Special Subject: Postseismic Deformation

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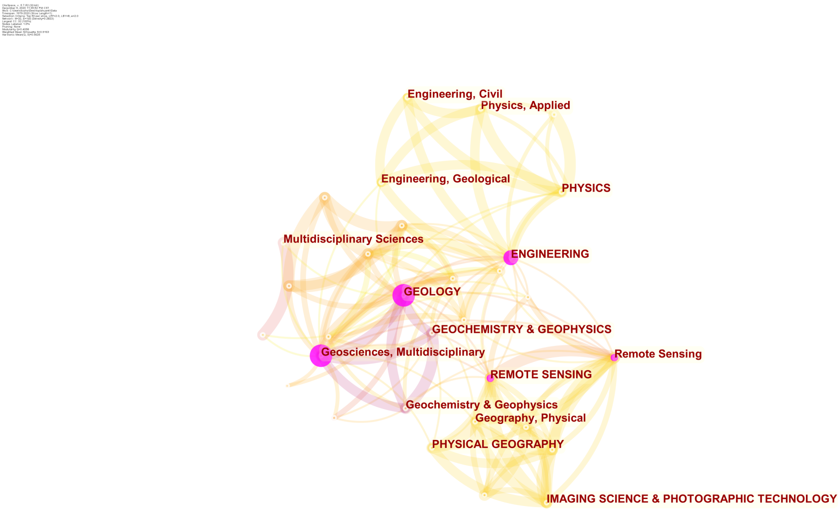
2021 年 1 月 5 日

Contents

CiteSpace:Categories



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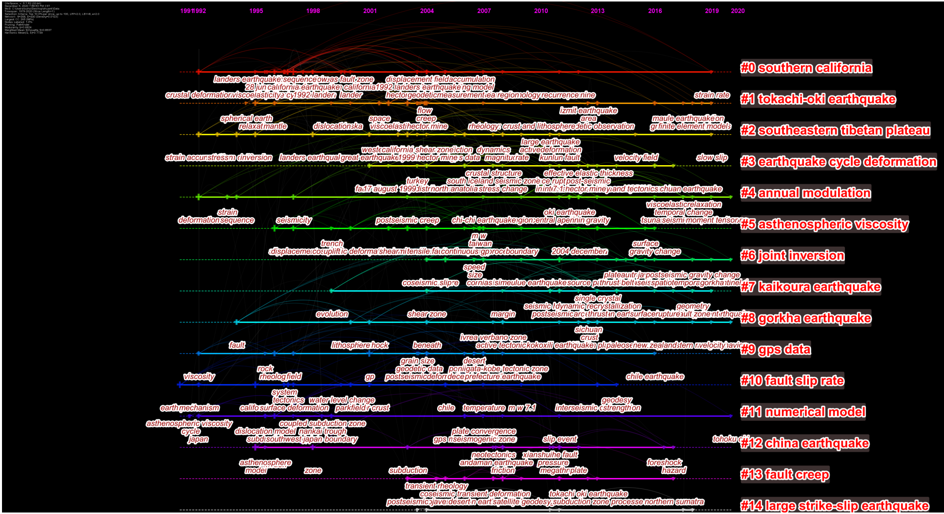

