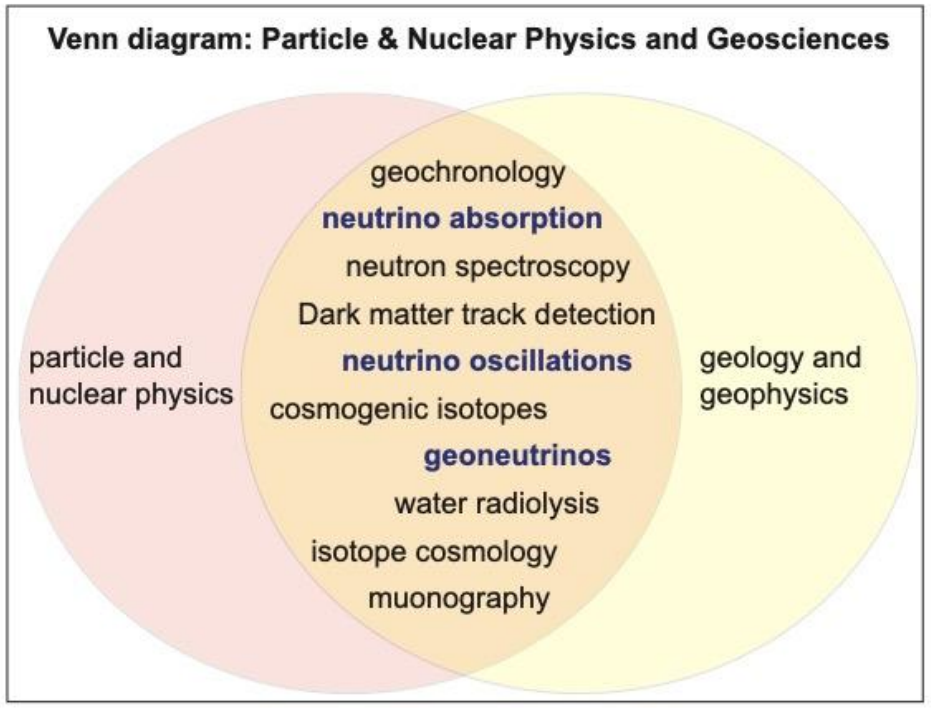
Imaging the crust beneath Gran Sasso for geoneutrino studies

Fabio Mantovani - fabio.mantovani@unife.it



Summer institute: using particle physics to understand and image the earth – L'Aquila – 2016

Neutrino Geoscience workshop 2026 Zhuhai



AGU ADVANCING EARTH AND SPACE SCIENCES

Earth and Space Science

RESEARCH ARTICLE
10.1029/2026EA005334

A Geophysical Crustal Model of Central Italy for Geoneutrino Predictions in Borexino

L. Rossi[1], M. Capponi[2], P. Conti[3], N. I. Elek[4,5], A. Ermini[3,6], K. G. C. Raptis[4,5], M. Reguzzoni[1], V. Strati[4,5], M. M. Tiberti[7], F. E. Maesano[7], R. Maffucci[7], M. Buttinelli[7], M. Abdelkader[4,5], M. Albèri[4,5], A. Albertella[1], G. Hasnain[4,5,6], F. Mantovani[4,5], L. Pagano[4,5], S. Ramouz[1], R. Salvini[3], D. Sampietro[2,8], and P. S. Dinani[3]

[1]Department of Civil and Environmental Engineering (DICA), Politecnico di Milano, Milan, Italy, [2]Geomatics Research & Development, Lomazzo, Italy, [3]Department of Physical Sciences, Earth and Environment and Centre of Geotechnologies CGT, University of Siena, San Giovanni Valdarno, Italy, [4]Department of Physics and Earth Sciences, University of Ferrara, Ferrara, Italy, [5]INFN Ferrara Section, Ferrara, Italy, [6]University of Trento, Trento, Italy, [7]Istituto Nazionale di Geofisica e Vulcanologia (INGV), Rome, Italy, [8]Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Catania - Osservatorio Etneo, Catania, Italy

Key Points:

- GUESS: a new probabilistic 3-D crustal model for the Gran Sasso region, built by Bayesian inversion of gravity, seismic, and borehole data
- Posterior densities validated against three independent benchmarks
- Structural uncertainty on the geoneutrino signal constrained to 1%–3%

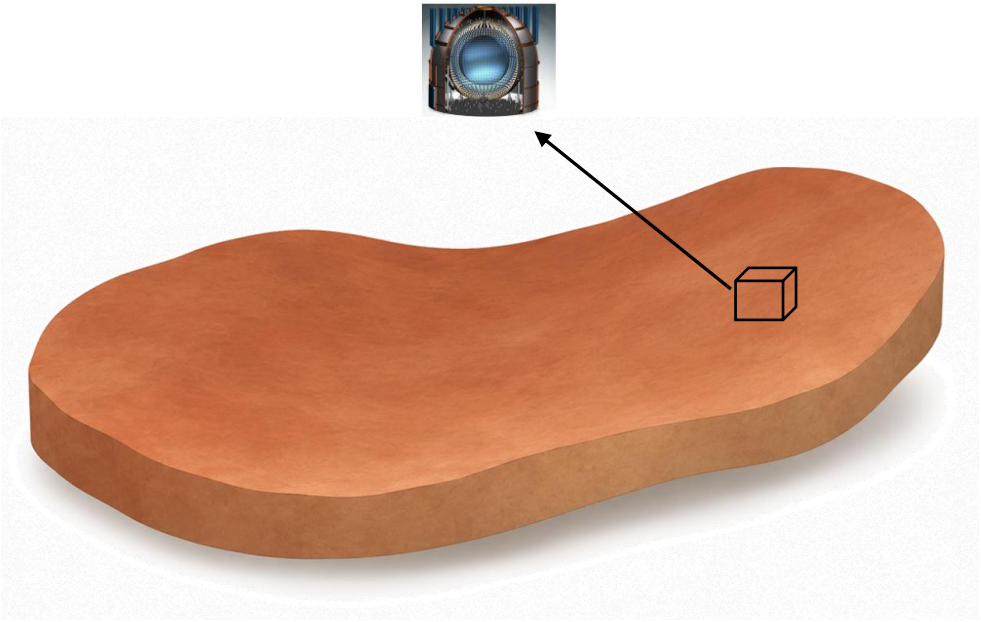
Supporting Information:

Supporting Information may be found in

GUESS project GeoneUtrinos: mESSengers of the Earth's interior
European Union
NextGenerationEU
Mission 4
Component 1
CUP F53D23001280006



Unitary geoneutrino signal



$$S(X,\vec{r}) = N_p \cdot T \cdot \varepsilon_{\bar{\nu}_e} \cdot \eta \cdot \int dE_{\bar{\nu}} \cdot \sigma(E_{\bar{\nu}}) \cdot S_p(X, E_{\bar{\nu}}) \cdot \int d^3r' \cdot P_{ee}(|\,\boldsymbol{r}-\boldsymbol{r}'\,|, E_{\bar{\nu}}) \cdot \frac{\rho(\boldsymbol{r}')}{4\pi\,|\,\boldsymbol{r}-\boldsymbol{r}'\,|^2} a(X,\boldsymbol{r}')$$

G = Response factor

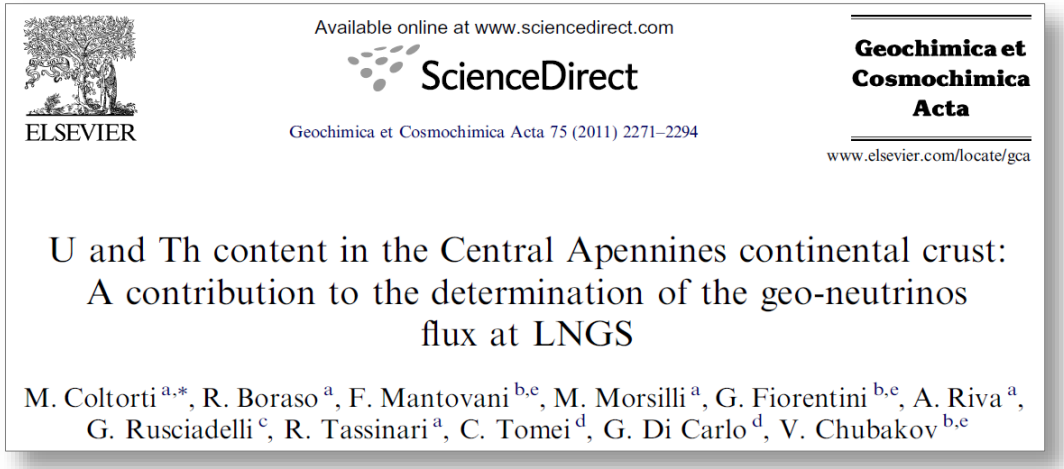


$$S(X) = G \cdot a(X)$$

Response factor G: signal at the detector from a unit with unitary abundance (1 µg/g), summing all voxels: it holds geometry, density and neutrino physics.

