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Towards a Hybrid Broadband Ground Motion Simulation Model for Strong Earthquakes in South Iceland

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ABSTRACT

A seismological model for the hybrid simulation of the three largest recorded earthquakes in the South Iceland Seismic Zone (SISZ) is presented. The previous lack of a region-specific physical broadband ground motion model may be due to sparse geotechnical information and availability of only three well-recorded strong earthquakes (M6-6.5) with inferred static slip distributions. To simulate broadband (0-20 Hz) seismograms, we combine low frequency deterministic kinematic synthetics with stochastic high frequency waveforms using the Specific Barrier Model (SBM). The deterministic representation of fault rupture is in described by spatially heterogeneous slip, rupture speed and rise time using an approximated Yoffe-type source time function. The model is calibrated to strong-ground motion records, aided by the existing finite-fault static slip distribution models, and path and site effects are constrained using records of several smaller earthquakes. Most model parameters were constrained jointly through a Bayesian approach using the Markov Chain Monte Carlo methodology. The synthetic strong-motion time histories fit the recorded data well. Moreover, based on insight into the physical earthquake source parameters provided by the SBM, the presented models are expected to be representative of strong earthquakes in South Iceland. That in turn provides the basis for future earthquake scenario modeling of larger earthquakes and has potential implications for seismic hazard estimates.

Recorded Earthquakes in Iceland

The accelerograms of seven well recorded earthquakes from the SISZ have been selected as database and any bad records or triggered secondary events have been removed. We note that the magnitude range is narrow and the stations' soil characteristics are not well determined due to lacking geotechnical information.

