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Pseudoprospective Evaluation of the Foreshock Traffic-Light System in Ridgecrest and Implications for Aftershock Hazard Assessment

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1	Pseudo-prospective evaluation of the Foreshock Traffic Light System in
2	Ridgecrest and implications for aftershock hazard assessment
3	
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5	
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12	
13	
14	Abstract
15	The Mw7.1 Ridgecrest earthquake sequence in California in July 2019 offered an
16	opportunity to evaluate in near real-time the temporal and spatial variations in the
17	average earthquake size distribution (the b-value) and the performance of the newly
18	introduced Foreshock Traffic Light System (FTLS). In normally decaying aftershock

20 10%-30% higher than the background b-value. A drop of 10% or more in 'aftershock' b-21 values was postulated to indicate that the region is still highly stressed and that a 22 subsequent larger event is likely. In this Ridgecrest case study, after analysing the 23 magnitude of completeness of the sequences, we find that the quality of the monitoring 24 network is excellent, which allows us to determine reliable b-values over a large range 25 of magnitudes within hours of the two mainshocks. We then find that in the hours after

sequences, the b-value of the aftershocks was in past studies found, on average, to be

26 the first Mw6.4 Ridgecrest event, the b-value drops by 23% on average, compared to the 27 background value, triggering a red foreshock traffic light. Spatially mapping the changes 28 in b, we identify an area to the north of the rupture plane as the most likely location of a 29 subsequent event. After the second, magnitude-7.1 mainshock, which did occur in that 30 location as anticipated, the b-value increased by 26% over the background value, 31 triggering a green traffic light. Finally, comparing the 2019 sequence with the Mw5.8 32 sequence in 1995, where no mainshock followed, we find a b-value increase of 29% after the mainshock. Our results suggest that the real-time monitoring of b-values is 33 34 feasible in California and may add important information for aftershock hazard 35 assessment.

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- 37

#### 38 Introduction

39

40 It is well known and almost universally observed that the stress changes caused by a 41 major earthquake strongly affect seismic activity in the vicinity, and the rate of 42 earthquakes increases near the mainshock rupture by several orders of magnitude (Okada, 1992; Stein, 1999; Ebel et al., 2000). In most sequences, on average, this 43 44 aftershock activity then decays exponentially back to the previous background rate (e.g. 45 Reasenberg and Jones, 1990), a process first described by Omori in 1895 and nowadays 46 often described with reference to the concept of Epidemic Type Aftershock Sequences 47 (ETAS) (Ogata, 1988). This systematic aftershock behaviour can be satisfactorily 48 explained and well modelled using models combining Coulomb stress changes and rate-49 and-state friction (Dietrich et al., 2000; Toda and Stein, 2003). It also constitutes the 50 baseline of probabilistic assessments of aftershock probabilities (e.g. Reasenberg and

Jones, 1994; Marzocchi et al, 2017; Omi et al., 2019). Today, the term Operational
Earthquake Forecasting (OEF) is often used when referring to aftershock forecasting in
near real- time (Zechar et al., 2016; Jordan et al., 2014).

54 Far less well established and not currently used in OEF is the fact that the stress 55 redistribution caused by a mainshock also systematically influences relative earthquake 56 size distribution, the b-value of the Gutenberg and Richter relationship (Gutenberg and 57 Richter, 1944; Ishimoto and Iida, 1939). Laboratory measurements taken since the 58 1960s have established that b-values are sensitive to stress (Scholz, 1968; Goebel et al., 59 2013; Amitrano, 2003) and this inverse dependency of b-value and the applied stress is 60 fully consistent with a number of observed b-value variations with depth, faulting style 61 and the loading state of faults (e.g. Petruccelli, 2019 a, b; Staudenmeier et al., 2019; 62 Scholz, 2015; Tormann et al., 2015; Gulia and Wiemer, 2010; Narteau et al., 2009). Mainshock stress changes are therefore expected to systemically change b-values, as 63 64 suggested by a number of case studies (Wiemer and Katsumata, 1999; Wyss and 65 Wiemer, 2000; Enescu and Ito, 2002). Just recently, Gulia et al. (2018) confirmed this 66 hypothesis in a systematic study. To establish generic b-value behaviours in aftershock 67 sequences, they applied a stacking approach to 31 high-quality aftershock sequences 68 from California, Japan, Italy and Alaska and demonstrated that the b-values of those 69 sequences generically increase by 20% after the mainshock. The higher b-value results 70 suggest a far lower probability of a subsequent large event. Gulia et al. (2018) also 71 presented a model based on Coulomb stress changes that explains the observations and 72 the observed dependencies on distance, magnitude and faulting style.

