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

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%
33 after the mainshock. Our results suggest that the real-time monitoring of b-values is
34 feasible in California and may add important information for aftershock hazard
35 assessment.

36

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
43 (Okada, 1992; Stein, 1999; Ebel et al., 2000). In most sequences, on average, this
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

51 Jones, 1994; Marzocchi et al, 2017; Omi et al., 2019). Today, the term Operational
52 Earthquake Forecasting (OEF) is often used when referring to aftershock forecasting in
53 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. Petrucci, 2019 a, b; Staudenmeier et al., 2019;
62 Scholz, 2015; Tormann et al., 2015; Gulia and Wiemer, 2010; Narteau et al., 2009).

63 Mainshock stress changes are therefore expected to systemically change b-values, as
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
83 indicates a precursory sequence that is more likely to be followed by a larger event (b-
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, M_c , for this variable fluctuates dramatically during
94 aftershock sequences (Hainzl, 2016; Helmstetter et al., 2006; Woessner and Wiemer,
95 2005). In the past, it 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.

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

108

109 **The 2019 Mw7.1 Ridgecrest sequence**

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

126 (Michael et al., 2020; Hardebeck et al., 2019). This figure was higher than the default
127 value of 5% obtained when using the standard Reasenberg and Jones (1990) parameter,
128 because of the higher than average aftershock productivity in the region (Hardebeck et
129 al., 2019). Just one day later, a Mw7.1 earthquake struck (at 8:20 p.m. local time on 6
130 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
133 common in California, were also cited in public. For example, after the second event
134 Dr Lucy Jones tweeted: *"So the M6.4 was a foreshock. This was a M7.1 on the same fault
135 as has been producing the Searles Valley sequence. This is part of the same sequence."*
136 This was followed by: *"You know we say 1 in 20 chance that an earthquake will be
137 followed by something bigger? This is that 1 in 20 time."* And then: *Yes, we estimate that
138 there's about a 1 in 10 chance that Searles Valley will see another M7. That is a 9 in 10
139 chance that tonight's M7.1 was the largest".*

140

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

146

147 **Data and method**

148 To compute a reliable and detailed b-value time series, we used a window approach,
149 moving a window with a fixed sample size, event by event. In order to provide a
150 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
158 plane, we selected all events recorded in the sequences within the first hour and within
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 (<https://earthquake.usgs.gov/fdsnws/event/1/>);
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 14th 2019, and then updated week
170 by week.

171

172 The computation of b-values critically depends on correct estimates of the magnitude of
173 completeness (M_c) (e.g. Mignan & Woessner, 2012). A specific M_c was assessed for each
174 window (250-event-long) after a pre-cutting level, established using the Maximum
175 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
183 first hours after a large event, M_c typically changes by two orders of magnitude,
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 M_c 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 M_c increased from the
189 background value ($M_c=1.2$) 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 M_c in each sample before computing a- and b-values,
193 a common observation is that during periods of very strong gradients the M_c 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 M_c 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
208 compared to the reference b-value was the final step. The values thus obtained allowed
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

213 Figure 3 schematically illustrates schematically the process of constructing b-value
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 M_c , after pre-cutting the dataset at the same M_c level already
237 adopted for the *pre* and *post* time period. We plotted the percentage difference of the
238 post $M_w \geq 6$ 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 $M_w 6.4$).

240

241 The sub-catalogs generated for each fault plane and for the three different catalogs are
242 provided as text files in the Supplement.

243

244 **Results**

245 *Automatic fault selection*

246 The $M_w 6.4$ earthquake on 4 July in Ridgecrest ruptured two conjugate strike-slip faults,
247 which intersected to form an "T" shape. It took days before geodetic, seismic and
248 relocated seismicity data provided an overall view of this complex sequence (Ross et al.,
249 2019; Hobbs, 2019). By kinematically inverting for subevents using seismograms from
250 the dense regional seismic network and global seismic stations, Ross et al. (2019)

251 identified three simultaneous subevents and hypothesised that the rupture had been a
252 cascading phenomenon, rather than a single continuous process. The three identified
253 subevents coincided with at least three faults: the 6-km-long northwest-trending fault
254 that slipped first; then the rupture propagated over a short southwest-trending fault
255 with only about 5 km of surface break, and finally the jump to a larger southwest-
256 trending 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
262 Gulia and Wiemer (2019), once the GCMT provided the focal mechanism, the algorithm
263 built the two fault planes, centred on the local hypocentre catalogue (see
264 <https://www.fdsn.org/networks/>). Between the two fault planes, the one with the
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*

273 Figure 4A shows the b-value time-series. All b-values after the Mw6.4 event are
274 substantially lower than the background b-value. A comparison of the Frequency
275 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*