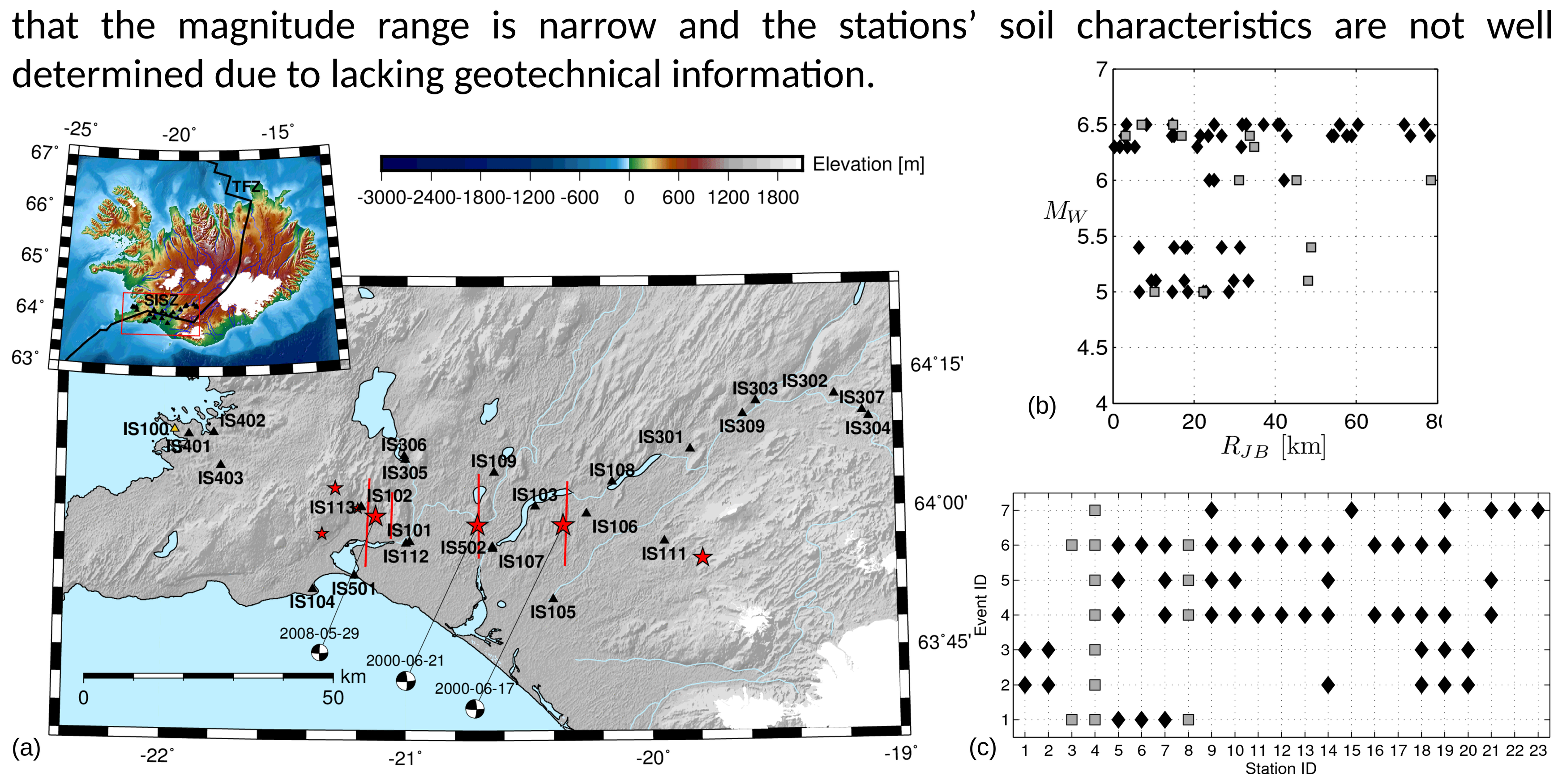

Figure 1. *(**a**) Map overview of the study area with stars indicating earthquake epicentres and triangles representing accelerometer stations. (**b**) Magnitude-distance distribution. (**c**) Distribution of records indicating which station has accepted data for a given event (rock sites are in black diamonds and soil sites are in grey squares.*

Stochastic Modeling Approach

To simulate high-frequency strong ground motion, we chose the stochastic modeling approach (e.g., Boore 1983), using the Specific Barrier Model (SBM) as source (Papageorgiou & Aki, 1983a,b), assuming frequency dependent attenuation ($Q(f)=Q_0f^\gamma$) and two-segment geometric spreading along the wave path (depth h, intermediate distance R_x), and apply a high-frequency decay correction (spectral decay parameter κ) additional to generic site response spectra as site model.

