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

Francisco Ortega and Mark Simons

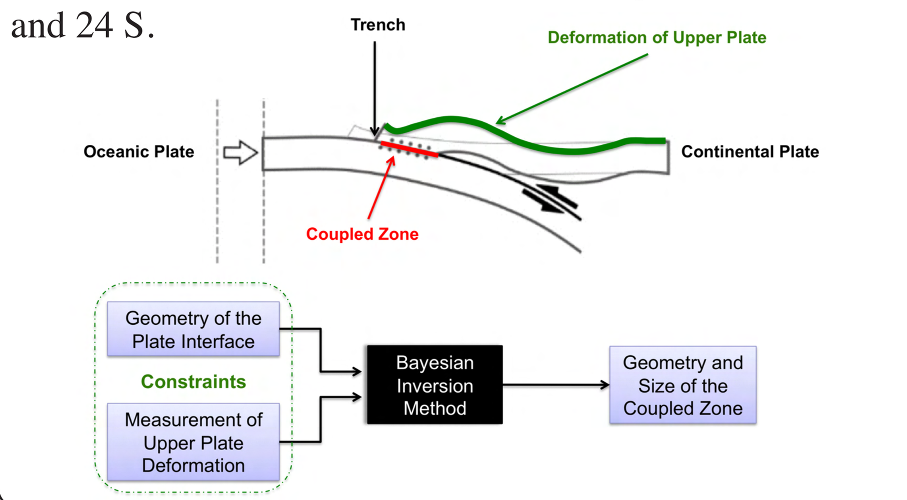
ortega@gps.caltech.edu simons@gps.caltech.edu

Seismological Laboratory, California Institute of Technology, Pasadena, California 91125.

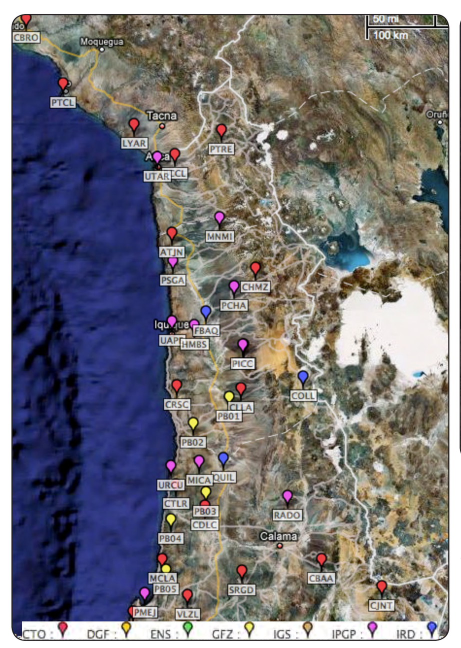
1. Introduction

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.



