QuakeCaster, an Earthquake Physics Demonstration and Exploration Tool

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Introduction

A fundamental riddle of earthquake occurrence is that tectonic motions at plate interiors are steady, changing only subtly over millions of years, but at plate boundary faults, the plates are stuck for hundreds of years and then suddenly jerk forward in earthquakes. Why does this happen? The answer, as formulated by Harry F. Reid in 1910 (Reid, 1910) is that the earth's crust is elastic, behaving like a very stiff slab of rubber sliding over a substrate of "honey"-like asthenosphere, and that faults are restrained by friction. The crust near the faults, zones of weakness that separate the plates, slowly deforms, building up stress until frictional resistance on the fault is overcome and the fault suddenly slips. For the past century, scientists have sought ways to use this knowledge to forecast earthquakes.

QuakeCaster enables people to test and explore the four leading hypotheses for earthquake occurrence, essentially trending from the most uniform and predictable behavior to the most irregular and unpredictable. Hypothesis 1 states that earthquakes are periodic, all the same amount of slip, and all separated by the same amount of time. In hypothesis 2, earthquakes are 'time-predictable:' the larger the slip in the last earthquake, the longer the wait until the next one. In hypothesis 3, earthquakes are 'slip-predictable,' meaning the longer the time since the last earthquake, the greater the next earthquake. In hypothesis 4, known as the 'Poisson' hypothesis, earthquakes occur randomly in time and have randomly varying sizes.

QuakeCaster, an interactive, hands-on teaching model that simulates earthquakes and their interactions, will help students explore and test these hypotheses and understand their extension to more complex earthquake interactions and Coulomb stress triggering.

QuakeCaster Design and Purpose

This model contains the minimum number of elements needed to reproduce most observable features of earthquake occurrence: a reel that steadily pulls in a line simulates the steady plate tectonic motions far from the plate boundaries, a granite slider in frictional contact with a porcelain surface simulates a plate boundary fault, and a rubber band connecting the line and the slider simulates the elastic character of the earth's crust (Figure 1). By stacking and unstacking sliders and steadily cranking the reel, one can see the effect of changing the shear and clamping (also called 'normal') stress on the fault. By placing sliders in series with rubber bands between them, one can simulate the interaction of several earthquakes along a fault, such as cascading (one leading to another) or toggling (one earthquake turning on when another turns off) shocks (Figure 2a). By inserting a load scale into the line, one can measure the Coulomb stress acting on the fault throughout the earthquake cycle (Figure 2b). With a stopwatch and ruler one can measure and plot the results (Figure 3a).

QuakeCaster is designed so that students or audience members can operate it themselves, and can measure its output. We have used QuakeCaster with people of all ages and scientific backgrounds, from school children to seismologists. They are able to measure the time between events, slip distance (a stand-in for earthquake size), and stress before and after an event occurs. Despite its simplicity, QuakeCaster exhibits remarkable fidelity to observed earthquake behavior. Students will get a memorable hands-on look at stress and rupture in the laboratory, and will understand why it is so difficult to predict earthquakes in the real world. For instructions on how to build QuakeCaster, and a more comprehensive guide to teaching with it, see Linton and Stein (2011). QuakeCaster costs $500-750 to build and will take about a week to construct.

Coulomb failure, stress triggering, and earthquake interaction

QuakeCaster can demonstrate the Coulomb failure criteria, which hold that when a fault is close to failure, either increasing the shear stress (by reeling in a bit more line) or unclamping the fault (by lifting a stacked slider), will promote failure. To demonstrate increasing shear stress, stack two sliders and reel in the line until the slider is on the verge of slipping (Figure 2b). Now crank a bit more and it will trigger an earthquake. To demonstrate unclamping the fault, reel in the line again until the slider is on the verge of slipping, then lift the top slider. Again it will trigger a quake. If the static friction coefficient of the fault is about 0.5, then increasing the shear stress will have twice the impact of unclamping the fault in triggering an earthquake. One way to measure the friction coefficient is to slowly tilt the tile until the slider begins to move, and then measure the angle between the table and the tile. The tangent of the angle is the friction coefficient. The Coulomb hypothesis and the concept of earthquake stress triggering is explained in plain English in Stein (2003).

