FAULT DIMENSIONS AND MAXIMUM MAGNITUDE

D. Weiser\textsuperscript{1}, N. Porto\textsuperscript{2}, and D.D. Jackson\textsuperscript{3}

ABSTRACT

Many researchers apply rupture dimension statistics to mapped fault dimensions to estimate maximum possible earthquake size. Here we examine the assumptions involved in this process, using seismic and geological data for a selection of southern California and northern Baja earthquakes. The hypothesis that mapped fault dimensions limit future earthquake size depends on two assumptions: that actual fault surfaces lie within the mapped areas, and that future ruptures will not cross the actual boundaries of the fault. For long shallow faults, the two assumptions imply that rupture will stop at both ends of their mapped traces. We show that earthquake ruptures rarely stop at the boundaries of previously mapped faults. Instead, they frequently extend beyond the mapped fault boundaries, and some extend into previously unmapped faults and/or may rupture un-faulted rock.

Another frequent assumption is that presently available information, such as fault maps and 3-D geologic mapping, include the full scope of all important faults capable of producing large-magnitude earthquakes. However, it is also known that we may not be able to accurately locate a blind thrust fault. How do we resolve these two opposing views? Often, it is still assumed that a majority of the major large faults are known, and then we make further assumptions on how faults may or may not rupture together. These assumptions on the fault locations are then used to calculate maximum earthquake magnitudes, using only the known fault dimensions. We demonstrate that these assumptions often lead to an underestimation of the magnitude. We also show that even in the best fault maps, there are still many unknowns regarding the fault location and potential fault systems. If we use fault maps to limit earthquake size, we must be constantly aware of these unknowns, and build them into our estimates of

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Many researchers apply rupture dimension statistics to mapped fault dimensions to estimate maximum possible earthquake size. Here we examine the assumptions involved in this process, using seismic and geological data for a selection of southern California and northern Baja earthquakes. The hypothesis that mapped fault dimensions limit future earthquake size depends on two assumptions: that actual fault surfaces lie within the mapped areas, and that future ruptures will not cross the actual boundaries of the fault. For long shallow faults, the two assumptions imply that rupture will stop at both ends of their mapped traces. We show that earthquake ruptures rarely stop at the boundaries of previously mapped faults. Instead, they frequently extend beyond the mapped fault boundaries, and some extend into previously unmapped faults and/or may rupture un-faulted rock.

Another frequent assumption is that presently available information, such as fault maps and 3-D geologic mapping, include the full scope of all important faults capable of producing large-magnitude earthquakes. However, it is also known that we may not be able to accurately locate a blind thrust fault. How do we resolve these two opposing views? Often, it is still assumed that a majority of the major large faults are known, and then we make further assumptions on how faults may or may not rupture together. These assumptions on the fault locations are then used to calculate maximum earthquake magnitudes, using only the known fault dimensions. We demonstrate that these assumptions often lead to an underestimation of the magnitude. We also show that even in the best fault maps, there are still many unknowns regarding the fault location and potential fault systems. If we use fault maps to limit earthquake size, we must be constantly aware of these unknowns, and build them into our estimates of maximum magnitude. Finally, if we do not incorporate scenarios where a fault can interact with neighboring faults, we may severely underestimate the maximum magnitude.

Introduction

It is generally assumed that fault traces constrain the location, orientation, and size of future earthquakes. Yet many earthquakes, like the M7.3 1992 Landers, CA, M7.9 1999 Denali, AK, and M7.8 2016 Kaikoura earthquake, rupture beyond previously mapped traces or are transferred onto a splay fault. Other events, like the M6.7 1994 Northridge, CA, the M7.0 2010 Darfield, New Zealand, and M6.3 2011 Christchurch, New Zealand earthquakes, show that large

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earthquakes can and do occur where no fault had been identified. This is important because regressions between magnitude and rupture dimensions are based on post-earthquake maps of the surface rupture and instrumental data. These regressions are then employed to estimate magnitude of future earthquakes, using existing fault maps. Since future magnitude estimates are based on the possible extent of a rupture, and are typically guided by the geometry of the fault trace or historical ruptures rather than the rupture trace, it is valuable to examine the relationship between mapped faults and earthquakes. Our study examines the relationship between earthquakes and pre-existing faults, including earthquakes for which surface rupture maps have recently been published.

