A Bayesian Approach for Inter-plate Coupling Models in Subduction Zones

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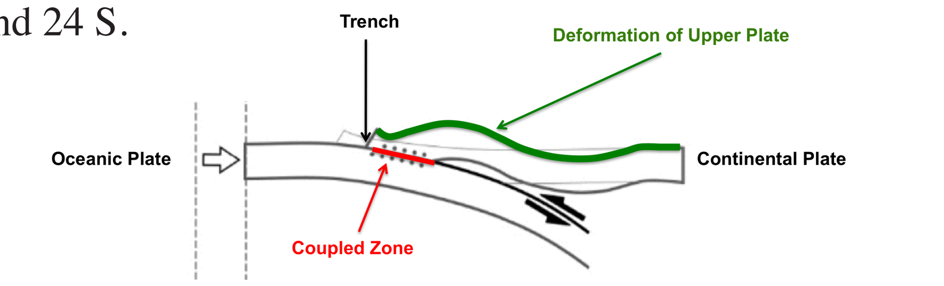
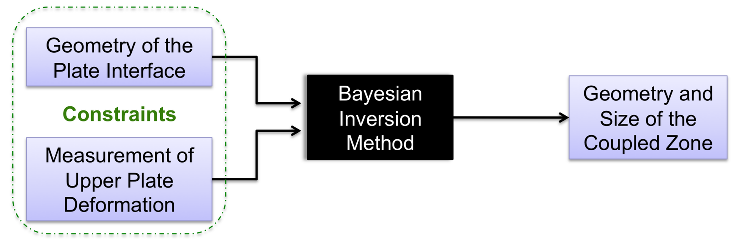
1. Introduction

Our primary goal is to characterize the extent of apparent plate coupling on the subduction zone megathrust with the eventual goal of understanding variations in fault zone rheology. In this initial study, in order to demonstrate the basic approach, we adopt a simple kinematic backslip model (Savage, 1983). This study differs from most (but not all - e.g., see Segall, 2002) analogous studies in that we use a Bayesian approach wherein we ask not for a single optimum model, but rather for a posteriori estimates of the range of allowable model parameters. This approach also allows us to explicitly define physically plausible a priori information on data uncertainties and model parameters, as opposed to assuming everything follows Gaussian statistics.

The Bayesian approach inherently depends on an ability to routinely compute millions of forward models that are consistent with a priori constraints and available geodetic measurements. Such computations are now viable with available computational resources. We apply this methodology to invert for a series of synthetic cases motivated by the desire to understand the state of inter-seismic coupling in the Chilean-Peruvian subduction margin between 16 S and 24 S.





