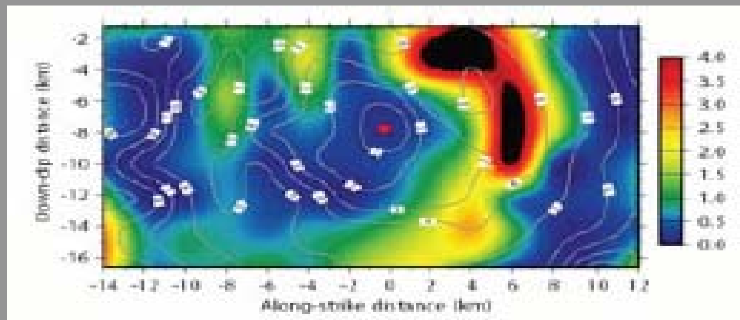
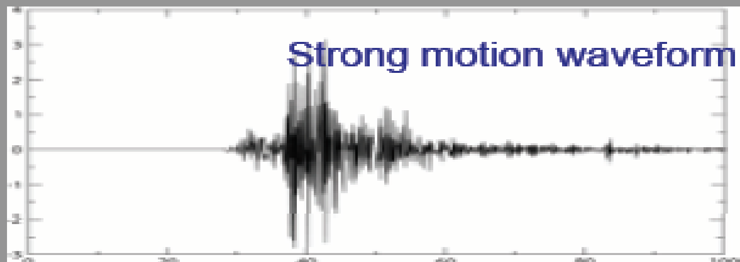
Fault governing laws
(constitutive equations)

Seismologists need traction

- ✓ To apply fracture mechanics on mathematical planes representing the fault surfaces;
- ✓ To numerically simulate the spontaneous rupture nucleation, propagation, healing and arrest in dynamic earthquake models;

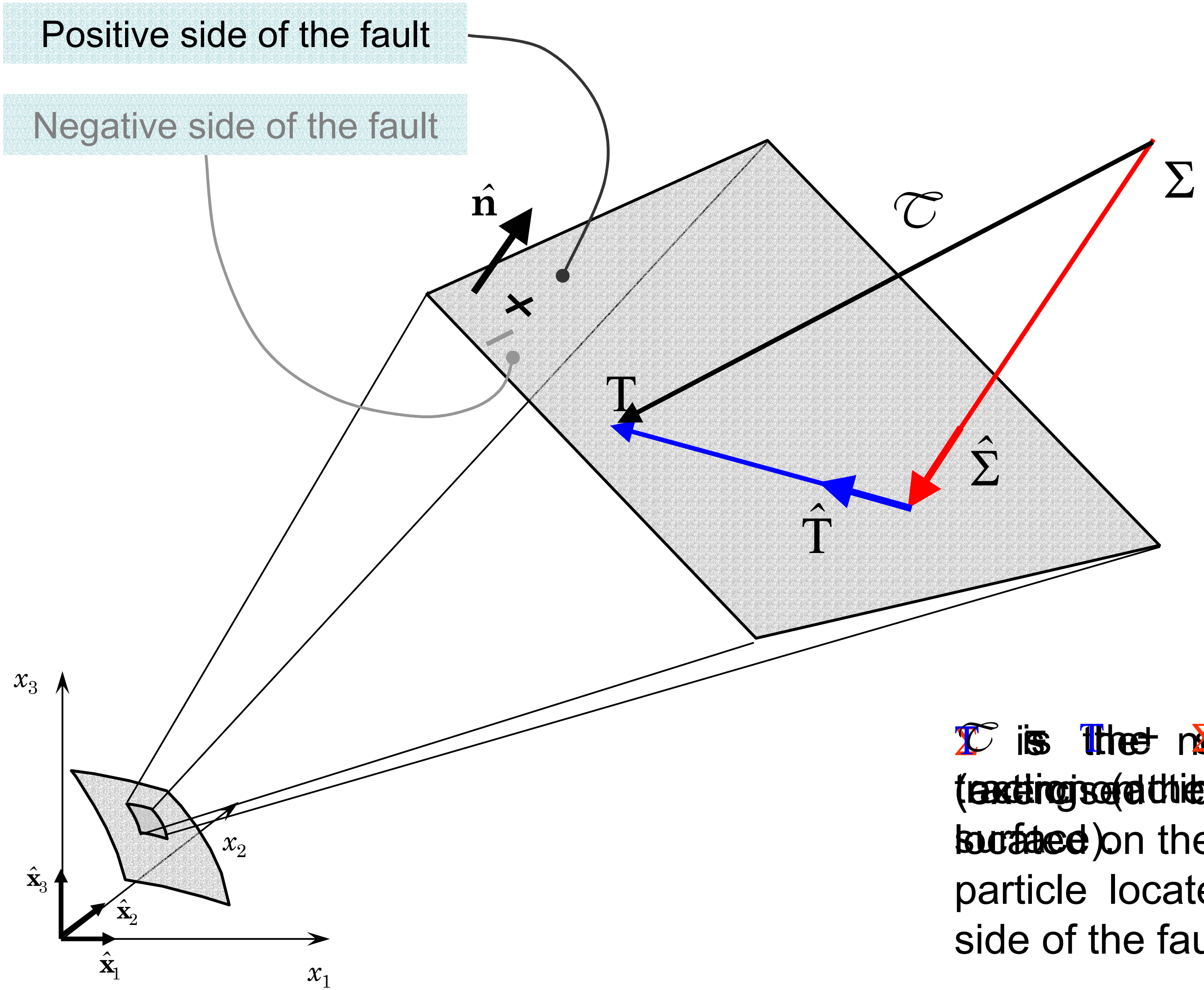


- ✓ To model seismic wave propagation in the surrounding medium;



- ✓ To predict ground shaking.

Notations and symbols



on the +ve side on a particle located on the –ve side of the fault surface)

$\mathcal{T}^{(\hat{\mathbf{n}})} = \mathrm{T}^{(\hat{\mathbf{n}})} + \Sigma^{(\hat{\mathbf{n}})}$ <u>total</u> traction (acting on the fault surface).

$\mathcal{T}_j^{(\hat{\mathbf{n}})} = n_i \sigma_{ij}^{eff}$ *Cauchy*' s formula, where $\mathcal{T}^{(\hat{\mathbf{n}})} = (\mathcal{T}_1^{(\hat{\mathbf{n}})}, \mathcal{T}_2^{(\hat{\mathbf{n}})}, \mathcal{T}_3^{(\hat{\mathbf{n}})})$,

$\mathbf{n} = (n_1, n_2, n_3)$ and

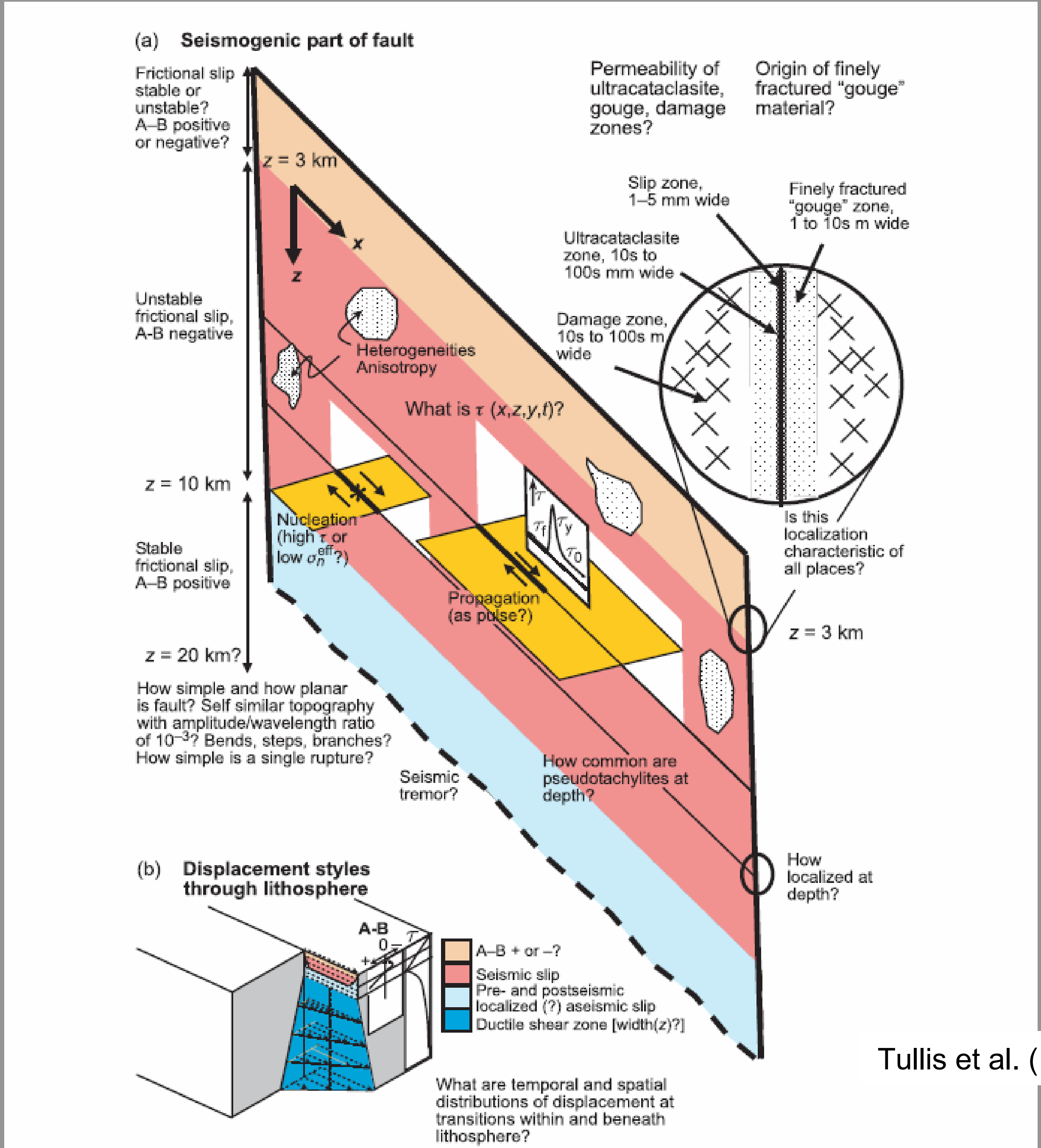
$$\sigma_{ij}^{eff} = \sigma_{ij} + p_{fluid}\,\delta_{ij} = \begin{bmatrix} -\sigma_{n_1}^{\ eff} & \sigma_{12} & \sigma_{13} \\ \sigma_{12} & -\sigma_{n_2}^{\ eff} & \sigma_{23} \\ \sigma_{13} & \sigma_{23} & -\sigma_{n_3}^{\ eff} \end{bmatrix}$$

where: $\sigma_{n_i}^{eff} = \sigma_{n_i} - p_{fluid} = -\sigma_{ii} - p_{fluid}$ *and stresses are assumed to be negative for compression*

$T_j^{(\hat{\mathbf{n}})} = n_i \sigma_{ij}^{eff} - n_j (n_i \sigma_{ik}^{eff} n_k)$ <u>shear</u> traction

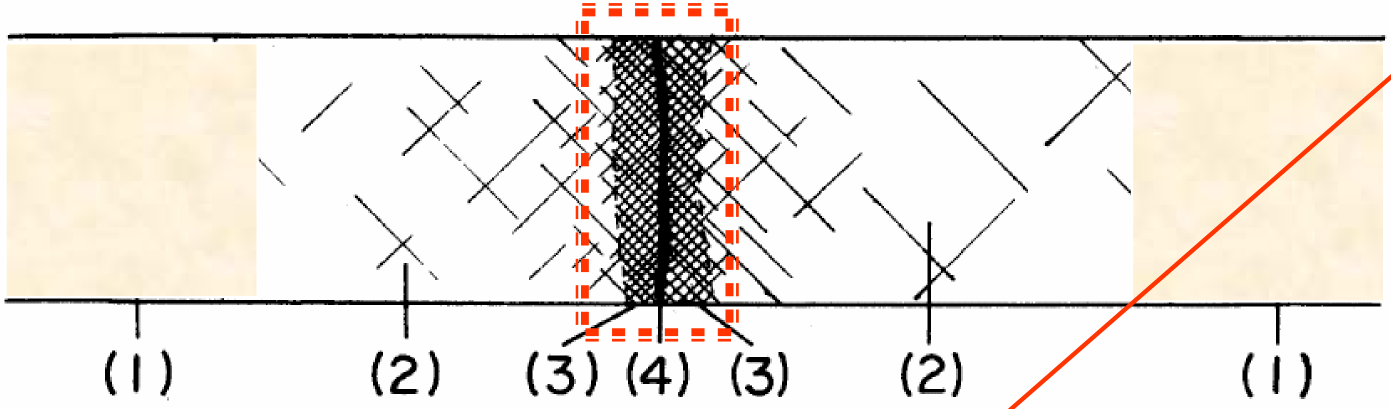
$\Sigma_j^{(\hat{\mathbf{n}})} = n_j (n_i \sigma_{ik}^{eff} n_k)$ <u>normal</u> traction

Fault models



Tullis et al. (2007, *MIT Press*)

Internal Structure of Principal Faults of the North Branch San Gabriel Fault



1) Undeformed Host Rock

Fault Zone {
2) Damaged Host Rock
3) Foliated Zone
4) Central ultracataclasite layer
} Fault Core

30 - 100 m (Damage ≈ *highly cracked rock*)

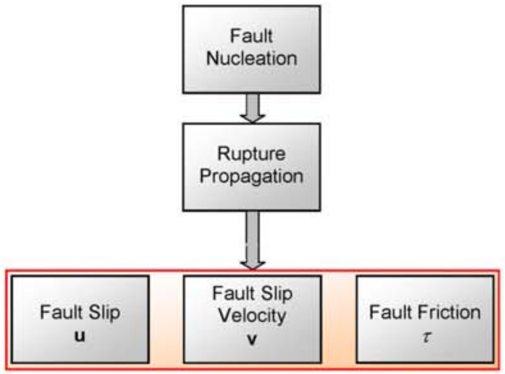
1 - 10 m (*foliated gouge* or *gouge*)

