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## Estimation of the Seismic Moment Rate from an Incomplete Seismicity Catalog, in the Context of the InSight Mission to Mars

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1           **Estimation of the seismic moment rate from an incomplete**  
2           **seismicity catalog, in the context of the InSight mission to Mars**

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25

26 **Abstract**

27 We evaluate methods to estimate the global seismic moment rate of a planet from the  $k \geq 1$  largest  
28 events observed during a limited and possibly short time span, as can be expected e.g. for lander mis-  
29 sions to Mars. The feasibility of the approach is demonstrated with a temporary broadband seismometer  
30 that was recording in the Mojave Desert, California, for 86 days in 2014, and by application to the Global  
31 Centroid Moment Tensor catalog, subsets thereof, and a catalog of stable continental regions seismicity .  
32 From the largest event observed at Goldstone alone ( $M_W \approx 7.9$ ) we estimate the Earth's global moment  
33 rate to be  $1.03 \times 10^{22} \text{ Nm/yr}$ , while an estimation based on the 10 strongest events yields a rate of  
34  $5.79 \times 10^{21} \text{ Nm/yr}$ . Summation of 42 years of GCMT solutions result in an average of  $7.61 \times$   
35  $10^{21} \text{ Nm/yr}$ . In general, a two years interval of GCMT solutions is sufficient to estimate the Earth's  
36 annual moment rate to within a factor 5 or better. A series of numerical experiments with more than 560  
37 million synthetic catalogs based on the Tapered Gutenberg-Richter distribution shows that the estima-  
38 tion is rather insensitive against an unknown slope of the distribution, and that bias and variance of the  
39 estimator depend on the ratio between moment rate and corner moment of the size frequency distribu-  
40 tion. Moment rates of published Mars models differ by a factor 1000 or more. Tests with simulated cata-  
41 logs show that it will be possible to reject some of these models with data returned by NASA's InSight  
42 mission after two years of nominal mission life time.

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## Introduction

46 The InSight mission (Banerdt et al., 2013) to Mars was launched on May 5, 2018 from Vandenberg Air  
47 Force Base, California, and touched down softly in the targeted landing ellipse on Elysium Planitia, Mars,  
48 on November 26, 2018. A combined very broad band and short period seismometer was deployed on  
49 the surface on 19th of December 2018 and is intended to operate until the end of 2020 (Lognonné &  
50 Pike, 2015, Lognonné et al., submitted).

51 Models for the seismicity of planet Mars usually estimate the long-term average annual seismic mo-  
52 ment rate (Table 1), and also the average annual event rate. This holds for estimations based on geologi-  
53 cal evidence (Golombek et al., 1992, Golombek, 2002, Taylor et al., 2013) as well as for models based on  
54 thermal evolution and cooling of the Martian lithosphere (Phillips, 1991, Knapmeyer et al., 2006, Plesa et  
55 al., 2018). All studies are compatible with the conclusion drawn from the non-observation of any unam-  
56 biguous seismic event by the Viking missions (Anderson et al., 1977, Goins & Lazarewicz, 1979), i.e. that  
57 Martian seismicity ranges somewhere between that of the Moon and that of Earth. However the range  
58 of predicted moment rates is wide and observational constraints of moment rate are therefore desirable  
59 to reject models and further our understanding of planetary heat engines. Here we investigate to what  
60 extent the InSight mission can be expected to contribute to the rejection of seismicity models. The main  
61 obstacles are that the detection threshold of a single station will be relatively high compared to a global  
62 network, while the expected life time is relatively short compared to the instrumental record available  
63 for Earth. Our approach basically relies on most of the seismic moment being released in a few, large  
64 events, and employs Monte Carlo methods to assess how likely any given seismicity model results in the  
65 moment rate estimation obtained from the recorded marsquakes.

66 Statistical seismology on celestial bodies other than Earth generally suffers from limitations in the life  
67 time and station spacing of seismic networks: On the Moon, the first long period seismometer was de-

68 ployed in 1969, later augmented by four more stations to form a triangle (Apollo 12 and 14 were rela-  
69 tively close together, compared with Apollo 15 and 16). The network was shut down in late 1977 (Vos-  
70 treys, 1980). One seismometer (Viking 2) was in operation on Mars from September 1976 to April 1978,  
71 i.e. for about 20 months (Toksöz, 1979). The Venera 13 and 14 missions each landed one seismometer  
72 on Venus on the 1<sup>st</sup> of March 1982 (Venera 13) and 3<sup>rd</sup> of March 1982 (Venera 14), respectively, and with  
73 lander life times of 127 and 57 minutes (Siddiqi, 2002). During these times, about 1.5 minutes of seismic  
74 waveforms and, additionally, statistical waveform parameters derived on board, were downlinked to  
75 Earth (Ksanfomaliti et al., 1982). The Huygens probe contained a suite of accelerometers to monitor its  
76 path through the atmosphere of Titan and to record the touchdown shock. Although not intended to  
77 conduct a surface seismic experiment, the HASI accelerometer onboard the Huygens probe continued to  
78 record data for approximately 30 min after touchdown (Hathi et al., 2009). A network of three triaxial  
79 accelerometers was deployed on comet 67P/Churyomov-Gerasimenko within the landing gear of Ro-  
80 setta's lander Philae, resulting in a network aperture of about 2.5 m (Knapmeyer et al., 2016). From this  
81 experiment, about 70 s of high-frequency data (sampling rates up to 16 kHz) were returned. With a de-  
82 sign life time of two terrestrial years, InSight will significantly surpass these recent experiments.

83 An instructive comparison to the much better coverage of the Earth arises from the Global Centroid  
84 Moment Tensor project (GCMT, Dziewonski et al., 1981, Ekström et al., 2012). At the same time the first  
85 seismometers were launched to Mars, the GCMT started producing its catalog of Earthquake source  
86 mechanisms, complete to magnitudes of about five and currently based on data from nearly 200 seismic  
87 observatories distributed worldwide. The GCMT continuously contributed to the picture of Earth's mo-  
88 ment-frequency distribution for the whole 42 years during which there was not even a single seismome-  
89 ter on Mars.

90 Besides the relatively short period of time covered by extraterrestrial seismicity catalogs so far, spa-  
91 tial coverage and completeness thresholds result in additional obstacles for the estimation of distribu-

92 tion parameters. Even within the Apollo network on the Moon, the most extensive network outside  
93 Earth so far, distance between stations was around  $30^\circ$ , i.e. the network triangle covered only a small  
94 fraction of the lunar surface. Limited spatial coverage results in a distance dependent detection thresh-  
95 old: small events will be detected only in the vicinity of the network or station, if there is but one. In  
96 turn, large, globally detectable events will be overrepresented in the catalog such that the moment-  
97 frequency distribution appears to be less steep than it actually is. Also, the estimation of event rates  
98 must rely on assumptions about source distribution in distant areas in order to extrapolate the detected  
99 local or regional seismicity to the entire planet.

100 The seismic moment of Earthquakes is predominantly released by the few largest events. This sug-  
101 gests that it is possible to obtain a reasonable estimate of the seismic moment rate from evaluating only  
102 a small number of large events, or even from the single largest event ever observed. Central questions  
103 are how such an estimate can be obtained and how accurate it will be, and also what accuracy is neces-  
104 sary to make a rate estimation a useful constraint to improve our understanding of Mars.

105 To answer the latter, we consider the moment rate estimates summarized in Table 1. Moment rates  
106 given there for Earth and Moon differ by almost exactly ten orders of magnitude, or 4.7 moment magni-  
107 tude units. The individual estimations for Mars cover a range of 2.1 moment magnitude units, or a factor  
108 of approximately 1150 in the seismic moment. It is thus desirable to estimate the moment rate with ac-  
109 curacy better than this in order to reject some or several of the published seismicity models.

110 In the following, we will first describe our proposed approaches for moment rate estimation, and how  
111 we generate synthetic seismicity catalogs for numerical testing (section "Methods"). The available cata-  
112 logs are described in section "Data". Since no event catalog is currently available for Mars, we briefly  
113 summarize the seismotectonic background information available for Mars. To test if reasonable results  
114 can be obtained, we evaluate several seismicity catalogs for the Earth, discuss the applicability to the  
115 Moon, and evaluate synthetic catalogs in a generic parameter study and for Mars-specific models (sec-



116 tion “Results”). Section "Single Station Completeness Threshold" specifically demonstrates that a single  
117 broadband station is sufficient to obtain a meaningful moment rate estimate for an entire planet within  
118 a relatively short time.

## 119 **Methods**

120 As Kagan & Schoenberg (2001) point out, a statistical consideration of magnitudes rather than mo-  
121 ments is advantageous by transforming multiplicative uncertainties into additive ones. Besides, taking  
122 the logarithm of the moment transforms the numerical values in to a more convenient range.

123 Throughout this work, we will frequently convert seismic moments  $M$  into equivalent moment magni-  
124 tudes  $m$  via

$$125 \quad m = \frac{2}{3}(\log_{10}M - 9.1) \quad (1)$$

126 (after Bormann et al., 2002). Using this formula, we also express moment rates as if the entire mo-  
127 ment was released in a single event. All magnitudes used throughout this paper are moment magnitudes  
128 following from the above equation, unless indicated otherwise. The coefficient  $2/3$  implies that a factor  
129 of 1000 in the moment  $M$  corresponds to a difference of exactly 2 moment magnitude units. We denote  
130 seismic moments by uppercase letters and magnitudes by lowercase letters to avoid the excessive index-  
131 ing that would result from the conventional lettering, and two indexed quantities  $M_x$  and  $m_x$  refer to  
132 moments and magnitudes connected by the above equation.

133 The coefficients of eq. 1 originate in a calibration of the seismic moment scale to other magnitude  
134 scales and thus carry a certain heritage of Earth’s seismological properties, e.g. via the decay of surface  
135 waves over distances not available e.g. on Mars. It must be kept in mind that relations to seismogram

136 amplitudes and, moreover, intensities will differ between Earth, Mars, and other bodies. Appropriate  
137 magnitude scales for Mars have been developed by Böse et al. (2018).

## 138 **Seismic Moment Rate Estimation**

139 Following the seminal works by Gutenberg & Richter (1941, 1944), the size-frequency distribution of  
140 earthquakes is often described by what we now call a power law, although Gutenberg & Richter were  
141 aware that the frequency of very large events cannot follow the same law as the frequencies of small  
142 and medium ones for physical reasons. Assuming a fault plane as large as the Earth's surface, and with a  
143 slip proportional to the square root of the fault area as in the relations given in Knapmeyer et al. (2006),  
144 we find a resulting seismic moment of  $7 \times 10^{28} Nm$  (corresponding to  $m = 13.2$ ) being a hard upper  
145 limit for quake size on Earth, as any geologically plausible fault would have a smaller rupture area. The  
146 extrapolation of the linear part of the size-frequency distribution of the GCMT predicts that events of  
147 this size occur every 10000 to 100000 years: The classical Gutenberg-Richter law, when interpreted na-  
148 ively, predicts that ridiculously large events recur on time scales that are short compared to e.g. the Wil-  
149 son cycle. Given that there are no traces at all of such events, we take it as an observational fact that this  
150 prediction is not true and the size-frequency distribution must bend down significantly somewhere be-  
151 tween  $5.3 \times 10^{22} Nm$  (the Tohoku event of March 2011) and  $10^{29} Nm$ .

152 We assume that the moment frequency distribution follows a tapered Pareto distribution (a.k.a. ta-  
153 pered Gutenberg-Richter distribution), which basically is a Gutenberg-Richter law tapered with an expo-  
154 nential function for the largest events (Figure 1).

155 In this distribution, the cumulative relative number of events with a seismic moment larger than  $M$  is  
156 given by (Kagan, 2002a, b, and references therein)

$$157 \quad \Phi(M) = \left(\frac{M_t}{M}\right)^\beta \exp\left(\frac{M_t - M}{M_c}\right) \text{ for } M_t \leq M < \infty \quad (2)$$

158 Here  $M_c$  is the “corner moment” where the exponential taper gains dominance over the classical  
 159 Gutenberg-Richter power law relation,  $M_t$  is the threshold moment above which the catalog is complete  
 160 (not to be confused with the detection threshold  $M_d$ , i.e. the smallest moment for which the catalog  
 161 contains some, but not all, events), and  $\beta$  is a slope parameter. The part of the graph of Figure 1 for  
 162  $M_d \leq M \leq M_t$ , i.e. the incomplete detection of events between detection threshold  $M_d$  and complete-  
 163 ness threshold  $M_t$ , is not described by eq. 2 as it is at least partially controlled by effects and properties  
 164 not related to the quake production, like background noise, anelasticity, and instrument sensitivity.

165 To obtain absolute numbers,  $\Phi(M)$  has to be multiplied with a calibration factor following Kagan  
 166 (2002b)

$$167 \quad \alpha_0 = \frac{\dot{M}_S M_c^\beta (1-\beta)}{M_t^\beta M_c \Gamma(2-\beta) \exp(M_t/M_c)} \quad (3)$$

168 where  $\dot{M}_S$  is the moment release rate per unit time of events exceeding  $M_t$ , and  $\Gamma(x)$  is the Gamma  
 169 function with  $\sqrt{\pi/4} \leq \Gamma(2-\beta) \leq 1$  for  $0.5 \leq \beta \leq 1$  (e.g. Weisstein, undated). The absolute rate  $\dot{N}(M)$   
 170 of events with a seismic moment larger than  $M$  is thus obtained from combining eqs. 2 and 3

$$171 \quad \dot{N}(M) = \alpha_0 \Phi(M) \quad (4)$$

172 In addition to the rate  $\dot{M}_S$  we introduce the cumulative moment  $M_S$  such that one event of size  $M_S$   
 173 per unit time would account for the entire moment rate.

174 If the completeness threshold can be made small enough,  $M_t \ll M_c$ , the exponential term approach-  
 175 es one and  $\dot{N}(M) \propto \dot{M}_S M_c^{\beta-1}$ , which plots as a straight line in log-log coordinates, such that the ob-  
 176 served event rate allows inferences on  $\dot{M}_S M_c^{\beta-1}$ .

177 For any catalog of observed events, one can estimate  $\dot{N}(M)$  via the number  $N$  of events listed in the  
 178 catalog (not taking into account those below  $M_t$ ), and the time span covered by it. The moment rate can  
 179 be estimated by summing up all events and dividing by the number of unit time intervals covered by the  
 180 catalog, as was done with the GCMT in Table 1.

181 The total moment released can be computed by integration over the distribution, but since the mo-  
 182 ment rate is a factor in  $\dot{N}(M)$  we can save the integration and solve  $\dot{N}(M)$  for  $\dot{M}_S$

$$183 \quad \dot{M}_S = \dot{N}(M) \frac{\Gamma(2-\beta)}{1-\beta} \frac{M^\beta}{M_c^{\beta-1}} \exp\left(\frac{M}{M_c}\right) \quad (5)$$

184 Although  $M_t$  cancelled out,  $\dot{M}_S$  is still only the moment rate resulting from events exceeding  $M_t$  by  
 185 implication via  $\dot{N}$ . If  $M_t \ll M_c$  and  $\beta < 1$ , the difference to the moment rate resulting from all events is  
 186 however negligible.

187 Now we consider only the largest event that ever occurred. By definition, the largest event ever (or  
 188 LVR, for short, from *Largest eVent eveR*) is contained in the catalog only once. Thus, if the catalog covers  
 189 a time interval of  $n$  unit intervals, we identify  $M = M_{LVR}$  and obtain  $\dot{N}(M_{LVR}) = 1/n$ , and eq. 5 allows  
 190 estimating the global moment rate from a single event, provided the corner moment  $M_c$  of the distribu-  
 191 tion and its slope parameter, or reasonable estimates, are given.

192 Using eq. 2 we find the relative frequencies of events exceeding  $M_c$  by a factor  $x$  is

$$193 \quad \frac{\Phi(xM_c)}{\Phi(M_c)} = \left(\frac{1}{x}\right)^\beta \exp(1-x) \quad (6)$$

194 With a convenient (and not entirely unrealistic) value of  $\beta = 2/3$ , this results in a drop of frequency  
 195 by a factor  $5 \times 10^{-15}$  for events one magnitude unit larger than  $m_c$ , while the frequency of events two  
 196 magnitude units larger is reduced by  $10^{436}$  with respect to the corner moment. Thus the former are

197 extremely rare, while the latter do practically not occur. This holds for slightly different choices of  $\beta$  as  
 198 well.