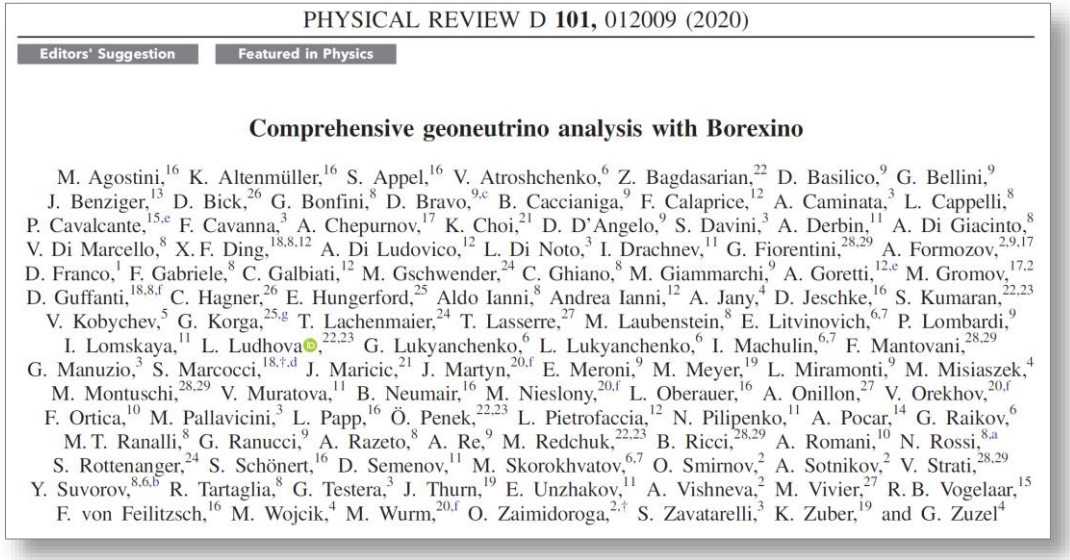
Scientific motivations

- Borexino (Agostini et al., 2020) measured a mantle signal of $21.2^{+9.5}_{-9.0}$ TNU, i.e. 24.6 $^{+11.1}_{-10.4}$ TW of radiogenic heat from U and Th in the mantle: a **relatively high value**, which depends directly on the predicted local crustal contribution.
- Sammon & McDonough (2022) suggested that including the **potassic volcanic rocks** would raise the U and Th content of the local upper crust, lowering the inferred mantle radiogenic heat.
- The reference model (Coltorti et al., 2011) is 15 years **old and deterministic**: refined Moho geometry from dense teleseismic monitoring and Bayesian gravity inversion now allow a probabilistic model with quantified uncertainty.


ELSEVIER
Available online at www.sciencedirect.com
ScienceDirect
Geochimica et Cosmochimica Acta 75 (2011) 2271–2294
Geochimica et Cosmochimica Acta
www.elsevier.com/locate/gca

U and Th content in the Central Apennines continental crust: A contribution to the determination of the geo-neutrinos flux at LNGS

M. Coltorti [a,*], R. Boraso [a], F. Mantovani [b,e], M. Morsilli [a], G. Fiorentini [b,e], A. Riva [a], G. Rusciadelli [c], R. Tassinari [a], C. Tomei [d], G. Di Carlo [d], V. Chubakov [b,e]


PHYSICAL REVIEW D **101,** 012009 (2020)
Editors' Suggestion
Featured in Physics

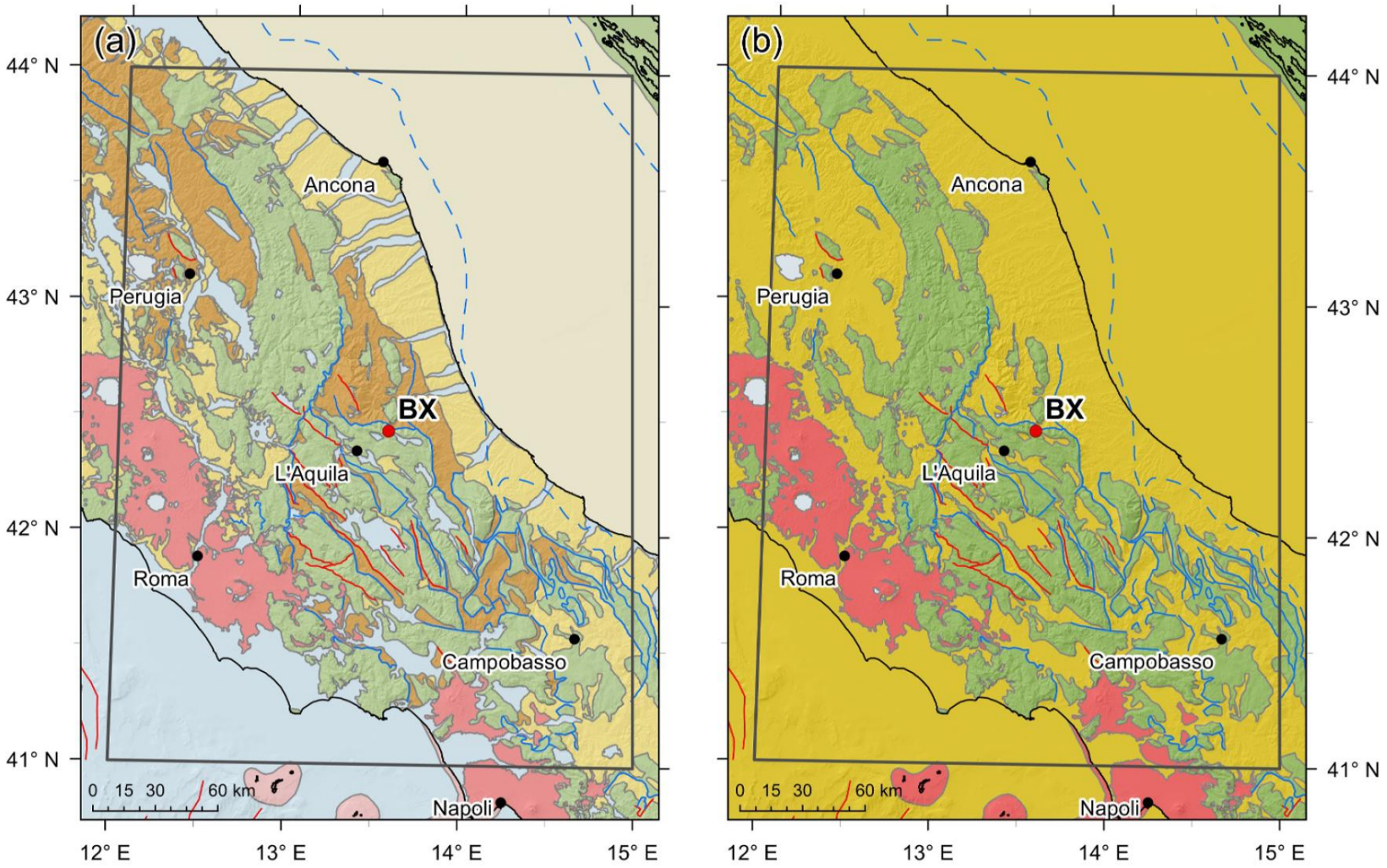
Comprehensive geoneutrino analysis with Borexino

