Towards Estimating Postseismic Parameters and Processes Using Ensemble Data Assimilation

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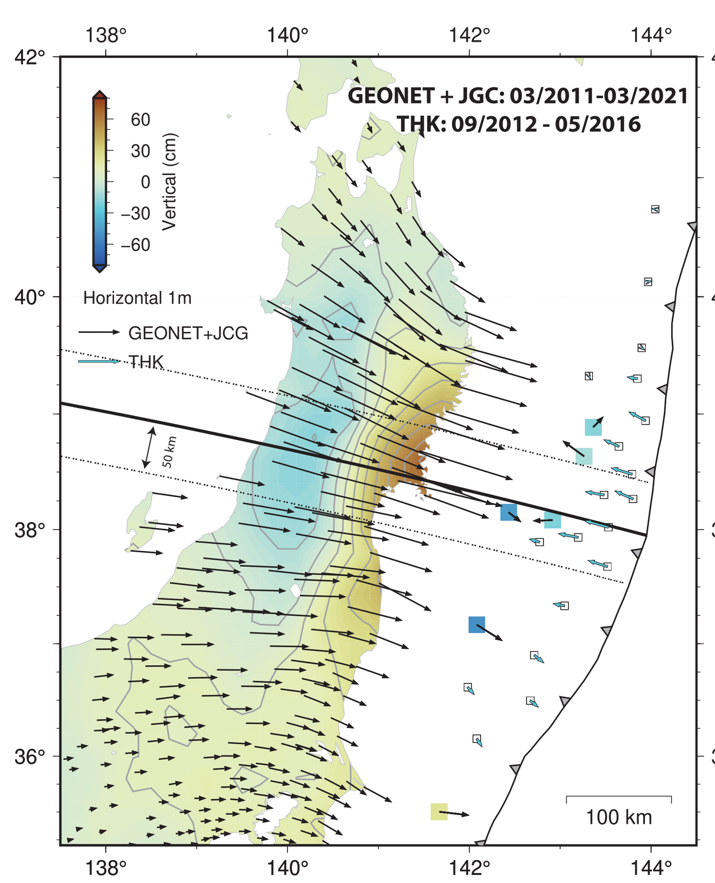
Motivation

The expanding collection of geodetic data provides a great opportunity to improve our understanding of processes and parameters controlling the dynamics at subduction margins. The relative contributions of dominant drivers during the postseismic phase, such as viscoelastic relaxation, afterslip and relocking, remain difficult to estimate individually and are often derived at the end of an observation period.
In this research, prior estimates of the imperfect physical model are combined with the likelihood of noisy observations to estimate the posterior pdf of model parameters using the Ensemble Smoother with Multiple Data Assimilation (ESMDA). We discuss a synthetic data experiment where observations are sampled from a 2D finite element model.

→ ***1) Can we retrieve true model parameters using ESMDA from sparse data for the case where we assume either a linear Maxwell rheology or a power-law rheology? 2) Can we identify correlations between model parameters?***

Postseismic displacements Northeast Japan

Fig. 1: Cumulative postseismic displacements following the 2001 Mw 9.0 Tohoku-Oki earthquake in Northeast Japan. The on-land GEONET (Nakagawa et al., 2009) time series are fitted to a parametric model that includes a linear trend, seasonal variations, steps and two log functions and an exponential function. The offshore data provided by the Japan Coast Guard (JCG) (Yokota et al., 2018) are fitted to a parametric model with a log and exponential function and the offshore data provided by Tohoku Univeristy (THK) (Honsho et al., 2019) consist of a linear trend due to the temporal sparsity.



