A Bayesian analysis of the 2016 M_w=7.8 Pedernales (Ecuador) earthquake

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1. Abstract

A Mw 7.8 earthquake struck Ecuador on April 16, 2016, causing significant damage and casualties. Long period W-phase and Global CMT solutions suggest that fault slip for this event agrees with the Ecuadorian subduction seismotectonic setting. We present a new co-seismic static slip model obtained from the joint inversion of multiple observations in an unregularized and fully Bayesian framework. Our solution includes the ensemble of all plausible slip models that are consistent with our prior information and fit the available observations within data and prediction uncertainties. We analyze the source process in light of the historical seismicity, in particular the Mw 7.8 1942 earthquake for which the rupture extent overlaps with the 2016 event. In addition, we conduct a probabilistic comparison of co-seismic slip with a stochastic interseismic coupling model obtained from GPS data.

2. Observations and model performance

We use a comprehensive static dataset composed of 2 descending and 1 ascending SAR interferograms, GPS static offsets from campaign and continuous stations, and tsunami waveforms from two nearby DART stations.
The descending Sentinel, descending ALOS, and ascending ALOS images include 8 days, 13 days, and 15 days of post-seismic deformation, respectively.

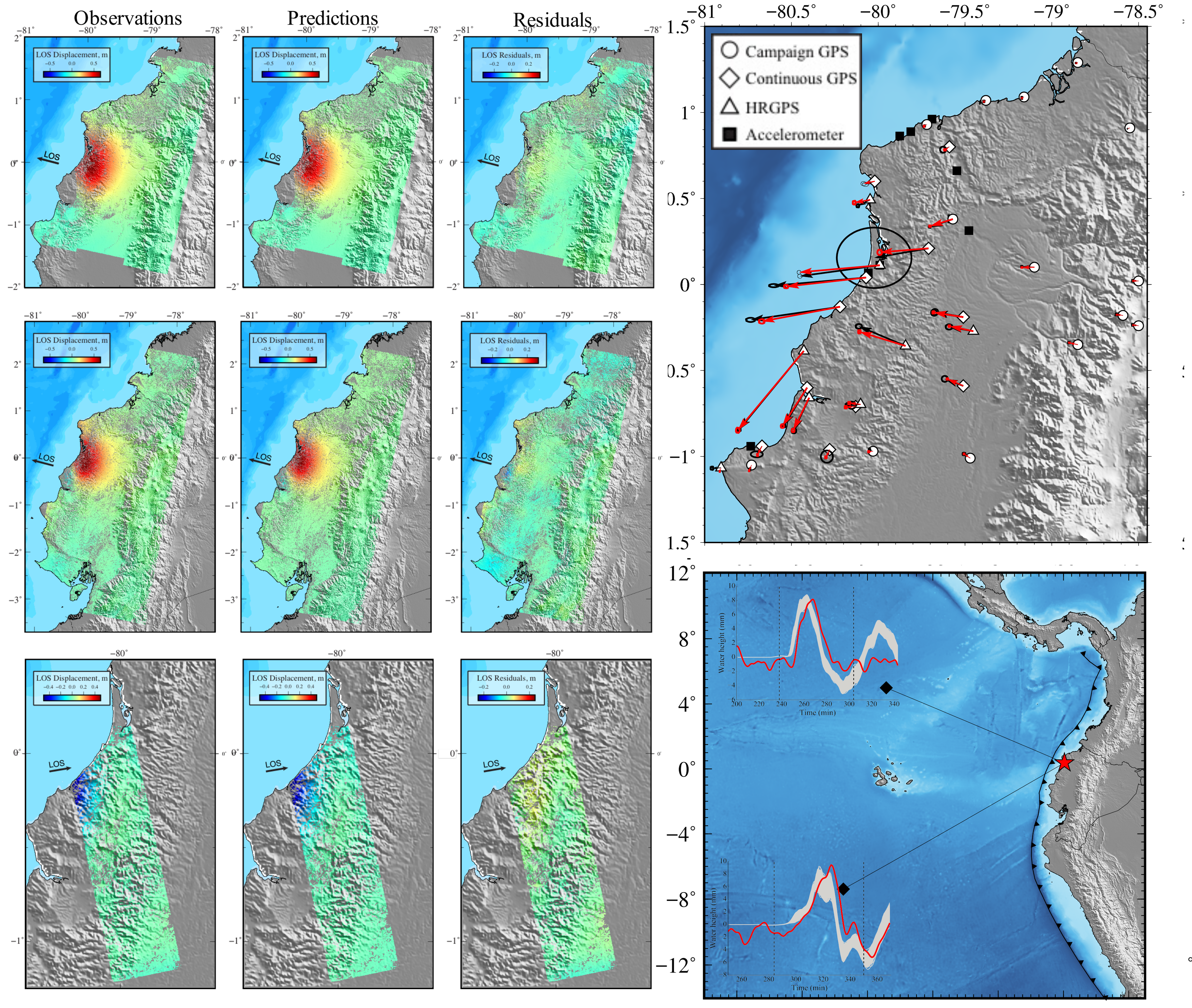