It is also possible for QuakeCaster to demonstrate how earthquakes converse with each other by the transfer of stress. Stress is defined as force divided by the surface area. With this model, since the slider area is constant, we use force as a proxy for stress. One QuakeCaster experiment involves adding a second slider behind the first so that they are pulled in series. The sliders are joined by an elastic rubber band. When stress overcomes the frictional resistance on the fault, the first slider jumps forward, which increases the shear stress on the second slider. Eventually, perhaps after several earthquakes of the first slider, the second slider slips, and this reduces the restraining force on the first slider, and the first slider may slip again. We ask the audience to 'wager' on which slider will rupture first, second, third, and fourth. They are almost always surprised by the outcome, which can change from one trial to the next, and the sliders' interaction, sometimes exhibiting chaotic behavior, is much richer than one might expect. By making predictions of their own, students become invested in the outcome and more curious about earthquake behavior.

Key QuakeCaster experiments

For our first experiment, we performed three trials to make 'staircase' plots in which we measure the time between events and the slip distance. This required a minimum of three participants. We placed a piece of white electrical tape along the side of the porcelain tile. Then, one person reeled at a constant rate (to simulate constant plate motion). A second person used a marker pen to mark on the tape the slip distance after each earthquake. A third person held a lap-timer stopwatch and recorded the time (one needs to measure in tenths of seconds) of each event.

After plotting the results (Figure 3a), one can see how the slip- and time-predictable hypotheses compared to the data by eyeballing and then drawing in the best fitting lines to the staircase plots. For a more quantitative comparison of data to the models, we also calculated the RMS (root mean square) misfit value for each hypothesis (slip- and time- predictable). (To calculate RMS misfit, we first subtracted the predicted slip distance from the observed slip distance for each data point. We squared each result, added all the results together, divided this total amount by the number of data points, and took the square root). At first glance, the earthquakes in this trial (Figure 3a) appear to fit the periodic hypothesis, but the RMS misfit values suggest differently. The misfit for the slip-predictable hypothesis is 1.7 cm, but for the time-predictable hypotheses it is 1.4 cm. Not all trials supported the time- or slip-predictable hypotheses, and none of the trials perfectly matched any of the four hypotheses. These tests show how difficult it is to accurately predict earthquakes: even when we grossly oversimplify the likely complexity and variability in the earth, we still do not get regular, predictable earthquakes. This is perhaps the most important message of QuakeCaster.

One can quickly transcribe the observations to a PC and plot the QuakeCaster results, project them onto a whiteboard, and annotate them. Here's how to plot them using Google Documents: 1. Open Google Documents and create a new spreadsheet. 2. Label one column, "Time (sec)" and another column "Cumulative Slip (cm)." These will be the x- and y-axis labels. 3. Choose "insert chart" and select "scatter plot." 4. Project the image onto a whiteboard. 5. Using a whiteboard pen and a straightedge draw in a stair-step diagram to connect the dots. 6. Draw in eyeballed best-fit lines for slip- and time-predictability (or these could be done using the PC), and let people assess them. 7. For college or high school students, have them calculate the RMS misfit to the two hypotheses as we did in Figure 3.

Another valuable experiment is to test whether the failure stress is a more accurate predictor of earthquakes than their inter-event times and sizes. For our second experiment, we measured the force with the dial load scale just before an earthquake occurred (the failure stress) and the force just after an earthquake occurred (the minimum or background stress). In order to ensure the most accurate data possible and to enhance involvement and interest, for this experiment we used four people. One person reeled, a second held the stopwatch and recorded the time of each event, a third recorded the force just before an event, and a fourth recorded the force just after an event. We performed three trials, and the results of one trial are shown in Figure 4a, together with laboratory data for Westerly granite (D.A. Lockner, in prep) that give comparable results (Figure 4b).

For each trial in the experiment testing the failure stress and minimum stress, we calculated the RMS misfit in order to see if the data are better fit by a constant failure stress (equivalent to the time-predictable hypothesis) or a constant minimum or background stress (equivalent to slip-predictability). In this trial, the RMS misfit to the minimum stress is 80 grams, whereas to the failure stress it is 210 grams. In the three trials, there was no fixed failure stress. Surprisingly, the trials indicate that the minimum stress is a better predictor of earthquakes than the failure stress. As with the staircase plots, no trials perfectly fit either hypothesis. It is important to notice that the stress never goes to zero: just as in actual earthquakes, the stress drop is much smaller than the total stress.

