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Numerical simulations for site effect estimation in a complex sedimentary basin: a comparison between different approaches for designing

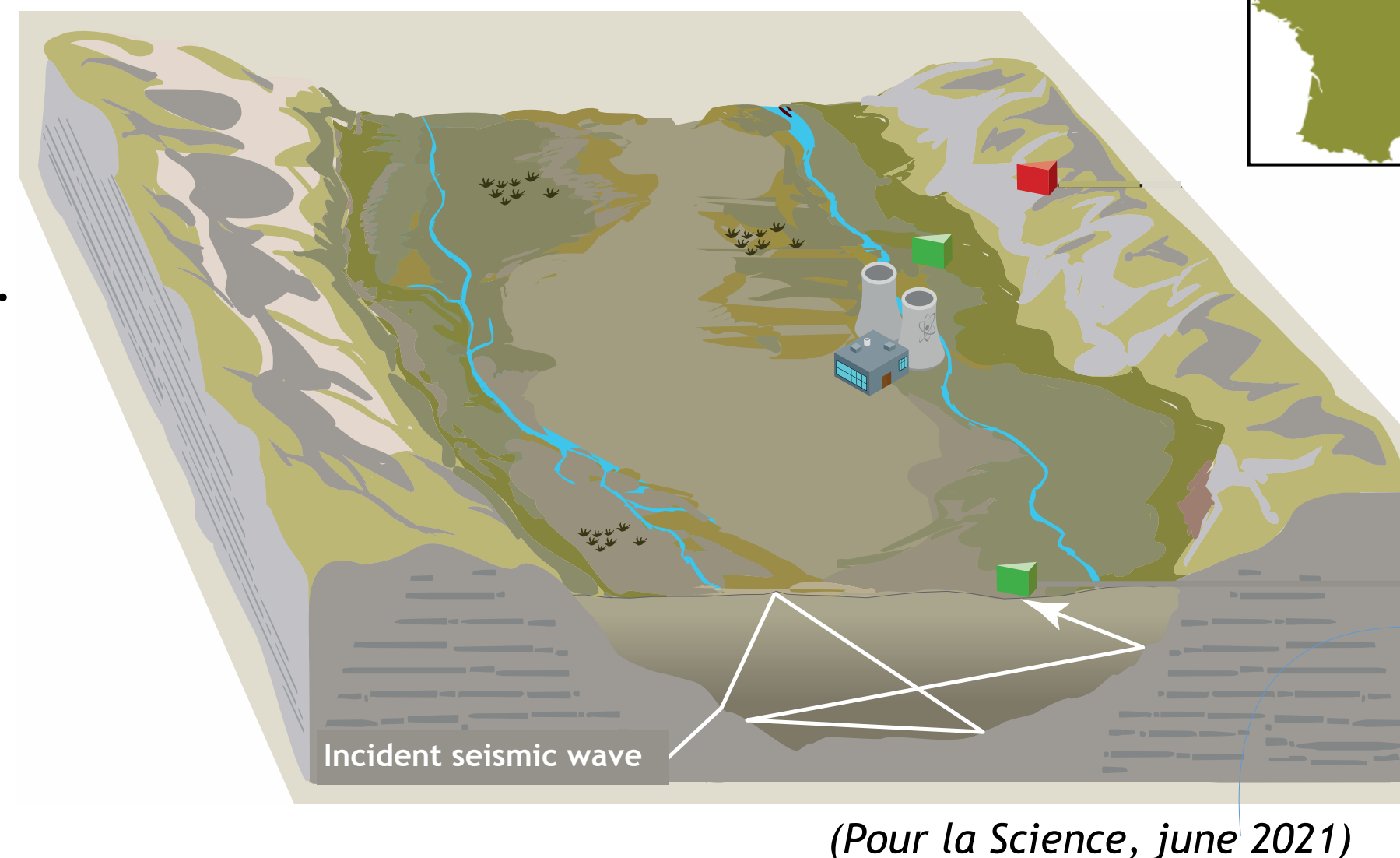


3D seismic models of the subsurface
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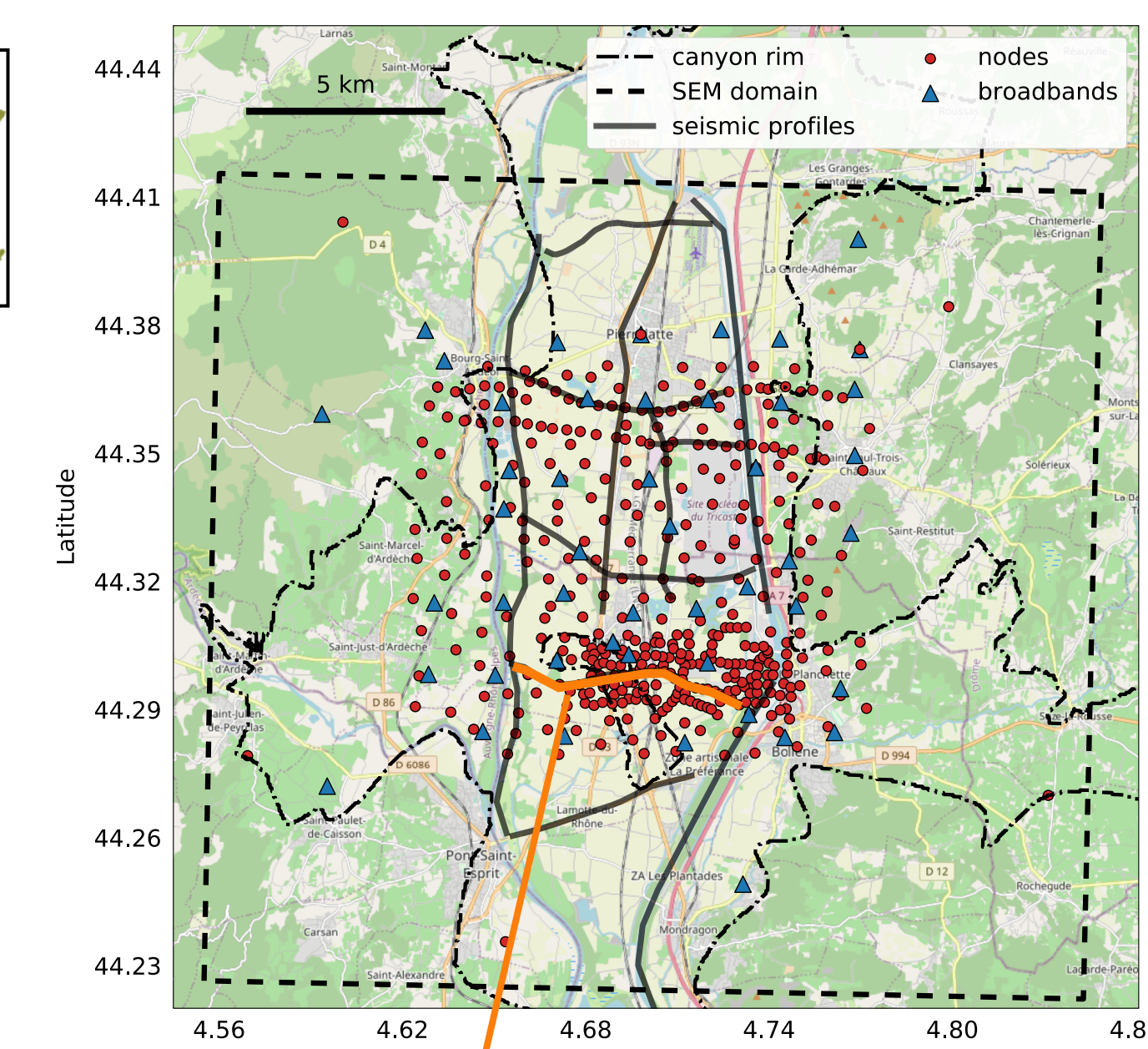


Context and objectives

- Context:** DARE project (*Dense ARray for seismic site effect Estimation*), Pls: Bérénice Froment (IRSN, France), Matthias Ohrnberger (Univ. Potsdam, Germany).
- Objectives:** assess the potential of using ambient noise to estimate seismic site effects in low-seismicity areas via empirical and numerical approaches.
- Case study:** Tricastin basin (Rhône valley, South of France), located above a paleo-canyon created during the Messinian salinity crisis and host of a nuclear plant (Tricastin Nuclear Site, TNS).



(Pour la Science, june 2021)



Data and models

Construction of 3D seismic models based on data from:

- Two seismic arrays (Pilz et al., 2021; Froment et al., 2022, 2023)
 - 400 3C nodes over 1 month: seismic noise recordings
 - 1D V_S and Q_S profiles via Q-SPAC analysis
 - 3D V_S model via ambient noise surface wave tomography (ANSWT)
 - 50 broadband stations over 6 months: earthquake recordings
 - computation of Standard Spectral Ratios (SSR)
- Active seismic profiles
 - interpretation of geological horizons (Do Couto et al., in rev.)
- Geotechnical surveys (Moiriat, 2019)
 - V_P , V_S , and density in the first 30 meters

