Seismic and Aseismic Moment Budget and Implication for the Seismic Potential of the Parkfield Segment of the San Andreas Fault

by Sylvain Michel,* Jean-Philippe Avouac, Romain Jolivet, and Lifeng Wang

Abstract This study explores methods to assess the seismic potential of a fault based on geodetic measurements, geological information of fault-slip rate, and seismicity data. The methods are applied to the Parkfield section along the San Andreas fault (SAF) at the transition zone between the SAF creeping segment in the north and the locked section of Cholame to the south, where $M_w \sim 6$ earthquakes occurred every 24.5 yrs on average since the 1857 $M_w 7.7$ Fort Tejon earthquake. We compare the moment released by the known earthquakes and associated postseismic deformation with the moment deficit accumulated during the interseismic period derived from geodetic measurement of interseismic strain. We find that the recurring $M_w 6$ earthquakes are insufficient to balance the slip budget. We discuss and evaluate various possible scenarios which might account for the residual moment deficit and implications of the possible magnitude and return period of $M_w > 6$ earthquakes on that fault segment. The most likely explanation is that this fault segment hosts $M_w 6.5–7.5$ earthquakes, with a return period of 140–300 yrs. Such events could happen as independent earthquakes in conjunction with ruptures of the Carrizo plain segment of the SAF. We show how the results from our analysis can be formally incorporated in probabilistic seismic hazard assessment assuming various magnitude–frequency distribution and renewal time models.

Electronic Supplement: Flowchart of the methodology and results of the methodology obtained using a Brownian passage time model.

Introduction

Crustal deformation is mostly taken up by slip localized on a limited number of large faults. This paradigm holds in particular in California (Meade and Hager, 2005) where the San Andreas fault (SAF) and its peripheral faults form the main fault system. Because earthquakes represent increments of fault slip and deformation of the upper crust is considered to be mostly seismic, these faults are also assumed to host the largest crustal earthquakes. The relationship between seismicity, faults, and geodetic strain has long been conceptualized by the elastic rebound theory of Reid (1910) which states that, on the long-term average, elastic strain accumulating around a fault should be balanced by elastic strain released during earthquakes. It is clear, however, that within the seismogenic depth range, slip can be either seismic or aseismic and the slip rate on a fault and the partitioning of seismic and aseismic slip are the primary factors determining the seismic hazard associated with a particular fault (e.g., Avouac, 2015). The long-term slip rate on a fault can be determined from geological and morphotectonic studies. Once this information is known, the partitioning of seismic and aseismic slip can in principle be derived from seismicity but would require catalogs long enough to be representative of the long-term seismicity. Such catalogs are generally not available. Another approach is based on the assumption that the partitioning of seismic and aseismic slip is determined by spatial variations of fault frictional properties, assumed constant with time. In that case, geodetic measurements of interseismic strain can be used to reveal locked asperities, where friction is presumably rate weakening, and estimate the accumulation rate of moment deficit building up in the interseismic period (between major earthquakes). This moment needs then to be balanced by the moment released by the large earthquakes and transient aseismic slip. Such slip budget offers ways to estimate the most probable magnitude and frequency of the larger earthquakes on a particular fault. This approach has been applied recently to the
Himalayan arc, the Sumatra subduction zone, and the longitudinal valley fault in Taiwan (Ader et al., 2012; Thomas et al., 2014; Stevens and Avouac, 2016).

Here, we test and refine this approach on the Parkfield segment of the SAF. This segment lies at the transition zone between the locked segment of the SAF to the south and the creeping segment of the SAF to the north. The white stars indicate the latest epicenters of $M_w \geq 6$ earthquakes in the region corresponding to the 2004 $M_w$ 6 Parkfield, 1983 $M_w$ 6.3 Coalinga, and 2003 $M_w$ 6.6 San Simeon earthquakes. The color version of this figure is available only in the electronic edition.

**Figure 1.** Setting of the Parkfield segment of the San Andreas fault (SAF). This segment lies at the transition between the 1857 $M_w$ 7.7 Fort Tejon earthquake rupture (thin arrow along the SAF), to the south, and the creeping segment of the SAF to the north. The white stars indicate the latest epicenters of $M_w \geq 6$ earthquakes in the region corresponding to the 2004 $M_w$ 6 Parkfield, 1983 $M_w$ 6.3 Coalinga, and 2003 $M_w$ 6.6 San Simeon earthquakes. The color version of this figure is available only in the electronic edition.

The rate of moment deficit accumulation $\dot{m}_0$ (in N·m/yr) can be written as

$$\dot{m}_0 = \int_{\text{Fault}} \mu D dA,$$

in which $\mu$ and $A$ are the shear modulus and the fault area, and $D$ is the slip deficit rate. The slip deficit rate can be expressed as $D = V_{\text{plate}} \times \chi$ in which $V_{\text{plate}}$ is the long-term plate rate and $\chi$ is the interseismic coupling. The interseismic strain. If the moment deficit rate is larger than the observed moment release rate, the observed maximum-magnitude earthquake might not be the most extreme event that can occur along the fault segment. We thus explore the space of magnitude and frequency of maximum-magnitude earthquakes to find which events can balance the moment budget and be plausible considering the current statistical distribution of earthquakes. We account for aftershocks, background seismicity, and postseismic slip for each maximum-magnitude earthquake tested. This method allows to assess seismic hazard considering uncertainties on the seismic and geodetic data and accounting for our understanding of the behavior of a fault segment. In the following, we detail the method. A flowchart describing the approach, step by step, is available in © Table S1 (available in the electronic supplement to this article). Table 1 lists the parameters used in this study.

We base our approach on the assumption that the rate of moment deficit accumulating in the interseismic period is, on average over the long term, equal to the rate of moment released by seismic and transient aseismic slip. Our objective is to derive a probabilistic estimate of the magnitude of the largest possible earthquake along a fault segment, together with an associated recurrence time for such an earthquake. To do so, we calculate the moment released by observed seismicity and afterslip, and divide by the duration of the catalog to get the average moment release rate. We compare this estimate with the moment deficit rate derived from models of interseismic strain. If the moment deficit rate is larger than the observed moment release rate, the observed maximum-magnitude earthquake might not be the most extreme event that can occur along the fault segment. We thus explore the space of magnitude and frequency of maximum-magnitude earthquakes to find which events can balance the moment budget and be plausible considering the current statistical distribution of earthquakes. We account for aftershocks, background seismicity, and postseismic slip for each maximum-magnitude earthquake tested. This method allows to assess seismic hazard considering uncertainties on the seismic and geodetic data and accounting for our understanding of the behavior of a fault segment. In the following, we detail the method. A flowchart describing the approach, step by step, is available in © Table S1 (available in the electronic supplement to this article). Table 1 lists the parameters used in this study.

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Table 1
List of Variables Used in This Study

<table>
<thead>
<tr>
<th>Variables</th>
<th>Symbol</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moment (N-m)</td>
<td>m</td>
<td>(\dot{m}_0): rate of moment deficit accumulation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\bar{m}_S): average total moment release rate of seismicity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\dot{m}_{S,j}): moment release rate of aftershocks and background seismicity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\dot{m}_{\text{int}}): moment release rate of the largest earthquake</td>
</tr>
<tr>
<td>Magnitude</td>
<td>(M_u)</td>
<td>(M_{\text{max}}): magnitude of the largest event</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(M_{\text{hist}}): magnitude of the largest observed event (in catalog)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(M_{\text{Tot}}): magnitude tested for the probability to have an earthquake with (M &gt; M_{\text{Tot}}) during a certain time period ((P_{\text{Hist}}))</td>
</tr>
<tr>
<td>Shear modulus (Pa)</td>
<td>(\mu)</td>
<td>(\tau_{\text{max}}): return period of the largest event</td>
</tr>
<tr>
<td>Slip deficit rate (N-m/yr)</td>
<td>(D)</td>
<td>(\tau_{\text{GR}}): return period predicted by the observed GR law for (M &gt; M_{\text{Hist}})</td>
</tr>
<tr>
<td>Fault area (m²)</td>
<td>(A)</td>
<td>(\tau_{M}): average recurrence time of independent events with (M &gt; M_{\text{Tot}}) predicted by a given GR law</td>
</tr>
<tr>
<td>Long-term plate rate (mm/yr)</td>
<td>(V_{\text{plate}})</td>
<td>(\alpha): percentage of aseismic afterslip moment release compared to the moment released seismically</td>
</tr>
<tr>
<td>Intereismic coupling</td>
<td>(\chi)</td>
<td>(\tau_{\text{Hist}}): time period covered by the earthquake catalog</td>
</tr>
<tr>
<td>Slip rate in the interseismic period (mm/yr)</td>
<td>(S)</td>
<td>Number of events per year (r)</td>
</tr>
<tr>
<td>Return period of events (yrs)</td>
<td>(\tau)</td>
<td>(a): total number of earthquakes recorded per year (from the GR law)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(b): relative distribution between small and large earthquakes (from the GR law)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(N): cumulative number of earthquakes per year over magnitude (M)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(r): number of events per year in a magnitude range</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(a): percentage of aseismic afterslip</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(t): time period covered by the earthquake catalog</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(n): number of events during the time period (t)</td>
</tr>
</tbody>
</table>