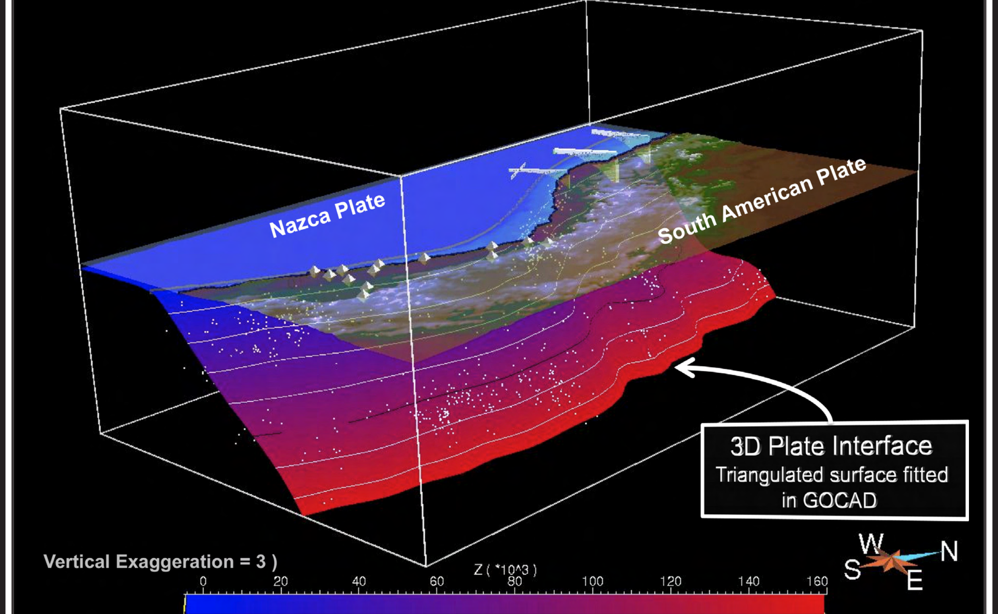
2. cGPS measurements



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

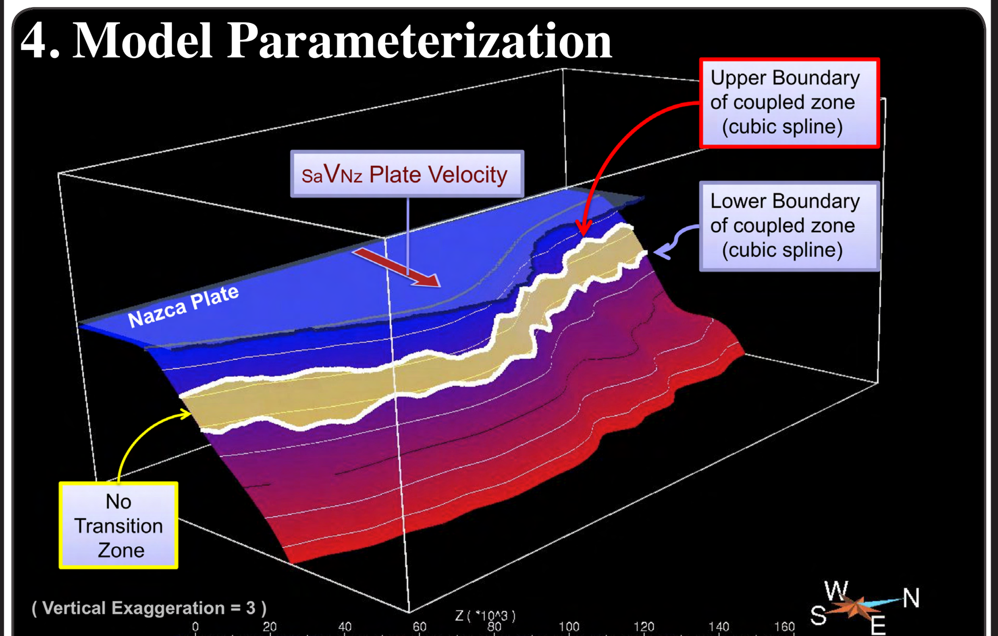
GPS data will provide constraints for the inter-seismic velocity field. Continuous GPS (cGPS) measurements can provide precise estimates of the 3 components of the inter-seismic velocity field. In this study, we consider an observational configuration that is taken from our existing network in Chile/Peru.

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 the example above, we illustrate a simplified case when a constant back-slip rate is imposed at the coupled zone, ignoring the possible existence of a transition zone (Case 'a') in the following figure).

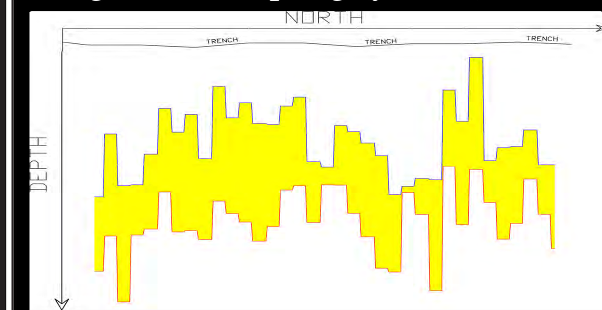
We assume an elastic half space (Okada, 1985) in order to calculate Greens functions.