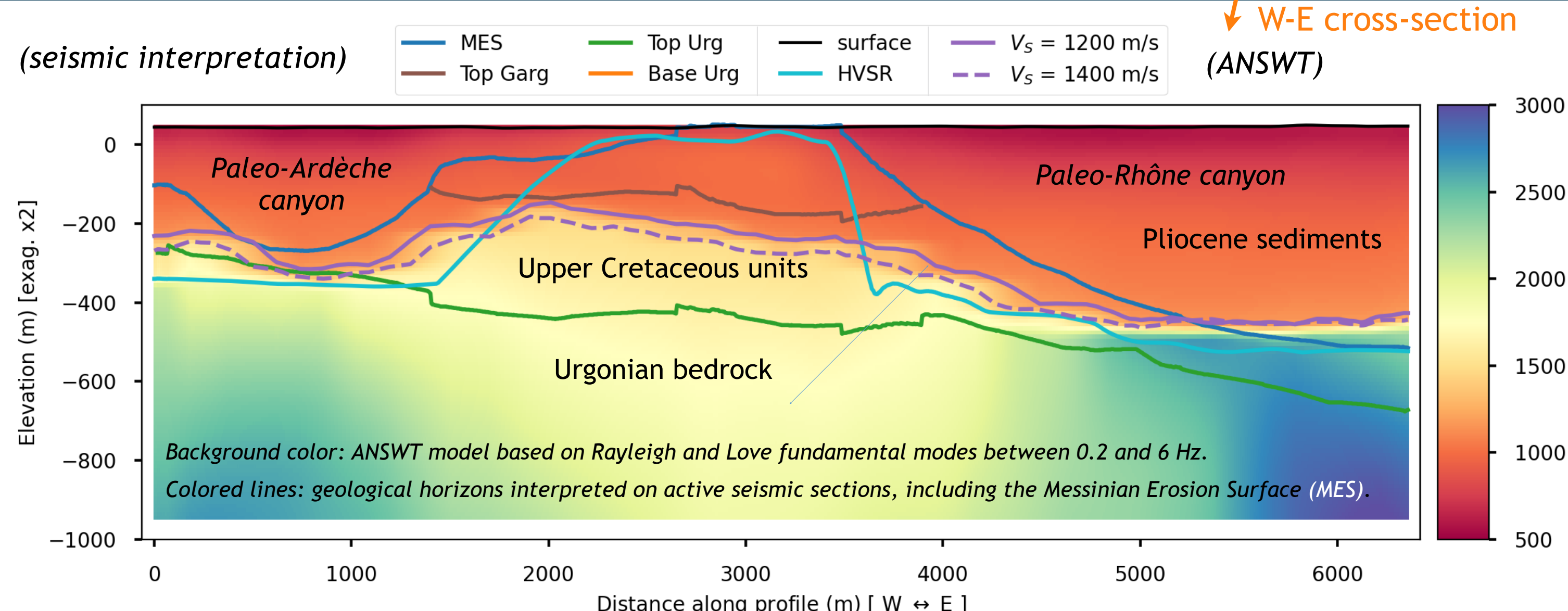


Fig. 1: Comparison of ANSWT model and geological horizons interpreted from an active seismic profile.

