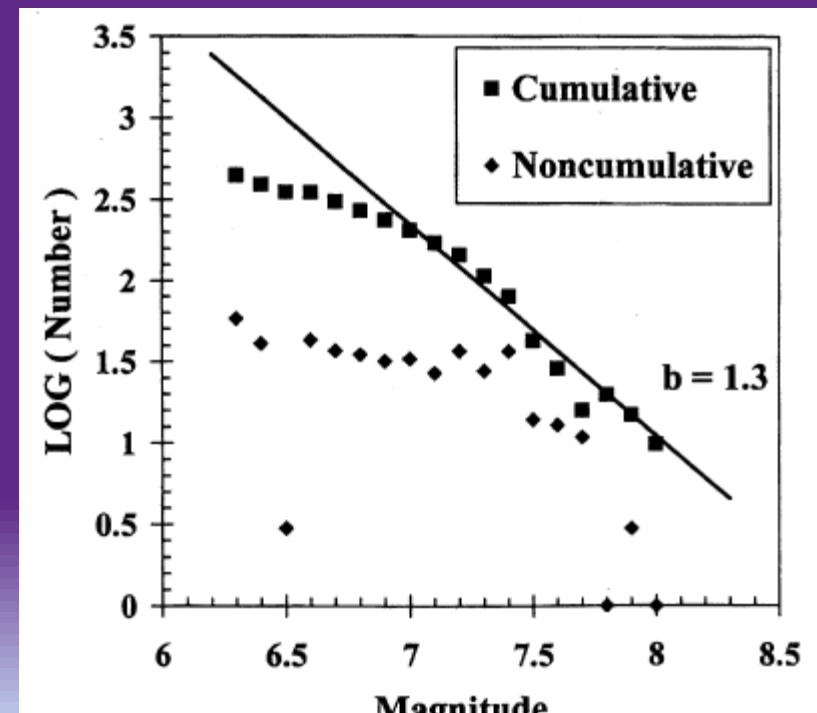
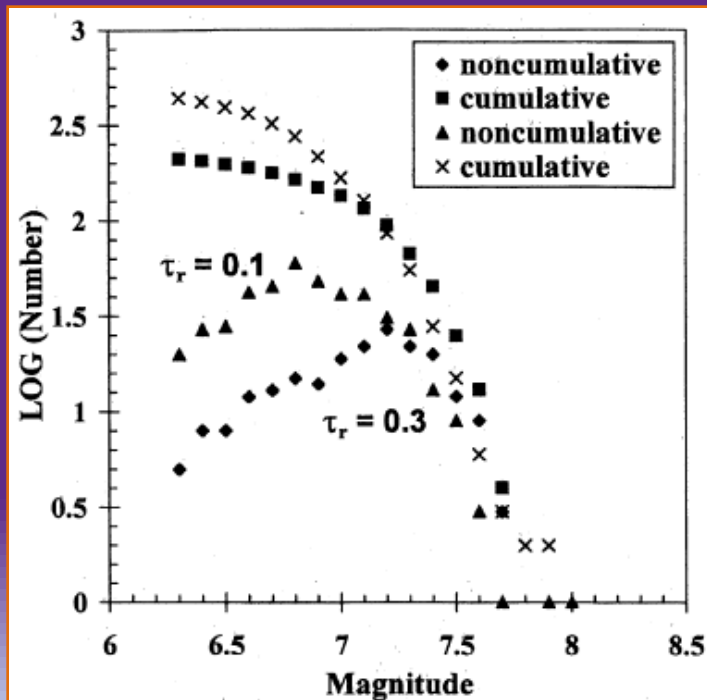


Earthquake cycle, fault zones, and seismicity patterns in a rheologically layered lithosphere

太田

要旨

- 既存モデルに改良を加えたHybridモデルにより、地震サイクルを再現
- ヒーリングの時定数によって地震活動の統計的分布は異なる



1.Introduction

- 地震・断層の長期的パターン
- 2-D先行研究の問題点
 - ①地震発生帯域とその他地域とのカップリング・3次元的な相互作用を無視
 - ②物性の時間変化を無視
- ダメージ・レオロジーに基づいた新たなモデルでシミュ