The degree of coupling along the plate interface is characterized by regions defined by nearest neighbor interpolated curves in depth. The knots depth of these curves are our model parameters along with the Euler pole of the relative plate motion between Nazca and South American plates.

For a given model we define a mask in depth for the degree of coupling (DOC) in function of the curves defining its boundary (yellow region) and we calculate the forward model weighting the Green's functions by the value of the degree of coupling that corresponds to the respective triangular fault patch.

4. Model Parameterization (cont)

In the following figures we how the parameterization is computed , Degree of Coupling (yellow) without transition zones.



We define the upper (blue) and lower (red) boundaries of the coupled zone (yellow). The depth of each linear segment is a parameter of the inversion.

The boundary curves are described by Nearest Neighbor interpolation of its knots.

Here Zk is the depth of the k-th knot of the curve Z(x), and H () is the Heaviside function.

$$Z(x) = \sum_{k=1}^{N} Z_k \cdot \square_k(x)$$

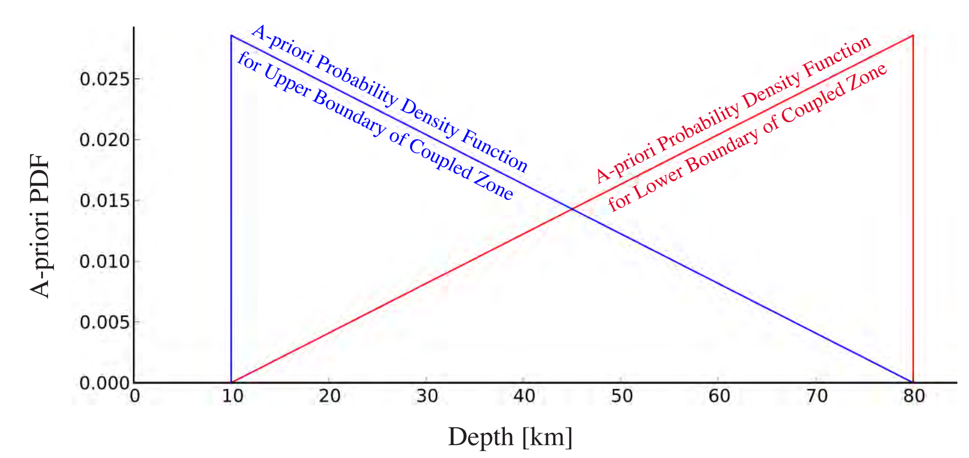
$$\square_k(x) = \begin{cases} 1 - H\left(x - \frac{1}{2}[X_1 + X_2]\right) & \textit{if } k = 1 \\ H\left(x - \frac{1}{2}[X_{k-1} + X_k]\right) - H\left(x - \frac{1}{2}[X_k + X_{k+1}]\right) & \textit{if } 1 < k < N \\ H\left(x - \frac{1}{2}[X_{N-1} + X_N]\right) & \textit{if } k = N \end{cases}$$

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 parameters of the model: Euler pole describing the relative convergence of the plates, depth of the k-th knot of the curves Z(x) defining the degree of coupling at the plate interface.

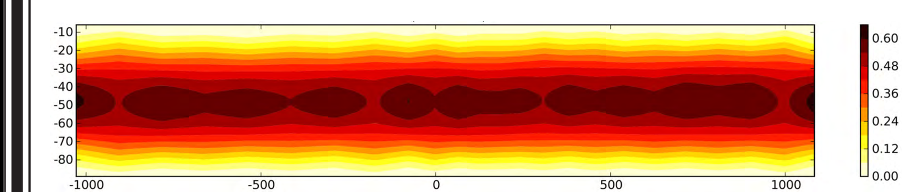
6. A priori information

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. 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 curves Z(x) do not intersect (red and blue curves in (4) will never cross). The net impact of such a constraint, is that even in the absence of data, the a-priori distribution on the upper and lower boundary of the coupled zone is not flat (or a boxcar). In that case the resulting a-priori PDFs are triangular in shape, as shown in the following figure.