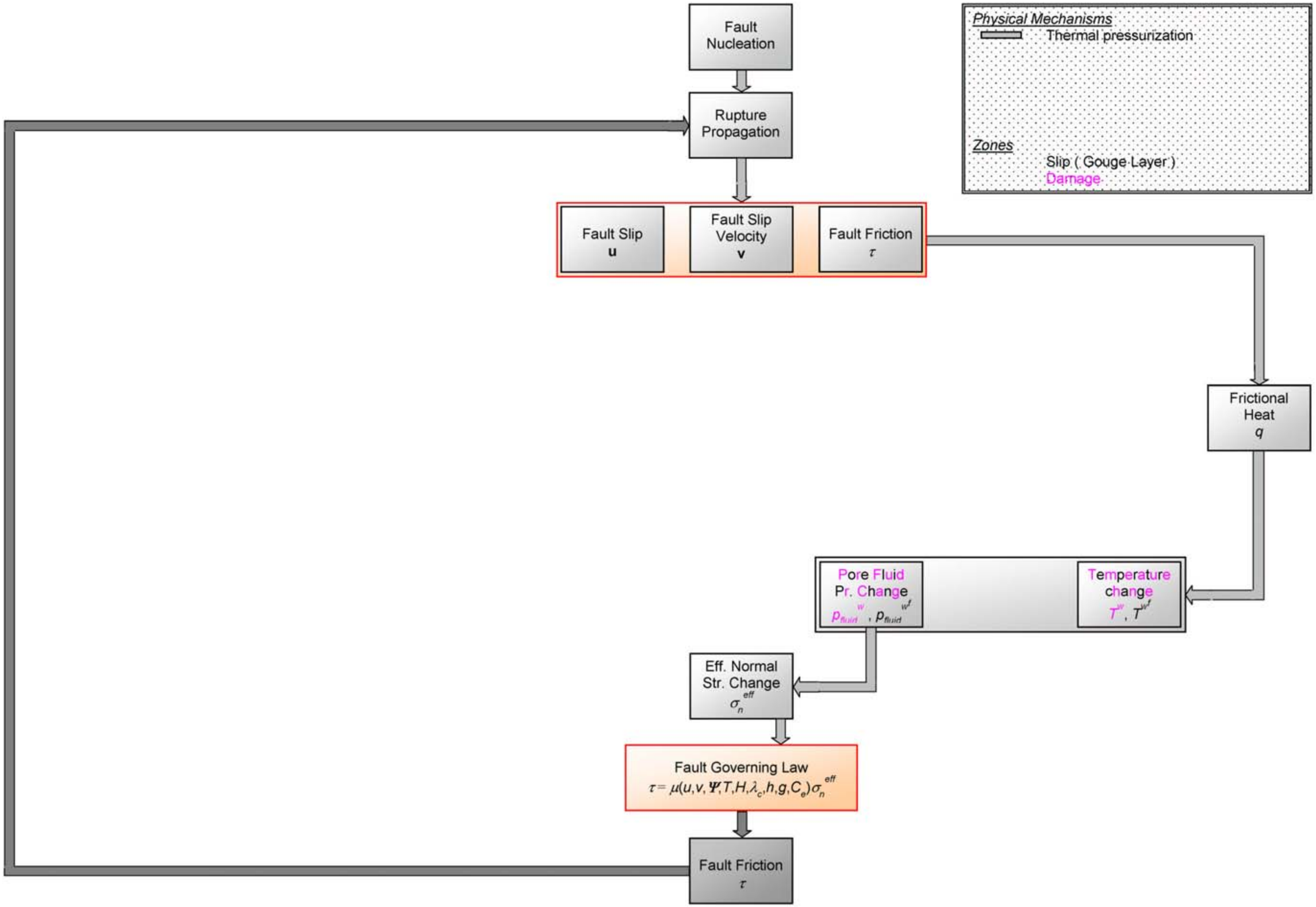
10s - 100s mm (containing the ***principal slipping zone***, *which* is *much thinner*, typically < 5 mm)

Fig. 2. Schematic section across the North Branch San Gabriel fault zone illustrating position of the structural zones of the fault. The diagram is not to scale.

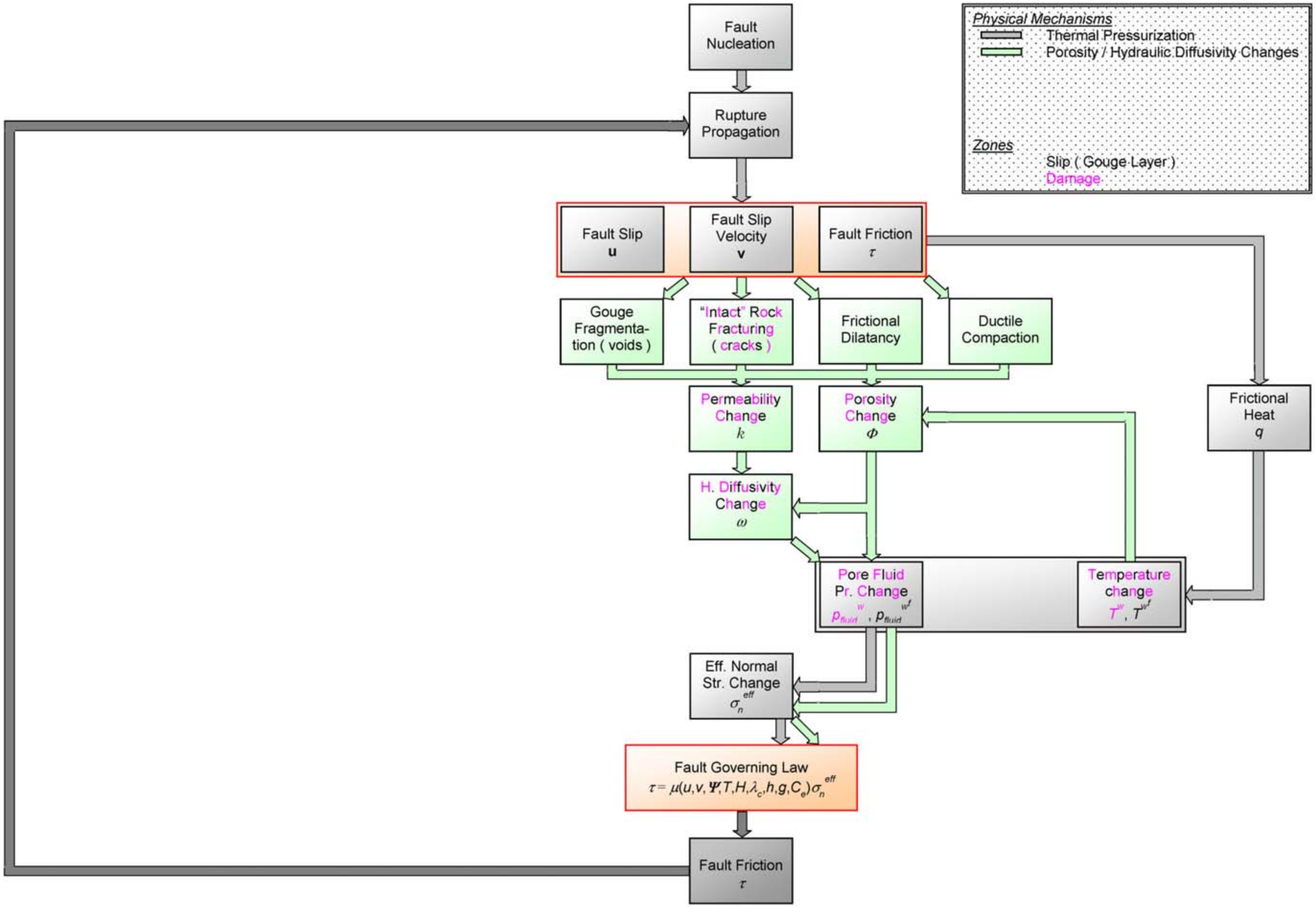
Chester, Evans and Biegel, *J. Geoph. Res.*,1993
Sibson, BSSA, 2003
Chester and Chester, SSA, SCEC meetings 2004

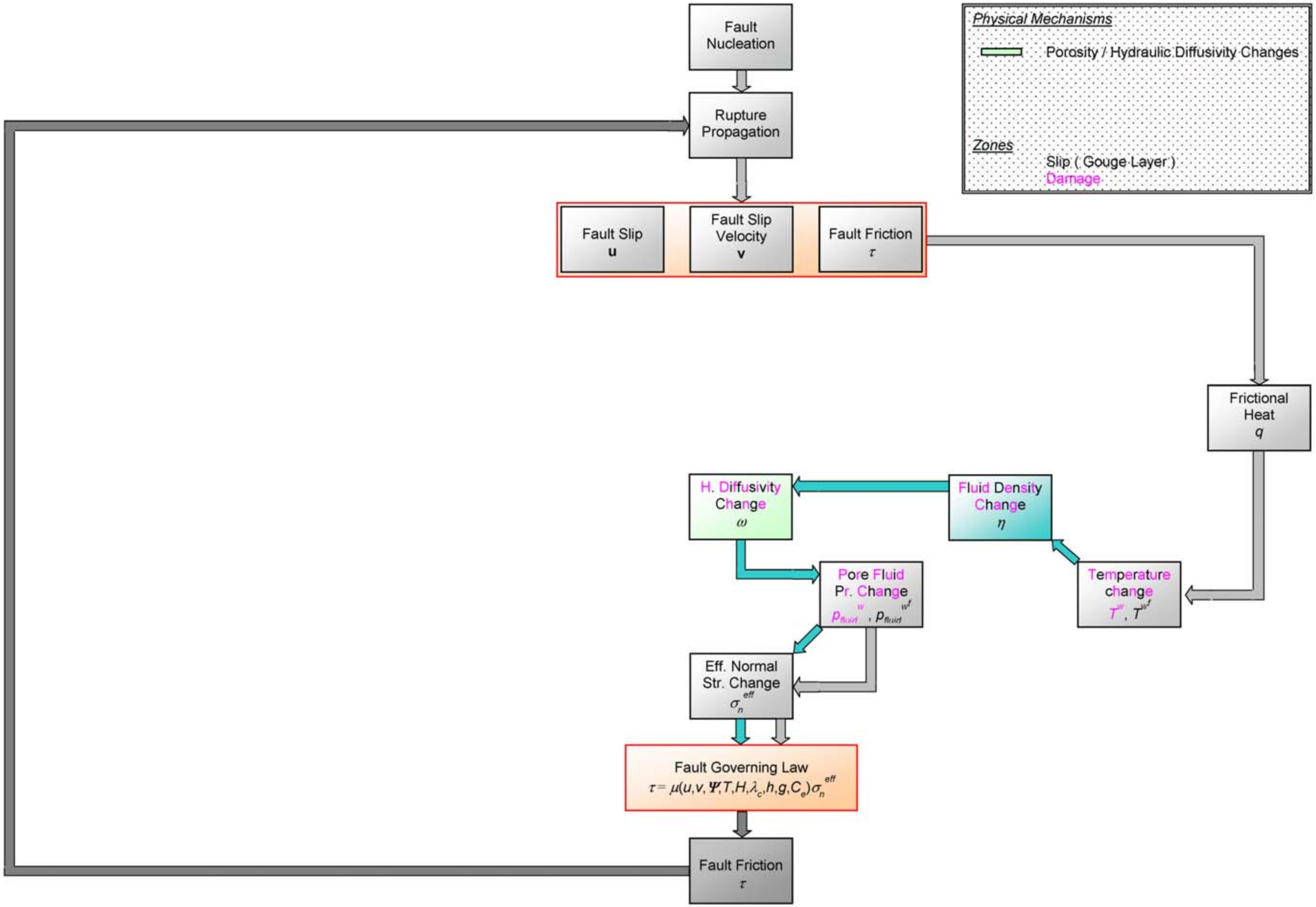
Physical Phenomena in Faulting



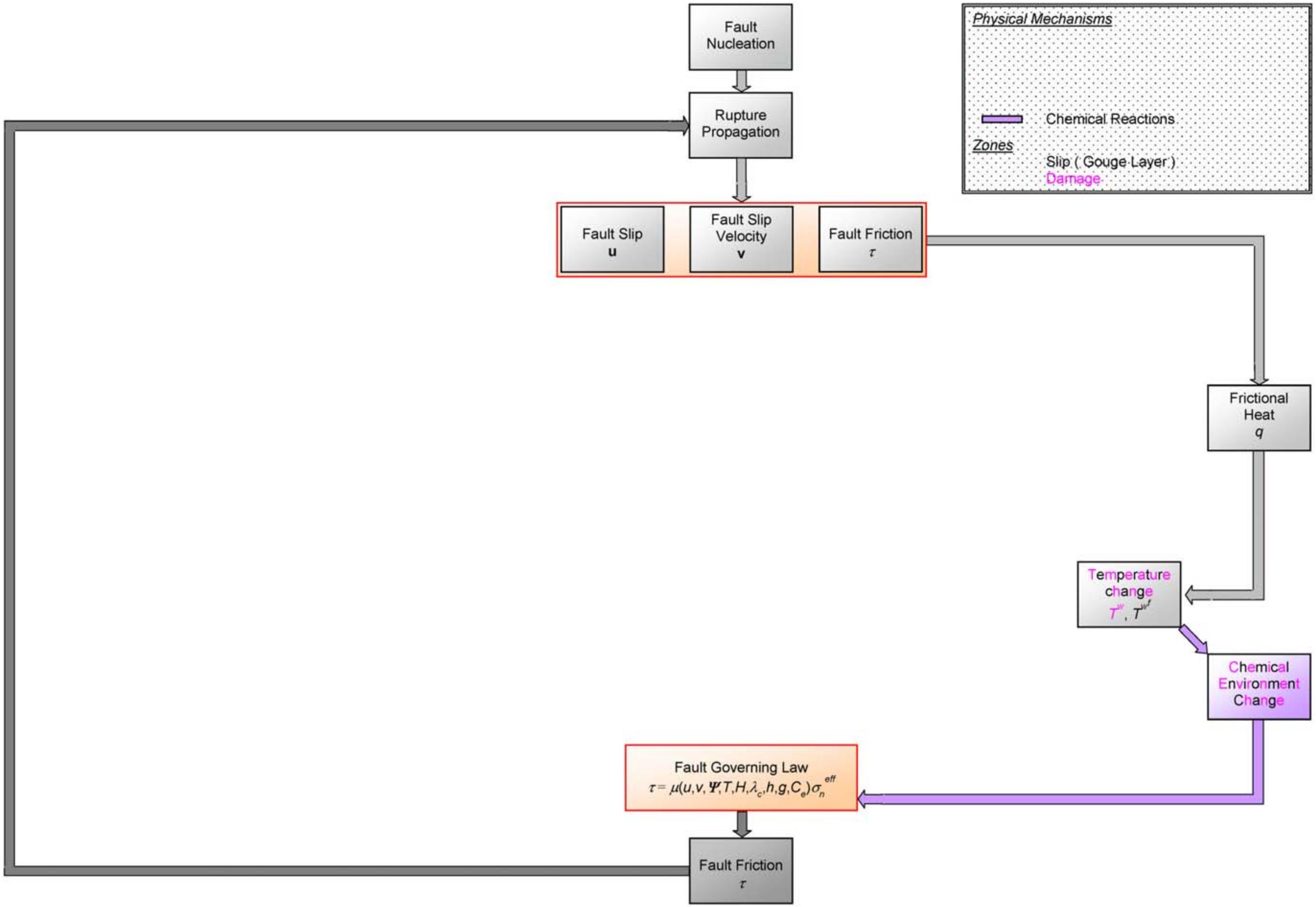


Physical Mechanisms
Thermal pressurization
Zones
Slip (Gouge Layer)
Damage
Fault Nucleation
Rupture Propagation
Fault Slip u
Fault Slip Velocity v
Fault Friction τ
Frictional Heat q
Pore Fluid Pr. Change
Temperature change
Eff. Normal Str. Change
Fault Governing Law
τ = μ(u,v,Ψ,T,H,λc,h,g,Ce)σn eff
Fault Friction τ

