3D seismic tomography of the Harmalière landslide (French Alps) by interferometry

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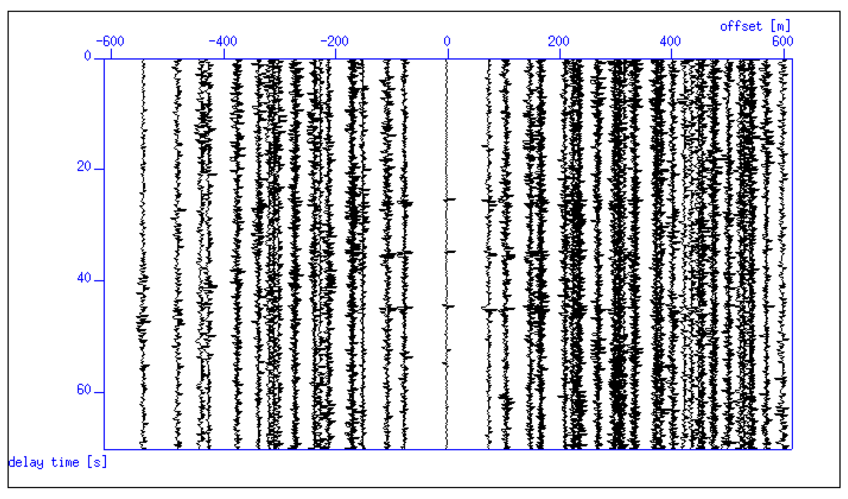
Introduction

Harmalière is an **active alpine landslide**: large episodic displacements unlike neighbouring slides [Fiolleau et al., 2020], e.g., Avignonet

Anatomy of the landslide? Simplified schemes with clay over bedrock. **Low-resolution knowledge** [Bièvre et al., 2011]

In the RESOLVE project: 3D acquisition of active-source seismic data and ambient noise [Simliar to the *Argentière glacier* survey]

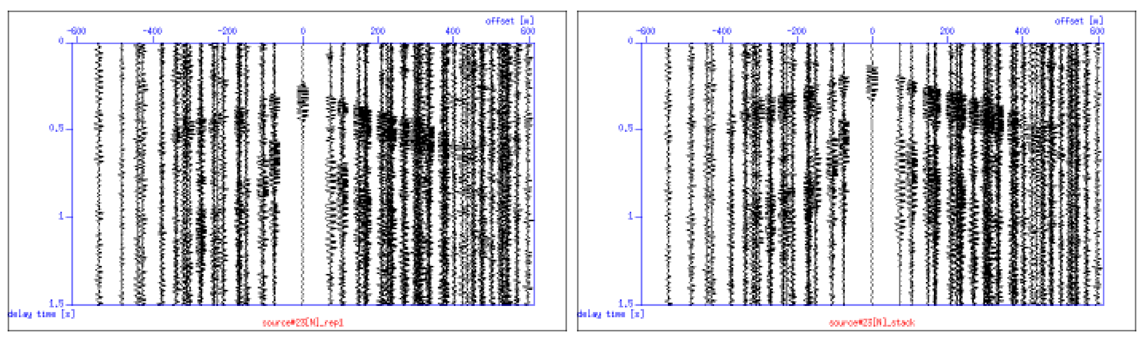


Exploit spectral diversity between ambient noise ($< 10Hz$, surface waves) and active-source data ($> 40Hz$, body waves)

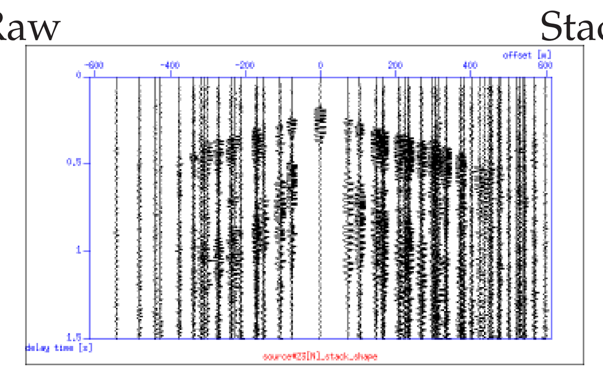
Target: **High-resolution 3D imaging** of the top 200 metres of the subsurface → improved understanding of landslide dynamics

Active data processing

For each source-point, three strikes
Missing synchronisation, irregular strike times, non repeatable source signature...→ **Band-pass filtering, synchronising, shaping deconvolution and stacking**



Raw Stack



Shaping+stack

However, SNR of large offset refractions is poor. How to fix this? **Redundancy** of the 3D multi-fold acquisition! → Interferometry-based signal reconstruction

SVRI - Refraction interferometry

An empirical transfer function between two stations at positions x and y is derived by stacking their **cross-coherence** over ensembles of sources (s) (*datuming step*).