M. Agostini,[16] K. Altenmüller,[16] S. Appel,[16] V. Atroshchenko,[6] Z. Bagdasarian,[22] D. Basilico,[9] G. Bellini,[9] J. Benziger,[13] D. Bick,[26] G. Bonfini,[8] D. Bravo,[9,e] B. Caccianiga,[9] F. Calaprice,[12] A. Caminata,[3] L. Cappelli,[8] P. Cavalcante,[15,e] F. Cavanna,[3] A. Chepurnov,[17] K. Choi,[21] D. D'Angelo,[9] S. Davini,[3] A. Derbin,[11] A. Di Giacinto,[8] V. Di Marcello,[8] X. F. Ding,[18,8,12] A. Di Ludovico,[12] L. Di Noto,[3] I. Drachnev,[11] G. Fiorentini,[28,29] A. Formozov,[2,9,17] D. Franco,[1] F. Gabriele,[8] C. Galbiati,[12] M. Gschwender,[24] C. Ghiano,[8] M. Giammarchi,[9] A. Goretti,[12,e] M. Gromov,[17,2] D. Guffanti,[18,8,f] C. Hagner,[26] E. Hungerford,[25] Aldo Ianni,[8] Andrea Ianni,[12] A. Jany,[4] D. Jeschke,[16] S. Kumaran,[22,23] V. Kobychev,[5] G. Korga,[25,g] T. Lachenmaier,[24] T. Lasserre,[27] M. Laubenstein,[8] E. Litvinovich,[6,7] P. Lombardi,[9] I. Lomskaya,[11] L. Ludhova,[22,23] G. Lukyanchenko,[6] L. Lukyanchenko,[6] I. Machulin,[6,7] F. Mantovani,[28,29] G. Manuzio,[3] S. Marcocci,[18,†,d] J. Maricic,[21] J. Martyn,[20,f] E. Meroni,[9] M. Meyer,[19] L. Miramonti,[9] M. Misiaszek,[4] M. Montuschi,[28,29] V. Muratova,[11] B. Neumair,[16] M. Nieslony,[20,f] L. Oberauer,[16] A. Onillon,[27] V. Orekhov,[20,f] F. Ortica,[10] M. Pallavicini,[3] L. Papp,[16] Ö. Penek,[22,23] L. Pietrofaccia,[12] N. Pilipenko,[11] A. Pocar,[14] G. Raikov,[6] M. T. Ranalli,[8] G. Ranucci,[9] A. Razeto,[8] A. Re,[9] M. Redchuk,[22,23] B. Ricci,[28,29] A. Romani,[10] N. Rossi,[8,a] S. Rottenanger,[24] S. Schönert,[16] D. Semenov,[11] M. Skorokhvatov,[6,7] O. Smirnov,[2] A. Sotnikov,[2] V. Strati,[28,29] Y. Suvorov,[8,6,b] R. Tartaglia,[8] G. Testera,[3] J. Thurn,[19] E. Unzhakov,[11] A. Vishneva,[2] M. Vivier,[27] R. B. Vogelaar,[15] F. von Feilitzsch,[16] M. Wojcik,[4] M. Wurm,[20,f] O. Zaimidoroga,[2,†] S. Zavatarelli,[3] K. Zuber,[19] and G. Zuzel[4]

Agostini et al. (2020), Phys. Rev. D, 101, 012009; Sammon & McDonough (2022), Earth Planet. Sci. Lett., 593, 117684; Coltorti et al. (2011), Geochim. Cosmochim. Acta, 75, 2271–2294

From the geological map to GUESS units



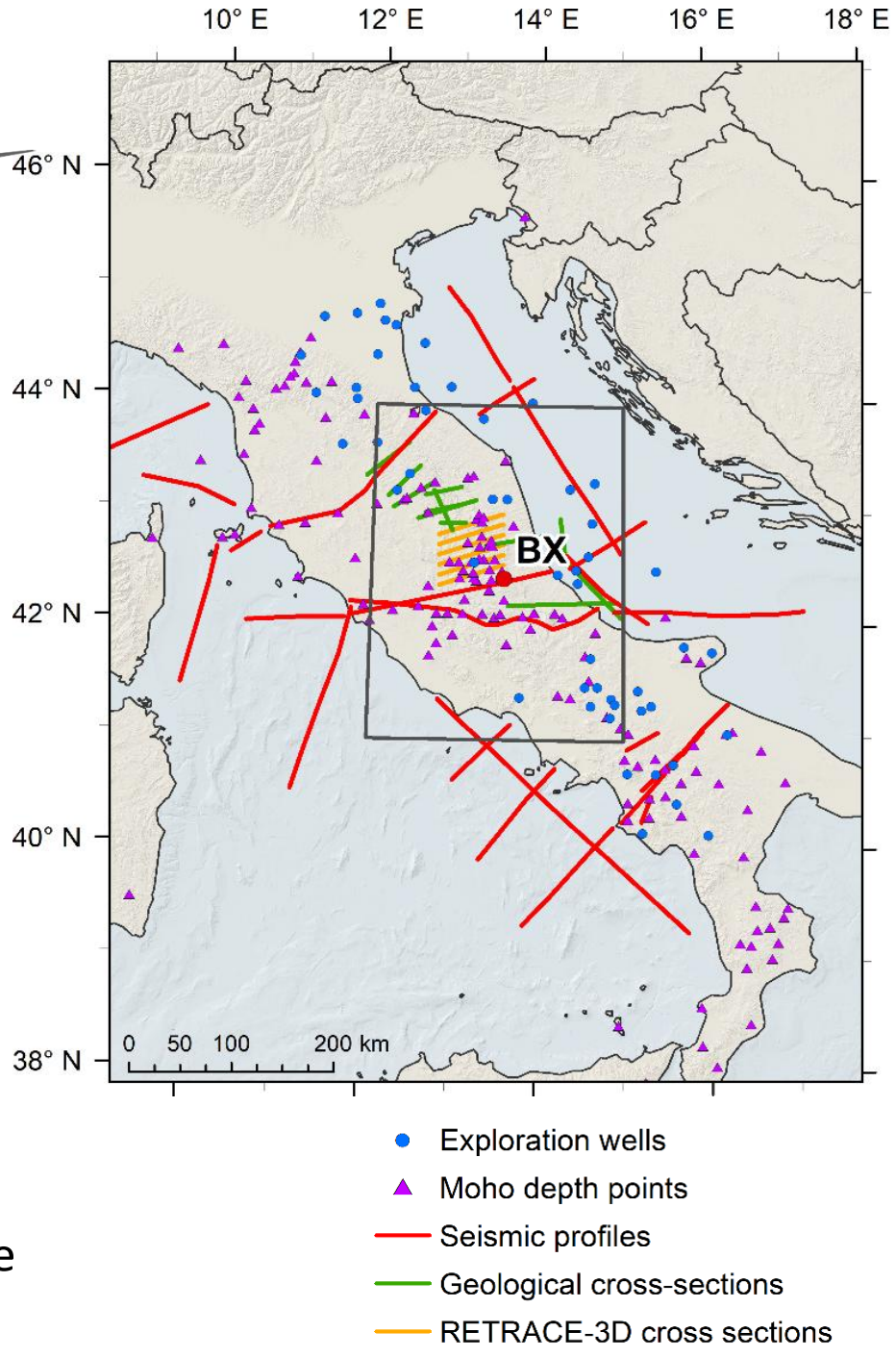


Geological units		GUESS units
Quaternary volcanic rocks	vo	Unit 1
Quaternary volcanic rocks, offshore	vc	
Quaternary deposits	qt	Unit 2
Pliocene-Quaternary Adriatic sea deposits	pc	
Foredeep Miocene siliciclastic deposits	pl	
Foredeep silciclastic deposits	fl	
Mesozoic-Cenozoic carbonates	ms	Unit 3
Permian clastic units		Unit 4
Upper Crust		Unit 5
Lower Crust		Unit 6

Multi-source data integration

We collected **geological and seismic constraints** in the 3° × 3° area, building an a priori model from sea level down to 50 km depth.