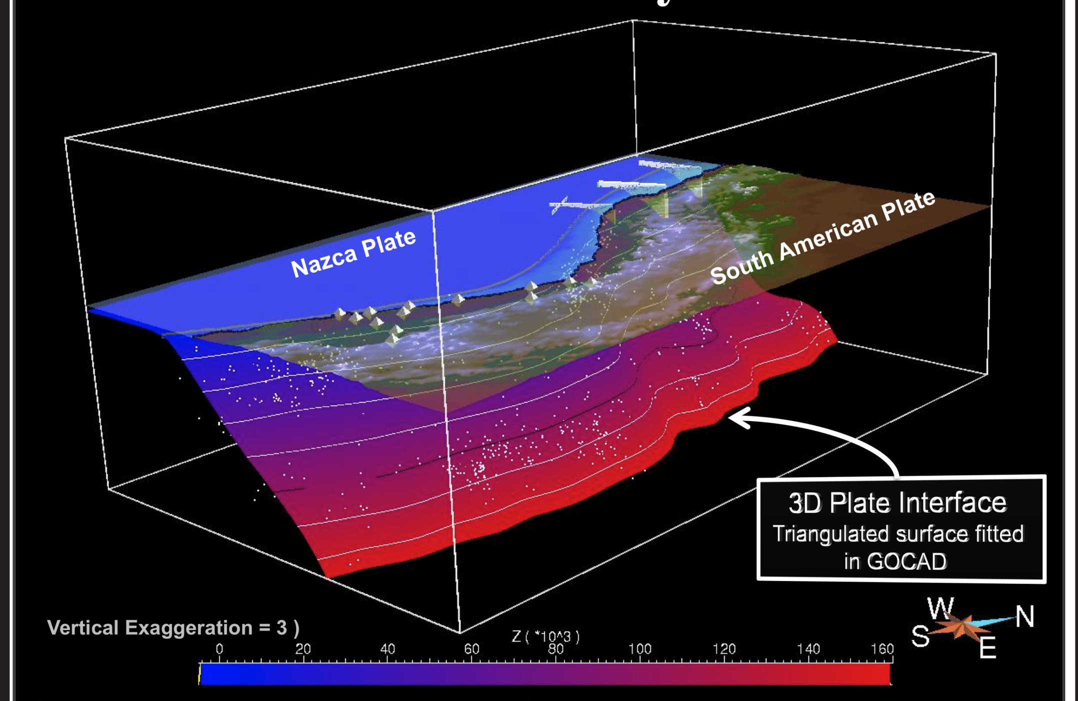
2. cGPS measurements

Location of CTO (Caltech Tectonics Observatory) continuous GPS sites installed beginning 2005 and sites installed by IPGP . The picture is for PTRE.

2. cGPS measurements (cont)

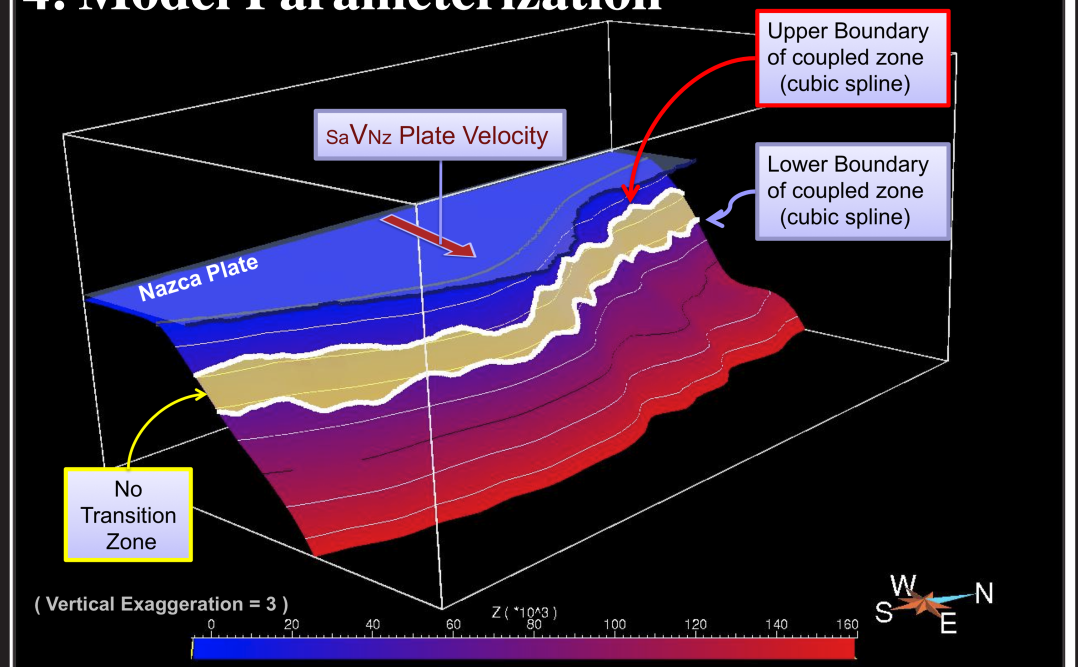
GPS data will provide constraints for the inter-seismic velocity field. Continuous GPS (cGPS) measurements can provide precise estimates of the 3 components of the inter-seismic velocity field. In this study, we consider an observational configuration that is taken from our existing network in Chile/Peru.