After running QuakeCaster just once (about 4-6 earthquakes), granite fault gouge is visible as a light dusting on the porcelain tile. Let people feel the gouge with their fingers. Gouge occurs in faults as a result of friction between the fault faces when they slide past each other, which grinds rocks into a pulverized powder. Moore and Rymer (2007) found Saponite and talc, in fault gouge within the San Andreas Fault at the SAFOD (San Andreas Fault Observatory at Depth) drill site. These minerals decrease friction within faults and could therefore be responsible for fault creep at shallower (Saponite) and greater (talc) depths along the San Andreas. Also, Lockner *et al.* (2011) found that smectite clay also contributes to the San Andreas Fault's weakness at the SAFOD drilling site.

Using QuakeCaster, students can calculate the friction coefficient by dividing the force before an event by the weight of the slider. Our tests have shown a friction coefficient around 0.5. However, the coefficient can change during the experiment. For example, if fault gouge accumulates over multiple trials, the coefficient will tend to decrease. If each slider has a polished upper surface, then flipping the slider over will drop the friction to about 0.1-0.2. Try it: This produces more creep-like behavior in experiments, and illustrates the profound importance of friction in earthquake occurrence.

How QuakeCaster relates to actual earthquakes

The Parkfield section of the San Andreas Fault is perhaps the most periodic earthquake sequence known on earth, but it is neither time- nor slip-predictable (Figure 3b). At first glance, Parkfield appears to be roughly periodic, with magnitude 6 earthquakes every 20-30 years. However, the 1934 Parkfield earthquake occurred roughly a decade earlier than the average interval (Scholz, 2002). Murray and Segall (2002) also concluded that the Parkfield magnitude 6 earthquakes are not time-predictable. Based on the 1850-1966 inter-event times, the most recent earthquake after 1966 should have occurred sometime between 1973 and 1987, but it did not strike until 2004, about 1-2 decades late, and it was also somewhat larger than its recent predecessors. This record emphasizes that even the most predictable earthquakes deviate from slip- or time- dependent hypotheses.

Even though the M~6 Parkfield shocks are neither periodic nor time- or slip-predictable, there is a class of very small shocks (M=1-3), known as repeaters, that are nearly exact repeats of each other in terms of slip and location (Figure 3c). Although the hypotheses fit the data for the repeaters better than for QuakeCaster or the M~6 shocks, in fact, these too, are neither periodic, time-predictable, nor slip-predictable (Rubinstein *et al*. 2011). It's worth noting that the sizes of QuakeCaster earthquakes are closer in magnitude to the Parkfield repeaters than the repeaters are to the Parkfield magnitude 6 shocks.

Conclusions

We created QuakeCaster to enable student, scientific and public audiences to develop an intuitive understanding of the Earth's earthquake machine. We believe that QuakeCaster could serve as a valuable hands-on demonstration tool in college and university geology and seismology classes, and would also help faculty and earthquake professionals communicate earthquake science to the public. It is inexpensive to build, and can be checked as airline baggage, so it is both affordable and transportable. But at 4' long, it is large and noisy enough that an audience of 100 people can easily see and hear what is happening.

We have found QuakeCaster speaks to middle school students, graduate students, the public, insurance executives and research seismologists. It illuminates earth processes and encourages experimentation while making learning fun. People are vocal and eager to share their observations, traits that are crucial to scientific inquiry and discovery. By involving audience members in experiments, QuakeCaster makes it easy to see why it is so difficult to predict earthquakes.