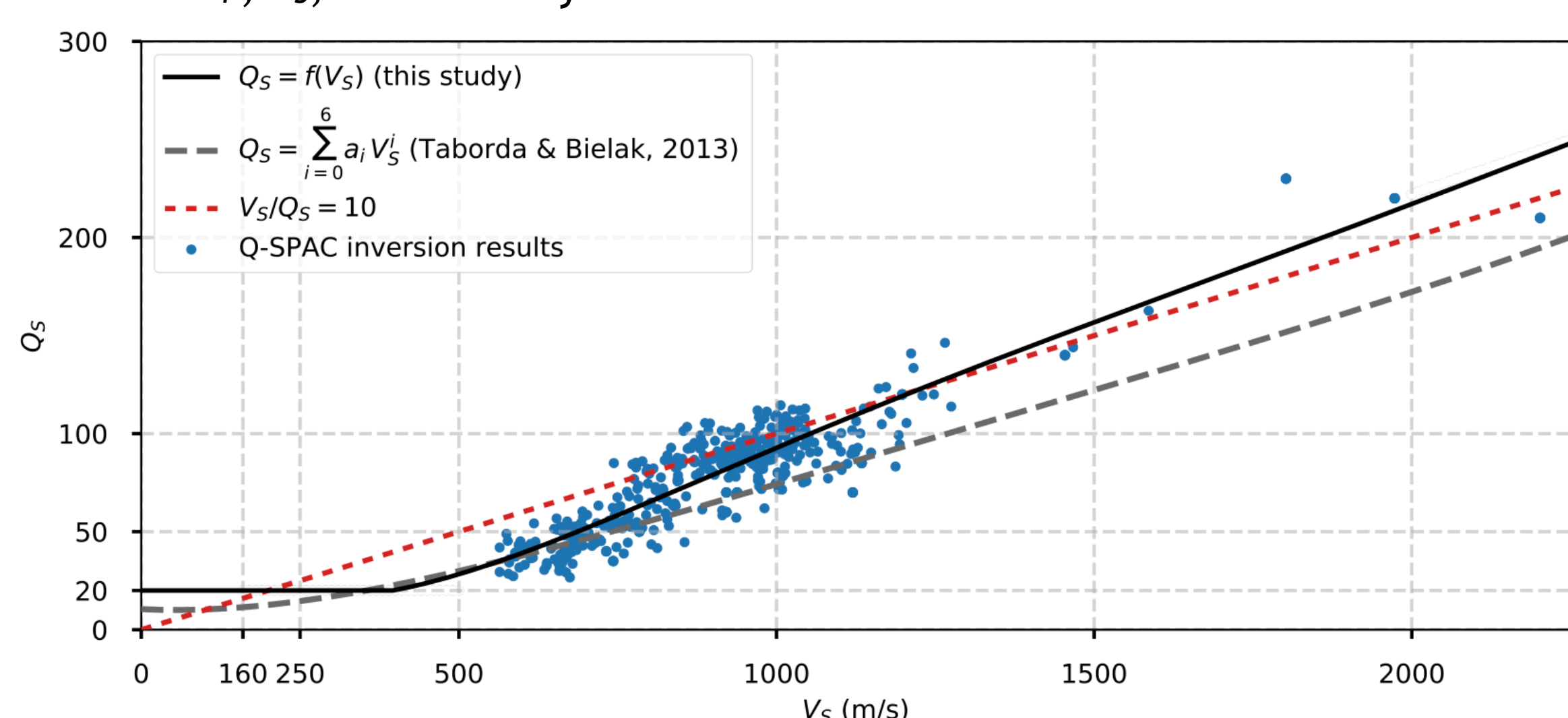
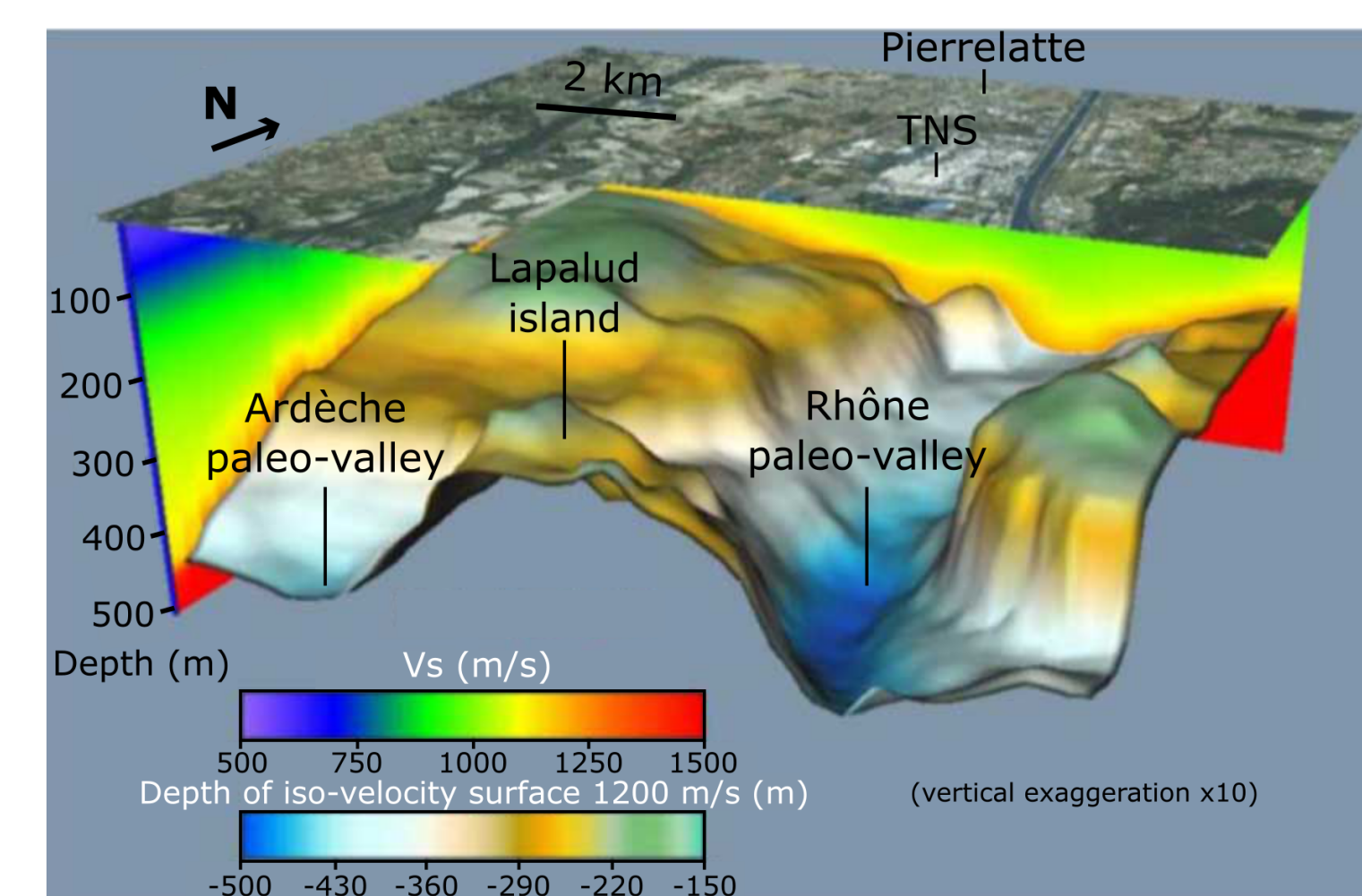


