Research Collaboration Network: Planning for a Modeling Collaboratory for Subduction Zone Science

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This is a slightly revised version of a collaborative proposal that was submitted to the National Science Foundation in July 2018, and funded as presented here in September of the same year. This document was prepared by the MCS RCN Steering committee that consists of:

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Project summary

Overview This RCN is intended to plan the specifics of a *Modeling Collaboratory for Subduction Zone Science* (MCS) and explore the science questions centered around developing physical models of short to long-term deformation associated with the megathrust and arc volcano systems, including and up to rupture and eruption. An effective MCS will be capable of integrating the constraints from international subduction zone observatories (*i.e.* heterogeneous sensor networks), as well as field and laboratory work into a physics-based, systems-level modeling framework that allows analysis of earthquake and volcano generating processes in subduction zones.

Such an ambitious goal requires developing new tools, integration of formerly separate modeling efforts, evaluating approaches for crossing spatio-temporal scales, and identifying the knowledge gaps that limit our understanding of the multiphysics processes related to subduction zone hazards. This RCN will foster, guide and focus the discussion of possible pathways for establishing an MCS through a series of targeted, in-person workshops and a webinar series on cyberinfrastructure needs and capabilities. These events and sustained support of sub-network interactions and exchange will enable new collaborations across the different disciplines and stakeholders required for building a successful Modeling Collaboratory for Subduction Zone Science.

The steering committee is charged with coordinating network activities, reaching out to different communities, and ensuring a diverse, open, and inclusive environment.

Intellectual merit The MCS will provide the platform to empower breakthroughs in our understanding of the interactions between the short and long-term subduction dynamics processes that shape the planet. In particular, numerical simulations of physical models representing subsets of the subduction system will be built and queried for how they interact, and which boundary conditions and feedbacks need to be incorporated for a more complete understanding of each component. The MCS may also further insights into how interseismic, possibly preparatory processes, of volcanic and megathrust earthquake systems can be interpreted in a predictive way, with implications for hazard, forecasting, and early warning. The new scientific interactions enabled and supported by this RCN can form the first steps toward building the MCS. In particular, this RCN will serve to identify knowledge gaps and serve to evaluate the tools and strategies needed to implement an MCS that is capable of leveraging the rich data sets from international subduction zone observatories to create a new generation of multiphysics and multiscale models.

Broader impacts Support of this RCN will strengthen international collaboration and leverage any future investment in observational efforts by helping to build the tools for experimental design and observatory integration. The community of subduction zone scientists will be exposed to diverse views from neighboring fields, making our science more creative and empowering discovery. The international collaborators are expected to initially include researchers from Chile, Costa Rica, Germany, Greece, Indonesia, Italy, Japan, Mexico, Switzerland, and the United Kingdom, and others are invited to join. The RCN will contribute to the training of a diverse workforce, and outreach efforts will publicize the relevance of subduction zone science to the larger public.

Context and Motivation for a Community Modeling Collaboratory

Subduction zones are fundamental expressions of the evolution of our planet as governed by thermo-chemical mantle convection. Transport of melt and volatiles through the mantle wedge and out the arc affects climate and the sites of ore deposits. Subduction zones also host cascading natural hazards, from volcanoes, to earthquakes, to landslides and tsunamis, often in regions with high population density. Any dynamic understanding of our planet therefore has to include a comprehensive theoretical framework for subduction zone dynamics, and such a framework should have utility for monitoring and physics-based forecasting in order to meet our fundamental responsibility to society.

Several recent community efforts laid out plans involving subduction zone science, here defined in a broad sense to include volcanic and megathrust processes within their geological context. U.S. reports include *Subduction Zone Hazards in 4-D* (SZ4D) (*McGuire et al.*, 2017), the USGS' *Reducing Risk Where Tectonic Plates Collide* (*Gomberg et al.*, 2017), *Volcanic Eruptions and Their Repose, Unrest, Precursors, and Timing* by the *National Academies of Sciences, Engineering, and Medicine* (2017), and *Challenges and Opportunities for Research in ESI (CORE)* for NASA (*Davis et al.*, 2016).

These plans discuss, for example, that there is mounting evidence for intermediate-timescale precursory processes before volcanic eruptions or megathrust ruptures. However, our physical understanding of earthquake cycles and volcanoes within a plate boundary remains incomplete, even though numerical models have seen tremendous improvements. This implies that more observations, laboratory data and better understanding of the underlying physical processes need to be integrated in better ways to explore interactions between different parts of the subduction system that affect the temporal evolution of tectonics and hazards. The time is right to unify existing data collection efforts, design new observational and infrastructural initiatives, and harness diverse international efforts with new integrative approaches.

The SZ4D report suggests to establish an interdisciplinary science program, develop new, large-scale infrastructure, and to create a Community Modeling Collaboratory (*McGuire et al.*, 2017). The objectives of such a ***Modeling Collaboratory for Subduction Zone Science*** (***MCS***, Figure 1) would be to support SZ4D observatories (*i.e.* existing and planned sensor networks and observational efforts on a national and international level), and the science program by: 1) helping to identify knowledge gaps; 2) developing multi-scale, multiphysics modeling frameworks; 3) providing a pathway for integrative model development and validation; and, 4) providing tools for transforming geological, rock mechanics, geophysical and geodetic data into formats that can be effectively assimilated into models and used for model validation.

The MCS would facilitate the ***development and enhancement of models, ranging from conceptual to numerical simulators, aimed at subduction zone megathrust cycles and associated tectonic processes including magma transport and volcanic eruptions***. These tools can be adopted and validated in several regional settings. An MCS could thereby provide the infrastructure for a range of ***data integration***, and so support a network of observatories. An MCS should eventually be able to provide **physics-based methods for**

