Numerical Modeling in Subduction Zone Science

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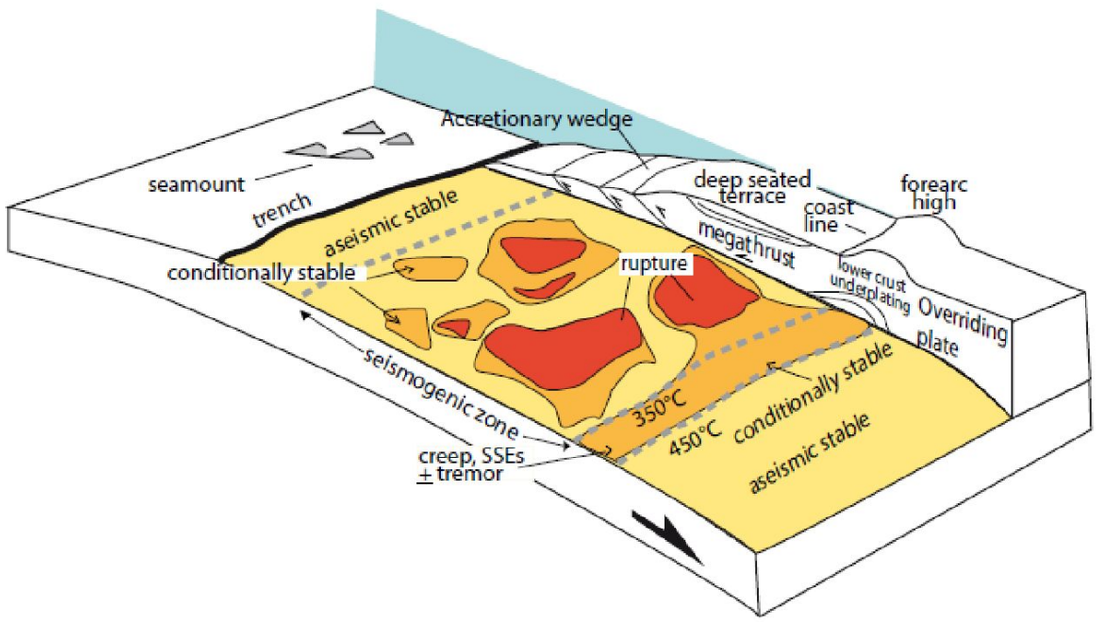
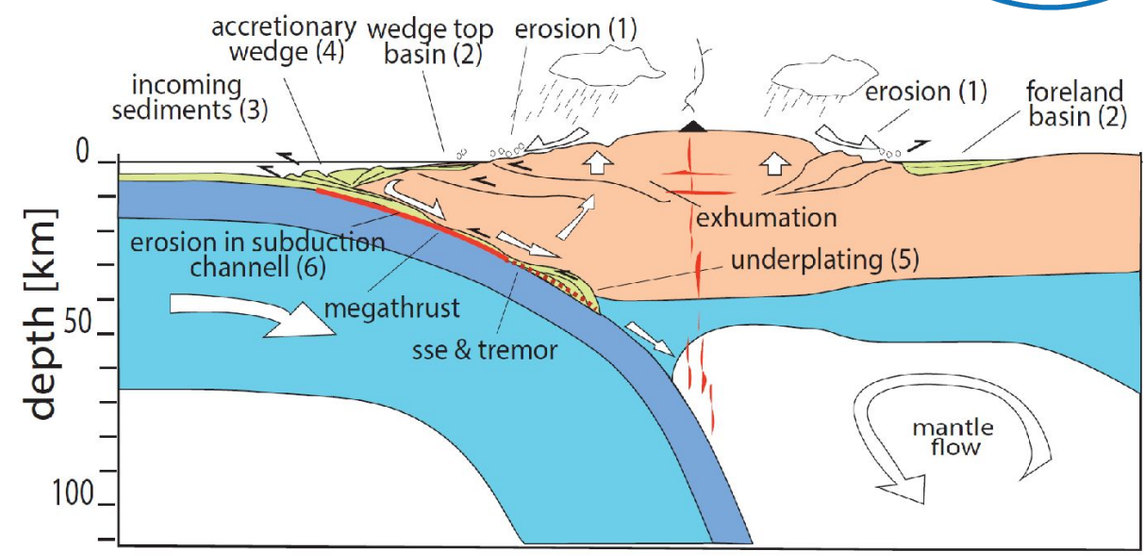
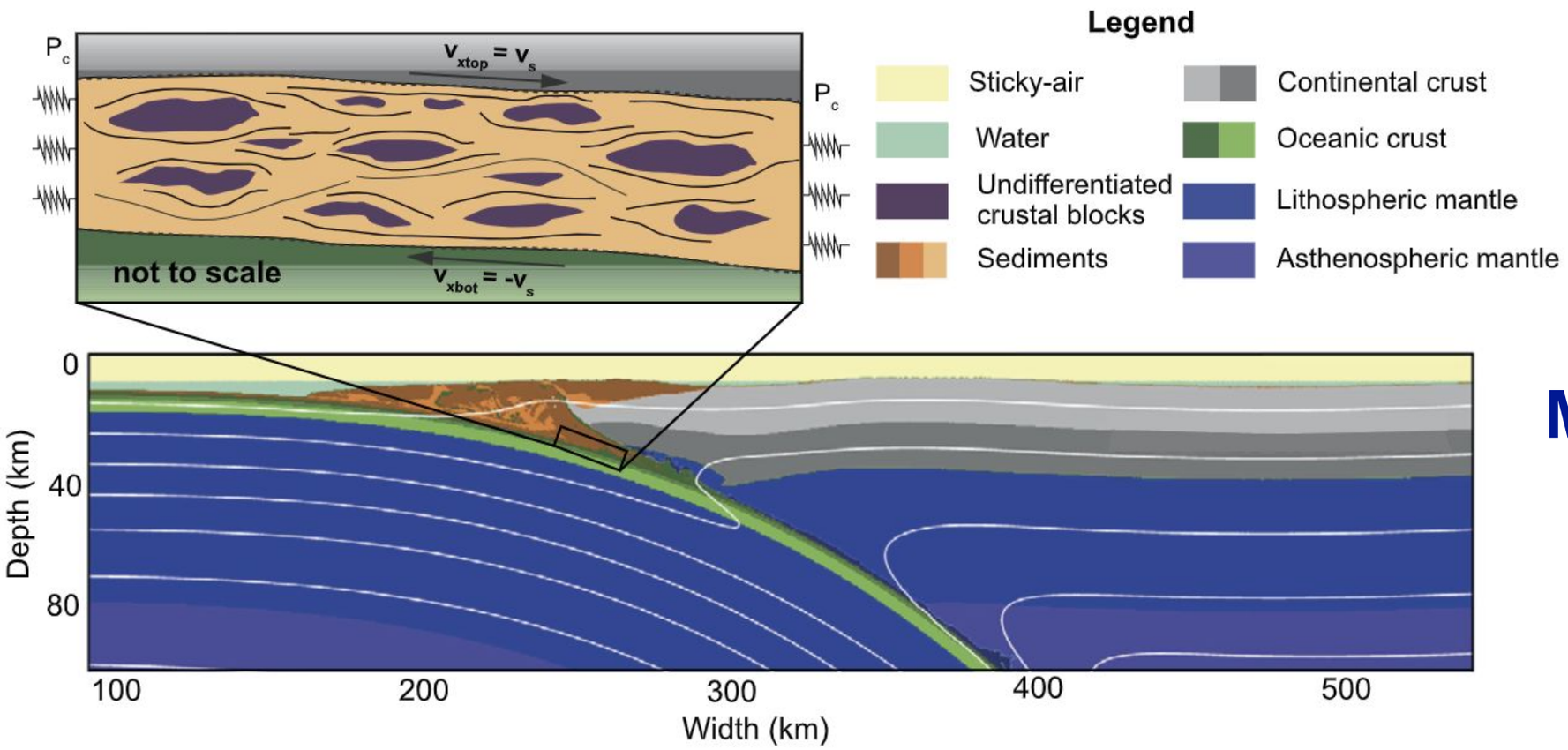
MCS RCN