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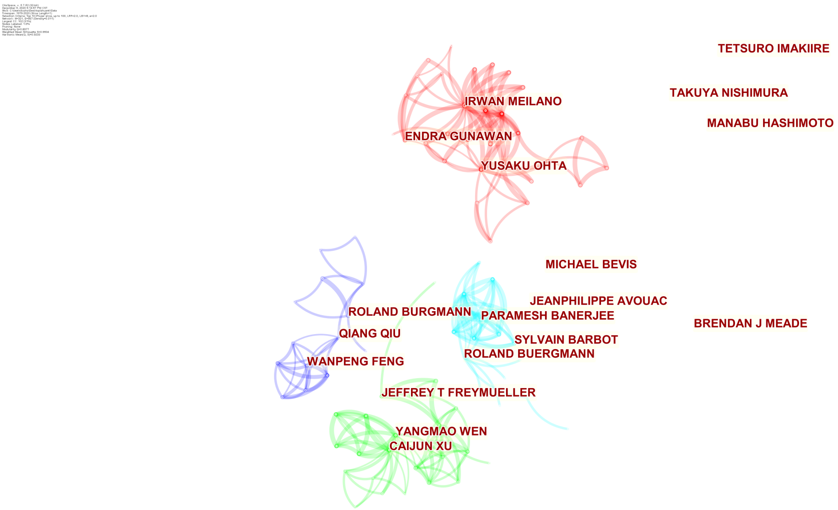
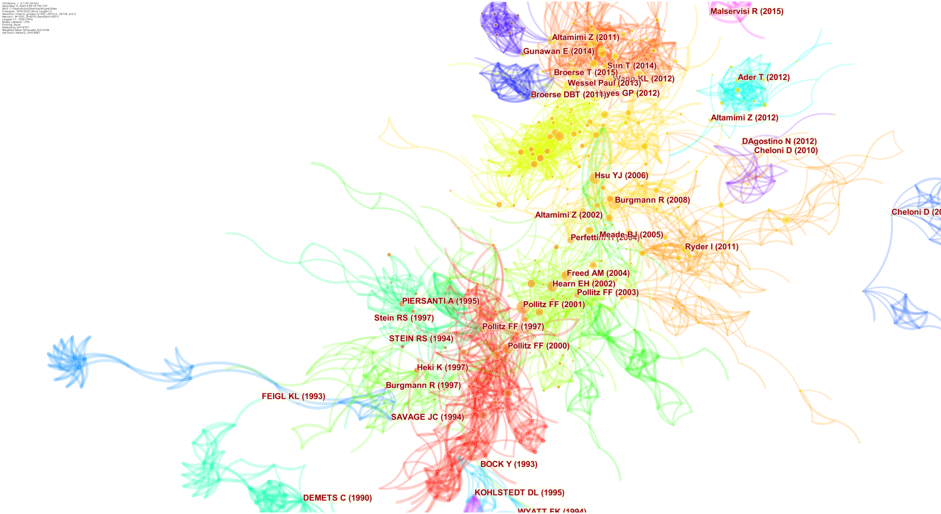


CiteSpace:References



Earthquake Cycle

The **earthquake cycle** is a theoretical framework used by earth scientists to describe the repeating process of tectonic stress accumulation between earthquakes and stress release during earthquake (Reid 1910; Boulton,2017).

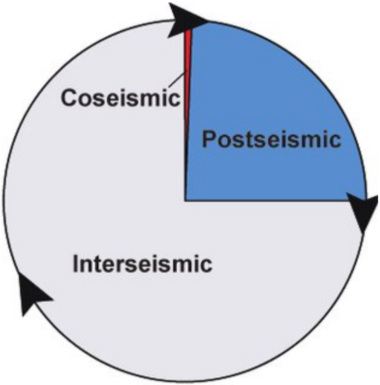


Figure: Schematic figure of the earthquake cycle

Earthquake Cycle

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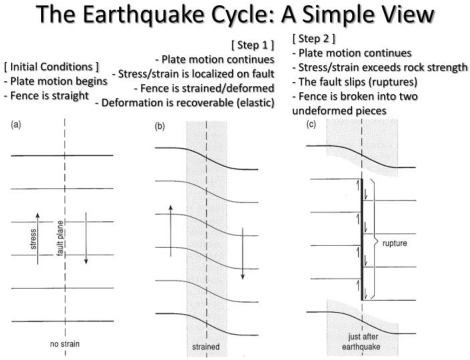

Figure: A simple view of the earthquake cycle

Postseismic Deformation

Immediately after the occurrence of the earthquake, the mechanism of stress release due to viscous flow in the ductile part of the Earth’s crust starts to operate, leading to **post-seismic deformation**.

The delayed deformation of the lithosphere caused by stress relaxation in the mantle or in the low viscosity layers of the crust is called **post-seismic deformation** (R. Sabadini & B. Vermeersen, 2004).

