Influence of heterogeneous coupling on the spatial pattern and recurrence of seismic ruptures

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Introduction

Inspired by the recent Sumatra subduction earthquake sequence (2004 - present) on the Sunda megathrust, we explore the behavior of a simple fault system with lateral variations of frictional properties designed to induce lateral variations of the proportion of seismic to aseismic slip. The model consists of two rate-weakening (potentially locked) segments surrounded by rate-strengthening (potentially creeping) zones. The width of the central rate-strengthening zone and the laboratory-derived frictional parameters were adjusted so that each locked segment can be ruptured independently or the rupture can propagate across the central creeping zone, producing a large earthquake event. We found that, despite its simplicity, the model produces complex earthquake cycles with a variety of earthquake slip patterns. The model can be used to qualitatively explain the relation of seismic coupling to asperities on the Sunda Megathrust. The model obeys neither the time-predictable nor the slip-predictable model.

Seismic and interseismic coupling on the Sunda Megathrust

The pattern of locking of the plate interface along the subduction zone offshore Sumatra is highly heterogeneous [*Chlieh, et al.*, in press]. The proportion of slip accommodated by creep varies spatially between 0, corresponding to full locking (interseismic coupling =1), and full interplate slip rate (interseismic coupling=0). This pattern shows lateral segmentation of the megathrust that seems to correlate to some degree with the extent of large megathrust rupture. There are in particular two areas with dominantly aseismic creep around the Batu Islands and around Sipora Islands. The creeping zone near the equator correlates with the subduction of the Investigator fracture zone as well as with a forearc islands ridge which disconnect the forearc basins northeast of Nias island and Siberut island respectively. Hence, the creeping zone is probably a permanent feature. Only moderate interplate events are known to have occurred there and the rupture extent of large Mw8.5 to 9.0 events are all abutting this creeping zone, which seems to act persistently as a barrier to rupture propagation. Although the creeping zone around Sipora island is a more subtle feature, it may have influenced the rupture extent of the Mw 8.5-9.1 events of 1797 and 1833.

