The Nature and Cause of Earthquakes

- What is an earthquake?
- Why do earthquakes occur?
- Where do earthquakes occur?
- How do we represent an earthquake kinematically?
- How do we represent an earthquake dynamically?

Most destructive 20th-21st century events:

DATE	LOCATION	DEATHS	MAG
December 16, 1920	China, Gansu	200,000	8.6
May 22, 1927	China, near Xining	200,000	8.3
December 25, 1932	China, Gansu	70,000	7.6
July 27, 1976	China, Tangshan	255,000-655,000	7.8
September 1, 1923	Japan, Kwanto	143,000	8.3
May 30, 1935	Pakistan, Quetta	30,000-60,000	7.5
June 20, 1990	Iran	50,000	7.7
October 5, 1948	USSR	110,000	7.3
December 28, 1908	Italy, Messina	70,000-100,000	7.5
May 31, 1970	Peru	66,000	7.8
December 26, 2004	Sumatra/Andaman Is.	~300,000	9.15

Recent destructive event:

August 17, 1999, Izmit, Turkey, M_w=7.4, > 10,000 deaths *{New York Times, 1999; USGS, 1999}*

Earthquake definitions:

The sudden slip on a fault (release of elastic energy), and the resulting ground shaking and radiated seismic energy caused by the slip, … *{USGS, 2002}*.

Other

- Quaking and subsequent shaking of Earth with varied causes (volcanic, impact, landslides, explosions, fault motion) *{Natural Disasters, 1999}*
- Sudden violent movement within the crust or upper mantle *{The Solid Earth, 1990}*

Sequence:

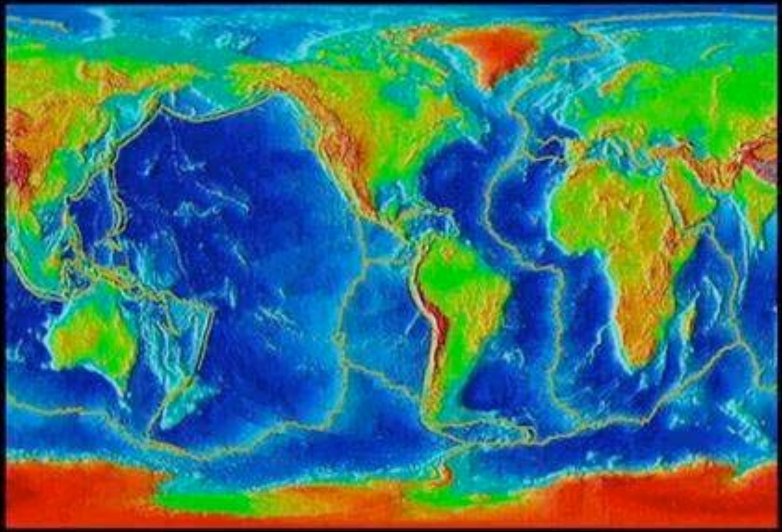
1) Tectonic loading of faults

2) Earthquakes

3) Seismic waves

4) Shaking (ground motion)

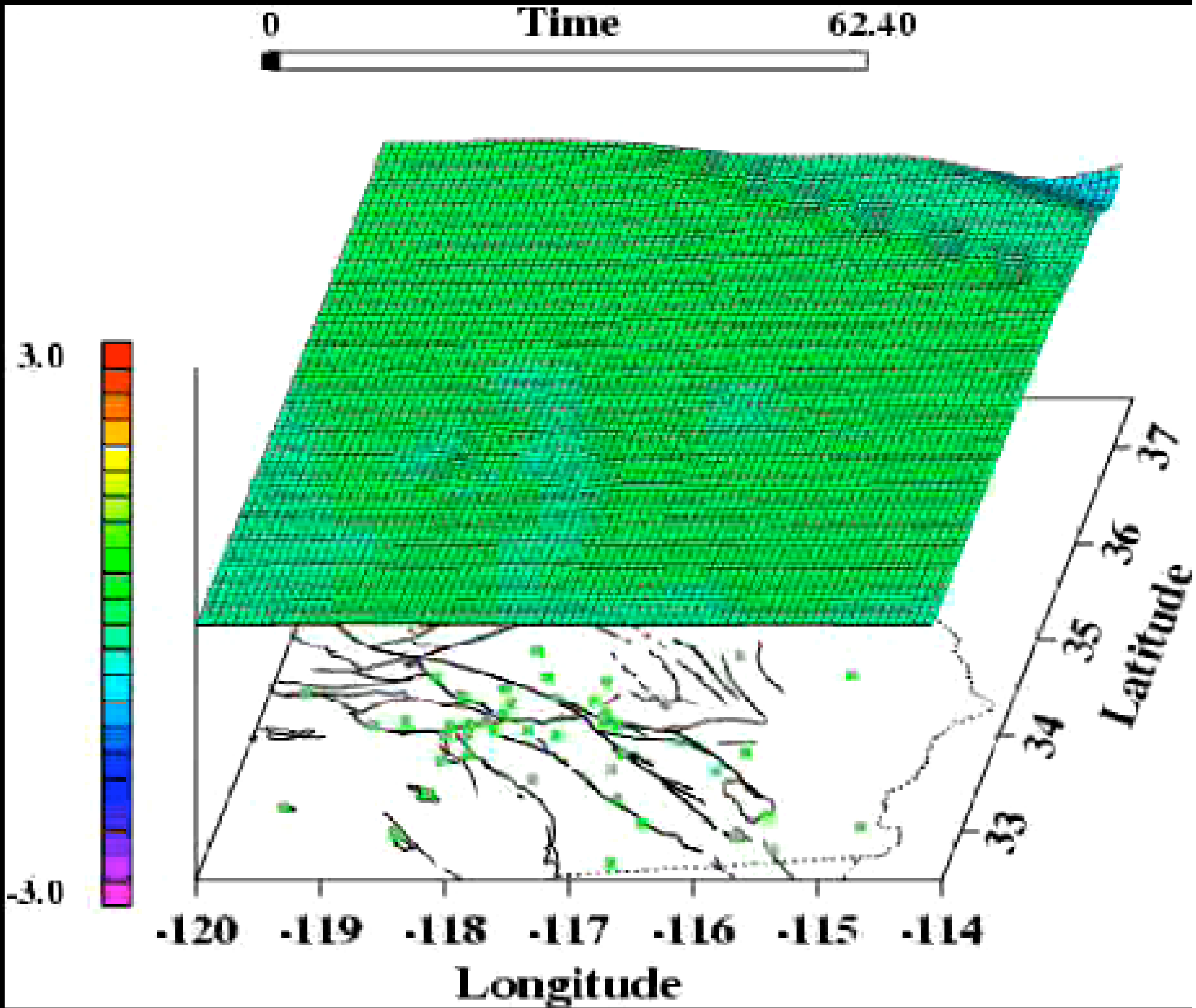
5) Structural failure



Structural failure: damage or collapse of structures (buildings, roads, dams, gas and electrical lines) that lead to a loss of life and property.

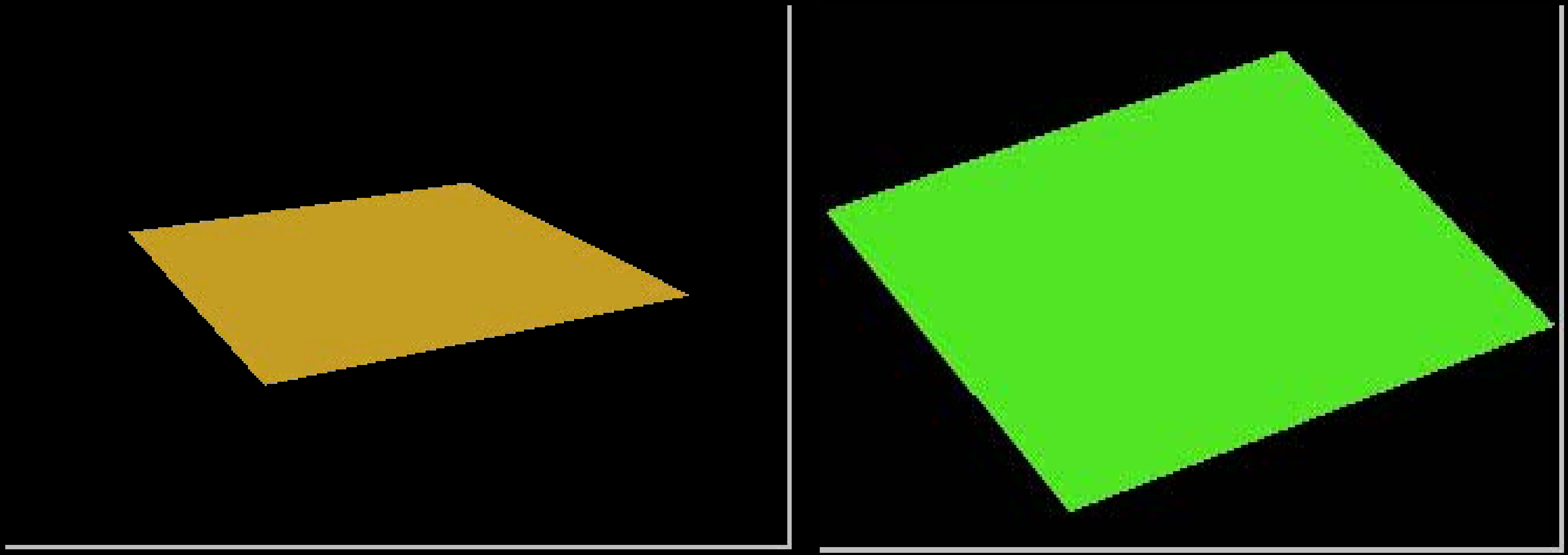
January 17, 1995, Kobe, Japan, M_w=6.9, > 5000 deaths

Shaking (ground motion): ground movement or motion of the earth that causes structures to react, i.e., that induces motion in the structure that can lead to failure.



An example of shaking in southern California due to the 1999 M7.4 Izmit earthquake in Turkey. [T. Tanimoto, UCSB]

Seismic waves: the propagation of the disturbance (energy) that we recognize as shaking.

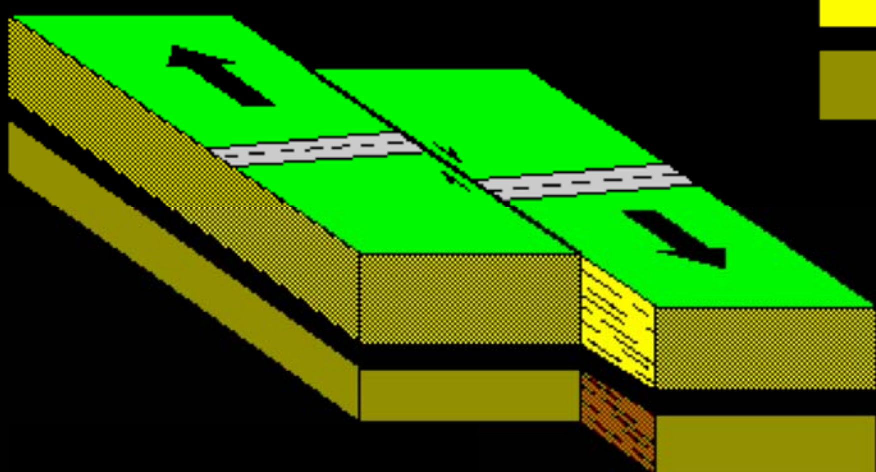


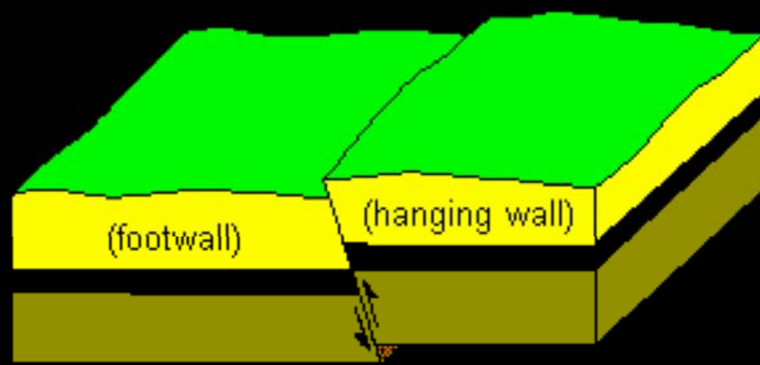
Center for Advanced Studies, Research and Development in Sardinia, 2002

Earthquake: The release of elastic energy by sudden slip on a **fault**, and the resulting ground shaking and radiated seismic energy caused by the slip.

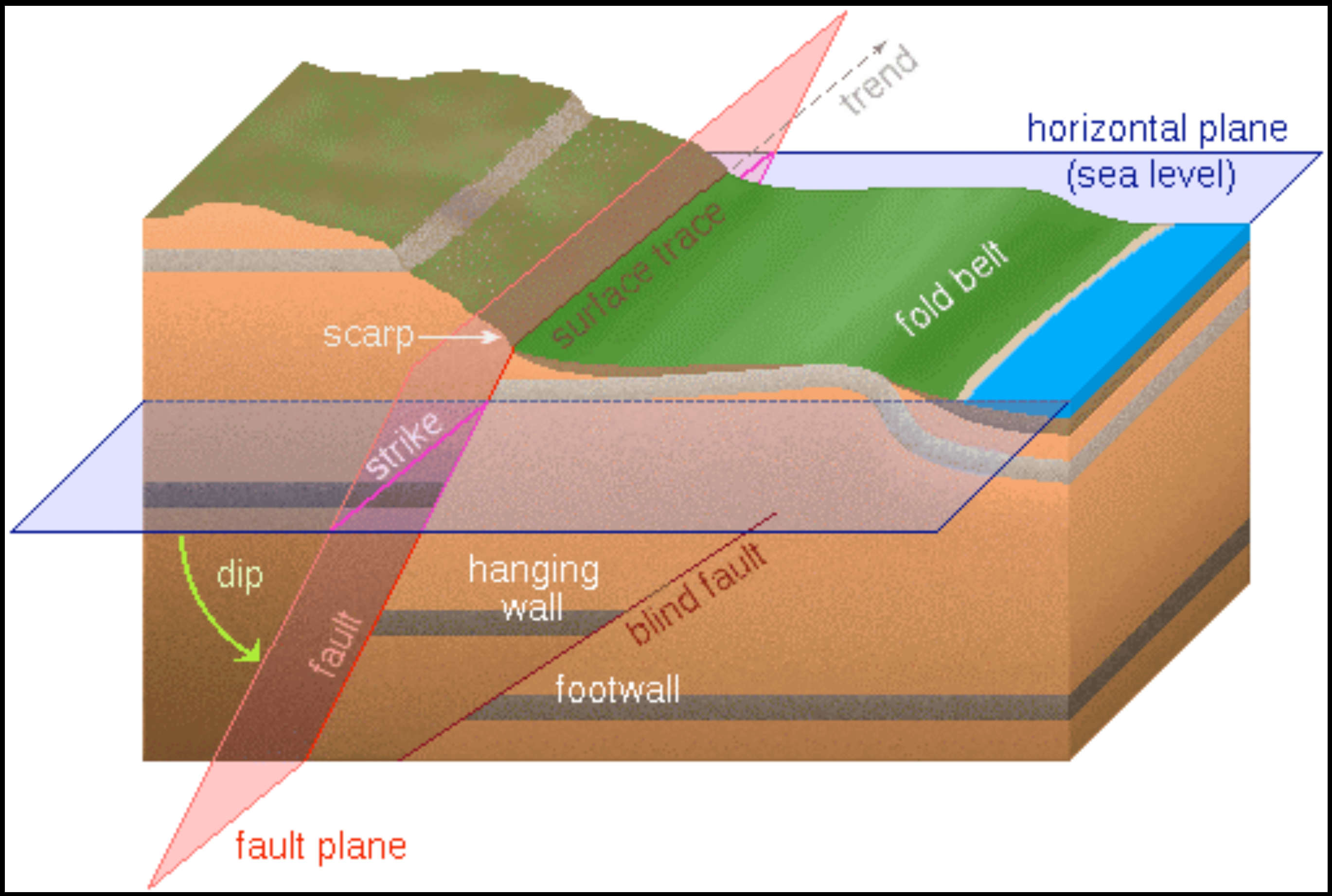
San Andreas M=7.75 simulation (Olsen, K. and R. Archuleta. UCSB)

Fault: A fracture (crack) in the earth, where the two sides move past each other and the relative motion is parallel to the fracture.