73 Based on these findings, Gulia and Wiemer (2019) postulated the hypothesis that 74 sequences in which the b-value of the aftershock decreased by 10% or more instead of 75 increasing as expected would indicate that a bigger event was not yet to occur. The

76 authors then extended their b-value analysis by successfully testing this hypothesis on 77 three sequences where a secondary larger mainshock occurred, and proposed a 78 Foreshock Traffic Light System (FTLS) which, taking b-value evolution over time as an 79 indicator of the average stress condition of faults in a region, defines three alert (or 80 concern) levels that can be used to determine in near real-time whether an ongoing 81 sequence is likely. The lowest, 'green' alert is triggered by a normally decaying 82 aftershock sequence (b-value increases by 10% or more). The highest, 'red' alert indicates a precursory sequence that is more likely to be followed by a larger event (b-83 84 value decreases by 10% or more). Sequences falling between these extremes trigger 85 'orange' alerts. Gulia and Wiemer (2019) tested the FTLS on 58 sequences and found it 86 to be more than 95% accurate. Differential b-value maps are proposed as an additional 87 step to estimate the likely location of subsequent larger events. The FTLS is thus 88 proposed as a tool for real-time discrimination between foreshocks and aftershocks, but 89 the authors also point out that additional, ideally fully prospective tests, are needed 90 before FTLS can be used in Operational Earthquake Forecasting (OEF) systems.

91

92 Key to the robustness of b-value based forecast is a correct assessment of the 93 completeness of reporting, Mc, for this variable fluctuates dramatically during 94 aftershock sequences (Hainzl, 2016; Helmstetter et al., 2006; Woessner and Wiemer, 95 2005). In the past, if often took weeks or even years to post-process the rich catalogues 96 of aftershock sequences to make them fully useful for statistical seismology. 97 Consequently, another objective of our study is to investigate the reliability of assessed 98 statistical parameters of aftershock sequences in the light of improved modern-day 99 network-processing capabilities and automation. A further, related objective is to 100 analyse whether high-precision and more complete datasets based on cross-correlation,

101 provided by Shelly (2020), can improve the reliability and lower the latency of 102 aftershock forecasting. We also investigate another potential limitation of near-real 103 time application, the availability of reliable focal mechanism data.

In many ways, the Ridgecrest sequence is an ideal case study for investigating the effects of mainshock on the size distribution of aftershocks, and our study is the first prospective evaluation of the FTLS as a purely data-driven decision support system.
Finally, we discuss the implications of our analysis for aftershock hazard assessment.

108

# 109 The 2019 Mw7.1 Ridgecrest sequence

On the morning of 4 July (at 17:33 UTC time) a Mw6.4 earthquake hit eastern California in the Mojave Desert (Ross et al., 2019), injuring about 20 people and damaging numerous buildings in the Ridgecrest area (earthquake.usgs.gov). Over the past 40 years, this part of southern California has experienced several moderate earthquakes, the largest being a Mw5.8 event on 20 September 1995, about 13 km away from the Mw6.4 event.

116

117 The earthquakes following the Mw6.4 quake outline two lineaments: one SW-NE and 118 the other NW-SE, on an unmapped fault, exhibiting a distinctive 'T' pattern created by 119 the simultaneous activation of two or more faults (Ross et al., 2019; Hobbs, 2019). 120 During the hours after the mainshock, United States Geological Survey (USGS) 121 seismologists estimated in near-real tine probabilities of aftershocks and subsequent 122 mainshocks, using in essence the Reasenberg and Jones (1990) approach 123 (https://earthquake.usgs.gov/earthquakes/eventpage/ci38457511/oaf/commentary). 124 Immediately after the mainshocks, this model estimated the weekly probability of one 125 quake being followed by a second mainshock of equal or larger magnitude at about 9%

(Michael et al., 2020; Hardebeck et al., 2019). This figure was higher than the default
value of 5% obtained when using the standard Reasenberg and Jones (1990) parameter,
because of the higher than average aftershock productivity in the region (Hardebeck et
al., 2019). Just one day later, a Mw7.1 earthquake struck (at 8:20 p.m. local time on 6
July, or 03:20 UTC) at a distance of about 7 km.

131

132 The aforementioned probabilities of a subsequent larger earthquake occurring, as is common in California, were also cited in public. For example, after the second event 133 134 Dr Lucy Jones tweeted: "So the M6.4 was a foreshock. This was a M7.1 on the same fault as has been producing the Searles Valley sequence. This is part of the same sequence." 135 136 This was followed by: "You know we say 1 in 20 chance that an earthquake will be followed by something bigger? This is that 1 in 20 time." And then: Yes, we estimate that 137 there's about a 1 in 10 chance that Searles Valley will see another M7. That is a 9 in 10 138 139 chance that tonight's M7.1 was the largest".

140

Here, we monitor fluctuating b-values and apply the FTLS in a near real-time application, comparing the FTLS forecast with currently used aftershock probabilities for California. We then compare the FTLS's performance with preliminary, revised and high-resolution datasets. A key aim in our research was to evaluate the feasibility of using b-value fluctuations for real-time hazard assessment.

146

## 147 **Data and method**

To compute a reliable and detailed b-value time series, we used a window approach, moving a window with a fixed sample size, event by event. In order to provide a prospective evaluation, the method strictly adheres to the approach used by Gulia and

