Synthetic inversions for density in the Earth's interior from seismic and geodetic data

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Questions? find Nienke

Why density?

In plate tectonics and mantle dynamics, density plays a major role in determining the forcings on the systems. Along with knowledge of local seismic velocities, density can help to determine whether tomographic anomalies are of thermal or compositional nature. However, density has thus far only been studied as an independent parameter on the very largest scales using normal modes. Here we try to answer the question: **how can we image density?**

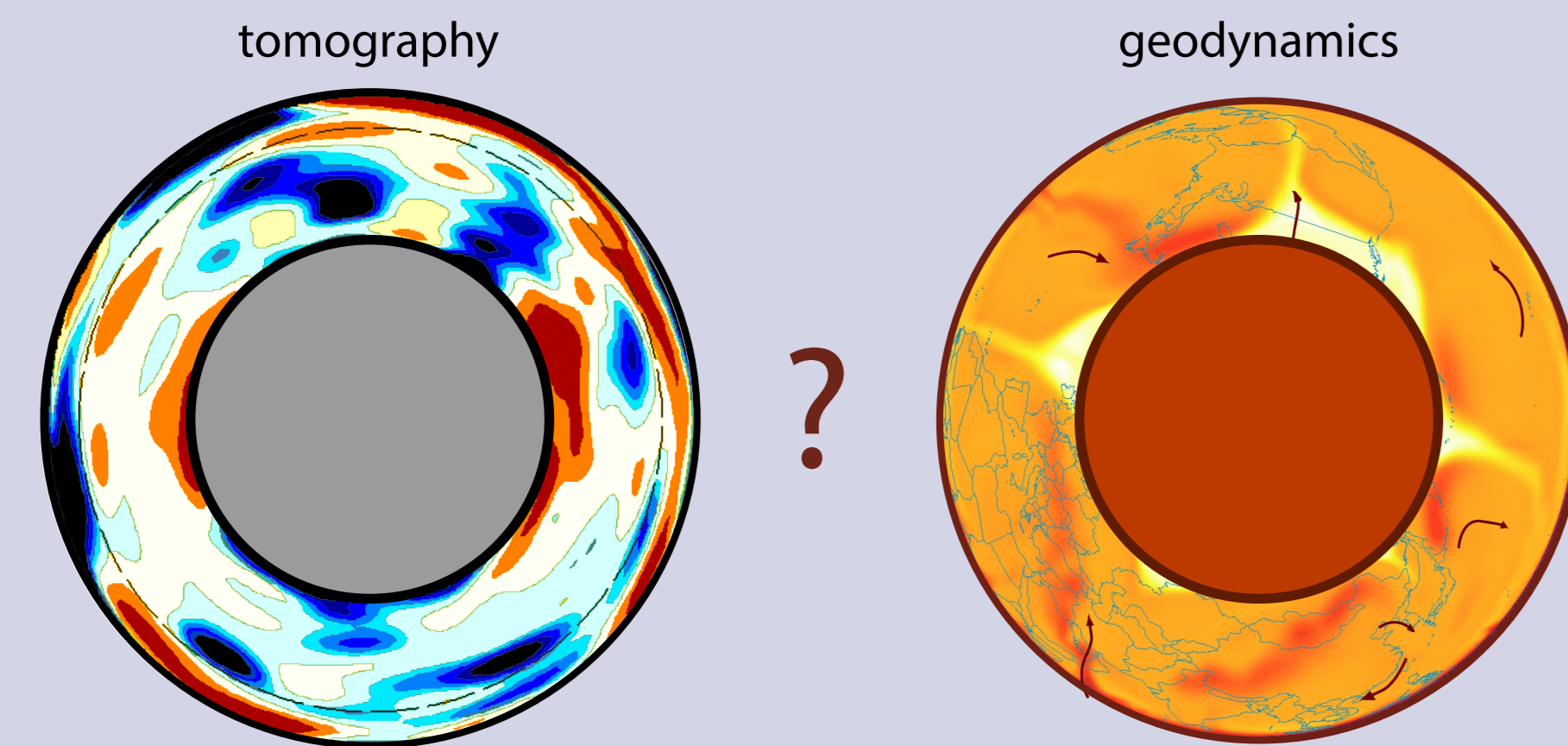tomography   geodynamics   ?

Figure 1. Tomography traditionally images variations in seismic velocities inside the Earth. However, links between tomography and geodynamics are based on assumptions which do not always hold. In order to understand the dynamics of the Earth's interior, it is therefore necessary to image density variations directly.