Fault specification:

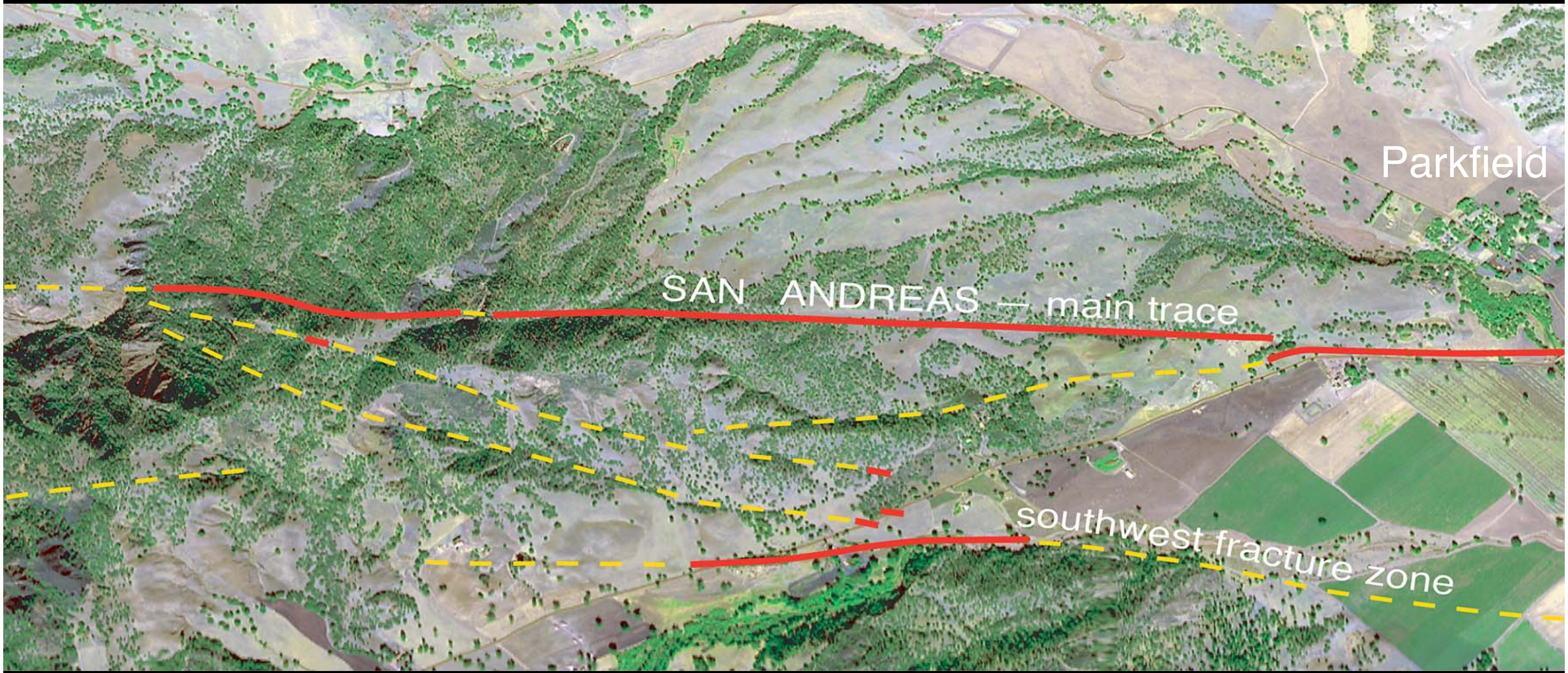


90˚ dip = vertical fault plane

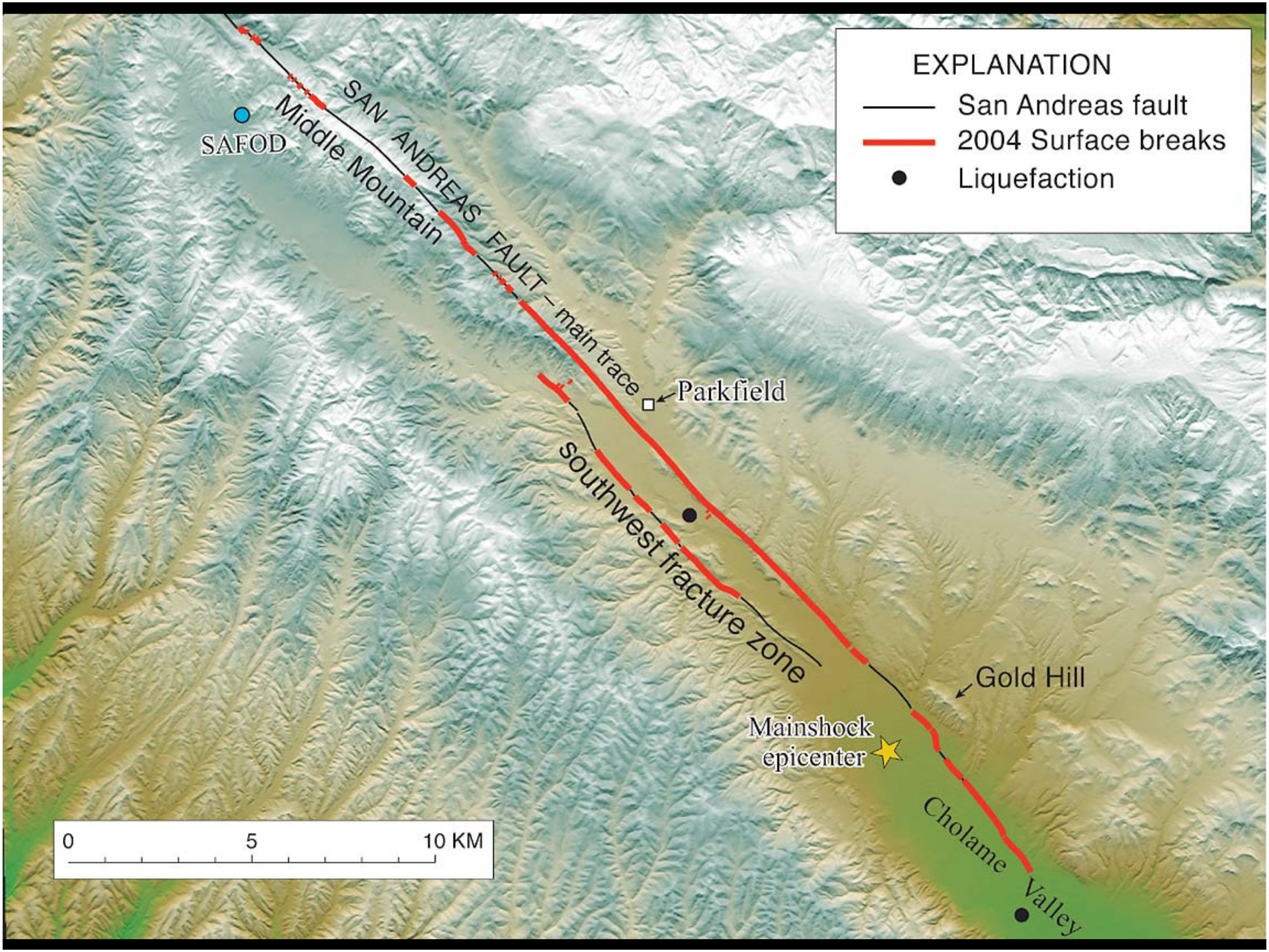
0˚ strike = north parallel fault plane

Surface trace (San Andreas, Carrizo Plain):

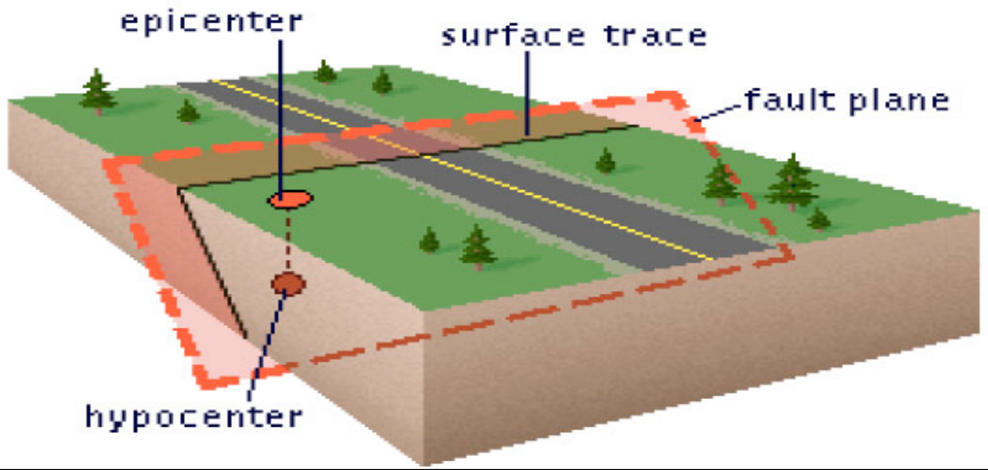
2004 SAF Surface Fractures (red) and Other Faults (yellow)



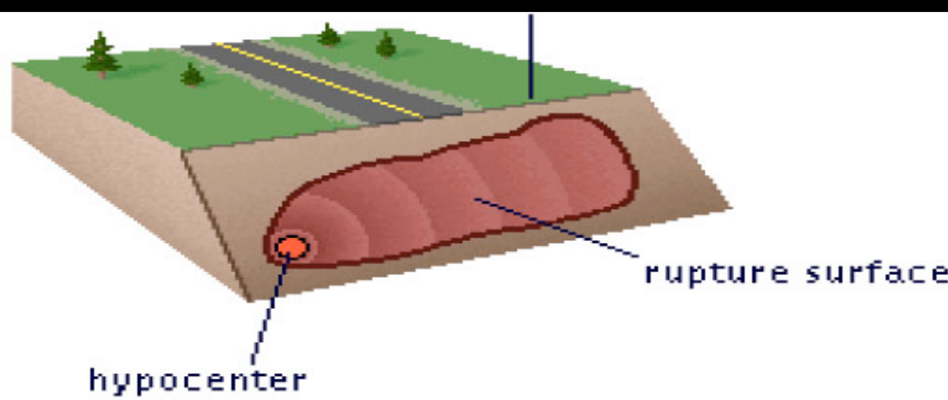
Mike Rymer, USGS, 2005


EXPLANATION
San Andreas fault
2004 Surface breaks
Liquefaction
SAFOD
SAN ANDREAS FAULT – main trace
Middle Mountain
Parkfield
Southwest fracture zone
Gold Hill
Mainshock epicenter
Cholame Valley
0
5
10 KM

Earthquake (initial slip) locations:



If one side of the fault is removed, the footwall is exposed showing the rupture covers the fault surface and is not simply some point on the surface of the earth.

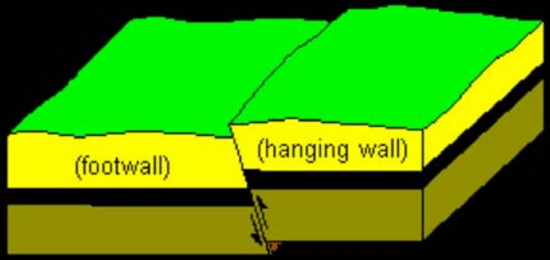


Fault types:

1) Dip-slip - major offset in the dip (vertical) direction

a) Normal - hanging wall moves down

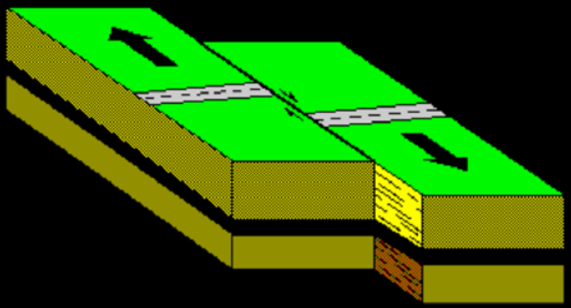
b) Reverse - hanging wall moves up



2) Strike-slip - major offset in the strike (horizontal) direction

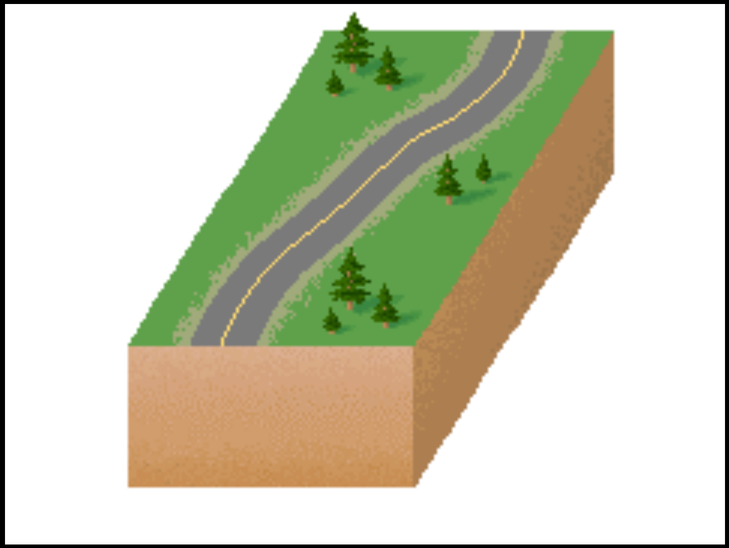
a) Left-lateral

b) Right lateral

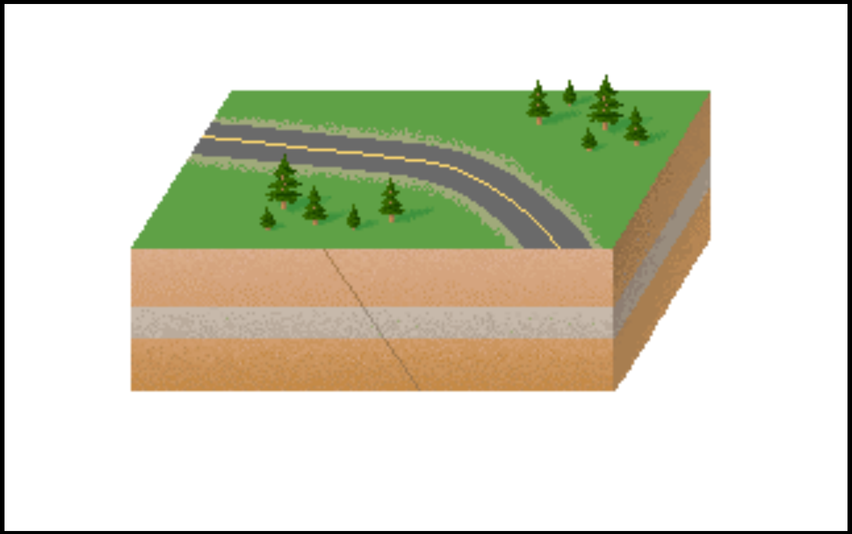


Movies: Styles of Faulting

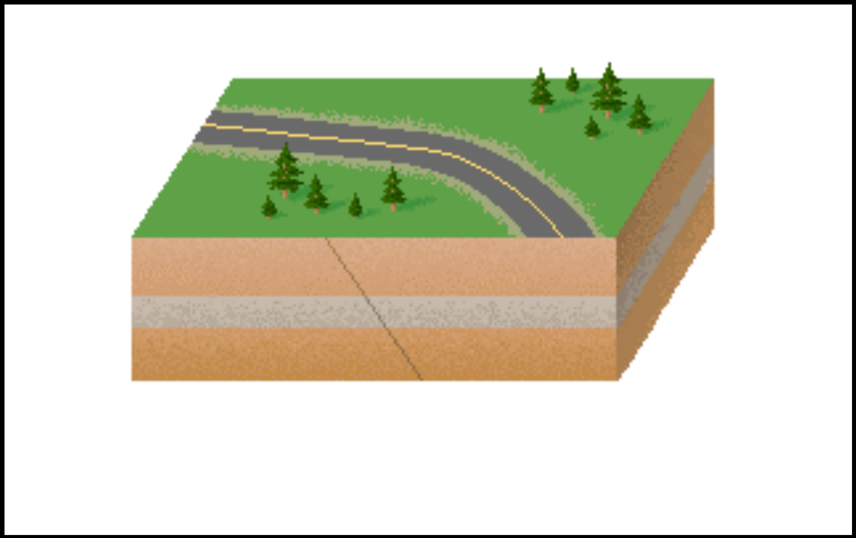
Strike-slip

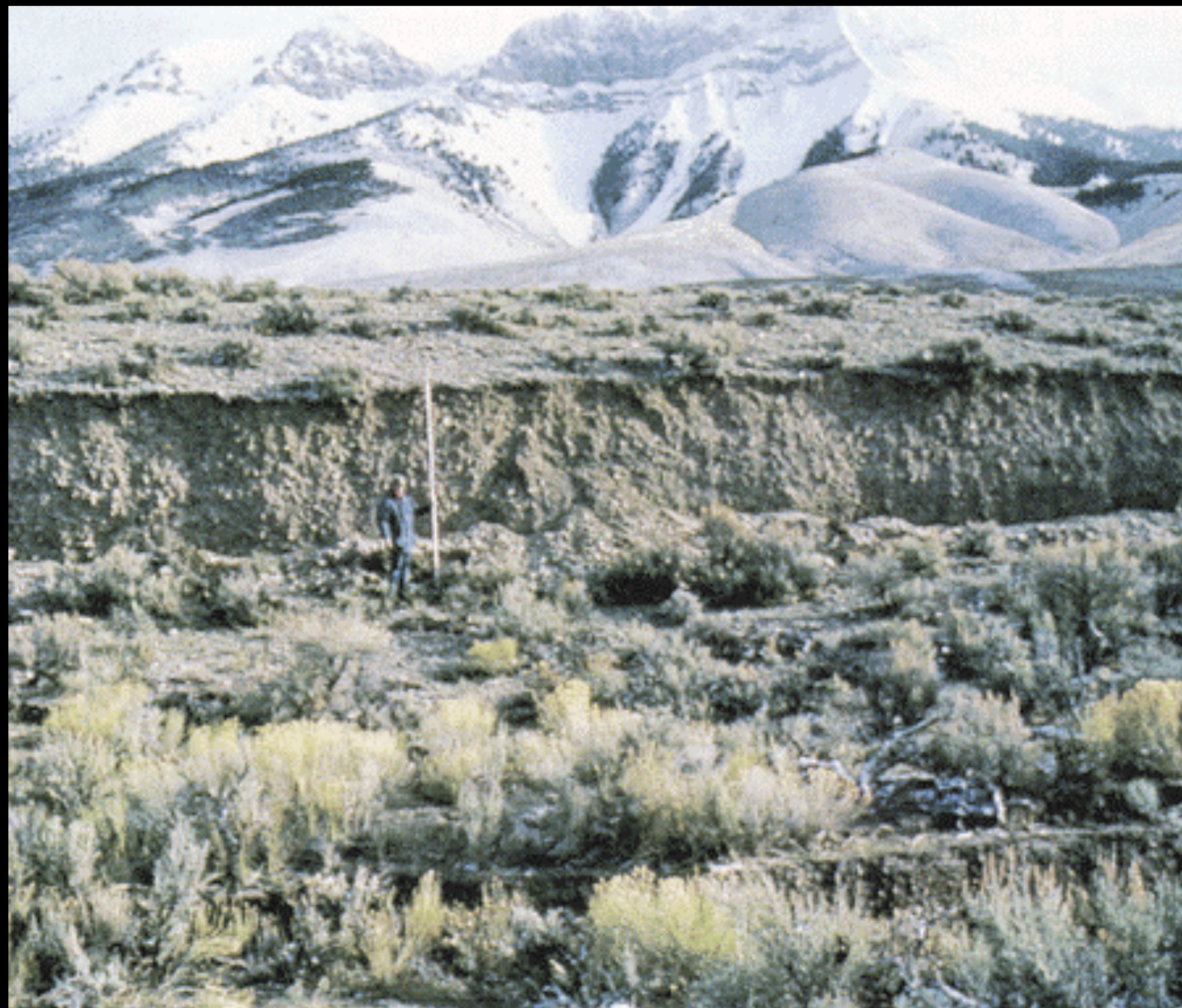


Dip-Slip: Reverse



Dip-Slip: Normal

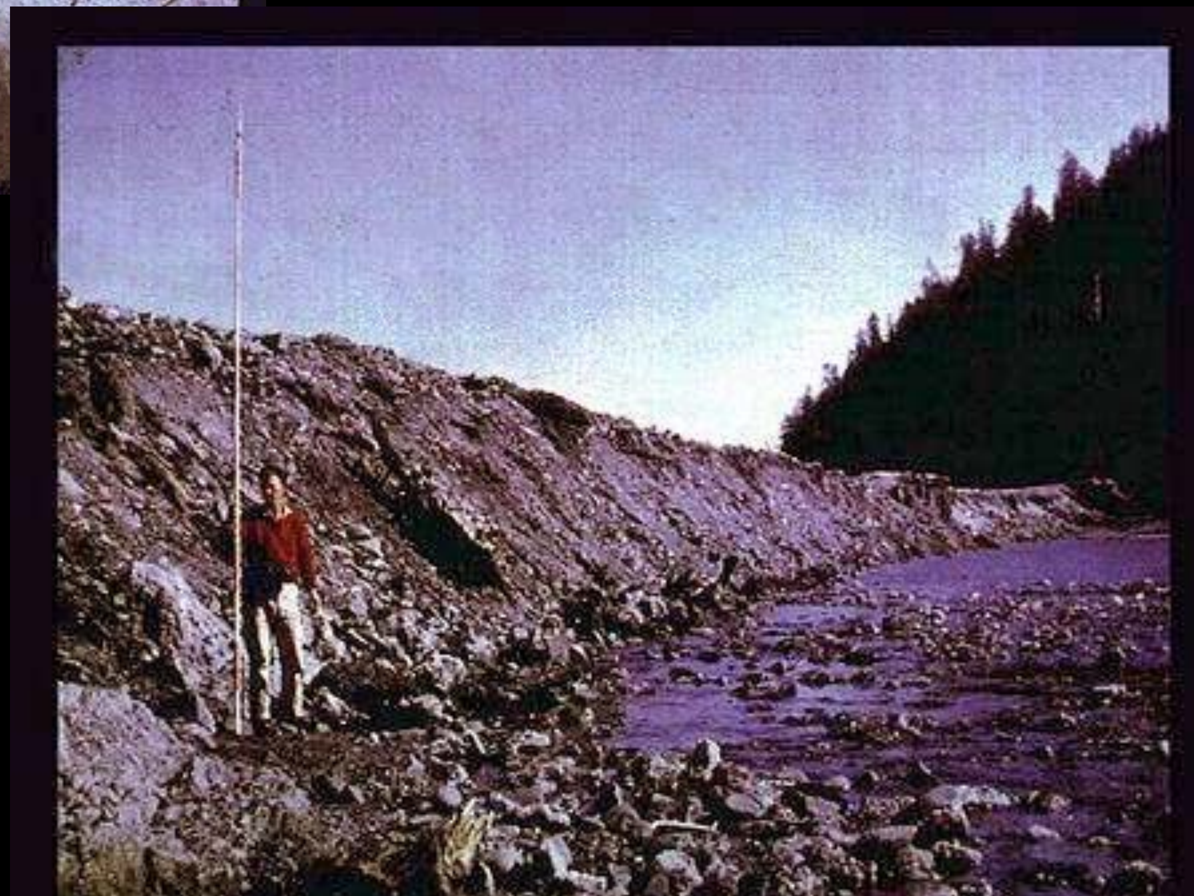




1983 Borah Peak Earthquake, Idaho

Thrust (reverse) faulting

1964 Alaska, Prince Edward Island



Strike-Slip Faulting 1979 Imperial Valley Earthquake

Sudden slip by elastic rebound theory:

1) Stresses (force/area) are applied to a fault.

2) Strain (deformation) accumulates in the vicinity of friction-locked faults.

3) Strain accumulation reaches a threshold and fault slips suddenly

4) Rupture (slip) continues over some portion of the fault.

Sequence:

1) Tectonic loading of faults

2) Earthquakes

    a) Fault definition

    b) Fault specification

    c) Fault types

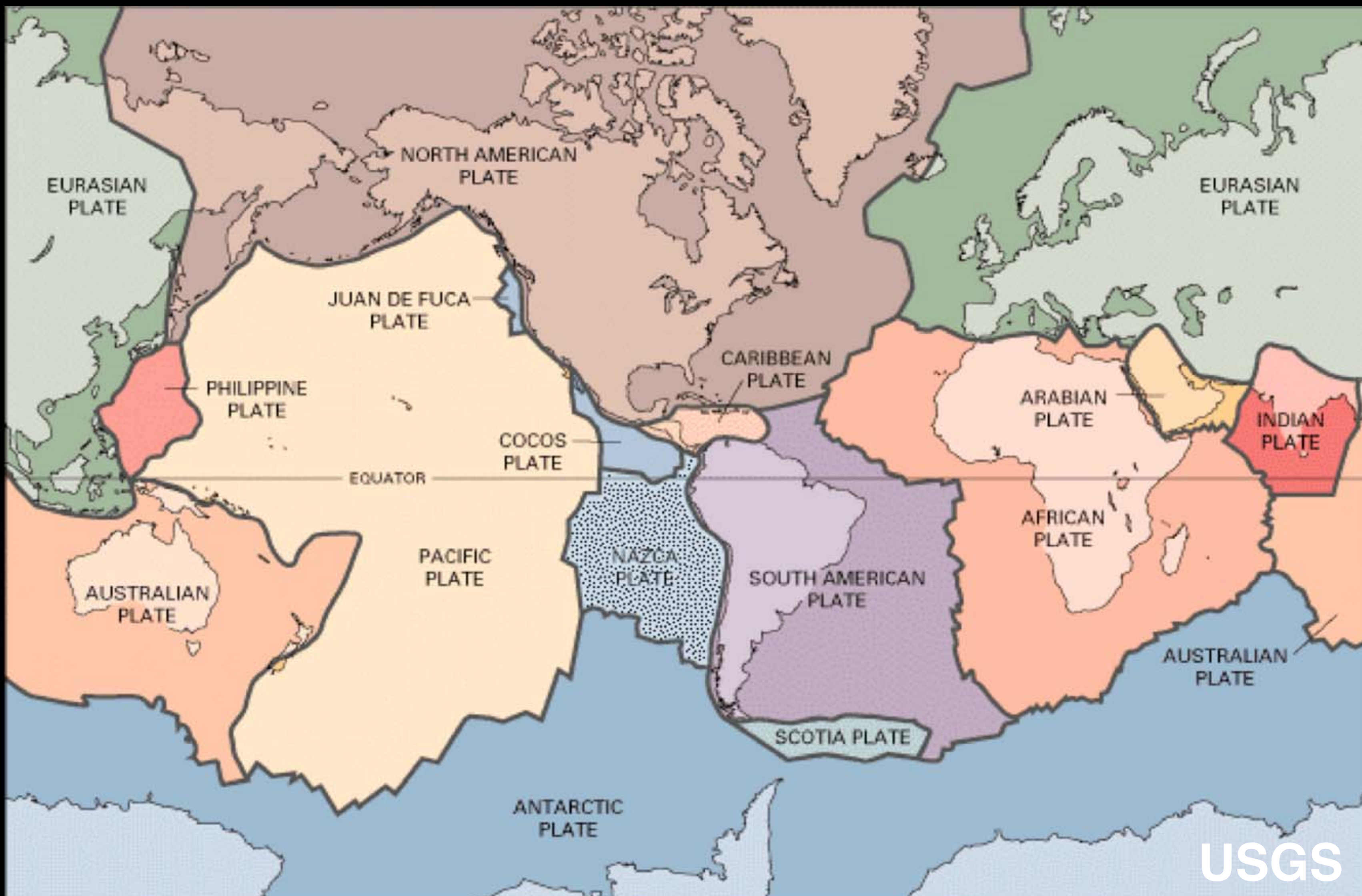
    d) Sudden fault slip

3) Seismic waves

4) Shaking (ground motion)

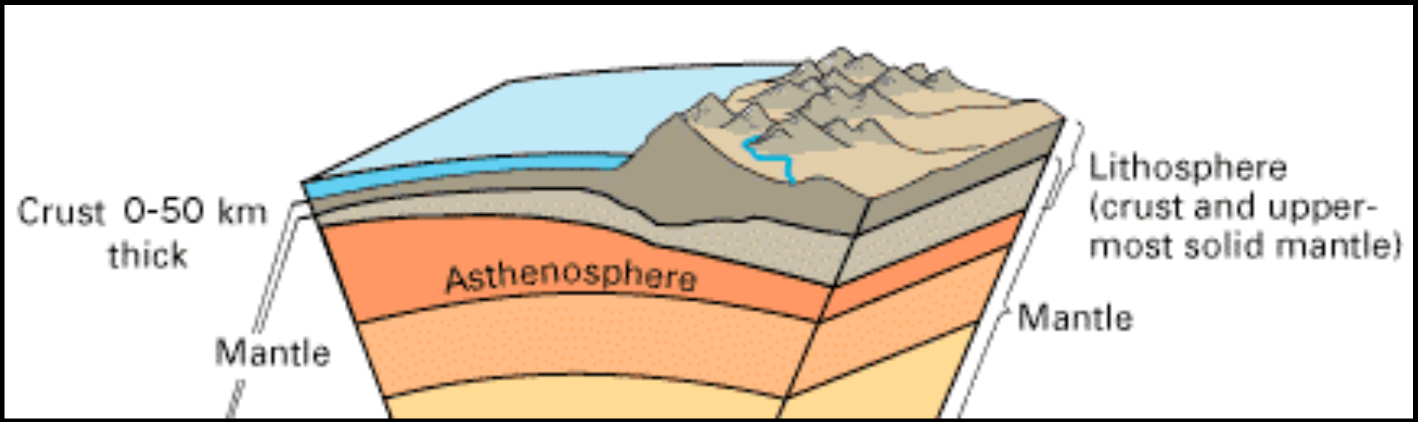
5) Structural Response (sometimes failure)

Tectonic plates:



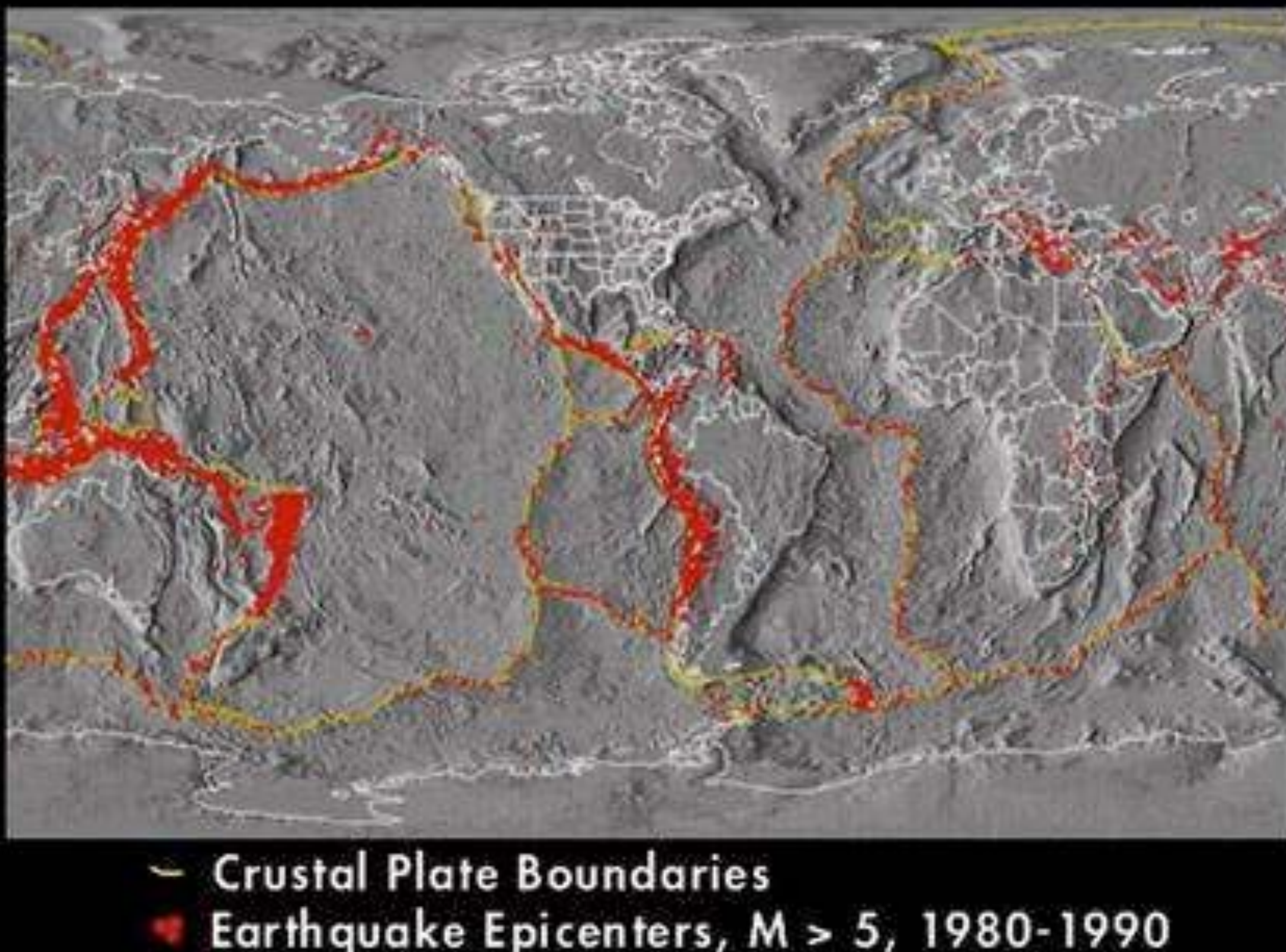
Tectonic loading of faults:

Plate tectonics: A theory of global tectonics in which the lithosphere is divided into a number of **plates** that act like rigid bodies and that **interact** with one another at their **boundaries** causing earthquakes, volcanism and deformation.