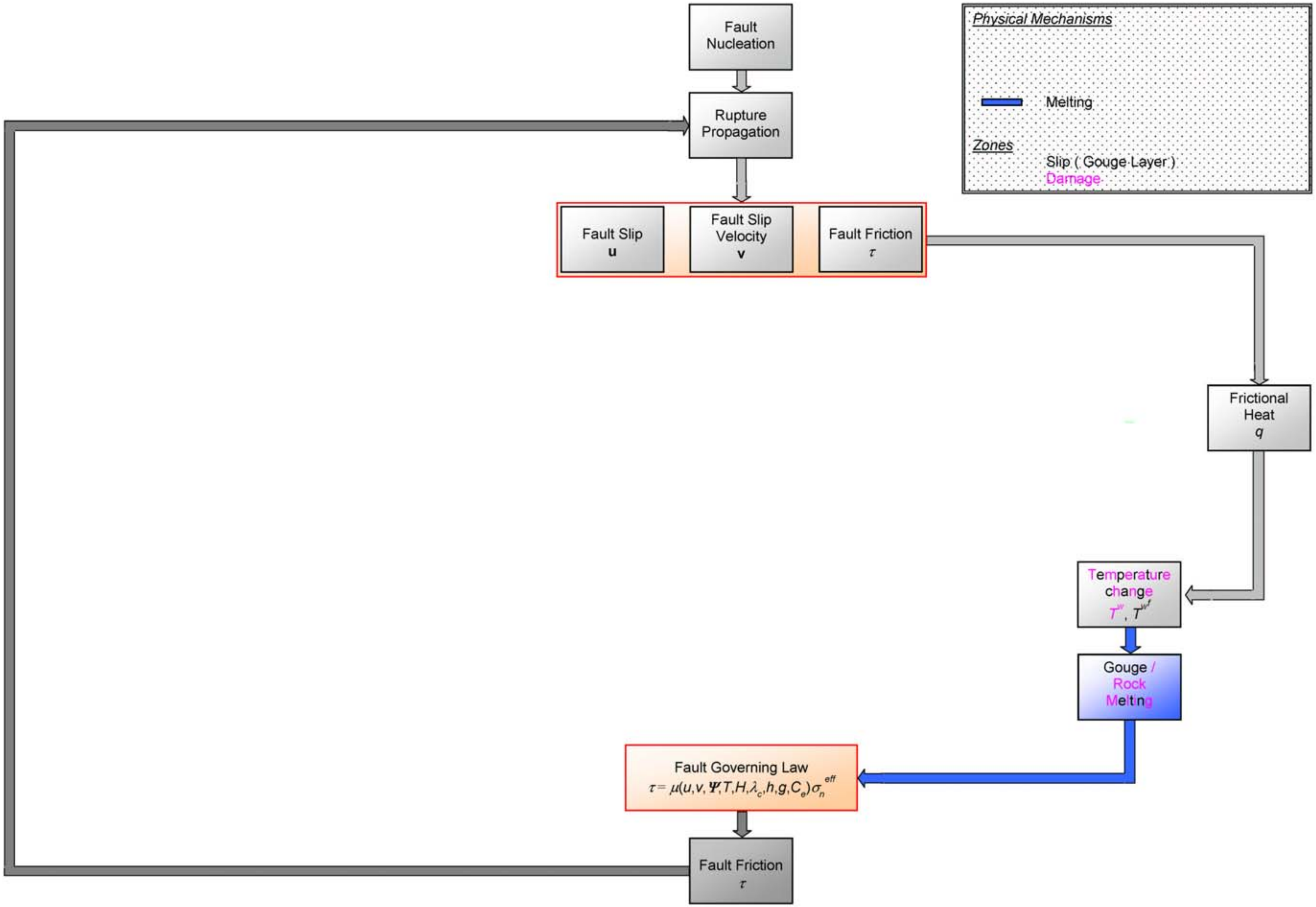

Physical Mechanisms
Thermal Pressurization
Porosity / Hydraulic Diffusivity Changes
Zones
Slip (Gouge Layer)
Damage
Fault Nucleation
Rupture Propagation
Fault Slip u
Fault Slip Velocity v
Fault Friction τ
Gouge Fragmenta-tion (voids)
"Intact" Rock Fracturing (cracks)
Frictional Dilatancy
Ductile Compaction
Permeability Change k
Porosity Change Φ
Frictional Heat q
H. Diffusivity Change ω
Pore Fluid Pr. Change
Temperature change
Eff. Normal Str. Change
Fault Governing Law
Fault Friction τ



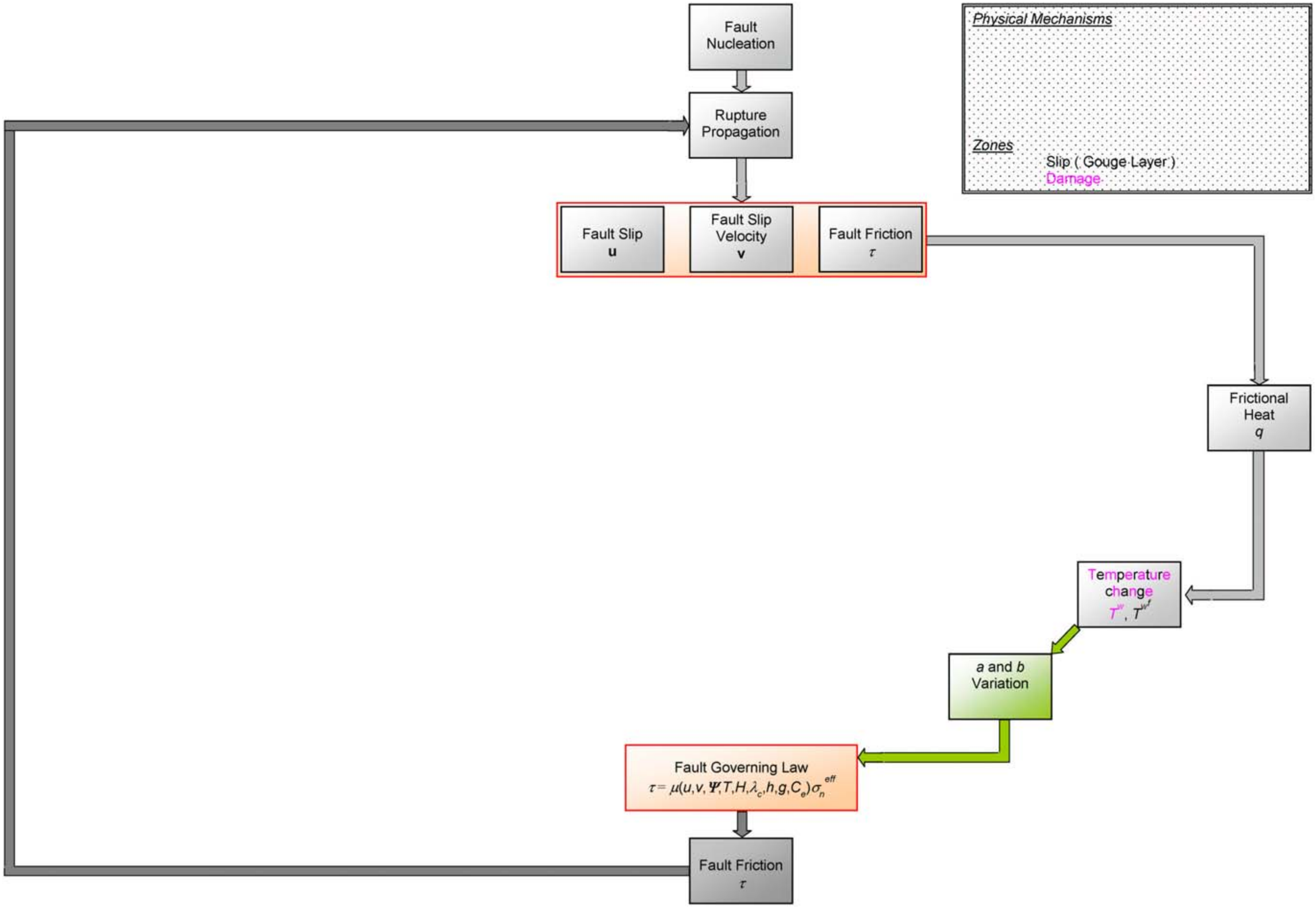
Fault Nucleation
Rupture Propagation
Fault Slip u
Fault Slip Velocity v
Fault Friction τ
Physical Mechanisms
Porosity / Hydraulic Diffusivity Changes
Zones
Slip (Gouge Layer)
Damage
Frictional Heat q
Temperature change T^w, T^{wf}
Fluid Density Change η
H. Diffusivity Change ω
Pore Fluid Pr. Change p_{fluid}^w, p_{fluid}^{wf}
Eff. Normal Str. Change σ_n^{eff}
Fault Governing Law
$\tau = \mu(u, v, \Psi, T, H, \lambda_c, h, g, C_e)\sigma_n^{eff}$
Fault Friction τ



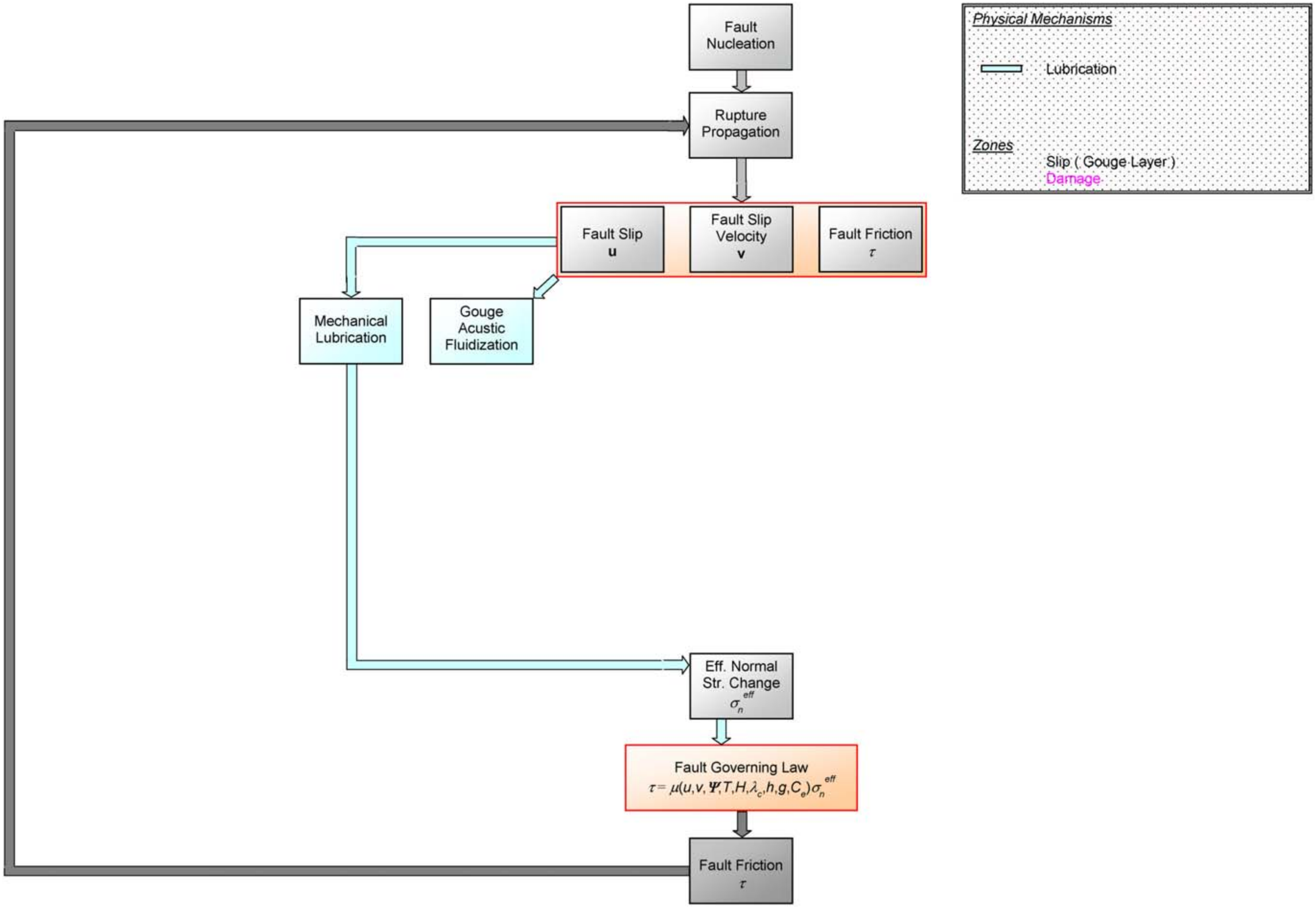
Fault Nucleation
Rupture Propagation
Fault Slip u
Fault Slip Velocity v
Fault Friction τ
Physical Mechanisms
Chemical Reactions
Zones
Slip (Gouge Layer)
Damage
Frictional Heat q
Temperature change
Chemical Environment Change
Fault Governing Law
$\tau = \mu(u, v, \Psi, T, H, \lambda_c, h, g, C_e)\sigma_n^{eff}$
Fault Friction τ