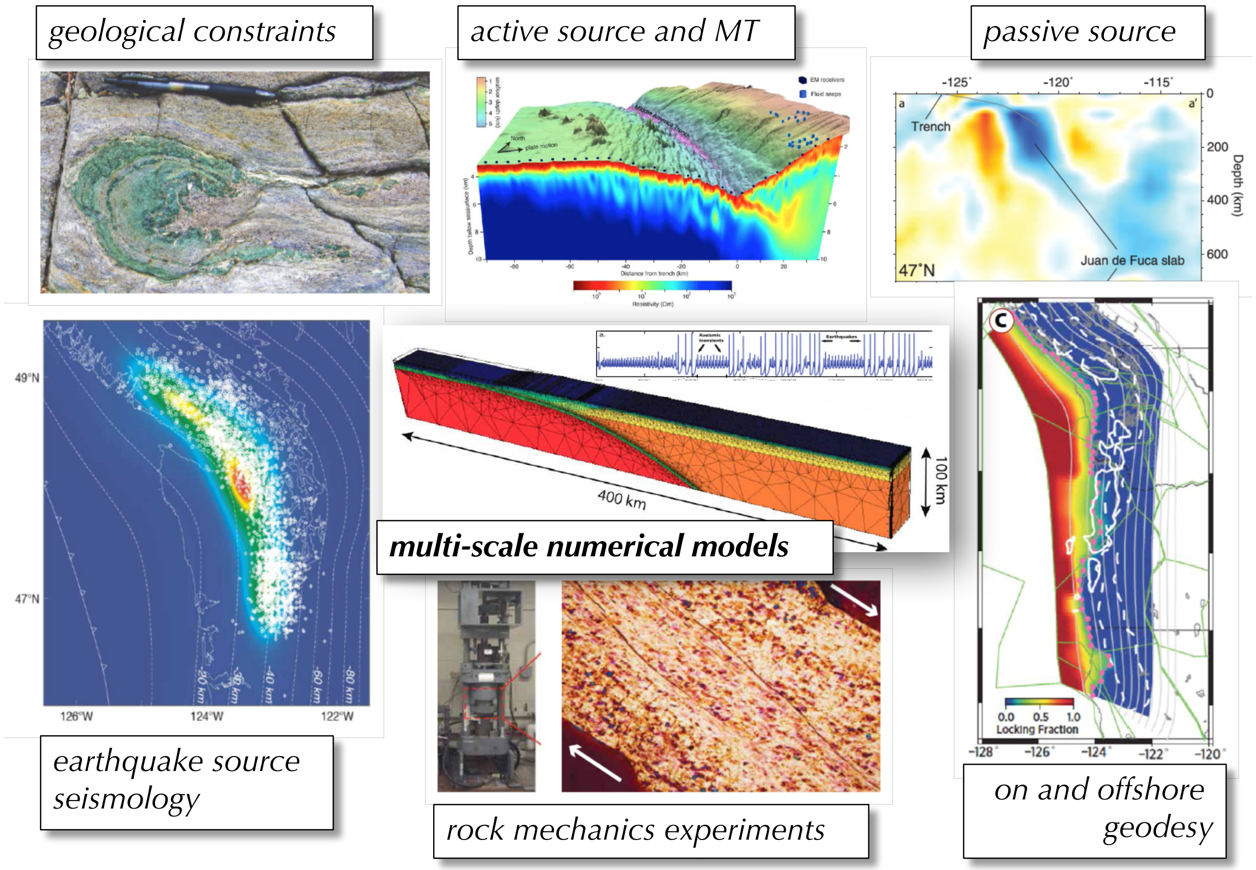

Figure 1: Data-integrative modeling collaboratory for subduction zone science. The modeling framework should be capable of capturing physico-chemical processes bridging convection, fractionation, tectonics, megathrust dynamics, and volcano dynamics while assimilating comprehensive datasets for improved hazard assessment. Such a framework was discussed by *McGuire et al.* (2017), and is here termed the *Modeling Collaboratory for Subduction Zone Science (MCS)*. Center figure is from *Tong & Lavier* (2016), figures illustrating constraints (top left, clockwise) are modified from: W. Behr (pers. comm., 11/2017), *Naif et al.* (2015), *Hawley et al.* (2016), *Schmalzle et al.* (2014), *Proctor & Hirth* (2015), and *Gomberg et al.* (2010).

decadal scale forecasting and hazard assessment.

No two volcanoes or subduction zones are alike, but there is only one Earth and one set of physical and chemical processes. In this sense, the MCS would provide a general forum for collaboration for subduction zone science, and leverage existing and future U.S. and international investment (Figure 2). Supporting an MCS should provide great science benefit for the U.S. and international community, help build a diverse cohort of integrative scientists, and transform and accelerate U.S. led synthesis efforts before large-scale infrastructure investments will come online. MCS details remain to be defined, but one can identify a few, core guiding principles, including:

- focus on providing model building blocks, to be used alone or combined in a num-

ber of ways, empowering hypothesis testing rather than pushing a consensus approach;
- fully open and documented datasets, tools, and models, as well as reproducible work flows;
- a provision of access to computational resources and expertise;
- close collaborations with other initiatives (*e.g.* CIG, EarthCUBE, SCEC, NGEO);
- capacity building for a diverse workforce, *e.g.* with regular workshops and an REU program.

The approach for an MCS is informed by the best practices learned from similar efforts in the wider community (*e.g.* climate modeling) and the solid Earth sciences, in particular, SCEC and CIG. However, the MCS is unique and complementary in its mission because it will support

- development and adaption of modeling tools for flexible frameworks;
- model integration from a range of domain sciences;
- observatory data integration using physics-based models for forecasting; and
- international collaboration and science integration from a range of subduction zones.

Objectives of this Research Collaboration Network

The MCS idea holds promise to make headway on longstanding problems related to megathrust occurrence and volcanic hazards, such as the growing need to understand the likelihood of event occurrence on timescales of decades using physics-based models. Further discussions among the wider community are, however, needed to define the requirements of different stakeholders partaking in the subduction zone science endeavor, to identify opportunities for advancing science, to establish the scope of an MCS, and to assure its optimal effectiveness.

This proposal is for a three year research collaboration network (RCN) with the objective to establish an inclusive process to further discussions about the value and shape of an MCS, identify knowledge gaps, and to arrive at a recommendation for an MCS implementation. A challenge for the MCS is to develop links and define a scope of integration for the processes that are relevant for subduction zones. Efforts should optimally utilize synergies between the disciplines and capture relevant interactions, yet it should be focused enough to enable advances in each sub-discipline, allow for testing of hypotheses in data rich environments, and it should lead to helpful hazards-centric products for the observatories.

For example, the goal of building an integrated model that captures million-year timescale tectonics such as slab rollback, mantle wedge mass transport, megathrust cycles, and volcanic eruptive state is exciting and resonates as a decadal-scale goal. It can be unified and guided by focusing on trying to understand, first, the general, isolated system behavior, *e.g.* for an earthquake and for a magmatic system, and then trying to elucidate how the components of the system interact to affect the boundary conditions for each other. One could focus on the stress-state and fluid transport, how to "coarse grain" and upscale those processes, and exploring model robustness, parameter sensitivity and formally quantifying the uncertainties. This would have to address which aspects of "roughness" have to be tracked and modeled to improve hazard assessment, for example as is beginning to happen for strike-slip fault systems (*e.g. Tullis et al.*, 2012).

The challenges here are manifold. They arise because the study of different components of the subduction zone system (*e.g.* earthquakes *vs.* volcanoes) appear at different levels of completeness of physical models, are subjected to different degrees of resolution for regional structure and knowledge of constitutive laws (none complete), and the extent of the applicability of general descriptions for homogeneous behavior of even idealized systems is unclear.

