A Bayesian Approach for Apparent Inter-plate Coupling in the Central Andes Subduction Zone

Francisco Ortega[1] (ortega@caltech.edu), Mark Simons[1], Jeff Genrich[1], John Galetzka[1], Diana Comte[2]
Bianca Glass[3], Carlos Leiva[3], Gabriel González[4], and Edmundo Norabuena[5]

(1) Seismological Laboratory, California Institute of Technology, Pasadena, California 91125, USA. (2) Universidad de Chile, Santiago, Chile.
(3) Universidad de Tarapacá, Arica, Chile. (4) Universidad Católica del Norte, Antofagasta, Chile. (5) Instituto Geofísico del Perú, Lima, Perú.

1. Introduction

We aim to characterize the extent of apparent plate coupling on the subduction zone megathrust with the eventual goal of understanding spatial variations of fault zone rheology, inferring relationships between apparent coupling and the rupture zone of big earthquakes, as well as the implications for earthquake and tsunami hazard. Unlike previous studies, we approach the problem from a Bayesian perspective, allowing us to completely characterize the model parameter space by searching a posteriori estimates of the range of allowable models instead of seeking a single optimum model. Two important features of the Bayesian approach are the possibility to easily implement any kind of physically plausible a priori information and to perform the inversion without regularization, other than that imposed by the way in which we parameterize the forward model. Adopting a simple kinematic back-slip model and a 3D geometry of the inter-plate contact zone, we can estimate the probability of apparent coupling (Pc) along the plate interface that is consistent with a priori information (e.g., approximate rake of back-slip) and available geodetic measurements. More generally, the Bayesian approach adopted here is applicable to any region and eventually would allow one to evaluate the spatial relationship between various inferred distributions of fault behavior (e.g., seismic rupture, postseismic creep, and apparent interseismic coupling) in a quantifiable manner.

We apply this methodology to evaluate the state of apparent inter-seismic coupling in the Chilean-Peruvian subduction margin (12ºS – 25ºS). As observational constraints, we use previously published horizontal velocities from campaign GPS [Kendrick et al., 2001, 2006] as well as 3 component velocities from a recently established continuous GPS network in the region (CAnTO). We compare results from both joint and independent use of these data sets. We obtain patch like features for Pc with higher values located above 60 km depth. We identify a strong correlation between the features of high Pc and the regions associated with the rupture process of the 1995 (Mw 8.1) Antofagasta, 2001 (Mw 8.4) Arequipa and the 2007 (Mw 8.0) Pisco, earthquakes; as well as the region identified as the Arica bend seismic gap, which has not experienced a large earthquake since 1877.

