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Forecasting the next largest earthquake during EGS stimulations

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Summary

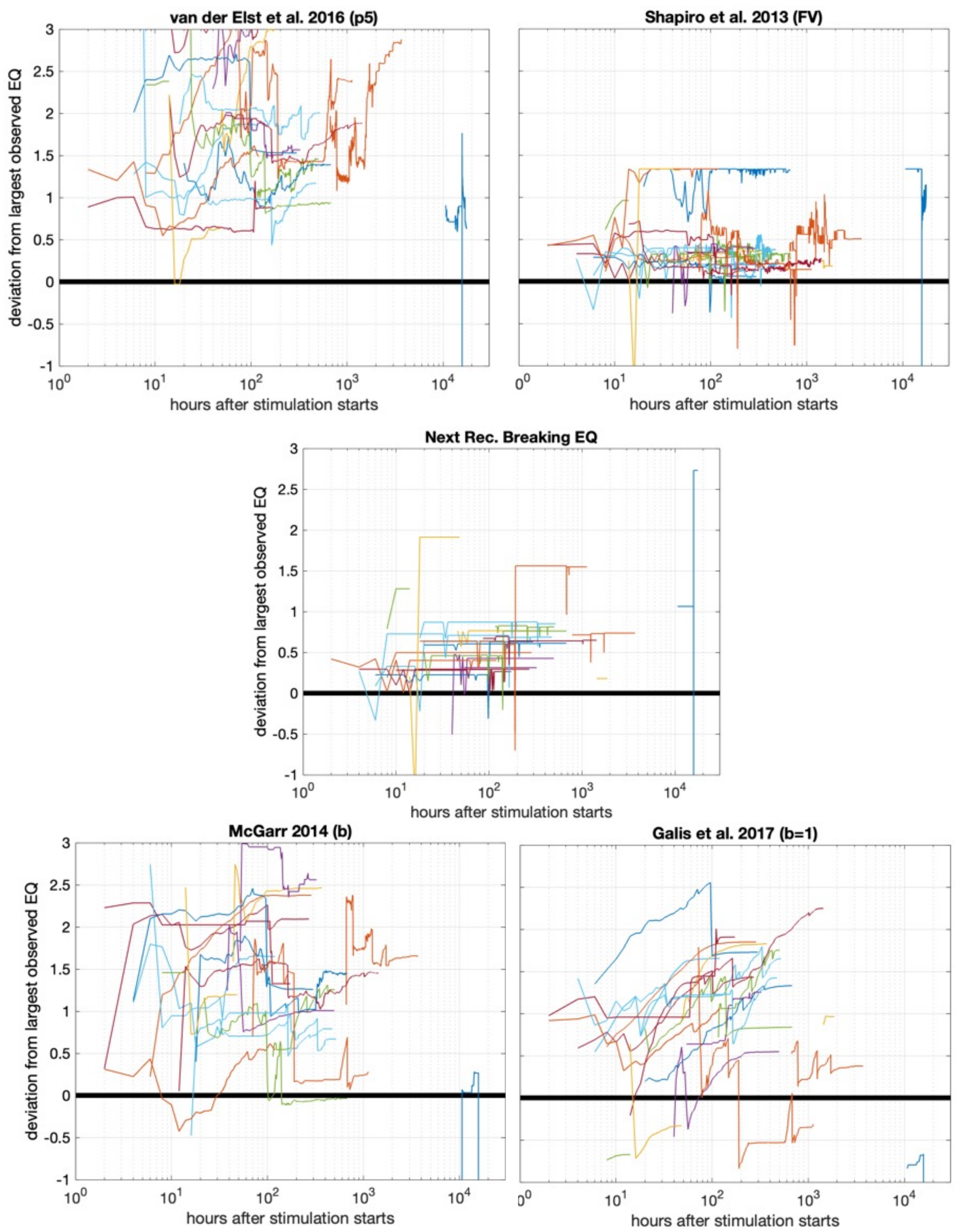
Most traffic-light protocols (TLP) related hydraulic fracturing stimulations still adopt the maximum observed magnitude as the decisive metric to aid decision making by stakeholders. However, waiting for the red-light magnitude to be observed is not a proactive stance, especially given that jumps of up to two magnitude units are evidently common enough between events. Clearly there is a need to actively forecast rather than to passively record the size of the next largest earthquake (NLE). In this study, we demonstrate that we can do just that using an ensemble of 6 existing models from the literature designed with similar purposes in mind (Shapiro et al. 2013; McGarr 2014; Mendecki 2016; van der Elst et al. 2016; Galis et al. 2017). Following a logic-tree approach, these 6 models are calibrated and dynamically weighted in near real-time using as sole inputs the initial parts of the earthquake catalogs and the reported injection rates (Kwiatek et al. 2024). The proposed forecasting tool performed very well when tested against 23 past stimulations from 9 different Enhanced Geothermal Systems around the world (Helsinki, Basel, Soultz, Cooper Basin, Pohang, FORGE, Paralana, Newberry, KTB, Berlin). We recommend that the forecasted NLE replaces the largest observed magnitude as the default metric adopted by future TLP governing any type of fluid-injection operation.