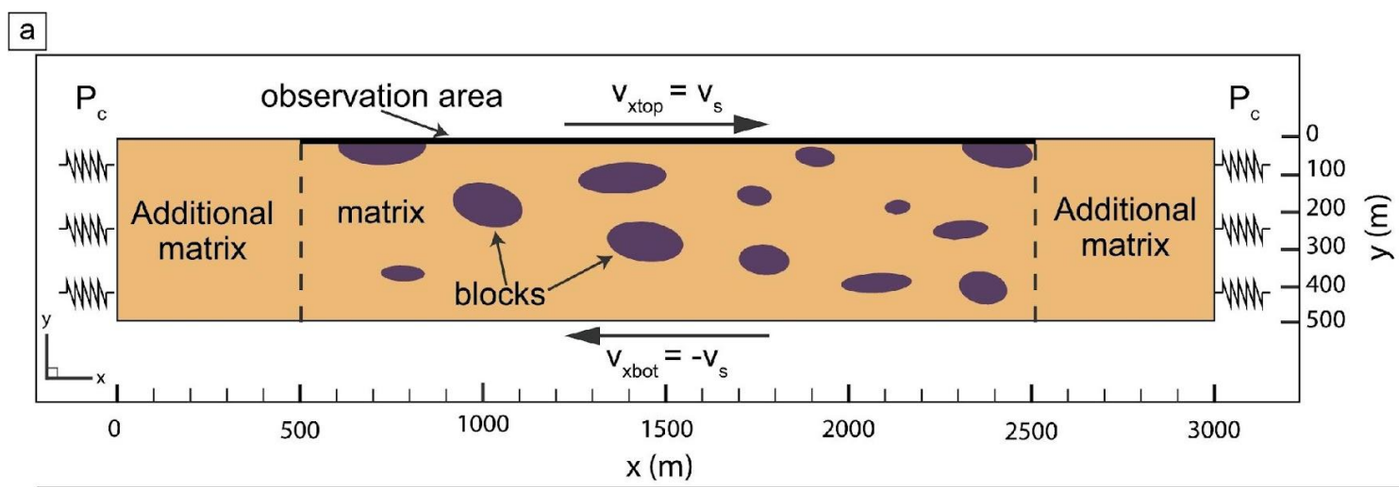


- How do we construct models that link subduction zone state and margin evolution to the forecasting of events?
- How can we best integrate observational constraints into models, and use models to define optimal observational strategies?
- How can we build physics-based, predictive models for volcano, earthquake, and geomorphic systems that couple across time and space?

What are models and how do we use them?



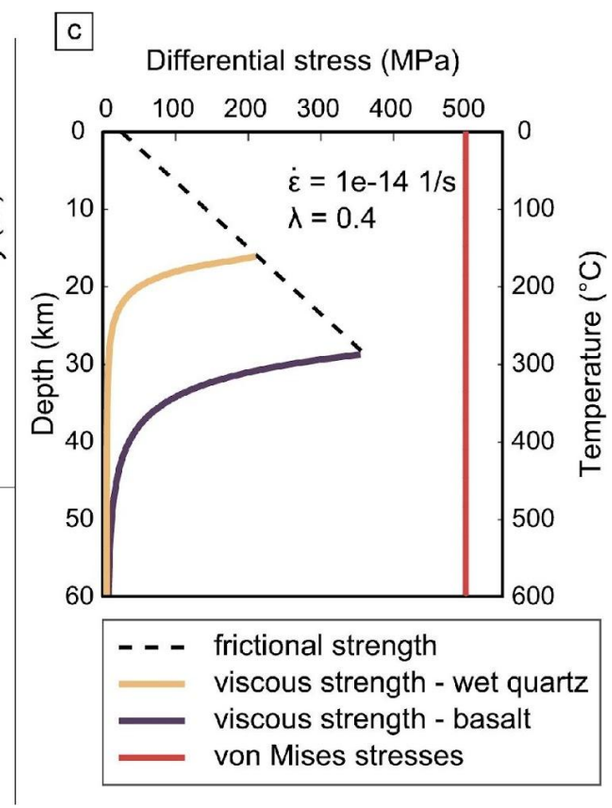
Models are idealized representations of natural systems



b

Dislocation creep parameters used.

