Understanding Earth's past, present and future with geophysical data.

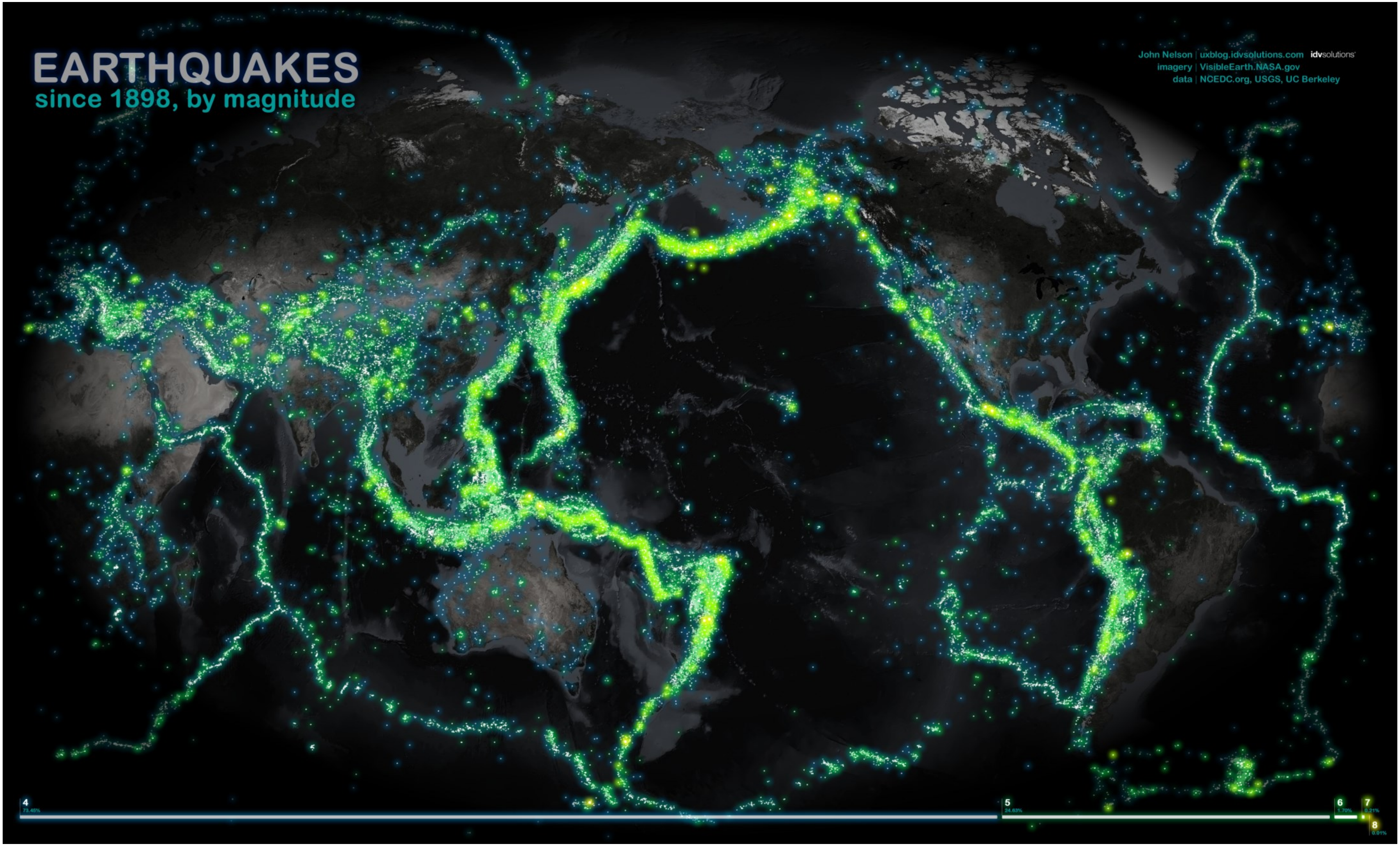
LUCA DE SIENA

Mainz Institute of Multiscale Modeling

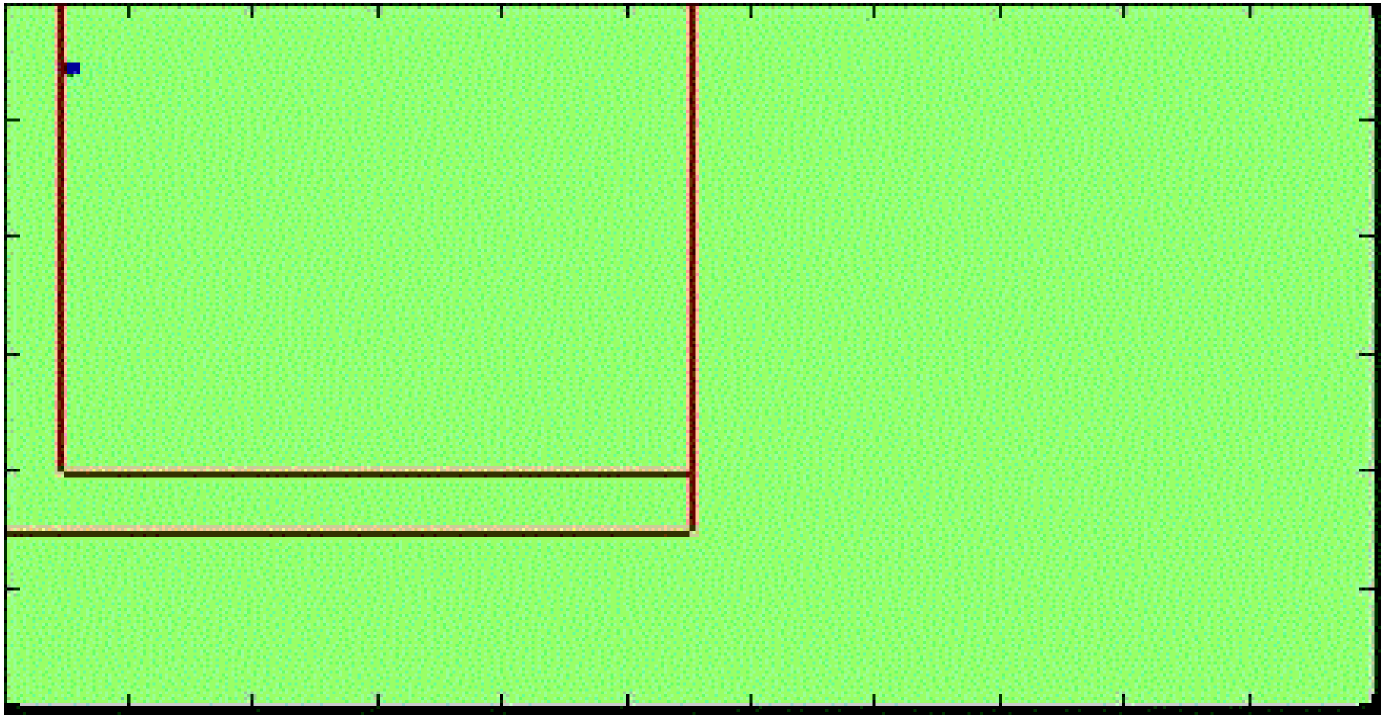
JG|U

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA
DIPARTIMENTO DI FISICA E ASTRONOMIA "AUGUSTO RIGHI"

Geophysical Responses



WAVE PROPAGATION



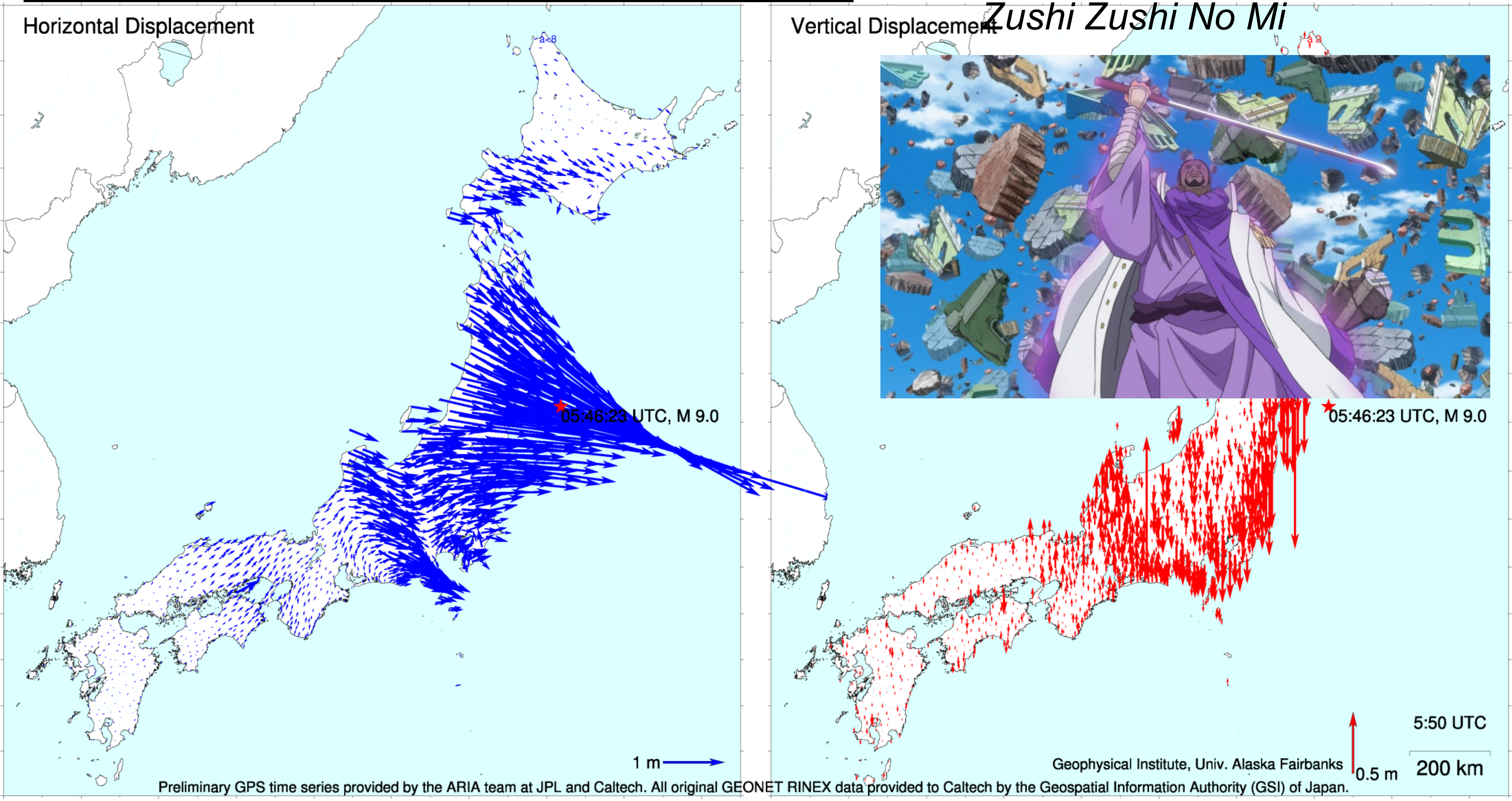
Gura Gura No Mi

GRAVITY & DEFORMATION

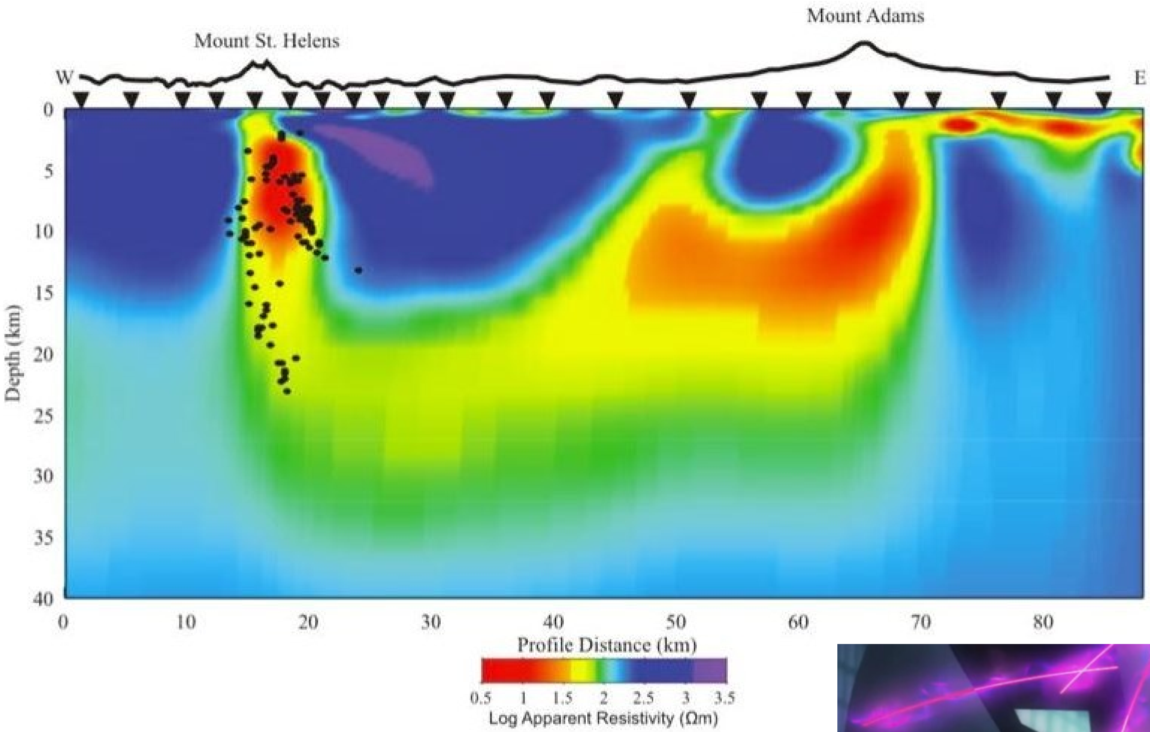
Gravity anomalies

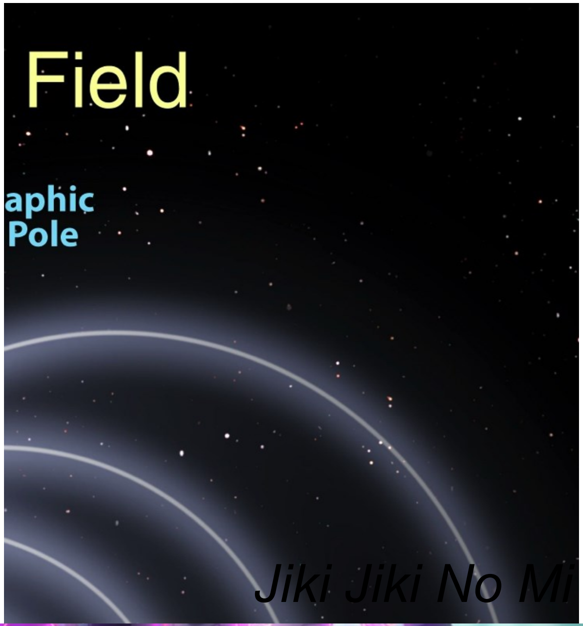
GPS velocities (deformation)

Zushi Zushi No Mi



Magnetic

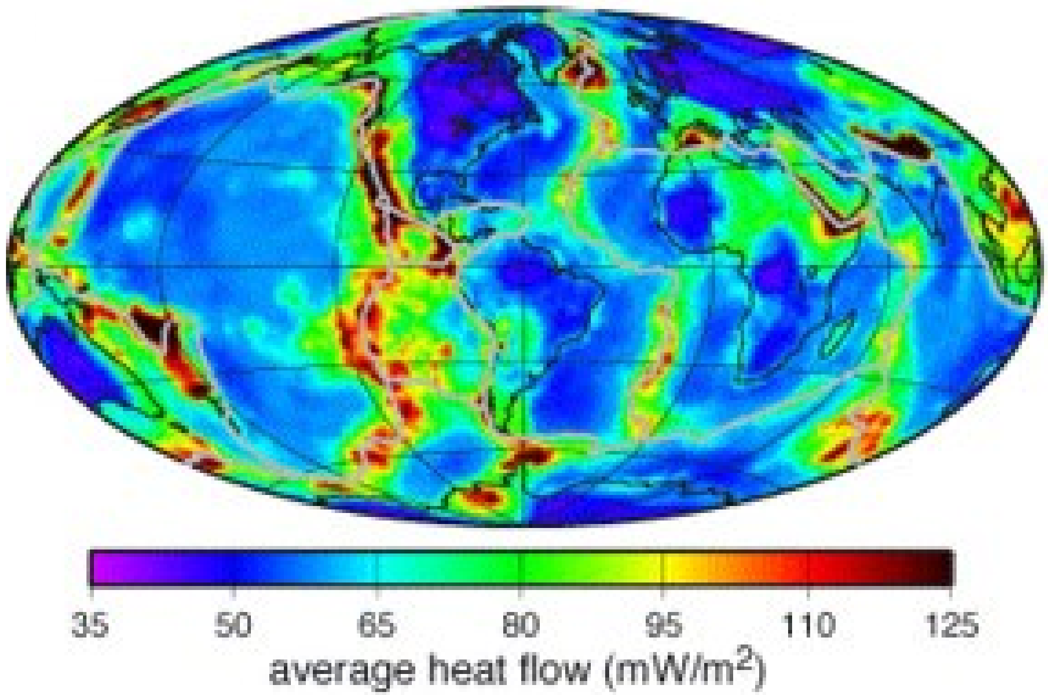

Mount St. Helens
Mount Adams
W
E
Depth (km)
0
5
10
15
20
25
30
35
40
0
10
20
30
40
50
60
70
80
Profile Distance (km)
0.5
1
1.5
2
2.5
3
3.5
Log Apparent Resistivity (Ωm)