Methods - synthetic experiments

We perform synthetic experiments where the target model is known. P- and S-wave emitting sources (×) lie at 56 km depth, and receivers (o) are located at the top of the domain. L+R boundaries are absorbing.

target model
density [kg/m³]   S-wave velocity [km/s]   P-wave velocity [km/s]
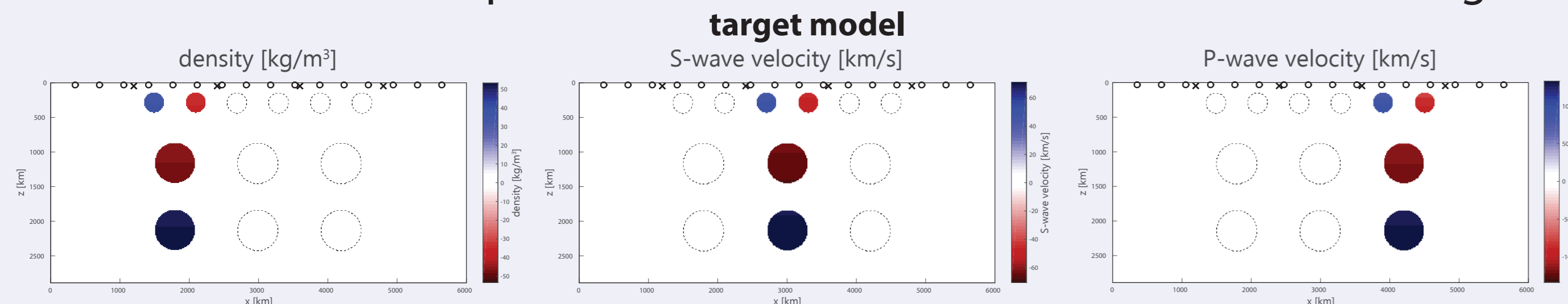
In this target model density, S-velocity and P-velocity are uncorrelated by design. This is because we want to **image density independently** without any prior constraints about its geometry and distribution.

starting model
density [kg/m³]   S-wave velocity [km/s]   P-wave velocity [km/s]
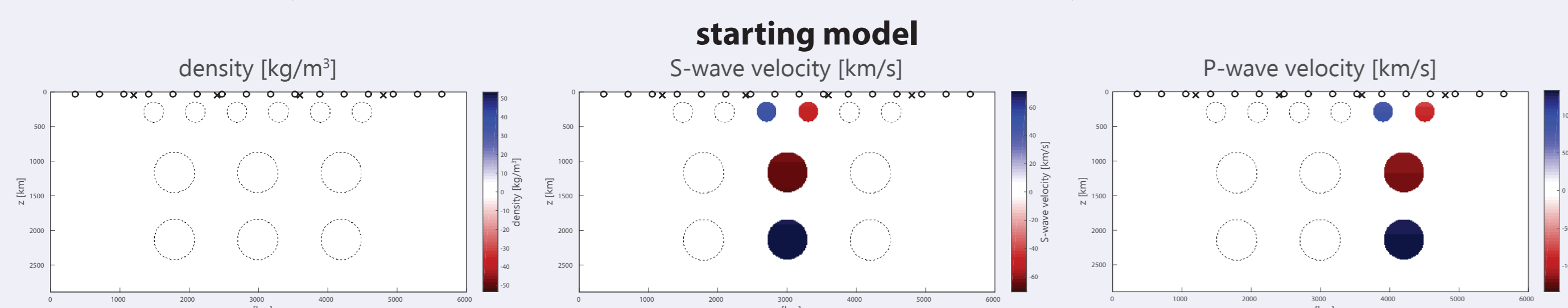
We test the following things:
• What is the effect of including prior information about the seismic velocities inside the model?
• To what extent does gravity information help the recovery of density?

Results - how can we best image density?

It is possible to image density using waveform inversion on a global scale, without the use of normal modes. Best results are obtained with an L-BFGS descent method where the lowest frequencies are inverted for first.

density [kg/m³]