151 Wiemer (2019; in review before the Ridgecrest mainshocks). The codes used can be 152 downloaded from https://doi.org/10.3929/ethz-b-000357449. Here is a brief 153 description of the approach and sequence-specific aspects. Using the quick focal 154 mechanism of the Mw6.4 (GCMT, Dziewonski et al., 1981; Ekström et al., 2012) and the 155 Wells and Coppersmith relationships (Wells and Coppersmith, 1994) corresponding to 156 the tectonic style of the event -strike slip-, we built two possible fault planes, with a 1-157 km spaced grid. To decide quickly and automatically which was the most likely fault plane, we selected all events recorded in the sequences within the first hour and within 158 159 a radius of 3 km from each grid point of the fault plane (from now on, the box), then 160 selected the plane where most of the aftershocks occurred. While more sophisticated 161 rupture planes using multiple fault segments, among other things, are often available 162 for larger events within days, we opted to apply a simple, quick and robust approach 163 that will facilitate independent testing as well as real-time application. We divided the 164 dataset into two parts: a *pre-* and *post-*initiating event catalogue. The start time of the 165 pre-catalogue depended on the quality and completeness of the local network: for the 166 Californian seismicity we downloaded from the ANSS Comprehensive Earthquake 167 Catalog (ComCat) via the FDSN web service (<u>https://earthquake.usgs.gov/fdsnws/event/1/</u>); 168 we started the analysis of the background seismicity from 1981, when the network was 169 greatly improved. The data were first downloaded on July 14<sup>th</sup> 2019, and then updated week by week. 170

171

The computation of b-values critically depends on correct estimates of the magnitude of completeness (Mc) (e.g. Mignan & Woessner, 2012). A specific Mc was assessed for each window (250-event-long) after a pre-cutting level, established using the Maximum Curvature method with a correction factor of 0.2 (Wiemer and Wyss, 2000). A b-value

176 was then calculated for each window, applying the maximum likelihood method (Aki,
177 1965). We then defined a pre-event reference b-value, which was the median of all the
178 single estimates preceding the Mw6.4.

179

180 For the post-event catalogue processing, we had to consider the temporal changes of the 181 magnitude of completeness following a big event (Helmstetter, et al., 2006; Tormann et 182 al., 2013), which can easily mask or bias the space-time b-value fluctuations. During the first hours after a large event, Mc typically changes by two orders of magnitude, 183 184 resulting in a somewhat heterogeneous dataset. Changes in completeness are network-185 specific, but also depend on mainshock magnitude (Helmstetter et al., 2006). Our 186 analysis of Ridgecrest's completeness (Figure 1) was fully consistent with previous 187 experience, since Mc increased much more and over a longer time span after the Mw7.1 188 than after the Mw6.4 event. Specifically, after the Mw6.4 Mc increased from the 189 background value (Mc=1.2) to about 1.8, before dropping back to a near-to-background 190 value within 12 hours. After the Mw7.1 event, it increased to between 3.3 and 3.5, then 191 recovered within three days to near-to-background values.

192 While we subsequently estimated Mc in each sample before computing a- and b-values, 193 a common observation is that during periods of very strong gradients the Mc estimate is 194 not conservative enough (e.g. Woessner and Wiemer, 2005), which potentially biases 195 the analysis towards lower b-values. Based on our Mc analysis (see Figure 1), typically 196 in keeping with such an analysis (e.g. Gulia et al., 2018), we therefore excluded from the 197 dataset those events recorded during the initial, most heterogeneous period after the 198 Mw6.4 and Mw7.1 events and introduced a minimum cut-off magnitude. In the 199 aftermath of the Mw6.4, we excluded events occurring during the first 12 hours and 200 pre-cut the dataset at M1.7. For the Mw7.1, we removed events occurring during the 201 first 48 hours and pre-cut at M1.2 (see the shaded areas in Figure 1). This 'no-alert-202 time' is of course one of the limitations affecting the method's practical application: for 203 the shorter this no-alert-time is, the more use FTLS decision support can be for practical 204 mitigating actions. We subsequently tested the choice of these expert-selected 205 parameters for sensitivity and confirmed that they did not critically influence our 206 results. Subsequently we also used an alternative, revised and higher-resolution dataset 207 (Shelly, 2020) to challenge and refine our analysis. Computing the percentage difference compared to the reference b-value was the final step. The values thus obtained allowed 208 209 us to define the level of alert. If the percentage difference of the post-Mw6.4 event was 210 plus or minus 10%, the alert was designated green or red, otherwise it was classified as 211 orange.

212

Figure 3 schematically illustrates schematically the process of constructing b-value 213 214 time-series and FTLS values for the Ridgecrest earthquake sequence. This figure 215 contains the b-value difference in percentage respect to the reference value to allow 216 comparison between the two fault planes. After the occurrence of the first event with M 217 greater or equal than 6, we calculate the b-value time-series on its box, as explained in 218 the previous lines, till the occurrence of a bigger event (Step 1 in Figure 3). Once a larger 219 event occurs, we automatically refocus the analysis of b-value changes and FTLS on this 220 new event, using the same procedures: We re-select the fault plane with the highest 221 number of early aftershocks, re-select a new dataset and finally re-run the code that 222 estimates the background b-value (Note: from 1981 to the M64, only, excluding the 223 aftershocks and mainshock of the first sequence) and aftershock b-values (Step 2 in 224 Figure 3). We normalize always the b-values relative to the background value, allowing 225 for comparisons between different sequences in one timeline (Figure 3B). Refocusing 226 on the new. Larger fault area is sensible, since the stress changes introduced by this 227 event (larger and more recent) will dominate the changes in seismicity, this is now also 228 the area of highest concern for larger events and the area the most seismicity for 229 analysis. Note that in essence all steps are automated and follow the procedure by Gulia 230 and Wiemer (2019), the only 'free' parameter is the starting date of the background b-231 value analysis (here: 1981).