Field
aphic
Pole
Jiki Jiki No Mi

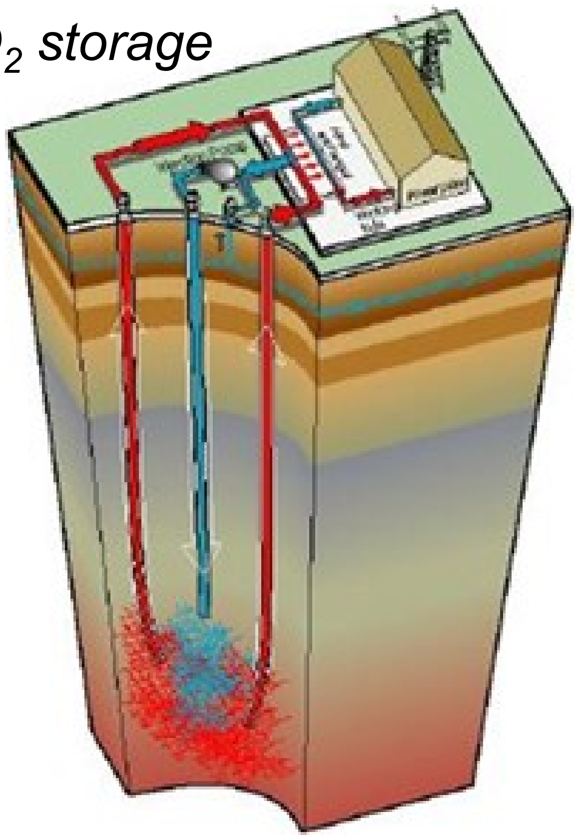

Geographic
South Pole

HEAT

Heat loss of the Earth

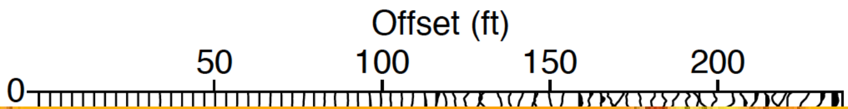


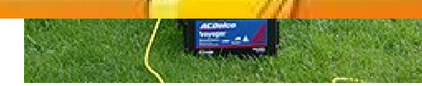
Geothermal energy and CO_2 storage



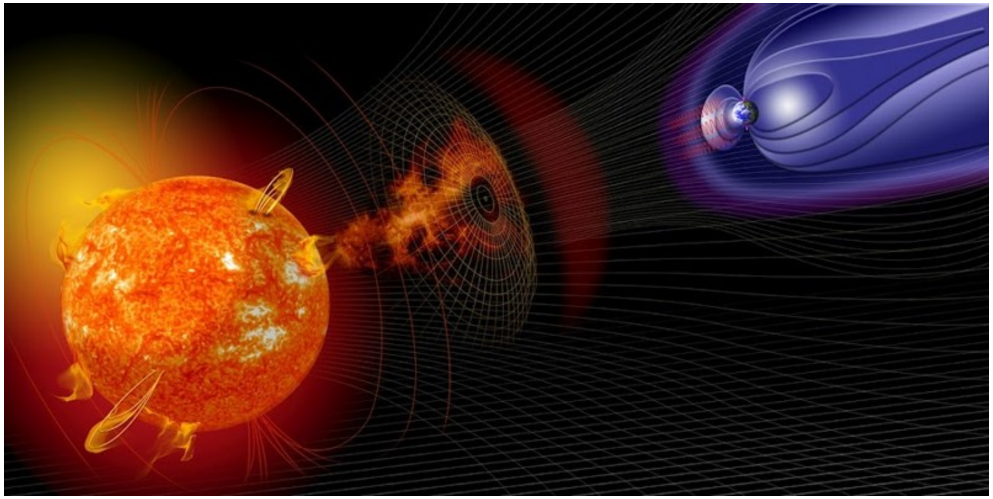
Netsu Netsu No Mi

Exploration

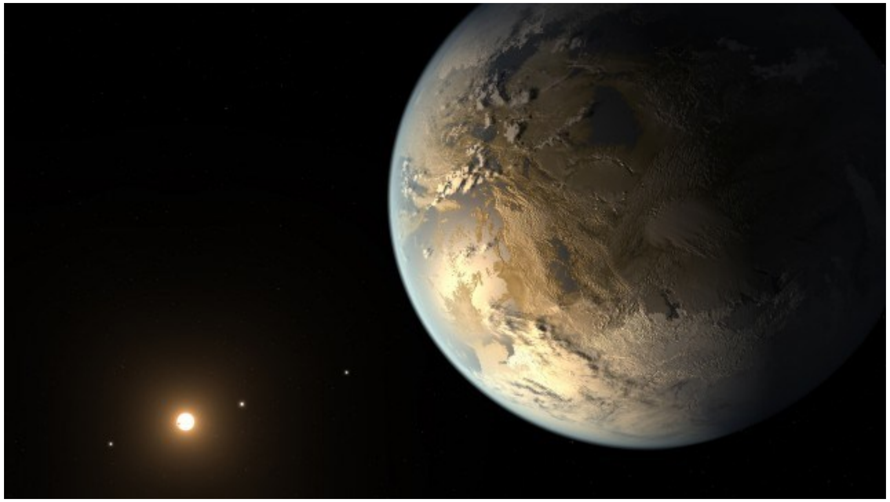




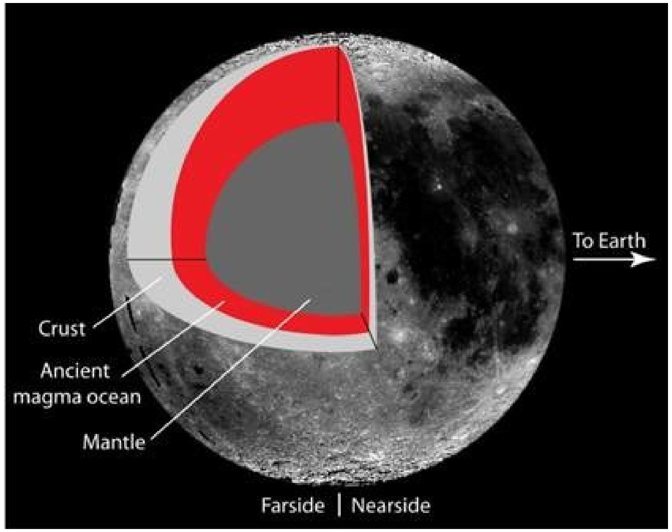
Planetary and Space Physics

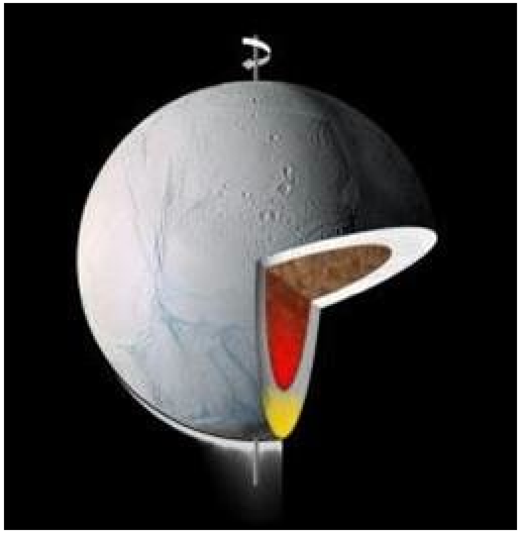


Magnetosphere & space weather

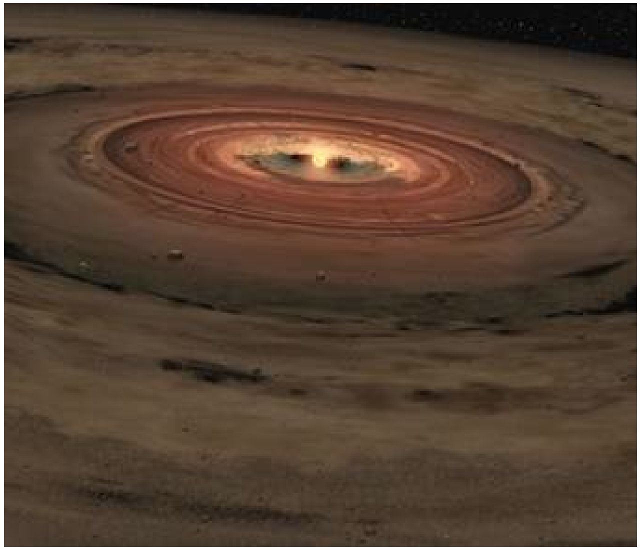


Exoplanets





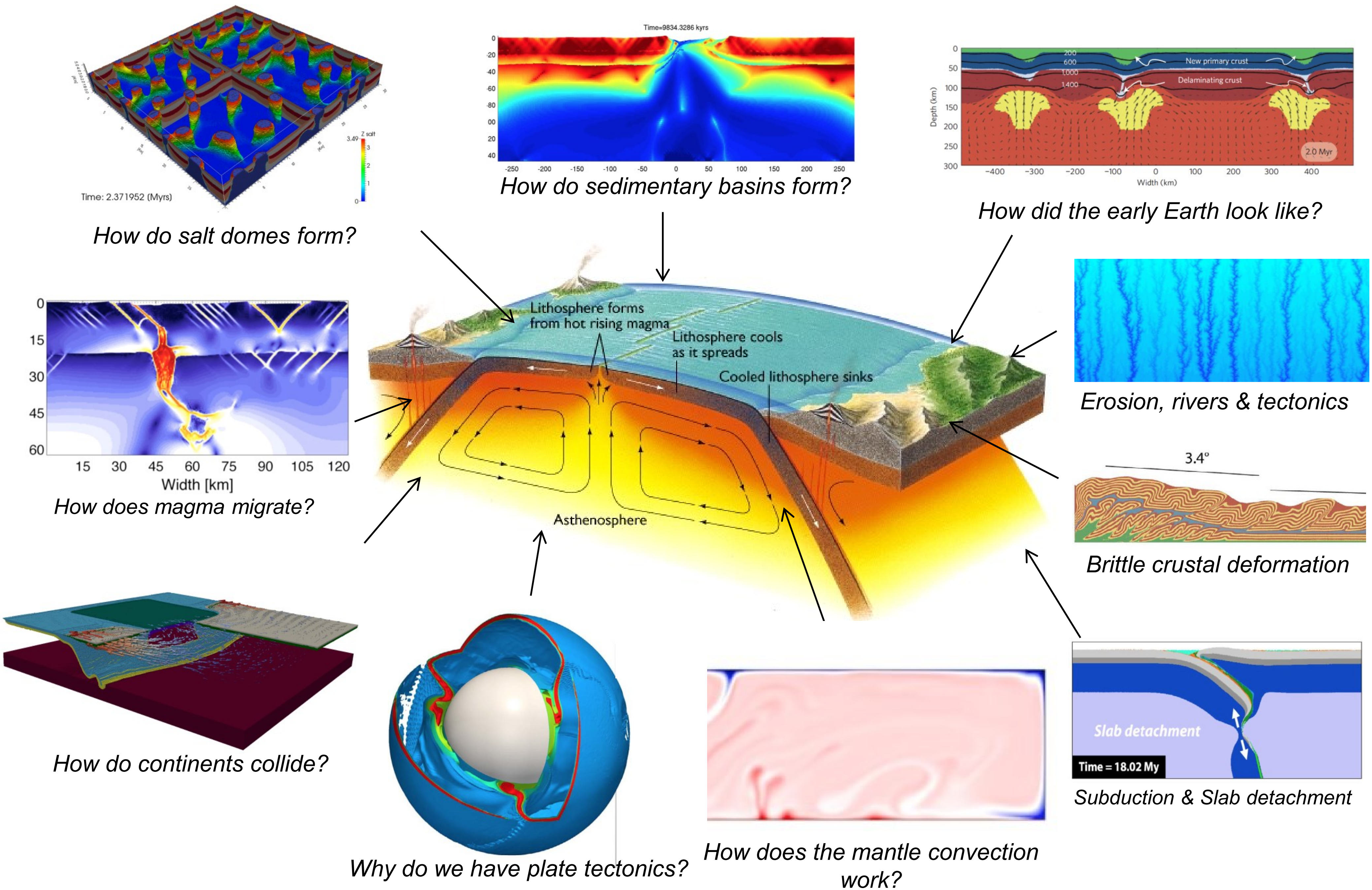
Structure and dynamics of other planets



Building planets

Planetary and Space Physics

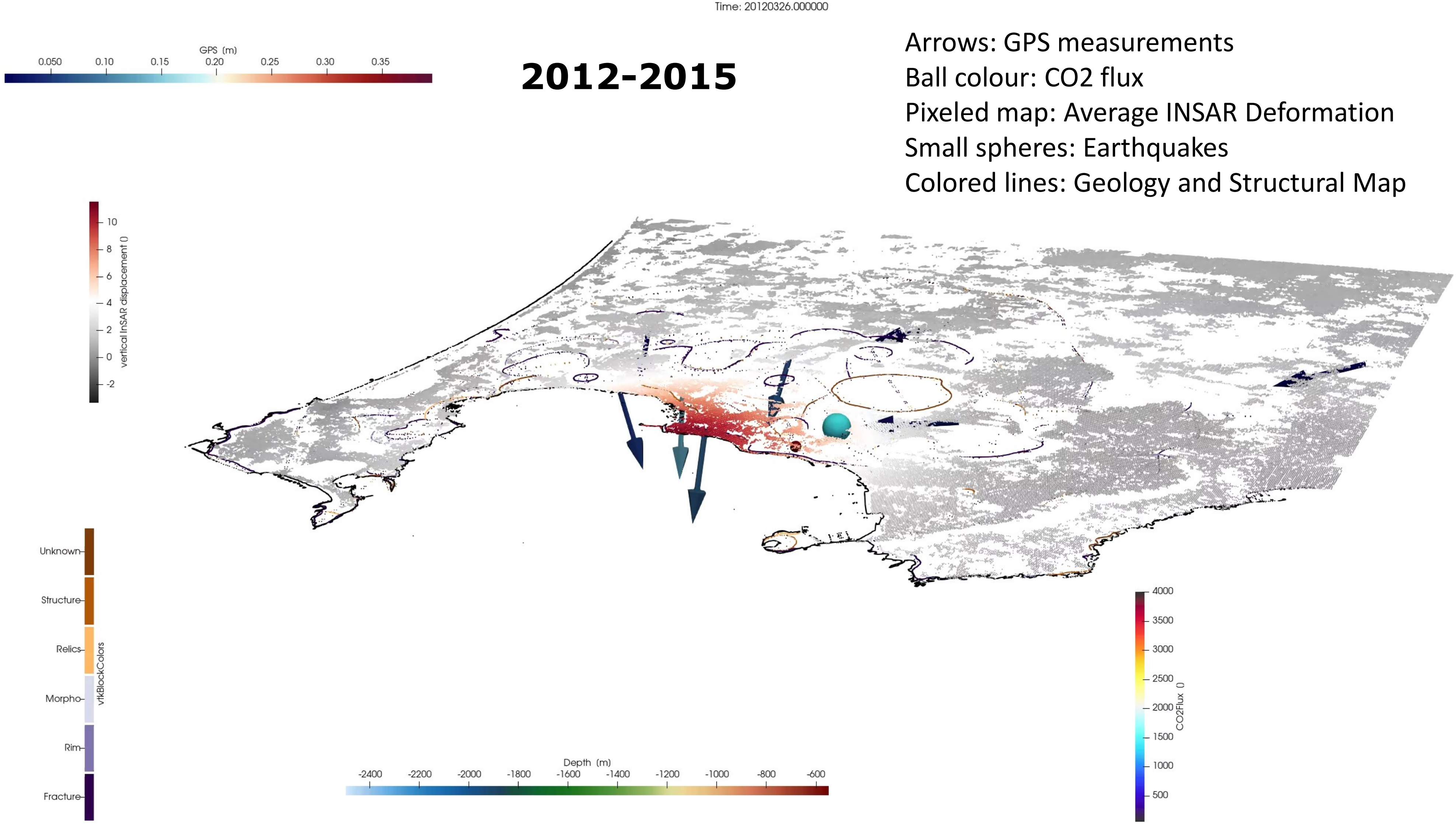
GEODYNAMICS



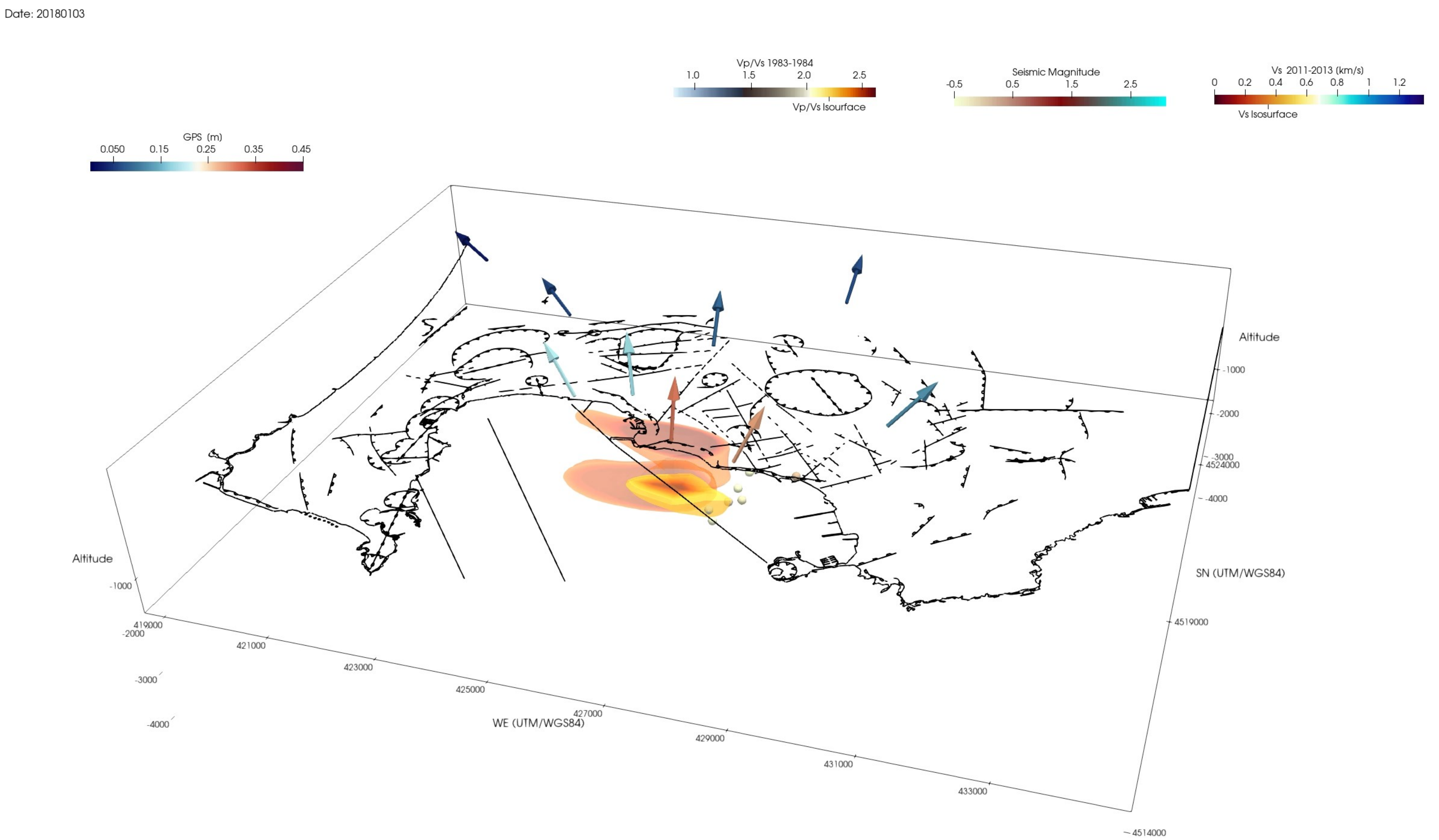
GEOPHYSICAL RESPONSE TO (WHAT?)

2012-2015

Arrows: GPS measurements
Ball colour: CO_2 flux
Pixeled map: Average INSAR Deformation
Small spheres: Earthquakes
Colored lines: Geology and Structural Map

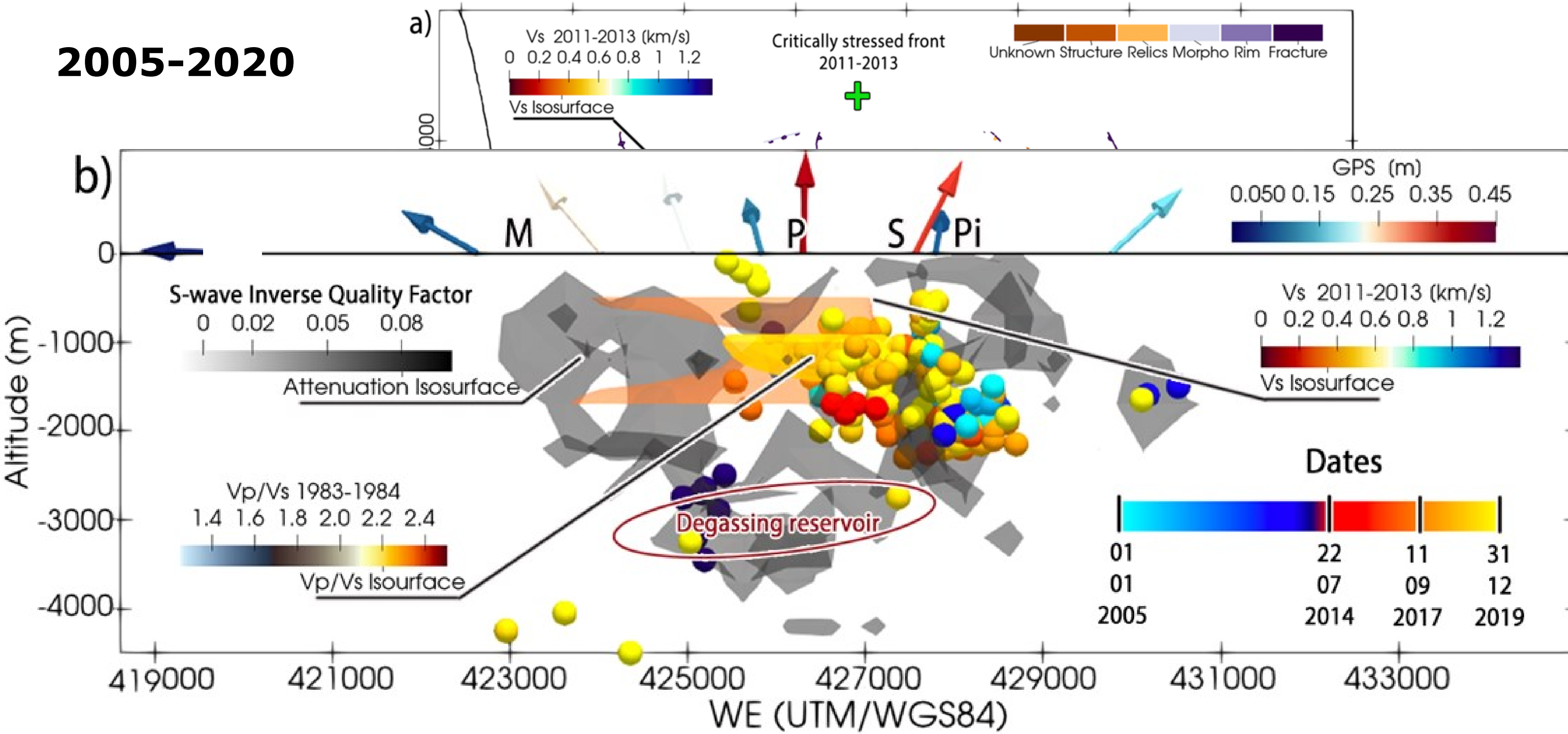


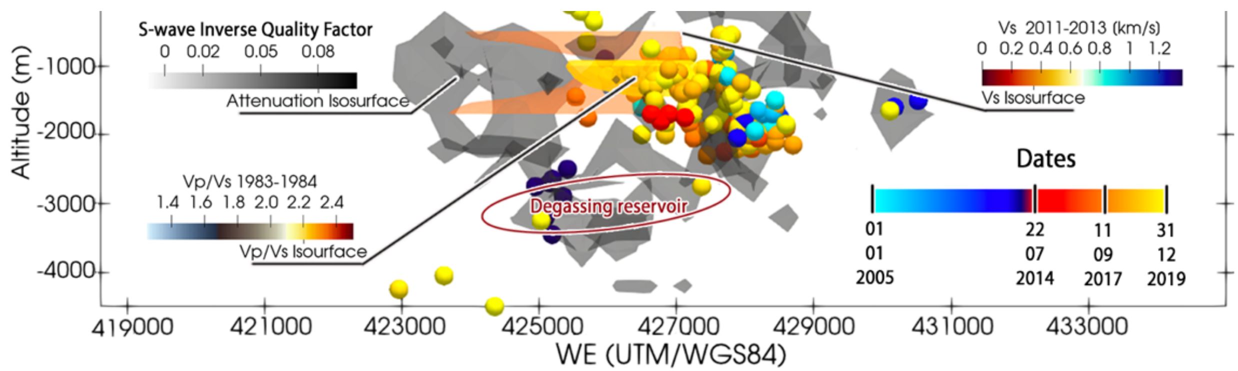
GEOPHYSICAL RESPONSE TO (WHAT?)



GEOPHYSICAL RESPONSE TO (WHAT?)

2005-2020

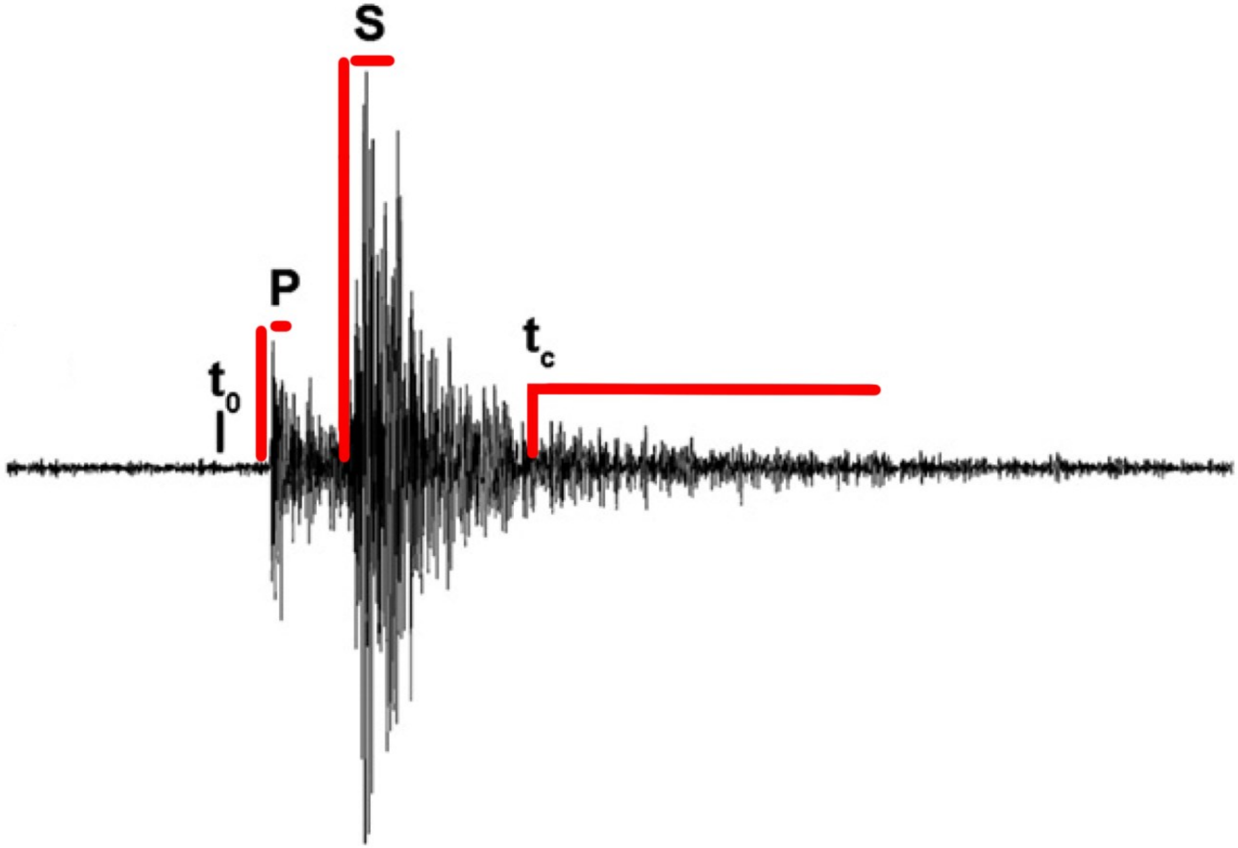




This is a seismogram.

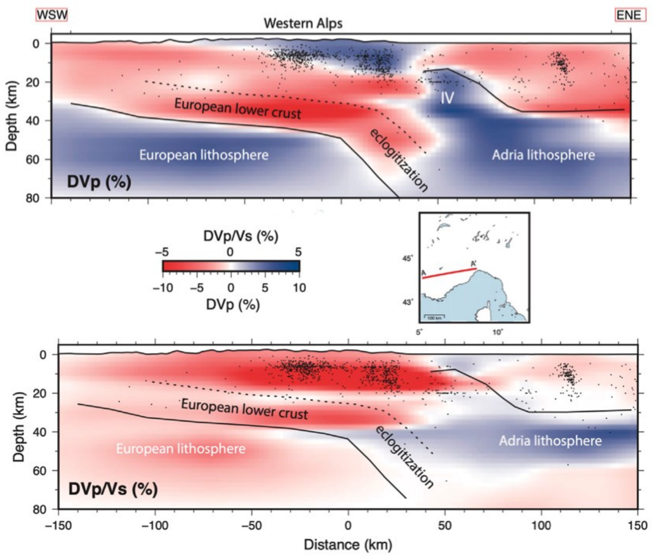
A time series of a few 10s of seconds duration, sampled at ≈100 Hz and representing sources of elastic waves produced down to 10^{-4} Hz.

Seismologists have long used the arrivals of seismic phases to do tomography; however, they have now learned how to use the rest to achieve better results.

