A Long-term Vision for Physics-based Forecasting of Earthquakes & Volcanic Hazards in Subduction Zones

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UCDAVIS

SZ4D Community Meeting, Long Beach | April 2026

Subduction Zones in Four Dimensions

SZ4D

A community-driven initiative for a long-term, interdisciplinary research program to **define the limits and possibilities of predicting geohazards**

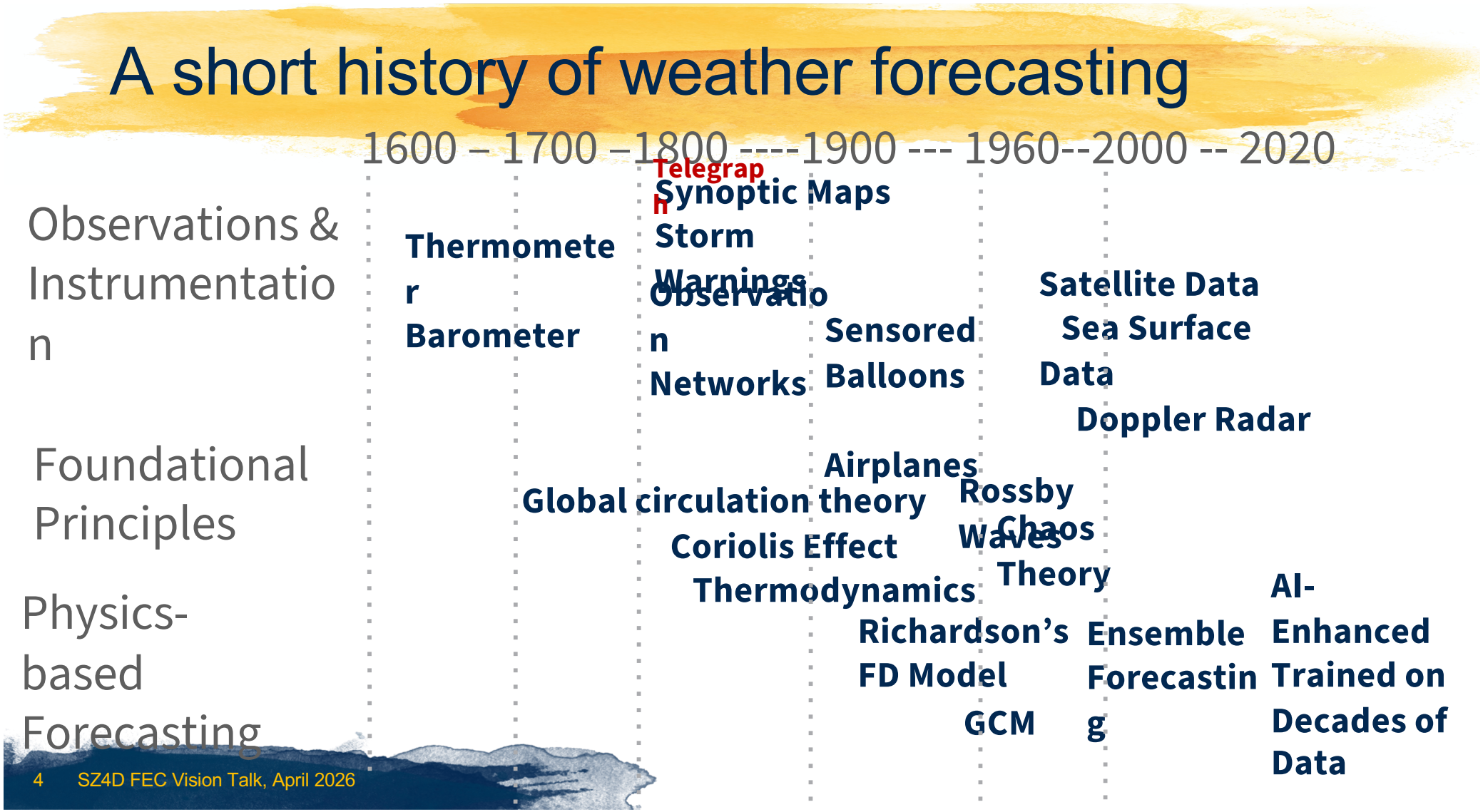
Subduction Zones in Four Dimensions

SZ4D

Global Physics-based Geohazards Forecasting

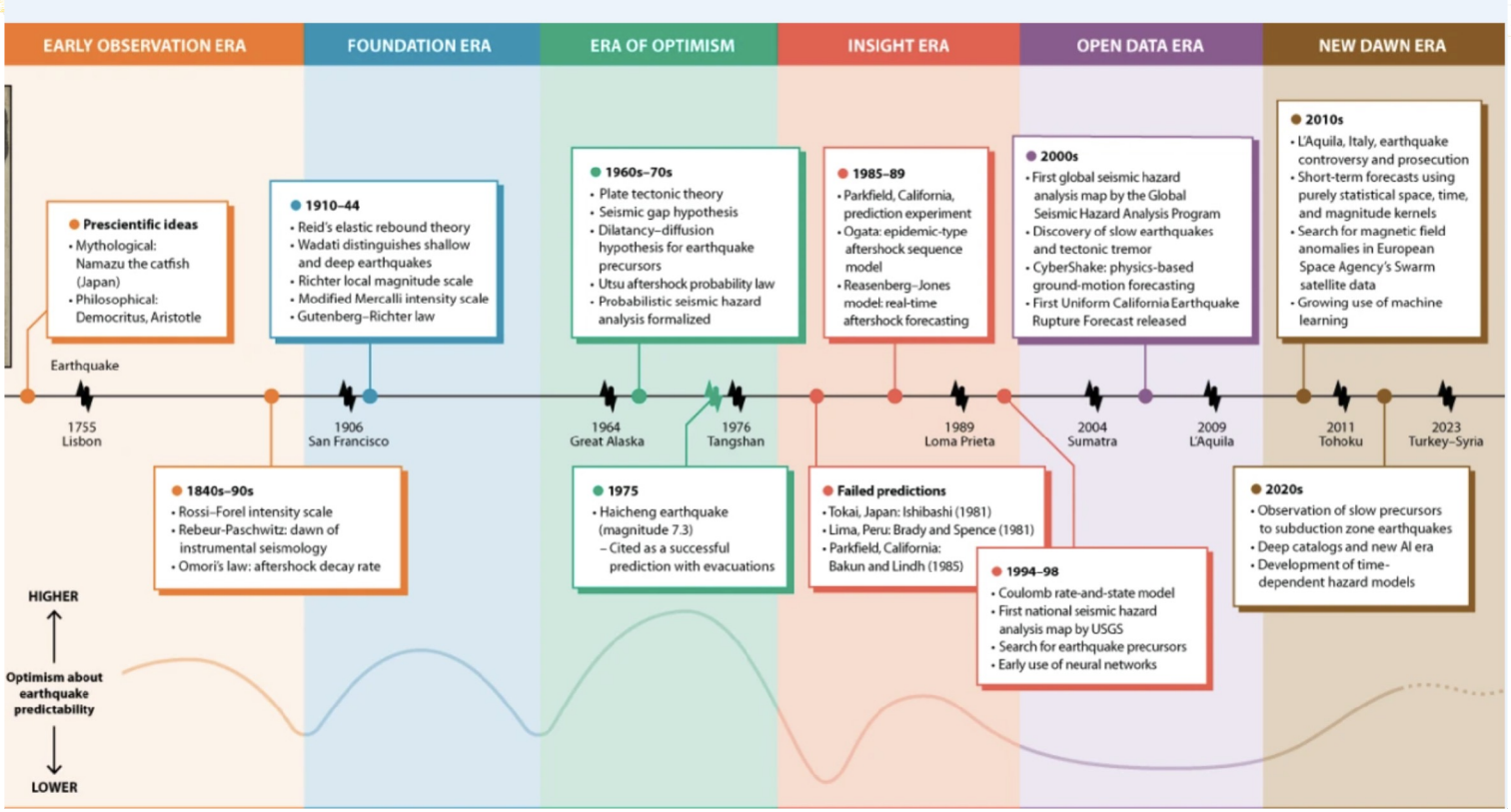
A community-driven initiative for a long-term, interdisciplinary research program to **define the limits and possibilities of predicting geohazards**

A short history of weather forecasting



History & State of the Art in Earthquake Science

The Pursuit of Reliable Earthquake Forecasting



Moustafa, Cattani & Beroza, Physics Today 2025

History & State of the Art in Earthquake Science

1890 → 1960

Moustafa, Cattani & Beroza, Physics Today 2025

History & State of the Art in Earthquake Science

seismology

Omori's law aftershock decay

1890s → 1960s

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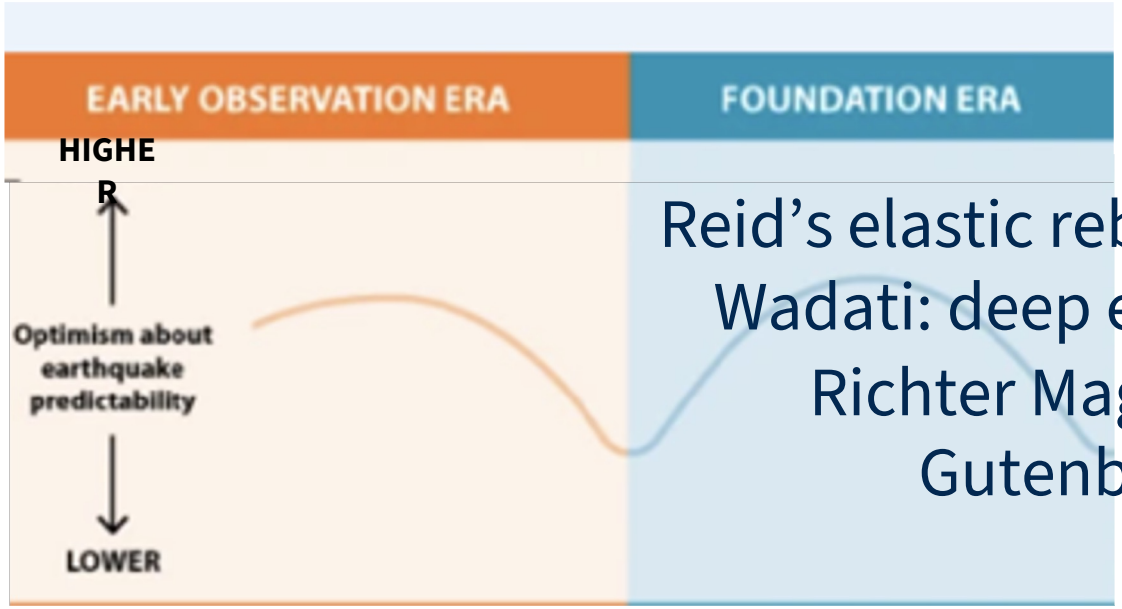
History & State of the Art in Earthquake Science



Reid's elastic rebound theory
Wadati: deep earthquakes
Richter Magnitude
Gutenberg Richter Law

1890s → 1960s

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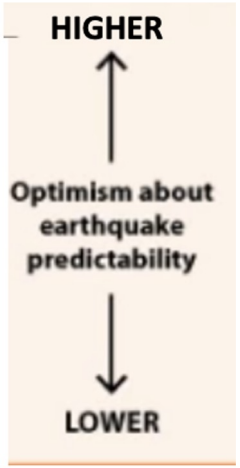
History & State of the Art in Earthquake Science



