Developing a solid Earth-hydrosphere modeling infrastructure for science and mission formulation

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Objectives

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

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

These objectives will link capabilities in whole Earth hydrosphere modeling with earthquake and volcano kinematic and dynamic models with uncertainty quantification considerations for the first time. These modeling capabilities allow addressing hydrosphere-solid Earth fault and volcano processes over broad spatial scales and over time scales from decades to days as needed for highly dynamic processes (such as fault slip and volcanic unrest) that may be affected by other forces, such as inter-annual hydrological changes. Consequently, this will provide JPL and Caltech with the capability to advance Solid Earth / Hydrosphere science using current data sets, and evaluate measurement strategies that could resolve these hypotheses.

Background

The Earth Science and Technology Directorate addresses science and technology across a broad range of Earth Science disciplines, with long-standing expertise in atmospheric physics, atmospheric chemistry, oceanography and solid Earth sciences. In early 2017 the Directorate identified “Linkages in the Earth System” as an area of strategic importance. This initiative addresses the fundamental theme of Solid Earth (SE)–Hydrosphere Interactions. Developing an integrated SE–hydrosphere 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–hydrosphere linkages, improve JPL’s capability to address science questions with future missions (e.g., NISAR, GRACE-FO), and advance the quality of our decision support products for solid Earth hazards through the Advanced Rapid Imaging and Analysis Project (ARIA).

Approach and Results

Approach: We followed two primary modeling development thrusts: 1) integrating kinematic fault and volcano source models with the global solid Earth (ISSM) model, including an improved ability to quantify uncertainties in source and Earth structure parameters. 2) developing dynamic fault and volcano models towards eventual integration with the ISSM framework.

Key steps are:

- Extend the Caltech-developed AlTar simulated annealing-Bayesian inference [1] modeling software to simple analytical volcano pressure-volume sources.
- Develop the quasi-dynamic rate and state friction fault model Qdyn for earthquake simulations. Qdyn modeling will be used to examine evolution of fault slip for both earthquake cycle and slow-slip events with hydrologic loads.
- Develop volcano fluid and continuum mechanical dynamic models and integrate them within the AlTar modeling software..
- Apply both kinematic volcano modeling to test case volcanic eruption response.
- Test different observing scenarios, addressing key questions for fault and volcano systems: 1) examine regional hydrosphere loading on transient fault slip and surface deformation; 2) test the ability to forecast volcano system dynamics with synthetic InSAR observations.

Results:

- Quasi-dynamic (QDYN) fault slip/earthquake cycle modeling was partially supported. Published work [2, 3] included periodic hydrosphere forcing to test model sensitivity of the earthquake fault slow-slip events to periodic and other time-varying loads (Figure 1).
- Dynamic volcano models were implemented in AlTar. This was first tested on local computers and then installed on the AMES HEC computer systems (Figure 2).
- Application of volcano kinematic modeling to a volcano response (Taal Volcano eruption, January 2020) in quasi-real-time [4].
- Based on volcano kinematic modeling with AlTar [5], we developed volcano dynamic models combining coupled fluid-solid mechanics using COMSOL Multiphysics (Figure 3).
- ISSM applied to groundwater induced uplift and fault stressing (Figure 4).

• Significance/Benefits to JPL and NASA

- Goal of development is to establish JPL in a leading position to perform cutting edge science with the future NISAR and GRACE-FO mission observations and to perform simulations to drive future mission formulation (e.g. STV - Surface Topography Vegetation). 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 allow researchers and projects to implement higher level earthquake and volcano models constrained by InSAR and GNSS time series with data and model uncertainty quantification.

Publications

A. Bato, M. G., Lundgren, P., Pinel, V., Solidum, R., Daag, A., & Cahulogan, M. (2021). The 2020 eruption and large lateral dike emplacement at Taal volcano, Philippines: Insights from satellite radar data. Geophysical Research Letters, 48, e2021GL092803.