2. cGPS measurements

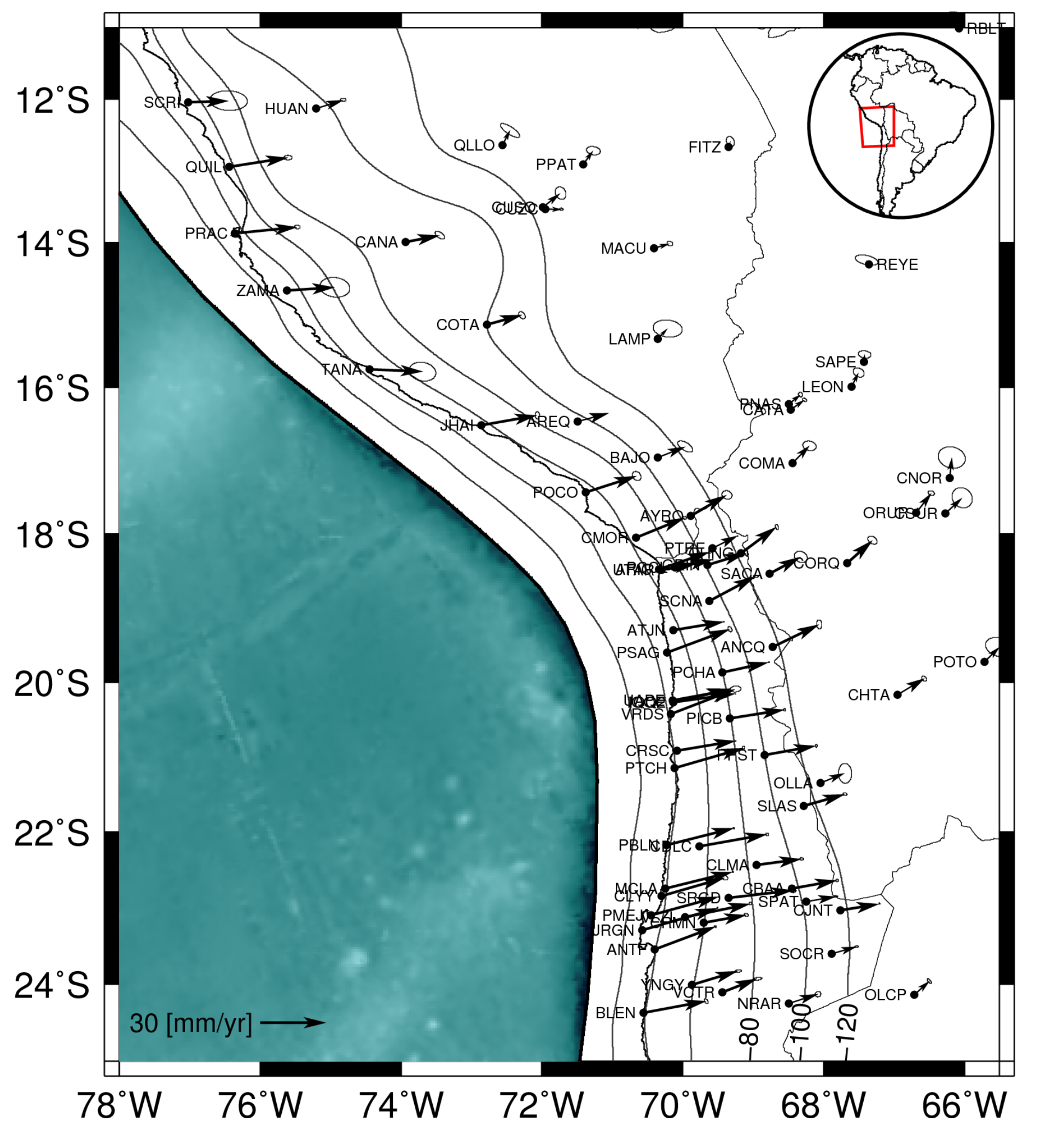


Figure 1: *GPS velocities from Kendrick et al. [2001, 2006], CAnTO (CALTECH), IPGP, IRD, DGF and IGS.*

