

# Mondaic



# Outline

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- Overview
- Components
- Applications
- Mondaic
- Tutorial (on Thursday)

# Salvus

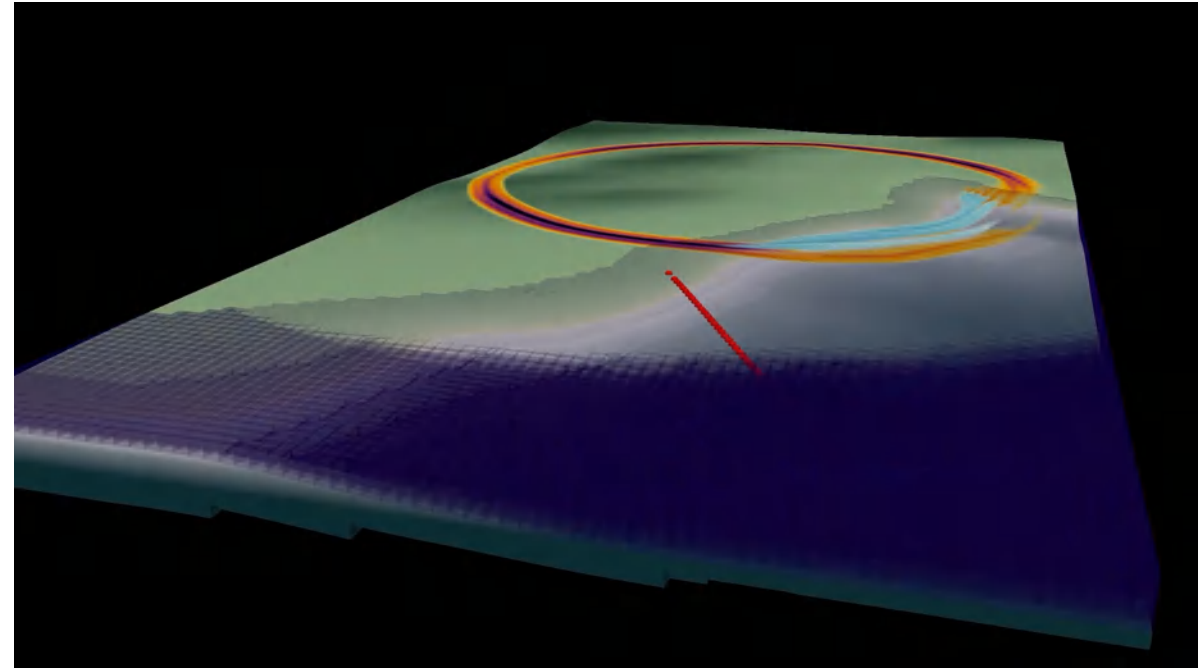
## Overview



# Waveform modeling and inversion across the scales



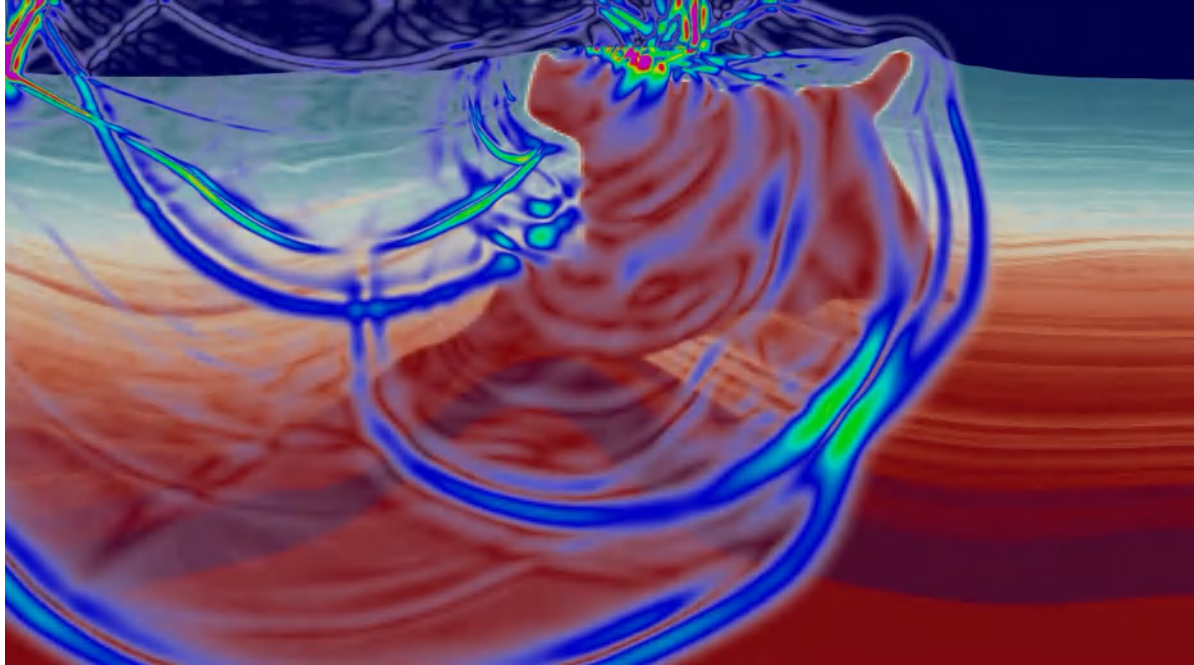
Global-scale Seismology



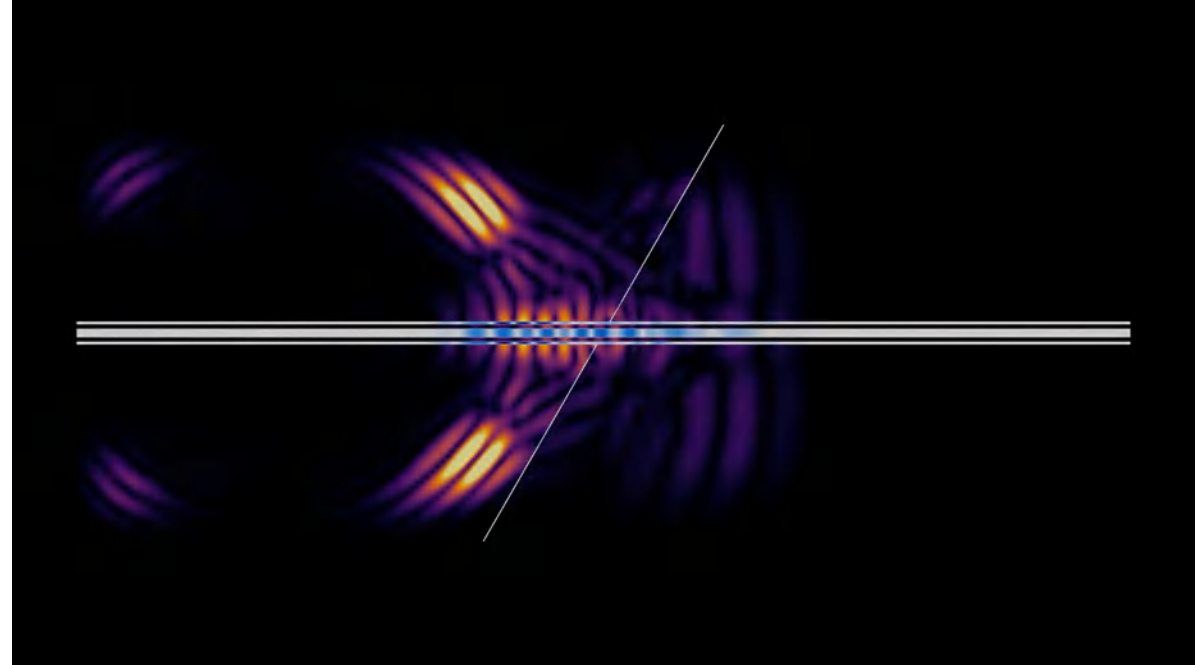
Regional-scale Seismology



# Waveform modeling and inversion across the scales



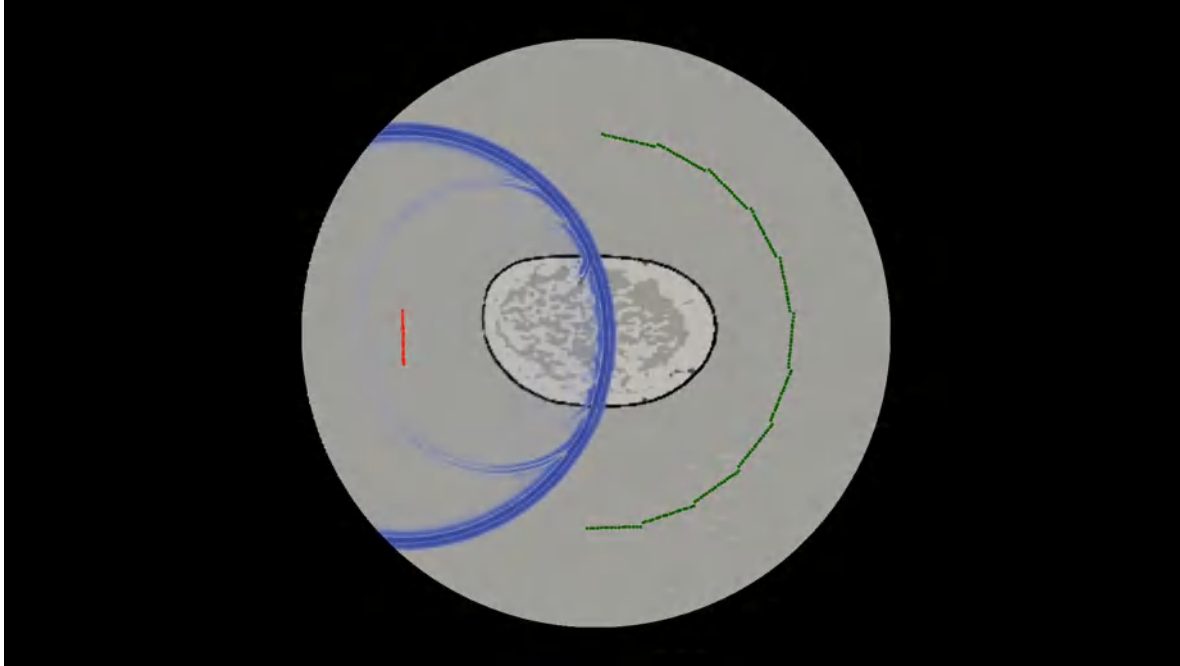
Exploration Geophysics



Borehole Acoustics



# Waveform modeling and inversion across the scales



Medical imaging



Nondestructive testing

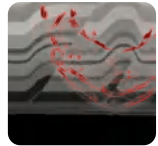


# Solving problems across the scales

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# Solving problems across the scales



2D

3D

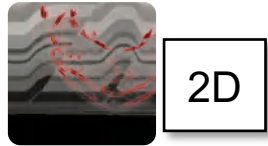


dimension

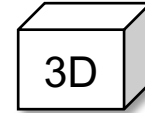




# Solving problems across the scales



2D



3D



dimension

acoustic

elastic

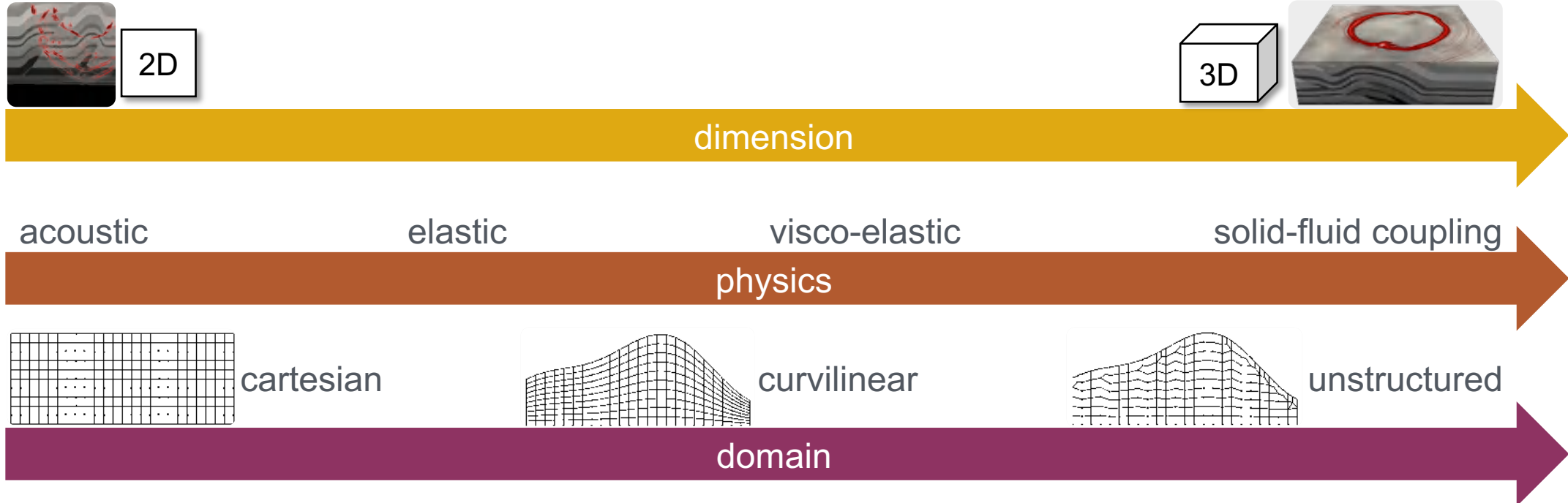
visco-elastic

solid-fluid coupling

physics

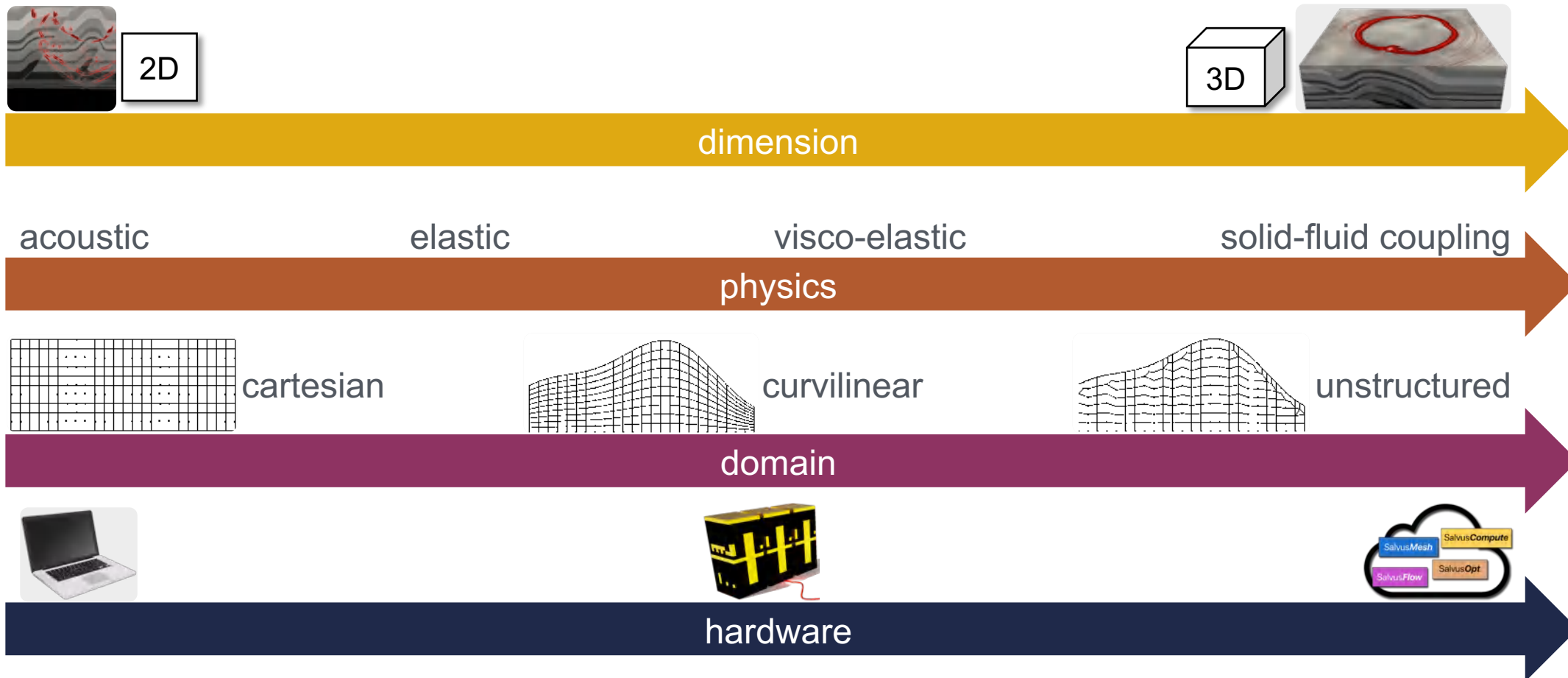


# Solving problems across the scales





# Solving problems across the scales





# Solving problems across the scales



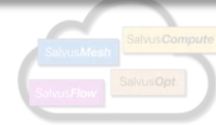
2D



3D



Salvus is a high-performance software package tailored for **applied waveform modeling and full-waveform inversion**, focusing on performance, reproducibility, and ease of use.



hardware

# Components

How does Salvus work?