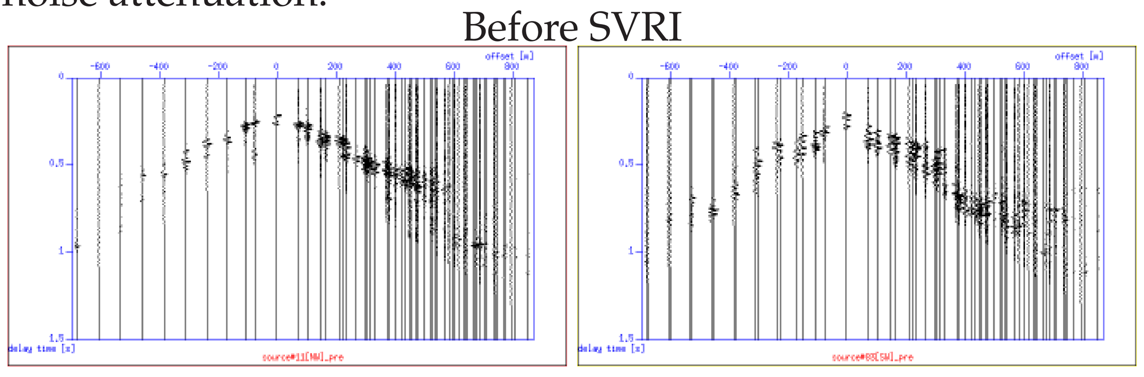
$$G_{xy} = \sum_s R^*_{sx} R_{sy} / (\|R_{sx}\| \|R_{sy}\|) \qquad (1)$$

For each source, the refracted signal at y is obtained by convolving the trasfer function G_{xy} from x to y with the signal at x and stacking (*de-datuming step*) [Bharadwaj et al., 2012]

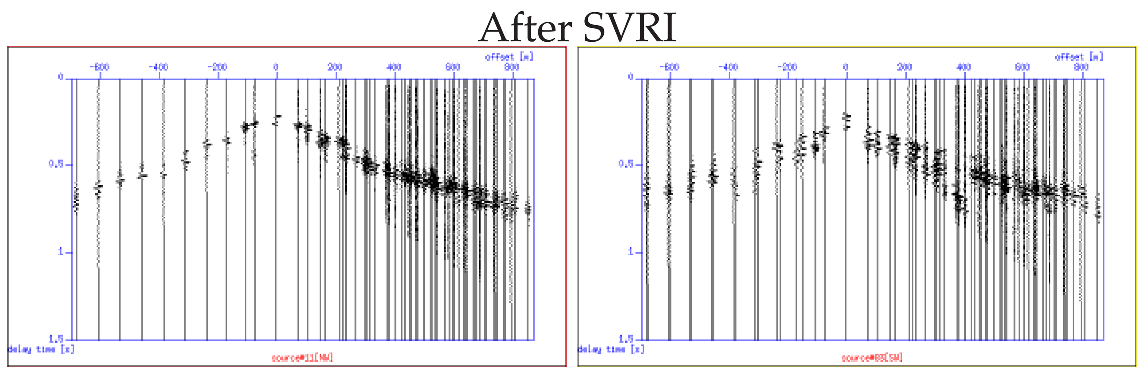
$$R^{SVRI}_{sy} = \sum_x R_{sx} G_{xy} \qquad (2)$$

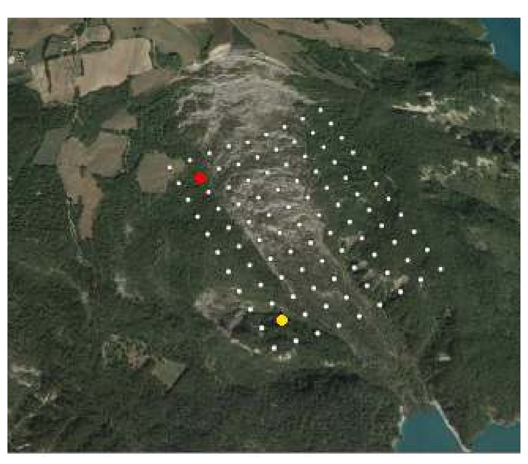
Iterative azimuth-varying SVRI on 3D survey (**stationary-paths!**). Cross-coherence prevents pulse spreading compared to cross-correlation, while **phase-weighted stacking** enhances noise attenuation.