Yet, before we build coupled models, we cannot truly assess if current numerical and analytical approaches are sufficiently efficient and robust to address the scientific and hazard related questions in subduction zones. This RCN therefore seeks to sharpen the discussion about the MCS implementation by focusing on bringing field, lab, and mod-

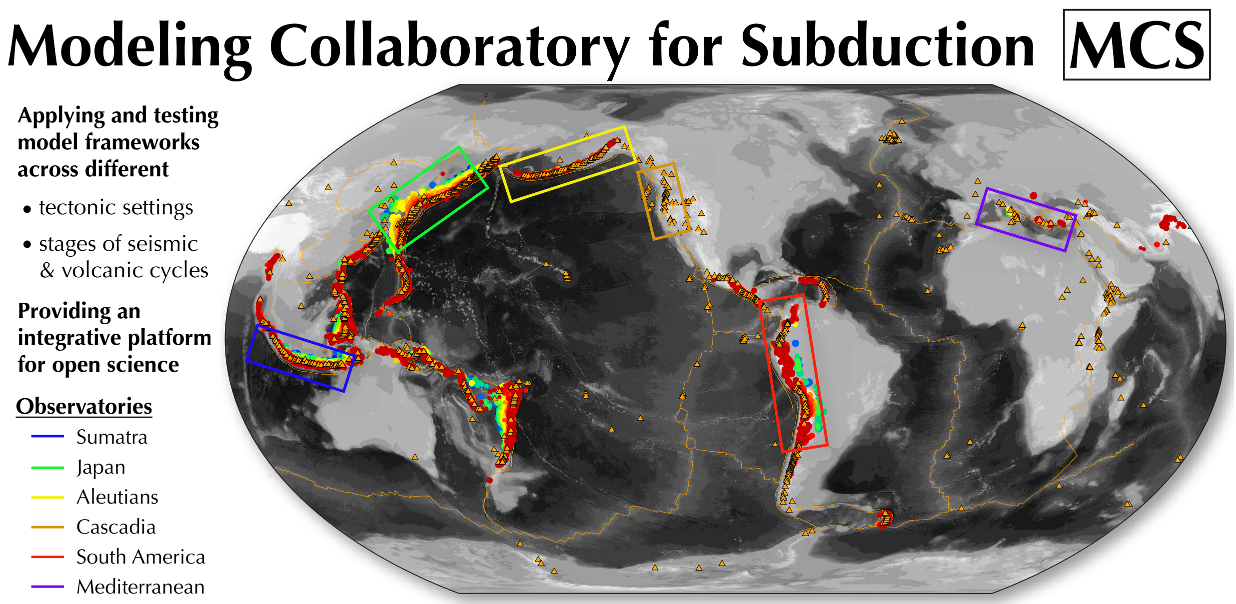

Figure 2: International collaboration and integration capabilities of an MCS framework for existing and potential future subduction zone observatories and different tectonic settings, facilitating scientific discourse and exchange by means of providing an integrative platform for open science. (Circles: $M > 4$ earthquake below 100 km (*Engdahl et al.*, 1998), red to blue colored with depth; orange triangles: volcanism (only those with defined eruption years; *Siebert & Simkin*, 2002-), plate boundaries from *Bird* (2003).)

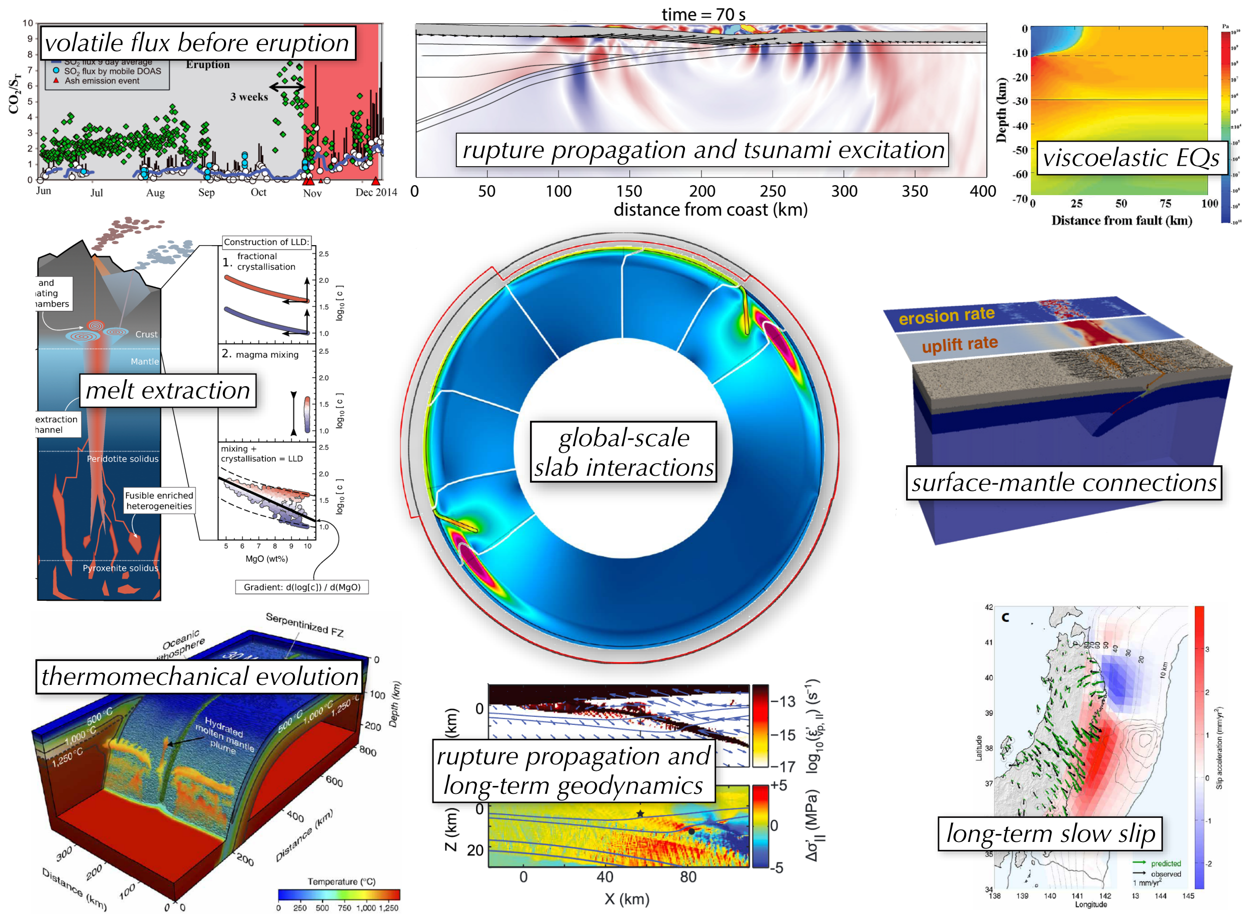

Figure 3: Coupled physics of earthquake and volcano systems. Potentially deterministic preparatory processes such as volatile flux variations before an eruption (top left; *deMoor et al.*, 2016) and long-term slow slip before rupture (bottom right; *Mavrommatis et al.*, 2014) need to be better understood within physics-based models that account for system interactions. From top, center, those include: solid-Earth/ocean dynamics (*Kozdon & Dunham*, 2014), lithosphere-asthenosphere stress transfer during the earthquake cycle (*Takeuchi & Fialko*, 2012), surface process-deep Earth feedback (*Ueda et al.*, 2015), long-term thermomechanical *vs.* rupture related stresses (*van Dinther et al.*, 2014b), and the regional thermo-mechanical dynamics (*Manea et al.*, 2014) affecting magma transport (*Shorttle et al.*, 2016), within the global convection system (*Gérault et al.*, 2012).

