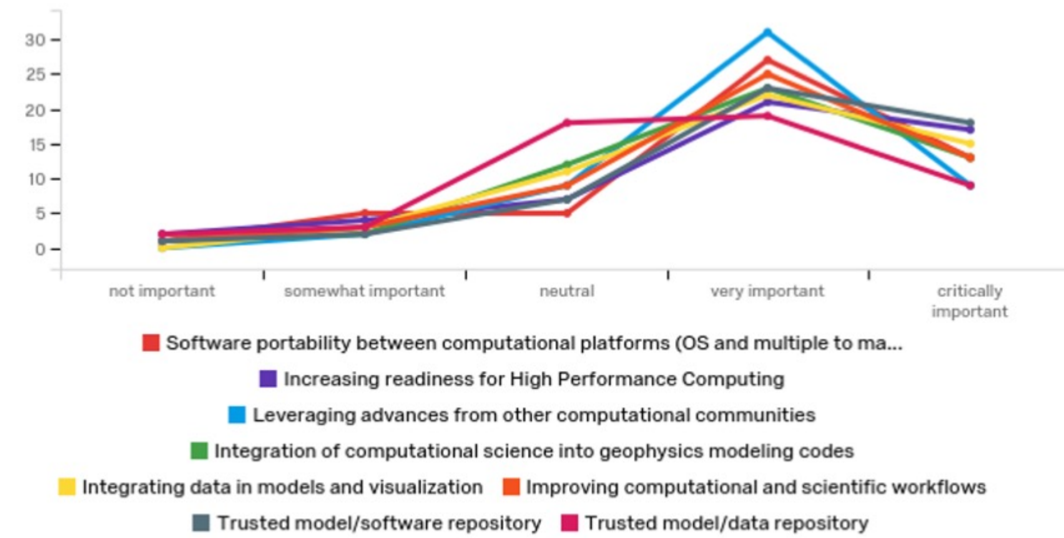
Involvement

I. I would like to be involved in CIG IV by: *choose all that apply*

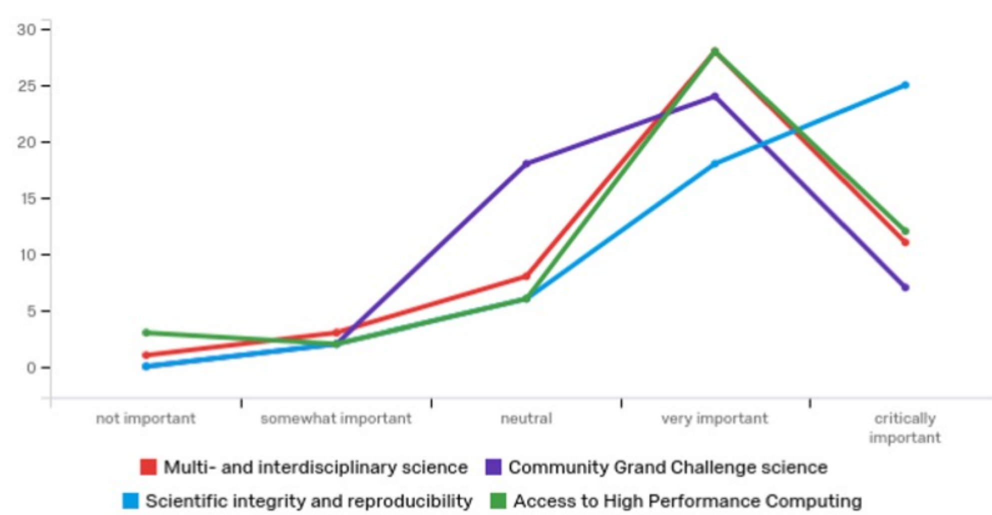


II. I am interested in engaging in the strategic planning process for CIG IV by: *choose all that apply*

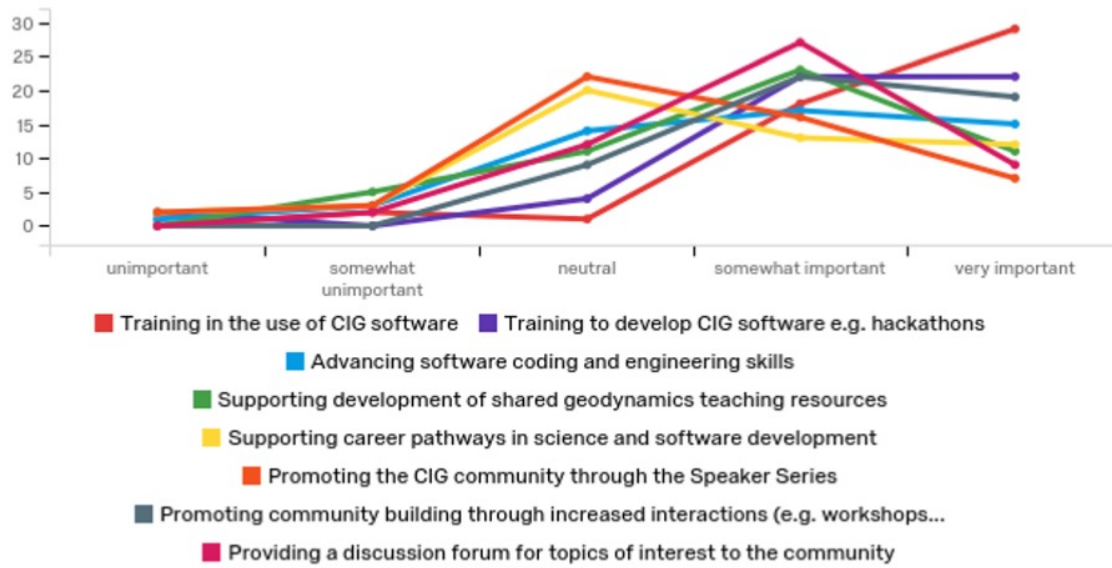
Software
Rank the importance of each of the following themes for CIG IV:



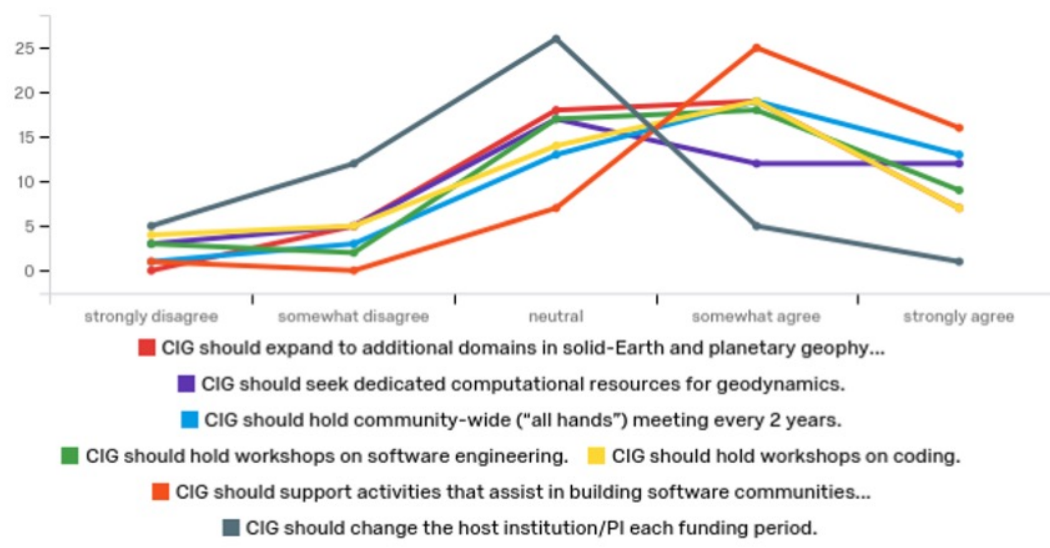
Science
Rank the importance of each of the following themes for CIG IV:



Outreach
Rank the importance of each of the following themes for CIG IV:



Activities
Indicate how strongly you agree or disagree with the following statements:



Appendix D: Privacy Policy

CIG is committed to protecting personal privacy and the personal information collected via this website (geodynamics.org).

Information Collected

We collect information to analyze the development and usage of community software, event offerings, outreach efforts, and other services we offer to evaluate their effectiveness in better serving our community. When visiting our website, we automatically store and collect your internet domain; the type of browser and operating system used; the date and time of access, pages visited, and if any, IP of website referred. This information is aggregated and anonymized. We do **not** track or record information about individuals and their visits. We do use a minimal number of cookies to optimize the users experience.

Registration Information

We collect personal information when you register for events that includes name, affiliation, contact, and other information. We may also collect other optional personal information such as research interests, dietary restriction and other background information. In addition, if you provide it, we may collect (1) personal information about disabilities, medical conditions, gender identity, and allergies in order to provide appropriate accommodations for attendees; and (2) personal information about your citizenship, date of birth, and passport details if you request assistance from us with obtaining a visa letter to travel to one of our events.

Third Party Privacy Policies

CIG uses and may supply hypertext links to third party websites. Our Privacy Policy does not apply to other websites. We advise you to consult the respective Privacy Policies for more information.

Online Privacy Policy Only

This Privacy Policy applies only to our online activities and is valid for visitors to our website with regards to the information that they shared and/or collect with CIG. This policy is not applicable to any information collected offline or via channels other than this website.

Distribution of Information

We do not sell or share personal information to third-party organizations such as telemarketers, direct mailers, or other related organizations.

Individual Choice

Individuals have the option to decline any online registration and may submit requests to use other registration methods by e-mail or U.S. mail. Users may review, modify, or delete their previously provided personal information by contacting us.