Ensemble Smoother Multiple Data Assimilation

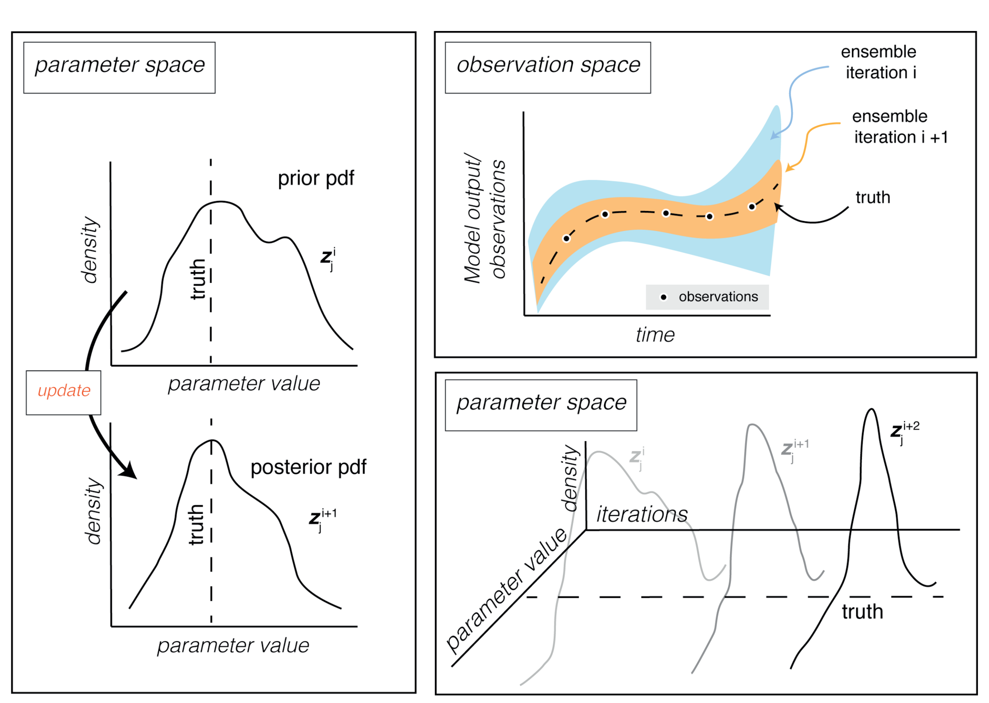


Fig. 2: Main components of the Ensemble Smoother Multiple Data Assimilation (ESMDA).

ESMDA (Emerick & Reynolds, 2013) iteratively updates parameter estimates by integrating observational data with model predictions in a Bayesian context. The relatively low computational cost makes the algorithm incredibly suitable for complex tectonic models.

In our simulations we run 100 models and 5 ESMDA iterations.

References

Emerick, A.A. & Reynolds, A.C. (2013). Ensemble smoother with multiple data assimilation. Computers & Geosciences, 55, 3-15.
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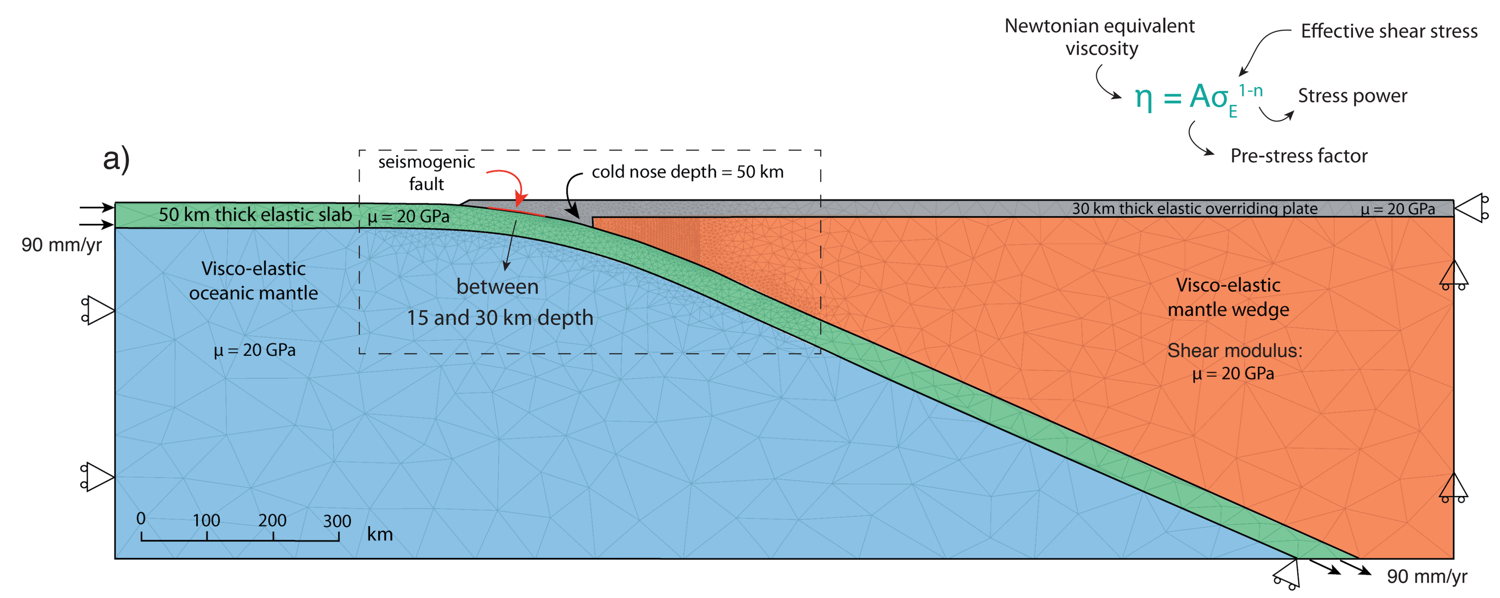
2D earthquake cycle model