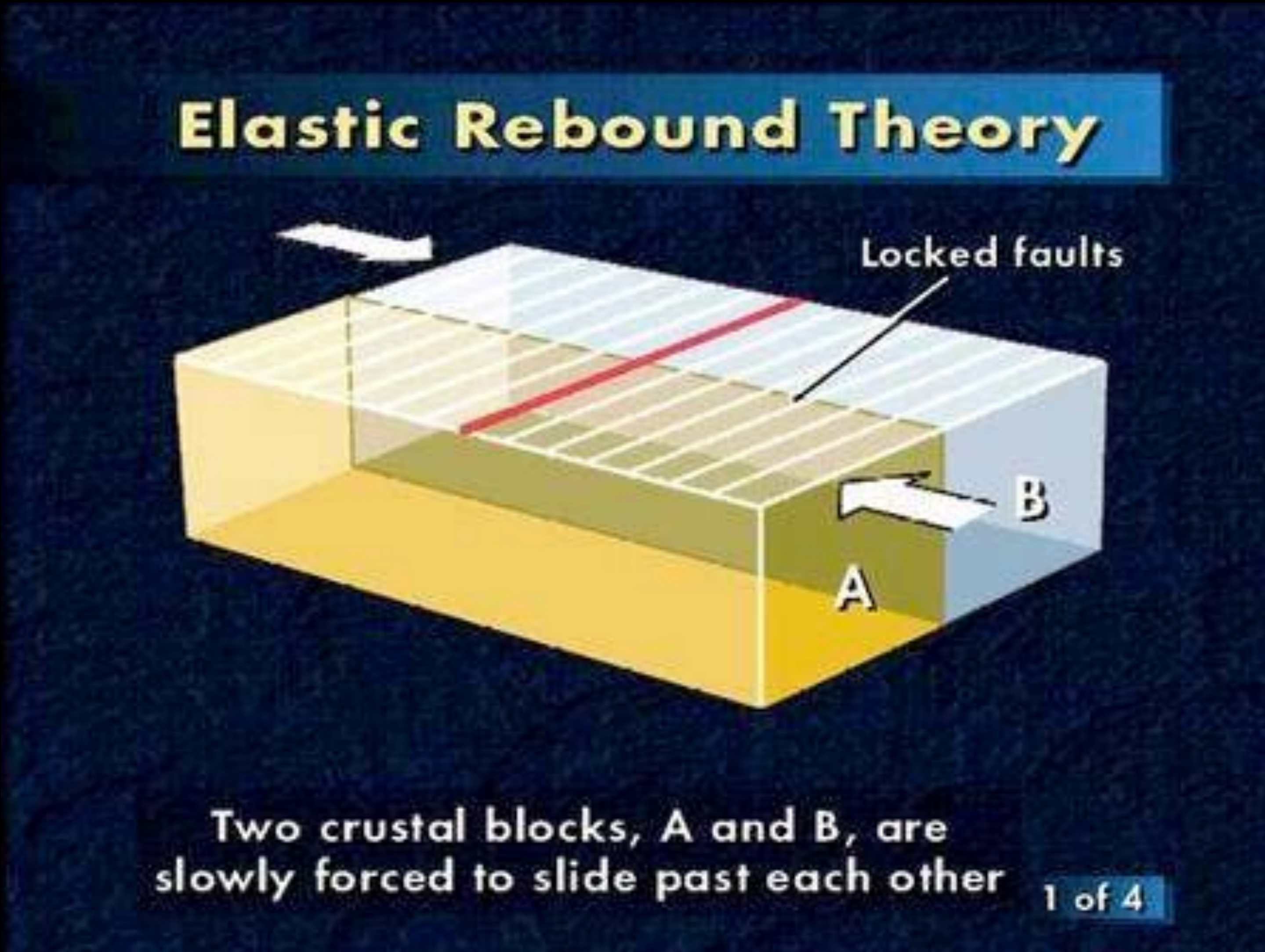


Tectonics: Study of the deformational features and movement [and their relations and historical evolution] of the outer part of the Earth.

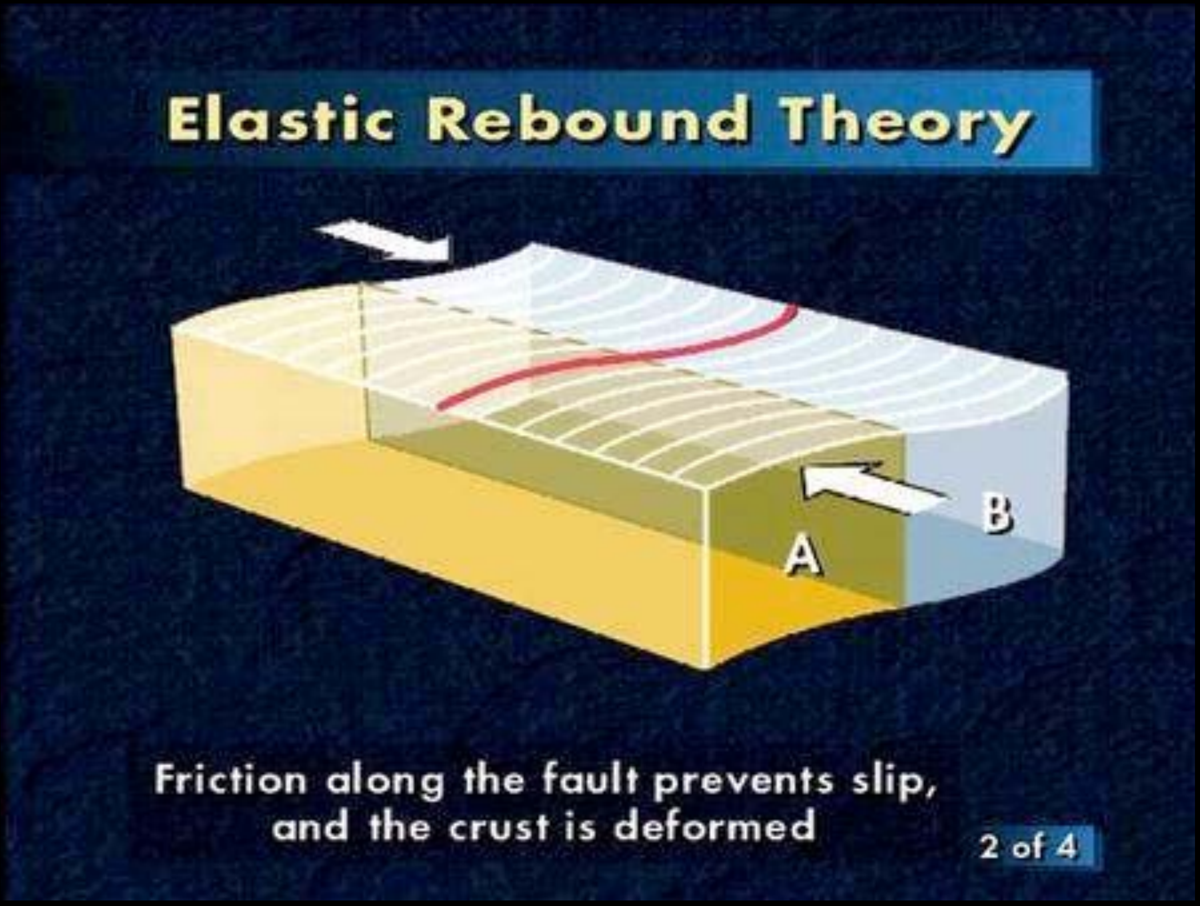
Earthquakes and plate boundaries:



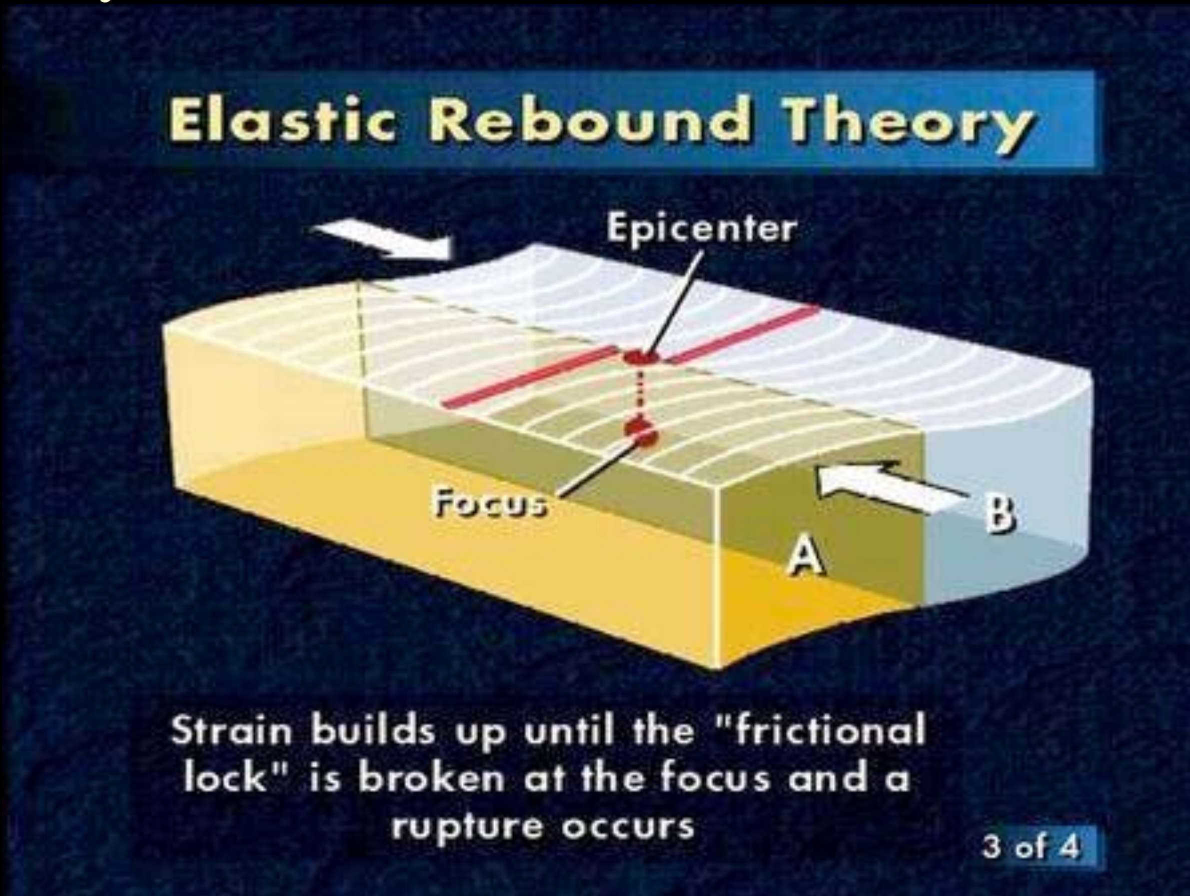
1) Stresses (force/area) are applied to a fault.



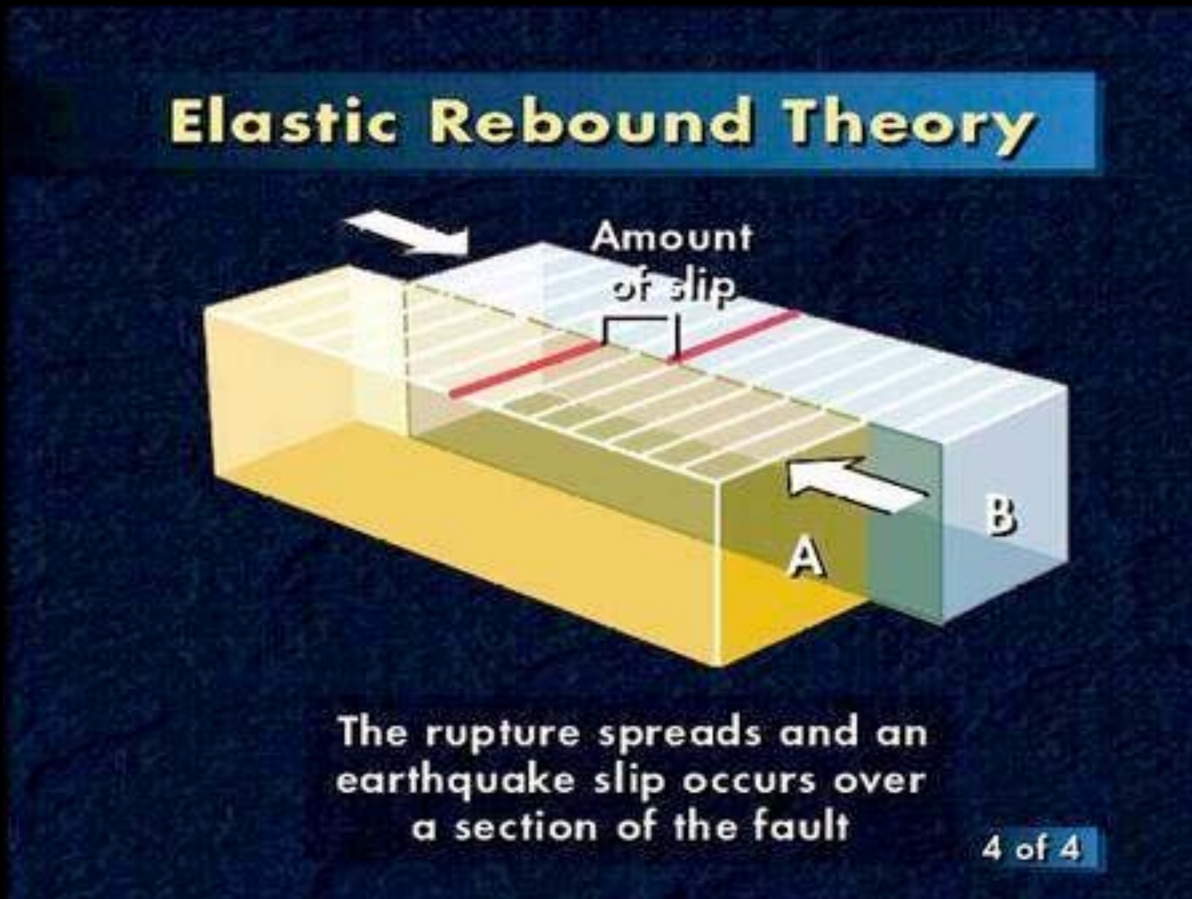
2) Strain (deformation) accumulates in the vicinity of friction-locked faults.



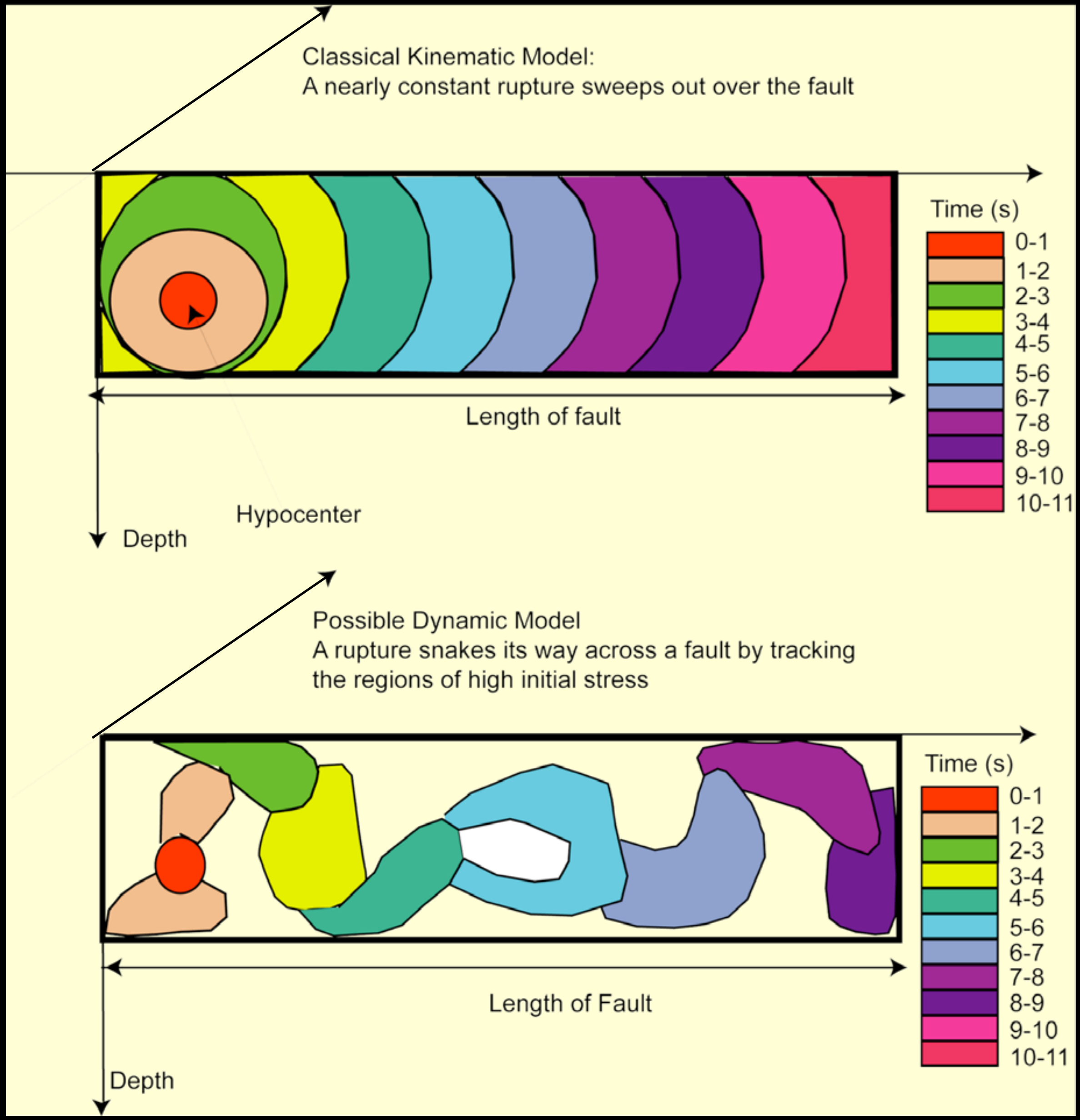
3) Strain accumulation reaches a threshold and fault slips suddenly.