232

233 Mapping of b-values to provide additional information on spatial changes was 234 performed on a regular 1x1-km grid, selecting the closest 200 events within a maximum 235 radius of 10 km. For the time series, we used the Maximum Curvature method (Wiemer 236 and Wyss, 2000) for Mc, after pre-cutting the dataset at the same Mc level already 237 adopted for the *pre* and *post* time period. We plotted the percentage difference of the 238 post Mw≥6 events with respect to the b-value map obtained for the background (i.e. the 239 time span from 1981 up to the last event preceding the Mw6.4).

240

The sub-catalogs generated for each fault plane and for the three different catalogs areprovided as text files in the Supplement.

- 243
- 244 **Results**

## 245 Automatic fault selection

The Mw6.4 earthquake on 4 July in Ridgecrest ruptured two conjugate strike-slip faults, which intersected to form an 'T' shape. It took days before geodetic, seismic and relocated seismicity data provided an overall view of this complex sequence (Ross et al., 2019; Hobbs, 2019). By kinematically inverting for subevents using seismograms from the dense regional seismic network and global seismic stations, Ross et al. (2019) identified three simultaneous subevents and hypothesised that the rupture had been a cascading phenomenon, rather than a single continuous process. The three identified subevents coincided with at least three faults: the 6-km-long northwest-trending fault that slipped first; then the rupture propagated over a short southwest-trending fault with only about 5 km of surface break, and finally the jump to a larger southwesttrending fault roughly 15 km long (Ross et al., 2019).

257

258 The FTLS method was developed to be applied in near real-time, when little other 259 information apart from data from the focal mechanism and the automatically derived 260 network catalogue is both known and publicly accessible. The seismic source used in 261 our analysis is thus represented by a single plane. Following the method described by Gulia and Wiemer (2019), once the GCMT provided the focal mechanism, the algorithm 262 built the two fault planes, centred on the local hypocentre catalogue (see 263 https://www.fdsn.org/networks/). Between the two fault planes, the one with the 264 265 largest number of early aftershocks within a 3 km radius was selected as the likely fault 266 plane. For Mw6.4, this purely statistical method chose the northwest-trending fault 267 plane (Figure 2) that represented the initial rupture, in the process described by Ross et 268 al. (2019), and is the one aligned with the eventual Mw7.1 hypocentre. The background 269 or reference b-value for this box containing 1275 events above M1 since 1981 is b = 270 0.97 (blue symbols in Figure 4).

271

272 Seismicity preceding Mw7.1

Figure 4A shows the b-value time-series. All b-values after the Mw6.4 event are
substantially lower than the background b-value. A comparison of the Frequency
Magnitude Distributions (FMDs) of events occurring between 4 and 6 July is in Figure

276 4B. During the time interval between the two big events, the b-value decreases from 277 0.97 to 0.75, a decrease by 23%, resulting in a red FTSL status (Figure 4B). We also 278 calculated the respective daily probability (Pr) commonly derived by extrapolating the 279 observed frequency-magnitude distribution to an Mw6.4 event or larger earthquake 280 (Figure 5C). These probabilities reached a peak value of 66% on 5 July a value about one 281 order of magnitude larger than the aforementioned ones derived by the USGS 282 (https://earthquake.usgs.gov/data/oaf/overview.php, 5% using default values, 9% 283 using sequence specific values according to Michael et al., (2020) and Hardebeck et al., 284 (2019)).

285

286 Next, we mapped the spatial distribution of the differential b-value (i.e. the background 287 b-value map subtracted from the current episode map) to infer information on the likely 288 nucleation region of a subsequent mainshock (Figure 6A). The expectation described by 289 Gulia and Wiemer (2019) is that a subsequent mainshock would nucleate near the 290 strongest b-value decrease, in our conceptual model represented by high stress 291 asperities. In the case of the Ridgecrest sequence, this low b-value patch locates to the 292 NW of the Mw6.4 epicentre and corresponds closely to the location of the subsequent 293 Mw7.1 quake on 6 July (marked in Figure 6B).

294

295 Seismicity following the Mw7.1

We then analysed b-value evolution over time in the Mw7.1 source volume, constructed following the same procedure as described above for the Mw6.4 event. We also determine a new background b-value of 0.87 for this much larger source volume, compared to the volume of Mw6.4. The b-value time series, plotted in Figure 3 and starting two days after the Mw7.1 earthquake, indicated a general increase from the 301 normalised background value of more than 10%, reaching a peak of 26% within the first 302 week (Figure 3C). This qualified it for green FTLS status and suggested that the chance 303 of a subsequent even larger event was lower than average. Figure 4C shows the FMD's 304 of the background (b=0.87) compared to the aftershocks (b = 1.1). We again calculated 305 the probability of a subsequent event of equal or larger magnitude at 0.4% per day two 306 days after the event and falling to 0.004% per day in subsequent weeks. These values 307 were one order of magnitude lower than the USGS aftershock probabilities 308 communicated during the sequence. The differential b-value map for events occurring 309 in the first week with respect to their background (Figure 6B) indicated a general rise in 310 b-values throughout the region.

