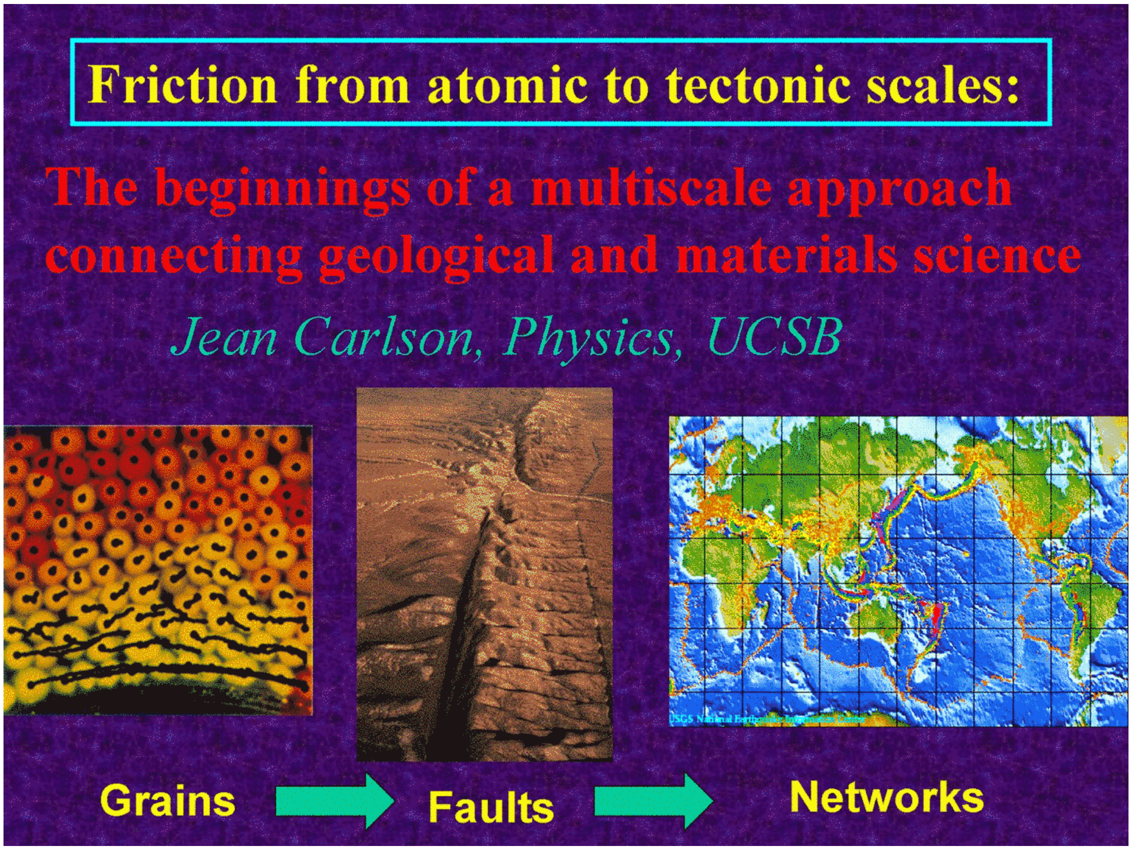
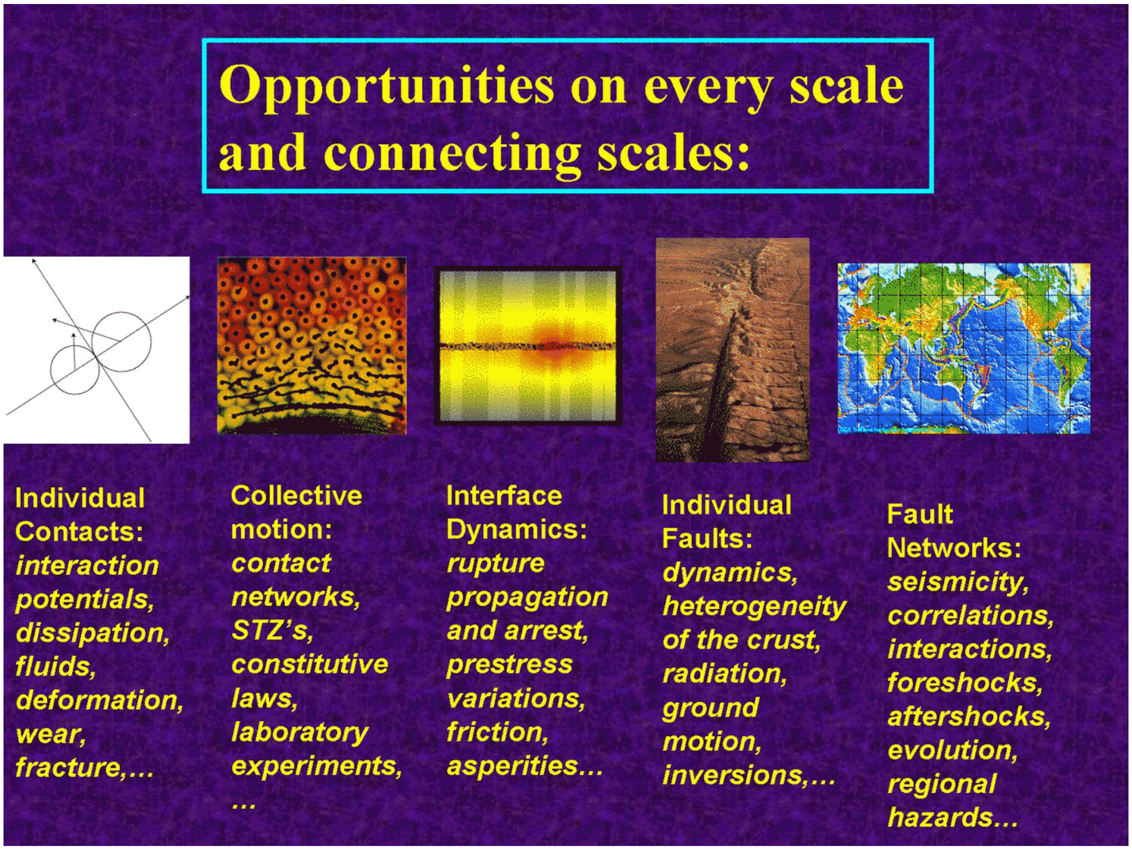


Friction from atomic to tectonic scales:

The beginnings of a multiscale approach connecting geological and materials science

Jean Carlson, Physics, UCSB



Opportunities on every scale and connecting scales:

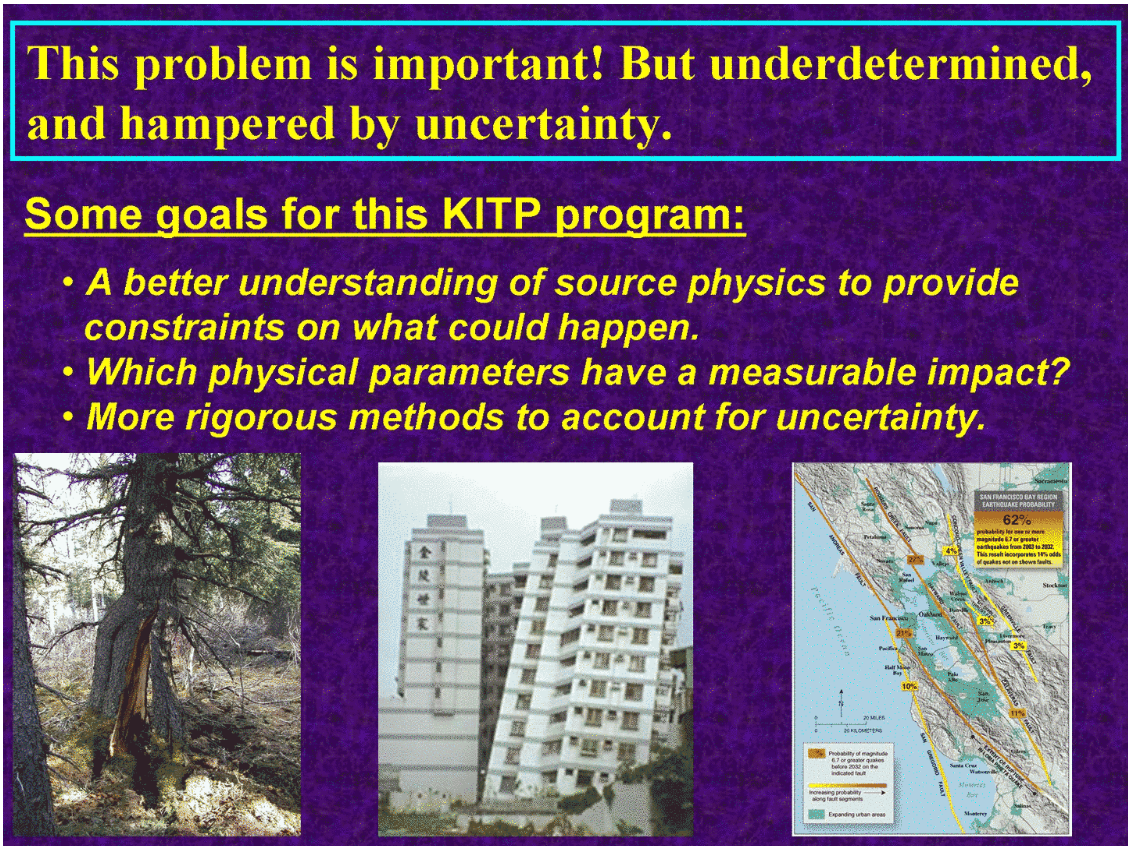
Individual Contacts: *interaction potentials, dissipation, fluids, deformation, wear, fracture,…*

Collective motion: *contact networks, STZ's, constitutive laws, laboratory experiments, …*

Interface Dynamics: *rupture propagation and arrest, prestress variations, friction, asperities…*

Individual Faults: *dynamics, heterogeneity of the crust, radiation, ground motion, inversions,…*

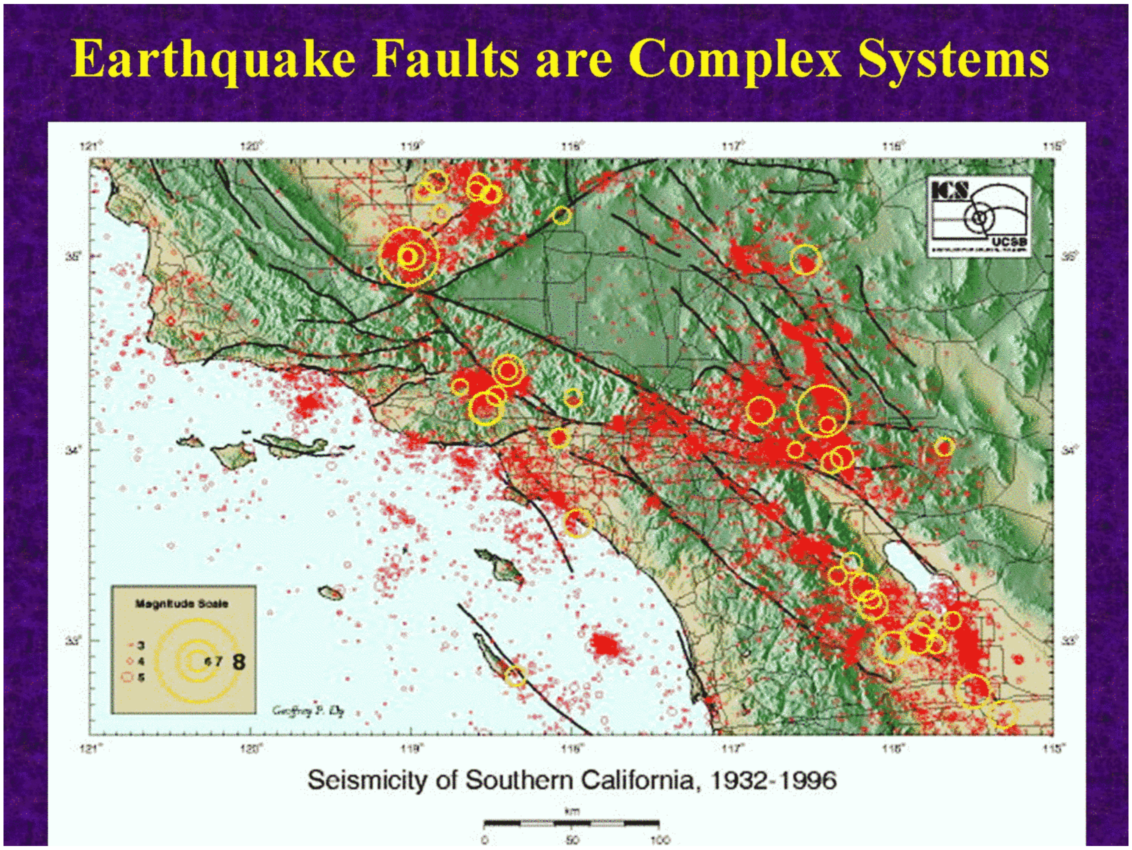
Fault Networks: *seismicity, correlations, interactions, foreshocks, aftershocks, evolution, regional hazards…*



This problem is important! But underdetermined, and hampered by uncertainty.

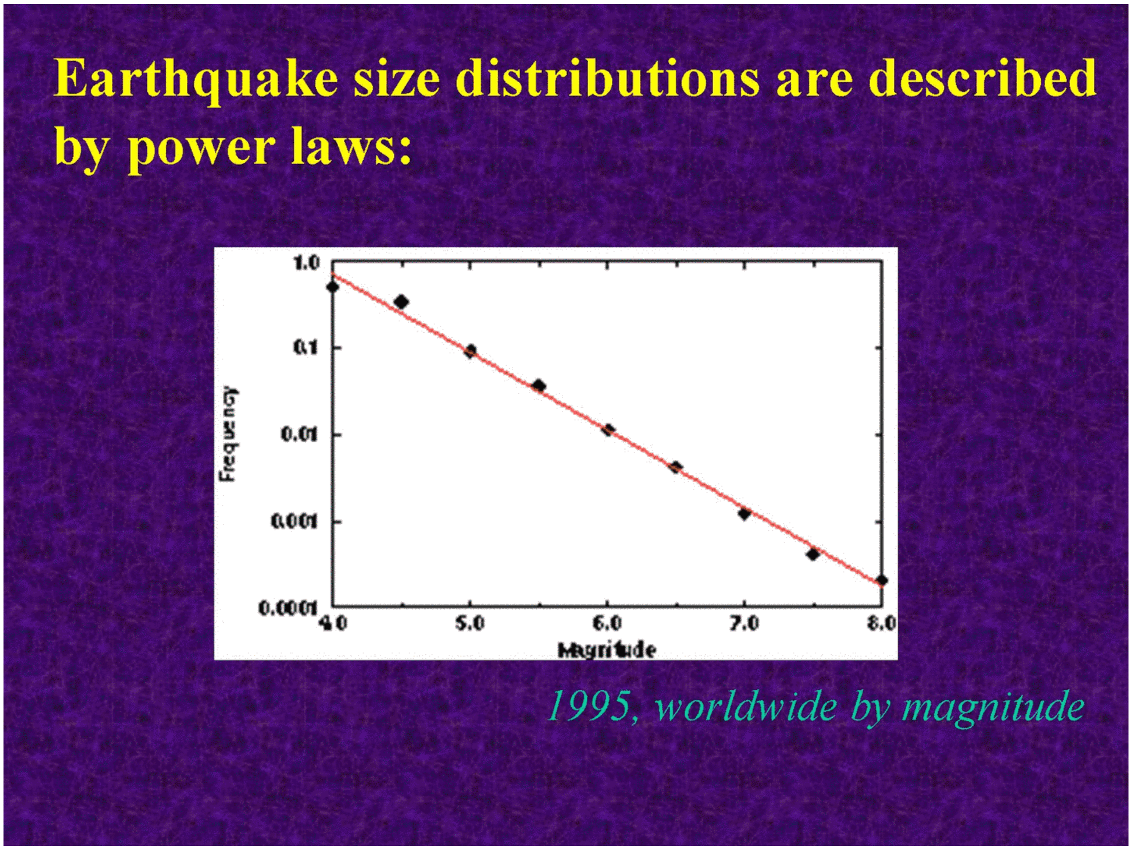
Some goals for this KITP program:

- *A better understanding of source physics to provide constraints on what could happen.*
- *Which physical parameters have a measurable impact?*
- *More rigorous methods to account for uncertainty.*



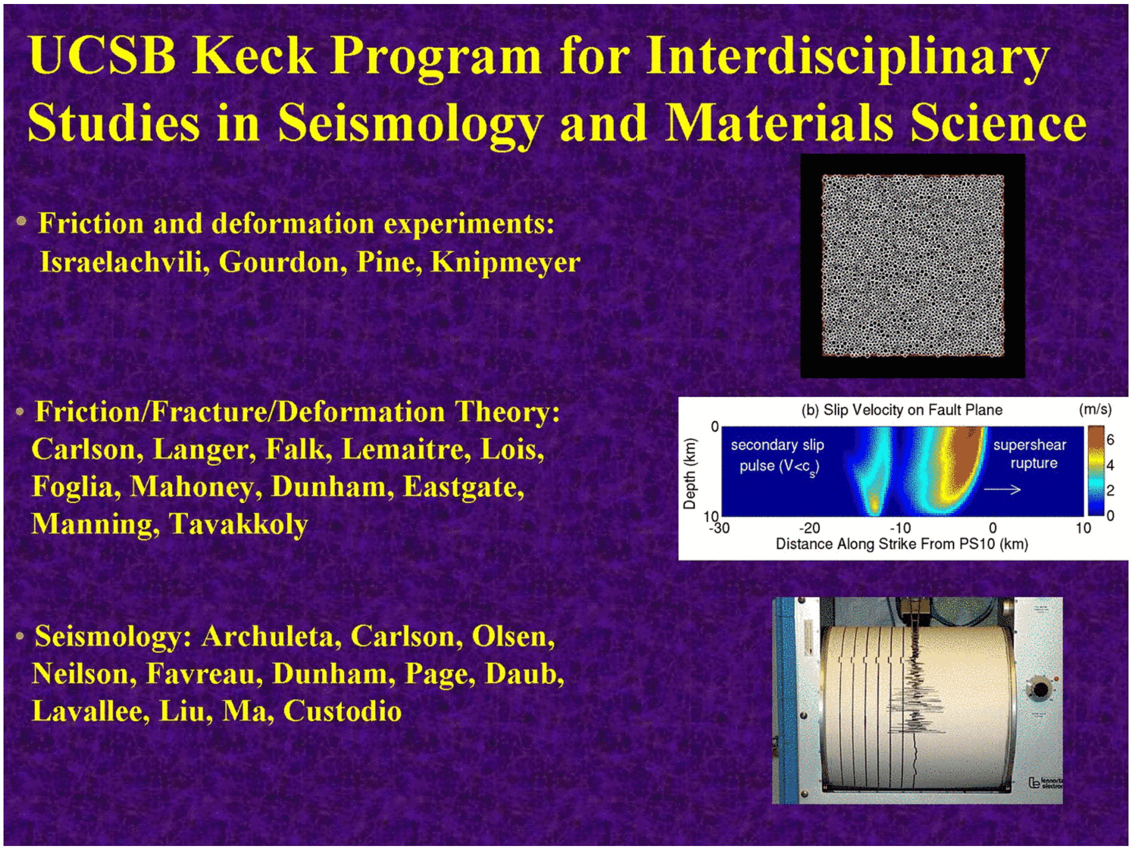
Earthquake Faults are Complex Systems

Seismicity of Southern California, 1932-1996



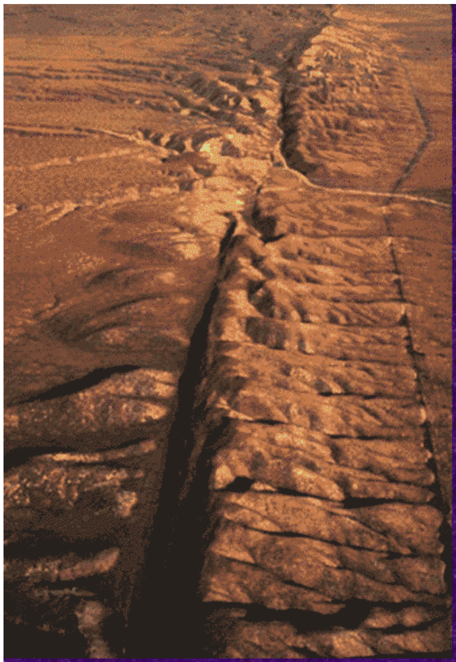
Earthquake size distributions are described by power laws:

1995, worldwide by magnitude



UCSB Keck Program for Interdisciplinary Studies in Seismology and Materials Science

- **Friction and deformation experiments: Israelachvili, Gourdon, Pine, Knipmeyer**
- **Friction/Fracture/Deformation Theory: Carlson, Langer, Falk, Lemaitre, Lois, Foglia, Mahoney, Dunham, Eastgate, Manning, Tavakkoly**
- **Seismology: Archuleta, Carlson, Olsen, Neilson, Favreau, Dunham, Page, Daub, Lavallee, Liu, Ma, Custodio**

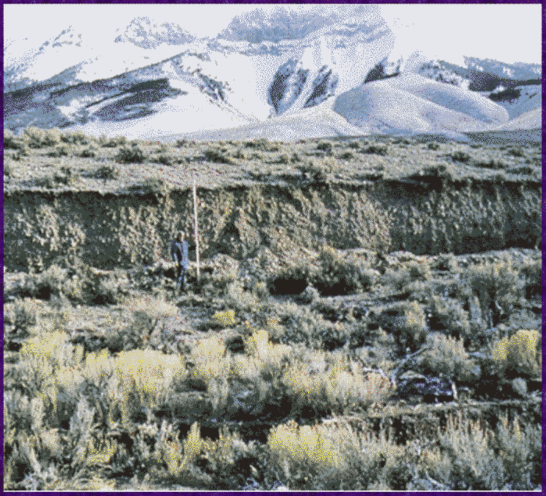


San Andreas Fault

Carrizo Plane

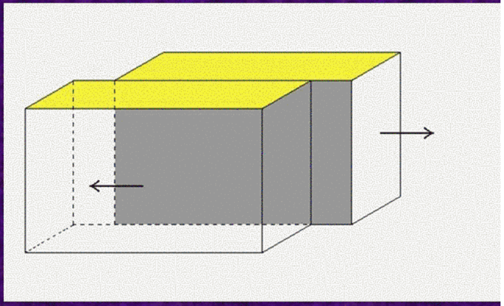
1983 Borah Peak

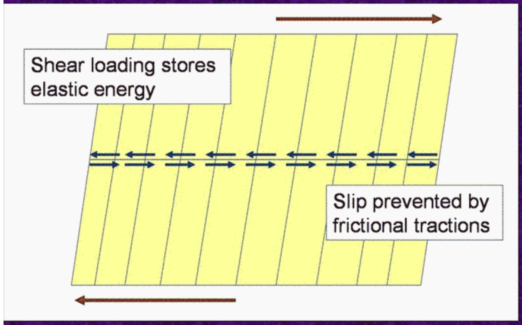
Earthquake, Idaho



The Earthquake Problem:

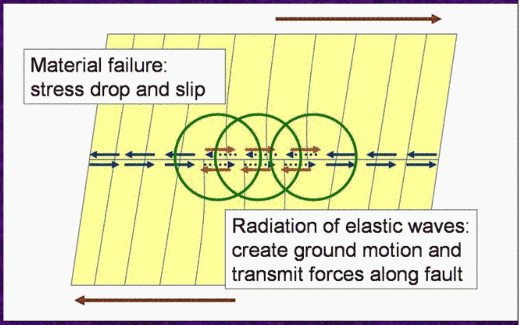
- Elastic half spaces separated by a weak interface (fault)
- Loaded by shear (plate tectonics, mantle convection)
- Friction/Fracture failure of the interface
- Slip propagates, radiates energy





Shear loading stores elastic energy

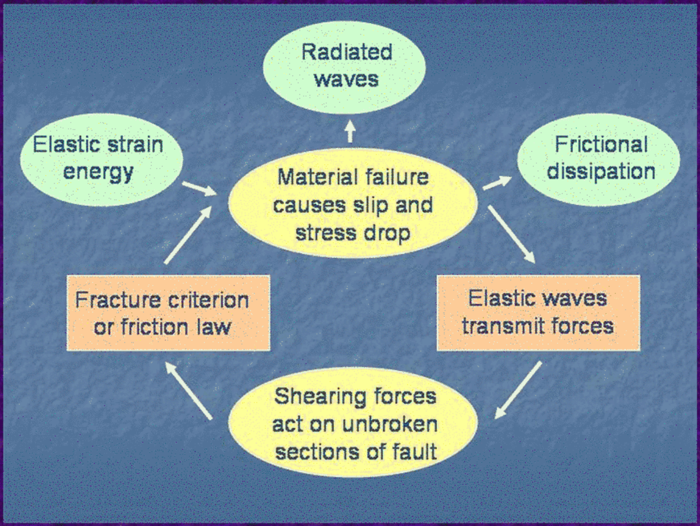
Slip prevented by frictional tractions



Material failure: stress drop and slip

Radiation of elastic waves: create ground motion and transmit forces along fault

Dynamics of the Rupture Process:



Radiated waves

Elastic strain energy

Material failure causes slip and stress drop

Frictional dissipation

Fracture criterion or friction law

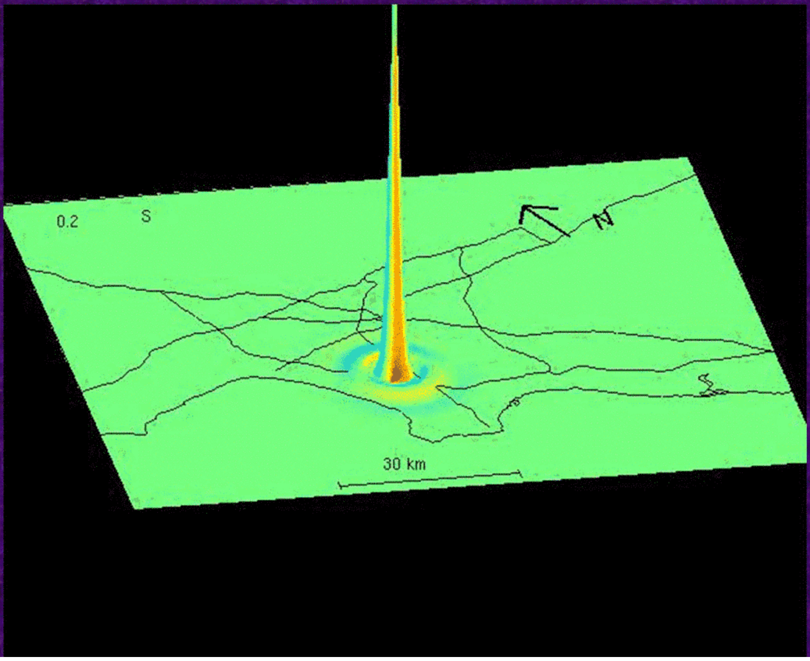
Elastic waves transmit forces

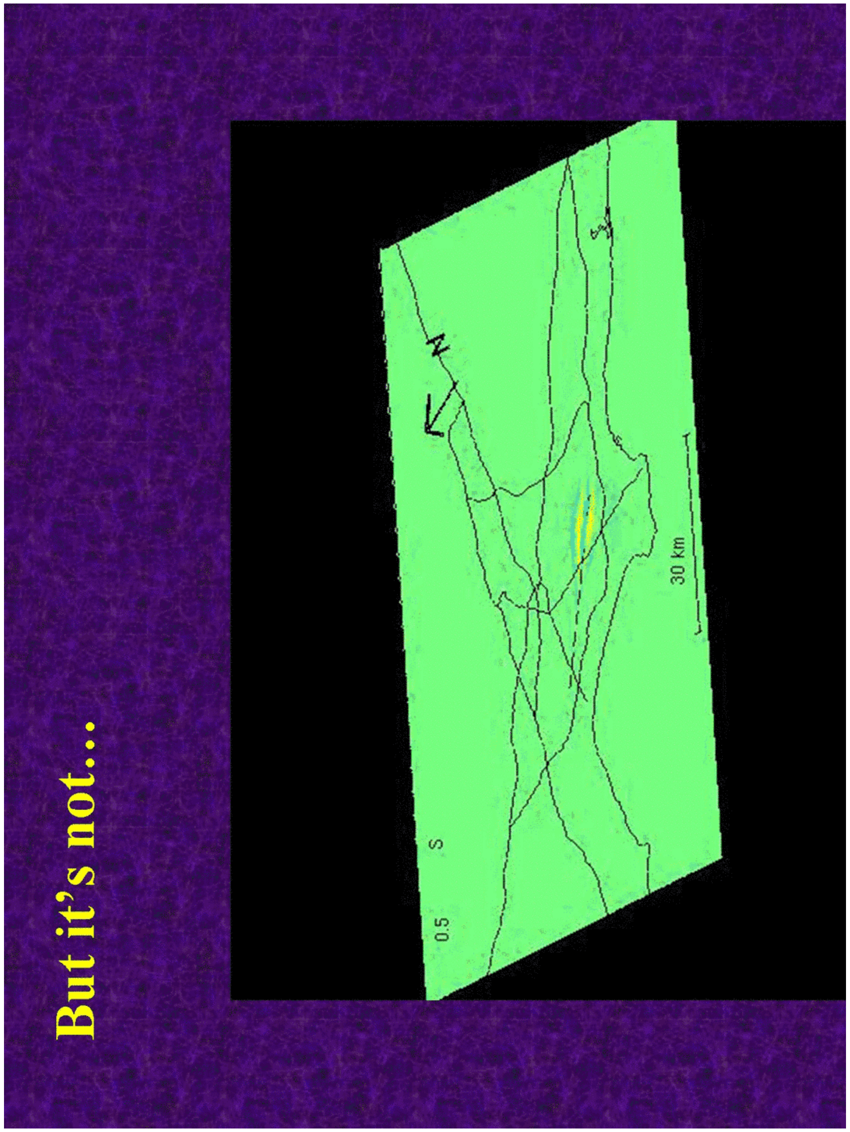
Shearing forces act on unbroken sections of fault

- Green bubbles: flow of energy within the system.
- Yellow and orange: energy conversion processes.