Consent

By using our website, you hereby consent to our Privacy Policy

Contact

If you have additional questions or require more information about our Privacy Policy, do not hesitate to contact us: **help@geodynamics.org**

Appendix E: 2019 Fall AGU Presentations

List of presentations by CIG scientists at the 2019 Fall AGU meeting. This list combines of self-reported abstracts with keyword search on software package names.

Monday, December 9

C14B-07	The Role of Dynamic Topography on Glacial Inception in North America. Sophie Coulson, Jacqueline Austermann, Mark Hoggard, Fred Richards, Marisa J Borreggine, and Jerry X Mitrovica.
DI12A-07	Lithosphere differentiation controls Archean tectonics and craton formation. Fabio A Capitanio, Oliver Nebel, Peter A. Cawood, Roberto Ferrez Weinberg, and Priyadarshi Chowdhury.
DI13C-0028	Convection Dynamics of Stagnant Slabs and Their Return Flows from Seismic Imaging. Ying Zhou and Zhen Guo.
IN11B-17	The Open-Source EarthCube Cyberinfrastructure BALTO: Applications in Earth Science. D Sarah Stamps, James H R Gallagher, Scott D Peckham, Anne F Sheehan, Nathan Potter, Maria Stoica, Emmanuel A Njinju, Zach M Easton, David W Fulker, and Daniel R Fuka.
S11E-0402	Simulations of Wave Propagation Effects on Far-Field Ground Motions from the SPE-5 Underground Chemical Explosion. Michelle Elyse Dunn, Arben Pitarka, John N Louie, and Kenneth D Smith.
S12B-06	Developing a Catalog of Slow Slip Events at the Hikurangi Subduction Margin, New Zealand. Charles A Williams, Laura M Wallace, Noel M Bartlow, and A. John Haines.
S13D-0472	Uncovering relationships between ground shaking and coseismic landsliding during the April 25, 2015 Gorkha Earthquake through full wavefield simulations using SPECFEM3D. Audrey Dunham, Eric Kiser, Jeffrey S Kargel, Daniel H Shugar, Umesh K Haritashya, and Scott Watson.
T13C-07	Spatial Distribution of Deep Earthquakes Controlled by Spatially-variable Strain-rate in Subducting Slabs. Magali I Billen.
T13D-0290	How the deformation is accommodated and distributed within active fault zones? Insights from satellite geodesy and realistic fault modeling. Mathilde Marchandon, James Hollingsworth, Mathilde Radiguet, and Kenneth W Hudnut.
T13D-0303	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.

T13D-0305	Characterizing Episodic Tremor and Slip in Cascadia. Noel M Bartlow and Charles A Williams.
T13H-0327	Characterizing seismic rupture scenarios for the Eastern Betic Shear Zone, Spain, using physics-based earthquake simulations: a preliminary approach. Paula Herrero-Barbero, Jose Antonio Alvarez Gomez, Jorge Alonso-Henar, and Jose J. Martínez-Díaz.
V11B-07	Investigation of Volcano-tectonic Interactions in the Natron Rift of the East African Rift System using Numerical Modeling. Joshua Robert Jones, D. Sarah Stamps, Brad Aagaard, and Christelle Wauthier.
V11E-0132	Magmatic compositional trends predicted by geodynamic models: The case of intraplate volcanism in the Eastern Atlantic. Antonio Manjón-Cabeza Córdoba, Maxim Ballmer, and Esteban Gazel.
V13B-01	A link between seamount volcanism and thermochemical piles in deepest mantle (Invited). Clinton P Conrad, Mathew Domeier, Kate Selway, and Björn H. Heyn.

Tuesday, December 10

DI21B-0019	Origin of Circular Pn Anisotropy in the Mississippi Embayment. Arushi Saxena, Christine Ann Powell, and Eunseo Choi.
DI21B-0035	Upper Mantle Dynamics and Seismic Anisotropy from Synthetic Waveforms. Wanying Wang and Thorsten W Becker.
DI21B-0036	Slab-driven Asthenospheric Weakening Facilitating Tectonic Plate Motion. Margarete Ann Jadamec, Simin Gao, Julia MacDougall, and Karen M. Fischer.
DI23B-0047	Observations of PKKPab Diffraction Waves Well Beyond Cutoff Distance. Yulin Chen, Sidao Ni, and Baolong Zhang.
DI23B-0064	On shear wave velocity in the top of the Earth's inner core. Dmitry Krasnoshchekov, Vladimir Ovtchinnikov, and Olga Usoltseva.
S21F-0568	Earthquake rupture modeling using Finite Element Method: fracturing vs. friction. Ekaterina Bolotskaya, and Bradford H Hager.
S23C-0651	Rapid Global Finite-Frequency Ambient Noise Source Inversion. Jonas Karl Hans Igel, Laura Ermert, and Andreas Fichtner.
S23F-0709	Synthetic Experiments on the Importance of Anisotropy in the Construction and Interpretation of Teleseismic P- and S- wave Tomographic Models of Subduction Zones. Brandon VanderBeek and Manuele Faccenda.