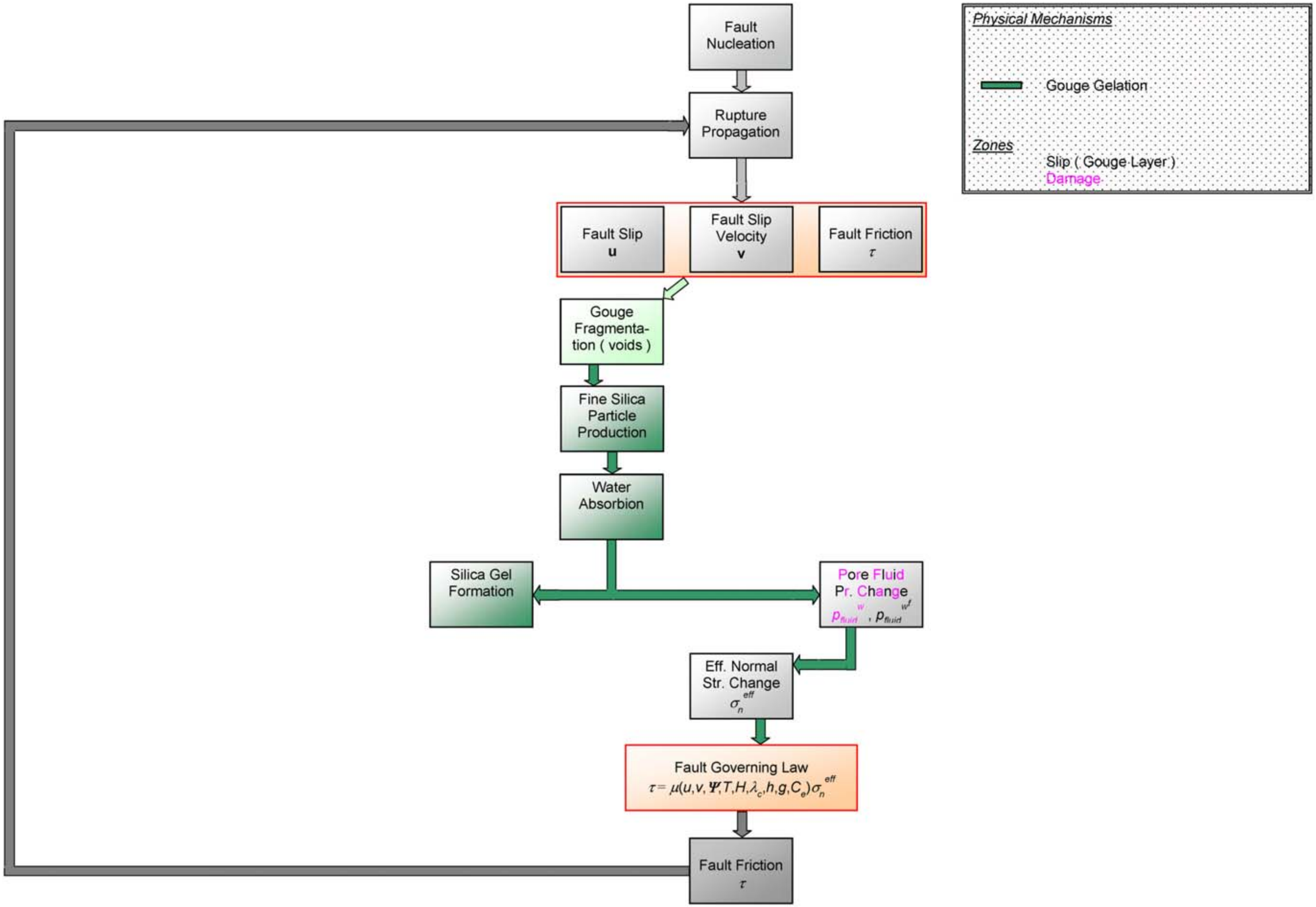
Fault Nucleation
Rupture Propagation
Fault Slip u
Fault Slip Velocity v
Fault Friction τ
Physical Mechanisms
Melting
Zones
Slip (Gouge Layer)
Damage
Frictional Heat q
Temperature change
Gouge / Rock Melting
Fault Governing Law
Fault Friction τ

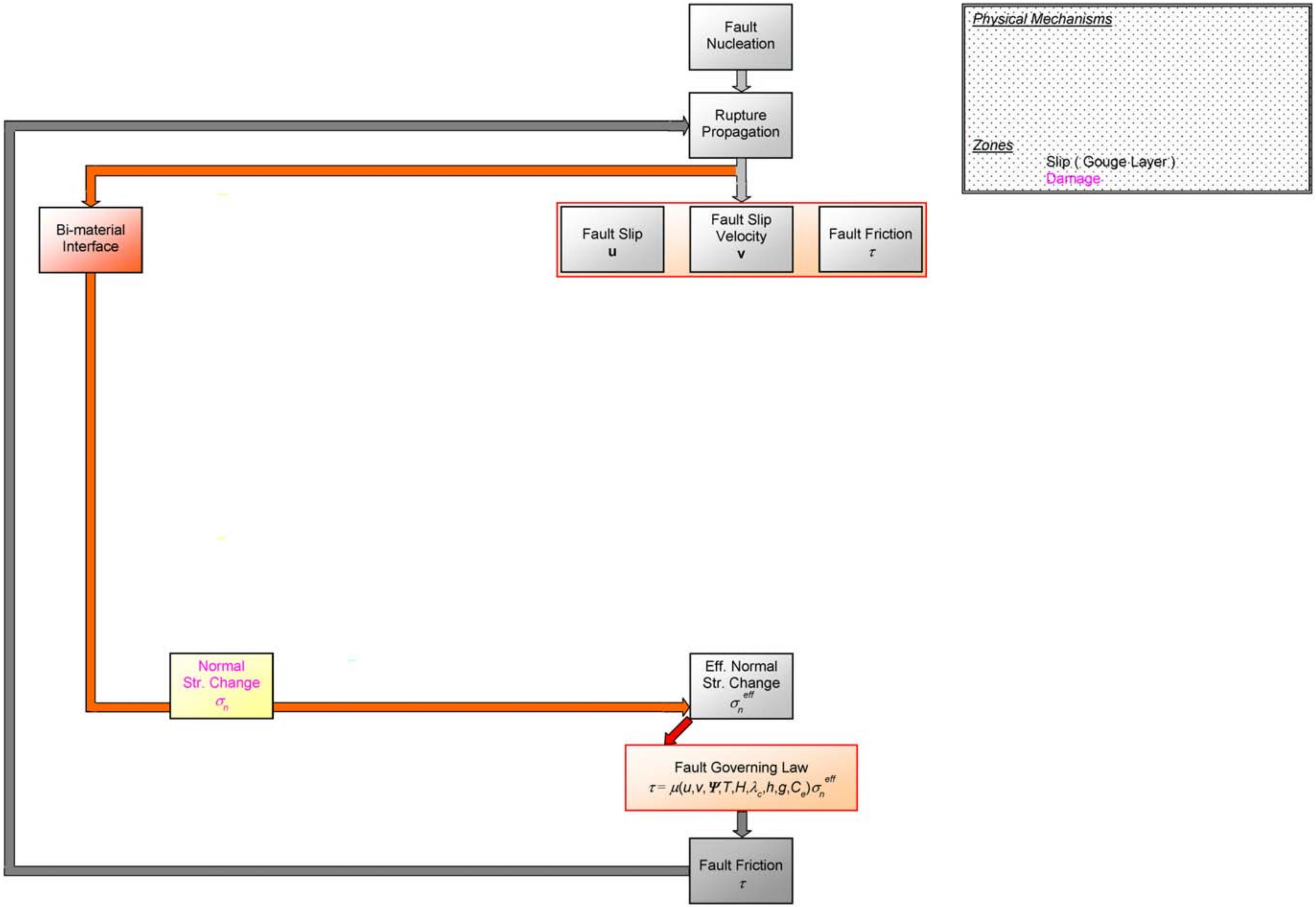


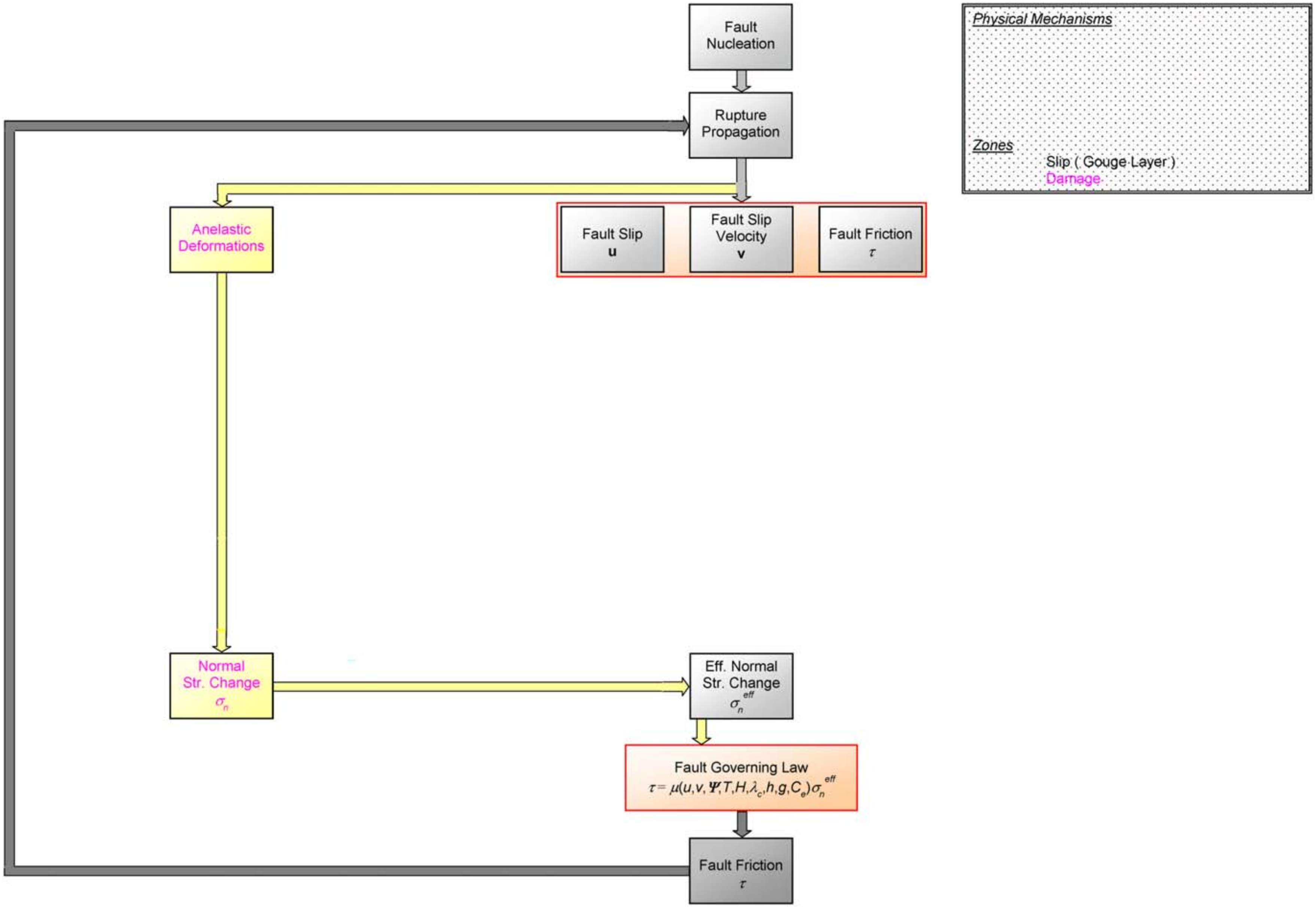
Fault Nucleation
Rupture Propagation
Fault Slip u
Fault Slip Velocity v
Fault Friction τ
Physical Mechanisms
Zones
Slip (Gouge Layer)
Damage
Frictional Heat q
Temperature change T^w, T^{wf}
a and b Variation
Fault Governing Law
$\tau = \mu(u, v, \Psi, T, H, \lambda_c, h, g, C_e)\sigma_n^{eff}$
Fault Friction τ



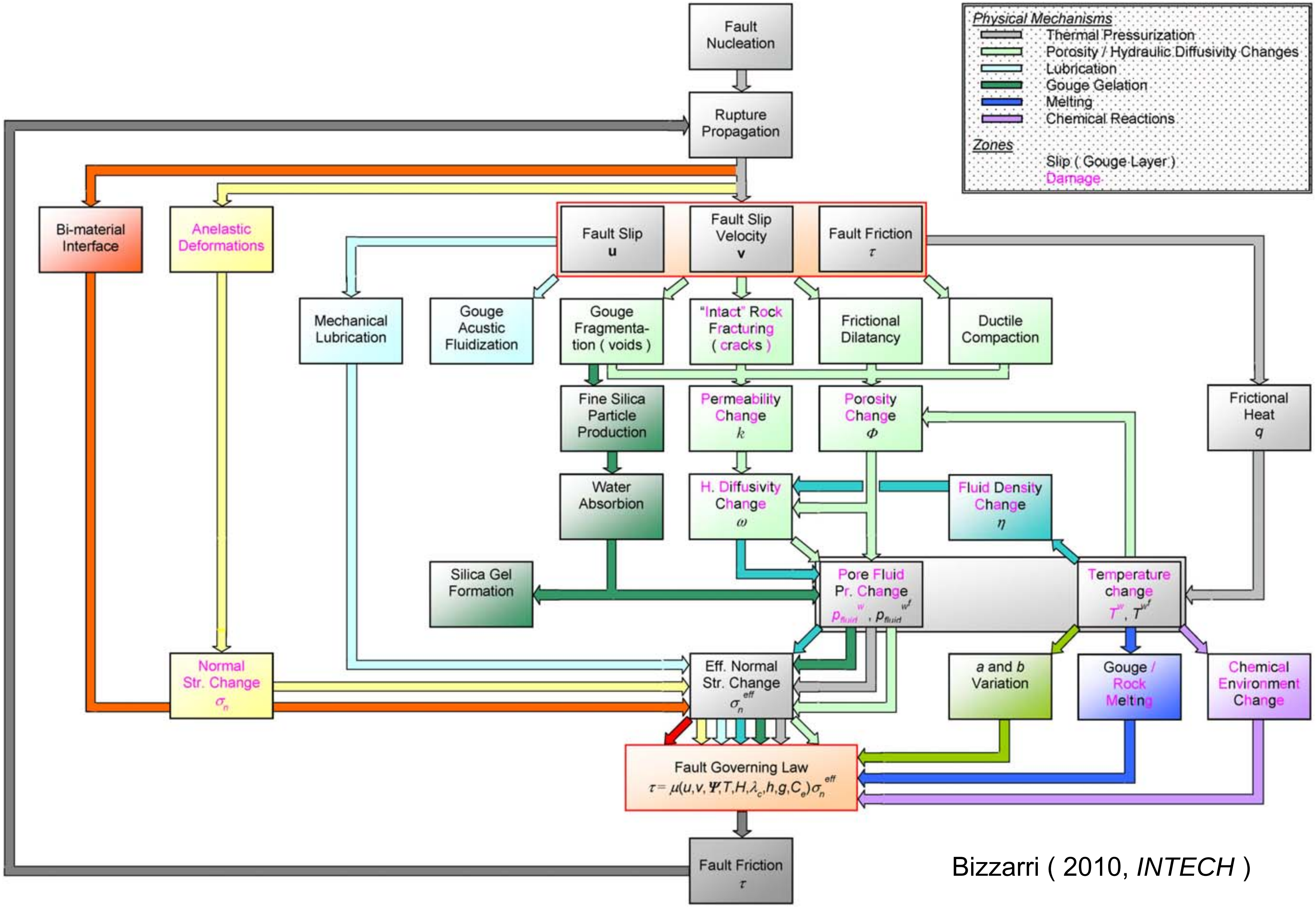
Fault Nucleation
Rupture Propagation
Fault Slip u
Fault Slip Velocity v
Fault Friction τ
Mechanical Lubrication
Gouge Acustic Fluidization
Eff. Normal Str. Change σ_n^{eff}
Fault Governing Law
$\tau = \mu(u,v,\Psi,T,H,\lambda_c,h,g,C_e)\sigma_n^{eff}$
Fault Friction τ
Physical Mechanisms
Lubrication
Zones
Slip (Gouge Layer)
Damage