data: *seis + grav*
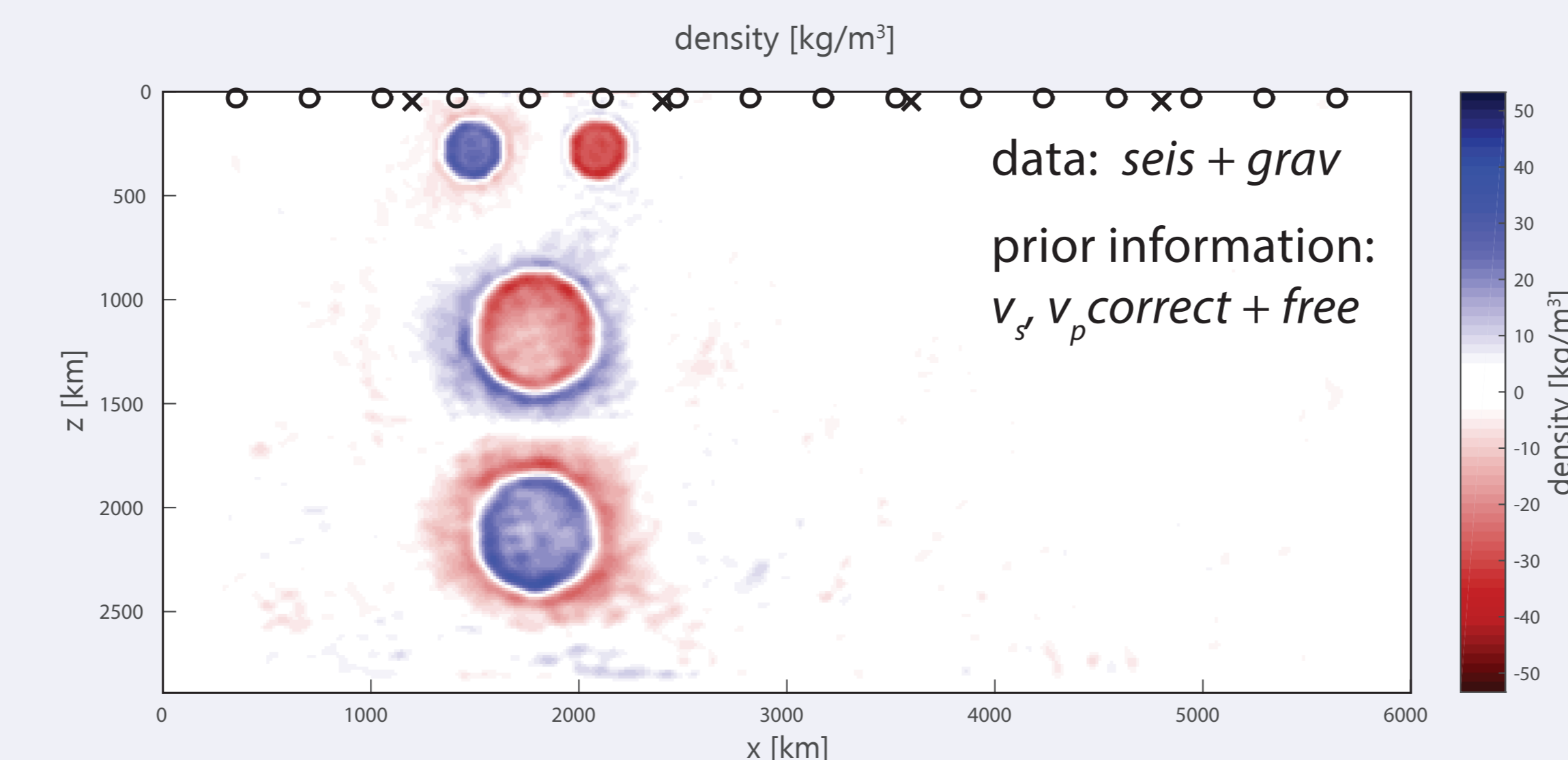
prior information: v_s, v_p correct + free

Figure 2. density result of an inversion run (144 iterations at frequencies increasing every 20 iterations), where the velocities are correct but not fixed.

Can waveform inversion identify density anomalies on a global scale?

Yes. The inversion scheme correctly identifies the waveform differences as being caused by density, with only minor contamination in S- and P-velocity structure. This is without the use of normal modes.

S-wave velocity [km/s]   P-wave velocity [km/s]

Figure 3. S- and P-velocity results only show minor contaminations from density structure

density [kg/m³]

