Partial rupture of a locked patch of the Sumatra megathrust during the 2007 earthquake sequence

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The great Sumatra-Andaman earthquake and tsunami of 2004 was a dramatic reminder of the importance of understanding the seismic and tsunami hazards of subduction zones

In March 2005, the Sunda megathrust ruptured again, producing an Mw 8.6 event south of the 2004 rupture area, the site of a similar event in 1861. Concern was focused on Mentawai area, where large earthquakes had occurred in 1797 (Mw 8.8) and 1833 (Mw 9.0).

A magnitude 8.4 and twelve hours later, a magnitude 7.9 earthquake indeed occurred on September 12, 2007. Here we show that these earthquakes ruptured only a fraction of the area ruptured in 1833, and consist of distinct asperities within a patch of the megathrust that had remained locked in the interseismic period.

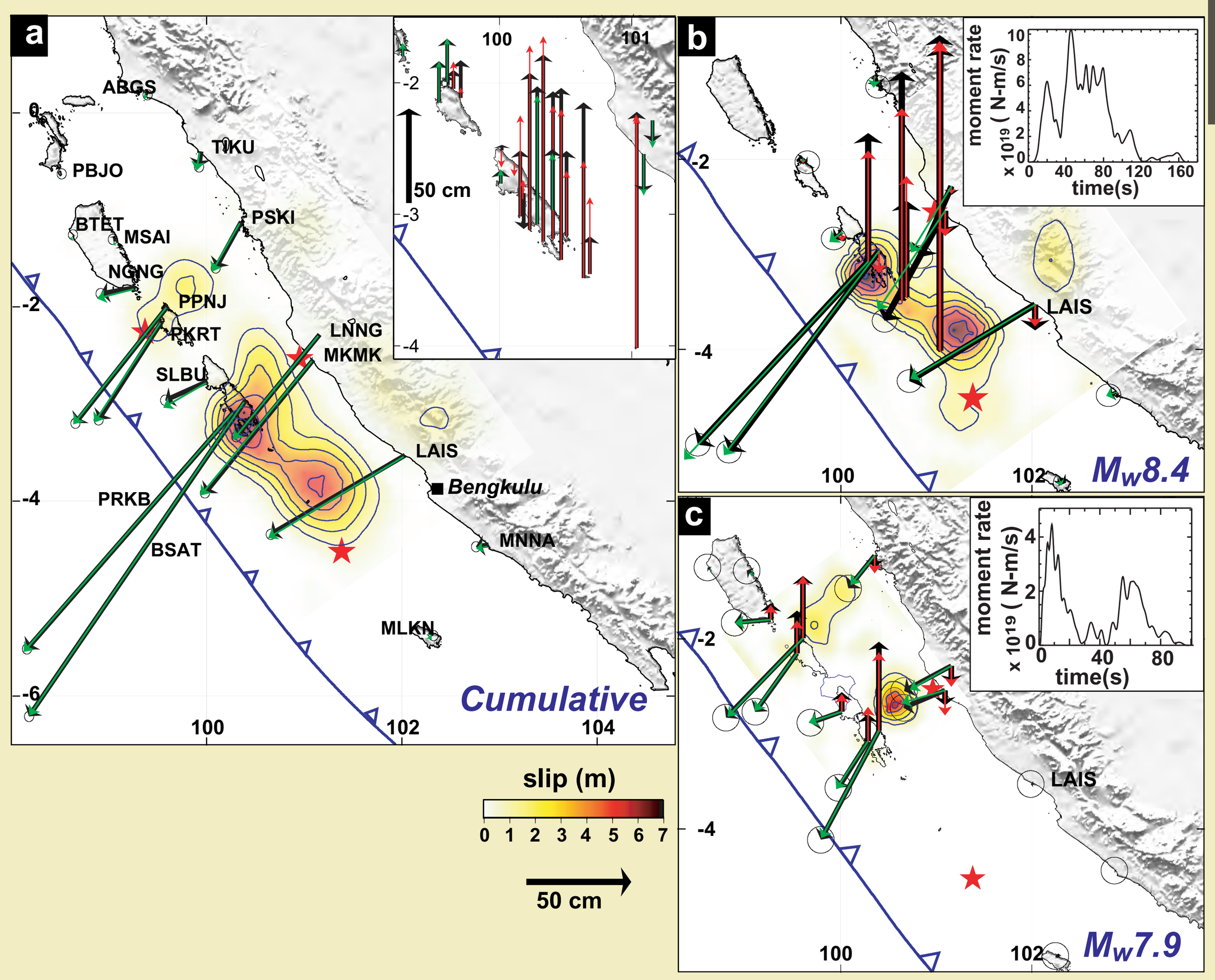

Figure 1 | Models of megathrust slip during the Mw 8.4 and Mw 7.9 earthquakes show principal slip on widely separated patches.