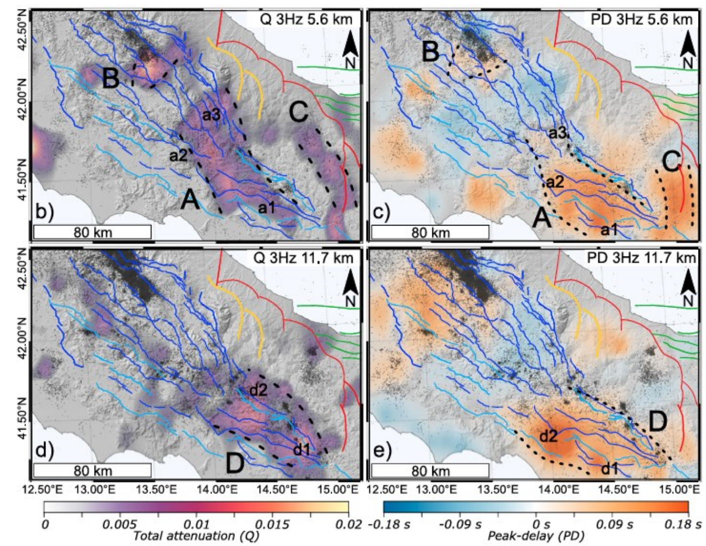


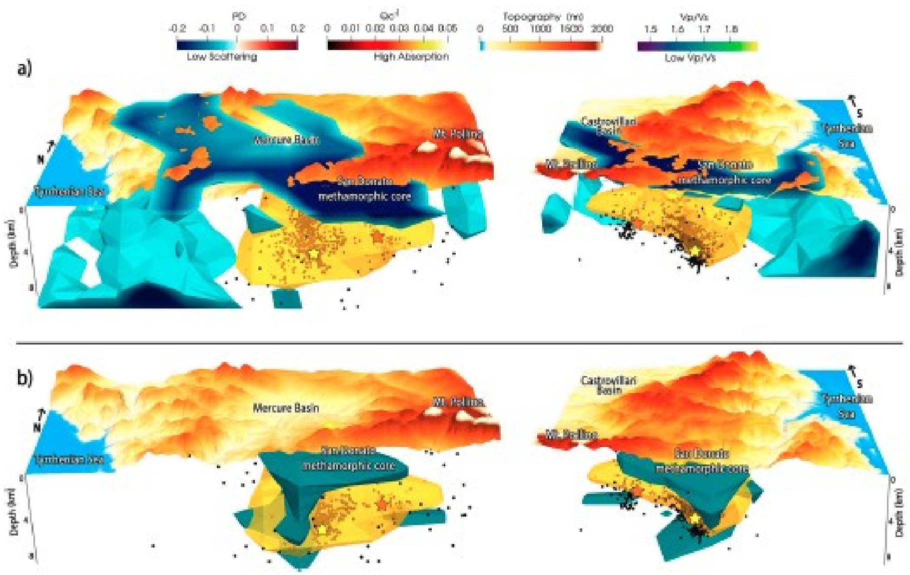
Seismic tomography in the Apennines.

Chiarabba et al. 2023

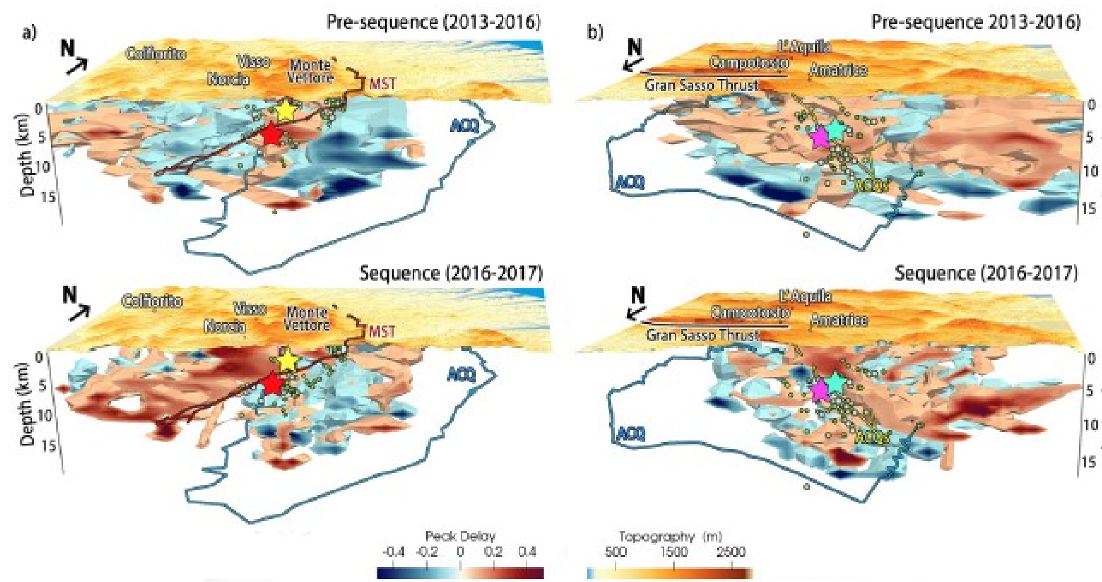


Talone et al. 2023





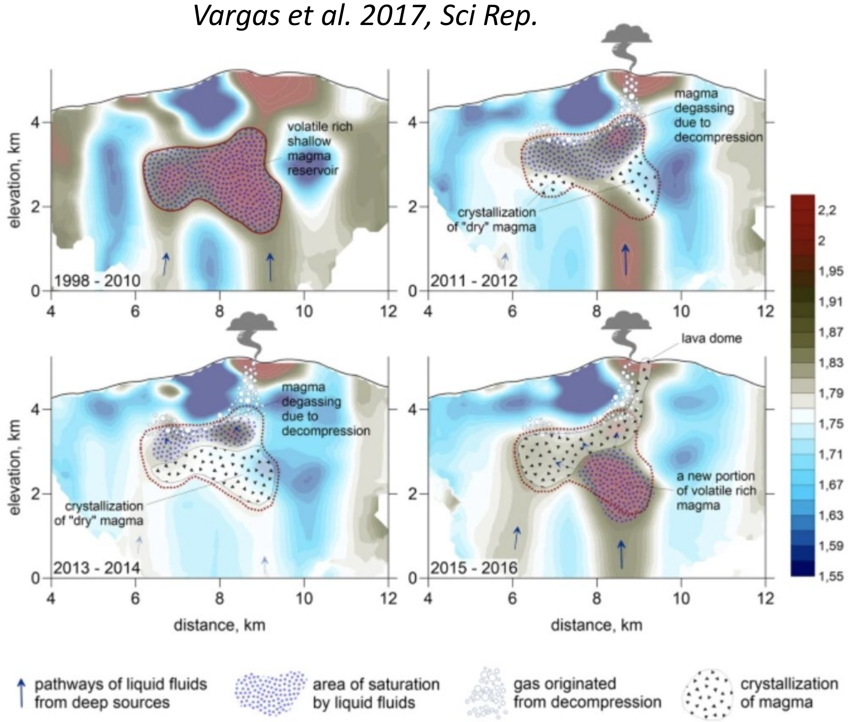
Napolitano et al. 2023



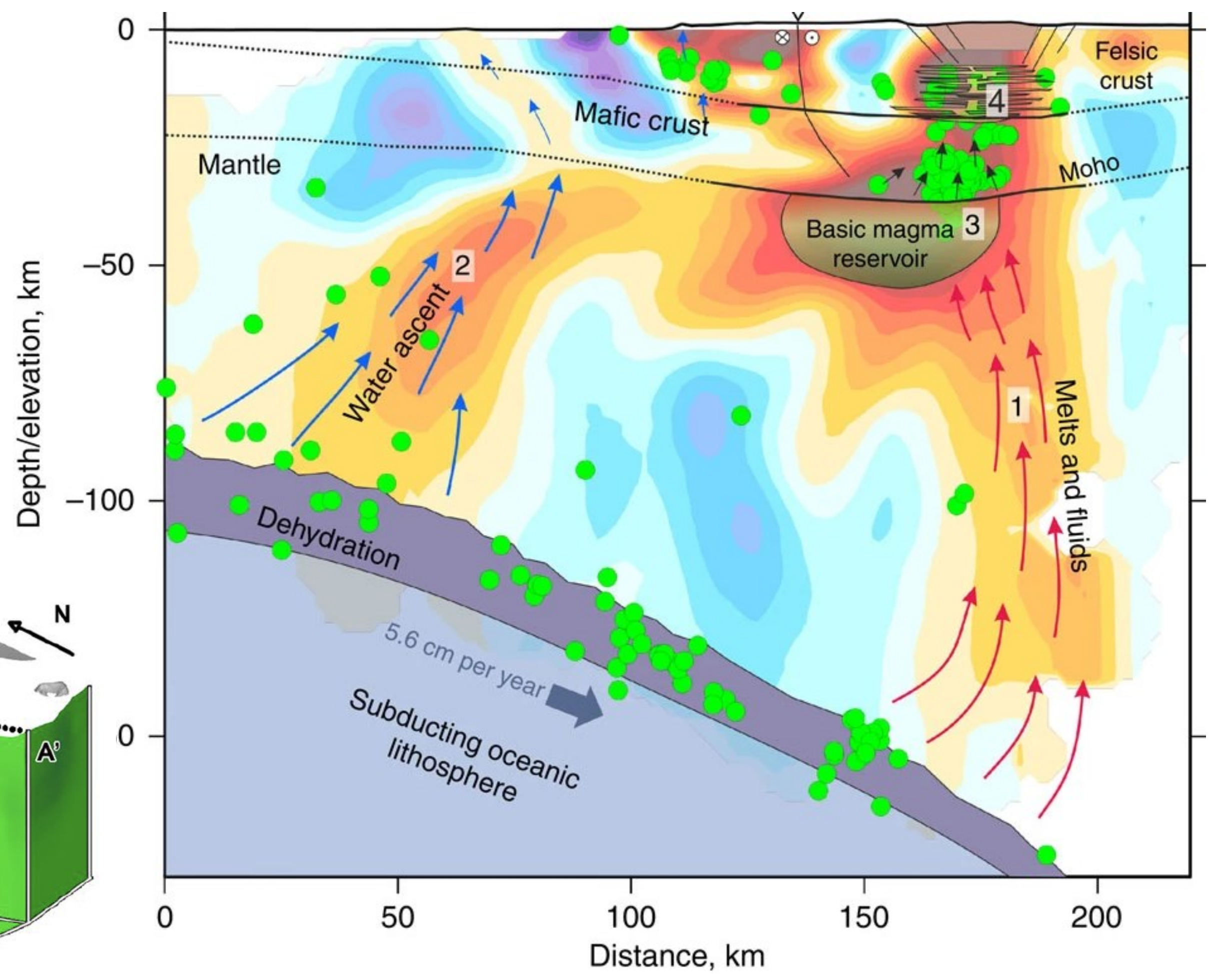
Gabrielli et al. 2023

Seismic tomography in volcanic regions.

Vargas et al. 2017, Sci Rep.



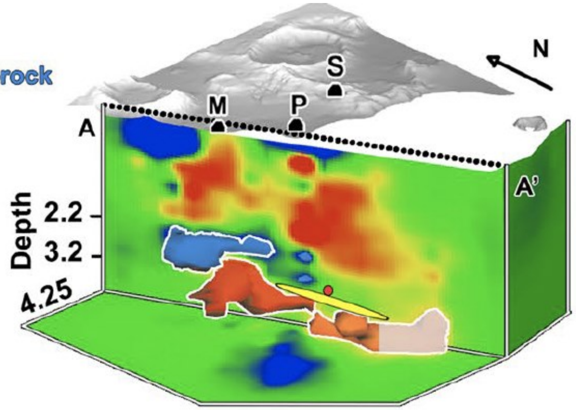
Koulakov et al. 2012, Nat. Comm



Cyan Isosurface (Qs^{-1}=0.012): Seismic fluids trapped by the caprock

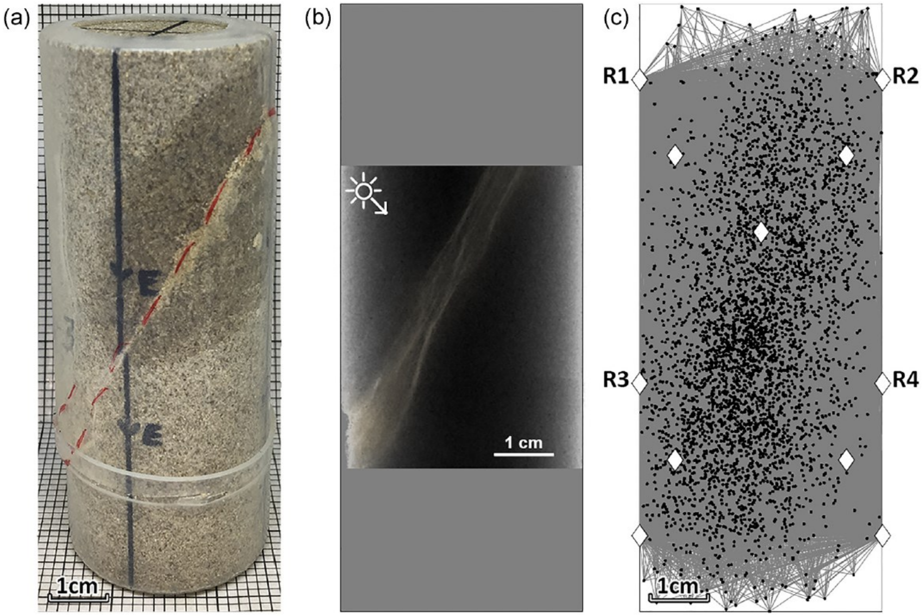
Red Isosurface (Qs^{-1}=0.04): Seismic supercritical fluid reservoir/foams

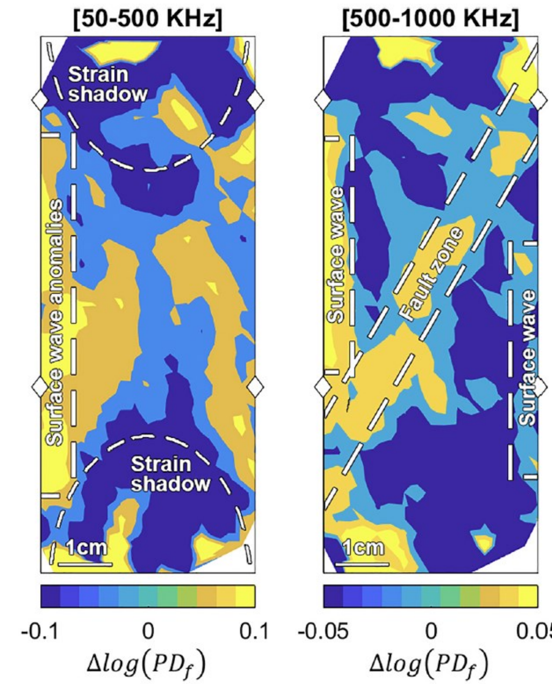
Orange Isosurface (Qs^{-1}=0.03): Aseismic hot zone, source of the deformation unrest

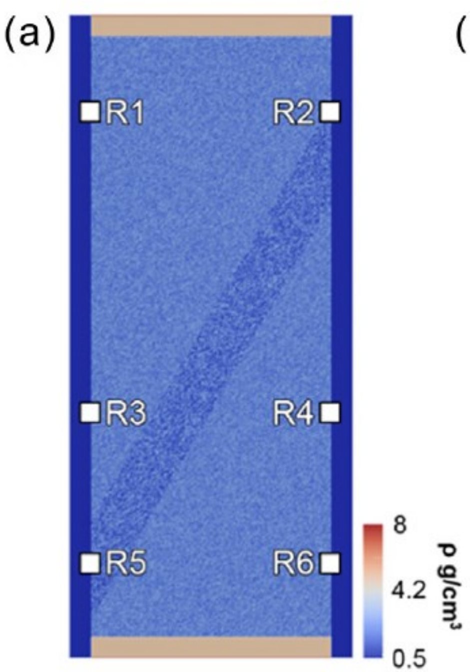


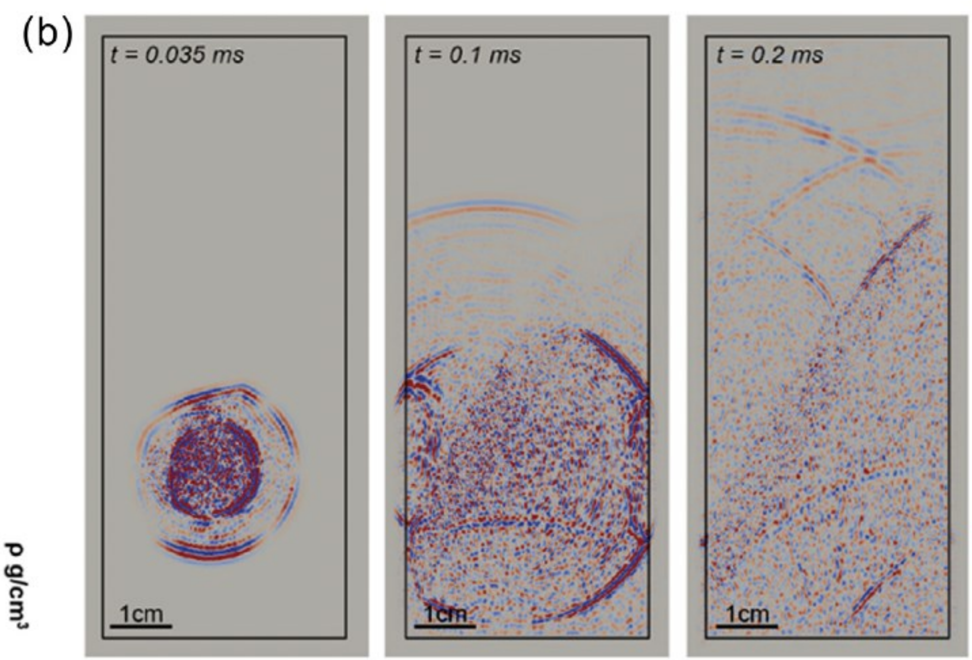
De Siena et al. 2017, Sci Rep.

Rock Physics



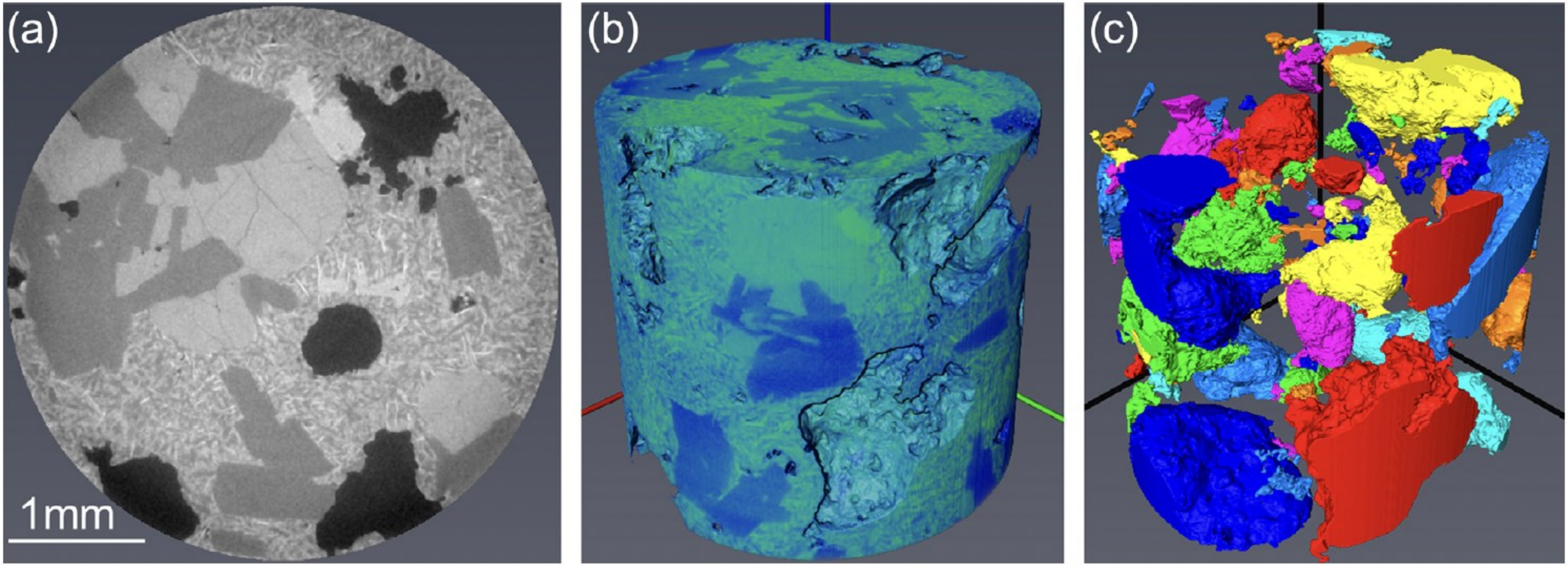


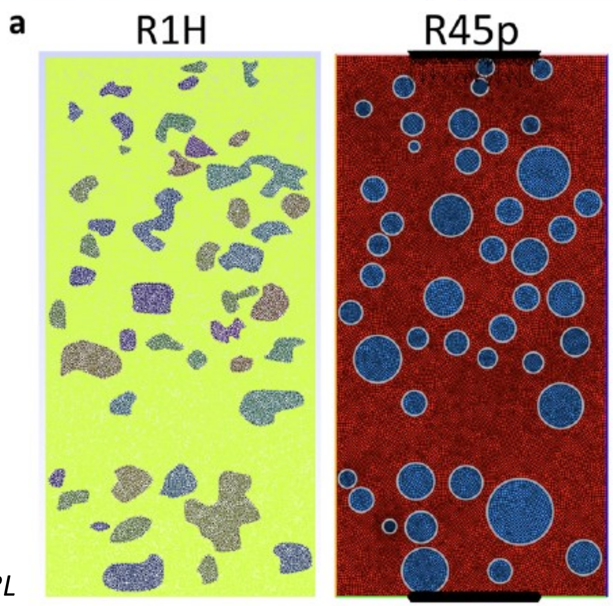


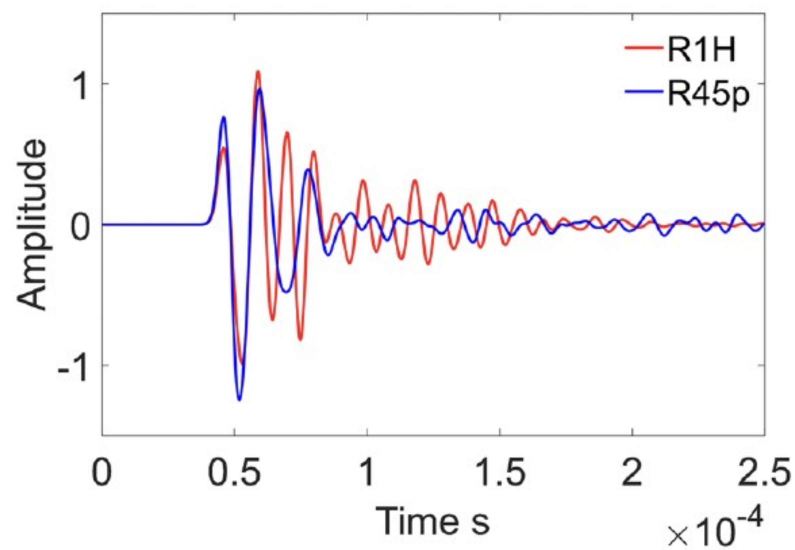


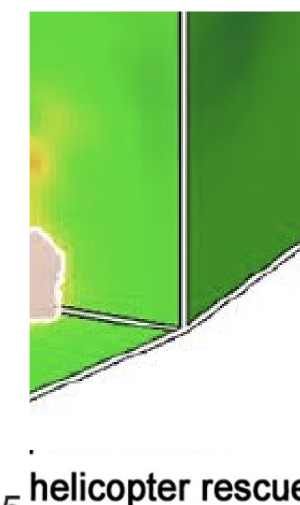
Seismic attenuation, scattering ad absorption tomography

a)









Di Martino et al. 2022, GRL

MuRAT - Multi-Resolution seismic Attenuation Tomography

MuRAT

Contributors 10

Deployments 126

github-pages 3 weeks ago

+ 125 deployments

Languages

MATLAB 100.0%

MuRAT (*De Siena, L., https://github.com/LucaDeSiena/MuRAT/tree/master*): open-source Matlab package for seismic scattering, absorption and attenuation tomography.

The Navier-Cauchy equation

The equation of motion for an elastic, linear, homogeneous, isotropic ***medium:***

$$\rho\ddot{\mathbf{u}} = \mathbf{f} + \mu\nabla^2\mathbf{u} + (\lambda+\mu)\nabla(\nabla\cdot\mathbf{u})$$

where **u** is the displacement, ρ the density, (λ, μ) the Lamé constants, and **f** the force.