# Components

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Salvus**Compute**

Salvus**Mesh**

Salvus**Flow**

Salvus**Opt**

Salvus**Project**



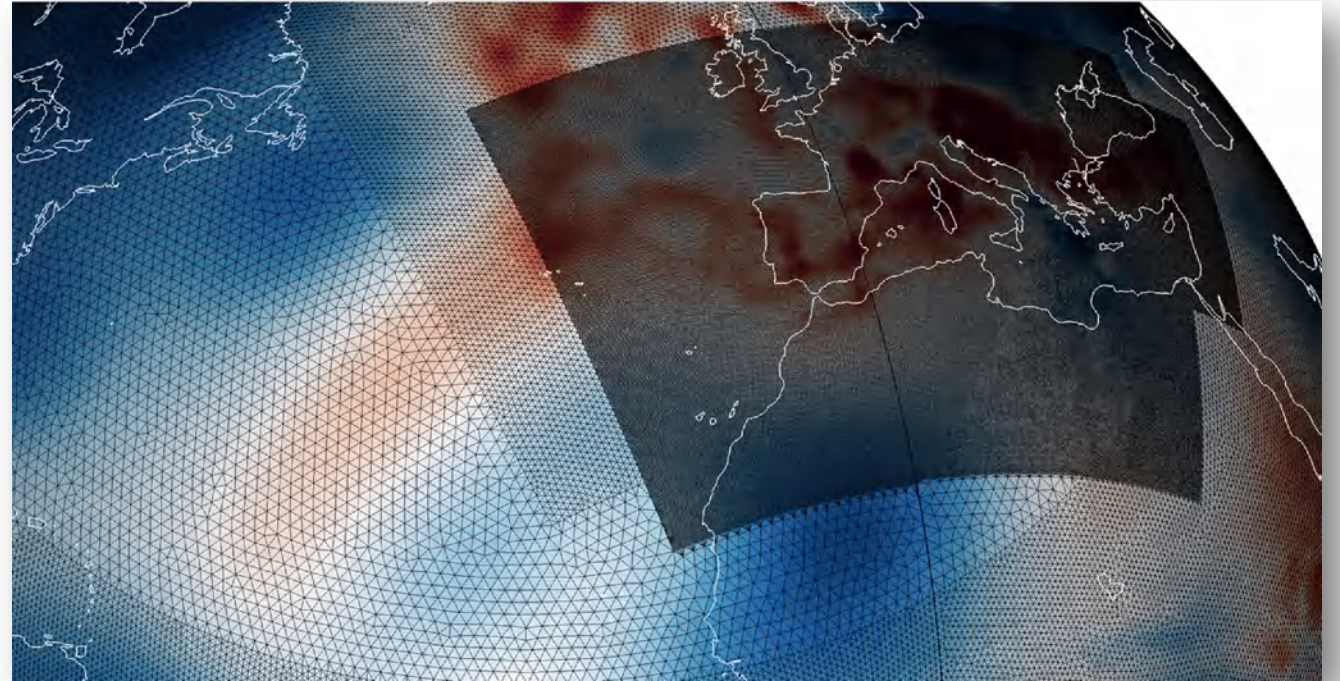
# Salvus**Compute**

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# SalvusCompute

- Began development within the Collaborative Seismic Earth Model project at ETH Zurich

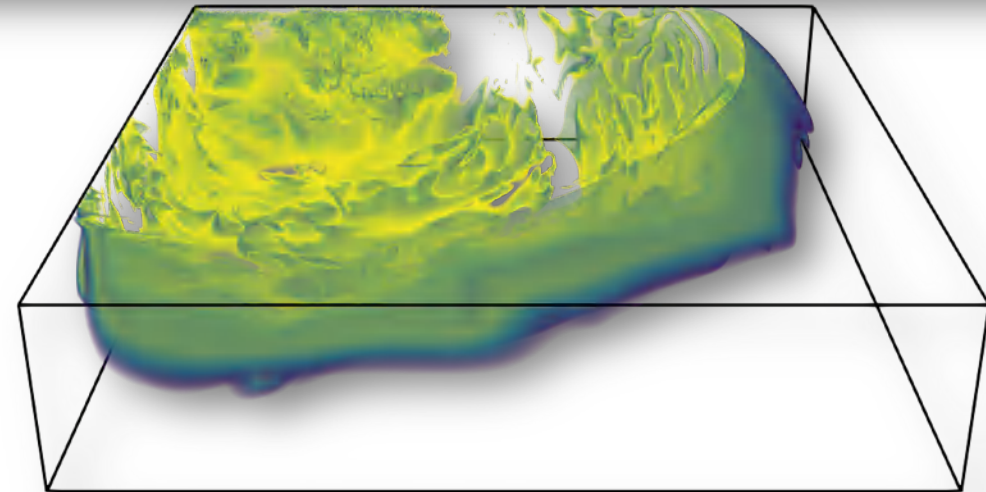
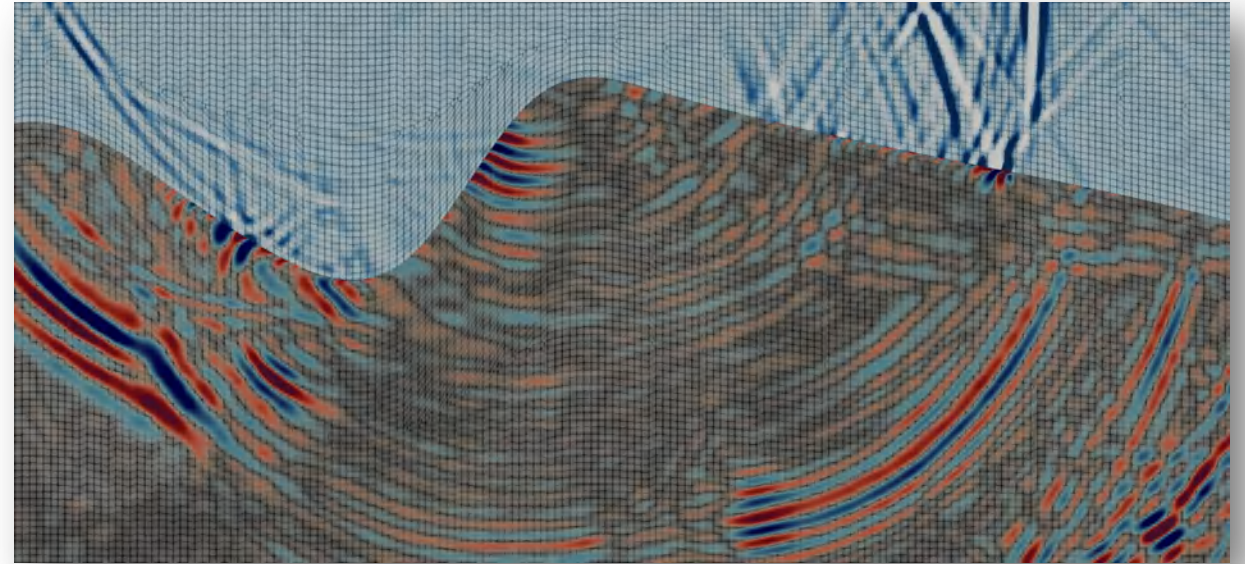






# SalvusCompute

- Began development within the Collaborative Seismic Earth Model project at ETH Zurich
- Arbitrary-order Continuous-Galerkin spectral-element solver<sup>1,2</sup>
  - 2- and 3-dimensions
  - Coupled fluid / solid physics



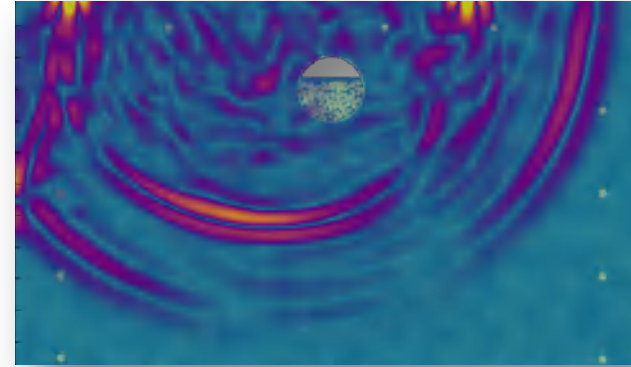
<sup>1</sup>Komatitsch and Tromp, Spectral-element simulations of global seismic wave propagation—I. Validation, *Geophysical Journal International*, Volume 149, Issue 2, May 2002

<sup>2</sup>Afanasiev et al., Modular and flexible spectral-element waveform modelling in two and three dimensions, *Geophysical Journal International*, Volume 216, Issue 3, 1 March 2019.



# SalvusCompute

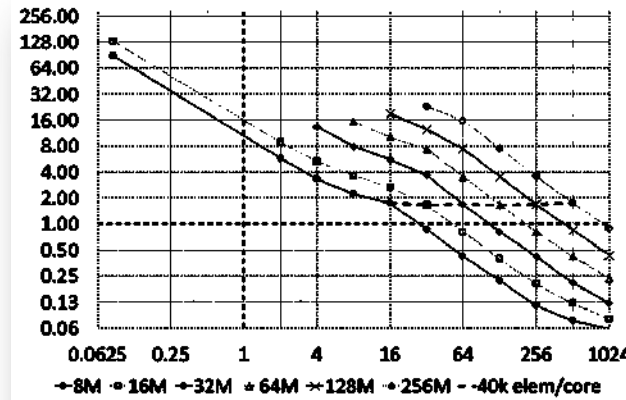
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- Arbitrary-order Continuous-Galerkin spectral-element solver<sup>1,2</sup>
  - 2- and 3-dimensions
  - Coupled fluid / solid physics
- Run-time parallel mesh decomposition
  - PETSc DMplex<sup>3</sup>
  - Scalable from laptops to supercomputers



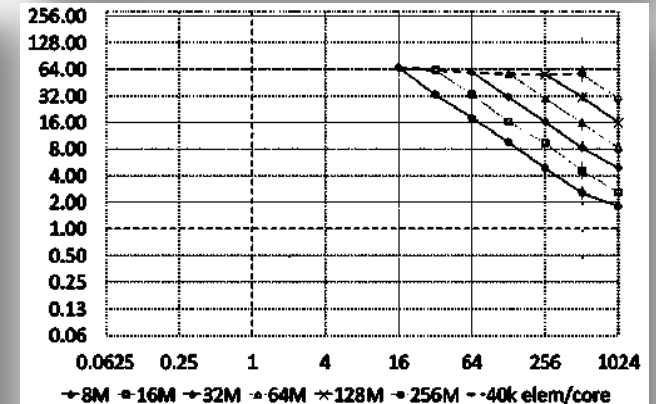
A successful simulation run of the 2020 Mw 7 Samos-Izmir earthquake  
19 APRIL 2021



ChEESE had successfully run a simulation of the Mw 7 Samos-Izmir earthquake that affected Turkey in 2020 as part of its work on Pilot Demonstrator 1 "Urgent Seismic Simulations". ChEESE researchers used waveform modelling software Salvus (provided by Mondaic) which is embedded in the project's Urgent Computing (UC)



(c) Topological interpolation



(f) 1000 Salvus timesteps

<sup>1</sup>Komatitsch and Tromp, Spectral-element simulations of global seismic wave propagation—I. Validation, *Geophysical Journal International*, Volume 149, Issue 2, May 2002

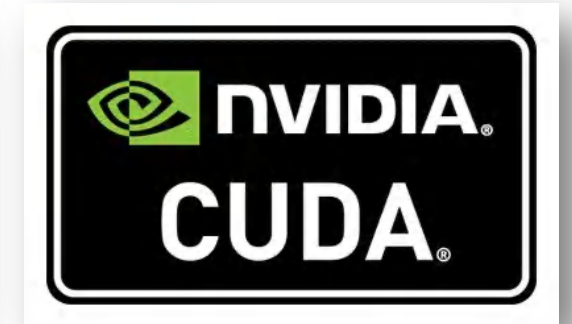
<sup>2</sup>Afanasiev et al., Modular and flexible spectral-element waveform modelling in two and three dimensions, *Geophysical Journal International*, Volume 216, Issue 3, 1 March 2019.

<sup>3</sup>Hapla et al., Fully parallel mesh I/O using PETSc DMplex with an application to waveform modelling, *Accepted by SIAM SISC*, 2020.



# SalvusCompute

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- Arbitrary-order Continuous-Galerkin spectral-element solver<sup>1,2</sup>
  - 2- and 3-dimensions
  - Coupled fluid / solid physics
- Run-time parallel mesh decomposition
  - PETSc DMPLex<sup>3</sup>
  - Scalable from laptops to supercomputers
- Modern C++ and CUDA



<sup>1</sup>Komatitsch and Tromp, Spectral-element simulations of global seismic wave propagation—I. Validation, *Geophysical Journal International*, Volume 149, Issue 2, May 2002

<sup>2</sup>Afanasiev et al., Modular and flexible spectral-element waveform modelling in two and three dimensions, *Geophysical Journal International*, Volume 216, Issue 3, 1 March 2019.

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**Mondaic.** Full waveform solutions

Salvus*Compute*

Salvus*Mesh*

Salvus*Flow*

Salvus*Opt*

Salvus*Project*

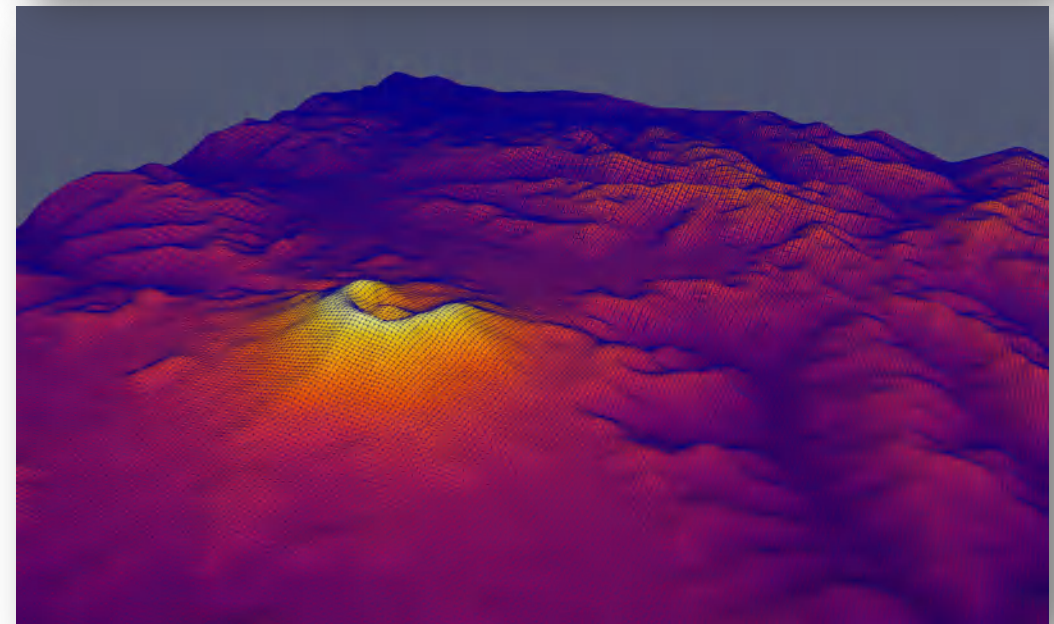
# Salvus*Mesh*

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# SalvusMesh

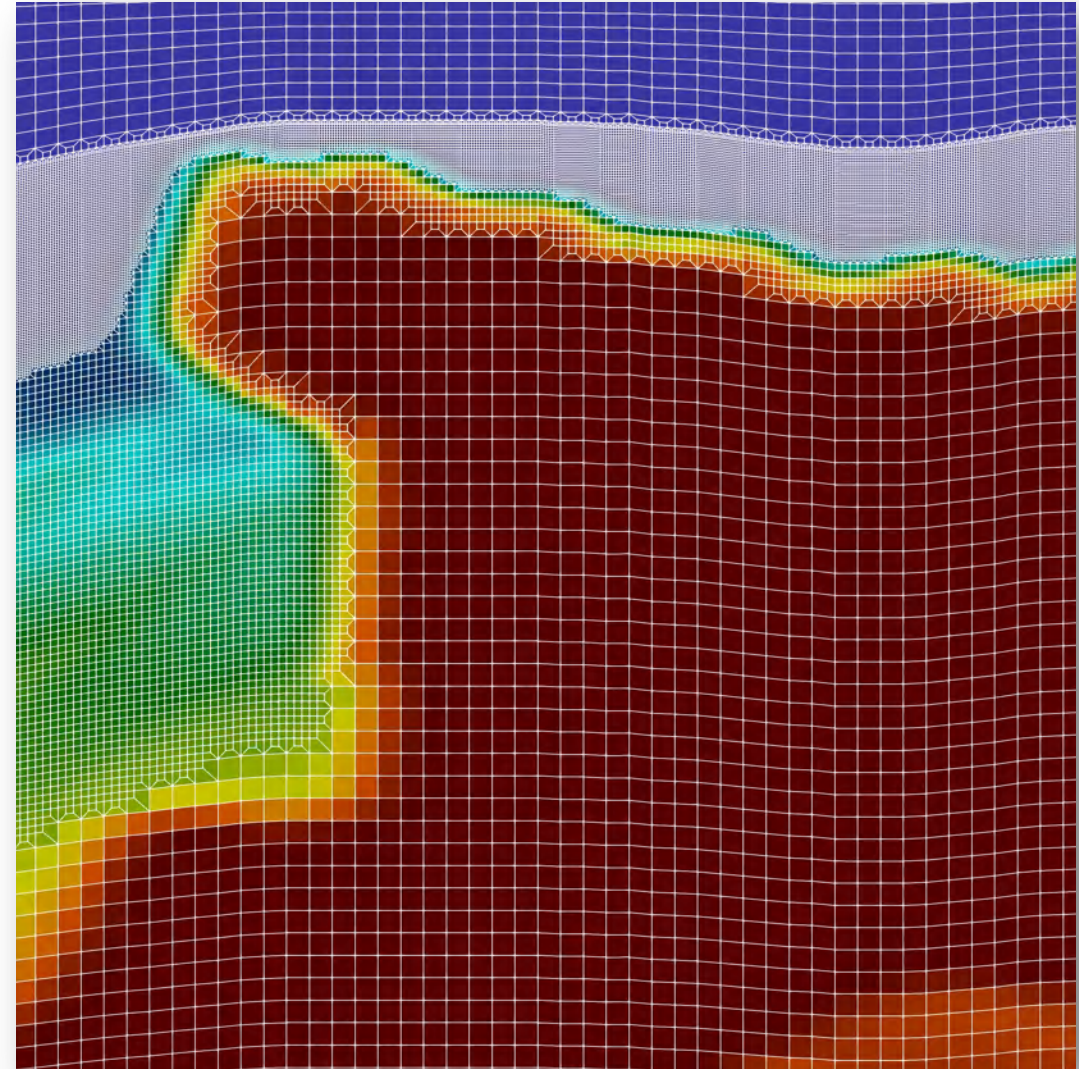
- Built for problems in geophysics
  - Variable velocity models
  - Automatic real-Earth topography





# SalvusMesh

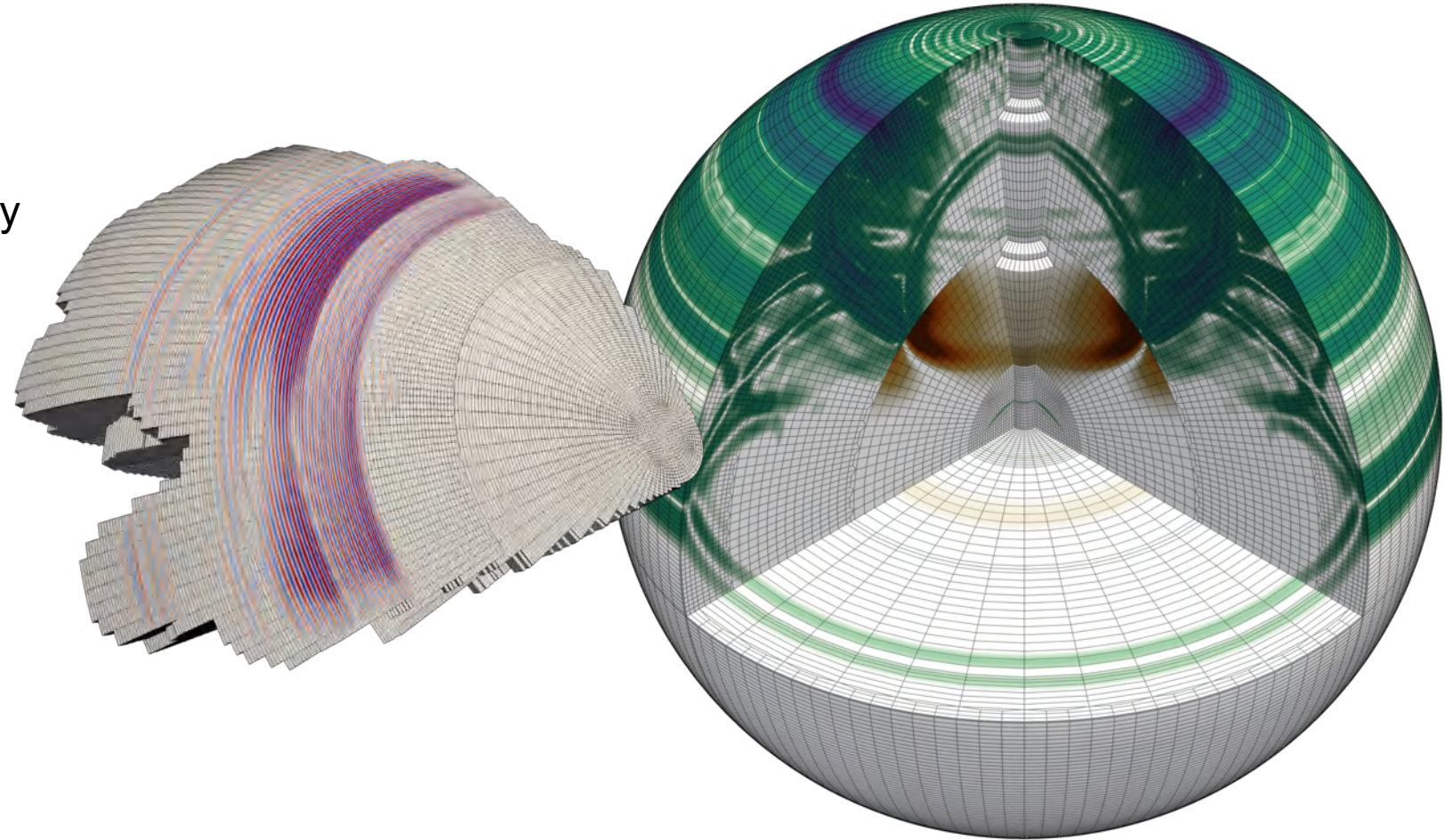
- Built for problems in geophysics
  - Variable velocity models
  - Automatic real-Earth topography
- Conforming quad / hex elements
  - Automatic refinements