Methods

- McGarr (2014) proposed an upper bound for the cumulative seismic moment that can be released during a fluid-induced earthquake sequence. It is based on volumetric changes inducing seismic slip in a linear fashion. It assumes a Gutenberg-Richter magnitude-frequency distribution (GR-MFD) and relies on the total injected volume.
- Assuming a Poissonian statistical process for the seismicity and a GR-MFD, van der Elst et al. (2016) used the Seismogenic Index (Σ) model (Shapiro et al. 2010) to compute the maximum expected magnitude. The earthquake catalog and the injection volume are key inputs. We enforced a very low 5% probability of occurrence to redefine the estimate as an upper bound.
- Galis et al. (2017) proposed an estimate for the maximum seismic moment M_o^{max} of an arrested rupture based on the notion that such rupture is controlled by a competition between the injection-induced fluid pressure and tectonic prestress. The value of M_o^{max} is dependent on the total net injected volume ΔV with an exponent of 3/2. We assumed that the GR b-value is equal to 1 to be able to link the free parameter γ to Σ.
- The Next Record Breaking Event (NRBE) estimates the upper bound of the next largest event expected to occur based on a given catalog of earthquakes (Mendecki 2016; Kwiatek et al. 2024). It is estimated using order statistics on random variables. It does not rely on any injection data, nor does it assume any magnitude frequency distribution.
- The finite-volume (FV) formulation of Shapiro et al. (2013) applies a geometrical constraint on the size of any rupture, assuming it can nucleate and propagate only within the stimulated rock-volume. As a proxy for the latter a fitted ellipsoid around the evolving seismicity cloud is used. The earthquake catalog and the injection volumes are the sole inputs.
- We constructed an ensemble of these 5 models by dynamically weighting them to produce a weighted mean estimate for the next largest magnitude. The deviation between each forecasted largest magnitude and the observed one guided the simple weighting scheme. We penalized underestimation more than overestimation to stay on the conservative side.

Results

Overall, the results indicate a consistent (across sites and time) and accurate estimation of the next largest magnitude with a tight uncertainty range (1σ) of less than 0.5 magnitude units. Our proposed framework outperformed every single stand-alone model, as it underestimated the next largest magnitude only in three instances, while reliably maintaining a tight safety margin of less than 1 magnitude unit.