GR, Gutenberg–Richter.

coupling is defined as the ratio between the deficit of slip and the long-term slip of the fault and is given by

\[
\chi = 1 - \frac{S}{V_{\text{plate}}},
\]

(2)
in which \(S\) is the creep rate observed during the interseismic period, \(\chi\) is 0 for a fault patch creeping at the long-term slip rate and 1 for a fully locked patch.

The amount of moment released seismically can be estimated from earthquake catalogs, for example, a historical catalog. The average total seismic moment released per year \(\bar{m}_S\) is given by

\[
\bar{m}_S = \sum_{j=1}^{N} \frac{m_{S,j}}{t_{\text{Hist}}},
\]

(3)
in which \(N\) is the total number of events in the catalog, \(m_{S,j}\) is the seismic moment of each earthquake \(j\), and \(t_{\text{Hist}}\) is the time period covered by the catalog. The observed seismicity might be seen as one particular realization of a stochastic process over a certain period of time. It might not be representative of the long-term average seismic moment rate if the period of time covered by the data is short compared to the return period of the largest possible earthquake.

The moment released by the known seismicity most often does not balance the moment deficit due to interseismic coupling. Many causes can lead to a deficit of seismicity (\(\dot{m}_0 > \bar{m}_S\)): (1) the largest possible earthquake is not present in the catalog because of its too short time span; (2) the largest possible earthquake is present in the catalog but the duration of the catalog is longer than the average return period of such an event; (3) the undetected seismicity contributes significantly to the moment budget; (4) transient aseismic slip such as afterslip or slow slip events contribute significantly to the moment budget; (5) a fraction of interseismic strain is aseismic and is therefore not to be released seismically; and (6) a large earthquake with its epicenter outside the study area may have extended into the area of interest and released a fraction of the moment deficit. In this case, the catalog does not capture the event. In the context of this study, this could have happened during the 1857 \(M_s \sim 7.7\) Fort Tejon mainshock or possibly as a foreshock. This earthquake ruptured the SAF south of Parkfield (Fig. 1), and might have ruptured the Parkfield segment as well (Sieh, 1978).

Alternatively, \(\bar{m}_S\), the rate of moment released seismically, can exceed \(\dot{m}_0\), the rate of moment buildup: (1) the largest possible event is in the catalog but the period of time covered by the catalog is shorter than the average return period of such an event; (2) such events have occurred more frequently over this period of time than over the long-term average; and (3) interseismic strain is not stationary in time and the period covered by the geodetic data corresponds to a loading rate that is less than the average over the long term. In any case, the comparison between \(\bar{m}_S\) and \(\dot{m}_0\) provides information on the magnitude and average return period of the largest earthquake needed to balance the slip budget on the long term.

The next step consists of calculating the probability of a seismicity model to balance the moment budget and be
consistent with the known seismicity. Key parameters of the seismicity model are the magnitude and return period of the largest earthquake.

The probability that the largest event is of magnitude \( M_{\text{max}} \) and has on average a return period of \( \tau_{\text{max}} \) can be written as the product of two probabilities:

\[
P(M_{\text{max}}, \tau_{\text{max}}) = P_{\text{Budget}}(M_{\text{max}}, \tau_{\text{max}}) \times P_{\text{Hist}}(M_{\text{max}}, \tau_{\text{max}}).
\]

\( P_{\text{Budget}}(M_{\text{max}}, \tau_{\text{max}}) \) is the probability that an earthquake of magnitude \( M_{\text{max}} \) and its associated aftershocks and aseismic afterslip will release a moment equal to the deficit of moment accumulated over the return period \( \tau_{\text{max}} \) (i.e., the probability that an earthquake of magnitude \( M_{\text{max}} \) balances the budget). \( P_{\text{Hist}}(M_{\text{max}}, \tau_{\text{max}}) \) is the probability that an event of magnitude \( M_{\text{max}} \) and return period \( \tau_{\text{max}} \) is the maximum possible earthquake based on the historical seismicity.

We calculate \( P_{\text{Budget}} \) based on the assumption that the maximum-magnitude earthquake is followed by aftershocks and that aseismic afterslip releases a moment proportional to the moment released seismically. For a given mainshock moment magnitude and recurrence time, we compare the moment released by the mainshock and postseismic relaxation (aftershocks and aseismic afterslip) to the estimated rate of moment deficit building up on the fault. Interseismic models of fault coupling derived using a Bayesian approach directly provide the probability density function (PDF) of the rate of moment accumulation (Wang et al., 2014; Jolivet et al., 2015).

We assume that, on average over the long term, seismicity follows the empirical Gutenberg–Richter (GR) law

\[
\log_{10}(N_M) = a - bM,
\]

(Gutenberg and Richter, 1944), in which \( a \) and \( b \) are constants relating respectively to the total number of earthquakes recorded per year and the relative distribution between small and large earthquakes, and \( N_M \) is the cumulative number of earthquakes per year over magnitude \( M_w \). We assume that the law applies to a catalog of independent events (with aftershocks removed through declustering) as well as to dependent events (a catalog including aftershocks) and that the \( b \)-value is the same in both cases (for a same given area). These assumptions are, for example, consistent with the earthquake statistics observed in southern California (Marsan and Lengline, 2008).

The number of events per year with magnitudes in the \([M - \frac{\partial M}{2}, M + \frac{\partial M}{2}]\) range is then

\[
r = 10^{N_M \frac{a}{b} + a} - 10^{N_M \frac{a}{b} + b}.
\]

The moment release rate of earthquakes with moment between 0 and \( m_a \), over a period of time, should then converge (in the limit of infinite time) toward

\[
\dot{m}_S \tau = \int_0^{m_a} rdm.
\]

We assume that earthquakes in the study area are bounded by a maximum event of moment \( m_{\text{max}} \) and magnitude \( M_{\text{max}} \). The largest aftershock has often a magnitude of about 1 unit less than the magnitude of the mainshock (Båth, 1965), which might imply a bimodal earthquake distribution. Assuming that the background seismicity does not reach magnitudes larger than the largest aftershock, the return period of the main event and that of the maximum aftershock is the same and the GR relationship runs through \( M = M_{\text{max}} - 1 \) and \( \tau = \tau_{\text{max}} \).

However, Båth’s law is not a physical law and is probably linked to a statistical finite size effect (the number of aftershocks above a certain magnitude is finite and this finite number determines the difference of magnitude between the mainshock and the largest aftershocks) (Helmstetter and Sornette, 2003). It is possible that at the limit of infinite time, although each single cluster of earthquakes could follow Båth’s law, the total GR distribution would apply up to the maximum value of the distribution \( M = M_{\text{max}} \) and \( \tau = \tau_{\text{max}} \).

In the following, we test both cases and assume that these hypotheses bracket the contribution to the total seismic moment release of earthquakes smaller than the maximum magnitude.

