Crustal composition of the Porcupine Basin from thermodynamically constrained joint inversion of seismic refraction, surface elevation and gravity data
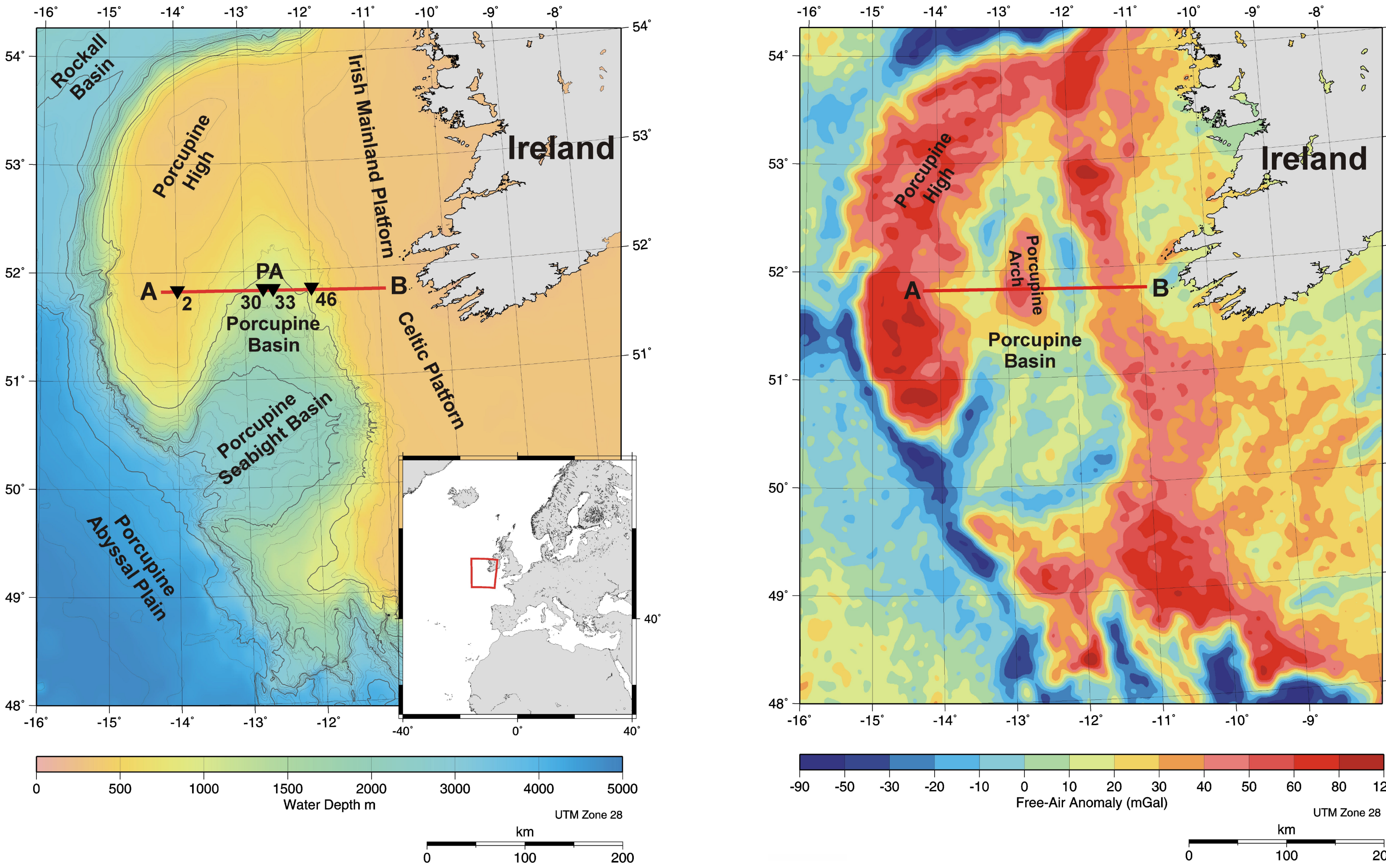
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Summary