# SalvusMesh

- Built for problems in geophysics
  - Variable velocity models
  - Automatic real-Earth topography
- Conforming quad / hex elements
  - Automatic refinements
- Target-oriented mesh design<sup>1</sup>
  - Data adaptive
  - Solution adaptive



<sup>1</sup>van Driel et al., Accelerating numerical wave propagation using wavefield adapted meshes. Part I: forward and adjoint modelling, *Geophysical Journal International*, Volume 221, Issue 3, June 2020



# SalvusMesh

- Built for problems in geophysics
  - Variable velocity models
  - Automatic real-Earth topography
- Conforming quad / hex elements
  - Automatic refinements
- Target-oriented mesh design<sup>1</sup>
  - Data adaptive
  - Solution adaptive
- Whole-earth topography and bathymetry
  - 3-D Fluid oceans
  - Interface to GMRT for local domains

```
In [1]: import salvus.namespace as sn

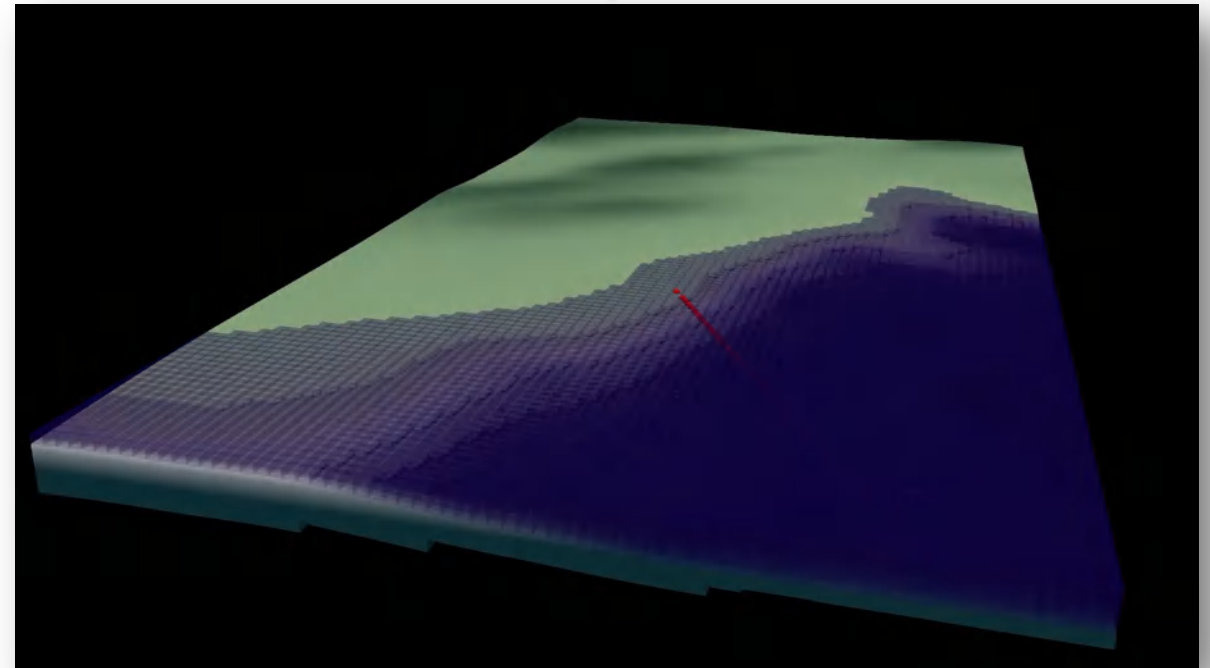
Define your spatial domain

In [2]: d = sn.domain.dim3.UtmDomain.from_spherical_chunk(
        min_latitude=36.6,
        max_latitude=37.0,
        min_longitude=-122.0,
        max_longitude=-121.0,
        )

Download topography and bathymetry

In [3]: d.download_topography_and_bathymetry(
        filename="topo.nc", buffer_in_degrees=2.0, resolution="default"
        )

Downloading topography: 2.88MiB [00:01, 1.65MiB/s]
```



<sup>1</sup>van Driel et al., Accelerating numerical wave propagation using wavefield adapted meshes. Part I: forward and adjoint modelling, *Geophysical Journal International*, Volume 221, Issue 3, June 2020





**Mondaic.** Full waveform solutions

Salvus*Compute*

Salvus*Mesh*

Salvus*Flow*

Salvus*Opt*

Salvus*Project*

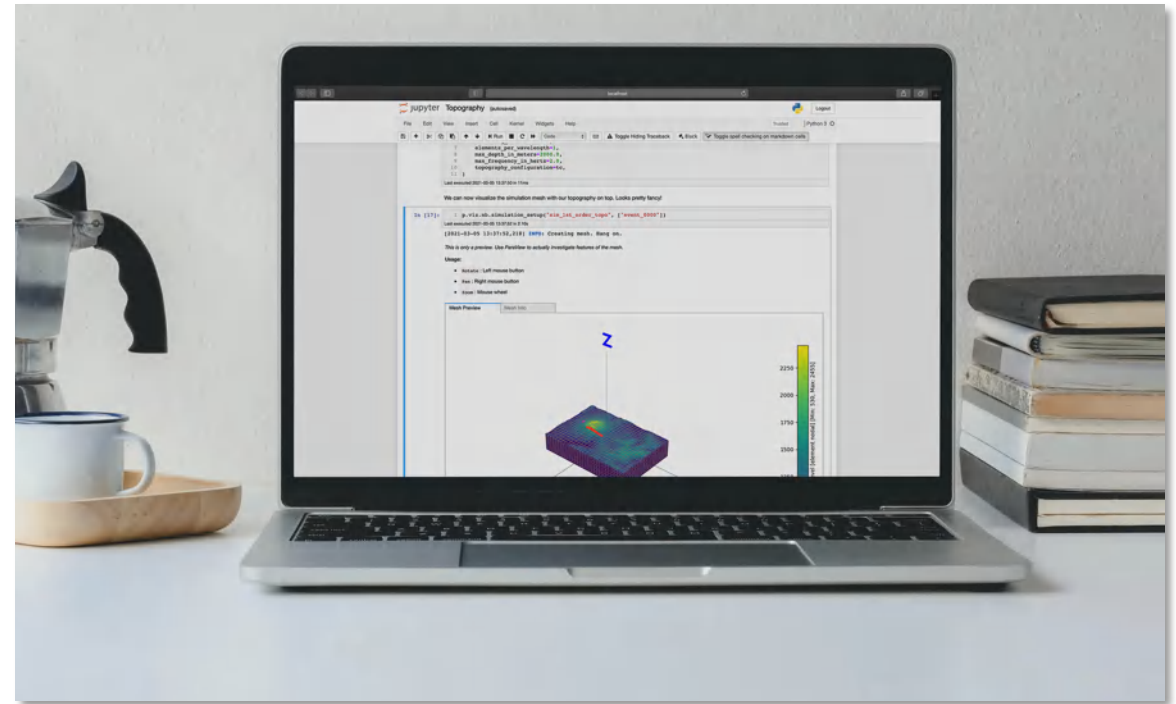
# Salvus*Flow*

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# SalvusFlow

- How the user interacts with Salvus
  - Python interface
  - Scripts or Jupyter notebooks

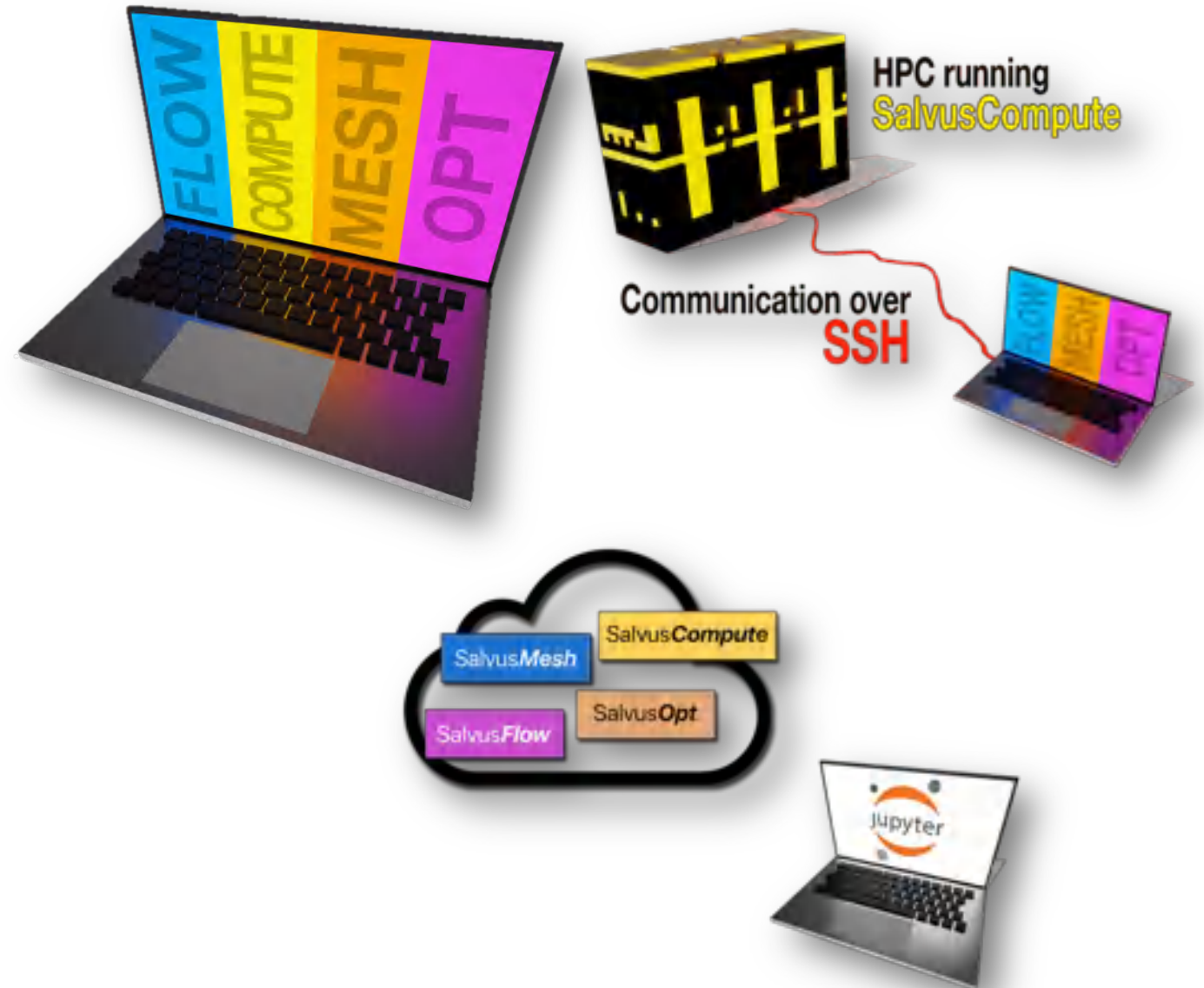


```
# Create the simulation object and combine all the information.
w = simple_config.simulation.Waveform(mesh=m.create_mesh())
# Sources and receivers will be placed exactly relative to the
# local mesh surface. Please refer to the sources and receivers
# documentation for more details.
w.add_sources(source)
w.add_receivers(
    simple_config.receiver.seismology.parse(
        inv, dimensions=3, fields=["displacement"]
    )
)
```



# SalvusFlow

- How the user interacts with Salvus
  - Python interface
  - Scripts or Jupyter notebooks
- Job execution on local and remote sites



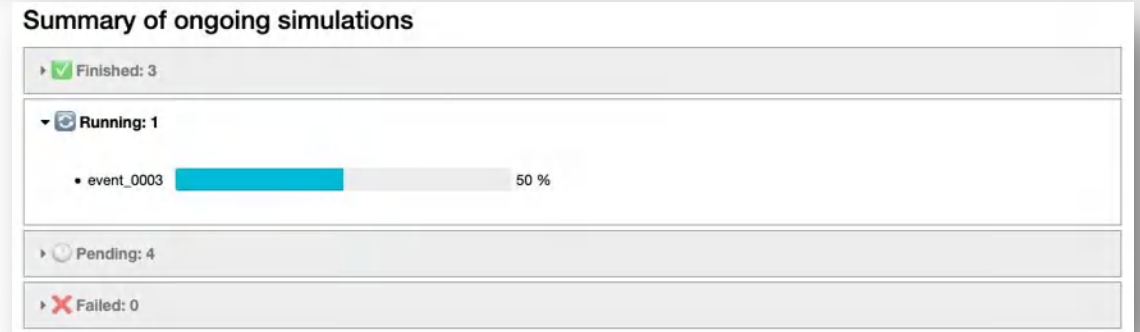


# SalvusFlow

- How the user interacts with Salvus
  - Python interface
  - Scripts or Jupyter notebooks
- Job execution on local and remote sites
- Uploading / downloading of input / output files
  - Input file validation
  - Queue monitoring

```
In [10]: import salvus  
  
In [11]: w = salvus.namespace.simple_config.simulation.Waveform()  
  
In [12]: w.output.volume_data.fields = ["stran", "displacement"]
```

```
ValueError: `item` must be one of: "displacement", "velocity", "ac  
celeration", "fem-ku-acoustic", "inverse-mass-matrix-acoustic", "f  
em-ku-elastic", "inverse-mass-matrix-elastic", "gradient-of-displa  
cement", "stress-tensor", "stress", "strain", "phi", "phi_t", "phi  
_tt", "gradient-of-phi", "m1-times-gradient-of-phi", "absorbing-ga
```





# SalvusFlow

- How the user interacts with Salvus
  - Python interface
  - Scripts or Jupyter notebooks
- Job execution on local and remote sites
- Uploading / downloading of input / output files
  - Input file validation
  - Queue monitoring
- “Abstracts away” the compute resources

```
(salvus_0.11) ~ salvus-flow init-site tiny_gpu
Successfully initialized site:
> Name: tiny_gpu
  Site Type: ssh
  Default Ranks: 2
  Max Ranks: 24
  Salvus Binary: /home/mafanasiyev/Development/salvus/build/release_single_clang/bin/salvus
  Run Directory: /home/mafanasiyev/Data/salvus_flow/run
  Temp Directory: /mnt/data/salvus_flow
  Update Interval in Seconds: 1.0
  Use License Tokens: False
  Use CUDA Capable GPUs: True
  SSH Settings:
    Hostname: tiny
    Username: mafanasiyev
  Site information:
    Salvus version: 0.11.16-30-g74ce34c6-dirty
    Floating point size: 32
    Available GLL orders: [1, 2, 4]
    Available shape mapping orders: [1, 2, 4]
    Available numbers of linear solids: [5]
    Last updated: just now (Configuration did not change since last update)
```



**Mondaic.** Full waveform solutions

Salvus*Compute*

Salvus*Mesh*

Salvus*Flow*

Salvus*Opt*

Salvus*Project*

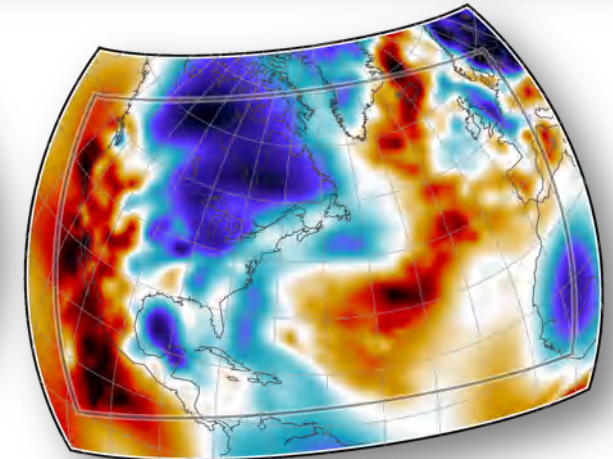
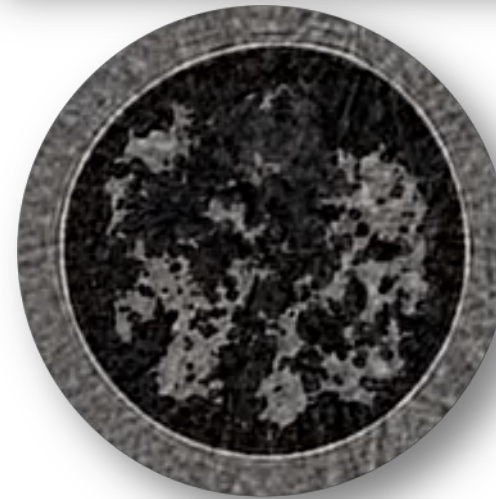
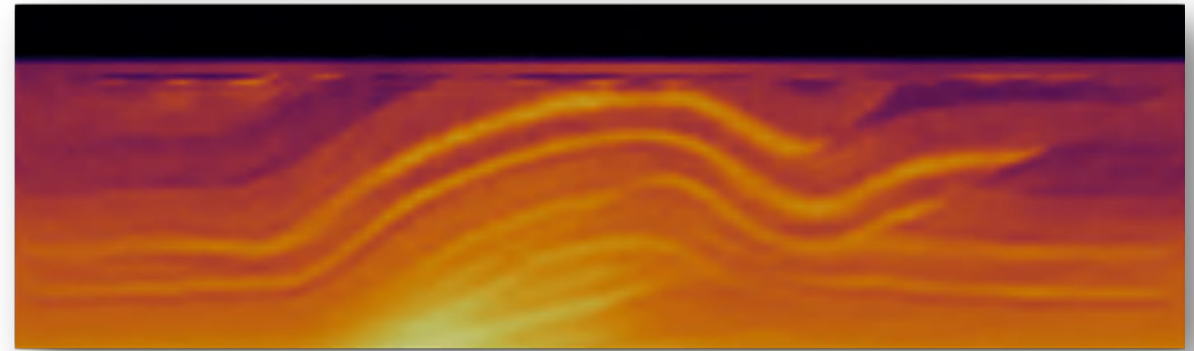
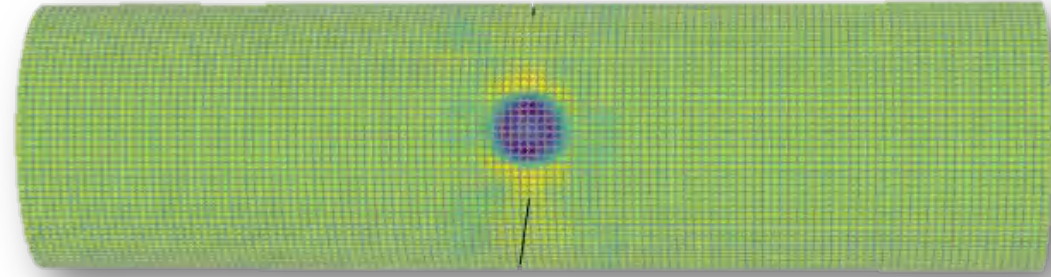
# Salvus*Opt*