**Present state of knowledge**

Currently accepted methods for estimating future earthquake magnitude on a fault involve relationships between rupture length and magnitude derived from previous earthquakes. Estimating limits on future magnitudes requires assuming that rupture extent is limited by presently mapped fault traces. The accuracy of surface fault traces is limited by numerous factors including amount of displacement, extent of sediment cover, complexity of surface geology, quality of mapping and urban development. A recent example of this inaccuracy is the 2010 Christchurch earthquake: the rupture was about 20 kilometers away from the nearest mapped fault (according to the New Zealand Active Faults Database [1]).

Magnitude and surface rupture length are certainly correlated (e.g., [2], [3]). However, rupture extent and prior fault extent are not equivalent, and rupture may extend beyond previously known fault limits [4]. Both of the references above deal only with earthquake rupture, without including any data of fault dimensions.

Comparing actual rupture to previously known fault boundaries (including anticipated subsurface links), there are several possible scenarios:

A. Rupture entirely fills the surface within the boundary and stops there, producing the maximum magnitude event implied by Wells and Coppersmith [2].
B. Rupture fills part of the surface and stops at part of the boundary, showing that the boundary does resist.
C. Rupture occurs on the surface but does not reach the boundary, providing no test of the boundaries influence.
D. Rupture breaches the boundary, or jumps more than anticipated, or occurs where no fault is known.

Fig. 1 shows the fault geometry mapped before and after the 2014 Napa Valley Earthquake, a category D event in the above classification. Clearly the rupture extended beyond the previously mapped fault, confounding any attempt to estimate a magnitude limit from the available data. Over the past two decades, we’ve seen numerous examples of multi-fault ruptures, such as in the Landers and Kaikoura earthquakes, and rupture extending beyond previously mapped fault traces, or occurring on previously unmapped faults, as with the Hector Mine and Napa Valley earthquake.
During this time estimated maximum magnitudes have also increased substantially. Many faults have been examined in more detail, and their estimated seismic capabilities have increased. Has the new fault data solved the problem of poor resolution of fault surface traces?

Are Landers-type surprises a thing of the past? Recent earthquakes such as Kaikoura suggest that answer is No. Have the definitions of gap and step between faults changed, requiring a new definition of multi-fault rupture? Many researchers have looked into this question. However, the data often uses post-earthquake surface rupture, and not the pre-earthquake maps, to create jump and bend statistics on rupture termination ([5],[6]). Do ruptures that appear to jump from one fault to another simply use surface faults not yet mapped? Do they follow subsurface faults that are not exposed or are covered over at the surface? Or do they break new ground and lengthen pre-existing faults during rupture? The above questions are moot regarding hazard estimation, which has to assess future from present data. These questions are not moot regarding earthquake physics, and the fundamental question of what stops rupture. For those questions, actual fault geometry is much more important than our presently mapped geometry.
Figure 1. Modified pre- and post-earthquake USGS Quaternary Fault and Fold Database (QFFDB) following the Napa Valley earthquake (NVE). The upper image shows the 2015 QFFDB in blue [7], the red traces are surface rupture from the NVE [8], and the yellow star shows the NVE epicenter [8]. Most of the NVE occurred on previously unmapped faults, only 4km of the rupture occurred on/adjacent to a mapped fault section (outline by white dashed box). The lower image is the current 2018 QFFD faults shown in yellow [9]. The main update in this region post-2015 was the addition of the surface rupture traces from the NVE. However,
the southern extent of the West Napa Fault, that would project towards the epicenter of the NVE, is still not include in the 2018 maps. We show this southern fault extent as a red dashed line. The fault line could also extend even farther south beyond the epicenter (marked by “?” in figure B). If another earthquake occurred on this same fault today, we may likely underestimate the hazard and magnitude.