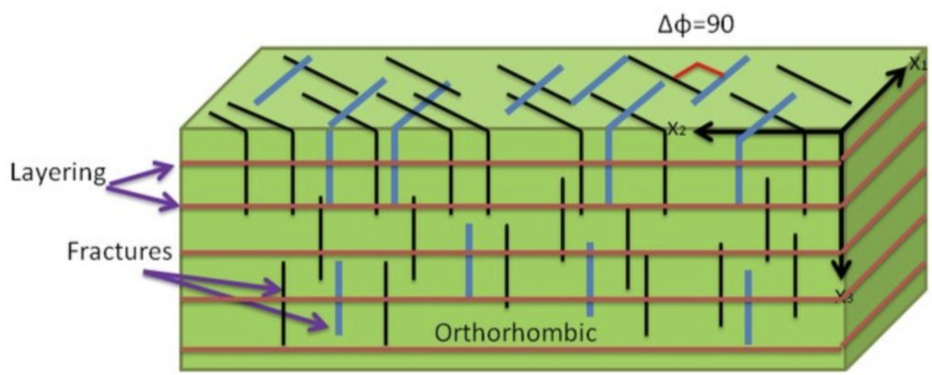
The past

The present and future

$$\sigma_{ij} = C_{ijkl}e_{kl} \quad i,j,k,l = 1,2,3$$

C_{ijkl} *: elastic modulus*

$$C_{ij} = \begin{vmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{13} & C_{23} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{vmatrix}$$

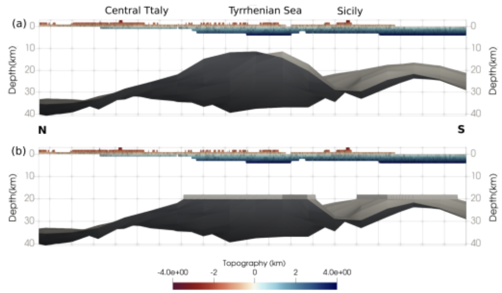


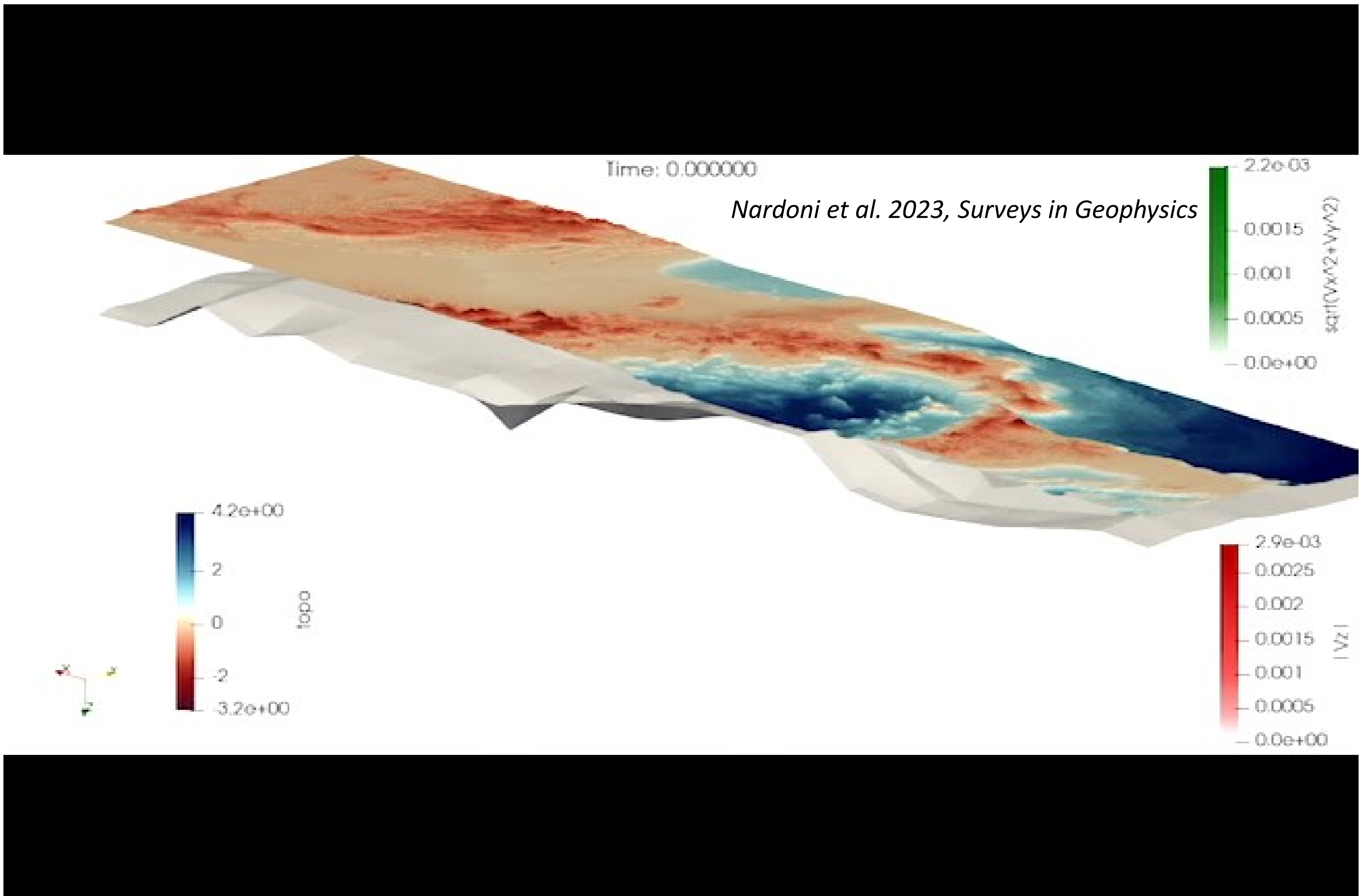
Orthotropic anisotropy

SEISMIC WAVEFILEDS

OpenSWPC

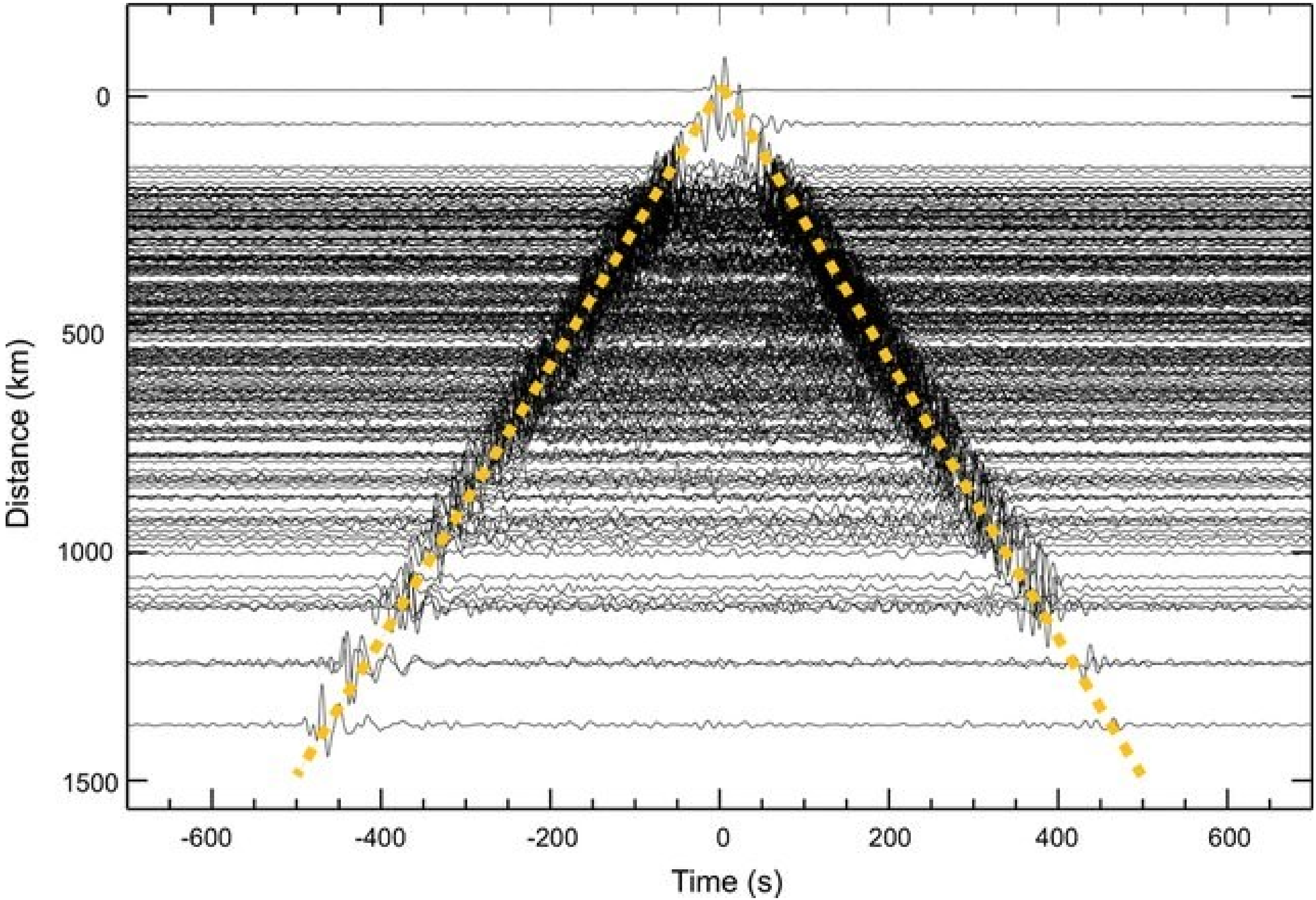
	Depth	
	Pinch	Continental crust
Moho10km	Manu-Marfo et al. (2019)	
EPcrust	Molinari and Morelli (2011)	
MohoEP18	18km	EPcrust
MohoEP20	20km	>25km





Nardoni et al. 2023, Surveys in Geophysics

SEISMIC NOISE

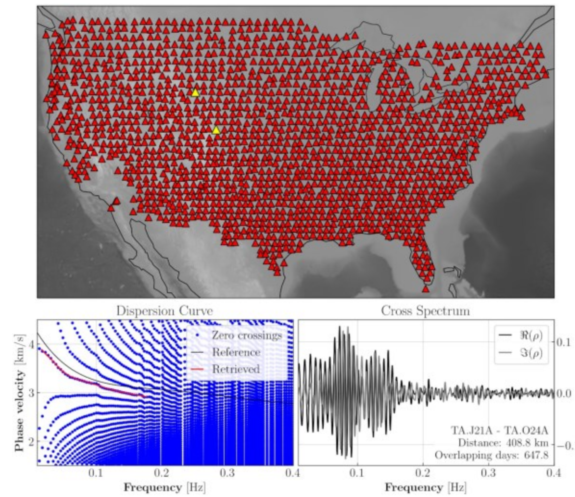


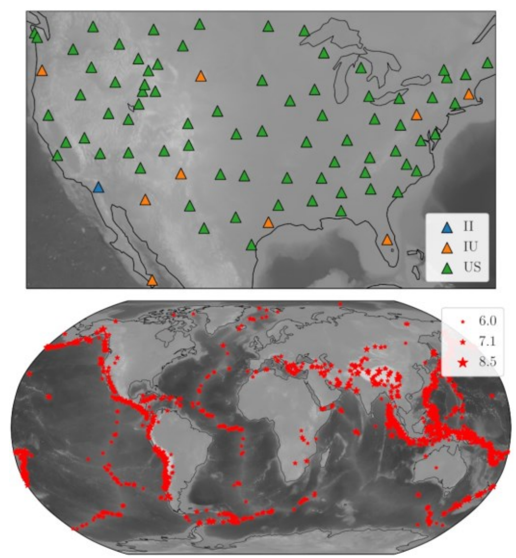
Bringing Alternative Imaging to the Apennines: Seismic Noise and teleseisms

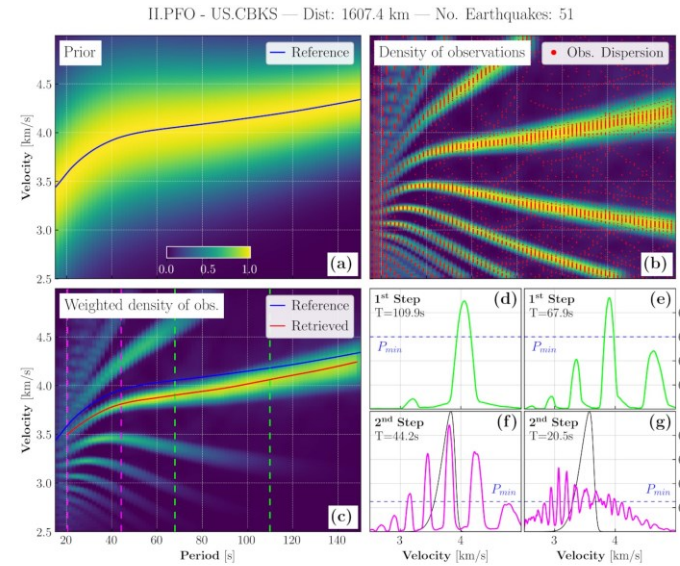
Surface-wave tomography using ambient noise and teleseismic earthquakes.

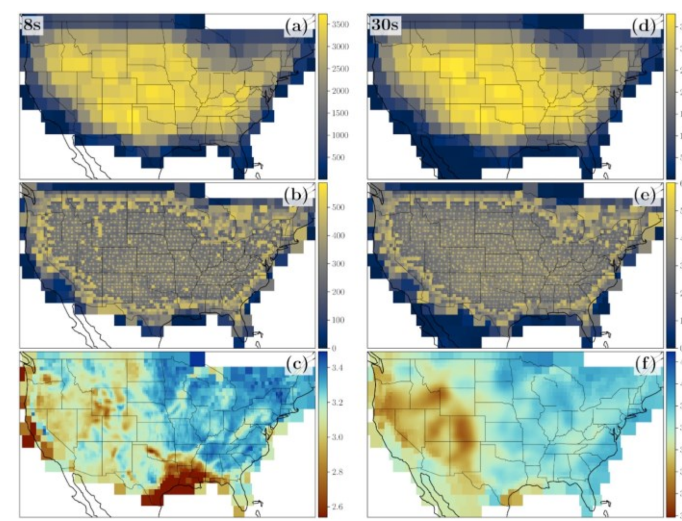
Joint inversion of Rayleigh and Love phase velocities using ambient noise, teleseismic earthquakes with adaptive parametrization.

Transdimensional Bayesian inversion for shear-wave velocities optimized with a reversible-jump Markov chain Monte Carlo sampling.



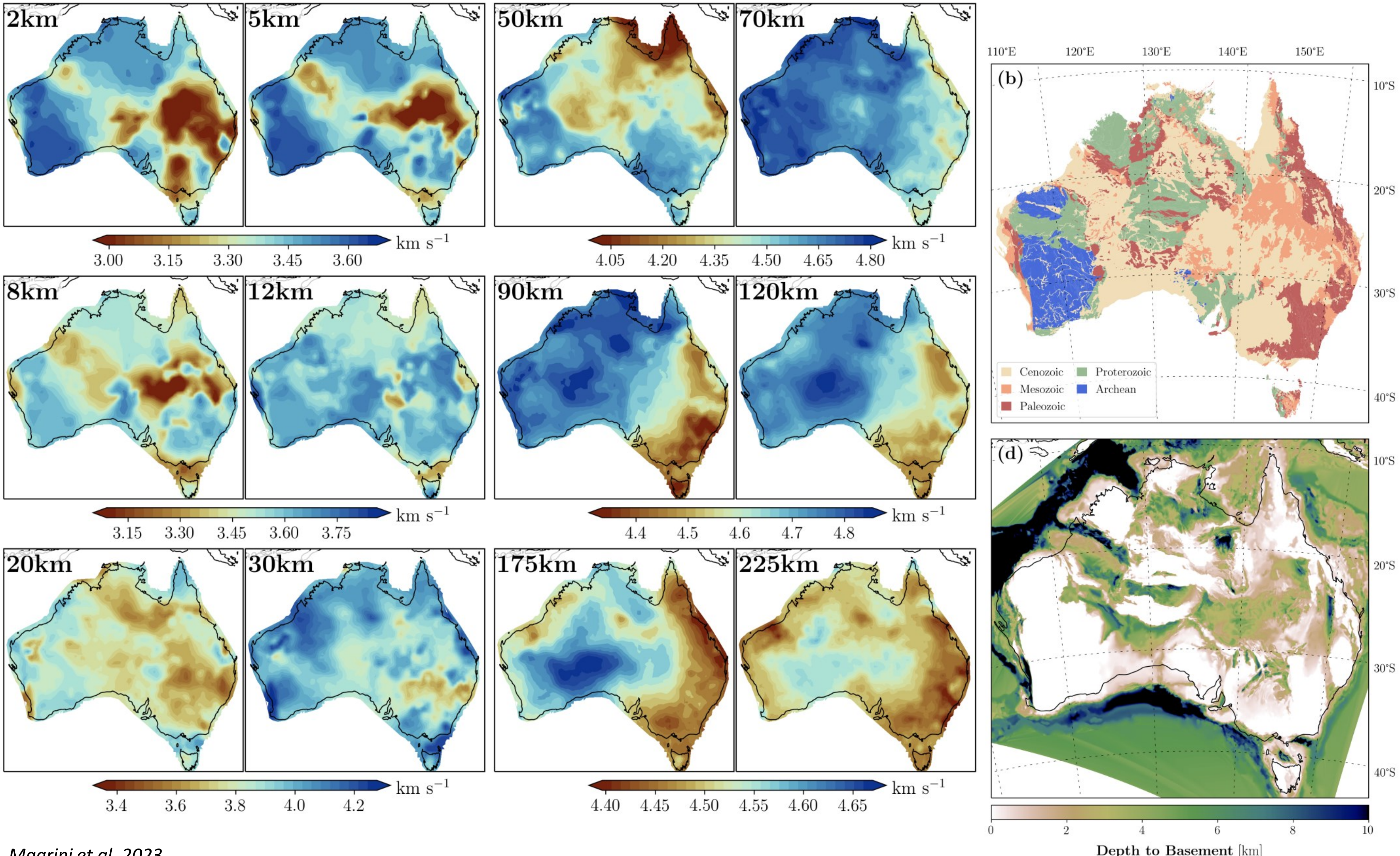






BayHunter (Dreiling and Tilmann, 2019)
SeisLib (*Magrini et al. 2022, https://pypi.org/project/seislib/*): open-source modular, automated Python package for surface-wave tomography.

ALTERNATIVE IMAGING: SEISMIC NOISE AND TELESEISMS

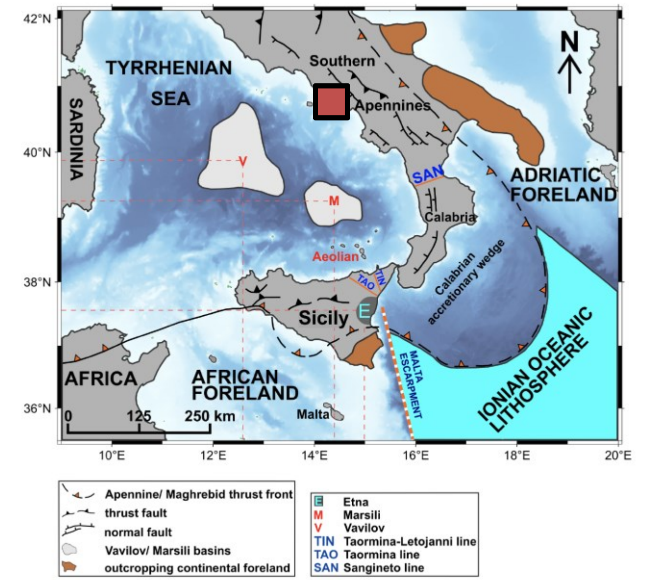


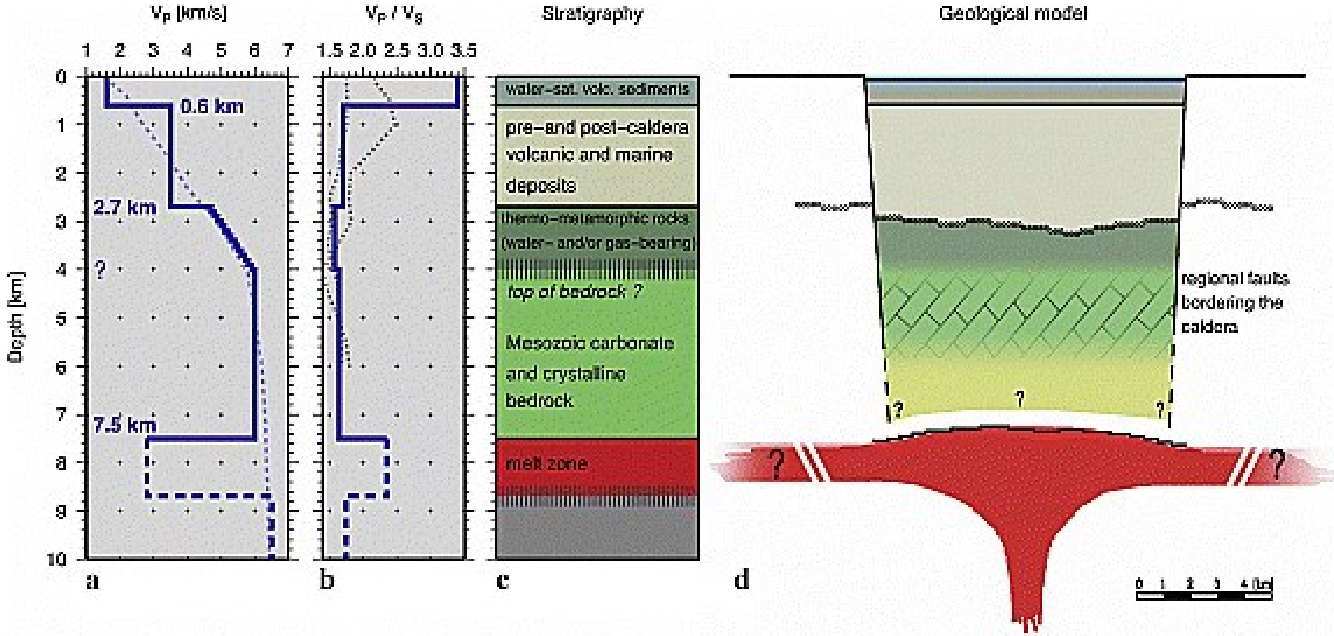
Magrini et al. 2023

Campi Flegrei

"…located along a NE–SW transfer zone connecting NW–SE regional normal faults. Volcanic activity along such NE–SW trend would be induced by the subvertical dip of the transfer faults." - Acocella et al. 1999, JVGR

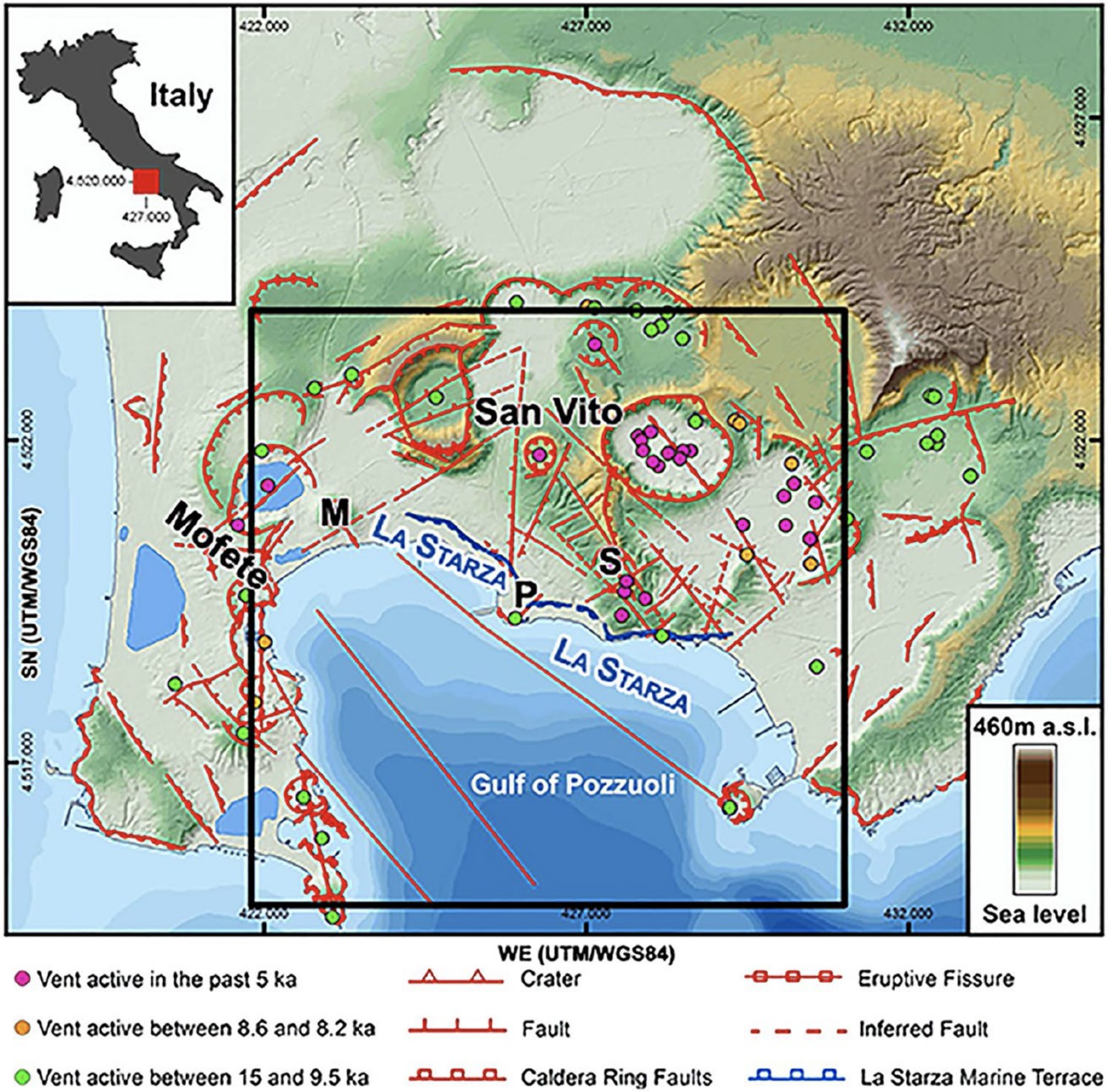
"… an extended supercritical fluid-bearing rock formation at about 3,000 m and of an about 7,500 m deep, 1,000 m thick, low velocity layer, which is associated with a mid-crust, partial melting zone beneath the caldera." – Zollo et al. 2008, GRL