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# SalvusOpt

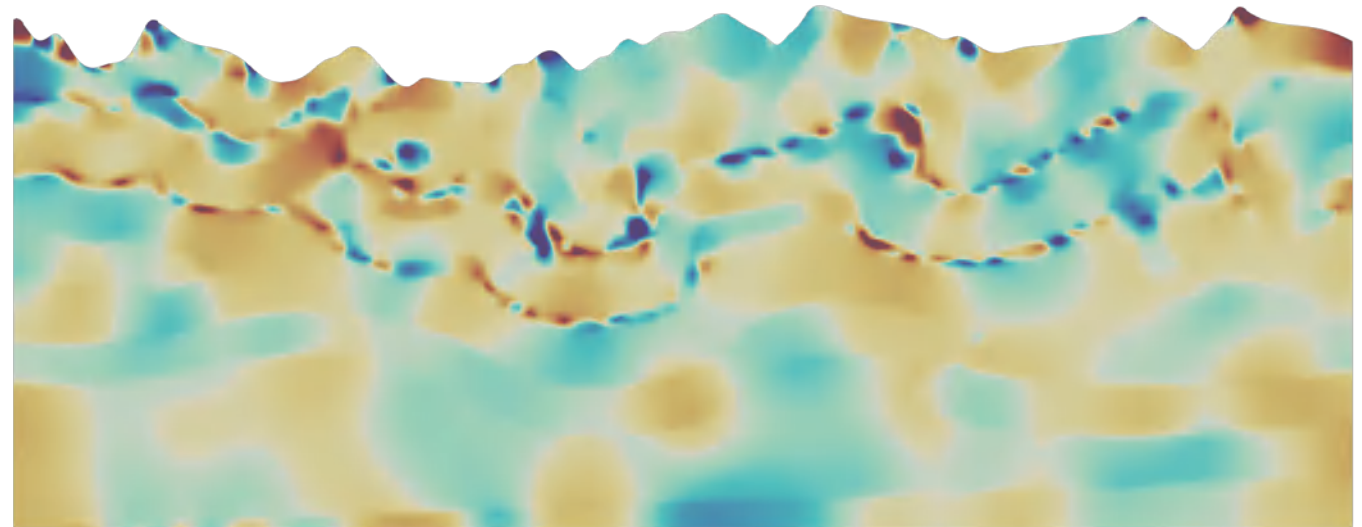
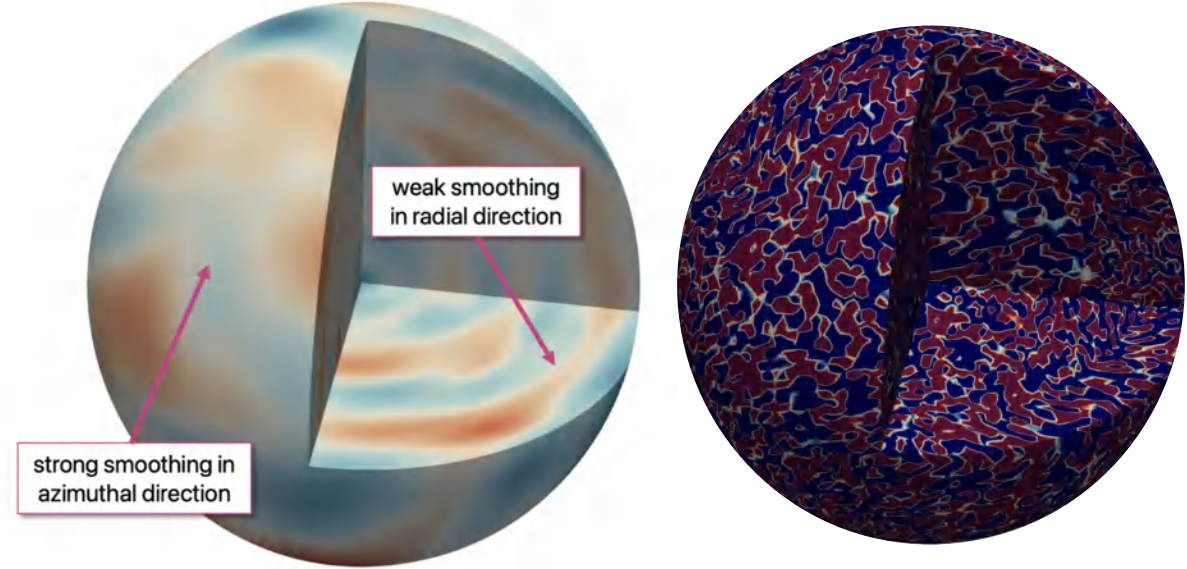
- Nonlinear optimization framework<sup>1</sup>
  - Built specifically for full-waveform inversion





# SalvusOpt

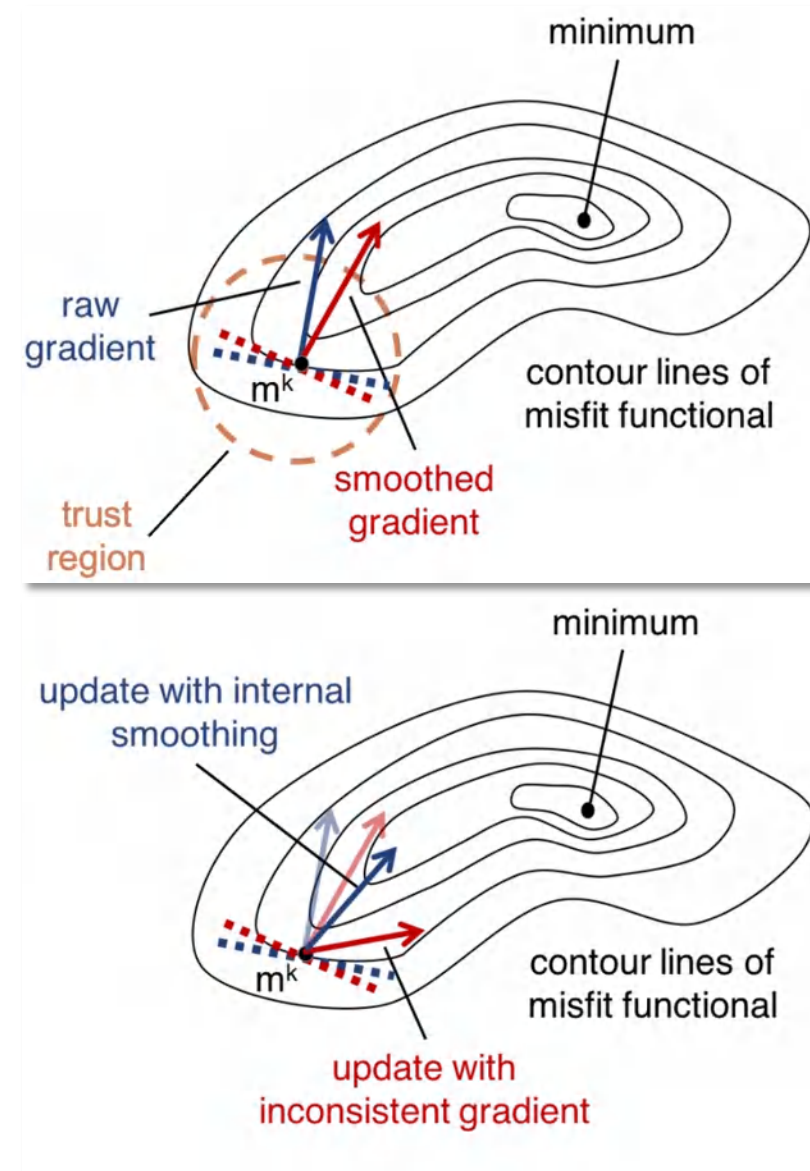
- Nonlinear optimization framework<sup>1</sup>
  - Built specifically for full-waveform inversion
- Regularization on unstructured grids
  - Wavelength and direction-dependent smoothing operators





# SalvusOpt

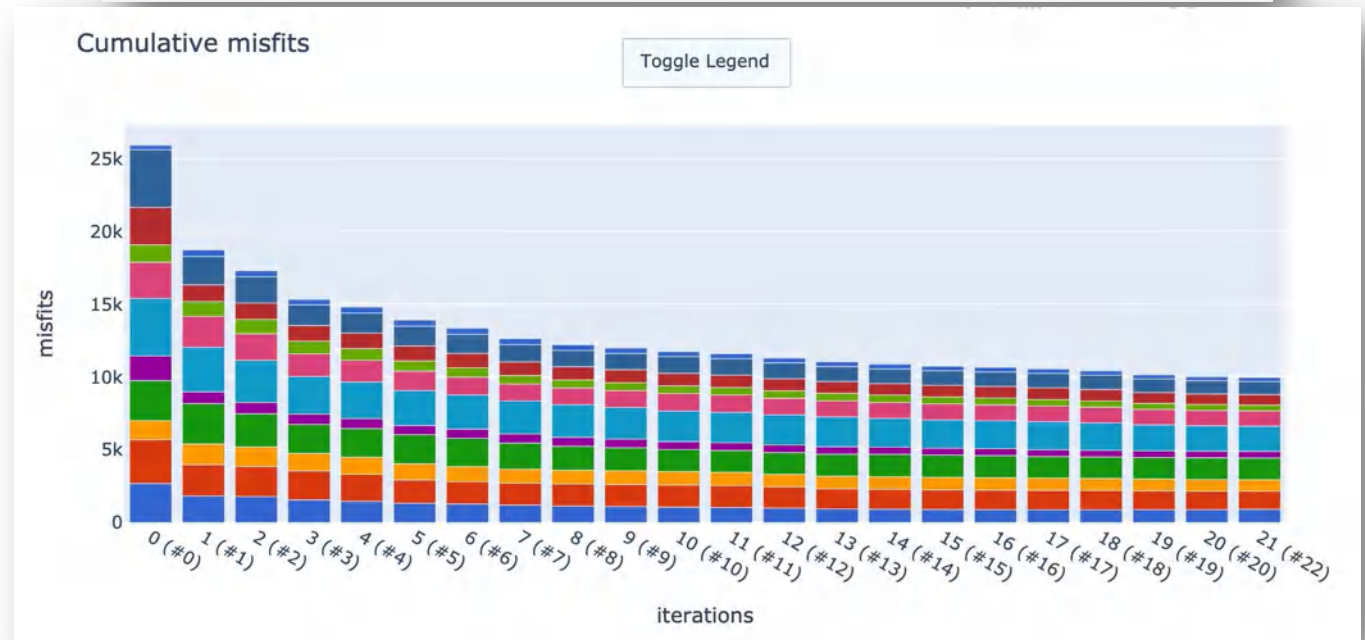
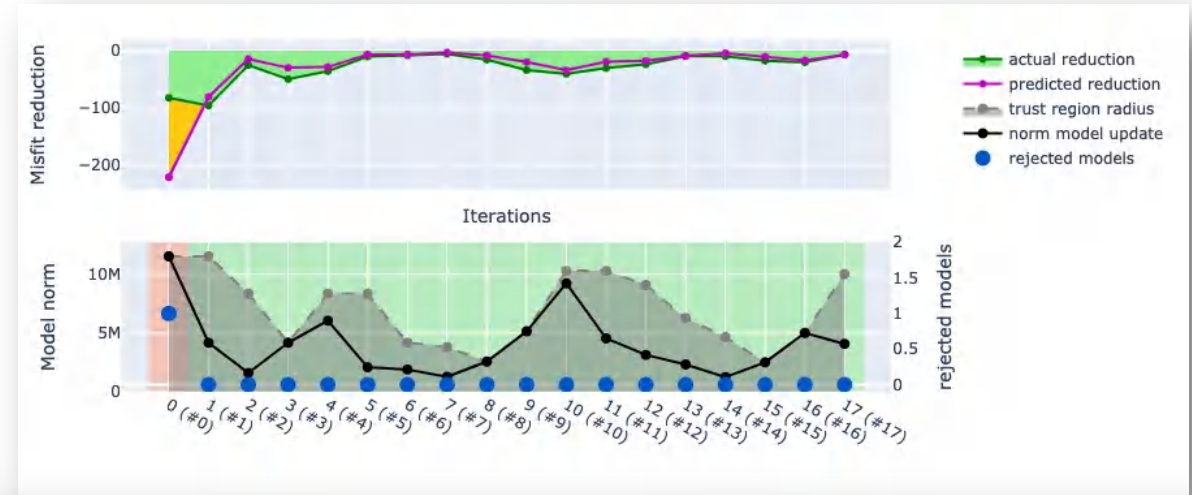
- Nonlinear optimization framework<sup>1</sup>
  - Built specifically for full-waveform inversion
- Regularization on unstructured grids
  - Wavelength and direction-dependent smoothing operators
- Trust-region Newton type methods
  - Automatic step-length determination
  - Custom or built-in parameter mappings





# SalvusOpt

- Nonlinear optimization framework<sup>1</sup>
  - Built specifically for full-waveform inversion
- Regularization on unstructured grids
  - Wavelength and direction-dependent smoothing operators
- Trust-region Newton type methods
  - Automatic step-length determination
  - Custom or built-in parameter mappings
- Interactive visual feedback
  - Model update magnitudes
  - Trust-region accuracy



<sup>1</sup>Boehm et al., Time-domain spectral-element ultrasound waveform tomography using a stochastic quasi-Newton method, *Proceedings Volume 10580, Medical Imaging 2018*, 105800H (2018)



# Salvus*Project*

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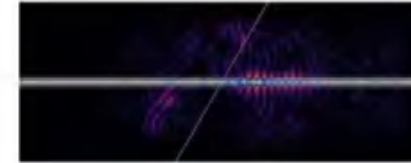
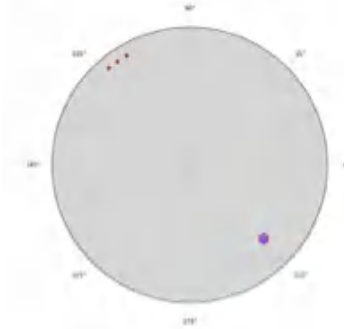


# SalvusProject

Built for...

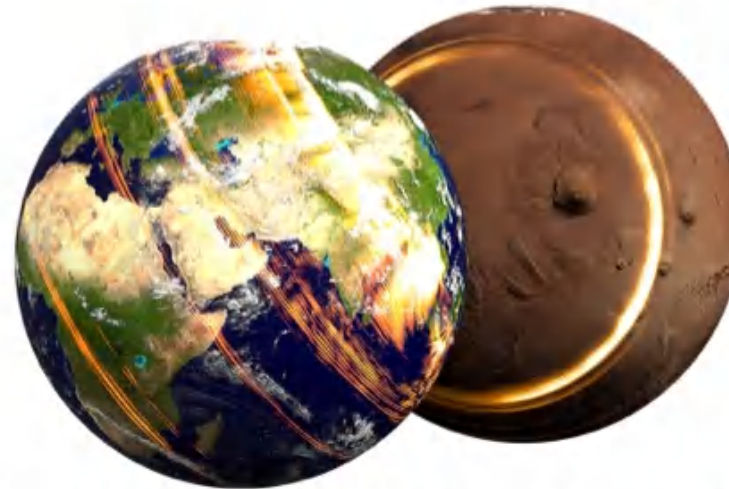
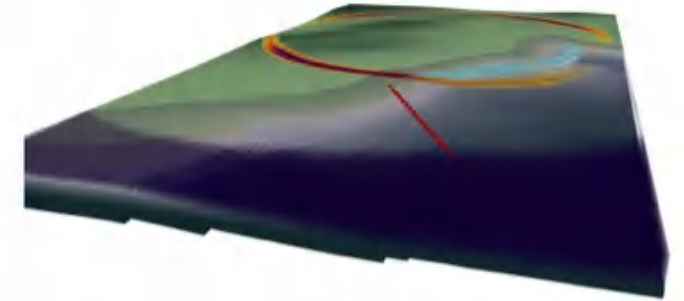
- Reproducibility
- Data management
- Visualization and QC

dim2.CircularDomain

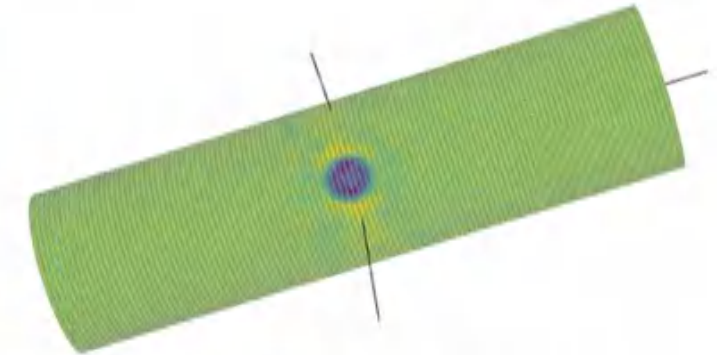


dim2.BoxDomain

dim3.UtmDomain



dim3.SphericalGlobeDomain



dim3.BoxDomain  
with custom mesh



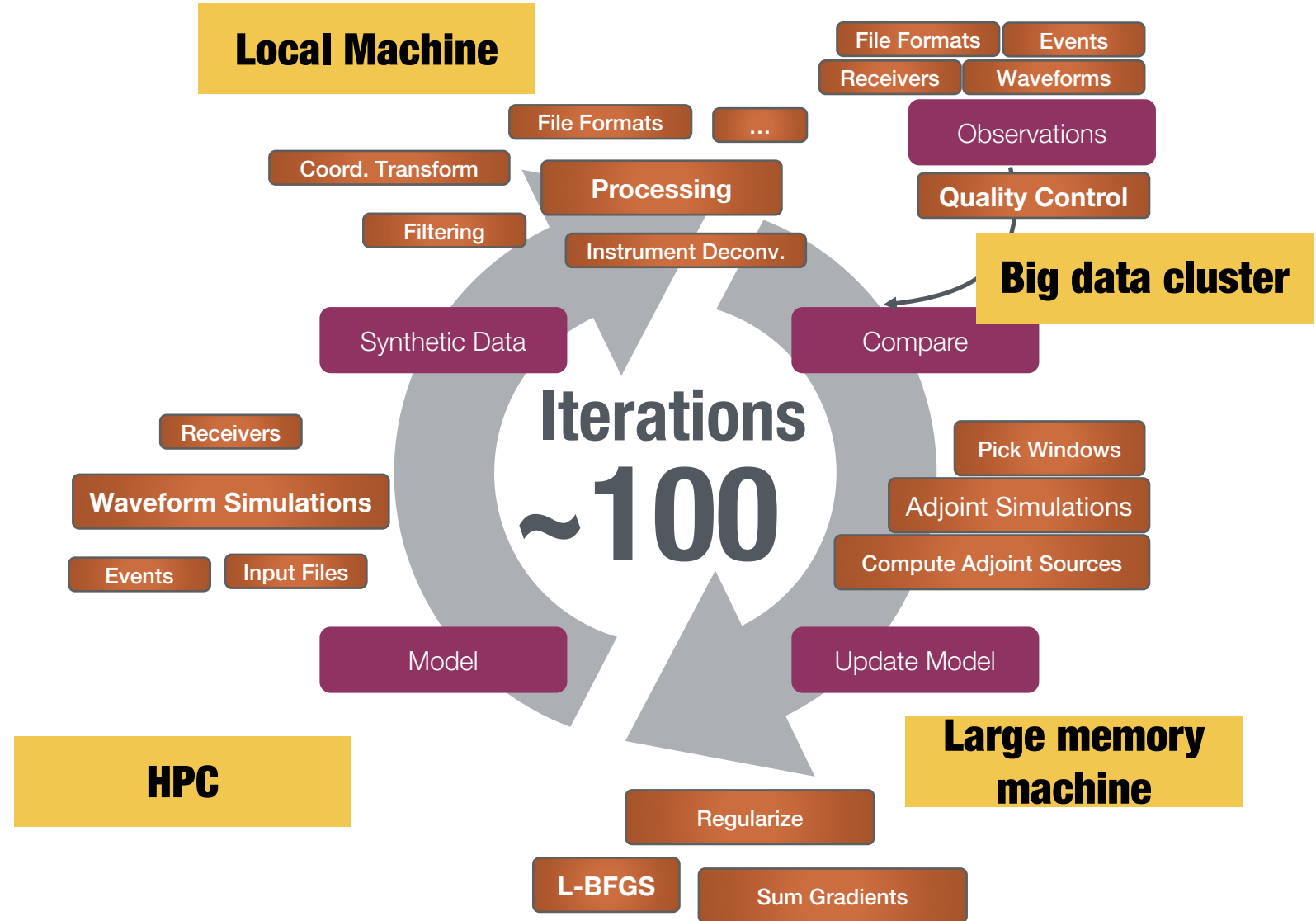
# SalvusProject

Built for...