Results

Earthquakes certainly change surface fault traces. Whether it be by adding new area to a mapped fault, exposing a buried fault trace, or simply showing us a fault system is more complex and interconnected than previously interpreted. Table 1 shows differences between the 2010 [10] and 1975 [11] Fault Activity Maps (FAM). Several faults were involved in the Landers earthquake. Prior to the earthquake, the longest strand was the Camp Rock-Emerson fault at 35 km long. After the earthquake, the ruptured faults combined to a length of 85-95 km. In the 1975 FAM, the Calico-Hidalgo fault was determined to have a surface trace of 50 km. In the 2010 FAM, the fault was mapped with a surface trace of 120 km. These differences correspond to predicted maximum moment magnitudes from Wells and Coppersmith [2] of 7.0 and 7.5, respectively.

Table 1. Varying lengths and maximum predicted magnitudes for the Landers and Calico-Hidalgo faults.

<table>
<thead>
<tr>
<th>Fault</th>
<th>Source</th>
<th>Fault Length</th>
<th>Maximum Predicted Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landers</td>
<td>1975 Jennings Map [10]</td>
<td>35 km⁴</td>
<td>6.9⁵</td>
</tr>
<tr>
<td>Landers</td>
<td>1994 Jennings Map [12]</td>
<td>85 km</td>
<td>7.3⁵</td>
</tr>
<tr>
<td>Landers</td>
<td>UCERF2: Ellsworth B [13]</td>
<td>94.5 km</td>
<td>7.40</td>
</tr>
<tr>
<td>Landers</td>
<td>UCERF2: Hans and Bakun 2002 [13]</td>
<td>94.5 km</td>
<td>7.30</td>
</tr>
<tr>
<td>Calico-Hidalgo</td>
<td>1975 Jennings Map [10]</td>
<td>50 km</td>
<td>7.0⁵</td>
</tr>
<tr>
<td>Calico-Hidalgo</td>
<td>1994 Jennings Map [12]</td>
<td>120 km</td>
<td>7.5⁵</td>
</tr>
</tbody>
</table>

We compared pre- and post-earthquake fault lengths for other shallow earthquakes over magnitude 6 on faults previously mapped or revealed by definitive evidence of their extent. For

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⁴ Measurement of 35 km is based on the Camp Rock-Emerson Fault. The Landers rupture occurred in 1992, and therefore had not occurred when the 1975 map was produced. We measured the longest faults that were ruptured or partially ruptured during the Landers earthquake, which were also mapped in the 1975 Fault Activity Map.

⁵ Maximum predicted magnitude determined by using Wells and Coppersmith’s [1994] surface rupture length (SRL) vs. moment magnitude regression, \( M = 5.08 + 1.16\times\log(SRL) \).

⁶ Measured using Google Earth. Exact numbers were 86.5 km for the Landers rupture, and 120.1 km for the Calico-Hidalgo fault.
surface rupturing earthquakes we used the most recent California Fault Activity Map [10]. Otherwise we used methods described by Black [4]. Results are displayed in Table 2. A fault is sufficiently revealed if it can be distinguished in the surface geology and could be mapped at the 1:62,500 scale from air photos or satellite images prior to the earthquake.

Blind thrust faults are tricky. Barnhart and Slosson [14] interpreted the Northridge Hills fault length as 19 km using available oil company data. After the earthquake, Jones et al. [15] estimated the fault rupture length to be 15 km.

Table 2. Previously mapped and ruptured fault lengths for select California earthquakes (modified from Black [4]). The percentage of the rupture that was previously unrecognized indicates that existing fault maps may not accurately estimate future rupture limits.

