Computational Infrastructure for Geodynamics

2017-2018
Annual Report

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COMPUTATIONAL INFRASTRUCTURE for GEODYNAMICS

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Executive Summary

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

We held regular meetings and workshops for software development projects, developed and offered tutorials for new codes, ran a first-ever hackathon for the short-term crustal dynamics code PyLith and an annual hackathon for the mantle convection code ASPECT. CIG continued to advance software development in mantle convection, crustal dynamics, geodynamo, long-term tectonics, seismology, and evaluated future directions for these codes. CIG supported community development and knowledge transfer through workshops, webinars, newsletters, tutorials, e-mail distribution lists, and joint workshops with other organizations. Our webinar series focused on new code features and use of geodynamics modeling in teaching. We continued work with the CIG community and other relevant communities to develop methods to provide attribution and citation of scientific software (Software Attribution for Geoscience Applications, SAGA).

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

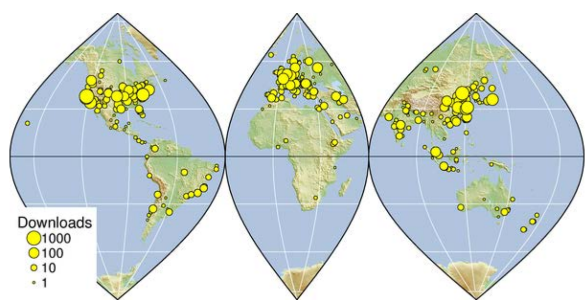

Figure 1. Download map of codes from CIG's software repositories 2017.

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 working groups plan to establish new community benchmarks in geodynamo and mantle convection, define scientific goals and capabilities in long-term tectonics, and support donations of codes for normal modes and workflows for seismology, multiphysics, ice sheet modeling, and other topics as code-donation requests arise through the year through our established approval process. We will support a delegation of early-career US scientists to the biannual EGU mantle and lithospheric dynamics workshop, now called the Ada Lovelace Workshop in Mantle and Lithosphere Dynamics, contribute to tutorials at CIDER, and plan to continue community activities and development (especially for early-career scientists) through workshops, meetings, tutorials, hackathons, and webinars. We plan to extend the CIG Distinguished Speaker program, currently a pilot program in outreach to colleges and universities that are underrepresented in computational geophysics. We continue to develop partnerships with national computing facilities and other partner organizations. These include managing and renewing CIG's allocation on XSEDE, collaborating with DOE's INCITE program on dynamo models, and working with library and information scientists to improve mechanisms for software citation.

CIG is a partner in a large INCITE allocation on Mira, now the 7th fastest computer in the world, operated by the Argonne Leadership Computing Facility (ALCF). The PI of this allocation was Jon Aurnou of UCLA, lead of the CIG Geodynamo Working Group, and the allocation was dedicated to running the planetary dynamos code Rayleigh, developed with CIG support by Nick Featherstone. Results and future plans for this high-visibility project are discussed later in this report.

CIG Director Louise Kellogg and Associate Director Lorraine Hwang continue to represent the CIG community at a variety of meetings and workshops. Associate Director Lorraine Hwang represented CIG to the Workshop on Sustainable Software for Science: Practice and Experiences (WSSSPE4) and FORCE11 (https://www.force11.org/) communities, to provide CIG participation in communities who are considering the role of cyberinfrastructure in scholarly communication. CIG held its annual business meeting at the Fall American Geophysical Union annual meeting, December 2017.

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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 geosciences 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 83 member institutions including 18 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, 2017 through July 31, 2018 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 available on our web site: https://geodynamics.org/cig/files/3415/3057/0459/2018_Bylaws_FINAL.pdf

Bylaws Update

CIG's Bylaws were last updated in 2012. Since then much has changed in the way CIG conducts business. The Bylaws were revised to reflect the adoption of a Code of Conduct for participation in CIG activities. Updates also covered revised election procedures, removal and vacancies of office, and definition of terms. As stipulated in the Bylaws, the revisions were approved by a vote of two-thirds of the electorate. See Appendix A.

Code of Conduct

CIG first established a code of conduct for its events in 2016. Since then, it has been revised and its Principles of Community and Code of Conduct have been officially approved by the EC. CIG's Code of Conduct is adapted from codes of conduct developed for online communities and geoscience organizations, including the WSSSPE Code of Conduct from the FORCE11 Code of Conduct, which was based on the Code4Lib Code of Conduct, inspired by the ADA Initiative; and the codes of conduct adopted by the Geological Society of America, and the American Geophysical Union. CIG leadership also advised other scientific communities and projects which have adopted similar statements. See Appendix B.

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 83 member institutions including 18 international affiliates. This year, CIG welcomed Tulane University, University of Louisiana, Lafayette; University of Melbourne, and University of Oslo. See Appendix C.

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- 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 (2018), University of Melbourne
- Magali Billen (2018), University of California, Davis
- Claire Currie (2019), University of Alberta
- Frederik Simons (2019), Princeton University
- Carl Tape (2020), University of Alaska, Fairbanks
- *Ex officio*, Katie Cooper (2018), Washington State University
- *Ex officio,* Louise Kellogg, 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,* Katie Cooper (2018), Washington State University
- Brad Aagaard (2019), United States Geological Survey
- David Ham (2020), Imperial College
- Jessica Irving (2020), Princeton University

- Boris Kaus (2018), University of Mainz
- Gabriele Morra (2020), University of Louisiana, Lafayette
- John Rudge (2019), Cambridge University
- Sabine Stanley (2018), University of Toronto
- *Ex officio,* Louis Moresi (2018), University of Melbourne
- *Ex officio,* Louise Kellogg, 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 forms goals and actions for the upcoming year.

CIG's seven working groups represent the main scientific domains active in CIG:

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.

Geodynamo

The long-term goal of the Geodynamo 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.

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 CIG Developed (D-CIG) codes: ASPECT, CitComS and CitComCU.

Short-Term Crustal Dynamics

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

Approximately 5% of the community (as determined from mailing list subscriptions) is actively involved in governing CIG through the EC, SSC and WGs, drawing from more than 3/5 of the member institutions. Appendix D provides a list of working groups and the 52 working group members who are engaged with the CIG community.

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

2.5 CIG Operations and Administration

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

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

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

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

CIG Staff are:

- *Director,* Professor Louise Kellogg*
- *Associate Director,* Dr. Lorraine Hwang
- *Research Scientist,* Dr. Hiroaki Matsui*
- *Assistant Research Scientist,* Dr. John Naliboff
- *Assistant Project Scientist,* Dr. Rene Gassmöller
- *Assistant Project Scientist,* Dr. Juliane Dannberg*

- *Software Engineer,* Tyler Esser*
- *HPC Support,* Bill Broadley*
- *HPC Support,* Terri Knight*

**part time effort for CIG*

2.6 The Planning Process

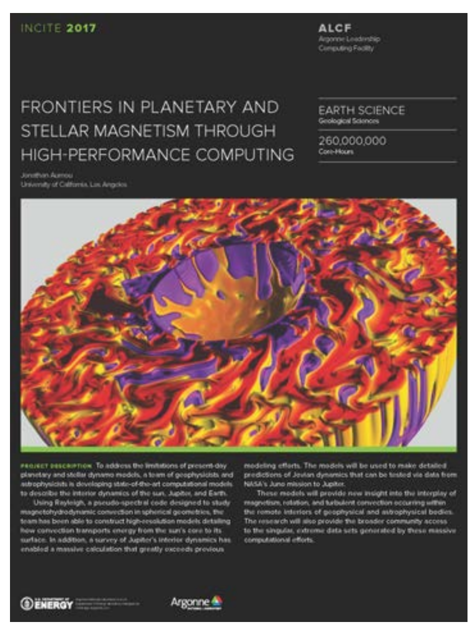
Concepts and ideas for CIG activities come directly from the community, member institutions, working groups and their elected committees. As members of the scientific community, WG and SSC members, and the Director are conduits for formal and informal dialog among the CIG community. Formally, users from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

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

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

2.7 Augmented Funding

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



This year was the final year for the project *Frontiers in Planetary and Stellar Magnetism Through High Performance Computing*. Through DOE's INCITE program, this effort led by the Geodynamo Working Group was awarded 493 million core-hours on Argonnne National Laboratory's (ANL) IBM Blue Gene/Q "Mira". http://geodynamics.org/cig/projects/dynamo-frontiers/

2.8 Communications

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

geodynamics.org

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

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

E-mail

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

For the period of January 1, 2017 through December 31, 2017, CIG's open e-mail lists distributed information to 928 unique individuals. Figure 2 displays activity by scientific domain, showing the

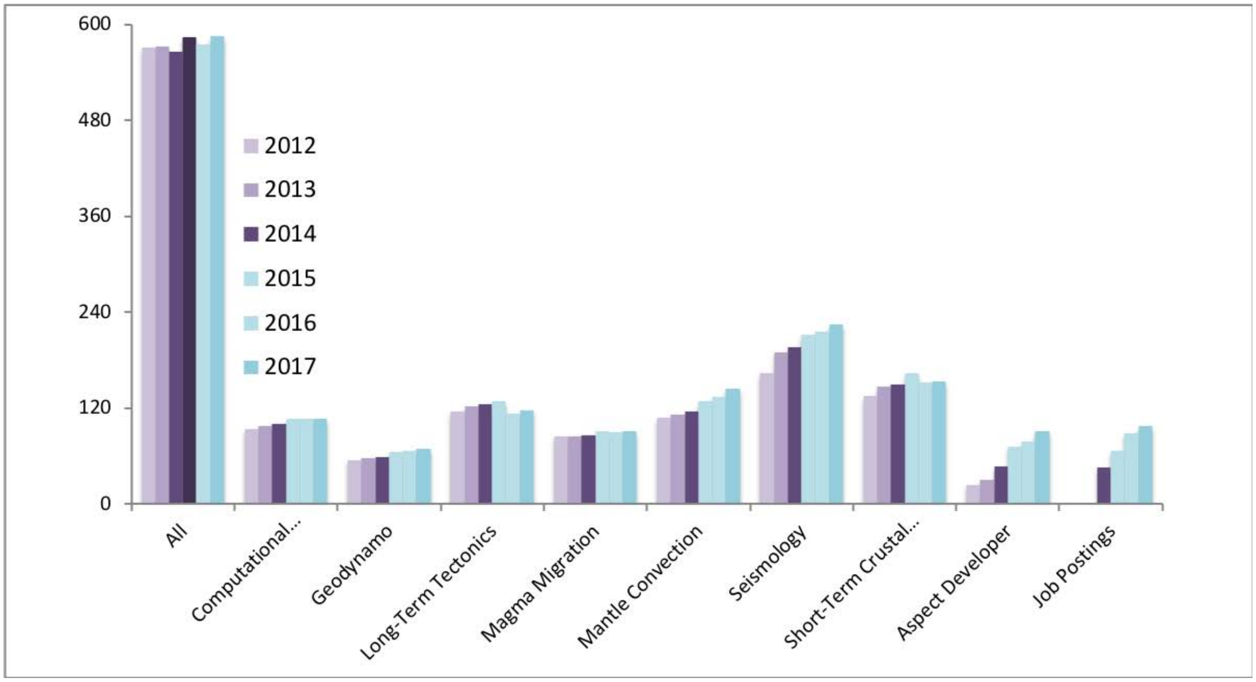


Figure 2a. CIG mailing list served 928 unique individuals in 2017.

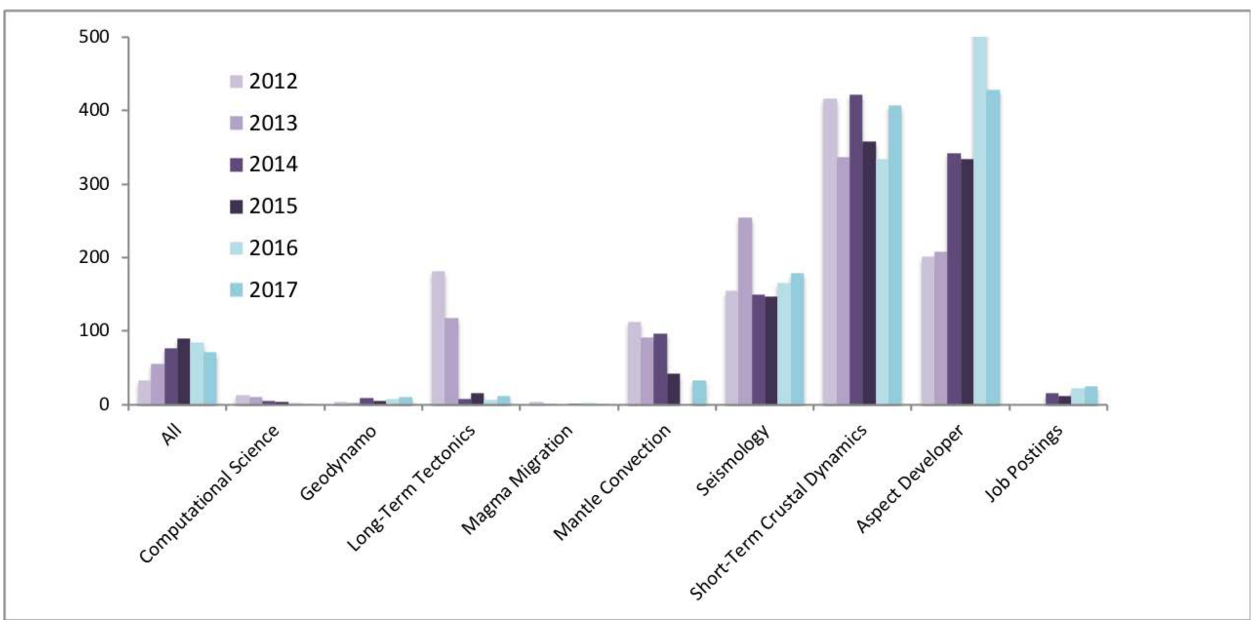


Figure 2b. CIG mailing list sent 1167 messages in 2017.

number of members for each list and number of messages sent. The domain-specific lists for groups that have released codes are used frequently for community support. Anyone may post a question or request for help; questions are wide-ranging from scientific application of a particular code to a problem, scientific methodology, to interpretation of error messages at compile or run time. Anyone may also respond. For active codes, developers and active users usually respond within a short time. CIG staff monitor the lists and will answer or redirect emails that remain unanswered. E-mail traffic for the year totaled approximately 1167 messages, with the most active domain-specific list, ASPECT, accounting for about 37% of the traffic, Short-Term Crustal Dynamics 35%, and Seismology 15%.