S23G-0716	On the joint inversion of seismic waveforms and gravimetric anomalies – Application to the Pyrenees. Nian Wang, Roland Martin, Plazolles Bastien, Sebastien Chevrot, and Dmitry Borisov.
T21E-0338	Modeling of Mantle Flow and Dynamic Topography in the Region of the Sierra Nevada de Santa Marta, Colombia. David Quiroga, Jillian Pearse, and Claire A Currie.
T21F-0380	Adjoint Tomography of South America based on 3D Spectral-Element Seismic Wave Simulations. Caio Ciardelli, Suzan Van der Lee, Ebru Bozdag, and Marcelo Assumpcao.
T21G-0428	Far-field Slabs Drive the North American Plate. Shangxin Liu and Scott D King.
T23A-07	Assessing the geodynamics of strongly arcuate subduction zones in the eastern Caribbean subduction setting. Menno Fraters, Wim Spakman, Cedric Thieulot, and Douwe J Van Hinsbergen.
V21B-04	The Role of Compositionally-Dependent Phase Transitions in Slab Deformation and Trench Motion (Invited). Magali I Billen.

Wednesday, December 11

DI31A-01	Slabs as Agents of Mixing and Material Recycling in the Earth's Mantle (Invited). Magali I Billen.
DI31A-02	Large and Small Scale Structures within the Marble Cake Mantle (Invited). Scott D King, Shangxin Liu, and Claudia Adam.
DI31A-03	Constraining dynamic topography in deep ocean basins. Nicholas Ellis and Jolante van Wijk.
DI32A-06	The morphology, evolution and seismic visibility of partial melt at the core-mantle boundary: Implications for ULVZs. Juliane Dannberg, Robert Myhill, Sanne Cottaar, and Rene Gassmoeller.
DI33A-07	Plume formation across scales: The influence of subducted slabs, chemical heterogeneities and a partially molten boundary layer (Invited). Juliane Dannberg, Rene Gassmoeller, and Philip Heron.
DI33B-0036	Slab-wedge Coupling Promotes Deep Subduction of Sediment: Geodynamic Insights to Mantle Geochemical Heterogeneity. Joe Schools, Jenna Adams, Kiran Chotalia, James Muller, Erik Weidner, Magali Billen, Louis Moresi, and Meghan Miller.
DI33C-0048	3D Immersive Visualization Facilitating New Paradigms and Scientific Reproducibility in Solid Earth Dynamics. Margarete Ann Jadamec, Oliver Kreylos, Benjamin Chang, M. Burak Yikilmaz, and Karen M. Fischer.

DI33C-0049	Capturing Dynamic Effects of Compressible Mantle Convection: New Formulations and Numerical Methods. Rene Gassmoeller, Juliane Dannberg, Wolfgang Bangerth, Timo Heister, and Robert Myhill.
DI33C-0059	Thermo-chemical plume interactions with mantle viscosity layering and phase transformations: comparisons with seismic imaging. Felipe Orellana Rovirosa, Mark A Richards, and Barbara A Romanowicz.
DI33C-0066	Global Mantle Structure from Multi-frequency Tomography using P, PP and P-diffracted Waves. Kasra Hosseini, Karin Sigloch, Maria Tsekhmistrenko, Afsaneh Zaheri, Tarje Nissen-Meyer, and Heiner Igel.
NH33C-0924	Modeling of ionospheric plasma and mesopause airglow responses to infrasonic acoustic waves generated by strong inland earthquake. Pavel Inchin, Jonathan B Snively, Matthew D Zettergren, Yoshihiro Kaneko, Attila Komjathy, and Olga P Verkhoglyadova.
S31C-0519	GPU-Based Simulation of Earthquake Ground Motions in the San Francisco Bay Area: Path and Site Effects from Suites of Ruptures and Evaluation of the USGS 3D Model with Moderate Magnitude Earthquakes. Arthur J Rodgers, Arben Pitarka, N. Anders Petersson, Bjorn Sjogreen, and Ramesh Pankajakshan.
S31C-0522	Heterogeneous source modelling by the earthquake cycle and dynamic rupture simulations and validation of results for a vertical strike-slip fault. Anatoly Petukhin, Percy Galvez, Paul Somerville, Ken Miyakoshi, and Kojiro Irikura.
S31C-0528	Dynamic simulation on the earthquake rupture jumping from the Leech River Fault to the Southern Whidbey Island Fault, southern Vancouver Island. Ge Li and Yajing Liu.
S31D-0541	High-frequency global seismic wave modelling with realistic ocean layers and bathymetry. Benjamin Fernando, Kuangdai Leng, Maria Tsekhmistrenko, and Tarje Nissen-Meyer.
S31D-0547	Cube2sph toolkit: Efficient continental-scale seismic-wave simulations by the SPECFEM3D package. Qinya Liu, Tianshi Liu, and Kai Wang.
S31D-0548	SPECFEM3D: An Improvement of the Internal Mesher for Full-Waveform Modeling with 3D Elastic Parameters, Acoustic/Elastic Propagation, and Bathymetry/Topography. Yujiang Xie, Catherine Rychert, Nicholas Harmon, Qinya Liu, and J Michael Kendall.
S31D-0549	A spectral element normal mode code for the generation of eigenfrequencies, dispersion curves and synthetic seismograms of 1D planets. Johannes Kemper, Federico Daniel Munch, and Martin van Driel.