data: *seis + grav*

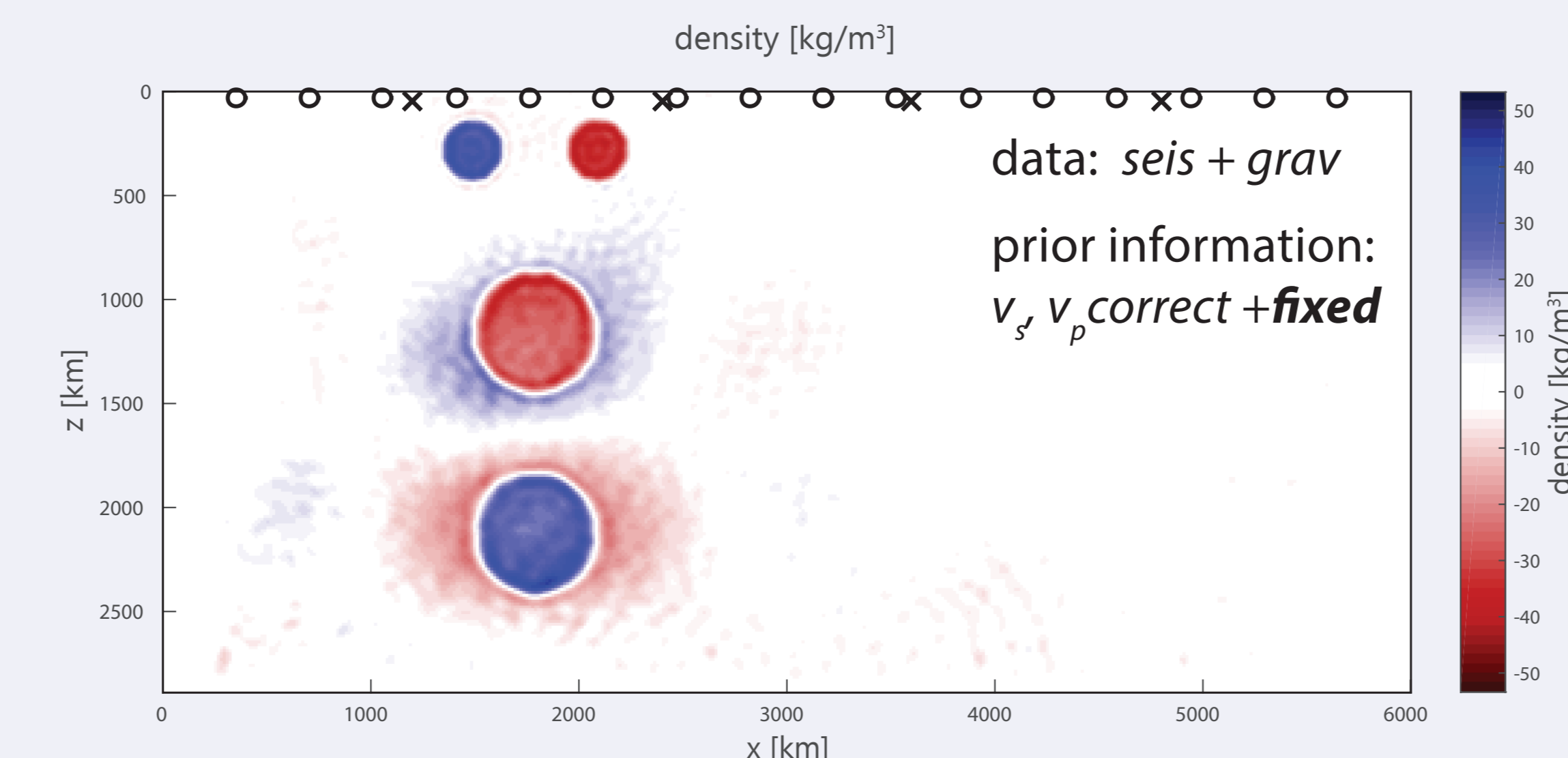prior information: v_s, v_p correct + **fixed**