B. 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.

C. 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.

D. 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.

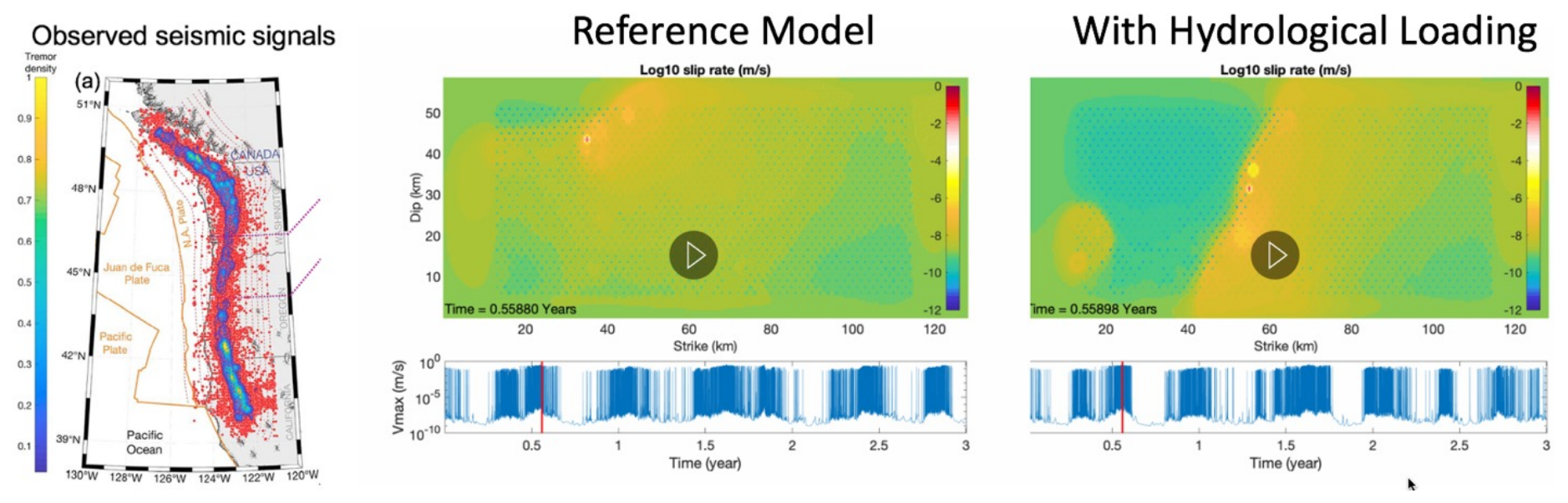

Figure 1. (*a*) Episodic tremor density (Luo and Liu, GRL, 2019). (*center and right*) QDYN simulations illustrate the effects of hydrological loads for Cascadia (far left). The model with hydrological loading (far right) shows changes in the timing and clustering of slow-slip events relative to the reference model (center). Work by Y. Luo, Z. Liu, & S. Adhikari.