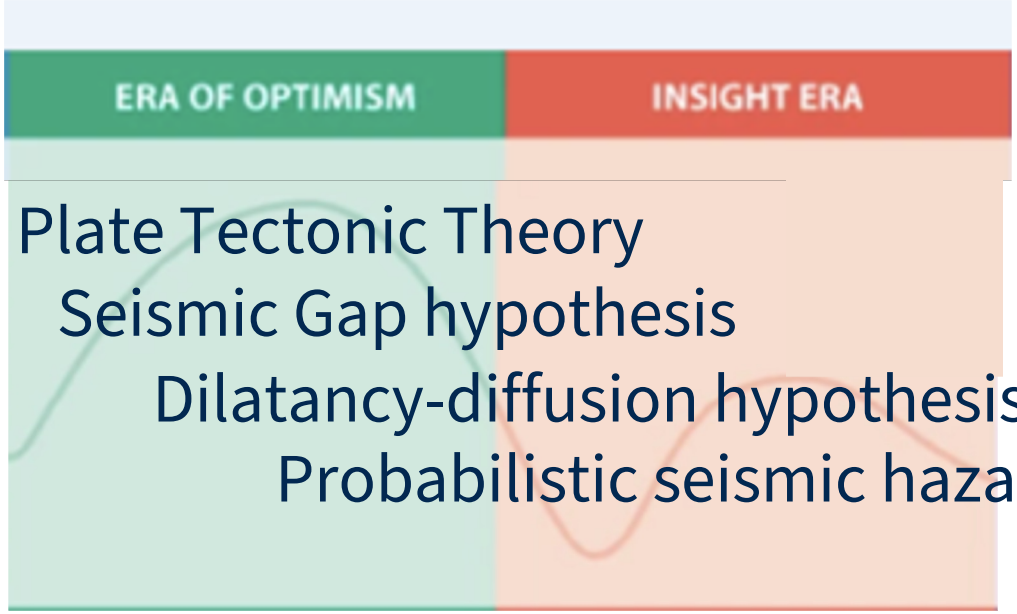


Plate Tectonic Theory

Seismic Gap hypothesis

Dilatancy-diffusion hypothesis

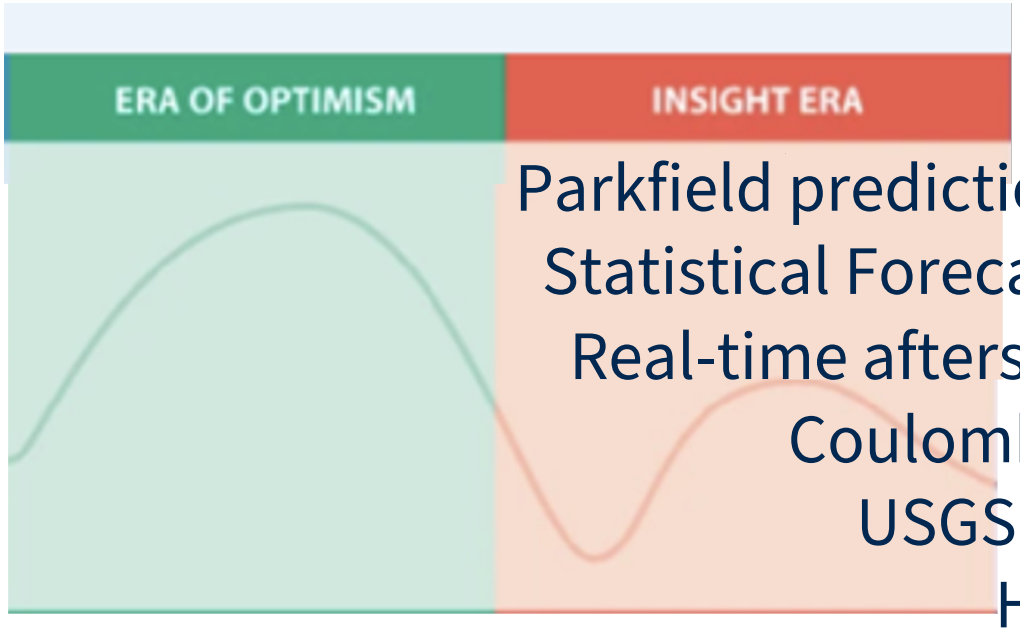
Probabilistic seismic hazard analysis

1960s → 1980s → 2000s

- 1975: Successful Prediction of Haicheng Earthquake

Moustafa, Cattani & Beroza, Physics Today 2025

History & State of the Art in Earthquake Science



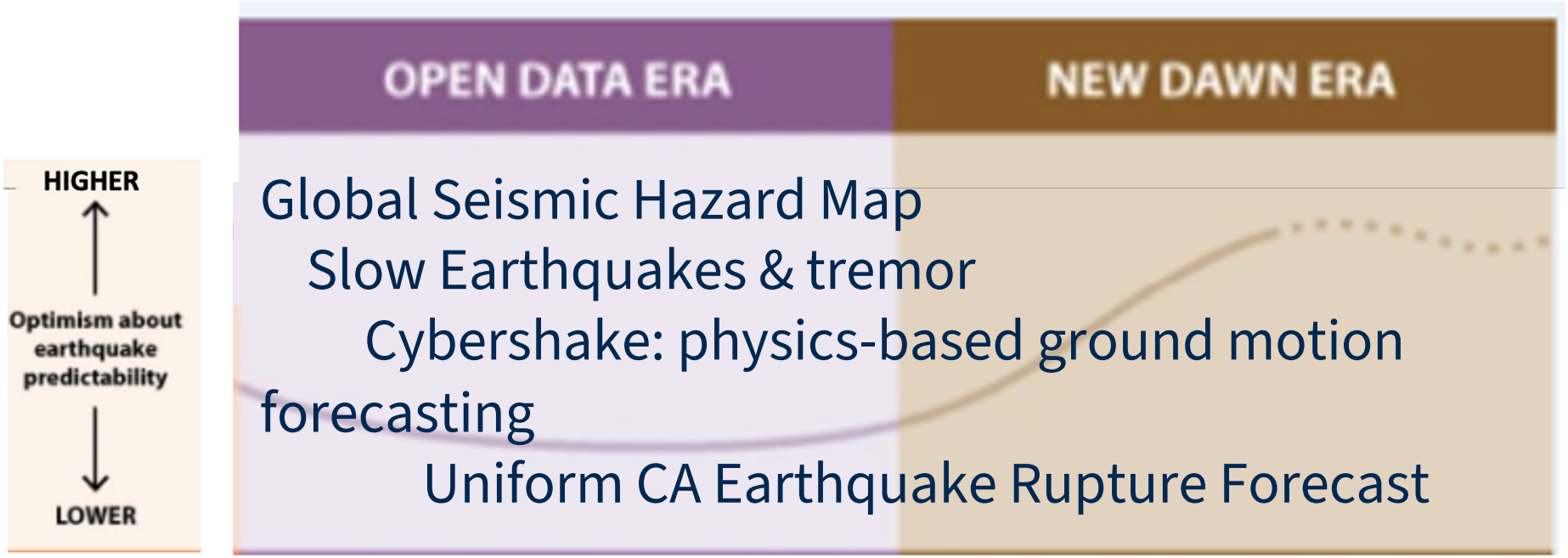
1960s → 1980s → 2000s

Parkfield prediction experiment
Statistical Forecasting (ETAS)
Real-time aftershock forecasting
Coulomb Rate-and state model
USGS National Seismic Hazard Map

? 1980s: several failed predictions

Moustafa, Cattani & Beroza, Physics Today 2025

History & State of the Art in Earthquake Science



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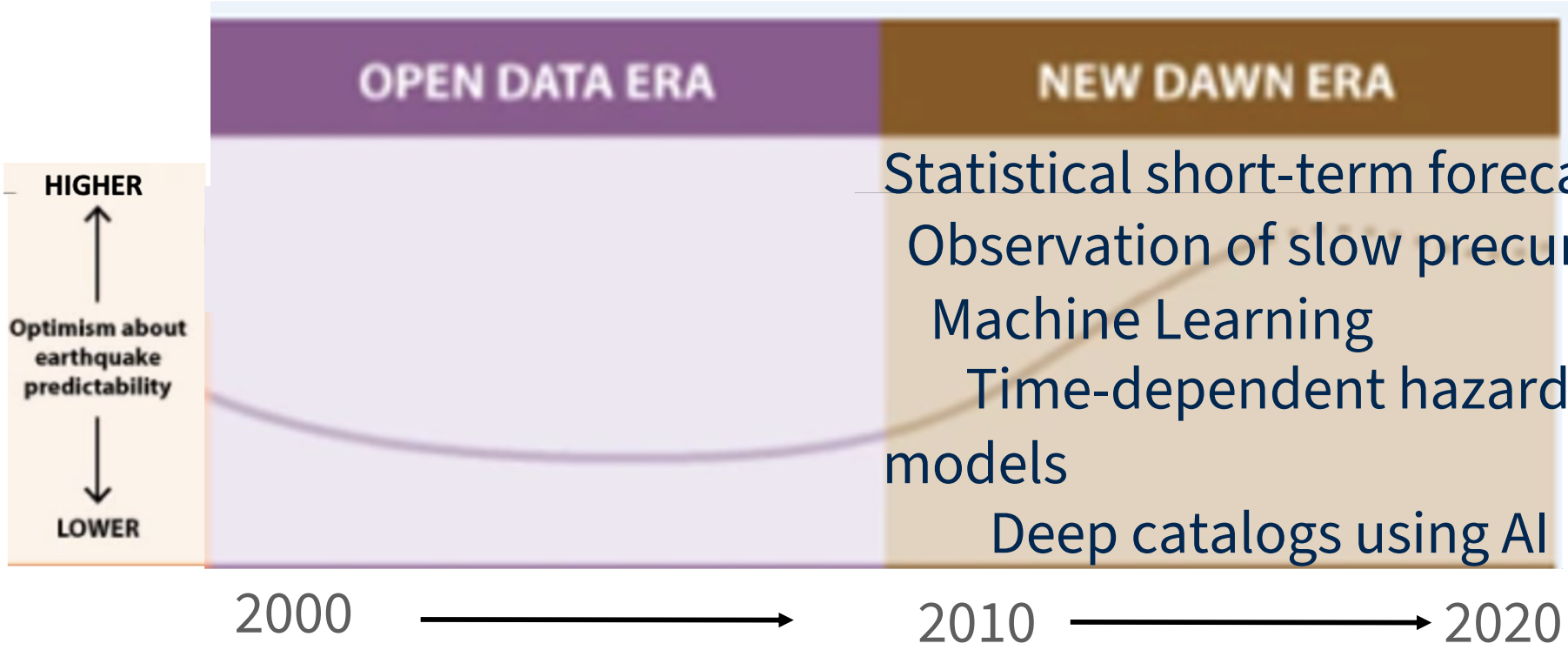

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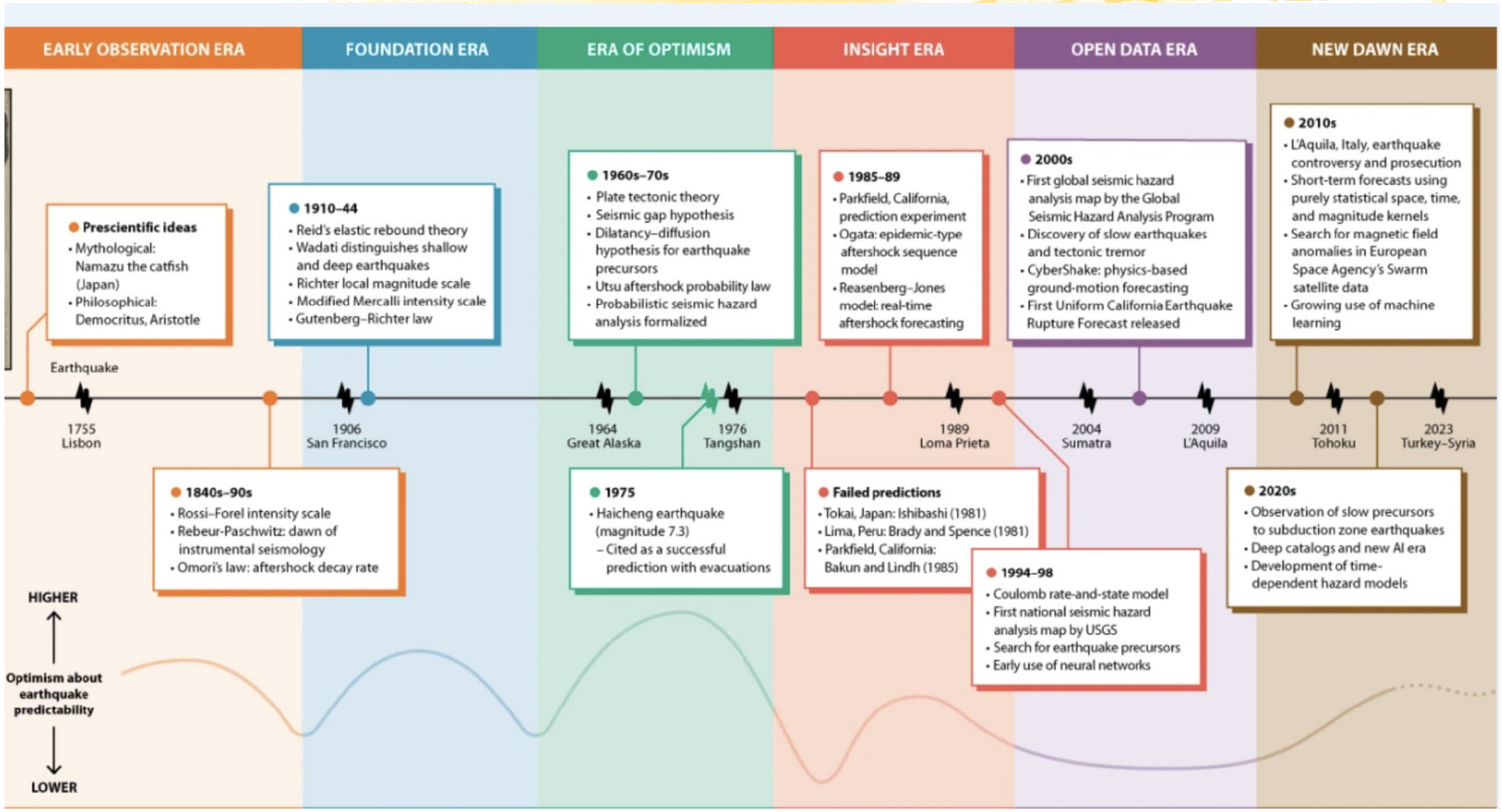


Observations & Instrumentation

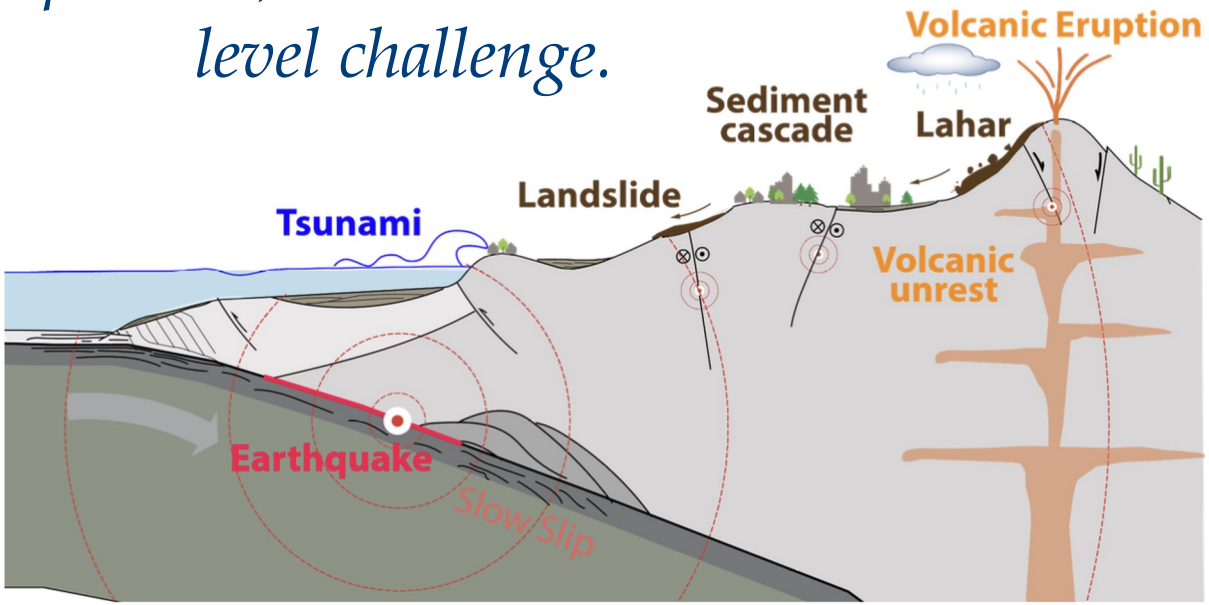
Theory & New Methods

Physics-based Forecasting

Moustafa, Cattani & Beroza, Physics Today 2025

The SZ4D Vision Forecasting SZ GeoHazards

Predicting geohazards, where possible, is a multidecadal level challenge.