4) Rupture (slip) continues over some portion of the fault.

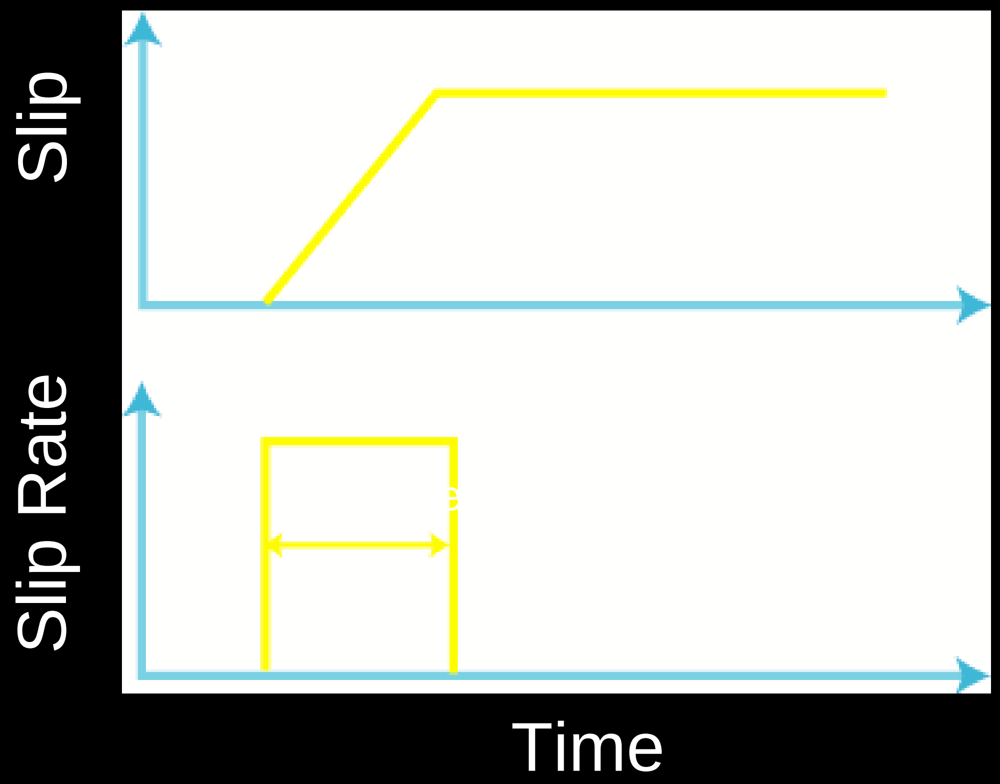


Kinematic Model

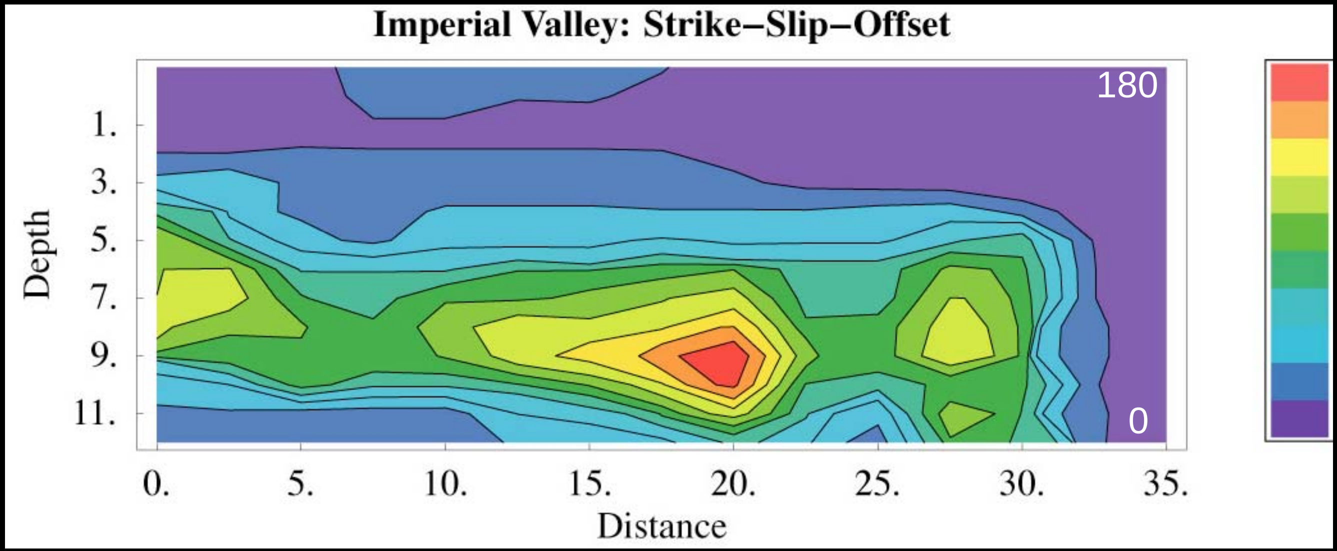


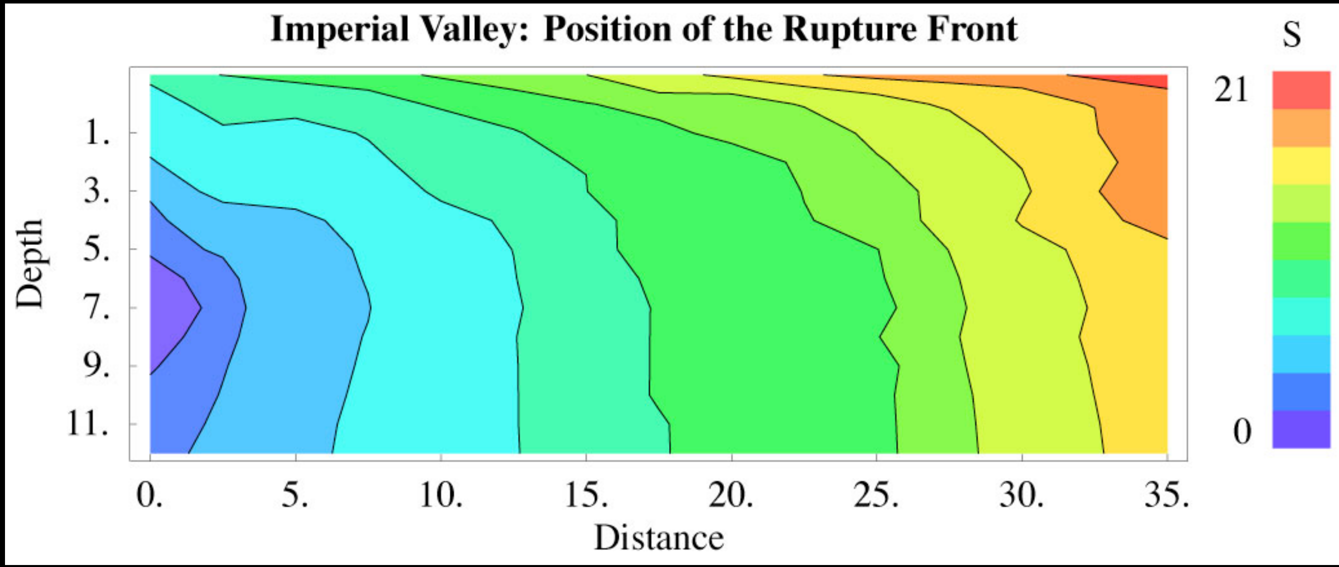
Finite Fault--Kinematic (Haskell, 1966)

- Fault Geometry: Length, Width
- Slip
- Rise Time
- Rupture Velocity



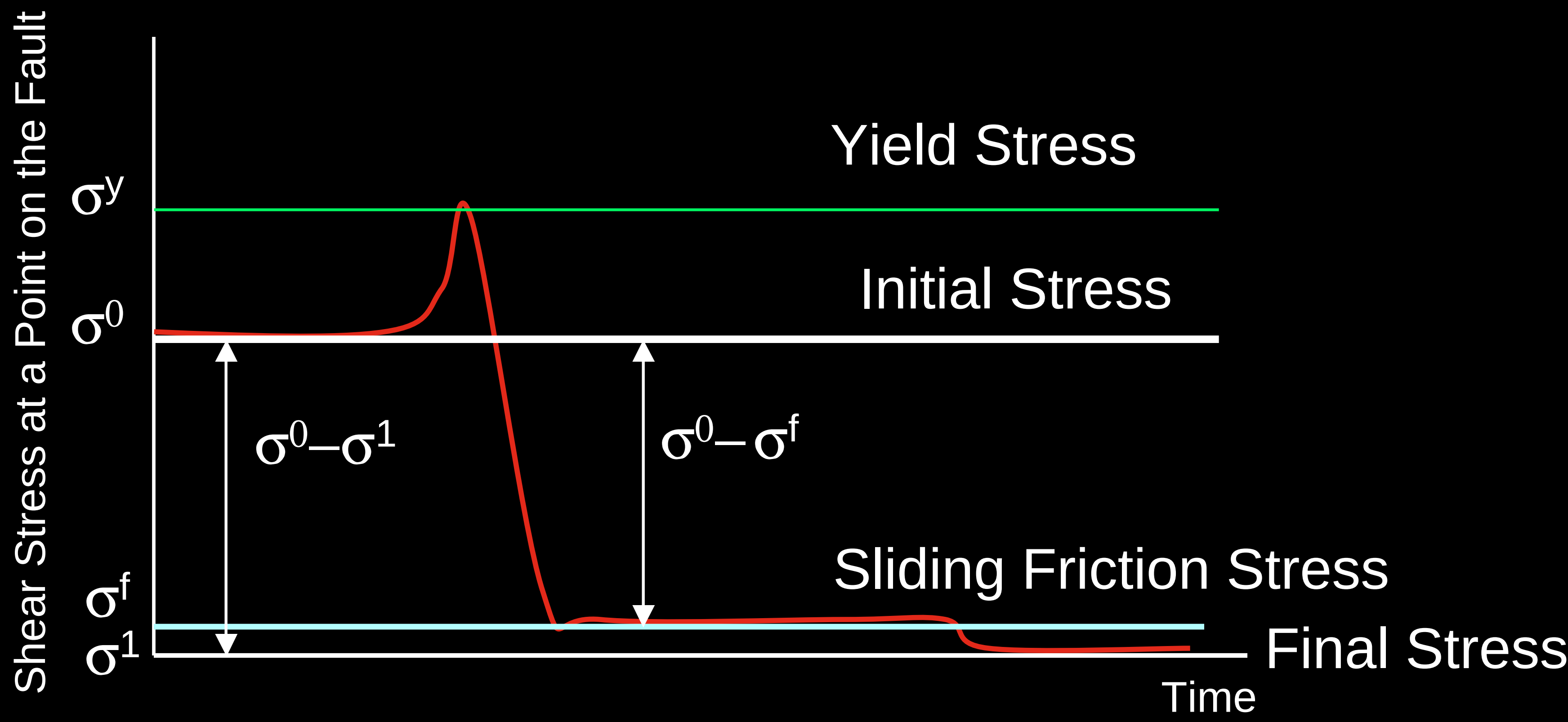
Imperial Valley Kinematic Parameters





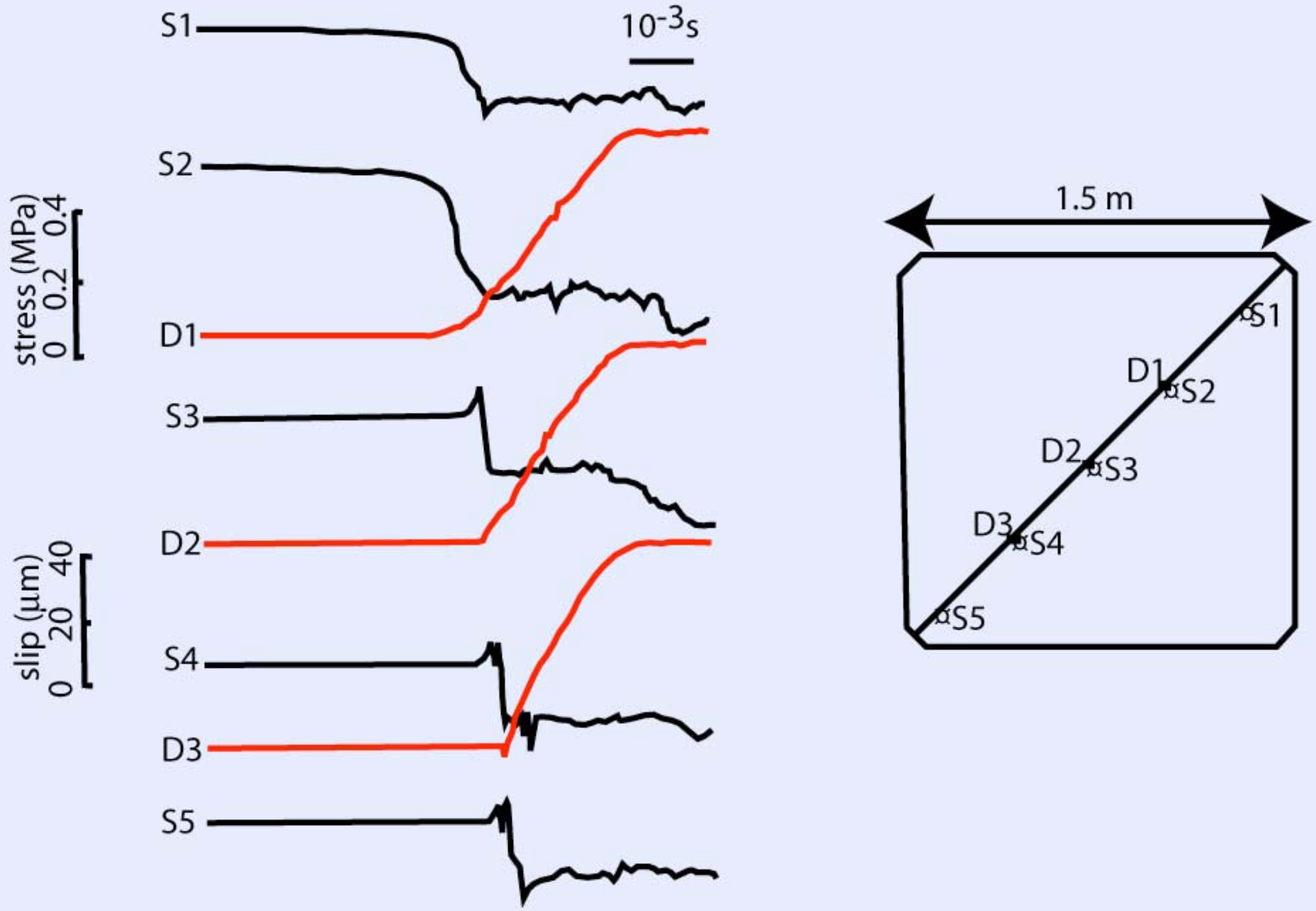
From Archuleta, 1984, JGR

Behavior of Shear Stress at a Point on the Fault



$S=(\sigma^y-\sigma^0)/(\sigma^0-\sigma^f)$=Strength Excess/Stress Drop

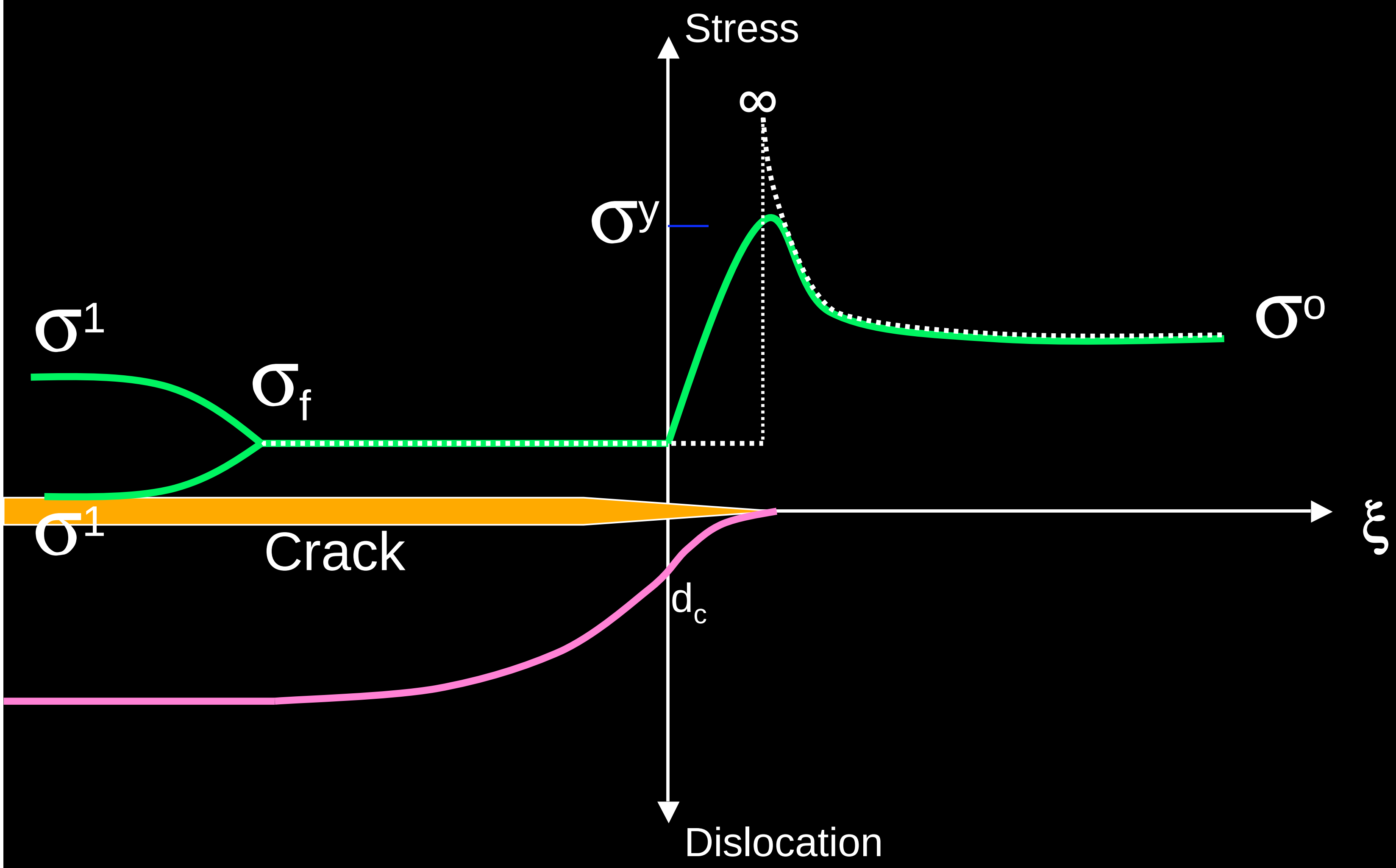
Dieterich's Experiments



S1–S5 give shear stress parallel to the fault. D1–D3 give slip on fault.