Figure 1: Static datasets used for this study. (left) InSAR observations (left column), predictions for the posterior mean model (middle column), and residuals (right column) of the descending Sentinel (top row), descending ALOS (middle row), and ascending ALOS (bottom row) scenes. **(top right)** GPS observations [*Nocquet et al. 2016*] (black arrows), and predictions for the posterior mean model (red arrows) along with their 1-sigma error ellipses. **(bottom right)** Tsunami observations (red curves) along with the stochastic predictions for our model (grey curves). The signal used in the inversion is delimited by the black dashed lines. The red dot marks the USGS hypocenter location.

3. Bayesian sampling

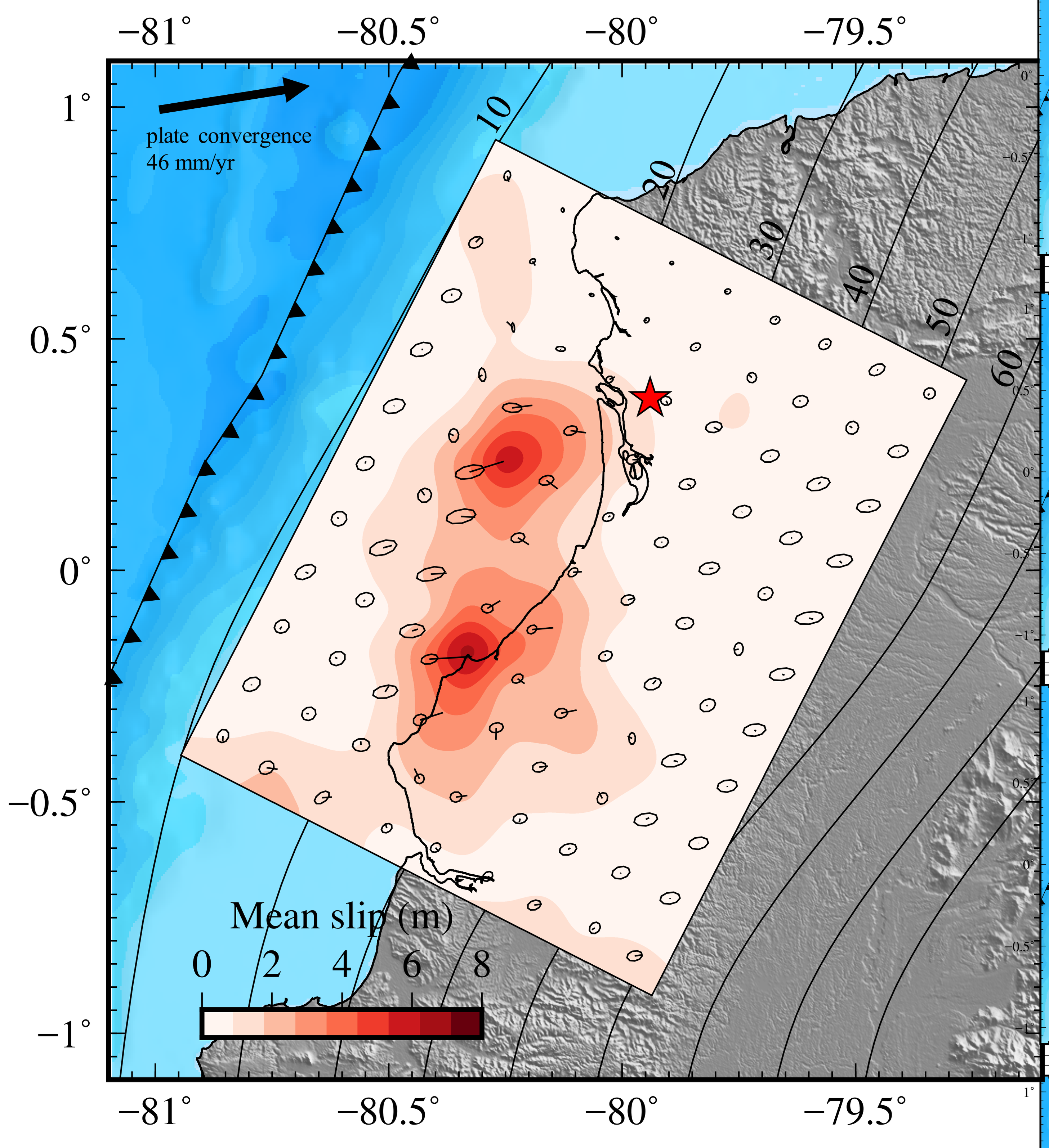
Our goal is to determine the *a posteriori* probability density function (PDF) of the slip distribution given the observations:

$$p(\mathbf{m}|\mathbf{d_{obs}}) \propto p(\mathbf{m}) \cdot \exp\left[-\frac{1}{2}(\mathbf{d_{obs}} - \mathbf{Gm})^T C_\chi^{-1}(\mathbf{d_{obs}} - \mathbf{Gm})\right]$$

where $\mathbf{m}$ is the vector containing the model parameters, $\mathbf{d_{obs}}$ is the data vector, $\mathbf{G}$ is the Green's functions matrix and $\mathbf{C_\chi}$ is the misfit covariance including both the data and prediction uncertainties (due to inaccuracies in Earth structure [*Duputel et al. 2014*]).

We use a AlTar, a Bayesian sampling approach based on Catmip [*Minson et al. 2014*], a parallel Markov Chain Monte Carlo algorithm allowing us to run 500 000+ chains in parallel. AlTar starts by sampling from the prior PDF $p(\mathbf{m})$ and then slowly increases the information brought by the data until it samples the posterior PDF.

4. Coseismic slip distribution



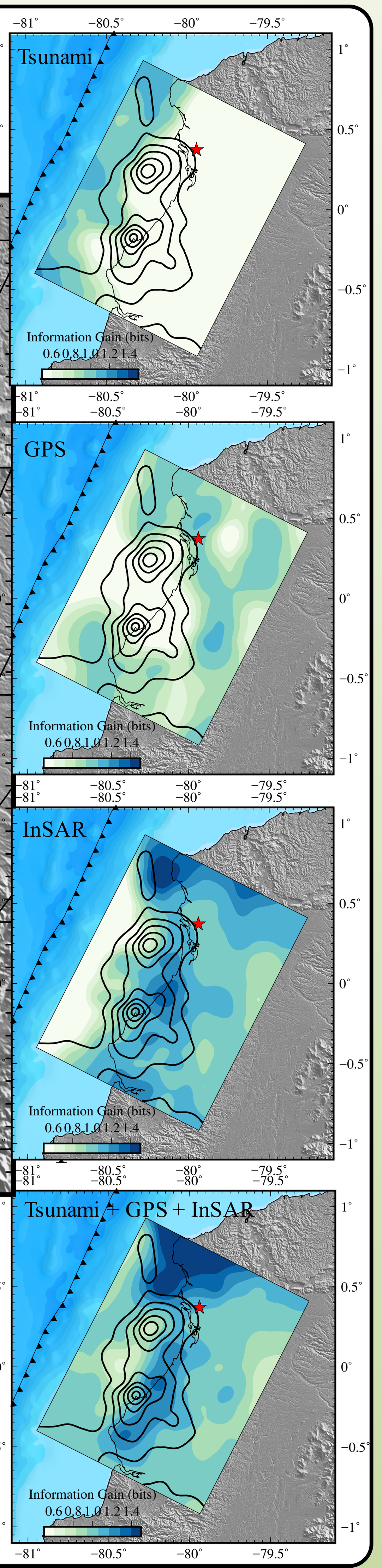


Figure 2: (left) Posterior mean coseismic slip model of the Pedernales earthquake. The color of each subfault patch indicates the slip amplitude. Arrows and their associated 95% confidence ellipse indicate the slip direction and uncertainty. For each fault patch, slip is inverted along the plate convergence direction and its orthogonal direction.
(right) The Kullback–Leibler divergence (i.e. information gain between the prior and the posterior PDFs) plotted for inversion results using different datasets combinations. A high value of the Kullback–Leibler divergence indicates a significant evolution from the prior PDF to the posterior PDF, meaning that the observations brought valuable information to the inversion.

5. Coupling model

We estimate the coupling along the Ecuadorian Subduction margin using inter-seismic GPS data. The inversion is performed with the same Bayesian framework as our co-seismic slip model. We find a 88% chance that the coupling is higher than 0.3 where the coseismic slip is larger than 2.5m, against 3% for the overall interface. Moreover, assuming that the 1942 reset the accumulated elastic strain, areas of large slip show a significant excess of co-seismic slip. ~73% of our solution shows a coseismic slip exceeding 2.5 times what has been accumulated since 1942. It is however possible that the 1942 did not release all the elastic strain accumulated or that it did not rupture this part of the fault