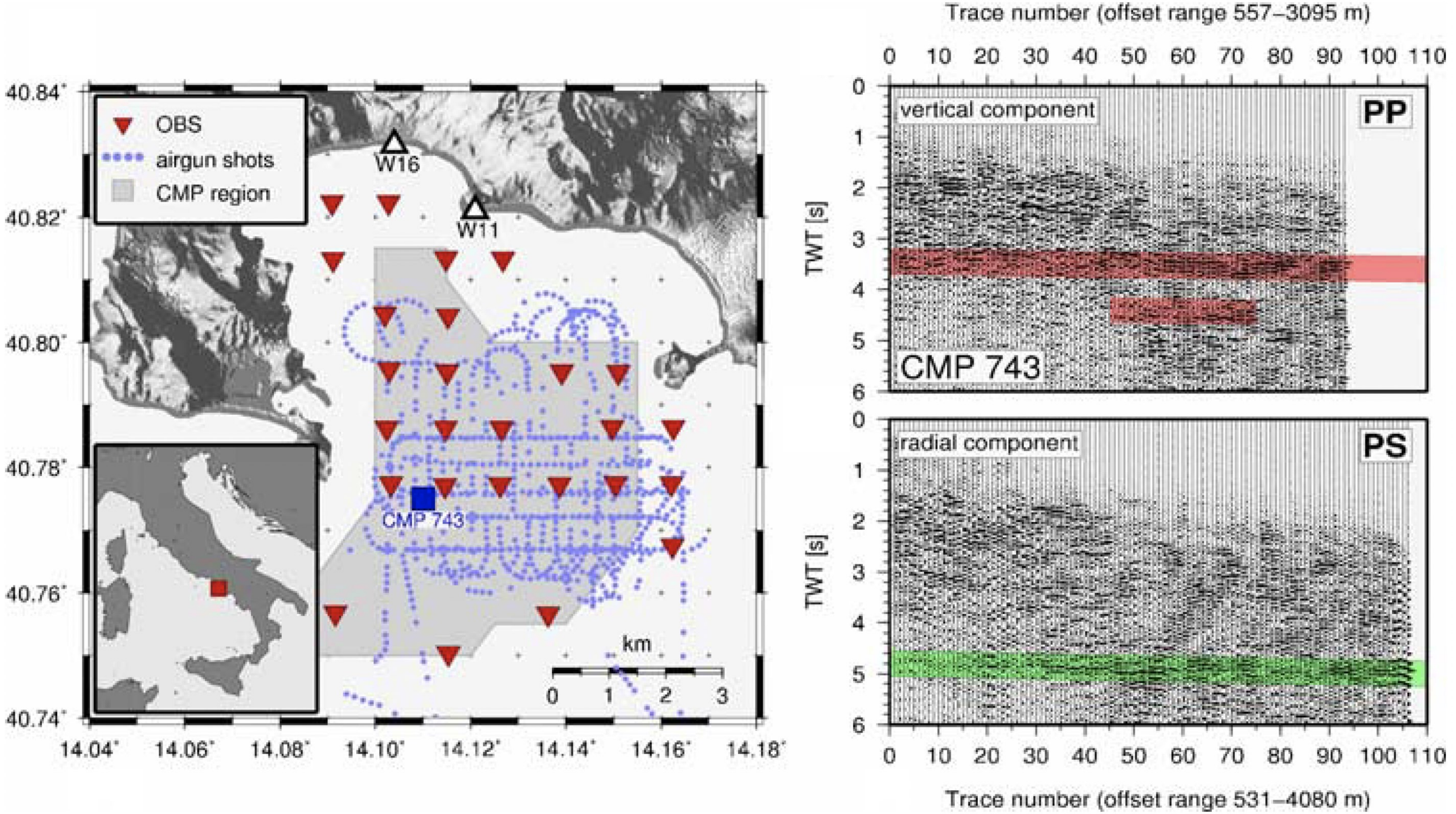
Campi Flegrei: a typical case study

CAMPI



FLEGREI

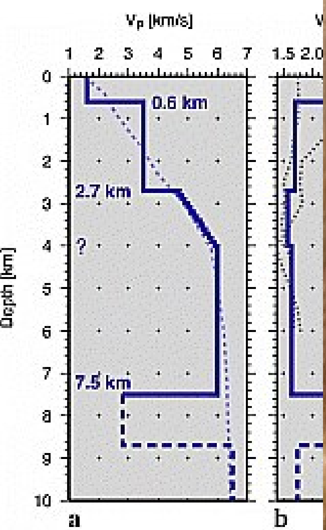
CAMPI FLEGREI: A TYPICAL CASE STUDY

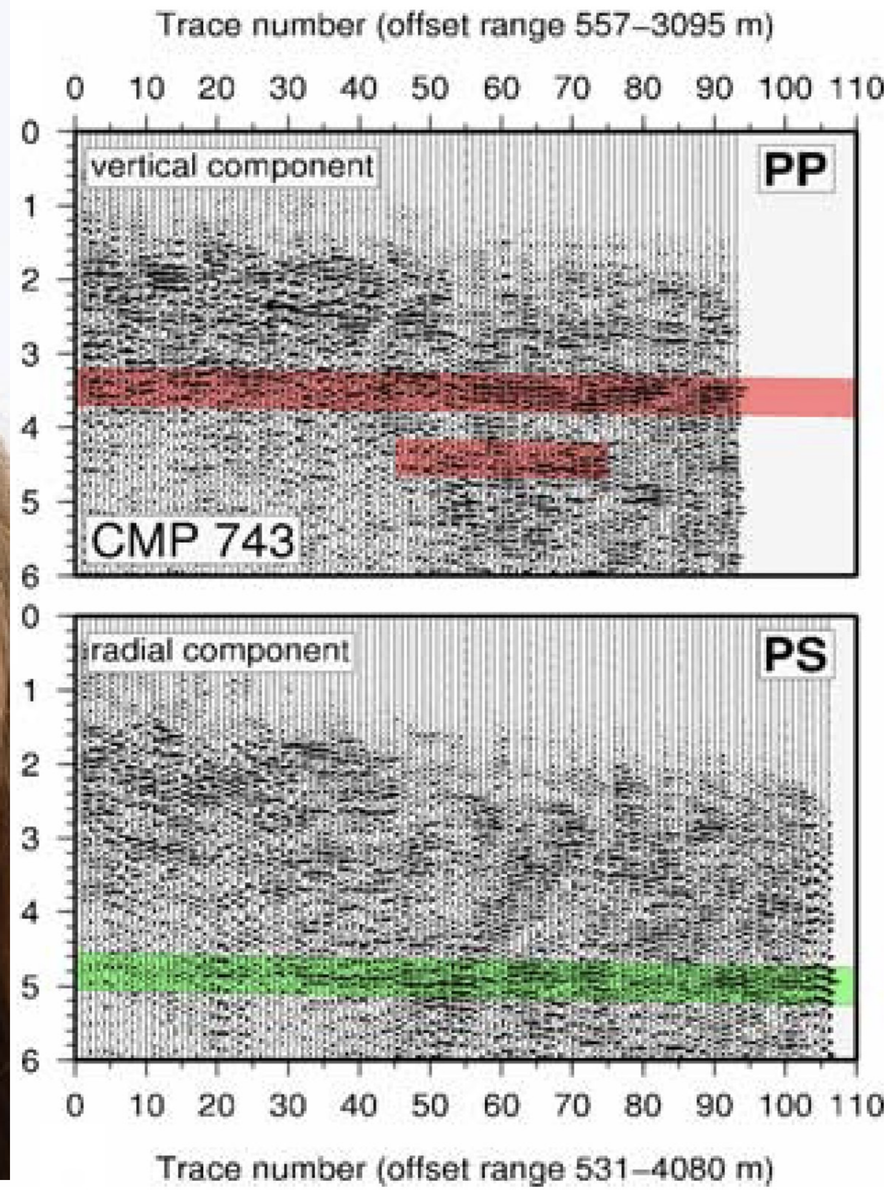


CAMPI FLEGREI: A TYPICAL CASE STUDY

"… The modelir
seismic velocitie
(in the range **80**

… by computing
for a two-phase

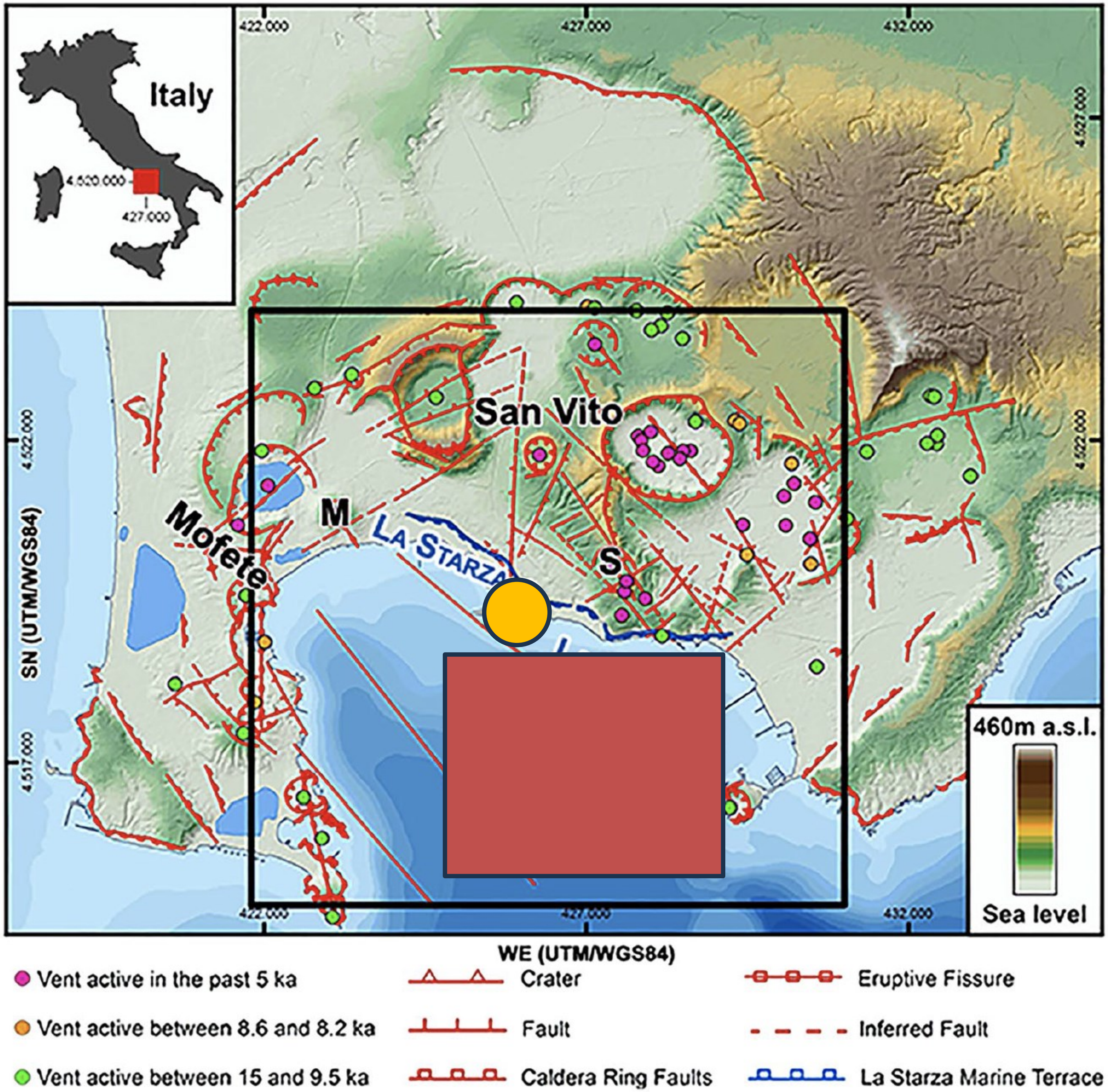




Much of our deep understanding of the present-day caldera depends on this work!

Joint Interpretation of Geophysical Responses: does the sill fit?

CAMPI

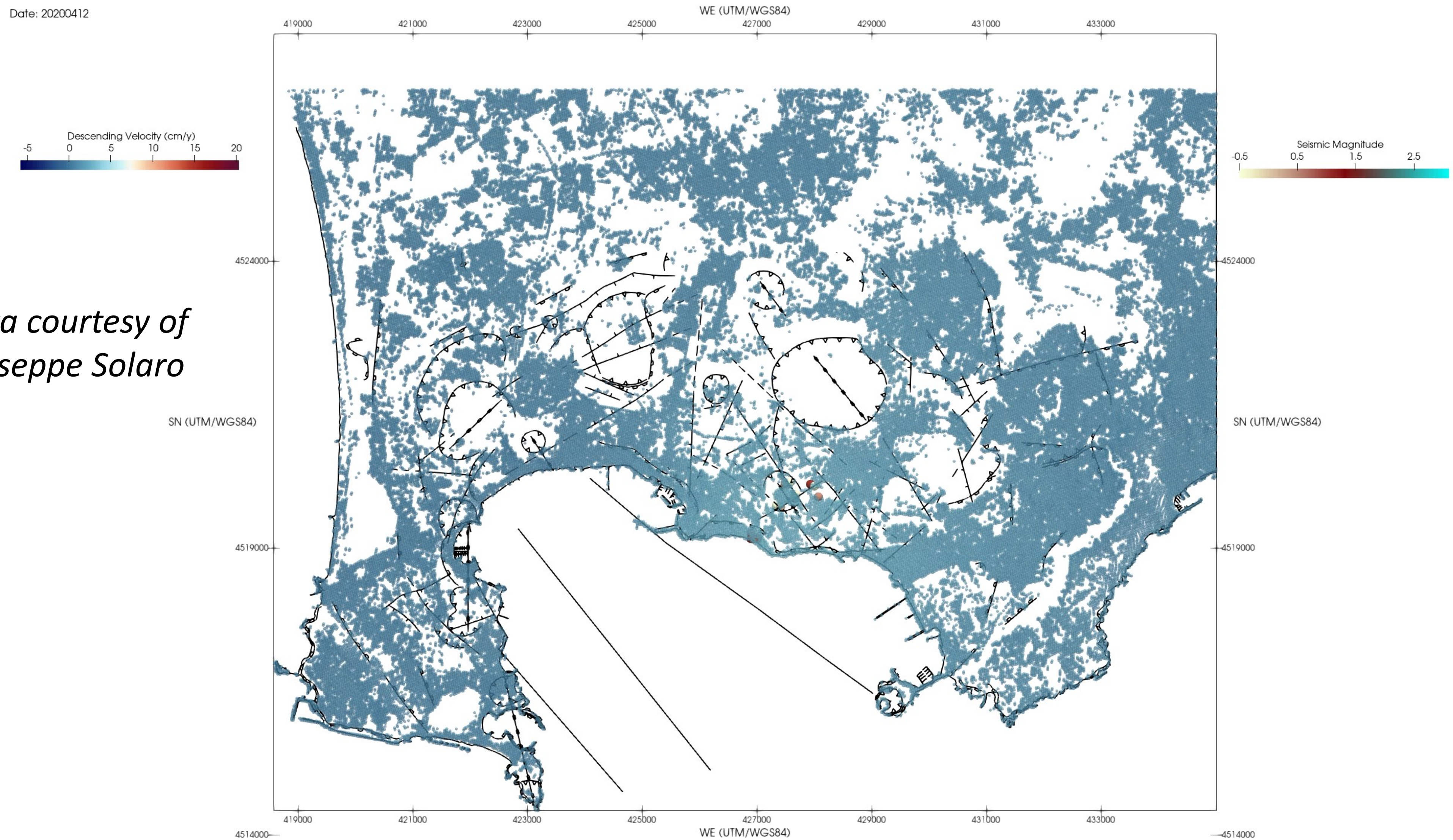


MAX DEFORMATION

SILL AT 7-8 km IMAGED BY SERAPIS

FLEGREI

FITTING DATA: INSAR, SEISMICITY



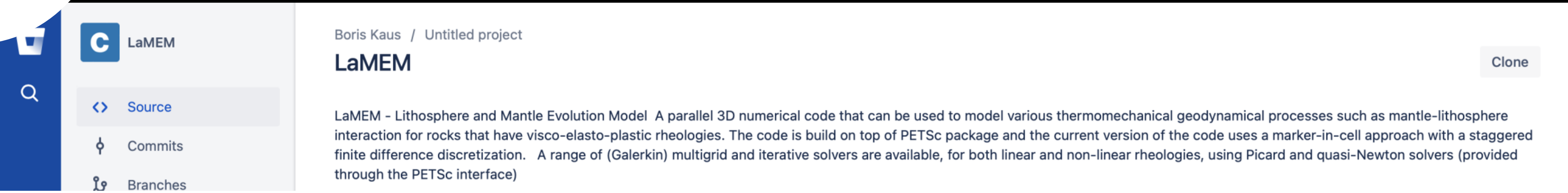
Data courtesy of Giuseppe Solaro

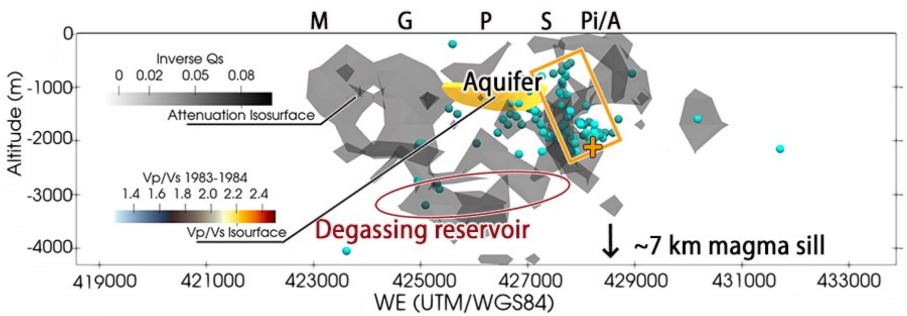
GPS from Di Martino et al. 2021, Remote Sensing
CO2 from Chiodini et al. 2021, JVGR
Seismicity from Tramelli et al. 2021, Scientific Reports

InSAR from Pepe et al. 2019, Remote Sensing of Env.
Geology and structural maps courtesy of Giuseppe Vilardo
Velocity tomography from Vanorio (2005) and De Siena (2018)

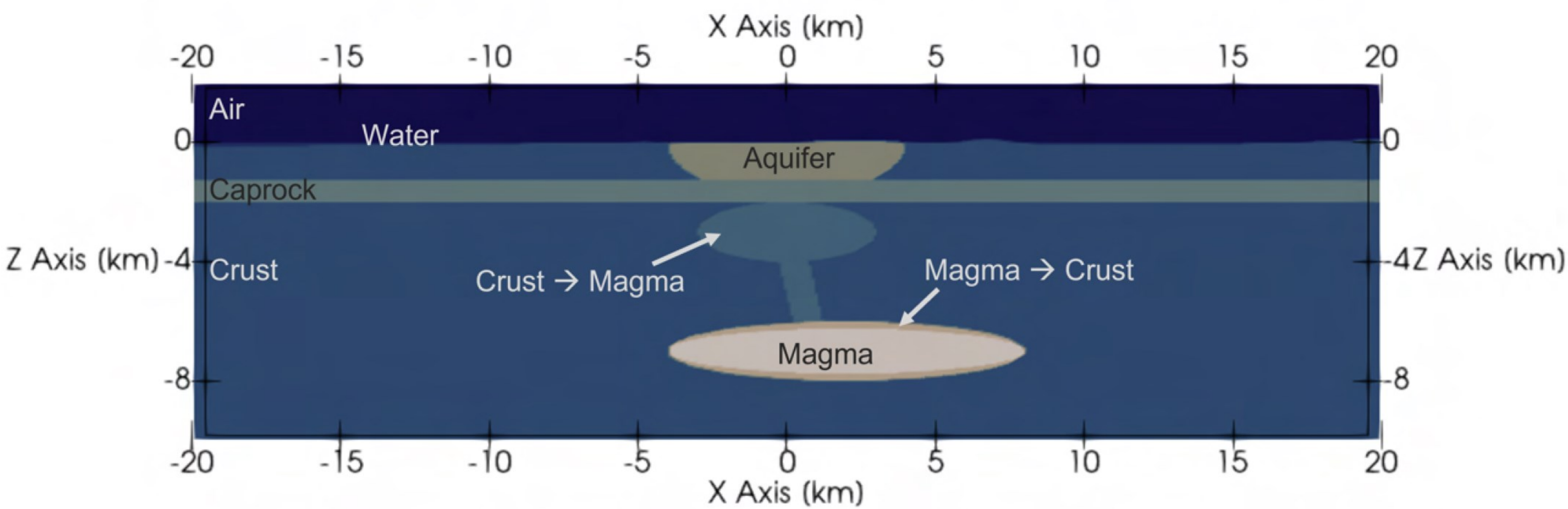
THERMOMECHANICAL SOLUTION

Walter et al. in preparation.