2. Model of Crustal Stress Distribution

➤ 問題設定

➤ モデルの比較

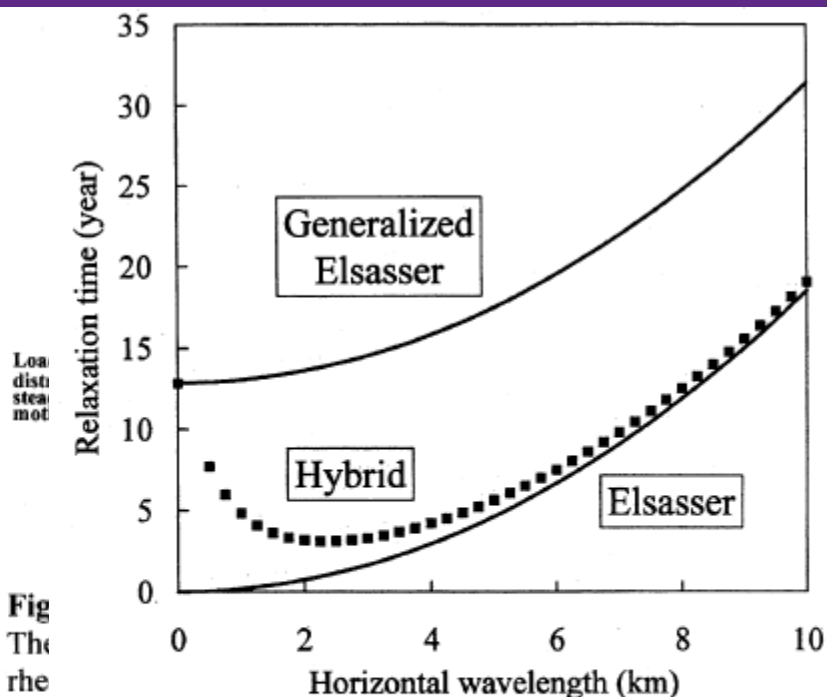


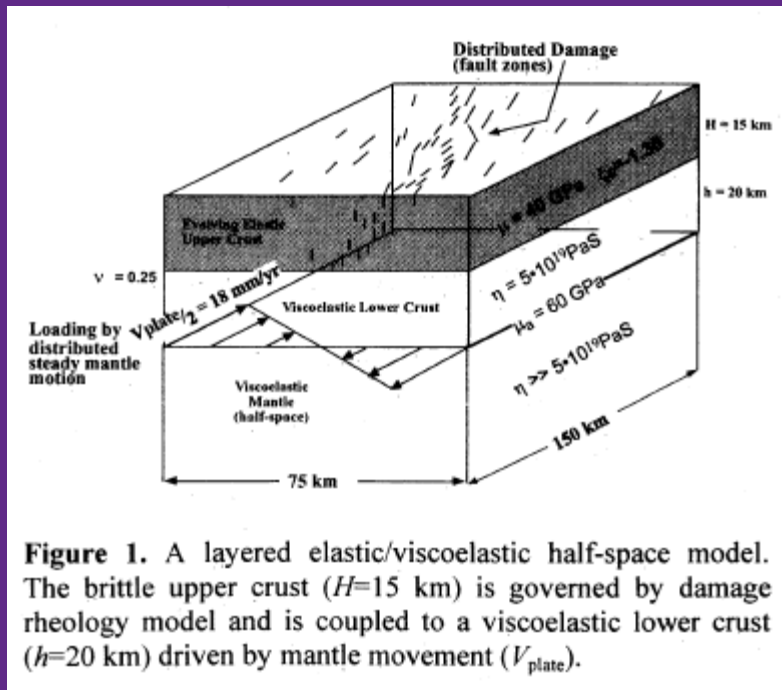
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Figure 2. Relaxation time versus horizontal wavelength for the Elsassser and generalized Elsassser models (heavy lines). The numerically calculated relaxation time for the hybrid model (symbols) is similar to that of the generalized Elsassser model for very short length scales, but it approaches the Elsassser solution for long wavelengths (viscosity of the lower crust $\eta=5 \cdot 10^{19}$ Pa s).

- Elsassser
 - ○上部地殻をシート⇒2D
 - ×基盤が粘性流体
- Generalized Elsassser
 - ○基盤を粘弾性体
 - ×変位など大きく見積もり
- Full 3D
 - ×時間がかかる
- Hybrid
 - ◎good!!

2.1 Generalized Elsassner Model(i)

2次元化



$$\sigma_{km}(x, y) = \frac{1}{H} \int_{-H}^0 \sigma_{km}(x, y, z) dz$$

$$\frac{\partial \sigma_{km}}{\partial x_m} = \frac{\tau_k}{H}$$



Maxwell粘弾性体の方程式

$$\frac{b}{\mu_a} \frac{\partial \tau_k}{\partial t} + \frac{h}{\eta} \tau_k = \frac{\partial u_k}{\partial t} - V_{plate}^{(k)}$$

変位の時間発展



$$\frac{Hb}{\mu_a} \frac{\partial}{\partial t} \frac{\partial \sigma_{km}}{\partial x_m} + \frac{Hh}{\eta} \frac{\partial \sigma_{km}}{\partial x_m} = \frac{\partial u_k}{\partial t} - V_{plate}^{(k)}$$

2.1 Generalized Elsasser Model(ii)

・・・他のモデルと比較するためにrelaxation timeを

$$\frac{Hb\mu}{\mu_a} \frac{\partial}{\partial t} \frac{\partial^2 u}{\partial x^2} + \frac{Hh\mu}{\eta} \frac{\partial^2 u}{\partial x^2} = \frac{\partial u_k}{\partial t} - V_{plate}^{(k)}$$

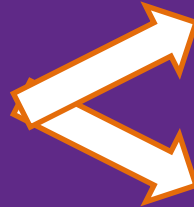
x軸限定に1次元化



変数分離

$$u(x, t) = f(t)\phi(x)$$

$$\frac{\frac{Hb\mu}{\mu_a} \dot{f} + \frac{Hh\mu}{\eta} f}{\dot{f}} = \frac{\phi}{\phi''} = -\lambda^2$$



