Solid Earth - hydrosphere modeling infrastructure

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Program: Strategic Initiative

Project Objective:

To build a modeling infrastructure that can use remote sensing and ground-based data to evaluate solid Earth processes (earthquakes, faults, and volcano dynamics) and how they respond to hydrosphere forcings.

Our specific objectives are to build solid Earth modeling and data assimilation tools to:

1. Constrain dynamic models of fault and volcanic systems with quantifiable uncertainties using time-varying surface deformation, hydrosphere loading on global to regional scales as constraints.
2. Quantify the observational requirements for future mission concepts to further reduce uncertainties in key earthquake and volcano dynamic process parameters.

This effort will (Figure 1):

- contribute to Linkages in the Earth System, focusing on solid Earth – hydrology interactions.
- enhance our ability to study earthquake and volcano sources and Earth structure constrained by surface deformation observations (GNSS, InSAR), and mass loading observations (GRACE, GRACE-FO)
- implement dynamic fault (Figure 2) and volcano system modeling (Figure 3) that will enable us to explore the forcings due to the hydrosphere to better understand these systems' dynamics and forecast their evolution.

FY19 Results:

The original high-level task plan has been adhered to and completed for FY19:

- *Develop the kinematic fault/volcano modeling capability to include hydrosphere forcings through a boundary element method (BEM) approach:* We have tested the dislocation boundary element method (BEM) software *cutanddisplace* (Davis, 2017; Figure 3), available from GitHub. The ISSM computation of internal Earth deformation and stress changes was implemented to produce stress calculations due to hydrosphere load changes that can be applied as source boundary tractions in CutAndDisplace BEM models for fault slip or magma reservoir pressure.
- *Prototype the quasi-dynamical BEM fault modeling code QDYN and add external forcings:* The QDYN software was tested and implemented first in 2.5-dimensions for fault transient slip and earthquake cycle modeling with and without external forcing from the hydrosphere. A 3D geometry version has now been tested and arbitrary spatial time-varying loads are the next step in its model development. A manuscript partially supported by this initiative has been published: Luo and Liu (2019a) (Figure 2), with another in press (Luo and Liu, 2019b).
- *Develop dynamic volcano model core capabilities including computation of surface deformation and volume flux in terms of magma input flow rate, chamber geometry and pressure change, density, conduit dimensions and magma properties, shallow reservoirs, surface gas and mass flux:* Volcano modeling development continued from Year 1 kinematic source inversion with AlTar. First, the original point (Mogi) and ellipsoidal cavity models in AlTar were optimized, with a manuscript enabled by the AlTar development in preparation. The volcano dynamic model prototypes have been written in Python and tested.
- *Implement an AlTar Bayesian analysis with dynamic models to estimate model parameter uncertainties and forecast time-varying evolution:* AlTar implementation of the volcano dynamic model is in progress. The Python dynamic model for tiered and single magma reservoirs have been written in C++ for higher performance.

Benefits to NASA and JPL (or significance of results):

Capability significance: There are two primary innovative features to this proposal: the first lies in the integration of the global loading capability with the kinematic fault-slip and volcano modeling. Currently global loading is modeled within the ISSM-SESAW framework, and is being improved through a parallel initiative led by Dr. Adhikari. The second lies in the development of dynamic fault-slip and dynamic volcano models and their integration with ISSM-SESAW. The quasi-dynamic rate and state friction fault mechanical code QDYN was developed at Caltech and will be a new capability for JPL. Its integration with ISSM-SESAW will allow JPL to examine fault and earthquake cycle processes in combination with time varying hydrosphere processes. Dynamic volcano models are currently used by only a few research groups, and through this initiative we bring that capability to JPL and link it with earthquake and hydrosphere processes.