Material	A ($MPa^{-n}s^{-1}$)	n	Q (kJ/mol)	Reference
Wet quartz (matrix)	3.2e-4	2.3	154	Ranalli, 1997
Basalt (blocks)	1.0e-4	3.5	250	Hacker & Christie, 1990



Ioannidi et al. [2021]

What are models and how do we use them?

Physics-based models:

Conservation Laws

$$\partial_k v_k = 0 \quad \textbf{(Mass)}$$

$$\partial_j \sigma'_{ij} - \partial_i P + \rho g = 0 \quad \textbf{(Momentum)}$$

$$\frac{\partial T}{\partial t} + v\nabla T = \nabla \cdot \left(\kappa \nabla T\right) + H \quad \textbf{(Energy)}$$

+

Constitutive Laws

$$\dot{\varepsilon}_{ij} = \underbrace{\frac{1}{2G}\frac{D\sigma_{ij}}{Dt}}_{\text{ELASTIC}} + \underbrace{\frac{1}{2\eta}\sigma_{ij}}_{\text{VISCOUS}}$$

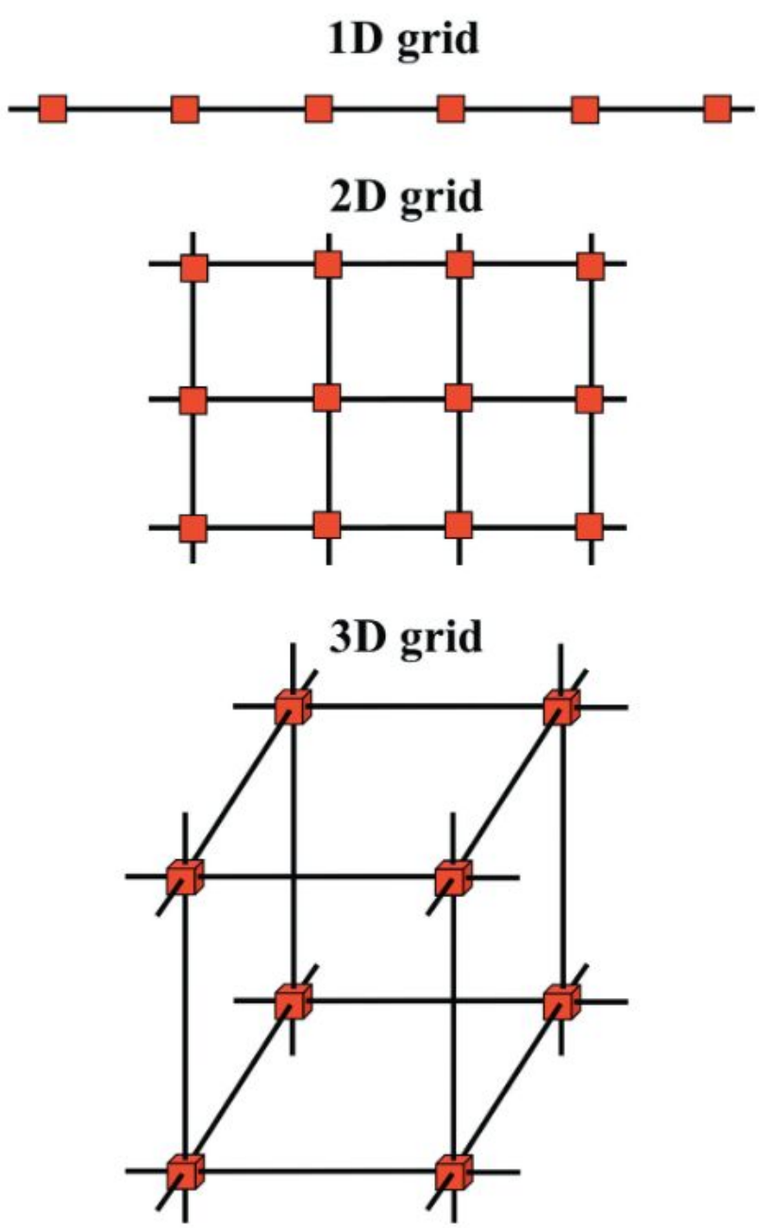
$$\eta = A^{-\frac{1}{n}} \dot{\epsilon}_{II}^{\frac{1-n}{n}} e^{\frac{E}{nRT}}$$