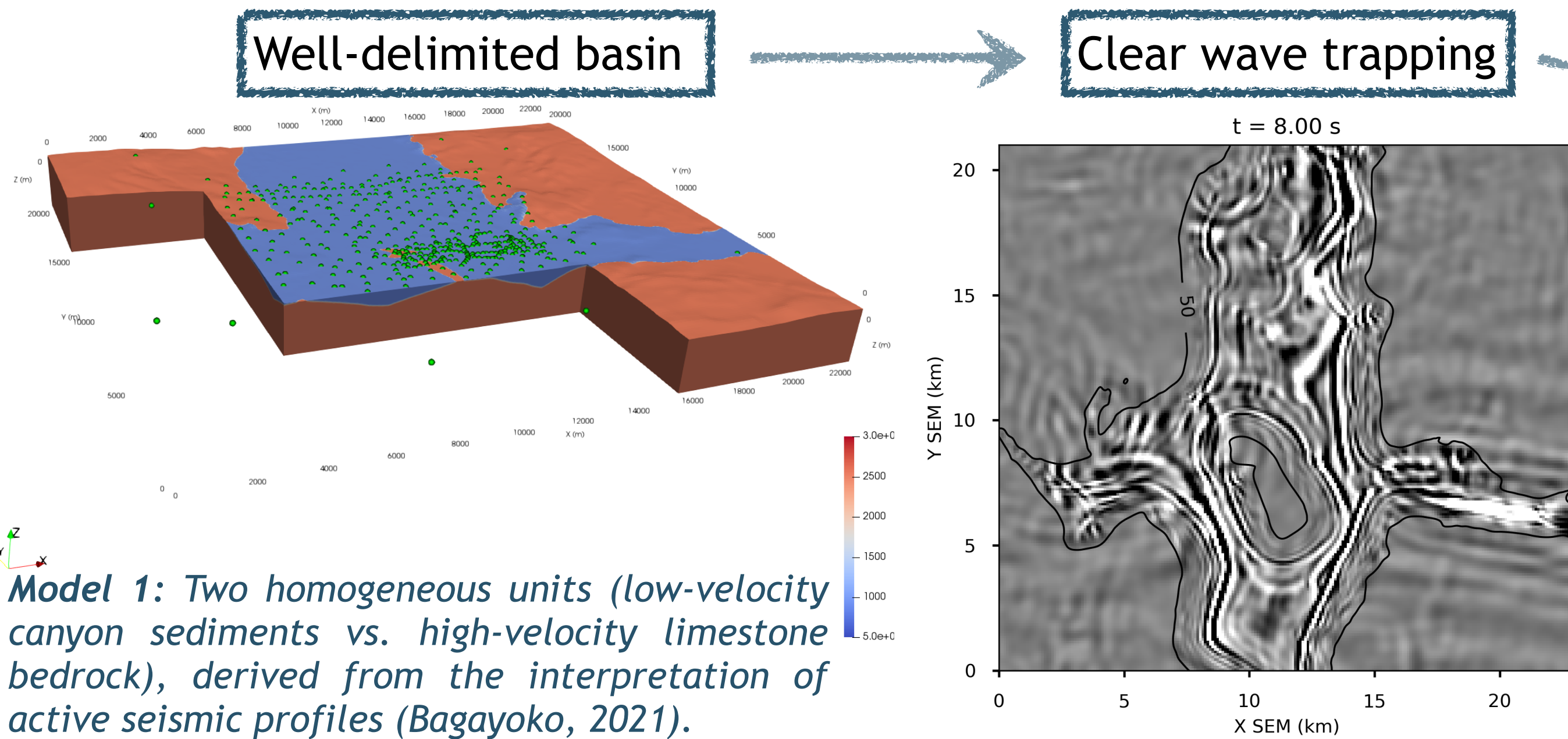
Fig. 3: V_S and Q_S values inferred from Q-SPAC analysis (blue dots). These values are used to derive a site-specific relationship between V_S and Q_S (black curve).

Fig. 2: 3D V_S model obtained by ANSWT, depicting the large-scale geometry of the paleo-canyon.