3. Plate Interface Geometry



3D triangulated surface modeling the plate interface between the Nazca and South American plates. The surface is obtained using earthquake catalogs of relocated seismicity (ISC, Engdahl and Villaseñor, etc), seismic reflection profiles (ANCORP Lines; Krabbenhoft et al 2004(shown here); etc) and any other type of data that can be used to constrain the geometry of the plate interface.

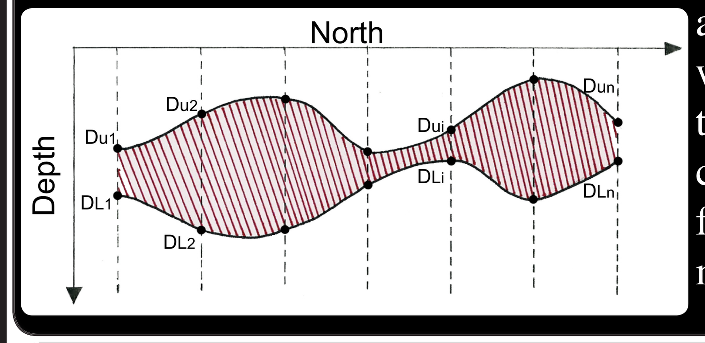
4. Model Parameterization



We use a Back-slip model (Savage, 1983) to represent the inter-seismic strain accumulation at the plate interface. In this initial approach we use a constant back-slip at the coupled zone ignoring the possible existence of a transition zone. We assume an elastic half space (Okada, 1985) in order to calculate Greens functions.

4. Model Parameterization (cont)

The coupled zone is defined by its upper and lower boundaries, each parameterized using cubic splines. The knots of these splines are our model parameters along with the background plate velocity. Note that the splines are defined in a vertical plane and they represent the depths of the coupling zone boundaries. For a given model we define a mask for depth (see hatched area in the figure) and we calculate the forward model using only the Green's functions that corresponds to triangular fault patches within the mask.

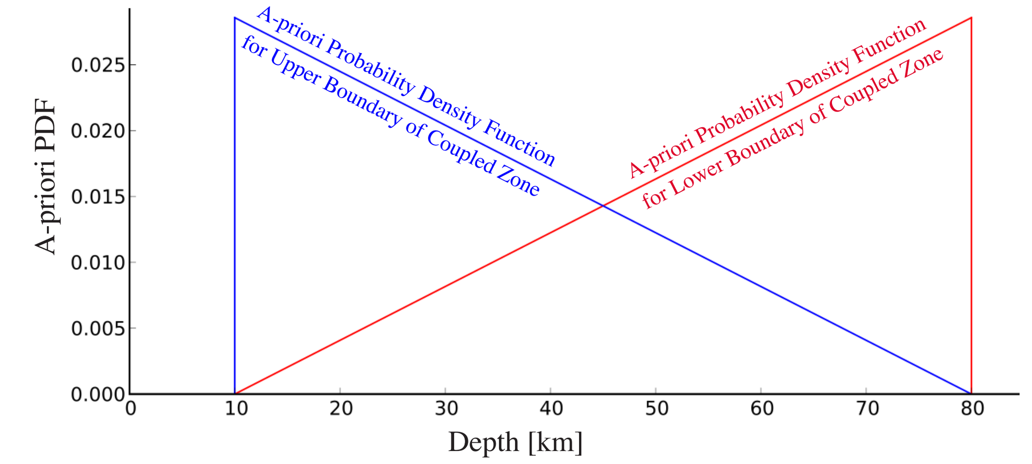


5. Inverse Method

We implement a Markov Chain Monte Carlo, Metropolis - Hastings (1970) algorithm for the inversion. The algorithm samples the a-posteriori probability density function of the model: SaVNz_N, SaVNz_E (components of the plate velocity vector), DL_i and DU_i (i-th knot of the splines defining the lower and upper boundary of the inter-seismic interplate coupled zone, respectively).