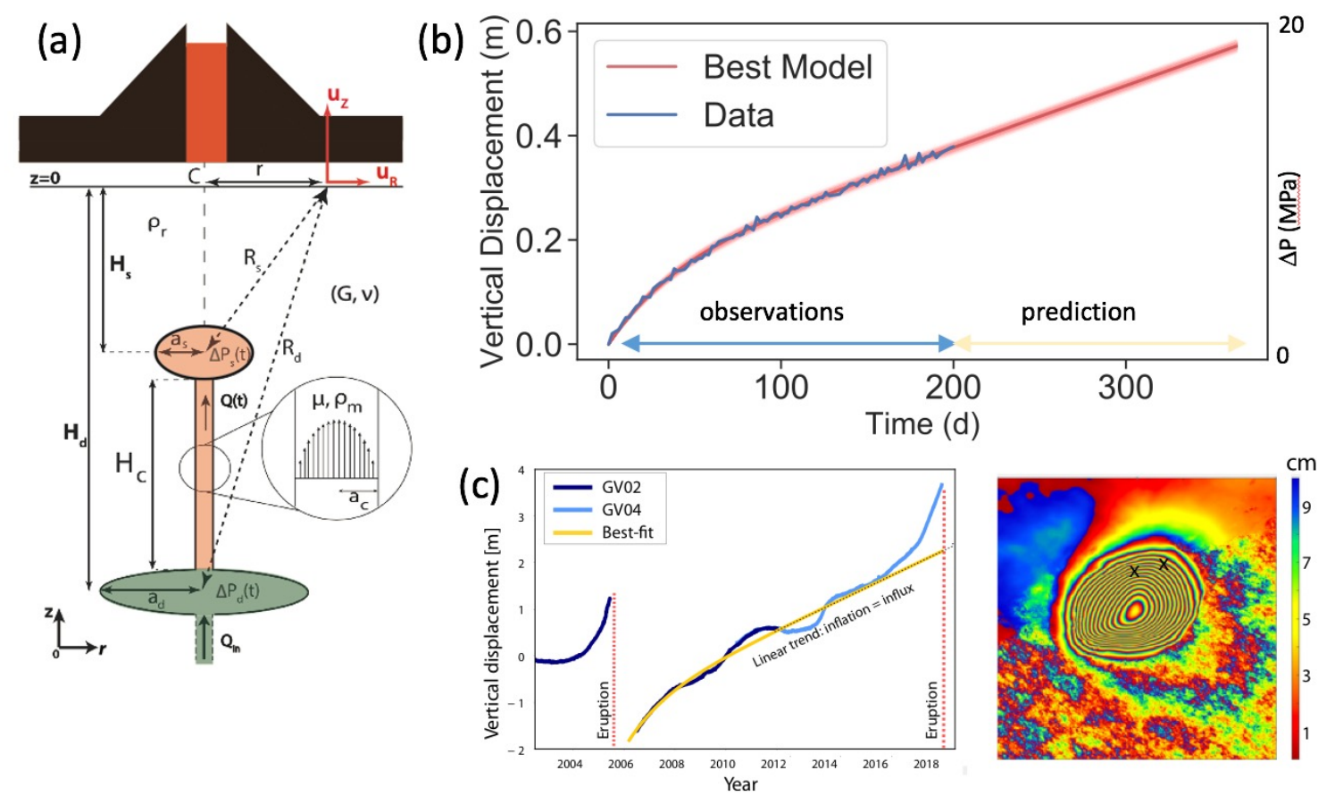

Figure 2. Volcano dynamic modeling example. (a) Fluid mechanical analytical solution after Reverso et al. (2014). (b) SRTD implemented AlTar example based on simulated vertical displacement time series representing reinflation of a shallow magma reservoir following a volcanic eruption. Over the time interval of the data the dynamic model parameters fit the data with model UQ and can also predict future behavior, both expected displacement which is proportional to over pressure (dP) in the reservoir, which might inform predictions of future eruption. (c) Future work will apply this to an actual eruption sequence at Sierra Negra volcano, Galapagos.

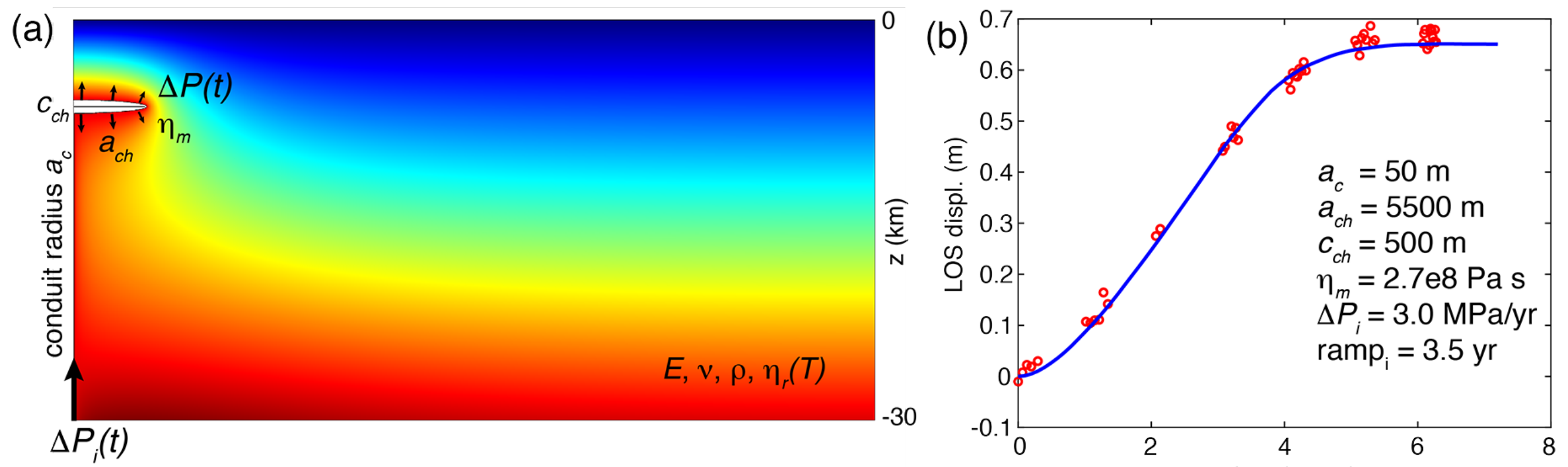

Figure 3. (a) Magma flow into shallow reservoir surrounded by a viscoelastic crust with a temperature dependent rheology. (b) Model time series of uplift (blue) compared to that observed at Domuyo volcano (red circles). Time-predictive, model can be used for system forecasting.