eling scientists from different disciplines together to explore what is needed to adopt, homogenize and upscale (if possible), and implement at full realism (if needed).

Intellectual merit

Several groups have built initial, integrative models as illustrated with a few examples in Figure 3. However, based on the summaries of *McGuire et al.* (2017) and *Gomberg et al.*

(2017), and the discussions we have had among the people involved in this RCN, there is, for example, not enough communication between those who model magmatic systems, those who model fluid flow in the wedge, and those who model the temperature, pressure, and deviatoric stress conditions of the mantle and lithosphere in subduction zones. This RCN will therefore strive to enable new discussions and collaborations within the subduction zone science community.

These new avenues of exchange will facilitate advances in establishing how interactions between parts of the subduction system, such as fluid transport, melt generation and transfer, stress heterogeneity evolution over several seismic cycles, or magma reservoir evolution and eruptive potential can be embedded in long term models, and how forcing from large-scale, long-term models is best incorporated in smaller scale, higher resolution efforts. These discussions will accelerate individual participant's research and contribute to the process of building a cohort of interdisciplinary subduction zone scientists within the Earth sciences and other fields, such as computer and data science, machine learning and engineering.

The interactions enabled through the RCN will help to identify the knowledge gaps that stand in the way of building a subduction zone modeling framework for deterministic hazard assessment and forecasting. Our RCN will explore the scope for improvements in theoretical and numerical modeling approaches, which provides collaborative links, *e.g.* to CIG's communities. The RCN will also serve to focus data collection efforts, laboratory experiments, and the design of the SZ4D science plan. We will arrive at an implementation recommendation for the Modeling Collaboratory, and RCN efforts will help formulate prototypes of components of the MCS. The latter may feed into the wider subduction zone science planning, and possibly the design of any large-scale infrastructure investments.

Broader impacts

This RCN is geared toward broadening the diversity of subduction zone modelers, in terms of disciplinary interactions and representation of manifold backgrounds. A key objective is to identify opportunities for interdisciplinary collaborations that will open new possibilities for training students and advancing early career scientists. The efforts of this RCN are expected to contribute to the benefits of the Modeling Collaboratory whose implementation it is intended to discuss.

The MCS' modeling capabilities will be of value for the entire subduction zone science community interested in earthquakes, volcanoes, and tsunamis. A general subduction zone system model can be adapted to a range of constraints from several regions and so provide the context, and the link between different subduction zone observatories (Figure 2). The MCS efforts have implications for our general understanding of plate tectonics, but also more immediately for hazard. A multiscale subduction system model is required to eventually answer one of the key questions society asks the Earth sciences: What is the degree of inherent predictability of natural hazards, or absence thereof? The RCN is intended to help refine some of the strategies in this renewed effort.

It will be a challenge to integrate subduction zone science and move toward fully open data sharing within the international community. To help address these challenges, the RCN is built around the close involvement of international partners, integrating them from the early stages of MCS discussion in order to get the broadest buy-in. In order to build a collaborative culture, we will also seek to involve a range of international researchers within hands-on components of our workshops to intensify knowledge exchange and sustainable capacity building.

For example, engagement in South American observatories and the lithospheric dynamics modeling community is strong in Europe. We will seek to help broaden partnerships with colleagues there, including within the *European Plate Boundary Observatory* (*EPOS*, 2017) framework and through a possible *European Cooperation in Science & Technology* (*COST*, 2017) program. As another example, Japan has lead the way in terms of instrumentation and is embarking on comprehensive, physics-based hazard modeling (*e.g. RIKEN AICS*, 2017). There are shared challenges in making the best use of the data for model building, and we will build on existing collaborations with researchers in Japan, trying to expand the level of participation of the scientists involved.

All materials produced within this RCN, workshop reports, and recorded lectures will be archived on the RCN web page and made publicly available. The RCN will support a part-time administrator whose duties will include maintenance of a web page that can serve the domain scientists involved and wider public, as well as a broad social media presence to engage the public and decision makers in the lead-up to possible MCS and SZ4D proposal submissions.

Research Collaboration Network implementation

This proposal reflects several rounds of discussions among a group of researchers who are interested in the MCS, some of which comprise the steering committee (SC), which will be open to restructuring as part of the RCN. The SC formed as the result of a self-organizing ground swell following the National Academy's *Workshop on Improving Understanding of Volcanic Eruptions* in 2016, the SZO workshop (*McGuire et al.*, 2017), as well as discussions with those involved in other nascent RCNs including the SZ4D coordination RCN, and townhalls led by Terry Plank at the CIDER 2017 summer program as well as IAVCEI and Fall AGU 2017. The PI also presented this MCS planning RCN effort at the NAS COSG Workshop *Integrative Subduction Zone Science: Moving into the Next Decade* in November 2017 in Washington DC for discussion.

Management plan

All activities of the RCN will be overseen by the SC, which is charged with defining the implementation of the RCN operations. The SC composition aims to be representative of the diversity of subduction zone modeling and institutions involved, while maintaining a group size that allows meaningful discussions in virtual collaboration meetings. The SC is to initially consist of

- Kyle Anderson (USGS Menlo Park) – volcano dynamics, multiphysics modeling;
- Thorsten Becker (PI, UT Austin) – mantle dynamics, global subduction zone models;
- Mark Behn (Boston College) – mantle dynamics, marine geophysics;
- Magali Billen (UC Davis) – mantle dynamics, regional dynamic subduction zone models;
- Chuck Connor (U South Florida) – volcano dynamics, volcano-earthquake interactions;
- Eric Dunham (Stanford) – rupture propagation, volcanic conduit and tsunami dynamics;
- Allison Duvall (Washington U) – landscape evolution;
- Helge Gonnermann (Rice) – volcano dynamics, fluid dynamics;
- Kaj Johnson (Indiana U) – fault system dynamics and geodesy;
- Amanda Thomas (U Oregon) – source seismology and fault constitutive laws;
- Ikuko Wada (U Minnesota) – mantle dynamics, regional thermo-chemical modeling.