Information on the composition of the crystalline crust and the uppermost mantle is crucial for understanding the tectono-magmatic processes involved in the formation of the Porcupine Basin. We infer this information by probabilistic joint inversion of seismic traveltimes, surface elevation and gravity data. The unknowns of the inverse problem are the proportions of metastable mineral phases within the crust, geometry of the Moho, interfaces between different petrologies and serpentinite content in the uppermost mantle. For a given petrology, elastic moduli and density of the composite are computed as functions of pressure and temperature; the temperature is found as numerical solution of the 3D steady-state heat equation. This petrological forward problem provides seismic velocities and density distributions on finite-difference mesh, which are used to predict seismic traveltimes, gravity anomaly and surface elevation. A Markov chain Monte Carlo algorithm is used to sample the posterior probability density function of the model parameters.
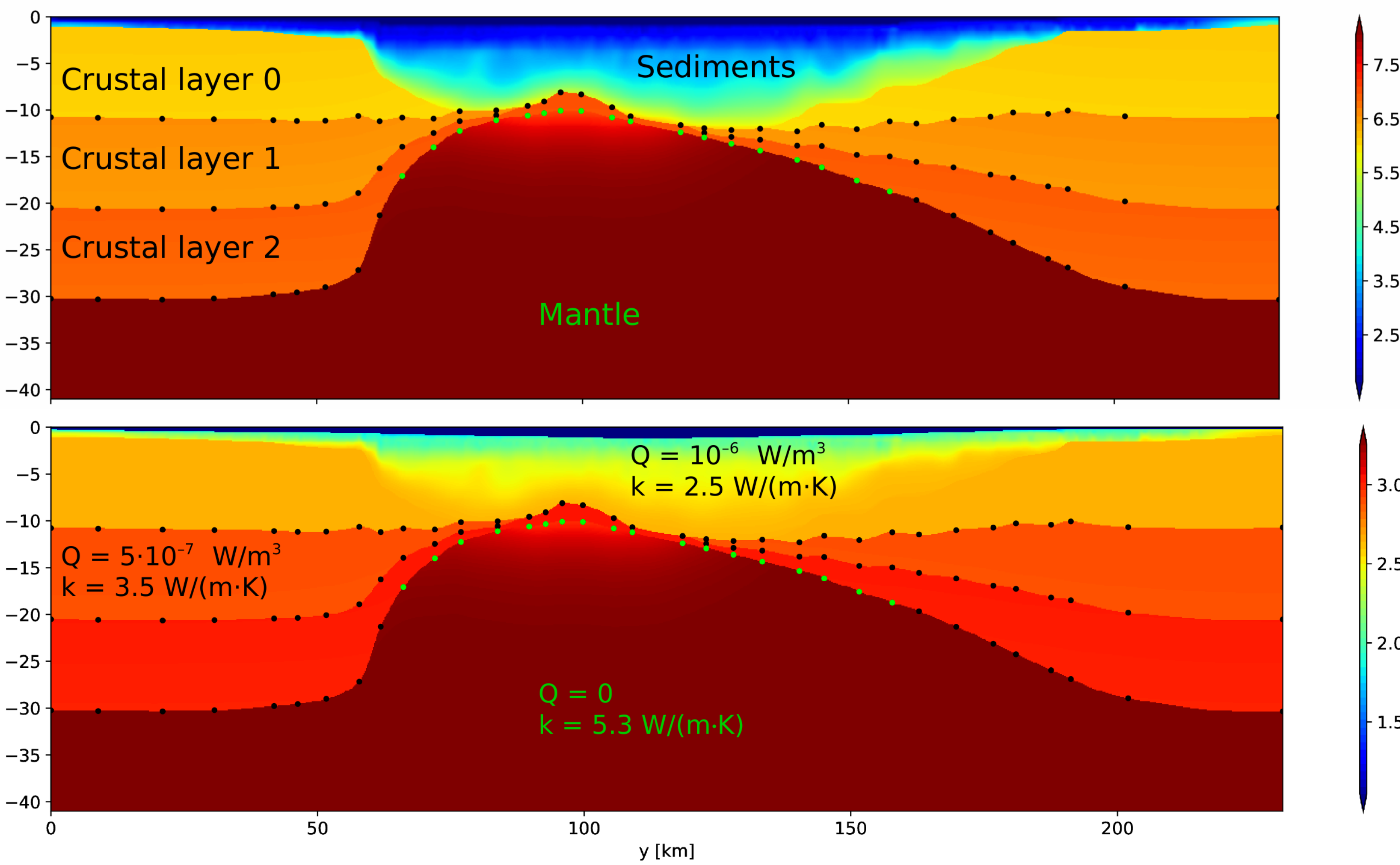
Our goal is to apply this methodology to inversion of the RAPIDS4 wide-angle seismic data, free-air gravity anomaly from satellite altimetry and bathymetric data. Here, we present the results of the first stage of the project – inversion of synthetic data simulating real RAPIDS4 experiment.