199 The largest event ever hence poses a (statistical) lower limit  $M_{LVR} \leq M_C$  simply by its existence.  
 200 Moreover, it will approach the corner moment with time, such that  $M_{LVR} \approx M_C$  becomes a reasonable  
 201 guess. Inserting this into eq. 5 yields

$$202 \quad M_S \approx \frac{1}{n} \frac{\Gamma(2-\beta)}{1-\beta} M_{LVR} \quad (7)$$

203 and we call this the normalized largest event ever, NLVR for short, estimation of the moment rate.

204 The middle term approaches infinity for  $\beta \rightarrow 1$ , but in reality  $1/2 \leq \beta \leq 2/3$  appears to hold, from  
 205 which  $\sqrt{\pi} \leq \Gamma(2-\beta)/(1-\beta) \leq 2.68$  follows.

206 We define  $n$  based on the duration of the observation: if the unit time interval has a duration  $\Delta T$ ,  
 207 seismicity is recorded between  $t_{start}$  and  $t_{end}$  (where  $t_{start}$  is not necessarily the time of the first event,  
 208 and  $t_{end}$  is continuously growing in an ongoing experiment), then the normalization factor for the largest  
 209 event ever which occurred at a time  $t_{LVR}$  between start and end is  $n = (t_{end} - t_{start} + 1)/\Delta T$ , and also  
 210 continuously grows in an ongoing experiment.

211 With this definition,  $1/n$  and thus the estimated value of  $\dot{M}_S$ , will approach zero for  $t_{end} \rightarrow \infty$ . Math-  
 212 ematically, this appears to be a flaw, but in the long run the observer can take the onset of a continuous  
 213 decay as indication that the largest event ever has exceeded the corner moment of the distribution.

214 A more sophisticated estimation of  $M_C$  is given by Kagan & Schoenberg (2001). As they found that a  
 215 maximum likelihood estimation of  $M_C$  is severely biased for small catalogs, they derive an alternate esti-  
 216 mator based on expressions for the first and second statistical moment of the tapered Gutenberg-  
 217 Richter distribution. With the seismic moment of the  $i$ -th event in the catalog termed  $M_i$ , a total of  $k$   
 218 cataloged events, the standard deviation  $\sigma$  of the  $M_i$ , and the mean moment

219 
$$\bar{M} = \frac{1}{k} \sum_{i=1}^k M_i \quad (8)$$

220 they obtain the estimator

221 
$$\tilde{M}_c = \frac{\sum(M_i^2/k) - M_t^2}{2[M_t^2\beta + (1-\beta)\bar{M}]} \quad (9)$$

222 from which a bias correction

223 
$$\tilde{M}_{bias} = \frac{(\beta-1)[2M_t^3 + 3M_t^2\tilde{M}_c\beta + (\sigma^2 + \bar{M}^2)(6\tilde{M}_c - 3\tilde{M}_c\beta - 2\bar{M})]}{4k[M_t\beta + (1-\beta)\bar{M}]^2} \quad (10)$$

224 has to be subtracted. The difference  $\tilde{M}_c - \tilde{M}_{bias}$  is then substituted for  $M_c$  in eq. 5.

225 The estimator  $\tilde{M}_c - \tilde{M}_{bias}$  holds for i.i.d. events, i.e. the parameters of the earthquake-generating  
 226 distribution must be constant in time, and the quakes must not trigger each other. Therefore the catalog  
 227 has to be declustered before estimating the corner moment. We call the combination of equations 5, 9,  
 228 and 10 the k-events Kagan-Schoenberg, or  $KS_k$  for short, estimator of the moment rate.

229 The  $KS_k$  estimator requires a catalog containing at least  $k$  events and a reasonable estimate about the  
 230 completeness threshold  $M_t$  of that catalog to be computable and useful. If only a single event is availa-  
 231 ble, one can either equate  $M_t$  with the size of that event, resulting in  $\tilde{M}_c = 0$ , or assume that  $M_t$  is  
 232 smaller than the event, resulting in  $\tilde{M}_c$  being dependent only on that assumption but not on the ob-  
 233 served event. Moreover,  $\sigma$  and hence  $\tilde{M}_{bias}$  are undefined for a single event. Therefore the  $KS_k$  estima-  
 234 tor cannot be used with a single event.

235 The event magnitudes or seismic moments in a real marsquake catalog will carry an uncertainty as  
 236 discussed by Böse et al. (2018). This uncertainty for individual events is propagated into the uncertainty  
 237 of NLVR and  $KS_k$  estimations in a Monte Carlo fashion by evaluating a number of modified catalogs,  
 238 where each event's seismic moment is perturbed according to a normal distribution with the standard

239 deviation cataloged for this individual event, and taking care for error propagation through conversion  
240 between different types of magnitudes or magnitudes and seismic moments.

## 241 **Emission Probabilities**

242 Due to the stochastic nature of the tectonic process generating the real quakes, as well as of any cata-  
243 log simulation process, simulated catalogs will never match observed quake sequences on an event-by-  
244 event basis even if the model underlying the simulation matches the real process perfectly, and all pa-  
245 rameters are known exactly.

246 Due to the limitations of the data set we expect to obtain for Mars, we do not consider a maximum-  
247 likelihood fit of an assumed type of distribution in order to estimate its parameters feasible.

248 The moment rate estimation described above is intended to be a direct estimation of one of the pa-  
249 rameters of the size-frequency distribution, but is likely to be biased and carry some variance, not the  
250 least due to the uncertainty of the seismic moments of observed events. Bias and variance will depend  
251 on several factors, such as the parameters of the Tapered Gutenberg-Richter distribution themselves,  
252 and the period of time covered by the simulated catalog.

253 We borrow (without intending to over-stress the analogy) from the field of hidden layer Markov  
254 chains the term "emission probability" for the probability that a stochastic process produces a statistical  
255 diagnostic with the same value as obtained from another, inaccessible process: In our case, a quake cata-  
256 log is a realization of a stochastic process which is transformed into a single-valued diagnostic using one  
257 of our estimators. This transformation is a secondary stochastic process of which the resulting diagnostic  
258 is a single realization. We aim to estimate the probability that a numerical simulation of seismicity cata-  
259 logs results in the same moment rate estimations as the observed catalog.

260 The catalog simulation we describe in the next section is a random number generator with three pa-  
261 rameters: moment rate, corner moment, and distribution slope. These parameters form a state space,

262 which we scan on a search grid with a regular node spacing when moment rate and corner moment are  
263 expressed as magnitudes following equation 1. For each node, we produce a large number of synthetic  
264 catalogs and evaluate the NLVR and  $KS_k$  estimators for all these catalogs, resulting in a distribution of  
265 estimations. Comparing these distributions with the respective estimations of the real catalog, we can  
266 determine the probability that a certain combination of state parameters makes the catalog simulation  
267 emit a moment rate estimation within the uncertainty limits of the moment rate estimation derived  
268 from the real catalog.

269 This finally yields a map of emission probabilities for the scanned part of the state space, which can  
270 then be compared with predicted parameters e.g. from Knapmeyer et al. (2006), or with values for Earth  
271 and Moon.

272 Examples will be shown below in sections dealing with seismicity catalogs for Earth and Moon, and  
273 synthetic catalogs for Mars. These are computed on a search grid with node spacing of 0.1 moment  
274 magnitudes in both moment rate and corner moment dimensions. For each grid node, we evaluate 1000  
275 catalogs, resulting in 3.1 million catalogs for the depicted grids. We evaluate for each node the probab-  
276 ility that a given state emits a value within 0.2 magnitude units (corresponding to a factor 2 in seismic  
277 moment) from the respective target values as given in figure titles (the GCMT comes without uncertainty  
278 ranges for the scalar moment, therefore we use a fixed interval width here). Computation time on a  
279 desktop computer fits into a lunch break and thus leaves room for refining the search grid or evaluating  
280 more catalogs per grid node.

## 281 **Simulation of Seismicity Catalogs**

282 Equation 2 only predicts the relative frequencies of events. In order to reproduce the seismicity ob-  
283 served during a time interval of duration  $\Delta t$ , it needs to be normalized in such a way that also the abso-  
284 lute number of events  $N(M)$  and the observed cumulative moment  $M_{cum} = \dot{M}\Delta t$  released by all events



285 in the catalog are reproduced. Following Kagan (2002b), the long term average  $\alpha_0$  is computed by evalu-  
286 ating eq. 3.

287 We adjust the – in our context entirely fictitious – completeness threshold  $M_t$  such that we obtain  
288 catalogs of approximately 10000 events.

289 The number  $N_{\Delta t}$  of events in an actual time interval, e.g. a given calendar year, follows a Poisson dis-  
290 tribution describing the probability that the value of  $N_{\Delta t}$  is  $n$  (e.g. Zhuang et al., 2012)

291 
$$P\{N_{\Delta t} = n\} = \frac{\lambda^n}{n!} e^{-\lambda} \quad (11)$$

292 where  $\lambda$  is the rate parameter of the distribution.

293 For a rate parameter exceeding about 10, the Poisson distribution can be approximated by a normal  
294 distribution with mean  $\bar{x} = \lambda$  and standard deviation  $\sigma = \sqrt{\lambda}$ . For time intervals of the order of years  
295 and a sufficiently low detection threshold, one can expect hundreds or thousands of quakes, such that  
296 this condition is met. We thus draw the number of events per time interval from a normal distribution  
297 with  $\lambda = \alpha_0$ .

298 The distribution of earthquakes in time (when disregarding aftershocks) also follows a Poisson distri-  
299 bution, as was first shown for California by Gardner & Knopoff (1974). With the number  $n$  of events oc-  
300 ccurring during interval  $\Delta T$  already being given by eqs. 3 and 11, is it thus sufficient to distribute the  
301 source times uniformly over the time interval (see Zhuang & Touati, 2015, algorithm 10).

302 Finally, for each source time generated thus, a seismic moment is drawn from the tapered Pareto dis-  
303 tribution, following the method described by Vere-Jones et al. (2001), which we reproduce here for self-  
304 containedness. We first generate a first set  $U_1$  of  $n$  uniformly distributed random numbers from the in-  
305 terval  $]0,1[$ . From these we compute

306 
$$y = U_1^{-1/\beta} \quad (12)$$

307 In addition, we employ the inverse method to produce  $n$  exponentially distributed random numbers  
 308 from a second set  $U_2$  of  $n$  uniformly distributed random numbers which are then filtered through the  
 309 inverse of the exponential distribution

310 
$$X = -\frac{1}{\lambda} \log(1 - U_2) \quad (13)$$

311 to obtain a set  $X$  of exponentially distributed random numbers, where

312 
$$\lambda = \frac{M + M_t}{M_c} \quad (14)$$

313 is the rate parameter of the exponential distribution  $f(\tau) = \lambda \exp(-\lambda\tau)$ . Finally,

314 
$$K = (M + M_t) * \min(y, 1 + X) - M_t \quad (15)$$

315 is a tapered Pareto distributed seismic moment value following the distribution given in eq. 2.

316 It should be noted that assuming a Poisson process is equivalent to the assumption that the individual  
 317 events are entirely independent of each other, i.e. the process has no memory of the past. This assump-  
 318 tion does not apply to foreshock/aftershock sequences, therefore a comparison of real catalogs with  
 319 synthetic ones generated with the above procedure requires the declustering of the real catalog. Moreo-  
 320 ver, this kind of catalog simulation might be unsuitable for sources with a periodic driving force, such as  
 321 deep moonquakes (DMQ).

322 It has been argued that the slope parameter  $\beta$  is actually not a free parameter but a universal con-  
 323 stant with a value  $\beta = 1/2$  (initially apparently by Vere-Jones, 1976, recently e.g. by Kagan, 2014). Anal-  
 324 yses of different tectonic settings (Kagan, 1997), Flinn-Engdahl regions (Kagan, 1999) and rectangular  
 325 regions defined by parallels and meridians (Godano & Pingue, 2000) support that  $\beta$  is a global constant

326 for quakes on Earth (except mid-oceanic ridges), however with a value  $0.6 \leq \beta \leq 2/3$ . Kagan (2014)  
327 argues that the deviation from the prediction is a combination of several observational biases.

328 Thermal moonquakes appear to follow a distribution where most of the moment is released by the  
329 small events (implying  $\beta > 1$ , Cooper & Kovach, 1975), and it is questionable that deep moonquakes,  
330 with a stress source that reverts direction on a monthly scale, fall under the same universal relation as  
331 subduction zone events resulting from a uniformly progressing slab. So although we follow Knapmeyer et  
332 al. (2006) that  $\beta = 0.625$  is a good initial choice for Mars, lacking a better one for now, we are aware  
333 that this needs to be established experimentally, and it must not be taken for granted.

334

335

## 336 Data

337 The following subsections describe three seismicity catalogs for the Earth and one catalog for the  
338 Moon that were used as test cases for moment rate estimation. In the absence of a Mars seismicity cata-  
339 log we give a brief summary of Martian seismotectonic properties that make us conclude that earth-  
340 quake statistics methods based on terrestrial circumstances are applicable to Mars as well.

### 341 GCMT catalog

342 We downloaded the complete catalog of the Global Centroid Moment Tensor project (GCMT,  
343 Dziewonski et al., 1981, Ekström et al., 2012) from IRIS (see "Data and Resources"). This catalog covers  
344 the 15456 days from 05. January 1976 (date of the first event in the GCMT) to 17. May 2018, or 42.32  
345 years of 365.25 days, and contains 49178 events with seismic moments between  $3.49 \times 10^{15} Nm$  and  
346  $5.32 \times 10^{22} Nm$ . The completeness threshold for the catalog as a whole is  $M_t \approx 2 \times 10^{17} Nm$ , but de-

347 creases with time; especially the year 1976 is significantly less complete, while  $M_t$  is lower for the more  
348 recent years.

349 The cataloged events released a cumulative seismic moment of  $\sum M_0 = 3.23 \times 10^{23} Nm$ . The ten  
350 largest events in this catalog released 47.5 % of  $\sum M_0$ , and the 615 largest events (i.e. 1.25 % of all  
351 events) released 90 % of  $\sum M_0$ .

## 352 **Stable Continental Regions catalog**

353 The Stable Continental Regions catalog of Schulte and Mooney (2005, see also "Data and Resources"  
354 represents a compilation for several sources of historically witnessed events and of events for which  
355 instrumental recordings exist, and covers the entire Earth for the time from 495 AD to 2003. Schulte and  
356 Mooney have estimated seismic moments for most of the 1373 events in the catalog. Cataloged mo-  
357 ments range from  $5.3 \times 10^{15} Nm$  to  $7.5 \times 10^{23} Nm$ , the latter however is assigned to a reservoir-  
358 associated event in India in September 2000 and is most likely erroneous. We exclude this and another  
359 reservoir-associated event for which a moment of  $> 10^{23} Nm$  is given from our analysis, leaving as the  
360 largest listed event an earthquake that occurred in July 1819, also in India, with a seismic moment of  
361  $6.6 \times 10^{20} Nm$  ( $M_w = 7.8$ ).

362 For each event, the catalog indicates if instrumental records, historical descriptions, or both are avail-  
363 able. For events after 1976, the catalog is informed by the GCMT.

## 364 **Temporary Installation at Goldstone, CA**

365 A single Nanometrics Trillium Compact seismometer (120 s eigenperiod) was installed temporarily  
366 during summer 2014, in a dry lake bed in the Mojave desert, approximately 60 km NNE of Barstow, Cali-  
367 fornia, and approximately 1 km southwest of the 70 m "Mars" antenna dish of NASA's Deep Space Net-  
368 work (Lorenz et al., 2015). The purpose of this experiment was to gather seismic and microbarometric

369 recordings of dust devils, to support the interpretation of dust devil recordings expected from Mars. The  
370 experiment was not intended to record earthquakes, but these are of course hard to avoid.