Modified from Dieterich (GRL, 1981):

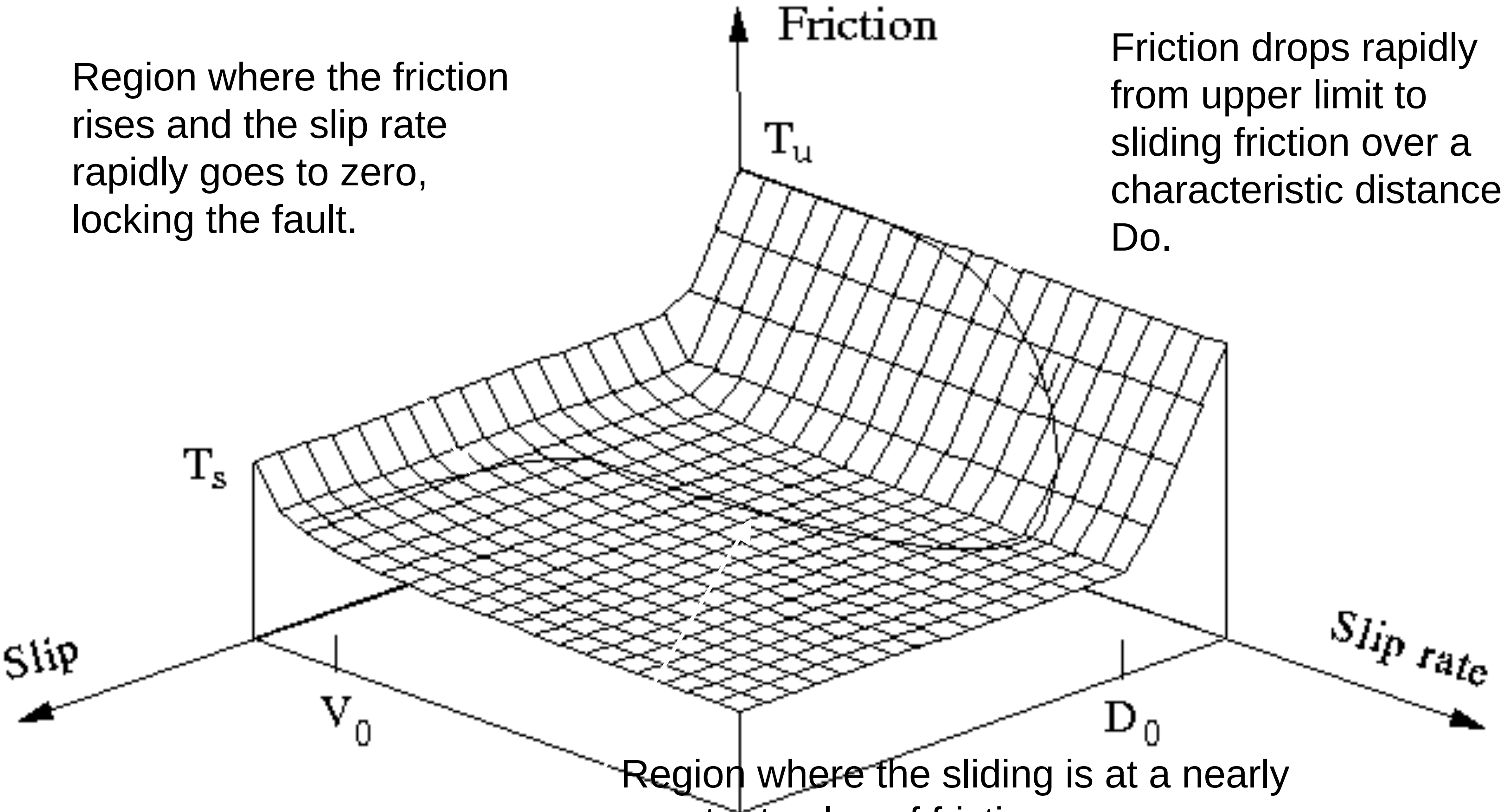
Anelastic Behavior at the Crack Tip to Eliminate the Stress Singularity



Ida, 1972

Region where the friction rises and the slip rate rapidly goes to zero, locking the fault.

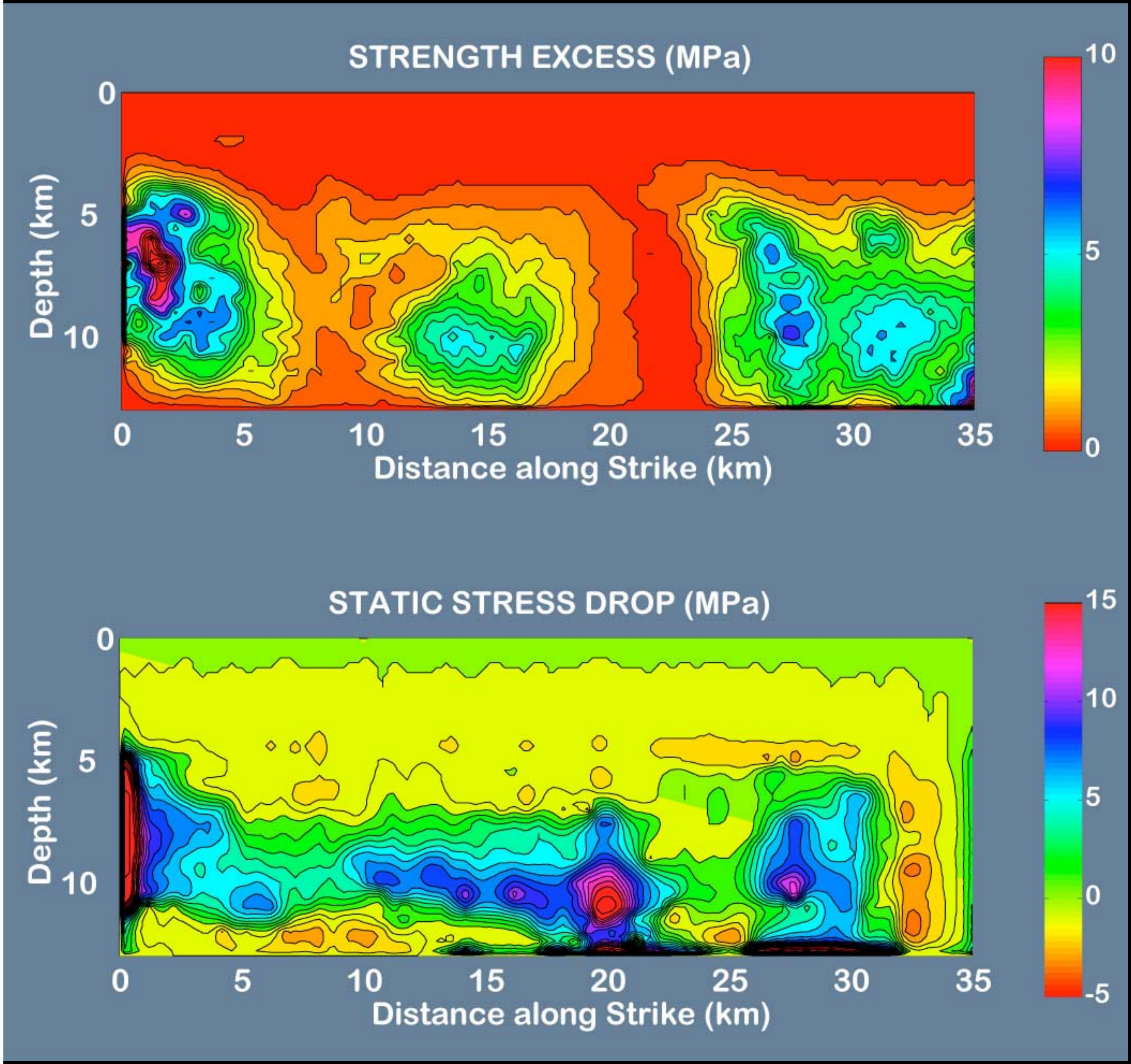
Friction drops rapidly from upper limit to sliding friction over a characteristic distance Do.

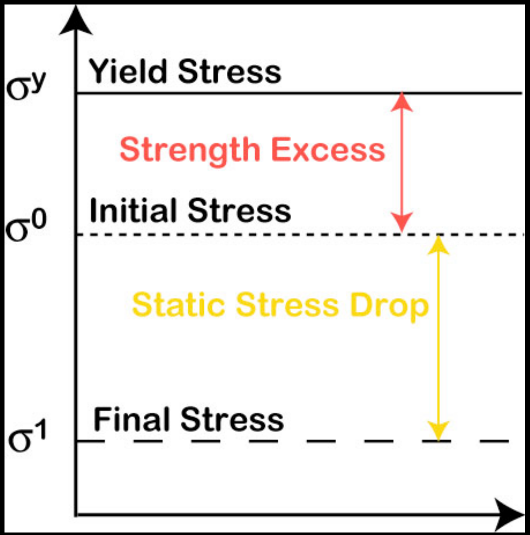


Region where the sliding is at a nearly constant value of friction.