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

Annual CIG Business Meeting

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

CIG Quarterly Newsletter

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

GitHub

Most active 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.

Webinars

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

2.9 Metrics for Success

Activities to fulfill CIG's mission fall into three broad categories: software, people, and research impacts. We use a variety of metrics to monitor activity in each of these areas throughout this annual report. These metrics do not, of course, encompass the impacts and improvements in computational capabilities in geodynamics that result from CIG's activities. Those are covered in the later sections of this report.

Software

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

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

People

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

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

Research

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

- publications (abstracts, thesis, papers) and readership,
- acknowledgements and citations of CIG codes in publications and reports,
- proposals by researchers that draw on or use CIG resources,
- partnerships with other organizations,
- diversity of funding sources,
- invited presentations, and
- special sessions of national meetings organized around CIG resources or codes.

3. Facility Status

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

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

CIG utilizes modern software tools to continue to harden its software engineering practice and maintains a robust repository to facilitate sharing of validated open source software. CIG's servers are continuously backed up to protect information in the case of catastrophic loss. All software is maintained with full version control and complete revision history in a Git open source repository. Doxygen routinely updates documentation as extracted from the source files. The build and test framework has been moved to 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, 2017.

3.1 CIG Code Repository

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

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

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

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

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

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

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

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

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

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

Table 1 lists current repository holdings including software version, number of unique IP addresses that has downloaded the software in 2017, total lines of code, % change in number of lines of code from

Table 1. Repository Statistics

	Version	# unique IPs	Lines of Code	% Change	Commits	# developers	Support Level
Short-Term Crustal Dynamics							
Pylith	*2.2.1	1001	443,075	-6%	424	8	D_CIG
Relax	1.0.7	256	1,415,756	0%	6	9	D_CONTRIB
VirtualQuake	*3.1.1	128	48,806	0%	35	15	D_CONTRIB
SELEN	2.9.12	160	69,483	-	-	3	S_CONTRIB
LithoMop	0.7.2	48	495,786	-	-	5	A
Long-Term Tectonics							
Gale	1.6.1/2.0.1	165	6,660,841	-	-	62	A
Plasti	1.0.0	47	10,967	-	-	1	A
SNAC	1.2.0	24	549,498	-	-	3	A
Mantle Convection							
ASPECT	*1.5.0	321	1,471,890	27%	1487	65	D_CIG
CitcomCU	1.03	85	69,995	-	-	5	D_CONTRIB
CitcomS	3.3.1	188	239,453	0%	6	21	D_CONTRIB
ConMan	2.0.0	14	360,453	-	-	6	S_CONTRIB
Ellipsis3d	1.0.2	59	51,602	-	-	2	A
HC	*1.0.7	43	491,010	0%	11	7	A
Seismology							
Axisem	1.3	97	111,584	8%	75	12	D_CONTRIB
Burnman	0.9	50	50,905	24%	226	14	D_CONTRIB
Mineos	1.0.2	265	331,364	-	-	7	A
Flexwin	1.0.1	54	95,412	-	-	8	A
Seismic CPML		9	16,800	-0%	2	6	S_CONTRIB
Specfem3D		96	9,864,234	-23%	454	49	D_CIG
Specfem3D Globe	7.0.0	366	2,180,154	1%	112	53	D_CIG
Specfem3D Geotech	1.1	70	2,038,521	1%	119	4	D_CONTRIB
Specfem2D		70	1,265,844	26%	267	33	D_CONTRIB
Specfem1D		25	5,367	-	-	9	S_CONTRIB
SW4	*2.01	224	267,537	27%	200	17	D_CONTRIB
Geodynamo							
Rayleigh							
Calypso	*1.2.0	41	214,963	1%	21	7	D_CIG
MAG	1.0.2	7	134,906	-	-	5	A
Computational Science							
Cigma	1.0.0	17	356,371	-	-	7	A
Exchanger	1.0.1	19	5,654	-	-	7	A
Nemesis	1.1.0	14	193	-	-	2	S_CONTRIB
Pythia	0.8.1.18	23	33,078	-	-	4	S_CONTRIB

*new releases in 2017 +released 2018

previous year, number of commits in the repository, number of lifetime developers and current level of support. Statistics this year are as reported by gitinspector[1] which does not discriminate between line types e.g. comments vs. code. CIG codes span 6 scientific domains and most use multiple programming languages. The majority of the executable code in the library use shell and scripting languages, C, C++, and Fortran77/90, or Python. Codes that have substantial active development, e.g. addition of new features (net increase) or code rewriting and cleanup (net decrease) are predominantly those that are actively supported by CIG staff, subawardees, or are cooperative efforts with other agencies and research groups.

Download statistics report the number of IP addresses that downloaded a code a single time to avoid bots; however, some bots are most likely still present in these statistics. The CIG Git repositories logged 3445 software commits during 2017. Over the repository lifetime, nearly 456 developers have contributed to code development.

3.2 Web Portal Statistics

This year, the web tool used to report web traffic statistics has been upgraded to remove bots. Hence, the appearance of reduced activity in comparison to prior years is due to better filtering for bots, worms, or replies with special HTTP status codes.

Website:	www.geodynamics.org
Unique visitors:	93,543
Visits:	343,896
Hits:	4,332,306 hits
Downloads	1072 files
Page Views:	294,153

3.3 High Performance Computing Statistics

CIG continues to provide opportunities to train scientists on HPC by maintaining allocations on HPC resources on community machines. For 2018, CIG applied for 64,160 SUs on Stampede2, 1,000,000 SUs on Comet, and 15,000 Comet GPU nodes. CIG was awarded:

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

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

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

CIG allocation for the INCITE project *Frontiers in Planetary and Stellar Magnetism through High-Performance Computing* has expired but continues to do follow on work using a Director's Allocation.

CIG Staff also plans to continue to participate in HPC Community activities by attending XSEDE conferences and workshops as a means to further their skills and reach out to other communities.

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

3.4 Knowledge Transfer and Capacity Building

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

Workshops, Training, and Engagement with Other Communities

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

Upcoming workshops and training are posted online and advertised through CIG e-mail lists and those of our partner organizations. In 2017, CIG has offered 5 workshops and tutorials (Table 2) involving 177 predominantly early career participants from educational institutions, U.S. agencies, and international partners. CIG partners with other organizations to expand its reach.

Table 2. 2017-2018 Workshops and Tutorials

Date	Title	Participants
August 27-31	15th International Workshop on Modeling of Mantle and Lithospheric Dynamics	6*
September 18-22	2017 CIG-LLNL Computational Seismology Workshop	73
March 7-10	SIAM Conference on Parallel Processing for Scientific Computing	5*
June 10-14	2018 CGU CIG Joint Mantle Convection and Lithospheric Dynamics Workshop	24*
June 11-13	CGU ASPECT Tutorial	35
June 18-24	2018 PyLith Hackathon	9
June 18-28	2018 ASPECT Hackathon	25

*Participants Supported non-CIG Workshop

15th International Workshop on Modeling of Mantle and Lithospheric Dynamics

The XV International Workshop on Modeling of Mantle and Lithospheric Dynamics, August 27-31, 2017 in Putten, The Netherlands was co-sponsored by Utrecht University, the Oslo University Centre for Earth Evolution and Dynamics, the European Geological Union and CIG. The workshop brought together 130 scientists from Europe, North America and Asia to discuss topics in crustal and lithospheric modeling, global modeling of early and recent Earth, subduction and mantle flow modeling, rheology, and methodological advances. CIG's sponsorship consisted of supporting attendance by US participants. For a full listing of abstracts see: https://nethermod.sites.uu.nl/wp-content/uploads/sites/173/2017/08/book_of_abstracts.pdf

2017 CIG-LLNL Computational Seismology Workshop[2]

The Computational Infrastructure for Geodynamics (CIG), in collaboration with Lawrence Livermore National Laboratory (LLNL), held a workshop focusing on computational seismology at LLNL's Livermore Valley Open Campus September 18-22, 2017. The workshop provided training on seismic waveform

[2] Rodgers, A. J., L. J. Hwang, and L. H. Kellogg (2018), Computational seismology workshop trains early-career scientists, Eos, 99, **https://doi.org/10.1029/2018EO090991**.

processing, visualization and high-performance computing (HPC) waveform simulation. Fifty-five (55) predominantly early career (graduate students and postdocs) participants from the US and 16 countries attended. The workshop was the first of its kind to feature full access to HPC resources for research-grade example problems.

Seismic data processing software and numerical codes for HPC simulation of the seismic wavefield have evolved substantially in recent years. The volume of seismic data has greatly increased as instrumentation and technology have advanced and barriers to deploying sensors and transmitting data have fallen. Capabilities for HPC simulation of seismic waves in realistic three-dimensional Earth models have greatly increased for source and Earth structure studies driven by advances in numerical methods and inexorable increases in computing power. Demand is increasing for the skills to process seismic data and run HPC simulations of the seismic wavefield.

The 5-day workshop had several elements. The main objective was practical hands-on tutorials on the workflow involved in simulating seismic waveforms using numerical models. Keynote lectures by leading researchers described how seismic simulations are advancing understanding of earthquake hazards and Earth structure and they outlined challenges that must be overcome for HPC simulations to gain broader impact. Participants shared their current work in poster and lightning talk sessions. The Incorporated Research Institutions for Seismology (IRIS) presented a primer on data access.

The workshop tutorials gave participants hands-on experience using four open-source codes for waveform processing and simulation. *ObsPy* is a Python-based software package for accessing, processing, and visualizing seismic waveforms, event data and metadata. Three methods for computing synthetic seismograms were covered. *InstaSeis* computes seismograms for global radially symmetric models and runs on a laptop. Two codes compute seismograms in three-dimensional Earth models on parallel computers: *SW4*, a Cartesian finite difference code developed at LLNL; and *SPECFEM3D*, a spectral element code developed by a large team led by Princeton University. Participants learned how to run these codes, and then had practical session on how to process and visualize the results. LLNL provided access to 7200 cores of the Quartz HPC cluster for 3 days during the workshop, enabling participants to simultaneously run simulations on 100’s of processors. During the workshop the 2017/09/19 magnitude 7.1 Mexico earthquake occurred. Participants ran a simulation of this and other earthquakes with SPECFEM3D to exercise their newly acquired skills. Figure 3 includes visualizations created by participants.

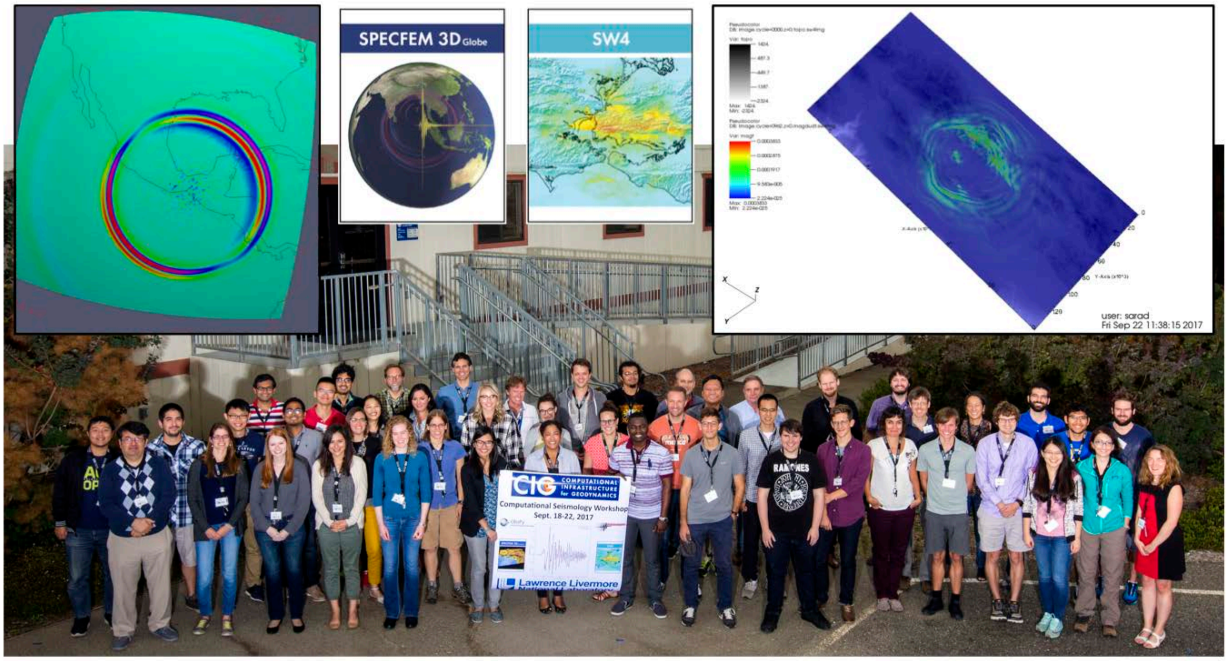


Figure 3. Group photo from the CIG-LLNL Computational Seismology Workshop held Sept. 18-22, 2017. Participants ran HPC simulations and visualized results: (inset left) SPECFEM3D_GLOBE simulation of the 2018/09/19 M 7.1 Mexico earthquake visualized with Paraview (Kelvin Tian, Columbia University); and (inset right) SW4 simulation of the 2007/07/20 M 4.0 Piedmont earthquake visualized with Visit (Sara Doherty, USGS).