Figure 4. density result of an inversion run (131 iterations at frequencies increasing every 20 iterations), where the velocities are correct and fixed.
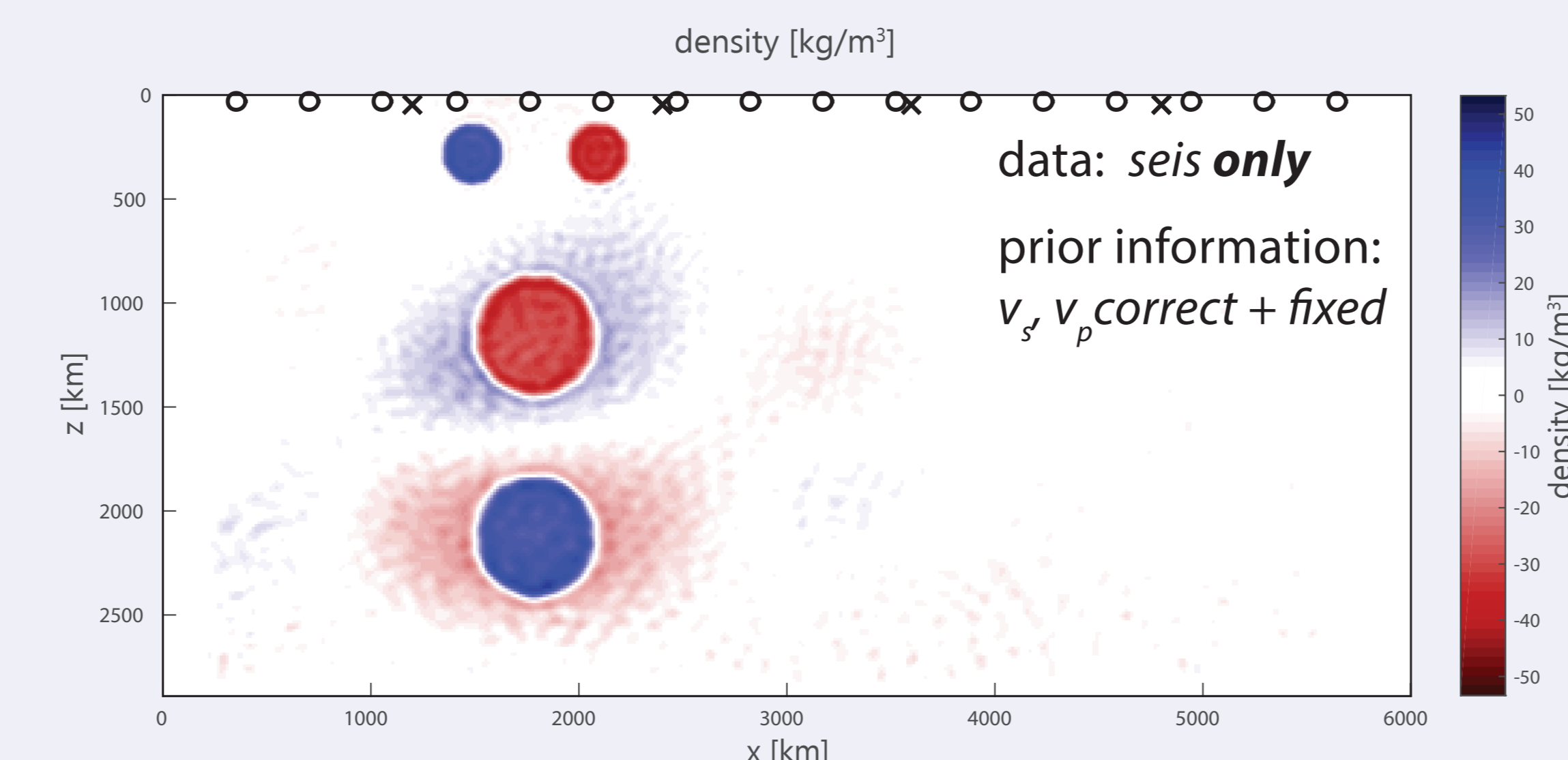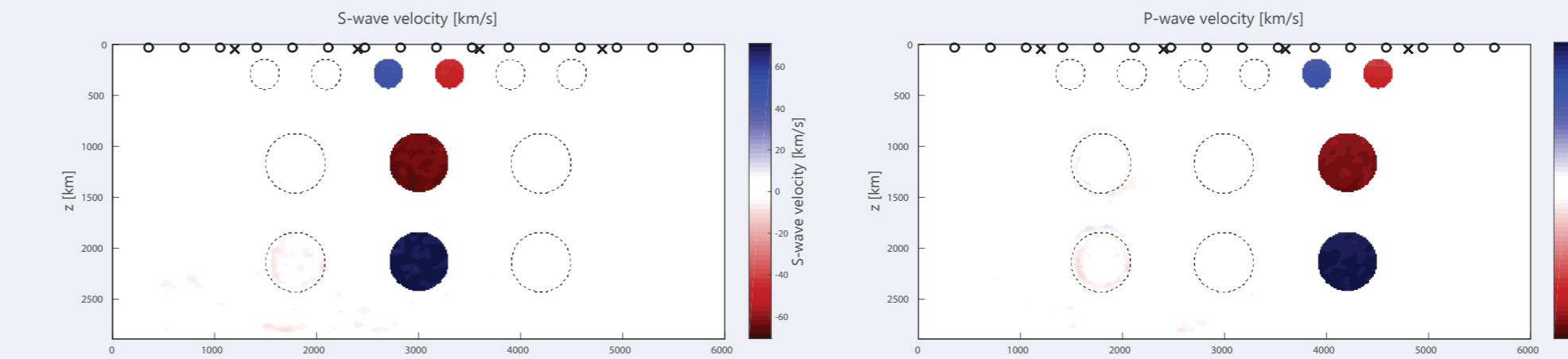
What is the effect of including prior information about the seismic velocities?

Because S- and P-velocities are well known inside the Earth, we can fix these values using a subspace method, and only update density. In this case, the inversion is much more efficient.
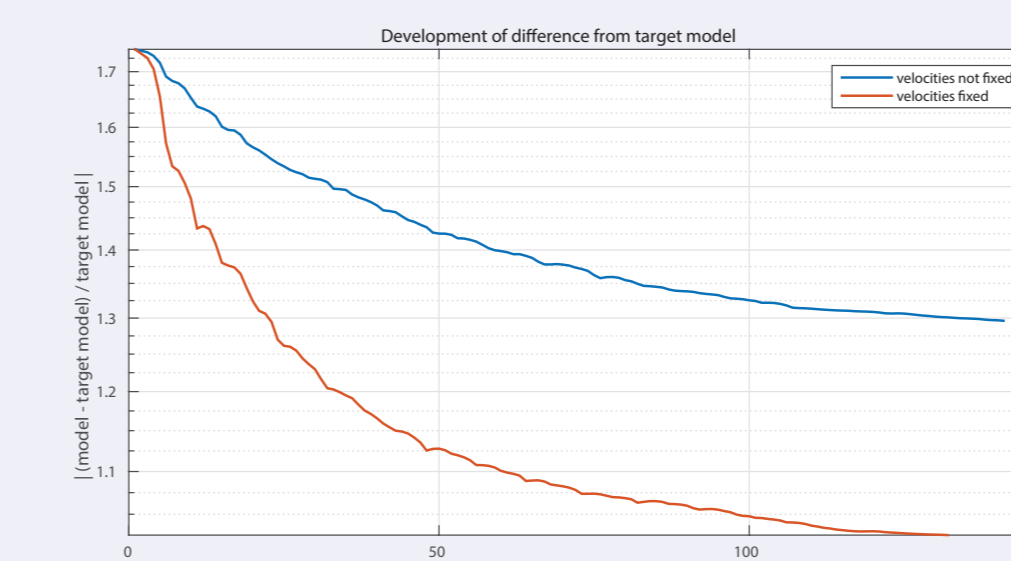

Figure 5. The lower the graph, the closer the result is to the target model. If seismic velocities are fixed, the inversion scheme is much more efficient at recovering density.

density [kg/m³]

data: *seis* **only**

prior information: v_s, v_p correct + fixed

Figure 6. density result of an inversion run (121 iterations with frequencies increasing every 20 iterations), where **no gravity** information is used.