371 The surface of the lake bed is composed of fine mud that grades into denser sediment overlying a  
372 rock with increasing seismic velocities with depth, which is likely analogous to the InSight landing site  
373 (see Lorenz et al., 2015, Golombek et al., 2017, and Knapmeyer-Endrun et al., 2017). The seismometer  
374 was shallowly buried and accompanied by a microbarometer and an anemometer on the surface. The  
375 seismic sampling frequency was 100 Hz, but we resampled to 2 Hz to simulate the continuous data  
376 stream that will be available from InSight (Lognonné et al., submitted). The seismometer operated from  
377 05. June 2014 to 29. Aug. 2014. Several downtime periods add up to 18 days (24h periods, not to be con-  
378 fused with the 24.6h of the martian rotation period) of lost data, such that a total of 68 days of seismic  
379 recordings remains.

380 During this experiment, the USGS National Earthquake Information Center (NEIC) catalog lists 304  
381 global events with magnitudes of 5 and larger.

382 We convert the 7 different types of magnitudes found in the NEIC catalog ( $M_s$ ,  $m_b$ ,  $M_L$ , and several  
383 versions of  $M_w$ ) into seismic moments to quantify source strength, using relations from Wason et al.  
384 (2012), and from Bormann et al. (2002).

385 By visual inspection, we categorize all events according to their signal quality with categories given in  
386 Table 2. We expect that magnitudes or seismic moments could be determined from InSight data for  
387 events comparable to categories A through E, and sufficiently precise locations to reduce the distance  
388 effect in magnitude uncertainty to below 0.3 magnitude units for categories A, B, and E (Böse et al.,  
389 2018).

390

## 391 **Moonquakes, deep and shallow**

392 Seismic observation of Apollo has detected more than 13000 seismic events (Nakamura, 2003; see  
393 "Data and Resources"), encompassing endogenous moonquakes, meteorite impacts, and artificial  
394 sources.

395 The most frequent type of events is the deep moonquakes (DMQ) at depths between 700 *km* and  
396 1100 *km* (Nakamura, 2005). They occur in clusters which are activated and deactivated in cycles corre-  
397 sponding to the orbital periods of the Moon-Earth-Sun system. Time lags between individual events of  
398 individual clusters are also not random (Bulow et al., 2007, Weber et al., 2010, and references therein).  
399 Kawamura et al. (2017) show that stress drops associated with DMQ are of the order of magnitude of the  
400 tidal stresses in their source regions. The DMQ are thus not only triggered but also caused by tidal  
401 stresses, i.e. the orbital motions in the Moon-Earth-Sun system can be considered as a part of the DMQ  
402 source mechanism. Since orbital motion is described by differential equations that allow evaluation for-  
403 ward and backward in time, the DMQ mechanism has a memory of the past and therefore cannot be  
404 i.i.d. Poissonian. The situation appears to be different for the (poorly understood) shallow moonquakes,  
405 which we discuss in section "Moon: High Frequency Teleseisms".

406 Therefore, we focus on shallow moonquakes in the following. The source mechanism of shallow  
407 moonquakes is not yet clear but they are likely to be caused by thermal contraction of the Moon (e.g.  
408 Binder & Lange, 1980), i.e. the same mechanism expected for marsquakes (Phillips, 1991, Knapmeyer et  
409 al., 2006, Plesa et al., 2018). If this is correct, shallow moonquakes can be regarded as lunar analogs of  
410 marsquakes.

## 411 **Martian Seismotectonics**

412 The seismic data available from Mars so far (up to late November 2018) contains only one candidate  
413 marsquake, which was recorded by the Viking 2 seismometer (Anderson et al., 1977), but could not iden-

414 tified as such unambiguously. At the time of writing, we are thus not in the possession of a seismic data  
415 set that allows for statistical evaluation. In this section we describe in more detail what is known about  
416 the seismotectonics of Mars, in order to support that our statistical approach is meaningful for Mars as  
417 well as for Earth.

418 After the successful deployment on December 19, 2018, broad band and short period seismic data  
419 from the InSight lander is expected to be received from January 2019 onwards. Routine evaluation of  
420 events, encompassing the identification of seismic phases, epicenter location based on multi-orbit sur-  
421 face waves and polarization analysis (Böse et al., 2017, Panning et al., 2015), will be conducted by a team  
422 at the Swiss Seismological Service located at ETH Zürich (Clinton et al., 2018), the Marsquake Service  
423 (MQS). Mars-specific magnitude scales were developed (Böse et al., 2018) and will be used by the MQS  
424 to quantify source strength on Mars. The event catalog produced by the MQS will also discriminate be-  
425 tween different source types (tectonic, impacts, landslides, and atmospheric effects) based on the expe-  
426 rience with Apollo data and physical differences in the source mechanism (see Daubar et al., 2018, con-  
427 cerning impacts, and Clinton et al., 2018, concerning the MQS).

428 Mars is a one-plate planet which shows no unambiguous indications of subduction zones or mid-  
429 ocean ridges, neither in topography nor in free air gravity anomalies or lithospheric magnetic field (e.g.  
430 Zuber et al., 2000, Hirt et al., 2012, Morschhauser et al., 2014). Nevertheless, it must have witnessed  
431 much seismic activity in the past, as its surface is crisscrossed with complex patterns of normal and  
432 thrust faulting. Knapmeyer et al. (2006) mapped more than 8500 normal and thrust faults with a cumula-  
433 tive length of about 680000 *km*, updated later on to approx. 14800 faults with a cumulative length of  
434 940000 *km* (Knapmeyer et al., 2008). The shortest of these has a length of approx. 600 meters, while the  
435 longest graben that dissects the Tharsis bulge is almost 1450 *km* long. The Knapmeyer et al. (2006) fault  
436 catalog appears to be complete for faults longer than 80 *km*. The overall size-frequency distribution of  
437 Martian faults can be described by a power law with exponent well in the range found for fault popula-

438 tions on Earth (see Knapmeyer et al., 2006, and references therein). If one assumes that all fault seg-  
439 ments are equally likely to break, and that large marsquakes require long breaking segments, then the  
440 length-frequency distribution of Martian faults is in favor for a power-law-like distribution of Marsquake  
441 sizes.

442 Taking the age of the youngest surface crossed by a fault as indicator of its age, no age preference for  
443 shorter or longer faults is found, i.e. the size frequency distribution appears to be independent of time. It  
444 must be noted, however, that 75 % or more of the total fault length was produced more than 3.5 Ga ago.  
445 The youngest faults are estimated to have an age of approx. 300 Ma.

446 Fault populations on Mars show features like fault linkage or relay ramps well known from Earth (see  
447 Schulz et al., 2010, and references therein, for a general treatment). The mechanisms of fault growth are  
448 considered to be the same on Earth and Mars (see Wyrick et al., 2018, for a recent analog study), alt-  
449 hough faults on Mars accumulate less displacement per length than faults on Earth. This can however be  
450 attributed to properties that all scale with gravity (Schulz et al., 2006).

451 Stresses resulting from differential cooling of the planetary interior are widely accepted as the main  
452 source of Martian seismicity (Phillips, 1991, Knapmeyer et al., 2006). Plesa et al. (2018) also investigated  
453 stresses resulting from mantle drag due to convection and found that these might under certain circum-  
454 stances contribute significantly to the moment rate, and especially modify the regional distribution of  
455 effective stresses. Knapmeyer et al. (2006) defined end-member and “typical” models with “strong”,  
456 “weak” and “medium” moment rates of  $4.78 \times 10^{18} \text{ Nm/yr}$ ,  $3.42 \times 10^{16} \text{ Nm/yr}$ , and  $5.99 \times$   
457  $10^{16} \text{ Nm/yr}$ , respectively. Due to different corner moments, their models *StrongFew*, *StrongMany*,  
458 *WeakFew*, *WeakMany*, and *Medium* produce  $m = 4$  events with recurrence rates between 13 hours and  
459 6.7 years. Based on these and other estimations of martian seismicity, Panning et al. (2017) expect about  
460 100 events per year that are detectable at distances beyond  $60^\circ$ .



461 While the Moon's seismic event rate is dominated by the deep moonquakes that are tied to Earth  
462 tides, Phillips (1991) found that although tidal loading by the sun produces high strain rates, the associ-  
463 ated strains are small, and concluded that tidal loading of Mars is unimportant from the seismicity point  
464 of view. We expect that Mars, unlike the Moon, has no significant periodic seismicity.

465 Mars is well known for its giant volcanos. These have been active through much of the Martian histo-  
466 ry. Although some of the youngest volcanic surfaces might be only a few million years old (Neukum et al.,  
467 2004), no actual volcanic activity has ever been reported. The wristwatch pattern of faults around the  
468 Alba Patera volcano actually shows that its magma chamber retreated (Cailleau et al., 2003). Volcanic  
469 contributions to seismic activity are thus considered unlikely.

470 Fresh impacts have been found on Mars in images taken repeatedly from the same area (Malin et al.,  
471 2006), and might provide semi-controlled seismic sources when the location of an impact detected by a  
472 seismometer can be identified in imagery. Quantitative analysis shows that the recurrence intervals of  
473 globally detectable impacts is between one year and 10 years (Teanby & Wookey, 2011), where the  
474 longer intervals are expected to be more likely due to expected noise conditions. Contrary to an intuition  
475 one might have based on the cratered surface of especially the southern hemisphere of Mars, impacts  
476 are also not expected to dominate the seismic record.

477

478

479

## Results

480 To assess the reliability of moment rate estimations we conduct numerical tests where we compare  
481 estimated rates with the GCMT catalog of earthquakes from the time interval 1976 to 2018 (section  
482 "Earth"), and also with the known true values of synthetic catalogs (section "Generic Synthetic Cata-

483 logs"). Finally, we generate synthetic catalogs for several models of Martian seismicity and investigate if  
484 and how we can distinguish between them (section "Mars-specific synthetic catalogs").

## 485 **Earth**

486  
487 Since the GCMT, as the most comprehensive and homogenous long-term catalog of moment tensor  
488 solutions, relies on a global network of about 200 stations, we first need to establish that a single station  
489 can provide data representative for Earth's global moment rate. The question here is what the global  
490 completeness threshold for a single (broadband) seismometer is, and how long it takes until the largest  
491 recorded event is above this completeness threshold.

492 We then compare how the output of different estimators evolves in time, i.e. re-evaluate all estima-  
493 tors for each new event in the catalog throughout the time covered. Finally, we compare estimations for  
494 different tectonic settings (subduction zones, mid-ocean ridges, and stable continental regions) by subdi-  
495 viding the GCMT catalog according to Flinn-Engdahl-Zones and by evaluation of an additional catalog  
496 dedicated to stable continental regions (as an analog for the single plate regime on Mars) which also  
497 contains events predating the instrumental recording of earthquakes.

498 Since we will likely not be able to determine reliably the slope parameter of the martian seismicity  
499 distribution, we use a fixed value of  $\beta = 2/3$  throughout all these tests.

### 500 ***Single Station Completeness Threshold***

501  
502 We use as single station the temporary installation at Goldstone described in section "Temporary In-  
503 stallation at Goldstone, CA". To find its completeness threshold, we compare the size-frequency (survi-  
504 vor) distribution of events detected at Goldstone with the size-frequency distribution of the GCMT

505 (Figure 2). Distributions from short recordings are less smooth than that of the whole GCMT data base,  
506 and also differ between independent time windows of the same duration. In addition, the magnitude-to-  
507 moment conversion is based on empirical relations between uncertain quantities and may thus provide  
508 an uncertain moment value only, thus adding to the roughness of the curve. We therefore do not at-  
509 tempt to pin down the completeness threshold very precisely, but only estimate that it is somewhere  
510 between  $10^{18} Nm$  and  $10^{19} Nm$  for events of grade A alone, and possibly lower when taking A and B, or  
511 A, B, and E together. The GCMT lists 1273 events exceeding  $10^{19} Nm$ , and 5891 events exceeding  
512  $10^{18} Nm$ , resulting in recurrence times of 12.2 and 2.7 days, respectively.

513 The strongest events in the grade  $A$ ,  $A \cup B$ , and  $A \cup B \cup E$  subsets are the same, so it is sufficient to  
514 use one of them for a moment rate estimation that relies on the strongest events. From the grade A  
515 events alone, we obtain a NLVR moment rate estimate of  $1.03 \times 10^{22} Nm/yr$  ( $m_S = 8.6$ ), while the  
516  $KS_{10}$  estimator returns  $5.79 \times 10^{21} Nm/yr$  ( $m_S = 8.4$ ).

517 For comparison, we subdivide the GCMT catalog into 180 non-overlapping time windows, each of  
518 which has the same 86 days duration as the Goldstone experiment. Using the NLVR estimator we obtain  
519 a moment rate equivalent to magnitude  $8.28 \pm 0.42$  from these time windows, while the  $KS_{10}$  estimator  
520 results in an equivalent magnitude of  $8.25 \pm 0.24$ .

521 Compared with the  $7.61 \times 10^{21} Nm/yr$  ( $m_S = 8.52$ ) obtained from the complete GCMT catalog,  
522 and comparing with Figure 3 and the  $KS_{10}$  emission probabilities in Figure 4, we conclude that the Gold-  
523 stone experiment suffices to estimate the Earth's global seismic moment rate with acceptable accuracy.

524 One can thus expect that a seismometer installation comparable to the one at Goldstone produces a  
525 globally representative "largest event ever" time series three months or less after deployment, meaning  
526 that all comparable installations worldwide would produce the same such time series. For any longer  
527 recording time it is thus justified to evaluate the GCMT catalog instead of a single station catalog.

528 ***Moment Rate Estimations: Entire Earth***

529 We compare the evolution in time of several different moment rate estimators. For this exercise we  
 530 use only events from 1977 onwards since the GCMT completeness threshold for 1976 is significantly  
 531 higher than for later years. We expect that the  $NLVR$  and especially the  $KS_k$  estimators have a certain  
 532 burn-in time: one cannot evaluate  $KS_k$  before having cataloged  $k$  events. Moreover, if the catalog con-  
 533 tains events below the threshold for global detectability, the first listed events will not be representative  
 534 for the global moment rate. By excluding 1976 from consideration we avoid mixing the burn-in time of  
 535 the GCMT project with that of the rate estimation.

536 As a baseline we consider the summation of all events contained in the catalog between a time  $T_{start}$   
 537 and up to a time  $t$ , and divide by the number of years (assuming 365.25 days per year) elapsed between  
 538  $T_{start}$  and  $t$  to obtain an annual rate. The resulting time series  $\dot{M}_{s,base}(t)$  is thus based on all data avail-  
 539 able at time  $t$ .

540 We compare this baseline with estimations based on the single strongest event ( $\dot{M}_{s,NLVR}(t)$ , based on  
 541 the  $NLVR$  estimator) and on the 2, 5, 10, and 50 strongest events ( $\dot{M}_{s,KS_k}(t)$ , based on the  $KS_k$  estima-  
 542 tor). The latter are computed only after a sufficient number of events is available, thus the respective  
 543 time series start somewhat later than  $\dot{M}_{s,base}(t)$  and  $\dot{M}_{s,NLVR}(t)$ . All time series are compiled in Figure 3.

544 A common feature of all time series is that they decay like  $1/t$  or shallower as long as no large new  
 545 contribution to the moment release occurs. This is of course most pronounced in  $\dot{M}_{s,NLVR}(t)$ , which can  
 546 have a new peak only if an event occurs that is larger than any event before. But the effect is also clear in  
 547 the  $\dot{M}_{s,KS_k}(t)$  time series, where smaller peaks indicate that new events entered the top- $k$  list. Since  
 548 new events can enter this list at any position, the value of the  $KS_k$  estimator will change more often with  
 549 increasing  $k$ , hence the time resolution of  $\dot{M}_{s,KS_k}(t)$  increases with  $k$ .

550 In analogy to taking the absolute value of the difference between two values we compute

$$551 \quad \exp \left( \left| \log \left( \dot{M}_{s,est}(t) \right) - \log \left( \dot{M}_{s,base}(t) \right) \right| \right) \quad (16)$$

552 to evaluate the deviation between an estimator and the baseline value, as it is sufficient to know that  
553 one of the two values has to multiplied by some factor to obtain the other one.