311

## 312 *Revised and high-resolution datasets*

313 While this manuscript was under review, revised GCMT and ComCat catalogues 314 (downloaded on 21 January 2020) became available, so we repeated our analysis, to 315 compare it with the FTLS's performance using near real-time data. The revised GCMT 316 focal mechanisms, available online since 8 November 2019, are very similar to their 317 quick equivalents (Table 1), both in orientation and dip. We then re-computed the fault 318 planes centred on the hypocentres of the two mainshocks (Mw6.4 and Mw7.1) for the 319 revised ComCat catalogue as well as for the high-resolution catalogue compiled by 320 Shelly (2020).

321

Minor displacement (by approx. 0.2 km) of the epicentre of the 4 July mainshock in the revised ComCat catalogue makes the revised boxes imperceptibly different with respect to their quick counterparts (Table 2). The overall completeness of the catalogues remains largely unchanged. Consequently, the result showed the same almost

imperceptible difference, with the overall b-value during the time interval between the two biggest events rising from 0.75 to 0.76, and the red alert from -23% to -22%. After the mainshock, we obtained the same b-values and the same green alert (+26%).

329

330 In addition, Shelly (2020) published a revised, higher-resolution catalogue containing 331 34,000 events during the period 4-16 July for the Ridgecrest sequence, allowing us for 332 the first time to evaluate the b-value evolution and FTLS performance with a partially independently calculated and presumably higher-quality dataset. This earthquake 333 334 catalogue is based on cross-correlation analysis of continuous wave-forms and 335 according to Shelly (2020) substantially more complete in magnitude, more consistent 336 through time and more precise in hypocentres. Shelly (2020) points out that crosscorrelation is not well suited for relocating M>5 earthquakes, especially the two events 337 338 with the highest magnitudes, because its wave forms are too dissimilar to those of 339 smaller events. Indeed, in this dataset, the two epicentres roughly correspond to the 340 location provided by USGS, albeit having different depths, with the Mw6.4 deeper (from 341 10.5 to 15 km) and the Mw7.1 shallower (from 8 to 3 km). For this reason, we use the 342 same source volumes determined for the previous analysis (i.e. revised GCMT moved to 343 the ComCat hypocentre).

344

This catalogue contains only 38 events preceding the Mw6.4 quake, not enough to establish a reference b-value for the FTLS, so we used the revised ComCat catalogue to estimate that value for the boxes of the Mw6.4 and Mw7.1 mainshocks. As shown in Shelly (2020), the cross-correlation analysis substantially lowers these events' overall magnitude of completeness, a finding supported by our Mc(t) analysis (Figure 8). The Shelly catalogue reaches an Mc of about 0.7, roughly half degree of magnitude lower

than the standard ComCat catalogue. However, the increase in Mc immediately after the mainshock is almost as high (rising to roughly Mc = 3.0-3.5), but completeness recovers faster and more systematically. Completeness for M1.5 is reached 24 hours earlier than using standard datasets (Figure 7). This improvement is extremely important for our approach, but also for other real-time methods used to assess time-dependent earthquake probabilities.

357

358 Using the Shelly catalogue, we repeated the b-value analysis using the same time-359 windows but lower completeness and found almost identical results (-21% after the 360 Mw6.4 and +29% after the Mw7.1), confirming that the results based on near-real time 361 data are in line with the more homogeneous, higher-quality catalogue. To exploit the possible improvements of higher quality data for aftershock hazard assessment, we 362 363 then moved the start of our analysis closer to the mainshock origin time, thus 364 shortening our no-alert-time. After the Mw6.4 earthquake, we were able to cut this no-365 alert-time from 12 hours to just one, and after the Mw7.1 from 48 hours to 24 hours 366 (using Mc pre-cuts of 1.5 in both cases). The time series of b-values is shown in Figure 8. The overall trend, the b-values themselves and FTLS status all remain unchanged. 367 However, it is worth noting that we can establish a low b-value after the M6.4 with just 368 369 one hour of no-alert-time when high-quality data is available.

370

## 371 Sensitivity analysis

Our method contains essentially three free parameters that we determined based on data analysis and expert choices: 1) the magnitude of completeness, 2) the no-alerttime, and the 3) the sample size analysed. The first two we have determined based on the completeness analysis (Figures 1 and 6), the last is a commonly used value in

376 studies. We introduce a novel sensitivity analysis to evaluate the impact of the changes 377 on the result our study. We scan systematically the parameter space of the pre-cut Mc 378 and no-alert-time parameters. The results shown in Figure 9 for the revised ComCat and 379 the Shelly catalogue are fully consistent with the previous interpretations: For all 380 choices of Mc and no-alter times, there is a string decrease in b-value (red colours and red FTLS status) subsequent to the M6.4. Following the M7.1, the picture is somewhat 381 382 different: for value at or below the estimated completeness (black dashed line in Figure 383 9), there is decrease in b-value – an expected bias due to incompleteness. Above Mc, 384 however, green colours indicate an increase in b-value and green FTLS status.

385

#### 386 Seismic sequence in 1995

In 1995, an Mw5.8 earthquake occurred in the same region, a few kilometres away from the Mw7.1 (Figure 2A). That event was not followed by a larger one. For comparison, we also applied the FTLS approach to this sequence, too. Figure 10 shows the FMDs and time series relative to the 1995 sequence, indicating a roughly 30% increase in the bvalue, resulting in a correct green traffic light classification. This result suggests that the FTLS approach can also be extended to events of smaller magnitude than the currently used Mw≥6.0 reference.