RAPIDS4 profile

Geographical position of the Leg 4 of the Rockall and Porcupine Irish Deep Seismic (RAPIDS4) wide-angle seismic experiment on bathymetry and satellite free-air gravity anomaly maps [O'Reilly et al., 2006]. The data were acquired in 2002 with 65 ocean-bottom seismometers. First arrivals are detectable at the offsets up to ~100 km.
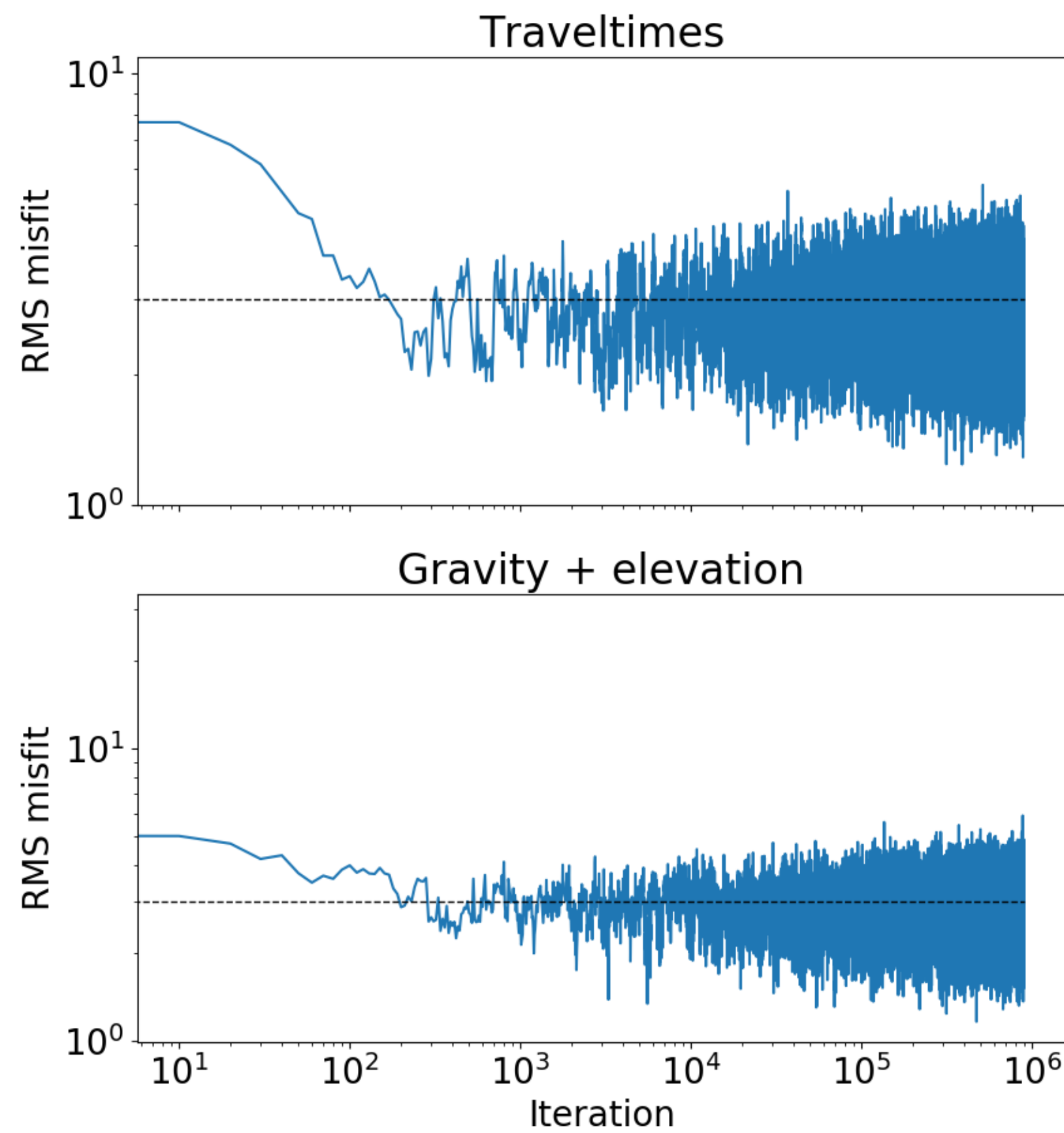
Synthetic model

	Crustal layer 0		Crustal layer 1		Crustal layer 2
Phase	**Vol.%**	**Phase**	**Vol.%**	**Phase**	**Vol.%**
Opx	0.49 2.22±2.03	Opx	16.73 4.77±4.34	Opx	21.61 7.83±6.95
Fsp	39.98 27.89±15.91	Fsp	4.22 28.68±18.45	Fsp	6.91 15.42±11.41
Fsp	8.10 15.49±12.20	Fsp	8.40 19.55±15.73	Fsp	0.37 18.33±13.40
Cpx	0.51 2.11±1.83	Fsp	47.19 22.00±16.95	Fsp	47.40 15.16±11.78
Bio	9.74 9.24±6.96	Cpx	8.56 8.04±6.20	Sp	2.99 11.50±8.10
q	41.18 43.06±18.33	Bio	6.15 5.43±4.76	Cpx	20.71 31.75±16.12
		q	8.75 11.54±10.38		
Oxide	**Mol.%**	**Oxide**	**Mol.%**	**Oxide**	**Mol.%**
H_2O	0.34	H_2O	0.36	H_2O	0.00
Al_2O_3	2.76	Al_2O_3	7.97	Al_2O_3	10.99
FeO	0.54	FeO	6.20	FeO	11.05
MgO	0.73	MgO	6.24	MgO	10.73
CaO	0.42	CaO	6.94	CaO	10.17
Na_2O	0.39	Na_2O	2.61	Na_2O	2.84
K_2O	2.03	K_2O	0.54	K_2O	0.63
SiO_2	92.79	SiO_2	69.13	SiO_2	53.59