Reference model parameters	
Cold nose depth (CND)	50 km
Maximum depth of decoupling (MDD)	100 km
Viscous medium (Newtonian)	
Stress power (n)	1.0
Mantle wedge- and oceanic mantle viscosity ($\eta_{wedge}/\eta_{ocean}$)	10^{19} Pa·s
Viscous medium (power-law)	
Stress power (n)	3.0
Pre-stress factor mantle wedge and oceanic mantle (A_{wedge}/A_{ocean})	10^{10} Pa·s$^{1/n}$

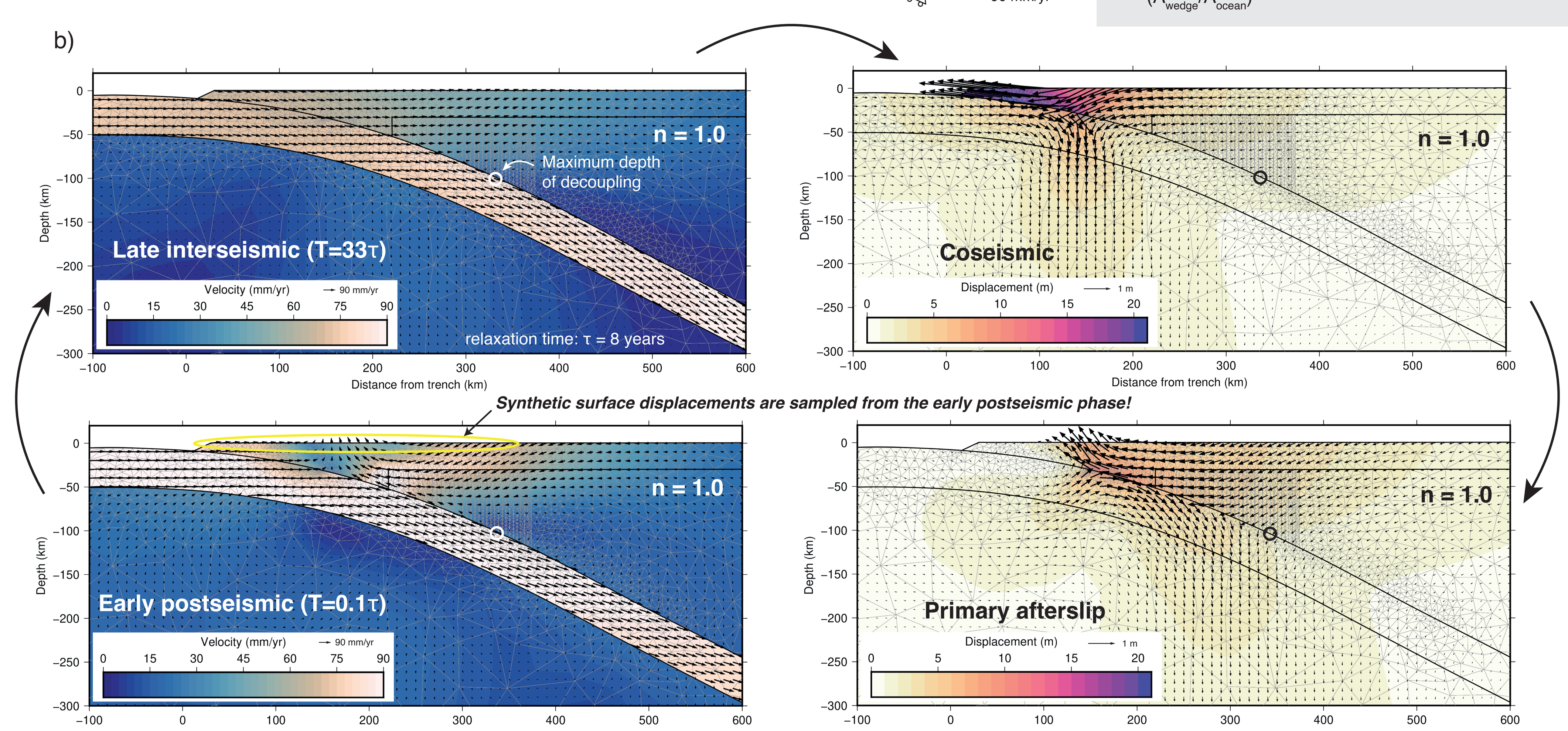


Fig. 3: a) Model setup. The curved geometry for the subduction interface is based on the Slab2.0 model (Hayes et al. (2018)) for Japan.
b) Simulated displacements and velocities during different stages of the earthquake cycle produced with the Newtonian reference model.

Can we retrieve the “right” parameter distribution given the (sparse) data?