Fault Nucleation
Rupture Propagation
Fault Slip u
Fault Slip Velocity v
Fault Friction τ
Gouge Fragmentation (voids)
Fine Silica Particle Production
Water Absorbion
Silica Gel Formation
Pore Fluid Pr. Change
Eff. Normal Str. Change
Fault Governing Law
Fault Friction τ
Physical Mechanisms
Gouge Gelation
Zones
Slip (Gouge Layer)
Damage


Fault Nucleation
Rupture Propagation
Bi-material Interface
Fault Slip u
Fault Slip Velocity v
Fault Friction τ
Normal Str. Change σn
Eff. Normal Str. Change σn eff
Fault Governing Law
τ = μ(u,v,Ψ,T,H,λc,h,g,Ce)σn eff
Fault Friction τ
Physical Mechanisms
Zones
Slip (Gouge Layer)
Damage



Fault Nucleation
Rupture Propagation
Anelastic Deformations
Fault Slip
u
Fault Slip Velocity
v
Fault Friction
τ
Normal Str. Change
σn
Eff. Normal Str. Change
σn eff
Fault Governing Law
τ = μ(u,v,Ψ,T,H,λc,h,g,Ce)σn eff
Fault Friction
τ
Physical Mechanisms
Zones
Slip (Gouge Layer)
Damage



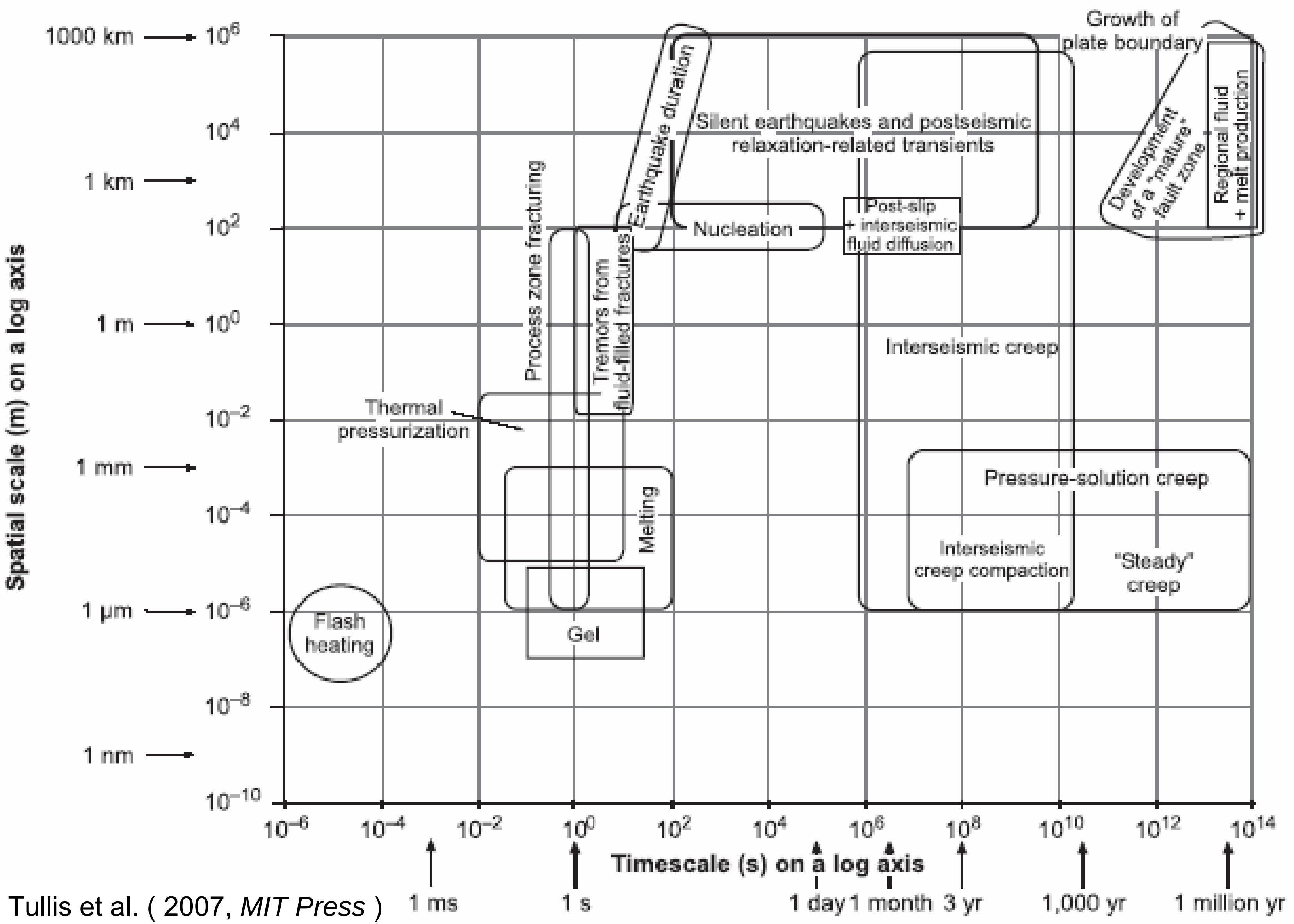
Bizzarri (2010, *INTECH*)

Occam' s razor

- We follow the logical principle of simplicity (i.e., the Occam' s razor):

  The simplest way to describe the fault complexity is to **start from the beginning** (i.e., canonical formulations of the governing equations) and then **add** to the model **one by one** all additional phenomena until the empirical (instrumentally recorded) evidence can be explained.

Spatial and temporal scales



Tullis et al. (2007, *MIT Press*)

Fracture Criteria & Constitutive Laws

1. FRACTURE CRITERION

- **Condition that specifies, at a given fault point and at a given time, if there is a rupture or not.**
- It can be expressed in terms of **energy**, in terms of **maximum frictional resistance**, and so on.
- It is based on (*i*) the *Benioff (1951)* hypothesis: The fracture occours when the stress in a volume reaches the rock strength
  or, analogoulsy,
  (*ii*) the *Reid (1910)* statement: The fracture takes place when the stress attains a value greater than the rock can endure.

2. CONSTITUTIVE LAW

- **Analytical relation existing between the components of the stress tensor and physical observable(s), like the slip, the slip velocity, the state variable, etc..**

- From a mathematical point of view it is a **Fault Boundary Condition** (**FBC**) that controls earthquake dynamics and its complexity in space and in time.

- Its simplest form consider only **two frictional levels**, τ_u and τ_f ; it accounts for stress drop (or stress realease), but the process is instantaneous: there is a singularity at crack tip.

- **Cohesive zone models**: *Barenblatt (1959a, 1959b)*, *Ida (1972)*, *Andrews (1976a, 1976b)*. In these models the singularity is removed and the sress release occours over a breakdown zone distance X_b and in a breakdown zone time T_b.

- Friction laws (Rate and State dependent f. l.): *Dieterich (1976)*, *Ruina (1980, 1983)*. They accounts for fault spontaneous nucleation, re – strengthening, healing, etc..

CONSTITUTIVE LAW (continues)

- “ The central issue is *whether* faults obey simple friction laws, and if so, what is the friction coefficient associated with fault slip “ (*Scholz and Hanks, 2004*).

CONSTITUTIVE LAW (continues)

- In full of generality we can express the constitutive (or governing) as:

$$\tau = \mu(u, v, \Psi, T, H, \lambda_c, h, g, C_e)\ \sigma_n^{eff}(\sigma_n, p_f)$$

where:

1st – order dependencies

- u is the Slip (i. e. displ. disc.) modulus,
- v is the Slip Velocity modulus (its time der.),
- $\Psi = (\Psi_1, \ldots, \Psi_N)$ is the State Variable vector,
- T is the Temperature (accounting for Ductility, Plastic Flow, Melting and Vaporization),
- H is the Humidity,
- λ_c is the Characteristic Length of surface (accounting for Roughness and Topography of asperity contacts),
- h is the Hardness,
- g is the Gouge (accounting for Surface Consumption and Gouge formation),
- C_e is the Chemical Environment

Strength & Constitutive Laws

1. THE STRENGTH PARAMETER

- **Hystorically introduced by *Das and Aki (1977a, 1977b)* to have a quantitative extimate of the ability to fracture for a fault**
- Its expression can be generalized as:

$$S = (\mu_u \sigma_n^{eff} - \tau_0) / (\tau_0 - \mu_f \sigma_n^{eff})$$

where μ are the friction coefficient.

- We can also define

2. THE FAULT STRENGTH

- **Is the parameter that quantify the Strenght in the more general case, in which a fault is described by a rhealistic friction laws**

$$S^{fault} = \mu(u, v, \Psi, T, H, \lambda_c, h, g, C_e)\ \sigma_n^{eff}(\sigma_n, p_{fluid})$$

Towards real – world conditions

u_{tot} ~ several m

v ~ several m/s

σ_n^{eff} = 100 – 200 MPa

Classical laboratory

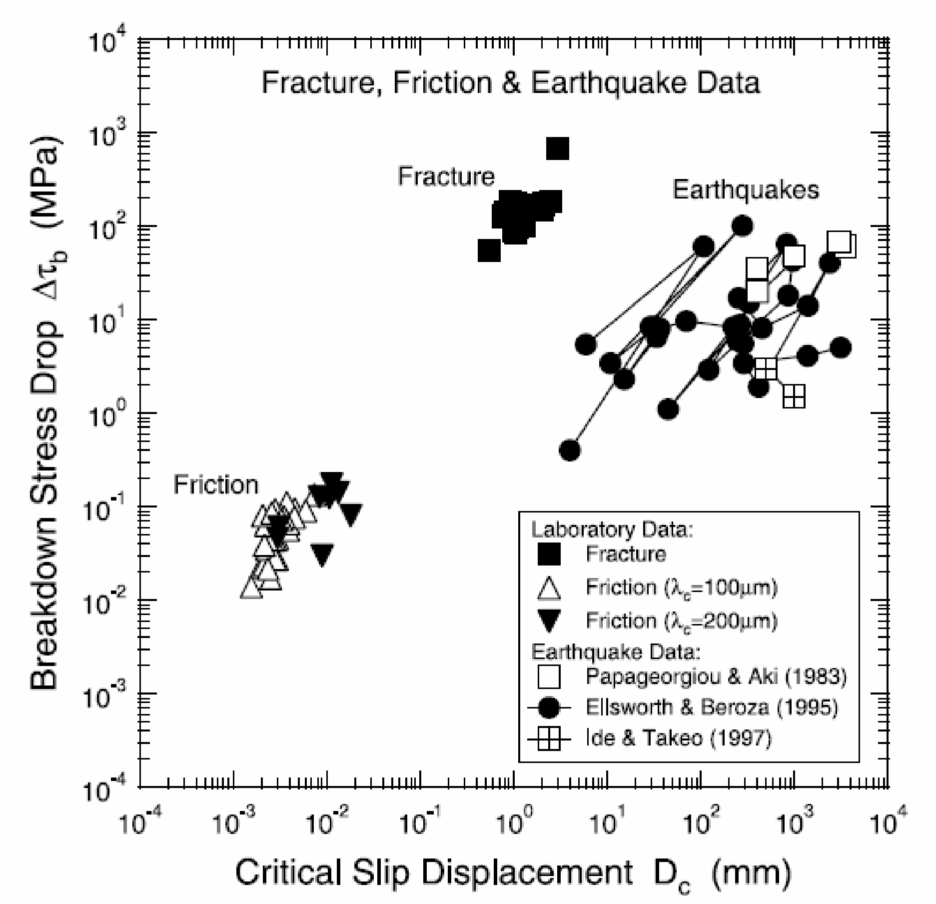
stick – slip experiments

(Dieterich, 1981)

u_{tot} up to 1.4 mm

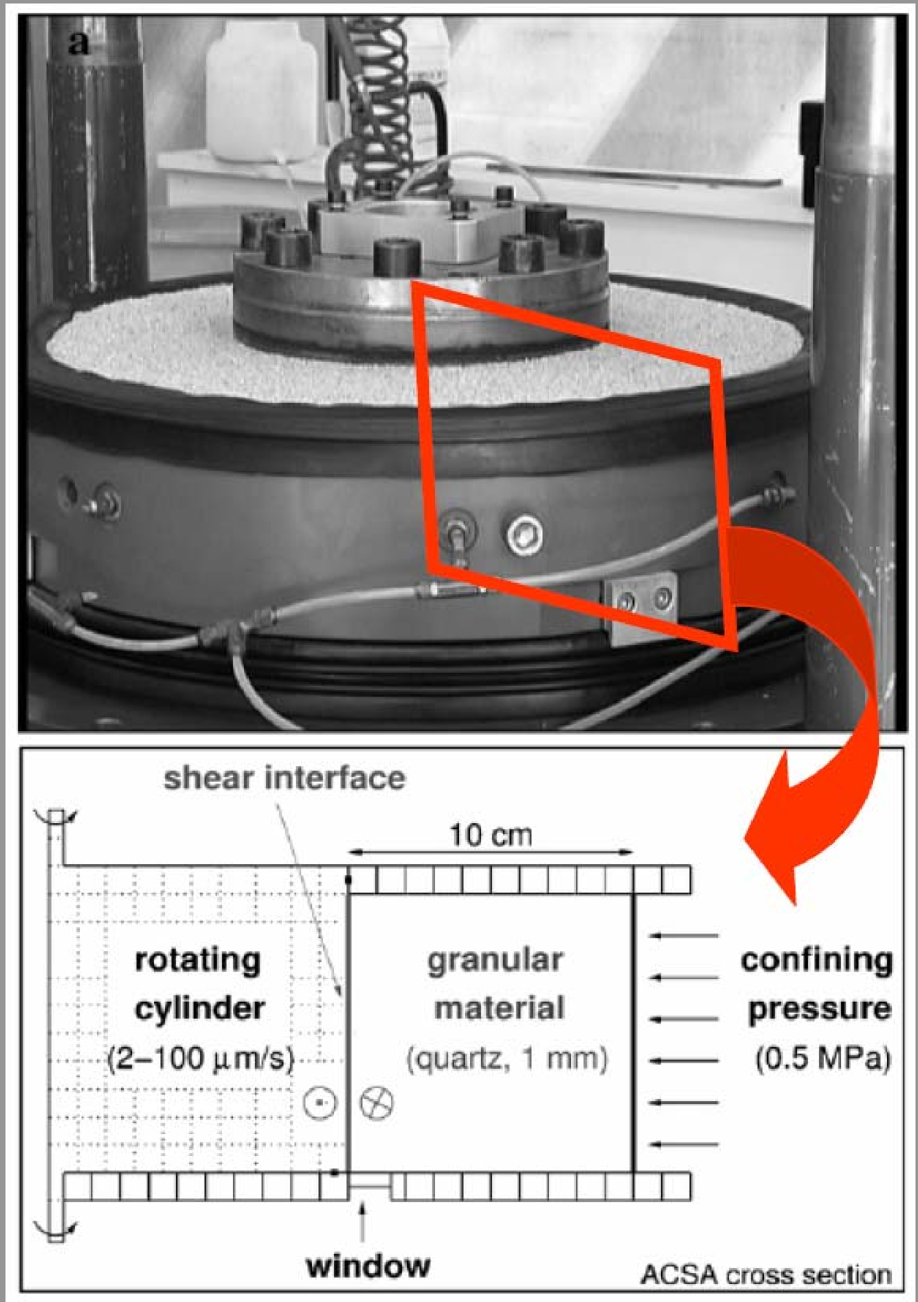
v up to 25 μm/s

σ_n^{eff} = 10 MPa



From Ohnaka (2003)