SZ4D NSF Geohazards Proposal

The SZ4D Vision

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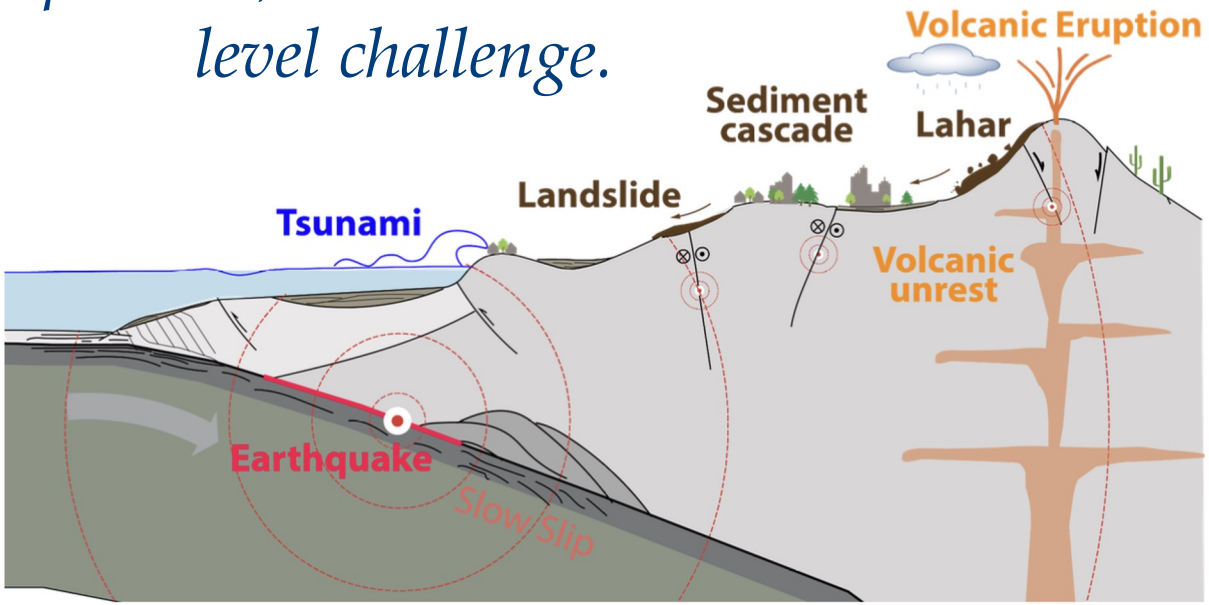
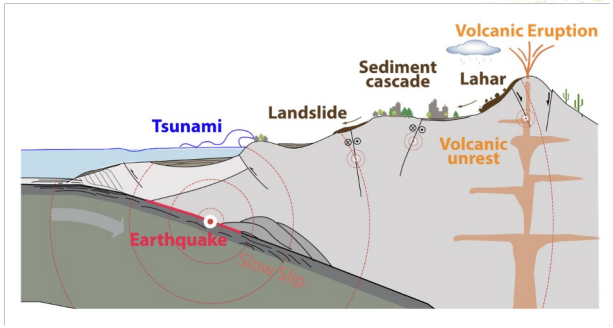


Developing the processed-based understanding of geohazards must be accelerated now if we are ever to reach this goal.

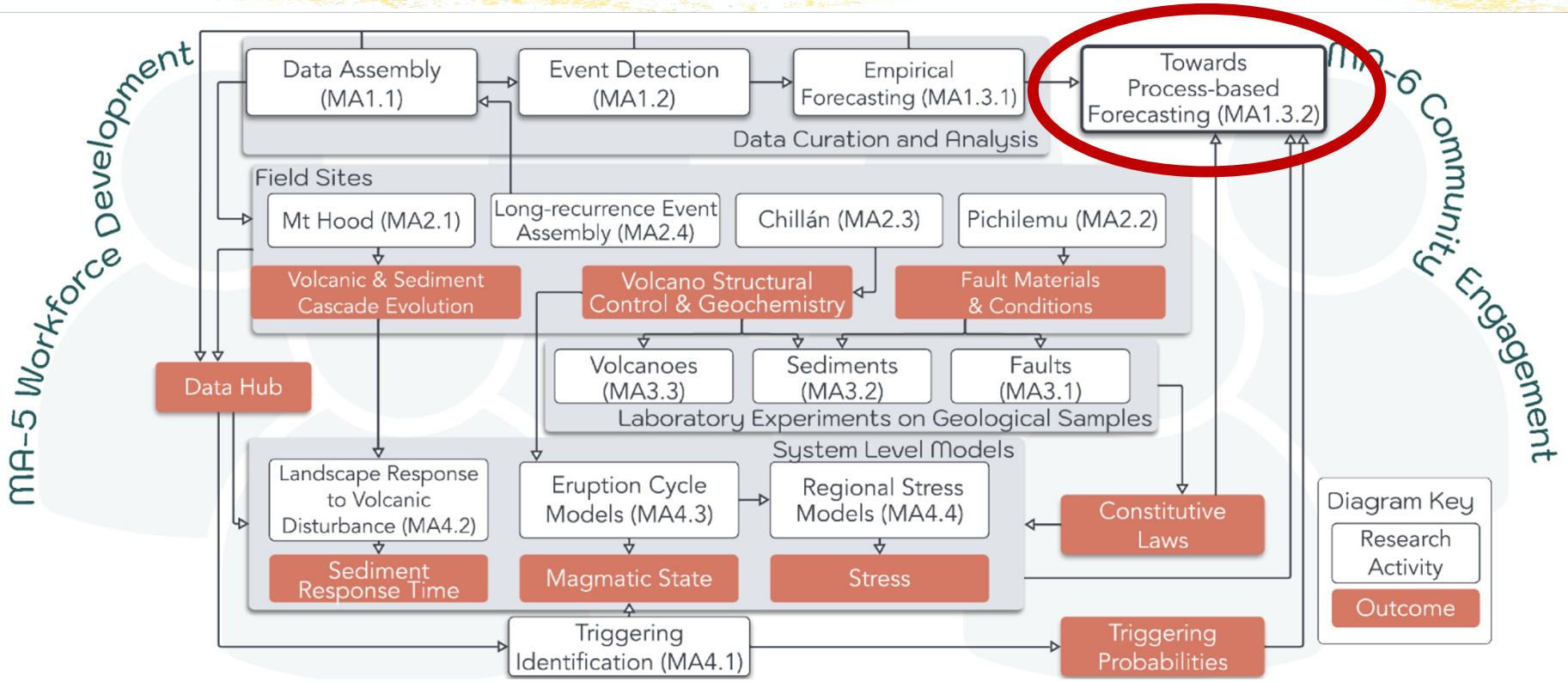
SZ4D NSF Geohazards Proposal

The SZ4D Community is Ready

- Shift from empirical forecasts
- Build on physics based models
- Fundamentally data driven including field observations and experiments
- Bringing together innovations in technology & methodology from across subdisciplines



Some first steps towards this vision have been mapped out …



SZ4D NSF Geohazards Proposal

Why do I think this Global Forecasting Vision is possible?

- History and state-of the art in Earthquake Science
- Advances in geodynamical models of tectonic deformation
- Advances in earthquake rupture models

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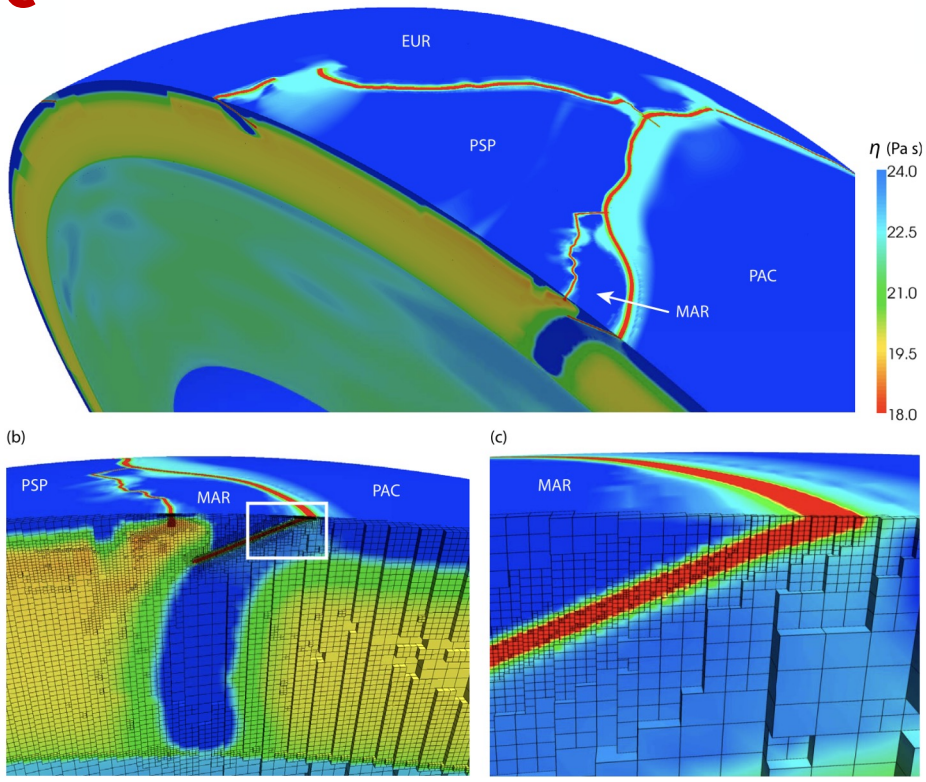
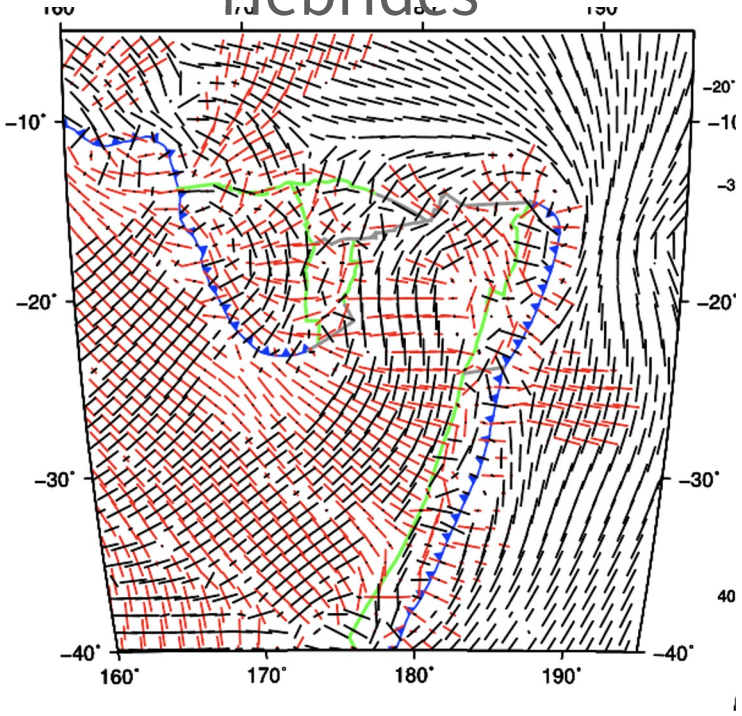
Global Geodynamic-Tectonic Models