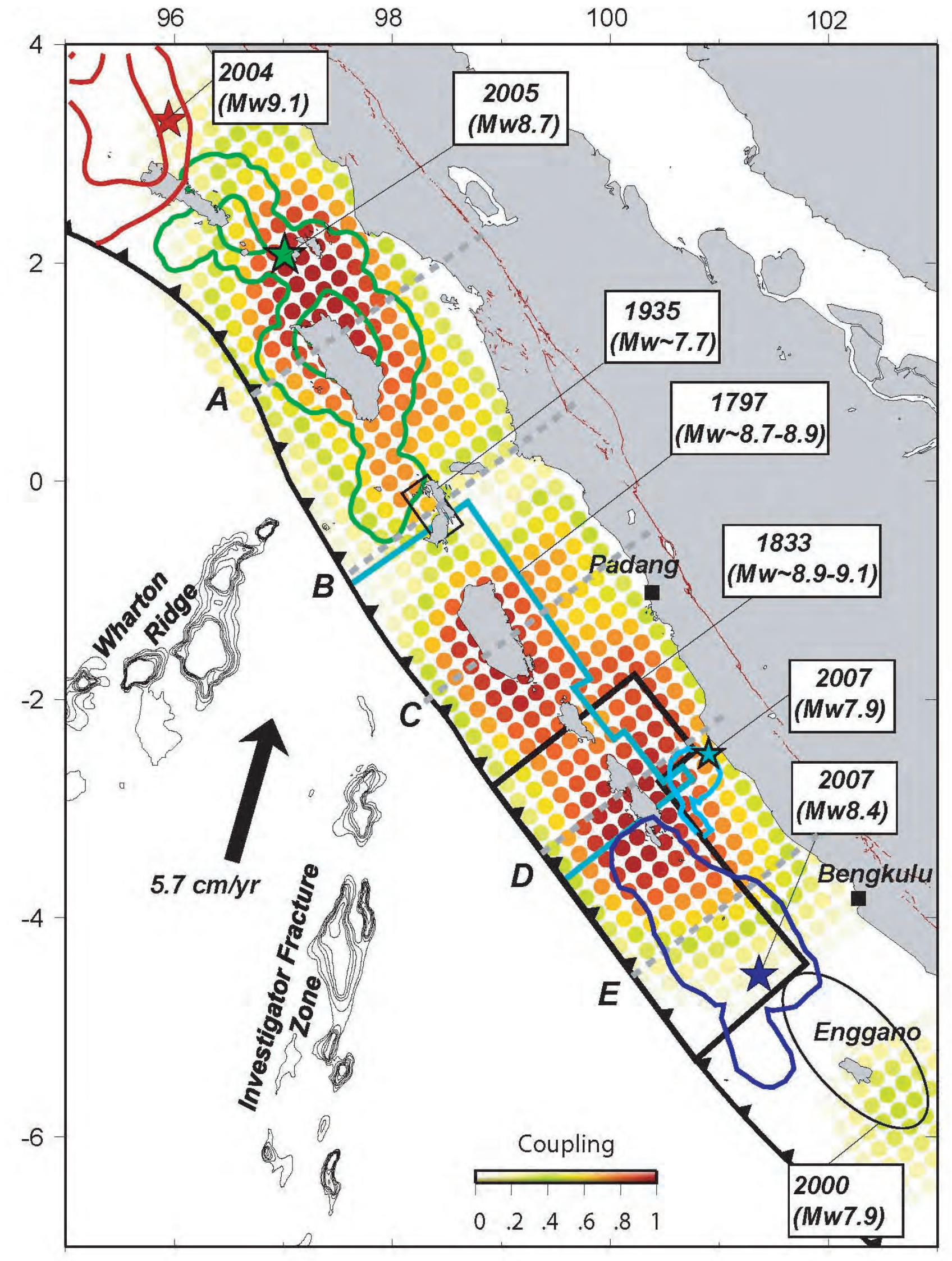


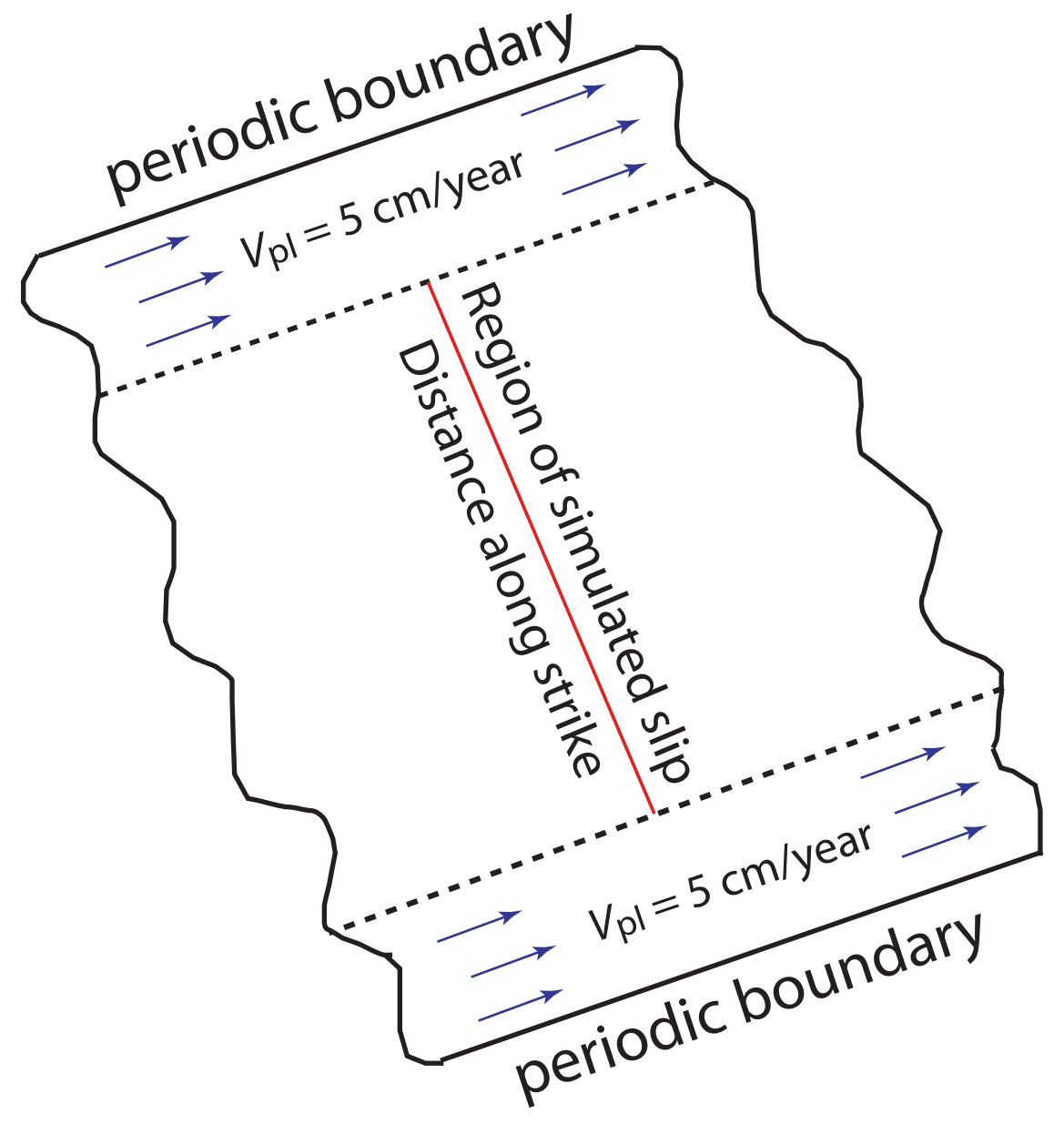
Figure 1. Comparison of interseismic coupling along the megathrust with the rupture areas of the giant 1797, 1833 and 2005 earthquakes [Chlieh, et al., in press]. Epicenters of the 2007 Mw 8.4 and Mw 7.9 earthquakes are shown for reference. Beneath the Batu Islands, where coupling occurs in a narrow band, the largest earthquake for the past 260 years has been a Mw 7.7 in 1935 [*Natawidjaja, et al.*, 2004; *Rivera, et al.*, 2002]. The wide zones of coupling, beneath Nias, Siberut and the Pagai islands coincide well with the source of giant earthquakes (Mw> 8.5) in 2005 from *Konca et al.*, [2007] and in 1797 and 1833 from *Natawidjaja et al.*, [2006]. The coincidence of the high coupling area (orange-red dots) with the region of high coseismic slip during the 2005 Nias-Simeulue earthquake suggests that strongly coupled patches during interseismic correspond to seismic asperities during megathrust ruptures. The source regions of the 1797 and 1833 ruptures also correlate well with patches that are highly coupled beneath Siberut, Sipora and the Pagai islands.