Annular simple shear apparatus



u_{tot} < 50 m

v = 1 µm/s – 0.1 mm/s

σ_n^{eff} < 1 MPa

Chambon et al. (2006a, 2006b, *JGR*, **111**, B09308, B09309)

High velocity rotary friction apparatus

u_{tot} = infinite

v = 0.1 μm/s – 10 m/s

σ_n^{eff} < 20 MPa

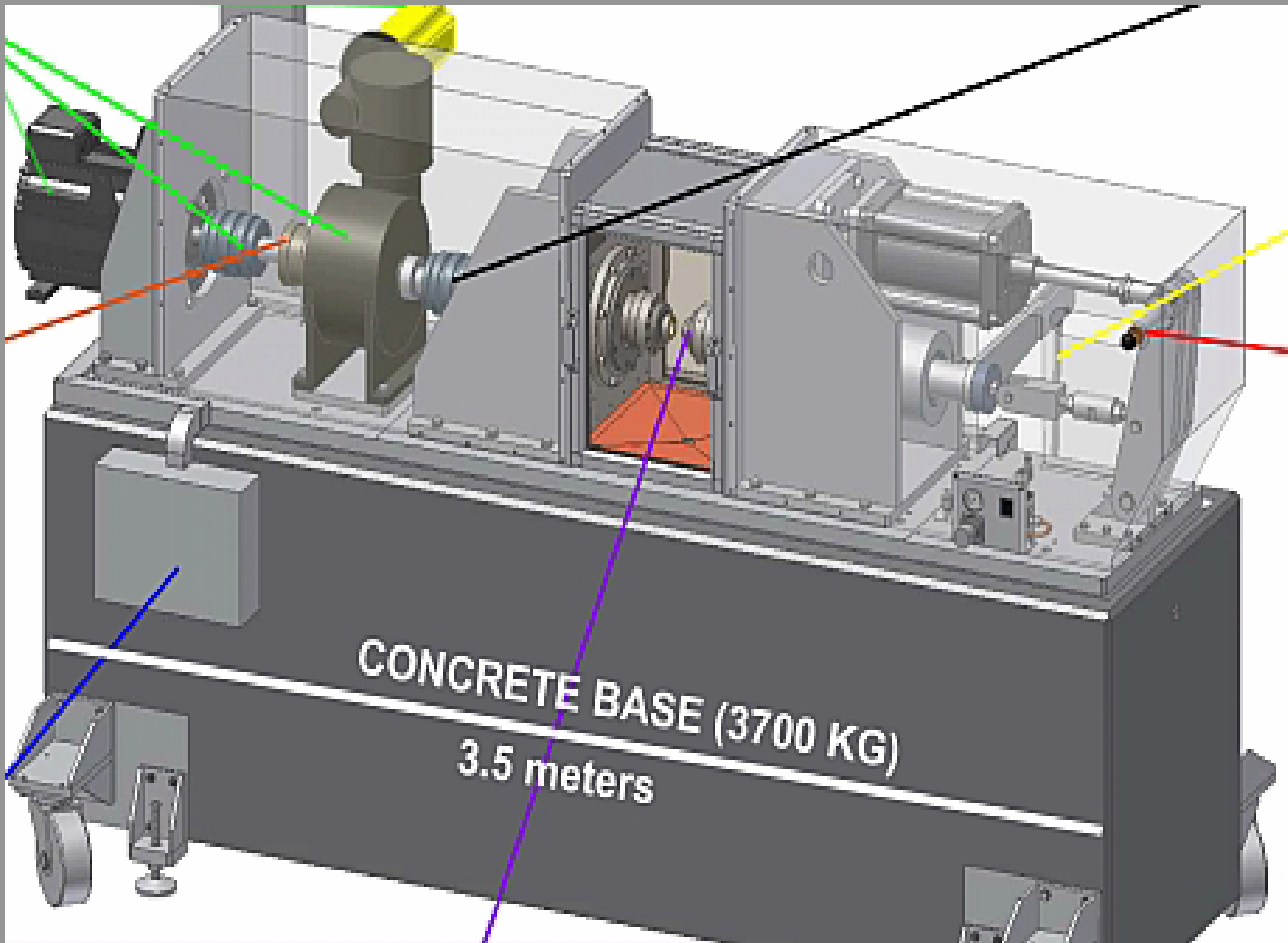
Shimamoto and Tsutumi (2004, *Str. Geol.*, **39**)

High velocity rotary friction apparatus @ INGV

u_{tot} = infinite

v = 1 μm/s – 9 m/s

σ_n^{eff} < 70 MPa



Niemeijer et al. (2009, *AGU Fall Meeting*)

Time - weakening Friction Law

$$\tau = \begin{cases} \left[\mu_u - (\mu_u - \mu_f) \dfrac{(t - t_r)}{t_0} \right] \sigma_n^{\ eff} & , t - t_r < t_0 \\ \mu_f \sigma_n^{\ eff} & , t - t_r \geq t_0 \end{cases}$$

`ilaw = 11`

TW

$t_r = t_r(\xi)$ is the rupture onset time in every fault point ξ (when $u > 0$).

Andrews (1985), *Bizzarri et al. (2001)* and other following Bizzarri' s papers

t_0 is the characteristic time – weakening duration.

Position - weakening Friction Law

$$\tau = \begin{cases} \left[\mu_u - (\mu_u - \mu_f) \dfrac{x}{R_0} \right] \sigma_n^{\ eff} & , -R_0 < x < 0 \\ \mu_f \sigma_n^{\ eff} & , -L < x < -R_0 \end{cases}$$

PW

x is the position on the fault (extending up to – L).

R_0 is the characteristic position – weakening distance.

Palmer and Rice (1973)

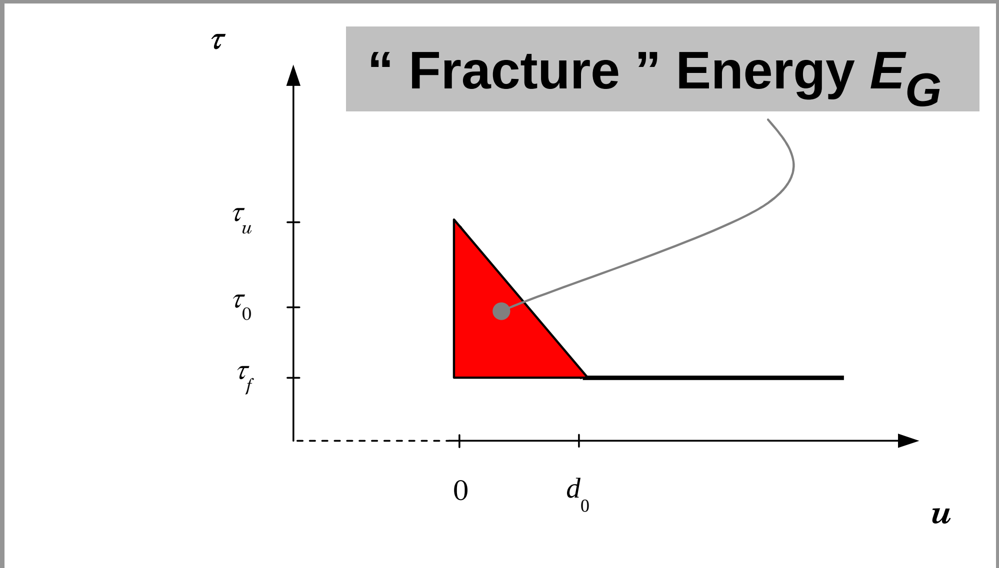
Slip - Dependent Friction Laws

1. LINEAR SLIP – WEAKENING LAW

$$\tau = \begin{cases} \left[\mu_u - (\mu_u - \mu_f) \dfrac{u}{d_0} \right] \sigma_n^{eff} & , u < d_0 \\ \mu_f \sigma_n^{eff} & , u \geq d_0 \end{cases}$$

ilaw = 21

SW



Barenblatt (1959a, 1959b), Ida (1972), Andrews (1976a, 1976b), and many authors thereinafter

d_0 is the characteristic slip – weakening distance ilaw = 22

IW

2. NON – LINEAR SLIP – WEAKEING LAW

$$\tau = \begin{cases} \left[\mu_u - \dfrac{\mu_u - \mu_f}{d_0} \left(u - \dfrac{(1 - p_{IW}) d_0}{2\pi} \sin\left(\dfrac{2\pi u}{d_0} \right) \right) \right] \sigma_n^{\,eff} & , u < d_0 \\ \mu_f \sigma_n^{\,eff} & , u \geq d_0 \end{cases}$$

Ionescu and Campillo (1999)

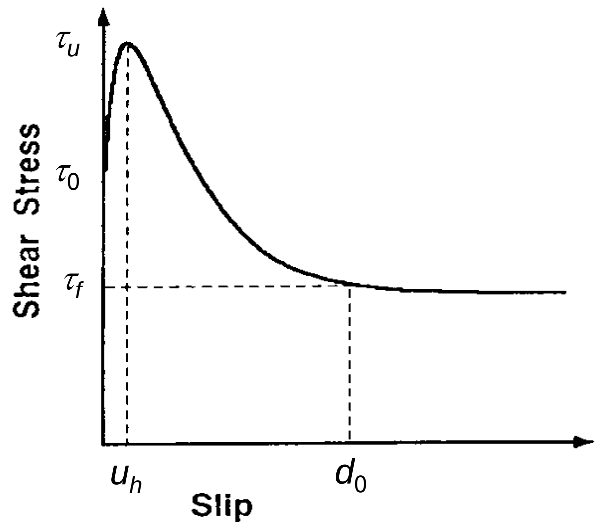
3. NON LINEAR SLIP – WEAKEING LAW WITH SLIP – HARDENING

$$\tau = \left\{ \left[\left(\frac{\tau_0}{\sigma_n^{eff}} - \mu_f \right) \left(1 + \alpha_{OY} \ln\left(1 + \frac{u}{\beta_{OY}} \right) \right) \right] e^{-\frac{u}{d_0}} + \mu_f \right\} \sigma_n^{eff}$$

ilaw = 23

OW

$$u_h : \left.\frac{d\tau}{du}\right|_{u_h} = 0 ; \qquad \begin{cases} u_h = r d_0 \quad (\text{e.g. } r = 0.1) \\ \tau(u_h) = \tau_u \end{cases}$$



Ohnaka and Yamashita (1989) and the following papers by Ohnaka and coworkers

u_h is associated with the preparatory phase of the imminent macroscopic failure in the cohesive zone. It accounts for micro–cracking

4. NON LINEAR SLIP – WEAKENING LAW WITH EXPONENTIAL DECAY

$$\tau = \left[\left(\mu_u - \mu_f \right) \mathrm{e}^{-\frac{u}{d_0}} + \mu_f \right] \sigma_n^{eff}$$

ilaw = 24

EW

5a. POWER LAW SLIP – WEAKENING

$$\tau = \left\{ \mu_u - \left(\mu_u - \mu_f\right)\left[\left(\frac{p_{PW}}{p_{PW}+1} \right) \frac{u}{d_0} \right]^{p_{PW}} \right\} \sigma_n^{\ eff}$$

```
ilaw = 25

PW
```

5b. POWER LAW SLIP – WEAKENING II

$$\tau = \left\{ \mu_f + \frac{\alpha_{CEA}}{\sigma_n^{\ eff}} \left(u - d_0\right)^{p_{CEA}} \right\}$$

α_{CEA} = 5.6 x 10^{-2} MPa $m^{p_{CEA}}$

p_{CEA} = 0.4

Chambon et al. (2006b)

Slip - and Rate - Dependent Friction Laws

$$\tau = \left\{ \mu^{ss}(v) + \left[F(u)\mu_i - \mu^{ss}(v) \right] e^{\frac{\ln(0.05)u}{d_0}} \right\} \sigma_n^{eff}$$

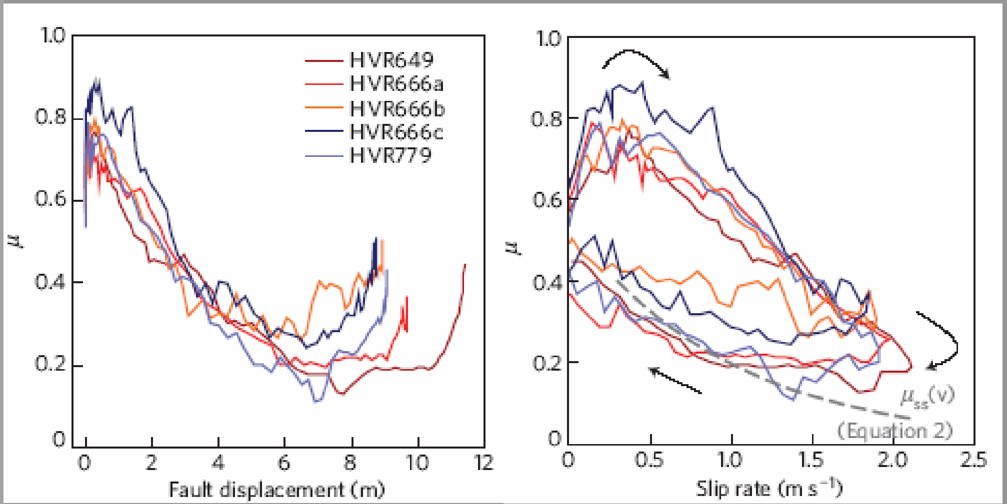
ilaw = 26

VW

$$\mu^{ss}(v) = \mu^{ss}(0)\, e^{-\frac{v}{v_{SS}}}$$

$$F(u) = \alpha_{SS} + (1 - \alpha_{SS})\, e^{\frac{\ln(0.05)u}{u_h}}$$

Sone and Shimamoto (2009)



u_h controls the duration in slip of the slip – hardening phase, described by the function $F(u)$.