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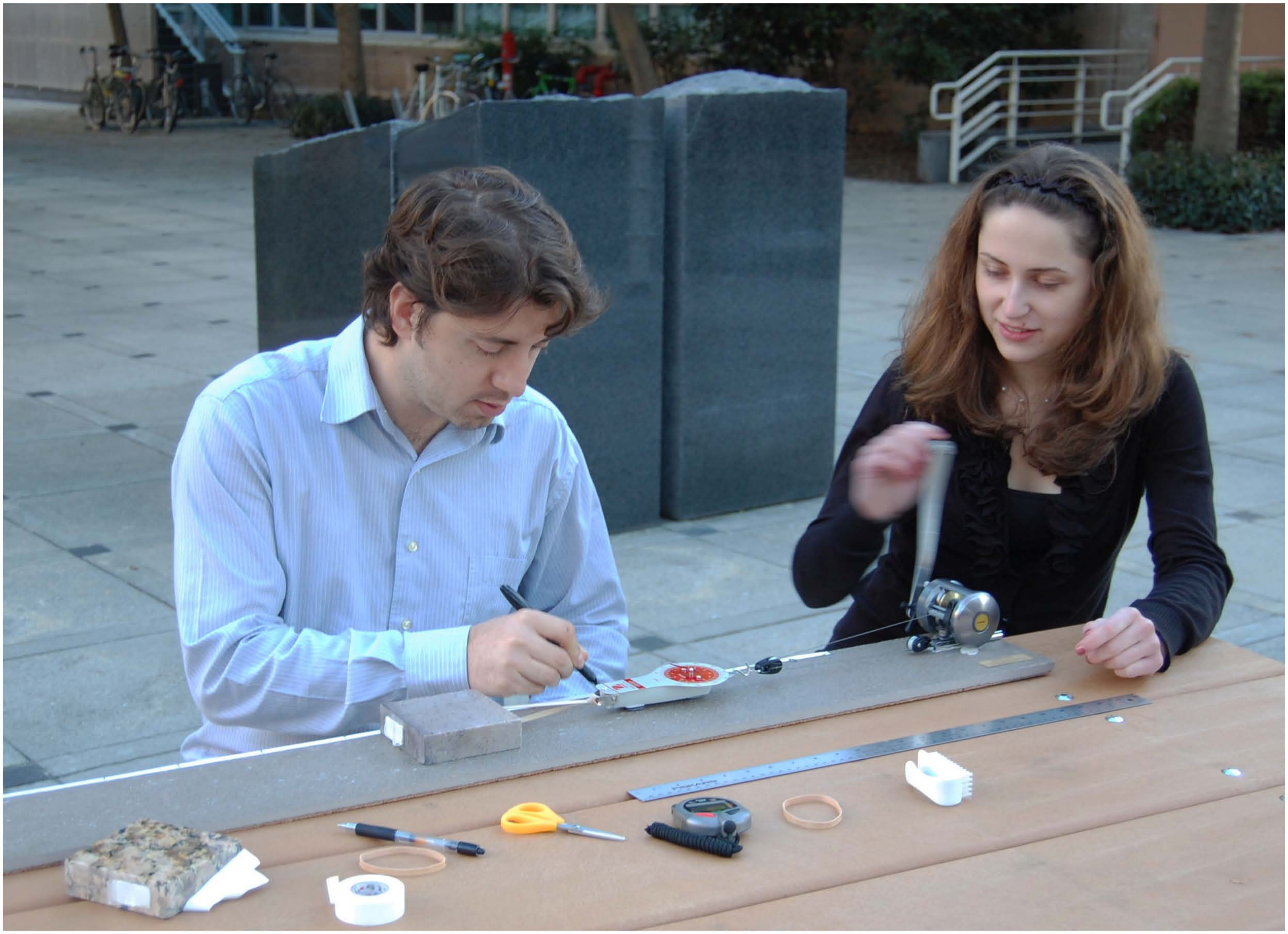
Figure Captions

Figure 1. Volkan Sevilgen marks the rupture length for each event while Kelsey Linton cranks the reel. A piece of white electrical tape has been placed along the edge of the porcelain tile. A force scale is used to measure the earthquake stress drop. The stopwatch on the table can be used to record the earthquake times.

Figure 2. (**a**) Three granite sliders in series, representing multiple earthquakes along a fault. Students make predictions about how sliders will interact through the transfer of stress. (**b**) Two stacked sliders with a stress gauge. Students make predictions about what stress earthquakes will occur at and what stress will drop to after an earthquake.