All slip models and GPS vectors are plotted with scales displayed on bottom left. Slip contour lines are plotted every 1 m starting at 1 m.

a. Cumulative slip distribution due to the Mw 8.4 and 7.9 earthquakes of September, 12, 2007. Contours show cumulative slip of best-fitting inversion of the GPS, coral and InSAR data. Vectors are observed (black) and modeled (green) horizontal displacement values at the SuGAr cGPS stations. Inset shows the vertical GPS displacements and measurements of coral uplift (black) and the fits from the model (green for GPS, red for coral).

b. Slip model of the Mw 8.4 earthquake obtained from the joint inversion of teleseismic waveforms, GPS data, InSAR data, and measurements of coral uplift unambiguously attributable to the Mw 8.4 event.

c. Model of the Mw 7.9 earthquake from the joint inversion of teleseismic waveforms and GPS measurements. Inset shows that the moment was released in two discrete episodes, about 20 s apart.

The slip models clearly show a patchy slip distribution where individual earthquakes have separated asperities while the the northern end of the M_W=8.4 earthquake abuts the southern initiation of the M_W7.9 earthquake. This patchiness is also observed from seismic data evident from the source time functions.

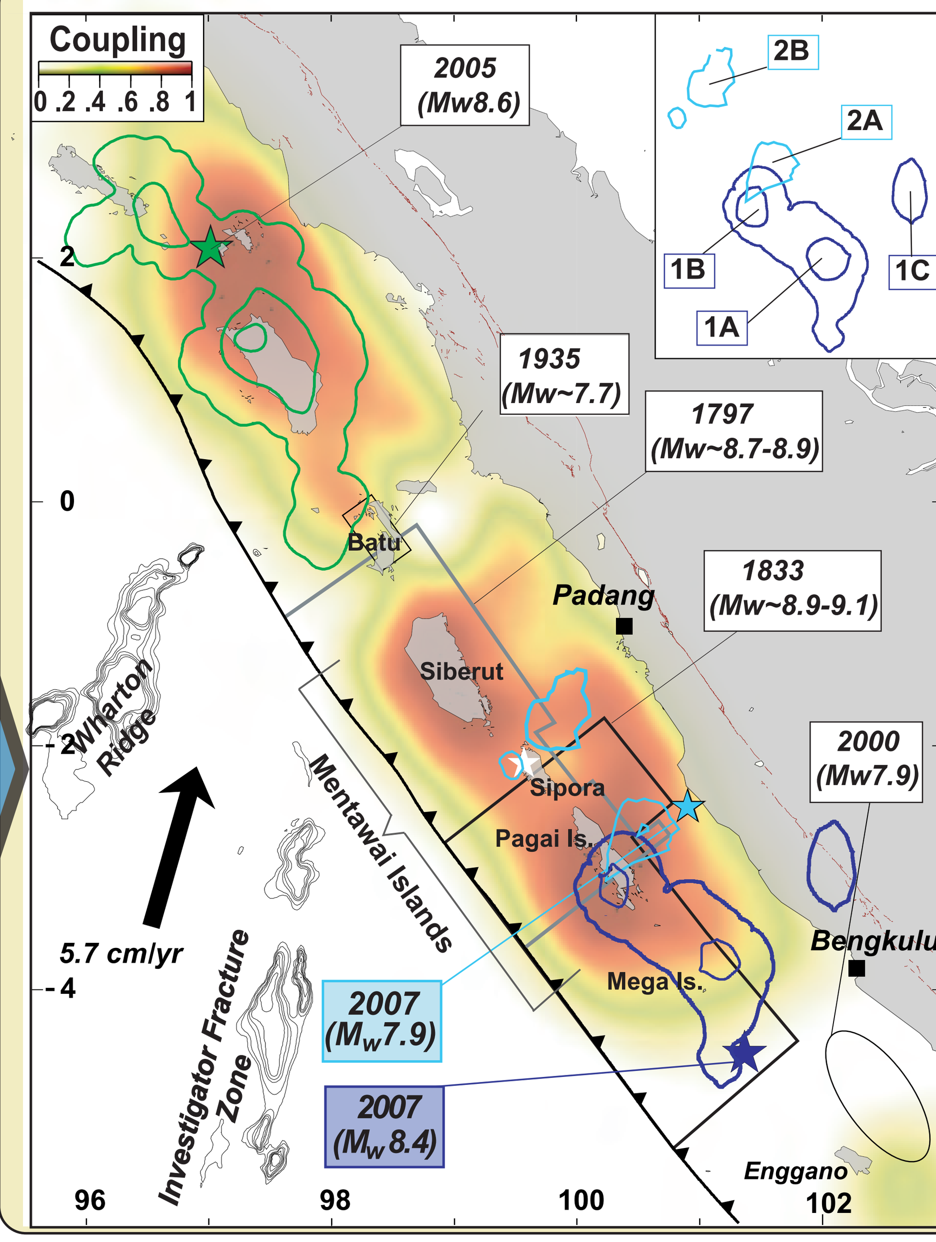

Figure 2 | Patches with strong interseismic coupling on the Sunda megathrust, offshore Sumatra, coincide with large seismic ruptures.

The pattern of coupling, defined as the ratio of interseismic slip rate to plate convergence rate, is derived from the modeling of geodetic and paleogeodetic data. The red colors indicate full coupling while white implies no coupling.

Gray and black polygons show estimated rupture areas of the 1797 and 1833 earthquakes. Dark and pale blue lines show the 1 m and 5 m slip contour lines of the Mw 8.4 and 7.9 seismic ruptures of 2007, stars show the epicenters.

The modeling of geodetic and paleogeodetic measurements of interseismic strain shows that the Sunda megathrust offshore Sumatra consists of a patchwork of creeping and locked areas.

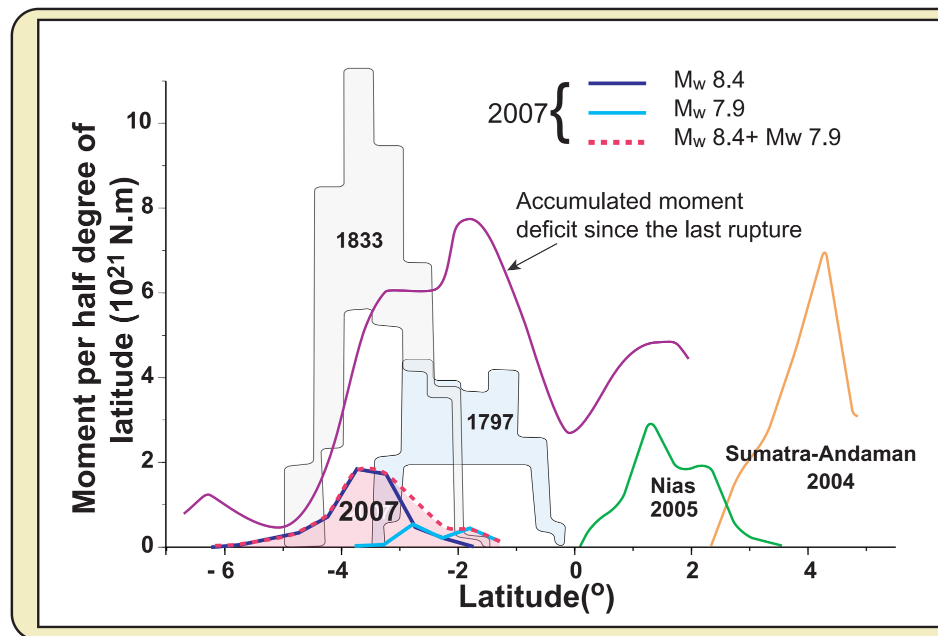

Figure 3 | The earthquakes of 2007 are far smaller than would be needed to relieve all moment deficit accumulated between 2007 and the previous great earthquakes in 1797 and 1833. The moment released in 2007 earthquakes are only 25% of the moment accumulated since the last rupture.