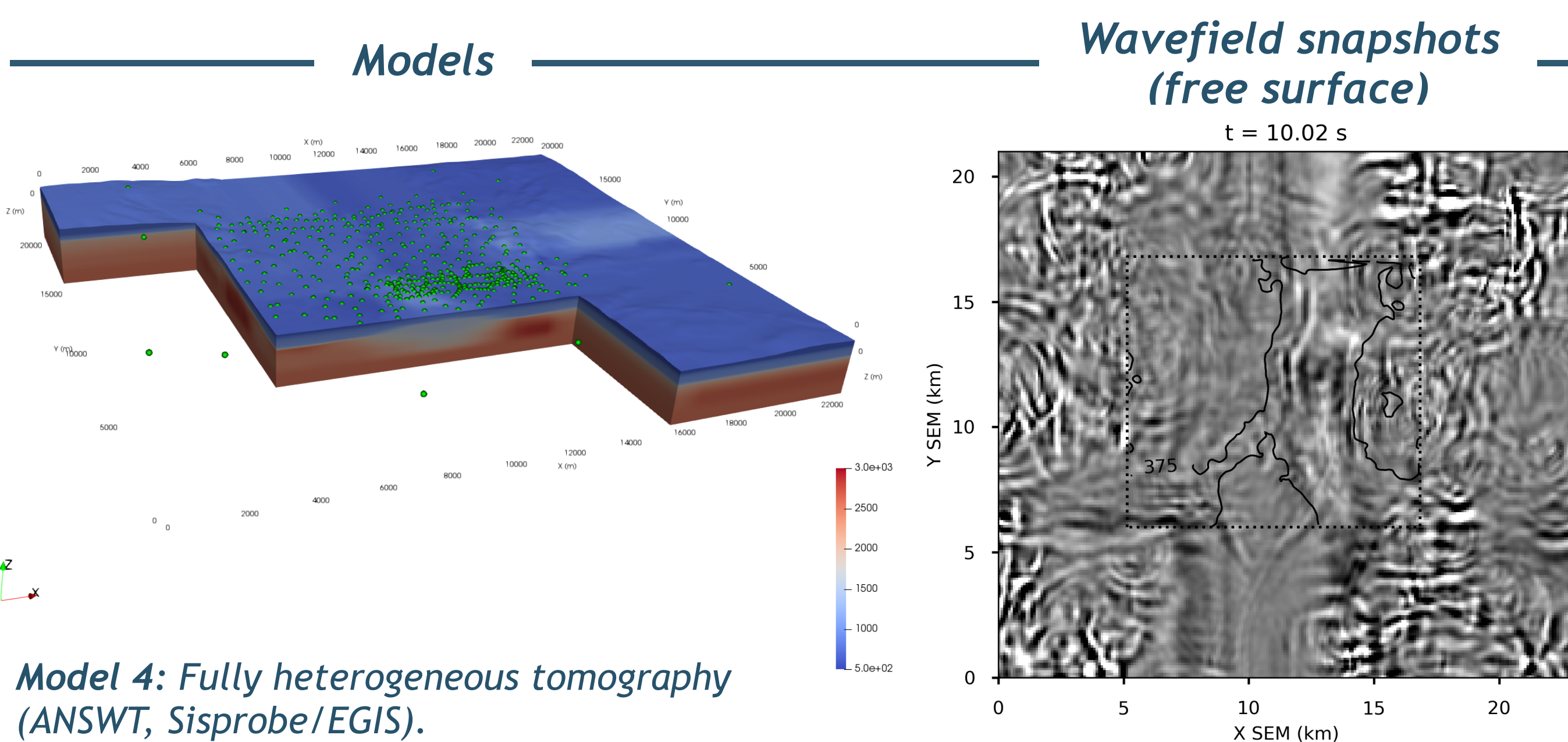
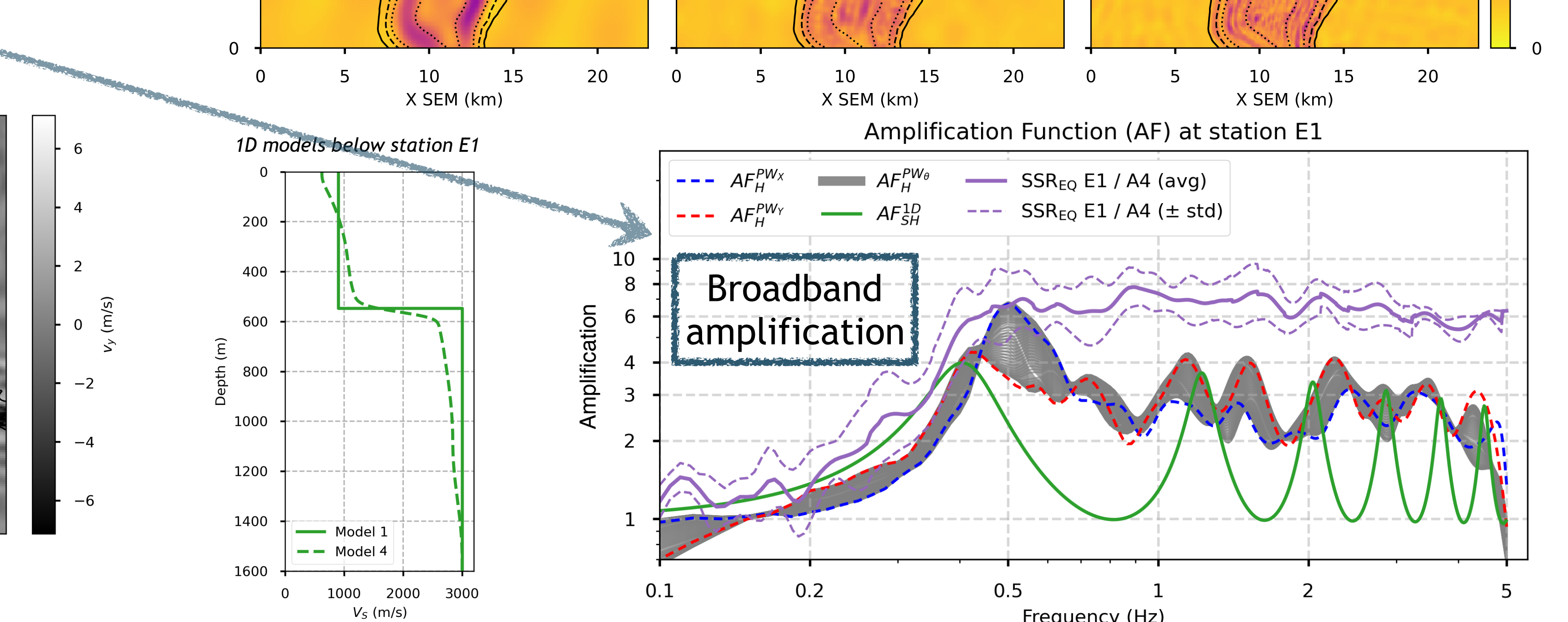