Strategic significance: This proposed development will establish JPL in a leading position to perform cutting edge science with the future NISAR and GRACE-FO observations and to perform Observing System Simulation Experiments (OSSEs) to drive future mission formulation. It will also allow us to simulate future mission observations such as high-resolution topography of fault-zones for fault processes, and topography change and hyperspectral gas observations to constrain volcano dynamics. The integrated hydrosphere-solid Earth modeling capability will enhance JPL's ability to study coupled system processes and their interactions (e.g. groundwater reduction and seismicity; earthquake-volcano coupling) and will allow the JPL/Caltech ARIA project to implement higher level earthquake and volcano models constrained by InSAR and GNSS time series with data and model UQ.

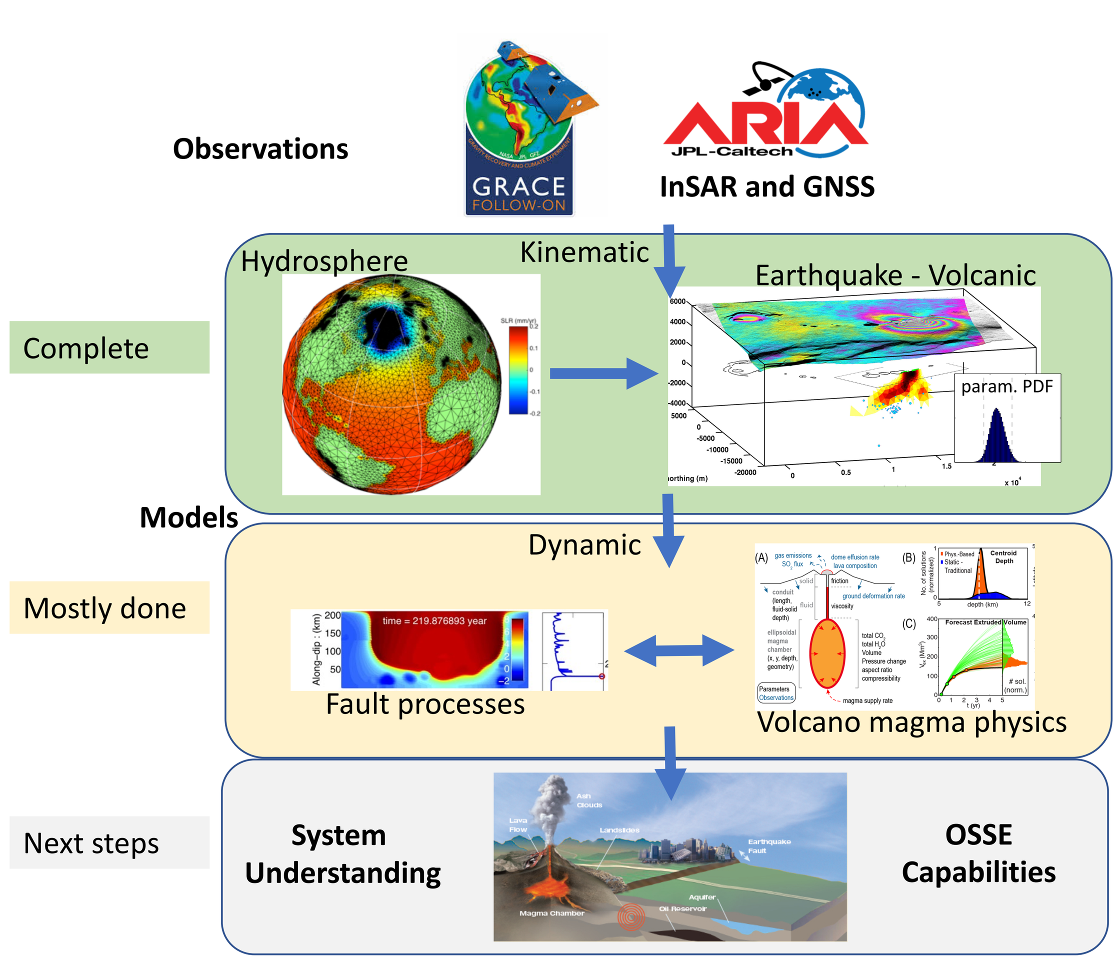

Figure 1. Solid Earth-Hydrosphere SRTD links primary space geodetic observations (top), with modeling linking hydrosphere (left;), fault slip, and volcano source kinematic and dynamic models. Blue arrows indicate connections between data, models, and understanding.