Additionally, we assume that the moment released by aseismic afterslip is a proportion \( \alpha \) of the moment released seismically. Assuming that the moment release rate of seismic and aseismic transient slip events balances the rate of moment deficit accumulation on the long run, we get

\[
m_0 = (m_{S\text{m}} + \dot{m}_S)(1 + \alpha),
\]

in which \( \dot{m}_{S\text{m}} \) is the moment release rate of the largest earthquake (the subscript \( S \) stands for seismic and \( m \) for mainshock), and \( \dot{m}_S \) is the moment release rate of aftershocks and background seismicity (the subscript \( S \) stands for seismic and the subscript \( a \) stands for aftershock).

With the assumptions listed above, it is possible to calculate the probability \( P_{\text{Budget}} \) of closing the moment budget for a given magnitude and return period of the maximum earthquake. Without taking Båth’s law into account, this probability is the highest along a straight line in the GR plot corresponding to the return period of the largest event

\[
\tau_{\text{max}}(m_{\text{max}}) = \frac{1}{1 - 2b/3} \frac{(1 + \alpha) m_{\text{max}}}{m_0} \text{ if } b < 3/2,
\]

(Molnar, 1979; Ader et al., 2012), in which \( m_{\text{max}} \) is the moment released by the largest mainshock. With Båth’s law, the contribution of smaller events becomes nearly negligible:

\[
\tau_{\text{max}}(m_{\text{max}}) = \frac{10^{-\beta}}{1 - 2b/3} \frac{(1 + \alpha) m_{\text{max}}}{m_0},
\]

(Molnar, 1979; Ader et al., 2012), in which \( m_{\text{max}} \) is the moment released by the largest mainshock. With Båth’s law, the contribution of smaller events becomes nearly negligible:
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Following the first approach, the probability of \((M_{\text{max}}, \tau_{\text{max}})\) being the magnitude and return period of the largest event depends on the magnitude of the largest observed earthquake \(M_{\text{hist}}\) and on the return period \(\tau_{\text{GR}}(M_{\text{max}})\) predicted by the GR law derived from a declustered catalog:

\[
\text{if } M_{\text{max}} < M_{\text{hist}}, P_{\text{Hist}}(M_{\text{max}}, \tau_{\text{max}}) = 0, \tag{12}
\]

\[
\text{if } M_{\text{max}} > M_{\text{hist}}, P_{\text{Hist}}(M_{\text{max}}, \tau_{\text{max}}) \propto P_{\text{Poisson}}(n = 1, \tau_{\text{max}}, \tau_{\text{GR}}(M_{\text{max}})) = (\tau_{\text{max}}/\tau_{\text{GR}}(M_{\text{max}})) e^{-\tau_{\text{max}}/\tau_{\text{GR}}(M_{\text{max}})}. \tag{13}
\]

We use the sign \(\propto\) to indicate proportionality, as the PDF is normalized.

Following the second approach, the probability of \((M_{\text{max}}, \tau_{\text{max}})\) being the magnitude and return period of the largest event depends on the magnitude of the largest observed earthquake \(M_{\text{hist}}\) and on time period covered by the catalog \(t_{\text{hist}}\). It can be defined as the probability to have no earthquakes of magnitude over \(M_{\text{hist}}\) occurring during the time period of the catalog:

\[
\text{if } M_{\text{max}} < M_{\text{hist}}, P_{\text{Hist}}(M_{\text{max}}, \tau_{\text{max}}) = 0, \tag{14}
\]

\[
\text{if } M_{\text{max}} > M_{\text{hist}}, P_{\text{Hist}}(M_{\text{max}}, \tau_{\text{max}}) \propto P_{\text{Poisson}}(n = 0, t_{\text{hist}}, \tau_{\text{max}}) = e^{-\tau_{\text{max}}/t_{\text{hist}}}. \tag{15}
\]

The probability drops rapidly to zero as \(\tau_{\text{max}}\) becomes smaller than \(t_{\text{hist}}\). It becomes uniform quickly as \(\tau_{\text{max}}\) gets larger than \(t_{\text{hist}}\).

Figure 2 shows a schematic representation of the probability \(P_{\text{Budget}} \times P_{\text{Hist}}\) in both cases. In the first case, the probability that an earthquake is the maximum possible earthquake in view of the observed seismicity and also closes the moment budget is the highest at the intersection between the GR law (equation 4) and the line representing the return period of the largest earthquake required to close the moment budget (equation 9 or 10). In the second case, the probability that an earthquake is the maximum possible earthquake in view of the observed seismicity and also closes the moment budget is the highest along the line representing the budget closure condition (equation 9 or 10). Any large magnitude \((M_{\text{max}} > M_{\text{hist}})\) and very infrequent maximum earthquake that closes the moment budget is considered acceptable as long as its return period is long compared to the observation period \((\tau_{\text{max}} > t_{\text{hist}})\).

In principle, we could also use phenomenological scaling laws, or physical constraints (Scholz, 1982) to limit the range of possible earthquake magnitude on a particular fault segment. For instance, we could impose the coseismic stress drop to be between 0.1 and 100 MPa, as generally observed (e.g., Kanamori and Brodsky, 2004). This would constrain...
the maximum possible moment given the size of the locked area. We find such constraints to be too loose to be useful and are therefore not included as a priori in our analysis. We use them a posteriori to validate our assessment qualitatively.

When it comes to seismic hazard, the two methods should not yield much different outcomes if the hazard is calculated over a period of time \( t \) similar in duration to the earthquake catalog \( t_{\text{hist}} \). They could however differ significantly for \( t \gg t_{\text{hist}} \). To assess the impact of choosing between approaches 1 and 2, we calculate the probability of an independent event over a period \( t \) exceeding a magnitude \( M_{\text{Test}} \) for different values of \( t \).

\[
P_{\text{Hazard}}(M > M_{\text{Test}}; t) = 1 - P_{\text{Poisson}}(n = 0, t, \tau_M)
\]

\[
= 1 - e^{-\tau_M / \tau_M},
\]

in which \( \tau_M \) is the average recurrence time of independent earthquakes with magnitude larger than \( M_{\text{Test}} \) that can be calculated from the GR law \((\tau_M = 10^{-a-bM_{\text{Test}}})\), with \( a \) and \( b \) being determined from a declustered catalog. The probability \( P_{\text{Hazard}} \) calculated this way does not account for aftershocks.

To construct Figure 3, we first choose a value of \( t \). We then grid the magnitude–frequency space and test systematically all magnitudes of the maximum possible earthquake and all the return periods within a search area. For each sample tested, we represent the probability \( P_{\text{Hazard}}(M > M_{\text{Test}}; t) \)
with a curve shaded according to the probability $P_{\text{Budget}} \times P_{\text{Hist}}$. We can thus apprehend visually the most likely earthquake scenarios that might happen during the time period $t$ (Fig. 3). A mean probability of all the possibilities tested, which we weight with the product $P_{\text{Budget}} \times P_{\text{Hist}}$, can be obtained from the following equation:

$$
\bar{P}_{\text{Hazard}}(M > M_{\text{Test}}, t) = \frac{\sum_{k=1}^{N} P_{\text{Hazard},k} \times P_{\text{Budget},k} \times P_{\text{Hist},k}}{N}.
$$

(17)

in which $N$ is the number of samples tested, $k$ is the sample index, $P_{\text{Hazard},k}$ is the probability of having an independent event with magnitude $M_{\text{Test}}$ during the time period $t$ for the sample $k$, and $P_{\text{Budget},k} \times P_{\text{Hist},k}$ is the probability of sample $k$ given the seismicity observations and the moment budget closure condition.