S31D-0560 Azimuthal Anisotropy in the Upper Mantle based on Global Adjoint Tomography. Samuel McRae Haugland, Ridvan Orsvuran, Ebru Bozdag, and Daniel B Peter.

S31G-0500 Postseismic deformation and stress evolution following the 2019 M 7.1 and M 6.4 Ridgecrest earthquakes. Jacob Dorsett, Kaj M Johnson, Simone Puel, and Thorsten W Becker.

S33A-03 Crustal heterogeneity along the Dead Sea Transform - implications to ground motions in Northern Israel. Michael Tsesarsky, Roey Shimony, and Zohar Gvirtzman.

S34A-02 A semi-automated adjoint tomography workflow applied to New Zealand's North Island. Bryant Chow, Yoshihiro Kaneko, Ryan Modrak, Carl Tape, and John Townend.

T31B-06 State-of-stress and stress rotations: quantifying the role of surface topography and subsurface density contrasts in magmatic rift zones (Eastern Rift, Africa). Sarah Jaye C Oliva, Cynthia J Ebinger, Eleonora Rivalta, Christelle Wauthier, Charles A Williams, and Claire A Currie.

T31B-08 Geodynamic Constraints on the Source of Syn-Rift Magmas in the West Antarctic Rift System. Dennis Lee Harry and Micah Mayle.

T31H-0305 Full-waveform inversion for the lithospheric velocity structure along a dense short-period seismic array in northeastern Tibet. Xiaofeng Liang, Yi Wang, Wentao Li, Zhen Liu, and Xiaobo Tian.

T33F-0413 Sources of Melt Generation in the Malawi Rift Implemented with ASPECT and the EarthCube Cyberinfrastructure BALTO. Emmanuel A Njinju, D Sarah Stamps, James H R Gallagher, and Kodi Neumiller.

T33F-0415 Numerical simulations of fault behavior during the transition from orthogonal to oblique extension. John Naliboff, Scott E K Bennett and Michael E Oskin.

T33F-0430 Finite-element modeling of syn-rift magmatism in a multi-layer Earth using ASPECT. Micah Mayle and Dennis Lee Harry.

T33G-0438 Numerical Investigation of Continental Extension in Heterogeneous Cratonic Lithosphere, Constrained by Observations From the Labrador Sea. Mohamed Gouiza and John B Naliboff.

Thursday, December 12

DI41C-0010 High-frequency full-wavefield assessment of ultra-low velocity zone scattering. Kuangdai Leng, Surya Pachhai, Michael Scott Thorne, and Tarje Nissen-Meyer.

ED43A-03	A Space Computer Named In Sight Landed on the Red World Last Year and Here is What We Found So Far. Sabine Stanley, William Bruce Banerdt, Suzanne E Smrekar, Benjamin Fernando, Heidi Fuqua Haviland, Anna C Horleston, Catherine Johnson, Scott D King, Martin Knapmeyer, Benoit Langlais, Angela G Marusiak, David Mimoun, Anna Mittelholz, Lujendra Ojha, Mark P Panning, Ana-Catalina Plesa, Christopher T Russell, Nicholas C. Schmerr, Aymeric Spiga, and Renee C Weber.
NG43A-0912	Numerical Simulation of a Laboratory Star. Fredy Ramirez, Nicholas Andrew Featherstone, and Jonathan M Aurnou.
S41E-0576	An Evaluation of SPECFEM3D for Local Infrasound Propagation Over Topography. Jordan W Bishop, David Fee, Ryan Modrak, and Carl Tape.
S43E-0705	Detection of velocity variation with a deep learning method. Yuancong Gou, Zhen Xu, and Tao Wang.
S41F-0589	Investigation of Local & Regional Site Response and Attenuation in the Central U.S. Rayan Yassminh and Eric A Sandvol.
S41F-0591	Azimuthal anisotropy of Lg attenuation: both real and synthetic data. Hongjun Hui, Eric A Sandvol and Ayoub Kaviani.
S42C-04	3D Ground Motion Simulations of the 2019 M7.1 Ridgecrest Earthquake. Evan Hirakawa.
S44A-06	3-D Synthetic Modeling of Anisotropy Effects on SS Precursors: Implications for Flow in the Mantle Transition Zone. Quancheng Huang, Nicholas C Schmerr, and Ross Maguire.
T41J-0263	Geodynamic modelling of subduction beneath the Pamir-Hindu Kush region. Yu Yang, Xiao Shuang, Scott D King, and Zuoxun Zeng.
V41A-04	Full moment tensor inversion of micro-earthquake sources beneath Mount St. Helens using dense 3-component array data. Han Zhang and Brandon Schmandt.