$\mu^{ss}(0) = 0.55 \pm 0.09$ $\mu_i = 0.6$

$v_{SS} = 0.99 \pm 0.23$ m/s

$\alpha_{SS} = 1.26 \div 1.54$

$u_h = 23 \div 160$ mm

Rate - Dependent Friction Law

$$\tau = \frac{v_*}{v + v_*} \mu_u \sigma_n^{eff}$$

Burridge and Knopoff (1967), *Carlson and Langer (1989)*, Madariaga and Cochard (1994), Cochard and Madariaga (1994)

Rate - and State - Dependent Friction Laws

1. DIETERICH IN REDUCED FORMULATION

$$\begin{cases} \tau = \left[\mu_* - a \ln\left(\frac{v_*}{v} \bullet \right) + b \ln\left(\frac{\Psi v_*}{L} \bullet \right) \right] \sigma_n^{eff} \\ \frac{d}{dt}\Psi = 1 - \frac{\Psi v}{L} \end{cases}$$

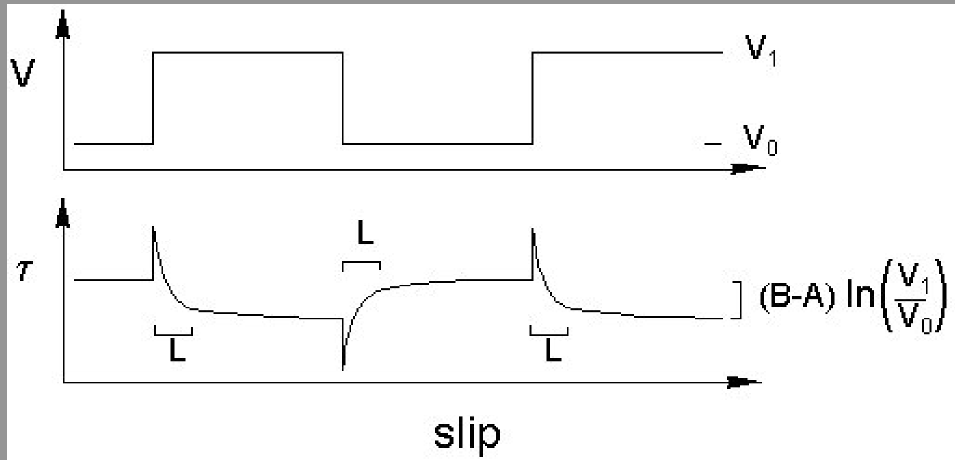
ilaw = 31

DR

However, while in velocity stepping experiments the traction response following the velocity variation is directly controlled by the parameter *L*, its effects are much less evident during the dynamic rupture propagation.

Bizzarri and Cocco (2005)

Response to an abrupt jump in load



2. RUINA – DIETERICH (RUINA ORIGINAL FORM)

$$\begin{cases} \tau = \left[\mu_* - a \ln\left(\dfrac{v_*}{v} \right) + \theta \right] \sigma_n^{eff} \\ \dfrac{\mathrm{d}}{\mathrm{d}t}\theta = -\dfrac{v}{L}\left[\theta + b \ln\left(\dfrac{v}{v_*} \right) \right] \end{cases}$$

Ruina (1980, 1983)

2bis. RUINA – DIETERICH (RUINA MODERN FORM.)

$$\begin{cases} \tau = \left[\mu_* - a \ln\left(\dfrac{v_*}{v} \right) + b \ln\left(\dfrac{\Psi v_*}{L} \right) \right] \sigma_n^{eff} \\ \dfrac{\mathrm{d}}{\mathrm{d}t}\Psi = -\dfrac{\Psi v}{L} \ln\left(\dfrac{\Psi v}{L} \right) \end{cases}$$

ilaw = 32

RD

Beeler et al. (1994), Roy and Marone (1996)

3. DIETERICH – RUINA WITH VARYING NORMAL STR.

$$\begin{cases} \tau = \left[\mu_* - a \ln\left(\frac{v_*}{v}\right) + b \ln\left(\frac{\Psi\, v_*}{L}\right) \right] \sigma_n^{eff} \\ \frac{\mathrm{d}}{\mathrm{d}t}\Psi = 1 - \frac{\Psi\, v}{L} - \left(\frac{\alpha_{LD}\Psi}{b\,\sigma_n^{eff}}\right) \frac{\mathrm{d}}{\mathrm{d}t}\sigma_n^{eff} \end{cases}$$

```
ilaw = 31
decis10=T
```

DR

Linker and Dieterich (1992), Dieterich and Linker (1992), Bizzarri and Cocco (2006a, 2006b)

4. RUINA – DIETERICH WITH VARYING NORMAL STR.

$$\begin{cases} \tau = \left[\mu_* - a \ln\left(\dfrac{v_*}{v}\right) + b \ln\left(\dfrac{\Psi\, v_*}{L}\right) \right] \sigma_n^{eff} \\ \dfrac{\mathrm{d}}{\mathrm{d}t}\Psi = -\dfrac{\Psi\, v}{L} \ln\left(\dfrac{\Psi\, v}{L}\right) - \left(\dfrac{\alpha_{LD}\Psi}{b\,\sigma_n^{eff}}\right) \dfrac{\mathrm{d}}{\mathrm{d}t}\sigma_n^{eff} \end{cases}$$

```
ilaw = 32
decis10=T
```

RD

Linker and Dieterich (1992), Bizzarri and Cocco (2006a, 2006b)

5. DIETERICH IN REDUCED FORM REGULARIZED

$$
\begin{cases}
\tau = \left[\mu_* - a \ln\left(\dfrac{v + v_*}{v + v_r} \right) + b \ln\left(\dfrac{\Psi\,(v - v_r)}{L} + 1 \right) \right] \sigma_n^{eff} \\[2ex]
\dfrac{\mathrm{d}}{\mathrm{d}t}\Psi = 1 - \dfrac{\Psi\,(v + v_r)}{L}
\end{cases}
$$

```
ilaw = 33
```

DE

v_r *is a regularization fault slip velocity*

<u>Perrin et al. (1995)</u>, Cocco et al. (2004)

6. RUINA REGULARIZED

$$\begin{cases} \tau = \left[\mu_* - a \ln\left(\dfrac{v_* - v_r}{v + v_r} \right) + \dfrac{\Psi}{\sigma_n^{eff}} \right] \sigma_n^{eff} \\ \dfrac{\mathrm{d}}{\mathrm{d}t}\Psi = -\dfrac{v + v_r}{L} \left(\Psi + b \ln\left(\dfrac{v + v_r}{v_* - v_r} \right) \right) \end{cases}$$

ilaw = 34

RE

v_r is a regularization fault slip velocity

Bizzarri (2002, unpublished work)

7. DIETERICH IN REDUCED FORM WITH HEALING

$$\begin{cases} \tau = \left[\mu_* - a \ln\left(\dfrac{v_*}{v} + 1 \right) + b \ln\left(\dfrac{\Psi\, v_*}{L} + 1 \right) \right] \sigma_n^{eff} \\ \dfrac{\mathrm{d}}{\mathrm{d}t} \Psi = \dfrac{\gamma_{fh} - \Psi}{t_{fh}} - \dfrac{\Psi\, v}{L} \end{cases}$$

```
ilaw = 35
```

DH

γ_{fh} = 1 s

t_{fh} is the time for healing (slip duration)

Evolution law proposed by *Nielsen et al. (2000)* and by *Nielsen and Carlson (2000)*. Used in this form by *Cocco et al. (2004)*

8. DIETERICH IN REDUCED FORM WITH 2 STATE VAR.

ilaw = 36

DW

Tullis and Weeks (1993). Used in this form by *Bizzarri (xxxx, unpublished work)*

9. PRAKASH – CLIFTON

$$
\begin{cases}
\tau = \left[\mu_* - a \ln\left(\dfrac{v_*}{v} \right) + b \ln\left(\dfrac{\Psi\, v_*}{L} \right) \right] \left(\dfrac{d}{dt}\Psi_1 + \dfrac{d}{dt}\Psi_2 \right) \\
\dfrac{d}{dt}\Psi = 1 - \dfrac{\Psi\, v}{L} \\
\dfrac{d}{dt}\Psi_1 = -\dfrac{v}{L_1}\left(\Psi_1 - \alpha_{PC_1} \sigma_n^{eff} \right) \\
\dfrac{d}{dt}\Psi_2 = -\dfrac{v}{L_2}\left(\Psi_2 - \alpha_{PC_2} \sigma_n^{eff} \right)
\end{cases}
$$

ilaw = 37

PC

Ψ_1 *and* Ψ_2 are additional state variables accounting for the coupling with effective normal stress. The formulation of friction law is not based on the Amonton – Coulamb law.

Coupling with effective normal stress proposed by *Prakash and Clifton (1993)* and *Prakash (1998)*. Used in this form by *Bizzarri (2005, unpublished work)*

10. RUINA – DIETERICH WITH FLASH HEATING

$$\begin{cases} \tau = \left[\mu_* - a \ln\left(\frac{v_*}{v}\right) + \theta \right] \sigma_n^{eff} \\ \frac{\mathrm{d}}{\mathrm{d}t}\theta = \begin{cases} -\frac{v}{L}\left[\theta + b\ln\left(\frac{v}{v_*}\right)\right] & , v \le v_{fh} \\ -\frac{v}{L}\left[\theta + b\frac{v_{fh}}{v}\ln\left(\frac{v}{v_*}\right) + \left(1 - \frac{v_{fh}}{v}\right)\left(a\ln\left(\frac{v}{v_*}\right) + \mu_* - \mu_{fh}\right)\right] & , v > v_{fh} \end{cases} \end{cases}$$

```
ilaw = 38
```

FH

where $v_{fh} = \frac{\pi\chi}{D_{ac}}\left(c\,\frac{T_{weak} - T^{wf}}{\tau_{ac}}\right)^2$ is a weakening velocity above which flash heating is activated, T^{weak} is a weakening temperature, τ_{ac} is the (average) shear strength of asperity contacts and D_{ac} their (average) size.

Beeler and Tullis (2003); Tullis and Goldsby (2003a, 2003b). Rice (1999, 2006). Modified from <u>*Noda et al. (2009)*</u>

11. RUINA – DIETERICH WITH TEMPERATURE DEPEN.

$$\begin{cases} \tau = \left[\mu_* - a \ln\left(\frac{v_*}{v}\right) + \theta + \frac{a\,Q_a}{R}\left(\frac{1}{T} - \frac{1}{T_*}\right) \right] \sigma_n^{eff} \\ \frac{\mathrm{d}}{\mathrm{d}t}\theta = -\frac{v}{L}\left[\theta + b \ln\left(\frac{v}{v_*}\right) + \frac{b\,Q_b}{R}\left(\frac{1}{T} - \frac{1}{T_*}\right) \right] \end{cases}$$

ilaw = 39

CH

where Q_a and Q_b are activation energies (Kato, 2001 assumes: Q_a = Q_b = 0.1 MJ/mol) and T_* is a reference absolute temperature.

Note that T is the absolute temperature.

Chester and Higgs (1992), Kato (2001)

Slip - and State - Dependent Friction Law

$$
\begin{cases}
\tau = \begin{cases}
\left[(\mu_u - \Delta\mu)\left(1 - \dfrac{u}{d_1}\right) \right] \sigma_n^{\,eff} & , u < d_1, \Psi \ge \Psi_1 \\
0 & , u \ge d_1, \Psi \ge \Psi_0 \\
\mu_{sp} \left(1 - \dfrac{\Psi}{\Psi_0}\right) \sigma_n^{\,eff} & , \Psi < \Psi_0, \Psi < \Psi_1
\end{cases} \\
\dfrac{\mathrm{d}}{\mathrm{d}\,t}\Psi = -\dfrac{\beta_{CM}}{d_0}(\Psi - v)
\end{cases}
$$

ilaw = 41

CM

$\Delta\mu$ is an initial artificial stress drop

$\Psi_1 \equiv \Psi_0 \, (u - u_1)/(d_1 - u_1)$

$U_1 \equiv - d_1 \, (\mu_{sp} - \mu_u + \Delta\mu)/(\mu_u - \Delta\mu)$

d_0 and d_1 are characteristic lengths

$\mu_{sp} = 0 \Rightarrow$ linear SW with d_1 as characteristic length

Cochard and Madariaga (1994)

Free Volume Friction law

$$\begin{cases} \tau = \sigma_d \,\mathrm{Arcsinh}\left(\dfrac{v}{v_*} \dfrac{\mathrm{e}^{f_* + \frac{\chi_s + \chi_h}{\chi}}}{1 - m_0} \right) \\ \dfrac{\mathrm{d}}{\mathrm{d}t}\chi = -R_c\, \mathrm{e}^{-\frac{\chi_c}{\chi}} + \alpha_{FV} \tau v \\ m_0 = \begin{cases} 1 & , \tau \le \tau_0 \mathrm{e}^{\frac{\chi_h}{\chi}} \\ \dfrac{\tau_0}{\tau} \mathrm{e}^{\frac{\chi_h}{\chi}} & , \tau > \tau_0 \mathrm{e}^{\frac{\chi_h}{\chi}} \end{cases} \end{cases}$$

```
ilaw = 51
```

FV

$\chi \equiv \Phi - \Phi_0$ free volume variable

χ_s reference value of χ for shearing

χ_h FV value required to create a Shear Transformation Zone (STZ)

χ_c FV value for compaction

R_c rate of compaction

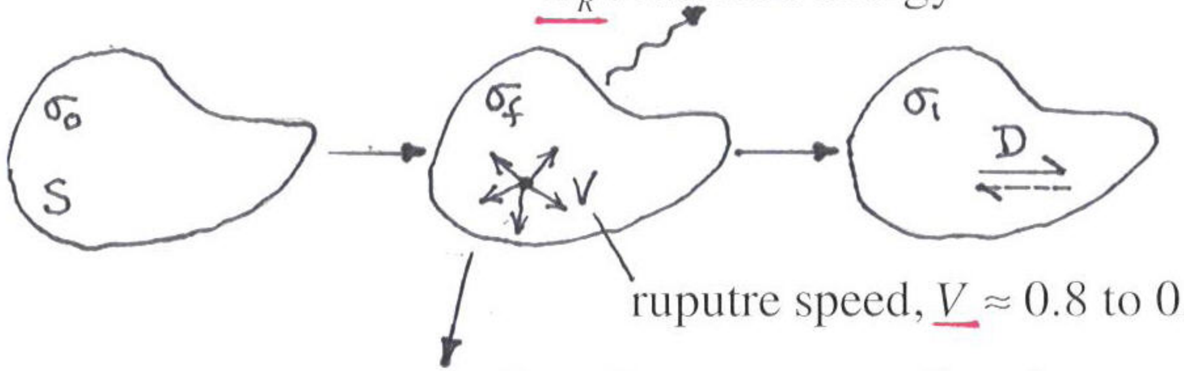
α_{FV} scaled dilatancy coefficient

Falk and Langer (1998, 2000); Lemaitre (2002); Daub and Carlson (2008)

How to relate relevant quantities to contitutive parameters

Dynamic Parameters

E_R : radiated energy

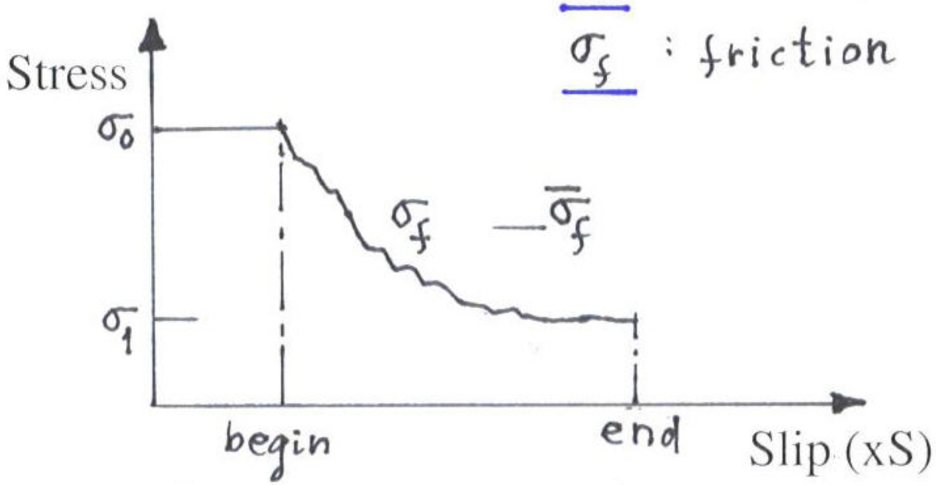


ruputre speed, $V \approx 0.8$ to $0.9\,\beta$

$E_{NR} = E_F + E_G + \ldots$: non-radiated energy

E_F : friction (heat), E_G : fracture energy

σ_f : friction



$\Delta\sigma_s = \sigma_0 - \sigma_1$: static stress drop

$\Delta\sigma_d = \sigma_0 - \bar{\sigma}_f$: dynamic stress drop

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Support Slides:
Parameters, Notes, etc.