Figure 3. Time- and slip- predictability in QuakeCaster and at Parkfield. (**a**) For QuakeCaster, the hypothesis in bold indicates better agreement with the observations for this trial. We did not count the time to the first earthquake because the spring starts fully unloaded. The M~6 shocks **(b)** are neither time- nor slip-predictable, while the repeaters **(c)** appear to be more periodic. Repeaters are near-identical earthquakes. Because their seismic waveforms are so similar, they must occur at the same spot and have the seam size and slip. However, upon closer inspection, the repeaters are neither. The M~6 chart was modified from Bakun and McEvilly (1984).

Figure 4. Test trials of whether there is a constant minimum or failure stress. **(a)** QuakeCaster suggests that minimum stress might be a better earthquake predictor than failure stress is. The hypothesis in bold indicates better agreement with the observations in this trial. **(b)** A 3-inch diameter cylinder of Westerly granite with a 30° saw-cut and 600-grit abrasive lapping of fault surfaces, sheared under constant confining pressure of 50 MPa and a constant loading rate of 0.1 micron/s (D. Lockner, in prep). Here, neither a constant failure stress nor a minimum stress forecasts future laboratory earthquakes. For stress conversion, 1,000 KPa = 1 MPa = 10 bar.



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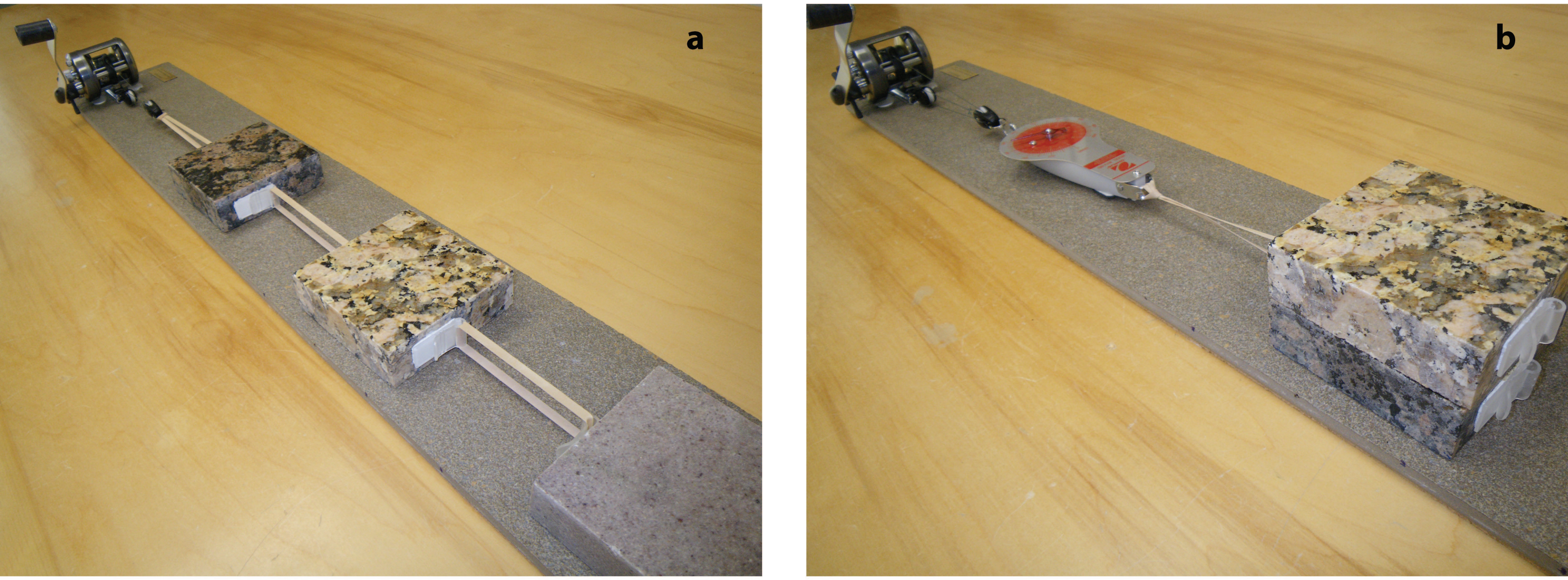