$$\phi = A \cdot \exp\left(i \frac{x}{\lambda}\right)$$

$$f = B \cdot \exp\left(-\frac{Hh\mu/\eta}{\lambda^2 + Hb\mu/\mu_a} t\right)$$

特徴的な時間スケール=relaxation time

$$t^* = \frac{\lambda^2 + Hb\mu/\mu_a}{Hh\mu/\eta}$$

2.2 Hybrid Model Incorporating 3-D GF

上部地殻と下部地殻の変形は相伴う

$$u_k = u_k^{(v)} + u_k^{(e)}$$

ok

修正

$$u_k^{(e)} = \iint_S G_{kn} \tau_k ds$$



$$H \iint_S G_{kn} \frac{\partial}{\partial t} \frac{\partial \sigma_{nm}}{\partial x_m} ds + \frac{Hh}{\eta} \frac{\partial \sigma_{km}}{\partial x_m} =$$



$$t^* = \frac{\lambda^2 + H\mu\tilde{G}_{xx}(\lambda)}{Hh\mu/\eta}$$

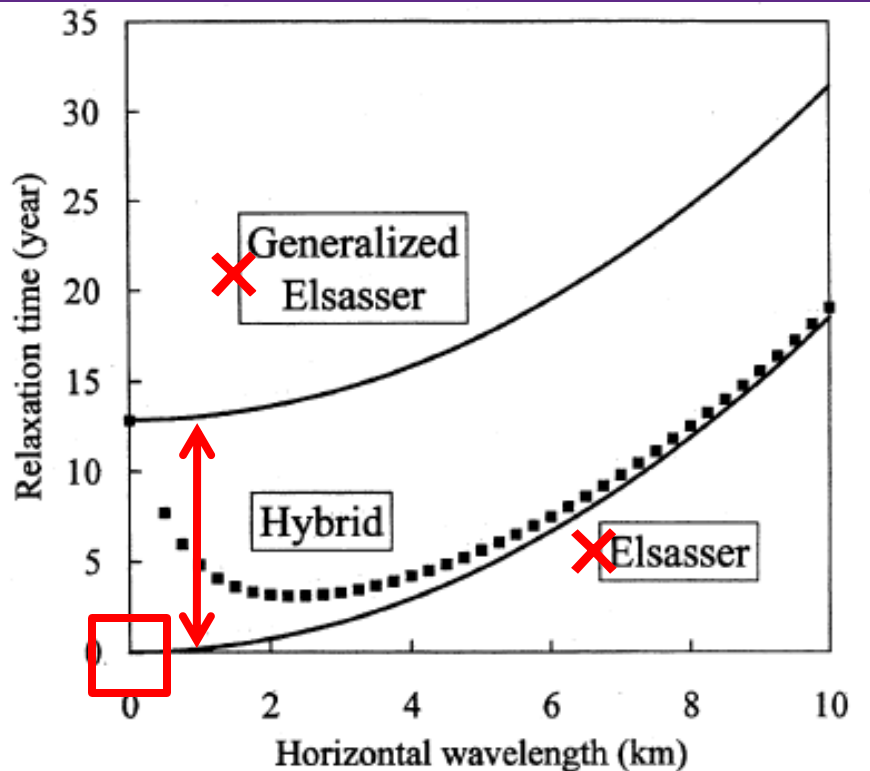


Figure 2. Relaxation time versus horizontal wavelength for the Elsasser and generalized Elsasser models (heavy lines). The numerically calculated relaxation time for the hybrid model (symbols) is similar to that of the generalized Elsasser model for very short length scales, but it approaches the Elsasser solution for long wavelengths (viscosity of the lower crust $\eta = 5 \times 10^{19}$ Pa s).

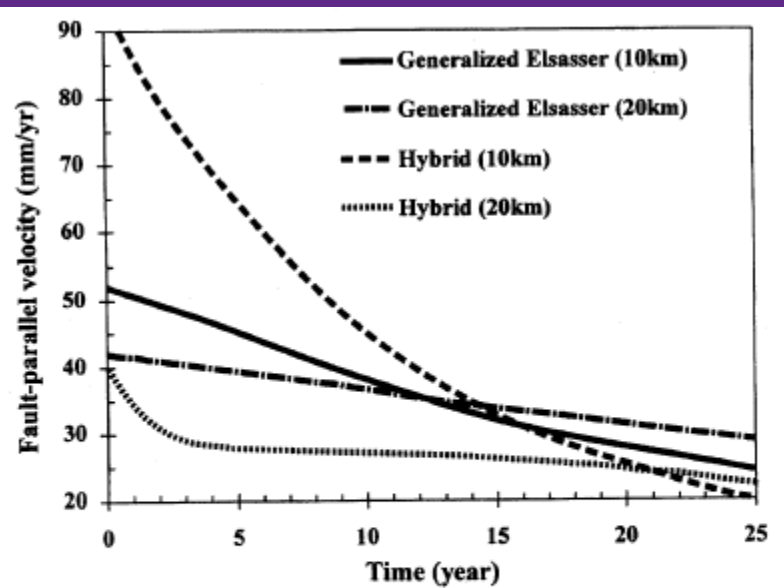


Figure 3. Fault-parallel velocity at two normal distances 10 and 20 km from the fault as a function of time after a seismic event, calculated with the generalized Elsasser model [*Li and Rice, 1987, equation (A6)*] and simulated with the hybrid model.