P-wave velocity, density and chemical composition of the crust for the synthetic model. Model geometry and velocity within sediments are based on the forward-modelling interpretation of the RAPIDS4 data [O'Reilly et al., 2006], empirical relation [Prada et al., 2018] was used to predict density of sediments. Crustal composition modified from global models of the Earth's crust [Guerri et al., 2015]. Q is volumetric heat production; k is thermal conductivity. The displayed nodes parameterize geometry of the crustal layers, those highlighted in green also parameterize serpentinite wt% in the mantle. The table shows both the true values and the mean ± standard deviation from the inversion (see next section).
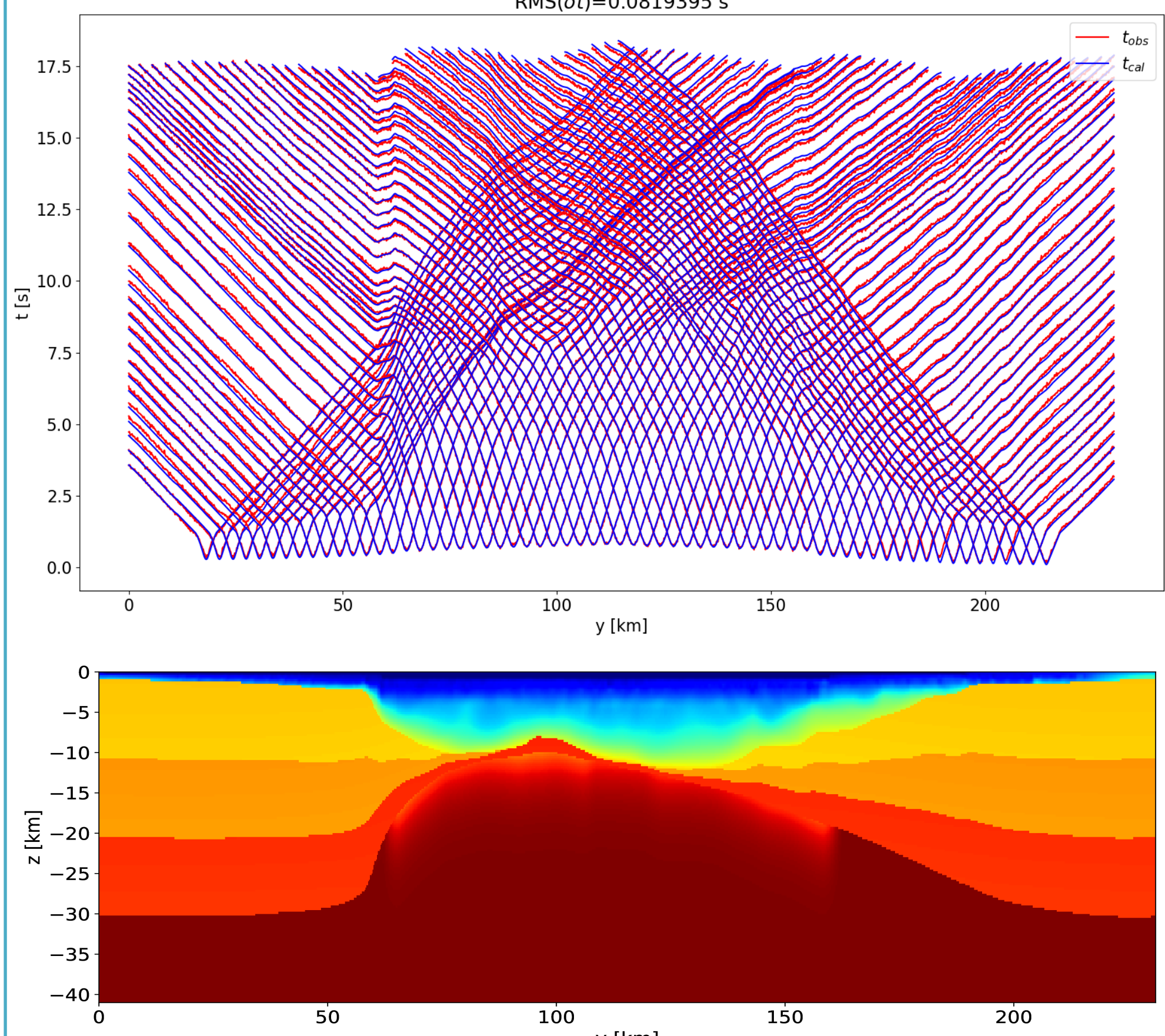
References