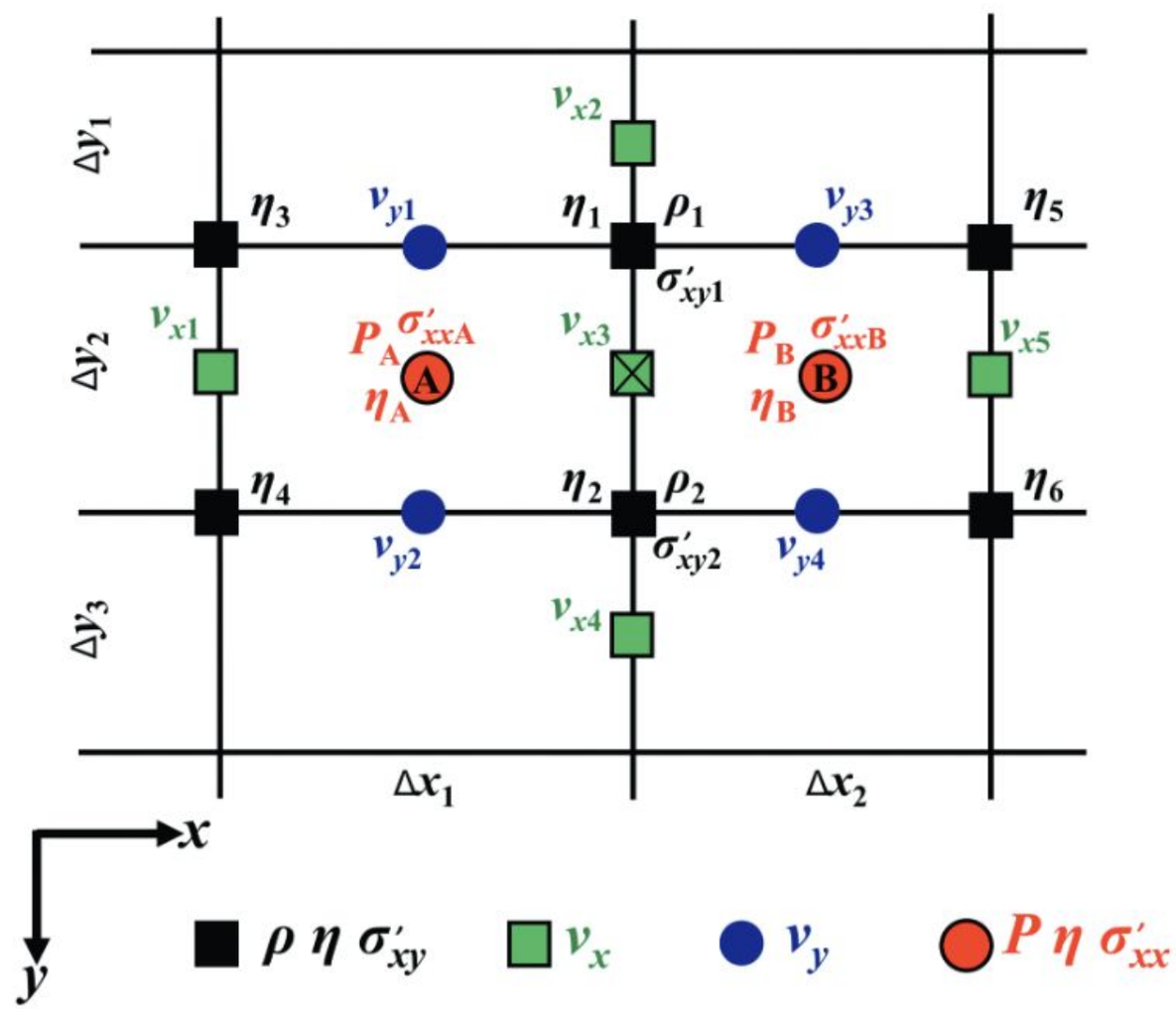
(Non-linear viscosity law + elasticity + plasticity)

What are models and how do we use them?

Physics-based models:

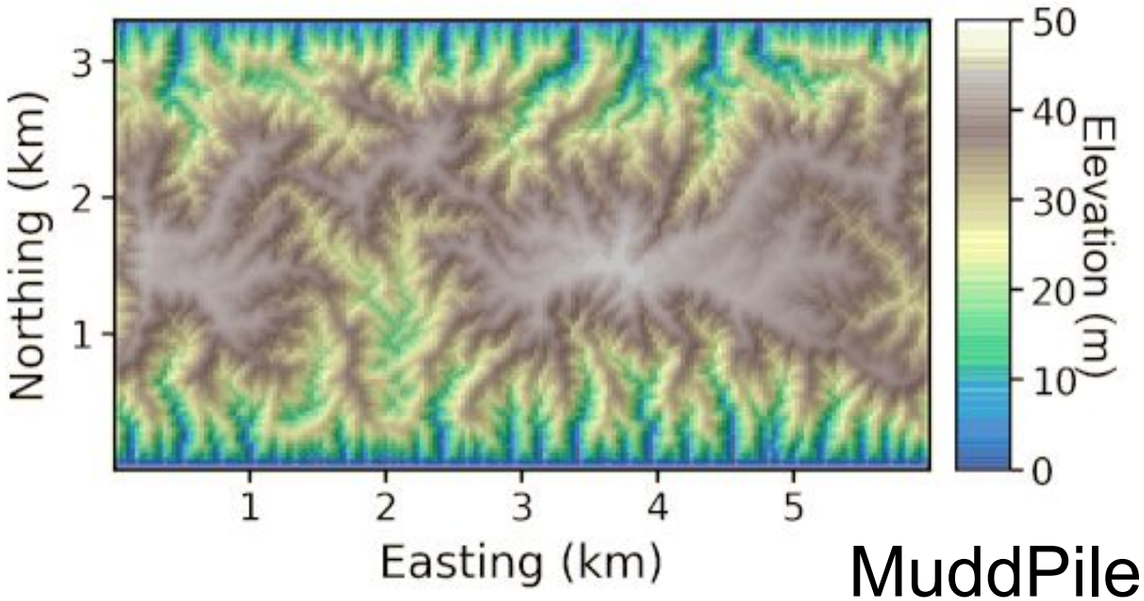
Define a grid (mesh) on which to solve these equations



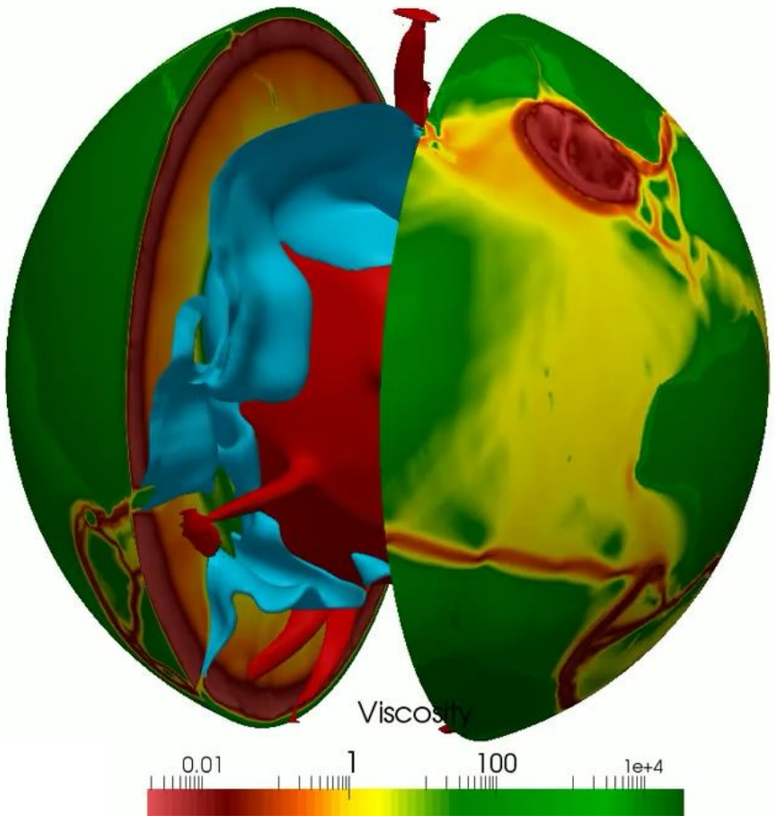


Gerya [2019]