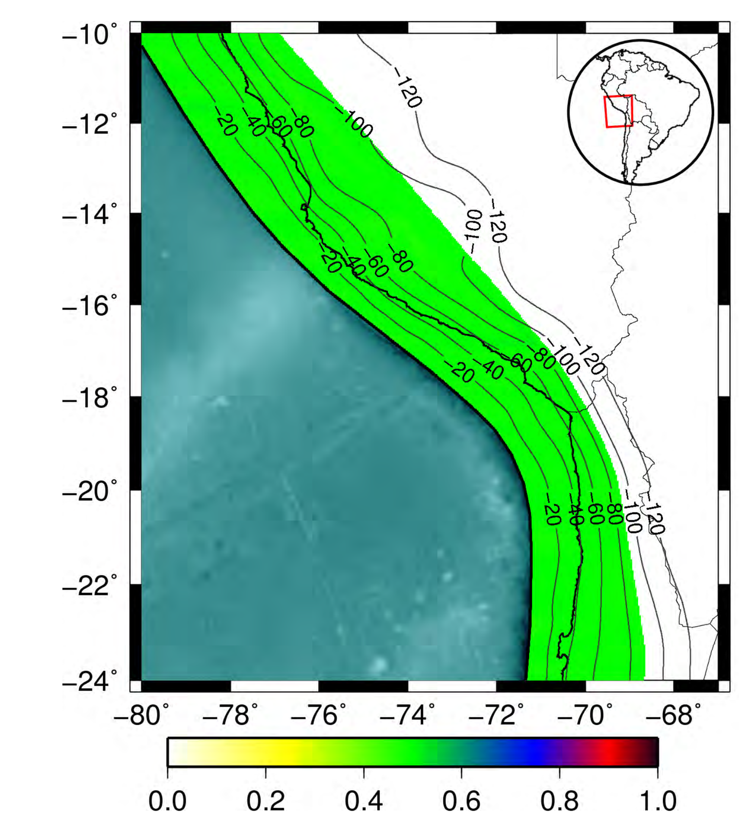
6. A priori information (cont.)

If we sample the A-priori probability density function of the model parameters using such a model parameterization and compute the probability 100% apparent coupling for each point on the plate interface, we find that such probability is not constant over the plate interface (see next figure).



In this figure we show the probability of 100% apparent coupling along the plate interface, the vertical axis is the depth of the plate interface and the horizontal axis is its Northing. Since we are sampling the a-priori probability density functions of the model parameters (no data involved) we can clearly see that the result shown in this figure is the product of the information that our parameterization adds to the PDFs of the model parameters. So it is important to always look to the a-priori (no data) results of our inversions in order to make a good interpretation of the a-posteriori estimates of our models parameters.

Comparing the a-posteriori estimates of the 100% apparent coupling with the one shown in the previous one can be hard. In order to simplify this comparison process, we can design a random walk (for Metropolis sampler) that give us a probability of 100% apparent coupling that is constant (and equal to P = 0.5) over all the plate interface when sampling the a-priori PDFs of the model parameters. The design process of the new random walk is out of the scope of this poster, but we show in the figure below, the a-priori estimates of the 100% apparent coupling probabilities along the Nz-Sa plate interface. For further inversions results in this poster, this will be the null-hypothesis to compare with.