Is it beneficial to include gravity into the inversion scheme?

No. The use of gravity information only works to deteriorate the inversion result. This is the case both if gravity is included in the misfit functional (and thus if gravity partial derivatives with respect to density are calculated), and if gravity is used as a so-called "hard constraint", i.e. if every update is forced to satisfy the gravity data.

Why does gravity not help?

gravity response

possible subsurface density anomaly — weak, moderate, strong, point mass
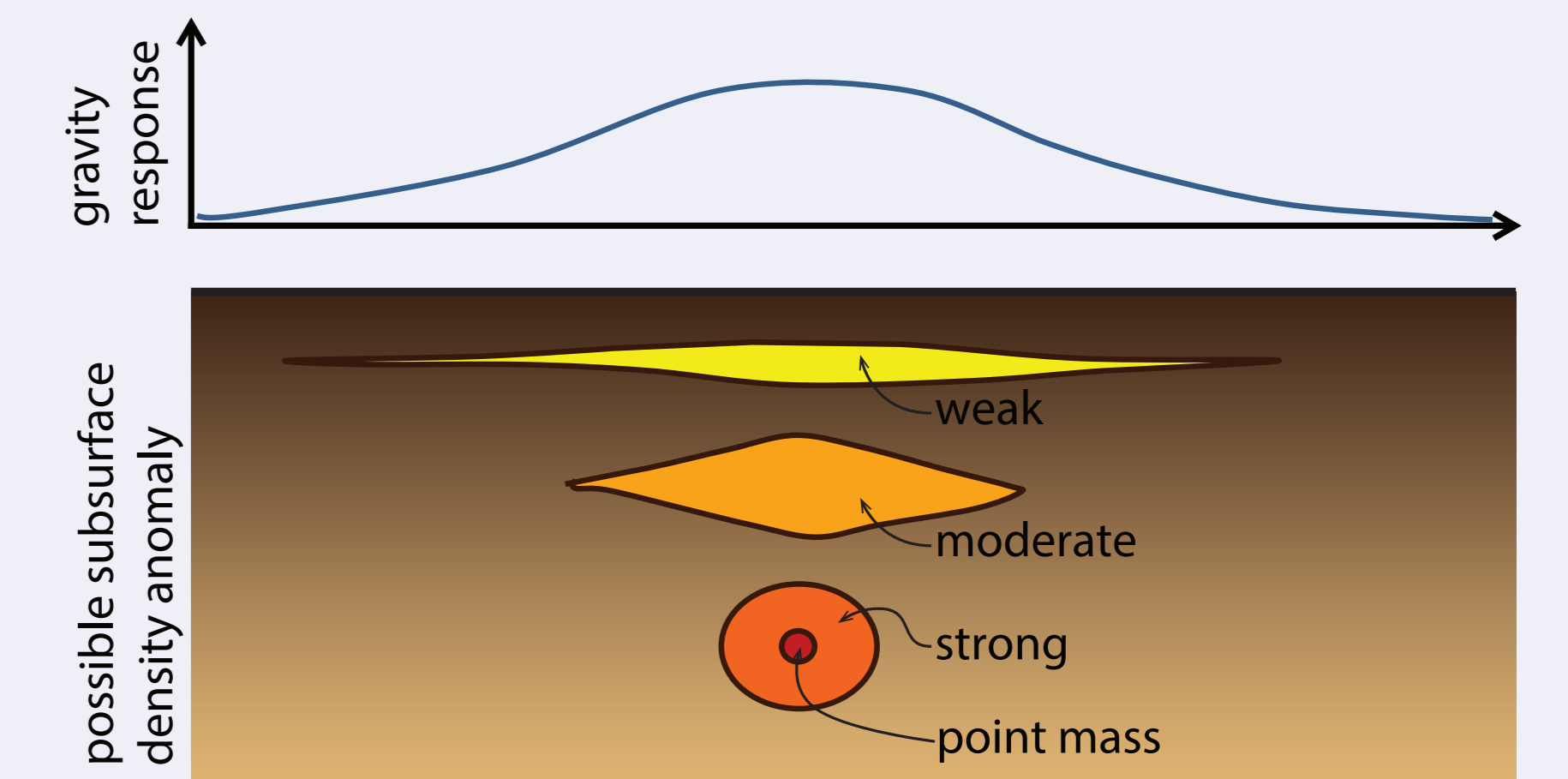
Gravity measurements are non-unique: infinitely many different structures can yield the same gravity response. The sensitivity of gravity falls off with $1/r^2$. The algorithm will thus put most of the density structure near the top of the domain - which is incorrect here.