If the Los Angeles Basin were a Homogeneous half space…

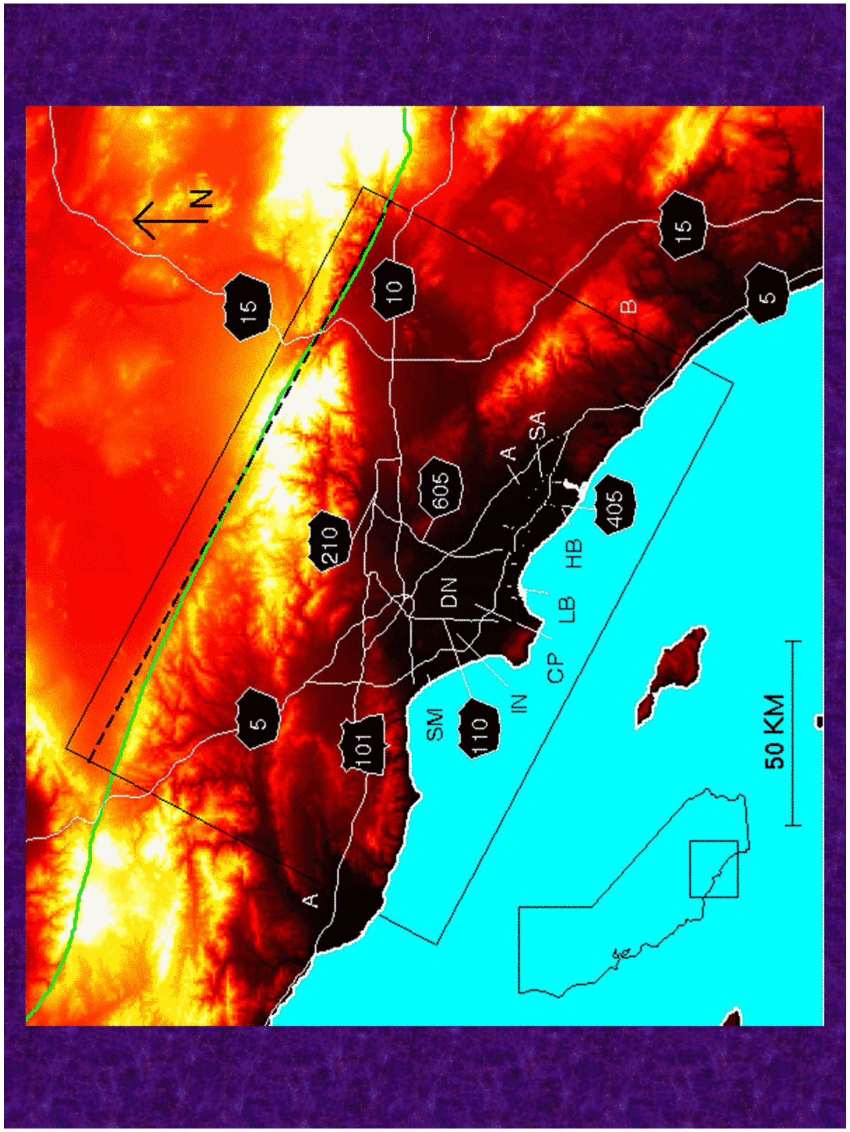
K.B. Olsen



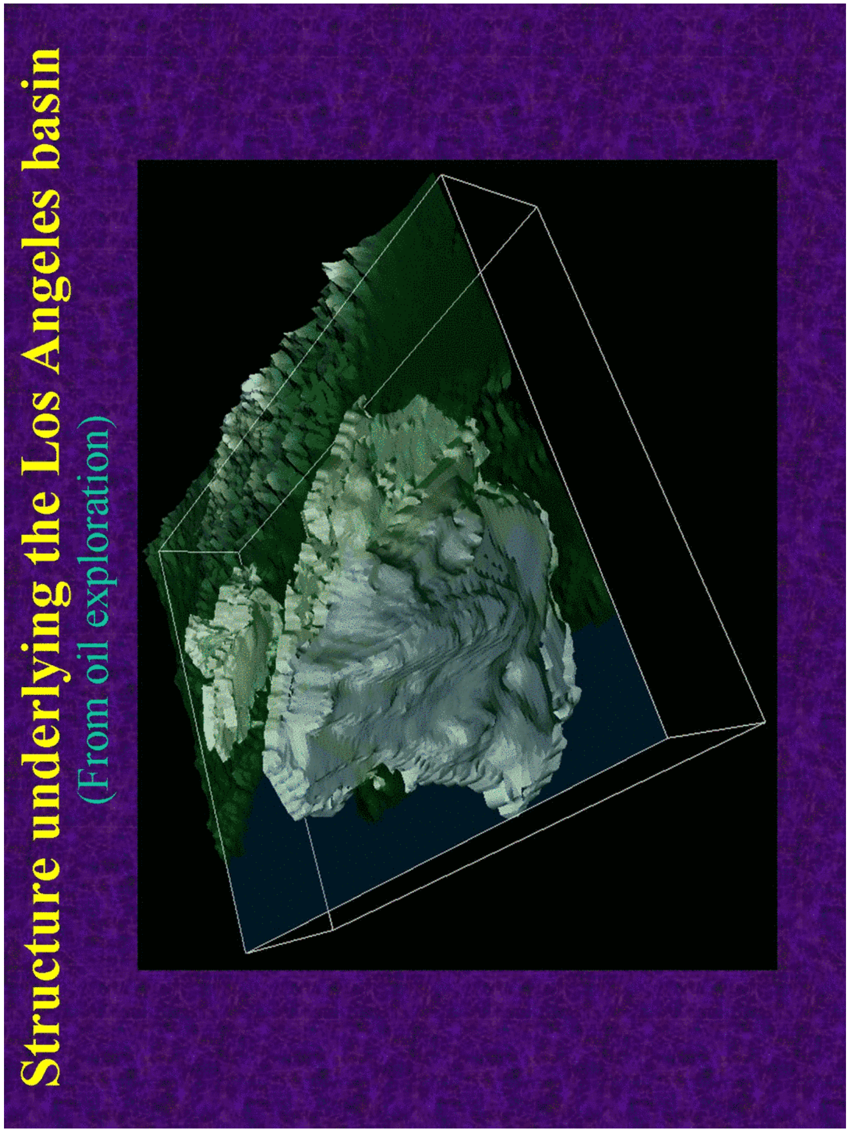


But it’s not…

N
30 km
S
0.5

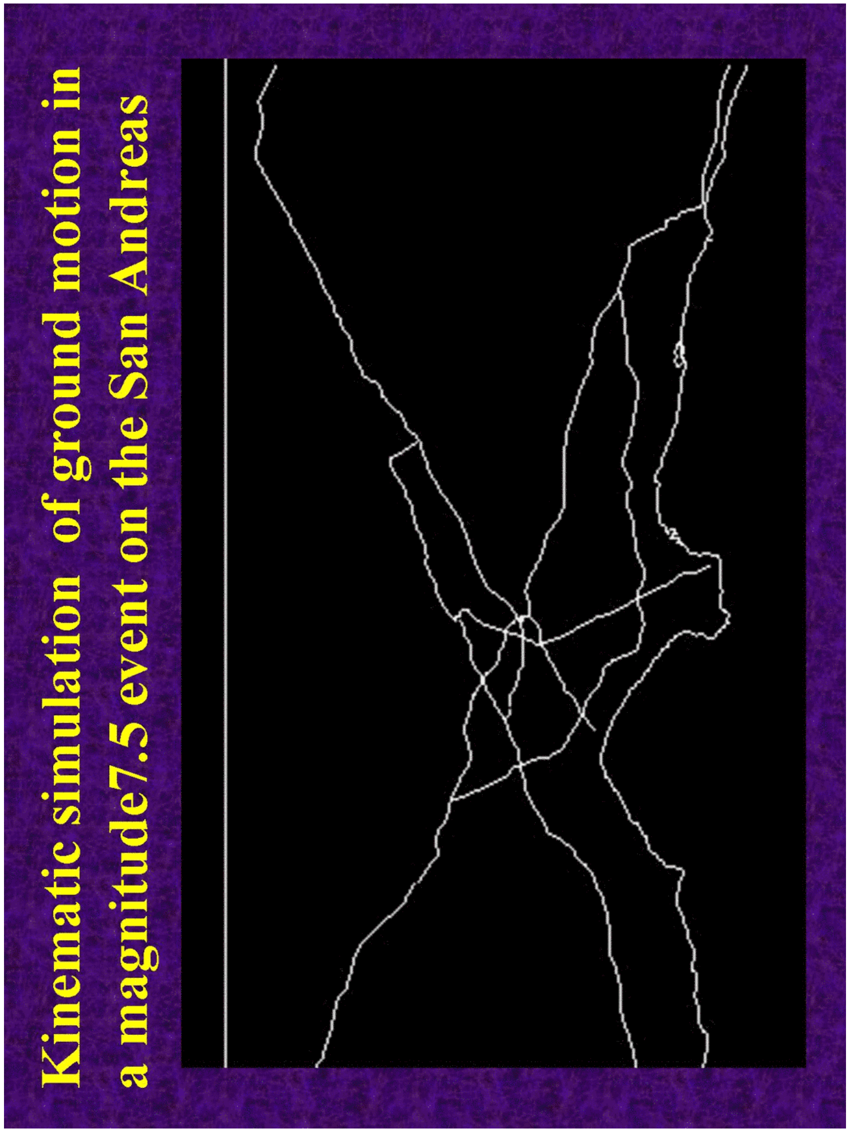


N
15
10
15
5
B
SA
A
605
405
210
HB
DN
LB
CP
IN
SM
110
5
101
A
50 KM

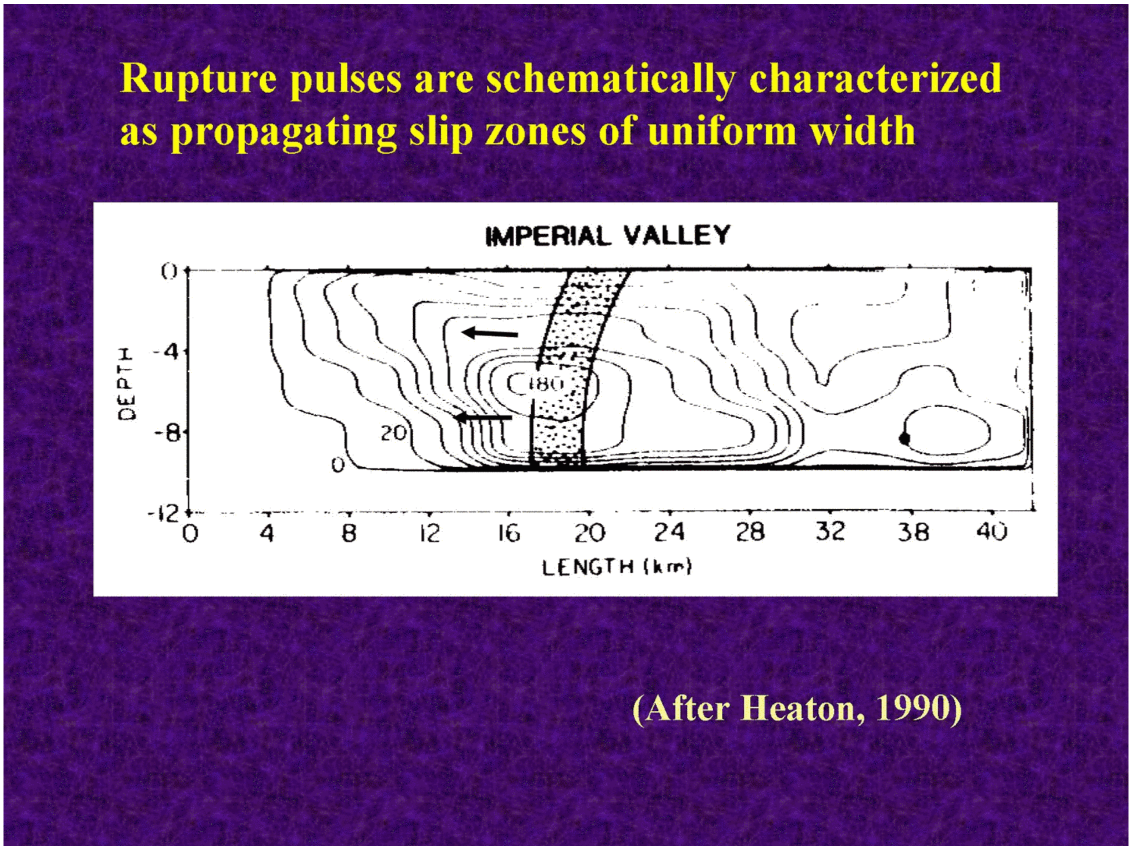


Structure underlying the Los Angeles basin

(From oil exploration)

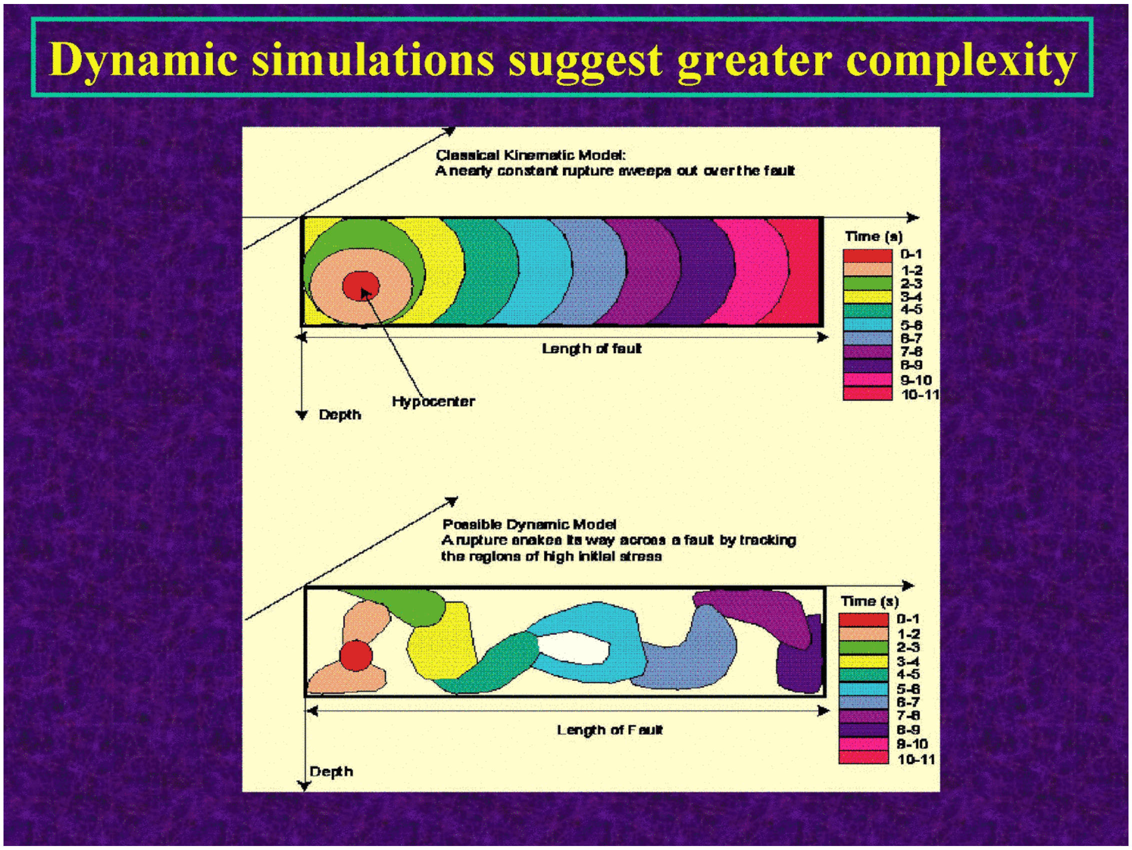


Kinematic simulation of ground motion in a magnitude7.5 event on the San Andreas



Rupture pulses are schematically characterized as propagating slip zones of uniform width