394

395

# **396 Discussion and conclusion**

397 Our analysis shows that the Ridgecrest earthquake sequence not only impacted the seismic 398 activity rate, increasing the productivity of earthquakes near the fault by between 3 and 5 399 orders of magnitude; it also changed the relative size distributions, the b-values, in both space 400 and time. This should come as no surprise, since the size distribution is known to be sensitive 401 to the applied shear stress on faults (e.g. Goebel et al., 2013), and also to depend on location 402 (e.g. Tormann et al., 2015). Thus, b-values are linked to the seismotectonic context and 403 evolution of events, but they also constitute an important factor influencing the probability of a 404 subsequent larger event. The FTLS concept introduced by Gulia and Wiemer (2019) exploits 405 the systematic differences in b-values observed between the majority of aftershock sequences 406 that will normally decay over time and the small percentage of sequences that are followed by 407 an even larger event. The FTLS method and codes were developed in the first half of 2019, but 408 only published in October 2019 (Gulia and Wiemer, 2019). The Ridgecrest sequence, 409 representing one of the best-monitored large mainshock-aftershock sequences, presented us 410 with an ideal opportunity to test the FTLS hypothesis and developed software. The analysis 411 presented is here is not yet a truly prospective, real-time application, because we were (and 412 still are not) set up computationally and, to a certain extent, methodologically to conduct such 413 an urgently needed but challenging test. However, it is meaningful in a pseudo-prospective 414 sense, an analysis that reproduces real-time condition. Our pseudo-prospective study is, 415 however, more rigours and we would argue more meaningful than typical such studies, 416 because the method and codes used to conduct the automatic analysis have been published 417 before and were here used unchanged from the version of the method submitted for

418 publication. In other words, they could not have been optimised to provide the best outcome419 for our hypothesis.

420

The results obtained and presented in this paper support the FTLS hypothesis: seismicity following the Mw6.4 event showed a substantially lower b-value (a drop of 23%, Figure 4), resulting in its correct red traffic light designation. The b-value also rose by 26% after the Mw7.1 quake, resulting in a correct green classification. This adds one correct positive and one correct negative to the confusion matrix analysis presented in Gulia and Wiemer (2019),

increasing the accuracy assessment to above 96%. A correct green traffic light was also
attributed after the 1995 Mw5.8 earthquake. Since the FTLS hypothesis is proposed and
evaluated for events with a magnitude of 6.0 and above, the Mw5.8 results are not factored into
the (retrospective) error matrix score.

430

The FTLS hypothesis itself needs to be further tested, and the error matrix approach carried 431 432 out on future sequences in a fully prospective, independently conducted way. Such tests are 433 now planned as part of the Collaboratory for the Study of Earthquake Predictability (CSEP, 434 Schorlemmer et al., 2018), financed by the European RISE project (www.rise-eu.org). In 435 addition, the observed changes in b-values can and should also be directly converted into time-436 dependent earthquake probabilities, as shown in Tormann et al. (2016) and Gulia et al. (2016) 437 for example. These probabilities are also reported for the Ridgecrest sequences (Figure 5), 438 which are very consistent with the FTLS results and will be tested in comparison to other 439 models, such as the Reasenberg-Jones or ETAS models. Note that the FTLS green alert may turn 440 out to be the most important one in terms of its practical implications, for the vast majority 441 (80%) of all sequences will fall into this category, and knowing that a larger event is unlikely 442 will be extremely valuable information. Indeed, after the M7.1, we estimate about a factor 10 443 lower probability for a subsequent larger one that the standard USGS model.

444

Naturally, in principle it would be great to extend the FTLS model to smaller mainshocks, because more data could be used to test the hypothesis. However, the data would have to be of very high quality and their inclusion would probably increase the uncertainty of the analysis. The smaller size of the fault planes involved in such events (an M5.5 source, for example, would be about 6 km long) would make it more challenging to identify the active fault. Because smaller mainshocks will generally result in fewer aftershocks, the spatiotemporal resolution of

451 b-values is reduced and the useful magnitude range between the largest events and Mc 452 decreases, making it more difficult to establish reliable b-values. Probably scaling works in 453 such a way that we would have to select events even closer to the mainshock fault only, which 454 in turn makes pinpointing the location even more challenging. Also, sample sizes may be too 455 small for robust analyses. Similarly, the relevant background (i.e. the reference level) would be 456 even more local and thus harder to determine. In addition, the Coulomb stress and failure 457 modelling in Gulia et al. (2018) suggests that the amplitude of the b-value increase is magnitude-dependent, so it is unclear whether b-value transients are scale-invariant. So, it 458 459 needs to be explored whether the evaluation of the FTLS hypothesis can be extended to smaller 460 events, but this will necessitate a very thorough analysis of any uncertainties and their 461 influence on the stability of the analysis. An analysis of that kind is beyond the scope of this Ridgecrest case study. 462

463

The spatial patterns of changes in b-values have been proposed as additional information on the future location of subsequent larger events, and here too the Ridgecrest case study is well in line with this loosely formulated and as yet not formally tested hypothesis: the Mw7.1 event occurred near the area of the steepest b-value decrease (Figure 6). More research and testing in needed to integrate this spatial information into aftershock forecasting in an automate way, for now we consider the information contained in b-value or earthquake probability maps additional information for experts to be considered.