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• Guerri, M., Cammarano, F. and Connolly, J.A., 2015. Effects of chemical composition, water and temperature on physical properties of continental crust. Geochemistry, Geophysics, Geosystems, 16(7), pp.2431-2449.
• Prada, M., et al., 2018. Across-axis variations in petrophysical properties of the North Porcupine Basin, offshore Ireland: New insights from long-streamer traveltime tomography. Basin Research.
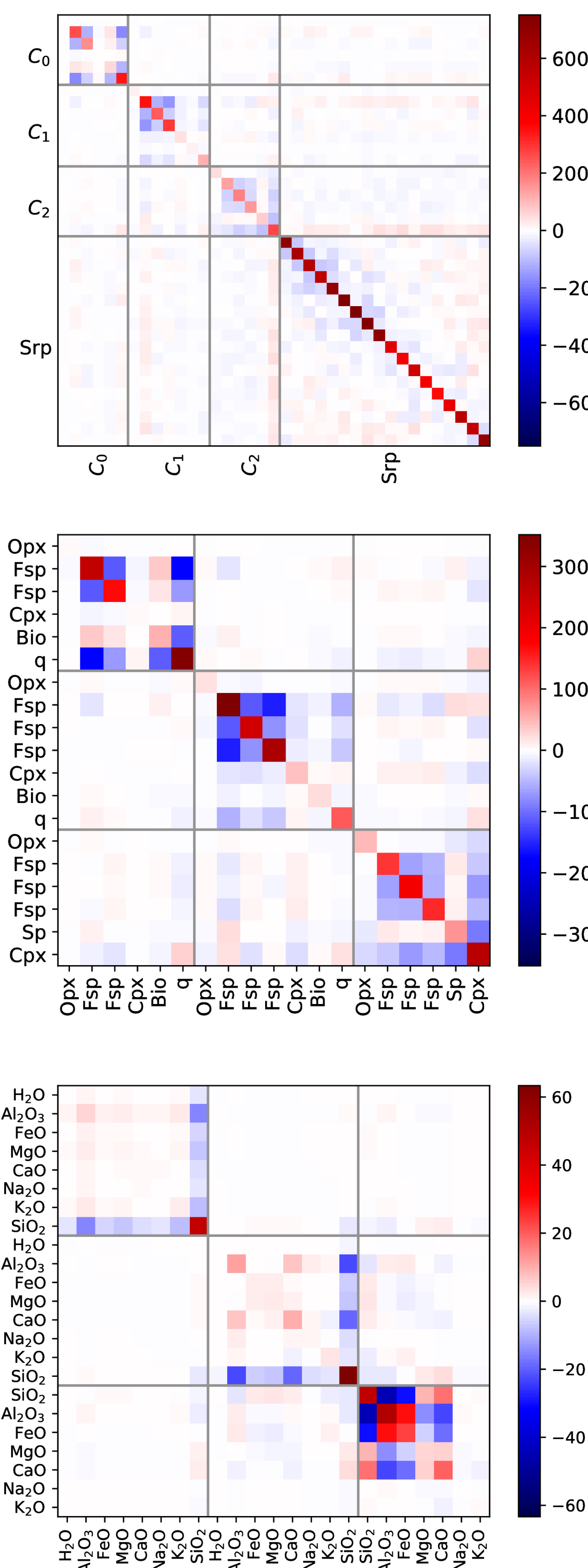
Inversion for composition with geometry fixed to the true values

RMS data misfits along the Markov chain. Only the samples with average RMS below 3 (dashed line) were considered for the statistical analysis.
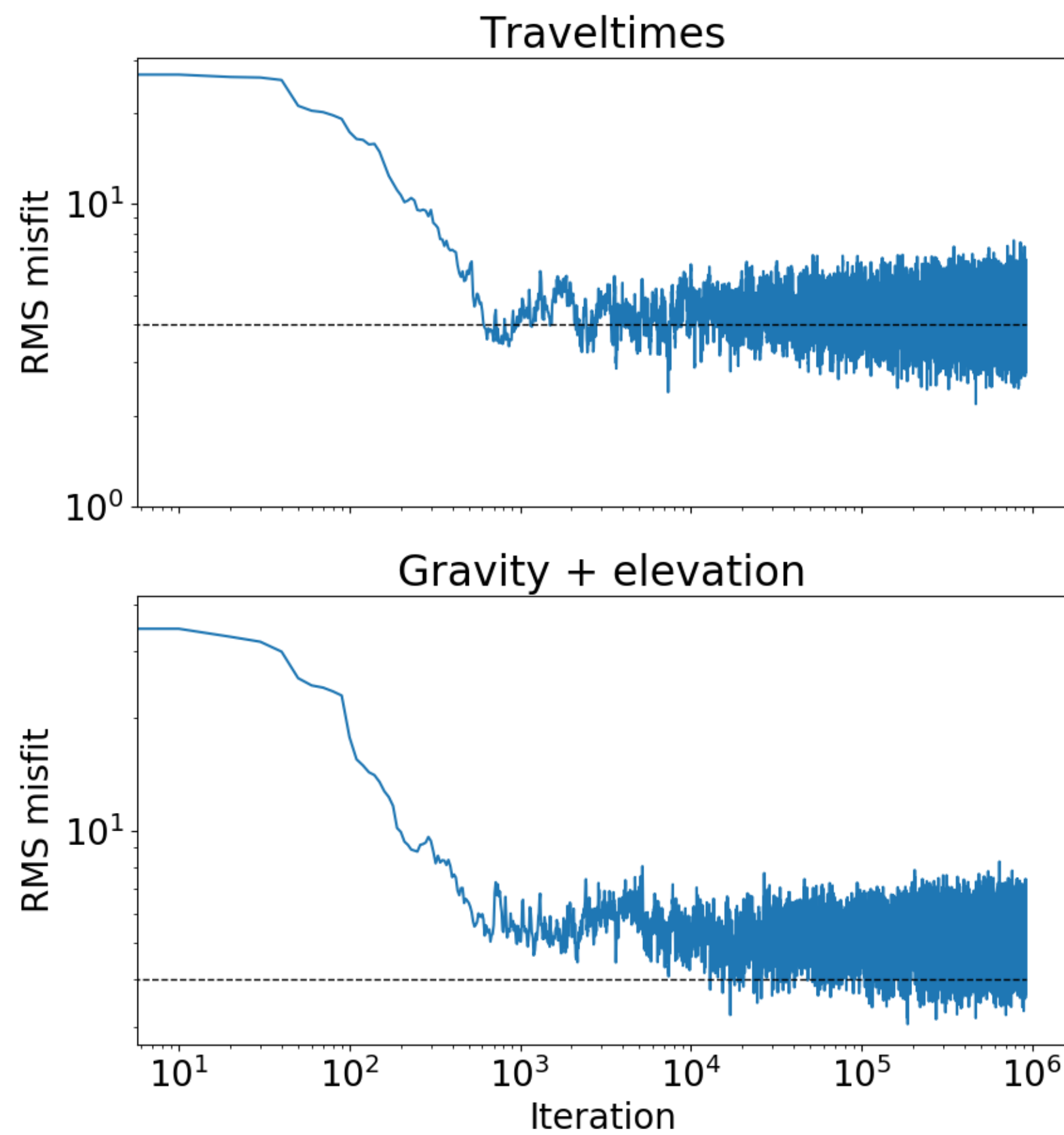

