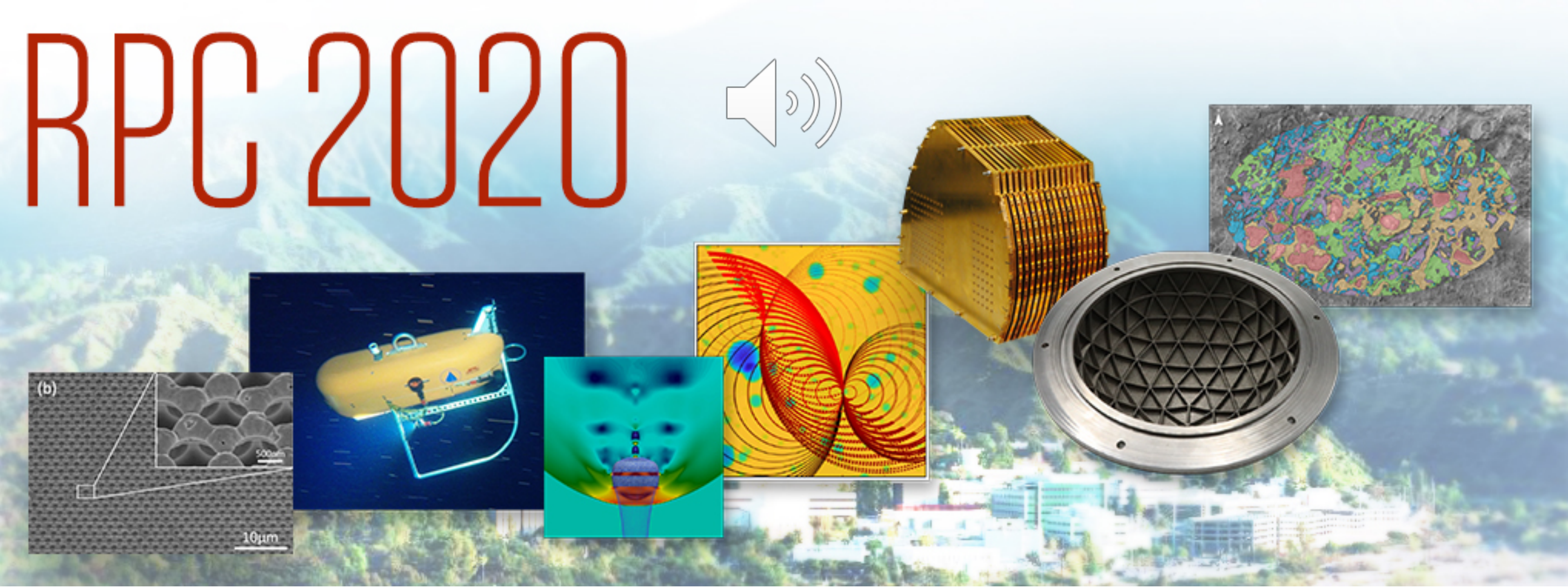

Virtual Research Presentation Conference

Developing a Solid Earth-Hydrosphere Modeling Infrastructure

Principal Investigator: Paul Lundgren (329)
Co-Is: Susan Owen (329), Surendra Adhikari (329), Grace Bato (329), Zhen Liu (329), John Worden (329), Eric Gurrola (334), Michael Aivazis (Parasim Inc.), Yingdi Luo (JIFRESSE, UCLA), Kurt Feigl (U. Wisconsin)
Program: Strategic Initiative