3. Model Parameterization

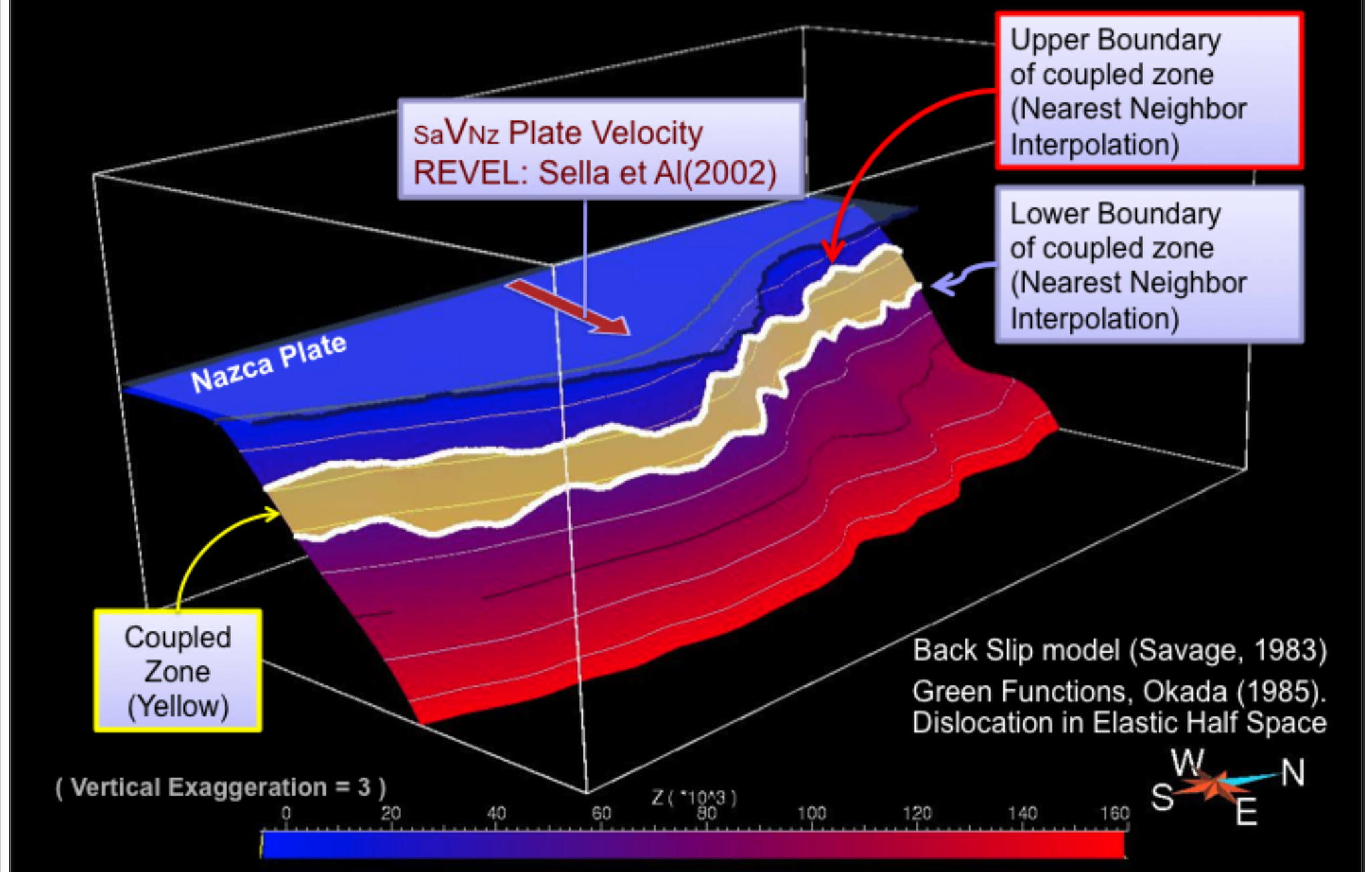
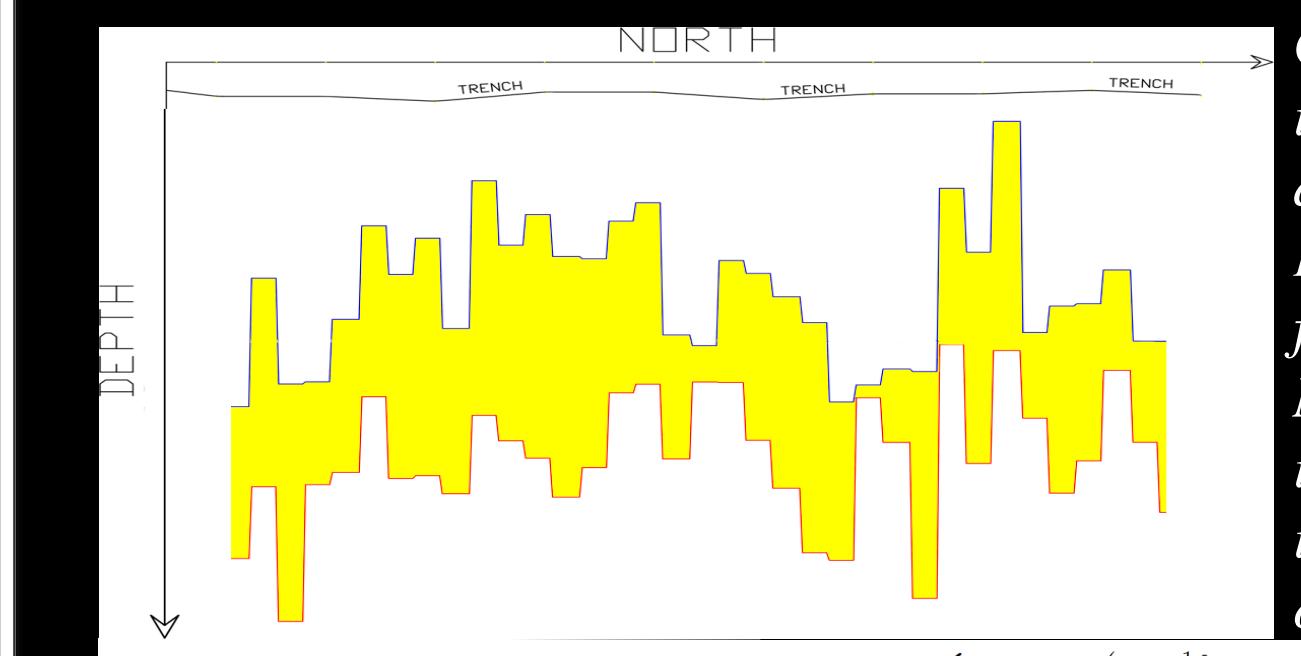


Figure 2: *Model parameterization and Geometry of the Nz - Sa Plate Interface.*

Coupling along the plate interface is characterized by two interpolated curves at depth, the upper and lower boundaries of the coupled zone, defining a mask in which the plate interface is coupled in the region enclosed by these curves (yellow area) and uncoupled outside it.

We use a back-slip model (Savage, 1983) to represent the inter-seismic strain accumulation at the plate interface, where a constant back-slip rate is imposed at the coupled zone. We ignore the possible existence of any transition zones. Plate convergence is represented by motion of a rigid plate on the sphere (Cox and Hart, 1986), with an Euler vector taken from the REVEL model (Sella et al, 2002). A finite dislocation in an elastic half space (Okada, 1985) is used to generate Green's functions. The geometry of the plate interface is built using GOCAD Suite, constrained with independent sets of geophysical data.

Free parameters of our model are the depth of the interpolation knots defining the updip and downdip boundary curves as well as a reference frame correction for each independent dataset (interseismic velocity field). Nearest neighbor interpolation is used in order to preserve the statistical properties of the knots depth for any interpolated point of the curve. Our approach has no regularization other than the spatial scale imposed by the knot spacing.



Coupled region projected into a vertical surface defined by the trench. Each boundary curve is formulated by Nearest Neighbor interpolation of its knots. The function Z(x) is used to describe the depth of each boundary.

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

H( ) is the Heaviside function.