Rhea

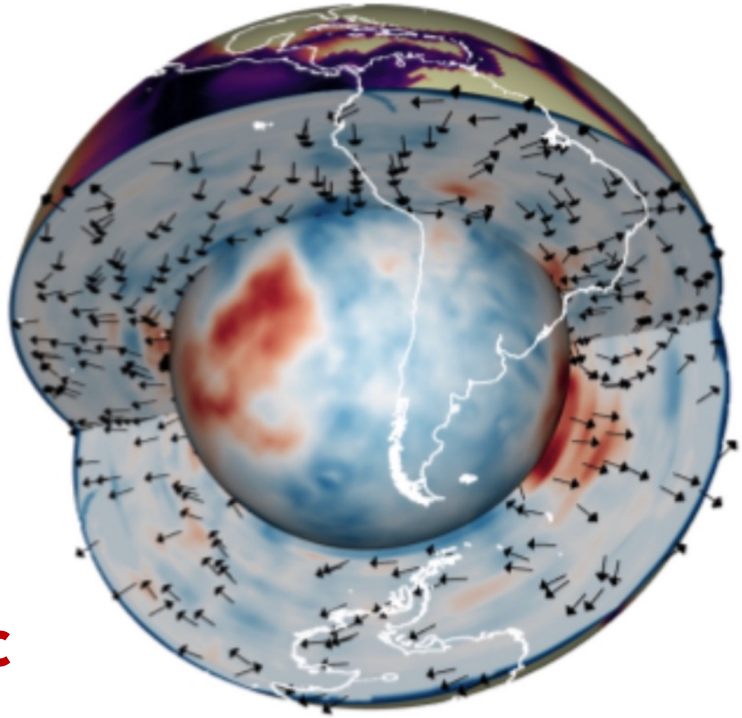


Stress state for Tonga New Hebrides

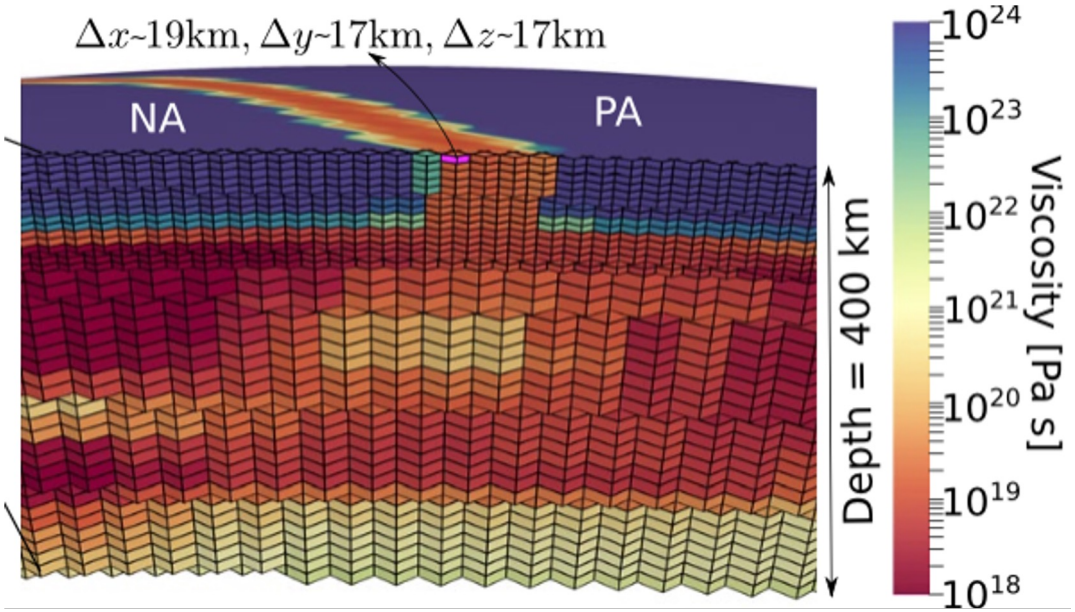


Alisic, Gurnis, Stadler, Burstedde & Ghattas, JGR 2012

Global Geodynamic-Tectonic Models

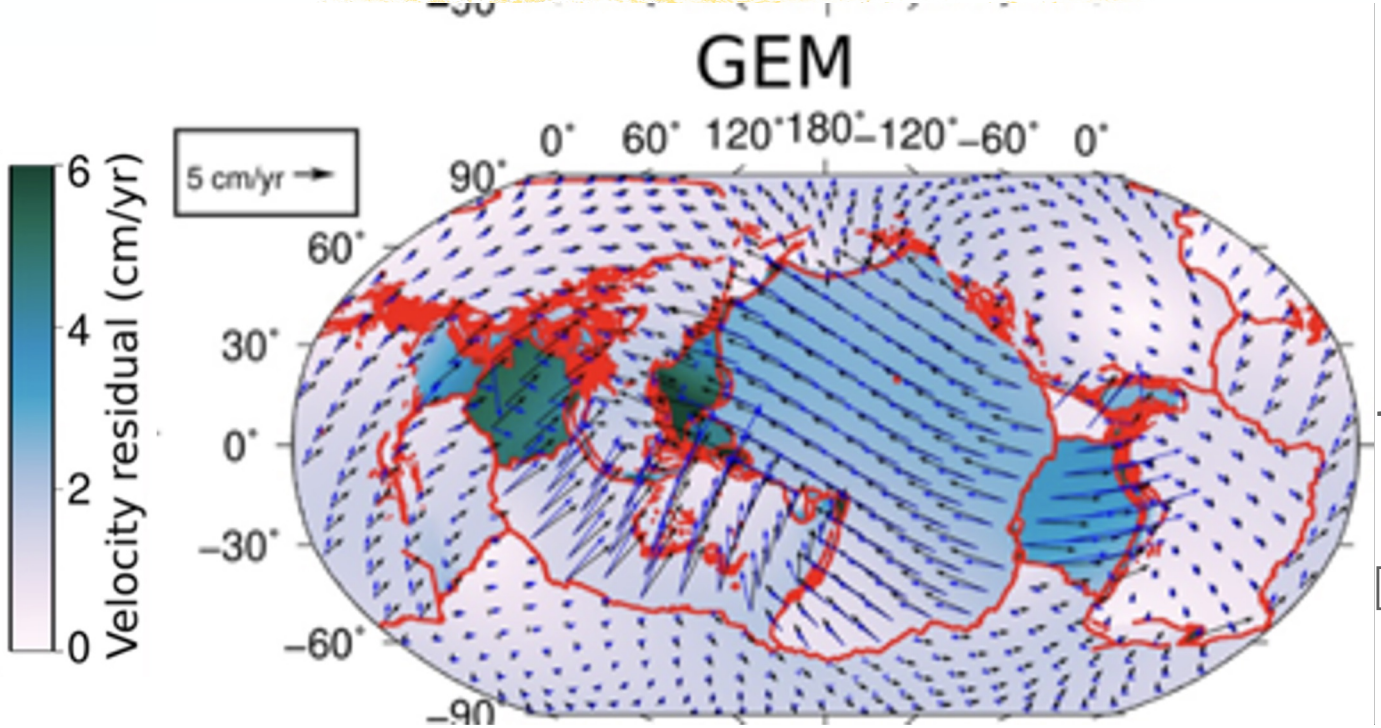


Aspect



Saxena, Dannberg, Gassmöller, Fraters, Heister, Styron, JGR, 2023

Global Geodynamic-Tectonic Models

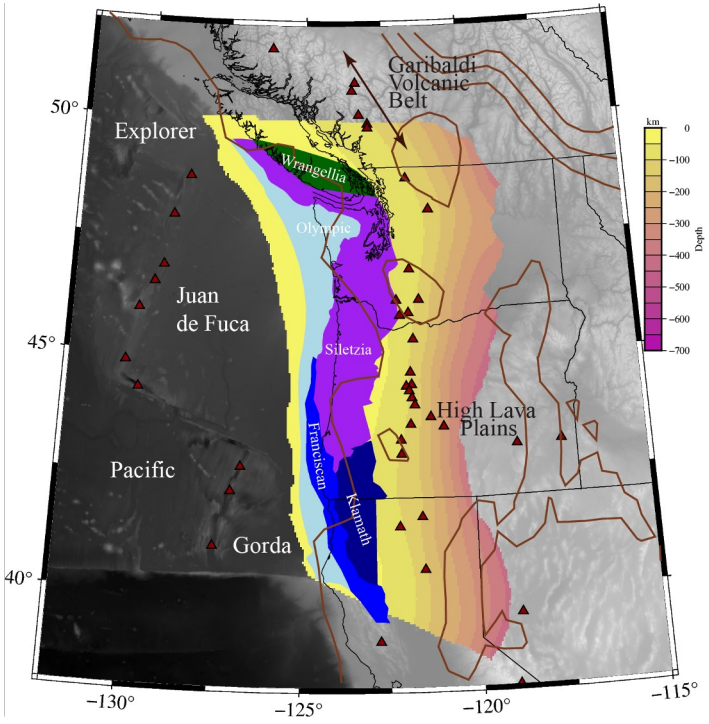


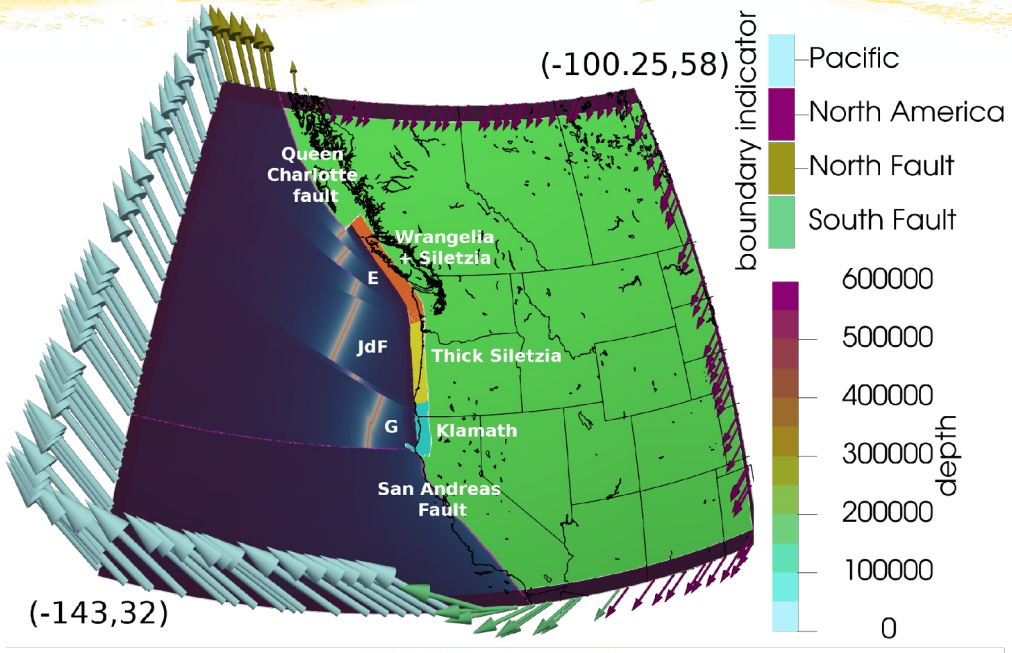
Lithospheric scale faults in oceanic plates with crustal-only faults on continents

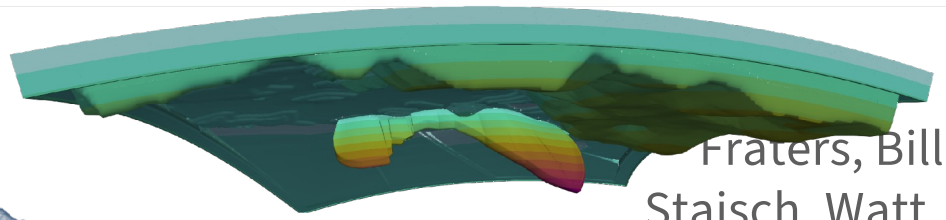
- Smallest residual

Saxena, Dannberg, Gassmöller, Fraters, Heister, Styron, JGR, 2023

Regional Geodynamic-Tectonic Models



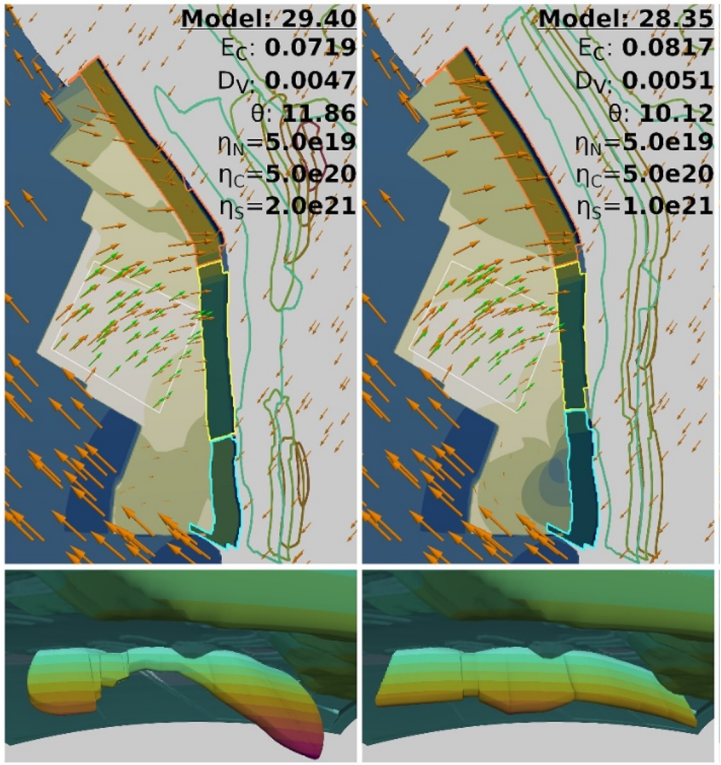




Aspect

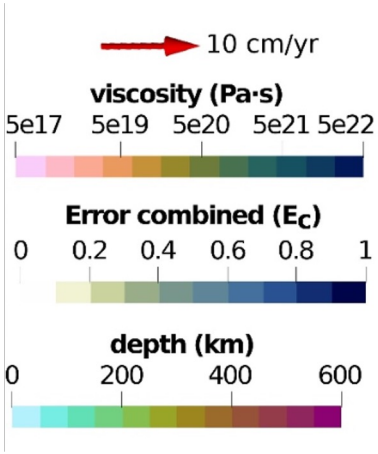
Fraters, Billen, Naliboff, Staisch, Watt, Li, G-cubed, 2025

Regional Geodynamic-Tectonic Models



Predicted Juan de Fuca plate motion

Trade-offs between slab shape & plate boundary viscosity



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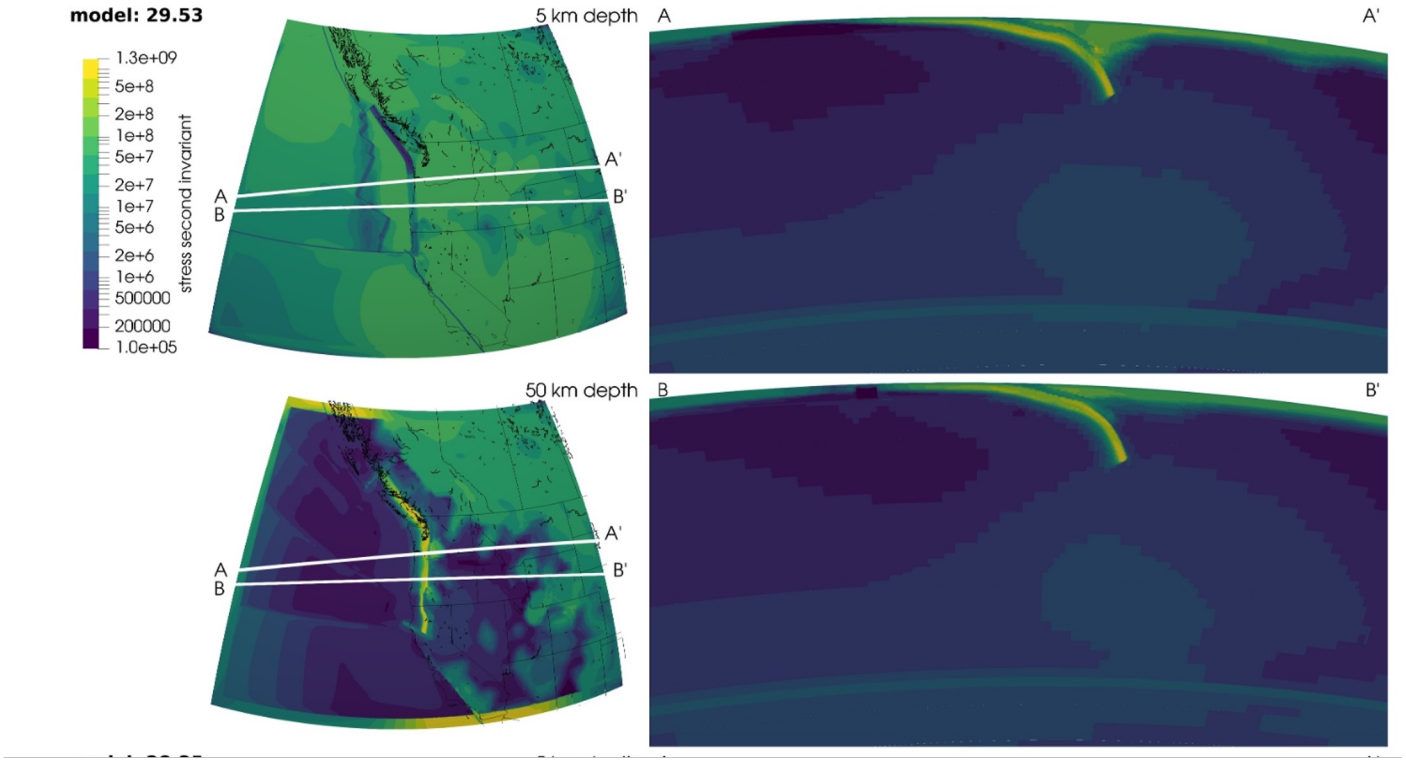
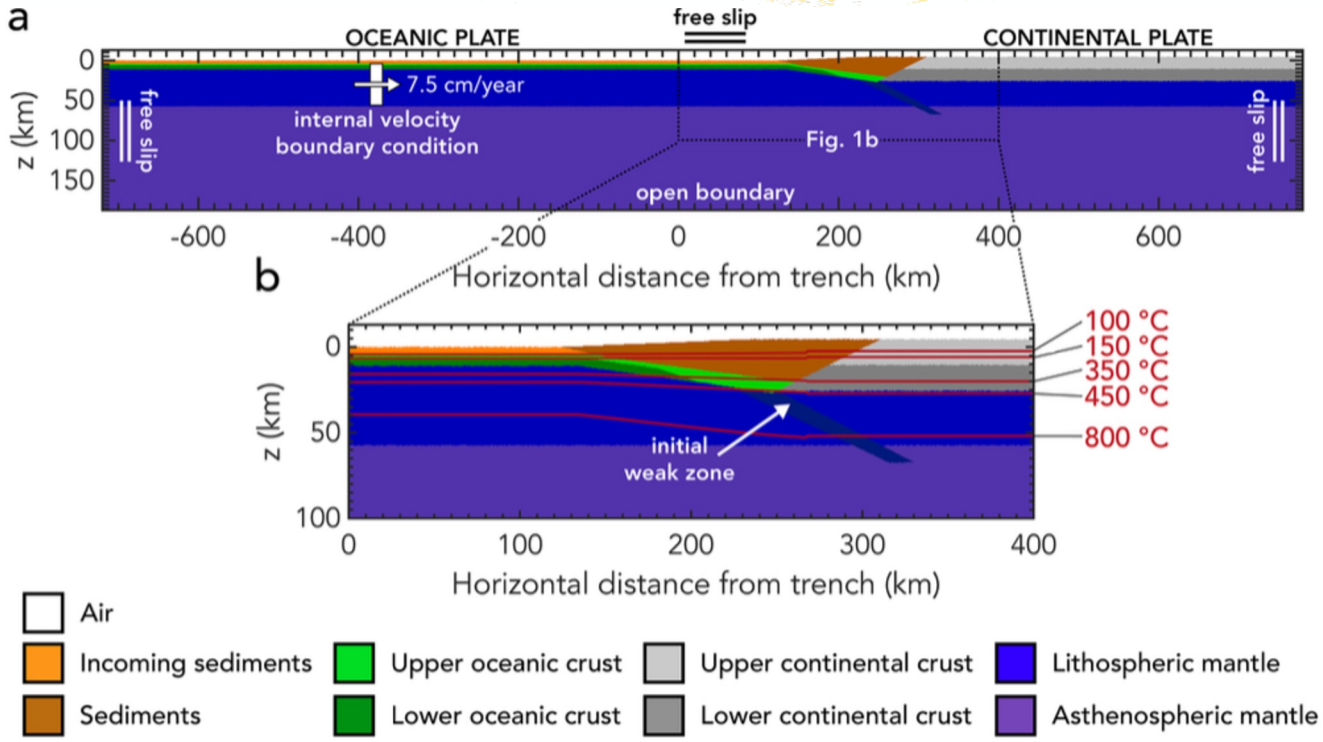