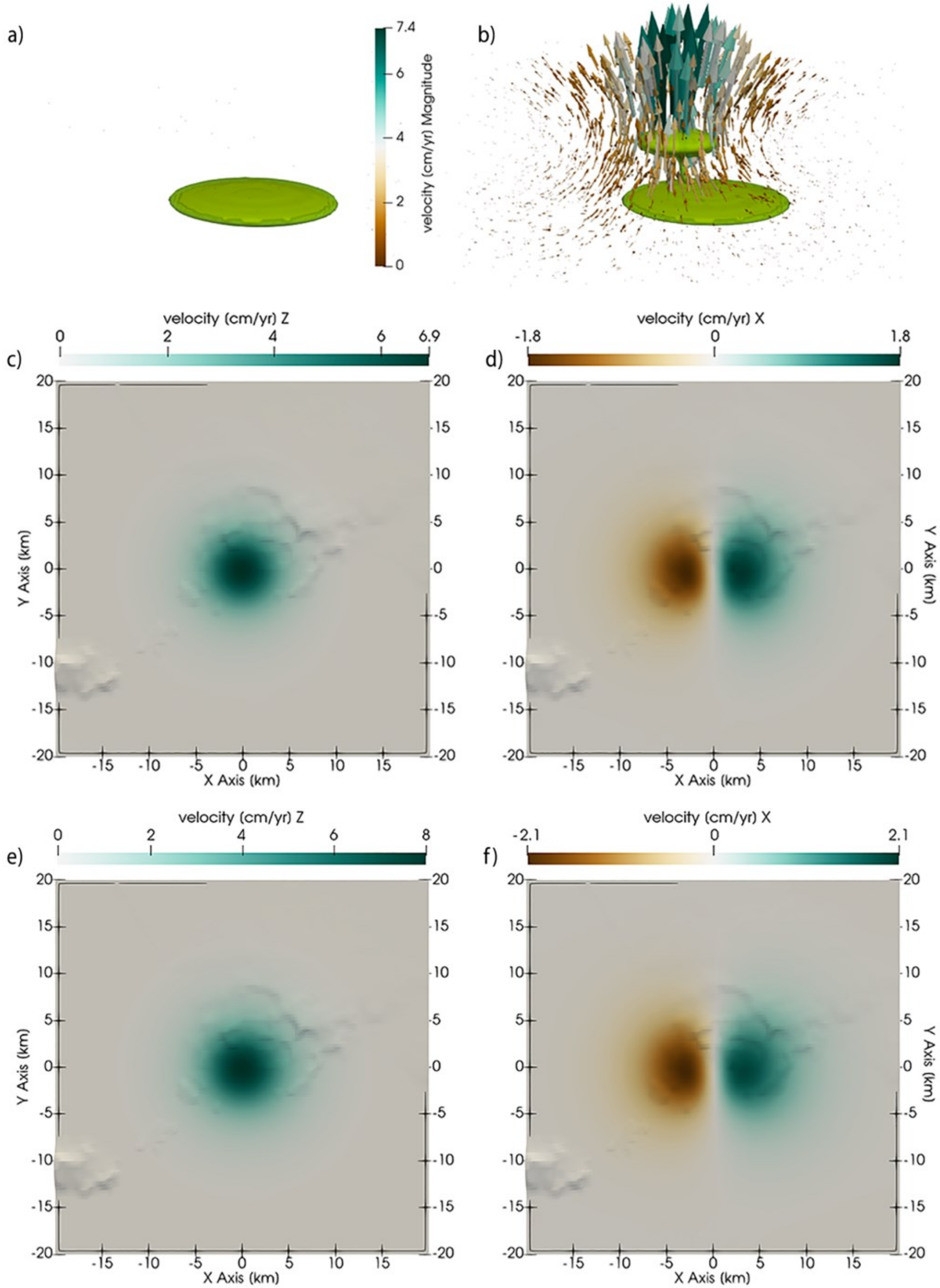


Material	$\rho\ [\frac{kg}{m^3}]$	$\eta\ [Pa \cdot s]$	$G\ [Pa]$	$k\ [\frac{W}{m \cdot K}]$	$C_p\ [\frac{J}{K \cdot kg}]$
Magma	2700	1×10^{18}	3×10^{9}	2	1000
Crust	2900	1×10^{23}	3×10^{10}	3	1000
Caprock	2900	1×10^{24}	8×10^{10}	3	1000
Aquifer	2900	1×10^{22}	2×10^{10}	3	1000
Water	1000	1×10^{17}	1×10^{9}	0.5	4200
Air	100	1×10^{16}	1×10^{9}	0.02	1000



PHYSICALLY-DRIVEN IMAGING AND INTERPRETATION

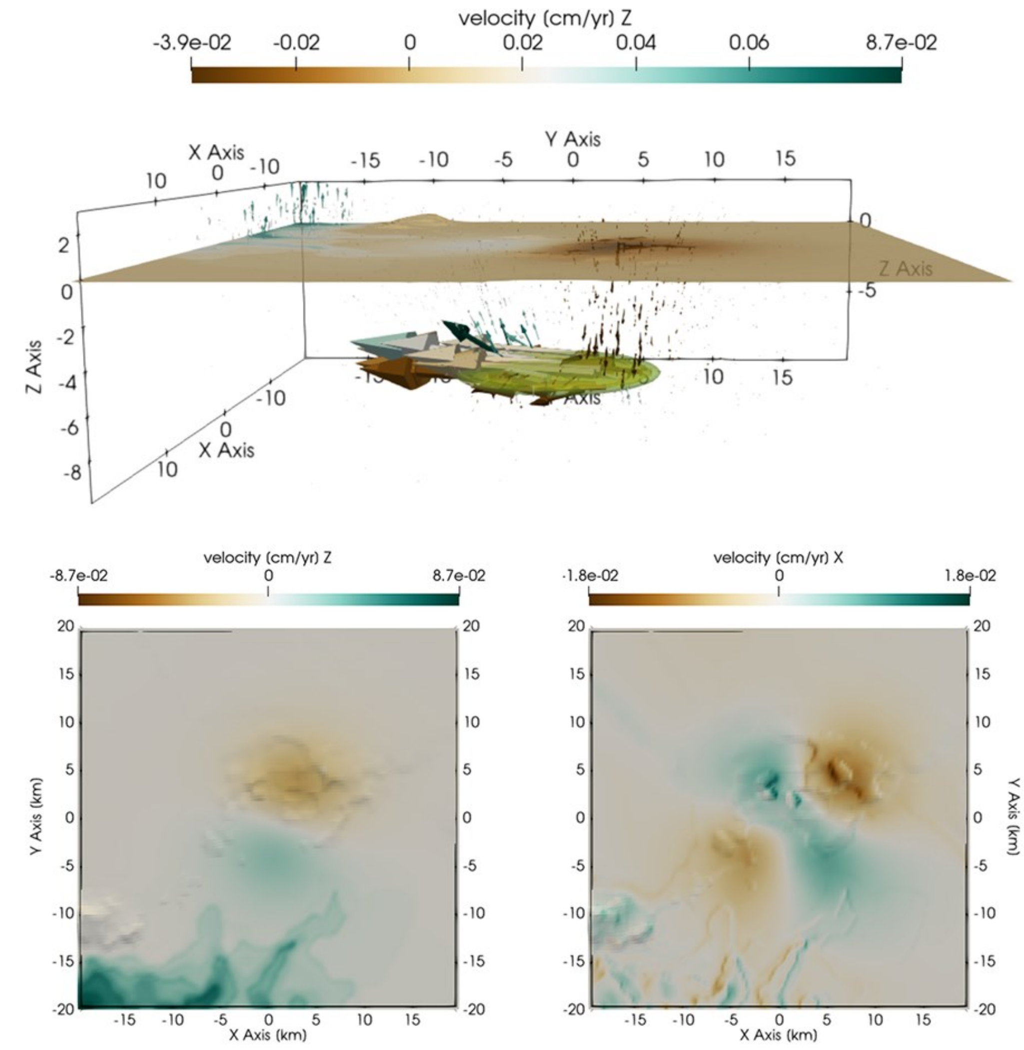
Walter et al. in preparation.



$$\frac{1}{K}\frac{Dp}{Dt} - \alpha\frac{DT}{Dt} + \frac{\partial v_i}{\partial x_i} = 0$$

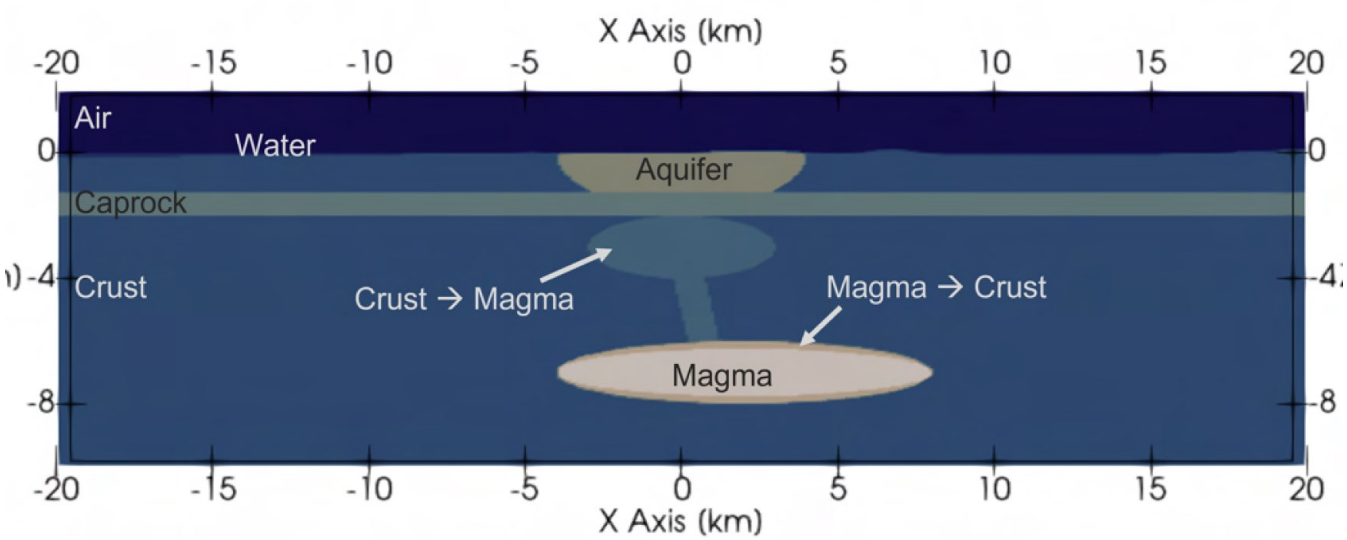
$$\frac{\partial \tau_{ij}}{\partial x_j} - \frac{\partial p}{\partial x_i} + \rho g_i = 0$$

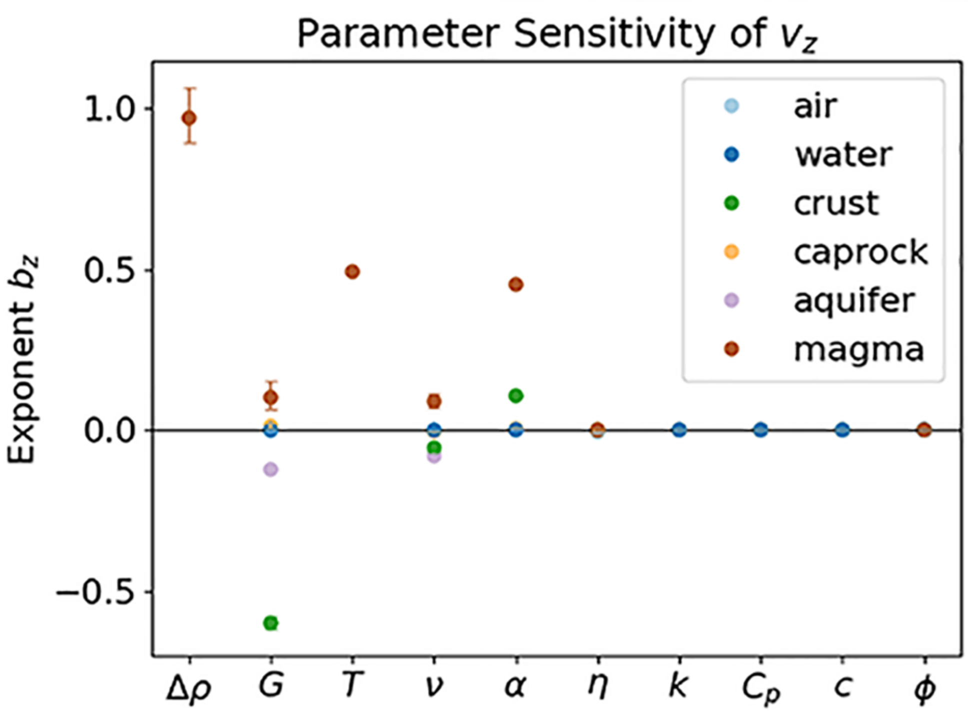
Depleting deep sill

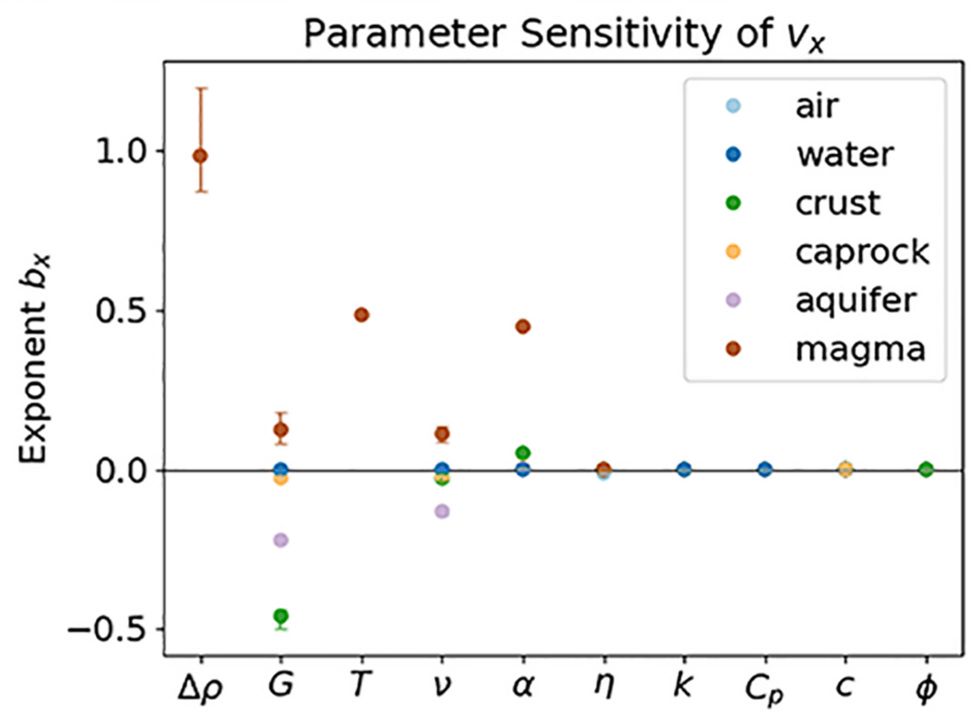


Sensitivity Analysis

Walter et al. in preparation.



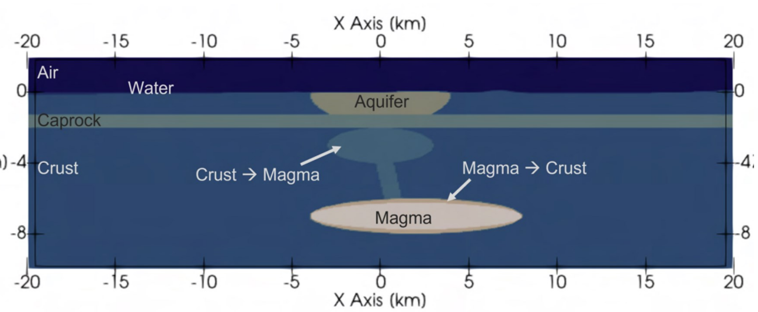


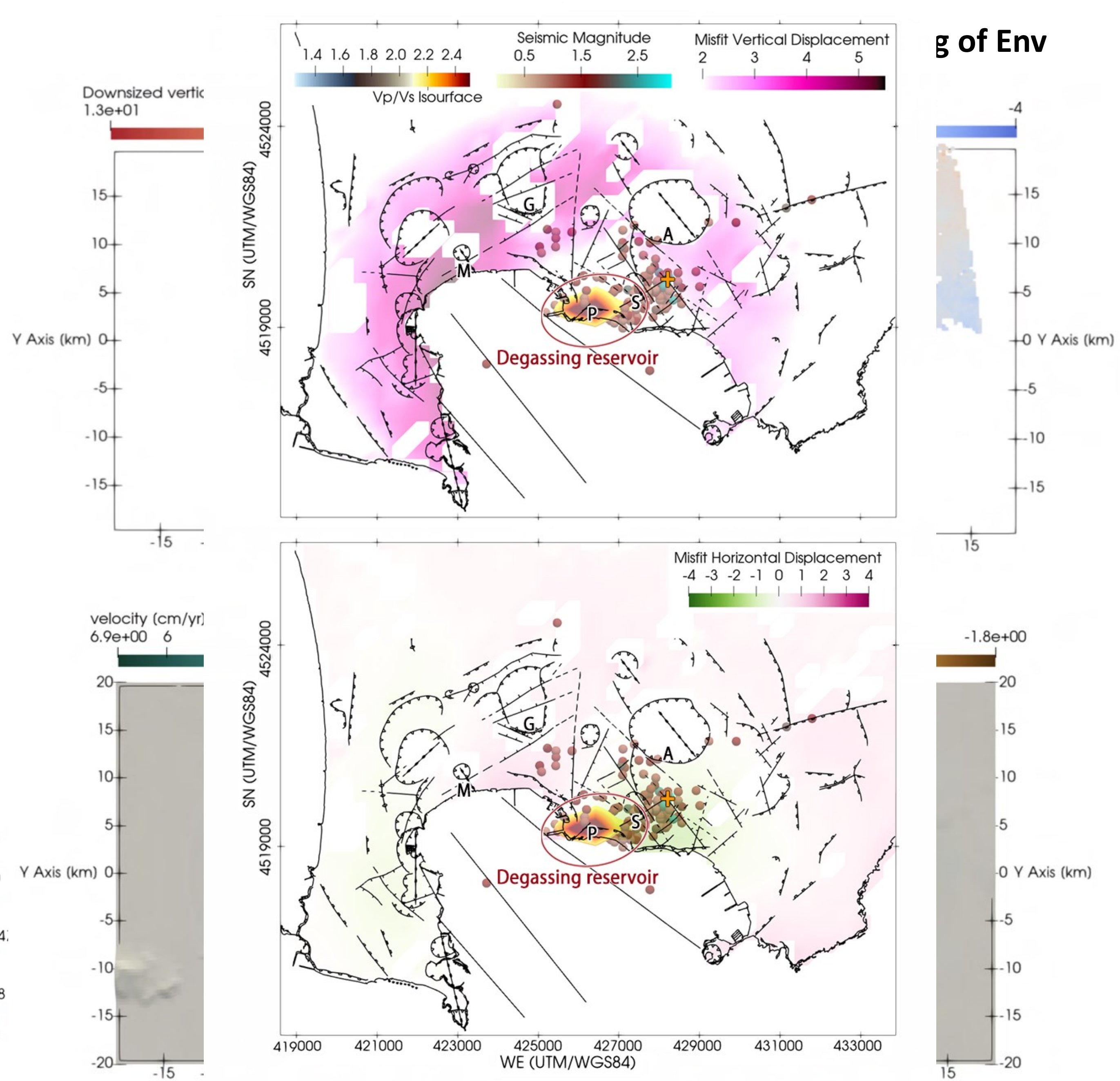


Walter et al. in preparation.

Shape and vertical displacements (or velocities) can be fitted extensively. The full numerical model predicted the same order of magnitude, for both vertical and EW deformation, as recorded during the unrest episode of 2012-2014.

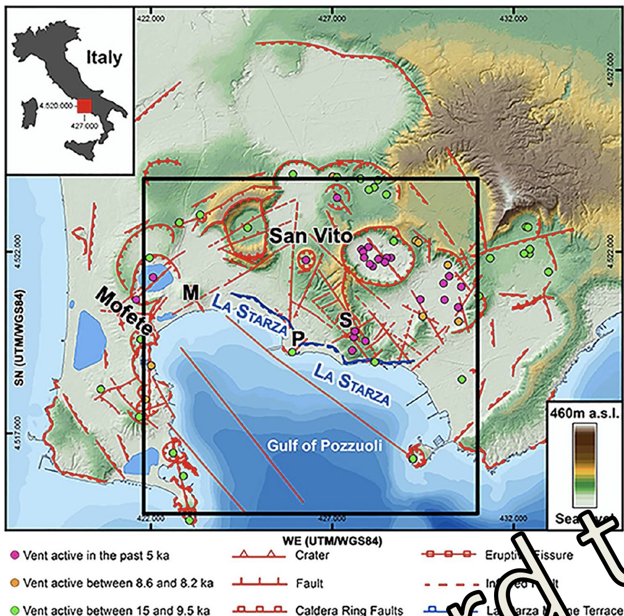
Removal of magma from the deeper reservoir agreed better than if the deeper reservoir remained unchanged.

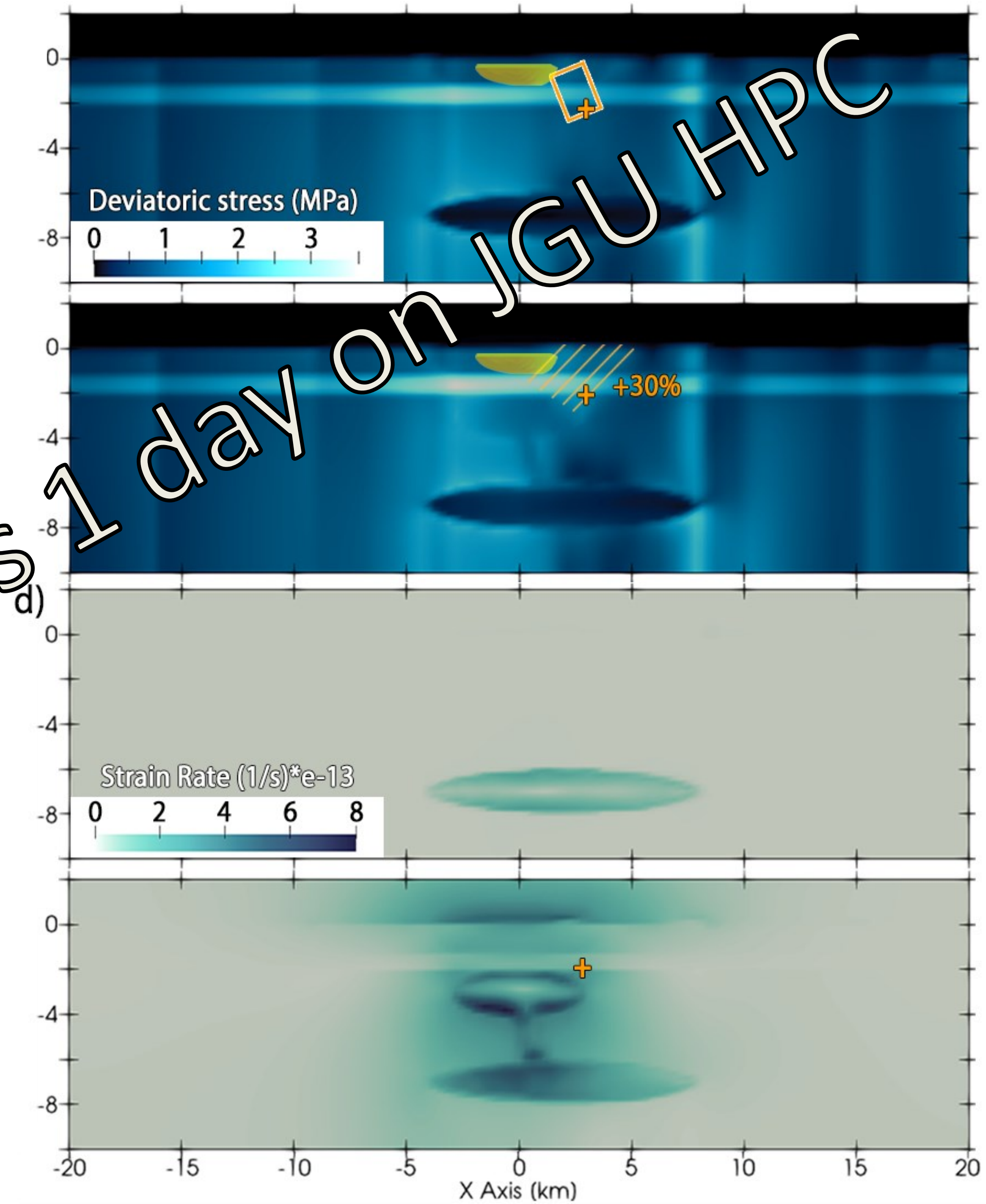




Walter et al. in preparation.

Every intrusion leads to an increase of up to 30% in deviatoric stress in the eastern caldera!