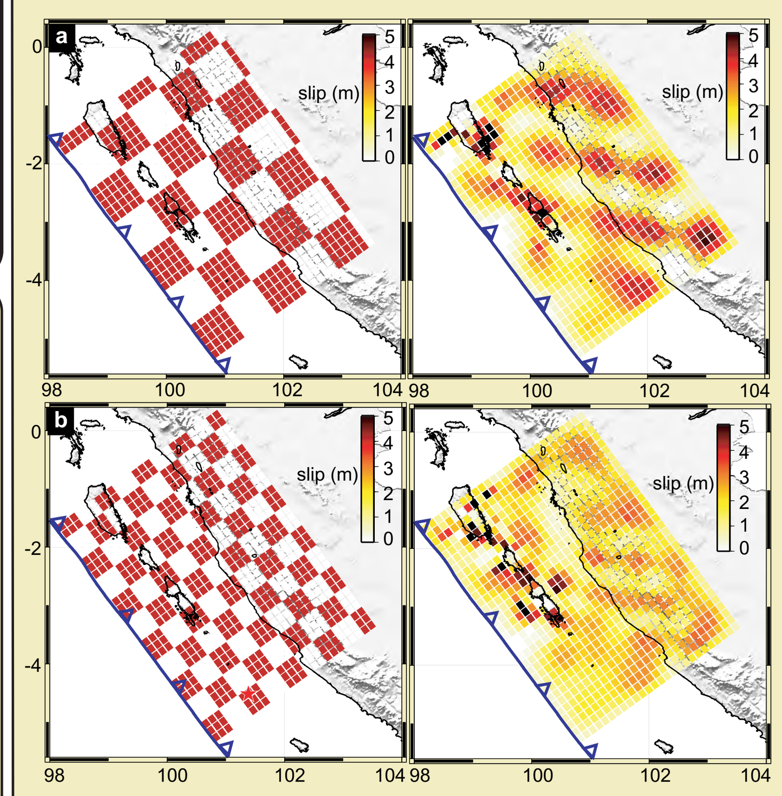

Figure 4 | Checkerboard resolution tests using InSAR, GPS and coral data.
a Input slip distribution corresponding to 80 km × 80 km slip patches (left) and model (right) derived from the inversion of the synthetic GPS and InSAR data. b Input slip distribution corresponding to 48 km × 48 km slip patches (left) and model (right) derived from the inversion of the synthetic GPS and InSAR data.

The results of the checkerboard tests show that the slip patches of 80 km by 80 km are well resolved over most of the study area (Figure 4a). The 48 km by 48 km slip patches (Figure 4b) are well resolved in the Pagai and Sipora islands area and beneath the mainland, where most of the slip actually

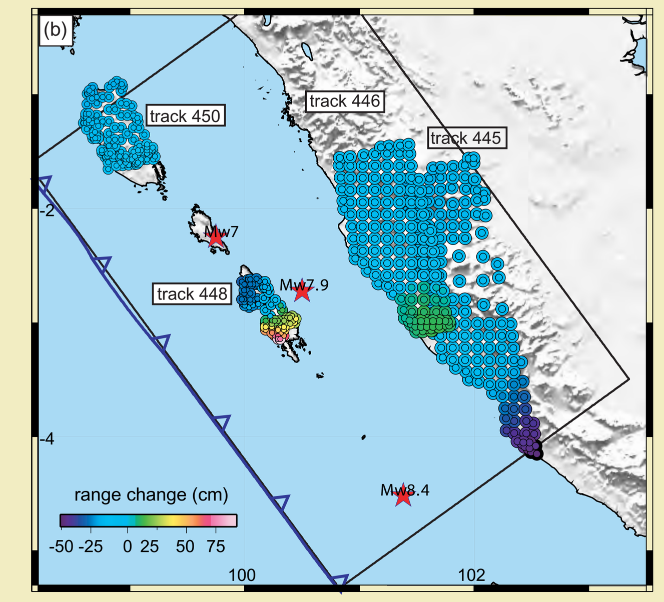

Figure 5 | Cumulative model fits to the InSAR data. InSAR data, and fits from the cumulative model of Fig 1a are shown. For each colored circle, the perimeter represents data point and the interior represents