554 All estimators except  $KS_2$ , which sometimes overestimates by three orders of magnitude, follow the  
555 full-catalog baseline closely. Even the single-event *NLVR* estimation never deviates by more than a fac-  
556 tor of nine, as does  $KS_5$ . Both  $KS_{10}$  and  $KS_{50}$  are always within a factor 2.5 or less from the baseline,  
557 most of the time the factor is smaller than 2. When subdividing the GCMT into 21 consecutive, non-  
558 overlapping intervals of 2 years, the  $KS_{10}$  value is always within a factor 5 of the 42-years average, and  
559 within a factor 2 in half of all cases. All estimators tend to underestimate. We however do not think that  
560 the evaluation of a single catalog is sufficient to declare this a rule.

### 561 ***Moment Rate Estimations: Specific Tectonic Settings***

562 Earth's seismicity is mainly due to plate tectonics, and by far most of its seismicity (approximately 75  
563 % of all events) occurs at active plate boundaries. Subduction zones alone account for approximately 60  
564 % of all earthquakes. Mars, on the other hand, is a one-plate planet. It is thus desirable to investigate if  
565 reasonable moment rate estimations can be made for selected, either Earth specific or Mars specific  
566 tectonic settings rather than for the entire Earth.

567 Based on the Flinn-Engdahl regionalization scheme of seismic regions (Young et al., 1995), we extract  
568 events belonging to mid-ocean ridges and subduction zones from the GCMT according to the region IDs  
569 listed in the appendix 0. Since the F-E-Regions define regions on the Earth's surface but not in its interior,  
570 we further subdivide the events classified as "subduction zone" into two depth layers, above and below  
571 100 km, in order to clearly separate subducting slabs from crustal events. The number of events sorted  
572 into each of the four resulting groups of events is given in Table 3.

573 As reported earlier (e.g. Bird & Kagan, 2004), the distribution for mid-ocean ridge events appears to  
574 be significantly steeper than for the other groups (Figure 5**Fehler! Verweisquelle konnte nicht gefunden**  
575 **werden.**), the slopes of which appear to be essentially identical with that obtained for the complete  
576 catalog. Especially a test using mid-ocean ridge events is thus a scenario different from the other groups,  
577 or the GCMT taken as a whole.

578 For each group we evaluate (a) the sum of all events divided by the number of years covered by the  
579 catalog (42.3 years), (b) the *NLVR* estimator, and (c) the *KS<sub>10</sub>* estimator, thus obtaining three values for  
580 each group. The resulting moment rates, expressed both in *Nm/yr* and as moment magnitude of a sin-  
581 gle event releasing the same amount of seismic moment, are also summarized in Table 3.

582 In most cases, both the *NLVR* and the *KS<sub>10</sub>* estimator underestimate the value obtained by summing  
583 up all events of a subset. The ratios between these estimators and the complete summation are well in  
584 the range found for the entire Earth. This holds for all four subsets.

585 Thus the results obtained for the GCMT are encouraging, but we note that an evaluation of a station  
586 installed e.g. in early 2004 would look different, since its event catalog would report two very strong  
587 events (Banda Aceh and Tohoku) within only 6 years.

588 Neither subduction zones nor mid ocean ridges exist on Mars. We thus use the Earthquake Catalog  
589 for Stable Continental Regions of Schulte & Mooney (2005, see also "Data and Resources") as a better  
590 analog of martian seismicity.

591 We subdivide the catalog into two groups: the first contains events for which no instrumental record  
592 is available, while the second contains events that were interpreted solely based on instrumental records  
593 (a third group of events, where historical information and instrumental data is interpreted together, was  
594 excluded from our analysis). The goal is to compare moment rate estimations resulting from the histori-  
595 cal events with independent estimations for the instrumental epoch.

596 We do not consider the 21 events listed for the time between 495 AD and 1500 AD (only three of  
597 which occurred before 1000 AD). This may look like a somewhat arbitrary modification of the catalog,  
598 but we think it is justified since an extension of the covered period by 1000 years biases the duration of  
599 observation in a more severe way than the omission of 21 events with moment magnitudes below 6.1  
600 biases the released seismic moment. We also delete two reservoir-associated events that occurred in  
601 India in 2000, since the catalog assigns unlikely seismic moments beyond  $10^{23} Nm$  (corresponding to  
602  $M_W > 9$ ) to both of them, which are also in clear contradiction with the listed magnitude values (around  
603 5). We thus obtain 226 events from 1500 AD to 1949 and 879 events from 1950 to 2003. Their size-  
604 frequency distributions are shown in Figure 5. Here the group of historical events shows a much lower  
605 slope than all other distributions shown. This is a property expected for incomplete catalogs, as this his-  
606 torical events list certainly is. The slope of the distribution of the instrumentally evaluated events is very  
607 similar to that of the GCMT, but this is not surprising since many of the corresponding catalog entries are  
608 based on the GCMT.

609 The resulting moment rate estimates are consistent within each of the two groups (see Table 3), but  
610 the values obtained for the events from the instrumental epoch are also consistently higher than those  
611 for the historical events, by factors between 1.7 and 4.1, with the *NLVR* estimator producing the largest  
612 deviation. Although these deviations are still in the range of variability seen for the different estimators  
613 in Figure 3, they exhibit a certain trend. If expressed as magnitudes, we find that the differences be-  
614 tween the individual estimates is no larger than the uncertainty attributed to the individual magnitude  
615 estimations as listed in the catalog, which is typically 1 magnitude unit, and never below 0.4 magnitude  
616 units.

617 In summary we find that the evaluation of the GCMT is encouraging, although it was purely accidental  
618 that its largest events occurred late. The deviations obtained with the Stable Continental Regions catalog  
619 might be attributed to the very circumstantial nature and general uncertainty of historic observations,

620 but might also point to a systematic shortcoming of our approach. To further investigate bias and vari-  
621 ance of our estimators, we conduct an extensive series of tests with synthetic catalogs.

## 622 **Moon: High Frequency Teleseisms**

623 For the shallow moonquakes, we use here the seismic moments estimated by Oberst (1987). In total,  
624 28 shallow moonquakes were detected by the Apollo network. We evaluated the annual seismic mo-  
625 ment release of the following subsets: 1) All shallow moonquake events; 2) Events during 1972-1973; 3)  
626 Events during 1974-1975; 4) Events during 1976-1977; 5) Events during 1973-1974; 6) Events during  
627 1975-1976. We tested if the seismic moment release evaluated from two-years subsets differ or agrees  
628 with that obtained from the complete observation period. We also tested how fast the obtained seismic  
629 moment converges to the reference value obtained with the full dataset. We reevaluate the seismic  
630 moment release every time a new shallow moonquake is detected and studied the evolution of obtained  
631 seismic moment rates like with the GCMT. The results are summarized in Figure 6.  $KS_{10}$  Emission proba-  
632 bilities for the moment rate resulting from all shallow moonquakes together are shown in Figure 7. The  
633 maximum emission probability coincides with the rate obtained from all events. In the case of the Moon,  
634 the scattering of obtained seismic moment rate is rather small and the difference is about 50% in maxi-  
635 mum. The small deviation is likely to be due to the smaller range of magnitude (from  $4.7 \times 10^{12} Nm$  to  
636  $1.6 \times 10^{15} Nm$ ) and the small number of events for shallow moonquakes. Likewise, the seismic moment  
637 rate converged relatively quickly after 4-5 events. Unlike on the Earth, the possible source of excitation is  
638 limited and result in smaller variety of events. This may be the case on Mars as well, allowing to obtain a  
639 representative seismic moment rate rapidly.

## 640 **Generic Synthetic Catalogs**

641 We set up a logarithmically equidistant grid of  $M_S$  and  $M_C$  values via an equidistant grid of equivalent  
642 magnitudes. We vary  $m_S$  from 3 to 10 in steps of 0.1 magnitude units. The equivalent magnitude of the



643 corner moment is varied relative to  $m_S$  from  $m_S - 4$  to  $m_S + 4$ , also in steps of 0.1 magnitude units. This  
 644 results in a  $81 \times 71 = 5751$  elements matrix of combinations of moment rates and corner moments.

645 The resulting event rates, computed for an assumed completeness threshold magnitude  $m_t = 2$   
 646 range from  $10^{-216}$  to  $10^9$  events per year (some parameter combinations result in even smaller rates  
 647 that were not numerically resolvable, these cases were excluded from the simulation process). Neither  
 648 of these extremal values is suitable to produce meaningful catalogs. We therefore adjust the complete-  
 649 ness threshold individually for each combination of moment rate and corner moment in order to obtain  
 650 catalogs of uniform sizes for all cases. A simple iterative search scheme is used to solve eq. 3 for  $M_t$  nu-  
 651 merically for this purpose. In analogy to the planned life time of the InSight mission, we generate cata-  
 652 logs covering 2 terrestrial years (or 730 terrestrial days), each containing approximately 10000 events (in  
 653 a few cases, where this requires  $m_t > m_c$ , we force  $m_t < m_c$  and obtain catalogs with about  $10^5$   
 654 events).

655 The result of any moment rate estimation will depend on the individual realization of the catalog  
 656 generator, depending on what the largest cataloged event actually is. To analyze the resulting variability  
 657 of the estimated moment rate, we thus generate a total of 1410 catalogs (a number chosen with respect  
 658 to the overall computation time) for each of the 5751 parameter combinations, resulting in approximate-  
 659 ly eight million usable catalogs. The complete simulation can be run overnight on a desktop PC.

660 For each catalog, we evaluate the NLVR and  $KS_{10}$  estimators and record the resulting bias between  
 661 the moment rate's equivalent magnitude  $m_S$  used during catalog generation and the estimated value's  
 662 equivalent magnitude  $m_{est}$ , defined as

$$663 \quad m_{bias} = m_S - m_{est} \quad (17)$$

664 i.e. the bias is positive for underestimation. From the biases obtained for catalogs resulting from the  
 665 same value of the ratio  $M_S/M_C$  (or from the same difference  $m_S - m_C$ ) we construct distribution densi-  
 666 ties, median values and the boundaries of 95% quantiles centered around the median, i.e. intervals  
 667 which contain 95% of all bias values.

### 668 ***Estimation with correct slope***

669 In a first test, we use the same slope  $\beta \in \{0.4, 0.5, 0.6, 0.625, 2/3\}$  during catalog generation as well  
 670 as during the evaluation. We generate independent sets of approximately 8 million catalogs for the eval-  
 671 uation using either the NLVR estimator or the  $KS_{10}$  estimator. Since we already established that the  $KS_k$   
 672 estimator gets better with increasing  $k$ , we now use a fixed value of  $k = 10$  which is realistic for Mars  
 673 and expected to perform well in the light of the evaluation of the GCMT.

674 If the corner moment is known (which can be expected only in synthetic cases) a two-dimensional his-  
 675 togram relating the bias between true and estimated moment rate to the difference  $m_S - m_C$  can be  
 676 constructed (left panels in Figure 8 (NLVR) and Figure 9 ( $KS_{10}$ )). Individual moment rate estimates may  
 677 vary strongly between individual catalogs, by as much as three or more units of equivalent magnitude.  
 678 The ratio  $M_S/M_C$  controls systematic variations of distribution median and width, and NLVR and  $KS_{10}$   
 679 show different behavior: While the NLVR estimator shows the greater variance for  $m_S - m_C < 0$ , the  
 680 variance of the  $KS_{10}$  estimator is larger for  $m_S - m_C > 0$ . Both estimators are near unbiased if  
 681  $m_S = m_C$ .

682 If the correct value of  $m_S - m_C$  is unknown, the 2D distribution densities depicted in the left panels of  
 683 Figure 8 and Figure 9 reduces to the marginal densities depicted in the right panels. These show that, for  
 684  $\beta = 2/3$ , the probability of overestimating the moment rate is approximately 10% for the NLVR estima-  
 685 tor, and 41% for the  $KS_{10}$  estimator. The probability that the estimated value is within  $\pm 1$  magnitude

686 units of the true value is 49 % for the NLVR estimator, and 72% for the  $KS_{10}$  estimator for the given  
687 range of possible  $m_s - m_c$  differences.

688 These percentages depend on the value of the slope parameter  $\beta$  and increase as  $\beta$  increases. As Fig-  
689 ure 10 (NLVR) and Figure 11 ( $KS_{10}$ ) show, the distribution densities get narrower and more symmetric  
690 with increasing  $\beta$ : The probability that the estimated moment rate is within  $\pm 1$  magnitude units from  
691 the true value increases as the distribution narrows, and the probability of an overestimation increases  
692 as the distribution become more symmetric about the zero bias.

### 693 ***Estimation with incorrect slope***

694 As mentioned in the introduction, estimating the slope parameter from a single station catalog is like-  
695 ly biased towards small slopes, since only a fraction of the smaller events will be observed. Since both of  
696 our moment rate estimators make use of the slope, we must ask how sensitive the outcome is to an in-  
697 correctly guessed slope.

698 We again generate catalogs with a true slope of  $\beta \in \{0.4, 0.5, 0.6, 0.625, 2/3\}$ , but use the same set  
699 of values used for the estimation from our synthetic catalogs. We thus obtain a matrix of true and as-  
700 sumed slopes and evaluate the fraction of moment rate estimates that falls within  $\pm 1$  or  $\pm 2$  magnitudes  
701 from the true value, and also how likely we overestimate the actual moment rate. As before, we evalu-  
702 ate approximately 8 million catalogs for each combination of true and assumed slope parameter.

703 In Figure 12 we show the resulting percentages, i.e. the width of distribution densities as shown in  
704 Figure 10 and Figure 11, for both the NLVR (top) and  $KS_{10}$  (bottom) estimator. Although the width pa-  
705 rameters depend on both the true slope and the slope assumed by the estimator, the influence of the  
706 latter on the number of cases where the estimated moment rate is within  $\pm 1$  or  $\pm 2$  magnitudes from  
707 the true value is much smaller than that of the true slope. It is thus sufficient if the assumed slope is ap-  
708 proximately correct within a relatively wide range. This holds for both estimators.

709 A notable difference is the fraction of cases where the actual moment rate is overestimated: For the  
 710 NLV estimator, this fraction depends mainly on the assumed slope and not as much on the true slope,  
 711 whereas it is about equally sensitive on both values for the  $KS_{10}$  estimator.

## 712 **Mars-specific synthetic catalogs**

713 The tests described so far indicate that variance and bias of both the NLVR and the  $KS_k$  estimator are  
 714 such that we cannot expect to solve the question of the Martian moment rate unambiguously, by invert-  
 715 ing some estimated value into a best fitting rate. The emission probability approach using a search grid  
 716 of moment rates and corner moments is more promising. Here we investigate in how far it is possible to  
 717 distinguish hypothetical states by these emitted rate estimates, and in how far longer experiment life  
 718 times support this distinction.

719 We consider the five end-member seismicity models of Knapmeyer et al., (2006), which mark some  
 720 extreme corners of their parameter space. These models were named *WeakFew*, *WeakMany*, *Medium*,  
 721 *StrongFew*, and *StrongMany* according to their relative moment rates (weak, medium or strong) and  
 722 event rates (few, medium, or many). Since Knapmeyer et al. (2006) use the truncated rather than the  
 723 tapered Gutenberg-Richter distribution, we have to convert their maximum seismic moment  $M_{Max}$  into  
 724 corner moments  $M_C$  in order to keep the moment rate unchanged when switching to the tapered distri-  
 725 bution, using

$$726 \quad M_C = M_{Max} \left[ \frac{\beta}{\Gamma(2-\beta)} \right]^{1/(1-\beta)} \quad (18)$$

727 after Kagan (2002b). The conversion factor amounts to approximately 0.416 for  $\beta = 2/3$ , or 0.391 for  
 728  $\beta = 0.625$  as used in the five models. Moment rates and corner moments of the models are summarized  
 729 in Table 4. It is worth noting that  $m_S - m_C$ , which proved crucial for variance and bias of the estimators

730 in the previous tests, is negative for the *StrongFew*, *Medium*, and *WeakFew* models (but close to zero for  
731 *Medium*), but positive for the *StrongMany* and *WeakMany* models (rightmost column of Table 4).