2018 SIAM Conference on Parallel Processing for Scientific Computing

CIG scientists delivered invited talks at the 2018 SIAM Conference on Parallel Processing for Scientific Computing, March 7-10, 2018 in Tokyo, Japan. This series of conferences has played a key role in promoting parallel scientific computing, algorithms for parallel systems, and parallel numerical algorithms. The conference is unique in its emphasis on the intersection between high performance scientific computing and scalable algorithms, architectures, and software. The conference provides a forum for communication among the applied mathematics, computer science, and computational science and engineering communities.

Community members participated and gave invited talks in sessions on Scientific Accomplishments on Massively Parallel Computing of Earth and Planetary Sciences, Large-Scale Simulation in Geodynamics, Scientific Accomplishments on Massively Parallel Computing of Earth and Planetary Sciences, Hazard and Disaster Simulation of Earthquake and Tsunami with HPC, and Changes in Parallel Adaptive Mesh Refinement. See Section 4 for invited talks.

2018 CGU CIG Joint Mantle Convection and Lithospheric Dynamics Workshop

The 2018 CGU CIG Joint Mantle Convection and Lithospheric Dynamics Workshop June 10-14, 2018 in Niagara Falls, Canada is the second joint meeting with the Canadian Geophysical Union (CGU) bringing together a group of international researchers predominantly from the U.S. and Canada who study the dynamics of the Earth's mantle and lithosphere through numerical modeling. The meeting focused on numerical modeling, mantle dynamics and the geodynamics of lithospheric evolution combining invited and contributed talks and poster sessions. Participants contributed 39 abstracts to CIG sponsored sessions. Xiaowen Liu of University of Alberta won the *Best Student Paper* award for the CGU Solid Earth Section for her presentation in a CIG session. Discussions included the need for adjoint and error estimation workshops for mantle and lithosphere dynamics, access to mesoscale computing, online public code reviews to include and train remote users helping software projects to better their practices, and shorter satellite hack events. A large 3D model of a Hawaiian plume with melt transport and topography was suggested as a community development direction and computational challenge.

Figure 4. The ASPECT tutorial attracted 35 participants for 3, 1 ½ hr sessions during CGU.

A tutorial on ASPECT (35 participants, Figure 4) was also offered over three days, emphasizing lithospheric deformation and two-phase flow.

See Appendix E for a full list of abstracts.

2018 PyLith Hackathon

The first PyLith Hackathon was held jointly with the ASPECT Hackathon at Walker Creek Ranch June 18-24, 2018 in Petaluma, California (Figure 5). The event facilitated community development of PyLith and encouraged some of the advanced users to become user-developers. The three main developers worked with 6 early career scientists to begin growing the user-developer community. During this period, the group worked on: (1) implementing poroelasticity (including unit and full-scale testing and documentation), (2) coupling PyLith with an elasticity boundary integral formulation for reduction of the finite-element domain, and (3) development of a new example suite for 3D strike-slip faulting. The group discussed other topics that may lead to continued collaboration on implementation of additional features.

2018 ASPECT Hackathon

The 5th ASPECT Hackathon was held jointly with the PyLith Hackathon at Walker Creek Ranch June 18-24, 2018 in Petaluma, California. Participants (25) worked over an 8 day period both continuing to work on existing projects as well as initiating new projects and collaborations. The group included 9 new user-developers. Over 40 projects were initiated with many new collaborative efforts to add new material models, benchmarks, improved performance and other features driven by research interests.

Figure 5. Participants at the 2018 PyLith (top) and ASPECT (bottom) Hackathons.

Future Workshops

CIG plans to organize the following community workshops in 2018-2019:

Table 4. 2017-2018 Workshops and Tutorials

Date	Title
September 15-19, 2018	Rayleigh Tutorial and Hackathon
June 2019	CDM Workshop

Promoting Community

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

Webinars

The CIG Webinar Series draws from a pool of experts including applied mathematicians, computer scientists, and geoscientists, to both inform and disseminate knowledge on the tools and methodologies employed to further the study of problems in geodynamics. The 2017-18 series expanded upon our previous code tutorials by targeting new code features and expanding our knowledge about teaching geodynamic modeling in the classroom. The one-hour webinars are recorded for later viewing on the CIG YouTube channel and linked to CIG website. A full listing is given in Table 3.

Table 3. 2017- 2018 Webinar Schedule

Date	Presenters	Title
October 12	Taras Gerya, *ETH Zurich*	Geodynamic modeling with staggered finite differences and marker in cell: theory, teaching and examples
November 16	Max Rudolph, *University of California, Davis*	Tools and approaches for teaching computation and modeling: geodynamics and beyond
February 8	Gabriele Morra, *University of Louisiana at Lafayette*	Pythonic Geodynamics
March 8	Eric Mittelstaedt, *University of Idaho*	Where have all the dimensions gone? Hands on methods for introducing students to non-dimensional numbers in laboratory and numerical modeling
April 17	Lion Krischer, Simon Staehler, and Martin van Driel, *ETH Zuri*ch; Tarje Nissen-Meyer, *Oxford University*	New developments in AxiSEM/Instaseis for seismic wave propagation on local scales
May 10	Rene Gassmöller, Juliane Dannberg and John Naliboff, *UC Davis*; and Menno Fraters, *Utrecht University*	*ASPECT* 2.0: Improved architecture, new features

YouTube

CIG's YouTube channel, *CIG Geodynamics*, hosts 364 videos produced from simulations contributed by the community, recordings of past webinars and tutorials, and links to playlists of other community members (such as recorded lectures). Visitors are directed to the site mainly as a referral through YouTube and through geodynamics.org. Visitors come from an international community with the top viewers from the North America, Europe, India, Asia, and South America. The page has 321 subscribers and approximately 34,703 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 24,000 geophysicists in one place. The evening meeting provides a forum for information exchange and discussion about CIG operations.

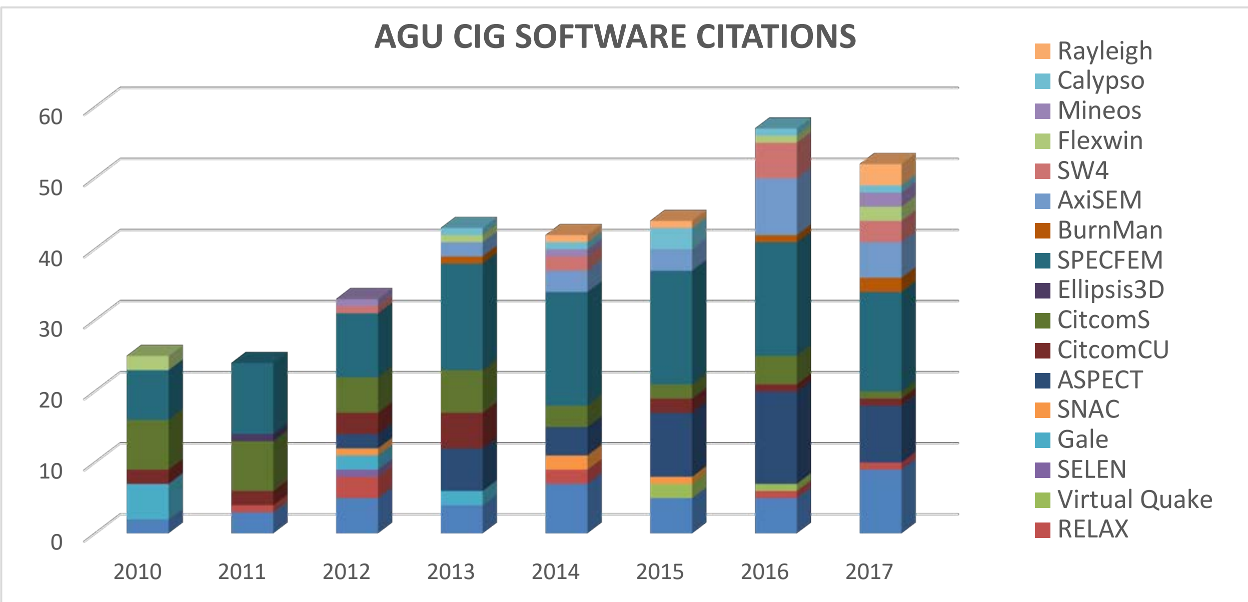


Figure 6. Number of CIG software mentions in an AGU abstract.

By searching for software mentions (Figure 6) and through community members reporting, 69 abstracts were accepted for the 2017 Fall Meeting in 11 disciplines including Study of Earth's Deep Interior, Earth and Planetary Surface Processes, Education, Geodesy, Informatics, Mineral and Rock Physics, Natural Hazards, Seismology, Planetary Sciences, Tectonophysics, and Union. See Appendix E.

Distinguished Speaker Series

CIG launched its Distinguished Speaker Series this 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.

CIG Distinguished Speaker Professor Sarah Stamps gave a presentation at Hampton University entitled *Advances in the Kinematics and Geodynamics of the East African Rift System*. The presentation highlighted research on continental rifting processes based in the CIG computational code ASPECT. This experience provided an opportunity to communicate CIG-based science and an overview of the community code ASPECT to an audience at an HBCU.

4. Software Development

4.1 ASPECT

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

ASPECT is being developed by a large, collaborative, and inclusive community. 8 Principal Developers maintain the openly accessible repository on GitHub and provide feedback to ASPECT's 45 user-developers who have made 1523 commits to the repository in 2017. These commits have added major new features to the code and were incorporated into a new release of the software in May 2018, ASPECT 2.0.0 (doi: 10.5281/zenodo.1244587).

Significant accomplishments of the past year

Major new features in ASPECT 2.0.0 release are:

- ASPECT now includes a Newton solver and a defect correction Picard solver scheme for the Stokes system, substantially improving the convergence for nonlinear problems.
- The solver for coupled magma/mantle dynamics has been reworked, leading to improved performance, stability and better integration with other plugins. This allows for new application models such as melt migration beneath mid-ocean ridges.
- ASPECT now supports modeling grain size evolution and grain-size dependent rheology.
- A temperature boundary condition that accounts for core evolution has been added.
- ASPECT can now compute the geoid in 3D spherical geometry.
- An option has been added to split advection and reactions in the time-stepping scheme, which allows for models where the time scales of these processes are vastly different, such as melting and freezing reactions.
- The PREM gravity profile can now be used in computations.
- A large number of performance improvements have been made, in particular, ASPECT now has a substantially reduced memory consumption in models that use many compositional fields.
- A number of structural changes have been made, allowing for greater flexibility when choosing boundary conditions, initial conditions, solver schemes, and additional terms used in the equations.
- The accuracy of the dynamic topography postprocessor has been improved by implementing the consistent boundary flux method for computing surface stresses.
- There is now a graphical user interface for the creation and modification of input parameter files.

Project goals for the upcoming year

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

- Implementing and testing gradient plasticity methods, making the width of shear bands caused by plastic yielding independent of the cell size.
- Incorporating a rheology that realistically describes fluid-rock interactions during brittle deformation, such as hydro-fracturing.
- Improving ASPECT's performance and scaling by implementing a geometric multigrid solver.
- Adding a basic interface for coupling ASPECT to surface evolution models.

- Adding self-gravitation to more accurately compute the gravity vector and the geoid.
- Benchmarking viscoelastic deformation and applying it to glacial isostatic adjustment models.
- Solving the adjoint equations in ASPECT to allow it to address inverse problems.
- Substantially extending the documentation of new features that have been added.