Figure 3: *Representation of the Coupled Zone in a vertical surface along trench.*

4. 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: the depth of the k-th knot of the curves $Z_{\text{upper boundary}}(x)$ and $Z_{\text{lower boundary}}(x)$ defining the coupling at the plate interface.

4a. Why a Bayesian approach?

To motivate the use of the Bayesian approach, we show 2 scenarios for the coupling at the plate interface: a plate interface coupled from the trench up to 50 km-depth with a linear transition zone from coupled at 50 km to uncoupled below 70 km-depth (Fig. 4a) and a hand made example using our parameterization (Fig. 4b). For ilustrative purposes, we only show the forward calculation for GPS velocities from Kendrick et al. [2001].

4a. Why a Bayesian approach? (cont)

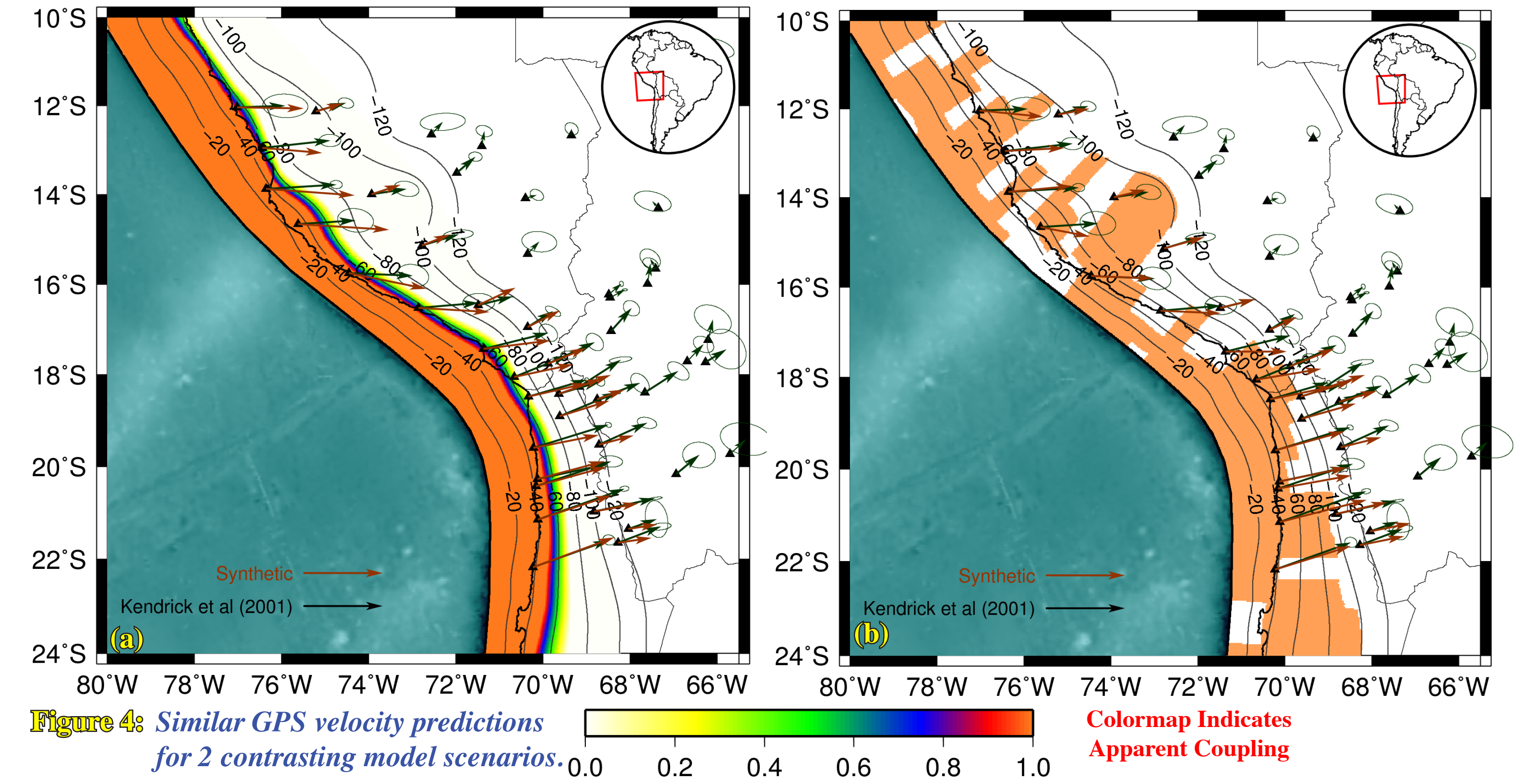


Figure 4: *Similar GPS velocity predictions for 2 contrasting model scenarios.*

The two cases can be considered as viable solutions of the problem, since the prediction of both models explain equally well the GPS velocities, suggesting big uncertainties in the location of the coupled zone. Here we note the importance of estimate the whole range of possible values for the model parameters, i.e., to properly sample their uncertainties. The Bayesian approach allows us to compute such uncertainties in a form of a probability density function (PDF) without assuming any functional form for the PDF and without prior regularization. Instead of a single solution to the inverse problem, we consider the entire PDF (thousands to millions sampled models). In the following, we explain how we represent this ensemble of models.