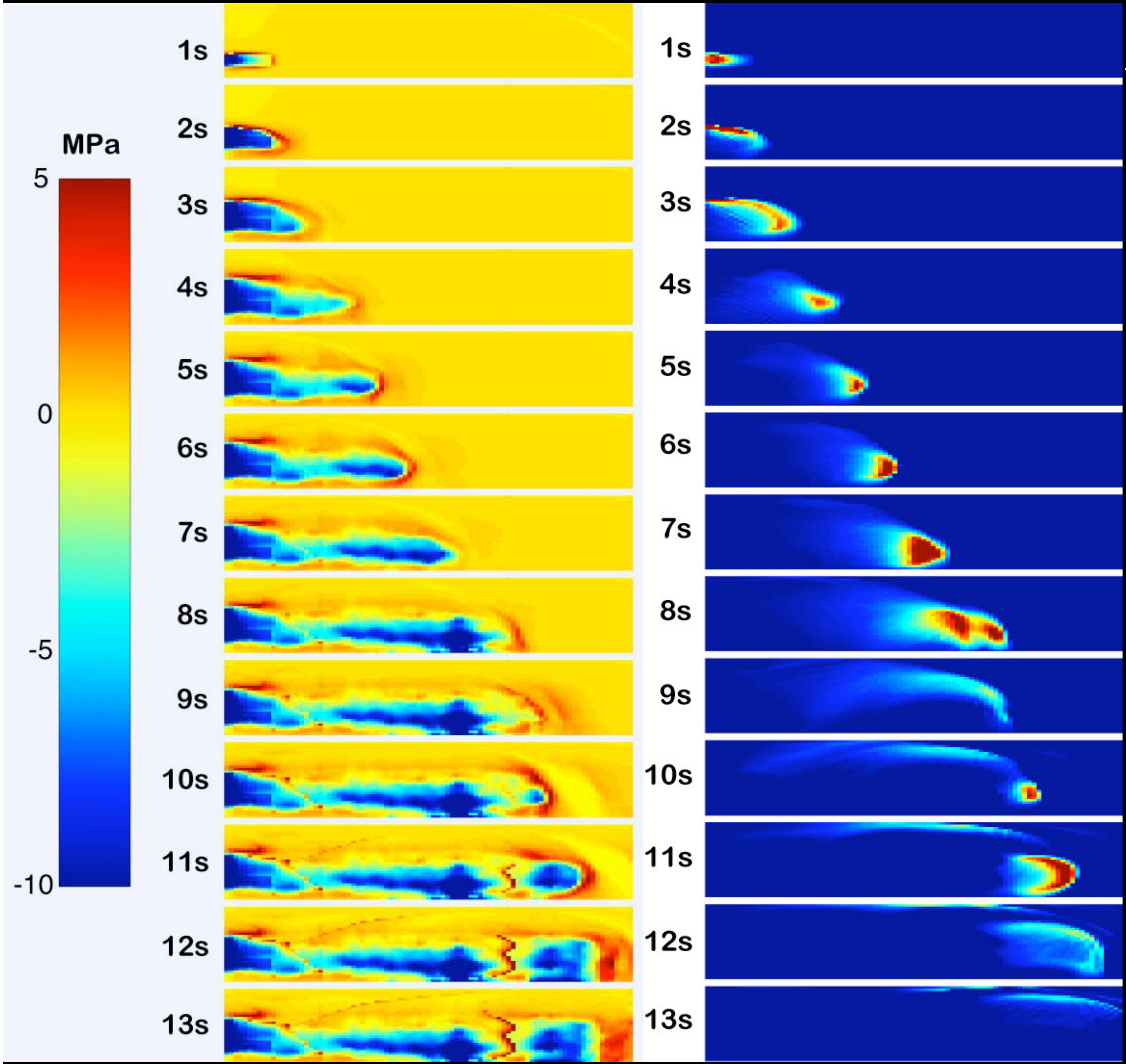
Madariaga, Olsen, Archuleta,

Static Stress Drop and Strength Excess





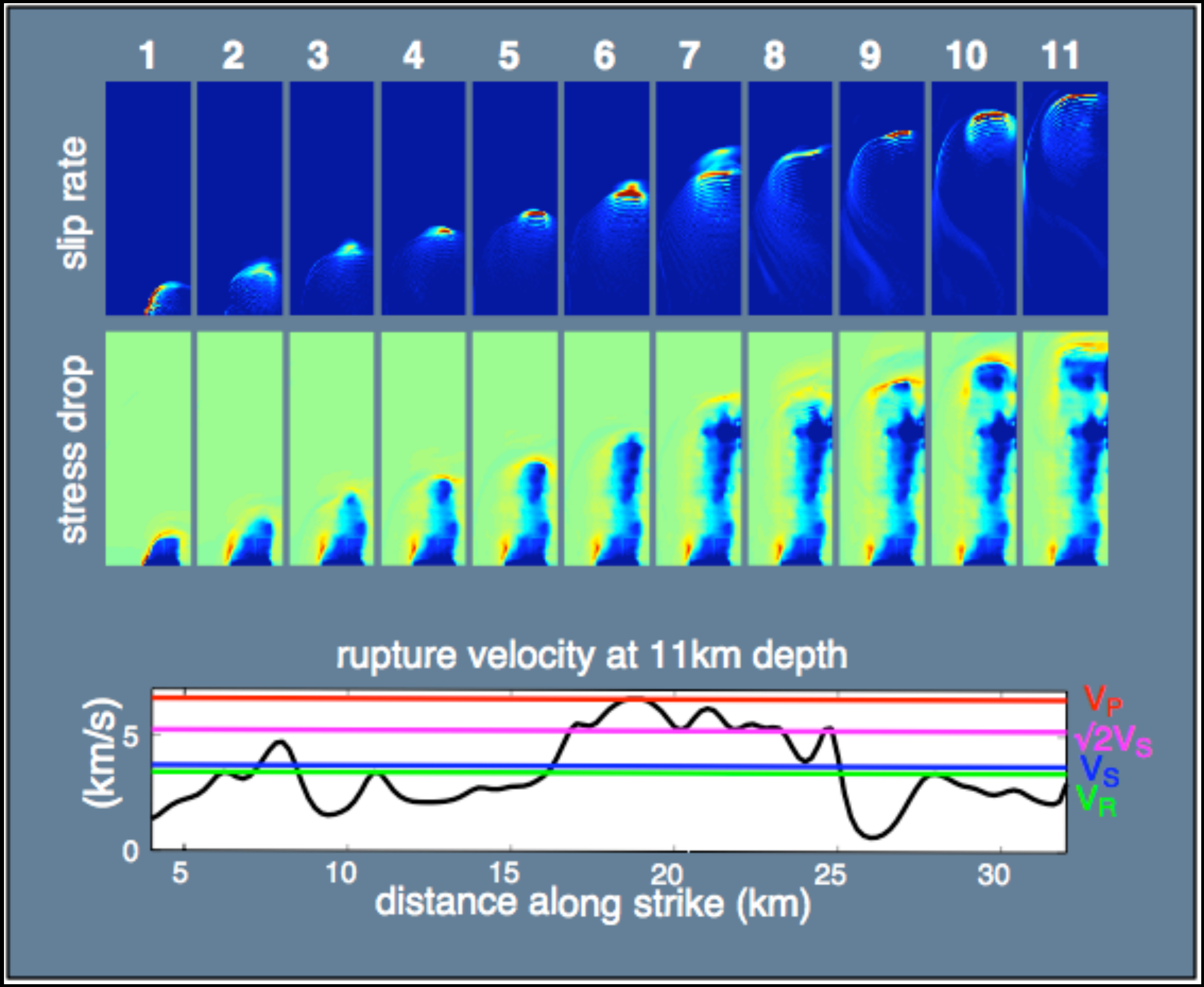
From Bouchon, 1997, JGR



Snapshots of Fault Plane Showing Evolution of

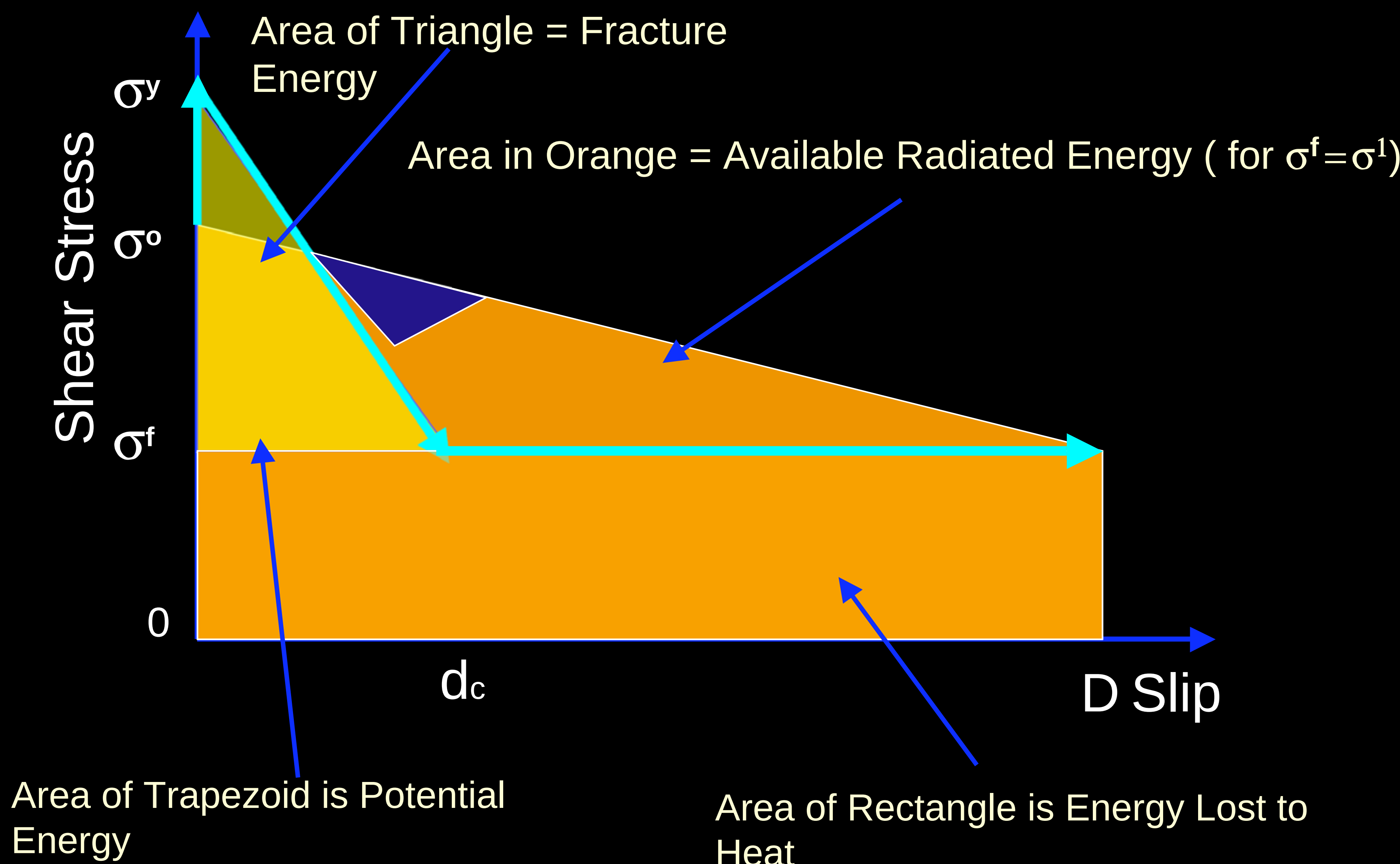
1) Stress Drop
2) Slip Rate

Imperial Valley Dynamic Rupture



Favreau and Archuleta, Geophys. Res. Lttr., 2003

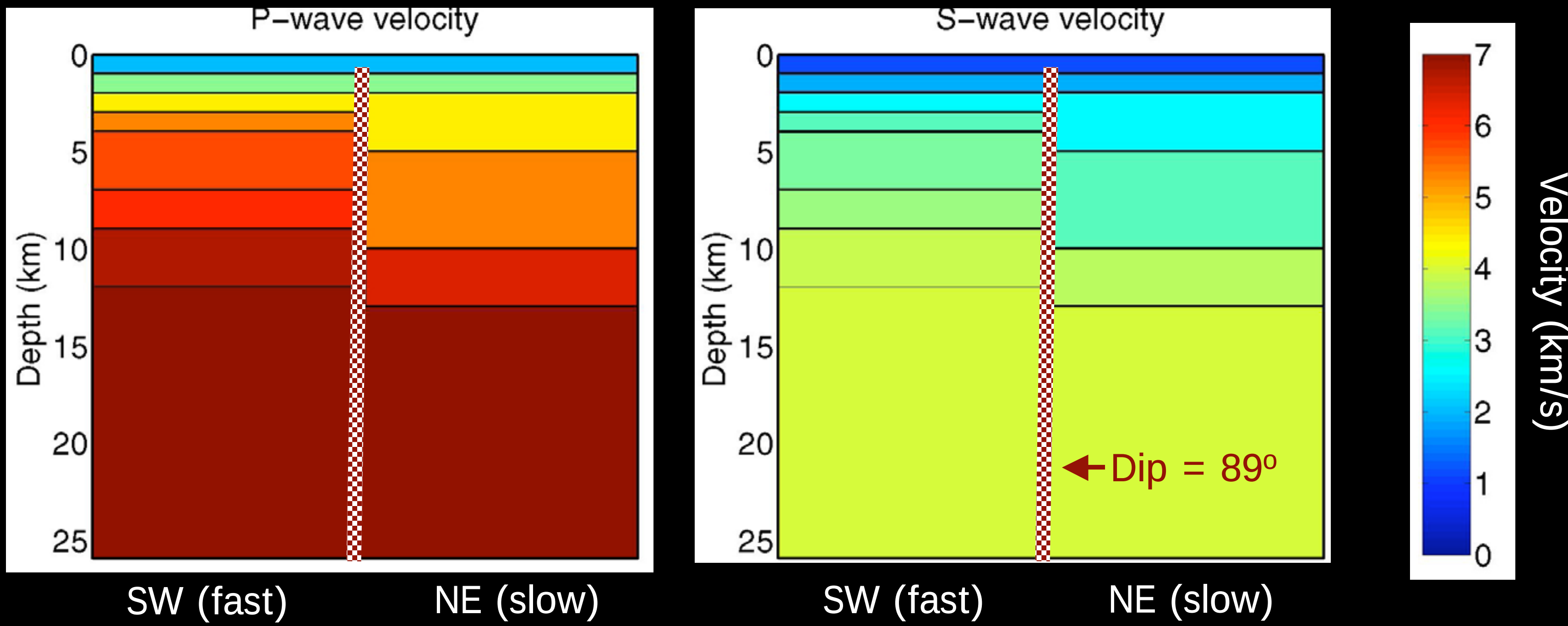
Seismic Energy Diagram: Slip Weakening



Ida, 1972

Parkfield – bilateral 1D velocity model

1D velocity model interpolated from the 3D velocity model of Thurber et al. (2003)