Outreach and Broader Impacts

Over the last year, CIG and the principal developers of ASPECT organized a number of outreach events to enable the community to use the code and to advance the development. These include:

- ASPECT Hackathon, 18-28 June in Petaluma, California
- Developer meeting, December 7-10, New Orleans, Louisiana
- Short course, University of the Chinese Academy of Sciences, June 20-28, 2017, Beijing, China with a one-day follow-up May 18, 2018
- Tutorials:
  - IMAGINingRIFTING workshop, September 24-27, 2017 Pontresina, Switzerland
  - Deep Earth Systems PhD Course, October 2-13, 2017 Aarhus University, Aarhus, Denmark
  - EON-ELSI Winter School, January 22 to February 2, 2018, Tokyo, Japan
  - ASPECT for lithospheric models, May 18, UC Davis, California
  - CGU/CIG meeting, June 10-14, 2018, Niagara Falls, Canada
  - CIDER, July 9 to August 3, 2018, Santa Barbara, California, USA,
- Invited presentations:
  - “Geodynamic modelling with ASPECT: Applications for magma/mantle dynamics, grain size evolution and chemical zonation in mantle plumes” in the Global Geophysics seminar, University College London, UK [J. Dannberg and R. Gassmöller]
  - “Coupling mantle convection and melt migration: 3D, adaptive simulations” in the MathLab Seminar at SISSA (Scuola Internazionale Superiore di Studi Avanzati), Trieste, Italy [J. Dannberg]
  - “Geodynamic models of coupled magma/mantle dynamics: Towards integrating thermodynamic data” in the Department of Geoscience Seminar at Aarhus University, Denmark [J. Dannberg]
  - A “Implementing flexible and scalable particle-in-cell methods for massively parallel numerical models” in the MathLab Seminar at SISSA (Scuola Internazionale Superiore di Studi Avanzati), Trieste, Italy [R. Gassmöller]

- Thermochemical convection in a compositionally stratified mantle: an intermodel comparison. *Louise H. Kellogg, E. Gerry Puckett, Ying He, Donald L. Turcotte, Harsha Venkata, Jonathan Robey* at 2018 NetherMod
- Advances in Mantle Convection Modelling: Nonlinear Solvers, Multiphysics, Linking Scales Rene Gassmoeller, Wolfgang Bangerth, and Juliane Dannberg, Timo Heister at the 2018 SIAM Conference on Parallel Processing for Scientific Computing
- Seminar talks at the University of Utah, the University of Colorado in Boulder, Boise State University, the Okinawa Institute of Science and Technology, the Chinese Academy of Sciences, the Beijing University of Technology, Nankai University in Tianjin, the Colorado School of Mines, the University of Colorado in Denver, and the Beijing Computational Science Research Center [W. Bangerth]
- Seminar talks by Rene Gassmöller and Juliane Dannberg at University of Texas in Austin and University of Colorado in Boulder about software development and scientific applications in ASPECT

4.2 Calypso

Calypso is a set of codes for MHD dynamo simulation in a rotating spherical shell using spherical harmonics expansion methods.

Significant accomplishments of the past year

Calypso1.2 (doi: 10.5281/zenodo.890016) was released with an improved Legendre transform implementation. Consequently, it is approximately 1.8 times faster than the previous version. In addition, visualization data output for cross sectioning and isosurface were implemented. Work is underway to implement new parallel visualization techniques to provide scalable, flexible visualization of the multidimensional fields produced by the software.

Project goals for the upcoming year

In the coming year, Calypso 2.0 will be released. Calypso v2.0 will implement more sophisticated data IO (binary and compressed data). A dynamic sub-grid scale (SGS) model is also under development. In addition, a whole sphere dynamo model to solve the Earth's dynamo more than billion years ago will continue to undergo testing in collaboration with a graduate student in Tohoku University, Japan.

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.

The code features:

- Quasi-static (implicit) and dynamic (explicit) time-stepping
- Cell types include triangles, quadrilaterals, hexahedra, and tetrahedra
- Linear elastic, linear and generalized Maxwell viscoelastic, power-law viscoelastic, and Drucker-Prager elastoplastic materials
- Infinitesimal and small strain elasticity formulations
- Fault interfaces using cohesive cells
- Prescribed slip with multiple, potentially overlapping earthquake ruptures and aseismic creep
- Spontaneous slip with slip-weakening friction and Dieterich rate-and state-friction fault constitutive models
- Time-dependent Dirichlet (displacement/velocity) boundary conditions
- Time-dependent Neumann (traction) boundary conditions
- Time-dependent point forces
- Absorbing boundary conditions
- Gravitational body forces
- VTK and HDF5/Xdmf output of solution, fault information, and state variables
- Templates for adding your own bulk rheologies, fault constitutive models, and interfacing with a custom seismic velocity model
- User-friendly computation of static 3-D Green's functions

Significant accomplishments of the past year

PyLith v2.2.1 (doi: 10.5281/zenodo.886600) was released with the following improvements:

- New examples added
    - New suite of examples for a 3-D subduction zone. This intermediate level suite of examples illustrates a wide range of PyLith features for quasi-static simulations.
    - Added quasi-static spontaneous rupture earthquake cycle examples (Steps 5 and 6) for slip-weakening and rate- and state-friction.

    - These new examples make use of ParaView Python scripts to facilitate using ParaView with PyLith.
- Manual improvements
    - Added diagram to guide users on which installation method best meets their needs.
    - Added instructions for how to use the Windows Subsystem for Linux to install the PyLith Linux binary on systems running Windows 10.
- Fixed bug in generating Xdmf files for 2-D vector output. Converted Xdmf generator from C++ to Python for more robust generation of Xdmf files from Python scripts.
- Updated spatialdata to v1.9.10. Improved error messages when reading SimpleDB and SimpleGridDB files.
- Updated PyLith parameter viewer to v1.1.0. Application and documentation are now available on line at https://geodynamics.github.io/pylith_parameters. Small fix to insure hierarchy path listed matches the one for PyLith.
- Updated PETSc to v3.7.6. See the PETSc documentation for a summary of all of the changes.
- Switched to using CentOS 6.9 for Linux binary builds to insure compatibility with glibc 2.12 and later.

Project goals for the upcoming year

The PyLith developers will continue their strong push towards release of PyLith v3.0. The focus will shift from the reimplementation of bulk rheologies and simple boundary conditions in the new multiphysics-compatible formulation to reimplementation of the prescribed slip and spontaneous rupture earthquake sources using the new multiphysics compatible formulation.

PyLith v3.0 will include higher order discretization and support for multiple governing equations and solution fields. Multiple, coupled governing equations will allow addition of more complex bulk rheologies such as poroelasticity. We have a couple of full-scale tests that demonstrate the higher-order spatial discretizations working.

This major version also includes a major overhaul of the top-level code to allow more flexible output and use of the PETSc time stepping algorithms. These tasks involve close collaboration between Matthew Knepley and Brad Aagaard, with Knepley focusing on extending the finite-element operations in PETSc via DMPlex and Aagaard focusing on the PyLith code. Charles Williams continues to contribute to the implementation of the bulk rheologies.

Outreach and Broader Impacts

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

Brad Aagaard continues to participate in the Southern California Earthquake Center spontaneous rupture code verification Technical Activity Group. In addition, developers from other communities have shown interest in the CIG Software Development Best Practices and multiphysics formulation being used in PyLith.

4.4 Rayleigh

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

Significant accomplishments of the past year

Development and optimization of Rayleigh has continued throughout the past year. It was officially released under the GPL 3 license in Q1 of 2018 (https://geodynamics.org/cig/software/rayleigh/) as v0.9.0 (doi: 10.5281/zenodo.1236565). Rayleigh exhibits efficient parallel scaling on up to 523,288 cores of the Mira supercomputer when run using problems of size 2048^3 grid-collocation points. The code is benchmarked and documented. Development efforts this year focused on writing the code documentation, clearing bugs reported by early users, and improving the diagnostics output package. The code has been used in three accepted and one submitted papers in 2018.

Rayleigh facilitates multiple methods of “observing” a simulation as it evolves. Many commonly-performed analyses are conducted in-situ during the run, rather than through post-processing. This approach prevents the need to perform costly post-analysis of full 3-D data dumps after a simulation has completed. Available analyses include the ability to output desired observables as bulk 3-D output, spatial spectra, 2-D slices, volume averages, and point-wise samples, among others. The latter facilities comparisons with laboratory experiments; those typically sample the temperature distribution point-wise using thermistors. The output cadence and observable set can be controlled independently for each analysis type.

Observables include quantities such as velocity field components, kinetic energy density, momentum and induction equation terms. There are roughly 1,000 observables in Rayleigh that a user may opt to output. A Reynolds decomposition is performed for each observable, allowing the user to output the zonal mean and fluctuations about that mean, if desired, for each of the linear terms. Similarly, nonlinear terms may be output as quadratic products of mean-mean, fluctuating-fluctuating, or fluctuating-mean terms.

Additional development efforts this year have been devoted to exploring the potential for using GPUs in the Rayleigh code, experimentation with new sparse Chebyshev representations for the linear solve, and improved performance of the Legendre transforms. These experiments are still preliminary in nature, but the sparse Chebyshev implementation will likely be completed in late 2018.

In addition to Rayleigh development, the Geodynamo Working Group has continued to analyze geodynamo simulation data obtained through the three-year INCITE grant based around the Rayleigh project. The group in now in the process of conducting significant post-analysis of those results, using checkpoint restarts to generate additional diagnostic outputs. One paper regarding those results is now submitted, and additional are expected to result from these efforts this year[3].

Outreach and Broader Impacts

Invited Presentations:

- Exploring Planetary and Stellar Convection Using the Rayleigh Code Nicholas A. Featherstone at the 2018 SIAM Conference on Parallel Processing for Scientific Computing

Rayleigh will hold its first hackathon September 2018 in Boulder, Colorado.

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[3] Karak, B. B., M. Miesch, and Y. Bekki (2018), Consequences of high effective Prandtl number on solar differential rotation and convective velocity, *Physics of Fluids* 30(4), 046602, doi:10.1063/1.5022034.
Miquel, B., J. - H. Xie, N. Featherstone, K. Julien, and E. Knobloch (2018), Equatorially trapped convection in a rapidly rotating shallow shell, *Physical Review Fluids* 3(5), doi:10.1103/PhysRevFluids.3.053801.
Orvedahl, R. J., M. A. Calkins, N. A. Featherstone, and B. W. Hindman (2018), Prandtl-number Effects in High-Rayleigh-number Spherical Convection, *The Astrophysical Journal* 856(1), 13.

4.5 SPECFEM

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

The main focus is the continued development of the spectral-element seismic wave propagation solvers SPECFEM3D and SPECFEM3D_GLOBE for exascale simulations, which are estimated to become feasible in the 2020–2022 time frame. The project is collaboration with NVIDIA and Intel's Exascale Lab to optimize the code for their processors. These exascale efforts will focus on the following aspects of code development and optimization: 1) GPU/Phi/ARM computing, 2) OpenMP, 3) MPI optimization, 4) I/O, and 5) fault tolerance. To achieve these goals, this project is one of eight partnerships selected for ORNL's Center for Accelerated Application Readiness program to prepare computational science and engineering applications for highly effective use on the OLCF system to be named Summit that will become available to users in 2018.

Significant accomplishments of the past year

Core Spectral-Element Code Developments

A SPECFEM3D–based quasi-static solver simulating post-seismic rebound is ready and will be released this year[4]. The effects of topography and bathymetry, 3D heterogeneity, and rheology on calculations of post-seismic relaxation are currently being investigated.

A version of SPECFEM3D that implements the full nonlinear equations of motion and a logarithmic strain tensor is under development. It is perhaps surprising that without much additional cost the existing linear solver can be modified to accommodate these complications. These modifications matter for large deformations.

Peripheral Software Developments

In collaboration with ORNL (Norbert Podhorszky), Kitware (Marcus Hanwell), and the ObsPy group (Lion Krischer), the group continues to make excellent 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. ADIOS file format continues to be used for other I/O,

[4] Gharti, H., Langer, L., and Tromp, J., 2018. Spectral-infinite-element simulations of coseismic and postearthquake deformation, Geophys. J. Int., Submitted.

e.g., kernels and check pointing. In addition, the project is working with NVIDIA and IBM to optimize ASDF and ADIOS I/O in the context of the Center for Accelerated Application Readiness (CAAR) program.

The seismic imaging and inversion toolkit SeisFlows[5], continues to be very actively developed, with lots of new (international) users trying it out, giving feedback, and making useful contributions. It is not only used for seismic imaging and inversion, but it has also attracted interest from users in medical imaging and nondestructive testing.

To move towards fully automated imaging and inversion workflows, the project is collaborating with Shantenu Jha at Rutgers University to develop an Ensemble Toolkit for Earth Sciences. This workflow management tool will stabilize and expedite seismic imaging and inversion, e.g., by providing recovery mechanisms for simulation failures. Adjoint tomography involves thousands of forward and adjoint simulations, and a robust workflow management system is badly needed for practical applications and productivity. A beta version of the toolkit for global adjoint tomography is now deployed on Titan at ORNL, and, in the context of the CAAR program, is being migrating the workflow from Titan to Summit, ORNL's next generation machine.