The SC will meet in person at the first and last workshop sponsored by the RCN, at the Fall AGU meeting, including in an open session where we invite the community to join the discussions, and virtually by means of teleconferencing every two months for updates, and to take stock of progress and workshop proceedings. SC decisions will be by simple majority vote, and its composition will be reassessed after year one of the RCN. The PI will be responsible for the overall implementation of the RCN, how funds are spent, and for ensuring that milestones are met.

The SC and PI will be assisted by a part-time administrator at UT, under the supervision of the PI. The administrator will participate in all telecons, and write meeting notes. The administrator will handle all workshop organization, and travel to workshops to assist with local logistics. The administrator will also work with part-time technical staff, who will assist the PI and administrator in establishing a comprehensive RCN web site and social media presence. The website will host workshop reports, workshop presentations, and planning documents. We will also support virtual collaboration for workshop followup efforts (*e.g.* model building, data sharing, collaboration of PhD students, postdocs, and researchers) by assisting with `Slack` or similar setups.

We will maintain a newsletter, distributed via an email list, that keeps track of RCN efforts, and actively work a RCN Twitter account for a wider audience. The administrator and technical support staff will also work on keeping the webinar series on track, archived, and well publicized.

Network management

The steering committee as a whole will solicit and review detailed workshop plans that include a list of potential attendees and review those for diversity and community participation. The SC will evaluate workshop plans in light of the milestones established and reviewed throughout. The SC will review suggested collaboration support allocations for emerging new science interactions, and suggest new in-person or virtual collaboration initiatives.

All RCN activities will be announced on a mailing list and via the Twitter account. Workshop chairs will consist of one steering committee member and one person from outside the SC or RCN, to ensure broadening of the network of collaborators. The workshops are intended to balance diversity and broad participation with being small enough to have detailed discussions and match logistics and funding constraints. We plan for an open invitation with in-person capacity for $\sim$60, with 20-30 participant's attendance cost covered, and virtual participation opportunities. A report will be written by the workshop chairs, distributed for comments, and published online. All workshop results, such as presentations, preliminary models and collections of constraints for model building, will be made available at the RCN web site, and organized for virtual collaboration.

After year one, a questionnaire will be sent out to get feedback on the MCS, if the RCN is meeting community goals and furthering the debate, and if the upcoming workshop program and webinar activities meet community needs. The steering committee will also evaluate its composition, and solicit nominations for new members. Importantly, the SC committee will also annually re-evaluate the workshop program for the second and third years, and adjust if needed.

International integration

We see this RCN and the MCS as important tools to engage the international subduction zone community and observatories, and we will work to build strong connections with researchers world-wide (Figure 2), with initial focus on Europe, Japan, South America, and Indonesia where many of us have personal contacts. Our budget for each workshop has 25% funding for international attendees and we will seek to have a mix of senior leaders and junior researchers involved at a more detailed science level. Representatives of our RCN will use attendance of international meetings to advertise the RCN, and we have done so already at the *European Mantle and Lithospheric Modeling Workshop* in the Netherlands in August of 2017, for example, to good response.

There are a number of new collaborations we will pursue. For example, we will coordinate with *EPOS* (2017), an EU effort to facilitate integrated use of data and data products from distributed research infrastructures (including *Volcano Supersites*) for solid Earth science. Their WP11 (*Volcano-Observations*) and WP16 (*Multi-scale laboratories*) involve a wide range of modelers with relevant interests and expertise. The development of models will be discussed with EPOS and the implementation of scientific products will be integrated in the EPOS plan. A promising avenue is a potential collaboration with an EU program discussed with Francesca Funiciello at Roma TRE (see letter of collaboration). Funiciello is exploring a volcano and earthquake focused EU *COST* (2017) action, where she is well positioned with collaborators and experience with previous EU funding. These efforts would entrain emerging leaders including, *e.g.*, Ylona van Dinther (ETH), Eleonora Rivalta (GFZ Potsdam), and Jessica Hawthorne (Oxford).

We will also seek to engage new contacts in Japan, where we have in the past been involved in US-Japan summer schools funded through SCEC VISES, for example. We will use the MCS planning process to get participation from new partners, including from JAMSTEC and Tohoku. Key partners we have begun to discuss the MCS with are Takane Hori (JAMSTEC) and Tsuyoshi Ichimura (ERI, U Tokyo), the leaders within the *post-K Computer Integrated Simulation Systems for Hazards* effort (*RIKEN AICS*, 2017), respectively (see letters of collaboration).

We will involve key international partners in our kick-off meeting, and explore joint workshops and model building exercises. We envision intermediate products from our workshops to be of interest to the international subduction science community, and illustrate the value added of a jointly planned MCS.

Coordination plan

The focus of this RCN was distilled from discussions with the leaders of the SZ4D workshop report efforts, Terry Plank and Jeff McGuire, and participation in the COSG workshop in 2017. We are in touch with a number of researchers including Einat Lev (LDEO) and Tobias Fischer (UNM) who are involved with different kinds of volcano centric RCNs, and we expect them to attend several of our workshops, and we may have joint steering committee members.

To ensure continued coordination on a larger scale, we will also invite representatives from initiatives such as CIG, EarthCUBE, the other SZ4D associated RCNs, and from centers, such as NASA's Ames Research Center, to join our steering committee telecons, and will invite leaders from these efforts to our workshops. Our general outreach activities are designed to fully document activities in a transparent way, and RCN operations are designed to respond to community feedback and expand inclusiveness and diversity.

Increasing diversity

Each steering committee member is charged with reaching out to their respective communities to solicit feedback on planned RCN activities, and help lead workshops in their sub-domains. SC composition is intended to be diverse with respect to type of institution, disciplinary background, and gender. Moreover, the SC is in charge of overseeing diversity of workshop attendance and administrative staff will assist by compiling statistics of attendance and presenters in terms of disciplinary, gender, and ethnic background. The social media presence will be used to reach out to the wider science community and advertise efforts outside the subduction zone science crowd.

The workshop program described below will usefully have some overlap in terms of who is attending, but we see each one as different enough to draw in $\gtrsim$50% of "new" people, either from other areas of subduction zone science, or from other, related fields (*e.g.* material science, hydrology, engineering, data science, industry, etc.).