6. A priori information

Typically, with a Bayesian approach one can easily implement a-priori constraints such as limiting the range of any given parameter. In our case, the entire coupled zone must lie between seafloor (trench) depth and a maximum depth (80 km in our case). In the absence of data and any other constrains, the a-priori PDF for each knot would be a boxcar function. However, an advantage of the Bayesian approach, lies in that we can also describe a-priori information in terms of relationships (or rules) between parameters. For instance, with the coupled zone parameterization described above (4), the upper boundary must by definition always be above the lower boundary (e.g.: $DU_i \leq DL_i$). The net impact of such a constraint, is that even in the absence of data, the prior distribution on the upper and lower boundary is not flat (or a boxcar). In our case, the resulting priors are triangular in shape.

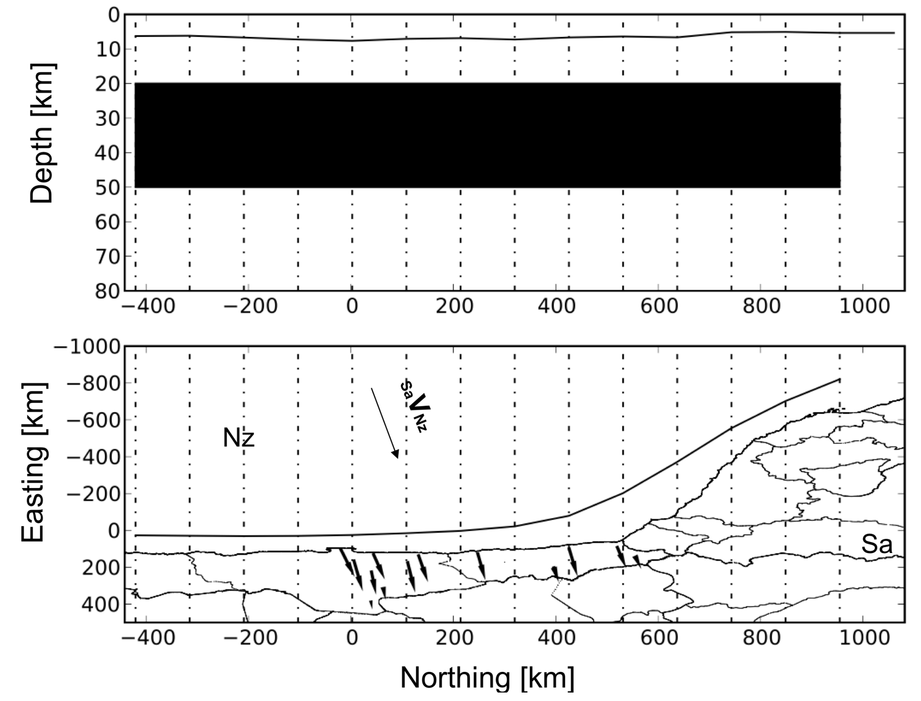


Note: this plot is rotated 90 degrees clockwise when showing inversion results.