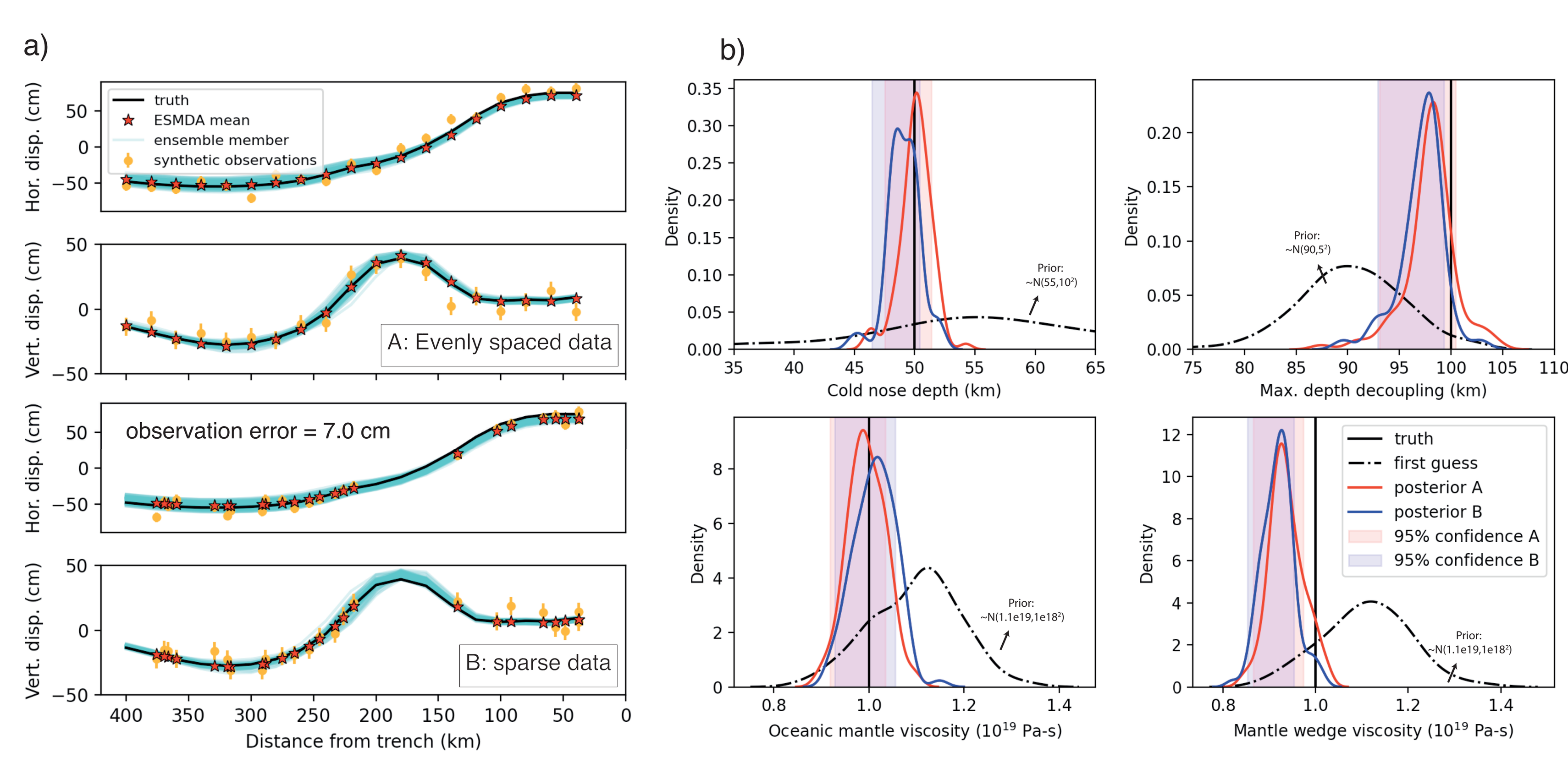