732 To assess the effect of experiment life time, we consider catalogs covering 1, 2, 4, 8, 16, and 32  
733 (earth) years. The exponential increase of durations was chosen in order to compensate for the power  
734 law decay of event probabilities with magnitude. Considering even longer times appears to be unneces-  
735 sary, since no lander with such a life time is known, and since we hope that improved follow-up experi-  
736 ments will make the entire discussion obsolete at some time.

737 We generate  $10^6$  catalogs, with approximately 10000 events per catalog, for each duration, and thus  
738 obtain six different probability density functions for estimated moment rates for each of the five models.  
739 We repeat this for both the NLVR and the  $KS_{10}$  estimator and compare the resulting probabilities graph-  
740 ically (Figure 13 and Figure 14). Independent realizations are used for the two estimators, but given the  
741 smooth PDFs that we obtain, we are convinced that this does not affect our results.

742 For both estimators, doubling the experiment life time moves the maximum of the histograms (i.e.  
743 the mode) in Figure 13 and Figure 14 by a constant amount towards larger values (meaning a multiplica-  
744 tion by a constant factor on the seismic moment scale). This shows that the choice of an exponential  
745 series of life times was appropriate to investigate the long term behavior.

746 The NLVR and  $KS_{10}$  estimators however show a significant difference concerning the width (i.e. stand-  
747 ard deviation) of the distributions: While the NLVR distributions become narrower in most cases (not  
748 very much in the case of the *WeakFew* model, left hand side of Figure 15), the  $KS_{10}$  standard deviation  
749 decreases not as much, or even grows (in the case of the *WeakMany* and *StrongMany* models, right  
750 hand side of Figure 15).

751 The changes in mode and standard deviation of NLVR work together in such a way that probabilities  
752 left of the maximum decrease quickly with time, while probabilities right of the maximum increase only

753 slowly with time. This makes the evolution of the curves look like a caterpillar pulling its rear end to-  
754 wards the head before moving its head forward.

755 The  $KS_{10}$  estimator behaves differently: here the whole curve moves towards the right essentially un-  
756 changed like the shell on the back of a crawling snail, with the notable exception of the *StrongMany*  
757 model which behaves like a caterpillar pushing its head forward towards the right with its tail fixed  
758 (Figure 14).

759 The two estimators also behave differently when it comes to the rejection of models.

760 After two years of registration, NLVR moment rate estimates between  $2 \times 10^{16} Nm$  and  $1.3 \times$   
761  $10^{18} Nm$  (equivalent magnitudes  $m_S$  between 4.8 and 6) would be rather inconclusive, since all five  
762 models have significant probabilities to produce estimates in this range. An estimated rate of less than  
763  $3.9 \times 10^{16} Nm$  ( $m_S = 5$ ) would exclude the *StrongMany* model. A NLVR estimation below  $1 \times 10^{16} Nm$   
764 ( $m_S = 4.6$ ) would additionally exclude the *Medium* and *StrongFew* models. A NLVR result larger than  
765  $1.6 \times 10^{17} Nm$  ( $m_S = 5.4$ ) obtained after two years, on the other hand, would exclude the *WeakFew*,  
766 *WeakMany* and *StrongMany* models.

767 With the  $KS_{10}$  estimator, the *StrongMany* model could be excluded if the rate estimate is below  
768  $8.9 \times 10^{17} Nm$  ( $m_S = 5.9$ ).  $KS_{10}$  estimates below  $5.6 \times 10^{16} Nm$  or above  $1.6 \times 10^{17} Nm$  ( $m_S$  between  
769 5.1 and 5.4) are crucial to distinguish between the *WeakMany*, *Medium*, and *StrongFew* models. More  
770 such thresholds could be identified.

771 As a sketch for the application to InSight data, we simulate a single two years catalog for the Knap-  
772 meyer et al. (2006) *Medium* scenario with parameters as given in Table 4, and evaluate the  $KS_{10}$  estima-  
773 tor. This results in an estimated moment rate of  $2.72 \times 10^{17} Nm/yr$ . The emission probability map  
774 favors moment rates close to the one used for catalog generation, and clearly allows the rejection of a  
775 moment rate as low as the Moon's (Figure 16). Based on the simulated catalog, a moment rate as high as

776 the Earth's could only be accepted when assuming that marsquakes larger than the largest known earth-  
777 quakes are possible.

778 The following observations are crucial here: Firstly, in principle, it is possible to reject at least some of  
779 the Knapmeyer et al. (2006) models using the NLVR estimator alone. Second, the moment rate thresh-  
780 olds to exclude models evolve with time, i.e. with the time span covered by the catalog. And third,  
781 thresholds excluding individual models differ between the NLVR and  $KS_{10}$  estimators. Also, the use of the  
782  $KS_{10}$  estimator was a decision made here to keep the amount of tests to run in a reasonable range. If  
783 more events become available, there is however no reason not to use them for a  $KS_{k>10}$  estimation. It is  
784 thus meaningful to use different estimators in parallel, and to also track the evolution of the estimators  
785 with time.

786

## Discussion

787 Our tests with terrestrial data demonstrate that the Earth's moment rate can be estimated from a  
788 single, short-lived broadband station, even if it is a temporary installation rather than being placed in a  
789 state of the art observatory shelter (the Lorenz et al., (2015) installation at Goldstone serves as an exam-  
790 ple). The list of the largest  $k$  events becomes representative within a few weeks. This minimum time  
791 frame of course depends on the actual moment and event rates and is likely longer on Mars. It will be a  
792 crucial exercise to determine from the observations what the duration of this "burn in" time on Mars is.  
793 Besides the usual methods to determine the completeness threshold of catalogs, a comparison of the  
794 actual Mars catalog with modeled detection probabilities might be useful. For the Earth, the moment  
795 rate can be estimated to within a factor 2.5 or better after a burn in of less than 2 weeks from the 10  
796 largest events (Figure 3).

797 A subdivision of Earth's seismicity into specific tectonic settings (subduction zones, subducting slabs  
798 alone, mid-ocean ridges, stable continental regions) still allows estimating the moment rate of these  
799 regions within the uncertainty of the seismic moments of the individual events used. For the stable con-  
800 tinental settings we however obtain larger deviations, indicating that either the approach is less reliable  
801 than the whole-GCMT results suggest, or that the estimators show a significant variance.

802 To assess more generic properties of our estimators, we conduct a series of Monte Carlo experi-  
803 ments, simulating seismicity catalogs for a variety of parameters, and compare the estimated moment  
804 rates with the known values used for the simulation.

805 The estimation of the uncertainty of the bias estimate critically depends on the assumed range of  
806  $M_S/M_C$ , while knowledge of the slope  $\beta$  is of minor importance, thus allowing to use a generic value like  
807  $\beta = 2/3$ . To our best knowledge, there is no self-consistent limitation of  $M_S/M_C$  in the origins of the  
808 tapered Gutenberg-Richter distribution. Maximum likelihood estimation of  $M_C$  often produces a lower  
809 limit only (Bird & Kagan, 2004), and any estimator will suffer from the fact that the necessary large  
810 events are also the most rare ones. Thus giving a range of  $M_S/M_C$  is hardly possible in advance and will  
811 remain challenging in the course of the experiment, as far as the InSight mission to Mars is concerned.  
812 We limited the difference of equivalent magnitudes to  $|m_S - m_C| < 4$ , motivated by the range  
813  $-2.4 < m_S - m_C < 1.7$  found with the end-member models of Knapmeyer et al. (2006), and adding  
814 some margin.

815 A physical argument creating an upper limit for the corner moment arises from geological considera-  
816 tions on the largest possible event, as discussed in section "Seismic Moment Rate Estimation" for the  
817 Earth, assuming an event with a fault plane as large as the planet's surface.

818 The estimation for the seismic moment upper bound used there scales with  $R^3$ , thus the correspond-  
819 ing estimation for Mars is about 15% of that obtained for Earth, or  $10^{28} Nm$  (or  $M_W = 12.6$ ). The crater-



820 ing record and derived surface ages for Mars show that no event involving the entire Martian surface  
821 occurred during the recent 3.8 billion years or so (taking the systematic age difference between Hesperian  
822 an northern lowlands and Noachian southern highlands as a reference for the creation of the dichotomy,  
823 whatever caused it), the longest faults of Knapmeyer et al., (2006) actually suffice for  $M_W \approx 9$  if the en-  
824 tire fault breaks in a single event. We thus predict that the corner moment of the Martian quake statistic  
825 is such that events of  $M_W = 12.6$  do practically not occur in the sense of the discussion in section  
826 "Seismic Moment Rate Estimation", i.e. that the corner moment is at least one magnitude below  
827  $10^{28} Nm$  and does not exceed  $10^{25} Nm$  (this is however a weak prediction given that the Knapmeyer et  
828 al. (2006) models hardly exceed  $10^{20} Nm$  for good reasons).

829 The InSight mission will have to deal with a physically reasonable subset of all possible parameters.  
830 Testable predictions that can be challenged individually by InSight data have been made in the literature,  
831 and a determination of the moment rate sufficiently accurate to reject some models would be a signifi-  
832 cant achievement.

833 Our simulations reveal that both the NLVR and  $KS_k$  estimations show considerable biases and vari-  
834 ances. Nevertheless the NLVR estimator, as the most simple one, will allow constraining the actual mo-  
835 ment rate of Mars when comparing its output with simulated distributions of given seismicity models.  
836 Depending on experiment life time and the chosen estimators, threshold exists that clearly discriminate  
837 between the Knapmeyer et al. (2006) models. The most promising approach for the interpretation of  
838 moment rate estimates appears to be to scan the moment-rate-corner-moment state space like in Figure  
839 4, Figure 7, and Figure 16, and determine the probability that a certain state emits the moment rate es-  
840 timated from observed events.

841 Our approach relies on several assumptions:

- 842 • Marsquakes are i.i.d. events resulting from a Poisson process.



865 sary to determine slope and corner moment reliably, we have discussed ways to estimate the moment  
866 rate based on sparse observations.

867 Two distinct approaches are proposed, the NLVR estimator which relies on the single largest event  
868 ever observed, and the  $KS_k$  estimator, which evaluates the  $k > 1$  largest events.

869 We have evaluated the performance of both estimators numerically. First we apply them to the cur-  
870 rent GCMT catalog, covering the time from January 1976 to May 2018 and containing nearly 50000  
871 earthquakes. Secondly, we use synthetic catalogs generated from the Tapered Gutenberg-Richter distri-  
872 bution and represented by a total of more than 560 million catalogs worth of almost 2.5 billion years of  
873 simulated seismicity.

874 We find that the proposed estimators will allow rejecting at least some of the published seismicity  
875 models by their predicted moment rates. The uncertainty of the estimates depends on  $\dot{M}_S/M_C$ , but is  
876 sufficiently small to discriminate several published seismicity models even after only two years mission  
877 life time on Mars.

## 878 **Data and Resources**

879 The Apollo seismic event catalog can be found at [http://www-](http://www-udc.ig.utexas.edu/external/yosio/PSE/catsrepts/)  
880 [udc.ig.utexas.edu/external/yosio/PSE/catsrepts/](http://www-udc.ig.utexas.edu/external/yosio/PSE/catsrepts/)

881 The Global Centroid Moment Tensor was retrieved from IRIS,  
882 <https://ds.iris.edu/ds/products/momenttensor/> on 17. May 2018.

883 Waveform data from the Goldstone experiment was obtained from Lorenz et al. (2015), we kindly re-  
884 fer to their Data and Resources section.

885 The Stable Continental Regions catalog of Schulte & Mooney (2005) was retrieved from the USGS at  
886 [https://earthquake.usgs.gov/data/scr\\_catalog.php](https://earthquake.usgs.gov/data/scr_catalog.php), last accessed 12. June 2018.

887 The coordinates of Flinn-Engdahl region boundaries was retrieved from USGS, at  
888 <ftp://hazards.cr.usgs.gov/web/hazdev-geoserve-ws/FE/>, last accessed 15.05.2018

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## Tables

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Table 1 Annual seismic moment rate of Earth, Moon, and Mars.

Planet	Reference	Method	Annual Rate [Nm/yr]	Annual Rate [Equiv. Mag. per yr]
Earth	GCMT	observed quakes, 1976-2018	$7.61 \times 10^{21}$	8.5
Moon	Oberst, 1987	observed HFT quakes	$7.27 \times 10^{14}$	3.8
Mars	Anderson et al., 1977	Viking non-observation of quakes	$Moon \leq Mars < Earth$	
	Goins & Lazarewicz, 1979	Viking non-observation of quakes	$< Earth$	
	Phillips, 1991	1D lithospheric cooling model	$4.8 \times 10^{18}$	6.4
	Golombek et al., 1992	Observed surface faulting	$10^{18}$	5.9

	Golombek, 2002	Observed surface faulting	$10^{18}$ to $10^{19}$	5.9 to 6.6
	Knapmeyer et al., 2006	1D lithospheric cooling model, weak, medium, and strong scenario	$3.42 \times 10^{16}$ $5.99 \times 10^{17}$ $4.78 \times 10^{18}$	4.96 5.8 6.4
	Taylor et al., 2013	Observed surface faulting	$> 5.5 \times 10^{16}$	>5.09
	Plesa et al., 2018	3D whole-mantle thermal evolution model	$5.7 \times 10^{16}$ to $3.9 \times 10^{19}$	5.1 to 7

1132       Equivalent magnitudes are moment magnitudes computed according to eq. 1 assuming that the en-  
1133       tire moment release of one year is put into a single event.

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Table 2 Quality levels used to categorize Goldstone seismograms

Category	Definition	Event count
A	prominent arrivals of various body and surface wave phases	38
B	P arrival and Rayleigh waves clearly above noise level	19
C	P arrival and Rayleigh waves barely above noise level	13
D	Only body waves visible	4
E	Only surface waves visible	60
F	Invisible	170

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1138 **Table 3 Annual moment rate estimations for different settings on Earth**

<b>Subset (No. of events)</b>	<b><math>\Sigma</math></b>	<b><math>KS_{10}</math></b>	<b><math>NLVR</math></b>	<b>Units</b>
All events (49178)	76.1	54.9	33.6	$10^{20}$ Nm/yr
	8.52	8.43	8.28	Magnitude
Subduction Zones (32855)	66.9	54.9	33.6	$10^{20}$ Nm/yr
	8.48	8.43	8.28	Magnitude
Mid-Ocean Ridges (7783)	1.63	1.11	1.07	$10^{20}$ Nm/yr
	7.41	7.3	7.29	Magnitude
Subduction Zones, $z \geq 100$ km (7297)	7.38	6.1	2.49	$10^{20}$ Nm/yr
	7.85	7.79	7.53	Magnitude
Subduction Zones, $z < 100$ km (26003)	59.8	52.1	33.6	$10^{20}$ Nm/yr
	8.45	8.41	8.28	Magnitude
Stable Continental Re- gions, historic events (226)	0.0571	0.0405	0.0415	$10^{20}$ Nm/yr
	6.44	6.34	6.35	Magnitude
Stable Continental Re- gions, instrumental	0.101	0.124	0.17	$10^{20}$ Nm/yr
	6.6	6.66	6.75	Magnitude

events (879)				
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1139 Annual moment rate estimations for several subsets of the GCMT catalog from 1976 to 2018, for histori-  
1140 cally witnessed events in stable continental regions between 1500 and 1949, and finally instrumentally  
1141 recorded events in stable continental regions, between 1950 and 2003. The first column is the estimate  
1142 resulting from summing up all events in the subset, the second is the KS for the 10 strongest events, and  
1143 the third column is the NLVR estimator resulting from the single strongest event. Each estimate is given  
1144 in Newton meters per year and as moment magnitude of a single event releasing the same amount of  
1145 Newton meters.