4b. Coupling Probability (Pc)

We need to represent statistically a given ensemble of several million models. We could compute the mean or median model among a percentage of the best suited sampled models. But we can not say for sure that the mean or median model is a viable model and, in the worst case, it may not even be a solution of the inverse problem or may not make physical sense. To avoid these complications, we represent the ensemble of models by computing the probability of coupling for each point $\mathcal{P}$ at the plate interface (Pc) from all the sampled models.

Given our parameterization, Pc can be easily estimated as:

$$\text{Pc}(\mathcal{P}) = \frac{\text{\# of sampled models in which point } \mathcal{P} \text{ is coupled}}{\text{\# of sampled models}}$$

5. A cautionary comment and selection of the a priori

With a Bayesian approach one can easily describe the *a priori* information in terms of relationships (or rules) between parameters. 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 constraints, the *a priori* PDF for each knot would be a boxcar function. However, in our model parameterization (Box3), the curves describing the updip and downdip boundary of the coupled zone must not intersect (red and blue curves in Fig. (3) will never cross). The net impact of such a constraint, is that the *a priori* PDF on each boundary of the coupled zone is not flat (or a boxcar), but triangular as shown in Fig. (5a), obtaining a Pc that is not constant in depth (see Fig (5b)). So, it is important to always first check the impact of the choice of priors before proceeding to estimate *a posteriori* estimates of our model parameters. Our goal is to have a uniform prior for Pc.

While beyond the scope of this poster, we must design a sampler that in the absence of prior information produces Pc = 0.5 (i.e., any given patch is equally likely to be coupled versus uncoupled). Thus, once we include data, if an area continues to have a value of Pc = 0.5 (grey), it implies that the data has not added information. It does not mean that there is partial coupling - especially since our current model parameterization does not include the possibility of partial coupling.

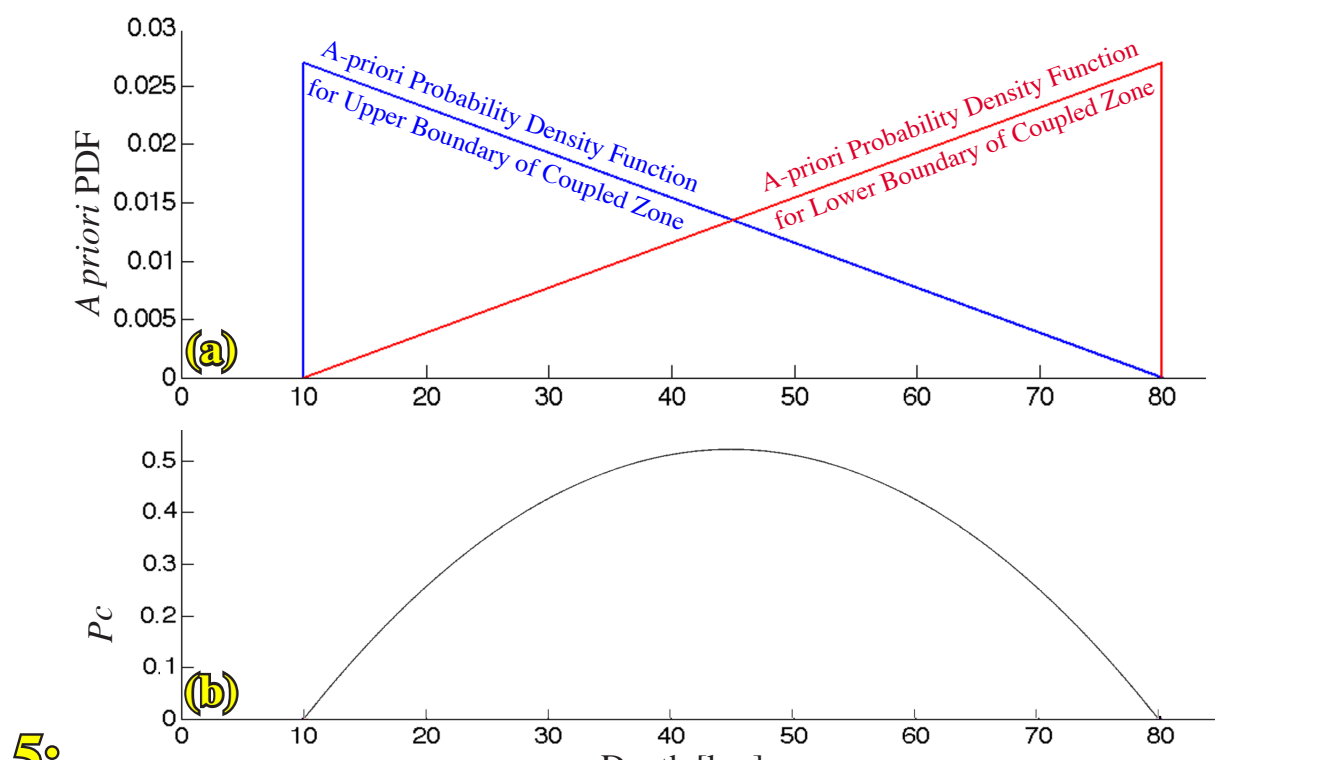


Figure 5:
(a) Triangular a priori PDF for the knots-depth defining the boundaries of the coupled zone due to an inadequate design of the Metropolis random walk.
(b) A priori Coupling Probability (Pc) obtained from the PDFs in Figure (5). Here Pc is NOT constant in depth because the parameterization of the model introduces information to the model parameters.