<table>
<thead>
<tr>
<th>Year</th>
<th>Earthquake</th>
<th>Previously Mapped Fault Length (km)</th>
<th>Fault Rupture Length (km)</th>
<th>Percentage of rupture length that was previously unrecognized (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1979</td>
<td>Imperial Valley</td>
<td>42</td>
<td>31.5</td>
<td>0</td>
</tr>
<tr>
<td>1984</td>
<td>Morgan Hill</td>
<td>124</td>
<td>30</td>
<td>0</td>
</tr>
<tr>
<td>1987</td>
<td>Elmore Ranch</td>
<td>3</td>
<td>9</td>
<td>67</td>
</tr>
<tr>
<td>1987</td>
<td>Superstition Hills</td>
<td>44</td>
<td>29</td>
<td>0</td>
</tr>
<tr>
<td>1989</td>
<td>Loma Prieta</td>
<td>0</td>
<td>60</td>
<td>100</td>
</tr>
<tr>
<td>1992</td>
<td>Landers</td>
<td>48</td>
<td>90</td>
<td>47</td>
</tr>
<tr>
<td>1992</td>
<td>Joshua Tree</td>
<td>10</td>
<td>12</td>
<td>17</td>
</tr>
<tr>
<td>1992</td>
<td>Big Bear</td>
<td>0</td>
<td>15</td>
<td>100</td>
</tr>
<tr>
<td>1993</td>
<td>Eureka Valley</td>
<td>16</td>
<td>26</td>
<td>38</td>
</tr>
<tr>
<td>1994</td>
<td>Northridge</td>
<td>19</td>
<td>15</td>
<td>0</td>
</tr>
<tr>
<td>1999</td>
<td>Hector Mine</td>
<td>78</td>
<td>48</td>
<td>0</td>
</tr>
<tr>
<td>2003</td>
<td>San Simeon</td>
<td>0</td>
<td>25</td>
<td>100</td>
</tr>
<tr>
<td>2004</td>
<td>Parkfield</td>
<td>1310</td>
<td>35</td>
<td>0</td>
</tr>
</tbody>
</table>

Discussion and Conclusions

There is a subtle but important problem with the hypothesis that boundaries stop rupture. If so, the scaling relationship between magnitude and rupture dimension for stopped earthquakes should differ from that of ordinary earthquakes. Only those quakes stopped by fault boundaries should be used in the regressions. Instead, the regressions are based on earthquakes with no reported links to actual fault dimensions. Most or all of the earthquakes in the regressions may be irrelevant to the effect of fault boundaries on rupture.

The use of existing fault data to estimate limits on earthquake magnitudes assumes that the boundaries of faults are known, and that they provide a barrier to rupture. Both of those assumptions are questionable. New faults are discovered frequently, often by the occurrence of earthquakes in unpredicted locations or much larger than anticipated. We are presently unaware of any earthquakes fitting the description of Category A above, those whose rupture is totally
constrained by a previously documented fault boundary. Examples of category B are relatively rare, and the resisting influence of fault boundaries could be attributed to random occurrence within the uncertainty of the boundary location.

Bluntly put, there is much contradictory evidence to the hypothesis that mapped fault dimensions imply limits on earthquake magnitude. The well observed correlations between magnitude and rupture dimension do not resolve the fundamental difference between rupture dimension and fault dimension.

References

1. New Zealand Active Faults Database, GNS Science, map at 1:100,000 scale, http://data.gns.cri.nz/af/.
10. Jennings, CW, Bryant WA. Fault activity map of California: California Geological Survey 2010; Geologic Data Map No. 6, map scale 1:750,000.
12. Jennings, CW. Fault activity map of California and adjacent areas with locations and ages of recent volcanic eruptions: California Department of Conservation, Division of Mines and Geology Data 1994. Map Series No. 6, 92 p., 2 plates, map scale 1:750,000.