Before SVRI



After SVRI

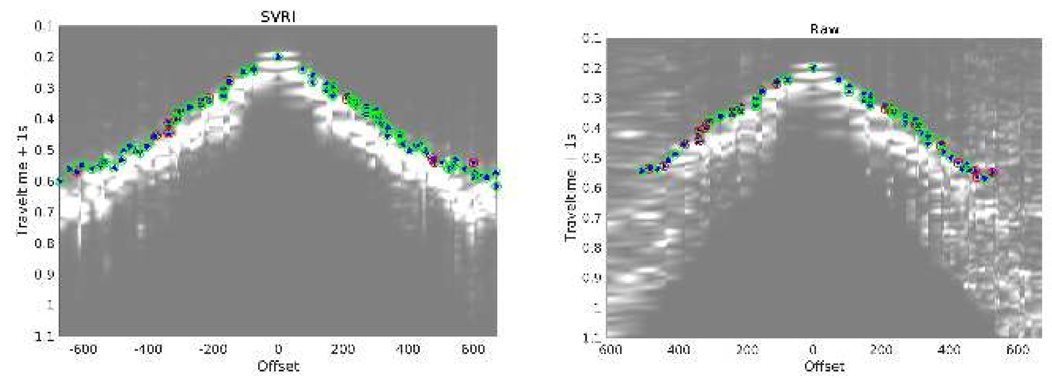




Southern gather shows earlier critical time (shallower bedrock) than northern one... how can we interpret this quantitatively? **Tomography!**