3 Upper Crust Deformation and Damage Evolution

➤ Seismic cycle

1. Preseismic
2. Coseismic
3. Postseismic
4. Interseismic

➤ Mode-switching activity

3.1 A Single Fault System

パラメタ/条件設定・ seismic cycle

3.2 Regional Earthquakes and Fault Networks

断層ネットワークの進展・ damage healingと地震活動

3.1 A Single Fault System(i)

- 境界条件・・・antiplane:ループ、plane:stress一定
- パラメタ・・・100年後の速度断面

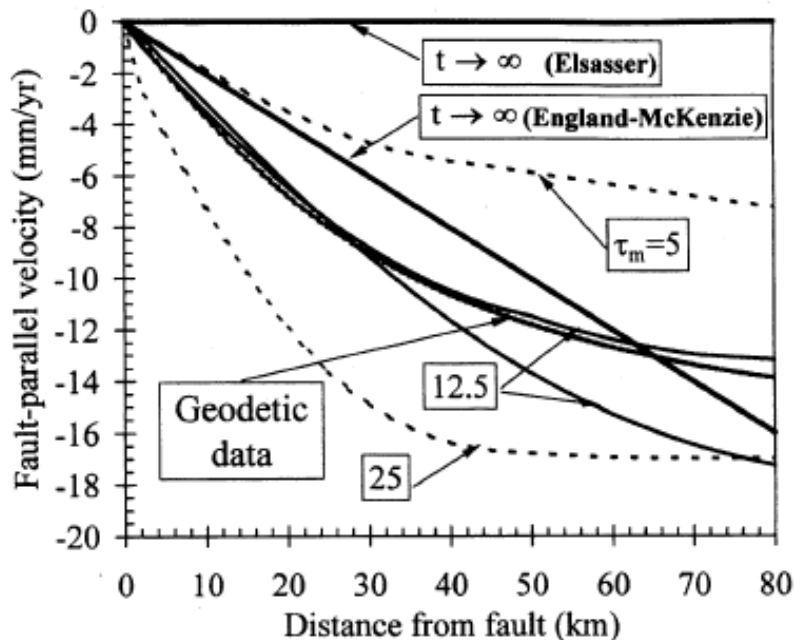


Figure 4. Velocity profiles 100 years after a large earthquake simulated for model relaxation times $\tau_m=5, 12.5$, and 25 years. The shaded line represents the best fit of geodetic data with dislocation model after Savage [1990]. Two asymptotic solutions (time $\rightarrow \infty$) for Elsasser and England-McKenzie boundary conditions are also shown.

Generalized Elsasser

$$\tau_m = \frac{\pi^2 H \eta}{16 h \mu_a} \quad b \sim (\pi/4)^2 \rightarrow (9)$$

Geodetic data (model)

$$V = V_0 \frac{1}{\pi} \arctan \left(\frac{x}{D} \right)$$

best fit!

$$\eta = 5 \times 10^{19} \text{ Pas}$$

$$\mu_a = 60 \text{ GPa}$$

Magnitude

モーメントあれこれ

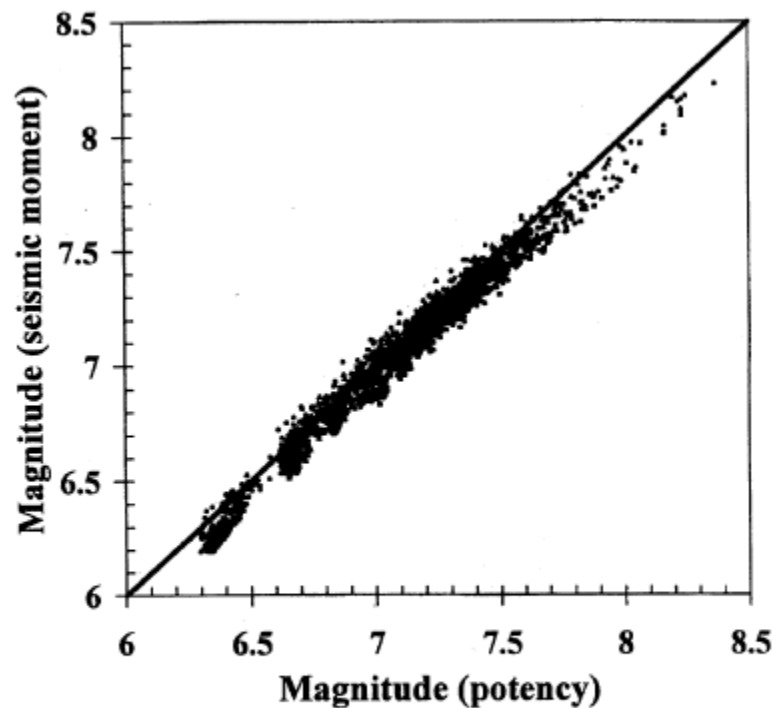


Figure 6. Correlation between earthquake magnitudes calculated using seismic moment and potency based on model runs with different parameters.