To illustrate the procedure, let us first choose a sample of maximum magnitude $M_{\text{max}}$, and its time recurrence $\tau_{\text{max}}$. We assume that this event belongs to a distribution of independent events that follows the GR law. Choosing $M_{\text{Test}} = 4$ (for example), we can calculate the probability of having an independent earthquake over magnitude 4 during a time period $t$, knowing that those events have a recurrence time given by the GR law (equation 16). Applying this to the full range of $M_{\text{Test}} \in [0, M_{\text{max}}]$, $P_{\text{Hazard}}$ will be represented by a line in Figure 3. This $P_{\text{Hazard}}$ is associated with a specific $M_{\text{max}}$ and $\tau_{\text{max}}$, and corresponds to a specific $P_{\text{Budget}}(M_{\text{max}}, \tau_{\text{max}}) \times P_{\text{Hist}}(M_{\text{max}}, \tau_{\text{max}})$. If we test each possible $M_{\text{max}}$ and $\tau_{\text{max}}$, and plot their $P_{\text{Hazard}}$ in the same representation, the shade of each line indicating $P_{\text{Budget}} \times P_{\text{Hist}}$, we then obtain Figure 3. We could then calculate the average $P_{\text{Hazard}}$ of all those lines, but it would not account for the probability to close the moment budget and be plausible considering the observed seismicity. We then weight each $P_{\text{Hazard}}$ obtained for a particular choice of $M_{\text{max}}$ and $\tau_{\text{max}}$ by its related $P_{\text{Budget}} \times P_{\text{Hist}}$, and use this to calculate the weighted average $\bar{P}_{\text{Hazard}}$ (equation 17) represented by the white dashed line in Figure 3.

We sample the probabilities using the Hasting–Metropolis Monte Carlo Markov Chain (MCMC) procedure (Metropolis et al., 1953; Hastings, 1970). We calculate for each sample $k$, with a given magnitude and frequency of the largest earthquake, the probability that it is realistic knowing the data $P_{\text{Hist},k}$ and the probability that it closes the budget $P_{\text{Budget},k}$. The final probability $P_{G,k}$ (i.e., the $a$ posteriori probability) of a given sample would thus be

$$
P_{G,k} \propto U_{M} U_{\text{Freq}} P_{\text{Budget},k} P_{\text{Hist},k},
$$

(18)
in which $U_{M}$ and $U_{\text{Freq}}$ are the uniform laws chosen for the MCMC sampling for the magnitude and frequency, respectively (i.e. the $a$ priori probability).

Application to the Parkfield Segment of the San Andreas Fault

Moment Budget

Interseismic strain around the Parkfield segment of the SAF has been investigated in a number of recent studies (Johnson, 2013; Wang et al., 2014; Jolivet et al., 2015; Tong et al., 2015). Here, we rely on the studies of Wang et al. (2014) and Jolivet et al. (2015), as they provide a probabilistic description of slip rate from Bayesian inversions which can be used directly as an input in our study. We consider the same fault geometry and focus on the same fault area as Wang et al. (2014; Figs. 4 and 5). To assess the moment budget, we use interseismic models from Wang et al. (2014) and Jolivet et al. (2015), which were both derived from inversion of interseismic displacements measured at the surface assuming a fault embedded in an elastic medium. Wang et al. (2014) assumed a homogeneous elastic half-space and Jolivet et al. (2015) considered depth variations of elastic moduli. We convert slip potency (the integral of slip over fault area) to moment according to the elastic structure assumed in these studies.

Wang et al. (2014) present three different Bayesian inversions of Global Positioning System (GPS) data from 14 stations covering the period from 1999 to 2004 including the mainshock of 2004 and five days of postseismic relaxation. They use a 70-km-long, ~19-km-deep fault subdivided into 180 patches, each 1.4-km-long along strike and 1 km wide. A steady slip rate is assumed at depth greater than 19 km. We considered their favored model (hereafter, MW), which was obtained from a joint inversion of the interseismic, coseismic, and five-day postseismic data, designed to maximize the consistency between the three slip distributions. The slip distributions therefore complement each other (Fig. 4): the coseismic rupture is restricted to the area that was locked during the interseismic period; the inversions assume that postseismic slip is driven by the coseismic stress change and thus yields a ring of afterslip surrounding the coseismic rupture. The steady slip rate on the deeper extension of the fault is estimated to 32.1 mm/yr in this model. The Bayesian framework provides uncertainties on all quantities determined from the inversion.

Jolivet et al. (2015; hereafter, MJ) also used a Bayesian approach and derived an interseismic model from GPS and Interferometric Synthetic Aperture Radar (InSAR) data covering the period from 2006 to 2010. The modeled fault zone extends over 200 km from the Cholame plain to north of San Juan Baptista. The patch size varies depending on the resolution from 4 km at the surface to 25 km at 20 km depth. The long-term slip rate varies along strike. In the Parkfield area considered in this study, it varies from 31.1 to 36.6 mm/yr. The model shows a gradual northward decrease of interseismic coupling from the locked zone in the southeast to the creeping zone in the northwest (Fig. 4). This model shows a deficit of slip extending to depth greater than...
19 km, thus deeper than the seismogenic depth. Given the absence of seismicity at such depth and the fact that temporal variations of strain rates in this depth range are probably primarily due to viscoelastic relaxation as was observed following the 2004 earthquake (Bruhat et al., 2011), we consider slip deficit accumulation only in the 0–19 km depth range of our fault model.

Both models yield deep slip rates in agreement with the geological long-term slip rate on the SAF which is estimated to $33.9 \pm 2.9$ mm/yr in the Carrizo plain south of the Parkfield segment (Sieh and Jahns, 1984). These rates are also consistent with those ($34.9$–$36.0 \pm 0.5$ mm/yr) derived from elastic block modeling of regional tectonics (Meade and Hager, 2005; Tong et al., 2014). They are, however, larger than the local estimate of $26.2$ + $6.4$/$-4.3$ mm/yr of Toké et al. (2011). Both models show high interseismic coupling in the area that ruptured in 2004. They differ significantly in part not only because of different interseismic observations but also because of different methods and a priori assumptions. In addition to enforcing consistency between the three phases of the earthquake cycle, the inversion used to derive MW was regularized via spatial smoothing. By contrast, MJ was obtained without any constraint on the smoothness of the slip-rate distribution or on the relationship between interseismic and coseismic slip. The long-term slip rate on the continuation of the fault at the depth is constant in MW but varies along strike in MJ. For MJ, fault patches are assigned the long-term slip rate of the deeper creeping patches. Those located astride different deep creeping patches are divided in subpatches. The shear modulus used to convert slip to moment is 30 GPa for MW and varies between 20.5 and 66.2 GPa for MJ (Jolivet et al., 2015).

The Bayesian approach used in Jolivet et al. (2015) and Wang et al. (2014) provides thousands of scenarios, which were tested against geodetic data. For both studies, we calculate the moment deficit rate of every scenario using equations (1) and (2) to derive the PDF of the moment deficit rate. The rate of accumulation of moment deficit for each model is indicated in Table 2 and the corresponding PDFs are shown in Figure 6.

We calculated and represented in Figure 7 the moment deficit rate on a completely locked $70 \times 20$ km section loaded at $32.1$ mm/yr (full black line) and a section with the coupling pattern from the MW model (black dashed line). Based on interseismic model MW the moment deficit builds up at a rate of $6.90 \pm 0.64 \times 10^{17}$ N·m/yr. The PDF associated with this estimate is shown in Figure 6. Some of this deficit was released by aseismic afterslip following the 2004 event, which released about $3.7 \times 10^{18}$ N·m (Bruhat et al., 2011). We do not use the afterslip model of Wang et al. (2014), as their model covers only five days after the mainshock. The dotted line in Figure 7 shows the remaining deficit of moment which amounts to $5.39 \times 10^{17}$ N·m/yr.