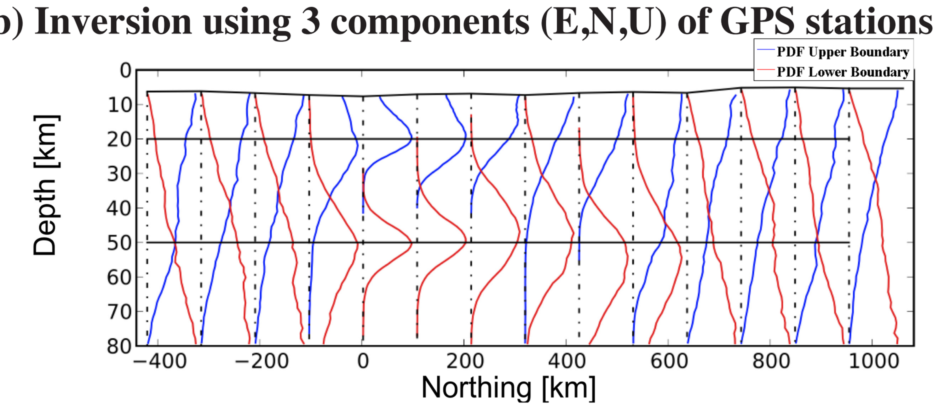
7a. Inversion with synthetic data

We generate synthetic data (with noise) using the model in panel (a), where the upper and lower boundaries of the inter-seismic interplate coupled zone are located at 20 and 50 km respectively. We perform inversions using this synthetic data using all 3 components of the GPS data (see panel b) as well as only the horizontal components (see panel c). We show the a-posteriori PDF of the model parameters for the upper boundary (blue) and lower boundary (red) of the coupled zone compared to input model (black). Note how the uncertainties of the lower boundary increase substantially when we invert without using the vertical component of the GPS data.