(After Heaton, 1990)



Dynamic simulations suggest greater complexity

Classical Kinematic Model:
A nearly constant rupture sweeps out over the fault

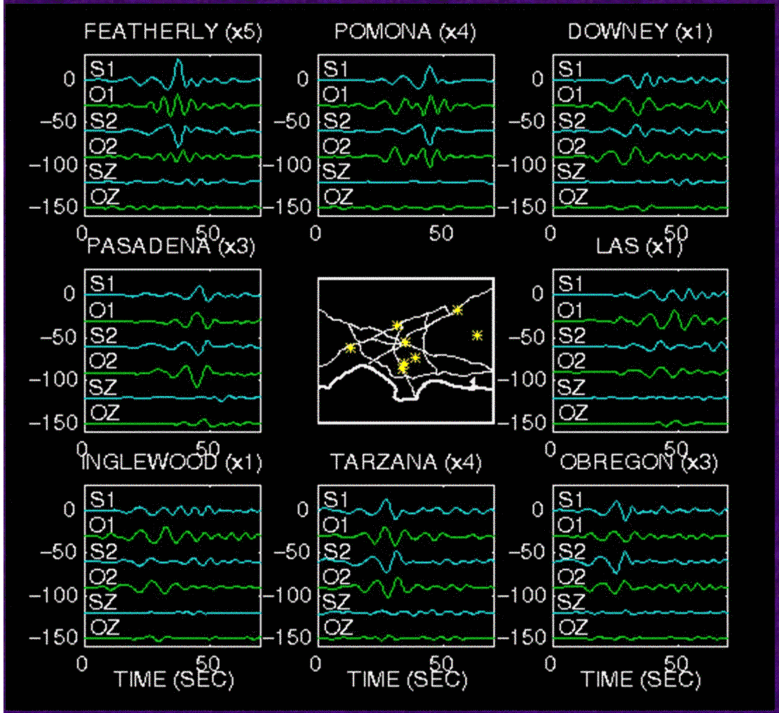
Possible Dynamic Model
A rupture snakes its way across a fault by tracking the regions of high initial stress

Dynamic simulation of slip along the fault Surface:

Dynamics of slip is complex

(Olsen, Archuleta, Matarese)

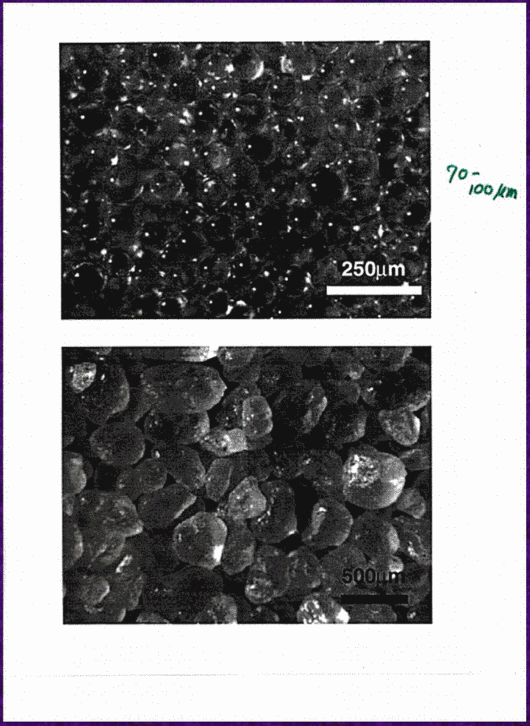
Comparison of Observed (O) and Synthetic (S) Seismograms for the 1992 Landers Earthquake



Dynamic Rupture Model:
Olsen, Archuleta, Matarese

What controls the dynamical properties of seismic rupture?

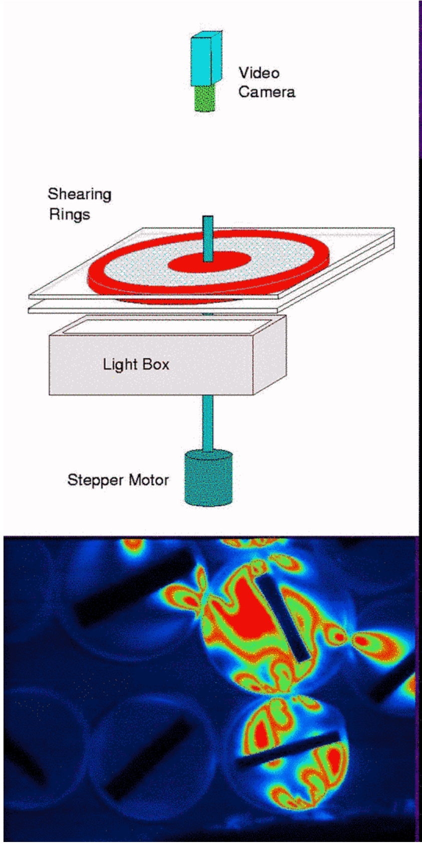
- Large scale geometric features: fault depth, orientation and boundary conditions, fault network properties
- Material properties: friction, fracture, deformation
- Obstacles (inhomogeneities on the fault surface), on what scale?

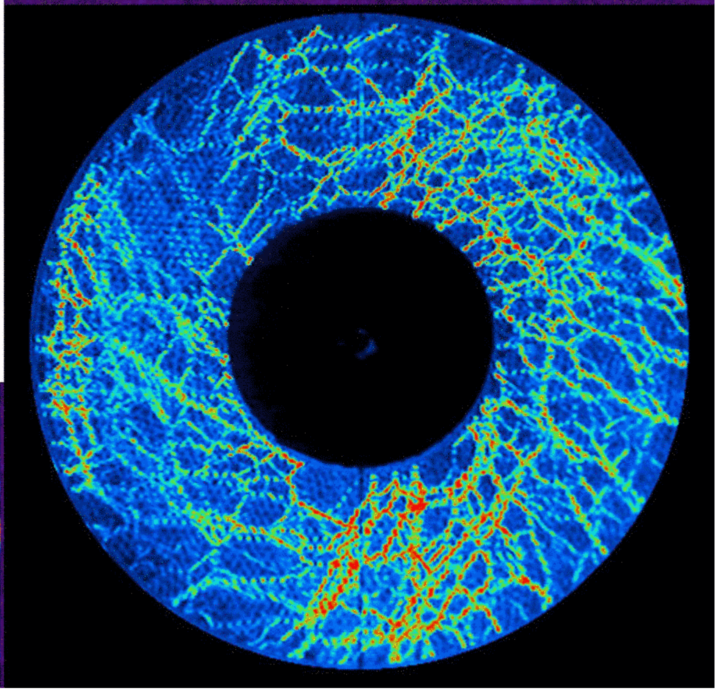


Laboratory studies of friction in granular materials:

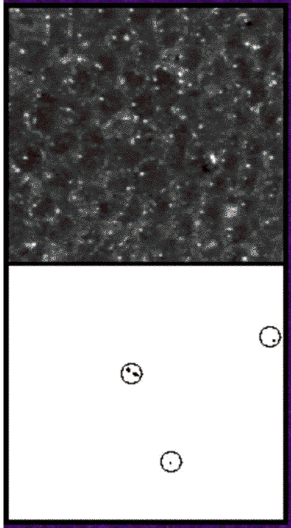
Gollub, Nagel, Jaeger, Behringer, Marone…

Stress is supported by a network of force chains

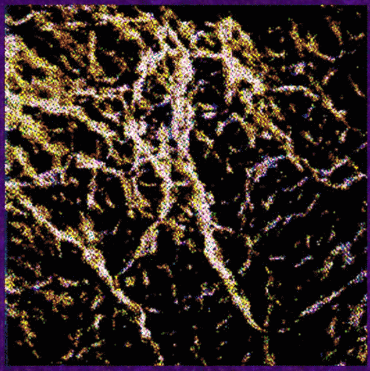




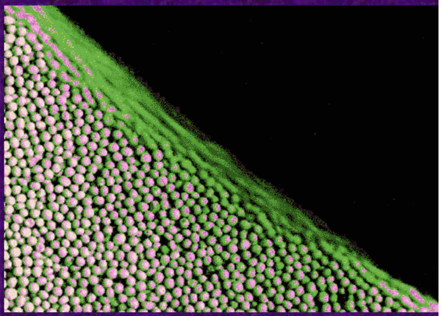
Internal dynamics associated with macroscopic motion:



Local changes

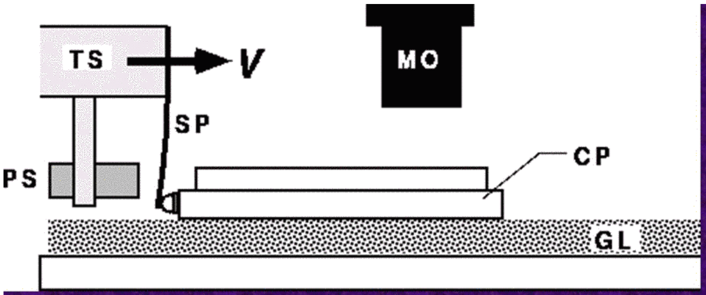


Force chains broken and created

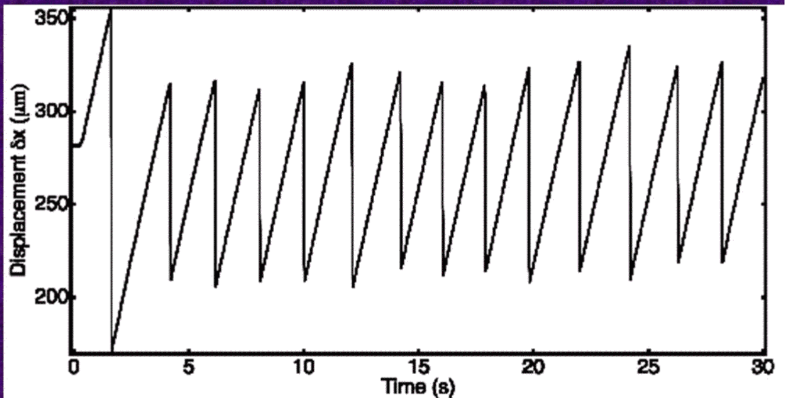


Dilation

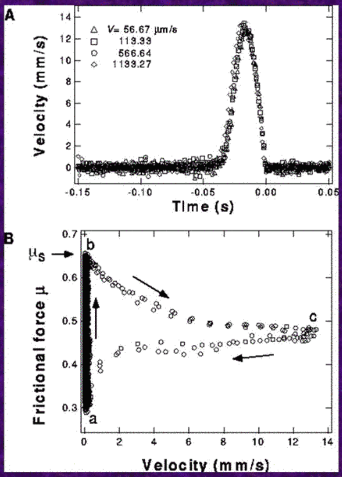
Macroscopic Consequences

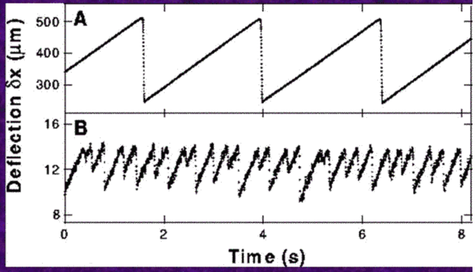


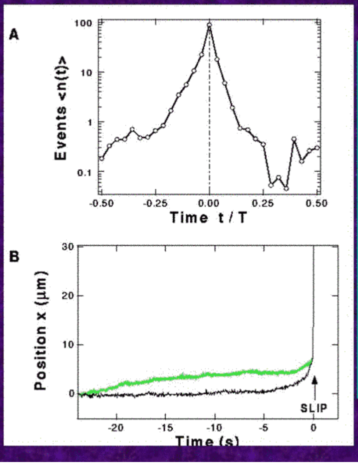
- •Transition: stick slip to steady sliding (k,v)
- •Frictional strengthening under shear stress
- •Creep
- •Hysteresis
- •And more…



More detailed analysis of stick-slip motion:

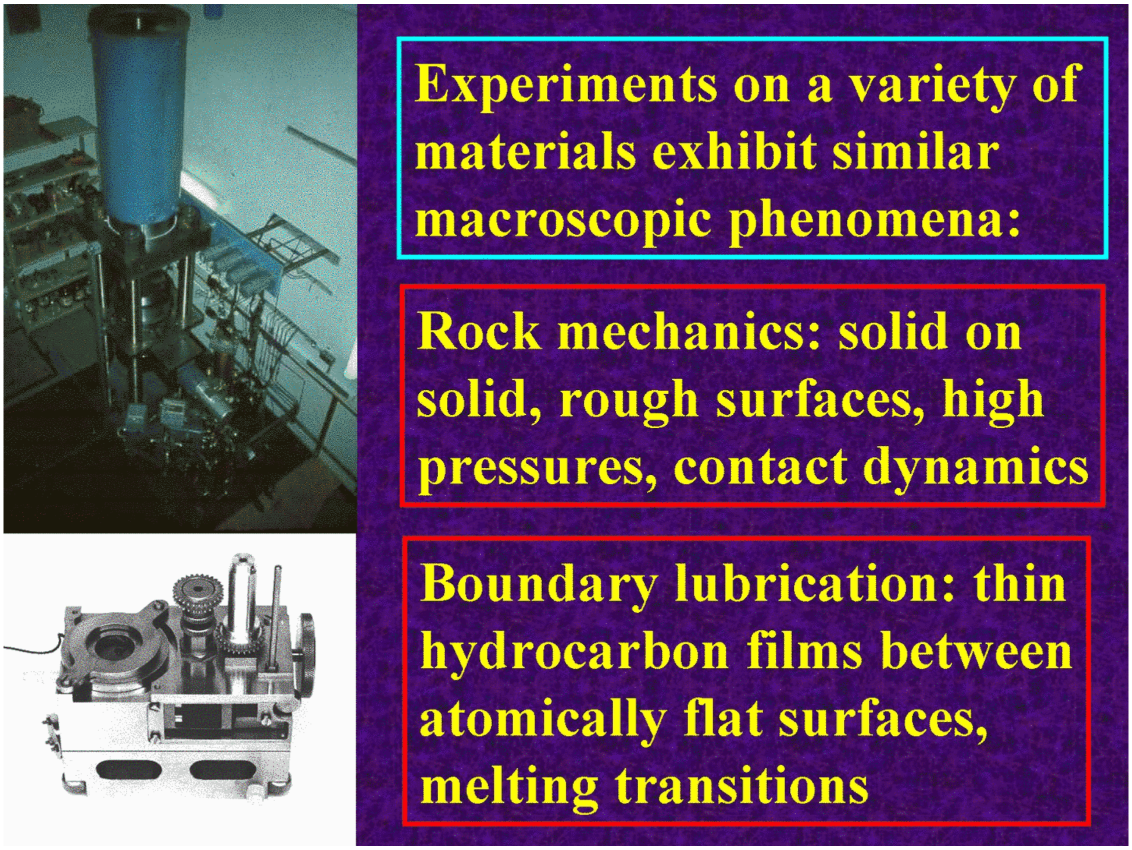






Microscopic events before and after slip, creep

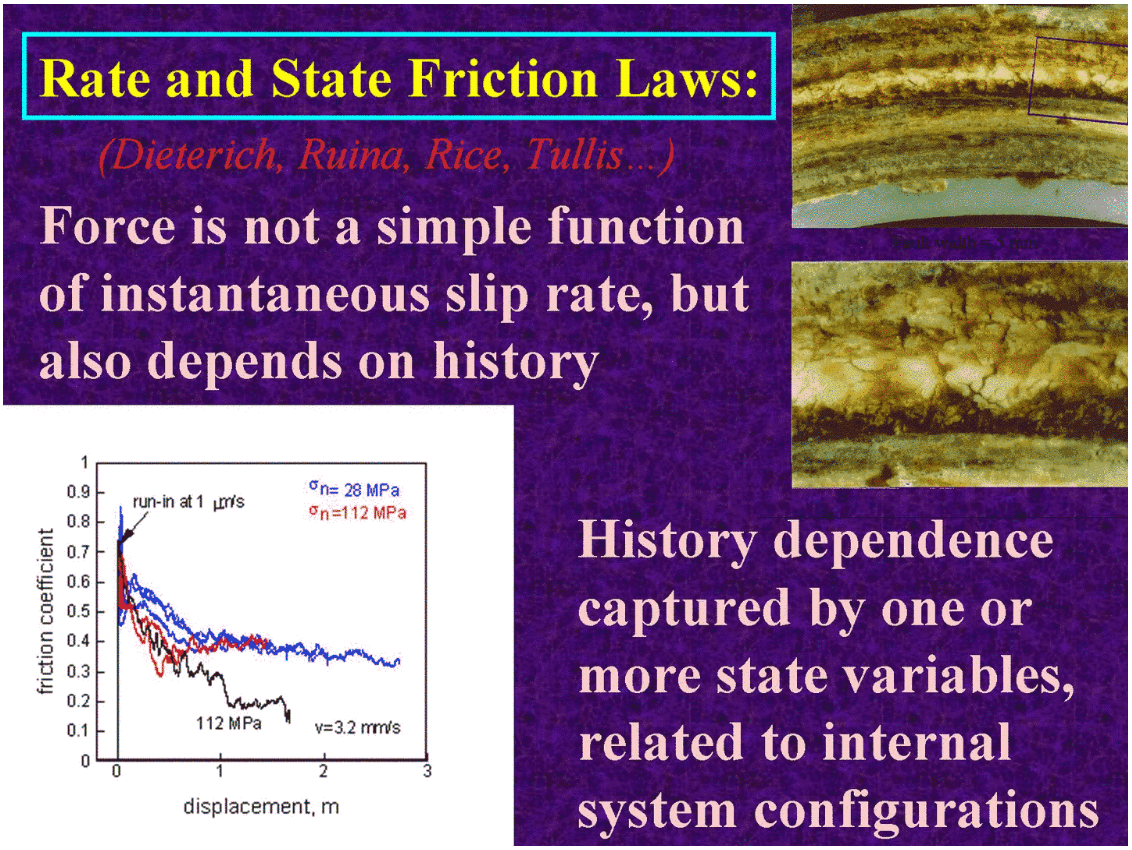
Friction is not a simple function of slip rate



Experiments on a variety of materials exhibit similar macroscopic phenomena:

Rock mechanics: solid on solid, rough surfaces, high pressures, contact dynamics

Boundary lubrication: thin hydrocarbon films between atomically flat surfaces, melting transitions

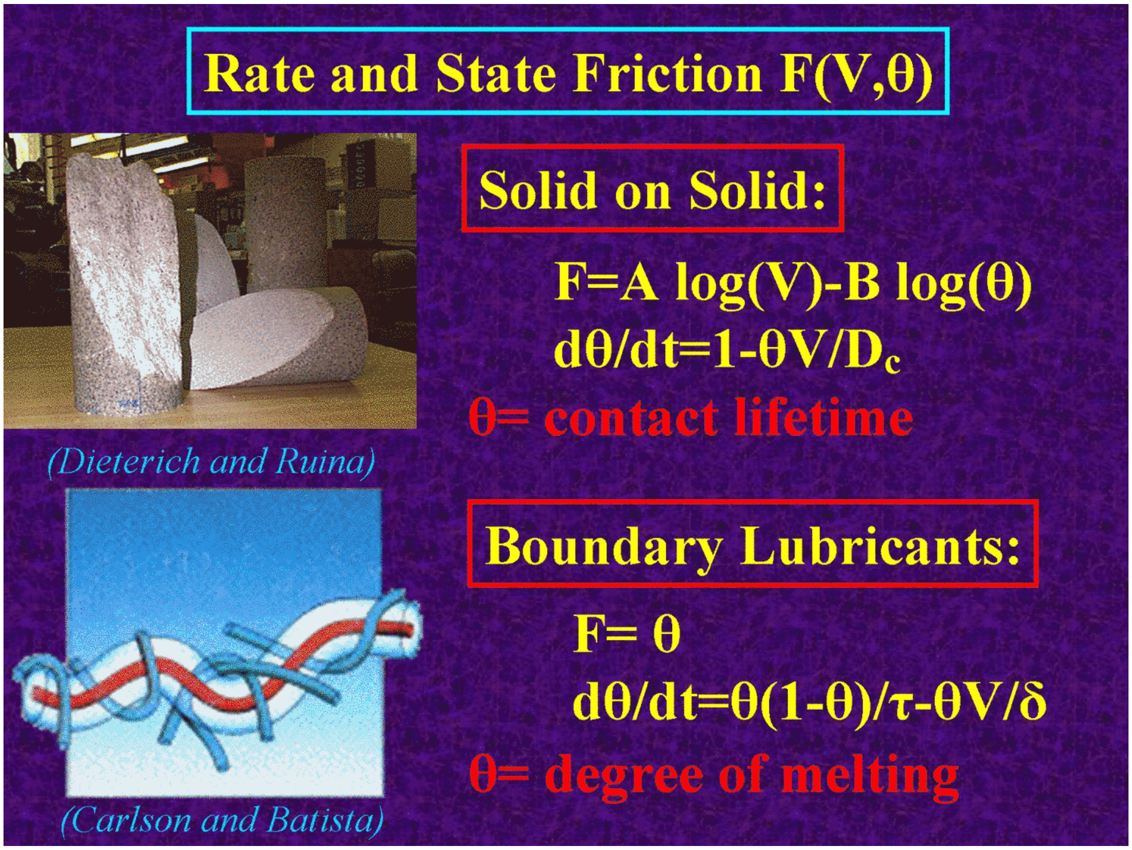


Rate and State Friction Laws:

(Dieterich, Ruina, Rice, Tullis…)

Force is not a simple function of instantaneous slip rate, but also depends on history

History dependence captured by one or more state variables, related to internal system configurations



Rate and State Friction $F(V,\theta)$

(Dieterich and Ruina)

(Carlson and Batista)

Solid on Solid:

$F = A \log(V) - B \log(\theta)$

$d\theta/dt = 1 - \theta V/D_c$

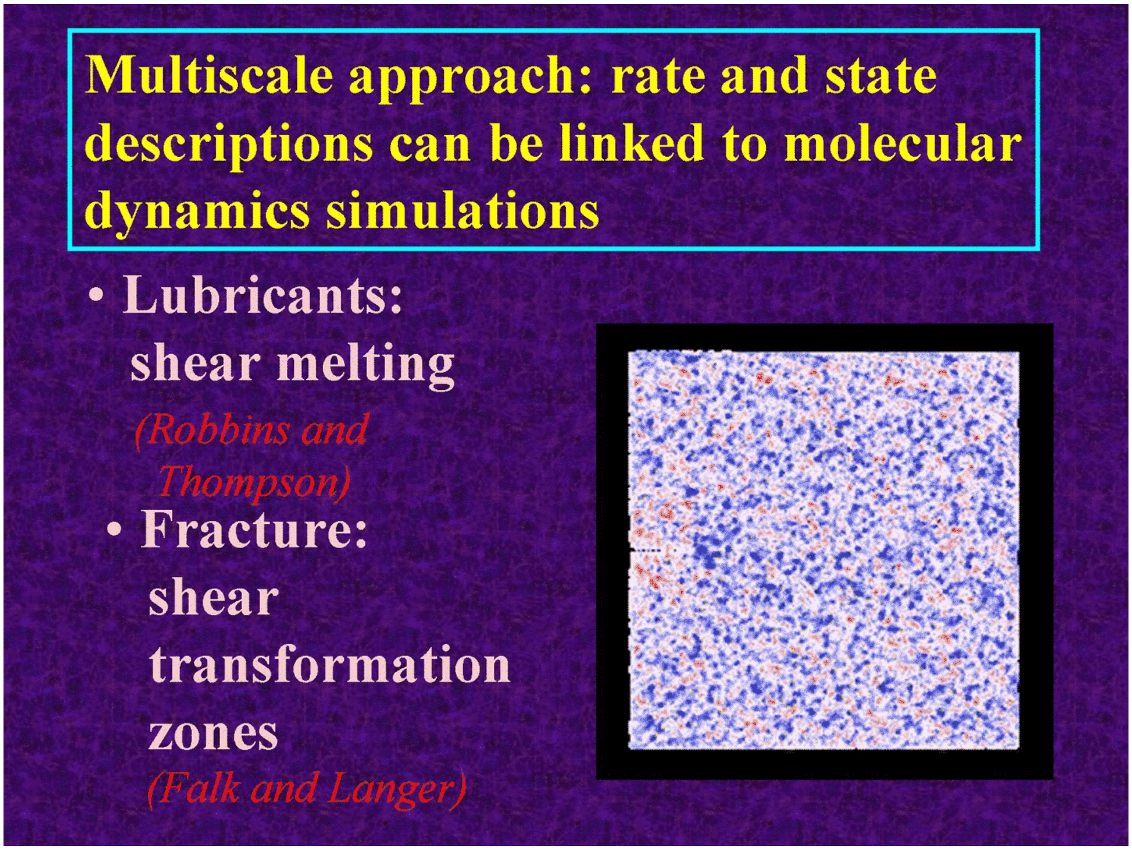
θ= contact lifetime

Boundary Lubricants:

$F = \theta$

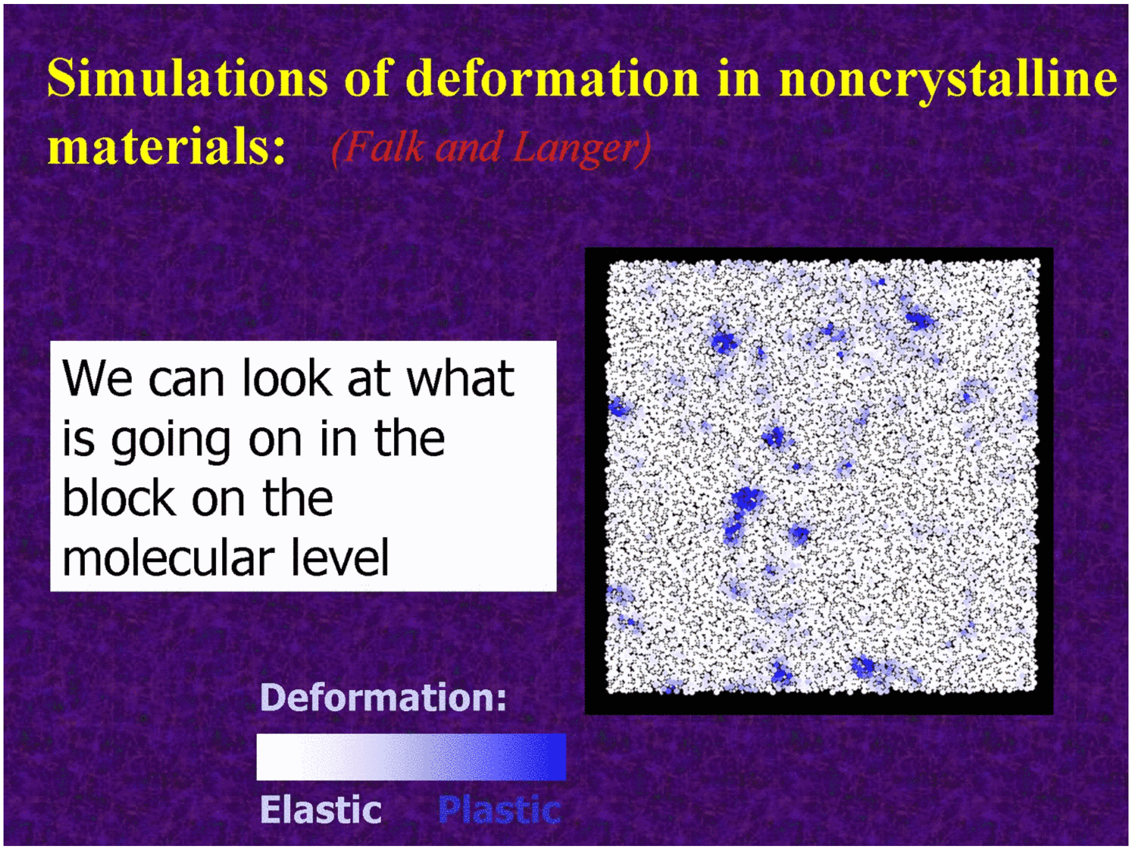
$d\theta/dt = \theta(1-\theta)/\tau - \theta V/\delta$

θ= degree of melting



Multiscale approach: rate and state descriptions can be linked to molecular dynamics simulations

- Lubricants: shear melting *(Robbins and Thompson)*
- Fracture: shear transformation zones *(Falk and Langer)*

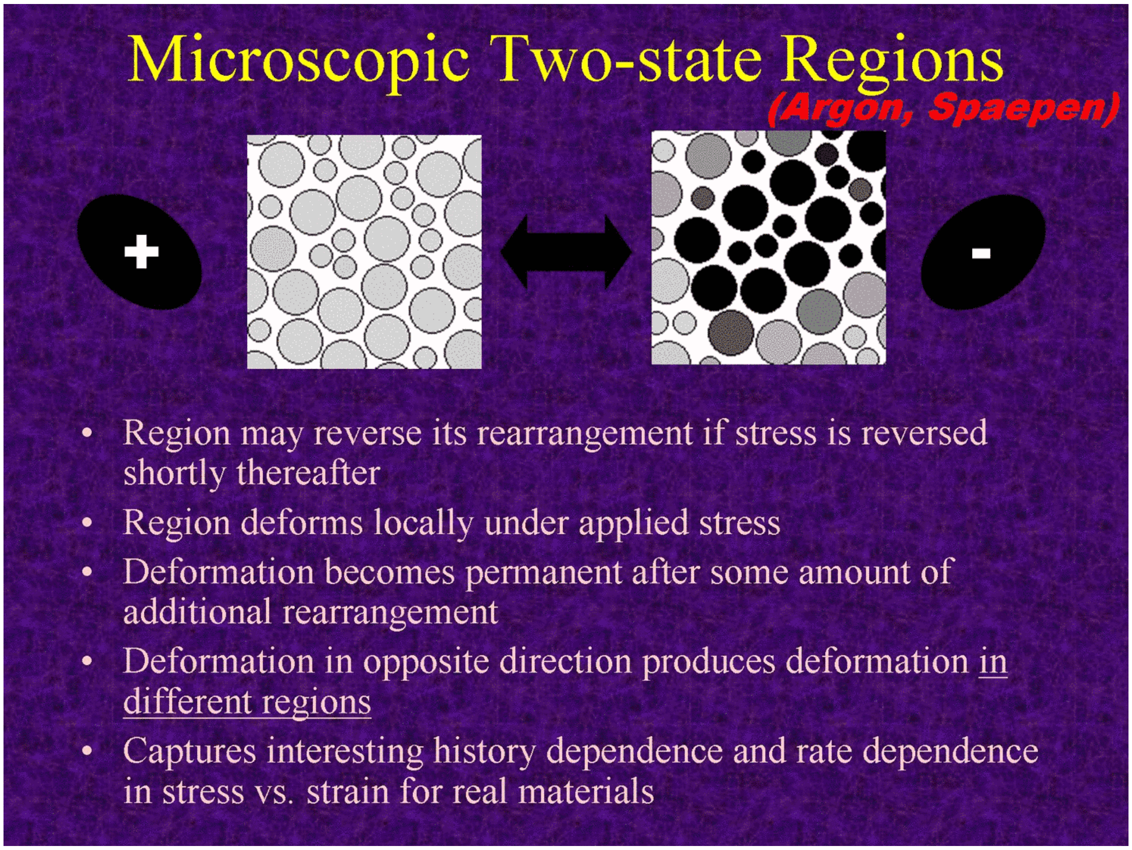


Simulations of deformation in noncrystalline materials: *(Falk and Langer)*

We can look at what is going on in the block on the molecular level

Deformation:

Elastic **Plastic**



Microscopic Two-state Regions

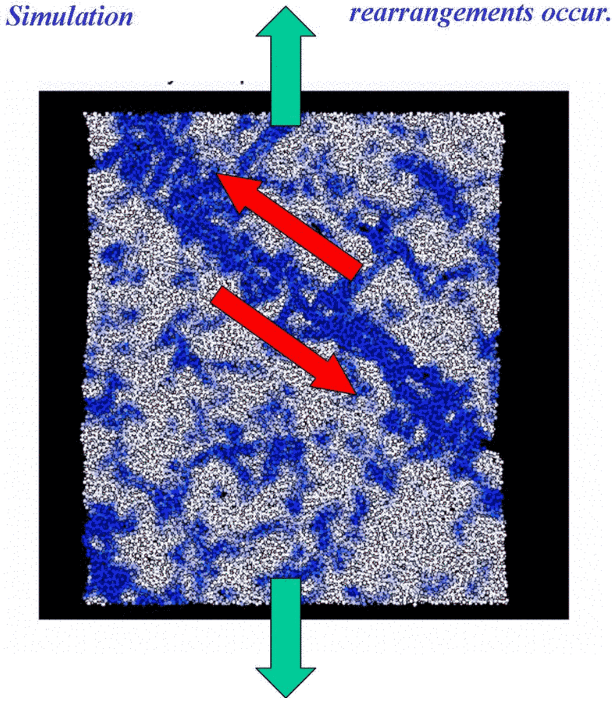
(Argon, Spaepen)

- Region may reverse its rearrangement if stress is reversed shortly thereafter
- Region deforms locally under applied stress
- Deformation becomes permanent after some amount of additional rearrangement
- Deformation in opposite direction produces deformation <u>in different regions</u>
- Captures interesting history dependence and rate dependence in stress vs. strain for real materials

Shear Transformation Zone (STZ) Activity

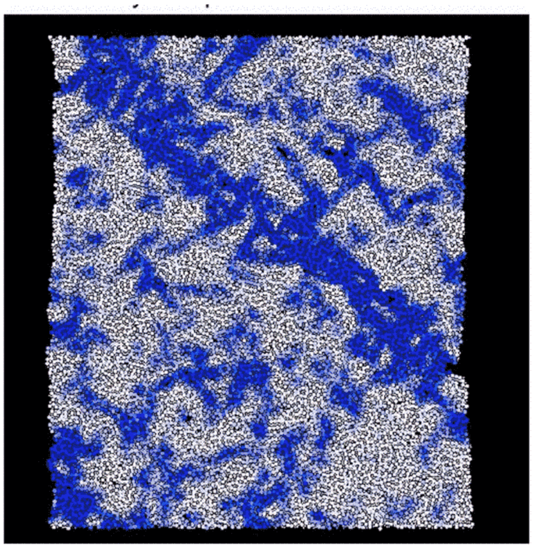
M. Falk, Molecular Dynamics Simulation

STZ's are sites where molecular rearrangements occur.

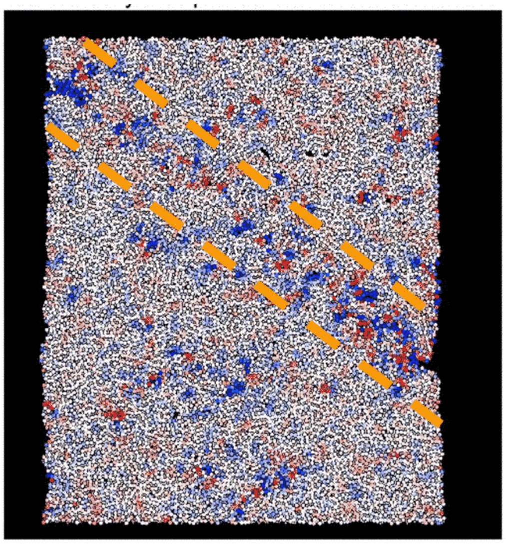


MD Simulation of Tensile Deformation (M. Falk)

STZ Activity

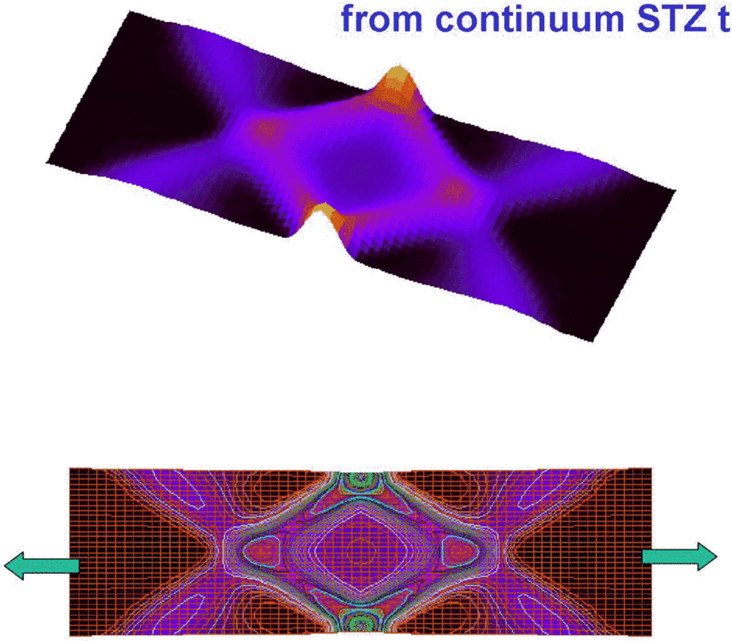


Dilation/Contraction

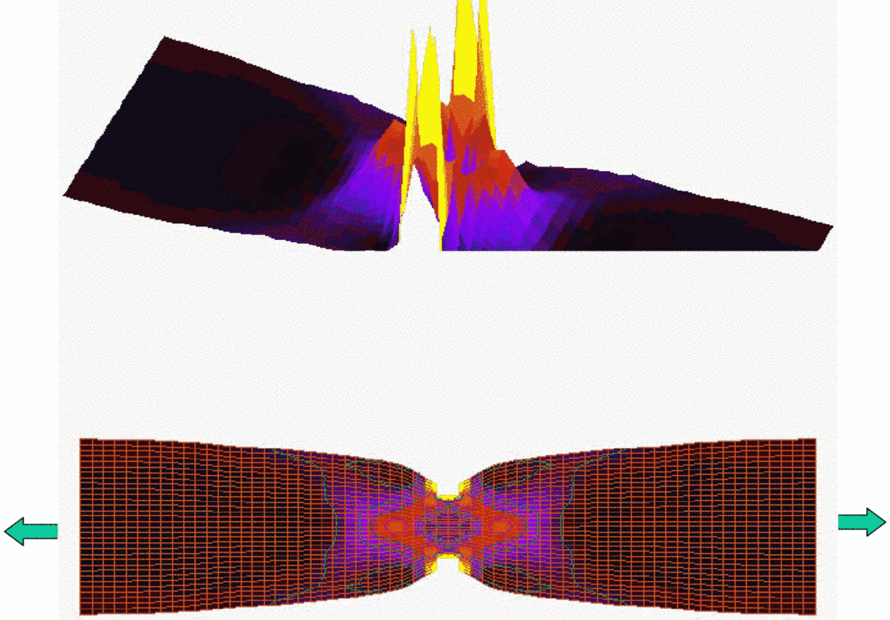


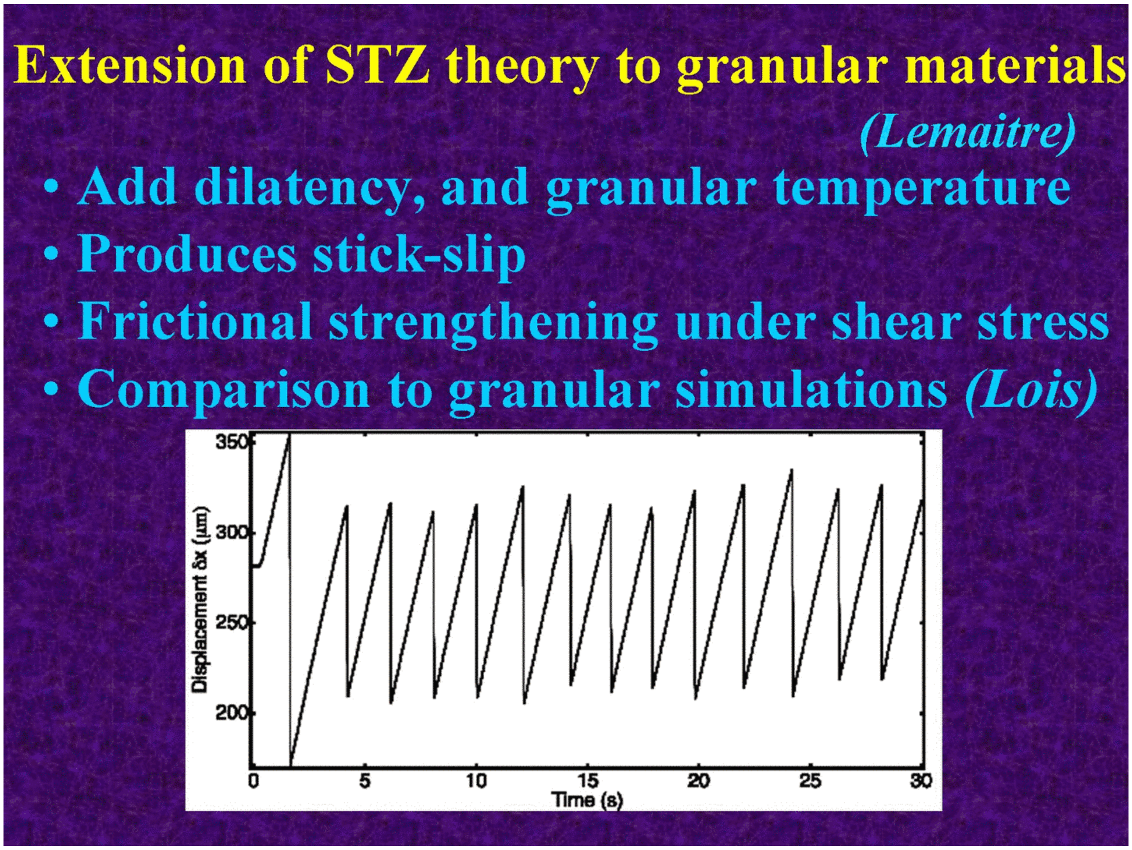
Region of increased disorder

Eastgate: Early-stage dissipation-rate contours from continuum STZ theory



Eastgate: Late stage dissipation-rate contours from continuum STZ theory





Extension of STZ theory to granular materials

(Lemaitre)

- Add dilatency, and granular temperature
- Produces stick-slip
- Frictional strengthening under shear stress
- Comparison to granular simulations *(Lois)*

STZ Theory for Granular Materials

$$\dot{\gamma}^{pl} \propto R_- n_- - R_+ n_+$$

$$\dot{n}_\pm = R_\mp n_\mp - R_\pm n_\pm + w(a - b n_\pm)$$

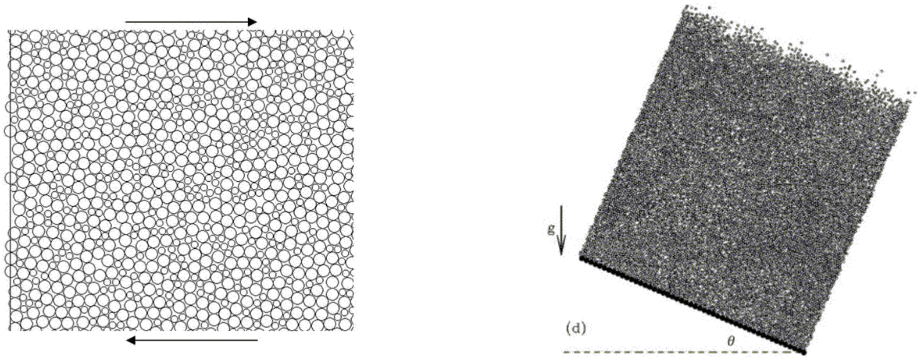
(Falk & Langer 1997)

$$\dot{\gamma} = \dot{\gamma}^{pl} \qquad w = \sigma\dot{\gamma}/p \qquad R_\pm \propto \sqrt{T} e^{\pm\kappa\sigma/p}$$

Lemaitre (2002)

$$\boxed{\begin{gathered} \dot{\gamma} \propto \sqrt{T}\,(\Lambda \sinh(\kappa\sigma/p) - \Delta\cosh(\kappa\sigma/p)) \\ \dot{\Delta} \propto \dot{\gamma}\,(1 - \Delta\zeta\sigma/p) \\ \dot{\Lambda} \propto \dot{\gamma}\sigma/p\,(1 - \Lambda) \end{gathered}}$$

Contact Dynamics Simulations: Specialize to Certain Geometries

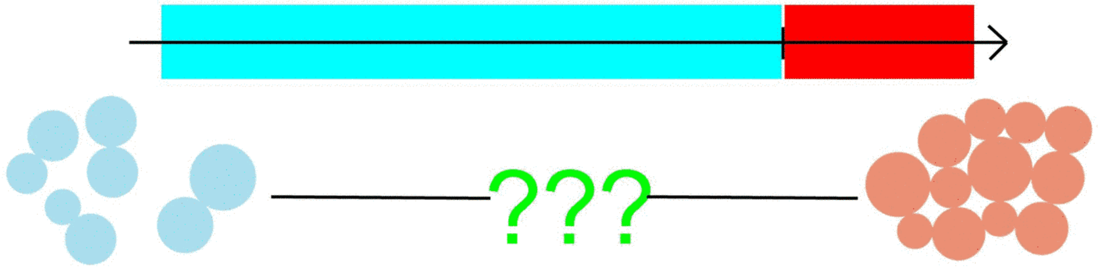


- **Test microscopic assumptions of hydrodynamic equations (kinetic theory and granular STZ)**
- **Predictions of macroscopic phenomena**

Density Phase Diagram for Granular Shear Flows

flowing,
low density

jammed,
high density

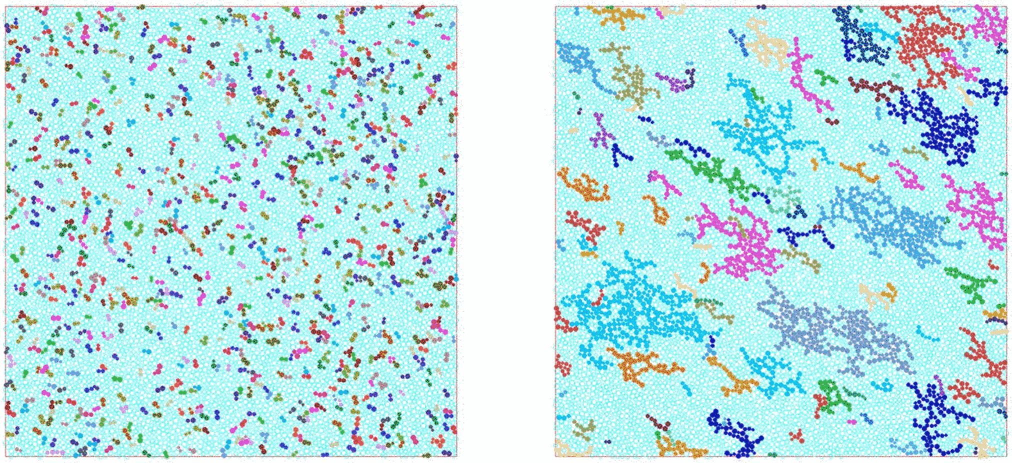


Kinetic Theory assumes binary collisions (dissipate energy)

Does Kinetic Theory fail?
If so, at what density?