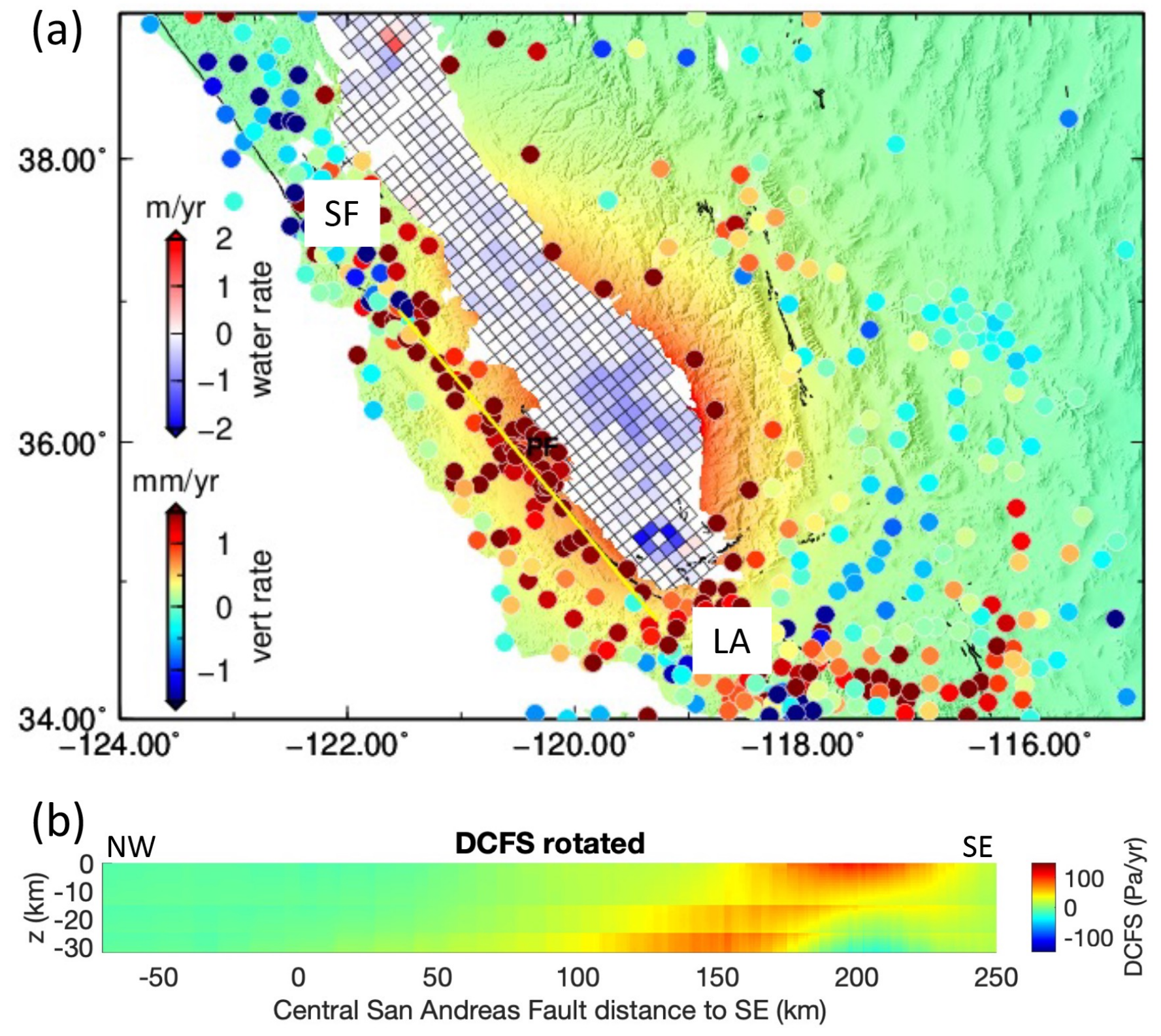

Figure 4. (a) Groundwater storage change loading (water thickness rate equivalent, m/yr) and resulting ISSM vertical (uplift rate, mm/yr). (b) Change in Coulomb fault stress (DCFS) rate (Pa/yr) over the upper 30 km of the central San Andreas fault (CSAF) based on the ISSM modeled stresses. Modeling using ISSM by S. Adhikari based on CV water loading estimates [6].

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4. Bato, M. G., Lundgren, P., Pinel, V., Solidum, R., Daag, A., & Cahulogan, M. (2021). The 2020 eruption and large lateral dike emplacement at Taal volcano, Philippines: Insights from satellite radar data. Geophysical Research Letters, 48, e2021GL092803.
5. 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.
6. Lundgren, P., Z. Liu, and T. Ali, San Andreas fault stress change due to groundwater withdrawal in California’s Central Valley, 1860-2010, Geophysical Research Letters, submitted.

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