Stress-state

Fraters, Billen, Naliboff, Staisch, Watt, Li, G-cubed, 2025

One-way Coupling of Tectonic & Rupture Models

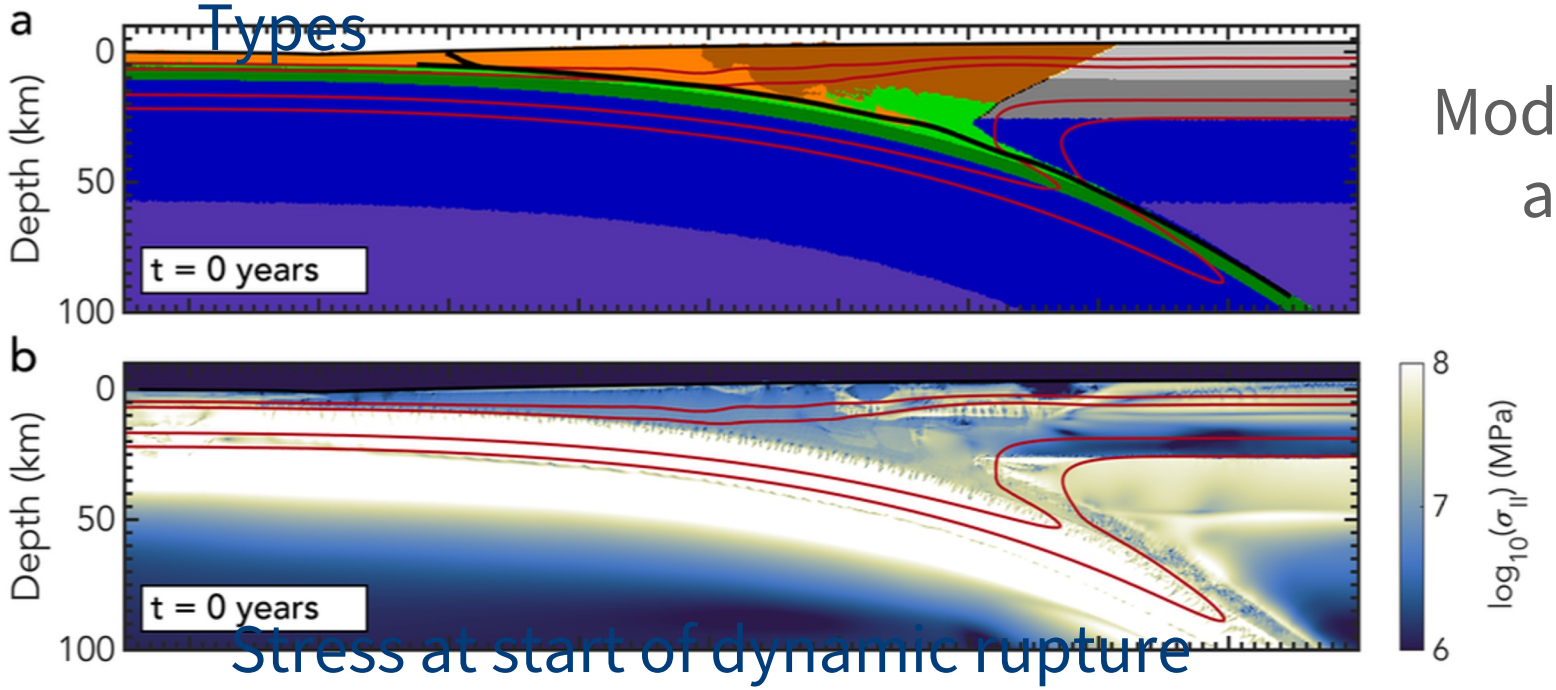


2D
Visco-elasto-plastic
Subduction
Compositional layers
Imposed plate motion

I2ELVIS

van Zelst, Wolherr, Gabriel, Madden, van Dinther, JGR, 2019

One-way Coupling of Tectonic & Rupture Models

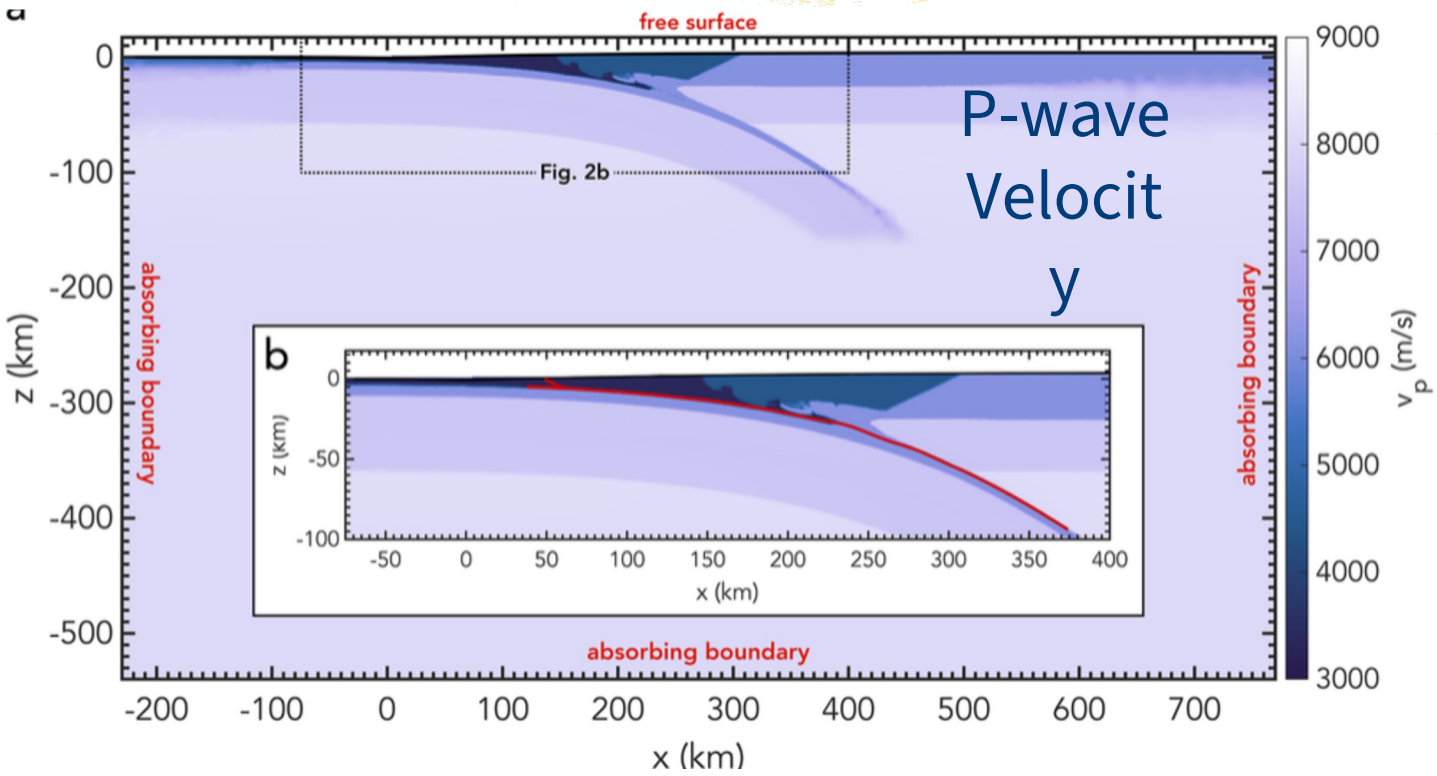


Model evolution after 4 my

Stress at start of dynamic rupture model

vanZelst, Wolherr, Gabriel, Madden, van Dinther, JGR, 2019

One-way Coupling of Tectonic & Rupture Models



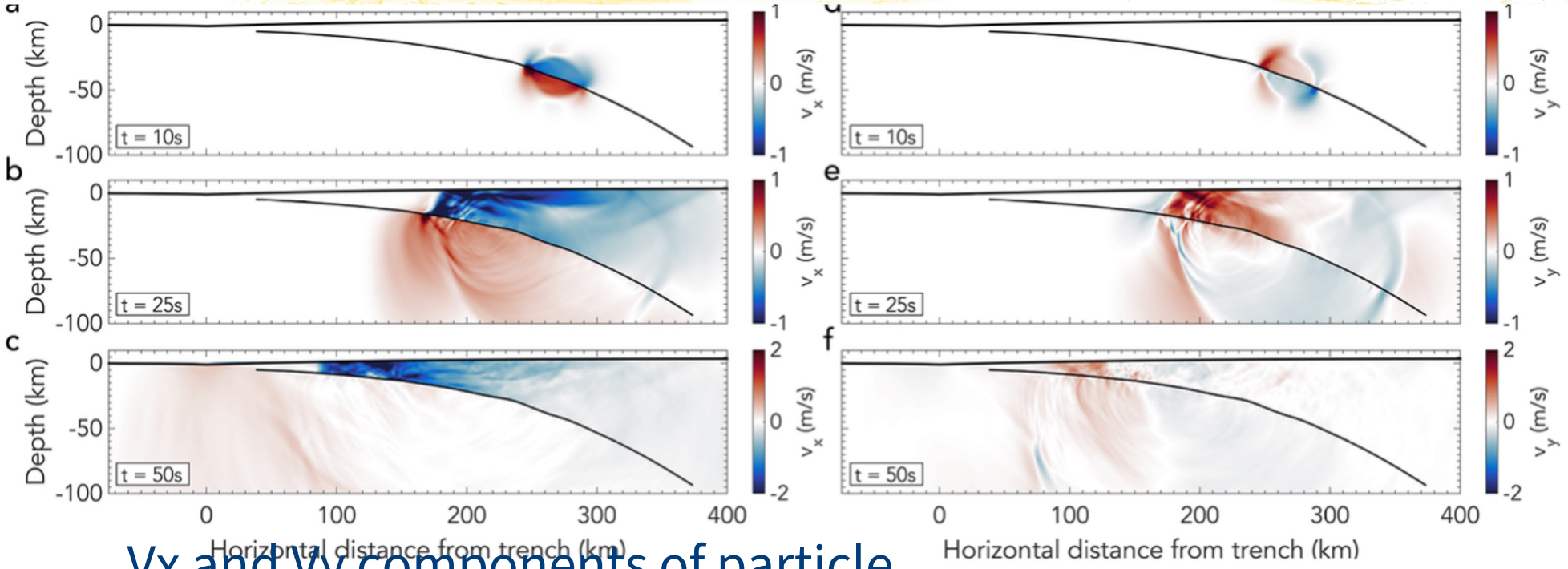
Output from the geodynamic model

becomes

Input to the dynamic rupture model

vanZelst, Wolherr, Gabriel, Madden, van Dinther, JGR, 2019

One-way Coupling of Tectonic & Rupture Models



Vx and Vy components of particle velocity

vanZelst, Wolherr, Gabriel, Madden, van Dinther, JGR, 2019

Advances in Geodynamic-Tectonic Models

- Framework for calculating and updating state of stress regionally and globally
- Numerical methods to deal with increasingly realistic geologic structures and material properties
- Capturing processes across length-scales and time-scales

Why do I think this Global Forecasting Vision is possible?

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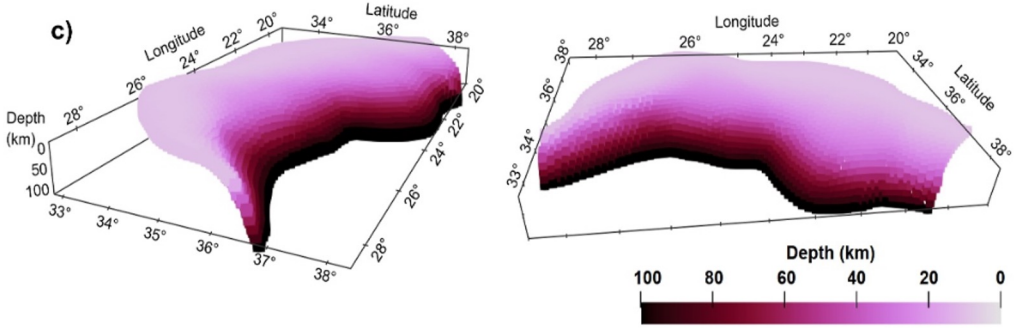
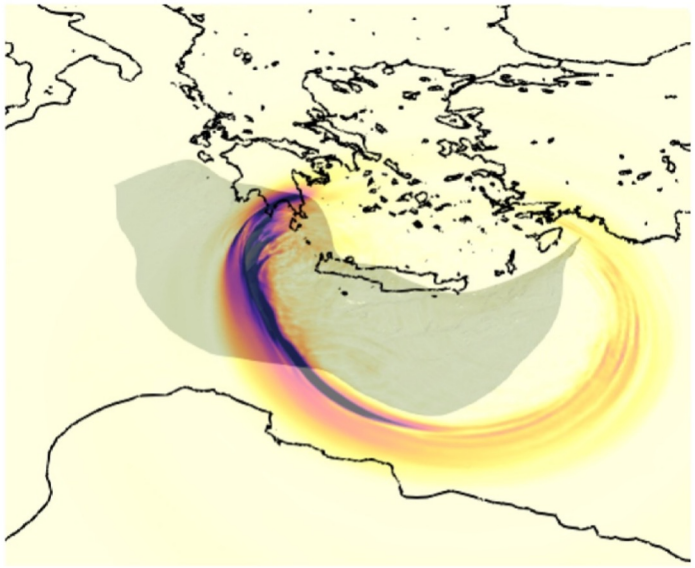
3D Earthquake Rupture Models