STZ Theory assumes non-affine deformations are local, oriented

Emergence of Clusters



e=0.92: nearly elastic

e=0: totally inelastic

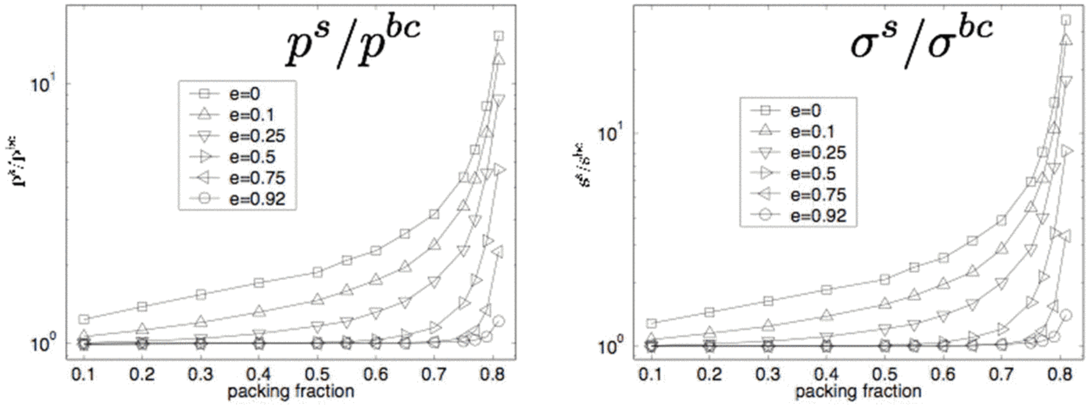
Test of the KT Binary Collision Assumption

The static part of the stress tensor is measured as

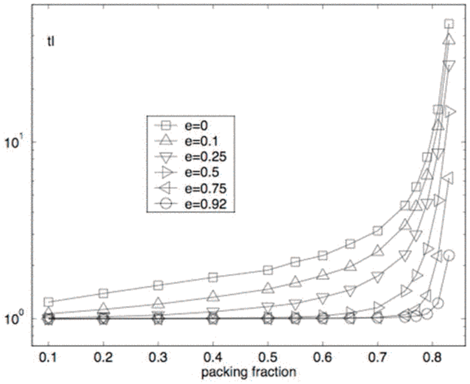
$$\Sigma_s^{\alpha\beta} \sim \sum_{\text{contacts}} \mathbf{R}^\alpha \mathbf{F}^\beta$$

If only binary collisions occur, then this can be written as

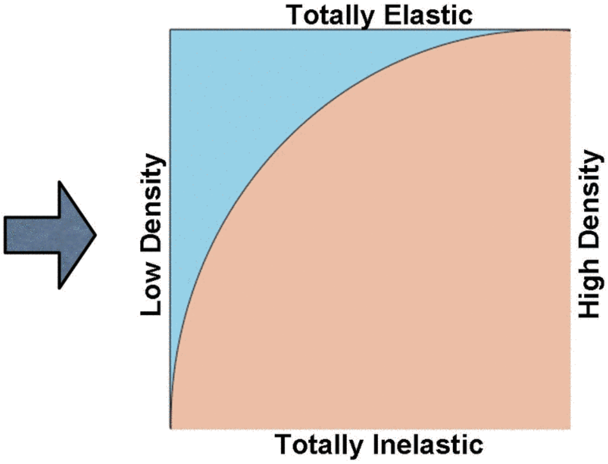
$$\Sigma_{bc}^{\alpha\beta} \sim \frac{1+e_n}{\Delta t} \sum_{\text{contacts}} \mathbf{R}^\alpha \mathbf{v_n}^\beta$$



Results of Numerical Test



p^s/p^{bc}



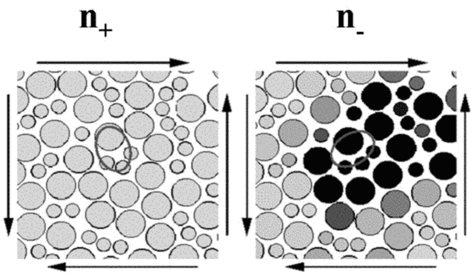
Blue: Kinetic Theory regime
Pink: Clustering regime

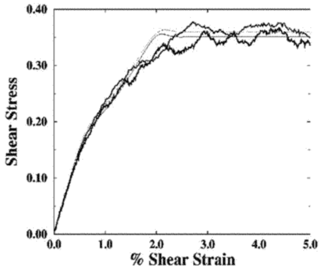
In much of the flowing phase space, kinetic theory fails.

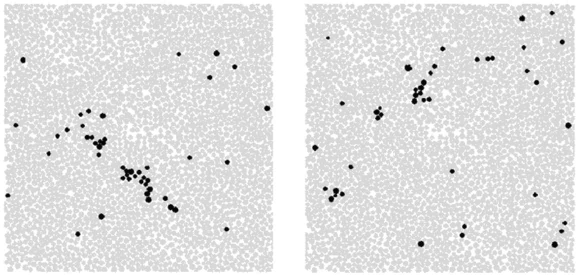
STZ Theory

Falk, Langer (1997):

(1) Non-affine (plastic) motion occurs in localized regions
(2) The regions undergoing non-affine motion have orientation







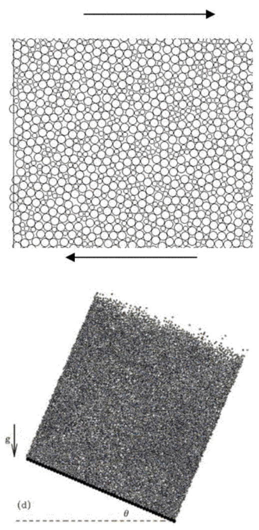
shearing forwards

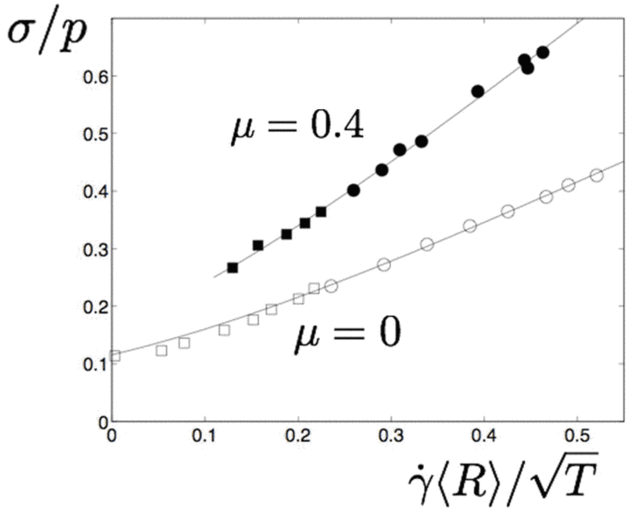
shearing backwards

Test of STZ Flowing Steady State

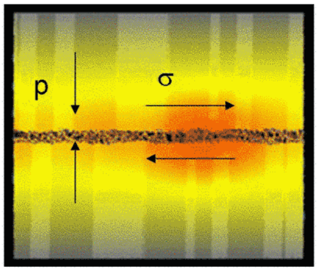
Two geometries, shear cell and incline flow, probe different ranges of stress vs. strain rate. Fit STZ parameters to one experiment, and test in other.

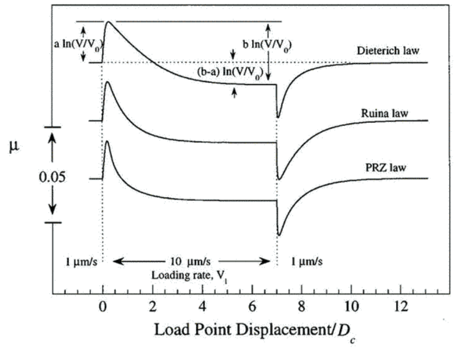
$$\frac{\dot{\gamma}}{\sqrt{T}} \propto \sinh(\kappa\frac{\sigma}{p}) - \frac{p}{\zeta\sigma}\cosh(\kappa\frac{\sigma}{p})$$

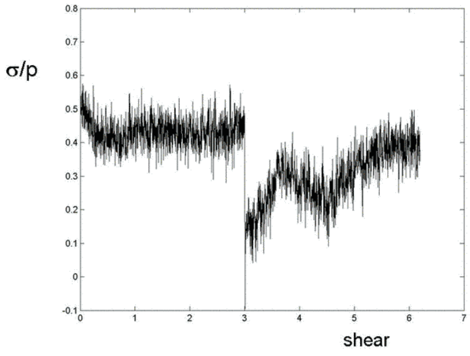




Future directions: transient dynamics in materials science, friction control, and geophysics







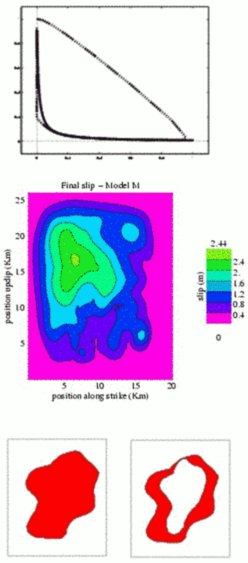
Back to Earthquakes….

How do assumptions about friction effect interpretations of seismic events?

- source dynamics
- heat anomaly
- radiation

(1979 Imperial Valley)

(Nielson, Olsen, Carlson)



Friction shows slip-weakening, rate dependance and includes state variables

Earthquake ruptures and earthquake distribution are complex; high level of heterogeneity is maintained

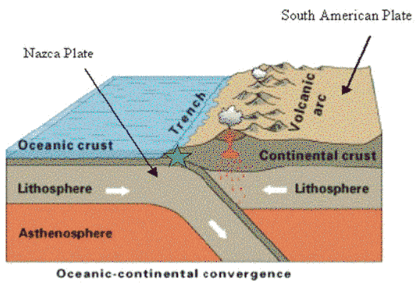
Observations of earthquakes are compatible with short slip duration, or pulse-like rupture (although it's not easy to prove)

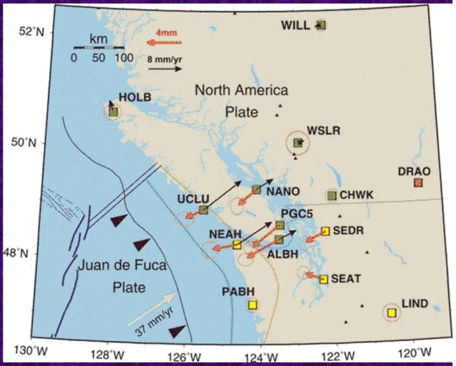
Variations in friction parameters can differentiate between dynamical regimes– crack vs. pulse and complexity.

Friction Gradients:

Friction gradients are important for subduction zones (friction depends on temperature and depth). These regions appear to exhibit slow earthquakes, which do not radiate energy (i.e. no trace on seismometers)

- GPS measurements are consistent with a slow, aseismic slip of ~2 cm about 40 km downdip from the earth's surface
- Slip velocity ranges from 10^{-8}-10^{-7}m/s (normal events: a few m/s)
- Slip traveled parallel to the strike of the plate boundary at a speed of ~6km/day (normal: a few km/s)





GPS stations and seismic events in Cascadia [Dragert *et al.* 2001]

Modeling Subduction Thrusts [Liu and Rice 2005]

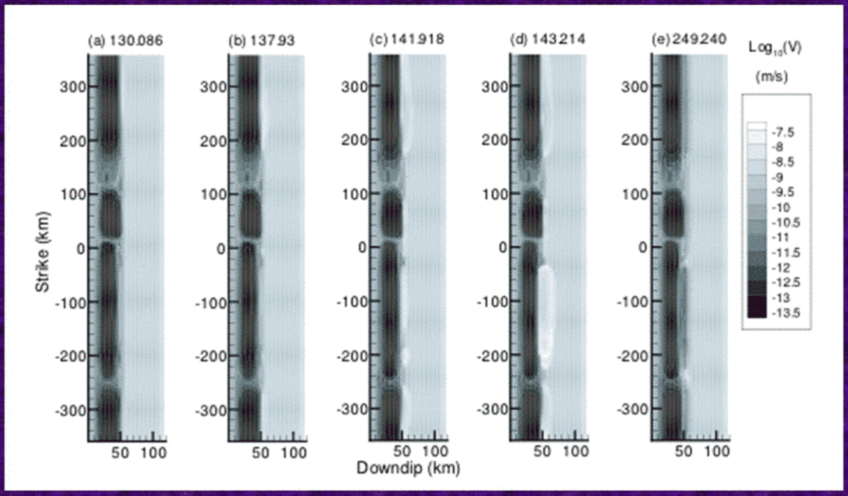
- Normally, at ~40 km depth temperature dictates that friction is rate strengthening, but there is some evidence that at small velocities friction changes to rate weakening (which allows slip events)
- Also, metamorphic fluid release at depth could weaken friction to allow slip

Use depth-dependent (Dieterich-Ruina) rate and state friction to model subduction zone dynamics, matching friction parameters to the geothermal gradient

- Rate weakening friction at depths above ~30 km (depth measured along the plate boundary)
- Rate strengthening friction below ~30 km, with velocity dependence growing with depth
- Below 120 km, steady ductile creep at the long term plate convergence rate is imposed

[Liu and Rice 2005]

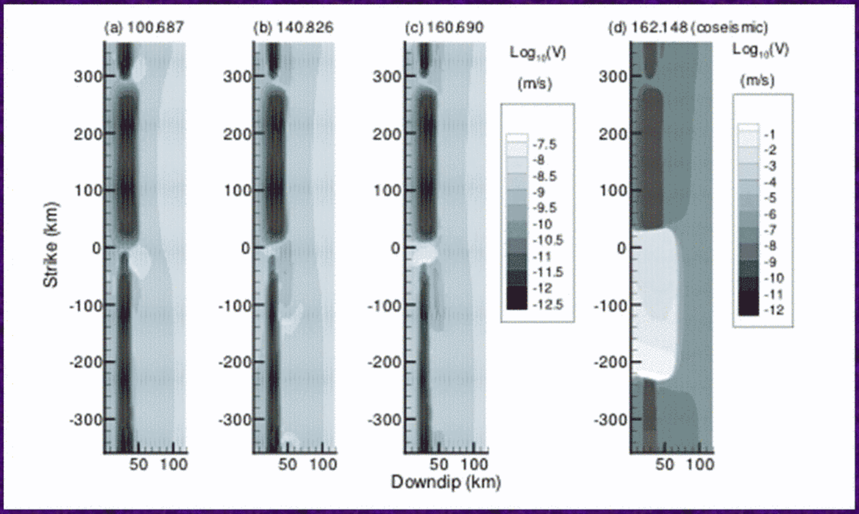
Numerical Simulation Results



Example of a silent slip event from simulation

[Liu and Rice 2005]

Numerical Simulation Results

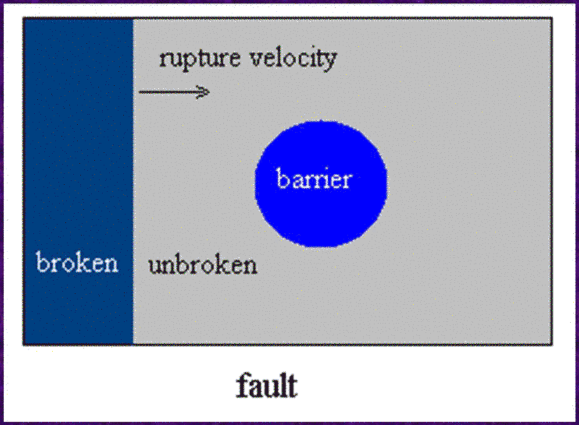


Transients can even trigger events in the seismogenic zone!