Jet Propulsion Laboratory
California Institute of Technology

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Tutorial Introduction

Abstract

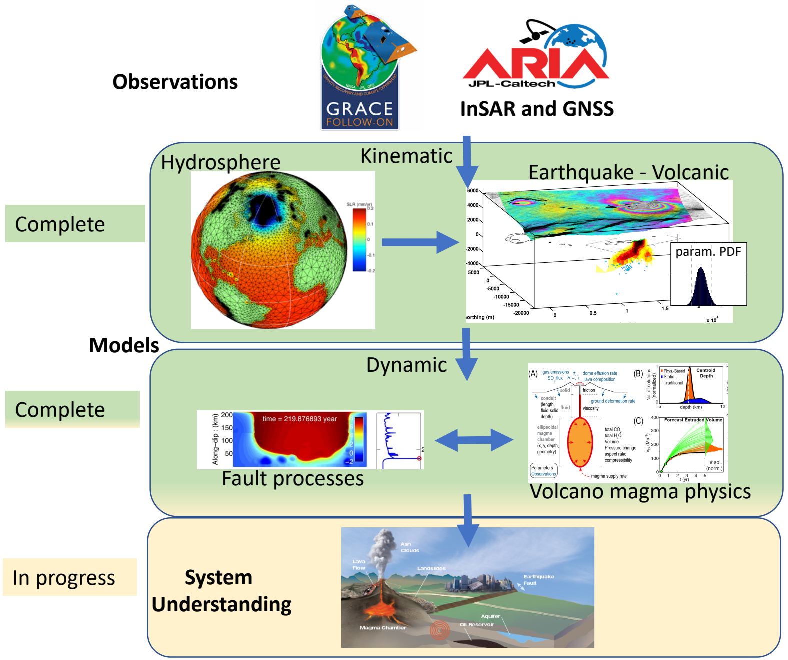
In early 2017 the Earth Science and Technology Directorate identified "Linkages in the Earth System" as an area of strategic importance. This initiative addresses the fundamental theme of Solid Earth (SE)–Hydrosphere (H) Interactions. Developing an integrated SE–H modeling infrastructure represents an untapped opportunity within Earth science for improved understanding and forecasting of earthquakes and volcanic unrest. This infrastructure will:

- Establish JPL as a leader in SE–H linkages,
- Advance decision support products for solid Earth hazards through the Advanced Rapid Imaging and Analysis Project (ARIA)
- Improve JPL's capability to address science questions with future missions (e.g., NISAR, GRACE-FO)

In this Initiative we have enhanced three modeling software packages:

- The Ice-sheet and Sea-level System Model (ISSM) framework that includes Earth rotation, sea level rise, and other surface loads
- Volcano and fault-slip models through AlTar (Bayesian inference code developed at Caltech) with uncertainty quantification (UQ)
- The quasi-dynamic fault slip earthquake cycle modelling code QDYN.

Particular emphases are on enhancing JPL's core capabilities in dynamic modeling of volcanoes and earthquakes and test their sensitivities to external stresses due to hydrosphere or other solid Earth processes.



The SE-H modeling framework combines geodetic data with models of the state and dynamic models to forecast future states of the volcano or fault system with uncertainty quantification

Problem Description

a) **Context:** SE-hydrosphere and SE–SE process interactions are increasingly recognized by the scientific community as important for both process understanding and hazard assessment. Currently there are significant gaps in understanding the interactions of the hydrosphere with solid Earth dynamic processes, such as fault mechanics and volcanic unrest, due to **gaps in our modeling** capabilities. JPL lacks an integrated SE-H modeling capability with 1) kinematic modeling tools for fault-slip/volcano sources with robust uncertainty quantification (UQ) and covariance estimation between model parameters; 2) time-varying fault mechanical and volcano magma dynamical models and associated UQ.

b) **State-of-the-Art:** Our proposed modeling infrastructure linking whole-Earth hydrosphere loading with kinematic and dynamic fault and volcano models represents a state-of-the-art capability for scientific understanding and for informing mission formulation. Currently, to our knowledge, no capability exists that couples hydrosphere changes with both kinematic and dynamic modeling of both fault and volcano systems. Kinematic fault slip and Earth structure modeling with UQ exists elsewhere, for example the AlTar and Classic Slip Inversion (CSI) developed at Caltech, but have not been widely used at JPL nor have they been integrated into hydrosphere loading models such as ISSM-SESAW.