1146



1147

1148 **Table 4 Annual moment rate models for Mars**

<b>Model</b>	$\dot{M}_S$ [Nm/yr]	$M_{Max}$ [Nm]	$M_C$ [Nm]	$m_S - m_C$
StrongFew	$4.78 \times 10^{18}$	$3.36 \times 10^{20}$	$1.31 \times 10^{20}$	-0.96
StrongMany	$4.78 \times 10^{18}$	$3.42 \times 10^{16}$	$1.33 \times 10^{16}$	+1.70
Medium	$5.99 \times 10^{17}$	$2.41 \times 10^{18}$	$9.42 \times 10^{17}$	-0.13
WeakMany	$3.42 \times 10^{16}$	$3.42 \times 10^{16}$	$1.33 \times 10^{16}$	+0.27
WeakFew	$3.42 \times 10^{16}$	$3.37 \times 10^{20}$	$1.32 \times 10^{20}$	-2.39

1149 Moment rates, maximum moments, and corresponding corner moments of the end-member seismicity  
 1150 models of Knapmeyer et al., 2006. All models use a slope parameter of  $\beta = 0.625$ .

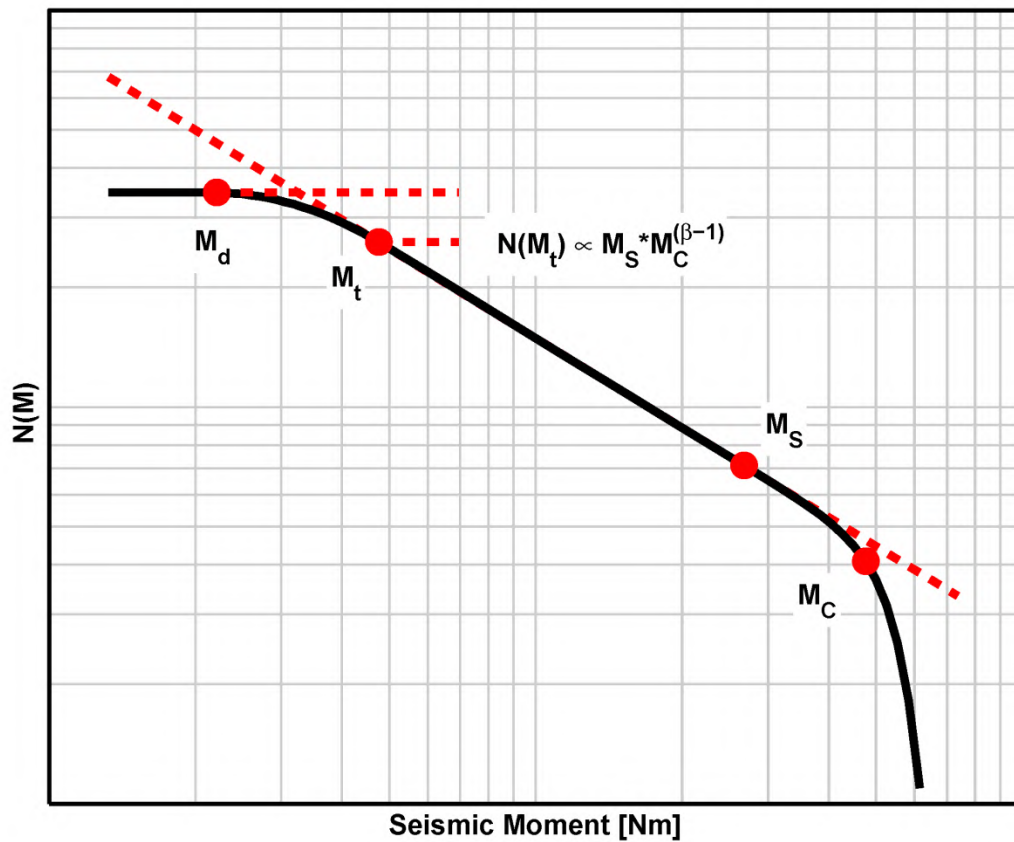
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## Figures

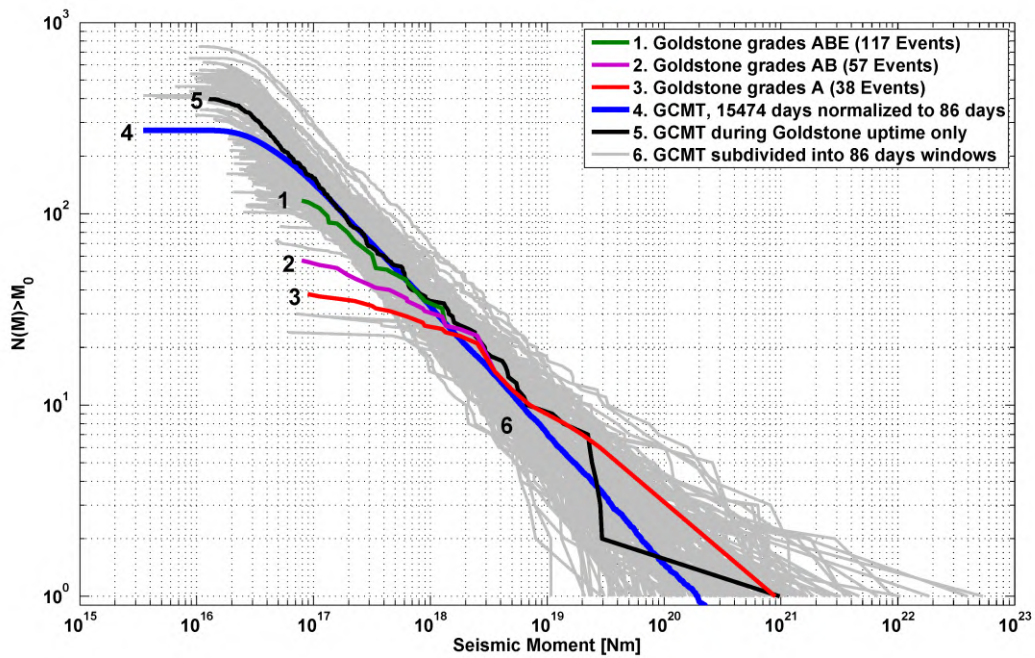


1155

1156 Figure 1 Schematic depiction of the tapered Gutenberg-Richter distribution in survivor form, showing the number  $N$  of  
 1157 events exceeding moment  $M$ . Bullets mark characteristic moment values:  $M_d$  - detection threshold, no event smaller than  
 1158 this is contained in a catalog;  $M_t$  - completeness threshold, all events above this are cataloged;  $M_S$  - size of an event corre-  
 1159 sponding to the average moment rate;  $M_C$  - corner moment. The corner moment may or may not be larger than  $M_S$ . slanted  
 1160 dashed line: prediction according to a Gutenberg-Richter law with the same slope. Horizontal dashed lines: (lower) number of  
 1161 events above completeness threshold  $M_t$ , to be used for event rate estimation; (upper) number of events in catalog. Gray: an  
 1162 arbitrary grid to indicate that the graph is drawn in log-log coordinates (at  $M_C$ , the tapered distribution is actually below the  
 1163 classical GR distribution by a factor  $e$ ).

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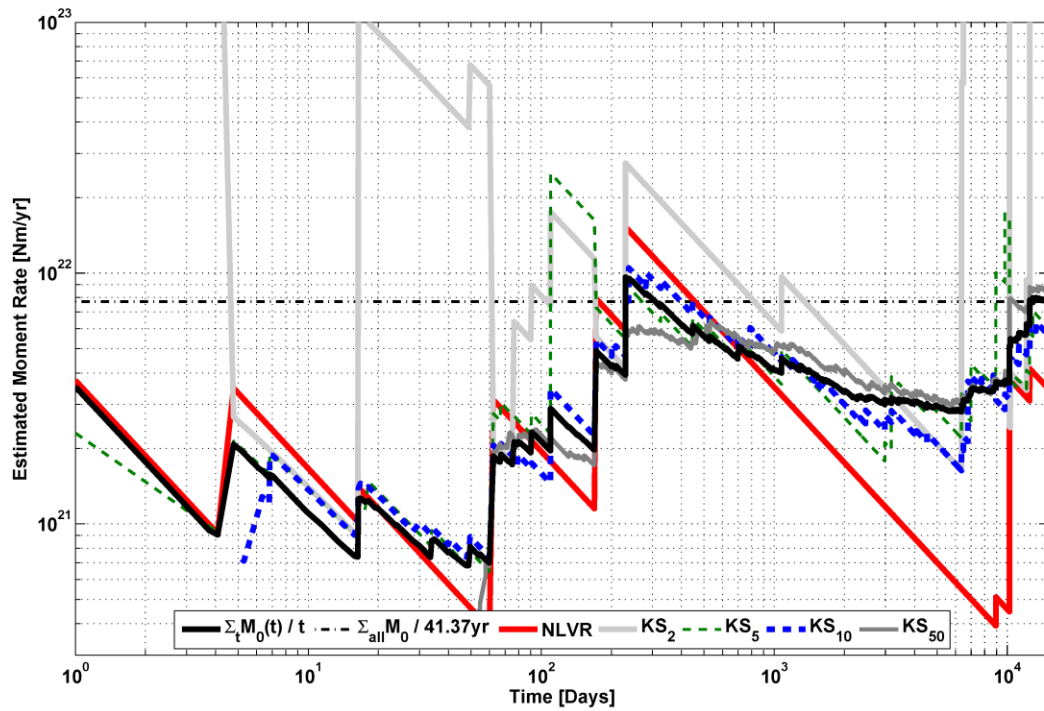
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1167 Figure 2 Size-frequency survivor distributions for events detected at Goldstone (in groups containing grade A only, or  
 1168 grades A and B, or grades A, B, and E, as indicated in legend. Note that the ABE line is partially covered by the AB line, which  
 1169 in turn gets covered by the A line), the subset of events listed in the GCMT for the uptime of the Goldstone experiment (la-  
 1170 beled 5), the whole GCMT scaled down to a duration of 86 days (labeled 4). The gray curves in the background show distribu-  
 1171 tions for consecutive 86-days time windows (i.e. days 1 to 86, 87 to 173, 174 to 260, ... etc.) throughout the entire GCMT  
 1172 catalog.

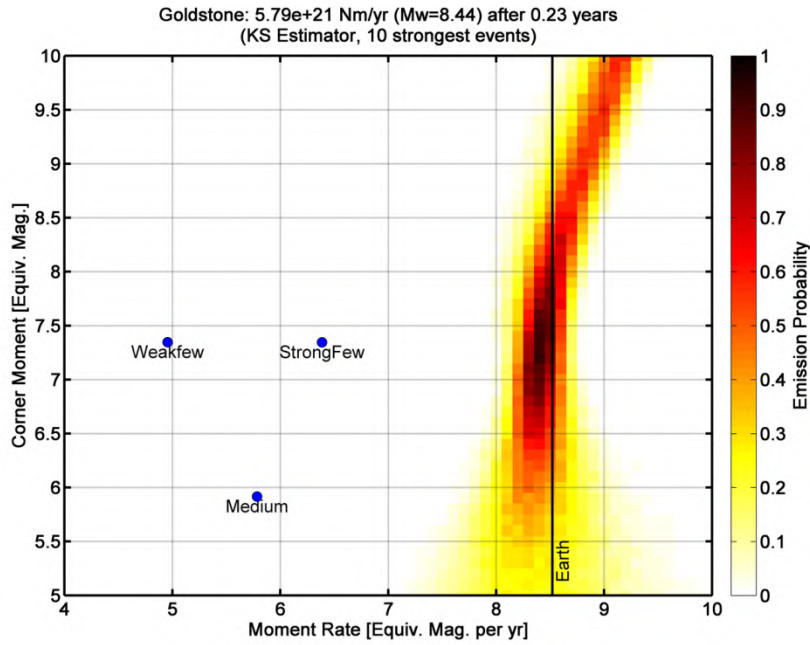
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1175 **Figure 3** Evolution in time of moment rate estimations for Earth. The bold black curve is based on summation of all events  
1176 in the GCMT catalog. The horizontal line marks its value at the end of the cataloged time (01.01.1977 to 18.05.2018). Other  
1177 lines show time series for the *NLVR* and *KS<sub>k</sub>* estimators according to the legend.

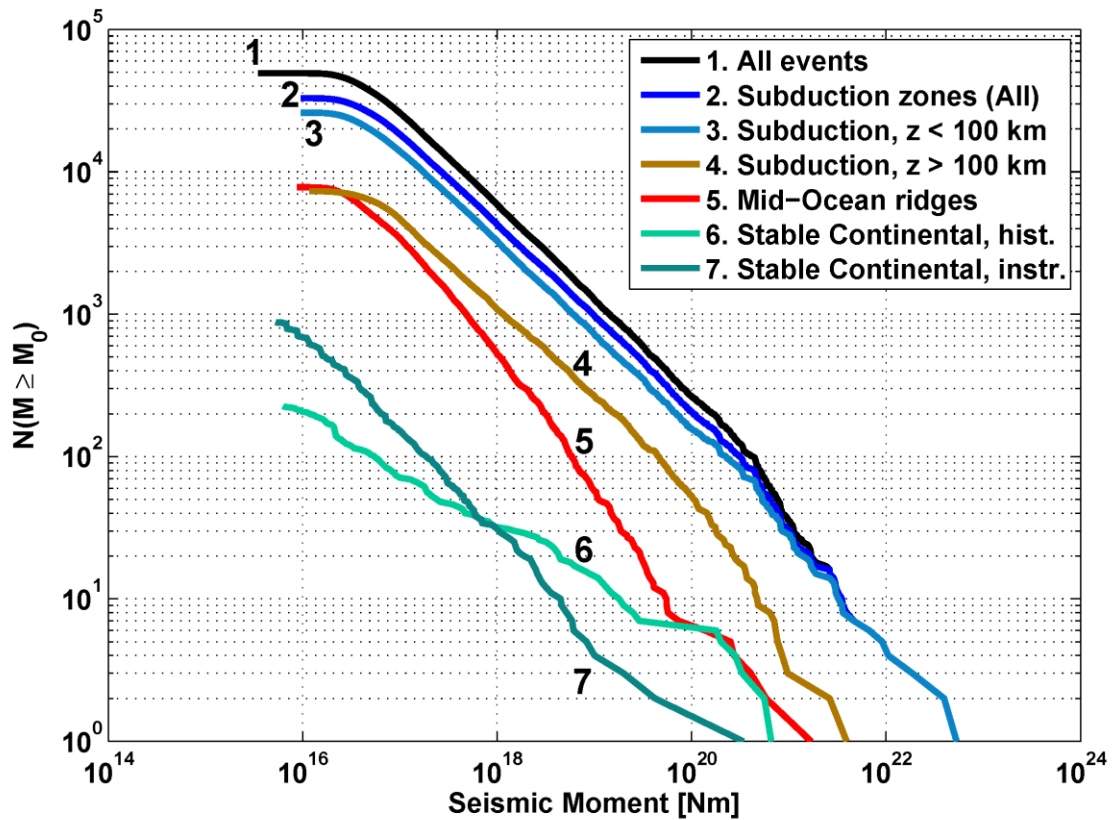
1178



1179

1180 Figure 4  $KS_{10}$  emission probability for the events detected at Goldstone (grade A events only). Dots mark the moment  
1181 rates and corner moments of all five Mars seismicity scenarios of Knapmeyer et al. (2006), pixel color encodes the emission  
1182 probability for matching the target rate within 0.2 magnitudes, as derived from 1000 simulated catalogs per pixel. Coordinate  
1183 axes are labeled in terms of equivalent moment magnitudes. The vertical black line to the right gives the moment rates of the  
1184 Earth, as listed in Table 1.