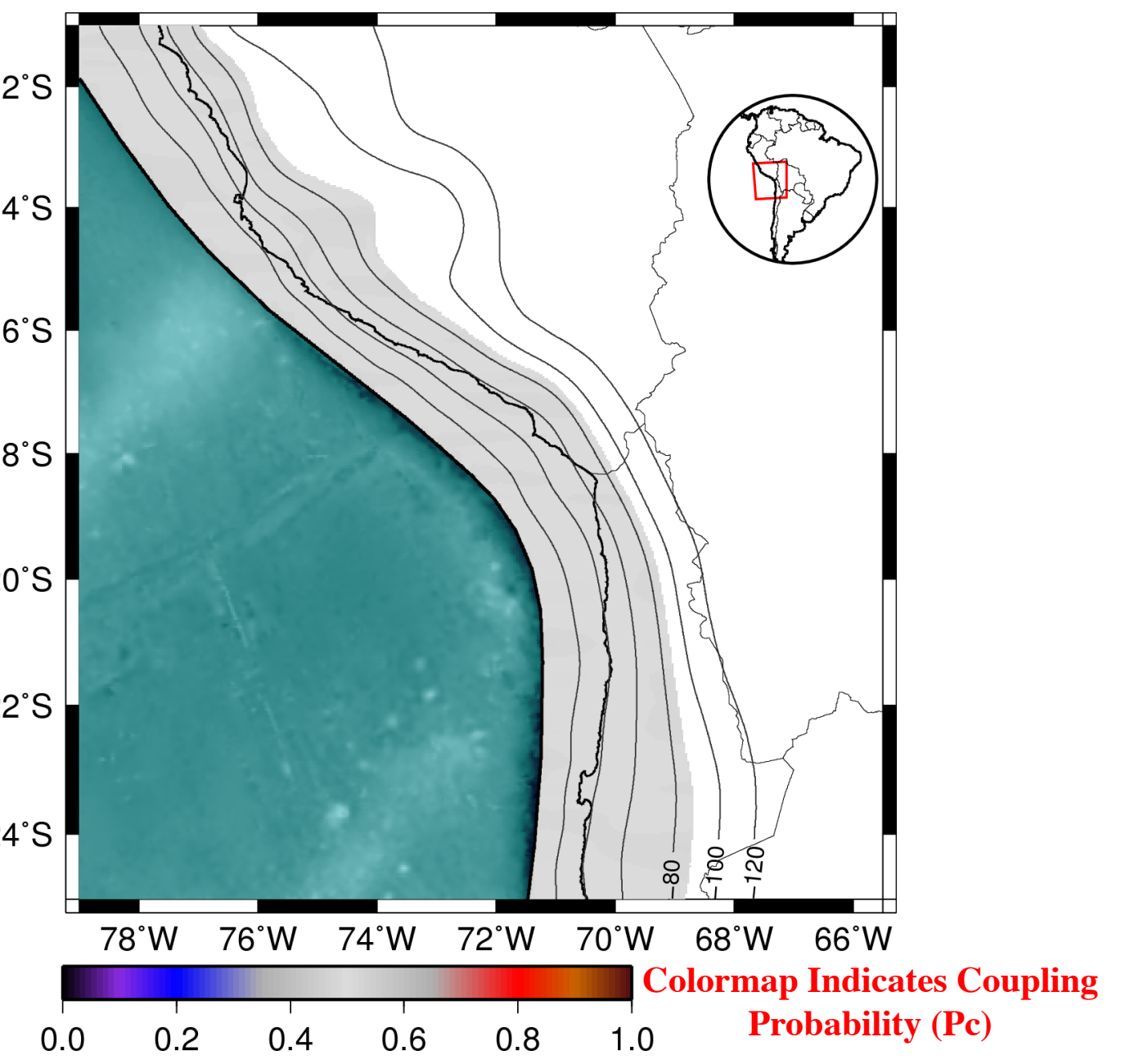
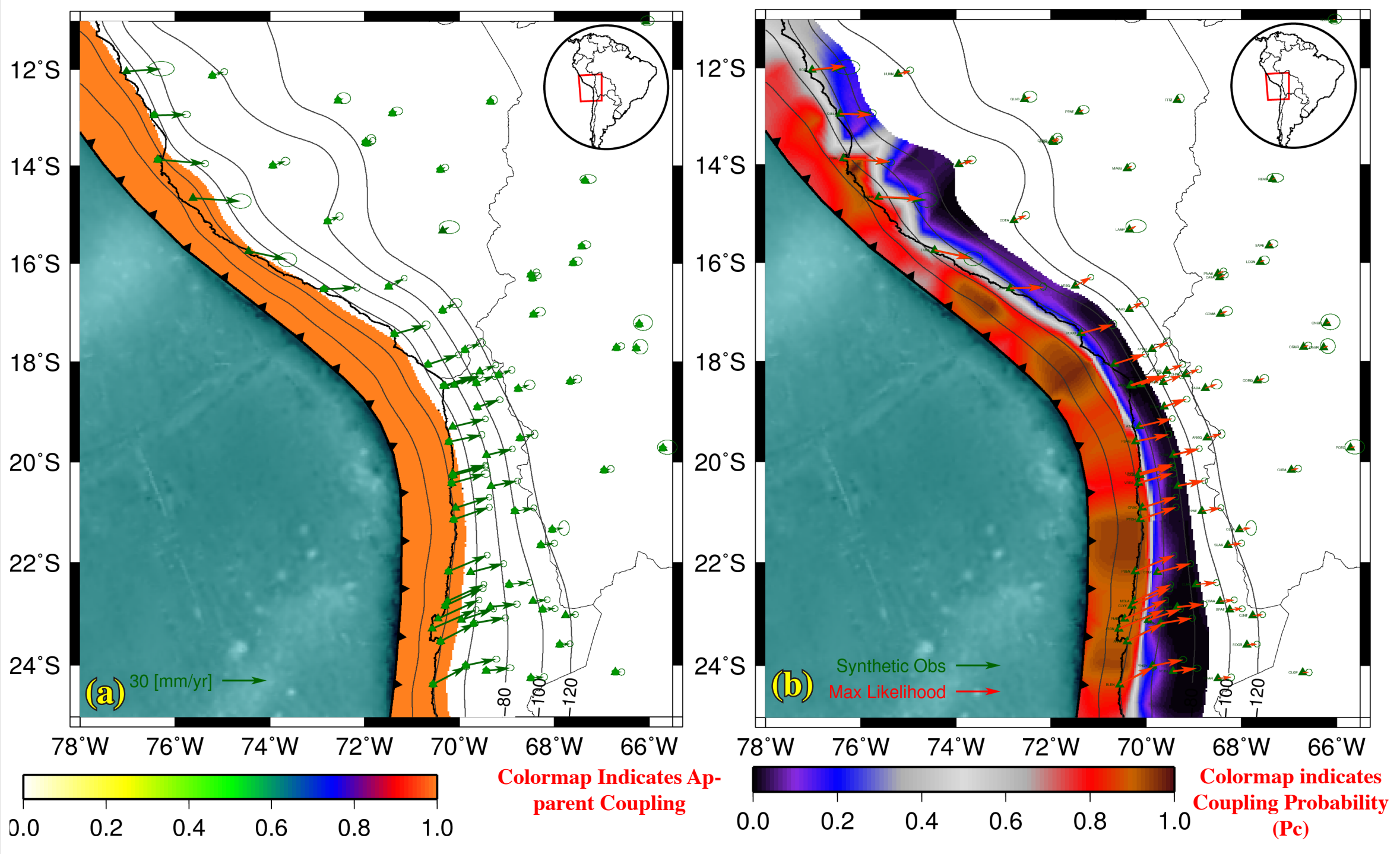