Typology	Input description	Unc. (1σ)
1-D	Interpreted stratigraphic data from n.53 exploration wells	-
	N°154 depth points of Moho discontinuity	3–13%
2-D	N°11 integrated geological cross-sections	20%
	N°21 interpretative cross-sections of seismic lines	20%
	N°6 virtual cross-sections (RETRACE-3D model)	20%
3-D	Topography	-
	Moho discontinuity map	25%
	Discontinuity interface between Adria and Tyrrhenian plate	40%

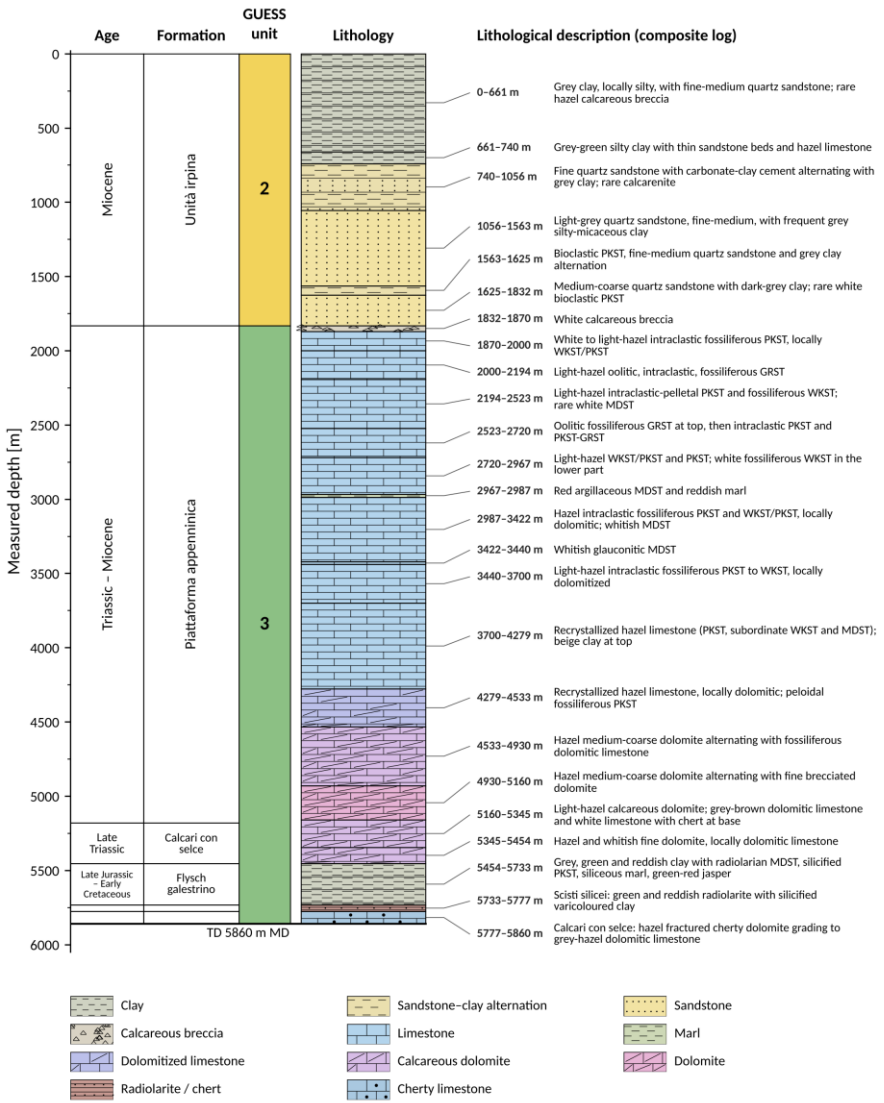


Gravity data **spatialize** the model where direct information is missing: the Bayesian inversion respects the geological and seismic constraints.

1-D constraints: two of the 53 exploration wells

Campobasso 1

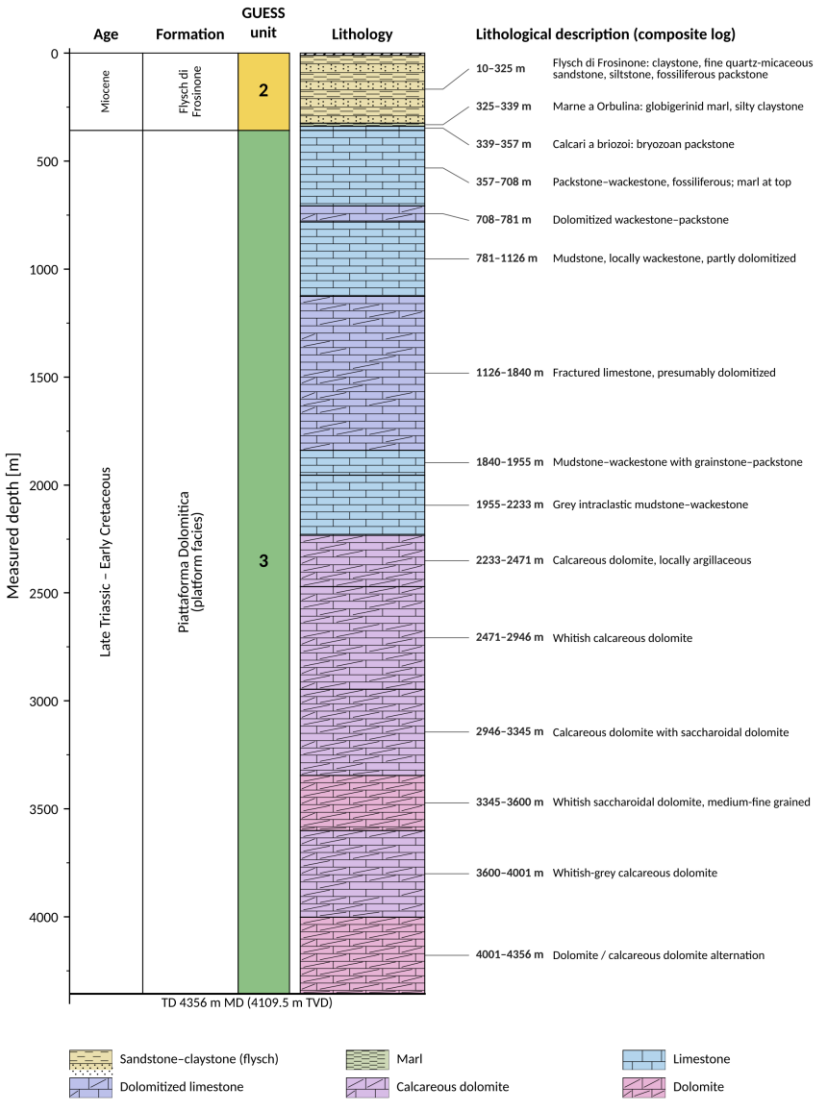
AGIP, 1971–72 · Molise (CB) · 41.484° N, 14.543° E · ground level 477 m a.s.l.



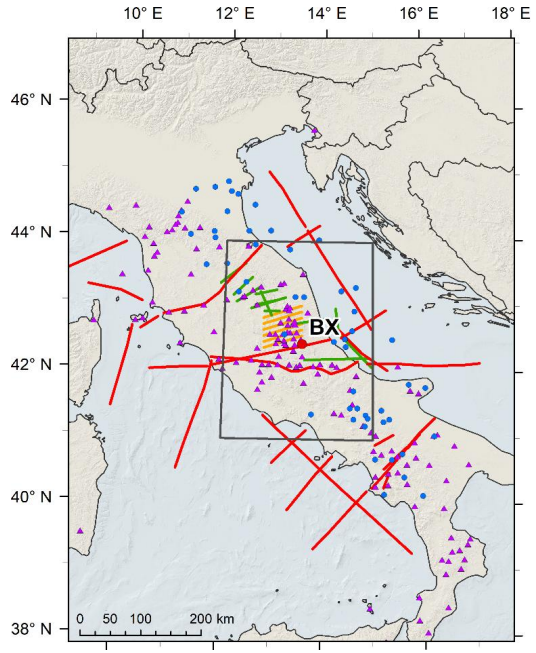
Formation, age and GUESS unit: 53_pozzi.xlsx. Lithology and descriptions: AGIP composite log (1992), interval descriptions on the log tracks. Depths are measured along hole. MDST/WKST/PKST/GRST: mudstone/wackestone/packstone/grainstone (Dunham).