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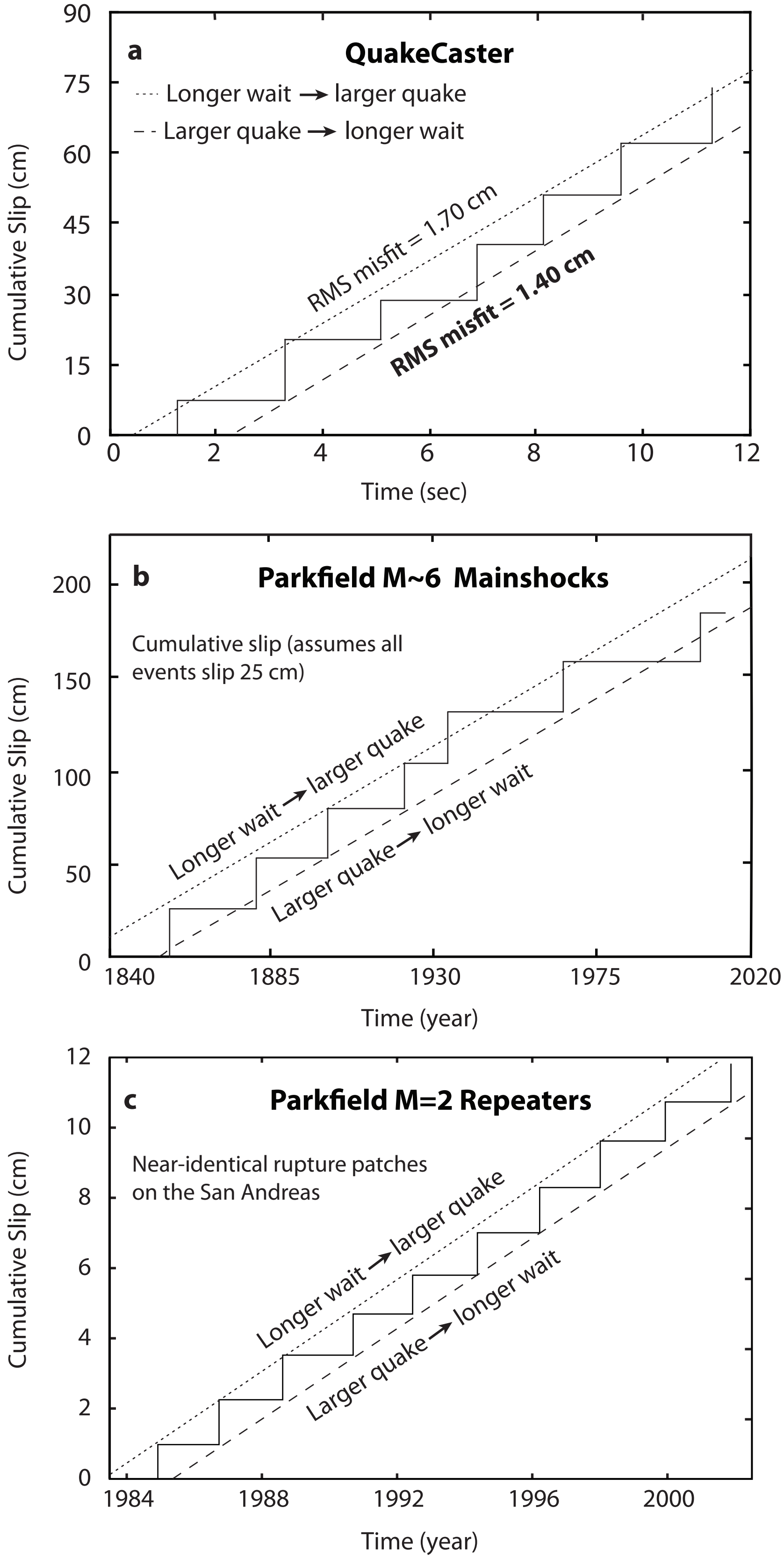