Model set-up

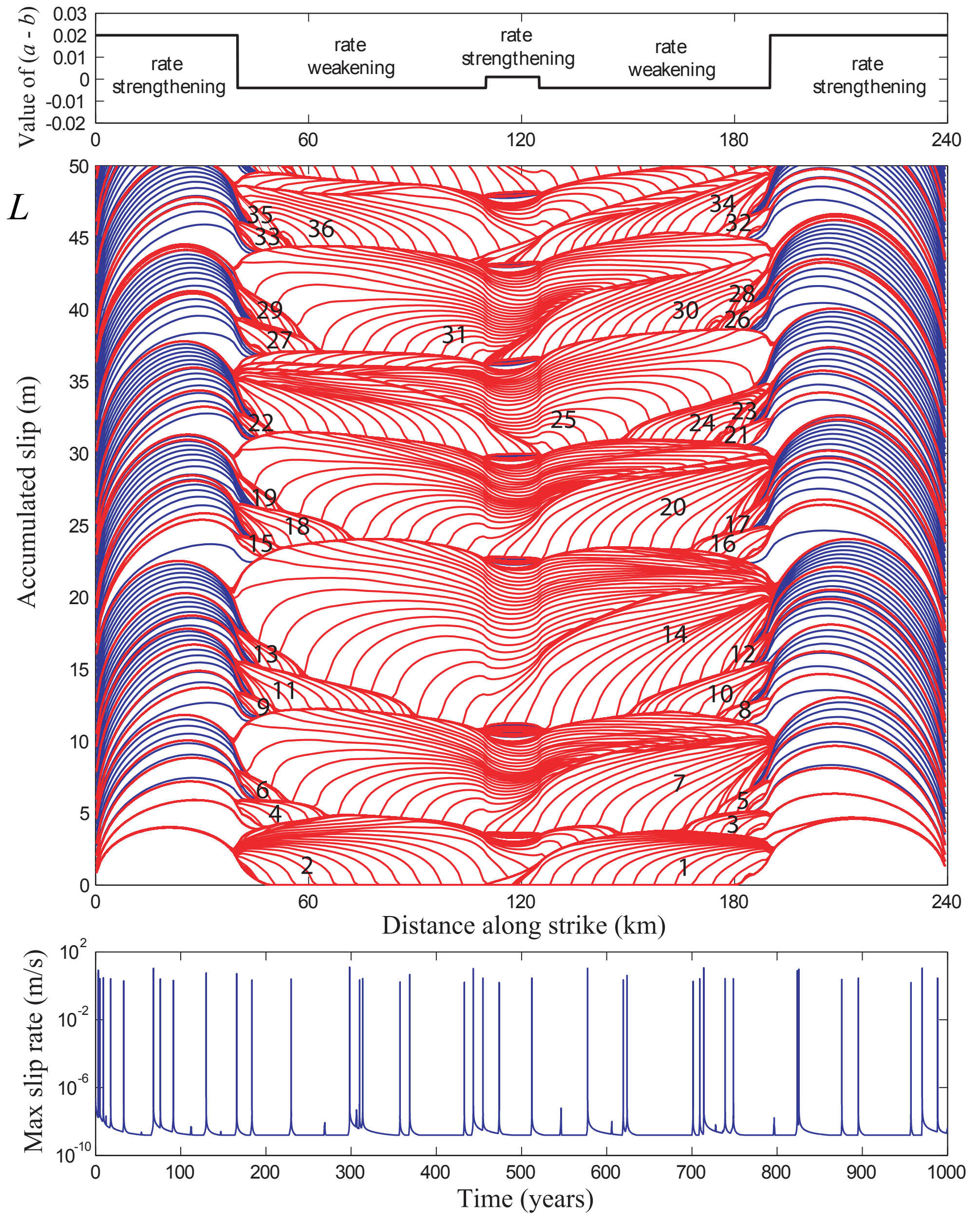
- Boundary integral method in its spectral formulation (*Lapusta et al.*, 2000)
- Laboratory derived rate and state friction:

$$\tau = \sigma\left[f_0 + a\ln(V/V_0) + b\ln(V_0\theta/L)\right],\quad d\theta/dt = 1 - V\theta/L$$

  - Potentially unstable when $a < b$ (rate weakening)
  - Stable when $a > b$ (rate strengthening)
- Anti-plane (2D) elasticity
- Variable time stepping
- Plate loading rate, V_{pl} = 5 cm/year
- Characteristic slip, L = 8 mm
- Effective normal stress, 50 MPa