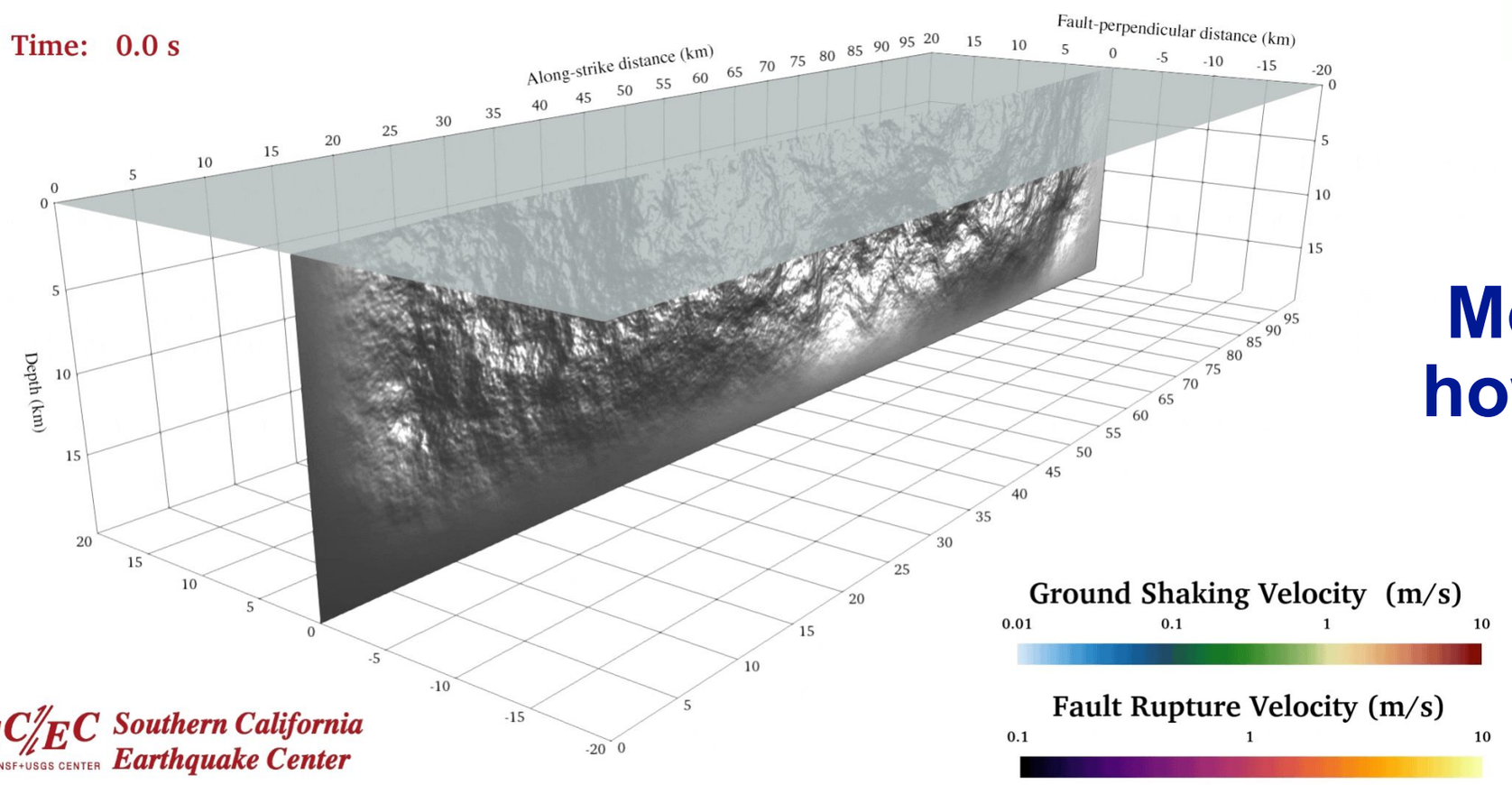
What are models and how do we use them?