typical 1st iteration gravity update (max: 4.15 kg/m³)
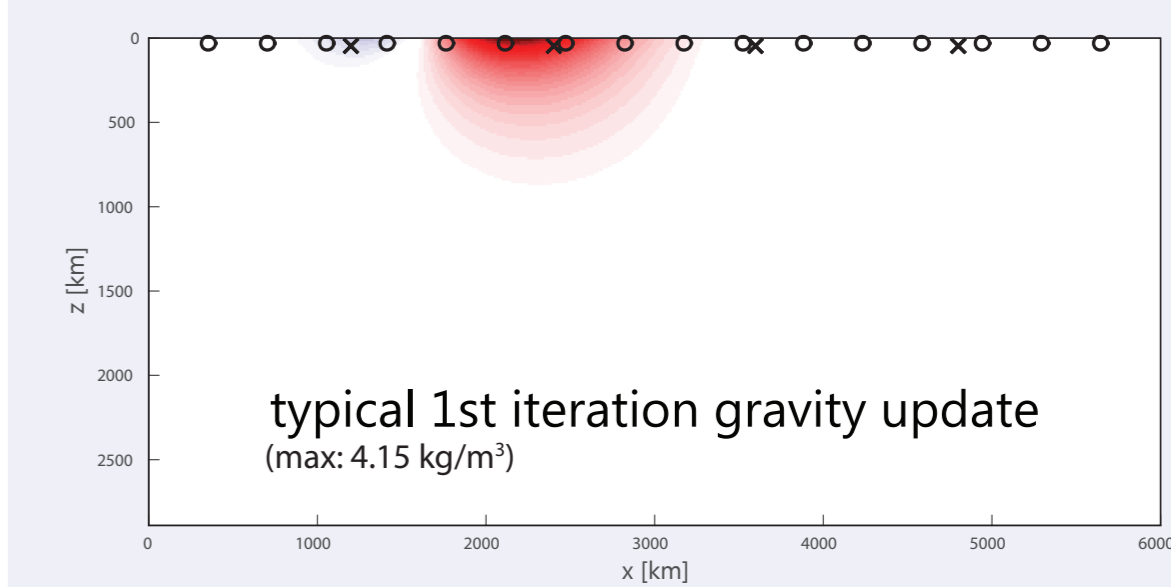
Unless prior information as to the relative distribution of density anomalies is supplied, this cannot be solved.

What if the wrong velocities are fixed?