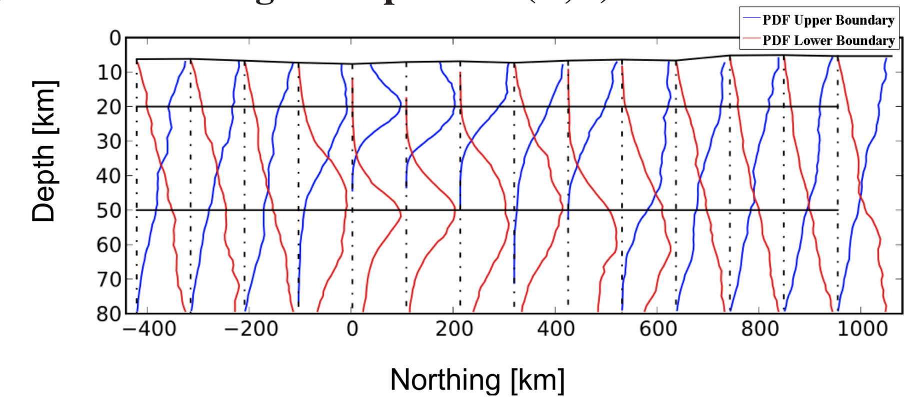
a) Synthetic Model and GPS Data



b) Inversion using 3 components (E,N,U) of GPS stations



c) Inversion using 2 components (E,N) of GPS stations

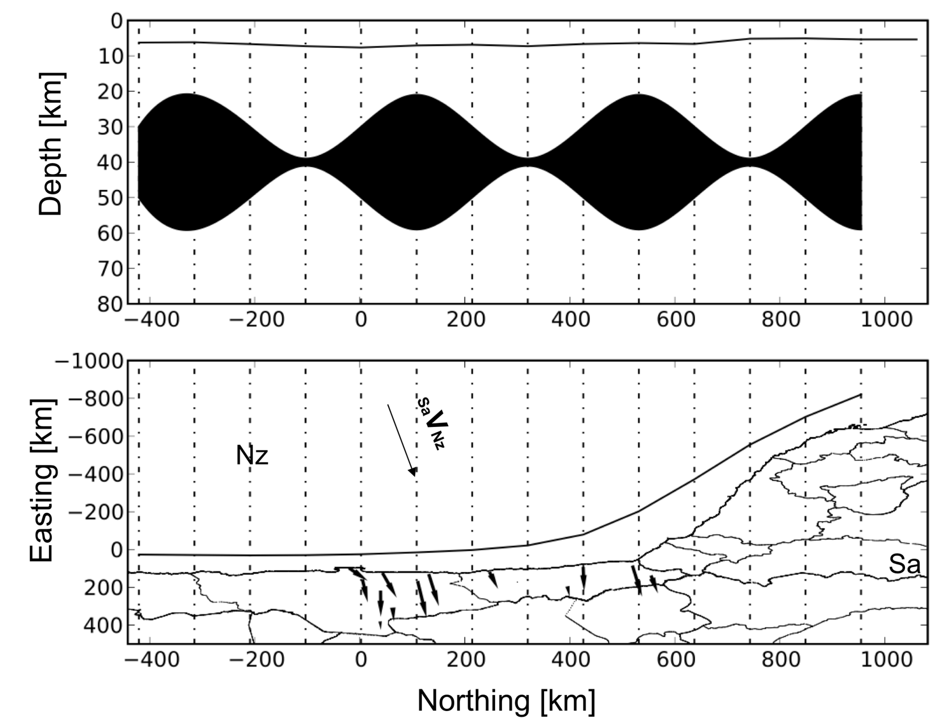


7b. Inversion with synthetic data

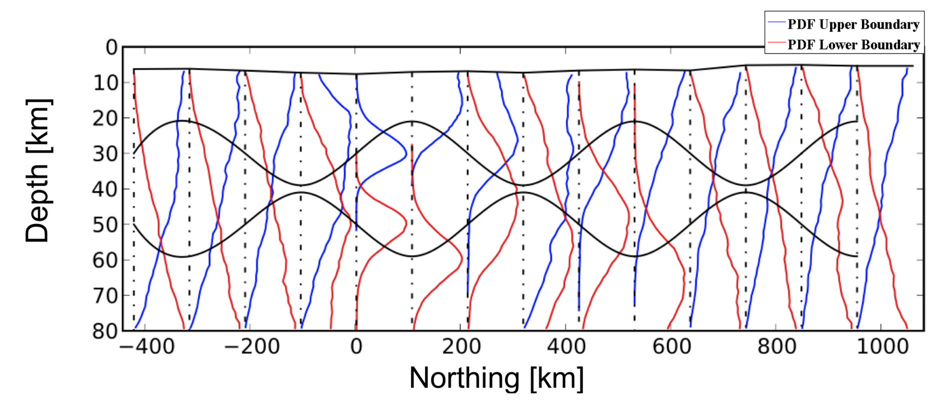
We perform a checkerboard style test inverting the synthetic data shown in panel (a), where the black shaded area indicates the locked region. The results of the inversion are shown in panel (b).

Note that the target model is being predicted by the inversion process at the region where the GPS network is densest (0 km < N < 200 km). Also notice that since there is no data at the edges of the model, for all tests shown here, only the a-priori probability density function is recovered at the edges of the model (N=-400 km and N=1000 km).

a) Synthetic Model and GPS Data



b) Inversion using 3 components (E,N,U) of GPS stations



The uncertainty of the model parameters have a high dependence on the spatial distribution of the GPS network. This dependence becomes clear analyzing the a-posteriori probability density functions of the parameters of the model. This perspective can help when planning deployment of new instruments.

8. What is next?

We are building a Bayesian inversion environment that allow us to estimate the range of allowable parameters in geodetic fault models. In particular, we have focussed on inter-plate coupling in subduction zones.

At present, we have made many assumptions to both simplify the problem and for computational expediency.

Moving to more complicated elastic structures will be trivial as it simply requires building a bank of Green's functions from a finite element code (e.g., PyLith). (Question: When will PyLith be able to do this efficiently?!) Similarly, we can easily expand the complexity of the parameterization to include transition zones and resolve for the Euler vector instead of the background plate velocity. This increase in number of model parameters will result on a greater computational burden that can be offset by use of a parallel sampler.

Our immediate near term goal is to apply this approach to available campaign and continuous GPS observations for Northern Chile and Southern Peru.

Eventually, we expect to apply this Bayesian approach not simply to kinematic models (e.g., backslip) but to models parameterized in terms of spatially variable fault zone rheological constants.

9. Acknowledgement

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10. References

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