296 We then analysed b-value evolution over time in the Mw7.1 source volume, constructed
297 following the same procedure as described above for the Mw6.4 event. We also
298 determine a new background b-value of 0.87 for this much larger source volume,
299 compared to the volume of Mw6.4. The b-value time series, plotted in Figure 3 and
300 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

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

326 imperceptible difference, with the overall b-value during the time interval between the
327 two biggest events rising from 0.75 to 0.76, and the red alert from -23% to -22%. After
328 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
333 independently calculated and presumably higher-quality dataset. This earthquake
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 cross-
337 correlation is not well suited for relocating $M > 5$ earthquakes, especially the two events
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 $M_w 6.4$ deeper (from
341 10.5 to 15 km) and the $M_w 7.1$ 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

345 This catalogue contains only 38 events preceding the $M_w 6.4$ quake, not enough to
346 establish a reference b-value for the FTLS, so we used the revised ComCat catalogue to
347 estimate that value for the boxes of the $M_w 6.4$ and $M_w 7.1$ mainshocks. As shown in
348 Shelly (2020), the cross-correlation analysis substantially lowers these events' overall
349 magnitude of completeness, a finding supported by our $M_c(t)$ analysis (Figure 8). The
350 Shelly catalogue reaches an M_c of about 0.7, roughly half degree of magnitude lower

351 than the standard ComCat catalogue. However, the increase in M_c immediately after the
352 mainshock is almost as high (rising to roughly $M_c = 3.0-3.5$), but completeness recovers
353 faster and more systematically. Completeness for $M_{1.5}$ is reached 24 hours earlier than
354 using standard datasets (Figure 7). This improvement is extremely important for our
355 approach, but also for other real-time methods used to assess time-dependent
356 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 $M_{w6.4}$ and +29% after the $M_{w7.1}$), confirming that the results based on near-real time
361 data are in line with the more homogeneous, higher-quality catalogue. To exploit the
362 possible improvements of higher quality data for aftershock hazard assessment, we
363 then moved the start of our analysis closer to the mainshock origin time, thus
364 shortening our no-alert-time. After the $M_{w6.4}$ earthquake, we were able to cut this no-
365 alert-time from 12 hours to just one, and after the $M_{w7.1}$ from 48 hours to 24 hours
366 (using M_c pre-cuts of 1.5 in both cases). The time series of b-values is shown in Figure 8.
367 The overall trend, the b-values themselves and FTLS status all remain unchanged.
368 However, it is worth noting that we can establish a low b-value after the $M_{6.4}$ with just
369 one hour of no-alert-time when high-quality data is available.

370

371 *Sensitivity analysis*

372 Our method contains essentially three free parameters that we determined based on
373 data analysis and expert choices: 1) the magnitude of completeness, 2) the no-alert-
374 time, and the 3) the sample size analysed. The first two we have determined based on
375 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 M_c
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 M_c and no-alter times, there is a string decrease in b-value (red colours and
381 red FTLS status) subsequent to the M6.4. Following the M7.1, the picture is somewhat
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 M_c ,
384 however, green colours indicate an increase in b-value and green FTLS status.

385

386 *Seismic sequence in 1995*

387 In 1995, an M_w 5.8 earthquake occurred in the same region, a few kilometres away from
388 the M_w 7.1 (Figure 2A). That event was not followed by a larger one. For comparison, we
389 also applied the FTLS approach to this sequence, too. Figure 10 shows the FMDs and
390 time series relative to the 1995 sequence, indicating a roughly 30% increase in the b-
391 value, resulting in a correct green traffic light classification. This result suggests that the
392 FTLS approach can also be extended to events of smaller magnitude than the currently
393 used $M_w \geq 6.0$ 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 rigorous 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 outcome
419 for our hypothesis.

420
421 The results obtained and presented in this paper support the FTLS hypothesis: seismicity
422 following the Mw6.4 event showed a substantially lower b-value (a drop of 23%, Figure 4),
423 resulting in its correct red traffic light designation. The b-value also rose by 26% after the
424 Mw7.1 quake, resulting in a correct green classification. This adds one correct positive and one
425 correct negative to the confusion matrix analysis presented in Gulia and Wiemer (2019),

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

430
431 The FTLS hypothesis itself needs to be further tested, and the error matrix approach carried
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 Reasenber-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 than the standard USGS model.

444
445 Naturally, in principle it would be great to extend the FTLS model to smaller mainshocks,
446 because more data could be used to test the hypothesis. However, the data would have to be of
447 very high quality and their inclusion would probably increase the uncertainty of the analysis.
448 The smaller size of the fault planes involved in such events (an M5.5 source, for example,
449 would be about 6 km long) would make it more challenging to identify the active fault. Because
450 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 M_c
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
458 magnitude-dependent, so it is unclear whether b-value transients are scale-invariant. So, it
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
462 Ridgecrest case study.