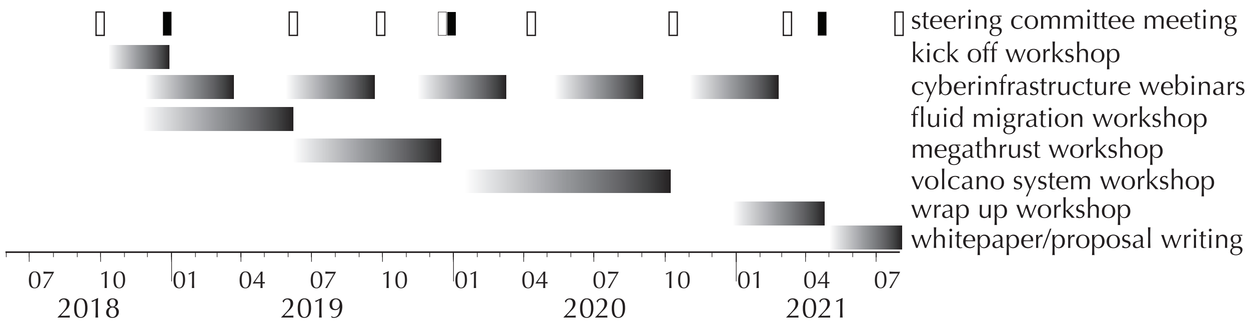

Figure 4: RCN timeline, shading for lead-up, and open and filled boxes for virtual and in-person meetings (updated after obtaining funding in 09/2018).

Workshop programs

The RCN's activities are to be kicked off with a one-day meeting on refining the RCN structure, preceded by a range of support activities based on discussion with the wider community in the beginning (Figure 4). The last one-day meeting of the RCN is held to summarize the lessons learned and to kick off writing an MCS implementation white paper. In between, more specialized, two day workshops will be held that will engage wider subsets of the community, and allow researchers to engage on a practical level that will advance their own science rather than just having planning discussions. We here list the fully RCN sponsored activities. However, we hope that we can leverage the efforts of our European and Japanese colleagues, for example, and also benefit from national co-sponsorship of other events, *e.g.* by means of a USGS/NSF Powell Center event.

Kickoff meeting: Setting the stage for an MCS and refining the RCN

The objectives will be to discuss the general MCS objectives, and how a planning RCN might best contribute to distill the MCS' scope, and best serve to bring together the subduction zone community. The entire steering committee will attend, plus representatives from other SZ4D RCNs and efforts and organizations such as SCEC and CIG. We will solicit input from the community as to their needs for specific workshops within an MCS context by email and sending representatives to townhall meetings. We will establish a website clearing house and circulate the RCN plans for discussion. The goal is to have a high level discussion of the following questions:

- What are the major challenges in building earthquake and volcano physics, and understanding ways of coupling them, and are our workshops aligned to answer these questions?
- What could an MCS achieve, and how can we best serve the range of communities engaged in subduction zone science?

The meeting will serve to set the topics for followup workshops, define milestones for years 1-3, discuss strategies for evaluating outcomes, and determine workshop chairs for year one.

Hands-on, project-oriented workshops

We envision three in-person workshops and one ongoing webinar series. Each workshop will be motivated by a big-picture goal, will identify science and collaboration opportunities, and will produce a document outlining the requirements and steps needed to achieve this goal. These white papers will serve as guidelines for implementation of an MCS. The level of detail of the workshops and the links to deterministic hazard assessment are variable, and this highlights some of the challenges as well as opportunities of an MCS. However, all workshops are related and there is clear commonality (*e.g.* upscaling, understanding feedbacks).

Science questions will be broken down by considering more limited sub-processes and we will start to design the computational module specifications, including their inputs and outputs, underlying equations and algorithms, benchmarks and verification, as well as documentation requirements. Existing numerical approaches will be used as a starting point, evaluating how a coupled model might be built eventually to address different interconnected processes for the larger scientific questions (Figure 5). We propose the following workshop themes:

1. **Linking microphysics and geodynamic models for fluid and melt migration (workshop 1)**

   Addition of slab-derived volatiles to the mantle wedge results in melt generation and, ultimately, the volatile content of magmas affects the style of arc volcanism (Figure 5). At the same time pore fluids may play a central role in controlling shear zone strength, earthquake stress drop and slip. Therefore, understanding the distribution and migration of aqueous fluids is critical to both the study of earthquake and volcanic hazards (workshops 2 and 3).

   Fluid transport has been studied using large-scale geodynamic models by assuming, for example, porous flow through a deforming matrix (*e.g. Wilson et al.*, 2014; *Cerpa et al.*, 2017) or both porous flow and channelized flow along faults (*e.g. Zheng et al.*, 2016). One of the questions is whether the macroscopic expressions used are compatible with the microphysical mechanisms. Those appear complex, depending on the temperature, deformation conditions (set by the large-scale dynamics), and the physical properties of the rock/matrix. It is unclear which effect is most important among the various proposed microscopic mechanisms, such as reaction-induced fracturing (*e.g. Okamoto & Shimizu*, 2015) and creep cavitation (*e.g. Précigout et al.*, 2017), and some of them are poorly characterized.

   Therefore, the robustness and upscaling character of geodynamic models is debated. This situation stems partly from a communication gap between those dealing with large-scale geodynamics and those dealing with observations/experiments and modeling of microphysics. We also need to connect magma-generation better with eruption modeling. Engaging volcano, magma-generation and convection modelers with volcanologists, geochemists, and geologists can move our understanding of this topic forward.

The RCN will help to remove road blocks by addressing such issues as:

- Where do which microphysical mechanisms controlling fluid migration operate?
- What spatio-temporal scales do these mechanisms affect, and how do they upscale?
- What are the theoretical and modeling commonalities in treating fluid, melt, and gas transport in earthquake and volcano systems?

The progress in addressing these key issues will help to coordinate modeling efforts, including those by the Magma Migration Working Group of CIG. We will address specific questions related to the effects of fluids on the sliding behavior of faults and the generation and plumbing systems of arc magmas and volcanoes. These questions include:

- How can we best model solid-fluid interactions, *e.g.* as applied to volcanic conduits and the seafloor-ocean interface?
- How are fractures and fluid migration coupled in the magma plumbing system?
- How does the process of fluid migration affect the transition between stick-slip (rate-strengthening) and stable (rate-weakening) sliding behavior at the megathrust?
- What is the role of fluid transport in explaining interseismic deformation phenomena, such as slow slip?

2. **Building a megathrust earthquake cycle model (workshop 2)**

   Dynamic rupture models combine processes controlling fault strength (*e.g.*, friction laws) with elastodynamics to solve for the fault slip history and radiated waves, recently including ocean response and tsunami generation (*e.g. Kozdon & Dunham*, 2014; *Cubas et al.*, 2015). Rupture models including predictions for ground shaking are currently limited by the lack of knowledge of *megathrust state*, *i.e.* stress, stressing-rate, pore pressure, and frictional properties along the plate interface and surrounding medium (*e.g. Avouac*, 2015). A major opportunity for the MCS is to identify the processes controlling state, to incorporate those processes in long-term geodynamic models, and then to integrate outputs from geodynamics into earthquake cycle and rupture models, testing constitutive laws (Figures 3 and 5).