P-wave velocity and calculated vs 'observed' traveltimes for the mean model (see the table).
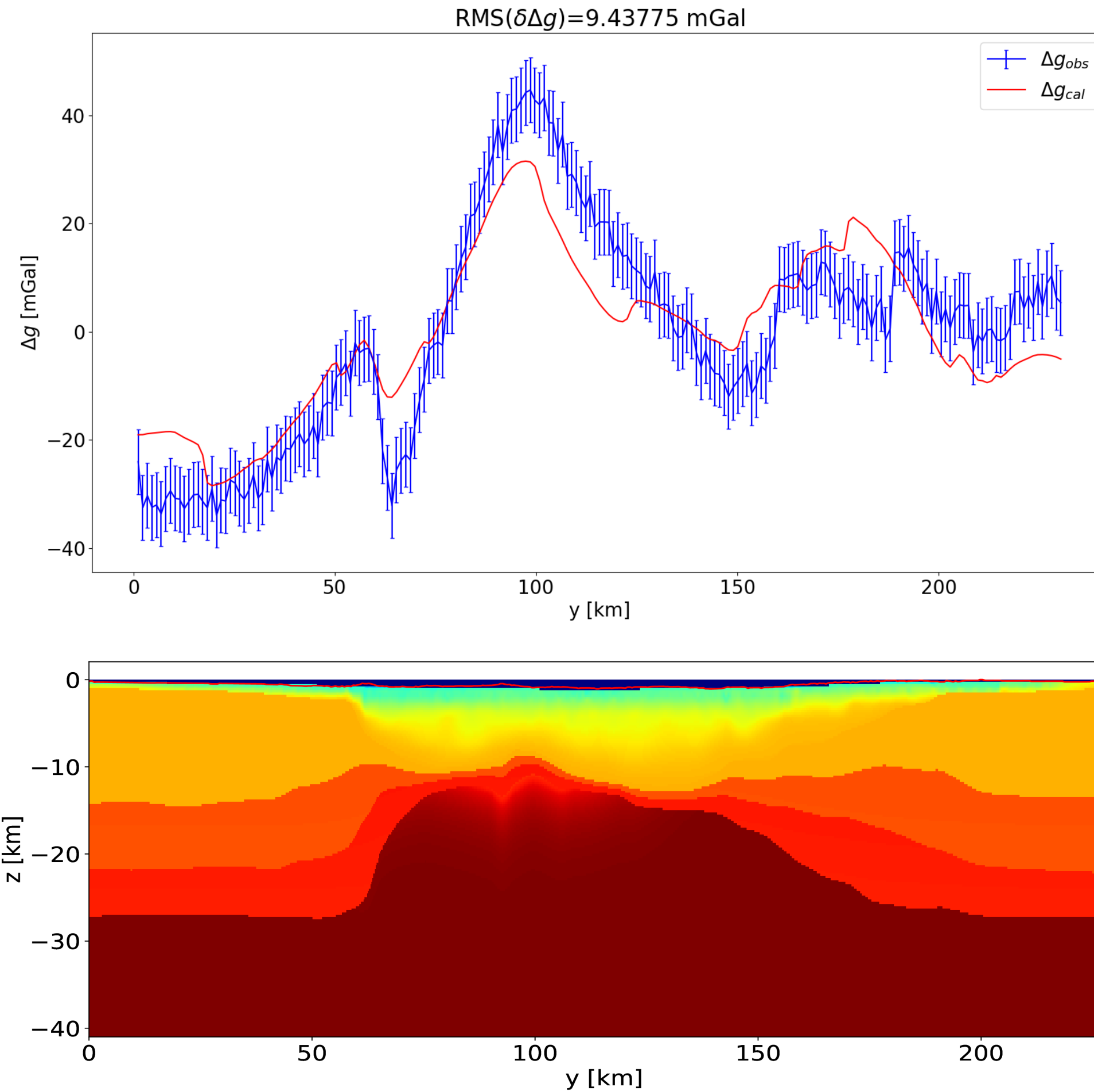