- Reproducibility
- Data management
- Visualization and QC

...and enables you to

- Organize results
- Pick up where you left off
- Share work with colleagues





# SalvusProject

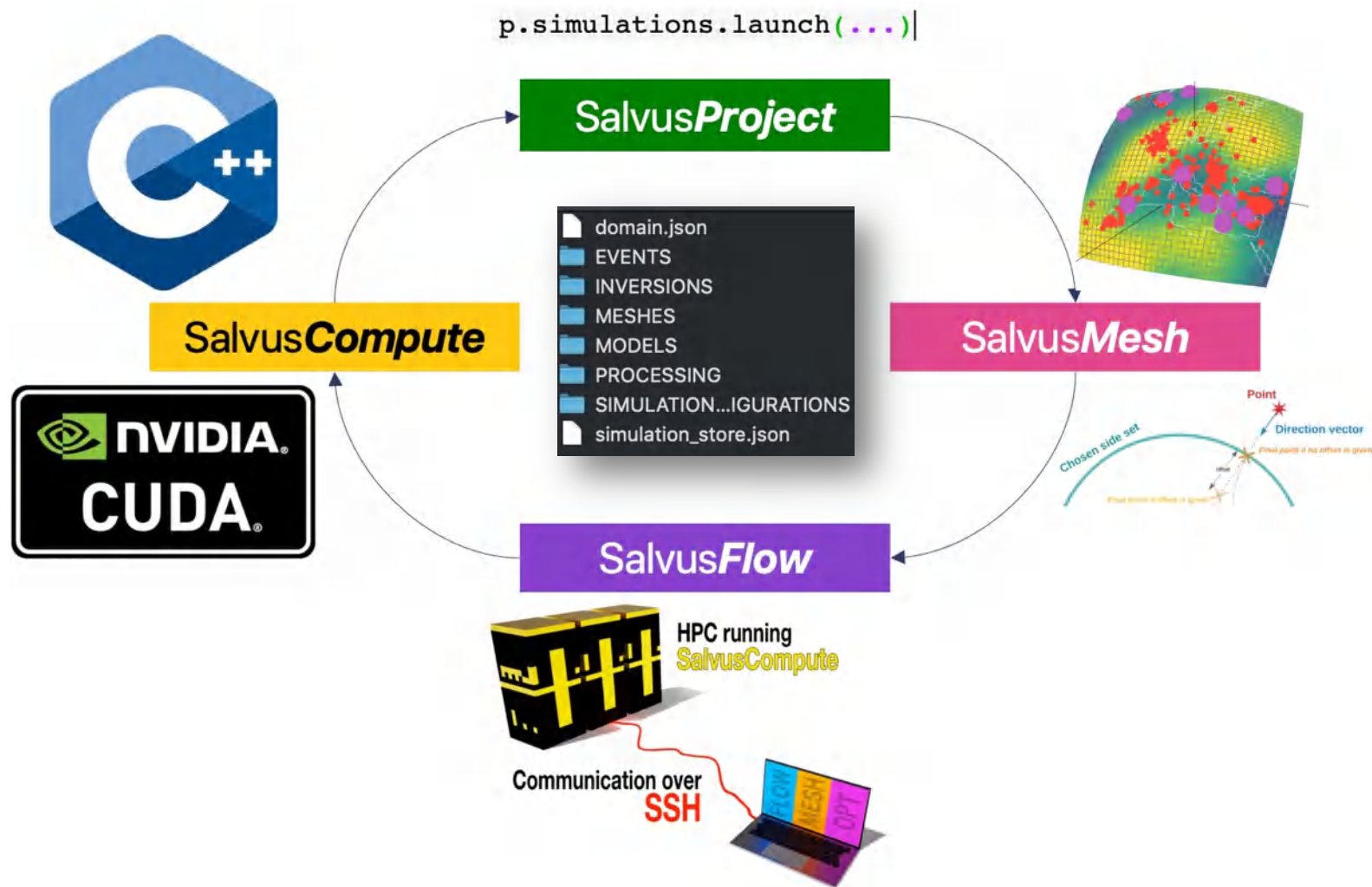
Built for...

- Reproducibility
- Data management
- Visualization and QC

...and enables you to

- Organize results
- Pick up where you left off
- Share work with colleagues

...by keeping a **serialized, and state-aware database** on your local machine.





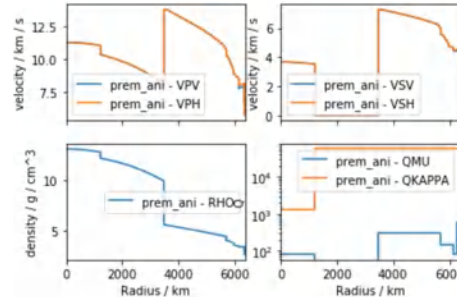
# Salvus*Project*

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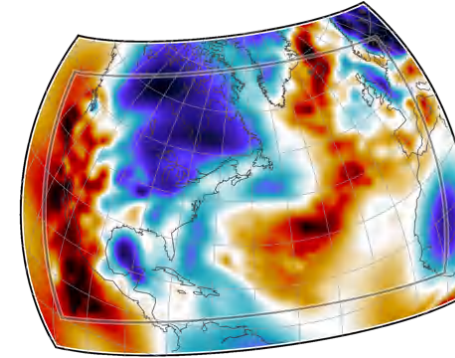


# SalvusProject

- Models, meshes, simulation parameters, etc, are given unique “hashes”



*ddd5ebc63702*



*0ee25249fdc*



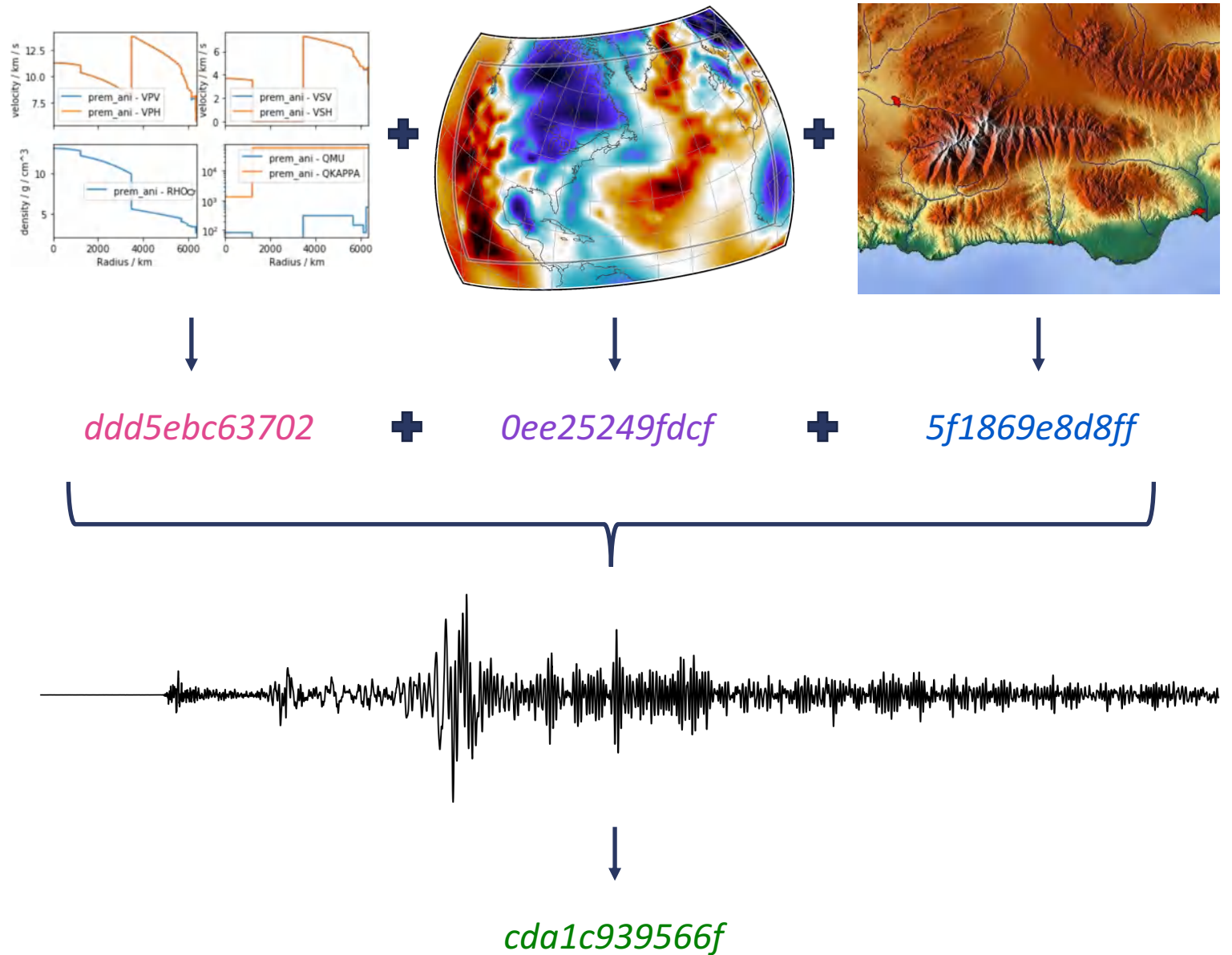
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# SalvusProject

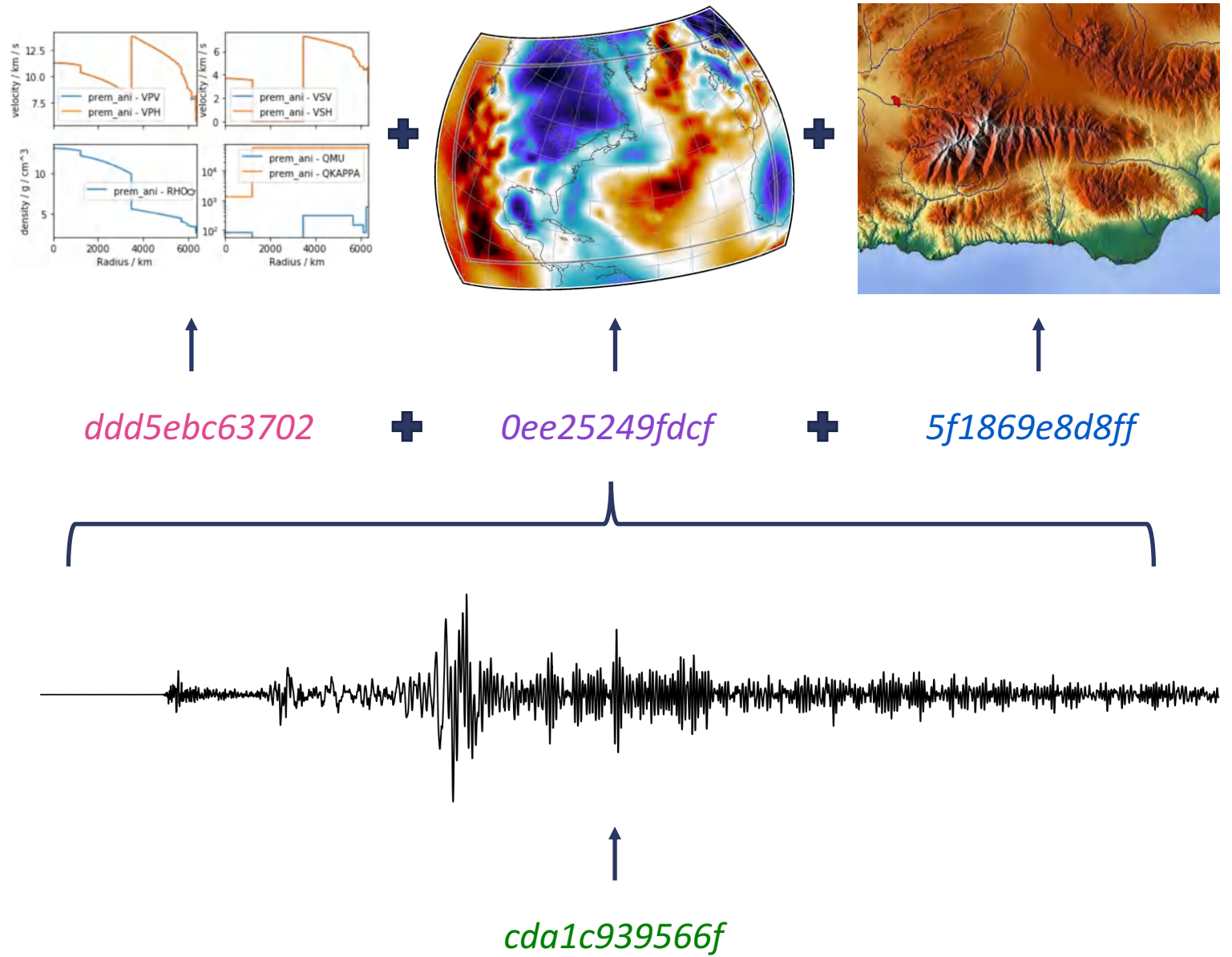
- Models, meshes, simulation parameters, etc, are given unique “hashes”
- Hashes are combined to uniquely refer to intermediate results





# SalvusProject

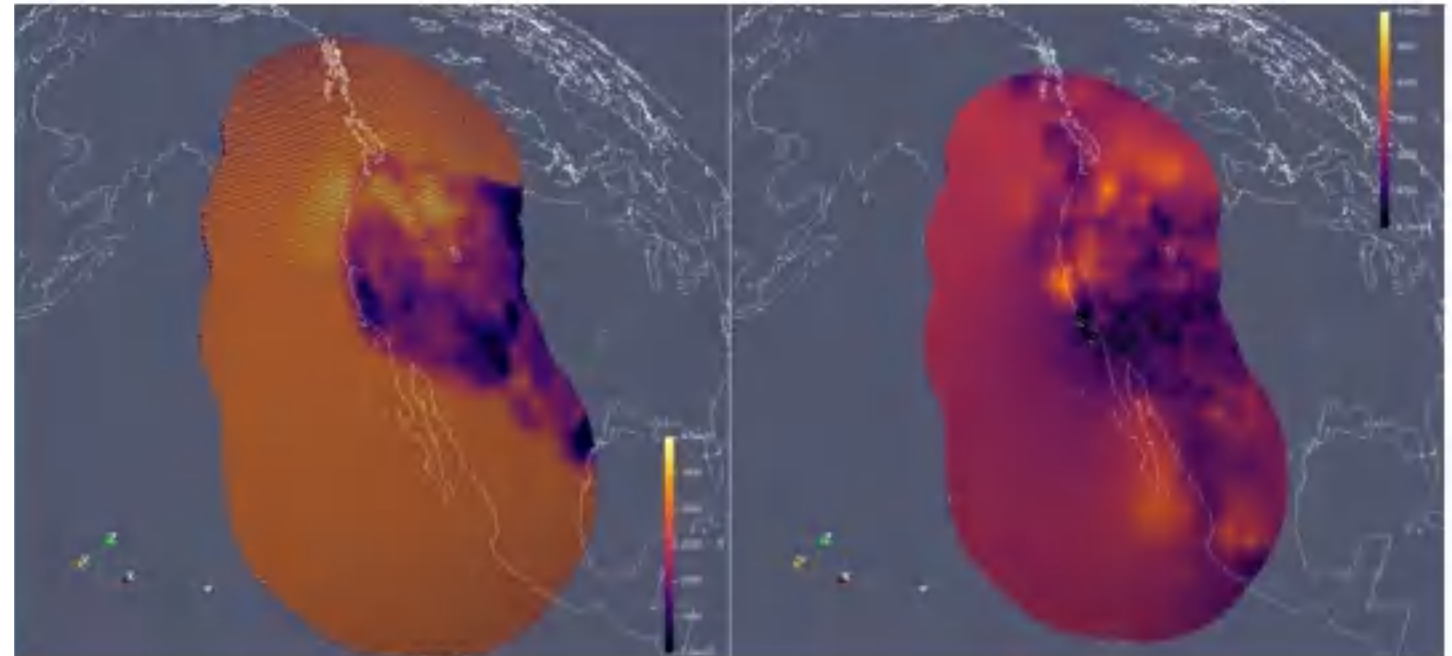
- Models, meshes, simulation parameters, etc, are given unique “hashes”
- Hashes are combined to uniquely refer to intermediate results
- If a hash:
  - Has no associated data, compute it!
  - Has associated data, just open it!