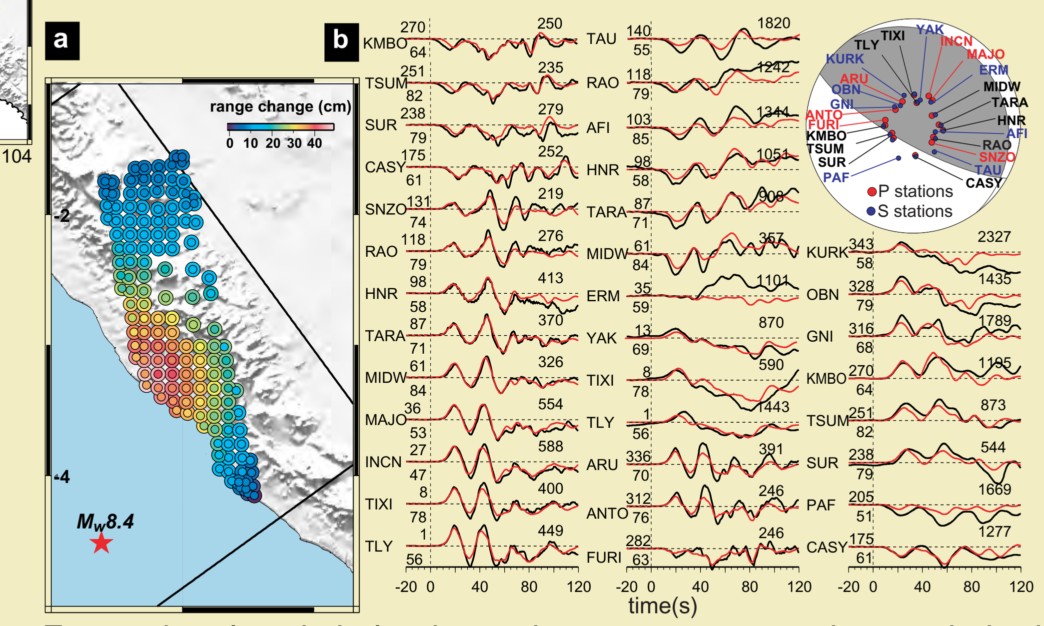

Figure 6 | Comparison of observed and predicted InSAR and teleseismic data, in the joint inversion for the Mw8.4 mainshock. **a** Observed and modeled LOS displacements to the InSAR data. Only the southernmost track (track 445), where the effect of the 7.9 earthquake can be assumed negligible, was used to constrain this event.
For each colored circle, the perimeter represents data and the interior represents the model. The more similar the perimeter and interior colors, the better the fit of the model to the data. **b** Observed (black) and synthetic (red) teleseismic P and SH waveforms. Station name, azimuth, and distance are indicated on the left of each trace. The maximum displacement is shown at the top right of each trace in microns.