1185



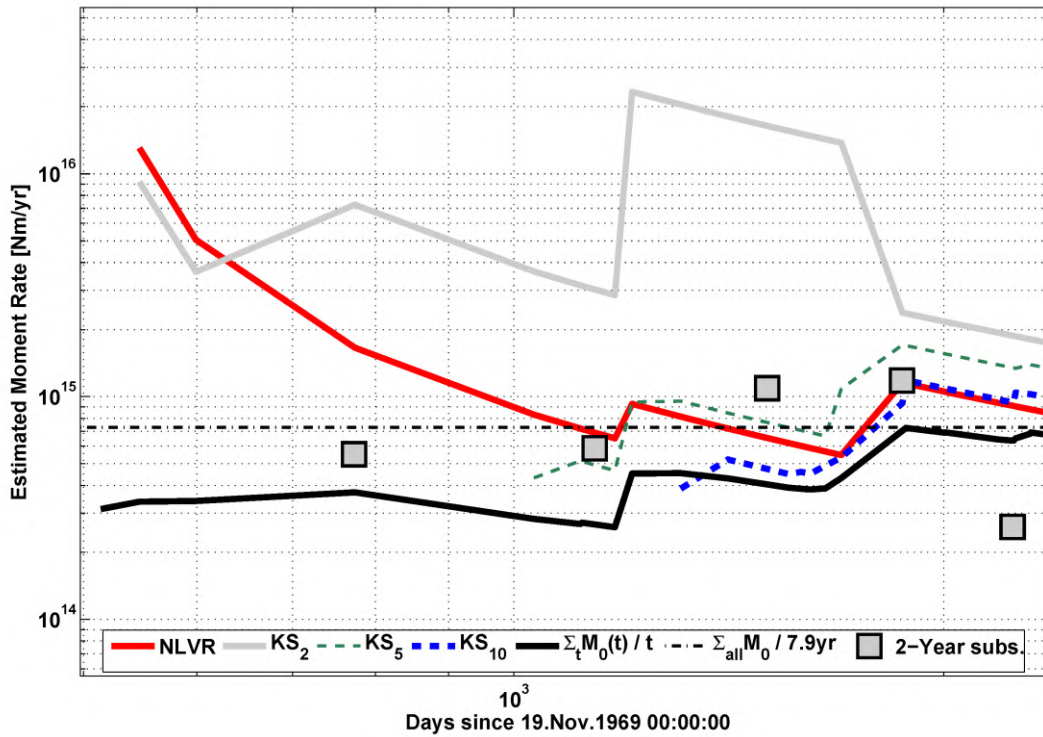
1186

1187 Figure 5 Size-Frequency distributions of several subsets of the GCMT catalog and of the Stable Continen-  
 1188 tal Regions catalog. Subduction zones and mid-ocean ridges are identified by using the Flinn-Engdahl  
 1189 regionalization scheme, and subduction zone events are further subdivided into events occurring above  
 1190 and below 100 km depth. The complete GCMT catalog is shown for comparison. For the Stable Continen-  
 1191 tal Regions catalog, the distributions of events from 1500 to 1949 and from 1950 to 2003 are shown  
 1192 separately.

1193



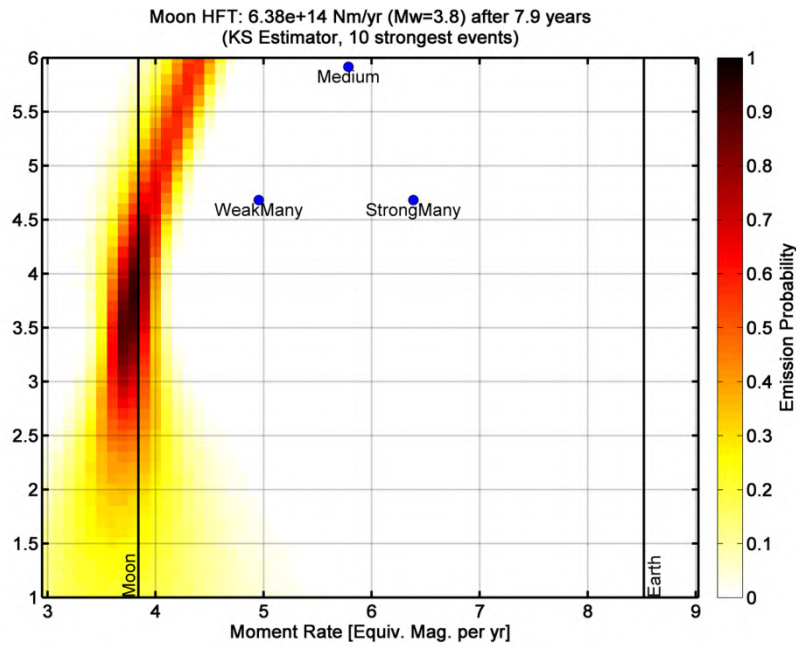
1194



1195

1196 Figure 6 Evolution in time of moment rate estimations for shallow moonquakes. Lines denote estimator output as in Fig-  
 1197 ure 3, applied to the seismic moments of Oberst (1987). Squares denote the sum of two calendar years of registrations, plot-  
 1198 ted at the relative time of the first of January of the first year, intervals used are 1972-1973, 1974-1975, 1976-1977, 1973-  
 1199 1974, and 1975-1976.

1200



1201

1202 Figure 7  $KS_{10}$  emission probability for shallow moonquakes. Dots mark the moment rates and corner moments of Mars

1203 seismicity scenarios of Knappmeyer et al. (2006) for comparison, pixel color encodes the emission probability for matching the

1204 target rate within 0.2 magnitudes, as derived from 1000 simulated catalogs per pixel. Coordinate axes are labeled in terms of

1205 equivalent moment magnitudes. The two vertical black lines give the moment rates of Moon and Earth, as listed in Table 1.

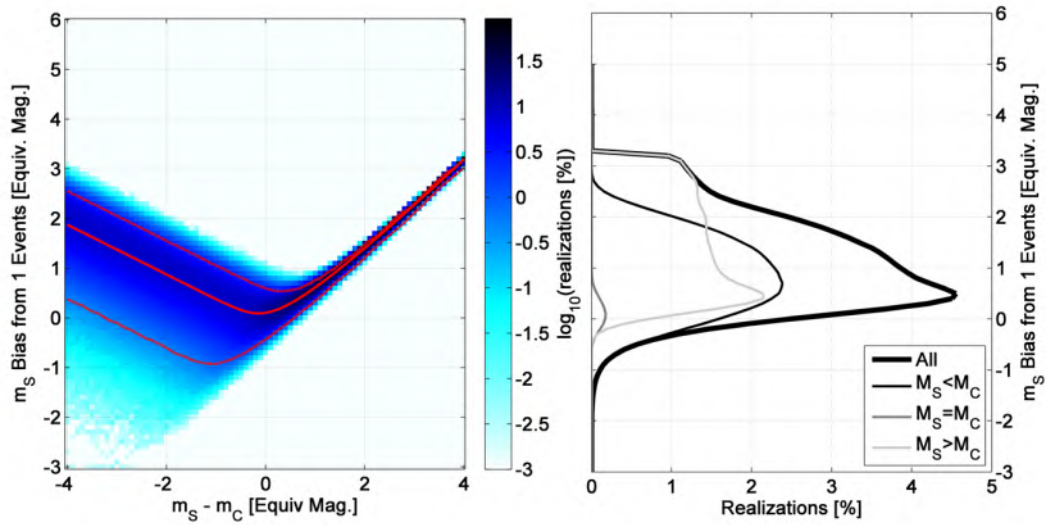
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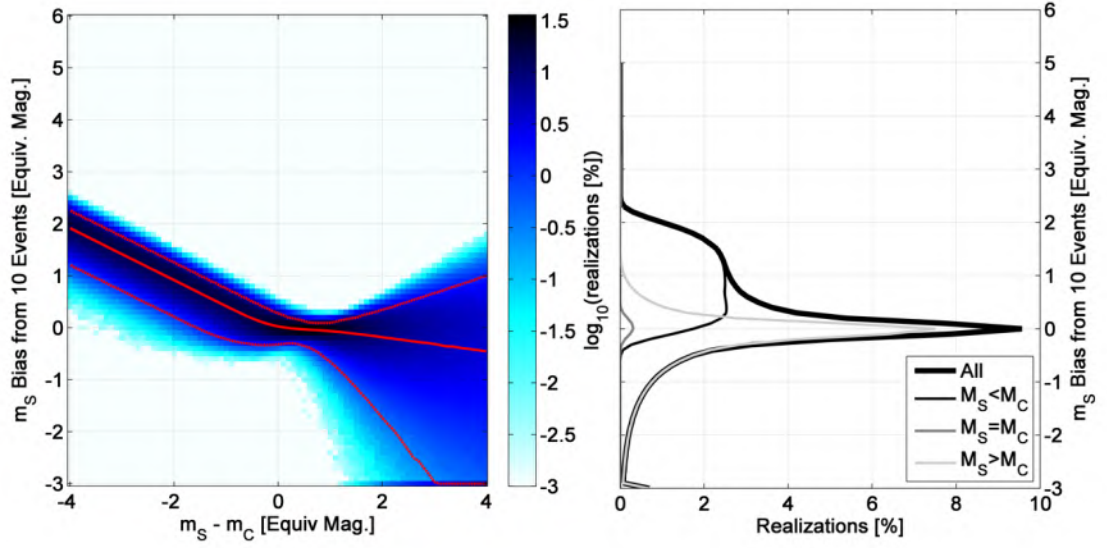
1210



1211

1212 Figure 8 NLVR Cumulative moment bias for synthetic catalogs, using  $\beta = 2/3$  in both generation and interpretation of  
 1213 catalogs. Left: Histograms resulting from the 8108910 synthetic catalogs generated for the cumulative moment to corner  
 1214 moment ratio indicated on the x-axis, shading encodes the logarithm of the percentage of realizations in each moment rate  
 1215 bias bin of width 0.1. Positive values on the y-axis indicate underestimation. Solid line: median, dashed lines: upper and  
 1216 lower boundary of the 95%-quantile centered around the median. Right: marginal distribution density resulting from row-  
 1217 wise integration of the figure to the left. Thick line: all catalogs, other: relation between moment rate  $M_S$  and corner moment  
 1218  $M_C$  as indicated in legend.

1219

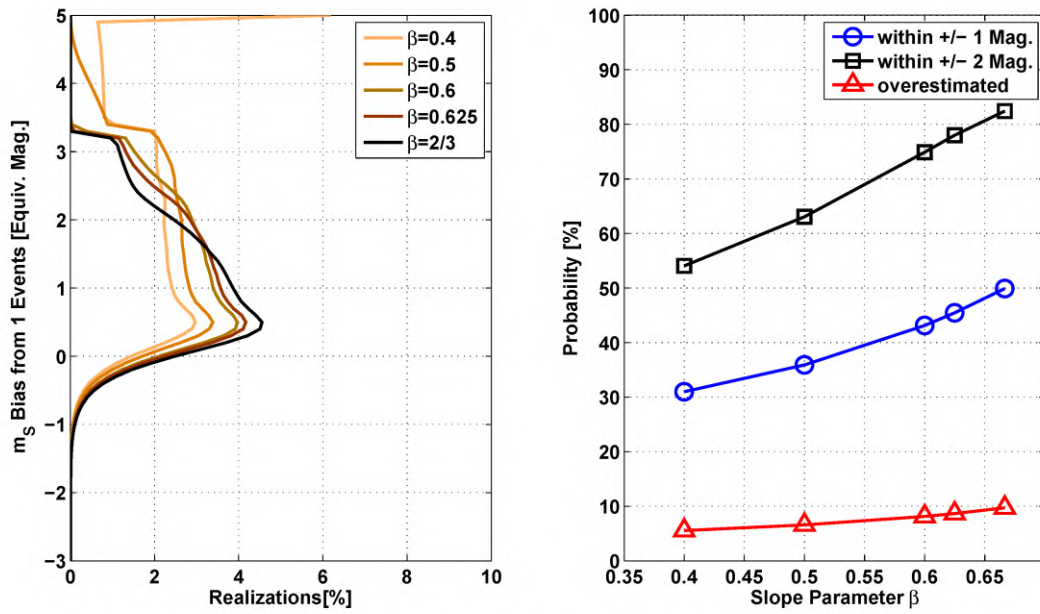


1220

1221 [Figure 9](#)  $KS_{10}$  Cumulative moment bias for synthetic catalogs, using  $\beta = 2/3$  in both generation and interpretation of cat-  
1222 [alogs](#). See [Figure 8](#) for a description of graph elements.

1223

1224

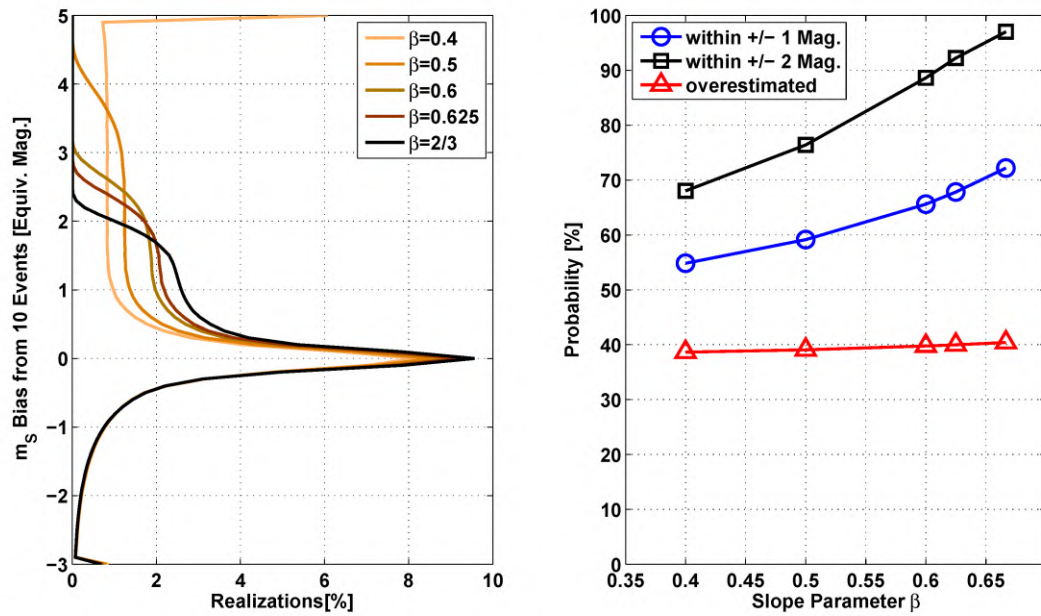


1225

1226 Figure 10 NLVR estimator marginal distribution densities for different slope parameters. Left: the marginal distribution  
 1227 densities for all catalogs (corresponding to the grey curve in Figure 8). Each curve represents approx. 8 million evaluated  
 1228 catalogs. Right: percentage of estimations that are within  $\pm 1$  (blue) or  $\pm 2$  magnitudes (black) from the true moment rate,  
 1229 and the fraction of overestimated moment rates (red).

1230

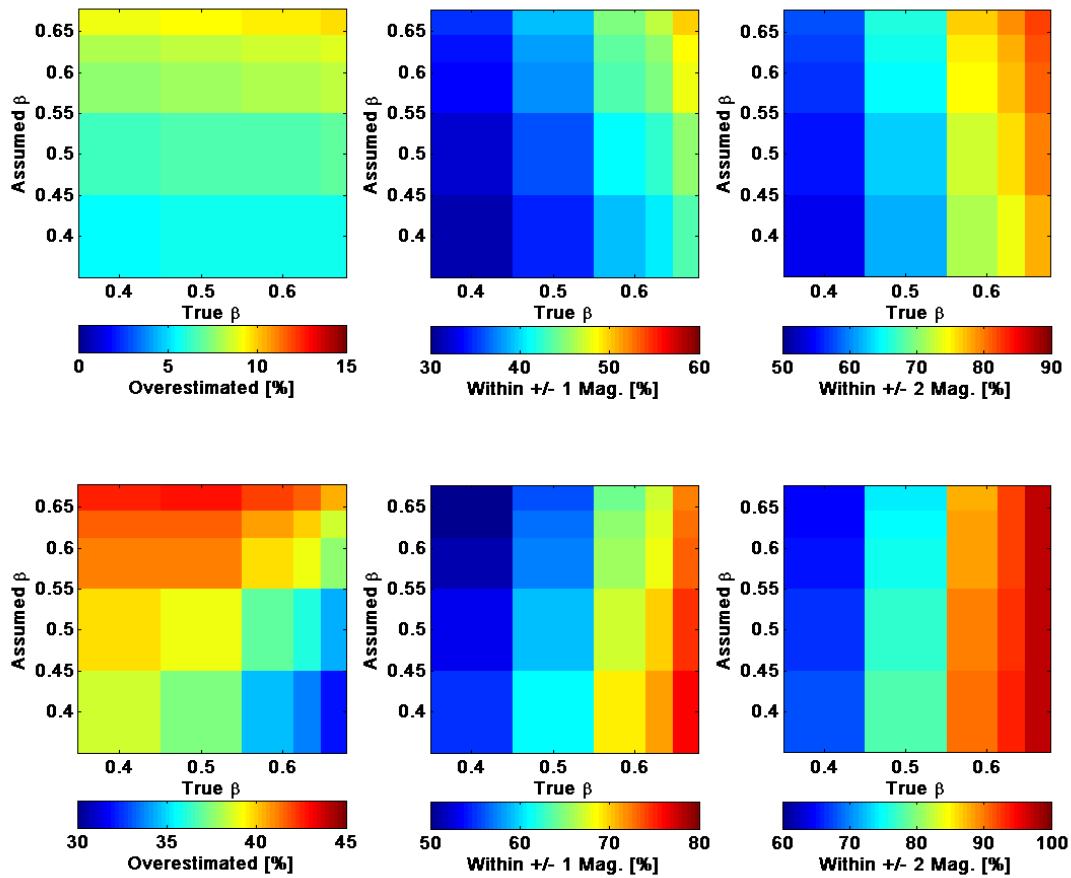
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1232

1233 Figure 11  $KS_{10}$  estimator marginal distribution densities for different slope parameters. See Figure 10 for a plot descrip-  
 1234 tion.