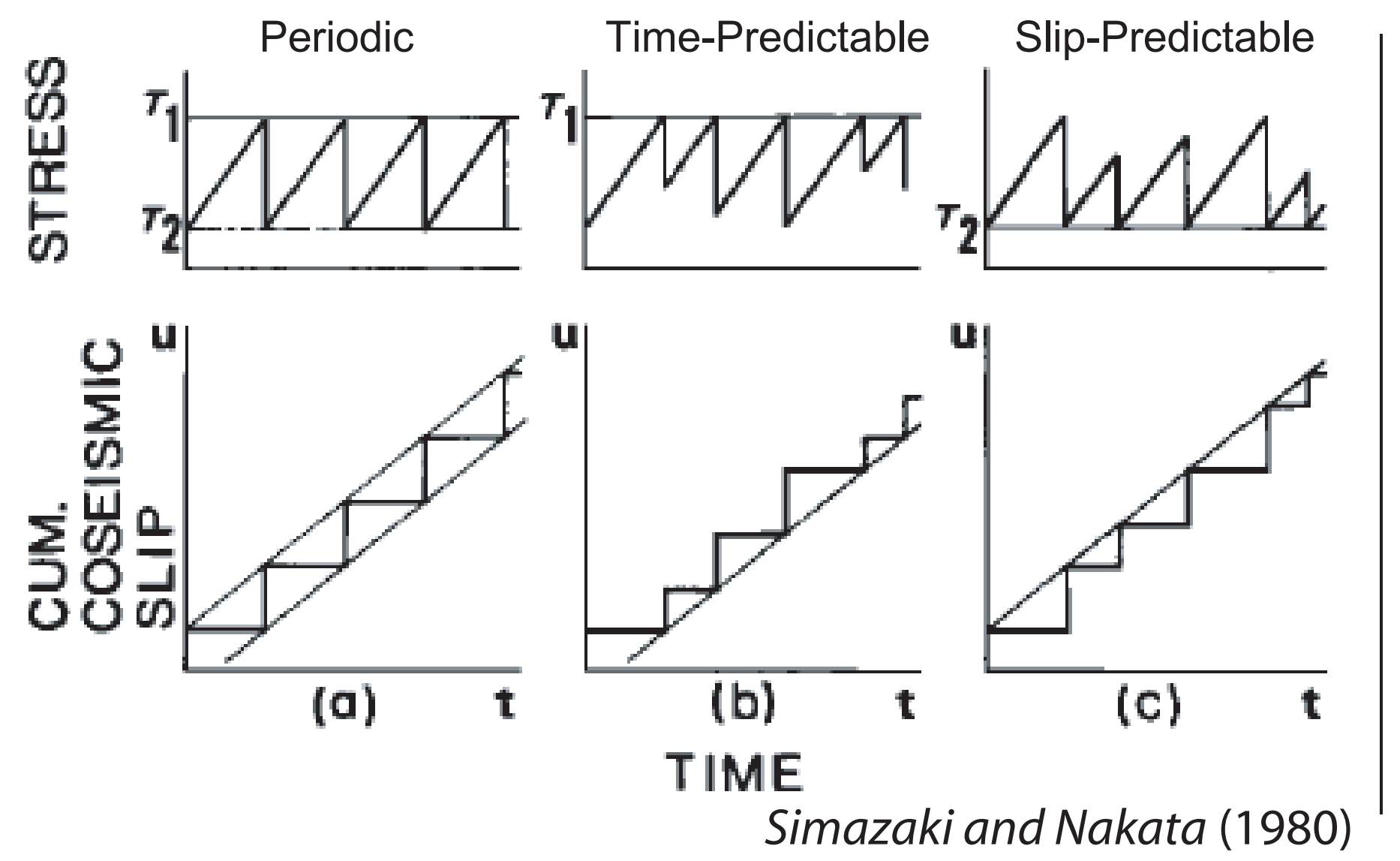
Simulated earthquake sequence



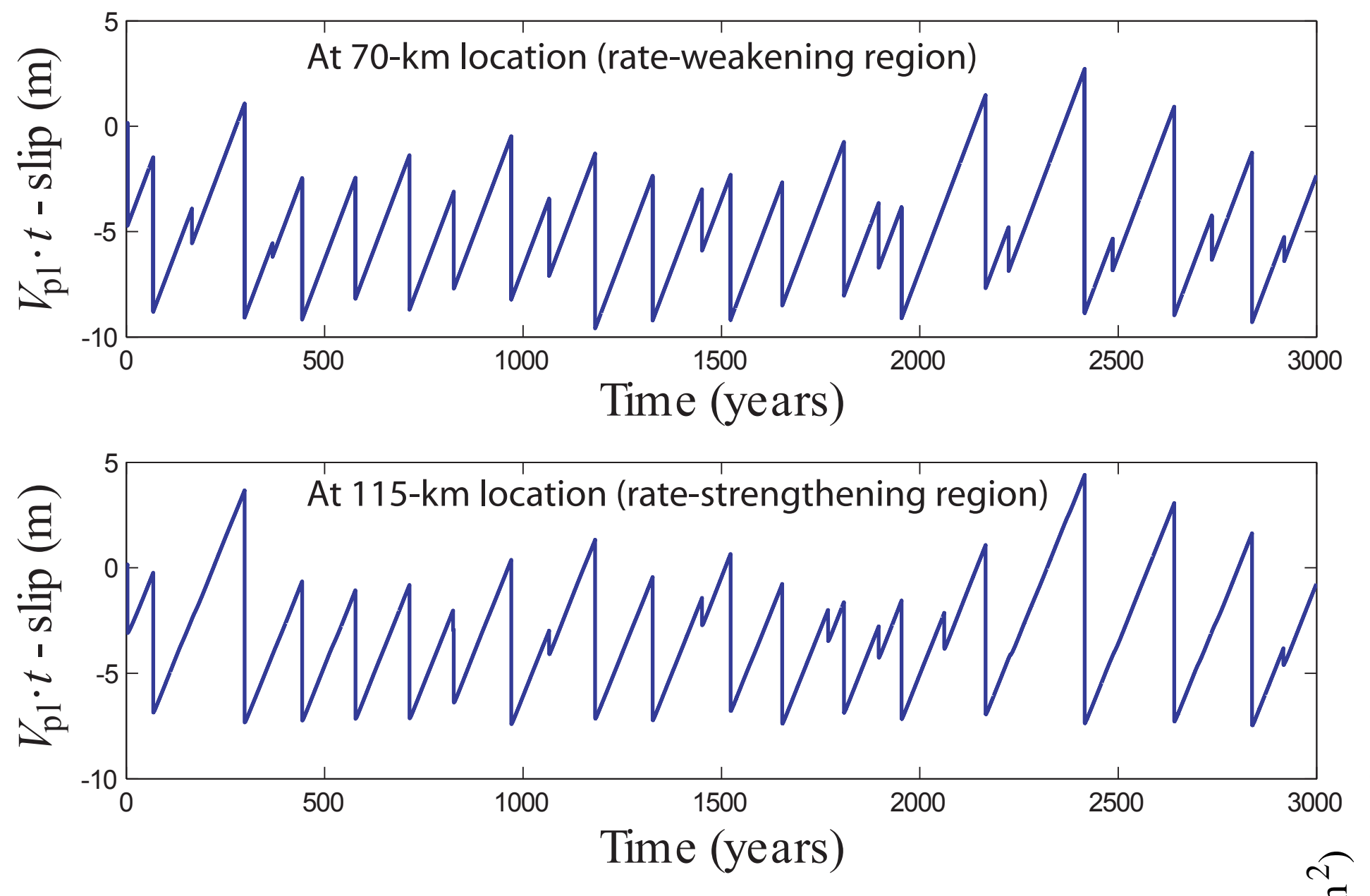
Left figures illustrate an earthquake sequence simulated in the model.
Top: The spatial distribution of the parameter (*a*-*b*).
Middle: Accumulated slip contours over 1000 year history. Red lines are intended to capture dynamic events and are plotted every 2 second during the simulated earthquakes. Blue lines show slip accumulation every 10 years. The temporal order of earthquakes are numbered.
Bottom: The maximum slip velocity over time.

Despite the simple geometry and constant loading history, the model produces a complex earthquake pattern with the following characteristics (similar to the one on the Sunda Megathrust):
(1) Since fault rheologies are stable over time, the asperities (areas of large slip) are stable over earthquake cycles.
(2) The regions of high seismic coupling correspond to the asperities.
(3) Rate-strengthening heterogeneity sometimes acts as a barrier.
(4) The slip at a given point is comparable or greater in large earthquakes than that in small earthquakes.
(5) Most earthquakes nucleate near the transitions from rate-strengthening to rate-weakening regions, where interseismic stress build up is maximum.