3D P-wave tomography

First arrival traveltime picks

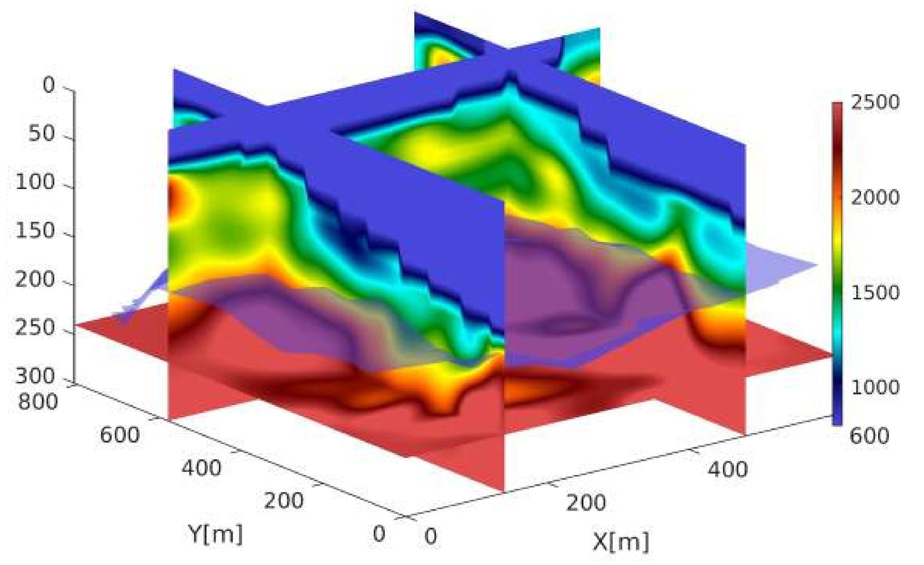


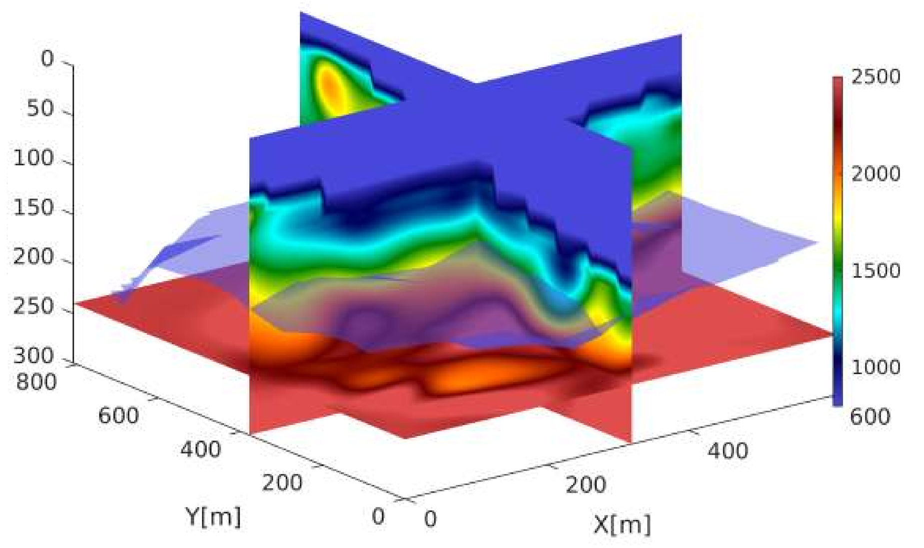
In the SVRI dataset, **50% more** valid picks [reciprocity, value of STA/LTA].

First-arrival traveltime inversion

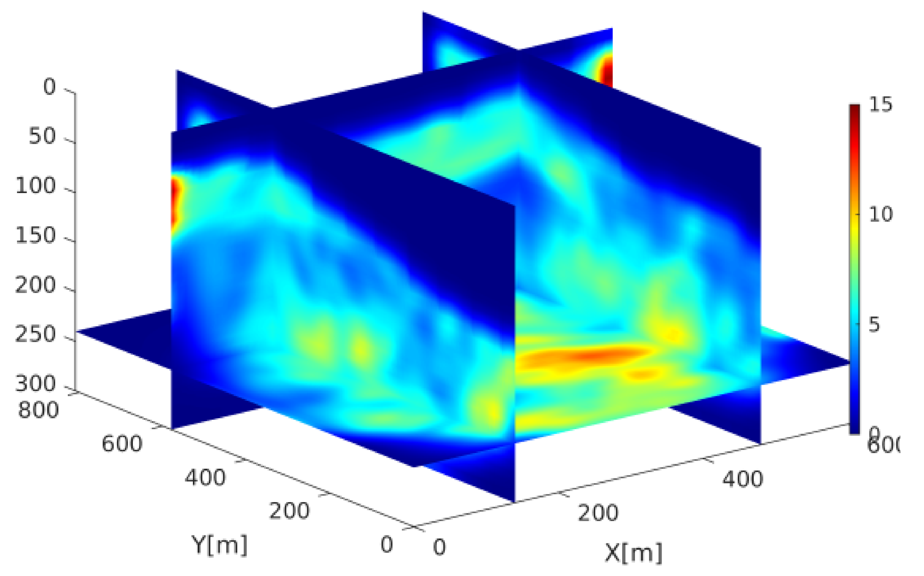
– [TOMO-TV, by Jean Virieux]: V_p inversion with optimal damping hyperparameter (L-curve) and 1D starting model by grid-search.
– Uncertainty estimation by bootstrapping [Vanorio et al., 2005]