$$M_{ij} = \int_V \Delta\sigma_{ij} dv$$

$$M_{ij} = \int_V C_{ijkl} \Delta\epsilon_{kl} dv$$

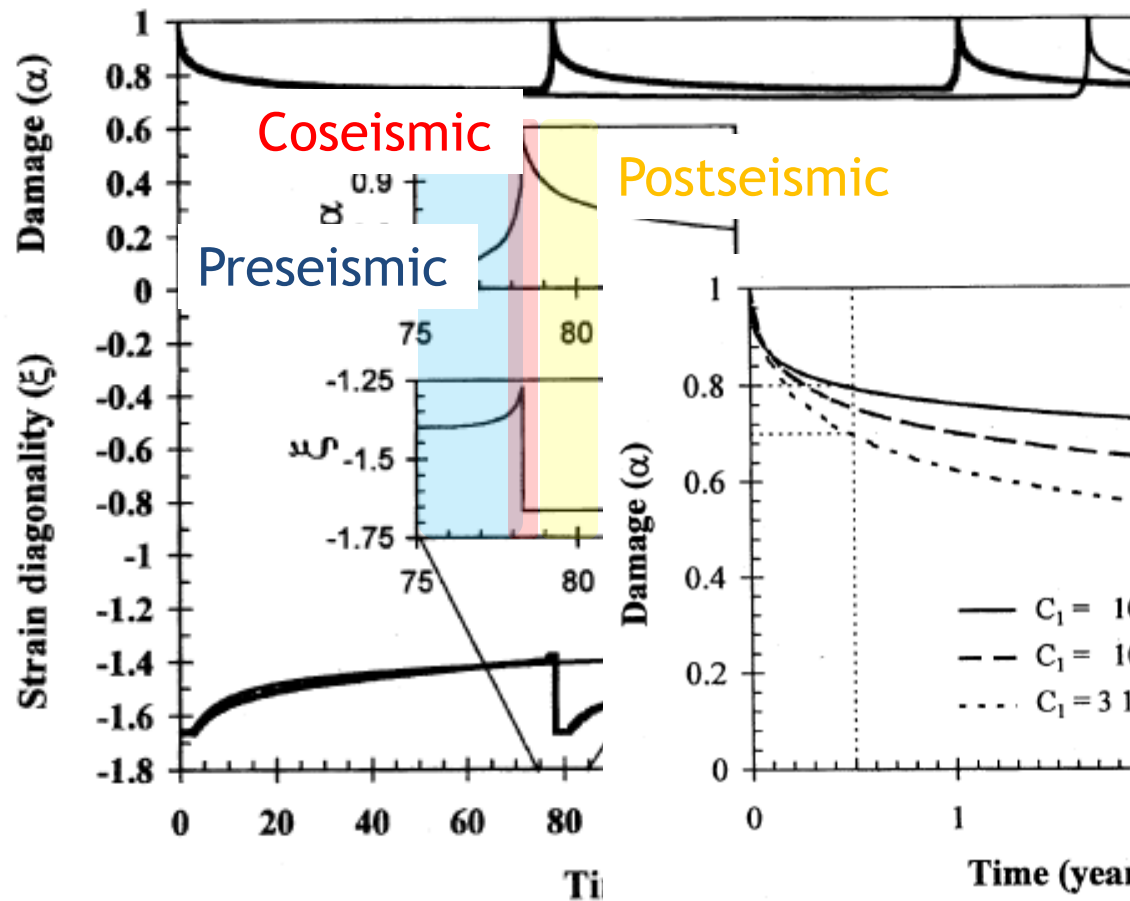
$$P_{ij} = \int_V \Delta\epsilon_{kl} dv$$

$$M = \left(\frac{2}{3}\right) \log_{10} P + 3.6_{ij} \quad \text{where} \quad P = (P_{ij} P_{ij})^2$$

断層運動の時間履歴

Strain diagonality $\xi < \xi_0$ (-140~-135)

Damage $\alpha < \alpha_{cr}$



時定数に関するパラメタ

C_d

C_1, C_2

$$i_c = \alpha_{cr} - \sqrt{\tau_r \frac{d\alpha}{dt}}$$

3.2 Regional Earthquakes and Fault Networks

τ_L :Loading の time scale

τ_h :Healing の time scale

τ_h/τ_L 大 $\rightarrow$ Slow healing(左)

τ_h/τ_L 小 $\rightarrow$ Fast healing(右)