   This effort has to be two-pronged: 1) to best-constrain the megathrust state in a certain region (for example, Cascadia; *e.g. Wang & Trèhu*, 2016), and, 2) to understand the pathways for state evolution. Long-term subduction models can be used to explore how changes in the large-scale system lead to changes in the thermal and mechanical structure that affect the state of stress on the megathrust, visco-elastic cycle

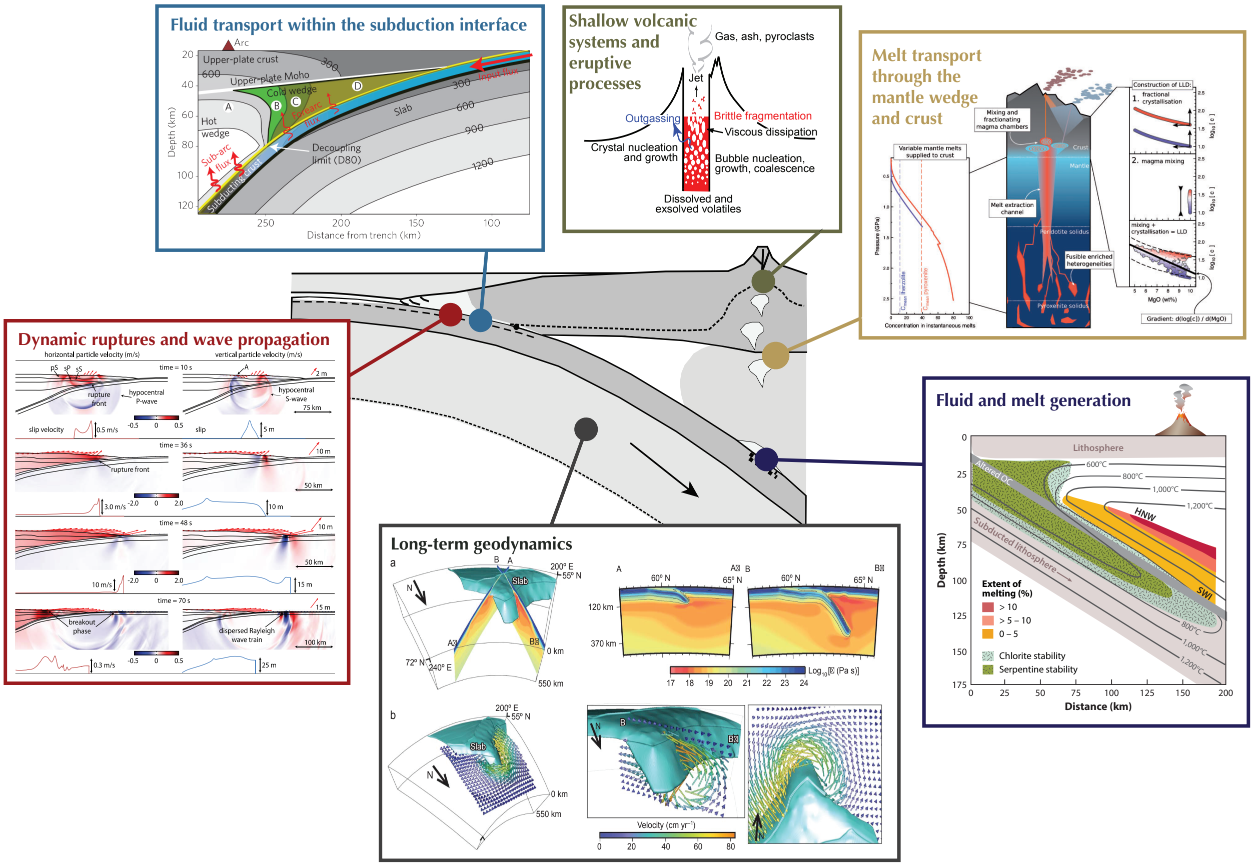

Figure 5: Model building block interactions to be explored in our workshops. Figures modified from (top left, clockwise): *Abers et al.* (2017), *Gonnermann & Manga* (2005), *Shorttle et al.* (2016), *Grove et al.* (2012), *Jadamec & Billen* (2010), *Kozdon & Dunham* (2013); background: *Hyndman & Peacock* (2003).

models, and volatile transport in the mantle wedge (*e.g. van Dinther et al.*, 2014a,b; *Corbi et al.*, 2017; *Rosenau et al.*, 2017; *Sobolev & Muldashev*, 2017).

The interactions between long- and short-term subduction dynamics are likely bidirectional, and results from dynamic rupture simulations can inform geodynamic models. For example, conditions for the initiation of subduction and a range of other evidence from geology and geophysics indicate that fault strength is likely lower than predicted by standard friction coefficients and hydrostatic pore pressures (*e.g. Toth & Gurnis*, 1998; *Ujiie et al.*, 2013; *Obara & Kato*, 2016). One suggestion is that the relevant fault strength determining lithospheric stress is not the static fault strength, but instead the much lower strength experienced during coseismic sliding. This workshop seeks to address a range of hierarchical questions:

- How are subduction zone faults loaded, and what is the best way to incorporate the insights from long-term and short-term models for seismic cycle descriptions?

  - How do large scale geodynamic properties of slabs such as morphology and buoyancy affect coupling and stress on the subduction interface, as well as interactions with other faults (*e.g.* outer rise or in the overriding plate)?
  - How can geodetic observations on land and offshore constrain the long-term and short-term rupture propagation computations?
  - How can we integrate results from rupture and geodynamic models? What variables need to be tracked and at what scale?
  - Besides dynamic earthquake simulations, what other multiphysics simulations could benefit from having initial conditions from longer-term simulations?
  - How can we take what is known about real physical/chemical processes occurring and correctly up-scale for the long-term subduction models?
  - Which interactions might be captured adequately by machine learning?
- Can integrated or coupled models be used to forecast the spatial distribution of earthquakes? Do we know the relevant physical parameters at the right conditions?
- What are the best tools to address the problems, how can they be integrated, and what needs to be developed?

3. **Building a subduction zone volcano system model (workshop 3)**

   Integrated multiphysics models of volcanic systems can be used to relate a range of geophysical, geochemical, and geological observations to magmatic processes and physical conditions (Figures 1 and 3). Nevertheless, current models of volcanic systems generally consider them in isolation from other subduction zone processes. A goal of this workshop is to find ways the MCS can help scientists place volcanic systems in a broader modeling framework.