Friday, December 13

DI51A-0003	Can Higher Mode Surface-Wave Dispersion Discriminate Between Different Mars Mantle Models? Caroline Beghein, Haotian Xu, Jessica C E Irving, Tilman Spohn, Francis Nimmo, and Attilio Rivoldini.
DI51A-0007	Detecting the Mantle Transition Zone of Mars From Seismic Reflected Waves. Quancheng Huang, Nicholas C Schmerr, Ross Maguire, Carolina R Lithgow-Bertelloni, Daniele Antonangeli, and Scott D King.
DI51A-0009	Effect of thermal variations in Mars' mantle on 3D seismic wave propagation. Ebru Bozdag, Ana-Catalina Plesa, Sebastiano Padovan, Nicola

Tosil, Daniel B Peter, Caio Ciardelli, Doris Breuer, Martin Knapmeyer, Tilman Spohn, Melanie Drilleau, Eric Clevede, Philippe Henri Lognonné, Jeroen Tromp, Mark Wieczorek, Josh Murphy, Scott D King, Benjamin Fernando, Kuangdai Leng, and Tarje Nissen-Meyer.

DI51A-0012 Modelling the effects of 3D shallow scatterers and atmospheric sources on Martian seismic signals at high frequencies. Tarje Nissen-Meyer, Benjamin Fernando, Kuangdai Leng, Nicholas C Schmerr, Mark P Panning, Eleonore Stutzmann, Ludovic Margerin, Nobuaki Fuji, Renee C Weber, William Bruce Banerdt, Domenico Giardini, Philippe Henri Lognonné, and William T Pike.

DI51B-0028 Can Mars Seismic Events be Successfully Modeled as Fluid Flow Induced Seismicity? Scott D King, Sharon Kedar, Mark P Panning, Suzanne E Smrekar, and Matthew P Golombek.

ED53B-09 Let Them Eat Cake! Using Cake to Teach About Planetary Interiors. Scott D King and Llyn Sharp.

G53A-06 Seasonal variations in crustal seismicity in the Western Branch of the East African Rift System. Liang Xue, Christopher W Johnson, Yuning Fu, and Roland Burgmann.

G53B-0624 Coulomb Stress Changes on the Southern San Andreas Fault Induced by Water Load Variations from Salton Sea, California. Reagan Flynn, Liang Xue, Christopher W Johnson, and Yuning Fu.

P51A-06 Modeling Melt Migration in the Lithosphere and Asthenosphere of Io, with Applications to Heat Pipe Evolution and Cyclical Volcanism. Joe Schools and Laurent Montesi.

P53D-3479 Estimating ice shell thickness of icy moons from flexural and Crary waves using 3D seismic simulations. Saikiran Tharimena, Mark P Panning, Simon C Staehler, Steve Vance, Christian Boehm, and Martin van Driel.

S51E-0449 Introducing Surface Topography Effects and the 3D Velocity Structure to Refine the Kinematic Source Inversion Models. Application to the Norcia, Mw 6.5, 30 October 2016, Central Italy Earthquake. Emanuele Casarotti, Elisa Tinti, Laura Scognamiglio, and Federica Magnoni.

S53C-0509 3D Full-Waveform Modeling at the Equatorial Mid-Atlantic Ridge from PI-LAB Experiment. Yujiang Xie, Catherine Rychert, Nicholas Harmon, and J Michael Kendall.

T51A-08 Controls on Overriding Plate Deformation in South-central Alaska: Flat Slab versus Oceanic Plateau Subduction. Kirstie L. Haynie, and Margarete Ann Jadamec.

T51C-09 Boosting performance of geodynamic finite element native-Python code using Numba and PyPy. Sangjin Park, Soojung An, and Byung-Dal So.

T51C-11	Efficient Wave Propagation in PyLith Using libCEED. Jed Brown, Joseph Geisz, and Matthew Knepley.
T51C-16	Towards robust shear band angle and width in visco-plastic rheology. Timo Heister, John B Naliboff, and Cedric Thieulot.
T51E-0306	3D mantle upwelling beneath the South China Sea and Southeast Asia: Insights from geodynamic modeling. Zyiyuan Zhou and Juan Lin.
T51E-0327	Permian to present tectonic and geodynamic evolution of the eastern Tethys. Sabin Zahirovic, Michael Gurnis, Huilin Wang, Kara J Matthews, Dan J Bower, and Dietmar Müller.
T52C-11	Evaluating the Accuracy of Hybrid Finite-Element/Particle-In-Cell Methods for Modeling Mantle Convection and Lithosphere Dynamics. Rene Gassmoeller, Elbridge Gerry Puckett, Harsha Venkata Lokavarapu, and Wolfgang Bangerth.

Appendix F: Publications

Articles in 2019 using CIG codes either reported by authors or discovered using keyword searches on google scholar.