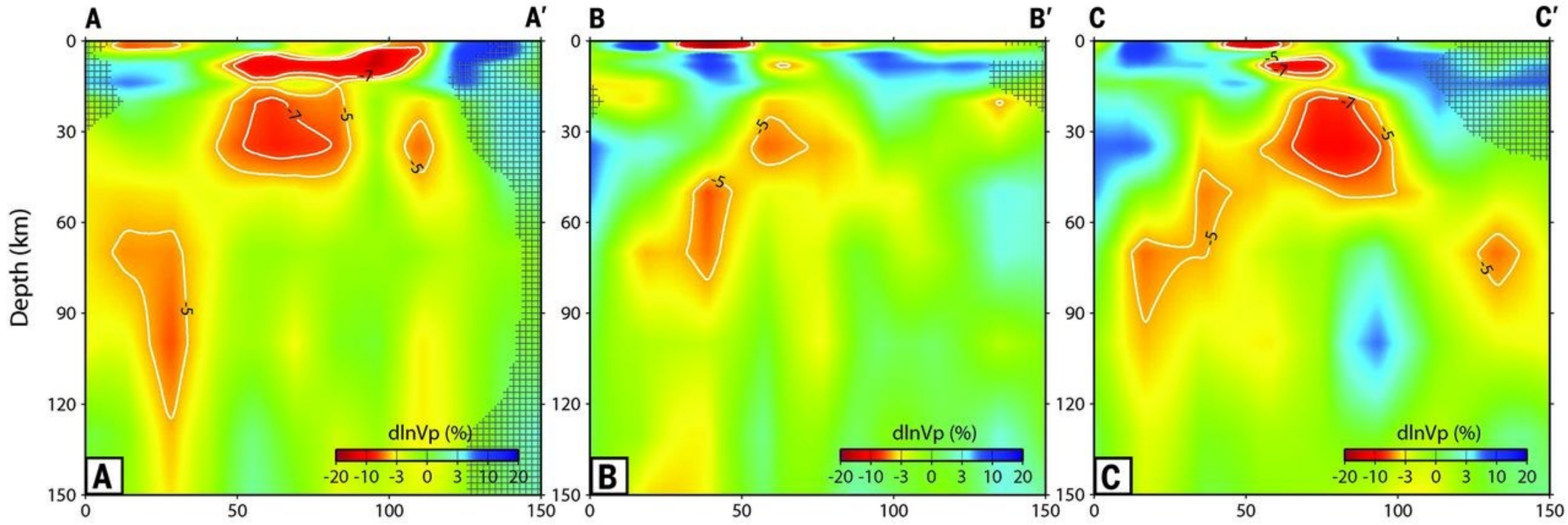


The decreases in strain rate within the caprock layer across the most fractured zones in the eastern caldera delineates a volume that corresponds to the area of maximum earthquake intensity since 2001 (Del Pezzo et al. 2022).

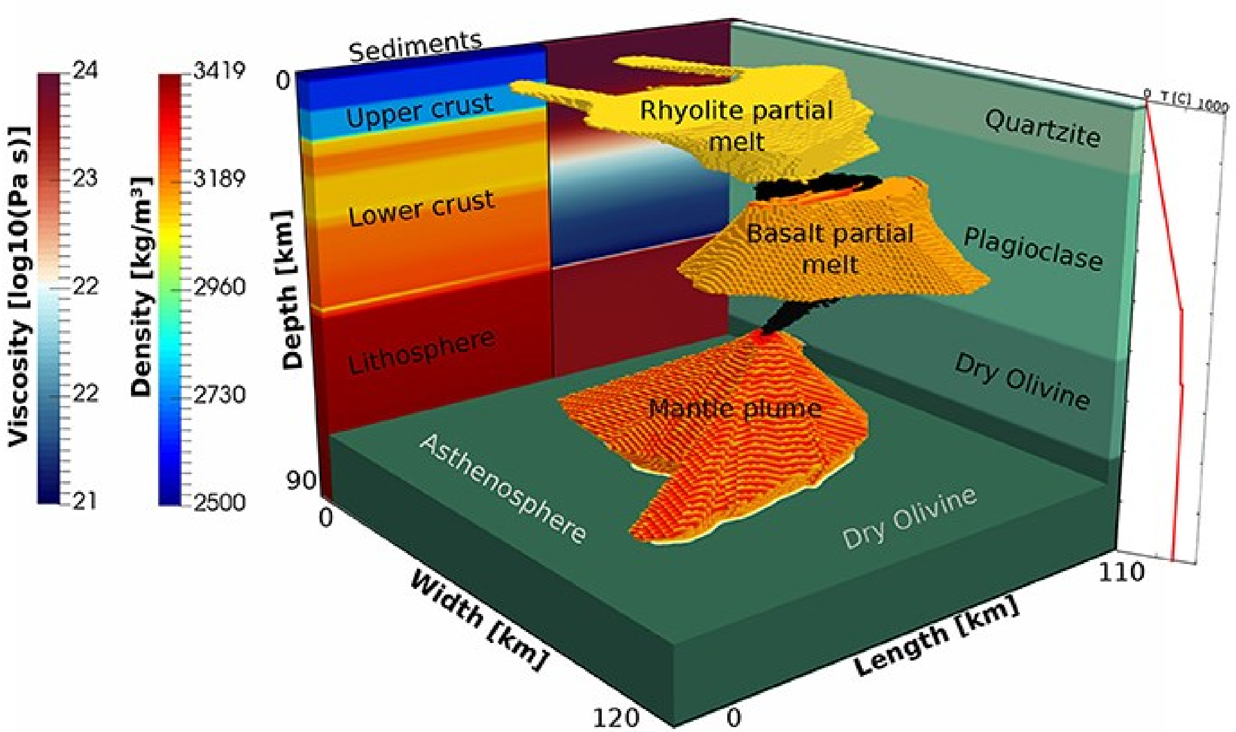
This forward takes 1 day on JGU HPC

Geodynamics from Geophysics

Tomography
(Yellowstone, Huang et al. 2015)



Modelling
(Reuber et al. 2018)



Lithosphere and Mantle Evolution Model

LaMEM

Source

Commits

Branches

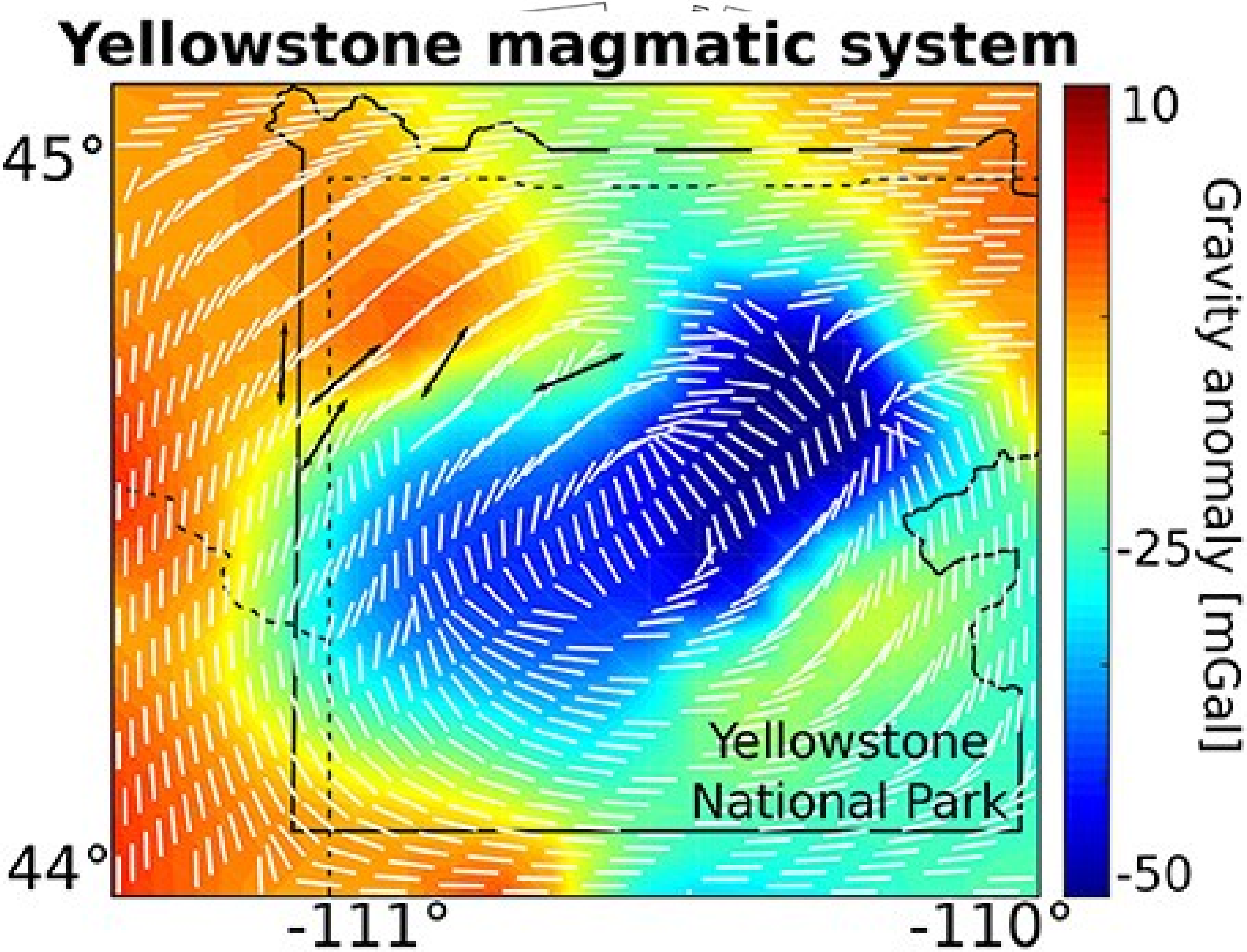
Boris Kaus / Untitled project

LaMEM

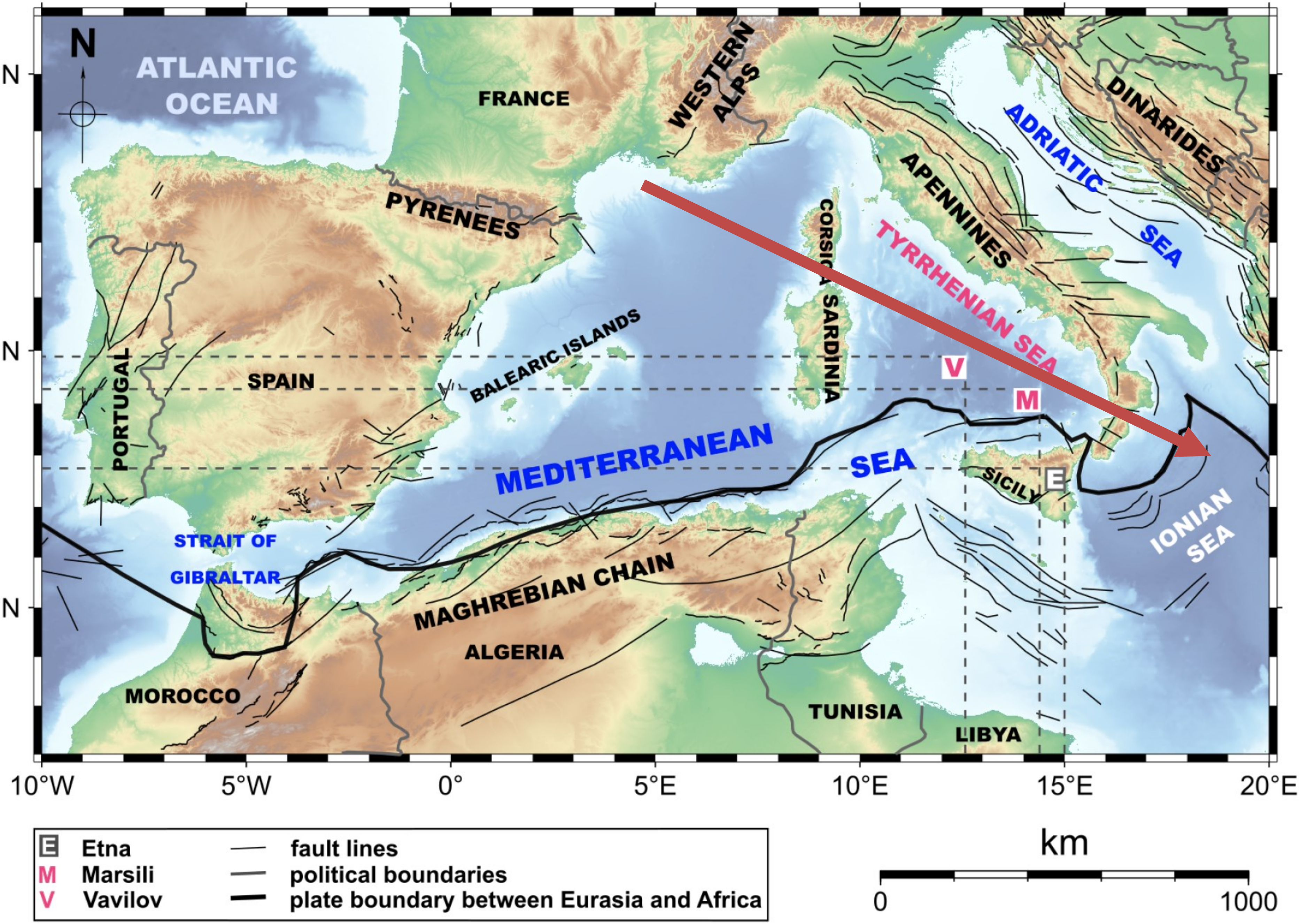
Clone

LaMEM - Lithosphere and Mantle Evolution Model A parallel 3D numerical code that can be used to model various thermomechanical geodynamical processes such as mantle-lithosphere interaction for rocks that have visco-elasto-plastic rheologies. The code is build on top of PETSc package and the current version of the code uses a marker-in-cell approach with a staggered finite difference discretization.   A range of (Galerkin) multigrid and iterative solvers are available, for both linear and non-linear rheologies, using Picard and quasi-Newton solvers (provided through the PETSc interface)

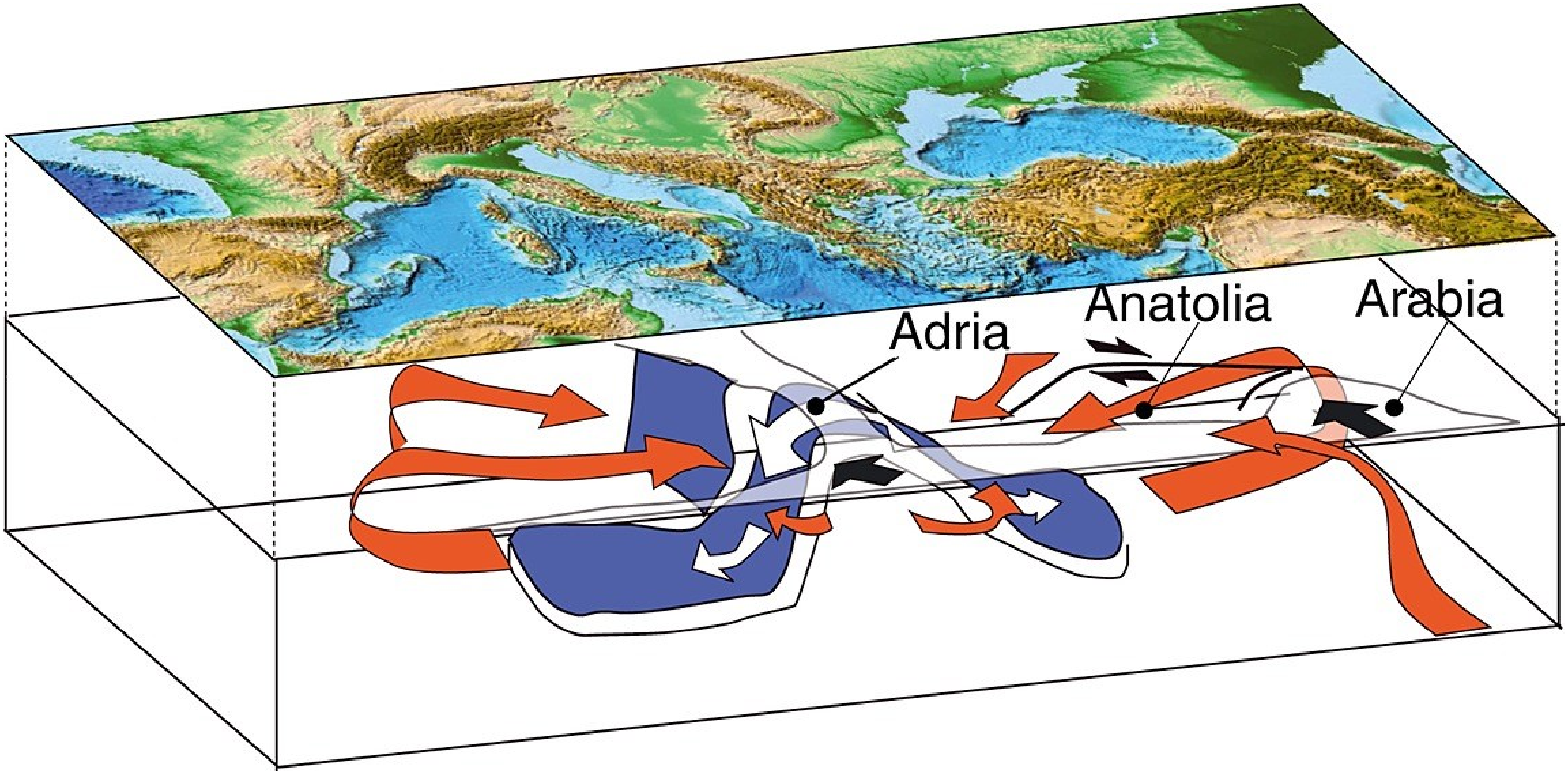
M
(F


Yellowstone magmatic system
45°
44°
-111°
-110°
10
-25
-50
Gravity anomaly [mGal]
Yellowstone
National Park

The Mediterranean Sea

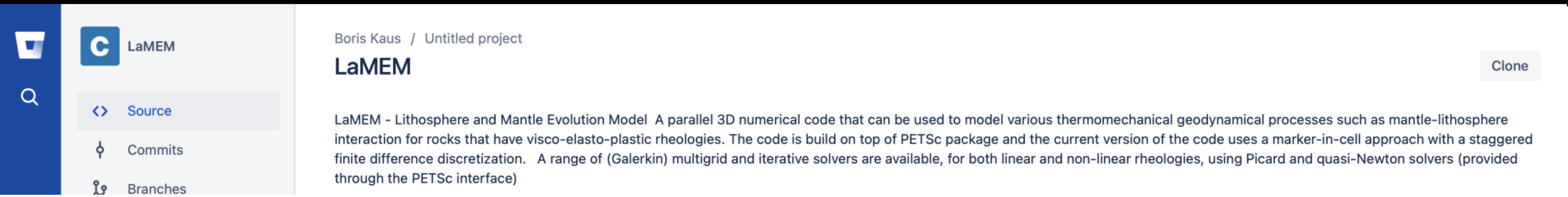


PREVIOUS HYPOTHESES

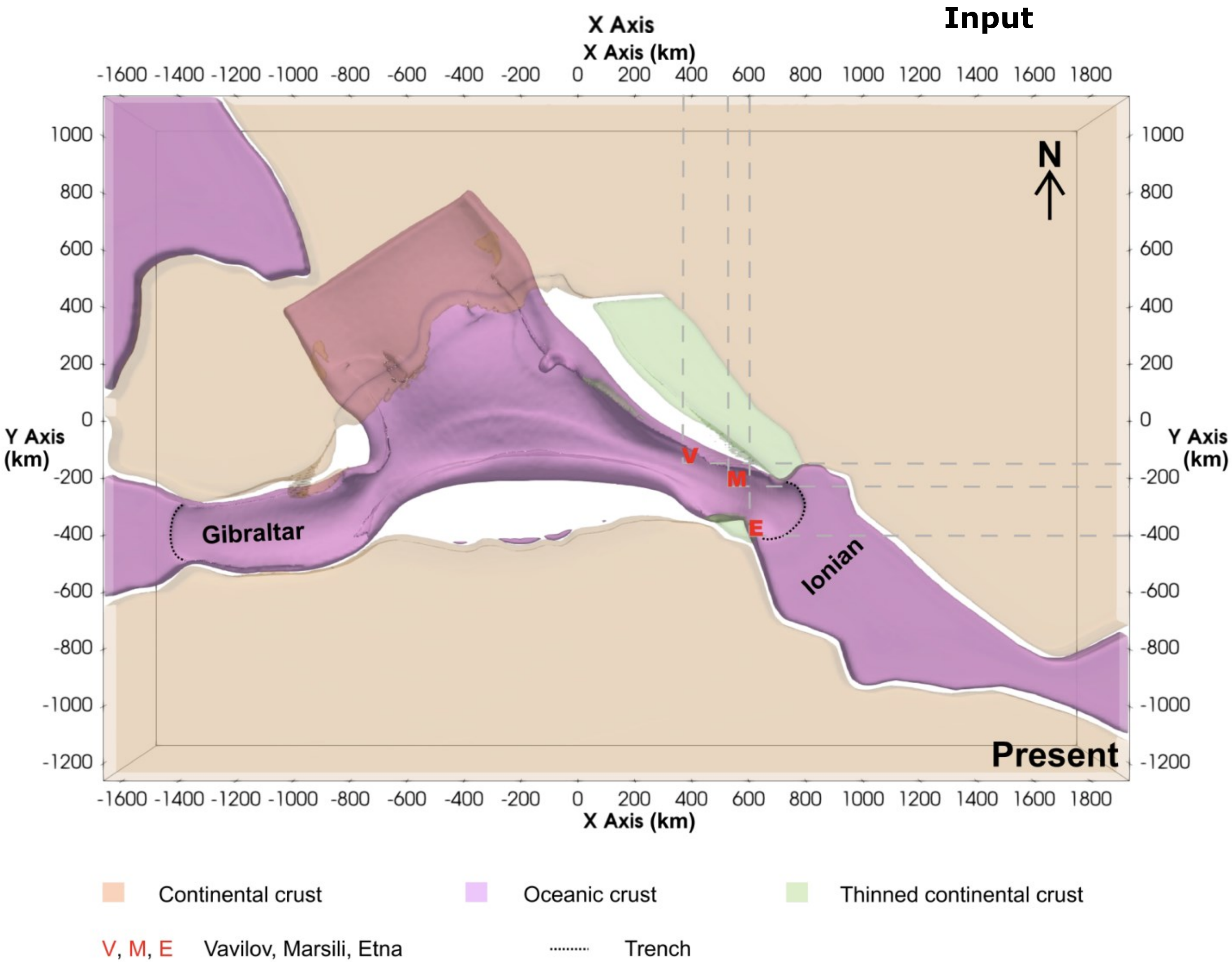


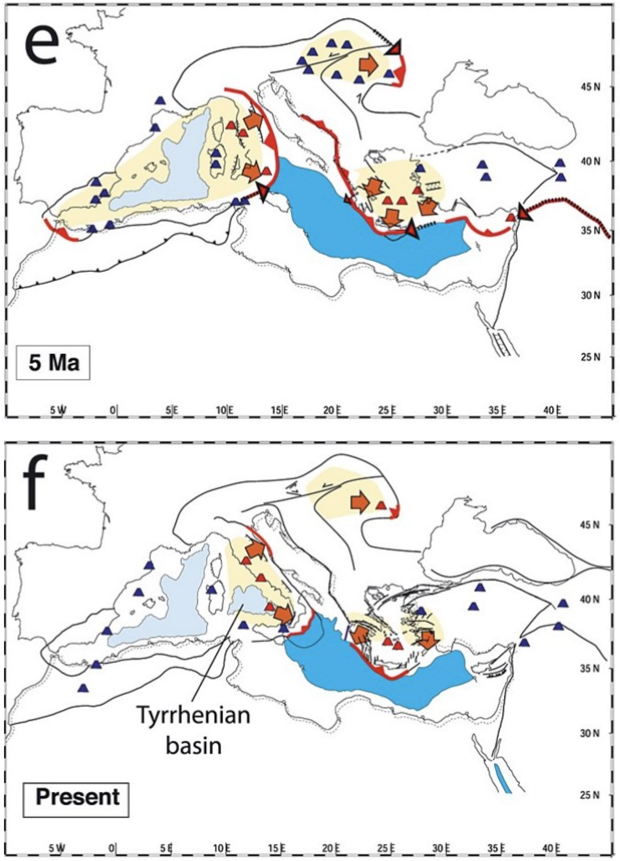
The hypothetical pattern of mantle convection presently active in the Mediterranean (Faccenna et al. 2014).