Average model with HVSR overlay

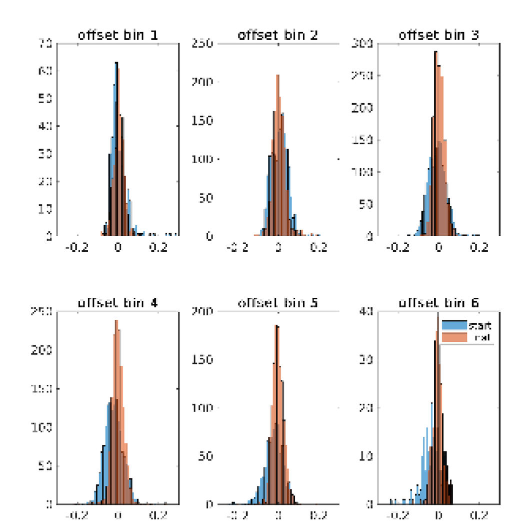




Relative (%) 2σ confidence interval



Residuals



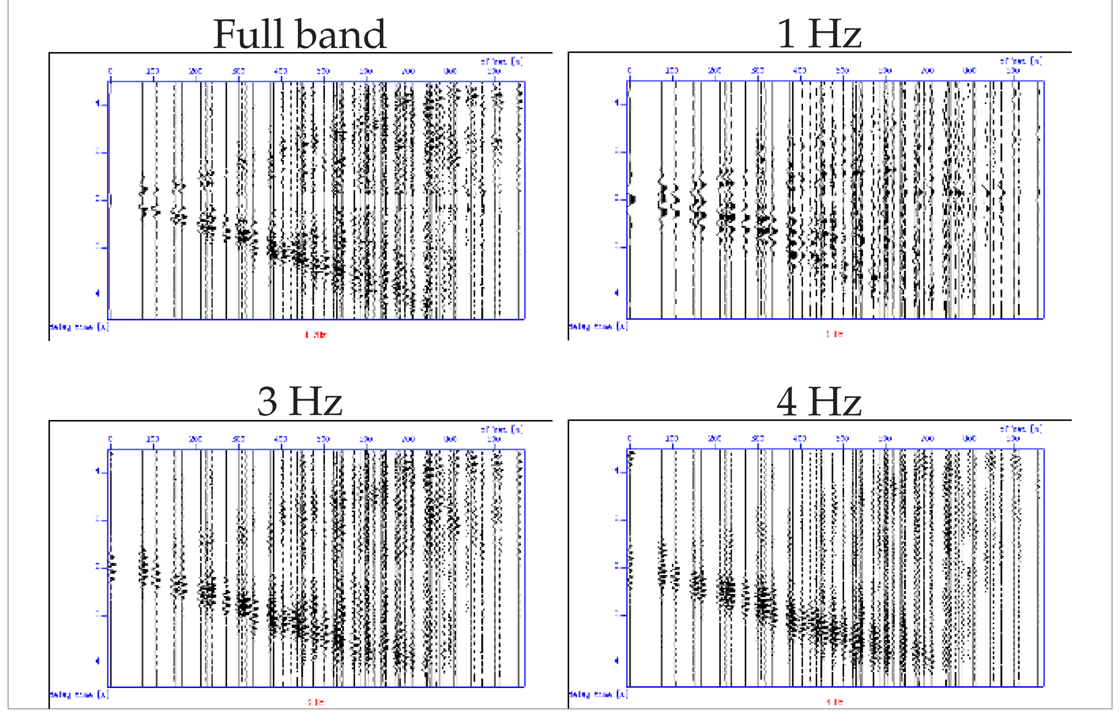
– Shallow P-wave velocities are sensible for non-consolidated partially-saturated sediments in the landslide body

– Comparison of HV spectral ratio bedrock depth estimates and low-to-high velocity transition in P-wave model is encouraging

Ambient noise interferometry

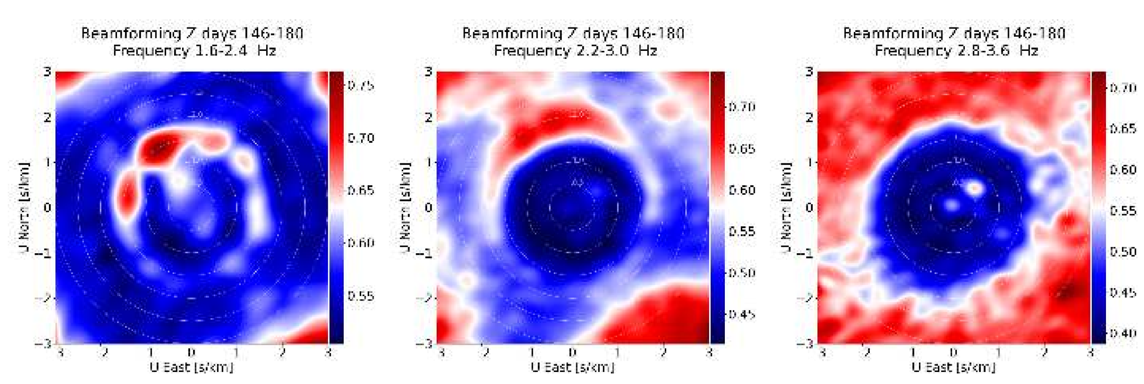
Cross-coherence of 15-minutes long noise segments, 1-bit normalization, maximum delay 5s, phase-weighted stacking over 36 days [1.-7.5 Hz]. → *Band-limited empirical Green's function* [Campillo, 2006]