Viscoelasticity

黏弹性 (Viscoelasticity)：在外加载荷作用下，应变落后于应力的性质。

麦克斯韦模型 (Maxwell model):。一种用以描述固体物质黏弹性质由一个弹簧和一个阻尼器串联组成的简化的理论模型。麦克斯韦体对施加的力的短时间响应像弹性固体，而长时间响应则像黏滞流体。

开尔文 -沃伊特模型 (Kelvin-Voight model): 一种用以描述固体物质的黏弹性质，由一个弹簧和一个阻尼器并联组成的简化的理论模型。

标准线性固体 (standard linear solid): 性质介于弹性与黏滞性的非完全弹性体，其本构方程可以表示为应力、应力的一阶导数与应变、应变的一阶导数呈线性关系的、既有弹性响应又有黏性响应的介质。

Viscoelasticity

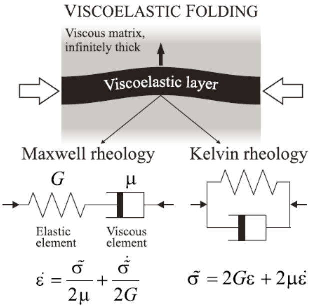

Figure: Sketch of viscoelastic folding and presentation of the two simplest viscoelastic rheologies: the Maxwell and the Kelvin rheology. In a Maxwell model strains are additive whereas in a Kelvin model stresses are additive. The equations are given for deviatoric stresses.(S.M. Schmalholz et al., 2001)

Viscoelasticity

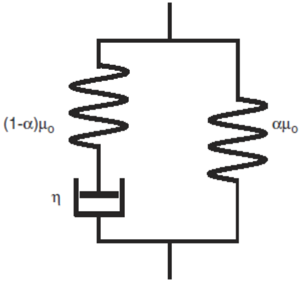

Figure: Model of SLS rheology(R. Wang et al., 2006)

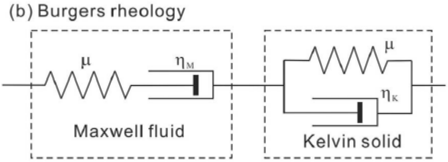

Figure: Cartoon illustration of the Burgers material consisting of the Maxwell fluid in series with the Kelvin solid.(Yan Hu et al., 2012)

Afterslip

Afterslip又称“后滑动事件 (post-seismic slip event)”。在一次大的构造地震 (突然的同震滑动) 后，断层的位移通过蠕滑增加，产生与主震相当的滑动量的现象。余滑可持续数年，小部分系由余震引起的，但大部分余滑的发生不产生地震波。余滑事件通常遵从大森定律 (Omori's law)。

大森定律 Omori’s law: 又称“大森关系式 (Omori's relation)”“双曲线定律 (hyperbolic law)”。日本大森房吉 (F. Omori) 于 1894 年得到的余震频次随时间呈反比衰减的定律。

Rate-and-state friction

At steady-state, both state evolution laws reduce θ to Dc/V, so that the steady-state coefficient of friction can be simply expressed as (M.P.A van den Ende et al., 2018):

$$\mu_{ss}(V) = \mu^* + (a - b) ln(\frac{V}{V^*})$$

1. The parameter (a—b) now describes the velocity-dependence of μ at steady-state, with **positive values** (i.e. a>b) resulting in **velocity strengthening**, and negative values resulting in velocity-weakening behaviour.
2. It has been demonstrated by Ruina (1983) that a material characterised by a negative (a—b) is prone to frictional instabilities, i.e. stick-slip behaviour, and thus it is assumed that **seismogenic fault segments exhibit a negative (a—b)**.
3. **Typical values for (a—b)** reported by experimental studies lie in the range of $\pm 10^{-3} - 10^{-2}$.

Poroelastic Rebound

After the earthquake, fluids will migrate from high-pressure areas to low pressure areas resulting in time-dependent surface deformation associated with **poroelastic rebound** (Peltzer et al., 1996, 1998; Yan Hu et al., 2014).

Significance

1. Understanding the mechanical strength (**rheology**) of the lithosphere and the processes that govern postseismic stress transfer is central to our **understanding of the earthquake cycle and seismic hazards** (Freed et al., 2006).
2. Inferences from postseismic studies provide insights into some of the most **basic properties of the lithosphere**, such as the constitutive properties and extent of faulting, the permeability of the crust and influence of fluid flow, the depth extent of the elastic portion of the crust, and the relative viscoelastic strength of the lower crust and upper mantle (Freed et al., 2006).
3. Important part of the **ITRF2014** (Altamimi et al., 2016).

Problems

1. List some of the **software** related to the postseismic deformation?
2. How to **extract** the 'pure' postseismic deformation?
3. How to get the **viscosity** or **frictional parameters**?