Project goals for the upcoming year

The project will continue development of:

- a SPECFEM3D_GLOBE-based quasi-static infinite-spectral-element method for simulations of post-glacial relaxation with full gravity. This solver will be the basis for fully 3D simulations of sea level change.
- a full gravity version of SPECFEM3D_GLOBE for simulations of the Earth's free oscillations. This topic turned out to be much more challenging than originally anticipated, because one can no longer use Gauss-Lobatto-Legendre quadrature for the mass matrix and must resort to Gauss quadrature. The new gravity solver will now be coupled to conservation of linear momentum solvers. Time- and frequency-domain solvers have been developed, and the focus now is on making these fast enough to be practical. Full development, testing and optimization of the full-gravity seismic wave equations solver will take approximately two years.

[5] Modrak, R., Borisov, D., Lefebvre, M., and Tromp, J., 2018. SeisFlows – Flexible waveform inversion software, Computers and Geosciences, **115**, 88–95.

Outreach and Broader Impacts

Invited Presentations:

- Imaging Earth's Mantle: Global Full-Waveform Inversion Based on Spectral-Element Simulations & Adjoint Methods Ebru Bozdag, Matthieu Lefebvre, Wenjie Lei, Ridvan Orsvuran, Daniel Peter, Youyi Ruan, James Smith, Dimitri Komatitsch, Jeroen Tromp at the 2018 SIAM Conference on Parallel Processing for Scientific Computing

4.6 SW4

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

Significant accomplishments of the past year

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

Outreach and Broader Impacts

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

4.7 Virtual Quake

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

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

elements slip back to equilibrium, transferring stress through the fault system via Okada Green's functions. Cascades of element failures are recorded as earthquakes.

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

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

Significant accomplishments of the past year

In the past year, we have released versions 3.1.0 (doi: 10.5281/zenodo.569592) and 3.1.1 (doi: 10.5281/zenodo.1098321). These releases add functionality to and address bugs in the fault mesher. It is now easier for researchers to run simulations on fault models with curved traces and shallow dips, a feature common to subduction zones where the largest earthquakes occur. We also greatly lowered the largest barrier to using Virtual Quake, the installation procedure, by distributing a Docker image of Virtual Quake releases. By simply installing Docker, users can easily run Virtual Quake on multiple platforms without having to compile from source or ensure their system has the required packages/libraries.

Significantly, Virtual Quake will play a key role in an upcoming physically-based simulation pipeline for tsunami early warning. Virtual Quake will provide large ensemble simulated catalogs of earthquakes and, via the included Quakelib library of tools, associated seafloor uplifts for tsunamigenic faults. These initial uplifts serve as the initial conditions for tsunami simulations. The resulting ocean water height information will then be passed to atmospheric and ionospheric simulations, producing a catalog of ionospheric signatures that can be detected by GNSS satellites.

5. Scientific and Broader Impacts

5.1 Science Highlights

ASPECT: modeling geochemical trends in ocean islands[7]

Geochemical and seismic observations suggest that hot, buoyant upwellings can carry chemical heterogeneities from the deep lower mantle towards the surface. However, the exact nature of this link between surface and deep Earth is debated and poorly understood. Dannberg and Gassmöller (2018) show that subducted slabs interacting with dense thermochemical piles can trigger the ascent of hot plumes that inherit chemical gradients present in the lowermost mantle (see Figure 7). The authors use the CIG-supported geodynamic modelling code ASPECT to study this process and to identify the key factors controlling it: (i) If slabs induce strong lower mantle flow towards the edges of these piles where plumes rise, the pile-facing side of the plume preferentially samples material originating from the pile and bilaterally asymmetric chemical zoning develops. (ii) The composition of the melt produced reflects this bilateral zoning if the overlying plate moves roughly perpendicular to the chemical gradient in the plume conduit. These results explain some of the observed geochemical trends of oceanic islands and provide insights into how these trends may originate.

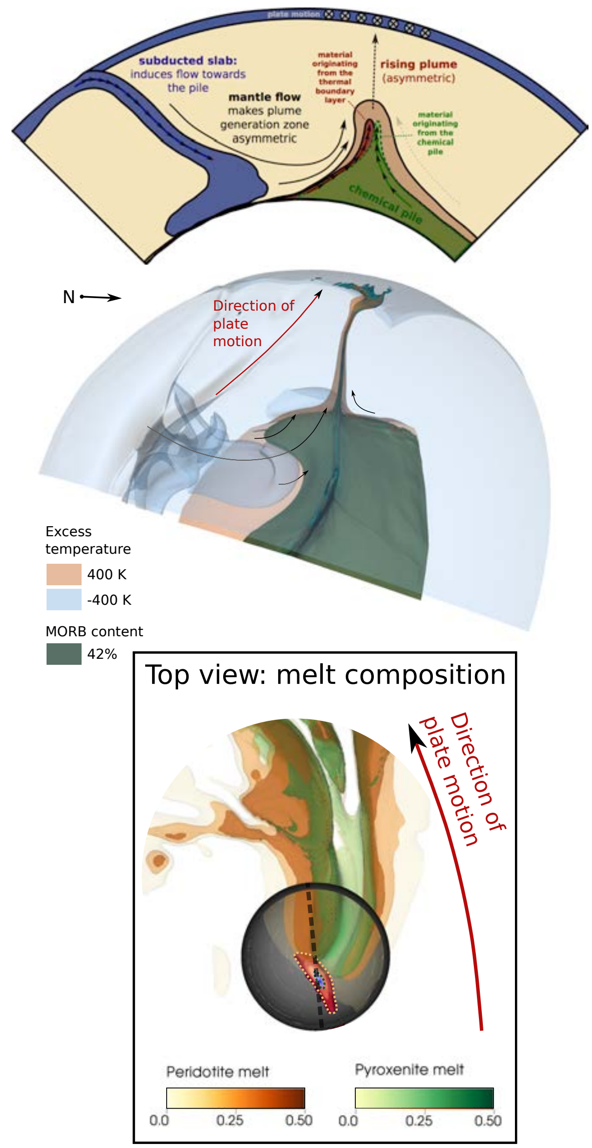

Figure 7. Time evolution of a simulation of a zoned plume in the geographical setting of the South Pacific. [movie]

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[7] Dannberg, J., & Gassmöller, R. (2018). Chemical trends in ocean islands explained by plume–slab interaction. Proceedings of the National Academy of Sciences, 115(17), 4351-4356.

Rayleigh: enabling solar and planetary sciences

Rayleigh is now enabling solar and planetary science at six U.S. institutions: Carnegie Institute, University of Colorado, IG/UT Austin, Harvard University, Johns Hopkins University, and California State University Chico and four foreign institutions: CEA Paris-Saclay, University of Exeter, Institute of Research in Astrophysics and Planetology, and University of Montreal. Rayleigh is used particularly extensively at the University of Colorado (CU), the home institutions of the lead developer. It forms the central tool in the thesis research of four graduate students, three of whom are National Solar Observatory CU Hale Fellowship recipients, three postdocs, two of whom are NSO Hale Postdoctoral Fellows, two senior researchers and one faculty member. Applications of Rayleigh by this group range from the geodynamo, to the solar dynamo, to dynamos in massive stars.

SW4 simulation featured on ABC News

This year marks the 150th anniversary of the 1868 Hayward Earthquake M 6.8. In the next 30 years, there is a 1 in 3 chance of a major earthquake occurring on the Hayward Fault. It is expected that strong ground motion from a Hayward fault earthquake will cause significant damage to the built environment and loss of life. Artie Rogers in his recent paper[8] uses SW4 to model a scenario for a M7.0 earthquake along the Hayward fault with rupture initiating near Richmond, California. A movie of his simulation was featured on the local ABC News affiliate (Figure 8).

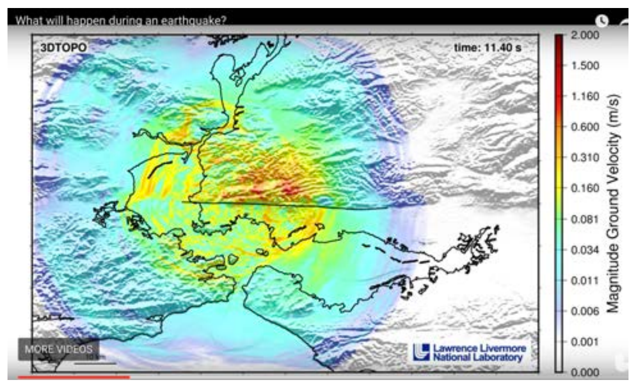

Figure 8. SW4 simulation of a rupture on the Hayward Fault in Northern California. Ground velocities from this scenario are much higher to the east (top)

5.2 Publications

Publications included in our database include refereed papers submitted by authors as well as those found using google scholar based on keyword search by author, software package name, or DOI. In 2017, the community published over 85 journal articles the past year using CIG codes. See Appendix F.

[8] https://doi.org/10.1002/2017GL076505

5.3 Cross Cutting Initiatives

IRIS -CIG HPC Initiative

A 2016 survey by the IRIS HPC Working group drew 340 responses from the IRIS seismological community revealing a broad interest in scientists wanting training and access to computational resources and software for data processing and modeling in seismology. The IRIS HPC Working Group reached out to CIG to lead an initiative to provide access to high-performance computing platform(s) and infrastructure to promote innovation and to enable efficient solutions to outstanding scientific problems in solid-earth geophysics. Activities would include training, and support for computational resources and software. The scope would include scientific topics in geodynamics and solid earth geophysics—including seismology, crustal deformation, mantle convection, geodynamo—and the computational needs for modeling and large-scale data processing for observed and model data.

2018 CTSP Workshop

A joint CSDMS-CIG workshop focused on Coupling of Tectonic and Surface Processes (CTSP) was held from April 25-27, 2018 to survey both questions and state of the art numerical techniques that simulate surface processes and long term tectonic (LTT) processes in an attempt to define a framework for the development of efficient numerical algorithms that couple across multiple length and time scales. Over 150 researchers attended, in person or virtually, the plenary talks and breakout sessions. The group is working on a white paper which will outline different mechanisms through which the LTT and surface processes communities can collaborate to tackle the science questions and the numerical challenges. CIG plans to continue to engage with the surface processes community as they define their next steps.

5.4 Beyond the Geosciences

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

CIG has been working to improve the ability of the community to cite software, an emerging need of the scholarly community, With the support of a now complete EAGER award from NSF's CISE directorate, we developed the *attribution builder for citation* (abc) and published an analysis of the CIG community's practices for software attribution (Hwang et al. 2017). The software citation project, has now been institutionalized as an integral part of CIG's operations. The *abc* tool was introduced to a number of communities at workshops and conferences inside and outside of the geosciences. The tool provides a single place to obtain attribution information for CIG software which may not have previously existed or was buried in user documentation. Users have commented how easy *abc* is to use. The tool has generated interest from and CIG has provided insight to other communities struggling with similar issues. The abc tool uses DOIs for its persistent identifier. CIG integrates its GitHub repository with Zenodo to obtain DOIs and has created a community for discovery of CIG software and related resources.

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

Appendix A: Revised Bylaws

Bylaws of Computational Infrastructure for Geodynamics (CIG)

As approved by the Electorate, February 28, 2005
As amended by the Electorate, December 12, 2006
As amended by the Electorate, January 9, 2012
As amended by the Electorate, June 30, 2018

PREAMBLE

The Bylaws of the Computational Infrastructure for Geodynamics (CIG) are adopted by the Member Institutions for the purpose of conducting CIG business in a collegial manner. They should not be construed as overriding the standard responsibilities and prerogatives of Principal Investigators or their respective institutions. However, situations and issues may arise from time to time for which resolution through standard procedures cannot be achieved. Should the Director and the Executive Committee not be able to reach agreement on any given issue, the Director, as Principal Investigator on the core CIG grants/contracts, will ultimately retain full authority to make and implement decisions on core CIG programs and policies.

Article I Name

Section 1. Name: The name of the Organization is Computational Infrastructure for Geodynamics (abbreviated as CIG).

Article II Member Institutions

Section 1. Membership: Institutions that are both educational and not-for-profit, chartered in the United States, with a major commitment to research in Earth Science with a particular emphasis on geodynamics and computational geophysics, and related fields, including single or multiple campuses of multi-campus university or college systems or organizations, may become Members of the Organization. Governmental research organizations with a close link to the academic research community in geodynamics and computational geophysics are also eligible for Membership. The current list of member institutions shall be maintained by the Director.

Section 2. Election: An institution applying for membership must be qualified as an educational or research and not-for-profit institution according to criteria adopted by the Electorate. Qualified institutions may be elected as members by the affirmative vote of two-thirds of the members of the entire Electorate, or by unanimous vote of the Executive Committee of CIG. The rights and privileges of

Members with respect to participation in the scientific activities of CIG will be according to policies established by the Electorate.

Section 3. International Membership: Institutions not chartered in the United States may be elected as an International Member for an indefinite term by the affirmative vote of two-thirds of the members of the entire Electorate or by a unanimous vote of the Executive Committee. An International Member will be entitled to designate a non-voting representative to the Electorate and will be able to participate in all activities in the governance of CIG other than voting as a regular CIG Member or serving in a position specifically restricted to Electors. The rights and privileges of International Members with respect to participation in the scientific activities of CIG will be according to policies established by the Electorate.

Section 4. Resignation or Removal: Any Member may resign at any time by giving written notice to the Chairperson of the Executive Committee or the Director of the Organization. Such resignation shall take effect at the time of receipt of the notice, or at any later time specified therein. A Member becomes inactive upon vacancy of the Elector and can be reinstated upon appointment of a new Elector. Given sufficient cause, any Member may be removed by the affirmative vote of two-thirds of the Members of the entire Electorate or by unanimous vote of the Executive Committee.