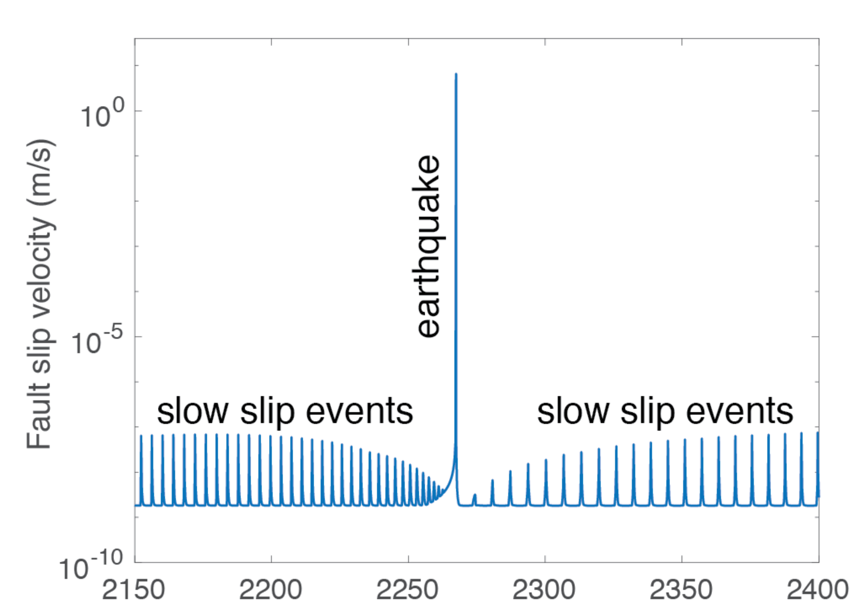

Figure 2. QDYN simulations show slow slip events slip more slowly and shorten their repeat times before major earthquakes. This has implications for fault mechanics and for forecasting system behavior for subduction zone earthquakes. (Luo and Liu, 2019a).