velocities fixed - 50% wrong
velocities fixed - 15% wrong
velocities fixed - 100% correct
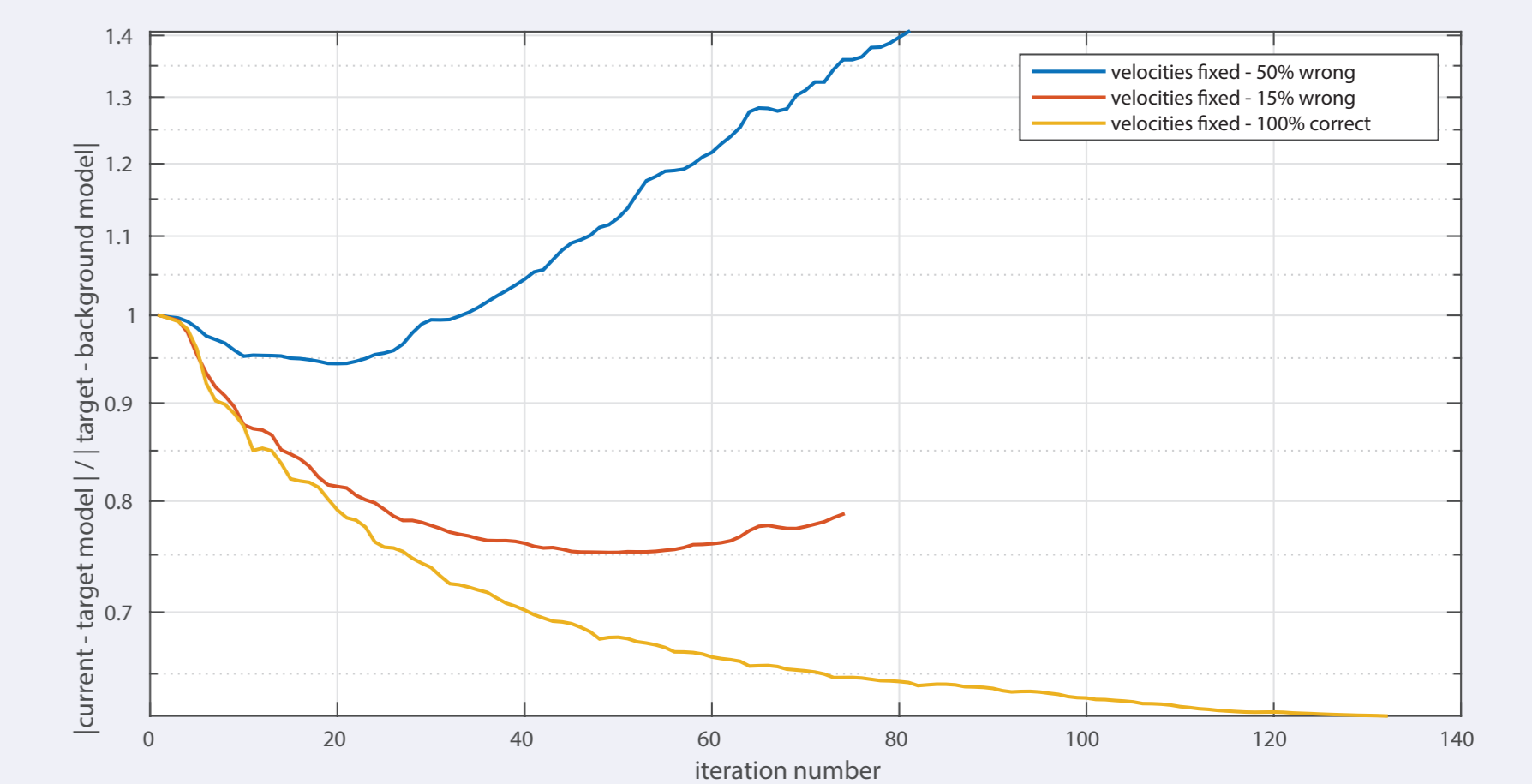
Fixing the seismic velocities to predetermined values improves the density inversion result, but if these velocities are wrong, un-accounted for velocity structure will map into density:
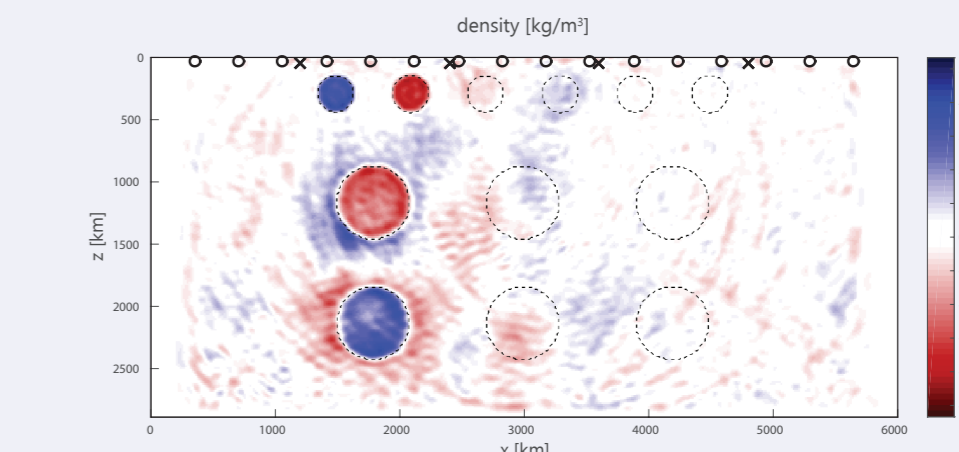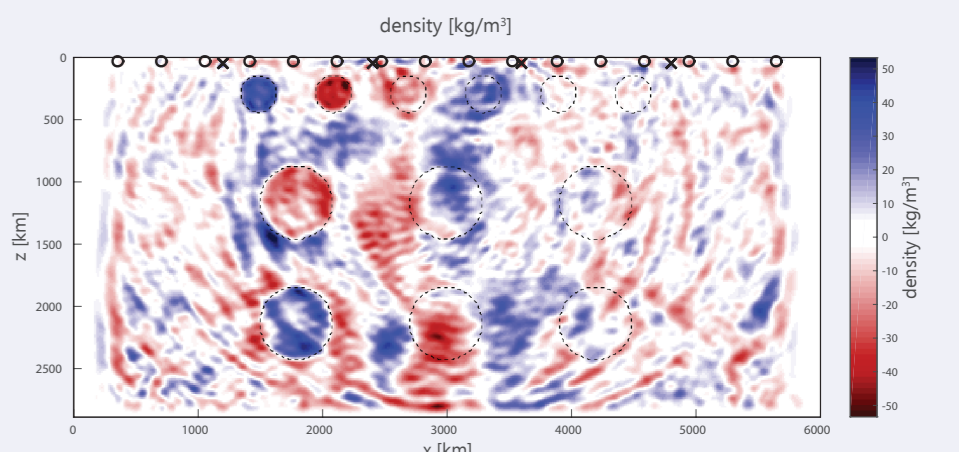

Figure 7. velocity model 15% wrong   Figure 8. velocity model 50% wrong