Figure 6: *We design the Metropolis random walk to produce an a priori coupling probability Pc = 0.5.*

6. Test with Synthetic GPS velocities



The inversion with the synthetic data allows us to test the resolution of the model parameters given the spatial distribution and uncertainties of the GPS observations. It does not test the effect of possible data inconsistencies on the model parameters.

The coupled portion of the plate interface is interpreted to be the one with high Pc (>0.75) and the uncoupled portion to be the one with low Pc (< 0.25).

Figure 8: *(a) Synthetic case. The plate interface is coupled from the trench depth up to 50 km depth. Green arrows are the synthetic observations generated with such coupling model. (b) A posteriori Coupling Probability constrained by the synthetic data. Red-brown colors (Pc > 0.75) indicate a high Coupling Probability and since our parameterization does not allow partial coupling, blue-black colors (Pc < 0.25) indicate a high probability for that point of the plate interface to be uncoupled (1 - Pc > 0.75).*

7. Results and Discussion

We obtain *a posteriori* estimates of Pc using the GPS velocities shown in Figure 1. Recall that wherever Pc is close to 0.5 (grayish color) it means that the model is poorly constrained in that region. When Pc is close to 0 it means that the probability for such point to be uncoupled (Pu) is close to 1, since Pu = 1 - Pc.

The higher anomalies for the probability of coupling (Pc > 0.8) are mainly located off-shore and above 40-50 km depth, which is in agreement with the conclussions of Tichelaar and Ruff [1993] in a study that characterizes the maximum locking depth of the subduction interface by an analysis of the seismicity of the region.