MuddPile



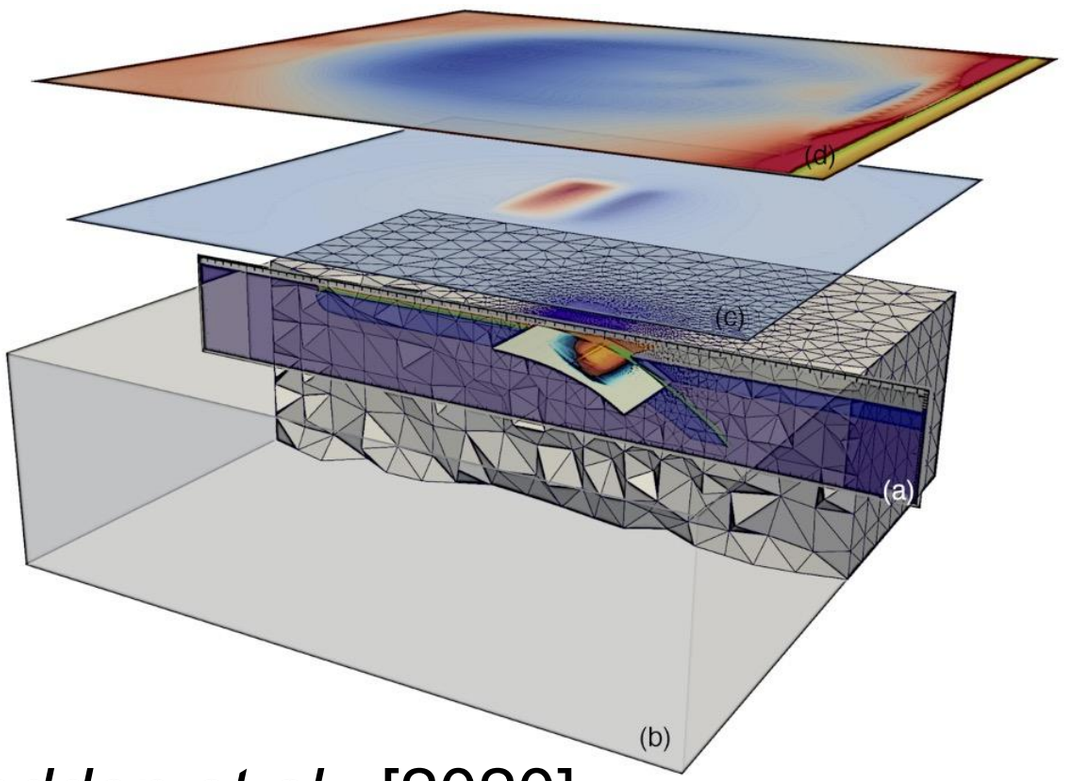
video by *Earthbyte*



Models let us explore how systems evolve in space and time.

SCEC Southern California Earthquake Center
AN NSF+USGS CENTER

What are models and how do we use them?



Madden et al. [2020]

Scenario A: Blind Rupture | **Scenario B: Surface-Breaching**

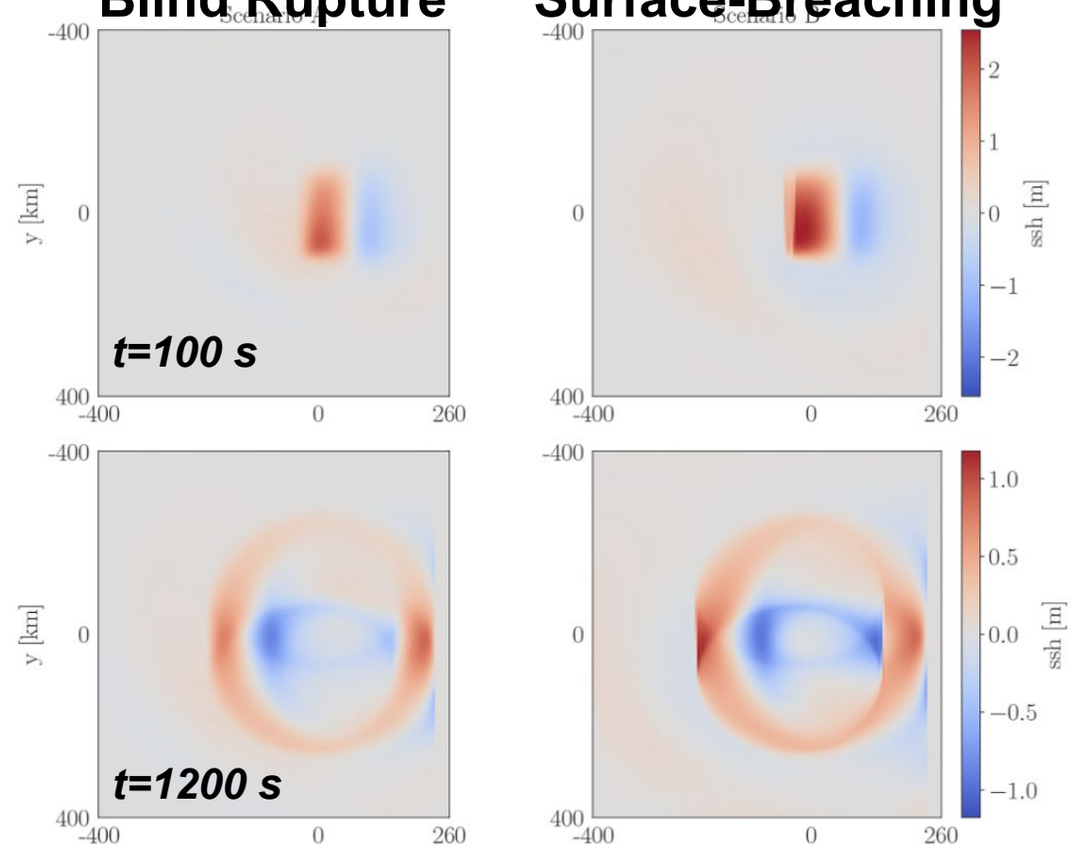
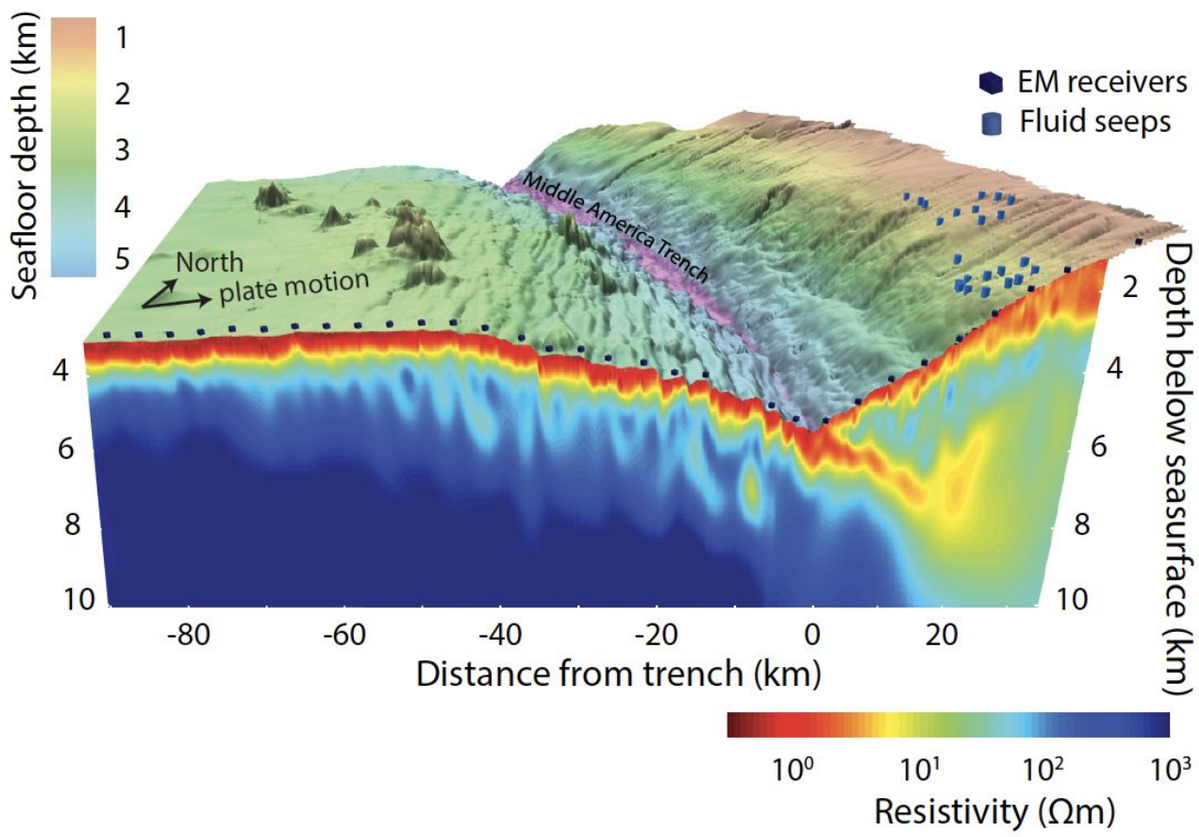