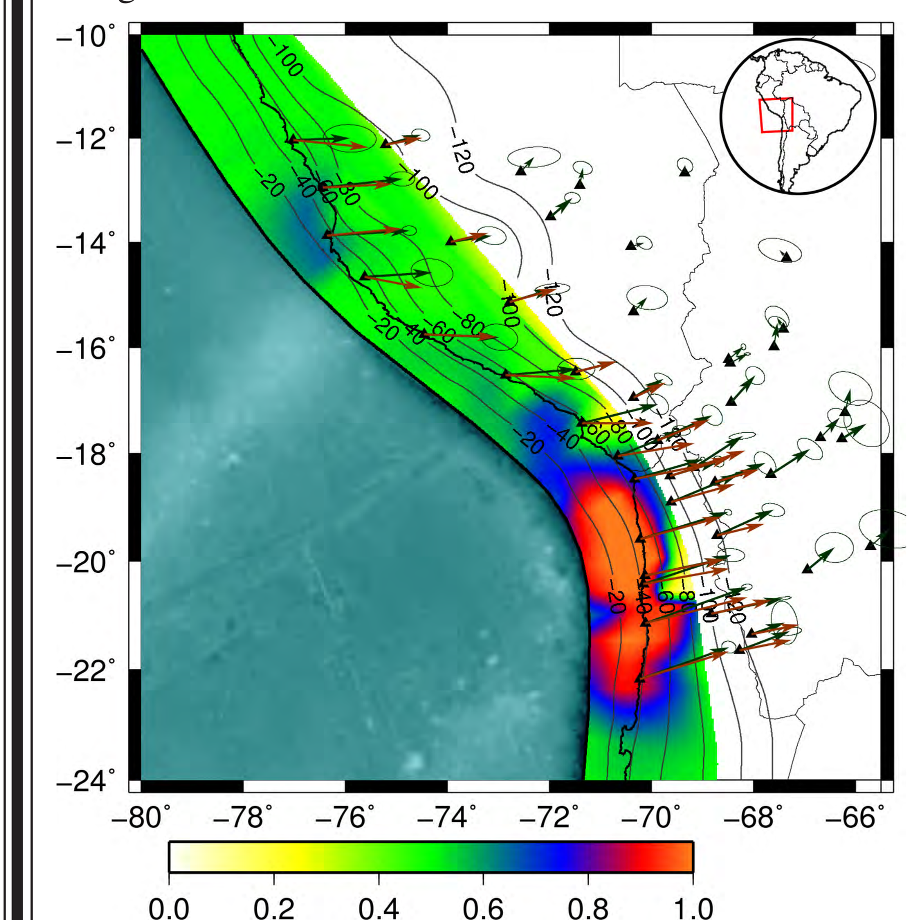


7. Inversion with GPS data

Using the GPS data from Kendrick et Al (2001). The GPS velocities are an integrated interseismic velocity field for the Central Andes and is obtained from repeated surveys spanning from January 1993 to March 2001, just before the ocurrence of the 2001 Arequipa Earthquake in southern Peru. This data is processed from several GPS campaigns (CAP and SNAPP projects) with observation time spans varying greatly from one GPS station to another, from 2 years to a maximum span of 7 years. This heterogeneity in time span is well reflected in the uncertainties of the Central Andes interseismic velocity field.

Since this dataset was obtained prior the occurrence of 2 big earhquakes (Arequipa 2001 and Pisco 2007, both in Peru) we can infer possible causal relationships between the probability of 100% apparent coupling along the plate interface and the co-seismic inferred slip distribution associated with these earthquakes.