c) **Relevance to NASA and JPL:** The modeling infrastructure will be used to formulate quantitative requirements for Earth Ventures missions, including Earth Ventures Suborbital concepts on fault mechanics and volcano system dynamics and Earth Ventures Mission concepts on volcano system dynamics, and Decadal Survey missions, including mission architectures for the Surface Deformation and Change Targeted Observable. This work will position JPL for competitive ROSES calls in the Earth Surface and Interior, NISAR Science Team and Applications programs (with USGS, FEMA, CA state agency partners).

Methodology

a) **Modeling:** We will achieve our goals through two main modeling thrusts: 1) integrating kinematic fault and volcano source models with the global solid Earth (ISSM-SESAW) model, including an improved ability to quantify uncertainties in source and Earth structure parameters. 2) integrating ISSM forces with dynamic fault and volcano models. Key steps include: 1) enhance ISSM to model stresses and strains within the entire solid Earth; 2) extend the AlTar software to model first kinematic volcano source models and then dynamic fluid-mechanical volcano models; 3) expand the QDYN earthquake cycle modeling software to 3-D and include time varying external forces.

b) **Innovation:** 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.

Results

a) Accomplishments first 3 years:

- Hydrosphere loading stress computation capability added to the JPL ice-sheet sea-level model (ISSM)
- Implemented volcano kinematic and dynamic modeling capability (AlTar)
- Implemented quasi-dynamic fault capability (Qdyn) coupled with hydrosphere loading
- Publications: Seven papers: published (3), in review (1), or in preparation (3).

b) Significance

- We can now link hydrosphere (e.g. precipitation, snow, GRACE water mass) loading to fault and volcanic dynamic behavior
- We can compute magma flow during an eruption and provide information to volcano observatories (see 2020 Taal eruption example)
- Dynamic volcano models can predict volcano behavior with uncertainty
- We can simulate earthquake fault-slip dynamics and the effects of hydrosphere loading on slow-slip earthquake events (see Cascadia, USA, episodic slow-slip example)

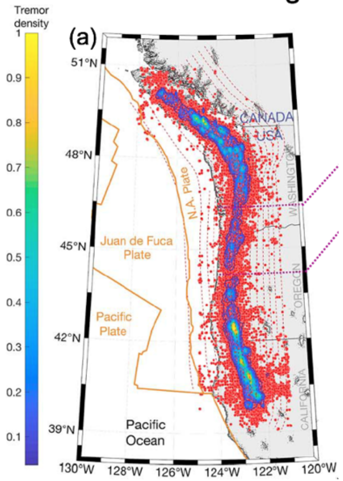
c) Next steps

- Expand NASA Ames HEC testing of the AlTar dynamic volcano modeling
- Add flexibility to the AlTar volcano kinematic modeling to handle multiple sources
- Explore multiphase magma volcano models with volatile diffusion to understand thermal – surface deformation linkages using COMSOL