Based on interseismic model MJ, the moment deficit accumulates in the interseismic period at a rate as large as $8.82 \pm 1.10 \times 10^{17}$ N·m/yr (Fig. 6). The difference with the rate obtained with MW is due partly to the different pattern of coupling and to the difference of deep creep rates ($31.1$ and $36.5$ mm/yr for MJ and $32.1$ mm/yr for MW). The rate is reduced to $7.31 \times 10^{17}$ N·m/yr if aseismic afterslip is subtracted (Fig. 8).
The moment released by seismicity is estimated from the northern California earthquake catalog (Northern California Earthquake Data Center [NCEDC], 2014) from 1984 to 2015 (up to 2 May 2015). We consider earthquakes located within 5 km of the fault (Fig. 5). Figure 7 shows the cumulative moment released by earthquakes of magnitude under Mw taken directly from the catalog (gray dashed line). This estimate might not be representative of the interseismic cycle. The inset in Figure 5 shows minor temporal fluctuations except for the strong increase of seismicity associated with the 2004 aftershocks. The moment released by seismicity over the 31 yrs covered by the catalog, representative of the 2004 event (87%), its aftershocks (7%), and the background seismicity (6%), accounts for only 5% of the deficit of moment that has accumulated over this time period according to the interseismic model MW, or 7% if the postseismic moment released is taken into account (Fig. 7). It represents an even lower fraction (4%) of the deficit of moment calculated based on the interseismic model MJ (5% if taking into account the aseismic moment released by afterslip; Fig. 8). As mentioned above, the deficit could suggest that the return period of the maximum-magnitude earthquake is overestimated or that larger magnitude events are needed on this fault segment. We now consider the first possibility.

Six Mw ~ 6 earthquakes occurred at Parkfield between 1857 and 2004, yielding an average return period of 24.5 yrs. The catalog covers 31 yrs and includes the 2004 event and its aftershocks. Some corrections might thus be needed to represent the long-term average seismicity. Let us assume that the 2004 Parkfield earthquake is characteristic of the sequence of Mw 6 earthquakes that have occurred since 1857. We assume that such an event and its associated aftershocks return every 24.5 ± 9.2 yrs on average, where the uncertainty is the 1σ standard deviation of the time intervals. We consider the moment released by such an event to be equal to the mean moment estimated for 2004 from various publications (Johanson et al., 2006; Langbein et al., 2006; Liu et al., 2006; Murray and Langbein, 2006; Barbot et al., 2009; Bruhat et al., 2011; NCEDC, 2014; Wang et al., 2014). We use the standard deviation of these estimates as an estimate of the uncertainty at the 67% confidence level. The average moment released is then 1.48 × 1018 ± 4.7 × 1017 N·m (Mw 6.08).

We estimate the moment released by aftershocks by comparing the seismicity rate over the 2004–2008 period with the 1984–2004 period. We also assume that each event triggered as much aseismic afterslip as the 2004 event. According to Bruhat et al. (2011), afterslip following the 2004 event released about 1.57 × 1018 N·m assuming viscous flow under 19 km depth, or about 3.7 × 1018 N·m if viscous relaxation is excluded, which is more than twice the coseismic moment release. Hereafter, we assume that afterslip released up to 200% of coseismic moment, which gives us an upper bound on the total moment released by this sequence of earthquake. The moment released by afterslip is subtracted from the moment released by the 2004 event to estimate the moment released by aseismic slip (Fig. 8). The moment released by aseismic afterslip is then estimated as 1.7 × 1018 N·m.

### Table 2

<table>
<thead>
<tr>
<th>Interseismic Models</th>
<th>Moment Deficit Rate (N m/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MW (Wang et al., 2014)</td>
<td>6.90 ± 0.64 × 10^{17}</td>
</tr>
<tr>
<td>MJ uncut (Jolivet et al., 2015)</td>
<td>1.40 ± 0.28 × 10^{18}</td>
</tr>
<tr>
<td>MJ cut at 19 km depth</td>
<td>8.82 ± 1.10 × 10^{17}</td>
</tr>
<tr>
<td>MW cut at 15 km depth</td>
<td>6.04 ± 0.52 × 10^{17}</td>
</tr>
</tbody>
</table>

The moment released by aseismic afterslip following the 2004 Parkfield earthquake is 1.7 × 10^{18} N·m.
from the deficit of moment accumulating in the interseismic period (Figs. 7 and 8). The values corresponding to this moment budget estimate are reported in Tables 2 and 3, and illustrated in Figures 6–8. Clearly, the moment released by 2004-like events returning every 24.5 ± 9.2 yrs on average falls still way short of balancing the moment budget (12.1% of MW’s model).

Returning $M_w$ > 6 earthquakes at Parkfield do not necessarily release the same moment as the 2004 event. The 1966 Parkfield earthquake is considered to be relatively similar to the 2004 one in terms of its moment release and rupture area (Bakan et al., 2005). According to the reported damages (Toppozada et al., 2002), the events of 1901 and 1922 may have been stronger ($M_w$ 6.4 and $M_w$ 6.3, respectively). Moreover, several $M_w$ > 5 earthquakes that occurred between 1857 and 2015 are considered to be independent from the $M_w$ > 6 earthquake ($M_w$ 5.5 in 1877 and $M_w$ 5.8 in 1908), or direct aftershocks of the 1901 and 1922 earthquakes. Figures 7 and 8 show that if we now consider the historical catalog of Toppozada et al. (2002), the moment released by seismicity is higher but still too small to balance the moment budget (Table 3). Assuming that the interseismic period covered by geodetic data is representative of the long-term average, we derive that seismicity and afterslip released at most 16.1% (MW) of the deficit of moment accumulated since 1857. The epicenter of the 1901 $M_w$ 6.4 earthquake is actually located slightly north of our study area. The damage distribution indicates that the rupture propagated within the Parkfield area, but it is not clear that the rupture area was confined to the fault area consider in our study. By assuming that the moment of this earthquake was entirely released by slip on the fault segment considered in this study we probably tend to overestimate the seismic moment release.

Considering this time only for the moment deficit rate from the seismogenic zone (~15 km depth) and reducing the recurrence time of the $M_w$ 6 to 17 yrs as estimated by Wang et al. (2015) does not close the moment budget either. The moment deficit rate is reduced to 3.86 ± 0.52 × 10¹⁷ N·m/yr based on the interseismic model MW cut at 15 km depth with afterslip subtracted, and the seismic moment released is increased to 9.32 × 10¹⁶ N·m/yr. Giving this extreme scenario, the percentage of seismic moment released compared to the moment deficit rate is still low (24%).

Some coseismic models of the 2004 $M_w$ 6 earthquake indicate slip up to 30 km south of the hypocenter (Wang et al., 2014, 2015) and a similar rupture extent to that proposed for the 1966 earthquake (Murray and Langbein, 2006). However, most models indicate that the 2004 rupture did not go further than 10 km south of the hypocenter (Johanson et al., 2006; Liu et al., 2006; Allmann and Shearer, 2007; Barbot et al., 2009; Bruhat et al., 2011). By limiting the extent of our area of study to 10 km south of the 2004 hypocenter and by cutting the interseismic models at an even more shallow seismogenic zone (10 km depth), we obtain a moment deficit rate of 2.93 × 10¹⁷ N·m/yr for MW and 2.99 × 10¹⁷ N·m/yr for MJ. The moment deficit rate PDF of the model MJ would then slightly overlap with the moment released by earthquakes and postseismic slip. The probability to close the moment budget is nevertheless 2%. On the other hand, the MW model would still not overlap.

This analysis shows that balancing the moment budget on the Parkfield segment of the SAF probably requires more frequent or larger earthquakes than what the instrumental and historical data suggest. All the seismic moment release rates discussed in this section are available in Table 3.

The Tong et al. (2015) integral method yields a moment deficit rate around 5.8 × 10¹⁷ N·m/yr, which is slightly smaller than the best-fitting value of MW but within the uncertainty range. We consider that the range of rates of moment deficit explored using the Bayesian inversions of MJ and MW models of interseismic coupling provides a reasonable estimate of the range of possible values given the uncertainties on the geodetic data and choice of the modeling technique.