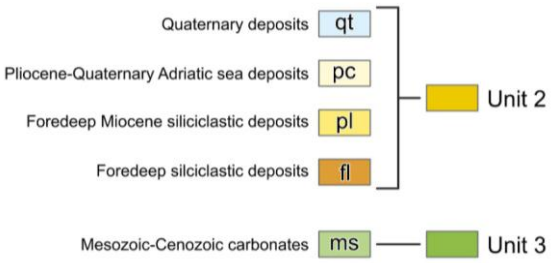
S. Giorgio a Liri 1 Dir

Petrex, 1995 · Lazio (FR) · 41.389° N, 13.777° E · ground level 98 m a.s.l. · deviated well

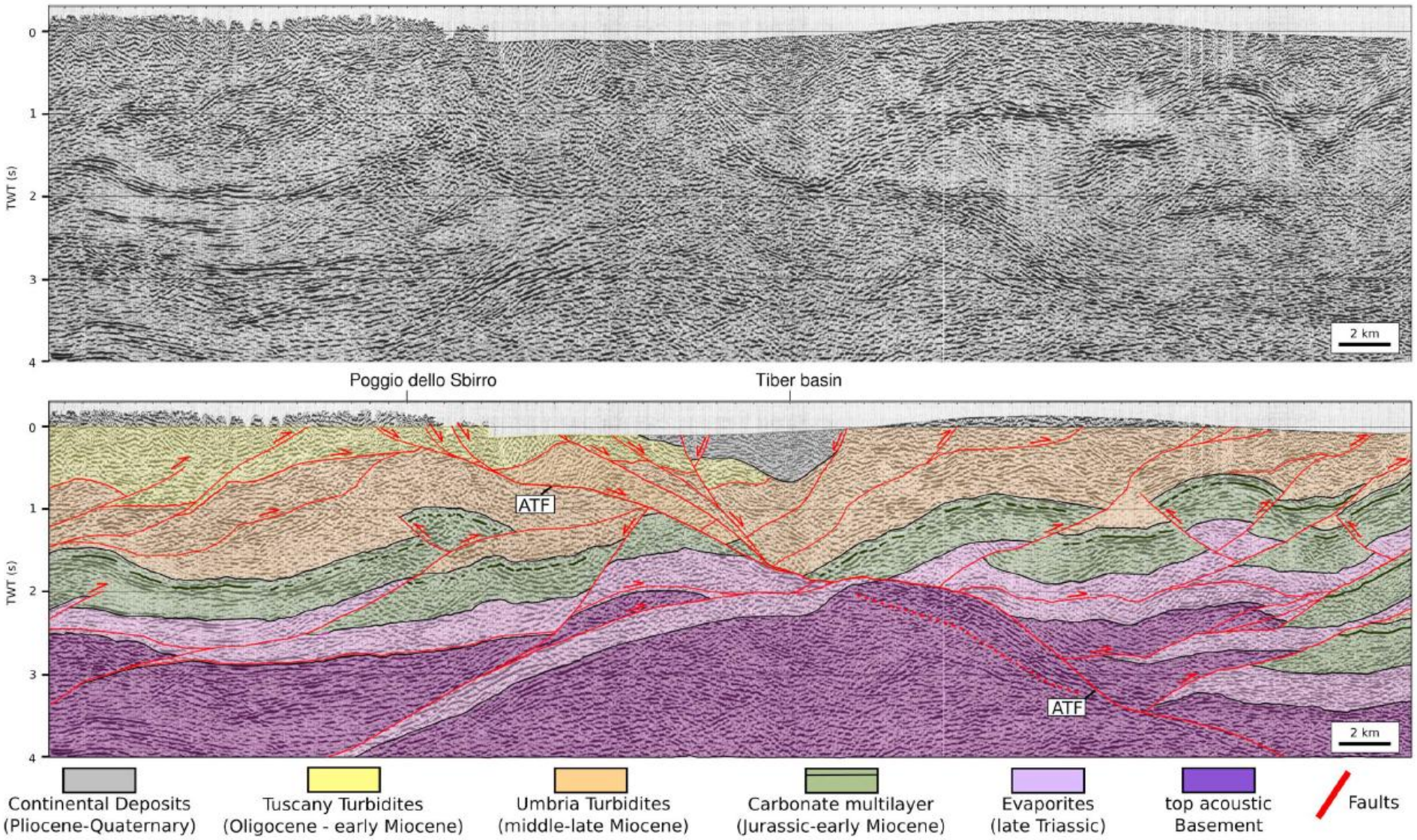


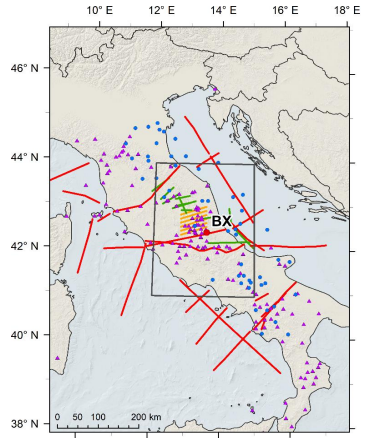
Formation, age and GUESS unit: 53_pozzi.xlsx. Lithology: Petrex composite log (1996), 'Descrizione litologica'. Depths are measured along hole; 0–10 m not logged. MDST/WKST/PKST/GRST: mudstone/wackestone/packstone/grainstone (Dunham).





2-D constraints: one of the 38 cross-sections

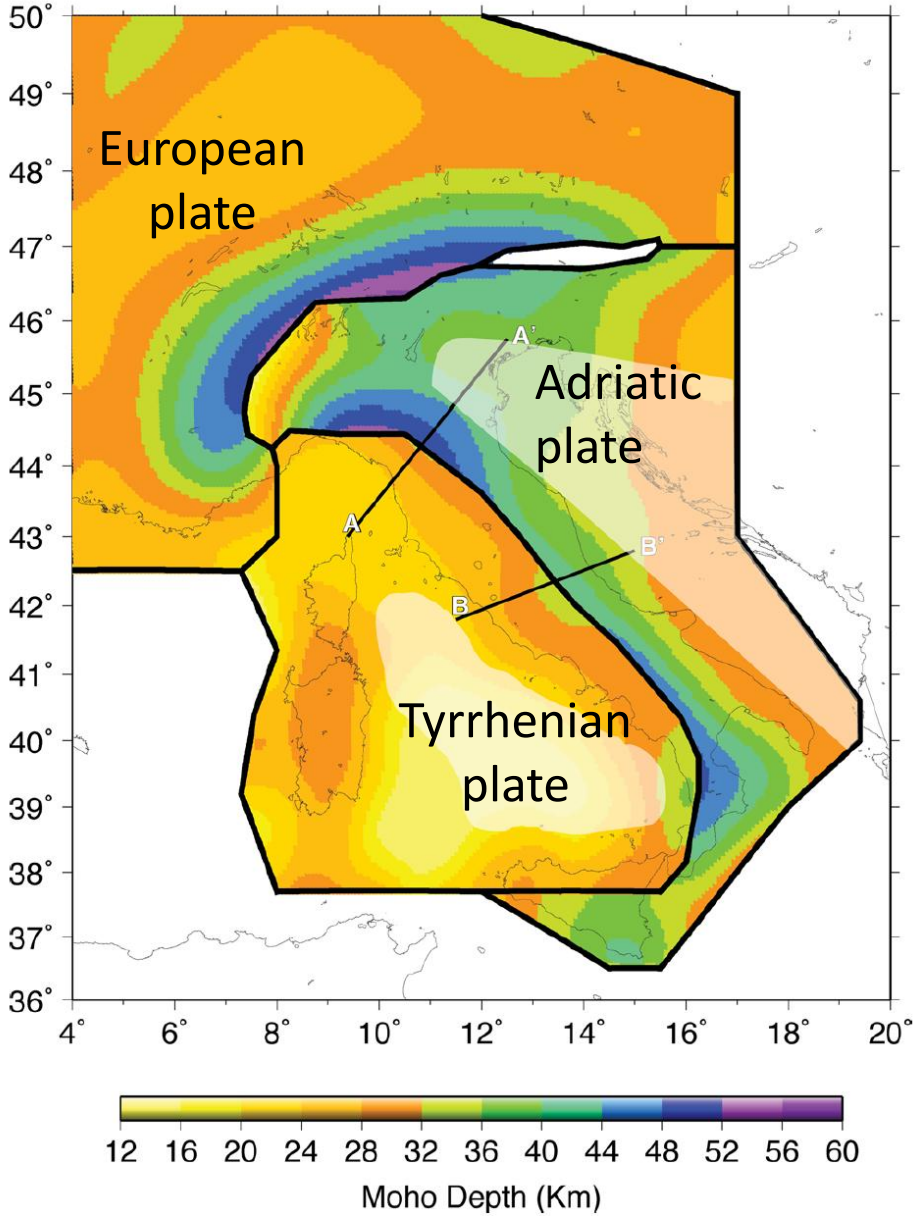




Seismic reflection profile (top) and its geological interpretation (bottom) across the Altotiberina Fault (ATF). The contacts between GUESS units are digitized and georeferenced.

Mirabella et al. (2011), Tectonics, 30, TC6002

3-D constraint: Moho depth map



- Spada et al. (2013) combined controlled-source seismology and receiver functions into a 3-D Moho topography for Italy.
- Three Moho surfaces, European, Adriatic, Tyrrhenian: 12–30 km below the Tyrrhenian side, 30–44 km below the Adriatic foreland. Used on a 2 km grid, 25% uncertainty.
- Independent check: 154 receiver-function Moho depths from five studies, each with uncertainty below 20%, constrain the Moho point by point.