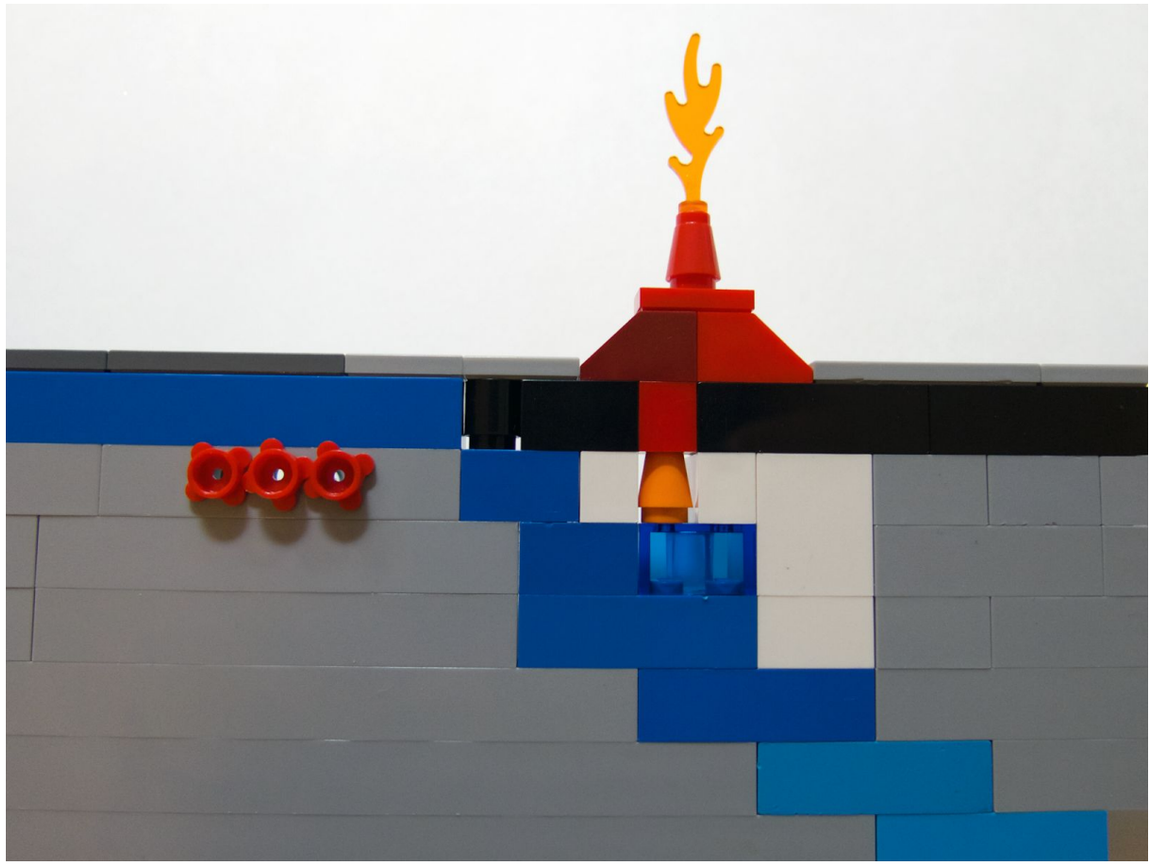
Table 1. Earthquake model results. Characteristics for the blind (Scenario A), surface-breaching (Scenario B) and subduction-initialized (Scenario C) dynamic earthquake rupture models.

	M_w (-)	max. s [a] (m)	Mean s (m)	Mean Vr [b] (km s^{-1})	mean $\Delta\sigma$ [c] (MPa)	min. D[d] (m)	max. D (m)	Mean D (m)	max. Df[e] (m)	Mean D[f] (m)
Scenario A	8.5	7.6	3.8	3.5	3.0	−1.0	2.6	0.6	1.9	0.9
Scenario B	8.6	10.9	6.5	3.7	3.9	−1.1	3.3	1.2	2.6	0.9
Scenario C	9.0	95.5	42.2	2.1	2.2	−5.6	28.1	3.6	15.7	3.3

Physics-based models are particularly useful for testing different scenarios or model assumptions