Time vs. slip predictable behavior

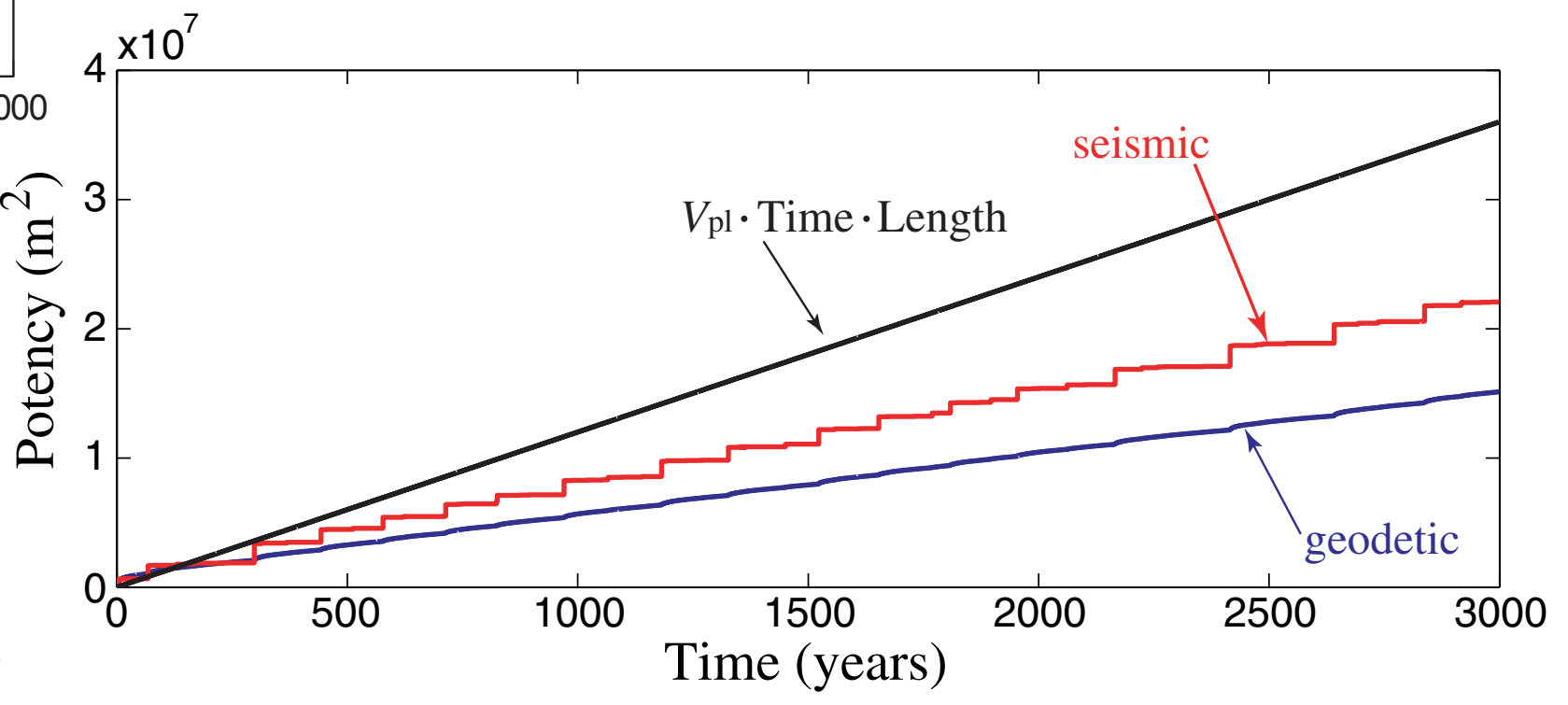


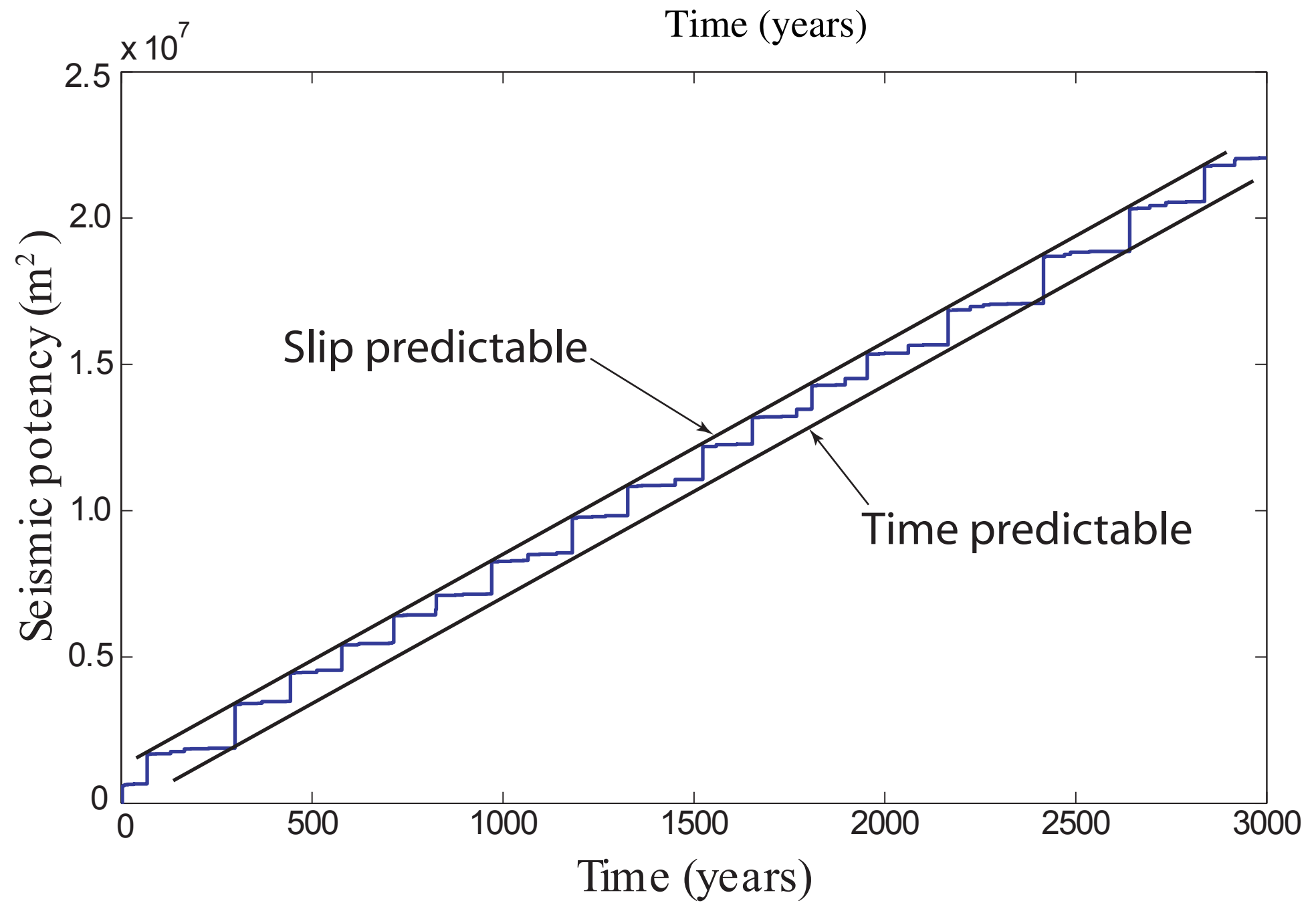
Simazaki and Nakata (1980)