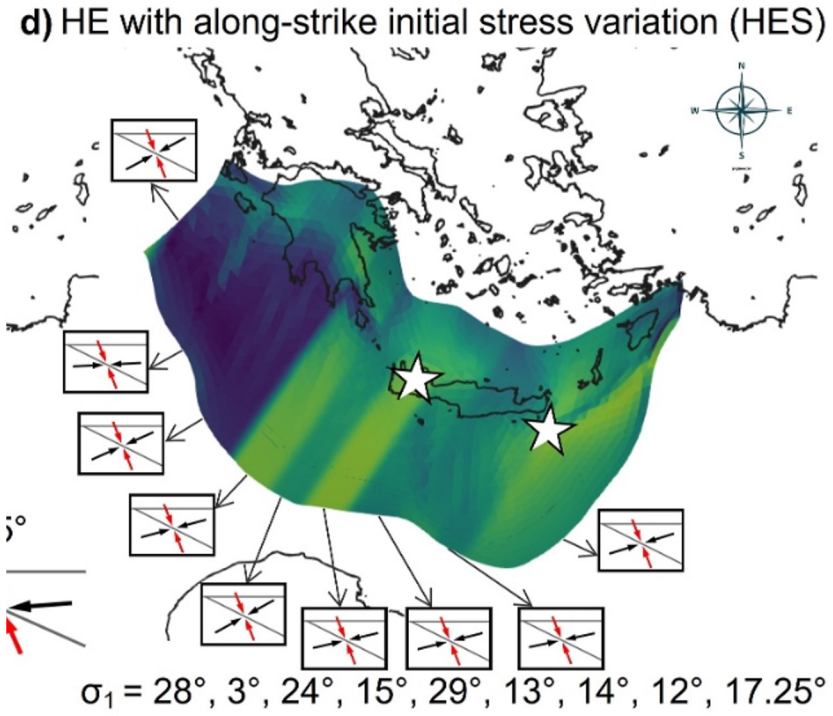
Hellenic Arc

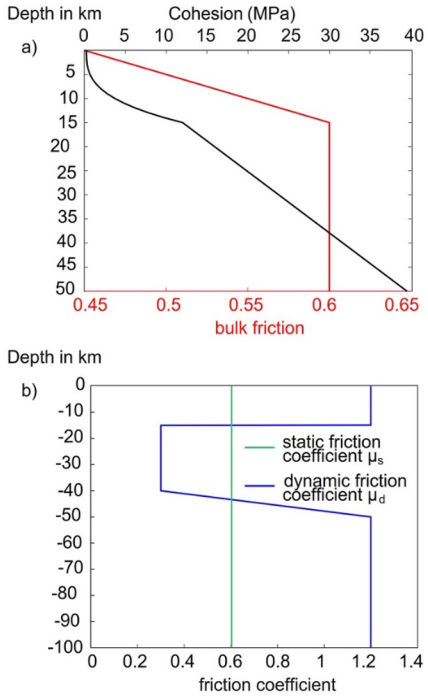


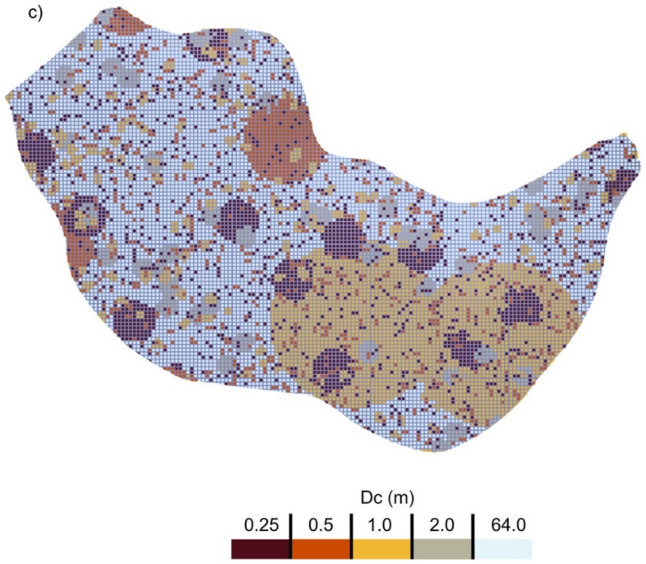


Wirp, Gabriel, Ulrich, Lorito, JGR 2024

3D Earthquake Rupture Models







Wirp, Gabriel, Ulrich, Lorito, JGR 2024

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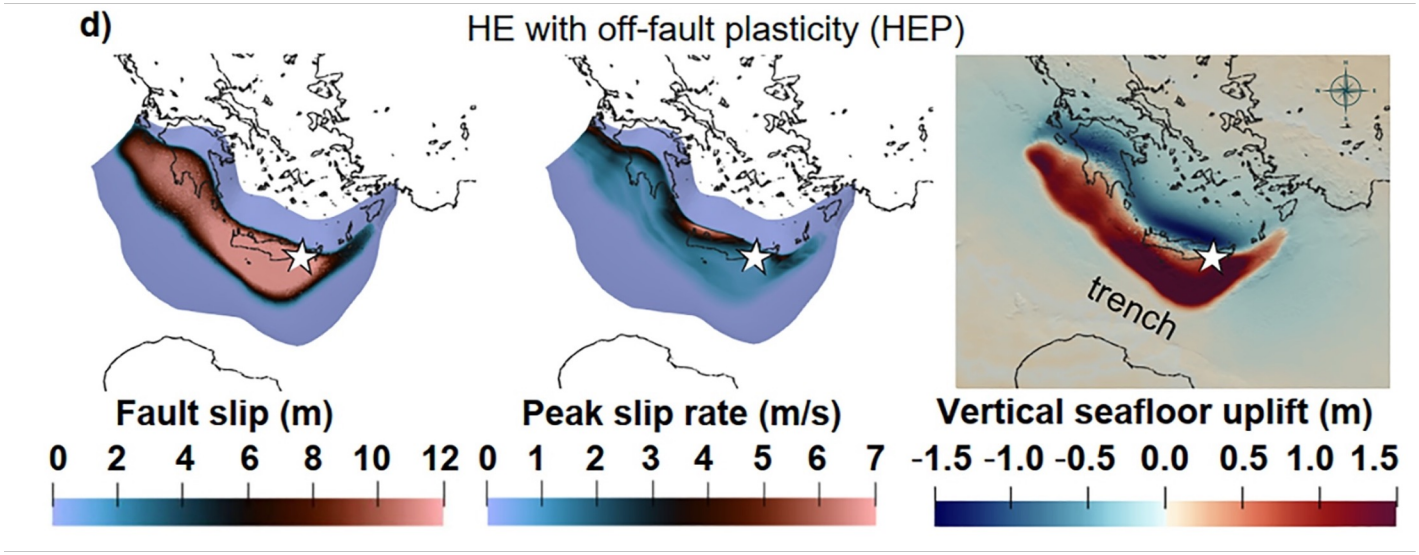

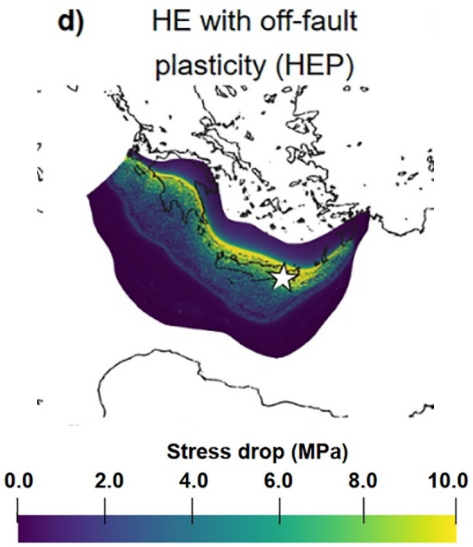

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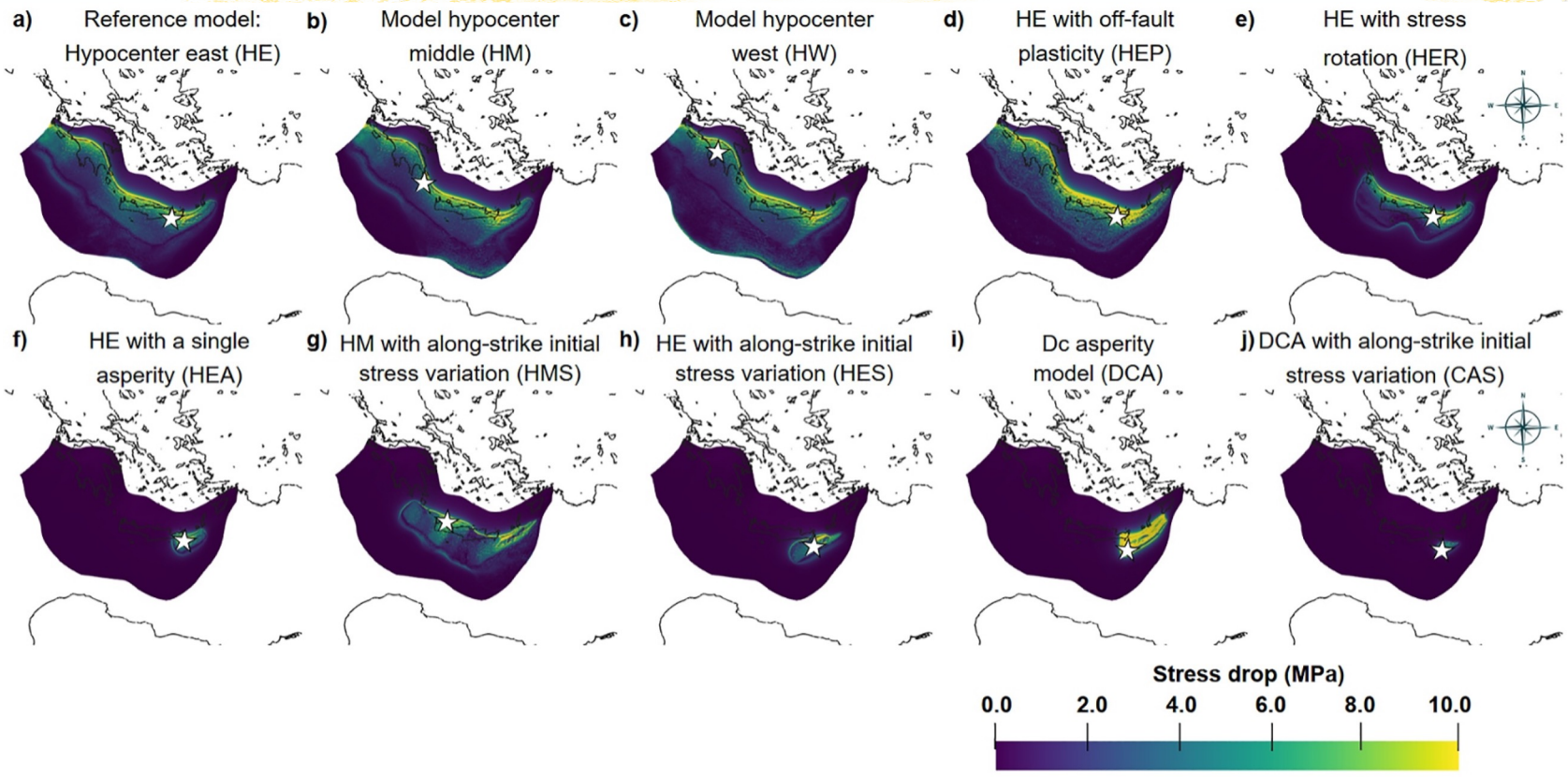

Wirp, Gabriel, Ulrich, Lorito, JGR 2024

How do we put this Vision together?

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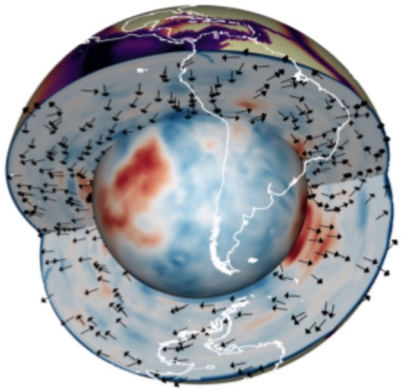
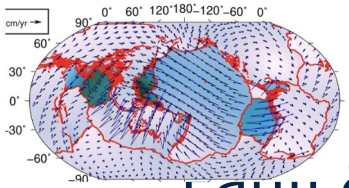
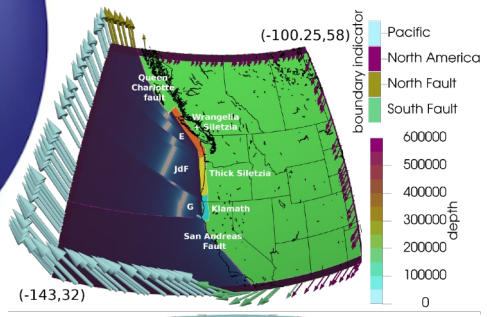
Vision for Physics-based Earthquake Forecasting





Global Tectonics Simulation



Geologic Terranes

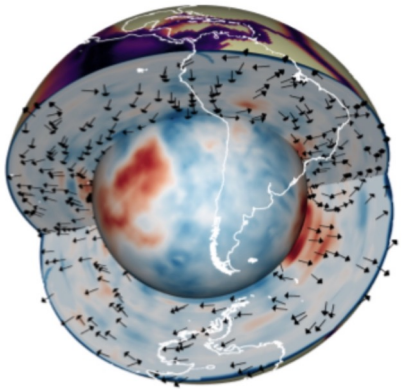
Fault & Plate Geometry

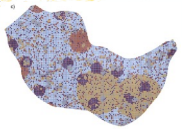
Composition

Temperature

Vision for Physics-based Earthquake Forecasting

Material Properties





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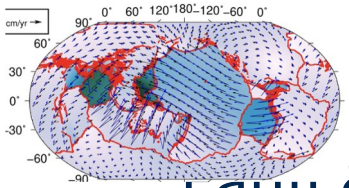

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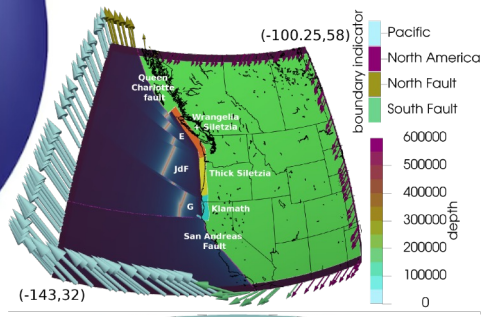

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Vision for Physics-based Earthquake Forecasting