Numerical simulations (1) : Two end-member models

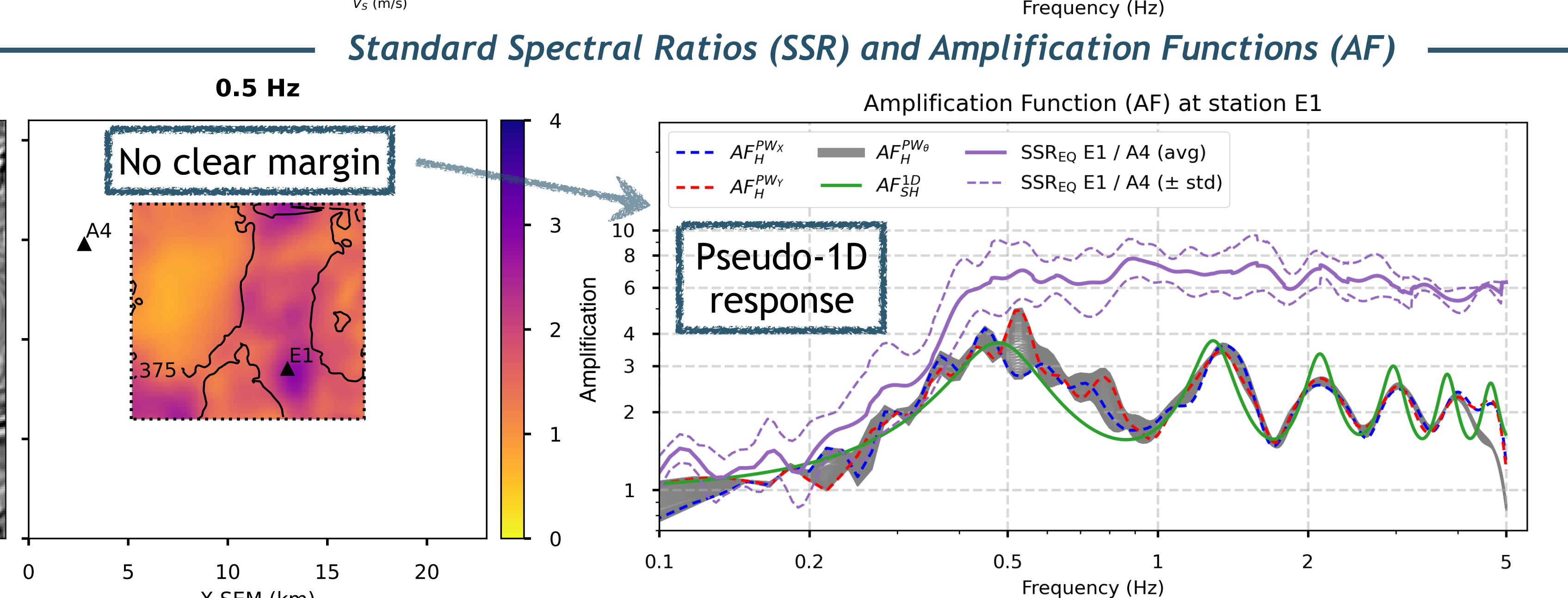
- Software:** EFISPEC (De Martin, 2011), spectral-element method (SEM), visco-elastic scheme.
- Seismic properties:** V_S from ANSWT (-500-3000 m/s), V_P from time-depth calibration of active seismic sections vs. borehole data (-2000-4500 m/s), density derived from V_P (Gardner et al., 1974), Q_S estimated by Q-SPAC analysis (-60-220), Q_P derived from Q_S .
- Simulations:** vertically-incident SH planewave with N-S polarization (PW_Y), $f_{max} = 5$ Hz.
- Amplification:** computed wrt theoretical free-surface response over a homogeneous halfspace.



Model 1: Two homogeneous units (low-velocity canyon sediments vs. high-velocity limestone bedrock), derived from the interpretation of active seismic profiles (Bagayoko, 2021).



Model 4: Fully heterogeneous tomography (ANSWT, Sisprobe/EGIS).



References:

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 • De Martin, F. (2011). Verification of a spectral-element method code for the Southern California Earthquake Center LOH.3 Viscoelastic Case. *Bull. Seismol. Soc. Am.*, 101(6):2855–2865.

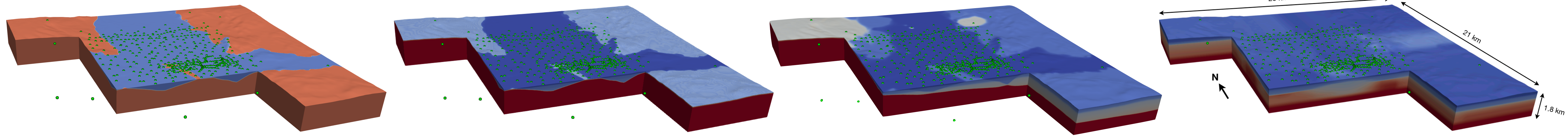
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DARE - Dense ARray for seismic site effect Estimation

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Numerical simulations (2) : Comparison of 4 models of increasing complexity



Model 1

2 homogeneous units
(Pliocene sediments / Urgonian bedrock)
 $V_S = 900 / 3000 \text{ m/s}$
 $V_P = 2200 / 5200 \text{ m/s}$
 $\rho = 2100 / 2600 \text{ kg/m}^3$
 $Q_S = 80 - 330$
 $Q_P = 315 - 750$

Model 2

2 units with gradients of properties
(Pliocene sediments / Urgonian bedrock)
 $V_S = 500 - 1100 / 1600 - 3100 \text{ m/s}$
 $V_P = 2000 - 2400 / 3000 - 5300 \text{ m/s}$
 $\rho = 2075 - 2160 / 2280 - 2650 \text{ kg/m}^3$
 $Q_S = 20 - 110 / 170 - 340$
 $Q_P = 260 - 370 / 425 - 760$