Spada et al. (2013), Geophys. J. Int., 194, 1050–1068

Methodology: Bayesian gravimetric inversion

$$P(\boldsymbol{x}|\boldsymbol{y}) \propto \mathcal{L}(\boldsymbol{y}|\boldsymbol{x}) \cdot P(\boldsymbol{x})$$

- $P(\boldsymbol{x}|\boldsymbol{y})$: **Posterior probability**
- $P(\boldsymbol{x})$: **Prior probability**
- $\boldsymbol{x} = [\boldsymbol{\rho}, \boldsymbol{L}]$ vector of model parameters, **densities** and **labels** (i.e. units)
- $\mathcal{L}(\boldsymbol{y}|\boldsymbol{x})$: **Likelihood probability distribution**
- $\boldsymbol{y}$: vector of **observed gravity data**

Observed gravity: measurements at ground stations are merged with the XGM2019e global model (satellite data) and interpolated on a regular 4 × 4 km grid, with an error standard deviation of a few mGal.

Output: about 1000 refinement inversions give each voxel its modal unit label and mean density, with their variability as uncertainty. The observed gravity field is fitted with a residual standard deviation of 5.7 mGal, 10 times better than the a priori model.

Prior model
wells, cross-sections, Moho, prior densities

↓

Observed gravity
ground and satellite gravity (XGM2019e), 4 km grid

↓

Maximum A Posteriori inversion
Simulated annealing with a Gibbs sampler

↓

Model calibration
~2200 inversions, 3 values per parameter

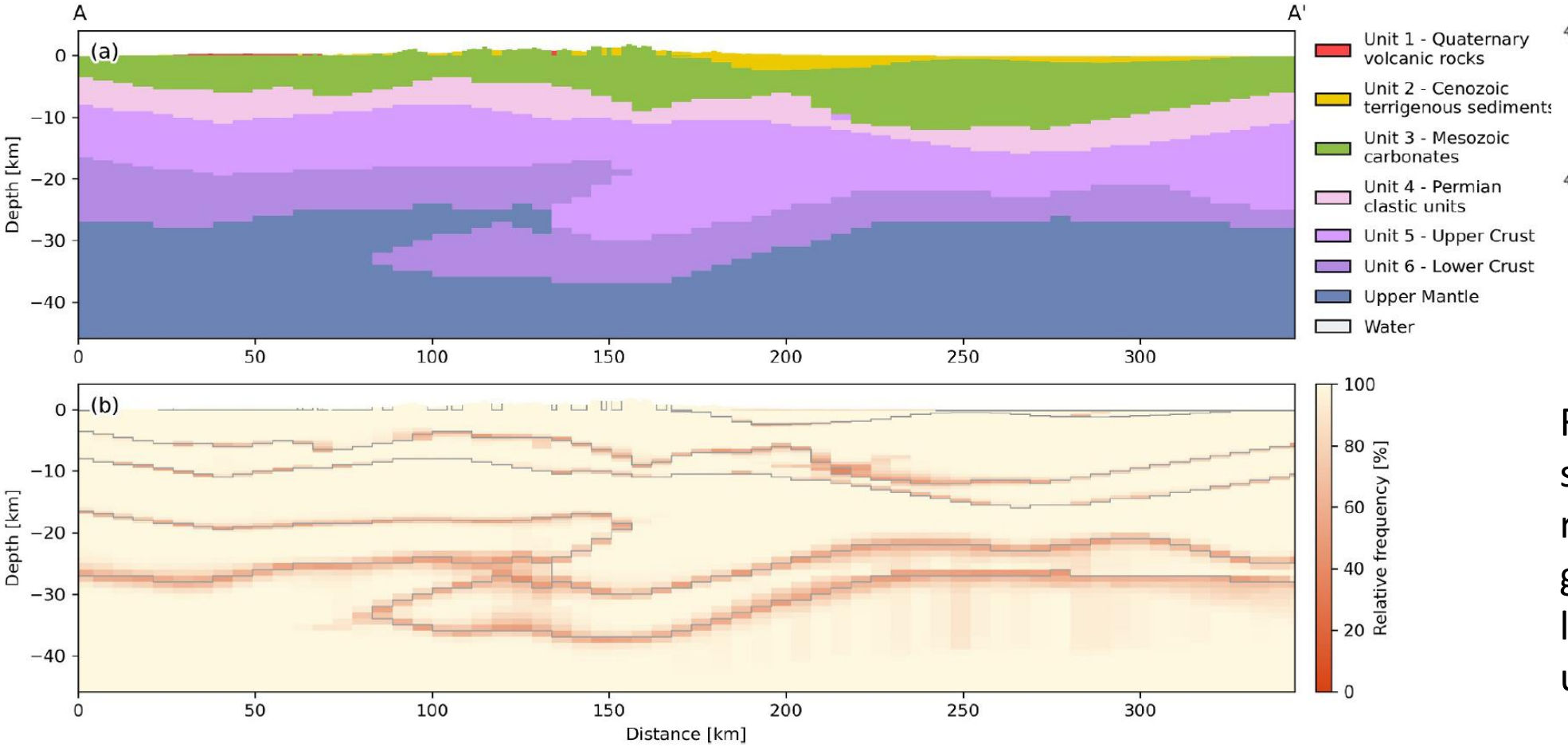
↓

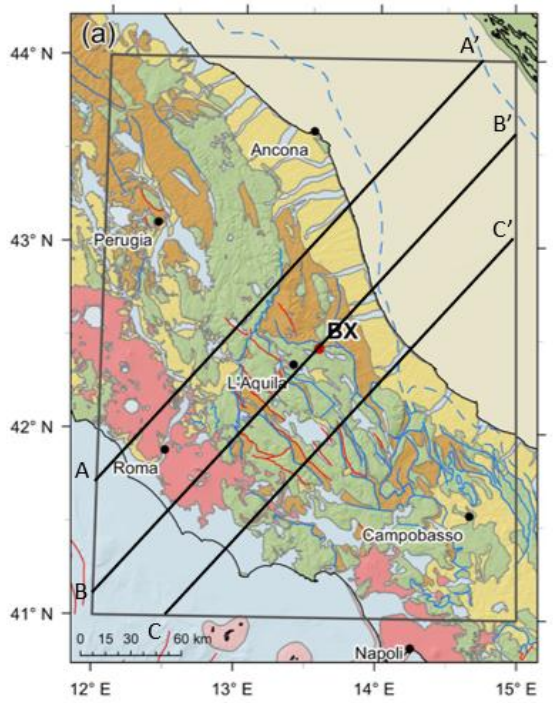
Selection & refinement
< 6 mGal, 12 clusters, 3 best: ~1000 inversions