Software

Software	Earth structural parameters	Maxwell	Burgers	Power law constitutive relation	lateral inhomogeneous
VISCO1D	ρ, B, M, η	yes	yes	no	no
PSGRN/PSCMP	$(V_p, V_s), \rho, \eta$	yes	yes	no	no
RELAX	$\dot{\gamma}$	yes	no	yes	no
VISCO2.5D	$(V_p, V_s), \rho, \eta$	yes	yes	no	yes

Figure: 粘弹性松弛软件比较 (赵斌, 2017)

Software

Code Name	Type	Modeler Name & Group Members	References
SCycle	FDM	**abrahams** (Abrahams/ Allison/Dunham)	*Erickson and Dunham* (2014) *Allison and Dunham* (2018) `https://github.com/kali-allison/SCycle`
FDCycle	FDM	**erickson** (Erickson/Mckay)	*Erickson and Dunham* (2014) `https://github.com/brittany-erickson/FDCycle`
QDESDG	DG-FEM	**kozdon** (Kozdon)	`https://github.com/jkozdon/QDESDG`
Unicycle	BEM	**barbot** (Barbot)	*Barbot* (2019) `http://bitbucket.org/sbarbot`
FDRA	BEM	**cattania** (Cattania/Segall)	*Segall and Bradley* (2012b); *Bradley* (2014)
BICyclE	BEM	**jiang** (Jiang) **lambert** (Lambert/Lapusta) **xma** (Ma/Elbanna)	*Lapusta et al.* (2000); *Lapusta and Liu* (2009)
QDYN	BEM	**luo** (Luo/Idini/ van den Ende/Ampuero)	*Luo and Ampuero* (2017) `https://github.com/ydluo/qdyn`
ESAM	BEM	**liu** (Liu) **wei** (Wei/Shi)	*Liu and Rice* (2007)

Figure: Codes for simulating sequences of earthquake and aseismic slip (SEAS)(Erickson et al.,2019)

Extract the 'pure' postseismic deformation

The raw time series obtained from GPS observations usually contain various signals, such as: **offsets** related to earthquake or antenna/receiver changes; **secular velocities** due to plate motion or fault locking; **seasonal variations** which mainly come from hy-drological loading (Zhen Tian et al., 2020).

Extract the 'pure' postseismic deformation

- **Preprocessing** the data, such as eliminating outliers, repairing nonseismic offsets and correcting coseismic offsets.
- **Interpolating** the interseismic 3-D velocities of the stations installed after the mainshock. The computer code VISR (velocity interpolation for strain rate) developed by Shen et al. (2015) is applied to interpolate the inter-seismic velocities of those stations without preearthquake observations.
- Determining the **logarithmic relaxation time** after removing longterm trends and seasonal items.
- **Improving** the signal-to-noise ratio of postseismic displacements using the PCA algorithm. (Z.S. Jiang et al., 2018)

Extract the 'pure' postseismic deformation

$$y(t)_{preseismic} = A + Bt + Csin(2\pi t) + Dcos(2\pi t) + Esin(4\pi t) + Fcos(4\pi t) + H(t)$$

$$y(t)_{postseismic} = \alpha ln(1 + \frac{t}{\tau}) + \beta sin(2\pi t) + \gamma cos(2\pi t) + H(t) + \delta$$

(Ingleby et al., 2020)

Extract the 'pure' postseismic deformation

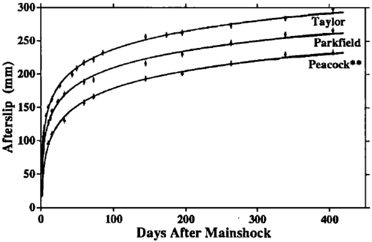

Figure: "**Transient after slip creep**" behavior [Marone et al., 1991; Perfettini and Avouac, 2004; Savage et al., 2005] tending to follow a **logarithmic** function.

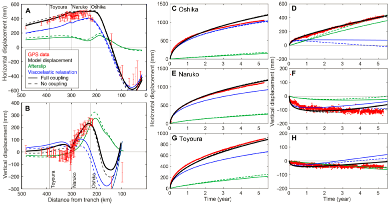

Figure: "**Viscoelastic relaxation**" type [Savage and Prescott, 1978; Pollitz, 1997] that is better described by an **exponential** decay (Muto et al., 2019).