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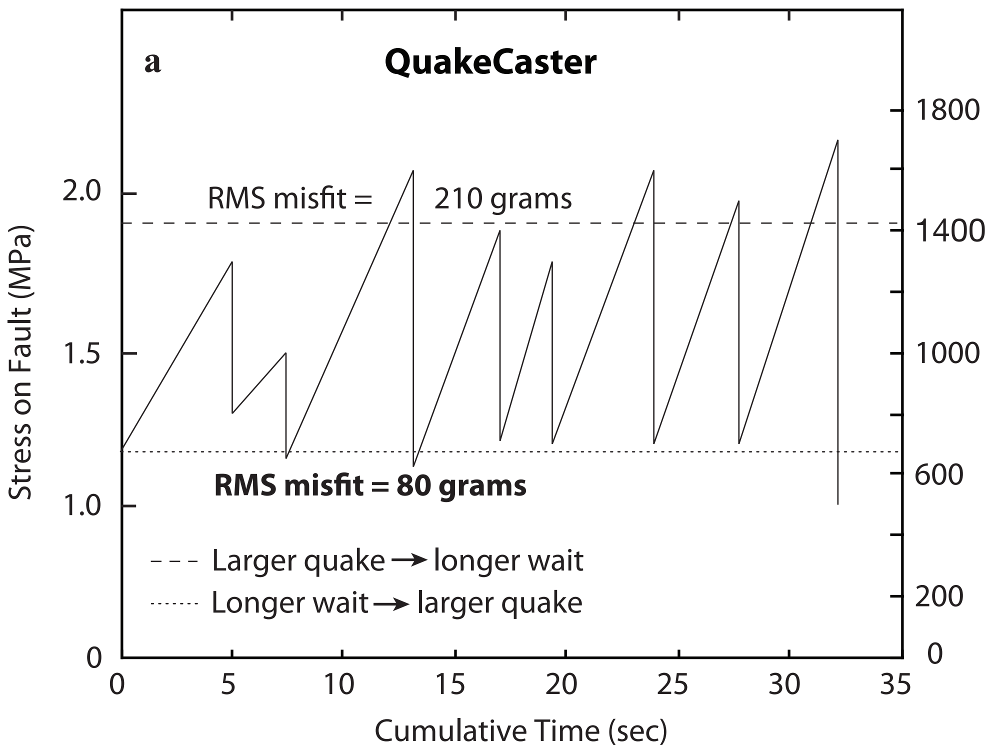

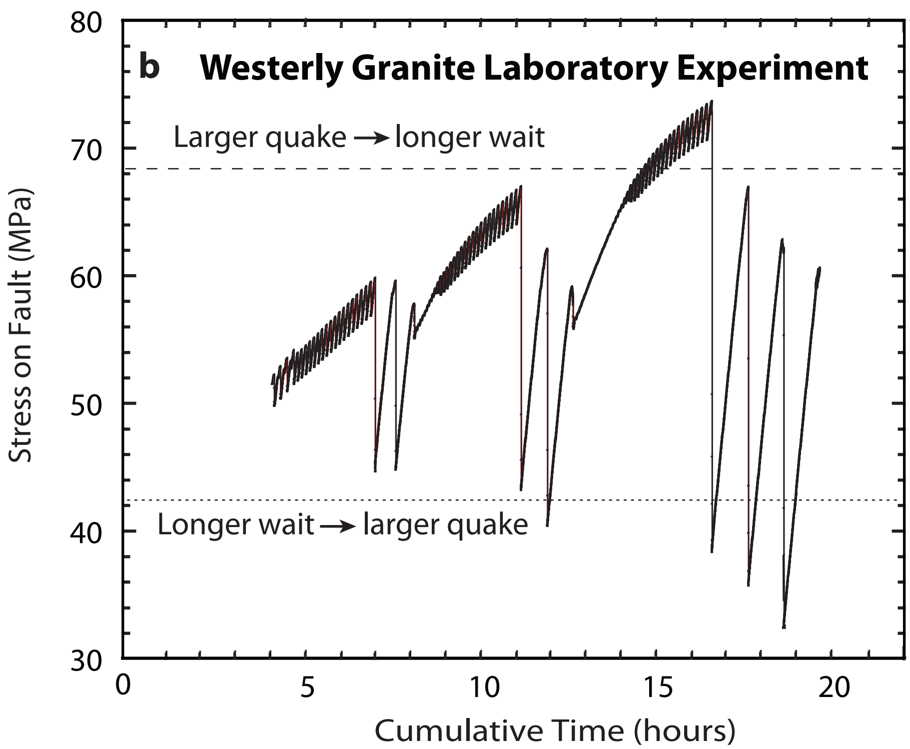

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