↓

Posterior GUESS model
most frequent label + mean density per voxel

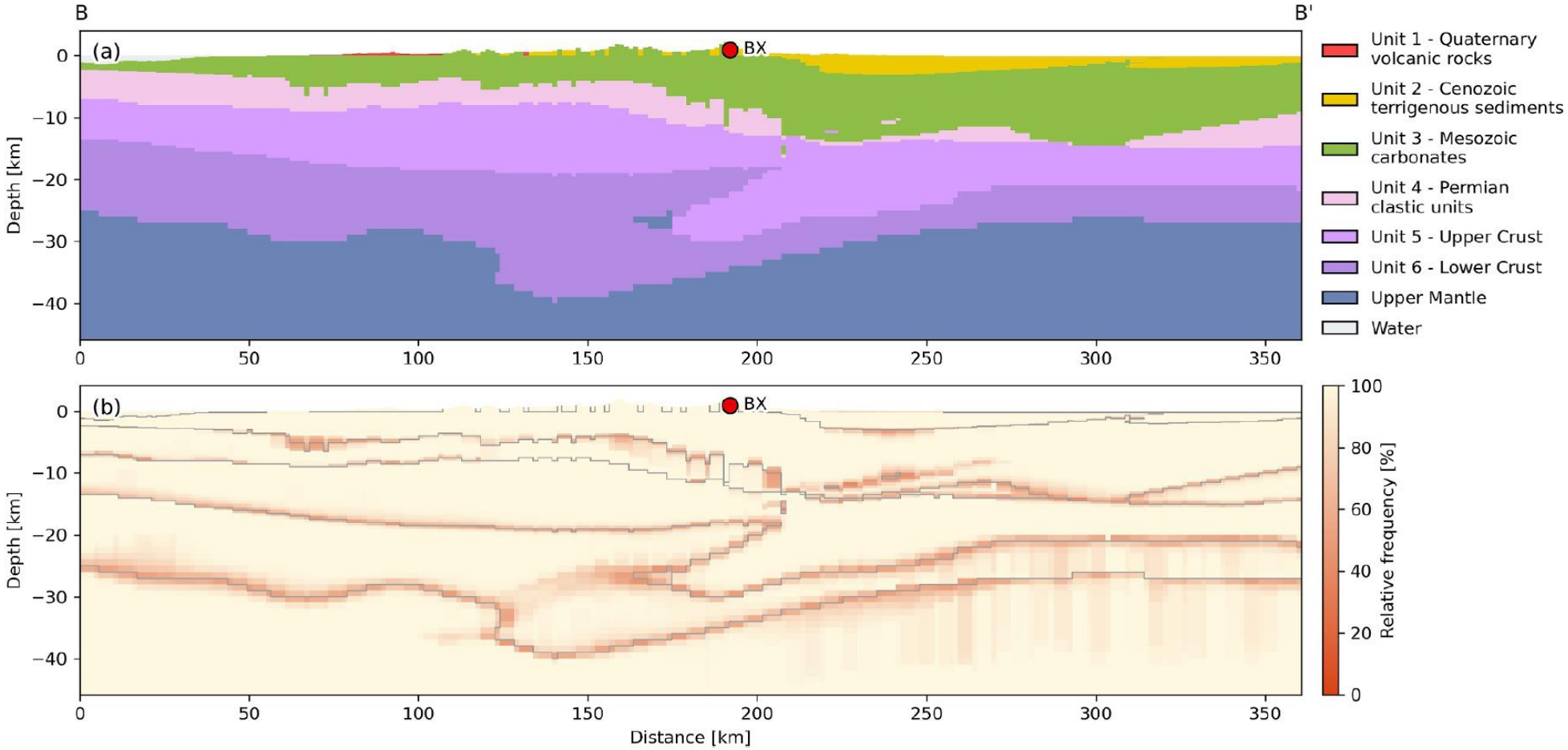
Virtual cross-section AA'

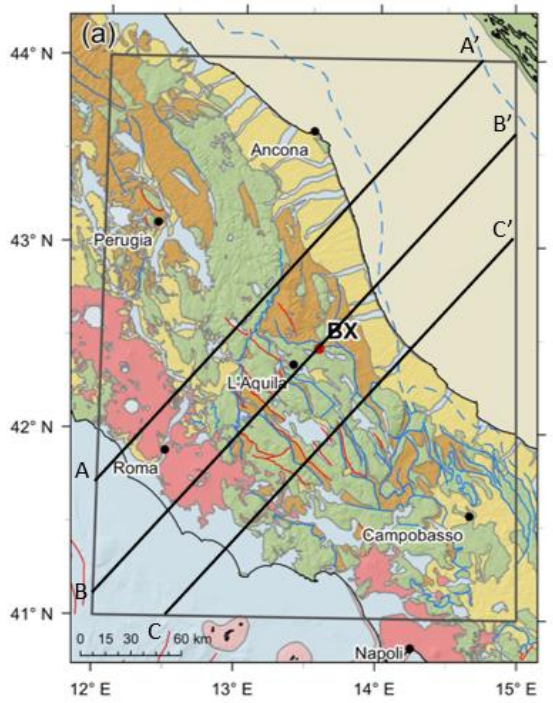




Relative frequency: share of the 1000 refinement inversions giving a voxel its final label. Low values mark uncertain boundaries.

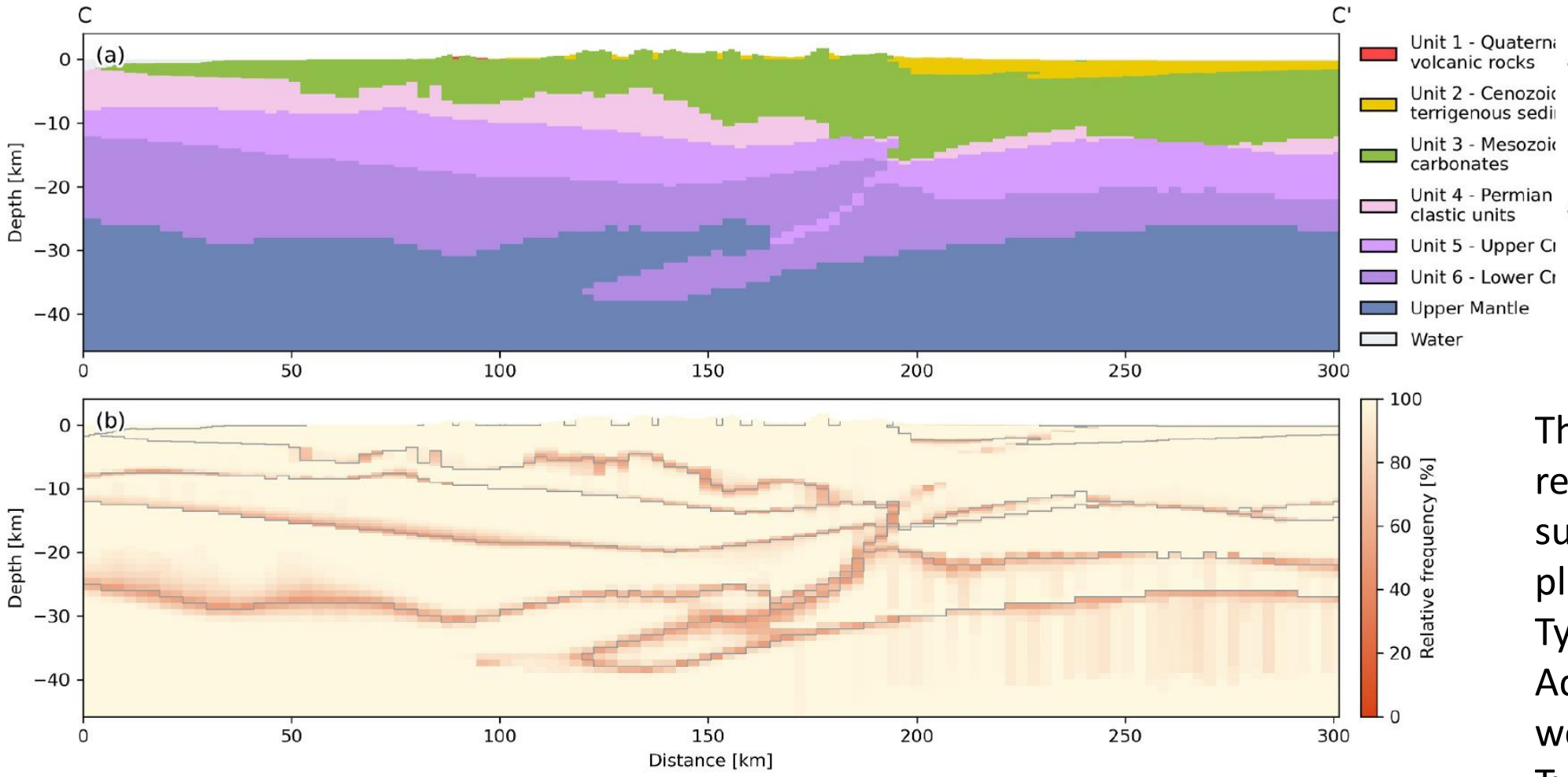
Virtual cross-section BB'

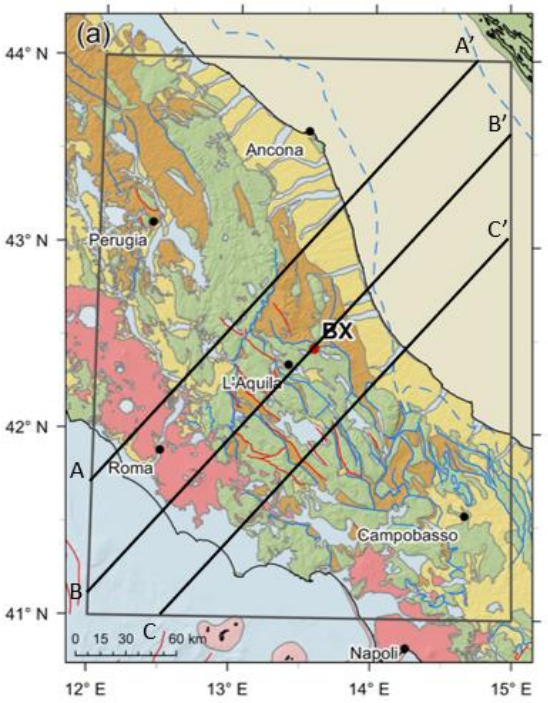




Voxels: 4 × 4 × 0.1 km, from sea level down to 50 km depth. For the geoneutrino signal they are refined to 0.1 km.