Lithosphere and Mantle Evolution Model



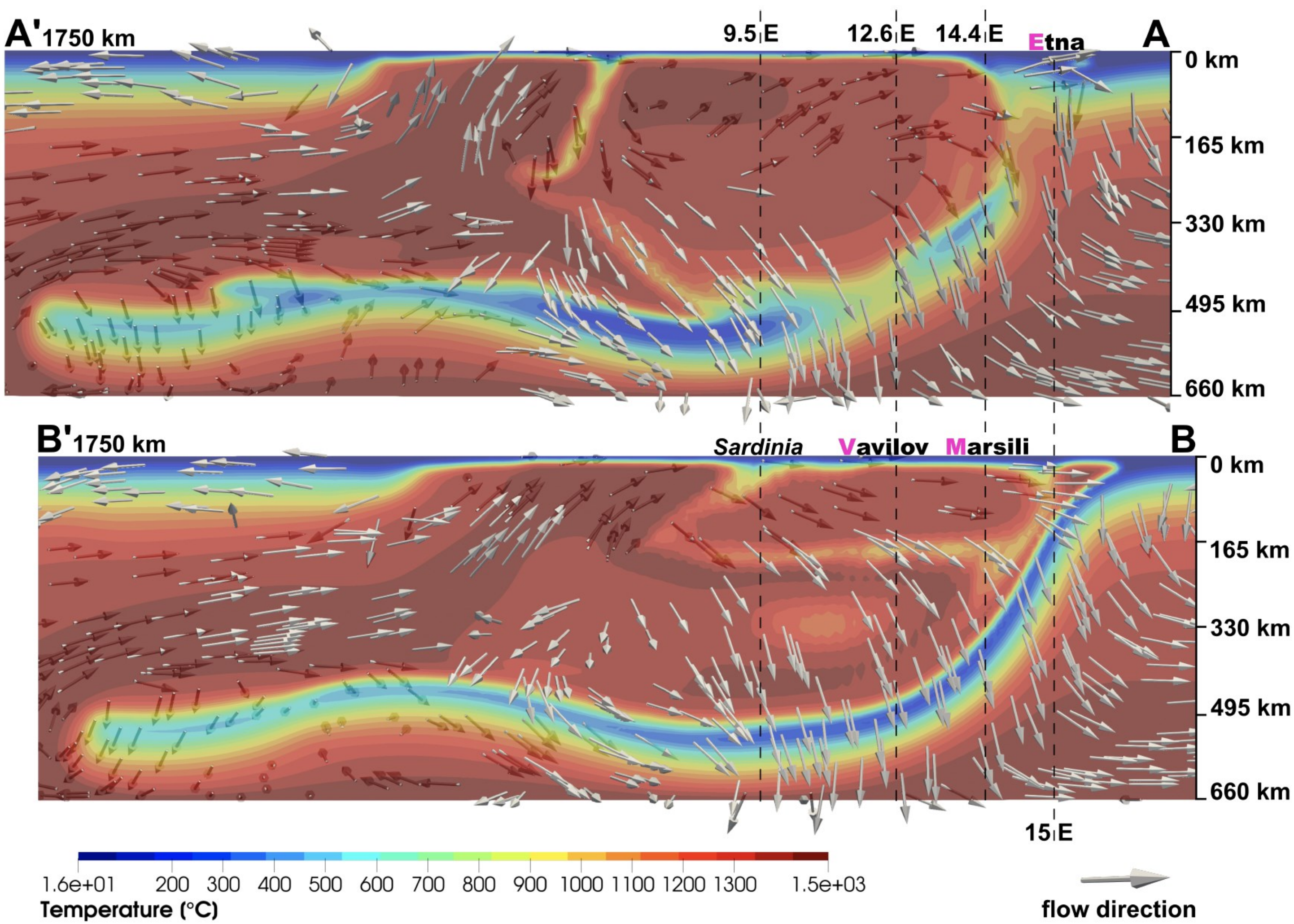
3D thermomechanical code including elasto-visco-plastic rheologies.

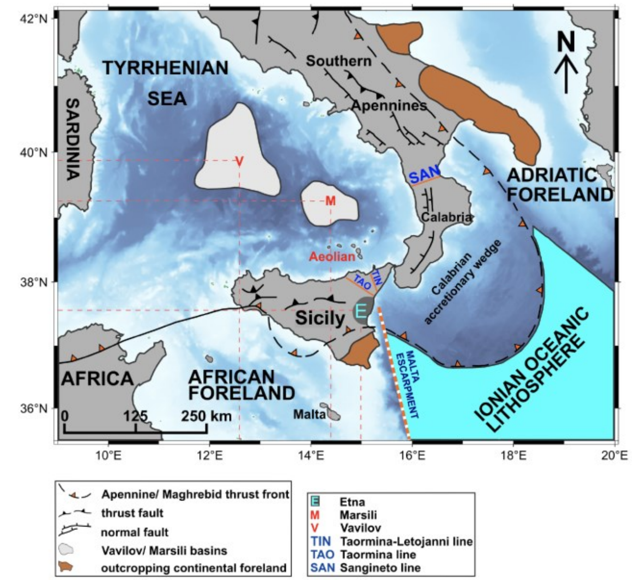


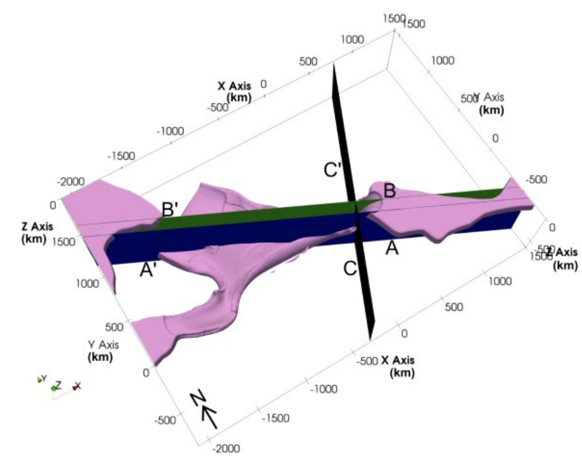


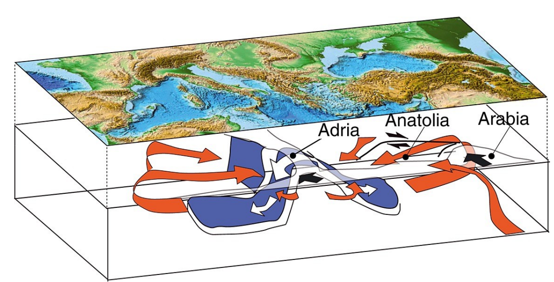
Development of two main subduction zones: Gibraltar and Ionian

Development of convection cells









Three convection cells develop, one in the middle of the slab and two along its edges. The temperature of the slab gradually increases towards the outside.

CONNECTION TO GEODYNAMICS: WAVE EQUATION

OpenSWPC -- An Open-source Seismic Wave Propagation Code

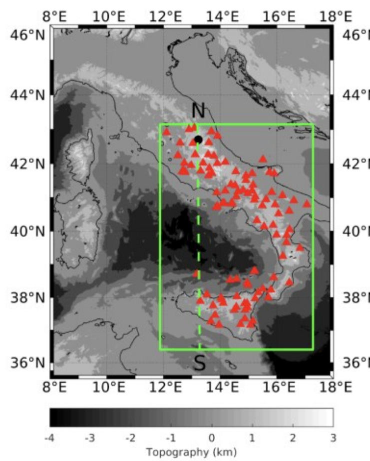
OpenSWPC

Corresponding Author: Takuto Maeda

Description

This software simulate seismic wave propagation by solving equations of motion with constitutive equations of elastic/viscoelastic medium by finite difference method (FDM) under message passing interface (MPI) environment in 3D and 2D (P-SV or SH) media.

Nardoni et al. 2023, Surveys in Geophysics



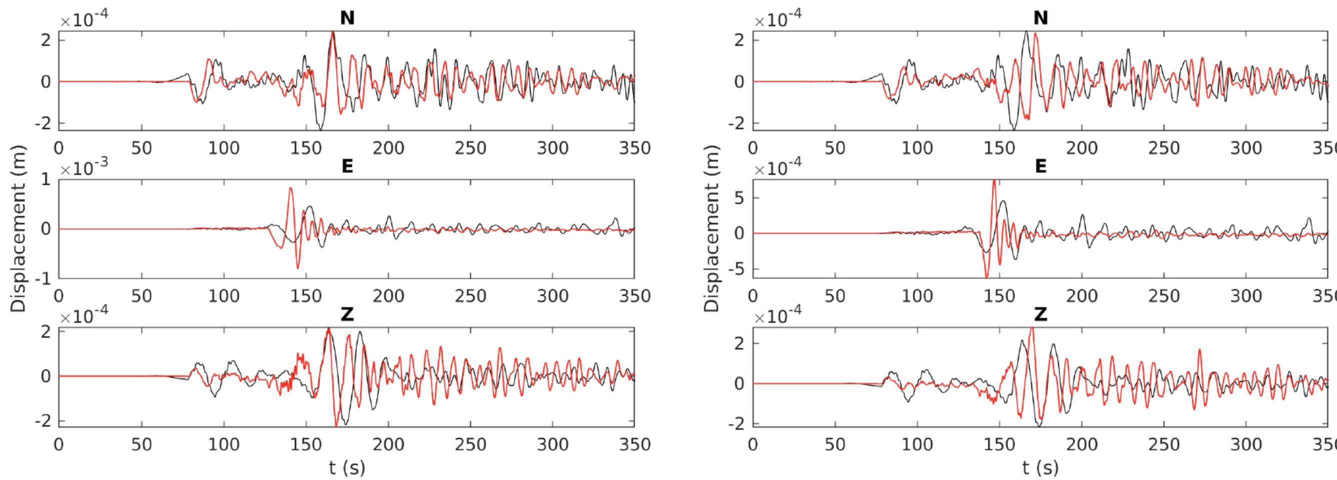
1. Finite difference, velocity-stress formulation includes source description and velocity fluctuations;
2. Testing the effective sensitivity to structural boundaries depths, velocity variations and source characteristics using recordings of the Amatrice earthquake;

Connection to geodynamics: wave equation

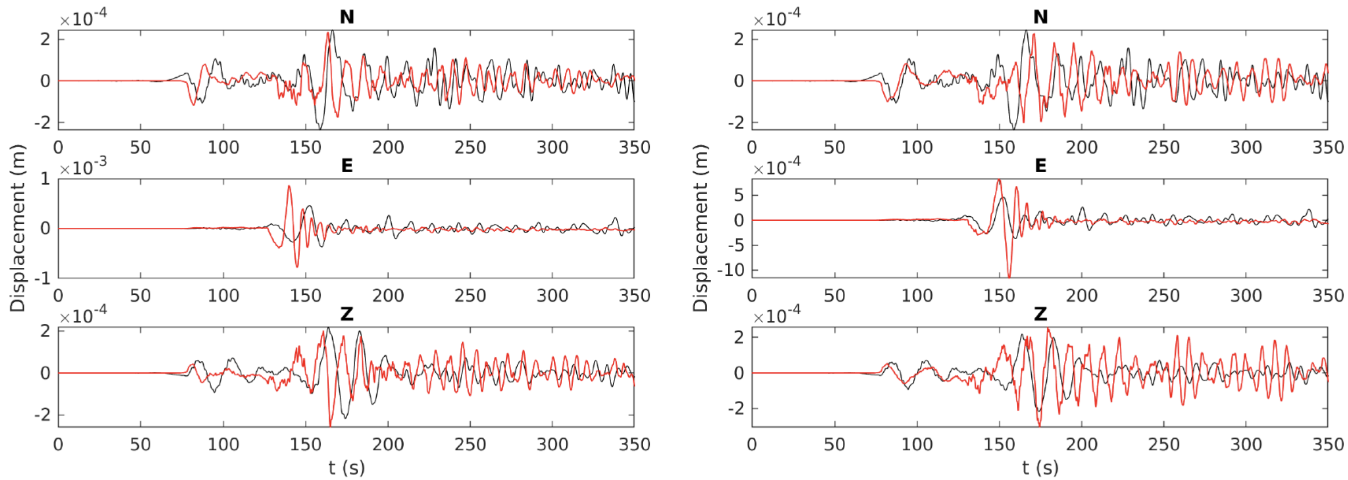
OpenSWPC

Testing velocities (Moho from Manu Marfo et al. 2019, SR)

	Model 1		Model 1.1		Model 1.2		Model 1.3	
	V_P	V_S	V_P	V_S	V_P	V_S	V_P	V_S
Sediments	5.2	2.9	4.9	2.9	5.0	2.8	5.0	2.8
Crust	6.0	3.9	6.0	3.8	6.4	3.9	6.4	3.5
Moho Transition	7.0	4.0	7.0	4.0	7.5	4.3	7.5	4.3
Mantle	7.7	4.5	7.7	4.5	7.7	4.5	7.7	4.5



(a) Model 1.0 (b) Model 1.1

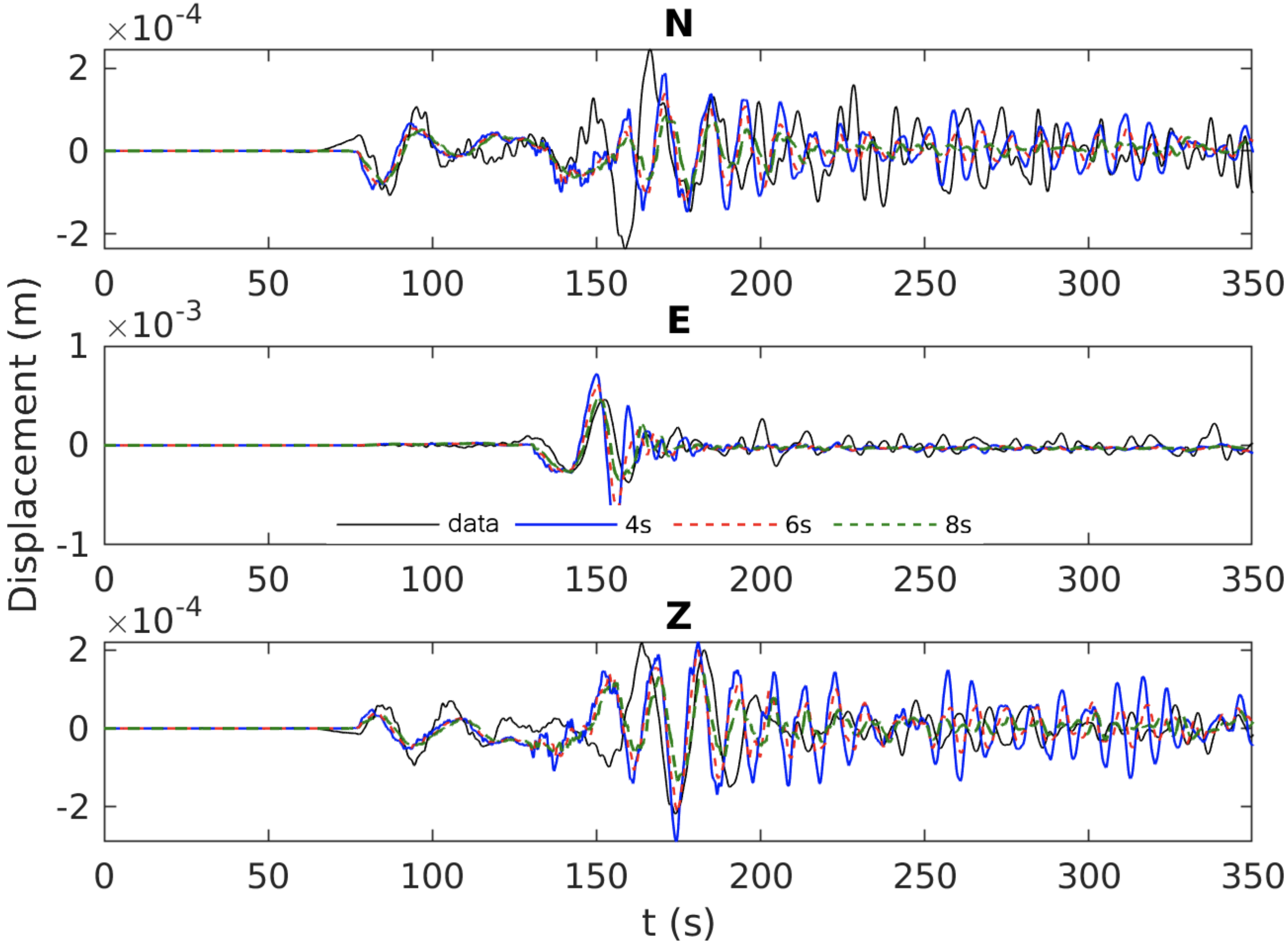


Connection to geodynamics: wave equation

OpenSWPC

Testing source rise times (Model 1.3)

	Model 1		Model 1.1		Model 1.2		Model 1.3	
	V_P	V_S	V_P	V_S	V_P	V_S	V_P	V_S
Sediments	5.2	2.9	4.9	2.9	5.0	2.8	5.0	2.8
Crust	6.0	3.9	6.0	3.8	6.4	3.9	6.4	3.5
Moho Transition	7.0	4.0	7.0	4.0	7.5	4.3	7.5	4.3
Mantle	7.7	4.5	7.7	4.5	7.7	4.5	7.7	4.5



Connection to geodynamics: wave equation

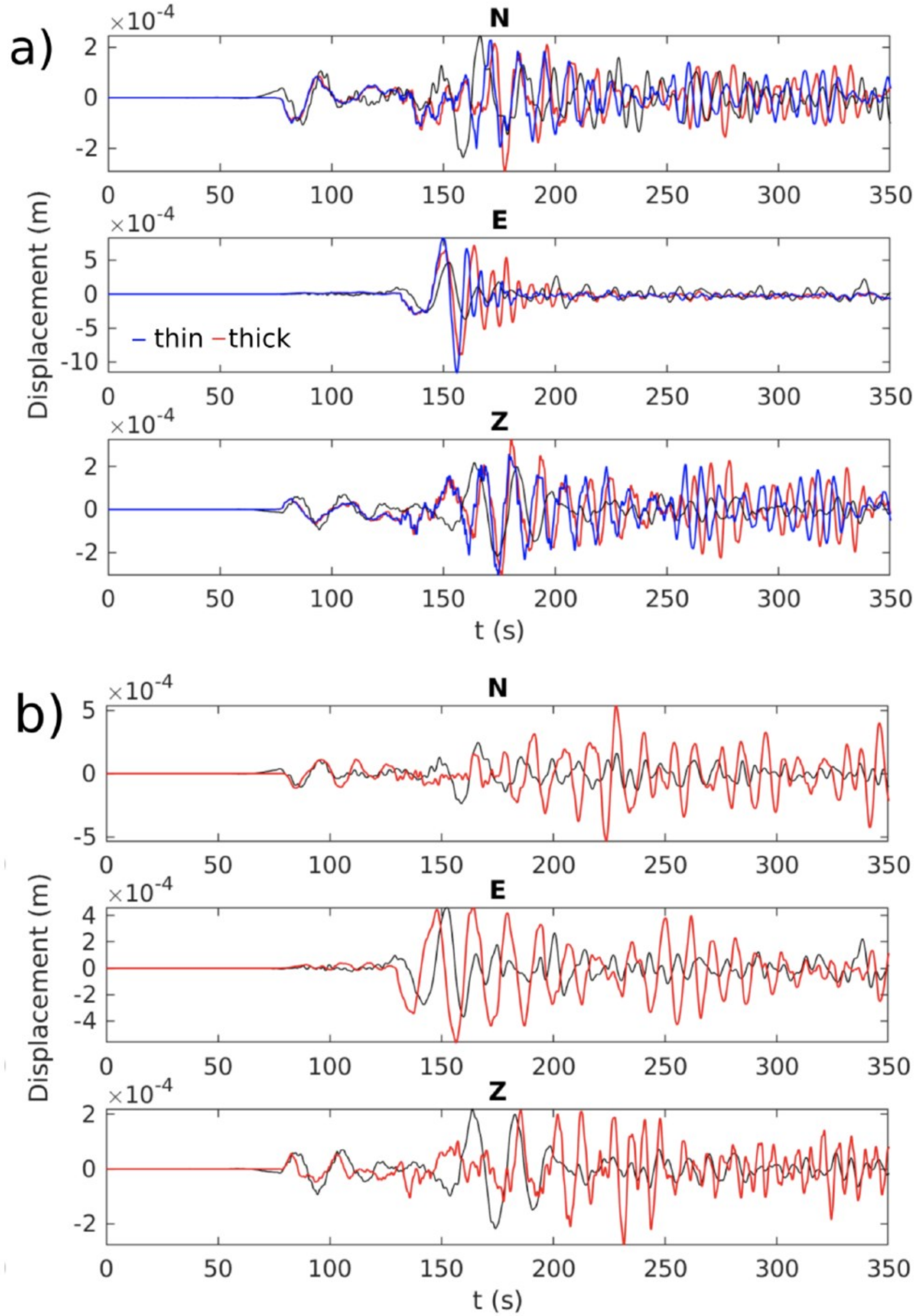
OpenSWPC

Testing sediment covers set:

a) at 2 km (blue) or from Molinari and Morelli (2011- red, Model 2);

b) As in Model 2 for lower velocities.

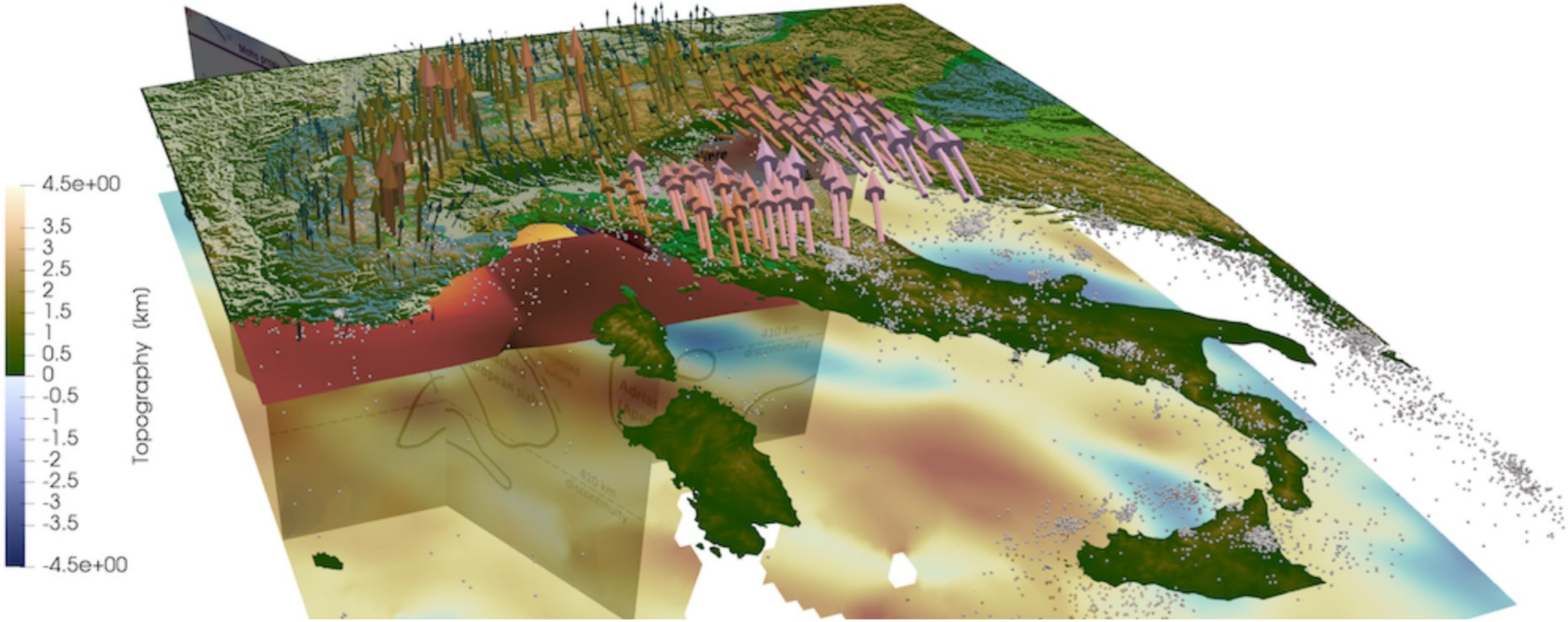
	Model 1		Model 1.1		Model 1.2		Model 1.3	
	V_P	V_S	V_P	V_S	V_P	V_S	V_P	V_S
Sediments	5.2	2.9	4.9	2.9	5.0	2.8	5.0	2.8
Crust	6.0	3.9	6.0	3.8	6.4	3.9	6.4	3.5
Moho Transition	7.0	4.0	7.0	4.0	7.5	4.3	7.5	4.3
Mantle	7.7	4.5	7.7	4.5	7.7	4.5	7.7	4.5



Geophysical Model Generator

docs stable | docs dev | CI passing

Creating consistent 3D images of geophysical and geological datasets and turning that into an input model for geodynamic simulations is often challenging. The aim of this package is to help with this, by providing a number of routines to easily import data and create a consistent 3D visualisation from it in the VTK-toolkit format, which can for example be viewed with Paraview. In addition, we provide a range of tools that helps to generate input models to perform geodynamic simulations and import the results of such simulations back into julia.



GMG (*Kaus et al. under review, https://github.com/JuliaGeodynamics/GeophysicalModelGenerator.jl*