To not be displayed directly. Referenced above.

Thermal pressurization:

Sibson (1973); *Lachenbruch (1980)*; *Mase and Smith (1985, 1987)*; *Andrews (2002)*; *Bizzarri and Cocco (2006b, 2006c)* .

Morrow et al. (1984) show that gouge contains water

Gouge behaviour:

Marone et al. (1990); *Marone and Kilgore (1993)*; *Mair and Marone (1999)*; *Mair et al. (2002)*; *Chambon et al. (2002)*; *Mizogichi et al. (2007)*

Frictional melting:

Jeffreys (1942); *McKenzie and Brune (1972)*; *Richards (1977)*; *Sibson (1977)*; *Cardwell et al. (1978)*; *Allen (1979)*; *Nielsen et al. (2007)*

Pseudo - tachylyte: Fault vein (*Sibson*, *1975*)

Mechanical lubrication:

Spray (1993); Brodsky and Kanamori (2001); Kanamori and Brodsky (2001)

Acustic fluidization:

Melosh (1979, 1996)

Gouge gelation:

Goldbsy and Tullis (2002); *Di Toro et al. (2004)*

Bi – material interface:

Andrews and Ben – Zion (1997); *Harris and Day (1997)*; *Andrews and Harris (2005)*; *Ben – Zion (2006a, 2006b)*; *Dunham and Rice (2008)*

MTL: Fractured mylonite, cataclasite and gouge

Humidity effects:

Dieterich and Conrad (1984); *Hirose and Bystricky (2007)*

Characteristic length of surface effects:

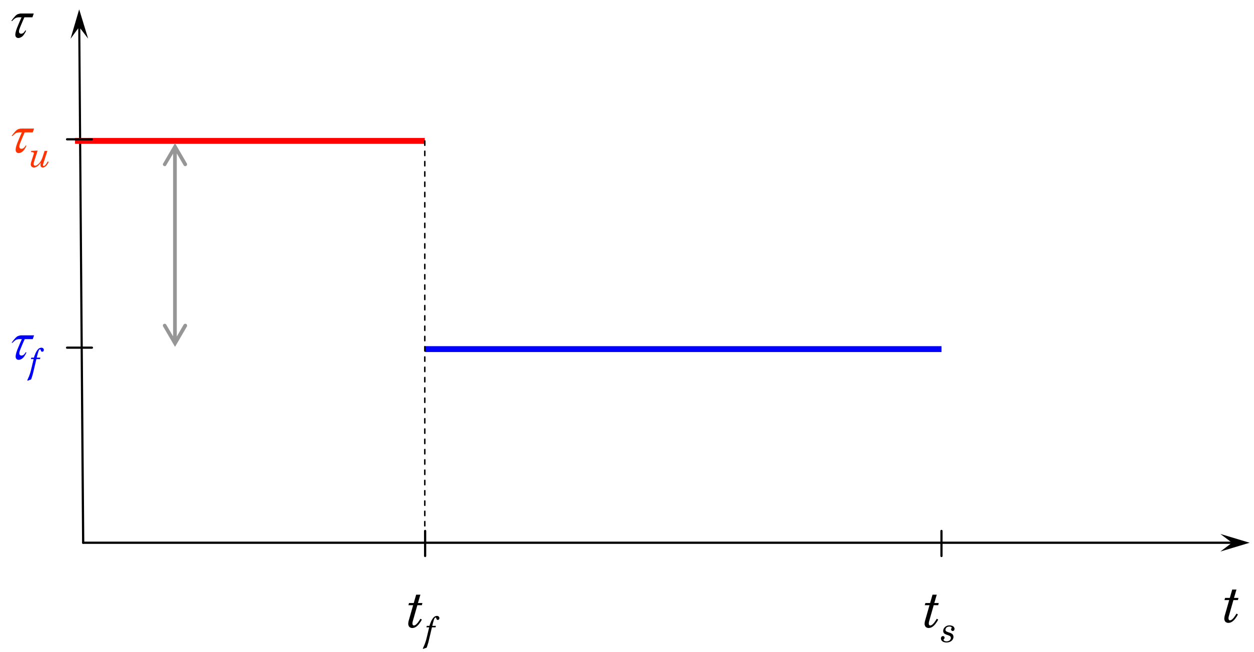
Ohnaka and Shen (1999); *Ohnaka (2003)*

Simplest friction models

At a particular fault point ξ (following *Savage and Wood, 1971*; *Scholz, 1990*)

Maximum (or upper, or yield) stress

Kinetic (or frictional) stress



Strength excess: $\tau_u - \tau_0 = 0$

Dynamic stress drop: $\Delta\tau_d = \tau_0 - \tau_f$

In the Dugdale' s model (*Dugdale, 1960*; *Barenblatt, 1962*) the drop occurs when $u = d_0$.

Failure time (or rupture onset)

Rupture arrest

Simplest friction models

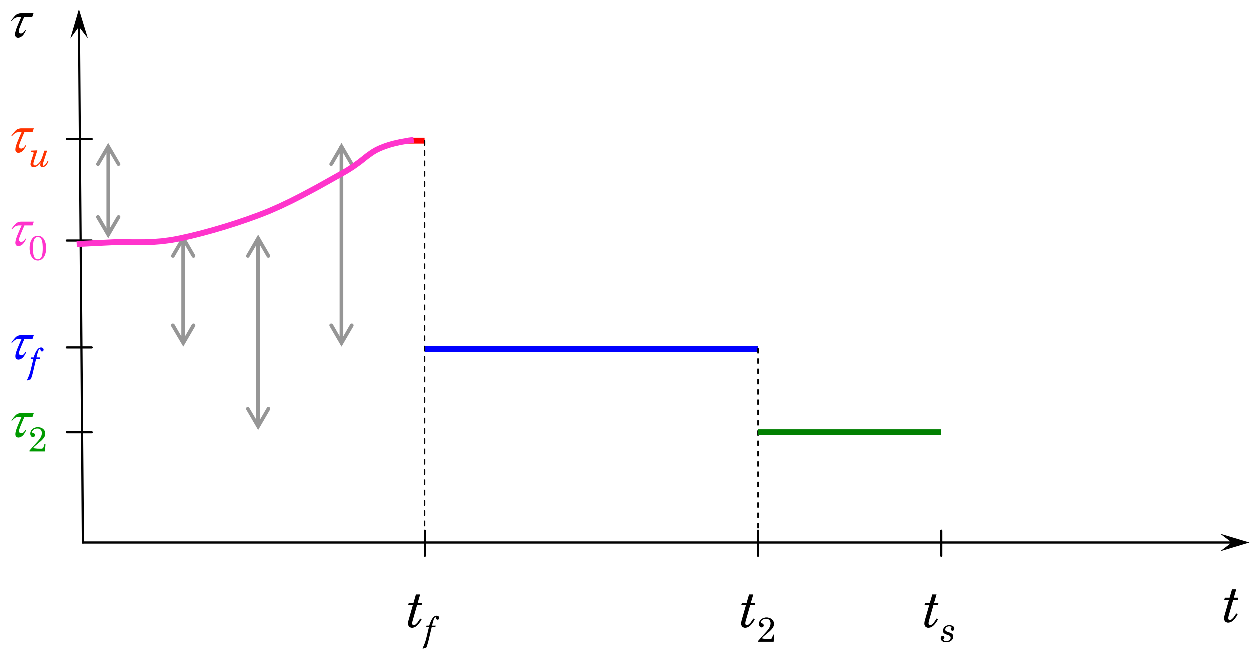
At a particular fault point ξ (following *Savage and Wood, 1971*; *Scholz, 1990*)

Maximum (or upper, or yield) stress

Initial stress

Kinetic (or frictional) stress

Residual stress



Strength excess: $\tau_u - \tau_0$

Dynamic stress drop: $\Delta\tau_d = \tau_0 - \tau_f$

Static stress drop: $\Delta\tau_s = \tau_0 - \tau_2$

Breakdown str. drop: $\Delta\tau_b = \tau_u - \tau_f$

Failure time (or rupture onset)

Dynamic overshoot

Rupture arrest

- *Savage and Wood (1971)* also define:

Mean stress: $<\tau> = \frac{1}{2} (\tau_u + \tau_2)$

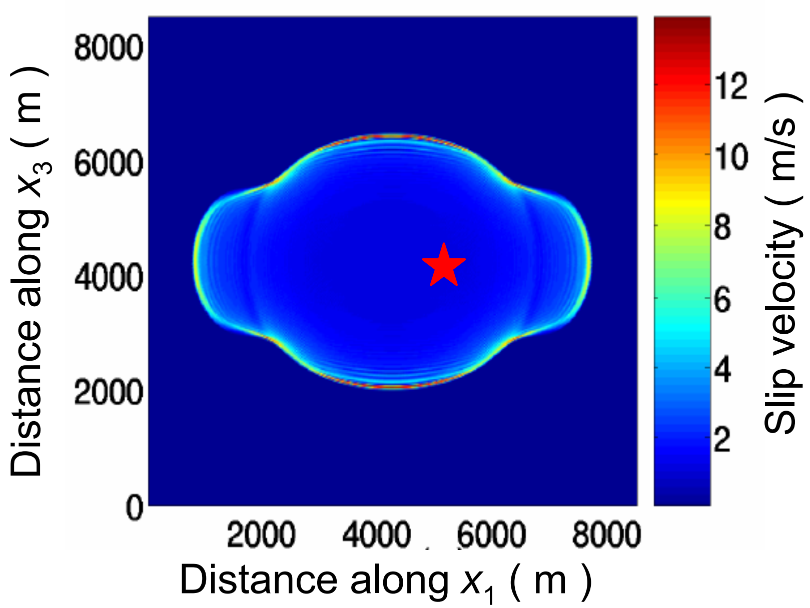
Seismic efficiency: $\eta = E_s/E$, where: E_s is the seismic energy
E is the total available energy

Apparent stress: $\tau_a = \eta <\tau>$

- Direct observation of the absolute stress near an earthquake is not feasible, but it is possible (*Wyss and Brune, 1968*) calculate τ_a and stress drop from physical observables.

The cohesive zone

Time snapshot (t = 0.8 s) - SW law



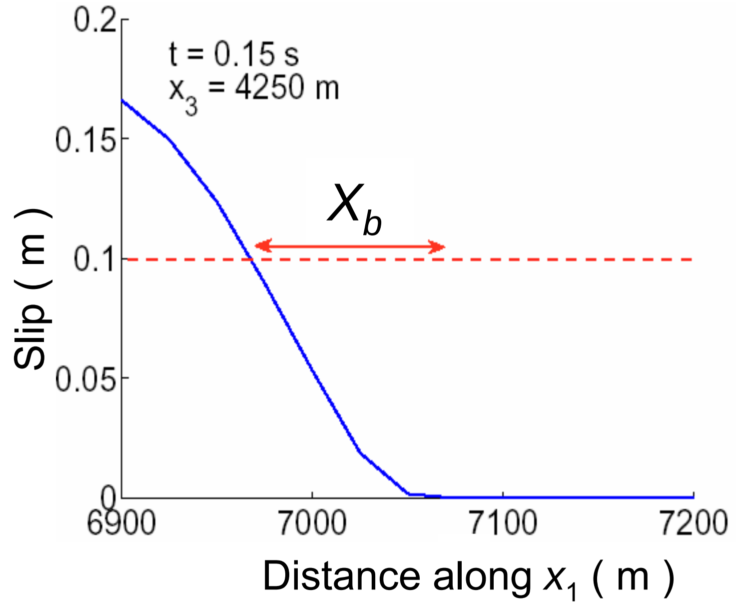
Local estimate

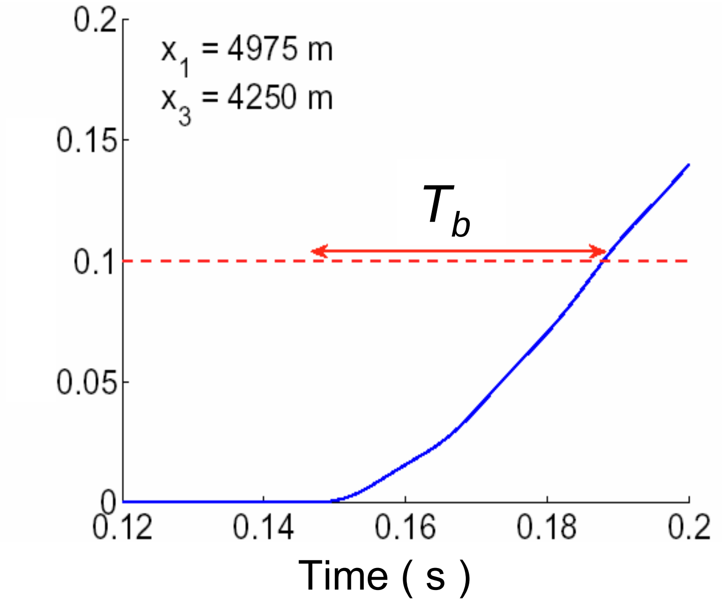
In the target location we can extimate:

X_b = 105 m T_b = 0.04 s

From these quantities:

$v_{rupt} = X_b/T_b$ = 2625 m/s





Slip - hardening effect

* The slip – hardening (SH) phenomenon has been also found in seismological inversion studies (e. g. *Quin, 1990*; *Miyatake, 1992*; *Mikumo and Miyatake, 1993*; *Beroza and Mikumo, 1996*; *Ide, 1997*; *Bouchon, 1997*).

Interpretation of the state variable