Virtual cross-section CC'





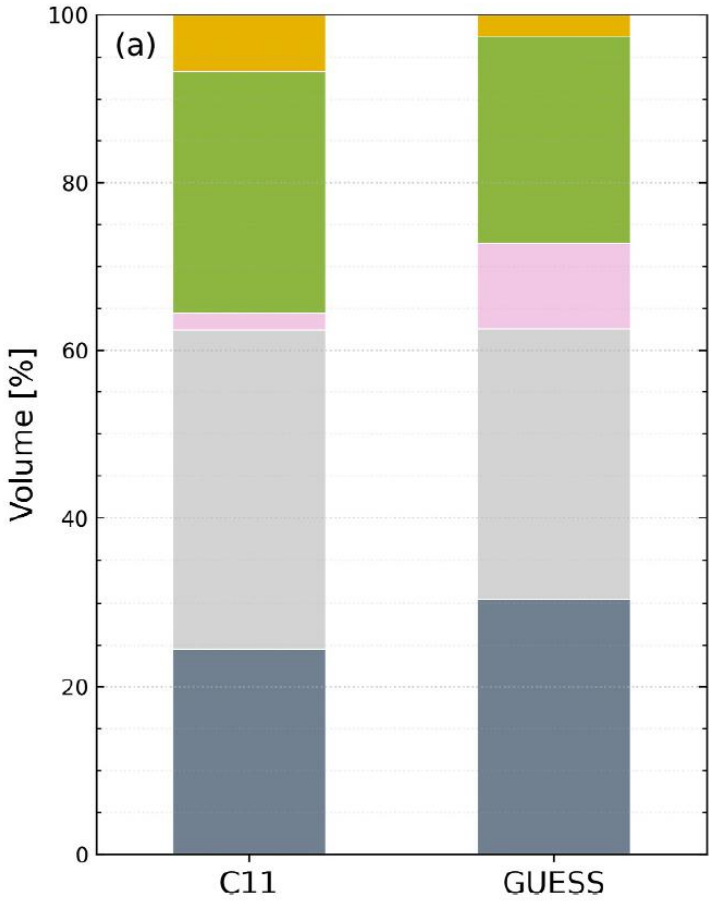
The gravity inversion reconstructs the subduction of the Adria plate below the Tyrrhenian one: the Adriatic crust deepens westward beneath the Tyrrhenian Moho.

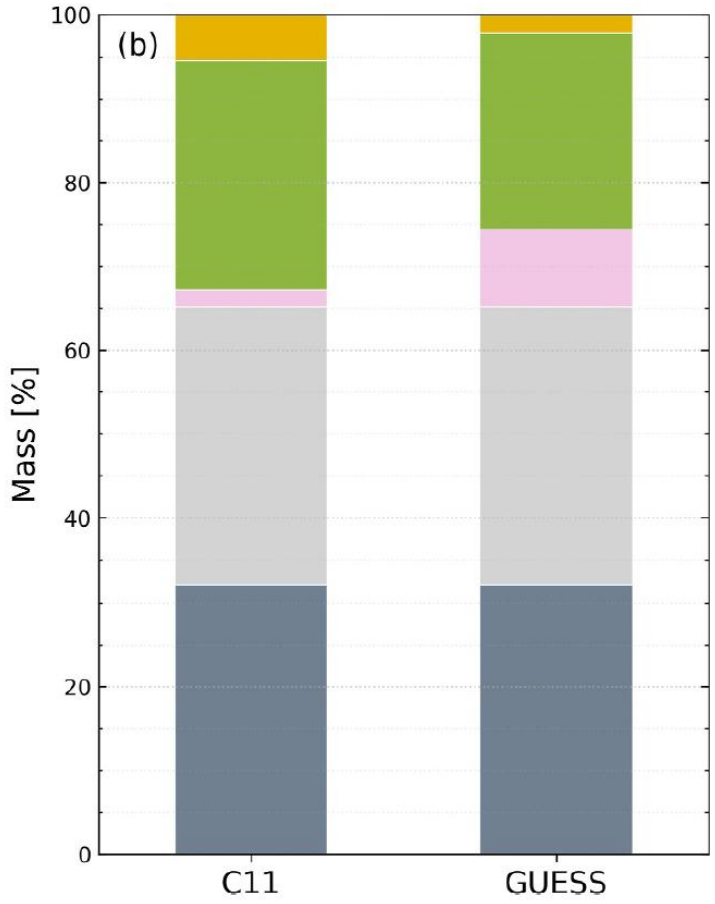
Results: geometry, masses & uncertainty

Unit	Volume [10^3 km^3]	Mass [10^{15} kg]	Density [kg/m^3]
1 – Quaternary volcanics	1.2	2.2	1801
2 – Cenozoic terrigenous sediments	55.8 ± 1.4	130.2 ± 3.3	2332 ± 83
3 – Mesozoic carbonates	585.1 ± 3.9	1533.8 ± 10.5	2621 ± 25
4 – Permian-Triassic succession	285.1 ± 4.9	724.0 ± 12.6	2539 ± 62
5 – Upper Crust	795.7 ± 8.2	2244.7 ± 23.4	2821 ± 41
6 – Lower Crust	737.0 ± 15.3	2150.2 ± 45.4	2918 ± 86

- The Lower Crust has the largest uncertainty, 2.1% on both volume and mass, reflecting the limited direct seismic constraint at depth and the geodynamic complexity of the Adria subduction.
- The Mesozoic carbonates (23.8% of the volume) form a well-constrained reservoir, with 0.7% relative uncertainty, consistent with the structural homogeneity of the Apennine carbonate platform.

Coltorti et al. 2011 vs GUESS 2026





- Unit 2 – Cenozoic terrigenous sediments
- Unit 3 – Mesozoic carbonates
- Unit 4 – Permian-Triassic succession
- Unit 5 – Upper Crust
- Unit 6 – Lower Crust

Validation & impact on the geoneutrino signal

- Posterior densities are validated against three independent data sets, none of which enters the prior (normalized deviation|Z| < 2).
- Sonic logs of 18 wells: average relative misfit of 1.9% for Unit 2 and 1.5% for Unit 3.
- G(U) and G(Th) are unitary signals (aU = aTh = 1 µg/g): the geophysical contribution to the predicted signal.
- Uncertainty on G: standard deviation over the 1000 refinement inversions.

Unit 2

Cenozoic terrigenous

1.9 %

relative misfit

GUESS: 2329 ± 18 kg/m³

Sonic logs: 2375 ± 72 kg/m³

Unit 3

Mesozoic carbonates

1.5 %

relative misfit

GUESS: 2629 ± 28 kg/m³

Sonic logs: 2669 ± 87 kg/m³

Unit	Description	G(U) [TNU]	G(Th) [TNU]
1	Quaternary volcanics	7.22×10^{-4}	4.89×10^{-5}
2	Cenozoic terrigenous sediments	0.17 ± 0.01	0.012 ± 0.001
3	Mesozoic carbonates	2.93 ± 0.02	0.201 ± 0.001
4	Permian-Triassic succession	0.49 ± 0.02	0.034 ± 0.001
5	Upper Crust	1.36 ± 0.02	0.095 ± 0.001
6	Lower Crust	1.20 ± 0.03	0.086 ± 0.001

1 – 3 %

structural uncertainty on G, major units (3, 5, 6)

Conclusions & perspectives

- GUESS is a new **3-D probabilistic crustal model** of the Gran Sasso region: 4 × 4 × 0.1 km voxels down to 50 km, with voxel-wise uncertainty.
- Wells, cross-sections, Moho constraints and gravity are fused by Bayesian inversion; posterior densities pass three **independent benchmarks**.
- The structural uncertainty on the geoneutrino signal is 1–3% for the major units, an order of magnitude below the typical uncertainty on U and Th abundances.
- Next: combining GUESS with local U and Th data to predict the absolute Borexino geoneutrino signal, isolating the mantle contribution and constraining Earth's deep radiogenic heat production.

Paper and model data are freely available at: www.fe.infn.it/radioactivity/GUESS/

Thank you