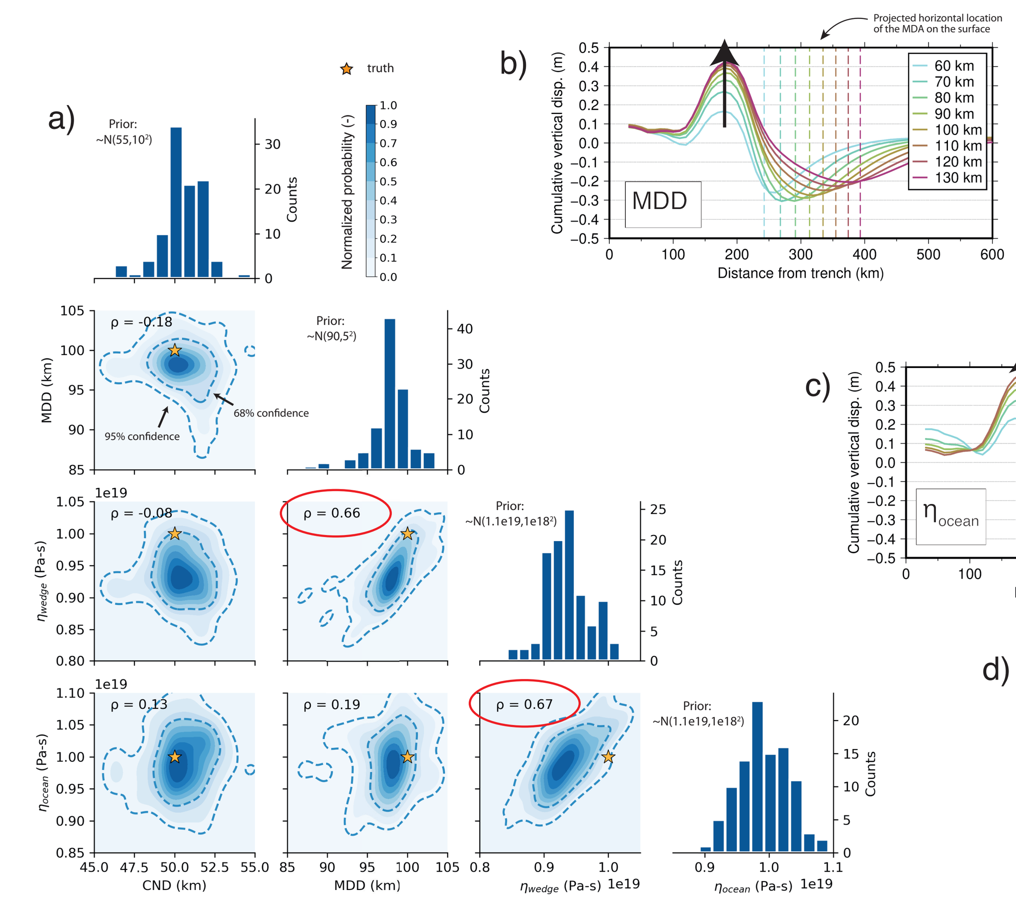