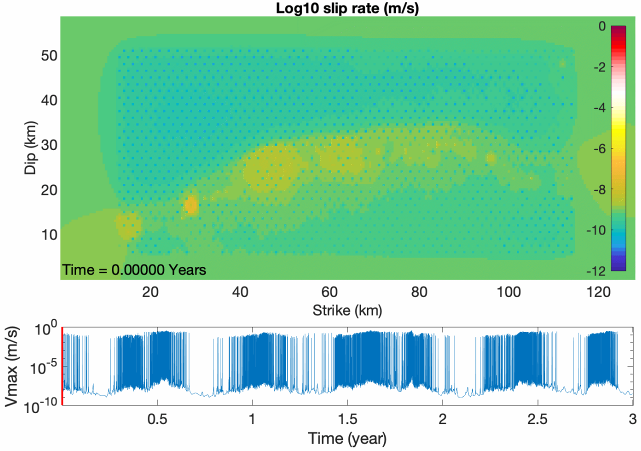
Results

Hydrosphere forcing perturbs slow-slip earthquakes

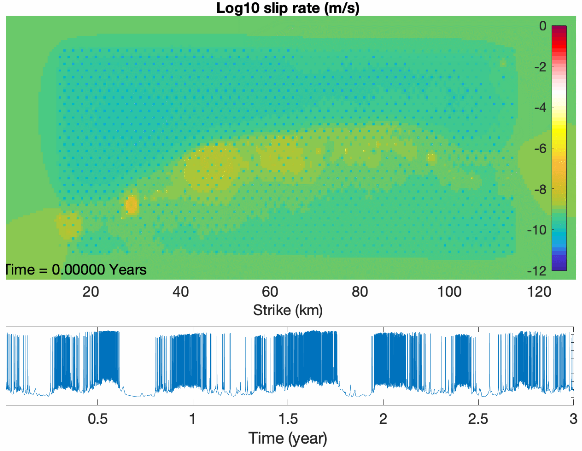
Observed seismic signals



Reference Model



With Hydrological Loading

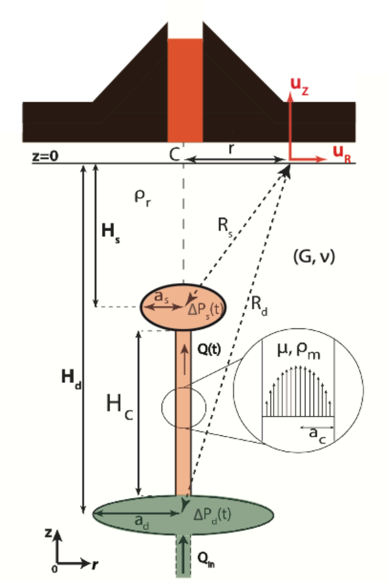


QDYN simulations illustrate the effects of hydrological loads for Cascadia (far left). The model with hydrological loading (far right) shows changes in the timing and clustering of slow-slip events relative to the reference model (center). Work by Y. Luo, Z. Liu, & S. Adhikari.

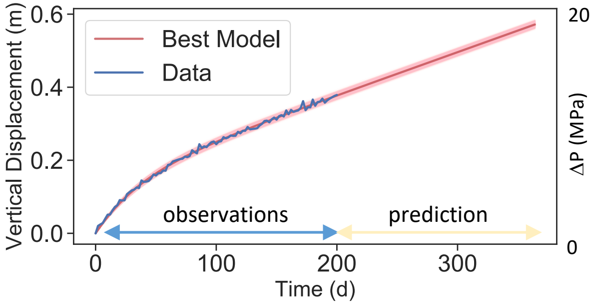
Results

Volcanic system forecasting using geodetic time series

Dynamical volcano models compute parameters over time and their uncertainties

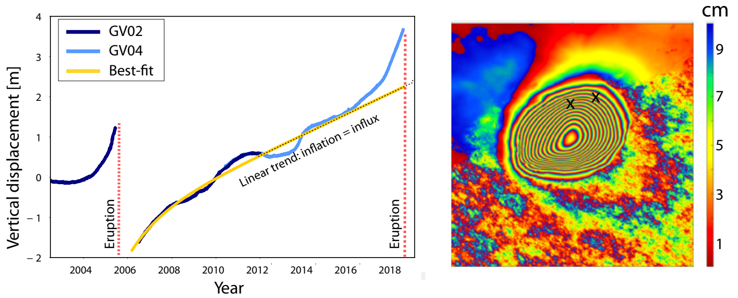


Fluid-mechanical analytical model modified after *Reverso et al.* (2014)



AITar now includes a volcano dynamical model. Model (red) can fit displacement data (blue) and predict future parameter changes, such as magma chamber overpressure (ΔP) and forecast when pressure might exceed a failure pressure.