それぞれの場合についてランダムダメージを与えた初期条件からシミュ

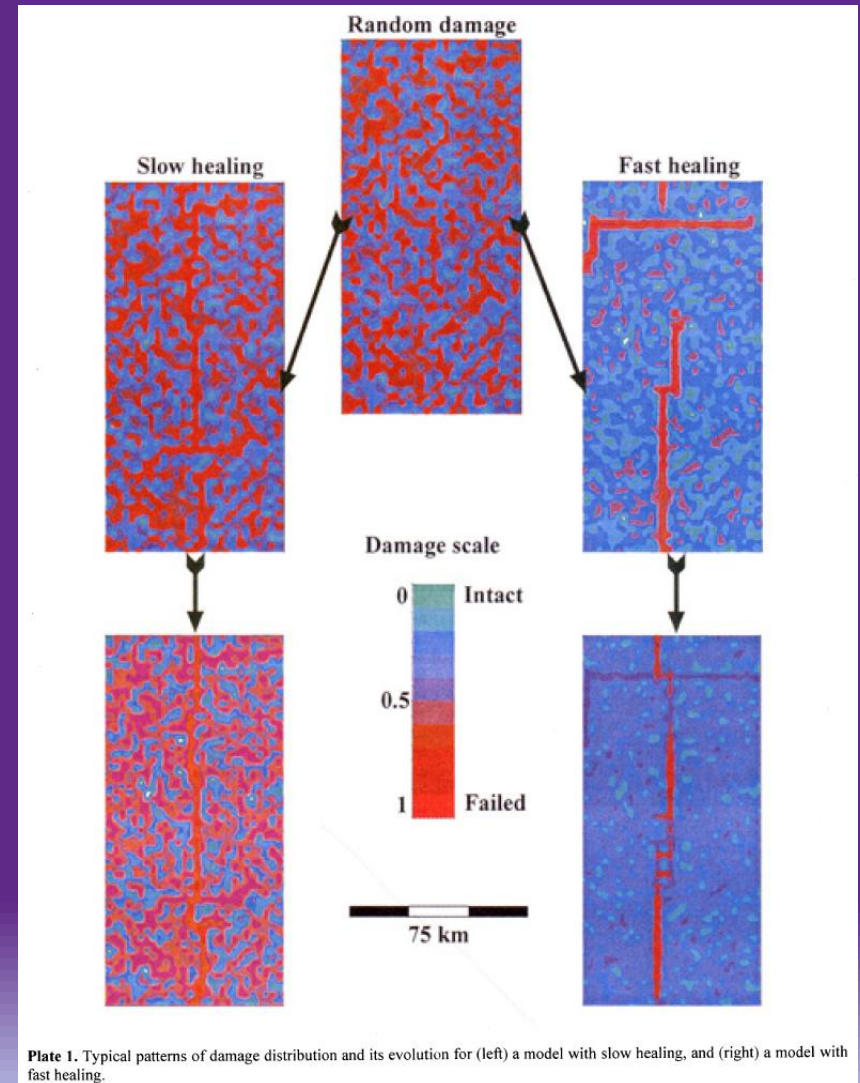


Plate 1. Typical patterns of damage distribution and its evolution for (left) a model with slow healing, and (right) a model with fast healing.

Slow healing

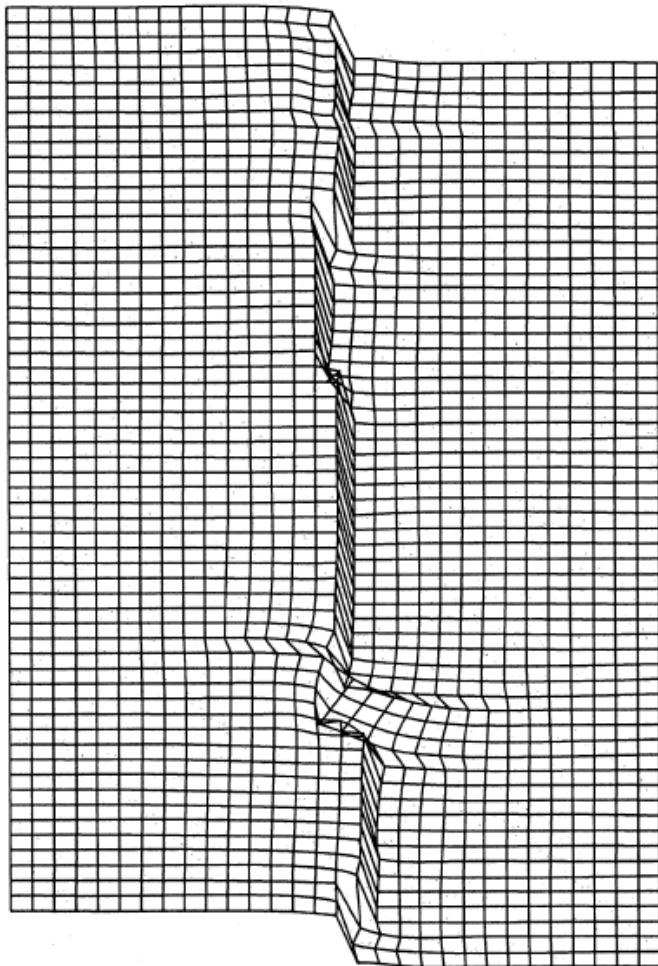


Figure 8. Typical distribution of the cumulative strain for the model with slow healing. The slip and high damaged material (Plate 1 on the left) are concentrated in relatively narrow and regular zone.

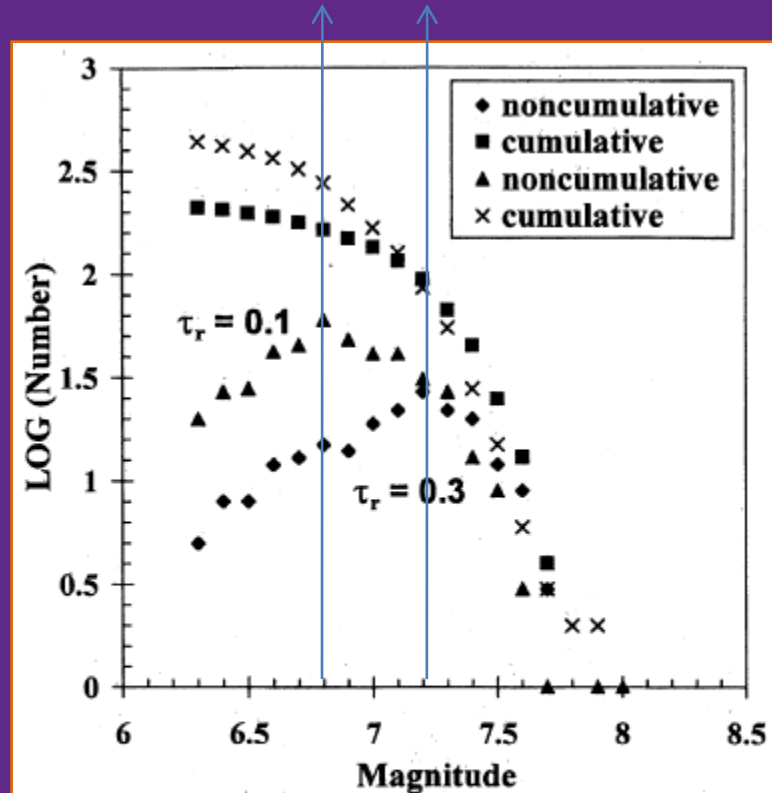


Figure 9. Cumulative and noncumulative frequency-size statistics of seismic events for slow damage healing (long material memory) and different τ_r . The statistics have a preferred event size manifested as a narrow local maximum in the noncumulative distribution.