Left: The product of plate velocity and time minus accumulated slip at two points. Simulated earthquake sequences are neither time nor slip-predictable at a particular location along the fault strike.

Bottom: Seismic and geodetic potency (integrated coseismic and interseismic slip respectively) over time. About 63 percent of moment is released seismically. The seismic potency exhibits behavior that is closer to the slip-predictable model than the time-predictable model.





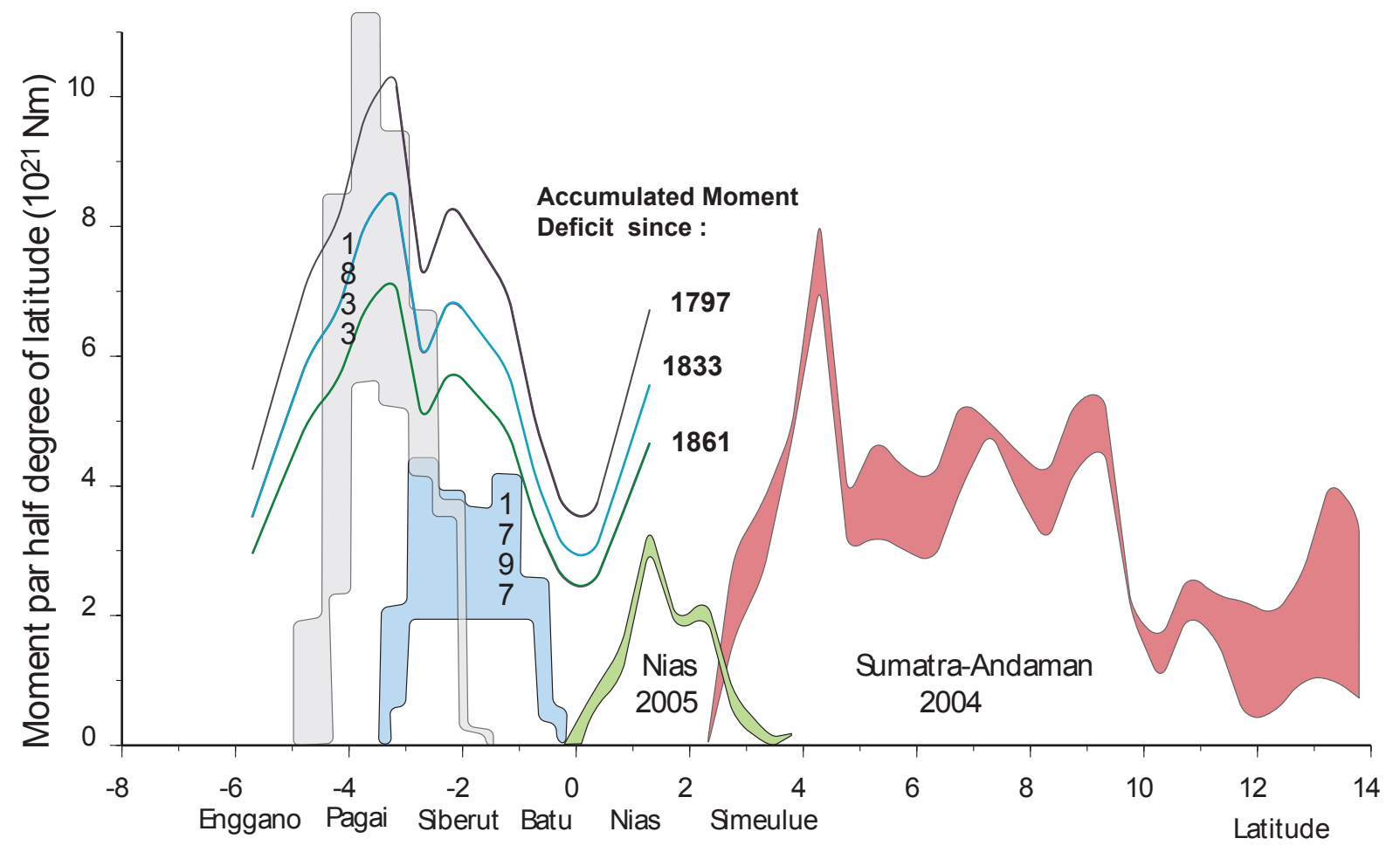


Figure 2. Latitudinal distribution of seismic moment released by large megathrust earthquakes and of accumulated deficit of moment due to interseismic locking of the plate interface [*Chlieh, et al.*, in press].