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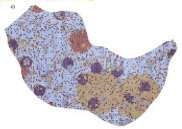
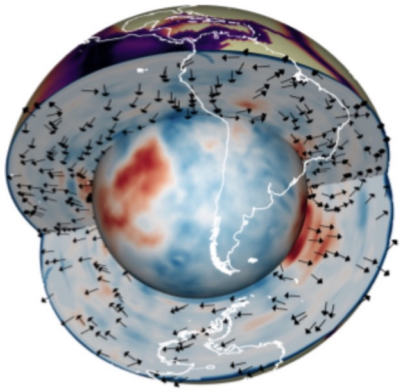
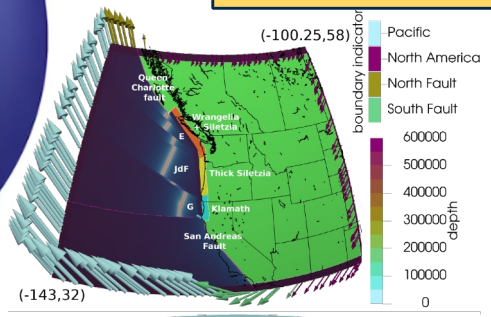


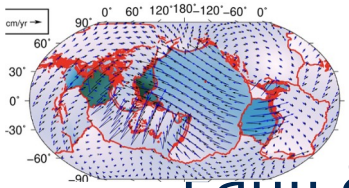


Global Tectonics Simulation

Rheology ToolBox

- Rock types
- Time-scales
- Conditions





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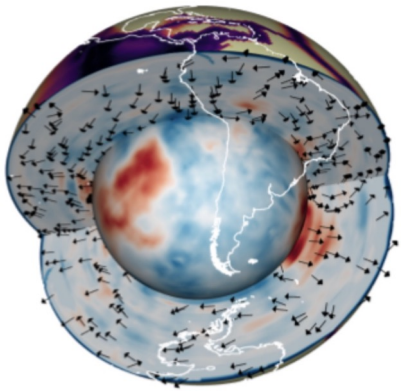
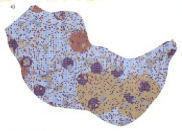
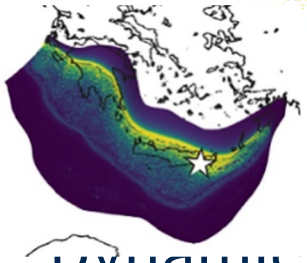
Vision for Physics-based Earthquake Forecasting

Material Properties



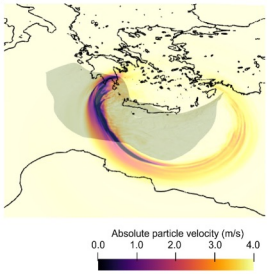


Global Geohazard & Tectonics Simulation

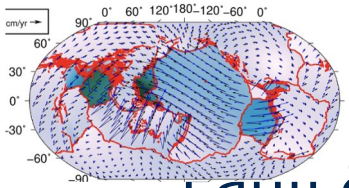


Two-way Coupling

Dynamic Rupture Simulation

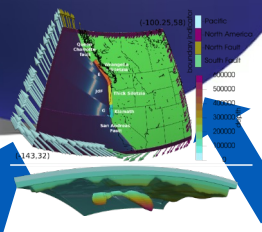


Embedded Physical Processes



Geologic Terranes

Fault & Plate Geometry



Composition

Temperature

Vision for Physics-based Earthquake Forecasting

Material Properties

Satellite Data

AI-enhanced Event Catalogs

Continuous Geodetic Data

Geologic Terranes

Fault & Plate Geometry

Global Geohazard & Tectonics Simulation

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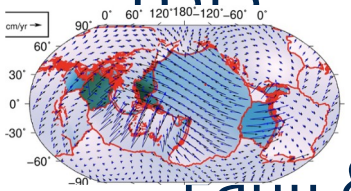
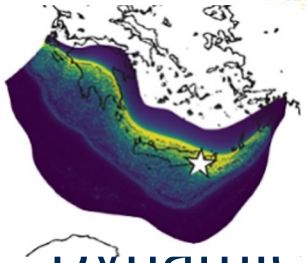
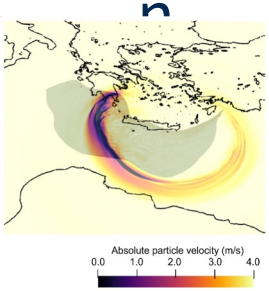
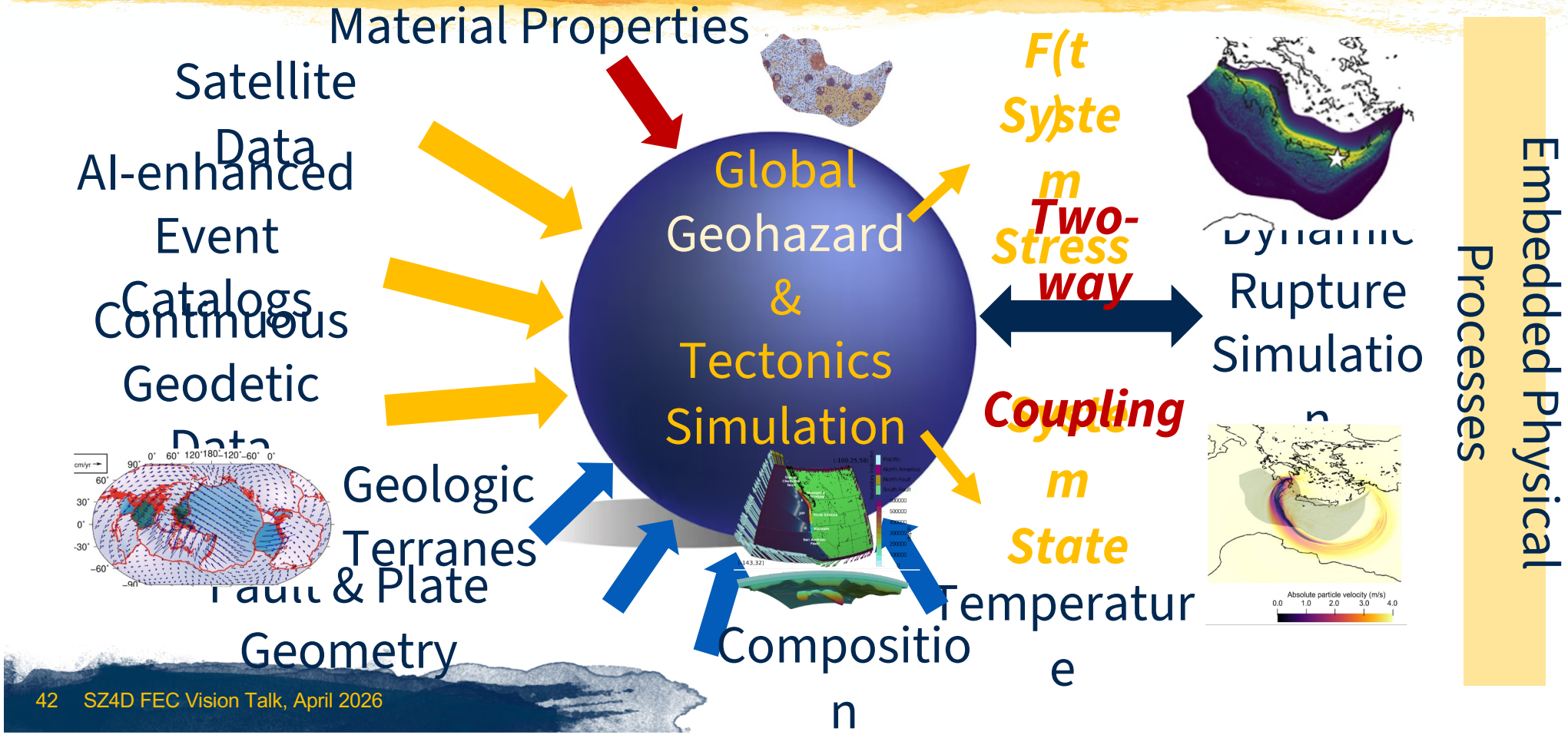
Embedded Physical Processes







Vision for Physics-based Earthquake Forecasting



Proposed workflow for regional stress-state and earthquake models

MA-4.4 | Outcomes and Milestones

Observations & Verification of Event Interactions

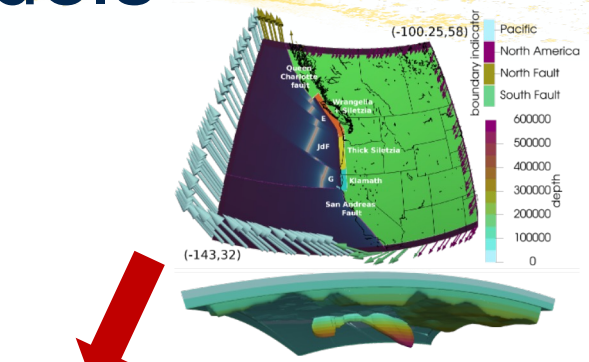
YEAR 2 Develop regional geodynamic model

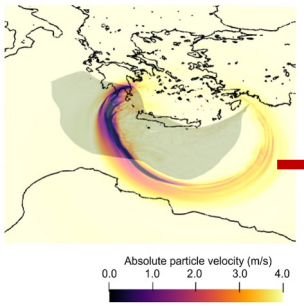
YEAR 3 Validate and release stress-state models on Data Hub with tools to extract stress on surface

YEAR 4 Develop and validate dynamic earthquake rupture models for 2010 Maule megathrust event

YEAR 5 Develop and validate dynamic earthquake rupture models for 2015 Ilapel megathrust event

With MA-1 intergrate information from the physics-based model results into the forecasting