Intermediate?

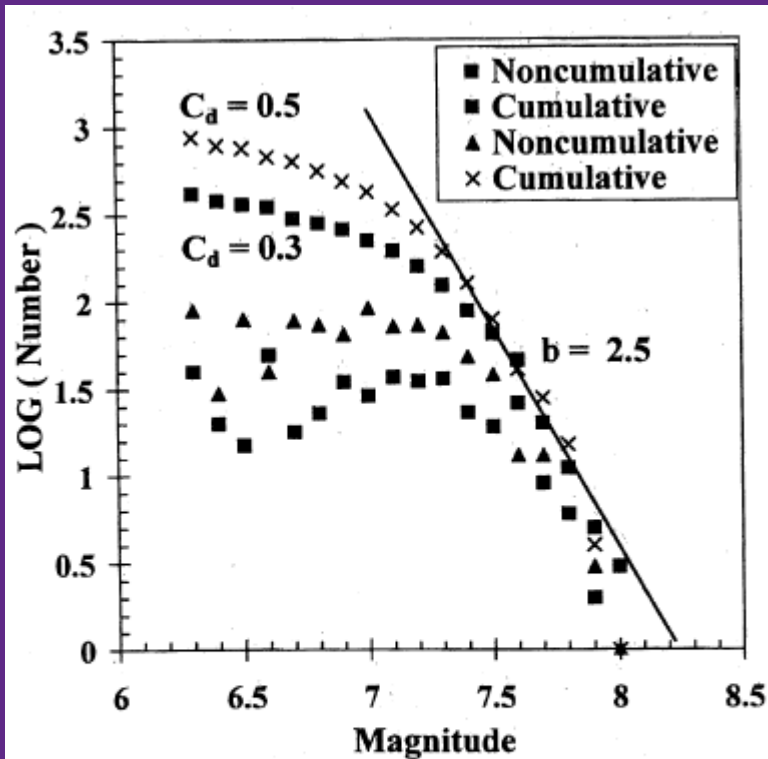


Figure 10. Frequency-size statistics of seismic events for medium damage healing and different damage rate constants C_d . The cumulative number of large events may be approximated by a linear relation with $b=2.5$, a value significantly larger than typically observed b values near unity.

Fast healing

ちょっぴり不均質

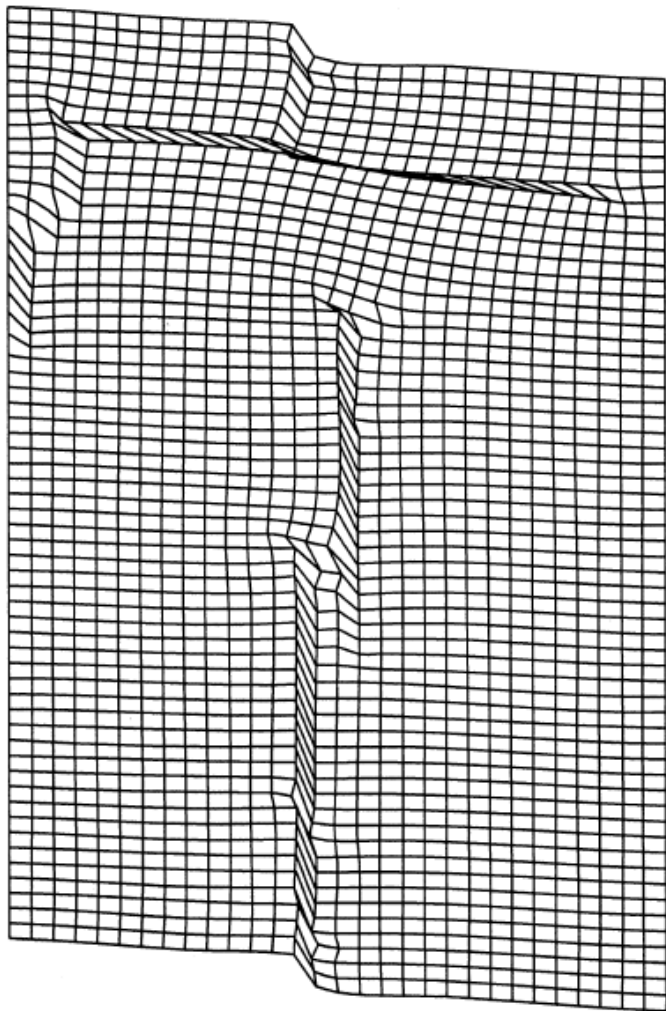


Figure 11. Cumulative strain for a model with fast healing. Large conjugate structures accommodate significant amount of displacement.