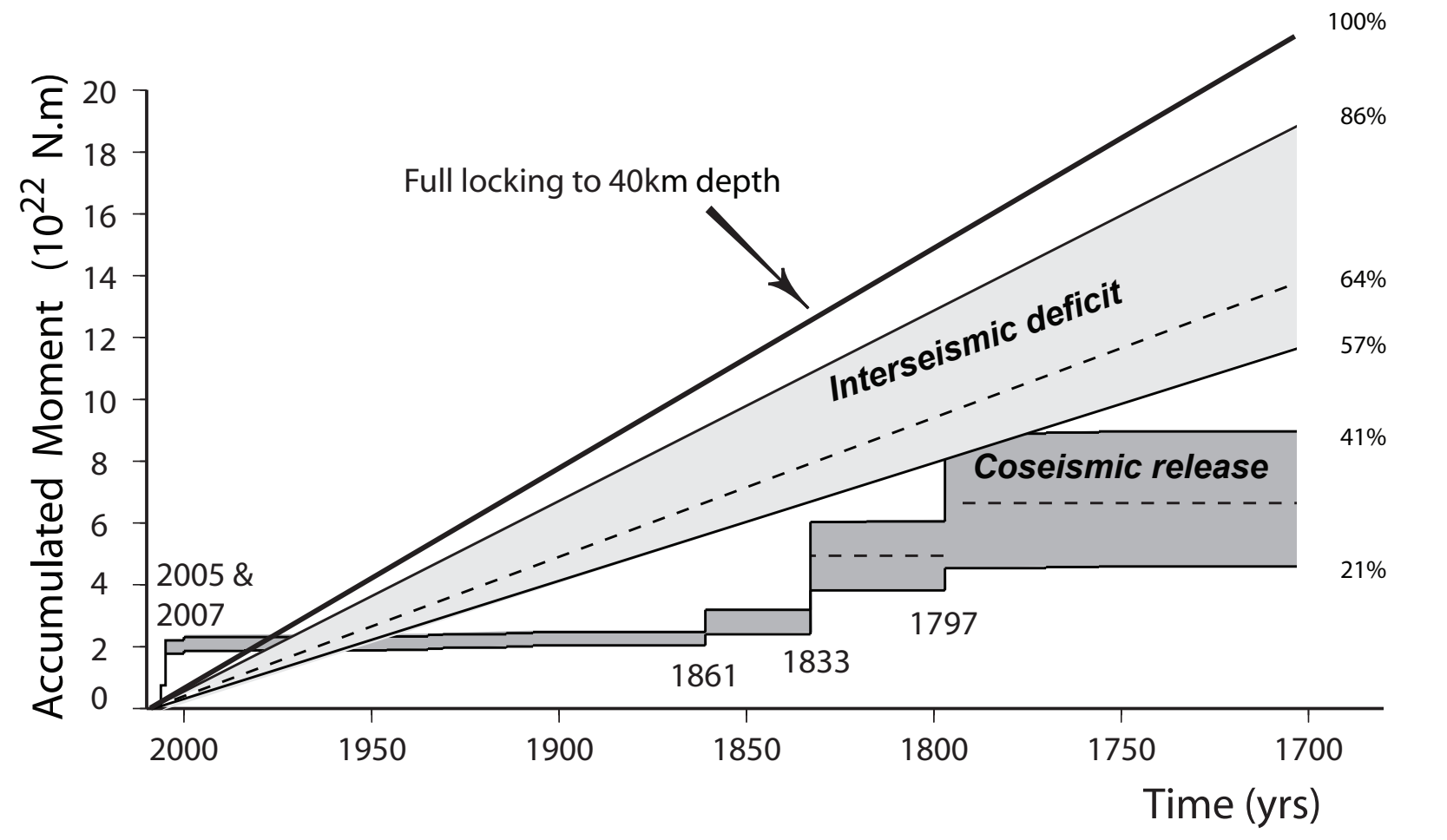
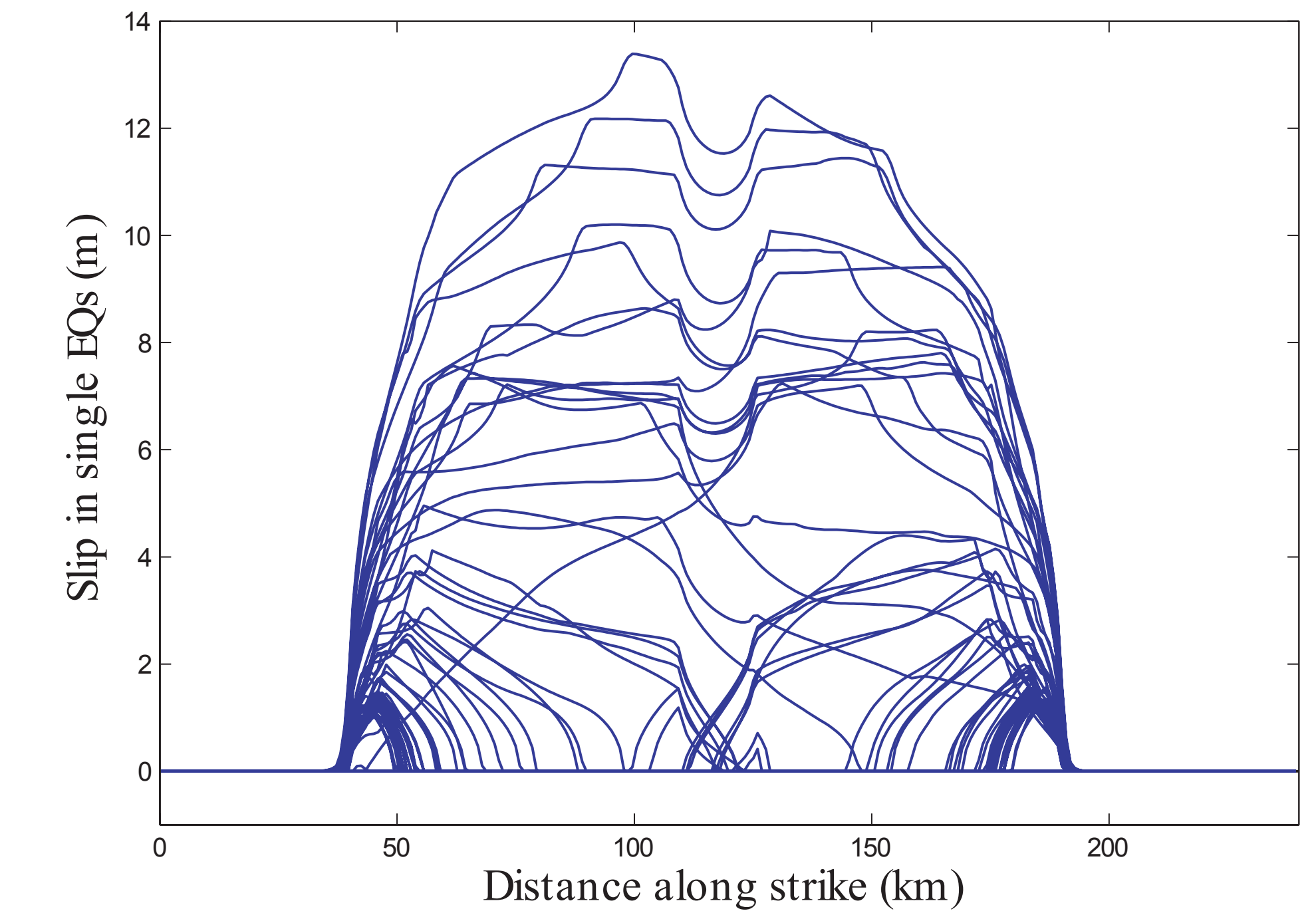
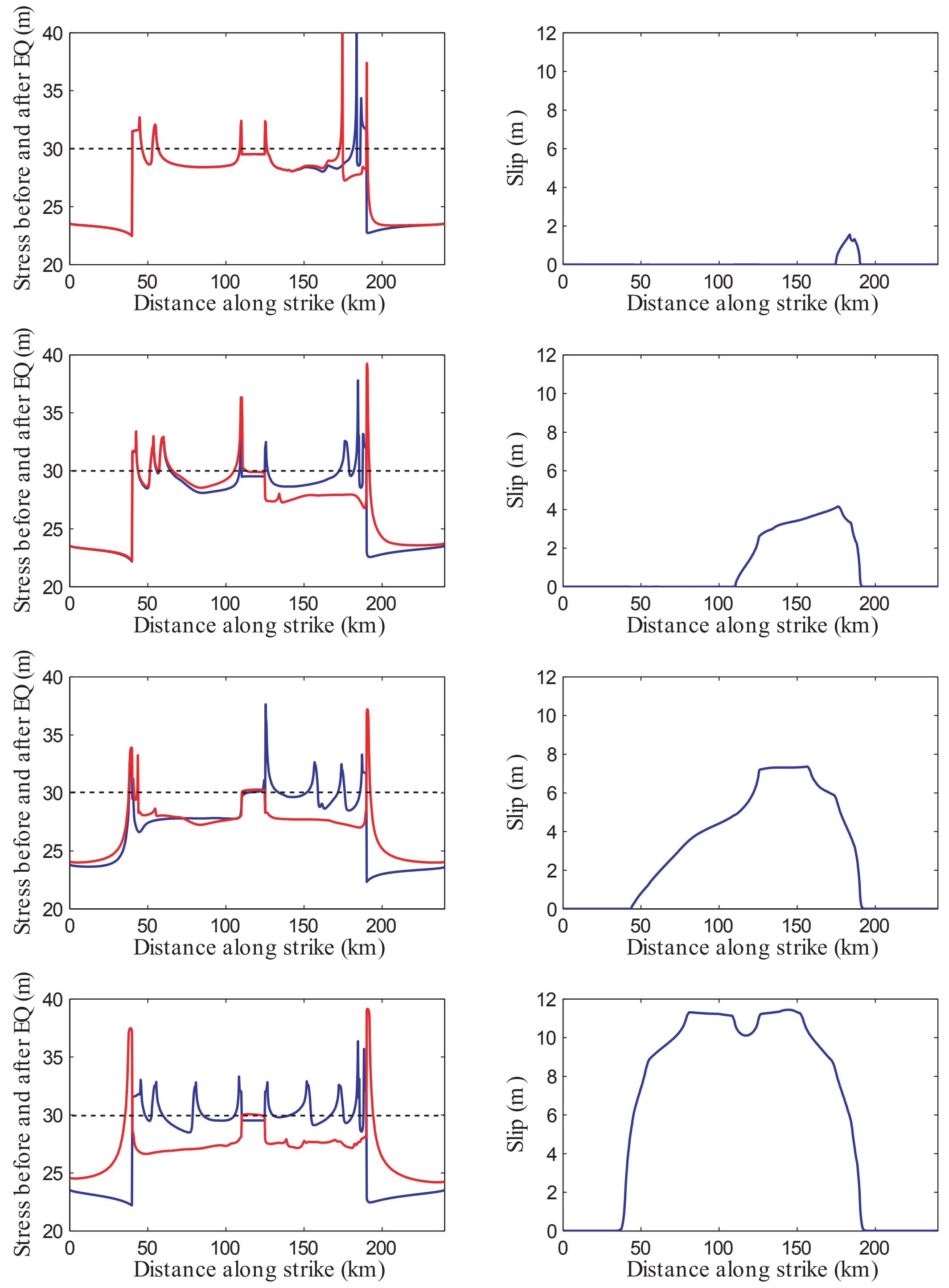


Figure 3. Accumulated moment deficit and seismic moment released due to major intraplate earthquakes between latitudes 2ºN and 6ºS since 1700. The accumulated moment deficit rate for a uniformly locked fault zone 150-km width extending to a depth of 40km is shown for reference.

Characteristics of individual earthquakes



Slip distribution of individual earthquakes. Most earthquakes nucleate near rheological transitions. There is a total of 109 earthquakes over 3000 years.



Stress distribution before (blue) and after (red) 4 earthquakes of different sizes. The details of each individual rupture depend on the stress distribution resulting from previous seismic ruptures, interseismic stress built up, and stress redistribution due to aseismic slip.

Conclusions

Despite its simplicity, complex slip behavior can emerge in our model due to the effects of aseismic slip combined with nucleation, propagation, and arrest of dynamic earthquake ruptures. The narrow central rate-strengthening zone in the model plays a key role in the seismic behavior of the model. Two types of large earthquakes are observed depending on whether or not they rupture the central creeping zone. The model allows us to study the conditions under which a rate-strengthening patch can act as a permanent barrier, and to understand the influence of pre-stress on the rupture extent and stress drop during seismic ruptures.