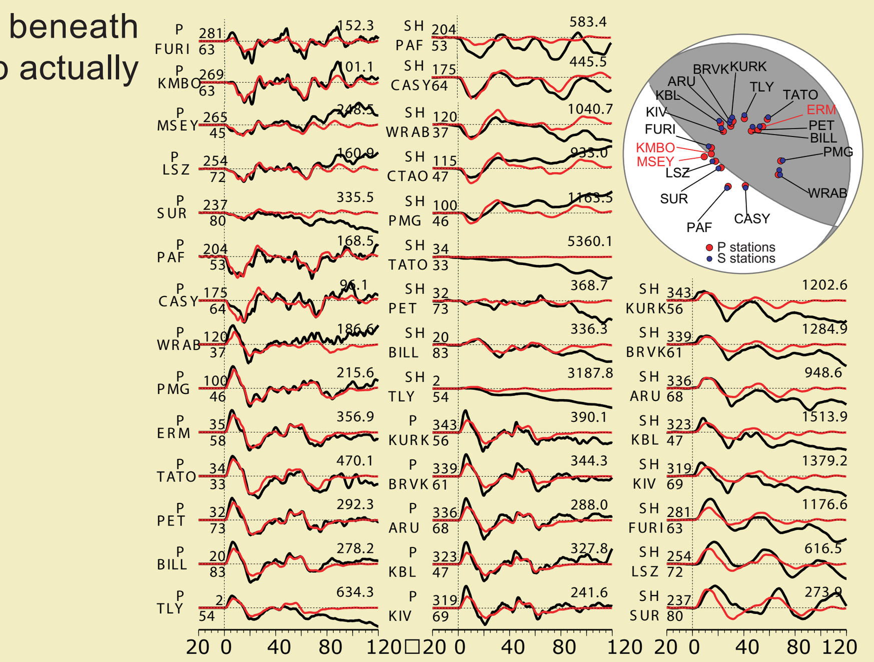

Figure S7 | Mw7.9 joint inversion model fits to the teleseismic data. Observed (black) and synthetic (red) teleseismic P and SH waveforms. Station name, azimuth, and distance are indicated on the left of each trace. The maximum displacement is shown at the top right of each trace in microns.

Implications

1. Similar rupture areas but different asperities in 1833 and 2007
Coseismic uplifts in 1833 (between 1 and 2.5 m from South Pagai to Sipora Island), are much larger than those observed in 2007. This is consistent with the cumulative 7.5 ×10^{21} N.m geodetic moment released by the 2007 earthquake sequence, representing a fraction of the 10–55 × 10^{21} N.m released in 1833 (Fig. 3). The coast of North Pagai Island was uplifted by 2.2 m in 183318. This area is clearly a low-slip patch in 2007, as indicated by the modest horizontal and vertical displacements recorded at SLBU (22cm and 7cm, respectively). Thus, it acted more like a 'barrier' during the coseismic slip in 2007.

2. Testing the time-predictable and the slip-predictable models
South of 2° S, the moment deficit accumulated since 1833 is still less than the moment released during the 1797 and 1833 events (Fig 3). North of 2° S, the accumulated deficit is far greater than the moment released during the 1797 and 1833 events. Thus, one might have expected the next great rupture to occur north of 2° S. Instead, the 2007 events occurred south of 2° S. Furthermore, the moment released during the 2007 sequence is far less than that released during the 1833 event and far less than what has accumulated since then. These relationships demonstrate clearly that the Mentawai patch is behaving in neither a slip- nor a time-predictable manner. If rupture were time-predictable, slip would already have occurred north of 2° S. If rupture were slip-predictable, slip would have been far greater in 2007 south of 2° S.

4 Significance of the surface deformation north of Bengkulu
InSAR and GPS data show that the Mw 8.4 rupture induced a localized surface deformation just north of Bengkulu. It is possible to model this signal as a deep slip patch on the megathrust that falls in a zone that creeps in the interseismic period (asperity 1C in Fig. 2).
This slip patch could reflect seismic rupture of a rate-weakening portion of the megathrust embedded in a dominantly creeping zone, or it may be an example of a triggered aseismic transient. Another possibility is that this deformation did not take place on the megathrust but at shallower depths. The available data do not resolve this ambiguity.

3 Why did the 2007 earthquakes not grow bigger?
The 2007 sequence probably consisted of several spatially and temporally separate asperities that did not cooperate effectively. The amount of uplift is much lower than the 1797 and 1833 earthquakes.

The intervening area beneath North Pagai Island experienced little coseismic slip in 2007, but is probably not a permanent barrier since the same area experienced the largest cumulative slip (of about 17 m), if the slip models from 1797 and 1833 earthquakes are summed. This area may therefore have acted as a barrier in 2007 because of a locally lower stress level before the earthquake, left over from previous earthquakes.

The state of stress was not adequate for a single large earthquake on the Mentawai Patch..

Conclusions

The rupture area of the 2007 Mentawai earthquakes was confined to a subset of a locked portion that is surrounded by creep during the interseismic period. Such permanent barriers, which are found to influence the down-dip as well as the lateral extent of megathrust ruptures, can be imaged from the modeling of interseismic strain.

The 2007 ruptures did not release much of the deficit of moment that had accumulated since the last rupture. The sequence essentially ruptured a set of asperities, which triggered each other through static and dynamic interactions, but did not cooperate efficiently because of the intervening barriers.

Some of these barriers are most likely not permanent and are related to the slip due to past earthquakes. While permanently creeping barriers should tend to favor some regularity and similarity of earthquakes, non-permanent barriers due to the stress distribution left over from previous ruptures is probably the major factor that is introducing irregularity, as observed in dynamic fault models.

This is likely the main reason that neither the slip-predictable nor the time-predictable models apply, and why the 2007 earthquakes didn't grow as big as in 1833.