1. Aaziz, O., Vaughan, C., Cook, J., Kuehn, J. & Richards, D. (2019). Fine-Grained Analysis of Communication Similarity between Real and Proxy Applications, *Proceedings, Supercomputing 2019*, 98–103, doi:10.1109/PMBS49563.2019.00016.
2. Ates, E., Zhang, Y., Aksar, B., Brandt, J., Leung, V. J., Egele, M. & Coskun, A. K. (2019). HPAS: An HPC Performance Anomaly Suite for Reproducing Performance Variations, *ICPP 2019 Proceedings of the 48th International Conference on Parallel Processing*, 1–10, doi:10.1145/3337821.3337907.
3. Atkinson, M., Filgueira, R., Klampanos, I., Koukourikos, A., Krause, A., Magnoni, F., Page, C.M., Rietbrock, A. & Spinuso, A. (2019). Comprehensible Control for Researchers and Developers facing Data Challenges, *IEEE eScience 2019 proceedings*.
4. Babikoff, J. C. & Dalton, C. A. (2019). Long period Rayleigh wave phase velocity tomography using USArray, *Geochemistry, Geophysics, Geosystems 20*(4), 1990–2006, doi:10.1029/2018GC008073.
5. Zhang, B., Ni, S. & Chen, Y. (2019). Seismic attenuation in the lower mantle beneath Northeast China constrained from short-period reflected core phases at short epicentral distances, *Earth and Planetary Physics 3*, 537–546, doi:10.26464/epp2019055.
6. Bauville, A. & Baumann, T. S. (2019). geomIO: an open-source MATLAB toolbox to create the initial configuration of 2D/3D thermo-mechanical simulations from 2D vector drawings, *Geochemistry, Geophysics, Geosystems 20*(3), 1665–1675, doi:10.1029/2018GC008057.
7. Bechor, B., Theodoulou, T., Spada, G., Dean, S. & Sivan, D. (2019). Medieval relative low sea-level indications from the Peloponnese and the Aegean Sea, *Quaternary International*, doi:10.1016/j.quaint.2019.11.026.
8. Benvenuti, E. & Maurillo, G. (2019). Finite Element Modelling of Coupled Fluid-Flow and Geomechanical Aspects for the Sustainable Exploitation of Reservoirs: The Case Study of the Cavone Reservoir, *Geosciences 9*(5), 213, doi:10.3390/geosciences9050213.

9. Bobrov, A. M. & Baranov, A. A. (2019). Thermochemical Mantle Convection with Drifting Deformable Continents: Main Features of Supercontinent Cycle, *Pure and Applied Geophysics 176*, 3545–3565, doi:10.1007/s00024-019-02164-w.
10. Borgeaud, A. F. E., Kawai, K. & Geller, R. J. (2019). 3-D S-velocity structure of the mantle transition zone beneath Central America and the Gulf of Mexico inferred using waveform inversion, *Journal of Geophysical Research: Solid Earth 124*(9), 9664–9681, doi:10.1029/2018JB016924.
11. Brissaud, Q. & Tsai, V. C. (2019). Validation of a fast semi-analytic method for surface-wave propagation in layered media, *Geophysical Journal International 219*(2), 1405–1420, doi:10.1093/gji/ggz351.
12. Broek, J. M., Magni, V., Gaina, C. & Buiter, S. J. H. (2019). The formation of continental fragments in subduction settings: the importance of structural inheritance and subduction system dynamics, *Journal of Geophysical Research: Solid Earth*, doi:10.1029/2019JB018370.
13. Buffett, B. & Matsui, H. (2019). Equatorially trapped waves in Earth's core, *Geophysical Journal International 218*(2), 1210–1225, doi:10.1093/gji/ggz233.
14. Chen, H. (2019). *Hydrogen in the Nominally Anhydrous Phases and Possible Hydrous Phases in the Lower Mantle* (Doctoral dissertation, Arizona State University).
15. Cheng, W., Hu, X. G. & Liu, L. T. (2019). Azimuthal anisotropy beneath the deep central Aleutian subduction zone from normal mode coupling, *Journal of Geodynamics 133*, 101673, doi:10.1016/j.jog.2019.101673.
16. Chow, B., Wassermann, J., Schuberth, B. S. A., Hadziioannou, C., Donner, S. & Igel, H. (2019). Love wave amplitude decay from rotational ground motions, *Geophysical Journal International* 218(2), 1336–1347, doi:10.1093/gji/ggz213.
17. Corti, G., Cioni, R., Franceschini, Z., Sani, F., Scaillet, S., Molin, P., … & Erbello, A. (2019). Aborted propagation of the Ethiopian rift caused by linkage with the Kenyan rift, *Nature Communications 10*(1), 1309, doi:10.1038/s41467-019-09335-2.
18. Dahm, J., Richards, D., Black, A., Bertsch, A., Grinberg, L., Karlin, I., … & Pearce, O. (2019). Sierra Center of Excellence: Lessons Learned, *IBM Journal of Research and Development*, 1, doi:10.1147/JRD.2019.2961069.