Maximum-Magnitude Earthquake Evaluation

We now explore the range of possible magnitudes and frequencies for the largest possible earthquake needed to
Seismic and Aseismic Moment Budget and Implication for the Seismic Potential of the Parkfield Segment of the SAF

Figure 7. (a) Representation of the budget of seismic and aseismic slip on the Parkfield segment of the SAF based on interseismic model MW (Wang et al., 2014). The gray dashed curve is the cumulated moment released per year by earthquakes with magnitude less than the value in abscissa. This curve is based on seismicity within 5 km of the Parkfield fault segment over 31 yrs, from 1984 to 2015. The catalog includes the 2004 earthquake, which is assigned a moment magnitude 5.97, and aftershocks. The black solid curve is the cumulated moment that would be released annually assuming that over the long term an event similar to the 2004 earthquake occurs every 24.5 yrs and is assigned a moment magnitude of $M_w$ 6.08, which represents some average value from various studies (see the Moment Budget section). The white dot is the moment released assuming an $M_w$ 6.08 every 24.5 yrs and neglecting the contribution of aftershocks and background seismicity to the seismic moment release rate. The black dots show the moment released by historical seismicity from 1857 to 2015 according to the catalog of Toppozada et al. (2002). The thin horizontal solid black line is the moment deficit accumulating per year if the modeled fault area was completely locked (for a loading rate of 32.1 mm/yr). The thin horizontal dashed black line shows the moment deficit rate based on the interseismic model of MW. The thin horizontal dotted black line takes into account the postseismic moment released after an $M_w$ 6 mainshock similar to the 2004 event. The shading represents the uncertainty associated with this estimate. (b) Zoom of the black box which enables the appreciation of the large impact of the mainshock magnitude change and the weak impact of the background seismicity and aftershocks on the total amount of moment released by earthquakes. The color version of this figure is available only in the electronic edition.

Moment Budget Closure $P_{\text{Budget}}$: We calculate the probability $P_{\text{Budget},k}$ of closing the moment budget based on the uncertainties on the parameters of interseismic models MJ or MW. We estimate the moment released by seismicity for a tested magnitude $M_0$ and recurrence time $\tau_{b}$ of the largest earthquake and estimate the probability that it balances the moment budget using interseismic models MJ or MW. The probabilities on the interseismic models are taken from the distribution of their moment deficit using a bin of $10^{16}$ N-m.

The moment released by aftershocks and independent events with magnitude smaller than the largest earthquake is integrated by assuming that their magnitude–frequency distribution follows the GR law. We consider two cases. In the first case, the aftershocks and independent events follow the GR law up to the largest earthquake included. In the second case, we account for Båth’s law; the largest aftershock is 1 magnitude unit lower than the mainshock, as it is observed in the 2004 event. We suppose also that the $b$-value is constant and equal to the one estimated from the modified 1984–2015 catalog. We use the maximum curvature method (Wiemer and Wyss, 2000) and Bender’s formula (Aki, 1965; Utsu, 1966; Bender, 1983) to evaluate the magnitude of completeness and the $b$-value. The estimated magnitude of completeness is increased by 0.2 to compensate for a methodological bias of the method (Woessner and Wiemer, 2005). The $b$-value, estimated at 0.91 ± 0.06, is then used to account for the magnitude–frequency distribution of both aftershocks and independent events. The $a$-value is easily calculated from equation (5).

Moment released by aseismic afterslip is accounted for by supposing that, for all earthquakes, it amounts to a fixed percentage of the seismic moment. This percentage might in fact depend on earthquake magnitude, but the available data are insufficient to derive a reliable law (Lin et al., 2013). We considered a value of 25%, close to the mean value observed from various case studies (Avouac, 2015), and a more extreme value of 200%, similar to that estimated for the 2004 sampling of the PDF. The magnitude–frequency space is then binned into cells of size 0.01 for the moment magnitude axis and logarithmically binned into cells of size 0.01 concerning the frequency axis. The number of samples in each cell divided by the total number of samples approximates the probability $P_{G,k}$ as defined by the MCMC method.
earthquake. The value of 200% is an overestimation of Bruhat et al. (2011).

$P_{Hist}$: First Approach. In the Method section, we proposed two different approaches regarding how the frequency–magnitude of the largest possible earthquake might be evaluated based on the known seismicity. The first case, the most restrictive, assumes that the distribution of a declustered catalog follows the GR law up to the largest event. Some declustered catalogs are available for California (Dutillieu et al., 2015), but they contain less than 200 earthquakes within 5 km from the fault segment considered in our study. This small number does not permit any reliable $b$-value estimation (Woessner and Wiemer, 2005). Therefore, we will rely on a nondeclustered catalog.

Assuming a postseismic moment release equivalent to 200% of the mainshock seismic moment, not accounting for Båth’s law and selecting MW as the interseismic model represents the most optimistic situation where the magnitude of the largest earthquake needed to close the moment budget is minimum. In this scenario, $P_G$ (equation 18) peaks around $M_w \sim 7.6$, corresponding to a seismic moment of $2.8 \times 10^{20}$ N·m, with a recurrence time period of $\sim 3300$ yrs (Fig. 9). The release of such a large moment on a 70-km-long segment seems however improbable, especially in view of the limited locked zone in the interseismic period. The average slip in such an event, supposing that the whole fault ruptures (20 $\times$ 70 km) and taking a 30 GPa shear modulus, would be of $\sim 7$ m. If we assume a rupture restricted to the locked portion of this fault segment, which represents only 1/3 of the fault area, the average slip would need to be as great as 21 m. This seems highly improbable.

We note in Figure 9 that the magnitude–frequency distribution of instrumental earthquakes does not align well with the historical seismicity. The earthquake rate is lower than expected if we assume the GR law extends up to larger magnitudes. The misalignment could be due to various causes. One is that the historical catalog essentially consists of independent events, whereas the instrumental catalog contains aftershocks. The two catalogs could belong to the same GR distribution if the $b$-value of the declustered catalogs was lower than when the aftershocks are included as some studies suggest (Frohlich and Davis, 1993). Extrapolating the GR law to the largest possible magnitude might be incorrect as a number of studies have argued that larger magnitude events are more frequent than would be expected from extrapolating the $b$-value estimated from lower magnitude seismicity (Schwartz and Coppersmith, 1984). Another possibility is that the seismicity rate between 1984 and 2015 would have been particularly low compared to a longer term average (Page and Felzer, 2015). In both cases, the method used here to estimate $P_{Hist}$ would overestimate the magnitude of the largest magnitude earthquake.

With the first approach, using the marginal cumulative probabilities, we can assess the probability that the largest event does not exceed a certain magnitude and the frequency of the largest event is inferior to a certain value (Fig. 10a,c). The probability of closing the moment budget on the Parkfield segment of the SAF with the magnitude of the

Table 3
Parkfield Seismic and Aseismic Moment Release

<table>
<thead>
<tr>
<th>Catalog Used</th>
<th>Seismic Moment Rate (N·m/yr)</th>
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</thead>
<tbody>
<tr>
<td>Initial catalog (31 yrs) (Northern California Earthquake Data Center [NCEDC], 2014)</td>
<td>$3.70 \times 10^{18}$</td>
</tr>
<tr>
<td>Modified catalog: $M_w \geq 6.08$ aftershocks every 24.5 yrs</td>
<td>$6.54 \times 10^{16}$</td>
</tr>
<tr>
<td>Toppozada’s catalog (Toppozada et al., 2002)</td>
<td>$8.67 \times 10^{16}$</td>
</tr>
<tr>
<td>Modified catalog: $M_w \geq 6.08$ aftershocks every 17 yrs</td>
<td>$9.32 \times 10^{16}$</td>
</tr>
</tbody>
</table>
Seismic and Aseismic Moment Budget and Implication for the Seismic Potential of the Parkfield Segment of the SAF

Figure 9. Maximum-magnitude earthquake probability assuming the case where large earthquakes should follow the GR law of a declustered catalog. We use here the model MW, do not account for Báth’s law, and suppose that the ratio between postseismic and co-seismic moment release is equal to 200%. The number of events from the declustered Advanced National Seismic System (ANSS) catalog being too low in the area selected, we apply the method on an undeclustered ANSS catalog. The results are thus biased and must be interpreted accordingly. The black curve represents the magnitude–frequency distribution of the Parkfield area using the ANSS catalog between 1984 and 2015. The gray curve is the modified magnitude–frequency distribution where the $M_w$ 6 and its aftershocks are fixed to occur every 24.5 yrs. The GR law (black dashed line) is taken from this distribution. The stars represent the historical data (Toppozada et al., 2002) and the black line represents an $M_w$ 7 earthquake with a recurrence time between 140 and 250. The color version of this figure is available only in the electronic edition.