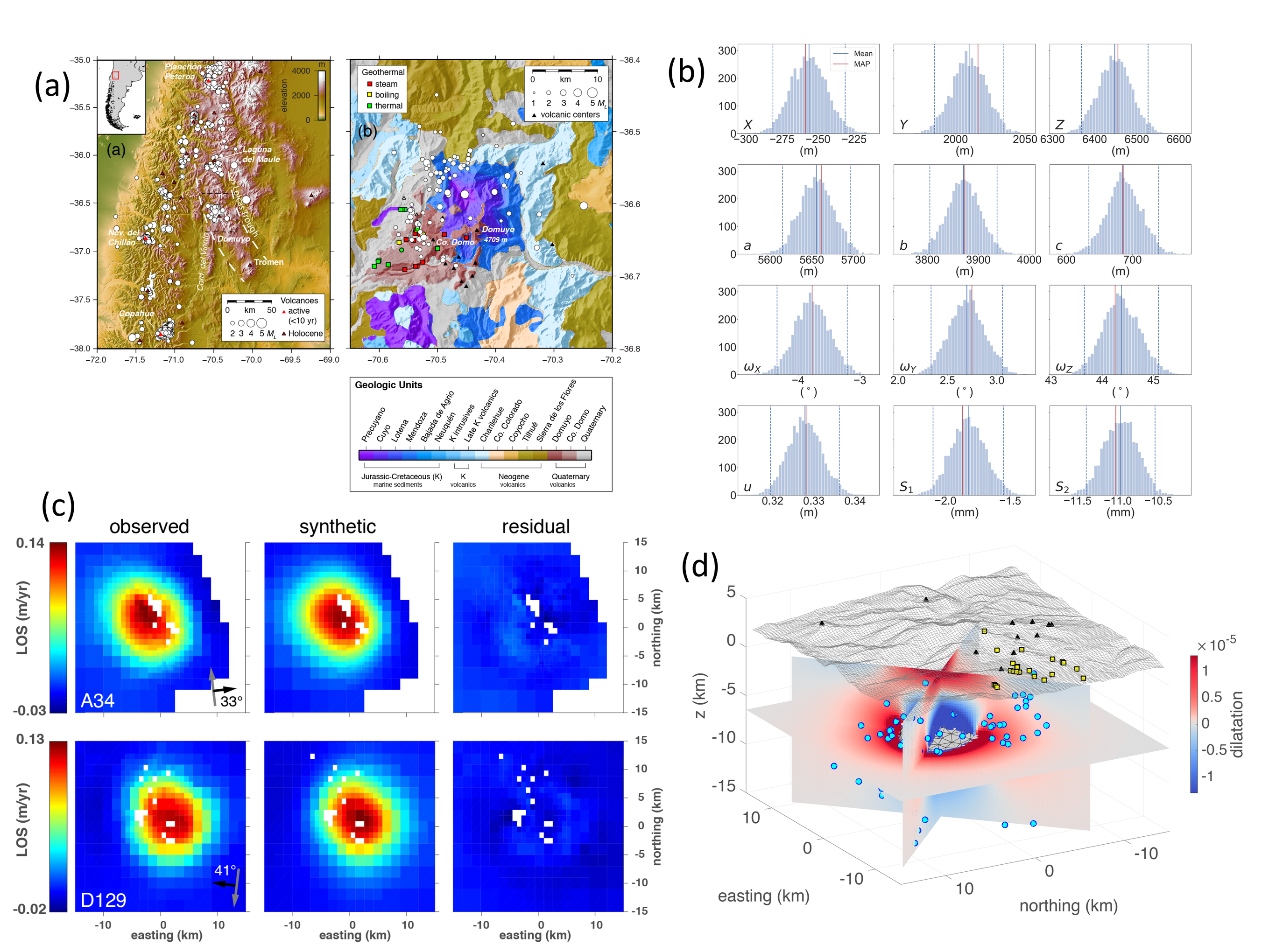

Figure 3. The AlTar Bayesian software developed in this initiative was applied to modeling the ALOS-2 (JAXA) measured inflation for the ongoing unrest at Domuyo volcano, Argentina (a). AlTar generates a posteriori model parameter distributions (b), in this case using the Compound Dislocation Model (CDM; Nikkhoo et al., 2017). (c) Comparison of the observed, model predicted, and residual line-of-sight (LOS) surface velocities (2015-2019). (d) Applied *cutanddisplace* (Davis, 2017) BEM model for the derived model parameters (b) allows computation of the dilatational strain, showing agreement between positive dilatation, observed seismicity, and possible magmatic gas pathways to the hydrothermal system (Lundgren et al., submitted).

Publications (contributed to by project):

Luo, Y., & Liu, Z. (2019a). Slow-slip recurrent pattern changes: Perturbation responding and possible scenarios of precursor toward a megathrust earthquake. Geochemistry, Geophysics, Geosystems, 20. https://doi.org/10.1029/2018GC008021.

Luo, Y., & Liu, Z. (2019b). Rate-and-state Model Casts New Insight into Episodic Tremor and 4 Slow-slip Variability in Cascadia. Geophys. Res. Lett., in press.

Lundgren, P., T. Girona, M.G. Bato, V. Realmuto, S. Samsonov, C. Cardona, L. Franco, E. Gurrola, and M. Aivazis, Dynamics of unrest at a large silicic system: Domuyo volcano, Argentina, submitted.

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References:

Davis, T., 2017. A new open source boundary element code and its application to geological deformation: Exploring stress concentrations around voids and the effects of 3D frictional distributions on fault surfaces (M.Sc thesis. Aberdeen University).

Nikkhoo, M., T. R. Walter, P. R. Lundgren, and P. Prats-Iraola (2017), Compound dislocation models (CDMs) for volcano deformation analysis, Geophys. J. Int., 208, 877-894, doi: 10.1093/gji/ggw427.

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