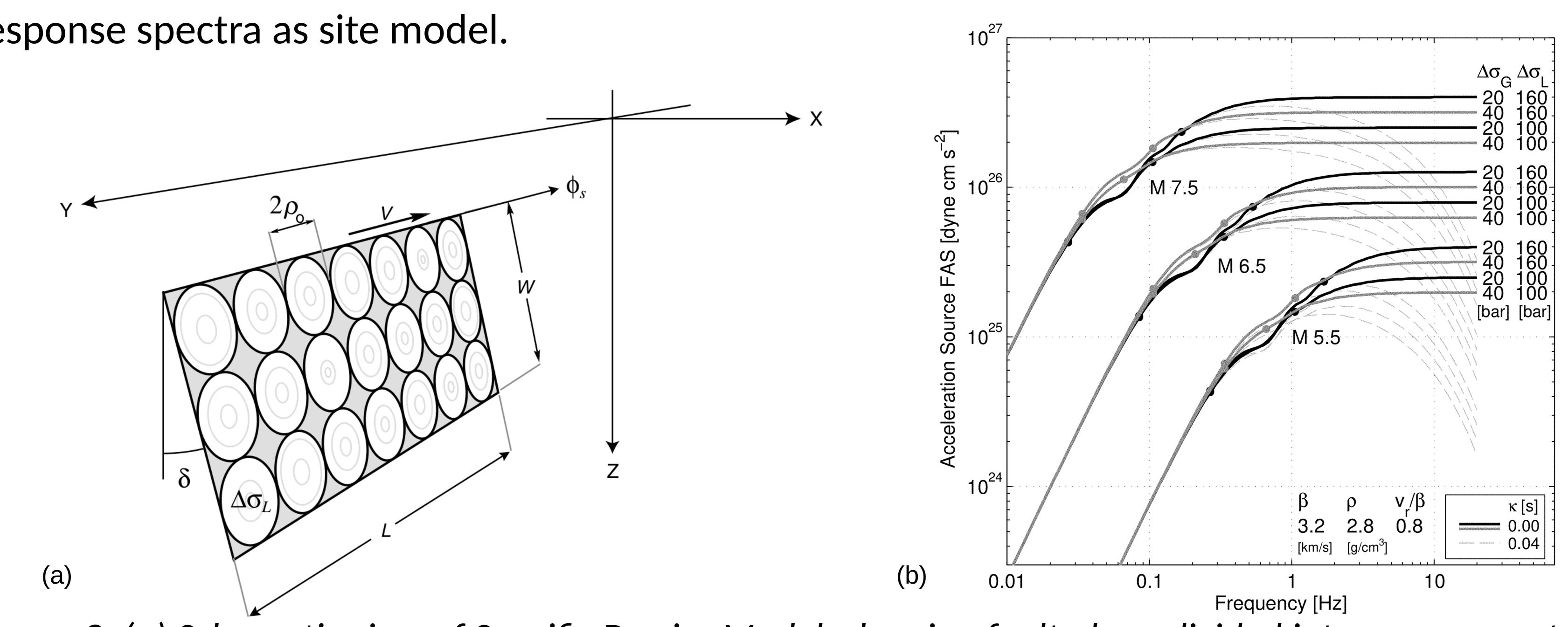

Figure 2. *(**a**) Schematic view of Specific Barrier Model, showing fault plane divided into an aggregate of circular cracks. (**b**) SBM source acceleration spectra for three different magnitudes with varying global ($\Delta\sigma_G$) and local ($\Delta\sigma_L$) stress drop. The associated corner frequencies are marked by large dots. Thin dashed lines include the Kappa filter effect.*

Statistical Model: Bayesian Random Effects

To allow for an event-dependent term, a random effects model is chosen such that inter- and intra-event sigmas (i.e. decadic logarithm of data to simulation residual standard deviance) are obtained:

$$\log(y_{ij})=f(M_i,r_{ij},\theta)+\eta_i+\epsilon_{ij}\ ,\quad \eta\sim Norm(0,\tau)\ ,\quad \epsilon\sim Norm(0,\sigma)$$

To infer the model parameters' marginal posterior probability distributions $\pi(\theta|y)$, a Bayesian inference using the Markov chain Monte Carlo approach is performed:
Bayes Rule: $\pi(\theta|y)\propto\pi(y|\theta)\pi(\theta)$, where $\pi(y|\theta)$ is the likelihood function or sample distribution, and $\pi(\theta)$ is the model parameter prior distribution (here: uniform with bounds based on conservative estimates). The assumption for the likelihood function is that the residuals of logarithmic pseudo-spectral accelerations are normally distributed.

Statistical Results

The posterior distributions of seismological parameters as inferred through the stochastic model as shown in Figure 3. Frequencies above 1 Hz are essentially unbiased and the range of uncertainties and their interrelationships can be analysed by inspecting the (2D) histograms.