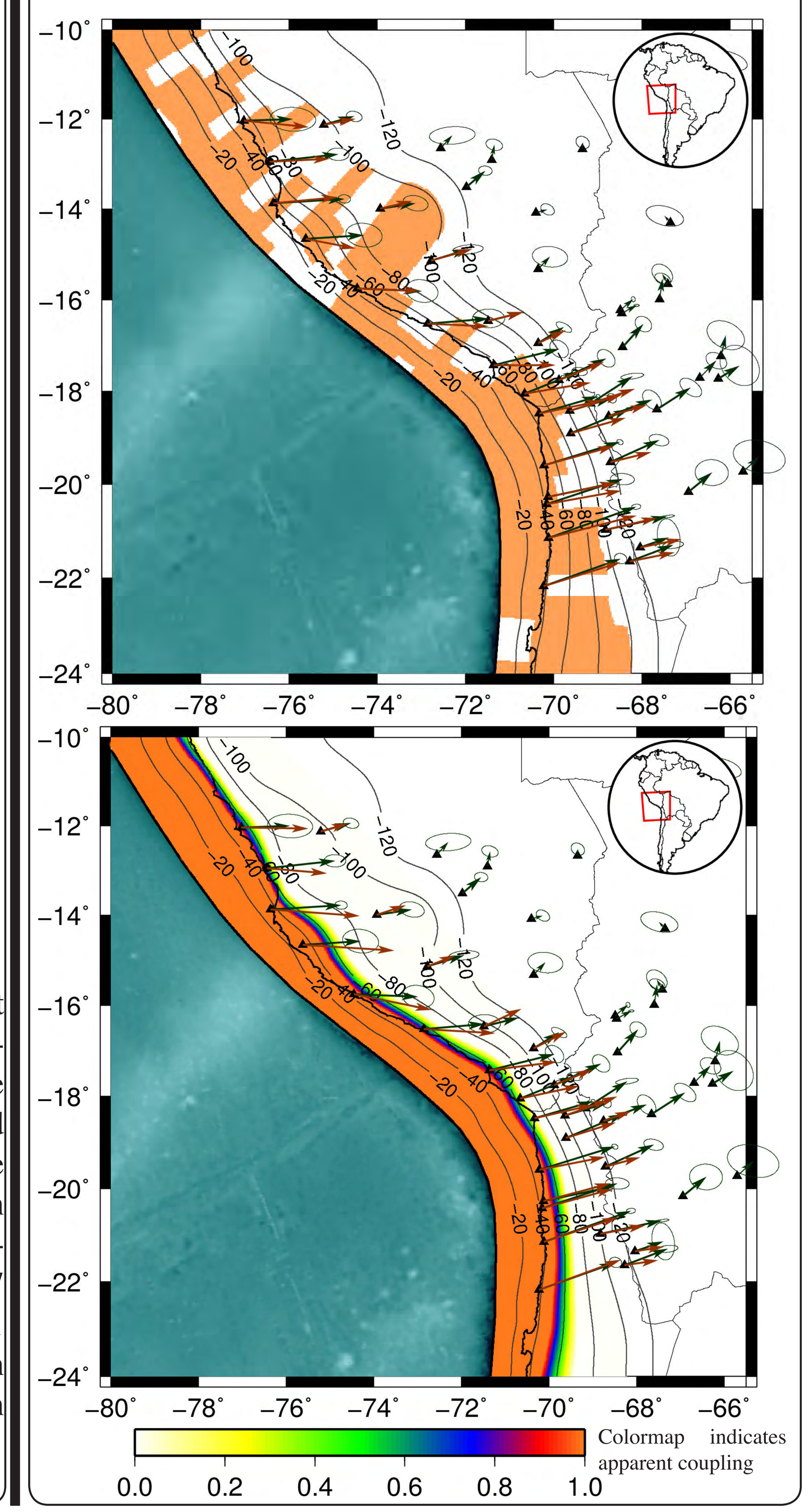
We show in the next figure the 100% apparent coupling probabilities obtained as a result of the inversion using Kendrick et Al. 2001 dataset.



We show in colormap the probabilities for 100% apparent coupling, the black arrows are the GPS velocities (with error ellipses) from Kendrick et al 2001 and the red arrows are the predictions of the Maximum Likelihood model, selected during the inversion process. In this representation of the range of allowable models, we can see several anomalies in the probability field, where we can identify 3 major anomalies of higher probability, the rupture area of the Pisco 2007 earthquake (~ 14 S), the rupture area of the Arequipa 2001 earthquake (~17S - 18 S) and a high probability zone in northern Chile, suggesting a strong coupling on the region of the Northern Chile Seismic Gap.

8. Discussion

Note the importance of sampling the whole range of possible values for the model parameters, ie, to properly sample their uncertainties. In the next 2 figures we show 2 possible cases to be considered as "good solutions" of the posed problem. The first one is the Maximum Likelihood model obtained durin the inversion (orange = coupled, white = uncoupled) and the second one is a "hand made" model which is 100% coupled from the trench to 50km depth, and then has a linear transition to be uncoupled below 70km depth. Note that the prediction both models explain equally well the dataset, suggesting big uncertainties in the estimated model parameters. A way to approach this problem is to represent the whole family of solutions like we did with the coupling probability maps, or look for the mean, median, etc. model among a percentage of the best suited sampled models, which we will do in the near future.



Colormap indicates apparent coupling