Attenuation Tomography Analysis in the Val d'Agri Oilfield

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1. Aim

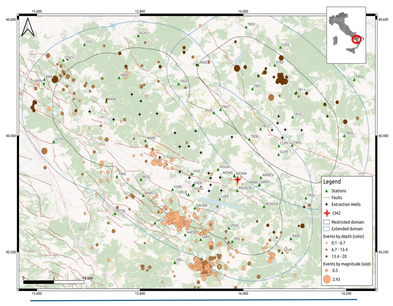
The Val d'Agri basin is a unique natural laboratory where industrial fluid operations intersect with natural seismicity. By imaging attenuation, a proxy for fluid content and rock damage, this work aims to advance our ability to monitor subsurface changes, improving both resource management and seismic risk assessment in active hydrocarbon systems worldwide.

2. Study Area and Geology

Tectonic Setting
Quaternary extensional basin in the southern Apennines, superimposed on a compressional fold-and-thrust belt. Europe's largest onshore hydrocarbon system and a well-documented site of induced seismicity.

Stratigraphy & Reservoirs
Reservoir hosted in Mesozoic carbonates (Lagonegro Basin & Apulia Platform) at 2–7 km depth, overlain by Miocene–Pliocene flysch and Quaternary clastics. Two structurally isolated compartments:
• **Val d'Agri (VA)**: 2–4 km depth, shallow carbonate culmination (larger western domain)
• **Tempa Rossa (TR)**: 5–7 km depth, deeper isolated block (smaller eastern domain)

Industrial Activity & Seismicity
• **Costa Molina 2 (CM2) Injection Well**: Wastewater injection at 2,890–3,096 m into the VA fault damage zone
• **Seismicity**: 664 events, 8,433 station-event pairs, 0.5 < M < 2.5
• **Production Network**: Extraction wells in both fields; long-term depletion modifies crustal stress and fracture networks



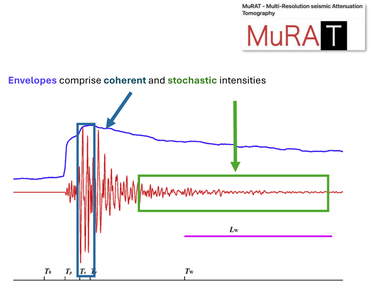
Local seismicity (2020–2025) overlaid on topography, active faults, and monitoring domains.

Dataset
Local earthquake catalog (2020–2025), dense station coverage, optimal ray paths through the 2–6 km reservoir interval.

3. Method

MuRAT4 Framework
Multi-Resolution seismic Attenuation Tomography (MuRAT4) provides a multi-parameter description of seismic energy loss.

What We Measure:
· **Peak Delay (PD):**
Time shift of peak amplitude relative to reference; mainly sensitive to **scattering** by heterogeneities
· **Q (Total Attenuation):**
Amplitude decay of direct waves; captures combined **scattering + absorption**
• **Qc (Coda Attenuation):**
Decay rate of coda wave envelope; primarily reflects **intrinsic absorption** (fluid/thermal losses)
· **Multi-Frequency Analysis:**
Simultaneous inversion at 6, 12, and 18 Hz to constrain scale-dependent structures



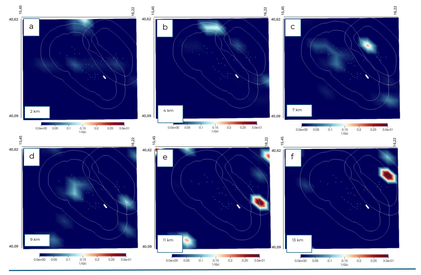
Energy window selection for attenuation analysis.

Key Improvements in MuRAT 4.0:
· **Differential kernels**: Numerically calculated sensitivity for stable contrast resolution (~2 orders of magnitude)
· **Frequency-dependent damping**: Explicit smoothing/damping parameters per frequency band
· **Positivity constraint**: Guarantees physical, non-negative Q and Qc values
· **Enhanced validation**: Stricter enforcement of diffusive regime, energy conservation, and coda-stability assumptions

Resources:
MuRAT4 is available at
github.com/LucaDeSiena/MuRAT

4. Results

MuRAT4.0

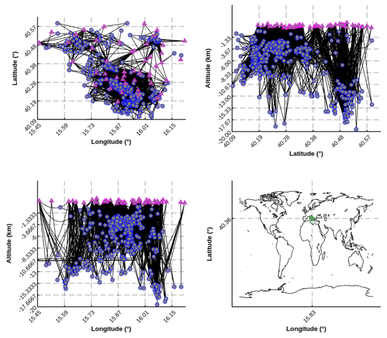


3D coda attenuation (Qc) distribution at 12 Hz across six depth slices. Red: high attenuation (low Qc). Blue: low attenuation (high Qc). Light blue points: extraction wells. White cylinder: extraction well CM2.