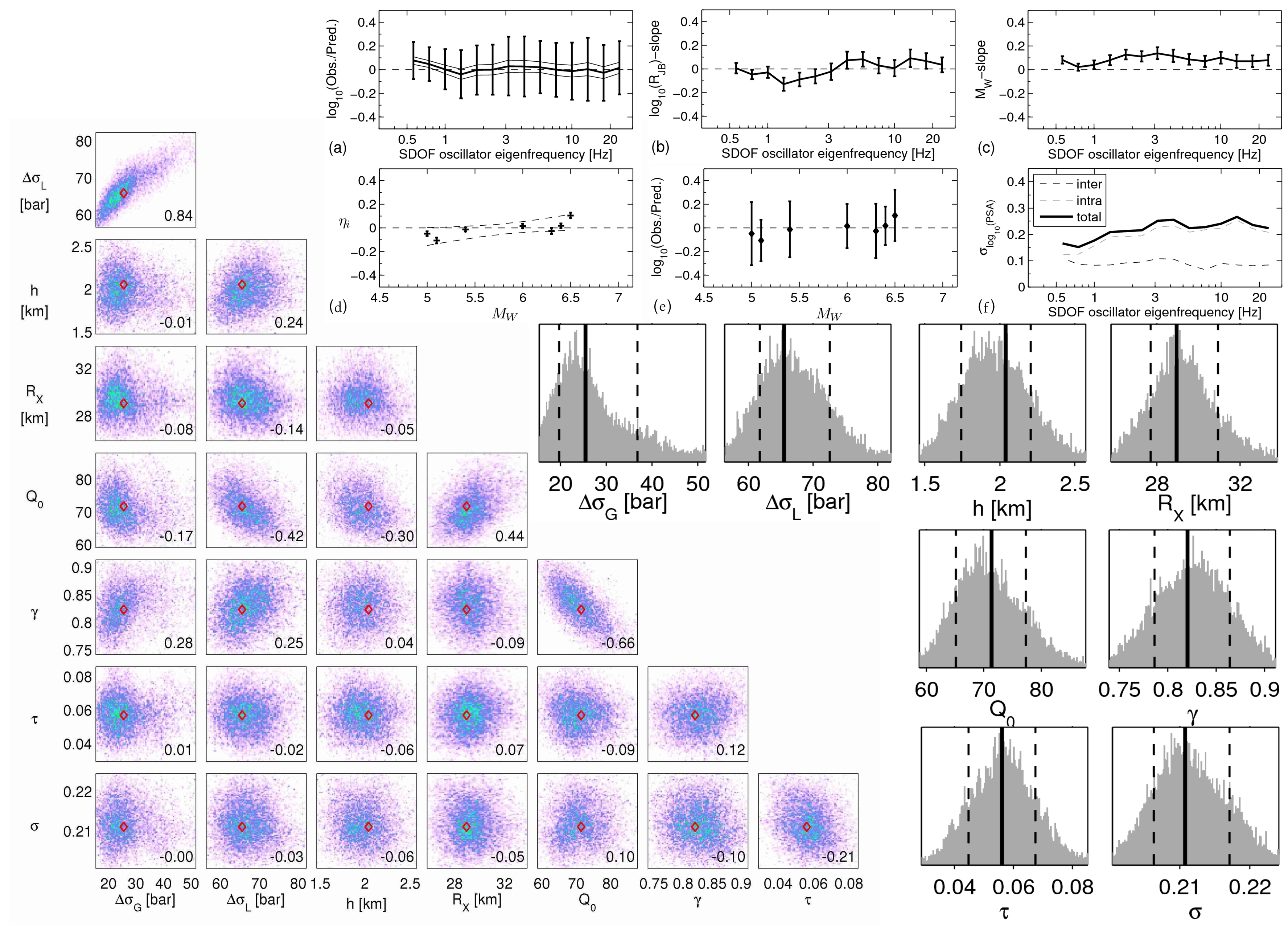

Figure 3. *Lower left: Correlation matrix of 2D posterior distributions for all parameter combinations. Lower right: Markov chain histograms indicating each parameter's marginal posterior densities. Top: (**a**) Mean residual bias, (**b**) slope of residuals versus log(R_{JB}) and (**c**) slope of residuals versus M_W, (**d**) event terms versus magnitude, (**e**) event-based mean residuals, (a-e) with one standard deviation, and (**f**) numerical total, inter- and intra-event sigmas versus oscillator frequency.*

Extended Fault Stochastic Simulation

To improve high frequency near-field synthetics, the point source representation of the SBM is substituted by a more realistic extended fault SBM with variable size subevents. Randomly distributed subevents produce waveforms showing directivity effects due to the involved geometry and spatiotemporal shifts. Inferred seismological parameters apply here as well.