# SalvusProject

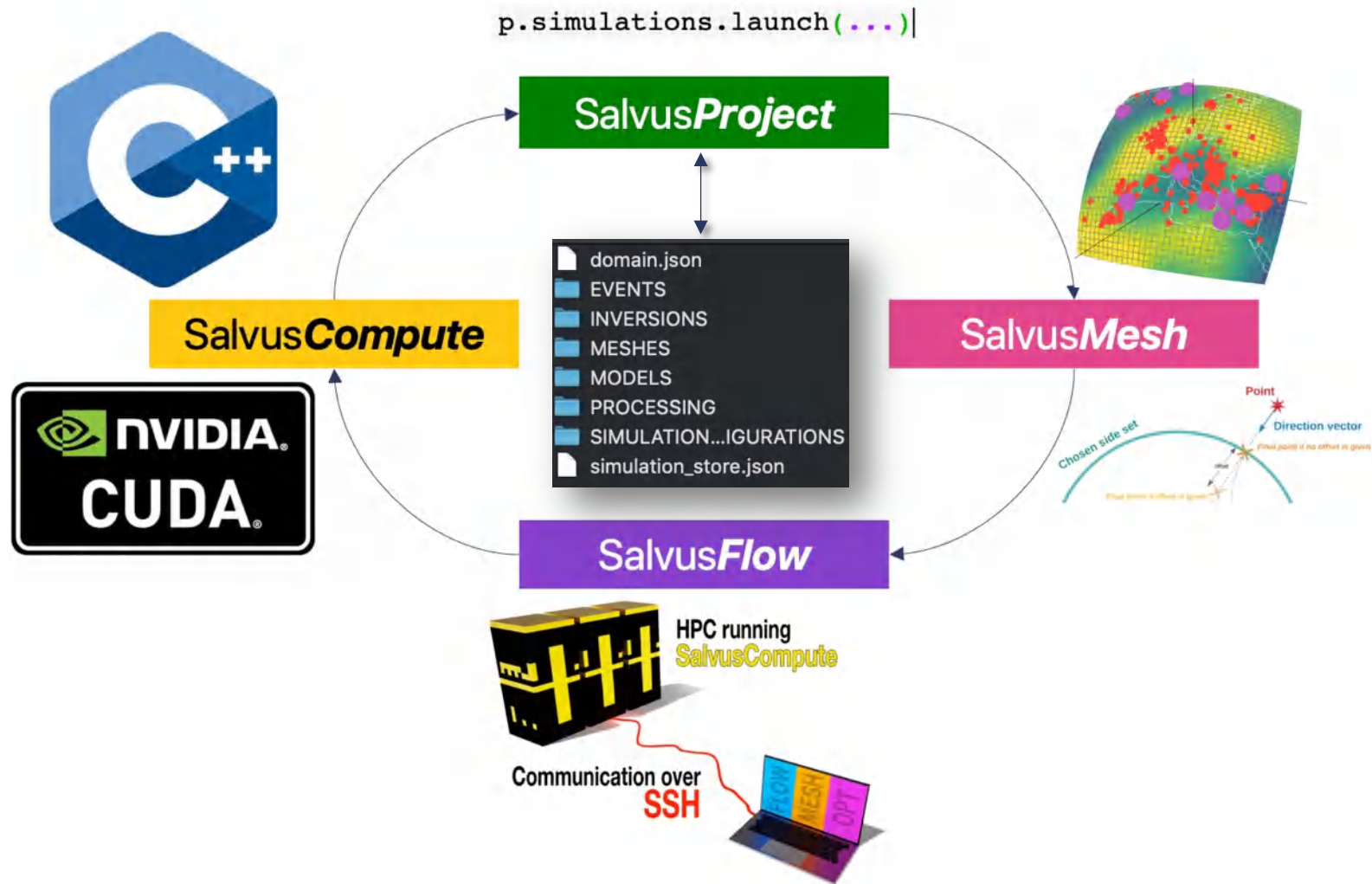
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- Hashes are lightweight and persistent on disk
  - Share projects and models with colleagues





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- All of this happens automatically: pay as much or as little attention as you like





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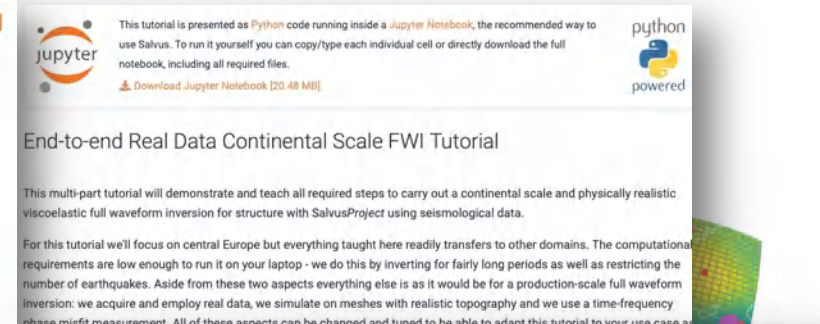


## Lamb's problem

### Part 1 - First simulation

An accurate solution to the wave equation is a requirement for a wide variety of research. In this tutorial, we will validate the accuracy of Salvus by comparing calculated seismograms to semi-analytical solutions of Lamb's Problem in 2-D giving us confidence in the synthetic data we will use in future tutorials, it also to gently learn some of the key features of the SalvusProject API.

Lamb's problem is concerned with the behavior of the elastic wave equation in half-space bounded by a free-surface condition. In our solution we expect both those reflected from the free-surface, along with a contribution from the 2-D P consider a half-space bounded at  $y = 2000$ , and excite waves using a Ricker frequency of 15 Hz. This setup keeps compute times very low, while also allowing amount of wavelengths to propagate within our domain. To get started, let's first Python tools we'll need.



Using the GMRT web service

The first step is to define the geographical domain of interest. A convenient way to do this is to use the specialized `UtmDomain.from_spherical_chunk` constructor that takes WGS84 coordinates and converts them to an appropriate UTM domain. The UTM zone and coordinates could of course also be specified directly.

```
d = sn.domain.dim3.UtmDomain.from_spherical_chunk(
    min_latitude=46.15,
    max_latitude=46.30,
    min_longitude=-122.28,
    max_longitude=-122.12,
)

# Have a look at the domain to make sure it is correct.
d.plot()
```

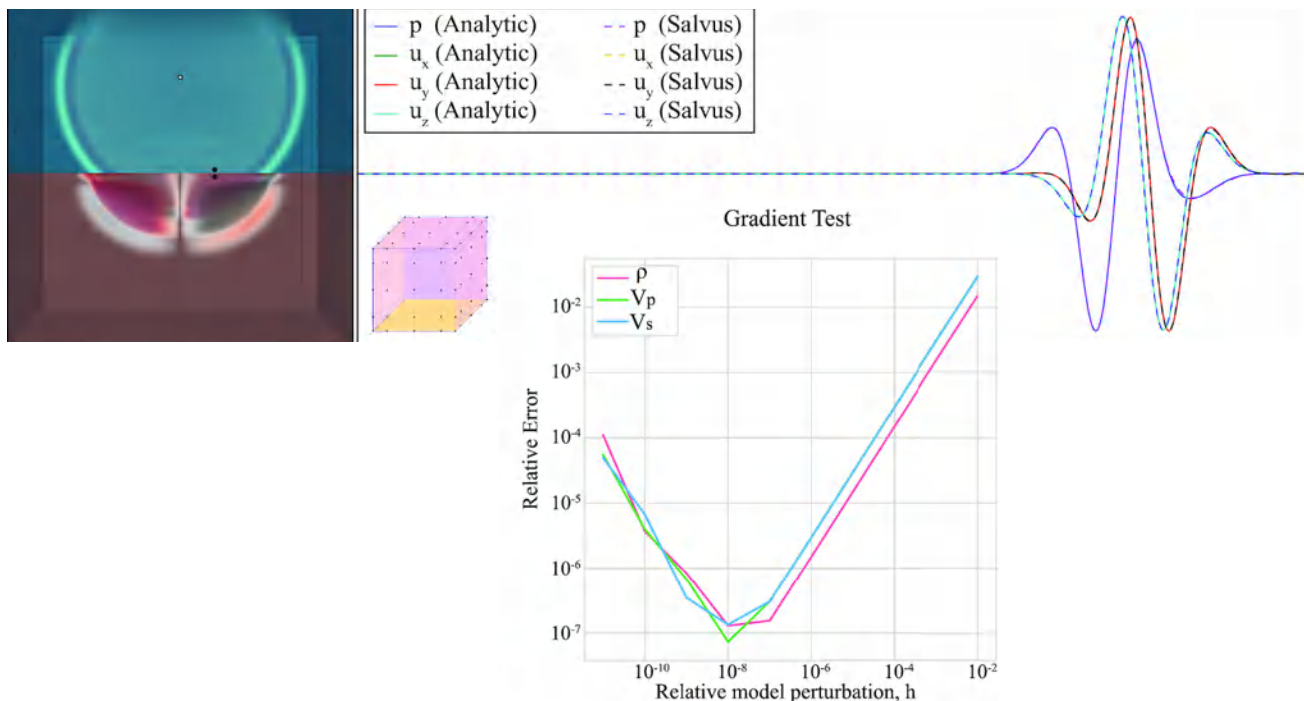




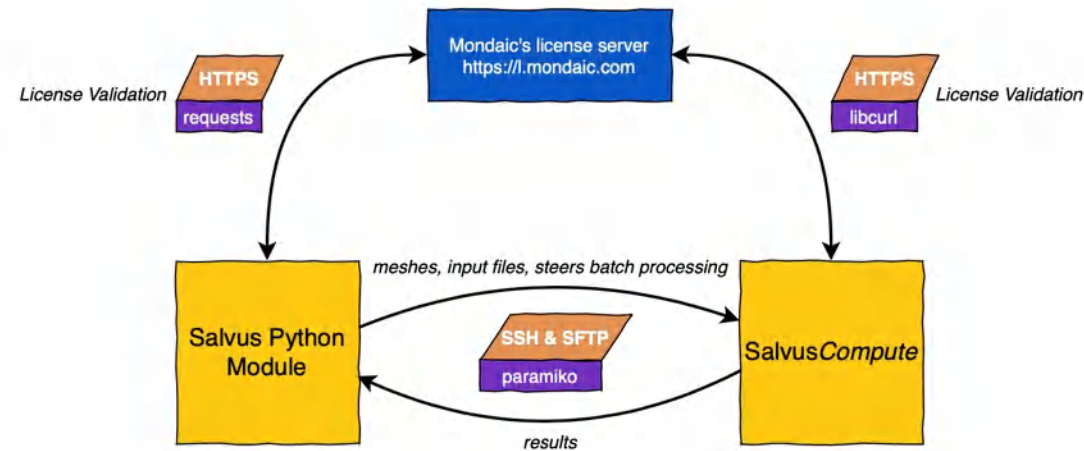
# Quality control: Validation, verification and security

Extensive continuous integration pipelines.  
Benchmark solutions for semi-analytic problems.

Static application security  
for SANS Top 25 vulnerabilities.



## Software architecture diagram



Continuous integration and testing ensure validity, integrity and security of the software.

# Case Studies

A variety of applications supported by Salvus

## Simulating strain recordings along transoceanic cables

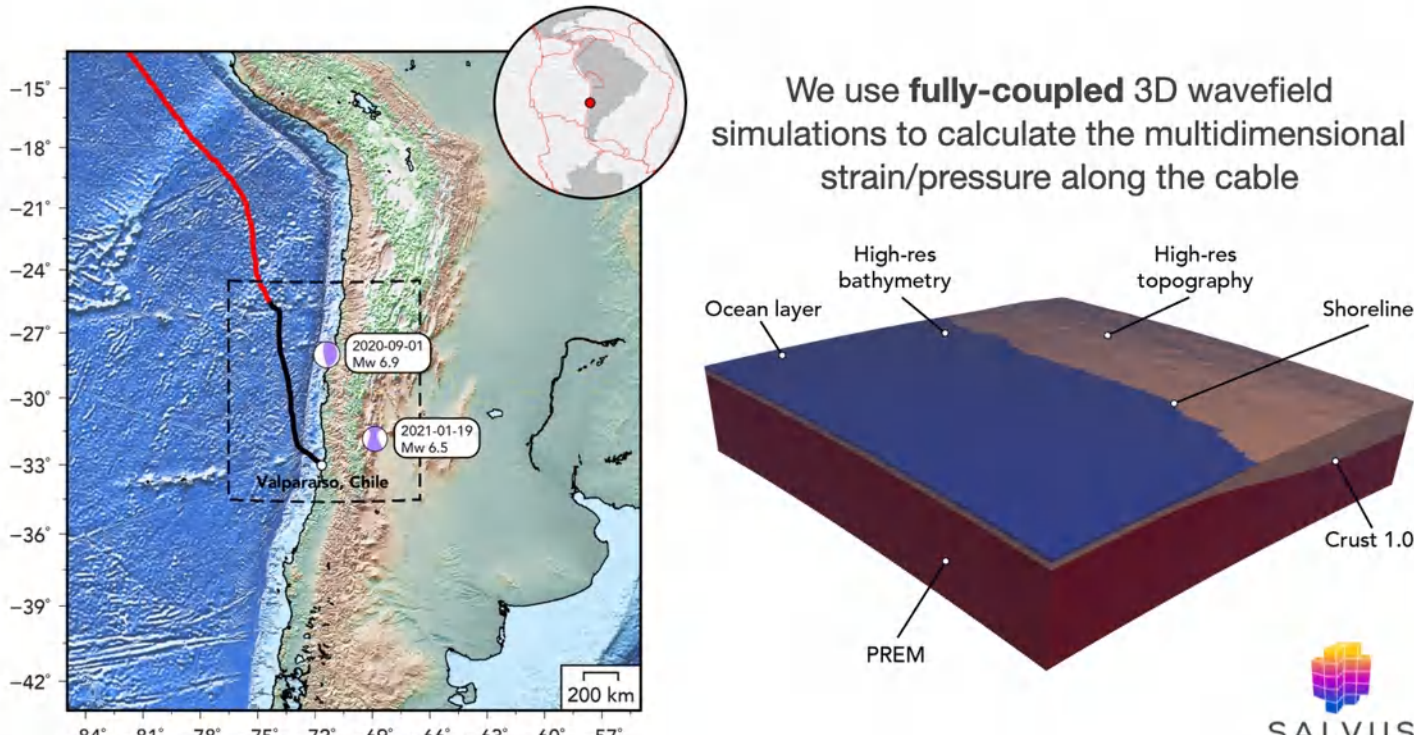
J. Castellanos et al. (2021). On the Sensitivity of Optical Polarization Transoceanic Cables to Seismic and Water Waves. SSA Annual meeting, April 19-23, 2021.



**Caltech**

## Estimating the EQ induced pressure along the cable

We use **fully-coupled** 3D wavefield simulations to calculate the multidimensional strain/pressure along the cable



The figure consists of two main parts. On the left is a map of Chile and the surrounding ocean region, showing a red line representing a transoceanic cable. Two earthquake events are marked: a purple circle for a 2020-09-01 Mw 6.9 event and another purple circle for a 2021-01-19 Mw 6.5 event. The city of Valparaiso, Chile is also labeled. The map includes latitude and longitude coordinates and a 200 km scale bar. An inset map shows the location of the study area within the South American continent. On the right is a 3D block diagram of the simulation domain. It shows a blue 'Ocean layer' on top of a brown 'Crust 1.0' layer. The domain is bounded by 'High-res bathymetry' on the left, 'High-res topography' on the right, and a 'Shoreline' on the right side. The 'PREM' model is indicated at the bottom of the crust. Labels with arrows point to each of these features.

**SALVUS**  
IMAGE EVERYTHING

jacastil@caltech.edu

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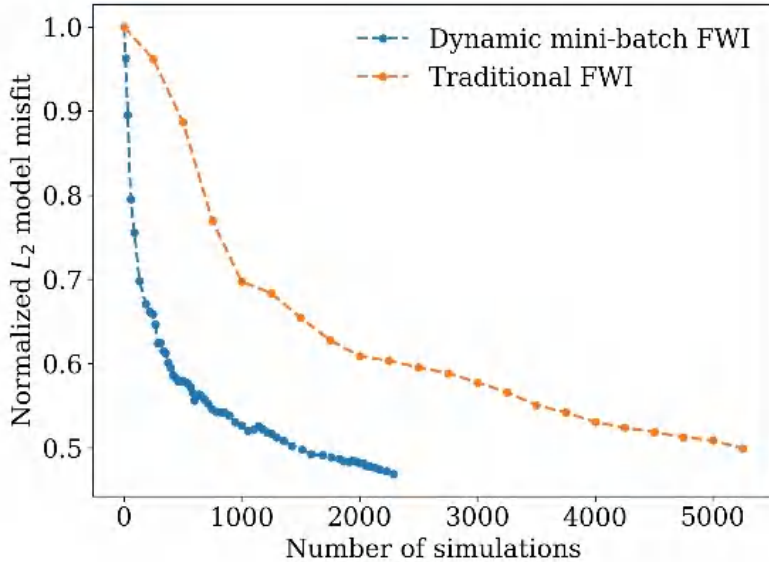


# Dirk-Philip van Herwaarden

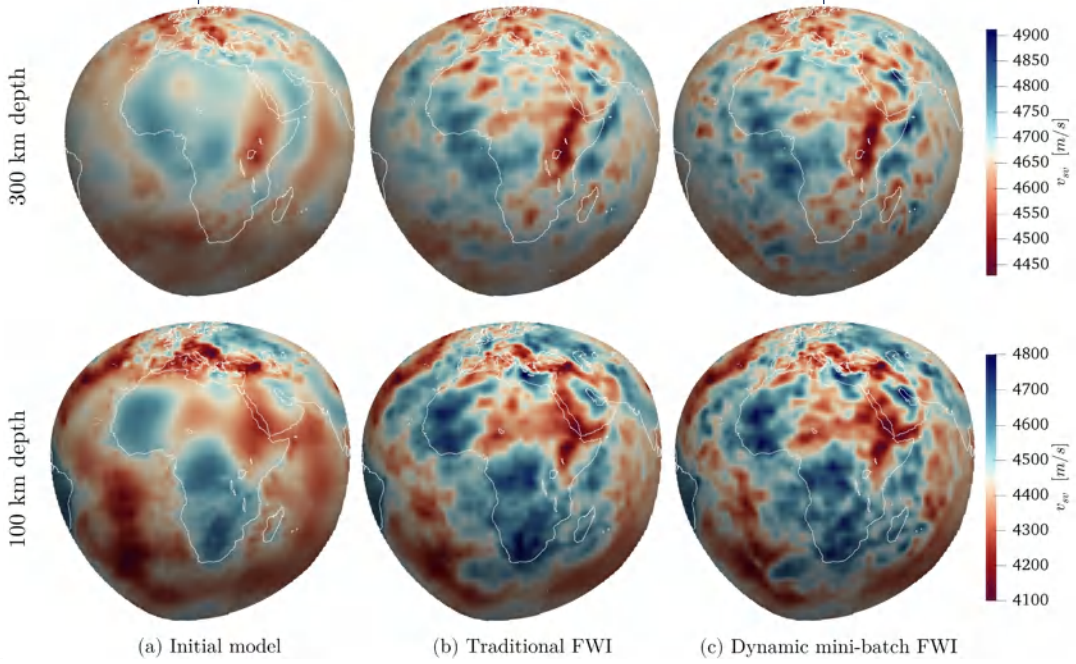
*Reducing the number of simulations required for full-waveform inversion through optimized quasi-random event selection*

van Herwaarden, et al., Accelerated full-waveform inversion using dynamic mini-batches, *Geophysical Journal International*, Volume 221, Issue 2, May 2020  
van Herwaarden et al., Evolutionary full-waveform inversion, *Geophysical Journal International*, September 2020, *in press*.