MuRAT4.0 Processing Parameters (Val d'Agri)

Peak Delay (Scattering):
· Window: 0.1-4 s; selection threshold = 2σ from average trend
· Regionalisation weighted by ray length (no forward inversion)

Coda Attenuation (Qc):
· Lapse time method: Constant (start = 10 s, window = 10 s)
· Measurement: Non-linear grid search (fit threshold $R^2 \geq 0.006$)
· Inversion parameters (frequency-dependent):
- Albedo (B_0): [0.1, 0.2, 0.1] @ [6, 12, 18] Hz
- Inverse extinction length: [0.1, 0.09, 0.08] km^{-1}
· Kernel threshold = 2 (computational grid refinement)



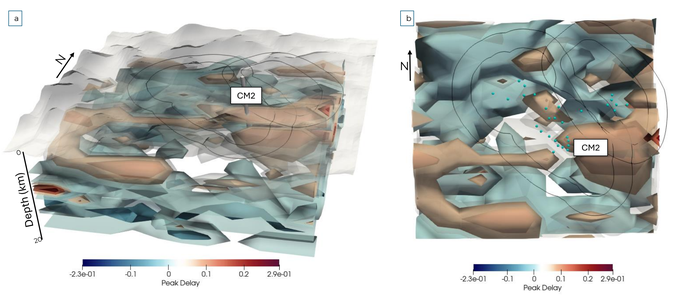
Ray-path density and hypocentre distribution used in tomographic inversion. Dense crossing geometry ensures robust sampling of the reservoir volume. Declustered dataset optimised for coda stability and uniform spatial coverage.

Solver: **Tikhonov** inversion via MATLAB Optimization Toolbox
· Positivity constraint enforced (non-negative Q, Qc)

Frequency-dependent damping:
· Qc: [0.3, 0.3, 0.1]
· Q: [0.001, 0.001, 0.001]
· Smoothing: [0, 0, 0] (no additional spatial smoothing)

Inversion grid:
· 12 × 12 × 10 nodes (Lat × Lon × Depth)
· Extent: 40.09-40.62°N, 15.45-16.22°E, +1 to −20 km depth

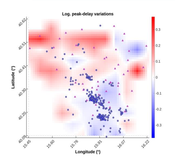
Validation:
· Checkerboard test: anomaly size = 2× node spacing
· Spike test: location [40.30-40.40°N, 15.80-16.10°E, −6 to −16 km]
· Picard condition analysis for parameter resolution



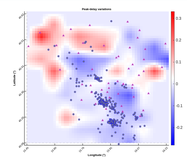
3D volume rendering of the 12 Hz Peak Delay model. The injection well CM2 is indicated in both images as a white cylinder. b) The light blue dots represent the extraction wells

5. Comparison

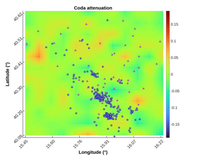
Feature	MuRAT 3.0	MuRAT 4.0
Inversion Solver	IRTools / regtools (Tikhonov, Iterative, Hybrid)	MATLAB Optimization Toolbox (this study uses Tikhonov with positivity constraint)
Inversion Parameters	Fixed scalar values (e.g., albedo = 0.5, Le = 0.02 km^{-1})	Frequency-dependent arrays (albedo & inverse extinction length defined per frequency band)
Sensitivity Kernels	Absolute diffusive kernels (Del Pezzo et al., 2018)	Differential kernels (Del Pezzo-based); updated philosophy yields realistic contrast resolution (~2 orders of magnitude) vs. unstable 6–7 orders in v3
Peak Delay Imaging	Regionalization via hit-count weighting	Same regionalization approach, now explicitly weighted by ray length (no forward inversion; preserves structural sensitivity)
Validation & Physics	Standard Picard condition & L-curve damping	Enhanced physical-consistency checks; stricter enforcement of diffusive regime, energy conservation, and coda-stability assumptions



MuRAT 3.0 peak-delay variations regionalised via simple hit-count weighting. Serves as reference for structural sensitivity before ray-length weighting implementation.



MuRAT 4.0 peak delay variations regionalised with explicit ray-length weighting.



MuRAT 3.0 coda attenuation map at 7 km depth for direct comparison. Uses absolute diffusive kernels and fixed MLTWA parameters. Highlights baseline resolution prior to MuRAT 4.0 improvements.

6. Conclusions

· MuRAT 4.0 introduces **critical methodological upgrades** over v3.0, including **differential sensitivity kernels, positivity-constrained inversion, and frequency-dependent inversion parameters**.
· These improvements enforce stricter **physical consistency**, ensuring better adherence to diffusive regime assumptions, energy conservation, and coda-stability criteria.
· Enhanced numerical stability and realistic contrast resolution (~2 orders of magnitude) yield **more reliable tomographic images** for complex reservoir systems.
· With its robust optimisation framework and improved validation protocols, MuRAT 4.0 is positioned to replace v3.0 as the **new standard for multi-resolution attenuation tomography**.

7. References

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