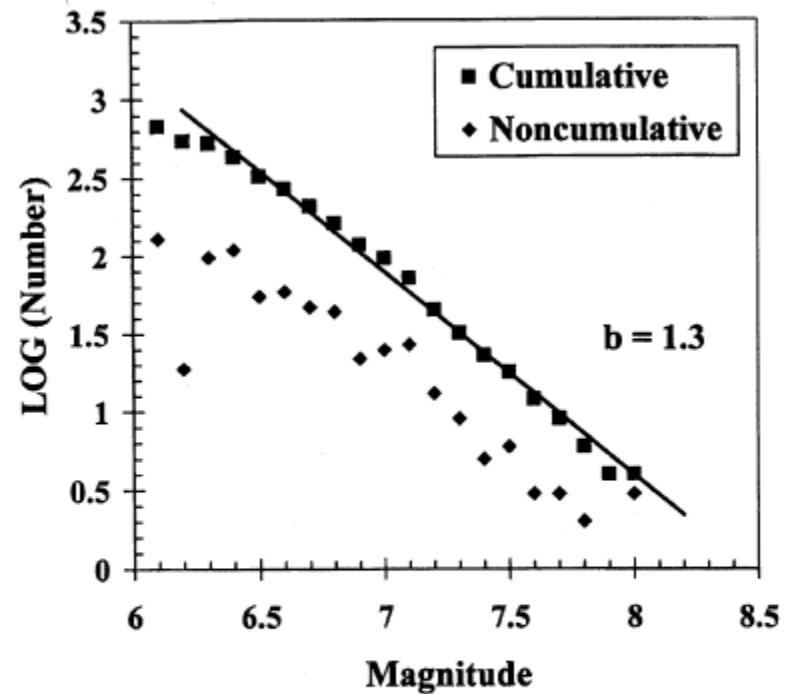


Figure 13. Frequency-size statistics of seismic events for fast damage healing and small spatial variations of material strength. The statistics are compatible with the Gutenberg-Richter power law distribution for the entire simulated magnitude range (compare with Figure 12).

Mode switching activity

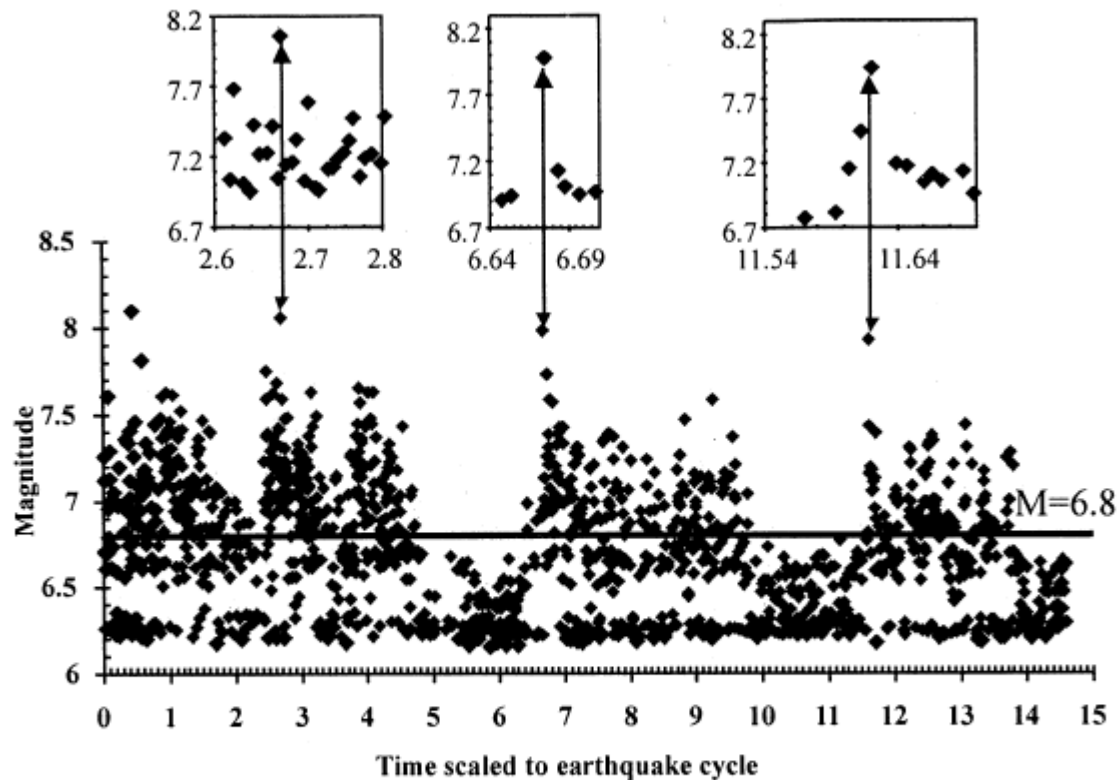


Figure 14. Seismicity record with mode-switching activity, consisting of time intervals of several large earthquake cycles with clusters of large events, separated by intervals of similar duration with only small and intermediate size earthquakes. The insets show a variety of different event sequences before and after the largest model earthquakes.

Discussion

- Generalized Elsassser modelを改良したHybrid modelによって
Preseismic, Coseismic, Postseismic, interseismic の4 stageを再現

- τ_h と断層運動、および地震活動との関係

τ_h/τ_L 大→Slow healing …断層運動は局所化。
小→Fast healing …無秩序な断層運動。リヒターに乗る。

- intermediateな大きさの τ_h/τ_L を通して地震活動が切り替わる。
Mode-switching activity