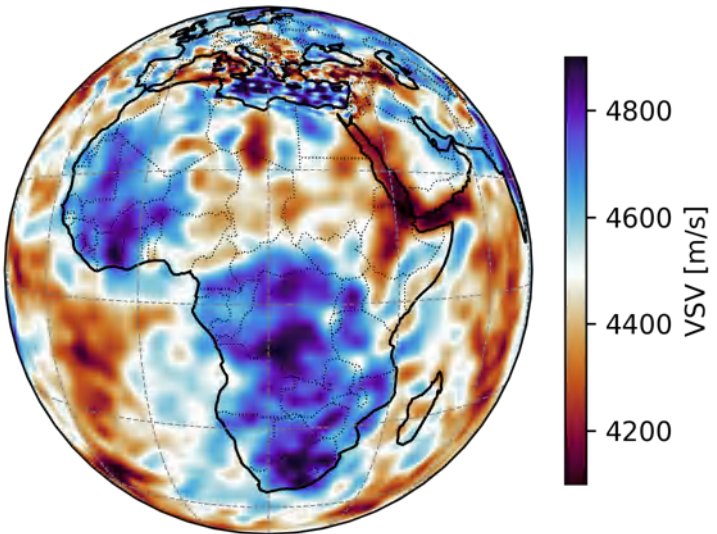
Reduction in total number of required simulations



Comparison of models using traditional or mini-batch FWI



VSV at 70.0 km depth



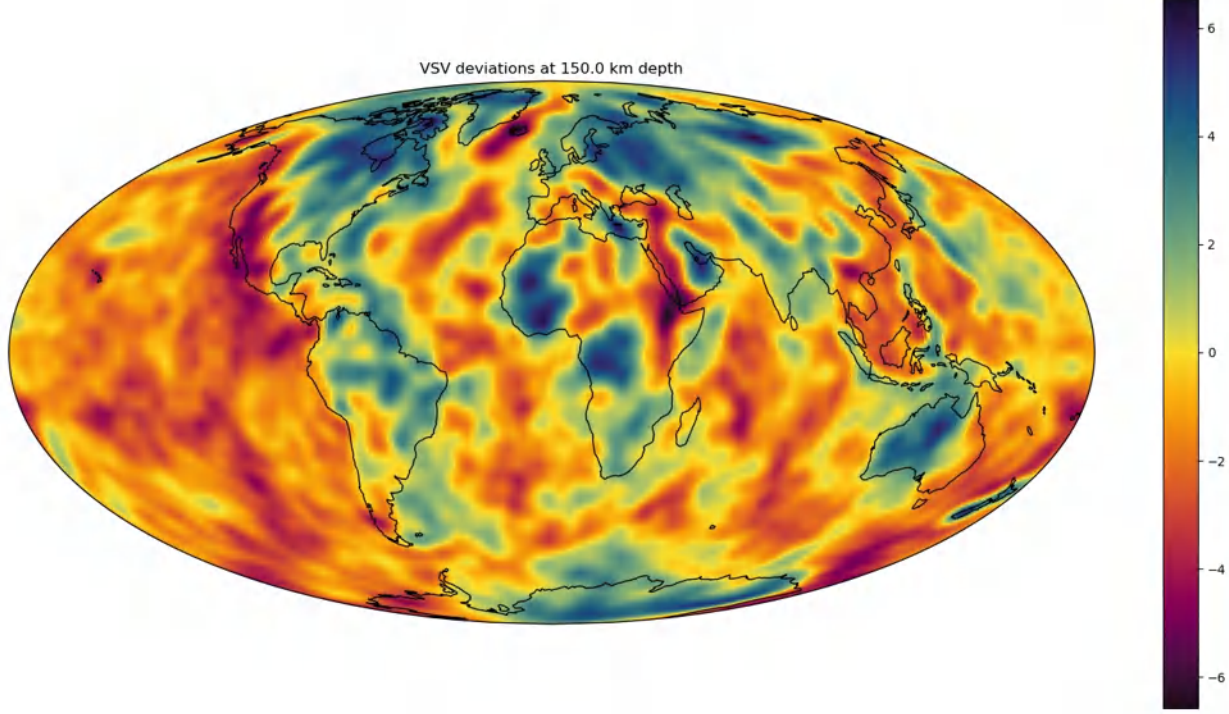
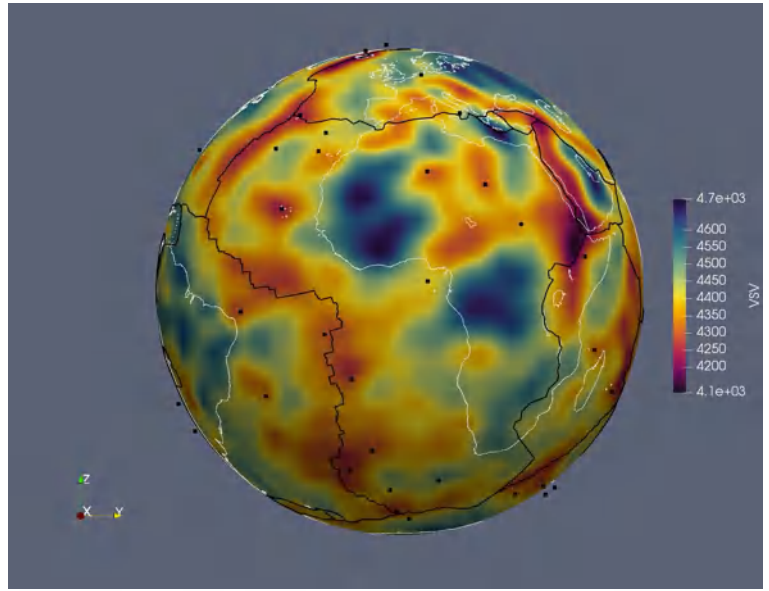
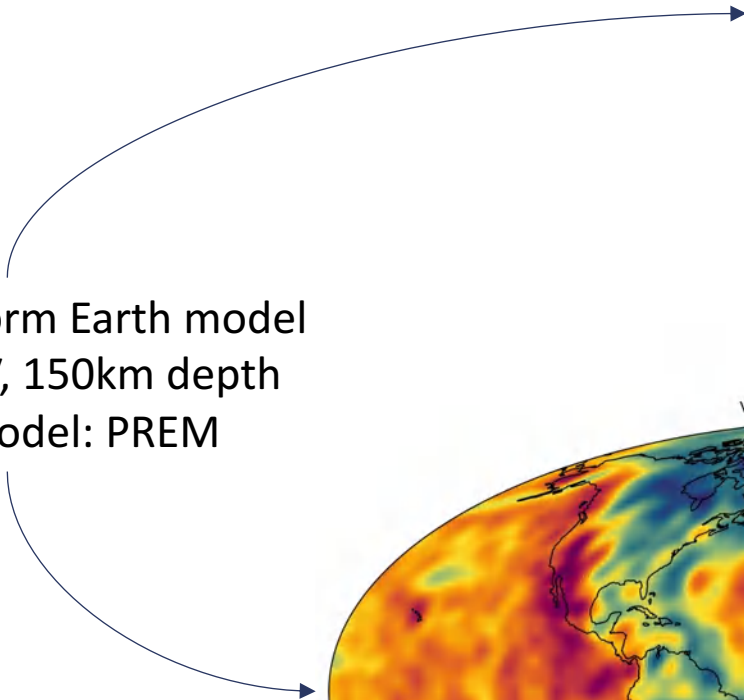
# Sölvi Thrastarson

*Increasing the efficiency of global-scale full-waveform inversion through the use of optimized event-specific meshes*

Thrastarson et al., Accelerating numerical wave propagation by wavefield adapted meshes. Part II: full-waveform inversion, *Geophysical Journal International*, Volume 221, Issue 3, June 2020



3-D full-waveform Earth model  
Quantity: VSV, 150km depth  
Starting model: PREM



# Laura Cobden

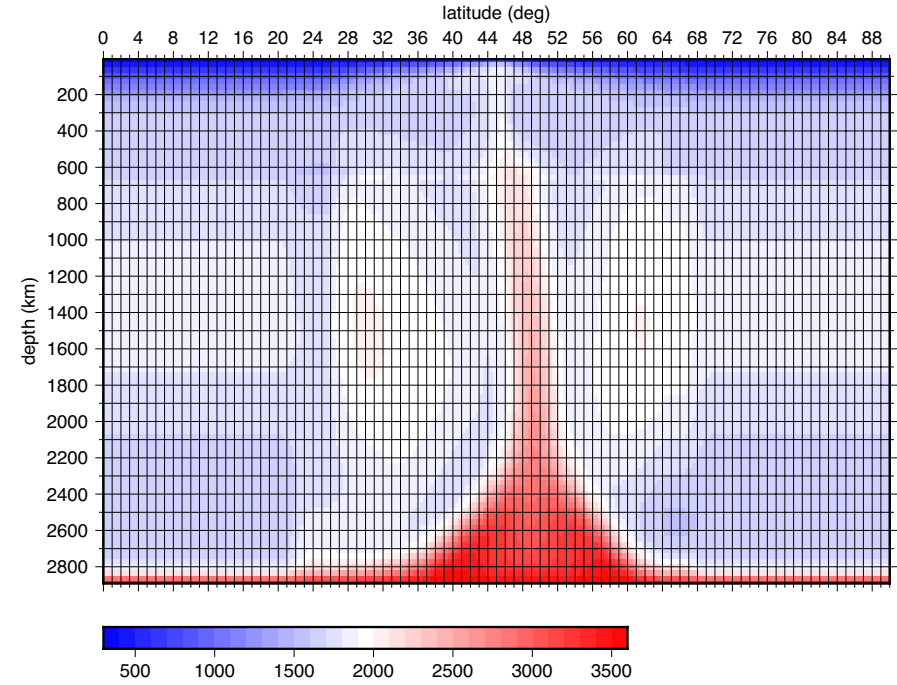
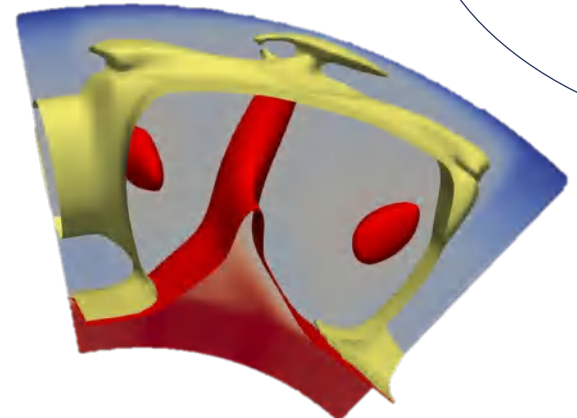
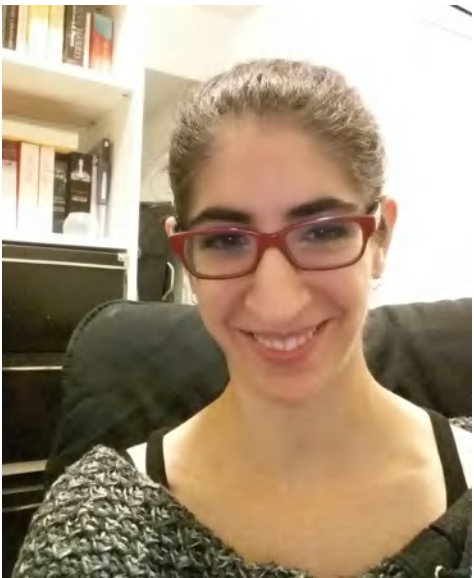
*Investigating the effect of mantle plumes on high-frequency seismic signals*

Cobden, Deschamps, Rost, Thomas, Tackley, et al., *Probing mantle plumes using seismic arrays, ongoing.*

Wavefield simulations and array analysis

Viscoelastic properties

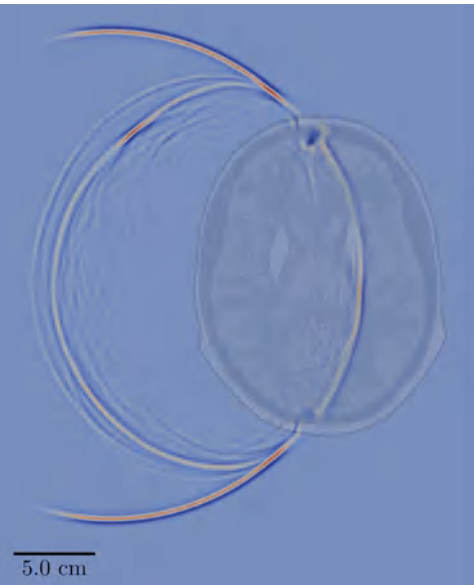
Geodynamic Plume models



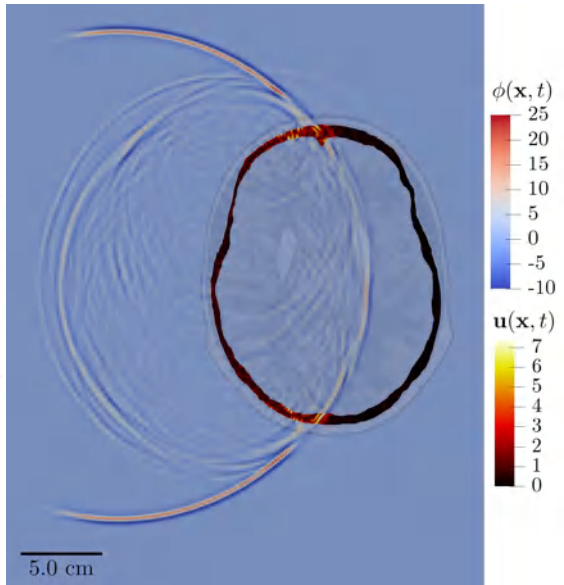
# Patrick Marty

## Full-waveform inversion for medical imaging and early cancer detection

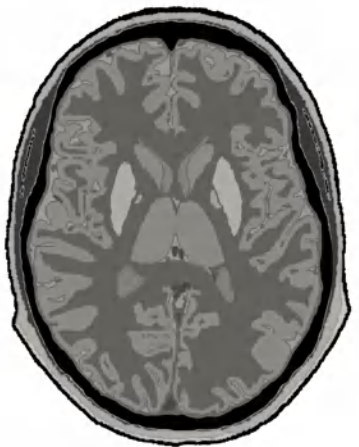
Marty et al., Acoustoelastic full-waveform inversion for transcranial ultrasound computed tomography, *accepted at SPIE Medical Imaging*, February 2021.



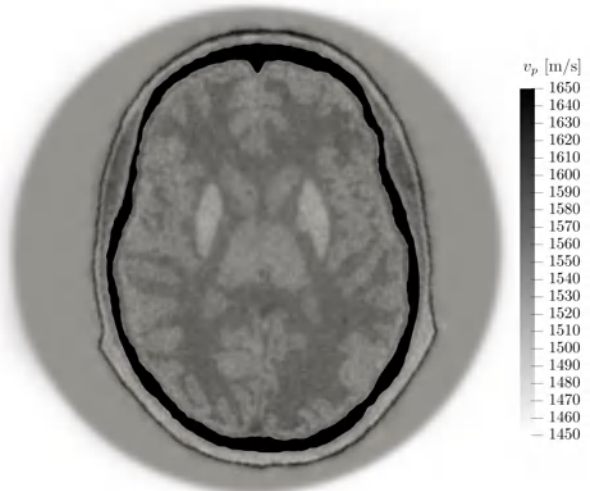
Acoustic Skull



Elastic Skull



Target brain model



Imaging result after FWI

# Mondaic

Why does it say “Spinoff”?

# Mondaic

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# Mondaic

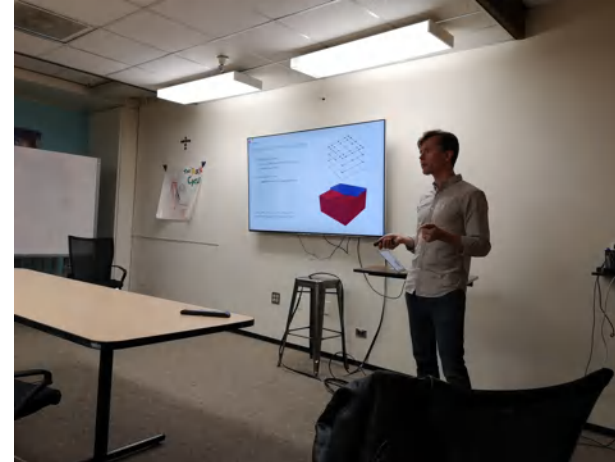
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- Salvus was originally conceived and developed during its developers' time at ETH



# Mondaic

- Salvus was originally conceived and developed during its developers' time at ETH
- Official spinoff founded in 2018, looking towards Salvus' long-term maintenance and growth