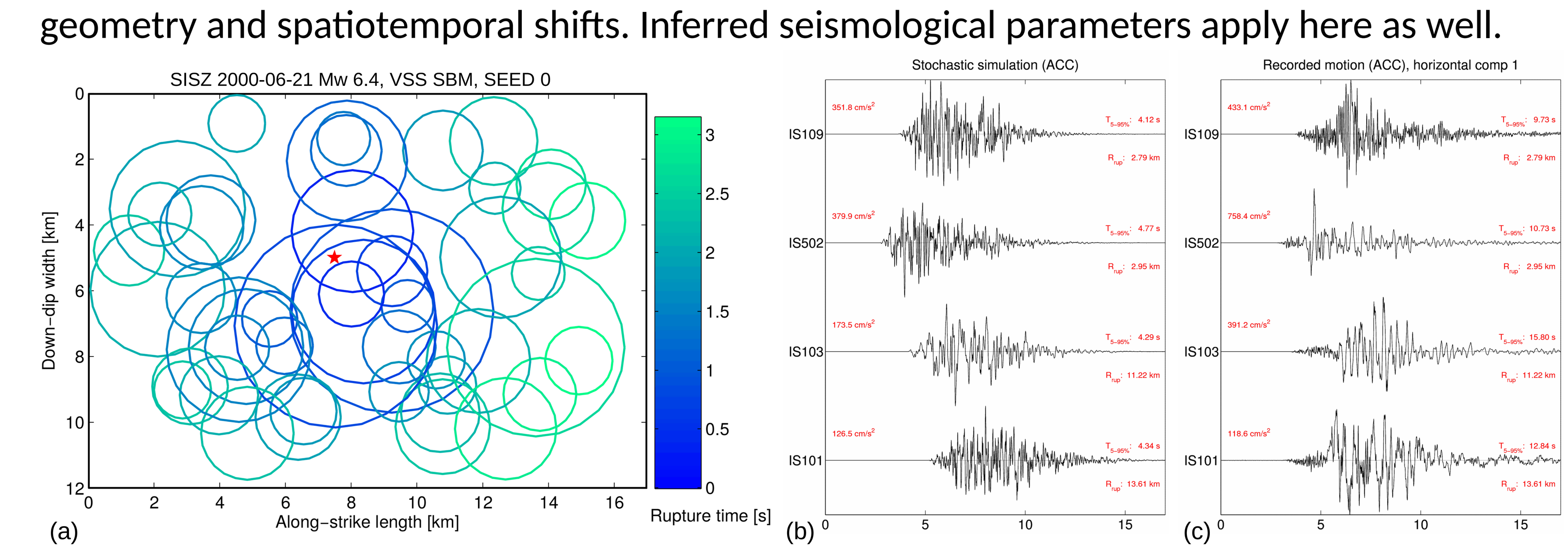

Figure 4. *(**a**) Subevent distribution over fault, colored according to their respective rupture initiation times. Also shown are corresponding simulated (**b**) and recorded (**c**) ground motions.*

Low-Frequency Waveforms by Deterministic Simulation

We note that kinematic models with simple parameter value assumptions can fit the low-frequency motions of the SISZ earthquakes reasonably well. For this, static slip inversion results are used as guideline while the dynamic parameters are taken from published relationships. We are currently also inferring the kinematic parameters with associated uncertainties from our data.