Note that in regions with high probability of coupling, this probability remains high up to the trench. This must not be interpreted directly as the configuration of asperities or coseismic slip region, since late in the seismic cycle, the inferred apparent coupling may reflect the stress shadows sourrounding those asperities. (Hetland and Simons [2010]).

We compare Pc against the co-seismic slip distribution of earthquakes in the region. Pisco (M8.0) 2007 and Arequipa (M8.4) 2001 earthquakes suggest that the region with high Pc is anticorrelated with the region of highest co-seismic slip. Such pattern is not clearly observed when comparing against Tocopilla (M7.7) 2007 and Antofagasta (M8.0) 1995 earthquakes.

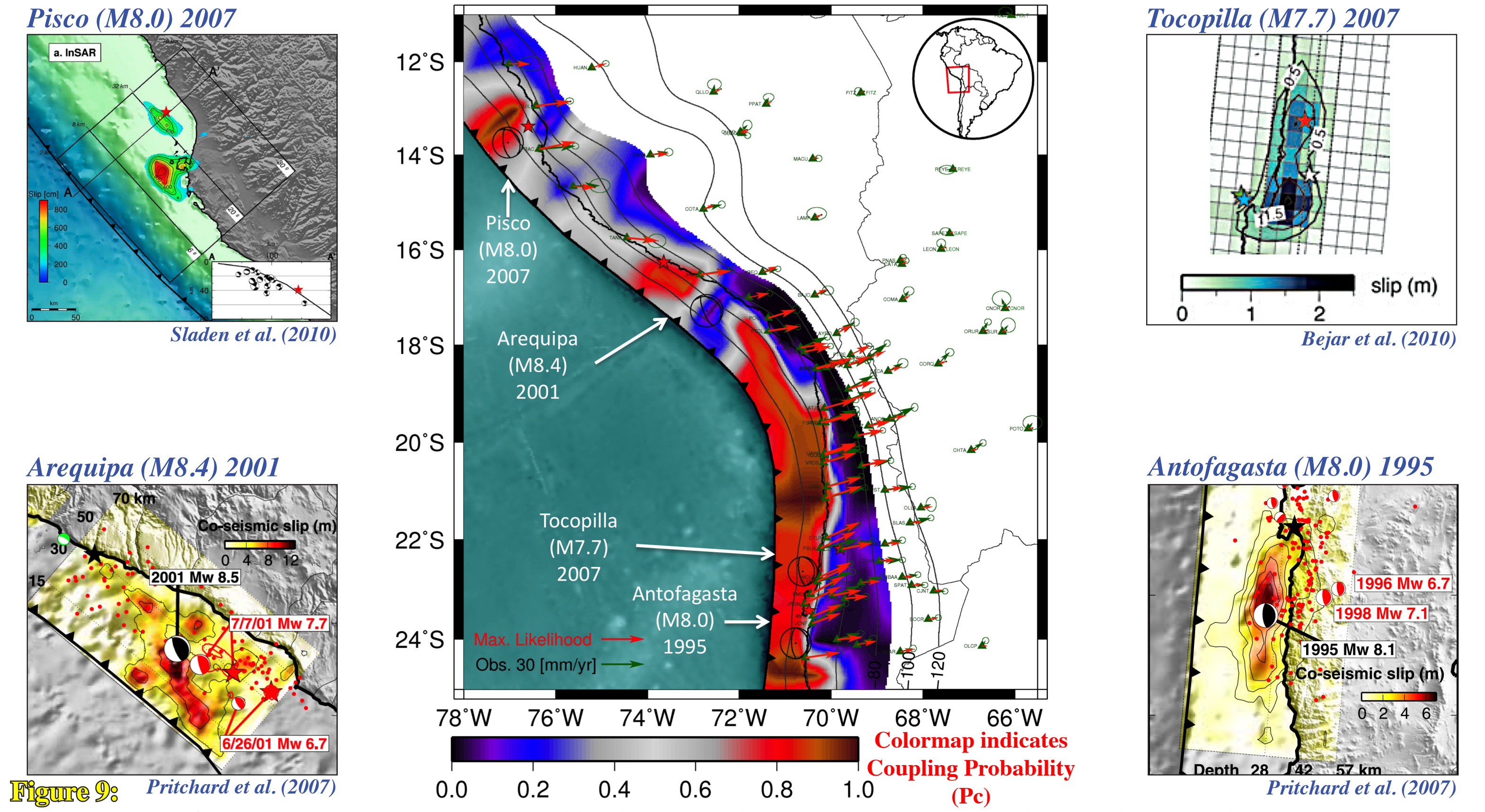


Figure 9: *Our estimates of the a posteriori Pc constrained by the GPS velocities (green arrows) along with GPS velocity predictions of the maximum likelihood model (red arrows). The focal mechanism and epicenter (red star) of past earthquakes are shown. Side boxes show a co-seismic slip distribution obtained by different authors for such earthquakes.*

8. References

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9. Acknowledgment

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