463
464 The spatial patterns of changes in b-values have been proposed as additional information on
465 the future location of subsequent larger events, and here too the Ridgecrest case study is well
466 in line with this loosely formulated and as yet not formally tested hypothesis: the Mw7.1 event
467 occurred near the area of the steepest b-value decrease (Figure 6). More research and testing
468 is needed to integrate this spatial information into aftershock forecasting in an automate way,
469 for now we consider the information contained in b-value or earthquake probability maps
470 additional information for experts to be considered.

471
472 Establishing with confidence a b-value time series critically hinges on the quality of the seismic
473 network, and judging from our analysis the southern California network performed extremely
474 well (Figure 1) in near real-time (much of our analysis was in fact conducted within days of the
475 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.
483 Our test using the higher-resolution catalogue provided by Shelly (2020) supports this
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 M_c and no-alert-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
495 The FTLS hypothesis is quite new, and while the successful Ridgecrest case provides additional
496 support for it, in our view it is too early to use it routinely for making decisions about civil
497 protection or public communications. More extensive sensitivity and robustness studies are
498 needed, the hypothesis should be independently evaluated by other research teams and the
499 hypothesis needs to be formally tested. There are plans for this, but it will take time. At the
500 same time, numerical modelling may allow the formulation of a better physical understanding

501 and maybe enhanced forecasting abilities. These efforts will take time, but given the potential
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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517

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693

694 **Tables**

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

698

699

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.

GCMT	Day	Lon FP1 (deg.)	Lat FP1 (deg.)	Depth FP1 (km)	Lon FP2 (deg.)	Lat FP2 (deg.)	Depth FP2 (km)
Quick	04	-	-	-	-	-	-
		117.3882	35.7822	5.9452	117.4049	35.614	5.8858
		-	-	-	-	-	-
		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

		-			-			
		117.4007	35.5422	1.2576	117.3302	35.9421	1.1164	
	06	-117.823	35.9809	1.2576	117.8634	35.5918	1.1164	
		-117.798	35.9968	14.7424	117.8684	35.5969	14.8836	
		-			-			
		117.3756	35.5581	14.7424	117.3353	35.9472	14.8836	
Revised	04	-			-			
		117.3926	35.7854	5.7213	117.6032	35.7951	5.7162	
		-117.61	35.6208	5.7213	117.4004	35.6186	5.7162	
		-			-			
	117.6151	35.6252	15.2787	117.4045	35.6155	15.2838		
	-			-				
	117.3977	35.7898	15.2787	117.6072	35.7921	15.2838		
	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			
Shelly, 2020	04	-			-117.598			
		117.3874	35.7885	10.2753		35.7982	10.2702	
		-			-			
		117.6048	35.6238	10.2753	117.3952	35.6216	10.2702	
	-			-				
	117.6098	35.6282	19.8327	117.3993	35.6185	19.8378		
	-			-117.602				
	117.3924	35.7929	19.8327		35.7951	19.8378		
	06	-			-			
		117.3896	35.5515	-3.5382	117.8582	35.5984	-3.6227	
		-			-			
		117.8172	35.9799	-3.5382	117.3302	35.9453	-3.6227	
-			-					
117.7987	35.9921	10.0202	117.3302	35.9453	10.1047			
-			-					
117.3711	35.5637	10.0202	117.8582	35.5984	10.1047			

702

703

704 **Figure captions**

705

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

711

712 **Figure 2**– A) Seismicity map with the events (white stars) on 4 July - Mw 6.4 (M64), 6 July - Mw
713 7.1 (M71) and subsequent events in black and red respectively. The two green fault planes
714 indicate the Mw 6.4 GCMT focal mechanism, with strike and dip directions. B) 3-D view of
715 Figure 2a, from a 200° azimuth and 40° elevation.

716

717 **Figure 3** – A) Schematic representation of the single time-series obtained on the M64 and M7.1
718 fault planes and B) the summary one with the 2 fault planes in the near-real-time analysis of the
719 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 $M > 6$
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

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

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

735

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

740

741 **Figure 7** – Time series of the magnitude of completeness (red lines) in the catalogue by Shelly
742 (2020) estimated using the maximum curvature method for samples containing 300 events,
743 moved through the data in overlapping windows. The grey lines represent uncertainty
744 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

755 **Figure 9** – A-B) Sensitivity analysis on no-alert-time and completeness. Color-coded is the b-
756 value difference in percentage with respect to the reference b-value as a function of magnitude
757 cut-off and time after the Mw 6.4 (left) and Mw 7.1 (right). We always analyzed the first 300
758 events above this magnitude and after this time. Black dashed line: A) the estimated magnitude
759 of completeness for the ComCat catalog reported in Figure 1; gray dashed line: the same with

760 the 0.2 correction factor, as adopted in our modeling; B) the estimated magnitude of
761 completeness for the high-resolution catalogue by Shelly (2020) reported in Figure 7; gray
762 dashed line: the same with the 0.2 correction factor, as adopted in our modeling.

763

764

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

769