Fig. 4: a) Displacements 10 years after the last earthquake (excluding primary afterslip) when assimilating evenly spaced data or sparse (spatially and temporally!) data (in accordance with the data locations within 50 km from the swath line in Fig. 1 using a Newtonian model. b) Prior and posterior distributions obtained with ESMDA after the 5th iteration when assimilating evenly spaced (A) or sparse data (B).

Yes! In fact, estimates (95% confidence) for the cold nose depth, maximum depth of decoupling and oceanic mantle viscosity overlap the truth. In both cases, the mantle wedge viscosity is difficult to retrieve and is underestimated by 10%, likely due to its correlation with the MDD (Fig. 6a).

Synthetic experiments with a Newtonian rheology



1) Increasing the MDD leads to larger vertical displacements between 100 and 250 km from the trench.
2) Increasing η_{ocean} leads to larger vertical displacements between 100 and 450 km from the trench.
3) Decreasing η_{wedge} leads to larger vertical displacements between 0 and 250 km from the trench.

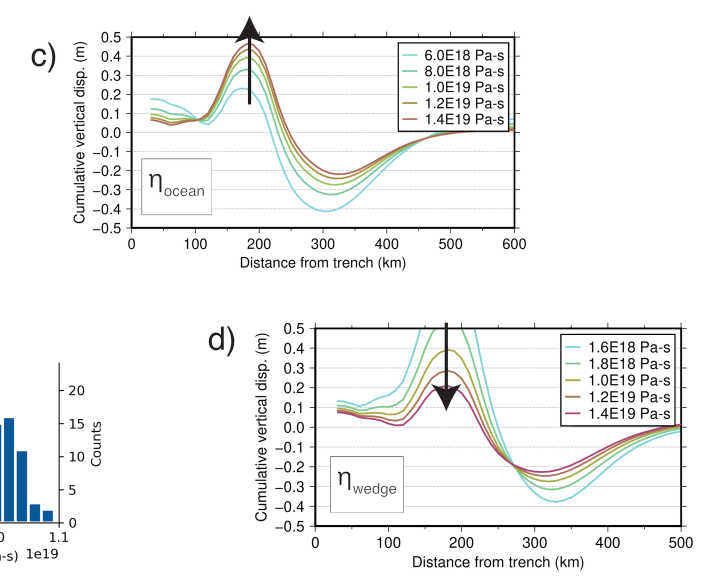
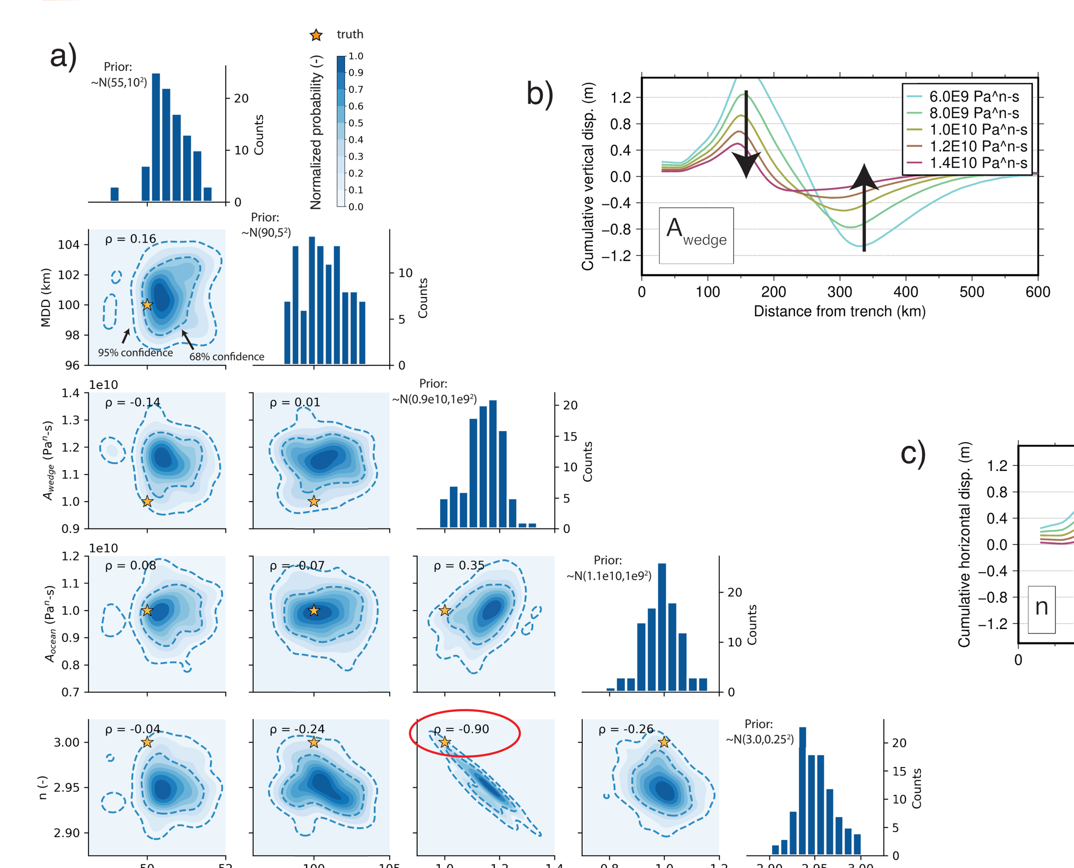