471

Establishing with confidence a b-value time series critically hinges on the quality of the seismic
network, and judging from our analysis the southern California network performed extremely
well (Figure 1) in near real-time (much of our analysis was in fact conducted within days of the
Mw6.4 event). The magnitude of completeness rapidly decreased (Figure 1) and the frequency

476 magnitude distribution (Figures 4 and 9) is among the best we have ever analysed, closely 477 following a linear Gutenberg-Richter distribution and leading within hours to reliable 478 observations of b-value changes. Based on our experience, the differential b-value maps 479 computed (Figure 6) are also very reliable. Progress made in station coverage and automated 480 network processing approaches are clearly delivering very rapidly high-quality data that are 481 useful for scientific analysis and risk assessment. Further improvements using advanced 482 automated post-processing methods may be feasible and desirable to decrease no-alert-time. Our test using the higher-resolution catalogue provided by Shelly (2020) supports this 483 484 (Figures 8 and 9). The catalogue confirms every aspect of the results obtained using ComCat 485 real-time data, so we consider the likelihood of data imperfection influencing our analysis to be 486 very low. Equally importantly, the Shelly catalogue allows us to reduce no-alert-time to just 487 one hour. Since the approach implemented by Shelly in principle reveals the real-time 488 capabilities of seismic networks in the not-too-distant future, we suggest that it may be 489 possible to produce an FTLS assessment within just one or a few hours. We also suggest that 490 the sensitivity analysis to Mc and no-alter-time we introduce in Figure 9 is a powerful tool to 491 quickly evaluate the robustness of an FTLS results. This may be also in real-time a graphical 492 representation a seismologist wants to consult in a crisis to ensure the results are not critically 493 dependent on the choice of parameters,

494

The FTLS hypothesis is quite new, and while the successful Ridgecrest case provides additional support for it, in our view it is too early to use it routinely for making decisions about civil protection or public communications. More extensive sensitivity and robustness studies are needed, the hypothesis should be independently evaluated by other research teams and the hypothesis needs to be formally tested. There are plans for this, but it will take time. At the same time, numerical modelling may allow the formulation of a better physical understanding

501	and maybe e	enhanced f	forecasting	abilities.	These ef	fforts will	take time	. but g	iven the	potential
								,~~~ ¬		p o e e e . e

502 implications and greater understanding, we consider them highly worthwhile.

- 503
- 504

# 505 **Data and resource**

- 506 The ComCat catalogue by USGS was downloaded from the website
- 507 https://earthquake.usgs.gov/fdsnws/event/1/catalogs
- 508 and ZMAP (Reyes and Wiemer, 2019).
- 509

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- 693
- 694 **Tables**
- **Table 1**: Nodal planes (np1 and 2) of the quick and revised GCMT catalogue for the two events

696 on 4 July 2019, 17:33 UTC (Day 04) and 6 July 2019, 03:19 UTC (Day 06)

697

GCMT	Day	Strike	Dip	Rake	Strike	Dip	Rake	Length	Width
		np1	np1	np1	np1	np1	np1	(km)	(km)
Orright	04	228	81	0	318	90	-171	27.28	9.65
Quick	06	322	78	-177	231	87	-12	61.9	13.79
Daviaad	04	227	86	3	137	87	176	26.84	9.58
Revised	06	321	81	180	51	90	9	61.3	13.73

698

- 700 **Table 2**: Vertices of the fault planes (FP1 and FP2) corresponding to the nodal planes in Table 1.
- 701 See Table 1 for details of the symbols.

CCMT	Day	Lon ED1	Lat	Depth ED1	Lon ED2	Lat	Depth
GCMT		(dog)	(dog.)	(lem)	(dog)	$\frac{\Gamma\Gamma 2}{(dog)}$	$\Gamma\Gamma 2$
		(deg.)	(ueg.)	(KIII)	(deg.)	(deg.)	(KIII)
		-			-		
	04	117.3882	35.7822	5.9452	117.4049	35.614	5.8858
		-			-		
Quick		117.6127	35.6181	5.9452	117.6071	35.7963	5.8858
Quick	04	-			-		
		117.6238	35.6281	15.4748	117.6071	35.7963	15.5342
		-			-		
		117.3993	35.7923	15.4748	117.4049	35.614	15.5342

	1						
	06	- 117.4007	35.5422	1.2576	- 117.3302	35.9421	1.1164
		-117.823	35.9809	1.2576	- 117.8634	35.5918	1.1164
	00	-117.798	35.9968	14.7424	- 117.8684	35.5969	14.8836
		- 117.3756	35.5581	14.7424	- 117.3353	35.9472	14.8836
		- 117.3926	35.7854	5.7213	- 117.6032	35.7951	5.7162
		-117.61	35.6208	5.7213	- 117.4004	35.6186	5.7162
	04	- 117.6151	35.6252	15.2787	- 117.4045	35.6155	15.2838
		- 117.3977	35.7898	15.2787	- 117.6072	35.7921	15.2838
Revised	06	- 117 3948	35 5492	1 2208	- 117 8633	35 596	1 1363
		- 117 8224	35 9776	1 2208	- 117 3353	35 943	1 1363
		- 117 8039	35 9898	14 7792	- 117 3353	35 943	14 8637
		- 117.3763	35.5614	14.7792	- 117.8633	35.596	14.8637
		- 117.3874	35.7885	10.2753	-117.598	35.7982	10.2702
		-	35 6238	10 2753	- 117 3952	35 6216	10 2702
	04	-	35 6282	19 8327	- 117 3993	35 6185	19 8378
Shelly		- 117 3924	35 7929	19 8327	-117.602	35 7951	19 8378
2020		- 117 3896	35 5515	-3 5382	- 117 8582	35 5984	-3 6227
		- 117 8172	35 9799	-3 5382	- 117 3302	35 9453	-3 6227
	06	- 117 7987	35 9921	10 0202	- 117 3302	35 9453	10 1047
		- 117.3711	35.5637	10.0202	- 117.8582	35.5984	10.1047