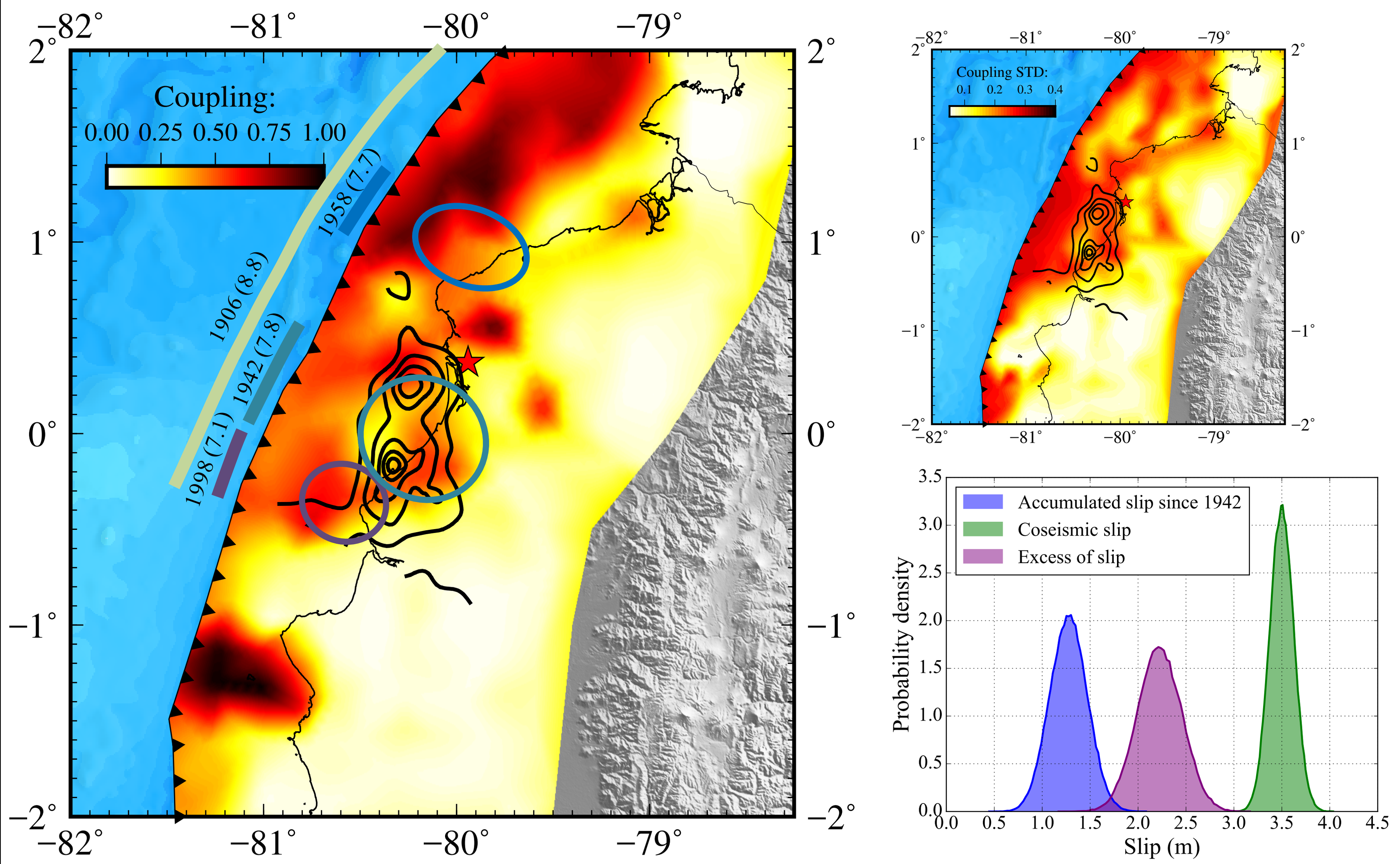


Figure 3: Comparaison of co-seismic slip with subduction interface coupling. (left) Posterior mean coupling model of the Ecuadorian subduction margin. Color ellipses indicate approximate location of historical seismicity [*Chlieh et al 2014*] . Black lines represent the 1m isoslip contour of co-seismic slip. **(top right)** Standard deviation of the coupling model**. (bottom right)** Probability density functions of co-seismic slip, accumulated slip, and excess of slip in the area exceeding 2.5m of co-seismic slip. The slip accumulated since 1942 is computed as Coupling × Convergence rate $(46mm/yr)$ × Time since last earthquake $(74yr)$

6. Conclusion

- Using a realistic uncertainty model, an extensive geodetic dataset, and a fully Bayesian framework we obtain an ensemble of plausible co-seismic static slip models of the Pedernales earthquake. We obtain a solution with a Mw = 7.8 and a peak slip of 7.0m +/- 0.55m. We observe two asperities which may have ruptured during the event.
- The coupling and co-seismic slip posterior mean models are in good agreement, with a spatial correlation of moderately coupled area with large co-seismic slip. Moreover, co-seismic slip on certain parts of the fault appears to be larger than what was accumulated since the last great earthquake in 1942. This means either that this earthquake is associated with significant overshoot or that the 1942 earthquake have not released all of the previously accumulated elastic strain in the region that slipped during the 2016 Pedernales earthquake
- The next step will be to incorporate temporal data (High-Rate GPS and accelerometric observations) in order to constraint the kinematic processes at play on the Ecuadorian subduction margin.

Acknowledgment

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