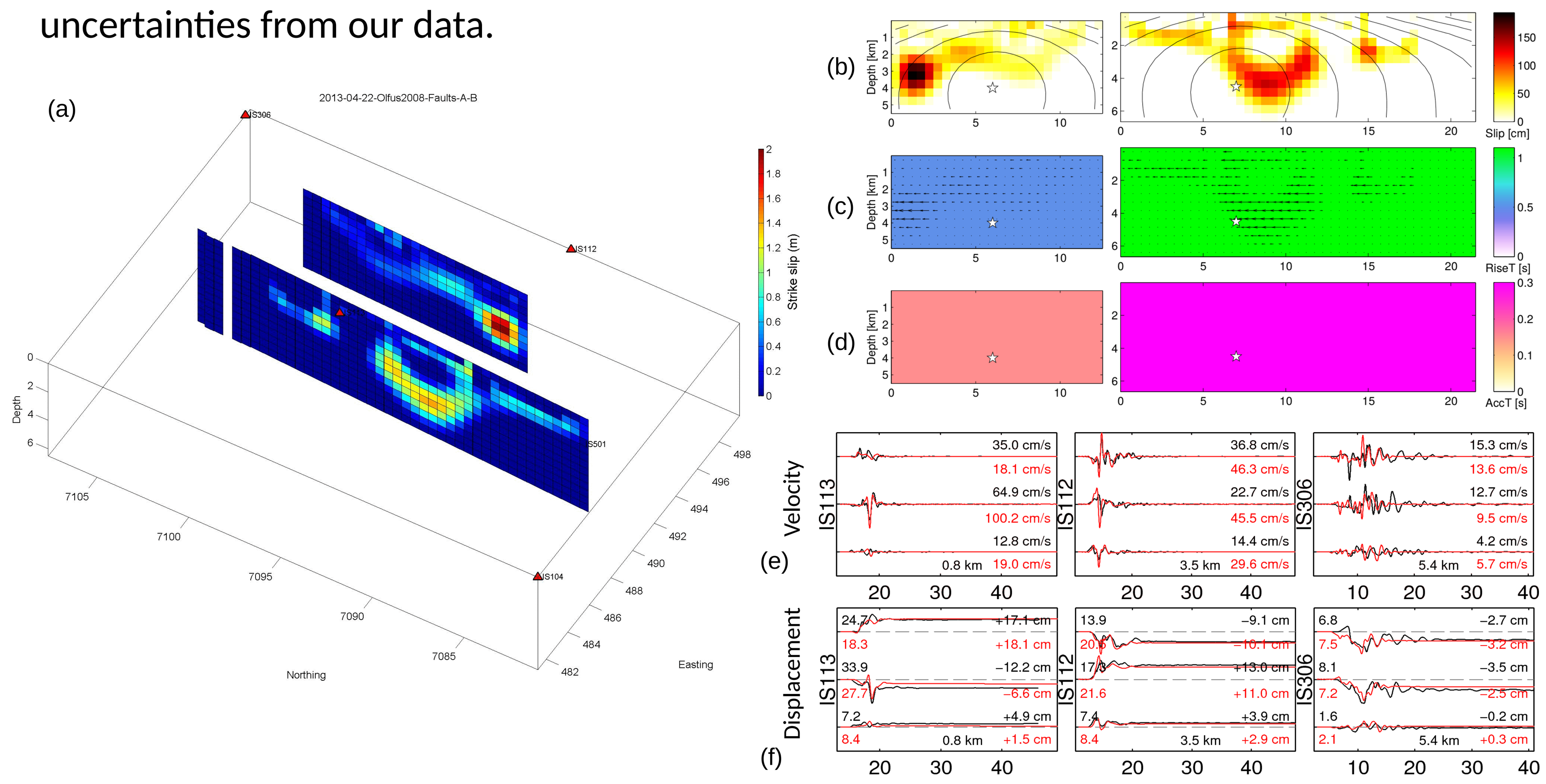

Figure 5. *(**a**) 3D representation of the 29 May 2008 earthquake doublet (M_W6.3) from the SISZ. The assumed slip (**b**), rise time (**c**) and acceleration time (**d**) for both fault segments are used to simulate velocity (**e**) and displacement (**f**) ground motion (synthetics: red, observed waveforms: black).*

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