Next: Application to Sierra Negra, Galapagos
Dynamic models can predict volcano behavior and eruptions



Sierra Negra volcano eruption cycle example. (left) GPS time series and dynamic model estimate. (right) InSAR map of surface displacements. The application of the dynamic model with the AITar Bayesian inference estimates parameters and predicts model evolution, including key parameters such as chamber overpressure and time to possible eruption.

Reference: Reverso, T., Vandemeulebrouck, J., Jouanne, et al. (2014). A two-magma chamber model as a source of deformation at Grímsvötn Volcano, Iceland. Journal of Geophysical Research: Solid Earth, 119(6), 4666-4683.

Publications

Publications:

Luo, Y., and Z. Liu, 2019, 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., and Z. Liu, 2019, Rate-and-state Model Casts New Insight into Episodic Tremor and Slow-slip Variability in Cascadia, *Geophysical Research Letters, 46*, 6352–6362. https://doi.org/10.1029/ 2019GL082694.

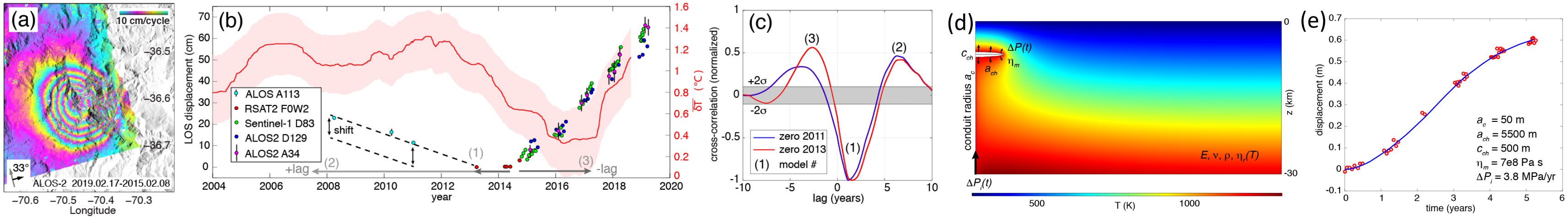
Lundgren, P., T. Girona, M. G. Bato, V. Realmuto, S. Samsonov, C. Cardona, L. Franco, E. Gurrola, and M. Aivazis (2020), The dynamics of large silicic systems from satellite remote sensing observations: the intriguing case of Domuyo volcano, Argentina, *Scientific Reports, 10*, 11642. https://doi.org/10.1038/s41598-020-67982-8.

Bato, M. G., P. Lundgren, V. Pinel, R.. Solidum, A. Daag, and M. Cahulogan, The 2020 eruption and the mega dike emplacement at Taal volcano, Philippines: Insights from satellite radar data, *Geophys. Res. Lett.*, submitted.

Adhikari, S., L. Caron, E.R. Ivins, S.A. Khan, J. Nilsson, G.A. Milne, K.K. Kjeldsen, E. Larour, A.S. Gardner (2019), Ongoing solid-Earth response to historical Greenland mass loss, in preparation.

Adhikari, S., L. Caron, E.R. Ivins, E. Larour, M. Poinelli, P. Lundgren, 2019: Computation of high-resolution planetary interior displacement and stress fields in the ISSM framework, in preparation.

Bato, M. G., M. Bagnardi, A. Roman, and P. Lundgren, Source dynamics of Sierra Negra volcano, Galapagos Islands 2005-2018, in preparation.



Domuyo volcano, Argentina example: InSAR spatial pattern (a) was used to solve for the shallow (6.5 km depth) magma reservoir. Temporal shifts between the thermal and InSAR time series (b) suggests competing physical models depending on their relative shift (c) (*Lundgren et al.*, 2020). Ongoing numerical modeling of magma flow through a deep conduit into a shallow reservoir (d) fits the observed InSAR time series for physically reasonable material properties. **Future work** will build on our work to **estimate** and **forecast** dynamic model parameters with UQ.