   For example, ground deformation data associated with pressure changes in magma reservoirs have elucidated the locations and depths of reservoirs. The evolution of the subduction zone can, however, change the thermal and mechanical state of the crust, altering the response of the crust to magma ascent, and ultimately altering the likelihood of eruption. The frequencies of earthquakes and eruptions are expected to both be sensitive to strain-rate and/or stress conditions. Petrological and geochemical data demonstrate that magma generation, storage, and composition is intimately connected to geodynamic setting and its evolution. We thus hope to improve our forecasts of location, frequency, and magnitude of volcanic eruptions by explicitly modeling the geodynamic setting of the volcano.

   At the same time eruption/conduit models are becoming increasingly sophisticated and furthering these advances is paramount to predictive modeling of volcanic eruptions. By the same token, enhancing our abilities to adequately model magma ascent is essential to understanding of the underlying magmatic system and requires coupling of conduit models with models of the eruption-feeding storage reservoir (*e.g. Anderson & Segall*, 2011; *Colucci et al.*, 2014). Such coupled models are, however, still in their early stages of development.

Because surface observations are naturally more sensitive to processes in the shallow crust, deeper processes are generally poorly resolved. For example, in many cases it is thought that eruptions may be triggered by the intrusion of "new" magma, derived from deeper levels of the magmatic system, into existing reservoirs. This has led to the emerging view of a dynamically interconnected trans-crustal, or perhaps trans-lithospheric, magma storage and transport system (*e.g. Sparks & Cashman*, 2017; *Cashman et al.*, 2017). Advancing our understanding about the trans-crustal transport system and, hence, our ability to adequately represent it in volcano models is at the forefront of volcano science.

The trans-crustal magma system encompasses a significant fraction of the subduction zone system and constitutes the link between the volcanic system and the parts of the mantle wedge where melt is produced. On time scales of $\sim$10-100 Myr magma fluxes can vary by $\sim$ one order of magnitude (*e.g. Miller et al.*, 2009; *Gehrels et al.*, 2009; *DeCelles et al.*, 2009). Over the same time, the evolution of the trans-crustal magmatic system will affect the overall dynamics of the subduction zone itself, as well as the nature of volcanic activity (*e.g. Ducea et al.*, 2015, and references therein). The dynamics of, and feedbacks, within this integrated subduction-magma transport-volcanic system remain inadequately understood. The ramifications for volcanism are not only profound over long time scales, but also on the time scale of the eruptive cycle. Even though many eruptions are often preceded or followed by ground deformation, consistent with deeper magma supply, geodetic observations are not sensitive to the deeper magma plumbing system. Although deeper magma transport can be associated with seismic activity, this may not always be the case. Therefore, how magma migrates from its origin in the subduction zone to sub-volcanic storage reservoirs remains poorly understood on either short or long time scales and complicates the assessment of eruptive potential, among other things.

This motivates the construction of a volcano system model to link deep and shallow parts, and probe this model for robustness and sensitivity to mechanical and structural parameters. Challenges and opportunities follow from one another:

- How do numerical simulations on an arc-scale constrain the location, timing, and magnitudes of volcanic eruptions?
- On the scale of volcanic systems, how does the lithosphere (*e.g.* material properties, stress state, temperature, structure) influence the ability of magma to collect in reservoirs and erupt?
- What is needed to build a model that predicts magmatic arc activity and evolution, and how should it be coupled to models of eruptive processes that would be able to integrate a range of observables?

- How can we best relate the large spatial and temporal scales of subduction zones and subduction zone processes with the monitoring data collected at volcanoes?
- Can we model melt production and transport and couple these, perhaps as "inputs" or boundary conditions, to subvolcanic reservoir and volcanic eruption models?
- Can we relate subduction zone processes with the volatile content of magmas?
- What are the best tools to address the problems, how can they be integrated, and what needs to be developed?

4. **Cyberinfrastructure and modeling needs (webinar series)**

   The operation of the MCS and the success of the RCN and its workshops is fundamentally linked to the availability and development of cyberinfrastructure resources, and making those available to the widest possible subset of the community of subduction zone scientists. These requirements include access to high performance computing platforms, co-development of modeling and data work flows that keep up with expected exascale computing, the scalable modeling tools and algorithms that go with this, training, geo-referenced databases, as well as big data integration, eventually in real time.

   These challenges have faced the community for a while, and experience with EarthCUBE, SCEC, and CIG have shown, for example, that communication and coordination is key. The RCN will therefore sponsor a three year program of webinars (Figure 4) that aim to explore, in partnership with other efforts such as CIG and NASA, how an MCS might be best set up to deal with the demands of the future subduction zone science community.

   We seek to pursue this important discussion by webinars and virtual meetings to ensure the widest possible community is engaged. Two members of the steering committee will be in charge of being a liaison to CIG and EarthCUBE, as well as NSF and NASA sponsored high performance modeling efforts, data centers, and modeling frameworks. Webinars will be scheduled in sync with the in person workshops, and the wrap-up workshop will prominently feature the extensive discussion of cyberinfrastructure components of the MCS.

   Issues to be discussed include:

   - Do we have the software tools available or under development to address the multiscale, multiphysics problems that need to be tackled?
   - What are the best practices to empower a diverse community of scientists to use cutting-edge hardware?
   - What are the database infrastructures and frameworks that we can rely on to build structural models, and access those structural models from physics-based modeling?

- How could an MCS best interface with efforts at other community cyberinfrastructure hubs?

Workshop 1 and the webinar series seek to bring scientists from the volcano and earthquake communities together, and workshops 2 and 3 seek to foster new scientific interactions with focus on, but not limited to, each community which themselves consist of a number of disciplines.

Wrap up meeting: Recommendations for an MCS implementation

This meeting is charged with summarizing the lessons learned from the RCN activities, and arrive at a recommendation for the community for the establishment of an MCS, and which shape an MCS proposal might have. In the run up, we will solicit input from the community via white papers and comments on previous workshop reports. The meeting proceedings will be web cast to allow virtual participation. The questions to be addressed include:

- Which stakeholders should an MCS serve, and is it added value to subduction zone science?
- Should the MCS attempt to capture both the earthquake and volcano system?
- How should an MCS interact with other community organizations, and how can the MCS serve its national and international role and potential?
- What cyberinfrastructure is needed to begin model building, integrate sub-domain models, and eventually allow interfacing with observatory data streams?
- What tools do we need to develop systems-level models capable of making hazard-relevant predictions that include uncertainty quantification, parameter sensitivity testing, and regional realism sufficient to guide experimental design?

A report writing committee will be formed, consisting of the steering committee and other members of the community. Lessons learned from the RCN will be compiled in a 15 page white paper. The report will go out for comments to the community, and after it is finalized and web published, a two page summary will be submitted to *Eos*. Should the community be at this stage, we will initiate the proposal writing process for the *Modeling Collaboratory for Subduction Zone Science* toward the end of the funding period.

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