2.0 km/s $< V_P <$ 8.0 km/s

1.1 km/s $< V_S <$ 4.5 km/s

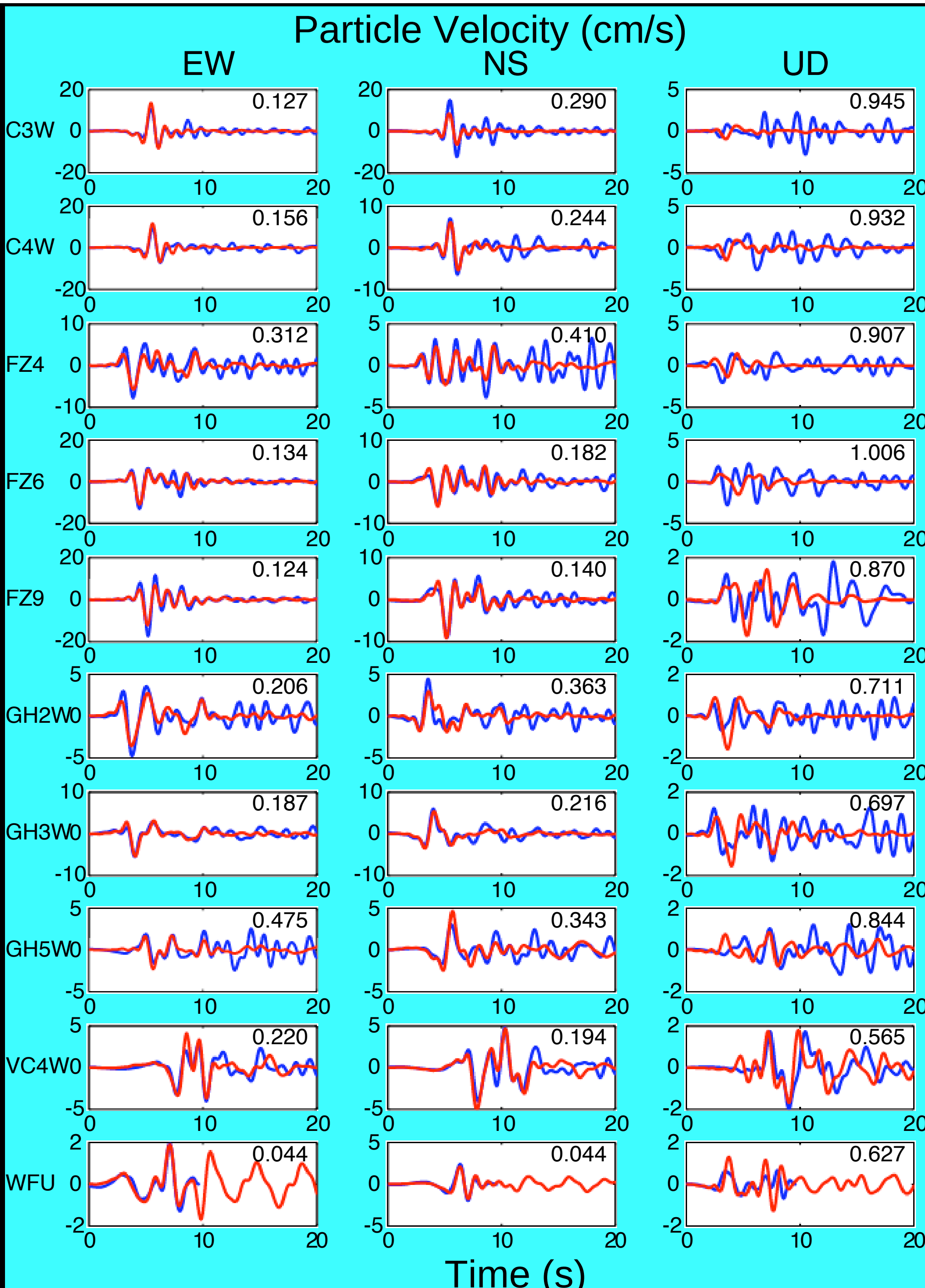
Fault dip = 89º

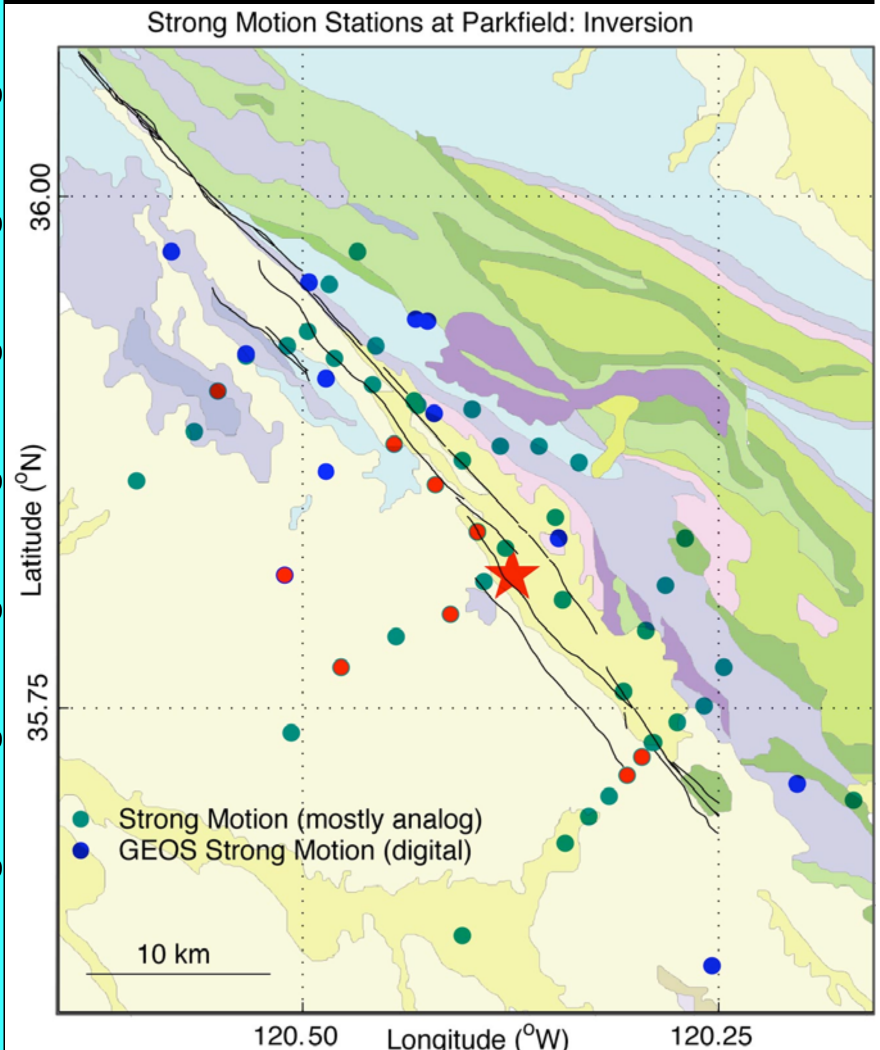
Fault buried 0.5 km below the surface

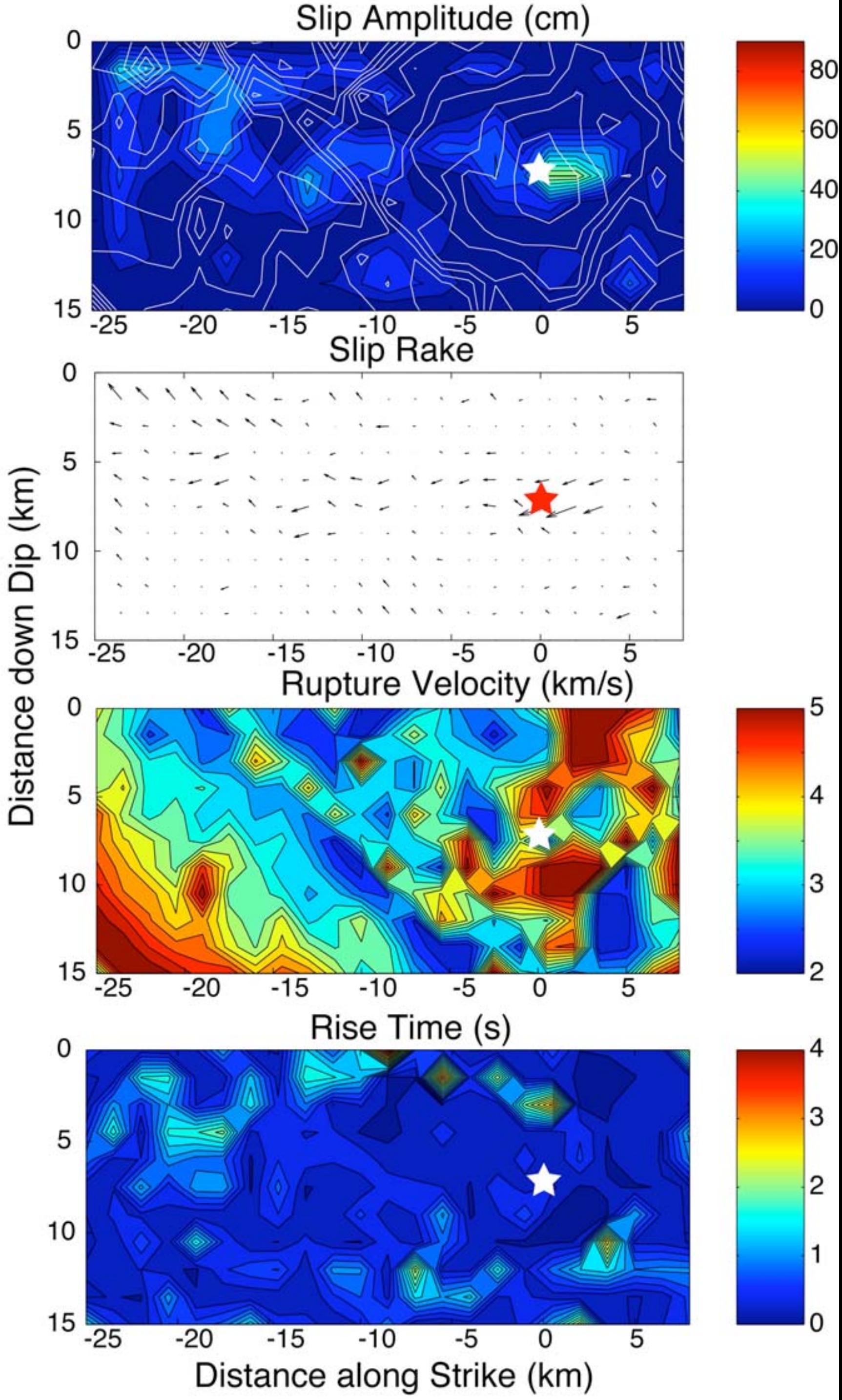
Inversion Results

Blue: Data

Red: Synthetic







Kinematic Parameters from One Inversion of 20 3-Component Stations

M_o: 1.0 x 10^{25} dyne-cm
Avg. Rupture Velocity: 3.3 km/s
Avg. Rake: 165˚
Avg. Misfit in Inversion: ~0.22
Avg. Misfit in Prediction: ~0.60

Dynamic Energy Balance

Fault Representation

$$E_q = W_{total} - W_{static} = \int_t \int_\Sigma \Delta\sigma \dot{D}(t)\, d\Sigma dt - \frac{1}{2}\int_\Sigma (\sigma^0 - \sigma^1)\, d\Sigma$$

$$E_q = \int_t \int_\Sigma [\sigma^0 - \sigma(t)] \dot{D}(t)\, d\Sigma dt - \frac{1}{2}\int_\Sigma (\sigma^0 - \sigma^1)\, d\Sigma$$

$$E_q = \frac{1}{2}\int_\Sigma (\sigma^0 + \sigma^1) D\, d\Sigma - \int_t \int_\Sigma \dot{\sigma}(t) D(t)\, d\Sigma dt$$

Potential energy change

Energy loss (fracture energy+frictional heat)

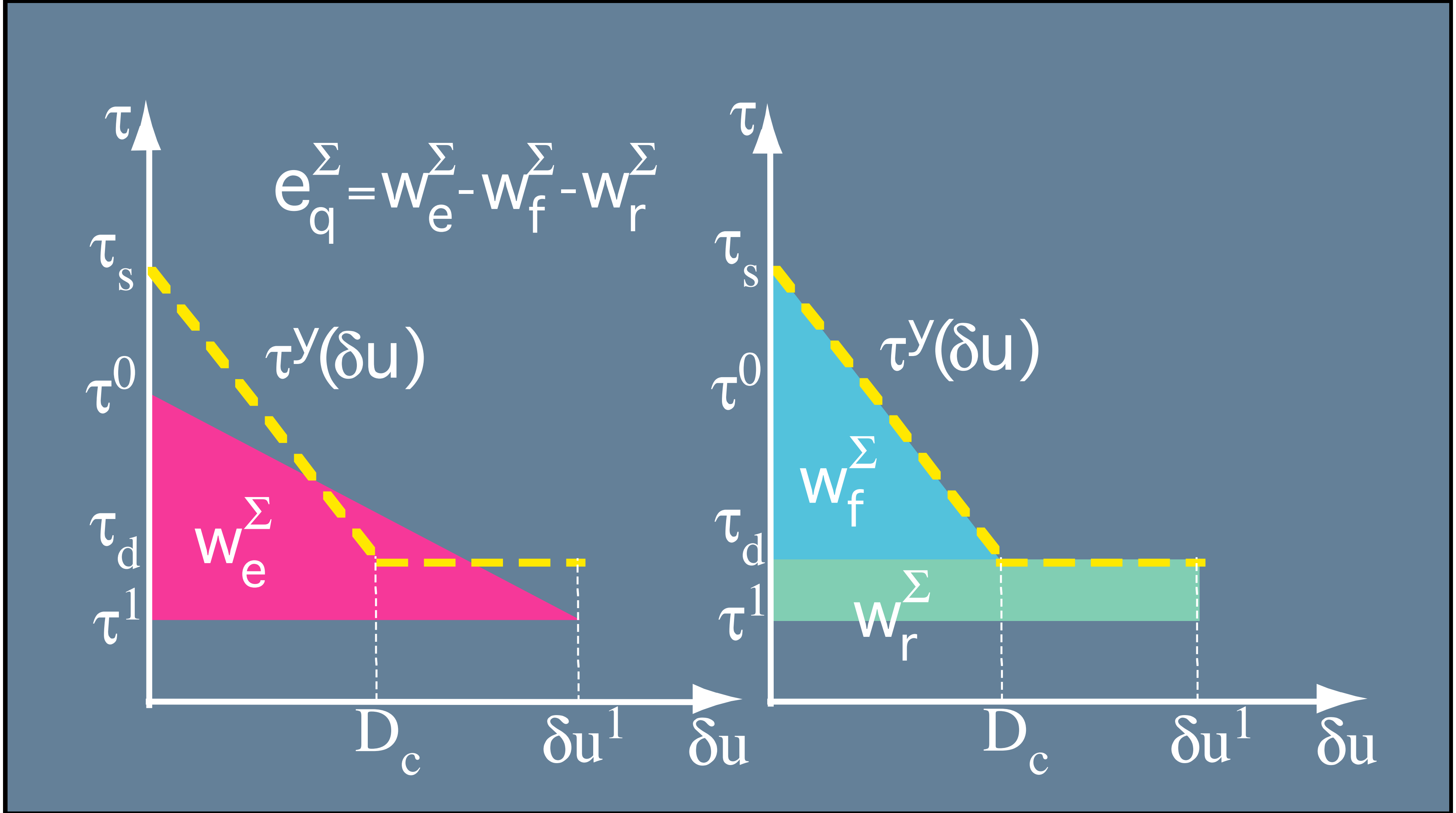
Surface Representation

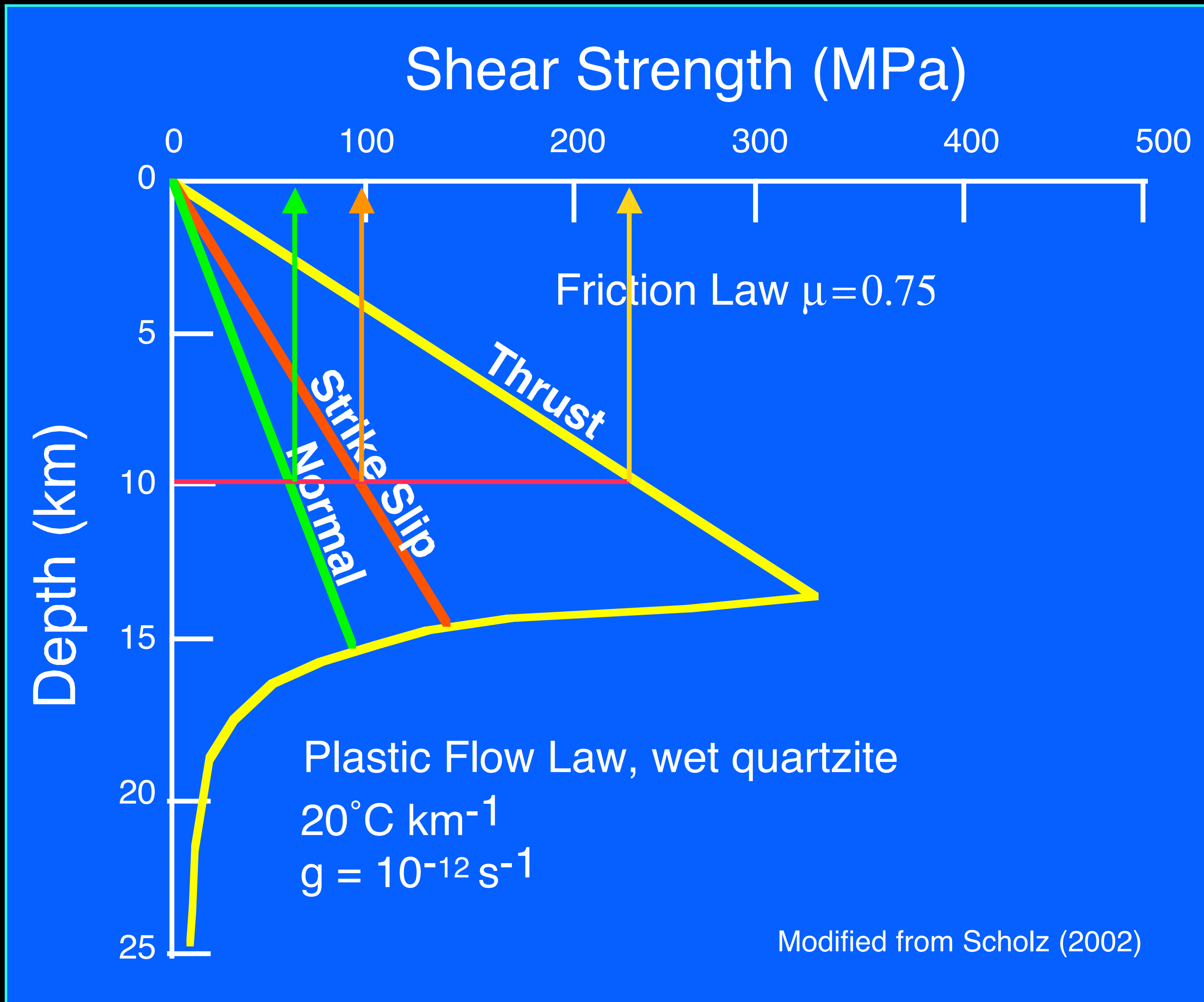
Total work done by seismic waves: $W_q^S = \int_S \int_0^{t_1} \left(\sigma_{ij} - \sigma_{ij}^0\right) \dot{u}_i n_j\, dt dS$

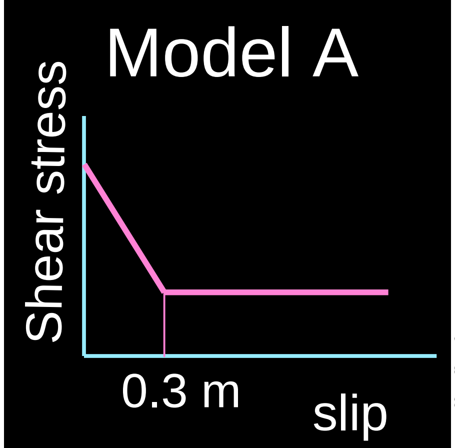
Static work: $W_e^S = -\frac{1}{2}\int_S \left(\sigma_{ij\,ij}^1 - \sigma_{ij}^0\right) u_i^1 n_j\, dS$

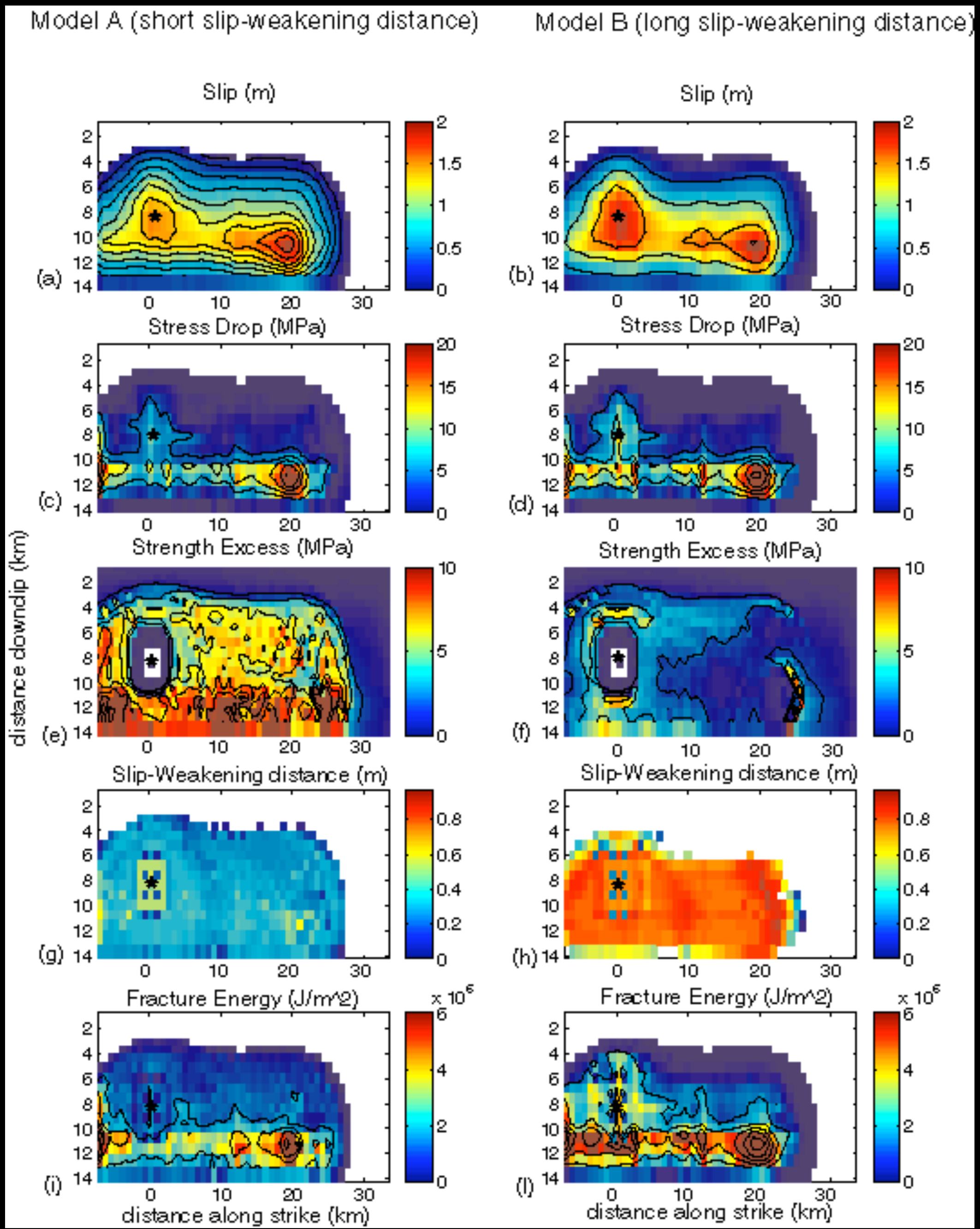
Radiated energy: $E_q = W_q^S - W_e^S$

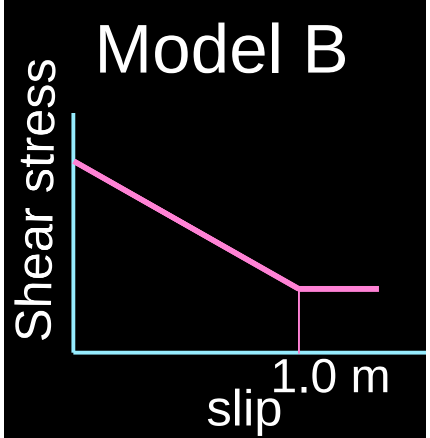
Energy Densities on the Fault




Shear Strength (MPa)
0
100
200
300
400
500
0
5
10
15
20
25
Depth (km)
Friction Law $\mu = 0.75$
Thrust
Strike Slip
Normal
Plastic Flow Law, wet quartzite
20˚C km^{-1}
g = 10^{-12} s^{-1}
Modified from Scholz (2002)







Guattieri and Spudich, 200