Viscosity or frictional parameters

1. Trial and error method
2. Grid search method
3. ABIC
4. Adjoint method

Viscosity or frictional parameters

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 117, B12405, doi:10.1029/2012JB009571, 2012

Postseismic deformation following the 1999 Chi-Chi earthquake, Taiwan: Implication for lower-crust rheology

Baptiste Rousset,[1,2] Sylvain Barbot,[1,3] Jean-Philippe Avouac,[1] and Ya-Ju Hsu[4]

Received 26 June 2012; revised 18 October 2012; accepted 24 October 2012; published 15 December 2012.

[1] On 1999 September 21, the Mw 7.6 Chi-Chi earthquake ruptured a segment of the Chelungpu Fault, a frontal thrust fault of the Western Foothills of Taiwan. The stress perturbation induced by the rupture triggered a transient deformation across the island, which was well recorded by a wide network of continuously operating GPS stations. The analysis of more than ten years of these data reveals a heterogeneous pattern of postseismic displacements, with relaxation times varying by a factor of more than ten, and large cumulative displacements at great distances, in particular along the Longitudinal Valley in eastern Taiwan, where relaxation times are also longer. We show that while afterslip is the dominant relaxation process in the epicentral area, viscoelastic relaxation is needed to explain the pattern and time evolution of displacements at the larger scale. We model the spatiotemporal behavior of the transient deformation as the result of afterslip on the décollement that extends downdip of the Chelungpu thrust, and viscoelastic flow in the lower crust and in the mid-crust below the Central Range. We construct a model of deformation driven by coseismic stress change where afterslip and viscoelastic flow are fully coupled. The model is compatible with the shorter relaxation times observed in the near field, which are due to continued fault slip, and the longer characteristic relaxation times and the reversed polarity of vertical displacements observed east of the Central Range. Our preferred model shows a viscosity of 0.5–1 $\times$ 10^{19} Pa s at lower-crustal depths and 5 $\times$ 10^{17} Pa s in the mid-crust below the Central Range, between 10 and 30 km depth. The low-viscosity zone at mid-crustal depth below the Central Range coincides with a region of low seismicity where rapid advection of heat due to surface erosion coupled with underplating maintain high temperatures, estimated to be between 300°C and 600°C from the modeling of thermo-chronology and surface heat flow data.

Citation: Rousset, B., S. Barbot, J.-P. Avouac, and Y.-J. Hsu (2012), Postseismic deformation following the 1999 Chi-Chi earthquake, Taiwan: Implication for lower-crust rheology, *J. Geophys. Res.*, *117*, B12405, doi:10.1029/2012JB009571.

Figure: Trial and error method

Viscosity or frictional parameters

Geophysical Journal International

Geophys. J. Int. (2014) **196,** 218–229
Advance Access publication 2013 October 15

doi: 10.1093/gji/ggt376

Overlapping post-seismic deformation processes: afterslip and viscoelastic relaxation following the 2011 M_w 9.0 Tohoku (Japan) earthquake

Faqi Diao,[1] Xiong Xiong,[1] Rongjiang Wang,[2] Yong Zheng,[1] Thomas R. Walter,[2] Huihui Weng[3] and Jun Li[1]

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Accepted 2013 September 16. Received 2013 September 9; in original form 2013 March 27

Figure: Grid search method

Viscosity or frictional parameters

Tomita *et al. Earth, Planets and Space* (2020) 72:84
https://doi.org/10.1186/s40623-020-01207-0
Earth, Planets and Space

FULL PAPER **Open Access**

Improvement on spatial resolution of a coseismic slip distribution using postseismic geodetic data through a viscoelastic inversion

Fumiaki Tomita[1*], Takeshi Iinuma[1], Yusaku Ohta[2], Ryota Hino[2], Motoyuki Kido[3] and Naoki Uchida[2]