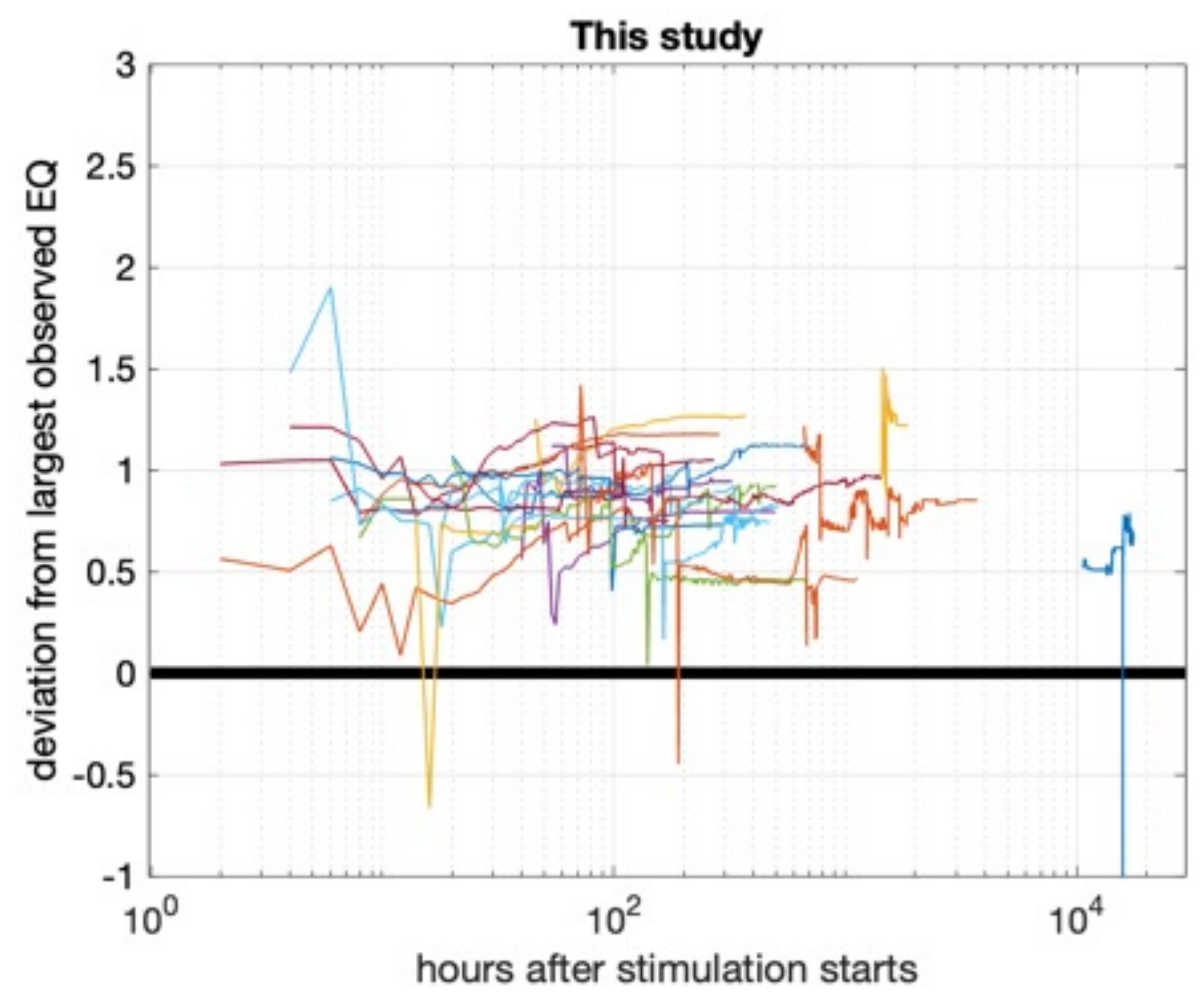


Figure 1. Performance of the models at forecasting the next largest EQ on a sequential basis, across all stimulations.