maximum earthquake not exceeding 6.4 is only 0.3%. Therefore, provided that the GR law is valid up to magnitude $M_w$ 6.4, which seems a reasonable assumption, the analysis requires larger earthquakes. Figure 10 indicates that there is a 95% chance that the maximum event does not exceed an $M_w$ 8.63. There is also a 95% chance that the return period of the largest magnitude event does not exceed $\sim$112,000 yrs. It seems very improbable that the Parkfield segment could host an earthquake of such a magnitude as it would require 253 m of slip in a 19 $\times$ 70 km area. The probability of balancing the moment budget with a maximum earthquake not exceeding 7.4 is about 50%, indicating that even with such a large maximum earthquake, balancing the moment budget remains unlikely if the GR law applies. If the largest earthquakes involve ruptures that extend beyond the Parkfield segment, our analysis only provides constraints on the moment released within the Parkfield segment. In that case, the assumption that this earthquake belongs to a GR distribution defined by earthquakes on the Parkfield segment is certainly incorrect and the second approach is then more relevant.

$P_{Hist}$: Second Approach. Our second approach only assumes that the largest possible earthquake needs to be less frequent than the largest known earthquake. The probability of its return period is estimated based on the historical catalog (only the duration of the period covered matters) assuming a Poisson process. If we consider the interseismic model MW, discard Báth’s law, and assume that postseismic deformation releases 200% of the coseismic moment we get a more reasonable result than with approach 1 (Fig. 11). An $M_w$ 6.7 every 140 yrs is then sufficient to balance the moment budget and is acceptable in view of the known seismicity. This point aligns well with the frequency–magnitude distribution of historical events but is off the distribution of instrumental events, essentially because of the break in slope around $M_w$ $\sim$ 4. This is our favored scenario. However, the method does not exclude $M_w > 6.7$ events.

Figure 12 shows that the PDF of the magnitude–frequency of the largest event varies depending on the choice of the interseismic model (MJ or MW), on whether or not Báth’s law is accounted for, and on the assumption that either 25% or 200% of the mainshocks seismic moment is released by postseismic effects. Báth’s law has a significant impact. If it is taken into account, aftershocks and independent events amount to only $\sim$8% of the moment released by the largest earthquake, compared to $\sim$156% if Báth’s law is discarded. Consequently, when Báth’s law is not accounted for, the aftershocks and independent events sequence decrease drastically the maximum magnitude needed for budget closure. Similarly, postseismic deformation amplifies the moment released by the largest earthquake, its aftershocks, and the associated independent events. The higher the ratio between the postseismic and coseismic effect, the lower the magnitude or the frequency of the largest event needed to balance the slip budget.
The two extreme cases illustrated by Figure 12a,f enable us to appreciate the range of magnitude and frequency for an earthquake to close the moment budget. For a 140-yr recurrence time, the largest earthquake required would range between $M_w$ 6.7 for the first case and $M_w$ 7.3 for the second. This underlines the sensitivity to the hypothesis regarding the contribution to the moment budget of aftershocks and postseismic deformation. As an example, if we suppose that there is a magnitude 7 occurring every 140 yrs and we assume Båth’s law, the postseismic moment released would be between 162% ± 34% (MW) and 236% ± 59% (MJ).

Following the second approach, the marginal cumulative probabilities reflect primarily the assumptions that the $a \text{ priori}$ probabilities are uniform, between 6.3 and 9 for the magnitude of the largest earthquake, and $10^4$ and $10^{-6}$ for its frequency (Fig. 10b,d). It shows that the historical catalog does not put any constrain on the magnitude of the maximum event for return periods much longer than the catalog. The magnitude for which 95% of the maximum noncumulative probability is reached can instead give us an indication of the magnitude and frequency needed to close the moment budget (Fig. S2). An $M_w$ 7.34 is sufficient to close the moment budget at a 95% confidence level, as well as a time recurrence of 2000 yrs. Higher magnitudes and recurrence times than those estimates are equally plausible but would not be necessary.

Scaling laws linking stress drop $\Delta \sigma$, area of rupture $A$, and moment released during an earthquake $m$ can give us an indication on the maximum magnitude through the equation $\Delta \sigma \approx C m A^{-3/2}$, in which $C$ is a geometric constant close to unity (Scholz, 1982). Earthquake stress drops generally vary between 0.1 and 100 MPa (Kanamori and Brodsky, 2004). Consequently, the rupture of the full fault ($70 \times 19$ km) would be equivalent to a maximum magnitude of between $M_w$ 6.39 and 8.38. For events that rupture half of the segment length and for which the down-dip extent is 13 km ($35 \times 13$ km), the maximum magnitude would vary between $M_w$ 5.92 and 7.92. For comparison, Parkfield 2004 stress drop is $\sim 0.61$ MPa (Wang et al., 2014). However, such range of stress drop and the corresponding magnitude is way too large to provide any constraints to our problem, and hence we decided not to include this criterion in our analysis.

Implications for Seismic Hazard

For each tested value of the magnitude and frequency of the largest event, one can determine a seismic hazard quantity such as the probability $P_{\text{Hazard}}$ that an independent earthquake (not an aftershock) would exceed a given magnitude $M_{\text{th}}$ over a given period of time $t$. Each curve can then be weighted according to the probability of the scenario. The weighted mean $P_{\text{Hazard}}$ then represents the overall hazard resulting from all possible scenarios. As explained in the section of the first approach, the number of independent events taken from the declustered catalog is too low to

Figure 11. Maximum-magnitude earthquake probability assuming the case where large earthquakes should have a recurrence time lower than the largest earthquake currently observed. We use here the model MW, do not account for Båth’s law, and suppose that the ratio between postseismic and coseismic moment release is equal to 200%. The black curve represents the magnitude–frequency distribution of the Parkfield area using the ANSS catalog between 1984 and 2015. The gray curve is the modified magnitude–frequency distribution where the $M_w$ 6 and its aftershocks are fixed to occur every 24.5 yrs. The stars represent the historical data (Toppozada et al., 2002) and the black line represents an $M_w$ 7 earthquake with a recurrence time between 140 and 250. The black circle defines the location of an $M_w$ 6.7 event occurring every 140 yrs, our favored scenario. The color version of this figure is available only in the electronic edition.
Figure 12. Probability distribution to have a maximum-magnitude event that might exist and close the moment budget. The black curve represents the original magnitude–frequency distribution of the Parkfield area using the ANSS catalog between 1984 and 2015. The gray curve depicts the modified magnitude–frequency distribution of earthquakes in the Parkfield region with an $M_w$ 6.08 and its aftershocks every 24.5 yrs. The stars represent the historical data (Toppozada et al., 2002) and the black line represents an $M_w$ 7 earthquake with a recurrence time between 140 and 250 yrs. The probabilities computed depend on the model chosen, either MW or MJ, on the ratio between the postseismic and the coseismic moment release, and on whether Båth’s law is applied or not. The color version of this figure is available only in the electronic edition.
Figure 13. Probability to have earthquakes over a certain magnitude in a period of time of t years considering the probability distribution of a maximum-magnitude earthquake to exist and close the moment budget. We test our favored scenario using model MW, with Båth’s law not accounted for and with a postseismic moment release equivalent to 200% of the coseismic one. The white dashed line corresponds to $P_{\text{Hazard}}$. (a,b) The results for $t = 30$ yrs and (c,d) for $t = 200$ yrs. (a) and (c) suppose a maximum-magnitude possible of $M_w 7.5$, and (b) and (d) suppose that the maximum magnitude possible is an $M_w 9$. The color version of this figure is available only in the electronic edition.

If we assume that the largest earthquake cannot exceed 7.5, the probability of an $M_w > 6$ event over 200 yrs is 96%, and 30% for an $M_w > 7$ (Fig. 13c). If we assume that the largest earthquake can be as large as magnitude 9, the probability is reduced to 68% for $M_w > 6$ and to 15% for $M_w > 7$. These tests illustrate the mild sensitivity of the method to the a priori assumption on the maximum value of the largest possible magnitude.