Article III Electorate

Section 1. Powers: So long as they do not conflict with the responsibilities of Principal Investigators, power in the management of the affairs of the Organization is vested in the Electorate. To this end and without limitation of the foregoing or of its powers expressly conferred by these Bylaws, the Electorate shall have power to authorize on behalf of the Organization rules or regulations for its management, create such additional offices or special committees and removal of its officers. The Electorate shall have the power to fill vacancies in, and change the membership of, such committees as are constituted by it.

Section 2. Power of Appointment: The term "Executive Officer" referred to in Sections III.6 shall mean a Senior Officer of a Member Institution above or at the level of Department Head.

Section 3. Composition: The Electorate shall be composed of one person from each of the Member Institutions. An Executive Officer of each such Member Institution shall designate one Elector, who shall be the holder of an academic or permanent research staff appointment, with major responsibilities for instruction and/or research in the earth sciences, in a department, program or other organizational unit of such Member Institution.

Section 4. Term of Office: Each Elector shall continue in office until a successor is chosen and qualifies or until he or she dies, resigns, is no longer affiliated with the Member Institution or is removed by an Executive Officer of the Member Institution.

Section 5. Resignation: Any Elector may resign at any time giving written notice to the Chairperson of the Executive Committee or the Director of CIG. Such resignation shall take effect at the time of receipt of the notice, or at any later time specified therein.

Section 6. Alternate Electors: An Executive Officer of each Member Institution may appoint from within the Member Institution an alternate Elector to serve for the term specified by such appointment. In the absence of an Elector from any meeting of the Electorate, his or her alternate may, upon written notice to the Director of the Organization from the Elector or from a duly authorized representative of the Member Institution of the Electorate, attend such meeting and exercise all the rights, powers and privileges of the absent Elector.

Article IV Meetings of the Electorate

Section 1. Annual Meeting: A meeting of the Electorate for the transaction of such other business as may properly come before it, shall be held once per year.

Section 2. Special Meetings: Special meetings of the Electorate may be called by the Chairperson of the Executive Committee or by the Director upon written request of at least four Electors or one-fifth (1/5) of the membership of the Electorate, whichever is greater.

Section 3. Place of Meetings: The Chairperson of the Executive Committee or the Director shall designate the place of the Annual Meeting or any special meeting and which shall be specified in the notice of meeting or waiver of notice thereof.

Section 4. Notice of Meetings: Notice of such meeting of the Electorate shall be given to each Elector by the Director, Chairperson of the Executive Committee, or by a designee directed by either to give such notice, by delivering to the Electorate written or printed notice not less than thirty nor more than sixty days before the date fixed for the meeting. Notice of any meeting need not be given to any Elector who submits a signed waiver of notice, whether before or after the meeting. The attendance of any Elector at a meeting without protesting prior to the conclusion of the meeting the lack of notice thereof shall constitute a waiver of notice by the Elector. When a meeting is adjourned to another place or time, it shall not be necessary to give any notice of the adjourned meeting if the time and place to which the meeting is adjourned are announced at the meeting at which the adjournment is taken.

Section 5. Quorum: At all meetings of any committee of the Electorate, a majority of the members of that committee shall constitute a quorum. For the purposes of election of Officers and Executive Committee members, a quorum shall be determined in accordance with Article VIII. If a quorum is not present, a majority of the Electors present may adjourn the meeting without notice other than by announcement at said meeting, until a quorum is present. At any duly adjourned meeting at which a quorum is present, any business may be transacted which might have been transacted at the meeting as originally called.

Section 6. Voting: Each Elector shall be entitled to one vote. Except as otherwise expressly required by law or these Bylaws, all matters shall be decided by the affirmative vote of a majority of the Electors present at the time of the vote, if a quorum is then present.

Section 7. Action without a Meeting: Any action required or permitted to be taken by the Electorate, or the Executive Committee, may be taken without a meeting if all Electors or the Executive Committee consent in writing to the adoption of a resolution authorizing the action. The resolution and the written consents thereto shall be filed with the minutes of the proceedings of the Electorate or the Executive Committee.

Section 8. Participation by Conference Telephone or Internet Conference: In any meeting of the Electorate or any committee thereof, any one or more Electors or members of any such committee may participate by means of a conference telephone or similar communications equipment allowing all persons participating in the meeting to hear each other at the same time. Participation by such means shall constitute presence in person at a meeting.

Article V Officers and Director

Section 1. Officers and Qualifications: The Officers of the Organization shall consist of the Chairperson of the Executive and Science Steering Committees, and such other officers as the Electorate may from time to time establish and appoint. Unless otherwise specified by Electorate action, Officers need not be Electors.

Section 2. Chairperson: The Chairperson of the Executive Committee shall, when present, preside at all meetings of the Electorate and shall perform such other duties and exercise such other powers as shall from time to time be assigned by the Electorate. The Chairperson of the Executive Committee shall be an ex officio member of all of the Organization’s committees.

Section 3. Vice Chairperson: The Vice Chairperson of the Executive Committee shall preside, in the absence of the Chairperson, at all meetings of the Electorate and shall perform such other duties and exercise such other powers as shall from time to time be assigned by the Electorate.

Section 4. Director: The Director shall be selected by the Executive Committee. Except as otherwise provided by the Electorate, the Director shall be the Chief Executive Officer of the Organization, and unless authority is given by the Electorate to other officers or agents to do so, the Director shall execute all contracts and agreements on behalf of the Organization. The Director shall be the Principal Investigator on proposals which fund the Organization's core facility. It is the duty of the Director, insofar as the facilities and funds furnished to the Organization permit, to see that the orders and votes of the Electorate and the purposes of the Organization are carried out. In the absence of the Chairperson or the Vice Chairperson of the Executive Committee, the Director shall preside at meetings of the Electorate. The Director or the Director's designee, shall be an ex officio, non-voting member of the all of the Organizations committees. The Executive Committee by consensus and with cause can recommend to the Organization's sponsor that the Director by removed.

Section 5. Election and Term of Office: The Chairperson and Vice Chairperson of the Executive Committee and Science Steering Committee shall each be elected by a vote of all members of each committee to a term not to exceed three years or until their successor is chosen and qualifies. All Officers of the Organization shall not be eligible for reelection until another person shall have served an intervening term, or a portion of a term of more than one year.

Section 6. Resignation: Any Officer may resign at any time by giving written notice to the Chairperson, the Vice Chairperson or the Director of the Organization. Such resignation shall take effect at the time of receipt of the notice, or at any later time specified therein.

Section 7. Vacancies: Any vacancy in any office may be filled for the unexpired portion of the term of such office by a vote of the Electorate.

Article VI Executive and Other Committees

Section 1. Executive Committee of CIG: There shall be established an Executive Committee of the Organization comprised of five voting members (the Chairperson, the Vice Chairperson, and three additional members elected by the Electorate) and two ex officio non-voting members (the Director, and the Chairperson of the Science Steering Committee). The elected members of the Executive Committee shall have terms not to exceed three years or until a successor is chosen and qualified. Members of the

Executive Committee may not simultaneously serve on the Science Steering Committee as a regular member.

Section 2. Powers of the Executive Committee of the Organization: Unless otherwise provided by resolution adopted by the affirmative vote of a majority of the entire Electorate, the Executive Committee may have and may exercise all the powers of the Electorate, except that it shall not have authority as to the following matters:

a) the amendment or repeal of the Bylaws, or the adoption of new Bylaws;

b) the amendment or repeal of any resolution of the Electorate, which by its terms shall not be so amendable or repealable; and

c) the levying or assessment of fees and dues.

The responsibilities of the Executive Committee include coordination of activities, meetings, and workshops. The Executive Committee shall review and approve priorities for software development undertaken by the Organization. In establishing these priorities, the Executive Committee will consider input obtained from the Electorate directly and from recommendations made by the Science Steering Committee.

At all meetings of the Executive Committee, the presence of a simple majority of its members then in office shall constitute a quorum for the transaction of business.

Section 3. Special Committees: The Electorate may create such special committees as may be deemed desirable, the members of which shall be appointed by the Chairperson of the Executive Committee or designee with the approval of the Executive Committee. Each such committee shall have only the lawful powers specifically delegated to it by the Electorate.

Section 4. Science Steering Committee: There will be standing committees as defined in Article VII for overseeing the major scientific and research programs to which the Organization provides scientific counsel and advice or management direction and fiscal recommendations.

Section 5. Other Committees: The Executive Committee may create committees other than Standing or Special committees to be Committees of the Organization. Such committees shall be appointed in such a manner as may be determined by the Executive Committee and shall have such lawful duties as may be specified by the Executive Committee. An individual or an institution may be a member of any such committee whether or not they are an Elector or Officer of the Organization.

Section 6. Removal: The Executive Committee or the Director may remove or suspend an appointed or elected committee members with or without cause. Elected or appointed committee members who have been officially sanctioned cannot participate on committees of the Organization.

Article VII Science Steering Committee

In order to carry out and oversee the Organization's operations, a Science Steering Committee (SSC) shall be established. The members will be elected by the Electors and shall have terms not to exceed three years or until a successor is chosen and qualified. A committee will be formed according to Article VI, section 4 to determine and prioritize software development from the perspective of the Earth science and Computational science disciplines represented by the Electorate. This committee will evaluate the utility of software developed and delivered to the community by the Organization. This committee will consider the community's needs and recommend changes in the levels of support of the Organization's development resources. The committee will formulate policies for evaluation of user proposals for the Organization's software development. At least twice per year, the committee shall report in writing to the Executive Committee priorities for software development and resource allocation.

Article VIII Elections

Section 1. Officers, Executive Committee, and Standing Committees: Officers, Executive Committee members, and Science Steering Committee members may be elected by the Electorate at the Annual Meeting or by electronic means in accordance with the procedures established in this Article.

Section 2. Nominating Committee: No less than 90 days before the Annual Meeting or the election by electronic means, the Executive Committee shall appoint a Nominating Committee, which shall prepare a slate of one or more nominees for each position to be filled. The Nominating Committee shall solicit the Electors for the names of suggested nominees. Any candidate shall be placed on the slate by the Committee upon receipt of written nomination signed by three Electors at least 40 days before the Annual Meeting.

Section 3. Notice of Election and Ballot: If the election is to be held at the Annual Meeting, the ballot prepared by the Nominating Committee shall be included in the Notice of Meeting. If the Election is to be held by email or online balloting, then the ballot shall be made available electronically and the Electorate notified not less than thirty nor more than sixty days before the date fixed for the close of the election.

Section 4. Election: If the Election shall take place at the Annual Meeting, it shall include the opportunity for nominations to be made from the floor. Election shall be by written ballot, which may be cast in person by an Elector at the meeting or may be submitted otherwise, if received by the Vice-Chairman ten (10) days before the meeting. Election shall be valid if ballots are received from one-half of the membership of the entire Electorate in accordance with this Article, even if a quorum is not present for the purpose of conducting other business.

Section 5. Method of Voting: In the election of officers, a valid ballot shall contain at most one vote for each office; election shall be decided in favor of the nominee receiving a plurality of votes. In the election of Executive and Science Steering Committee members, a valid ballot shall contain no more votes than vacancies being filled; election to each vacancy shall be determined in sequence in favor of those qualified nominees with the most votes.

Section 6. Counting of Ballots: Ballots shall be counted by the Vice-Chairman, Chair of the Nominating Committee and/or by the Director or their designee.

Article IX Compensation

Section 1. Compensation: No Elector shall be paid any compensation for serving as Elector. All Electors may be reimbursed for the actual expenses incurred in performing duties assigned to them by the Electorate.

Article X Participation in the Organization

Section 1. Activities of the Organization: In carrying out the business of the Organization, the Organization shall from time to time appoint committees and convene meetings, workshops, tutorials and similar in person or electronically.

Section 2. Participants: A Participant is any person who attends an activity of the Organization regardless of elected or appointed status in the Organization.

Section 3. Code of Conduct: The Executive Committee shall maintain the Code of Conduct of the Organization.

Section 4. Removal: All Participants must adhere to the Code of Conduct as established by in Article X.3. A Participant maybe removed or excluded from any activity of the Organization if they violate the Code of Conduct or their actions can be considered to cause harm to the Organization.

Article XI Amendments to the Bylaws

Section 1. Amendments: All Bylaws of the Organization shall be subject to amendment or repeal and new Bylaws may be made by the affirmative vote of two- thirds of the entire Electorate at any annual or special meeting, the notice or waiver of notice of which shall have specified or summarized the proposed amendment, repeal or new Bylaws.

Article XII Definitions

Officer — The *Officers* of the Organization shall be the Chairperson of the Executive Committee and the Chairperson of the Science Steering Committee

Elector — An *Elector* is the representative of the Member Institution

Electorate — The *Electorate* is the body comprised of all Electors.

International Affiliate

An *International Affiliate* is an organization similar to Members but not chartered in the United States.

Member Institution

A *Member Institution* or *Member* are institutions that are both educational and not-for-profit, chartered in the United States, with a major commitment to research in Earth Science with a particular emphasis on geodynamics and computational geophysics, and related fields, including single or multiple campuses of multi-campus university systems or organizations

Organization

The Organization is the Computational Infrastructure for Geodynamics (CIG).