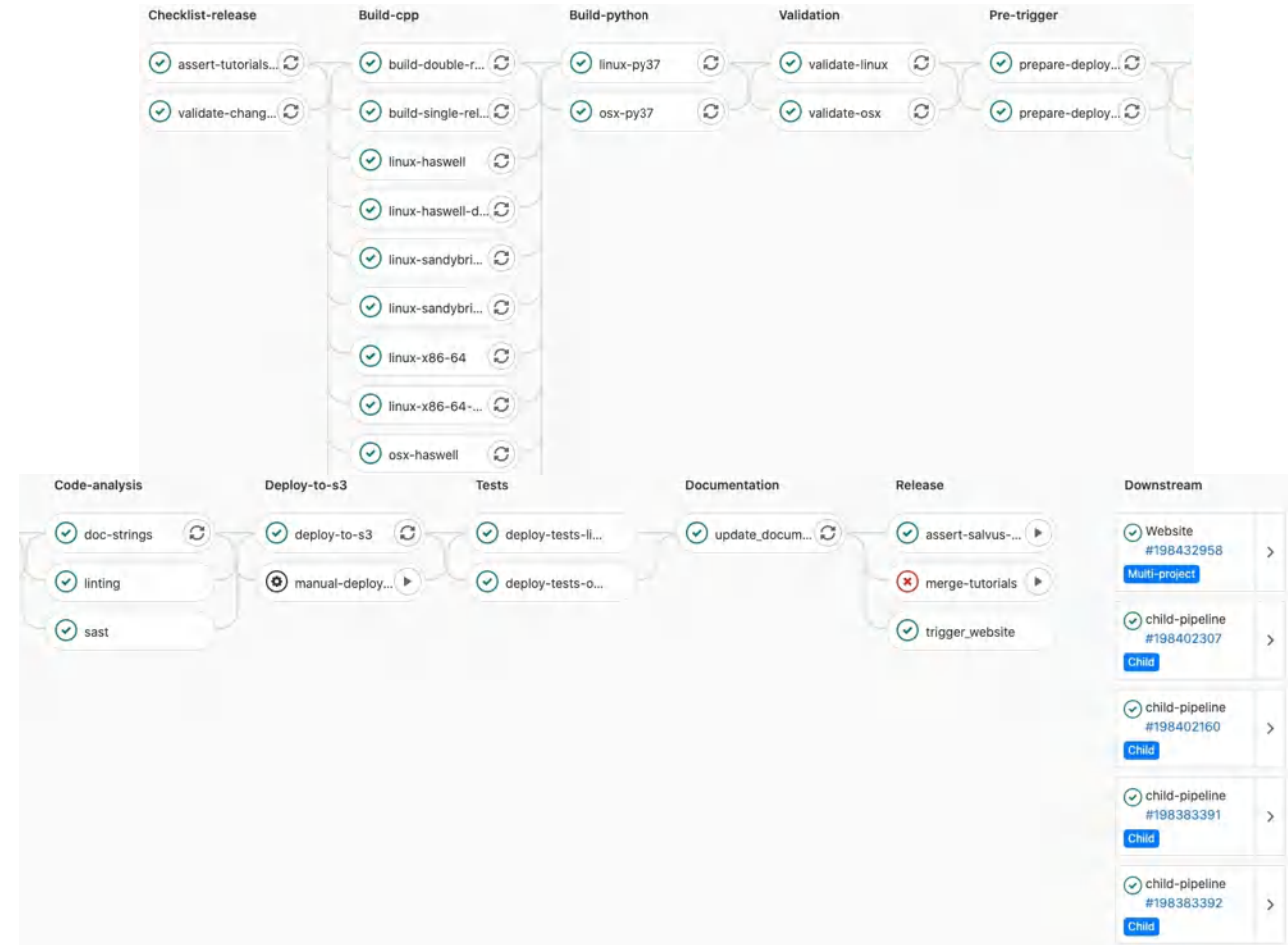






# Mondaic

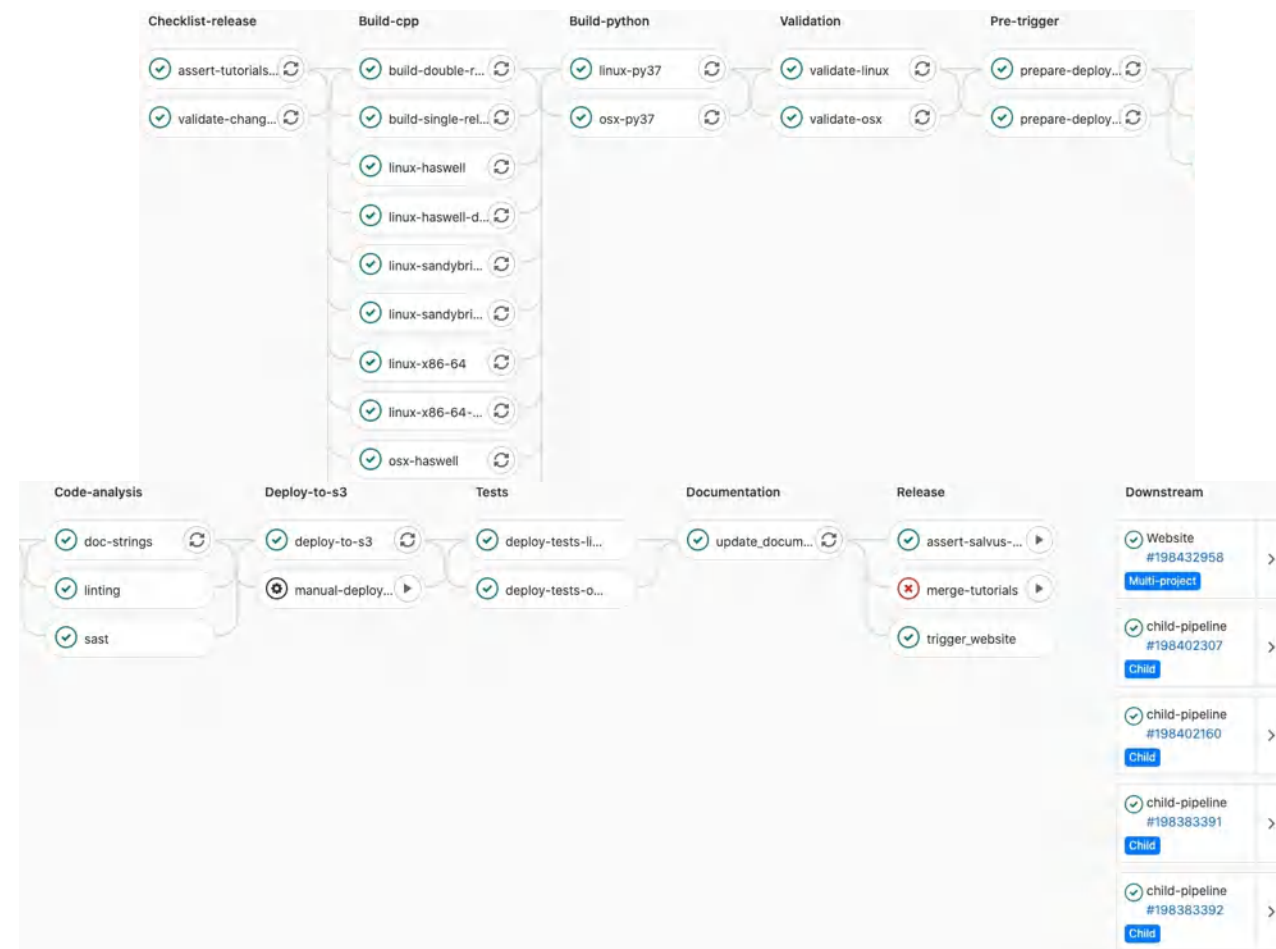
- Salvus was originally conceived and developed during its developers' time at ETH
- Official spinoff founded in 2018, looking towards Salvus' long-term maintenance and growth
- Behind-the-scenes engineering and continuous deployment





# Mondaic

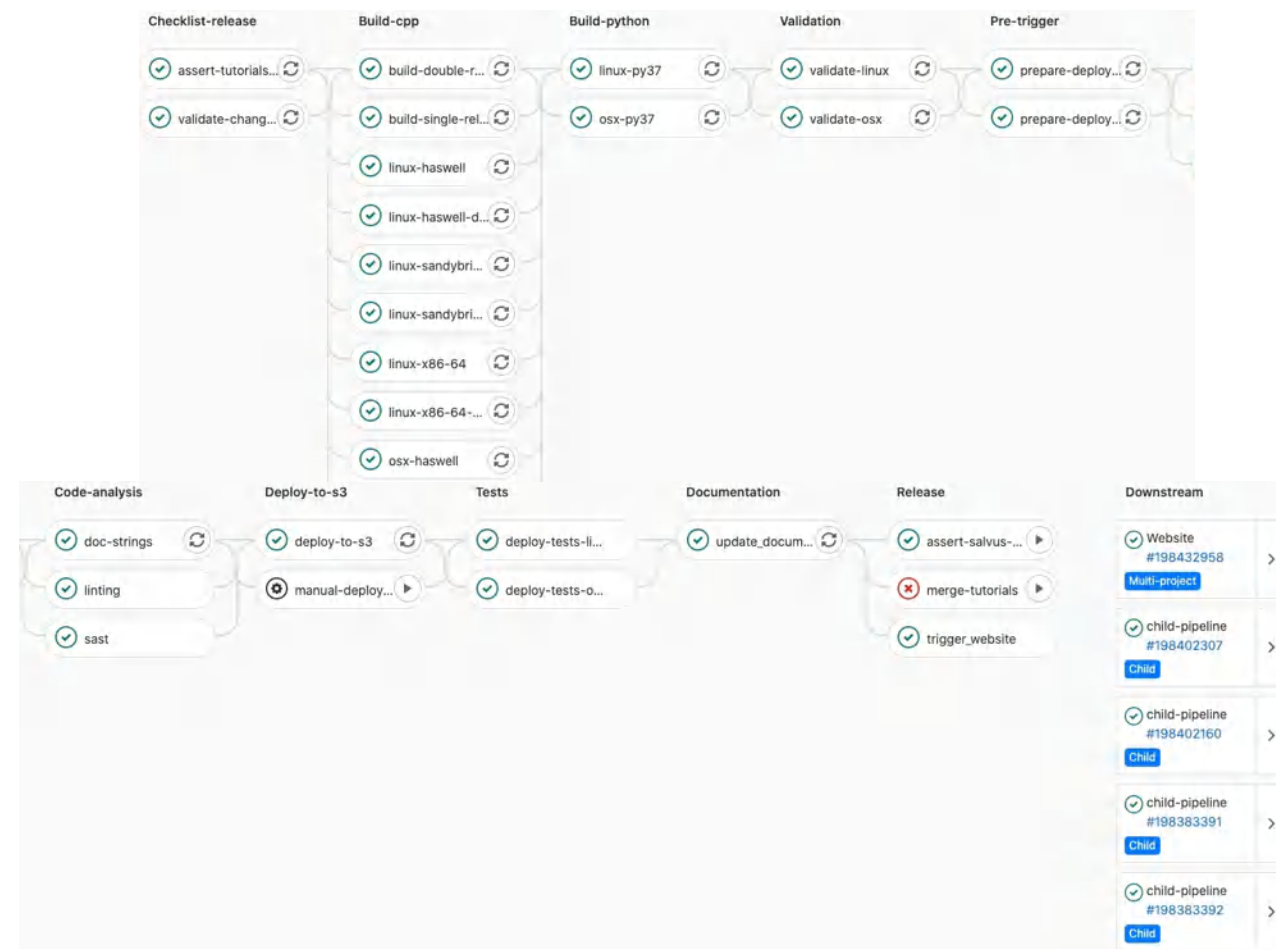
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- Hope to support and enable research in the Earth science community through the provision of professional and robust software





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- Salvus was originally conceived and developed during its developers' time at ETH
- Official spinoff founded in 2018, looking towards Salvus' long-term maintenance and growth
- Behind-the-scenes engineering and continuous deployment
- Hope to support and enable research in the Earth science community through the provision of professional and robust software
- Flexible academic pricing



# Tutorial

What will we do on Friday?



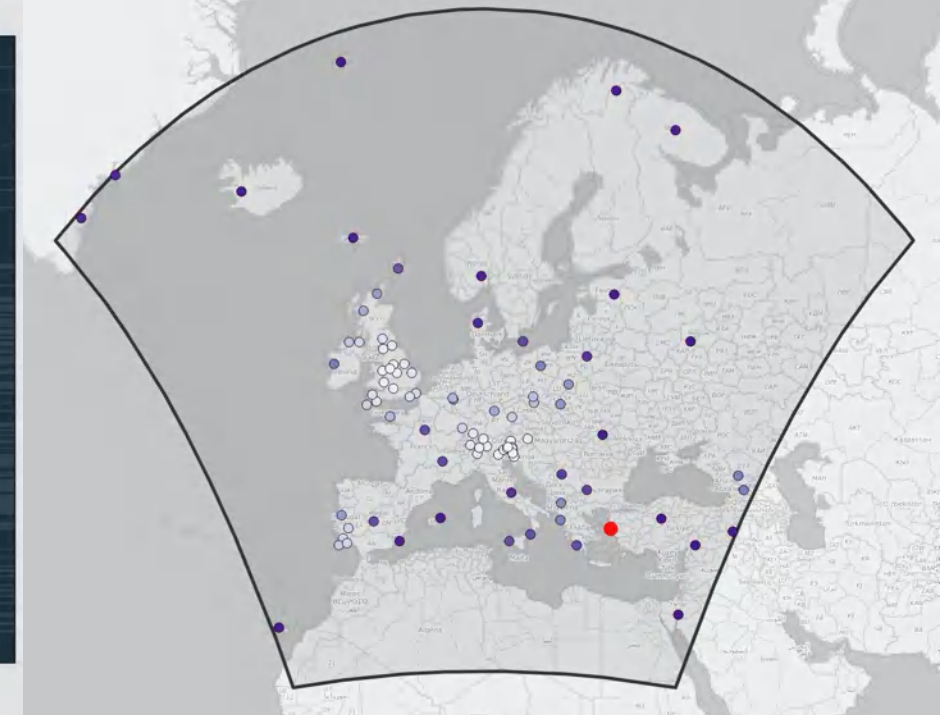
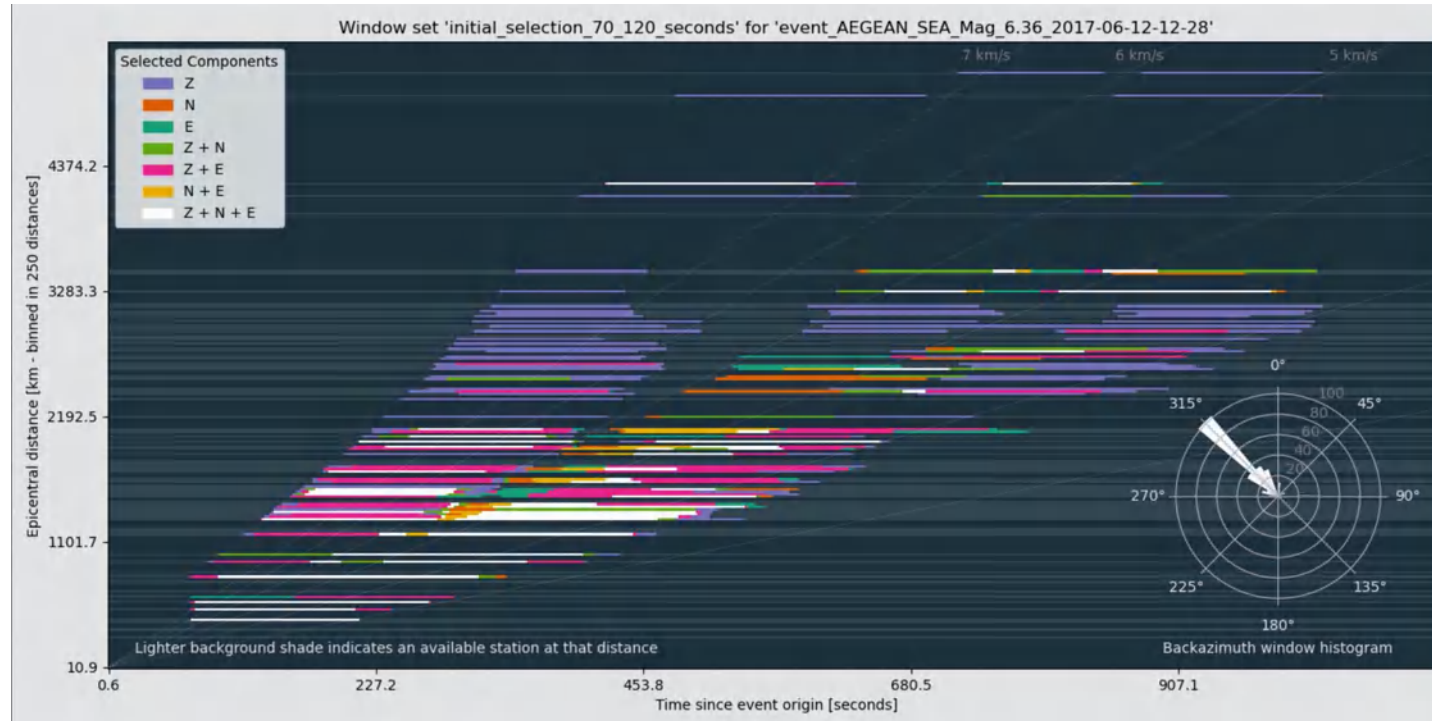
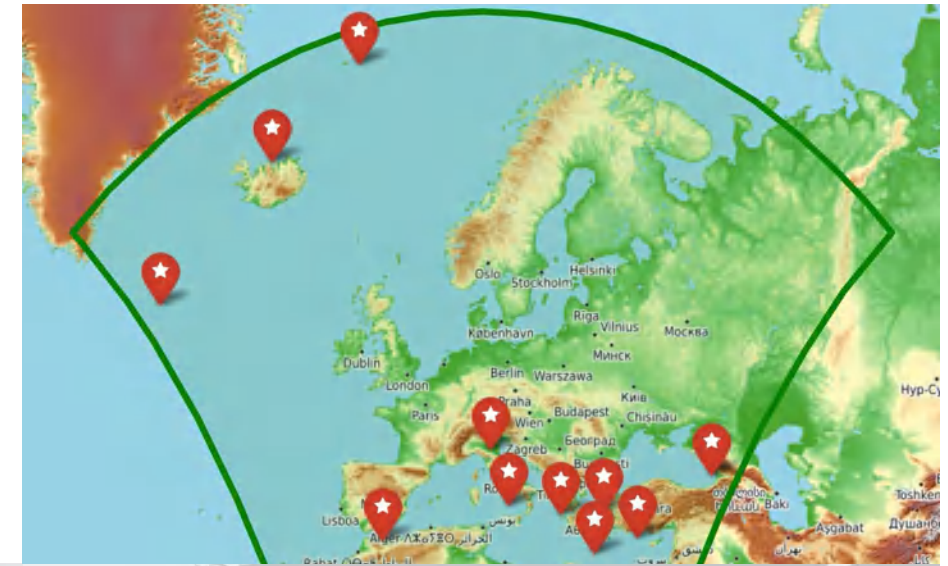
# Continental-scale full-waveform inversion

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# Continental-scale full-waveform inversion

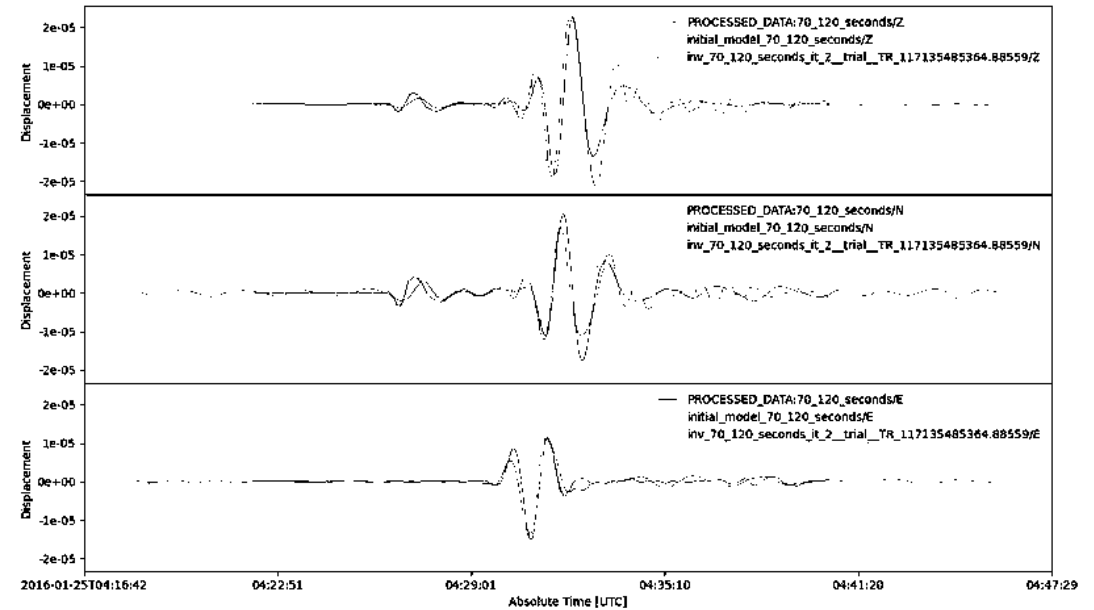
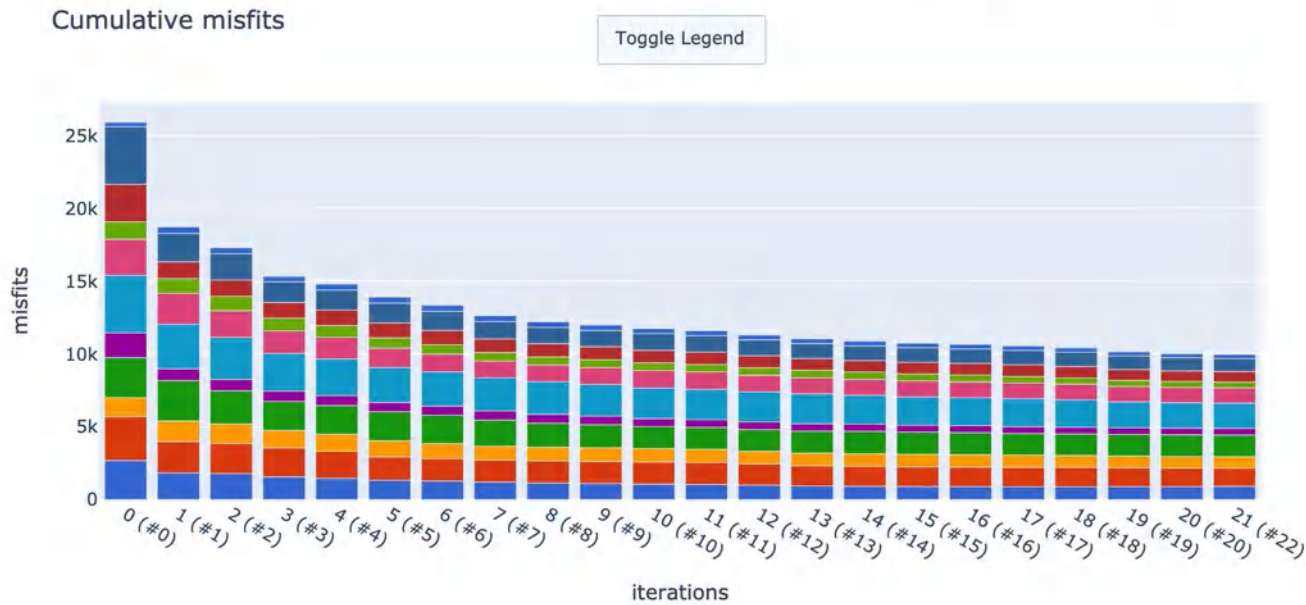
- “From scratch” using real data





# Continental-scale full-waveform inversion

- “From scratch” using real data
- Learn the steps involved with a practical example
  - Inspect data, compute misfits, and iteratively update the model





# Instructors

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Christian Böhm



Lion Krischer



Michael Afanasiev





Thanks for listening