Fig. 5: a) Posterior distributions after the 5th ESMDA iteration with assimilation of evenly distributed synthetic data using a model with a Newtonian rheology. Vertical displacements 10 years after the last earthquake (excluding primary afterslip) for different values of b) coupling depth (CN), c) oceanic mantle viscosity (η_{ocean}) and d) mantle wedge viscosity (η_{wedge}). The parameter pairs MDD - η_{wedge} and η_{ocean} - η_{wedge} are correlated to each other due to their combined effect on the vertical displacements within the considered time frame. The posterior distributions are closer to the truth and have a smaller uncertainty than the prior distributions.

Synthetic experiments with a power-law rheology



1) Increasing A_{wedge} leads to smaller vertical displacements between 0 and 250 km from the trench and larger vertical displacements between 250 and 500 km from the trench.
2) A similar pattern is seen for n.
3) The high correlation between A_{wedge} and n is due to their relation to the Maxwell time.

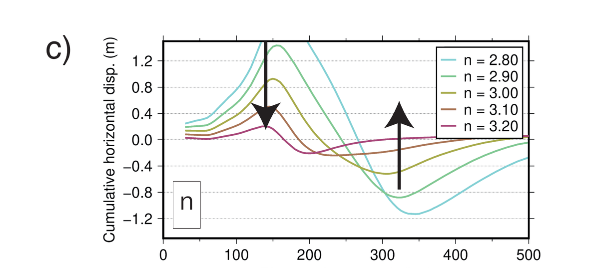


Fig. 6: a) Posterior distributions after the 5th ESMDA iteration with assimilation of evenly distributed synthetic data using a model with a power-law rheology. Vertical displacements 10 years after the last earthquake (excluding primary afterslip) for different values of b) pre-stress factor for the mantle wedge (A_{wedge}), c) the stress power (n). The posterior distributions are closer to the truth and have a smaller uncertainty than the prior distributions.

Key points

1) Synthetic tests with the truth sampled from a Newtonian model indicate a) similar parameter posteriors can be obtained with sparse and evenly distributed data and b) that the mantle wedge viscosity is correlated to the maximum depth of decoupling (ρ = 0.66) and oceanic mantle viscosity (ρ = 0.67) for the considered time frame (10 years after the earthquake) and the selected truth.

2) Synthetic tests with the truth sampled from a power-law model indicate that there is a high correlation (ρ = -0.90) between the stress power and the mantle wedge pre-stress factor for the considered time frame (10 years after the earthquake) and the selected truth. The high correlation is expected due to their relation to the Maxwell time.