Participant

A *Participant* is any persons who attends an activity of the Organization regardless of elected or appointed status in the Organization.

Appendix B: Principles of Community and Code of Conduct

The Computational Infrastructure for Geodynamics (CIG) is a community-driven organization that advances Earth science by developing and disseminating software for geophysics and related fields. CIG is supported by the US National Science Foundation, headquartered at the University of California, Davis and has institutional members across the US and internationally.

CIG supports a variety of activities, online and in person, to foster best practices in scientific software development and promote learning, networking, and collaboration. We value the participation of every member of the community and want all participants to have an enjoyable and fulfilling experience in their interactions with the CIG community. Accordingly, all who participate in CIG activities are expected to show respect and courtesy to others, whether interacting in person or online. CIG's project leaders, meeting organizers, and committee and working group members are expected to act as representatives of CIG in carrying out their responsibilities.

CIG is dedicated to providing a harassment-free environment, regardless of gender, gender identity and expression, age, sexual orientation, disability, physical appearance, race, ethnicity, national origin, age, religion (or lack thereof), technology choices and experience level, or other group status.

Reporting

If you are the subject of unacceptable behavior or have witnessed any such behavior, please immediately notify CIG's Director or Associate Director (**contact**), or a member of CIG's Executive Committee (**contact**).

Anyone experiencing or witnessing behavior that constitutes an immediate or serious threat to public safety, or a criminal act is expected to contact 911. Those witnessing a potential criminal act should also take actions necessary to maintain their own personal safety.

Consequences

Behavior that violates CIG's Code of Conduct will not be tolerated. Anyone asked to stop behavior that violates the Code of Conduct is expected to comply immediately.

If a participant in CIG activities engages in behavior that violates the Code of Conduct, the activity's organizers or CIG leadership may take any action they deem appropriate, up to and including a temporary ban or permanent expulsion from CIG activities without warning.

As a project funded by the National Science Foundation at a US institution of higher education, CIG leadership and staff follows all requirements of the NSF and under Title IX for reporting unacceptable behavior

Sources

This document draws on codes of conduct developed for online communities and geoscience organizations, including the **WSSPE Code of Conduct** from the **FORCE11 Code of Conduct**, which was based on the Code4Lib Code Of Conduct, inspired by the ADA Initiative) **Geological Society of America**, and the **American Geophysical Union**

Appendix C: Institutional Membership

U.S. Academic Institutions

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

International Affiliates

Australian National University
Cardiff University
Earth Observatory of Singapore
Geological Survey of Norway (NGU)
GNS Science
Johanes Gutenberg University Mainz
Monash University
Munich University LMU
University of Alberta
University College London
University of Bristol, UK
University of 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 D: CIG Working Group Members

Computational Science (8)

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

Geodynamo (10)

- *Lead,* Jon Aurnou, University of California, Los Angeles
- Bruce Buffett, University of California, Berkeley
- Nick Featherstone, University of Colorado, Boulder
- Gary Glatzmaier, University of California, Santa Cruz
- Moritz Heimpel, University of Alberta
- Hiroaki Matsui, University of California, Davis
- Peter Olson, Johns Hopkins University
- Krista Soderlund, University of Texas, Austin
- Sabine Stanley, Johns Hopkins University
- Rakesh Yadav, Harvard University

Long-Term Tectonics (4)

- *Lead,* Claire Currie, University of Alberta
- Susanne Buiter, Norwegian Geological Survey
- Katie Cooper, Washington State University
- Lijun Liu, University of Illinois, Urbana-Champaign
- Eric Mittelstaedt, University of Idaho
- John Naliboff, University of California, Davis
- Cedric Thieulot, Utrecht University
- Jolante van Wijk, New Mexico Tech

Magma Migration (8)

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

Mantle Convection (8)

- *Lead,* Scott King, Virginia Polytechnic Institute
- *Lead,* Shijie Zhong, University of Colorado, Boulder
- *Lead,* Thorsten Becker, University of Texas, Austin
- Juliane Dannberg, Colorado State University, Fort Collins
- Timo Heister, Clemson University
- Margarete Jadamec, University of Houston
- Mark Richards, University of California, Berkeley
- Max Rudolph, Portland State University

Seismology (6)

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

Short-Term Crustal Dynamics (4)

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

Appendix E: Selected Meeting Presentations by CIG Scientists

E.1 2018 CGU CIG Mantle Convection and Lithospheric Dynamics Workshop Presentations

CIG_01: Mantle Convection

Geodynamic mechanisms for the preservation of large-scale primordial heterogeneity in the Earth's mantle. *Maxim D Ballmer*
Constraints on early Earth tectonics via convection models with grainsize evolution. Bradford J Foley
The influence of curvature on convection in a temperature-dependent viscosity fluid: implications for the 2D and 3D modeling of moons. *Joshua M Guerrero*, Julian P Lowman, Frederic Deschamps, Paul J Tackley*
Composition dependent properties and their effects in the early Earth. Keely O'Farrell, Sean Trim,
Combining Large-scale Numerical Simulations with Observational Data Sets to Constrain the Thermochemical History and Interior Dynamics of Mars. *Ana-Catalina Plesa*
Investigating different patterns of slab deformation in the lower mantle. *Jiaxin Zhang*, Allen K McNamara*
Incident angle of subducting slabs against the 410- and 660-km discontinuities. *Siobhan M Campbell*, Robert Moucha*
Three-dimensional thermal convection in a spherical shell with a free surface. *Ludovic Jeanniot, Cedric Thieulot*
The influence of compositional heterogeneity in mantle convection models on a plate-like surface velocity field. *Sean M Langemeyer*, Julian P Lowman, Paul J Tackley*
The effect of dynamic tracer repositioning on conservation properties in thermochemical convection models. *Julian P Lowman, Sean J Trim, Samuel L Butler*
A scaling relationship for impact-induced melt volume. *Miki Nakajima, David C Rubie, Kai Wuennemann, Lukas Manske, Gregor Golabek, Henry J Melosh, Seth A Jacobson, Francis Nimmo, Alessandro Morbidelli*
Power Spectrum Measurements of Mantle Convection in a 2D Annulus Domain. *Cedric Thieulot, Rens S. Elbertsen, Inge Loes ten Kate*

CIG_03: Lithosphere Dynamics

Topographic controls on magmatism during rifting. *Mark D Behn, Paris Smalls, Jean-Arthur Olive, Roger Buck*
Lithosphere dynamics in the central Andes: Implications for magmatism and surface topography. *Claire A Currie, Huilin Wang, Peter G DeCelles*
Insights on fore-arc sliver processes from 3D geodynamic models of flat slab subduction in Alaska. *Kirstie L Haynie*, Margarete A Jadamec*
Western Pacific subduction dynamics: Slab dips, plate velocities, and mantle pressure. *Adam F Holt, Leigh H Royden, Thorsten W Becker, Claudio Facenna*
Global Lithosphere Models Coupled to 3-D mantle Convection: Examples from North America and Central Asia. *William E Holt, Xinguo Wang, Ali Bahadori, Attreyee Ghosh*
Width of imbricated thrust blocks and the strength of accretionary wedges. *Garrett Ito, Gregory F Moore*
Numerical modeling of flat-slab subduction: Influence of lithosphere structure and rheology on slab depth. *Xiaowen Liu*, Claire Currie*

The Effects of Ridge Axis Width on Mantle Melting at Mid-Ocean Ridges. *Laurent Montesi, Valentina Magni, Carmen Gaina,*

Grain by Grain to Plate Tectonics. *Elvira Mulyukova*, David Bercovici*

Convective instability in horizontal decompaction channels in planetary lithospheres. *Joe Schools*, Laurent Montesi*

Response of a continental rift zone to a passing weak plume: insights from the Rio Grande rift. *Jolante Van Wijk*

Evolution of Long-Term Tectonics across the Indo-Burman Range. *Patcharaporn Maneerat**

In situ rheology of the oceanic lithosphere along the Hawaiian Ridge. *Alexandra Pleus*, Garrett Ito, Paul Wessel, L. Neil Frazer,*

Continent-scale lithospheric models constrained by multiple seismic observables made by large scale seismic arrays. *Weisen Shen*

Modelling of overriding plate deformation and slab rollback in the Mediterranean. *Cedric Thieulot, Luuk Schuurmans, Menno Fraters, Wim Spakman, Douwe van hinsbergen*

CIG_04: New Developments in Geodynamic Modeling and Computational Infrastructure

A new solver for large-scale, 3D models of coupled magma/mantle dynamics. *Juliane Dannberg, Timo Heister, Ryan Grove, Rene Gassmoeller*

Adaptive Multigrid Solvers for Stokes flow. *Timo Heister*

Toward Community Software Ecosystems for High-Performance Computational Science. *Lois Curfman McInnes*

Progress and remaining challenges in incorporating detailed chemical kinetics models in simulations of reactive flows. *Kyle E Niemeyer*

Best practices for sustainable and open research software in computational research. *Kyle E Niemeyer*

Present and Future of Earthquake Ground Motion Simulation. *Ricardo Taborda*

Advances in the geodynamic code ASPECT: Investigating compressibility approximations, modular boundary conditions, and flexible surface deformation. *Rene Gassmoeller, Juliane Dannberg, Timo Heister, Wolfgang Bangerth*

A new conceptualization of three-dimensional slab interactivity visualized with ShowEarthModel. *Margarete A Jadamec, Oliver Kreylos, Benjamin Chang, Karen Fischer, Burak Yikilmaz*

Slab dehydration and fluid migration beneath arc volcanoes using COMSOL Multiphysics®. *Changyeol Lee*

MeltMigrator: A MATLAB-based software for modeling three-dimensional melt migration and crustal thickness variations at mid-ocean ridges. *Laurent Montesi, Hailong Bai, Mark Behn*

Efficient and Practical Newton Solvers for Nonlinear Stokes Systems in Geodynamic Problems. *Cedric Thieulot, Menno Fraters, Wolfgang Bangerth, Anne Glerum, Wim Spakman*

*Student Presenter

E.2 2017 Fall AGU Presentations

A mostly self-reporting list of presentations by CIG scientists at the 2017 Fall AGU meeting. List was augmented with key word searches for by software name.

Monday, December 11

DI11A-0269. Plate like convection with viscous strain weakening and corresponding surface deformation pattern, Lukas Fuchs.
DI11A-0273. 3-D numerical modelling of oblique continental collisions with ASPECT, Lev Karatun.
DI13A-0284. Unraveling the origin of the Bermuda rise using receiver functions: insights from mantle discontinuity structure, Alexander Burky.
DI14A-06. A reservoir model study of the flux of carbon from the atmosphere, to the continental crust, to the mantle, Louise H. Kellogg, Harsha V. Lokavarapu, Donald L. Turcotte and Sujoy Mukhopadhyay.
ED13F-08. Where inside the world is the stuff that makes the wood things we write with and the small pretty rocks that women wear on their fingers? And where does that stuff go over time?, Louise H. Kellogg.
ED13F-16. How to make hot, up-going rock inside big round space bodies stay in one place for a long time, Scott D. King.
S11B-0582. Earthquake cycle modeling of multi-segmented faults: dynamic rupture and ground motion simulation of the 1992 Mw 7.3 Landers earthquake, Percy Galvez.
S12B-01. Coupled hydrodynamic and wave propagation modeling for the source physics experiment: study of Rg wave sources for SPE and DAG series, Carene S Larmat.
S12B-08. Simulation of local seismic ground motions from the FLASK underground nuclear explosion near the source physics experiment dry alluvium geology site, Arthur J Rodgers.
S13A-0634. High-resolution seismic modeling of deep Earth interior based on hybrid methods: preliminary results, Chuangxin Lin.
S31A-0783. Mechanical strain measurement from coda wave interferometry, Jérôme Azzola.
T14A-02. Structure and evolution of the Central Appalachians from the mantle to the surface: results from the MAGIC Project (invited), Maureen D. Long, Margaret H. Benoit, Robert L. Evans, Scott D. King, Eric Kirby, John C. Aragon, Scott R. Miller, Shangxin Liu and James Elsenbeck.
U13B-04. Full waveform adjoint seismic tomography of the Antarctic Plate, Andrew Jason Lloyd.

Tuesday, December 12

DI21A-0392. The devil in the dark: a fully self-consistent seismic model for Venus, Cayman T Unterborn.
DI23A-0422. Modelling the possible interaction between edge-driven convection and the Canary Islands mantle plume, Ana M Negredo.
DI23B-02. Rheology gradients at the base of the lithosphere and the stabilization of deep mantle plumes in stagnant-lid planets, Scott D. King.
NG21A-0144. Design Aspects of the Rayleigh Convection Code, Nicholas Andrew Featherstone.
S21C-0760. Seismic wave propagation from underground chemical explosions: sensitivity to velocity and thickness of a weathered layer, Evan Tyler Hirakawa.
S23A-0776. Transdismensional approach applied to the measurement of higher mode surface wave dispersion, Haotian Xu.