Figure: ABIC

$$\begin{pmatrix} \mathbf{d}_{\mathrm{c}} \\ \mathbf{d}_{\mathrm{p}_1} \\ \mathbf{d}_{\mathrm{p}_2} \\ \vdots \\ \mathbf{d}_{\mathrm{p}_K} \end{pmatrix} = \begin{pmatrix} \mathbf{G}_{\mathrm{e}} & & \cdots & & \mathbf{0} \\ \hat{\mathbf{G}}_{\mathrm{v}_{1,0}} & \mathbf{G}_{\mathrm{e}} & & & \\ \hat{\mathbf{G}}_{\mathrm{v}_{2,0}} & \hat{\mathbf{G}}_{\mathrm{v}_{2,1}} & \mathbf{G}_{\mathrm{e}} & & \vdots \\ \vdots & \vdots & & \ddots & \\ \hat{\mathbf{G}}_{\mathrm{v}_{K,0}} & \hat{\mathbf{G}}_{\mathrm{v}_{K,1}} & \cdots & \hat{\mathbf{G}}_{\mathrm{v}_{K,K-1}} & \mathbf{G}_{\mathrm{e}} \end{pmatrix} \times \begin{pmatrix} \mathbf{a}_{\mathrm{c}} \\ \hat{\mathbf{a}}_{\mathrm{p}_1} \\ \hat{\mathbf{a}}_{\mathrm{p}_2} \\ \vdots \\ \hat{\mathbf{a}}_{\mathrm{p}_K} \end{pmatrix} + \begin{pmatrix} \mathbf{e}_{\mathrm{c}} \\ \mathbf{e}_{\mathrm{p}_1} \\ \mathbf{e}_{\mathrm{p}_2} \\ \vdots \\ \mathbf{e}_{\mathrm{p}_K} \end{pmatrix}. \tag{13}$$

Figure: Model

Viscosity or frictional parameters

Kano et al. Earth, Planets and Space (2020) 72:159
https://doi.org/10.1186/s40623-020-01293-0
Earth, Planets and Space
FULL PAPER Open Access

Adjoint-based direct data assimilation of GNSS time series for optimizing frictional parameters and predicting postseismic deformation following the 2003 Tokachi-oki earthquake

Masayuki Kano[1*], Shin'ichi Miyazaki[2], Yoichi Ishikawa[3] and Kazuro Hirahara[4,5]

Figure: Adjoint method

Geophysical Journal International
Geophys. J. Int. (2017) **208,** 845–876 doi: 10.1093/gji/ggw414
Advance Access publication 2016 November 5
GJI Gravity, geodesy and tides

Forward and inverse modelling of post-seismic deformation

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Accepted 2016 November 4. Received 2016 October 17; in original form 2016 June 3

SUMMARY
We consider a new approach to both the forward and inverse problems in post-seismic deformation. We present a method for forward modelling post-seismic deformation in a self-gravitating, heterogeneous and compressible earth with a variety of linear and nonlinear rheologies. We further demonstrate how the adjoint method can be applied to the inverse problem both to invert for rheological structure and to calculate the sensitivity of a given surface measurement to changes in rheology or time-dependence of the source. Both the forward and inverse aspects are illustrated with several numerical examples implemented in a spherically symmetric earth model.

Key words: Numerical solutions; Inverse theory; Transient deformation; Dynamics of lithosphere and mantle.

Figure: Adjoint method

1. Develop **softwares** that simulate the postseismic deformation
2. Compare the methods of **extracting 'pure'** postseismic deformation
3. Propose **new methods or ways to invert** for the viscosity and frictional parameters
4. Analyse the postseismic deformation to find **new phenomenon or knowledge**.

Problems

1. Could we use the postseismic deformation to **constraint the fault geometry**?
2. How to **seperate** the effect of various postseismic mechanisms?
3. What is the **relationship** among the coseismic slip distribution, afterslip distribution, and occurrence of aftershocks?
4. When do viscoelastic relaxation and afterslip **begin** and **how long** will they last in near- and far-field?
5. Is the friction properties of the fault **stationary**?

- Postseisimic Deformation
  - Afterslip
    - Stress driven afterslip model
      - Frictional afterslip model(marone et al,1991)
      - Frictionless afterslip model(Huang et al.(2014)
    - Kinematic Afterslip model
      - Shear band low viscosity sheet model(Hearn et al.(2002))
  - Viscoelastic Relaxation
    - Analytical method
      - RELAX (Sylvain Barbot, 2014)
      - VISCO1D /VISCO2.5D(Pollitz,1997,2014)
      - PSGRN/PSCMP(Wang et al,2006)
    - Finite element method
      - PYLITH (Aagaard Brad, 2014)
      - COMSOL Multiphysics
      - ......
  - Poroelastic Rebound
    - Common poroelastic rebound(Jonsson et al., 2014)
    - Stratified poroelastic rebound(Hu et al.,2014)
  - Unified Model
    - 3D FEM VR +Shear zone with low viscosity sheet stress driven Afterslip model.(Hu et al. (2016))
    - Longitudinal stratified VR + FAM(Rousset et al.(2012))
    - Longitudinal stratified VR + KAM(Huang et al.(2016))
    - PB + Kinematic Afterslip model.(Fialko (2004))