Example virtual gather from ambient noise



Asymmetry suggests care in interpreting these results quantitatively

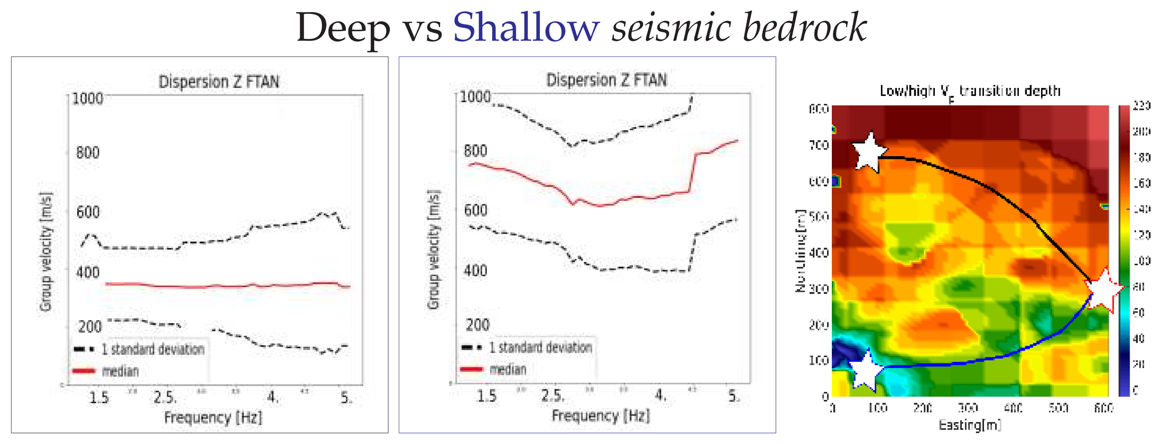
Preliminary dispersion analysis



– Plane-wave Beamforming revelas dominant NW-sources
– Frequencies > 2.5 Hz seem incoherent (topography?)

Are the observed group-velocities consistent with the P-wave and HVSR models?

Deep vs Shallow *seismic bedrock*



The observed dispersive behaviour seems influenced by seismic bedrock depth, although uncertainties are large

Conclusions

Partial conclusions

1. Dedicated processing and reconstruction of virtual refractions by interferometry is applied successfully to 3D shallow seismic data
2. P-wave tomography results are encouraging and consistent with indepedent geophysical and geological information
3. Preliminary analysis of the ambient noise field reveals challenges related to noise sources anisotropy, but promising dispersive behaviour is observed

In progress

1. Ambient noise inversion for S-wave velocity model → $\mathbf{V_p/V_s}$ **ratio** → Fluids, overpressures...
2. Bridging the spectral gap between active and passive data? (interferometry on active data Rayleigh wave recordings)
3. Starting model for **wave-equation tomography**?

References

[Bharadwaj et al., 2012] Bharadwaj, P., Schuster, G., Mallinson, I., and Dai, W. (2012). Theory of supervirtual refraction interferometry. *Geophysical Journal International*, 188:263–273.

[Bièvre et al., 2011] Bièvre, G., Kniess, U., Jongmans, D., Pathier, E., Schwartz, S., van Westen, C. J., Villemin, T., and Zumbo, V. (2011). Paleotopographic control of landslides in lacustrine deposits (trièves plateau, french western alps). *Geomorphology*, 125(1):214–224.

[Campillo, 2006] Campillo, M. (2006). Phase and correlation in 'random' seismic fields and the reconstruction of the green function. *Pure and applied geophysics*, 163:475–502.

[Fiolleau et al., 2020] Fiolleau, S., Jongmans, D., Bièvre, G., Chambon, G., Baillet, L., and Vial, B. (2020). Seismic characterization of a clay-block rupture in harmaliére landslide, french western alps. *Geophysical Journal International*, 221:1777–1788.

[Vanorio et al., 2005] Vanorio, T., Virieux, J., Capuano, P., and Russo, G. (2005). Three-dimensional seismic tomography from p wave and s wave microearthquake travel times and rock physics characterization of the campi flegrei caldera. *Journal of Geophysical Research*, 110:B03201.

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