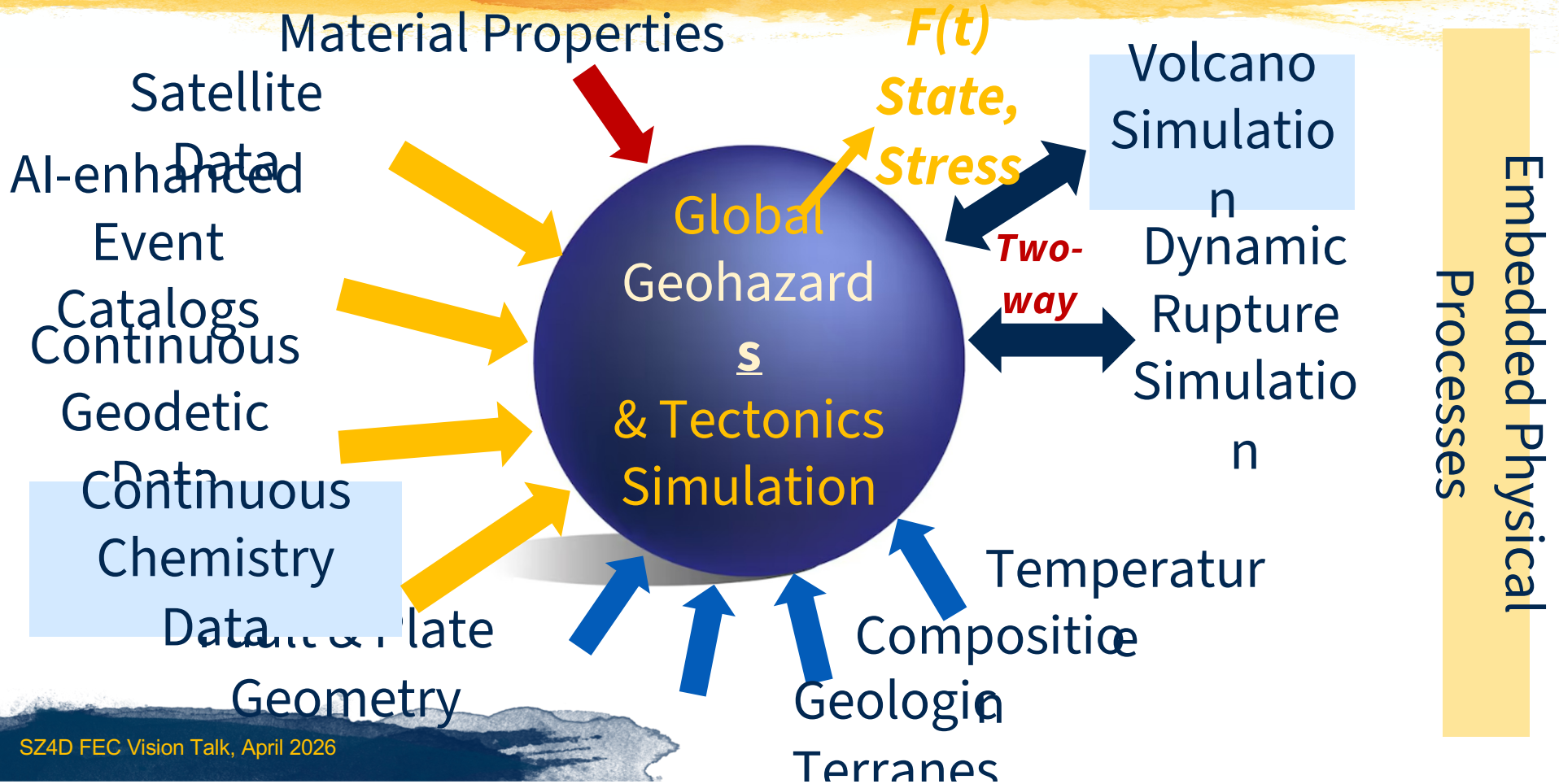


AI-enhanced catalogs

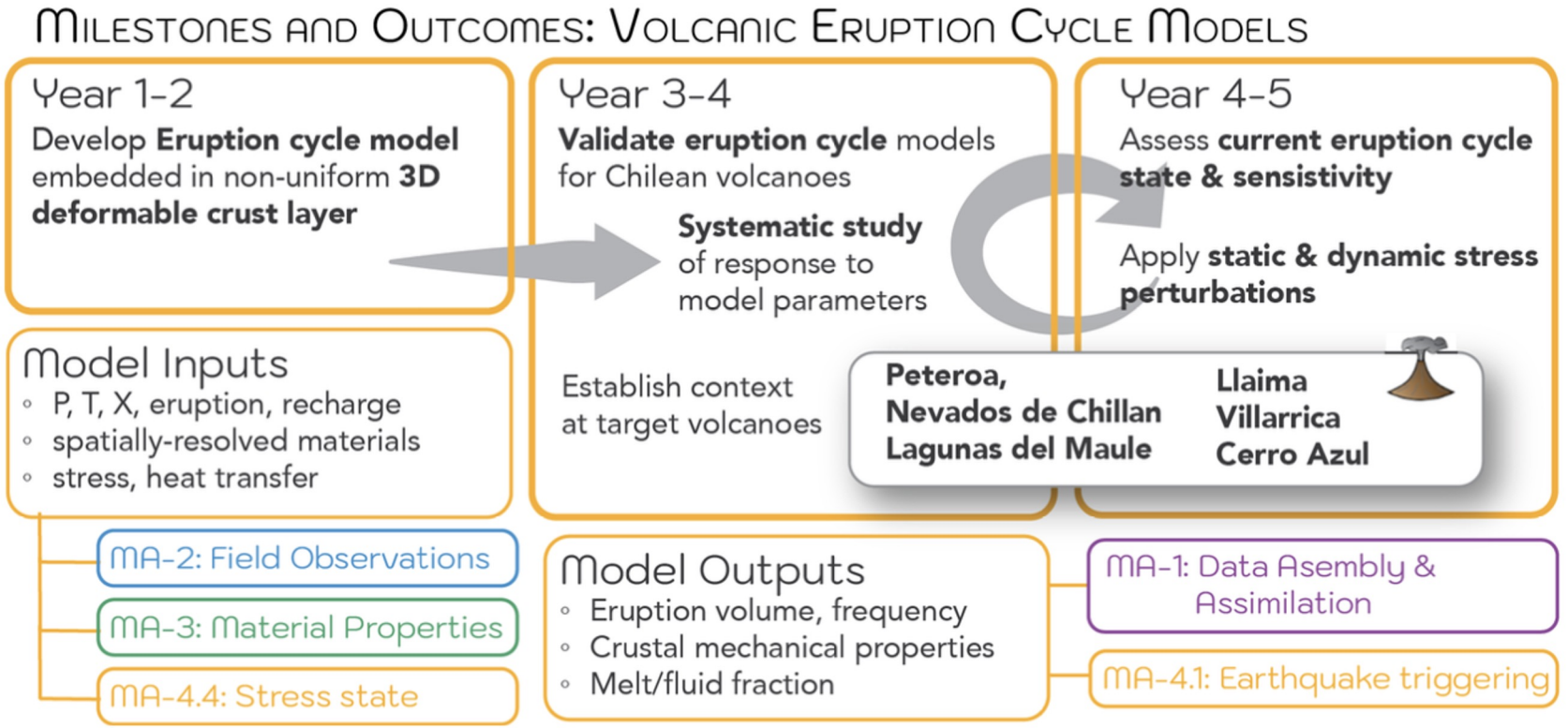
Physics-based Forecasting Model

SZ4D NSF Geohazards Proposal

Vision Extends to Volcanic Hazards

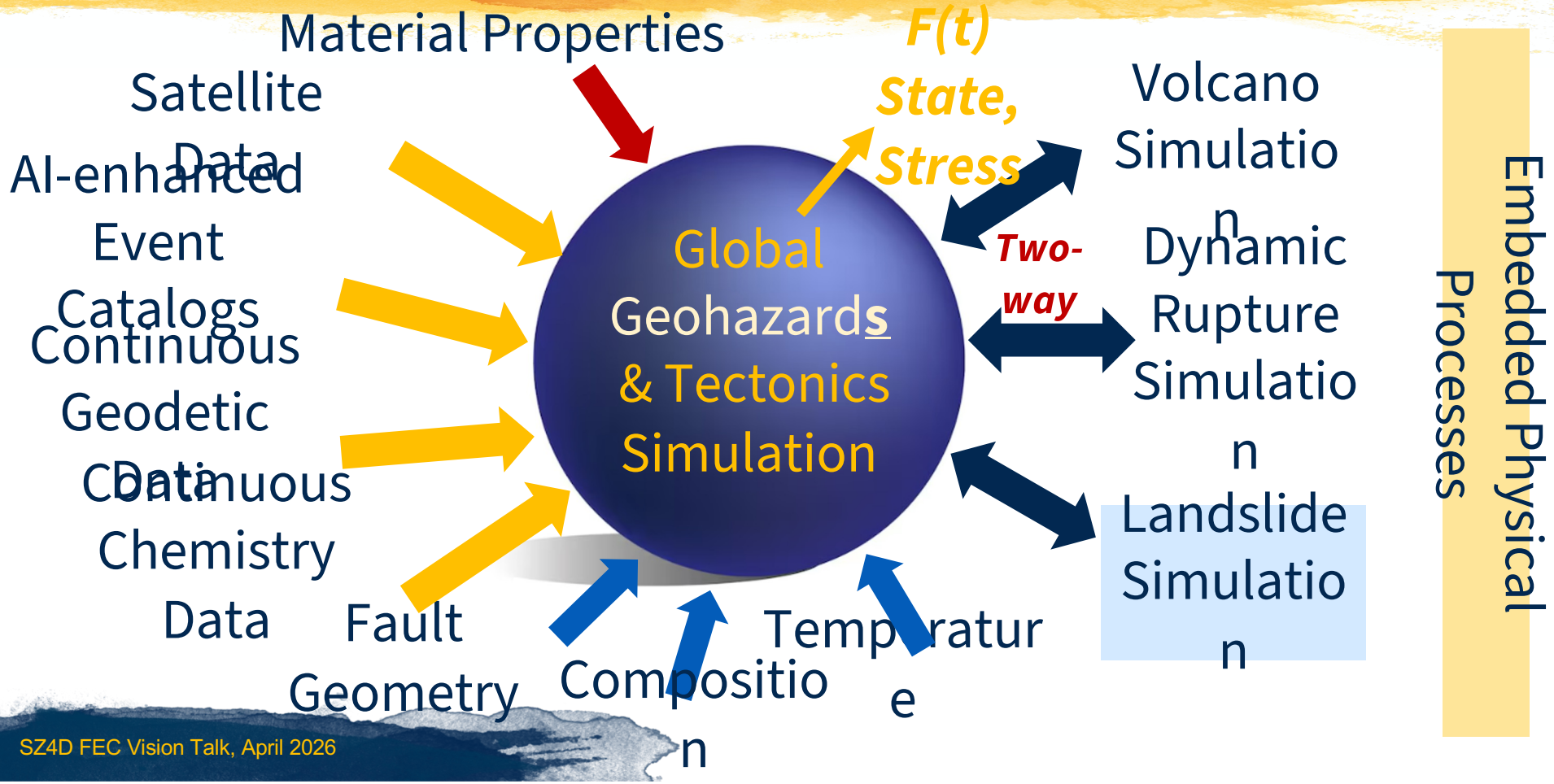


Proposed Workflow for Coupled Volcanic Eruption & Stress-state model

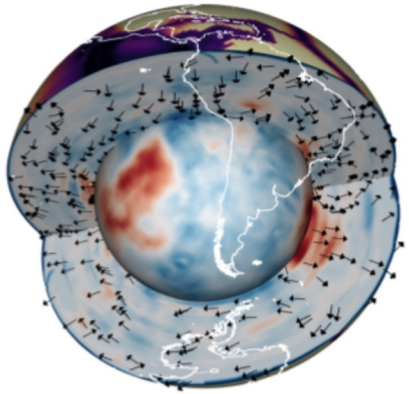


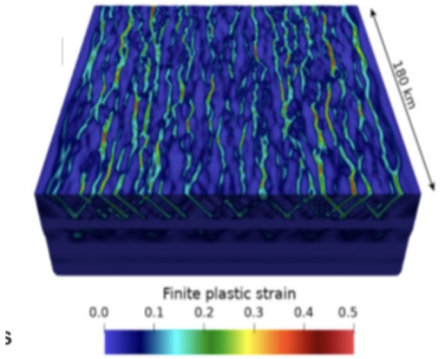
SZ4D NSF Geohazards Proposal

Vision Extends to Landslides

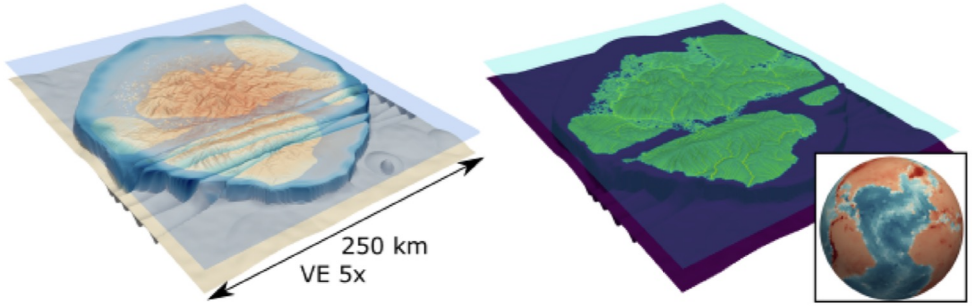


Coupling LandLAB & Aspect



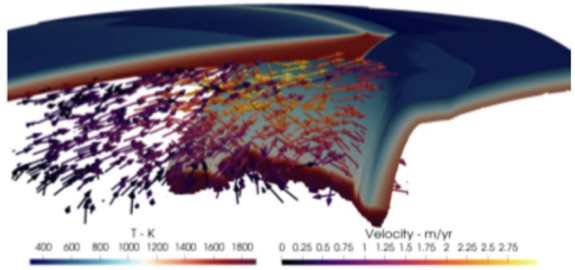


LandLAB



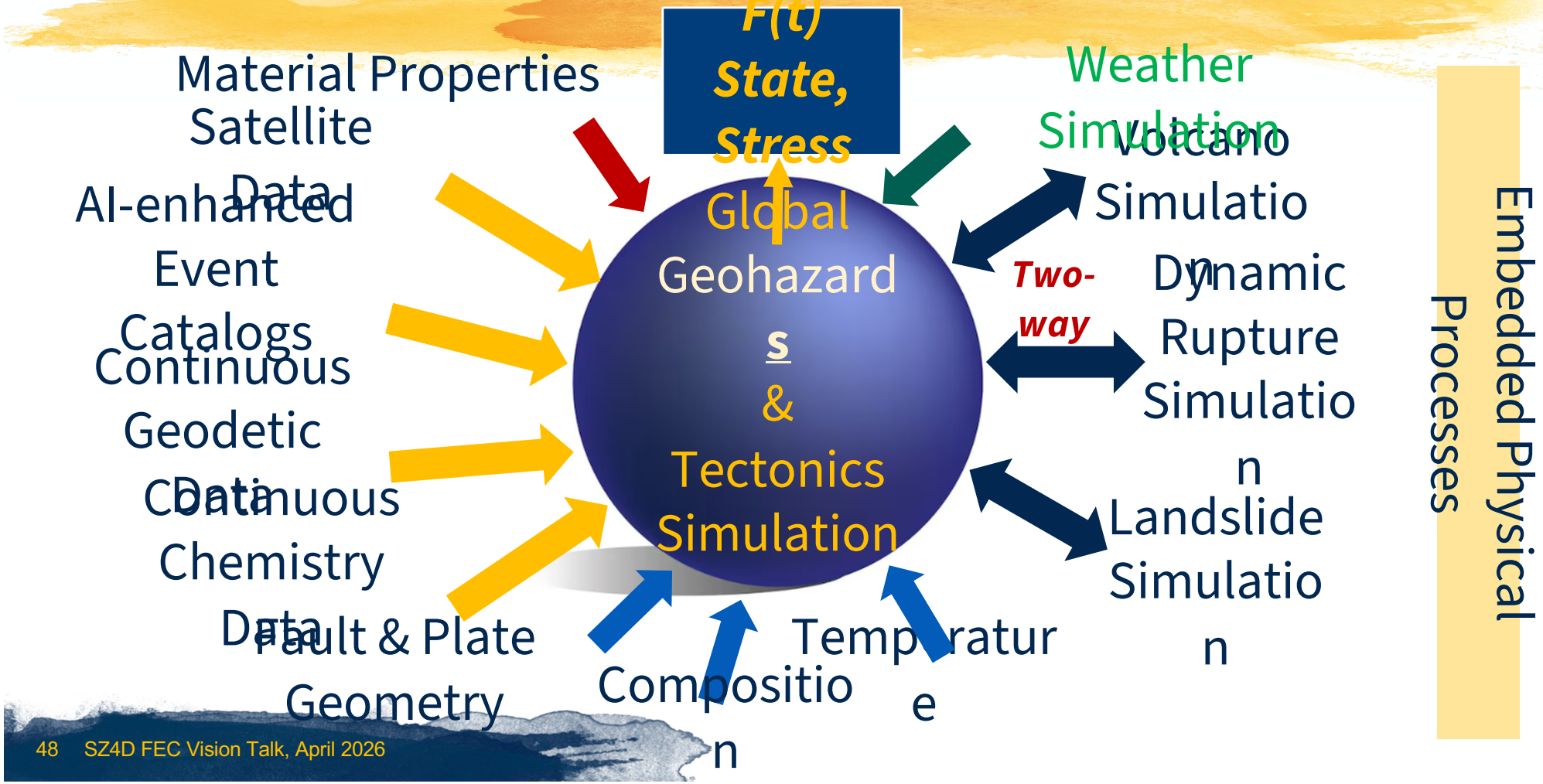
Example of a Landlab-based Surface Processes Model

Aspect



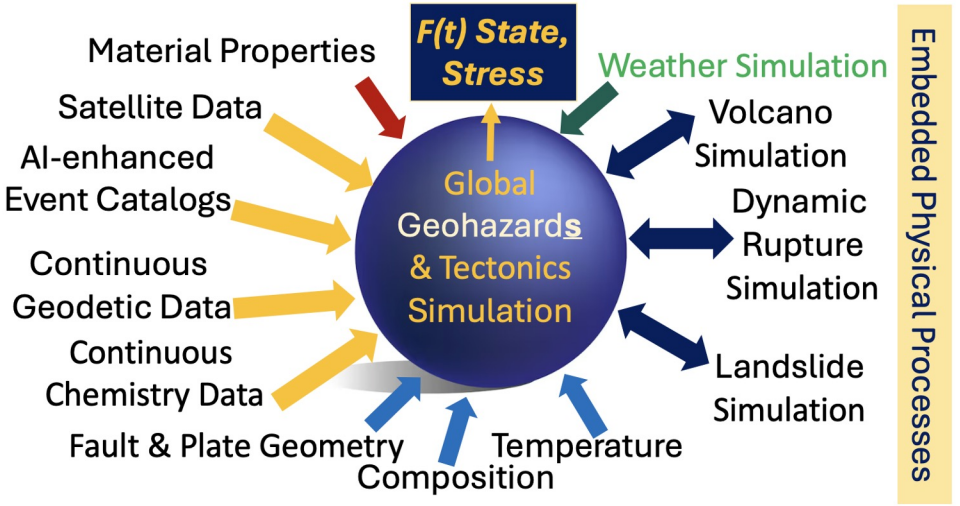
Gan, Tian; Bangerth, Wolfgang; Behn, Mark D.; Heister, Timo; Hutton, Eric; Karlstrom, Leif; et al. (2025). Coupling Bulk and Surface Processes in Simulating the Solid Earth with ASPECT and Landlab. figshare. Poster. https://doi.org/10.6084/m9.figshare.29646971.v1

Vision Extends to All Solid Earth GeoHazards



Why do we need this vision?

Placing events in their full temporal, spatial and scientific context is critical, as multiple hazards share similar physical processes of flow and failure, and react to the same stressors.



Why do we need this vision?

- Organize
- Catalyze
- Inspire

Placing events in their full temporal, spatial and scientific context is critical, as multiple hazards share similar physical processes of flow and failure, and react to the same stressors.