19. Dando, B. D. E., Goertz-Allmann, B., Iranpour, K., Kühn, D. & Oye, V. (2019). Enhancing CO2 monitoring at the Decatur CCS site through improved microseismic location constraints, *SEG Library*, 4893–4897.
20. Dando, B. D. E., Oye, V., Näsholm, S. P., Zühlsdorff, L., Kühn, D. & Wuestefeld, A. (2019). Complexity in microseismic phase identification: full waveform modelling, travel-time computations, and implications for event locations within the Groningen gas field, *Geophysical Journal International 217*(1), 620–649, doi:10.1093/gji/ggz017.
21. Daubar, I. J., Banks, M.E., Schmerr, N. & Golombek, M. P. (2019). Recently Formed Crater Clusters on Mars, *Journal of Geophysical Research: Planets 124*(4), 958–969, doi:10.1029/2018JE005857.
22. de Gelder, G., Fernández-Blanco, D., Melnick, D., Duclaux, G., Bell, R.E., Jara-Muñoz, J., Armijo, R. & Lacassin, R. (2019). Lithospheric flexure and rheology determined by climate cycle markers in the Corinth Rift, *Scientific Reports 9*(1), doi:10.1038/s41598-018-36377-1.
23. Dhabu, A. C. & Raghukanth, S. T. G. (2019). Influence of Himalayan Topography on Earthquake Strong Ground Motions. In *On Significant Applications of Geophysical Methods* (pp. 175-177). Springer, Cham.
24. Dong, X., Yang, D. & Niu, F. (2019). Passive adjoint tomography of the crustal and upper mantle beneath eastern Tibet with a W2 norm misfit function, *Geophysical Research Letters 46*(22), 12986–12995, doi:10.1029/2019GL085515.
25. Fokker, E. B. (2019). *Seismic acquisition using Radar Interferometry* (Master's thesis, Utrecht University).
26. Eddy, C. L. & Ekström, G. (2019). Comparisons between measurements and predictions of Rayleigh wave amplification across the contiguous United States, *Physics of the Earth and Planetary Interiors* 299, 106407, doi:10.1016/j.pepi.2019.106407.
27. Fehr, M., Kremers, S. & Fritschen, R. (2019). Characterisation of seismic site effects influenced by near-surface structures using 3D waveform modelling, *Journal of Seismology 23*(2), 373–392, doi:10.1007/s10950-018-09811-0.
28. Fontaine, F. R., Roult, G., Hejrani, B., Michon, L., Ferrazzini, V., Barruol, G., … & Staudacher, T. (2019). Very- and ultra-long-period seismic signals prior to and during caldera formation on La Réunion Island, *Scientific Reports 9*(1), 8068, doi:10.1038/s41598-019-44439-1.

29. Fraters, M., Thieulot, C., van den Berg, A. & Spakman, W. (2019). The Geodynamic World Builder: a solution for complex initial conditions in numerical modeling, *Solid Earth 10*(5), 1785–1807, doi:10.5194/se-10-1785-2019.
30. Galvez, P., Petukhin, A., Irikura, K. & Somerville, P. (2019). Dynamic Source Model for the 2011 Tohoku Earthquake in a Wide Period Range Combining Slip Reactivation with the Short-Period Ground Motion Generation Process, *Pure and Applied Geophysics*, 1–19, doi:10.1007/s00024-019-02210-7.
31. Gassmöller, R., Lokavarapu, H., Bangerth, W. & Puckett, E. G. (2019). Evaluating the accuracy of hybrid finite element/particle-in-cell methods for modelling incompressible Stokes flow, *Geophysical Journal International 219*(3), 1915–1938, doi:10.1093/gji/ggz405.
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33. Grant, G. R., Naish, T. R., Dunbar, G., Stocchi, B. P., Kominz, M. A., Kamp, P. J. J., Tapia, C. A., McKay, R. M., Levy, R. H. & Patterson, M. O. (2019). The amplitude and origin of sea-level variability during the Pliocene epoch, *Nature 574*, 237–241, doi:10.1038/s41586-019-1619-z.
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35. Gunawan, E., Widiyantoro, S., Zulfakriza, Meilano, I. & Pratama, C. (2019). Postseismic deformation following the 2 July 2013 M 6.1 Aceh, Indonesia, earthquake estimated using GPS data, *Journal of Asian Earth Sciences 177*, 146–151, doi:10.1016/j.jseaes.2019.03.020.
36. Yang, H., Feng, Y., Wang, H., Wang, F. & Jeremic, B. (2019). Seismic energy flow calculation for earthquake soil structure interaction system, *Transactions, SMIRT-25*.
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43. Jouanne, F., Gajurel, A., Mugnier, J. -L., Bollinger, L., Adhikari, L. B., Koirala, B., … & Huyghe, P. (2019). Postseismic deformation following the April 25, 2015 Gorkha earthquake (Nepal): afterslip versus viscous relaxation, *Journal of Asian Earth Sciences 176*, 105–119, doi:10.1016/j.jseaes.2019.02.009.
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