**Figure captions** 

Figure 1 –A): time/magnitude plot for the events following the Mw 6.4 on 4 July. Shaded areas indicate times when the dataset was least complete. B): time series of the magnitude of completeness (red lines) estimated using the maximum curvature method for samples containing 300 events, moved through the data in overlapping windows. Grey lines represent uncertainty estimates obtained by bootstrapping.

711

Figure 2- A) Seismicity map with the events (white stars) on 4 July - Mw 6.4 (M64), 6 July - Mw
7.1 (M71) and subsequent events in black and red respectively. The two green fault planes
indicate the Mw 6.4 GCMT focal mechanism, with strike and dip directions. B) 3-D view of
Figure 2a, from a 200° azimuth and 40° elevation.

716

Figure 3 – A) Schematic representation of the single time-series obtained on the M64 and M7.1
fault planes and B) the summary one with the 2 fault planes in the near-real-time analysis of the
Ridgecrest earthquake sequence.

720

721 Figure 4 – Performance of the FTLS in near real-time. A) b-value time series for the Mw 7.1 722 sequence superimposed on the FTLS assessment (Wiemer and Gulia, 2019); the blue dashed 723 line is the reference b-value; the black dashed vertical lines indicate Mw 6.4 and Mw 7.1 724 respectively. The black rectangle zooms in on the time series in the interval between the two 725 M>6 events. All the estimates are below the reference value. Grey indicates uncertainty (one 726 standard deviation by Shi and Bolt, 1982). B) Frequency-magnitude distributions for the source 727 of the Mw 6.4 event for two time periods: background in blue, time between the two Mw>6 728 events in red. C) Frequency-magnitude distributions for the source of the Mw 7.1 event for two 729 time periods: background in blue, maximum b-value reached in the first week of aftershocks.

730

Figure 5 A-F: Daily time series on the fault planes of the two major events. A-C) Fault plane of
the Mw 6.4 event: b-value (A), daily a-value (B) and daily probability of a Mw 6.4+ (C). D-F)

Fault plane of the Mw 7.1 event: b-value (D), daily a-value (E) and daily probability of a Mw 6.4+(F). The blue dashed lines represent the mean value of all the background estimates.

735

Figure 6 – Mapped b-values with the difference in percentage with respect to the background
for two different periods: A) between Mw 6.4 and Mw 7.1; B) the first week after Mw 7.1. The
original maps were produced by ZMAP (Wiemer, 2000; Reyes and Wiemer, 2019) and postprocessed in the Matlab using GMT, generic mapping tools (http://gmt.soest.hawaii.edu)..

740

Figure 7 - Time series of the magnitude of completeness (red lines) in the catalogue by Shelly
(2020) estimated using the maximum curvature method for samples containing 300 events,
moved through the data in overlapping windows. The grey lines represent uncertainty
estimates obtained by bootstrapping.

745

746 **Figure 8** – Performance of the FTLS with the high-resolution catalogue by Shelly (2020): A) b-747 value time series for the Mw 7.1 sequence superimposed on the FTLS assessment (Wiemer and 748 Gulia, 2019); the blue dashed line is the reference b-value; the black dashed vertical lines 749 indicate Mw 6.4 and Mw7.1 respectively. Grey indicates uncertainty (one standard deviation by 750 Shi and Bolt, 1982). B) Frequency-magnitude distributions for the source of the Mw 6.4 event 751 for two time periods: background in blue, time between the two Mw>6 in red. c) Frequency-752 magnitude distributions for the source of the Mw 7.1 event for two time periods: background in 753 blue, maximum b-value reached in the first week of aftershocks.

754

**Figure 9** – A-B) Sensitivity analysis on no-alert-time and completeness. Color-coded is the bvalue difference in percentage with respect to the reference b-value as a function of magnitude cut-off and time after the Mw 6.4 (left) and Mw 7.1 (right). We always analyzed the first 300 events above this magnitude and after this time. Black dashed line: A) the estimated magnitude of completeness for the ComCat catalog reported in Figure 1; gray dashed line: the same with the 0.2 correction factor, as adopted in our modeling; B) the estimated magnitude of completeness for the high-resolution catalogue by Shelly (2020) reported in Figure 7; gray dashed line: the same with the 0.2 correction factor, as adopted in our modeling.

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764

Figure 10 – A) Frequency-magnitude distributions for the Mw 5.8 sequence in 1995: in blue,
the background b-value (1981-1995) and in green the highest b-value reached by the
aftershocks during the first week after Mw 5.8; B) b-value time series for the same sequence.
The blue dashed line represents the reference b-value (see Data and method).