Posterior covariance matrices for the whole composition vector (C_{0-2} denote crustal layers, Srp – serpentinization), mineral phases and oxides.
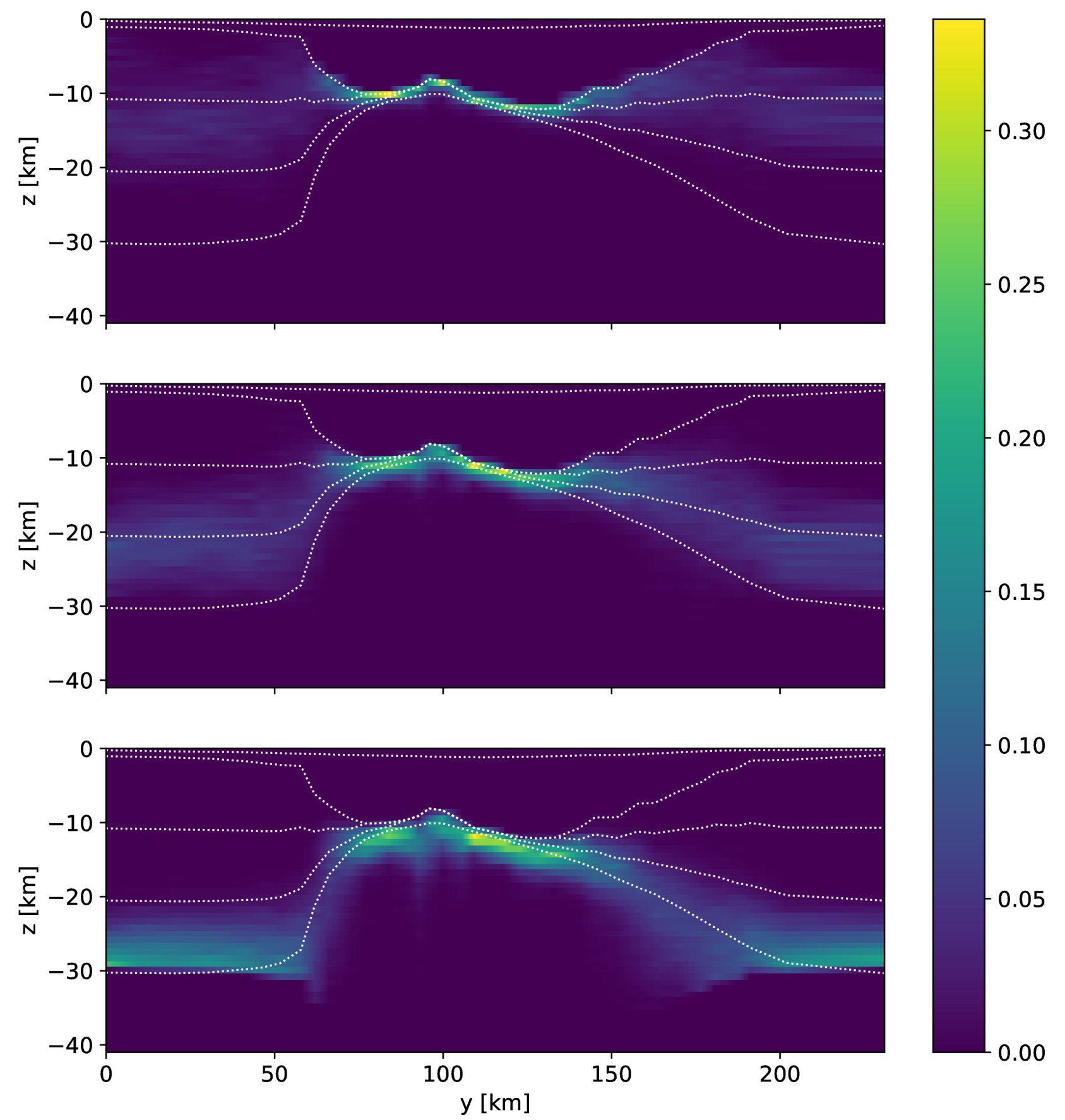
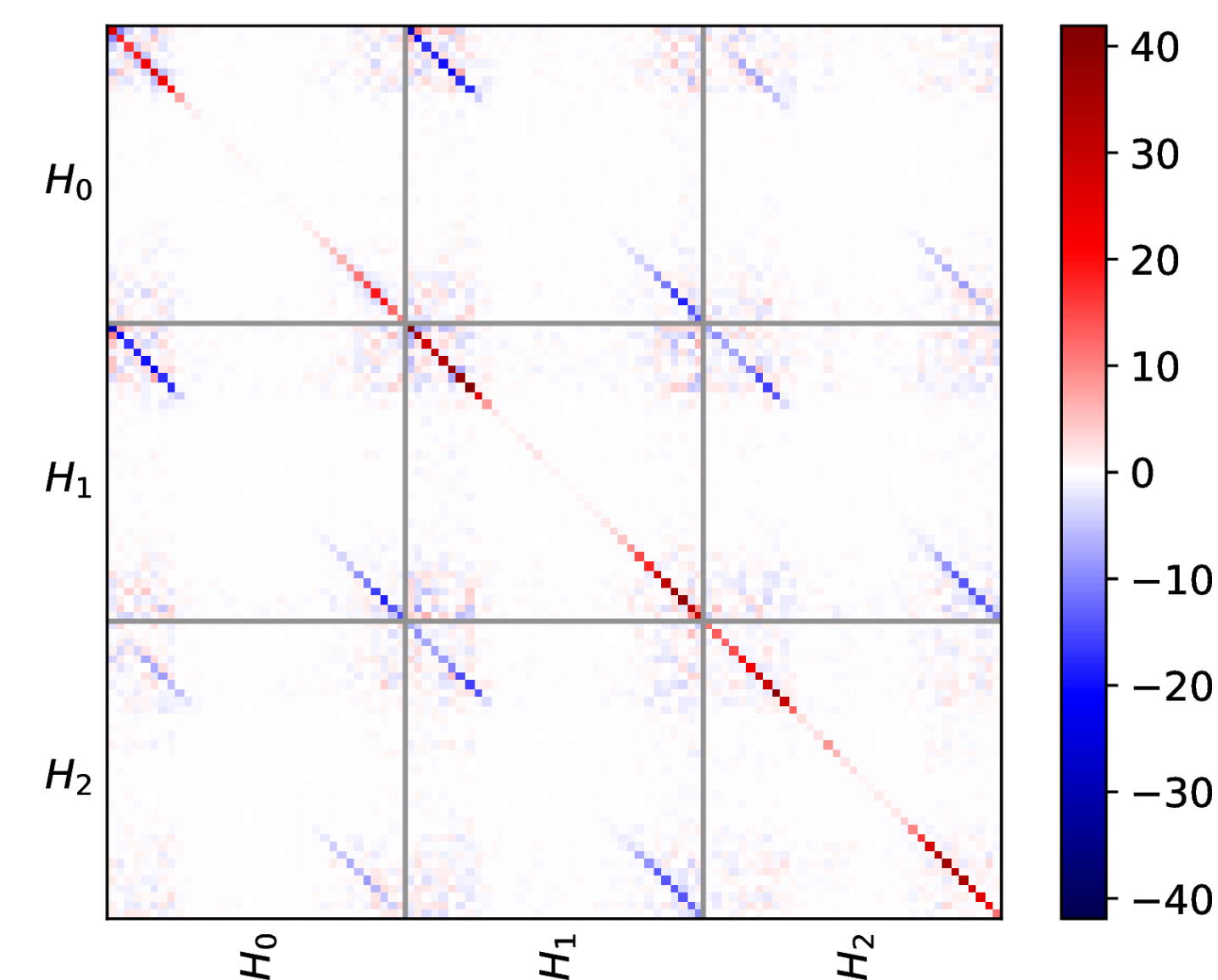## Inversion for geometry with composition fixed to the true values

RMS data misfits along the Markov chain. Only the samples with average RMS below 4 (dashed line) were considered for the statistical analysis.

Posterior PDFs of within-crust boundaries and Moho vs true geometry.

Density, calculated bathymetry (red line) and calculated vs 'observed' free-air gravity anomaly for the mean model.

Posterior covariance matrix of the thicknesses of the crustal layers.

Conclusions and future work

• Even within the subspaces of composition and geometry, the uncertainties and crosstalk between different parameters are very high. The results confirm importance of joint inversion of first arrivals with gravity and elevation data, with the former being relatively more sensitive to composition and the latter two – to geometry of the crust.
• Simultaneous inversion for composition and geometry requires running multiple Markov chains with different random starting models. Varying proposal distributions and acceptance probability with iterations similarly to the simulated annealing may help to improve the data fit.
• Narrowing prior constraints on composition may be needed for inversion of real data.
• Aitchison statistics is required for more informative analysis of compositional data.