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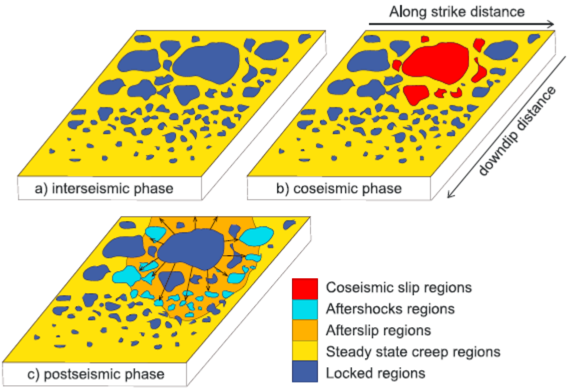

Figure 1. Schematic sketch of the model: (a) During the interseismic phase, a population of asperities (dark blue patches) are loaded by the surrounding interseismic creep (yellow region), occurring at a steady state (plate) velocity; (b) during the coseismic phase, some asperities slip coseismically (red patches), transferring large positive Coulomb stress into the nearby creeping regions; (c) during the postseismic phase, the creeping regions loaded by the mainshock show large amount of afterslip (orange region). As this afterslip increases along the fault with time, aftershocks (light blue) are produced accordingly when a significant amount of afterslip (of the order of U_a given in equation (19)) is reached. The black vectors describe the afterslip migration.

Figure: H. Perfettini et al., 2018. A model of aftershock migration driven by afterslip. GRL.

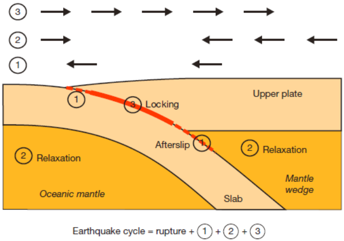

Figure 2 | Three primary processes after a subduction earthquake. (1) Aseismic afterslip occurs mostly around the rupture zone, (2) the coseismically stressed mantle undergoes viscoelastic relaxation, and (3) the fault is relocked. Arrows at the top show the sense of horizontal motion of Earth's surface, relative to distant parts of the upper plate, caused by each of these three processes.

Figure: Kelin Wang et al., 2012. Deformation cycles of subduction earthquakes in a viscoelastic earth. Nature.

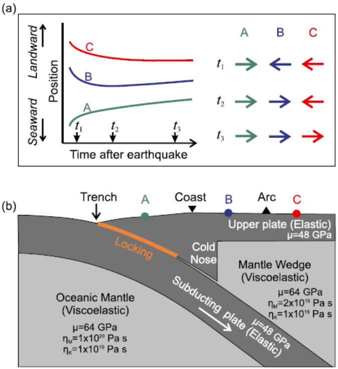

Figure: Haipeng Luo et al., 2020. EPSL

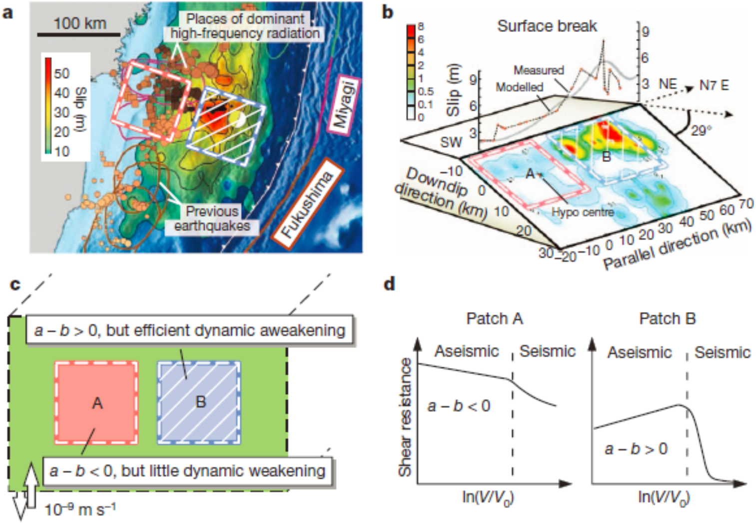

Figure: Noda et al., 2013. Nature.