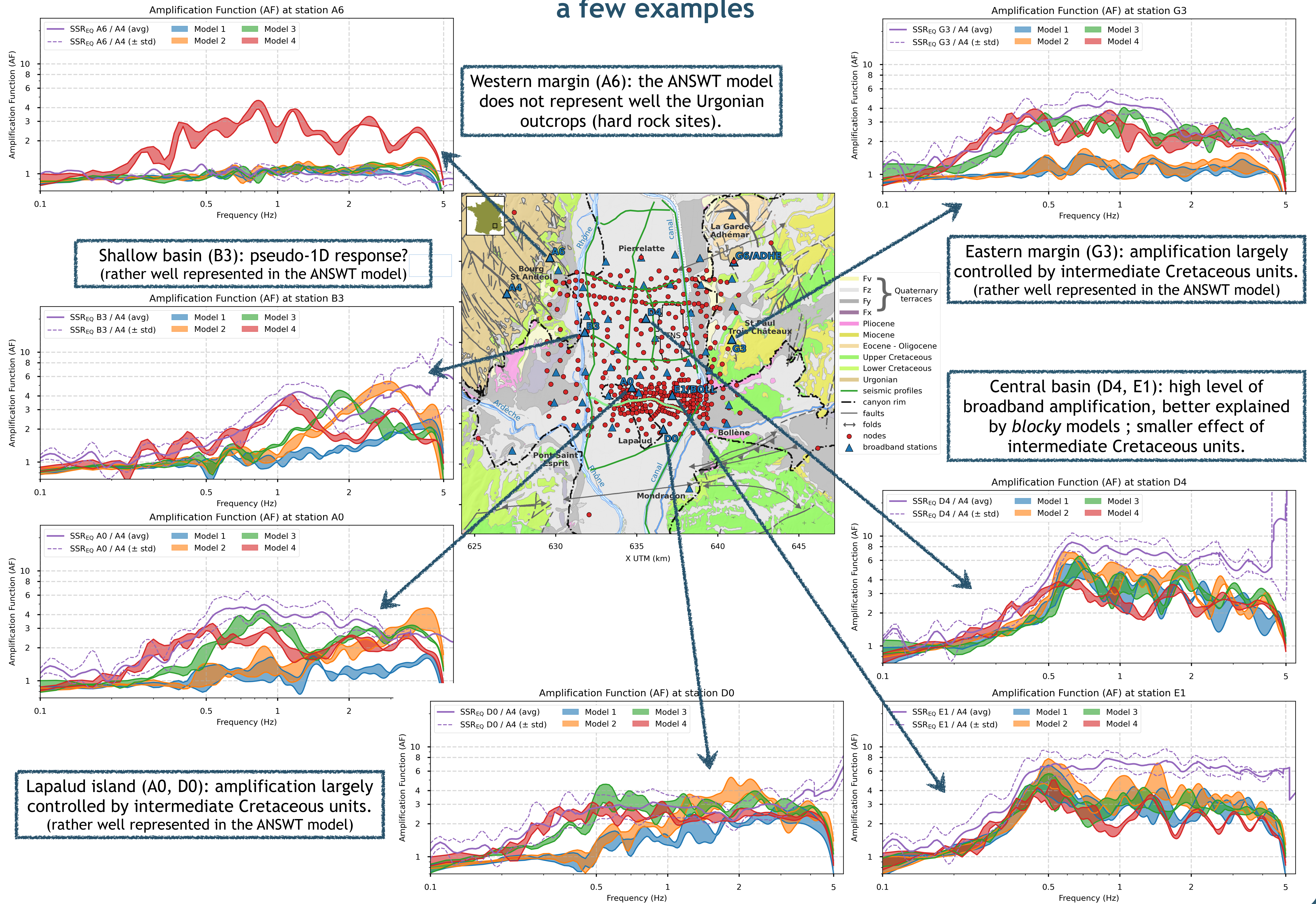
Model 3

3 units with gradients of properties
(Plio. sed. / Cretaceous / Urgonian)
 $V_S = 500 - 1000 / 800 - 2300 / 800 - 3150 \text{ m/s}$
 $V_P = 2000 - 2300 / 2200 - 4000 / 2200 - 5500 \text{ m/s}$
 $\rho = 2070 - 2150 / 2100 - 2500 / 2100 - 2650 \text{ kg/m}^3$
 $Q_S = 30 - 90 / 65 - 260 / 65 - 350$
 $Q_P = 345 - 365 / 360 - 590 / 360 - 790$

Model 4

ANSWT model
 $V_S = 500 - 3100 \text{ m/s}$
 $V_P = 2000 - 5300 \text{ m/s}$
 $\rho = 2075 - 2650 \text{ kg/m}^3$
 $Q_S = 20 - 340$
 $Q_P = 260 - 760$

Seismic amplification vs. subsurface geology: a few examples



Conclusions

- In *blocky* models (1,2,3), derived from seismic interpretation, waves are trapped in a well-delimited basin, resulting in a broadband amplification due to 3D propagation effects (esp. laterally-propagating surface waves generated at basin edges) that well explains the observations in the center of the basin.
- However, if over-simplified (homogeneous properties or missing units), these *blocky* models hardly reproduce the observations in other parts. In particular, it is important to distinguish the hard Urgonian bedrock from lower-velocity Cretaceous units within the substratum embedding the sedimentary basin.
- In contrast, Model 4, derived from ANSWT, produces a pseudo-1D amplification within the basin with less pronounced 3D effects, mostly due to a lack of lateral basin boundaries.
- On the other hand, this tomographic model seems effective in characterizing the deep subsurface velocity structure, including in complex areas where intermediate Cretaceous units are present.

Future work

- Design a new ANSWT model specifically for numerical site effect estimation (sharper basin edges: need for prior information in the tomographic process).
- Take shallow Quaternary alluvions into account (< 20 m, expected effect above 2 Hz).
- Systematically study the sensitivity of the site response to model parameters (geometry of units and interfaces, seismic properties), and to seismic sources (location, mechanisms).