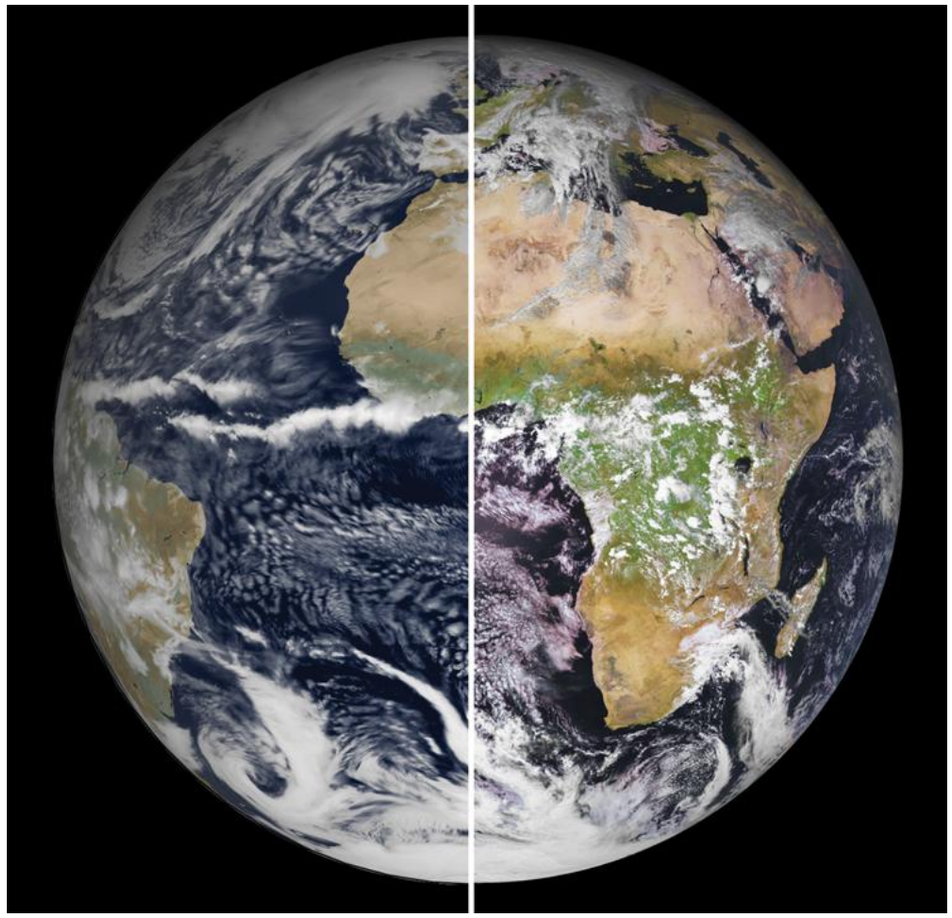
A Digital Subduction Zone

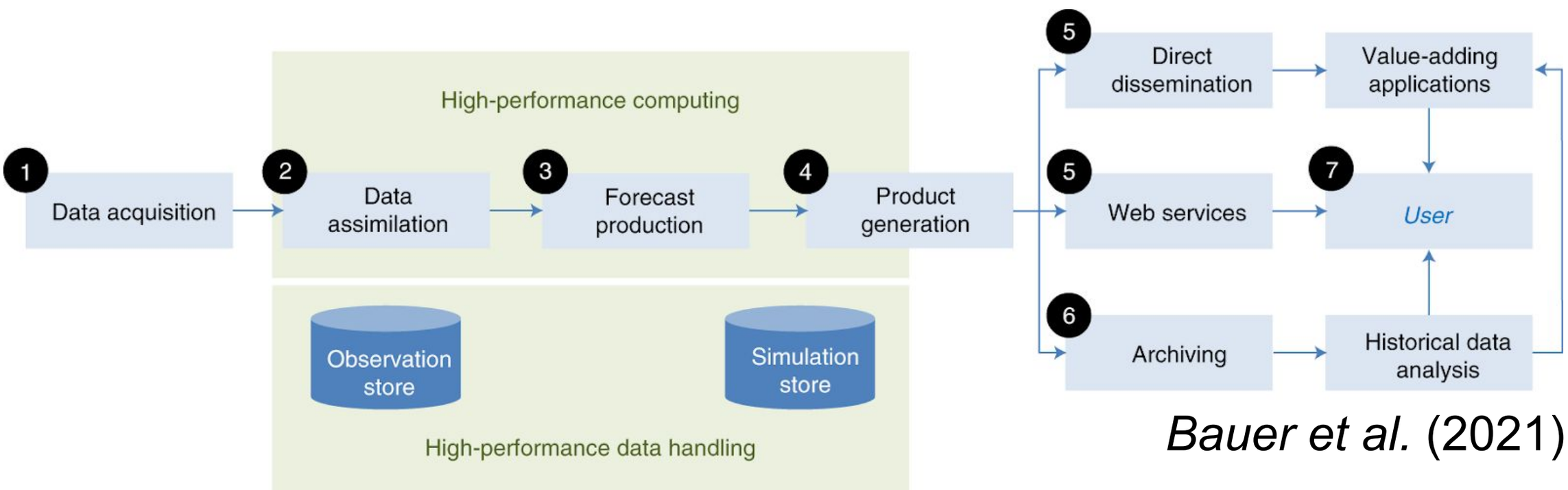




Digital Twin: models that use machine learning (ML) / artificial intelligence (AI) and large amounts of data to accurately mimic a real-world object (used in industry, as well as basic science).

Example: Digital Twins in Climate Science





Bauer et al. (2021)

Specific modeling goals identified in SZ4D Implementation Plan

1) **3D earthquake cycle model for subduction zones**, capable of assimilating SZ4D array data.

2) Models to linking crustal magma transport, thermo-mechanical structure, and volcanic activity: **Melt production to eruption**

3) **Long-term geodynamic model** to characterize feedbacks between magmatic and surface processes and mantle convection for subduction zones.

4) Models that **capture cascading hazards**, e.g.,

   earthquake → landslides → tsunami

   volcanic eruption → flooding and sediment transport

Modeling Collaboratory for Subduction Zone Science (MCS)

MCS was funded by NSF as an RCN in 2018

Goal: Decadal scale, physics-based modeling and forecasting for megathrust and arc volcano systems in tectonic context

- **Sustained, science focused code development**, striving for a transformative advance of interdisciplinary research questions based on a collaborative effort
- **Data integration** to constantly refine and update models
- Incorporate information from other subduction systems outside SZ4D arrays
- **Inclusive and equitable community building** for observational and model science
- Distributed, open, FAIR, and sustainable model and code-development
- **Capacity building** and access to leading-edge computing