The first approach, assuming a GR distribution up to the largest event, yields very similar results (Fig. S4) showing that these curves are not very sensitive to the choice of method, essentially because the periods chosen (of 30 and 200 yrs) are small compared with the return period of the maximum earthquake.

Discussion

Our assessment of the moment budget on the Parkfield segment of the SAF suggests that the sequence of $M_w \sim 6$ events returning every $\sim 24$ yrs as observed since 1857 accounts for only about 12.1% of the deficit of moment that is accumulating in the interseismic period. This conclusion would imply that this fault segment must hold larger less frequent earthquakes. Before discussing this possibility, we examine various factors that could be responsible for the moment deficit. The hypothesis of a larger earthquake is indeed not the only scenario that can explain residual moment deficit. Our analysis relies on a number of assumptions that might be questioned.

First, we assume that interseismic coupling is stationary and use models of interseismic coupling derived from decades of geodetic data (GPS and InSAR). The time period covered by these data might seem in fact short if the moment deficit is balanced primarily by events with a return period on the order of centuries. Furthermore, significant changes in interseismic coupling have been reported on subduction megathrusts (Meltzner et al., 2015; Tsang et al., 2015; Yokota and Koketsu, 2015). The stationary hypothesis is supported locally by the consistency between the model MJ proposed by Jolivet et al. (2015) based on InSAR and GPS data from 2006 to 2010, and the model MW proposed by Wang et al. (2014) based on GPS data ranges from 1999 to 2004. However, according to Barbot et al. (2013), the southern end of the Parkfield segment underwent some changes before and after the 2004 $M_w 6$ event. The boundary between the Parkfield and Cholame segments appears to creep faster following the 2004 earthquake than previously, which would indicate a variation in time of the coupling.
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pattern. Moreover, except for an aseismic transient slip coincident with three $M_w \sim 4.5$ earthquakes in the mid-1990s (Gwyther et al., 1996; Langbein et al., 1999; Nadeau and McEvilly, 1999; Gao et al., 2000; Roeloffs, 2001; Murray and Segall, 2005), no strong changes in the interseismic slip rate seems to have been detected between 1966 and 2004 (Murray and Langbein, 2006; Barbot et al., 2013). This suggests no modification of the locked section pattern or presence of other creep events during this time. However, if an event equivalent to the one in the mid-1990s ($M_w \sim 5.6$) occurred once every 24.5 yrs (the period of the mic cycle (Ben-Zion, 1993; Loveless and Meade, 2011; Tong et al., 2014) or could be due to distributed anelastic strain during the interseismic period (Oskin et al., 2008). In that regard, it is interesting to note that the deep creep rates that we used to estimate interseismic loading (31.1 and 36.5 mm/yr for MJ and 32.1 mm/yr for MW) are larger than the local estimate of 26.2 + 6.4/−4.3 mm/yr of Toké et al. (2011). This discrepancy could reflect either distributed anelastic strain or temporal variations in interseismic loading.

Our analysis thus suggests that the Parkfield segment of the SAF needs to release more seismic moment on the long-term average than was released by the $M_w \sim 6$ events that have occurred repeatedly since the 1857 Fort Tejon earthquake. This imbalance points to occasional larger events. This fault segment could probably host significantly larger events. We note that the zone of high coupling derived from modeling interseismic geodetic data seems larger than the area that ruptured in 2004 (Fig. 4a). If we assume an average stress drop similar to the 0.61 MPa observed during the 2004 earthquake (Wang et al., 2014), which was at the lower end of commonly observed values, and a complete rupture of the locked area of Figure 4b (equal to 632 km$^2$ for $\gamma > 0.7$), we could expect an $M_w \sim 6.3$ event. Assuming an average stress drop of 1.5 MPa, larger than in 2004, this fault segment could produce an $M_w 6.6$ earthquake. In fact, the locked area of Figure 4a appears to be made of two locked patches separated by a zone of lower interseismic coupling. The partially creeping zone could act as a barrier to the propagation of seismic rupture. This pattern, analog to that investigated by Kaneko et al. (2010), is favorable to generate a bimodal seismic behavior with moderate earthquakes rupturing one or the other asperity and larger infrequent earthquakes rupturing the whole patch. Another possibility is that the Parkfield segment would occasionally rupture together with large events on the Carrizo plain segment of the SAF. In that case, the interaction between the two fault segments could lead to a larger moment release on the Parkfield segment than in the case of rupture confined to it (a longer rupture length requires larger slip if the stress drop is similar).

There are actually hints that the $M_w 7.7$ 1857 Fort Tejon earthquake may have ruptured the Parkfield segment. Paleoseismic studies (Sieh, 1978; Lienkaemper, 2001) indicate 2–6 m of slip at sites near highway 46 due to this earthquake. The northernmost observation attributed to the 1857 earthquake is a 4.5 m offset, 1.7 km north of highway 46 (Lienkaemper, 2001), whereas a 3.5 m offset has also been measured 1.3 km south of it (Sieh, 1978). Such large surface-slip measurements show that the Parkfield segment can occasionally slip much more than during the 2004 earthquake (i.e., typically ~20 cm).

Assuming a 3.8 m slip (as averaged over the measurements along the Cholame section; Sieh, 1978; Zielek et al., 2012) with a 10-km along-dip width rupture that reaches 22 km northwest of the highway 46, the moment released within the limits of the model of Wang et al. (2014) is of 4.35 × 10$^{19}$ N·m, equivalent to an $M_w 7.03$ earthquake. The moment includes the aftershocks and postseismic effects because no distinction between them and the mainshock can be estimated from paleoseismic data. Assuming aftershocks contribute between 8% and 156% (depending on whether we assume Bähr’s law or not) and that the postseismic impact is about 200% of the coseismic released, then the seismic rupture alone would be equivalent to a magnitude between 6.47 and 6.72.

In the literature, the recurrence time of 1857-like earthquakes, if there are any characteristic earthquakes (Zielek et al., 2012), is suggested to be roughly between 140 and 255 yrs (Sieh, 1978; Zielek et al., 2010). In this case, the return of coseismic ruptures similar to that of 1857 would contribute between 2.88 × 10$^{19}$ and 1.58 × 10$^{19}$ N·m/yr to the moment release rate. This would reduce the moment deficit rate, that is, between 42% and 23% for MW (between 61% and 33% of the moment deficit residual rate), and 21% and 11% for MJ (between 24% and 13% of the moment deficit residual rate).

Finally, it has been proposed that enhanced fault weakening could occasionally allow large ruptures to propagate in creeping areas (Noda and Lapusta, 2013). In such case, the Parkfield segment could also occasionally release much more seismic moment than during an $M_w \sim 6$ event confined to the locked area of the Parkfield segment.

Conclusion

In principle, the rate of accumulation of moment deficit on a fault, determined from modeling of interseismic strain measurements, can be used to constrain the frequency and magnitude of the largest possible earthquake by requiring
the moment budget to balance over the seismic cycle. Testing this approach on the Parkfield segment shows that an $M_w \sim 6$ earthquake returning about every 24 yrs, as has been observed over the last 150 yrs, falls short of balancing the rate of moment deficit accumulation. The conclusion seems robust in view of the uncertainties on the data and model assumptions.

The most likely explanation is that this fault segment hosts larger earthquakes, in the $M_w$ 6.5–7.5 range, with a return period of 140–300 yrs. Such episodes of seismic moment release could happen as independent earthquakes rupturing the locked asperities revealed by interseismic coupling models or in conjunction with rupture of the Carrizo plain segment of the SAF, as potentially happened in 1857. The methodology presented in this study allows the incorporation of formal geodetic constraints on the rate of moment deficit accumulation into probabilistic seismic hazard assessments.

Data and Resources

The Advanced National Seismic System (ANSS) catalog was searched using http://www.quake.geo.berkeley.edu/anss/catalog-search.html (last accessed February 2015).

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References


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