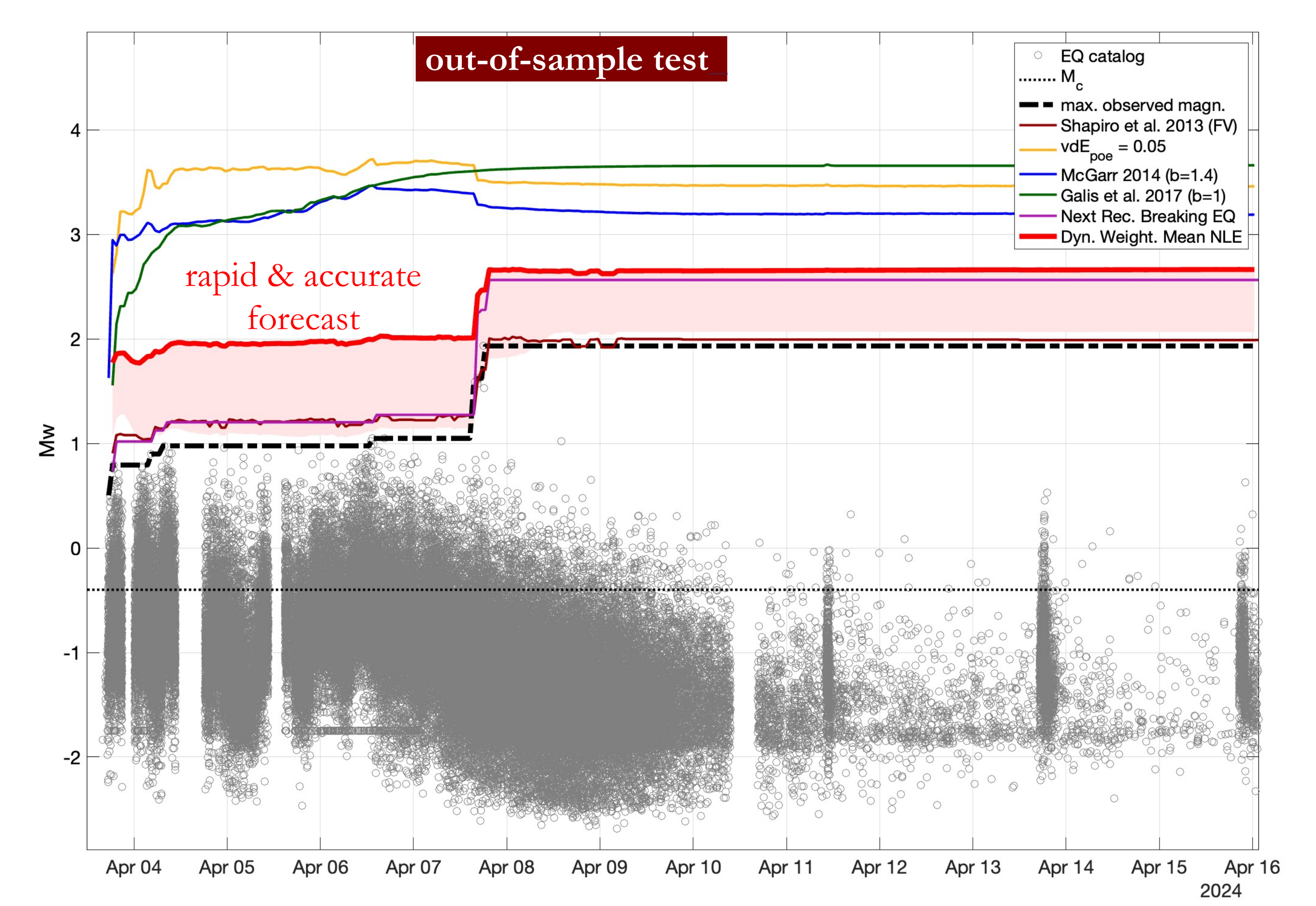


Figure 2: Hindcasting the NLE for the 2024 FORGE stimulation, using the real-time SED catalog.

References

Galis et al. [2017]. Sc. Adv. | Kwiatek, Grigoratos, Wiemer [2024]. SRL | McGarr [2014]. JGR | Mendecki [2016]. Institute of Mine Seismology | Shapiro et al. [2010]. Lead. Edge | Shapiro et al. [2013]. JGR | van der Elst et al [2016]. JGR |

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