1235

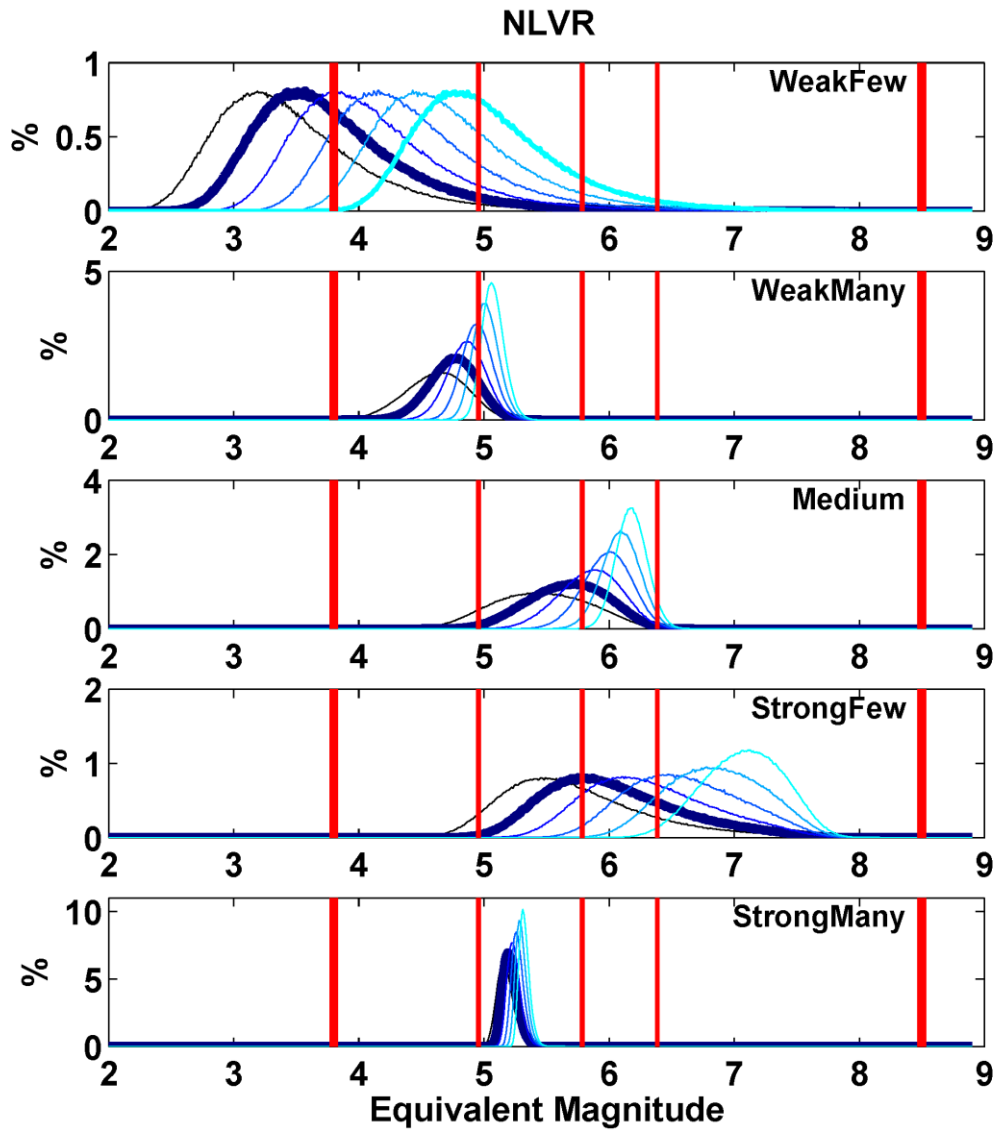


1236

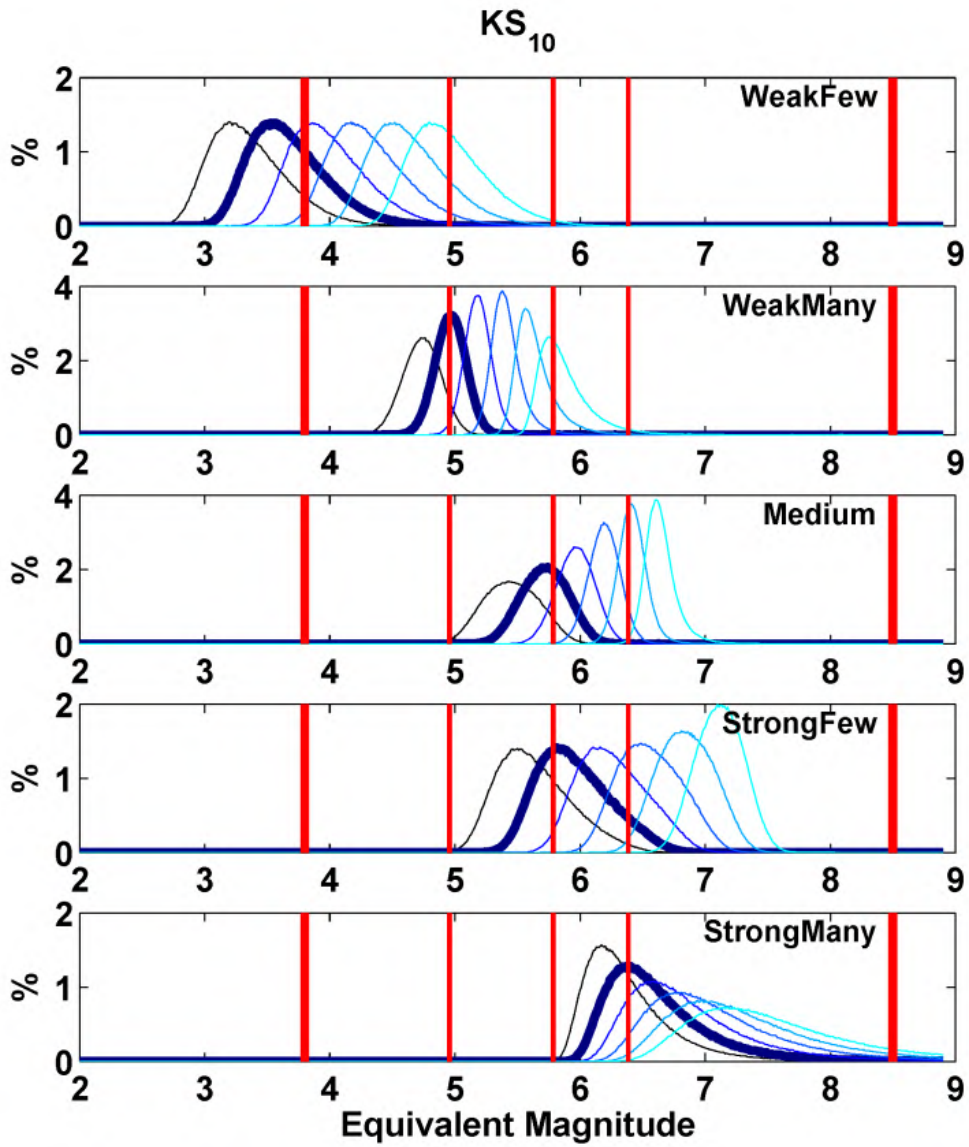
1237 Figure 12 Distribution width parameters for NLVR (top row) and  $KS_{10}$  (bottom row) estimators. Each uniformly colored  
 1238 patch indicates the width parameter of distribution densities as shown in Figure 10 and Figure 11. True slope and slope as-  
 1239 sumed during catalog evaluation were taken from  $\{0.4, 0.5, 0.6, 0.625, 2/3\}$  to form a square matrix of test cases. From left  
 1240 to right: percentage of cases with overestimated moment rate, percentage of moment rate estimations within  $\pm 1$  magnitude  
 1241 of true value, or within  $\pm 2$  magnitudes, respectively. Panels in the same subplot column share the same color range width,  
 1242 although the absolute values differ.

1243





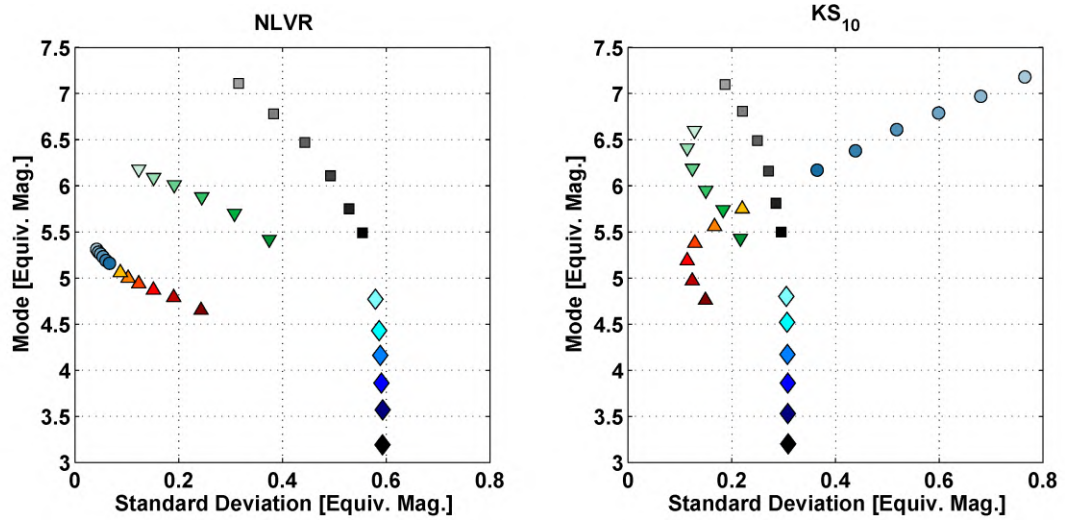
1244  
 1245 Figure 13 Distribution of NLVR estimators for Mars-specific seismicity models of Knapmeyer et al. (2006) and registration  
 1246 times of 1, 2, 4, 8, 16, and 32 years (envelopes of histograms with bin width 0.01 magnitudes, scaled to percents). Panels from  
 1247 top to bottom show the distributions for seismicity models as indicated in the panel. Note the different y axis ranges.. The  
 1248 seismic moment rate is given as the moment magnitude of a single event that releases the entire moment in one event (the  
 1249 axis range corresponds to  $1.3 \times 10^{12} \dots 4 \times 10^{22} Nm$ ). Darker hues correspond to shorter registration times, the two-year  
 1250 case also uses a thicker line. Vertical lines from left to right denote moment rates (as equivalent magnitudes) for the Moon,  
 1251 both *Weak* scenarios, *Medium* scenario, both *Strong* scenarios, and Earth .



1252

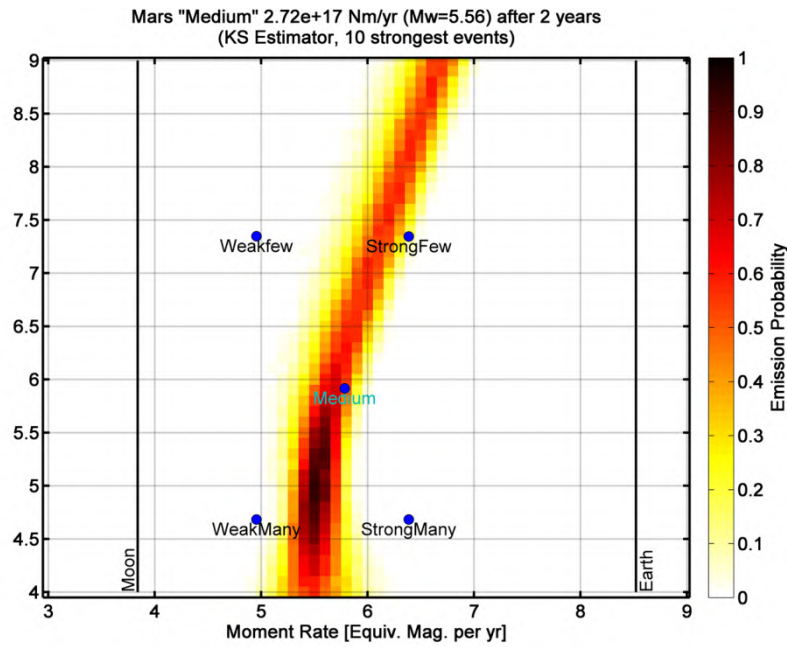
1253 [Figure 14](#) As [Figure 13](#), but for the  $KS_{10}$  estimator.

1254



1255  
 1256 Figure 15 Standard deviations and modes of the distribution densities shown in Figure 13 and Figure 14. Brighter shades  
 1257 indicate longer registration times, symbols encode the end member models of Knapmeyer et al. (2006). Diamonds: *WeakFew*,  
 1258 Upward triangles: *WeakMany* Downward triangles: *Medium*, Circles: *StrongMany*, Squares: *StrongFew*

1259



1260  
1261 Figure 16  $KS_{10}$  emission probability for a synthetic Mars *Medium* catalog. Dots mark the moment rates and corner mo-  
1262 ments of Mars seismicity scenarios of Knapmeyer et al. (2006) for comparison, pixel color encodes the emission probability  
1263 for matching the target rate within 0.2 magnitudes, as derived from 1000 simulated catalogs per pixel. Coordinate axes are  
1264 labeled in terms of equivalent moment magnitudes. The two vertical black lines give the moment rates of Moon and Earth, as  
1265 listed in Table 1.

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## Appendix

1269

### 1270 **Flinn-Engdahl zones**

1271 In the analysis of the GCMT catalog, we used the Flinn-Engdahl zonation scheme, in the revision of  
1272 Young et al. (1995), to classify events as belonging to either subduction zones or mid-ocean ridges.

1273 We consider as mid-ocean ridge events all events in zones

1274 143 149 150 401 401 402 403 404 405 406 408 409 410 411 413 419 424 425 426 427 428

1275 429 433 634 635 636 637 638 641 648 681 682 683 688 691 692 693 694 698 699 727 729 735

1276 737 738 739 753 754

1277 We consider as subduction zone event all events in zones

1278 1 2 4 5 6 7 9 10 12 13 14 57 58 59 60 61 66 68 69 70 71 73 74 76 77 78

1279 91 92 95 99 102 103 105 106 107 108 109 110 111 112 113 114 115 116 117 118 119 120

1280 121 122 123 124 125 127 127 128 129 130 131 132 134 135 136 136 137 138 139 141 144 145

1281 153 159 160 169 171 171 172 173 174 175 176 176 177 178 180 181 182 183 184 185 188 189

1282 191 192 193 199 200 201 202 206 209 210 211 212 214 215 216 217 218 219 220 221 223 226

1283 227 228 229 231 233 234 236 237 242 244 245 247 248 249 250 255 258 261 262 263 264 265

1284 266 268 269 271 272 273 274 275 276 277 278 279 281 282 283 284 285 286 290 366 367 368

1285 387 388 396 654 657 658 659 660 685 700 701 702 703

1286 We consider as subducting slabs all events in the subduction zones as listed above, and deeper than  
1287 100 km.

1288