T21A-0554. Time-dependent inversions of slow slip at the Hikurangi subduction zone, New Zealand, using numerical Green's functions, Charles A Williams.
T21A-0555. Building a catalog of time-dependent inversions for Cascadia ETS events, Noel M Bartlow.
U23B-05: AxiSEM3D: broadband seismic wavefields in 3-D aspherical Earth models, Kuangdai Leng.

Wednesday, December 13

DI31A-0391. Interpreting the GyPSuM tomography model in terms of thermal heterogeneity and major oxide composition, Paul M Bremner.
DI33A-0398. A study of the required Rayleigh number to sustain dynamo with various inner core radius, Yuki Nishida, Yuto Katoh, Hiroaki Matsui and Atsushi Kumamoto.
DI33A-0399. Comparison of large eddy dynamo simulation using dynamic Buffett sub-grid scale (SGS) model with a fully resolved direct simulation in a rotating spherical shell, Hiroaki Matsui and Bruce A.
DI33B-0408. A two-pronged approach to detecting ICB Stoneley modes, Hope Abigail Jasperson.
DI33B-0411. Scaling up planetary dynamo modeling to massively parallel computing systems: the Rayleigh code at ALCF, Jonathan M. Aurnou, Nicholas A. Featherstone, Rakesh Kumar Yadav, Moritz H. Heimpel, Krista M. Soderlund, Hiroaki Matsui, Sabine Stanley, Benjamin P. Brown, Gary Glatzmaier, Peter Olson, Bruce A. Buffet, Lorraine J. Hwang and Louise H. Kellogg.
IN32B-04. Immersive visual data analysis for geoscience using commodity VR hardware, Oliver Kreylos and Louise H. Kellogg.
S31B-0816. Site amplification in the Central U.S.: towards and understanding of factors influencing the site effect, Rayan Yassminh.
S32C-03. Comparison of approaches to the prediction of surface wave phase velocity, Karen E Godfrey.

Thursday, December 14

DI41B-03. Deep subduction in a compressible mantle: observations and theory, Scott D. King.
DI43A-0335. Modeling submarine lava flow with ASPECT, Erika Regan Storvick.
DI43A-0337. Numerical aspects of compressible mantle convection, Timo Heister, Wolfgang Bangerth, Julianne Dannberg and Rene Gassmoeller.
DI43A-0339. New numerical approaches for modeling thermochemical convection in a compositionally stratified fluid, Elbridge Gerry Puckett, Donald L. Turcotte, Ying He, Harsha V. Lokavarapu, Jonathan Robey and Louise H. Kellogg.
DI43A-0341. Poroelastic modeling as a proof of concept for modular representation of coupled geophysical processes, Robert Lewis Walker.
DI43B-0364. Insight on the anisotropic nature of the D'' layer through the analysis of SKS−SKKS splitting obtained via 3D spectral element modeling, Andrea Tesoniero.
DI43C-02. Structure in the lowermost mantle from seismic anisotropy, Jack Walpole.
DI44A-06. The importance of grain size to mantle dynamics and seismological observations, Rene Gassmoeller, Julianne Dannberg, Zach Elton, Ulrich Faul, Pritwiraj Moulik and Robert Myhill.
G43A-0911. InSAR analysis of post-seismic deformation following the 2013 Mw 7.7 Balochistan, Pakistan Earthquake, Katherine Peterson.
G43A-0915. Investigating the importance of 3D structure & topography in seismic deformation modeling: case study of the april 2015 Nepal Earthquake, Leah Langer.
IN42B-04. Improving seismic data accessibility and performance using HDF containers, Jingbo Wang.
IN43A-0068. GeoTrust Hub: a platform for sharing and reproducing geoscience applications, Tanu Malik.
IN43F-04. The computational infrastructure for geodynamics: an example of software curation and citation in the geodynamics community, Lorraine J. Hwang and Louise H. Kellogg.

MR43B-046. Strain localization and weakening processes in viscously deforming rocks: numerical modeling based on laboratory Torsion experiments, Maximillian Doehmann, Sascha Brune, Livia Nardini, Erik Rybacki and Georg Dresen.
P43B-2880. Effects of variable surface temperatures on the dynamics of convection within Enceladus' ice shell, Matt B Weller.
S31A-0783. Mechanical strain measurement from coda wave interferometry, Jérôme Azzola.
S41B-0748. Hazard-to-Risk: high-performance computing simulations of large earthquake ground motions and building damage in the near-fault region, Mamun Miah.
S41D-07. Fully automatic time-window selection using machine learning for global adjoint tomography, Yangkang Chen.
S41E-07. Multi-mode 3D Kirchhoff migration of receiver functions at continental scale with applications to USArray, Florian Millet.
S41F-01. A penalty-based nodal discontinuous Galerkin method for spontaneous rupture dynamics, Ruichao Ye.
S43G-02. Wavefield complexity and stealth structures: resolution constraints by wave physics, Tarje Nissen-Meyer.
T44D-03. Immersive visualization of the solid Earth, Oliver Kreylos and Louise H. Kellogg.

Friday, December 15

DI51B-0312. Tomographic and geodynamic constraints on convection-induced mixing in Earth's deep mantle, David Phillip Hafter.
DI51B-0318. Integrating thermodynamic models in geodynamic simulations: the example of the community software ASPECT, Juliane Dannberg.
DI52A-03. Seismic anisotropy in mantle transition zone: constraints from observations and synthetic modeling of SS precursors, Quancheng Huang.
DI52A-08. Present mantle flow in North China craton constrained by seismic anisotropy and numerical modelling, Wulin Qu.
EP53C-1761. Seismic analysis of the 2017 Oroville Dam spillway erosion crisis, Phillip Goodling.
G53A-0764. Constraining slip distributions and onset of shallow slow slip in New Zealand by joint inversions of onshore and offshore geodetic data, Ryan Michael Yohler.
IN42B-04. Improving seismic data accessibility and performance using HDF containers, Jingbo Wang.
NH51B-0120. Signals in the ionosphere generated by tsunami earthquakes: observations and modeling suppor, Lucie Rolland.
S51D-0618. Preliminary results of the full-waveform tomography of South America and surrounding oceans using spectral elements and adjoint methods, Caio Ciardelli.
T51A-0445. Effects of pre-existing structures on the seismicity of the Charlevoix Seismic Zone, Oluwaseun Idowu Fadugba.
T51B-0468. CO2 degassing estimates from rift length analysis since Pangea fragmentation: a key component of the deep carbon cycle?, Sascha Brune, Simon Williams and Dietmar Muller.
T51C-0480. 3D numerical simulation of multiphase continental rifting, John Naliboff, Anne Glerum and Sascha Brune.
T51C-0481. Plate speed-up and deceleration during continental rifting: insights from global 2D mantle convection models, Martina Ulrova, Sascha Brune and Simon Williams.
T51D-0502. 3D numerical rift modeling with application to the East African rift system, Anne Glerum, Sascha Brune and John Naliboff.

T52A-03. 3D Instantaneous dynamics modeling of present-day Aegean Subduction, Cedric Thieulot, Anne Glerum, Wim Spakman, Douwe JJ Van Hinsbergen and Casper C. Pranger.

T52A-08. 3D Numerical Examination of Continental Mantle Lithosphere Response to Lower Crust Eclogitization and Nearby Slab Subduction, Payman Janbakhsh, Russell Pysklywec.

T54A-05. Stress concentration on intraplate seismicity: numerical modeling of slab-released fluids in the New Madrid Seismic Zone, Arushi Saxena.

Appendix F: Publications

Articles in 2017 using CIG codes either reported by authors or discovered using keyword searches on google scholar.

1. Agata, R., T. Ichimura, T. Hori, K. Hirahara, C. Hashimoto, and M. Hori (2017), An adjoint-based simultaneous estimation method of the asthenosphere's viscosity and afterslip using a fast and scalable finite element adjoint solver, *Geophysical Journal International*, doi:10.1093/gji/ggx561.
2. Agius, M. R., and S. Lebedev (2017), Complex, multi-layered azimuthal anisotropy beneath Tibet: Evidence for co-existing channel flow and pure-shear crustal thickening, *Geophysical Journal International*, doi:10.1093/gji/ggx266.
3. Agrusta, R., S. Goes, and J. van Hunen (2017), Subducting-slab transition-zone interaction: Stagnation, penetration and mode switches, *Earth and Planetary Science Letters* 464, 10–23, doi:10.1016/j.epsl.2017.02.005.
4. Attanayake, J., A. M. G. Ferreira, A. Berbellini, and A. Morelli (2017), Crustal structure beneath Portugal from teleseismic Rayleigh Wave Ellipticity, *Tectonophysics*, doi:10.1016/j.tecto.2017.06.001.
5. Attreyee Ghosh, G. Thyagarajulu, Bernhard Steinberger (2017), The Importance of Upper Mantle Heterogeneity in Generating the Indian Ocean Geoid Low, *Geophysical Research Letters* 44, 9707–9715, doi:10.1002/2017GL075392.
6. Baron, J., and A. Morelli (2017), Full-waveform seismic tomography of the Vrancea, Romania, subduction region, *Physics of the Earth and Planetary Interiors* 273, 36–49, doi:10.1016/j.pepi.2017.10.009.
7. Borgeaud, A. F. E., K. Kawai, K. Konishi, and R. J. Geller (2017), Imaging paleoslabs in the D" layer beneath Central America and the Caribbean using seismic waveform inversion, *Science Advances* 3(11), e1602700, doi:10.1126/sciadv.1602700.
8. Clinton, J. F., D. Giardini, P. Lognonné B. Banerdt, M. van Driel, M. Drilleau, N. Murdoch, M. Panning, R. Garcia, D. Mimoun et al. (2017), Preparing for InSight: An Invitation to Participate in a Blind Test for Martian Seismicity, *Seismological Research Letters*, doi:10.1785/0220170094.
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10. Feng, L., and M. H. Ritzwoller (2017), The Effect of Sedimentary Basins on Surface Waves That Pass Through Them, *Geophysical Journal International*, doi:10.1093/gji/ggx313.
11. Freeburn, R., P. Bouilhol, B. Maunder, V. Magni, and J. van Hunen (2017), Numerical models of the magmatic processes induced by slab breakoff, *Earth and Planetary Science Letters* 478, 203–213, doi:10.1016/j.epsl.2017.09.008.
12. Gade, M., and S. T. G. Raghukanth (2017), Simulation of strong ground motion for a MW 8.5 hypothetical earthquake in central seismic gap region, Himalaya, *Bulletin of Earthquake Engineering*, 1–27, doi:10.1007/s10518-017-0146-2.
13. Galassi, G. and Spada, G. (2017), Tide gauge observations in Antarctica (1958--2014) and recent ice loss, *Antarctic Science*, 1–13.
14. Gharti, H. N., D. Komatitsch, L. Langer, R. Martin, V. Oye, J. Tromp, U. Vaaland, and Z. Yan (2017), *SPECFEM 3D Geotech: an open-source, parallel and cross-platform geotechnical engineering application*., doi:10.5281/zenodo.820154.
15. Giaime, M., C. Morhange, M. Á. Cau Ontiveros, J. J. Fornós, M. Vacchi, and N. Marriner (2017), In search of Pollentia's southern harbour: Geoarchaeological evidence from the Bay of Alcúdia (Mallorca, Spain), *Palaeogeography, Palaeoclimatology, Palaeoecology* 466, 184–201,

doi:10.1016/j.palaeo.2016.11.023.
16. Godfrey, K. E., C. A. Dalton, and J. Ritsema (2017), Seafloor age dependence of Rayleigh wave phase velocities in the Indian Ocean, *Geochemistry, Geophysics, Geosystems*, doi:10.1002/2017GC006824.
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18. Harff, J., N. C. Flemming, A. Groh, B. Hunicke, G. Lericolais, M. Meschede, A. Rosentau, D. Sakellariou, S. Uscinowicz, W. Zhang et al. (2017), Sea Level and Climate, *Submerged Landscapes of the European Continental Shelf: Quaternary Paleoenvironments*, 11.
19. Haugland, S. M., J. Ritsema, P. E. van Keken, and T. Nissen-Meyer (2017), Analysis of PKP scattering using mantle mixing simulations and axisymmetric 3D waveforms, *Physics of the Earth and Planetary Interiors*.
20. Haynie, K. L., and M. A. Jadamec (2017), Tectonic drivers of the Wrangell block: Insights on fore-arc sliver processes from 3-D geodynamic models of Alaska, *Tectonics* 36(7), 1180–1206, doi:10.1002/2016TC004410.
21. Henderson, S. T., F. Delgado, J. Elliott, M. E. Pritchard, and P. R. Lundgren (2017), Decelerating uplift at Lazufre volcanic center, Central Andes, from A.D. 2010 to 2016, and implications for geodetic models, *Geosphere*, doi:10.1130/GES01441.1.
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26. Johansen, H., A. Rodgers, N. A. Petersson, D. McCallen, B. Sjogreen, and M. Miah (2017), Toward Exascale Earthquake Ground Motion Simulations for Near-Fault Engineering Analysis, *Computing in Science & Engineering* 19(5), 27–37, doi:10.1109/MCSE.2017.3421558.
27. Kangchen Bai, Jean- Paul Ampuero (2017), Effect of seismogenic depth and background stress on physical limits of earthquake rupture across fault step-overs, doi:10.1002/2017JB014848.
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