How do dynamical ruptures interact with irregularities on the fault plane?

- Faults are inhomogeneous in shape, prestress conditions, and material properties
- How do these inhomogeneities interact with dynamic ruptures?

The Numerical Experiment: Breaking a Circular Asperity/Barrier

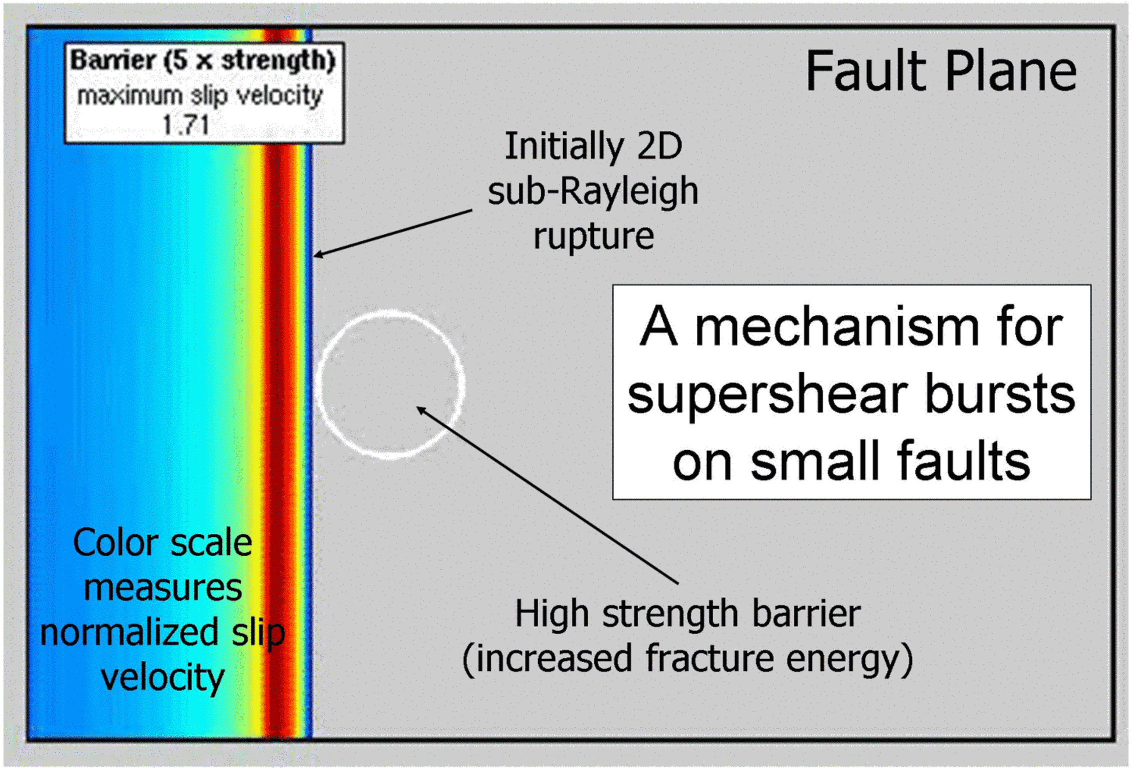


Eric Dunham, Pascal Favreau

Planar mode II rupture front (just below Rayleigh speed) incident on barrier of decreased prestress (anti-asperity) or increased peak stress (barrier)

Expectation: *It should slow down...*

Fault Plane



Initially 2D sub-Rayleigh rupture

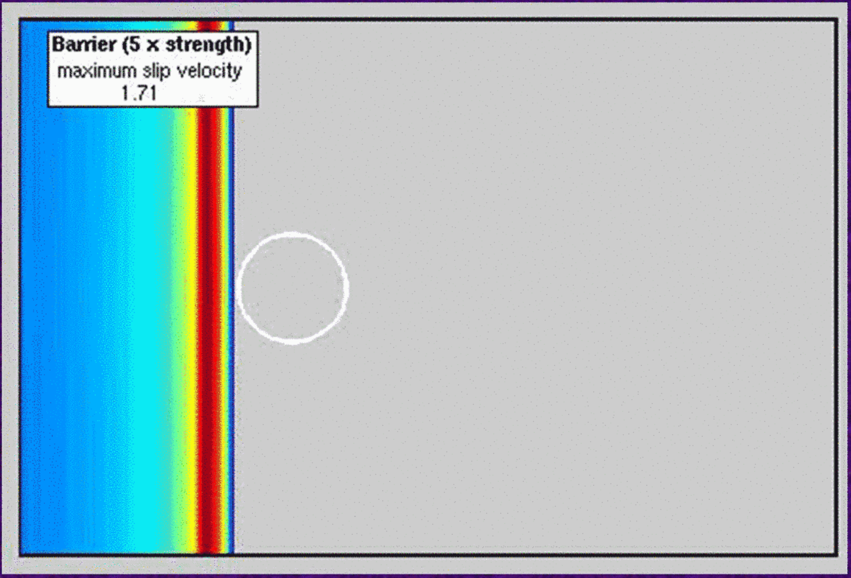
A mechanism for supershear bursts on small faults

High strength barrier (increased fracture energy)

Color scale measures normalized slip velocity

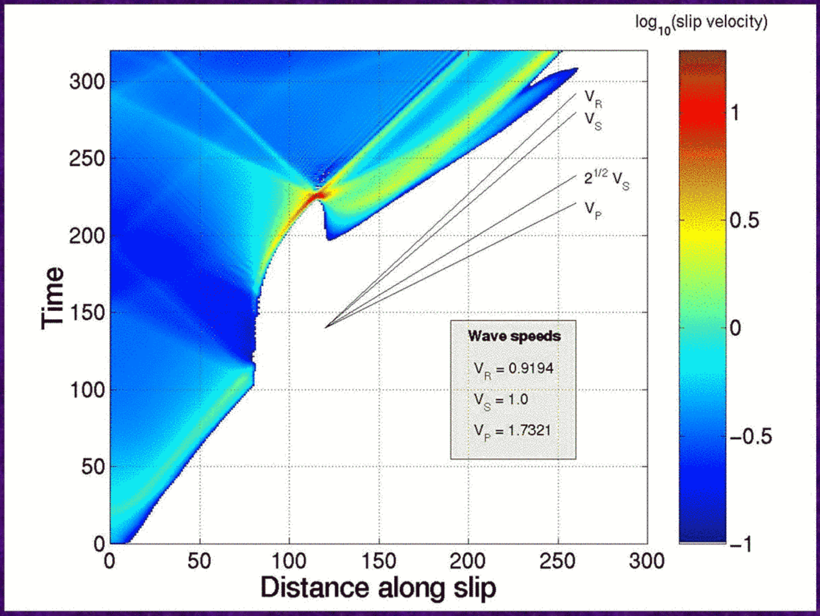
Dunham et al. [2003]

Barrier: local region of increased strength

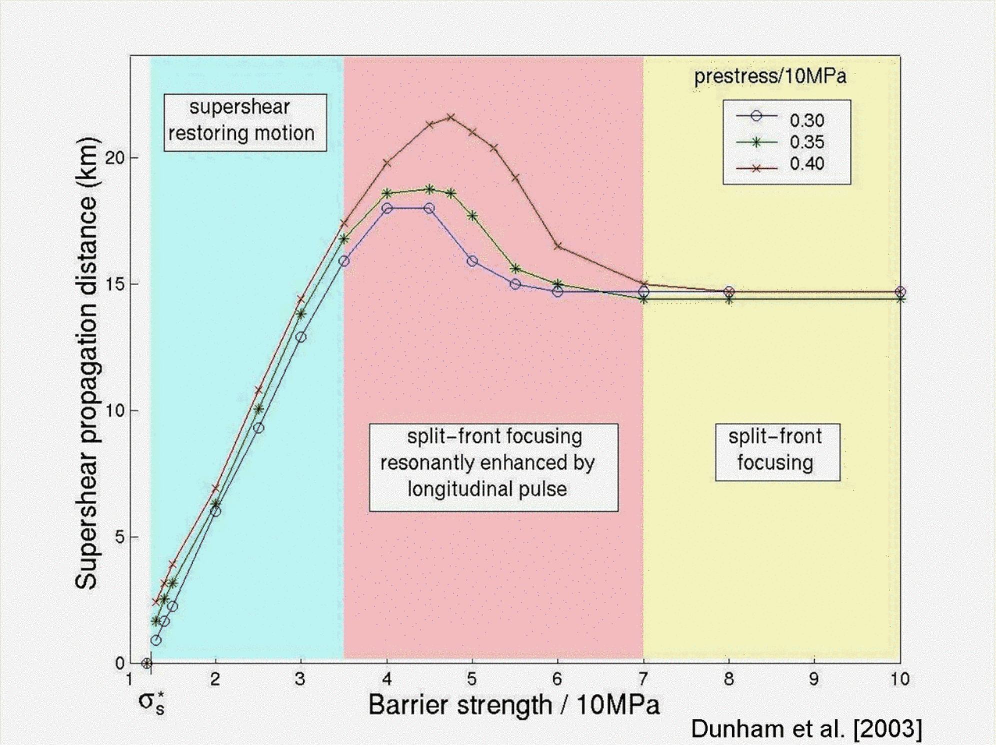


- *High energy concentrations, rapid release!*
- *New mechanism for damage!*

Barrier focusing leads to supershear rupture speeds. Duration scales with barrier strength.

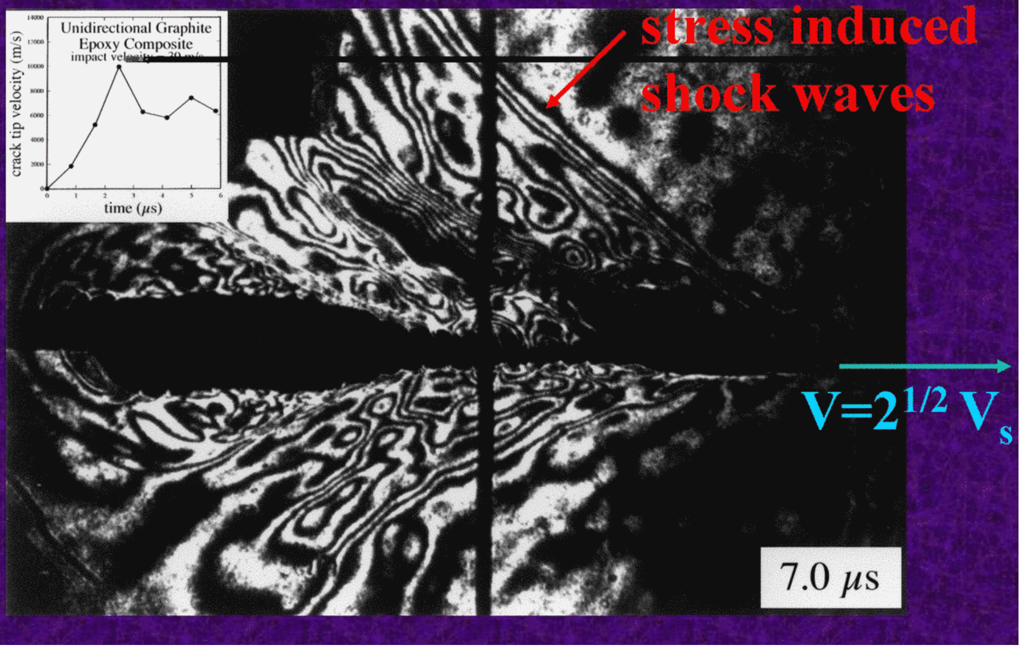


Supershear Bursts

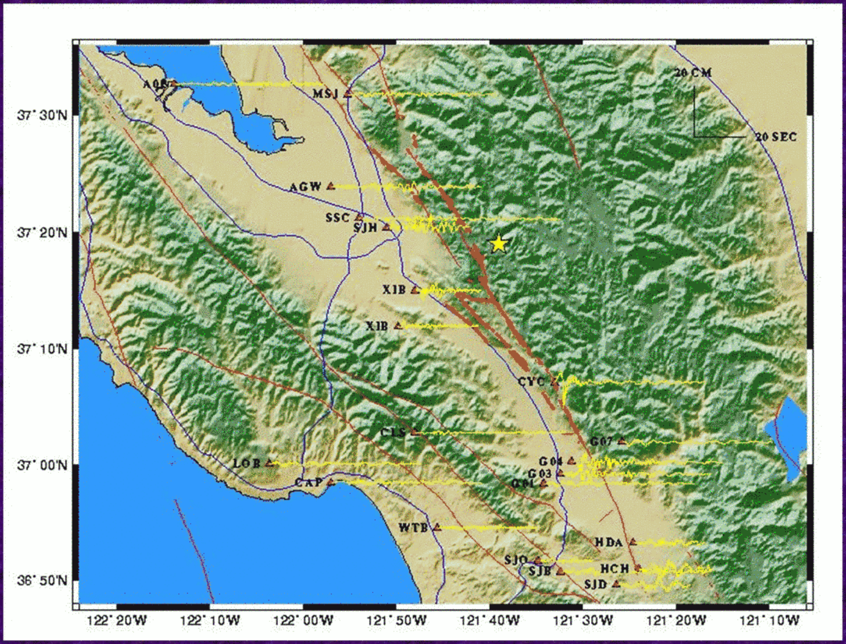


Dunham et al. [2003]

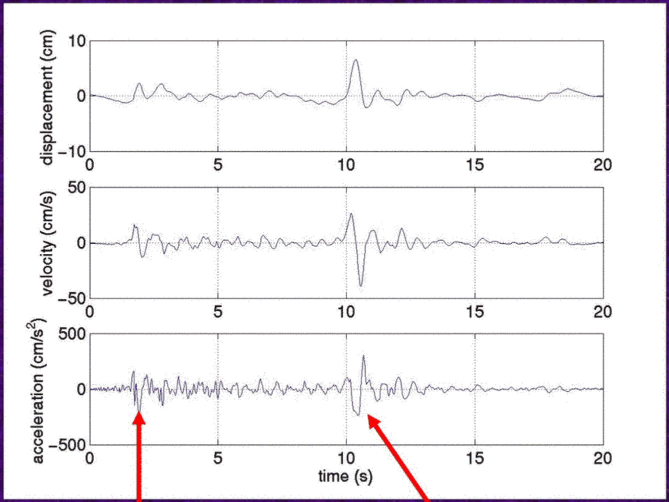
Rosakis (Caltech) observes supershear cracks in birefringent materials (high speed imaging)



Morgan Hill 1984 Magnitude 6.2 Earthquake



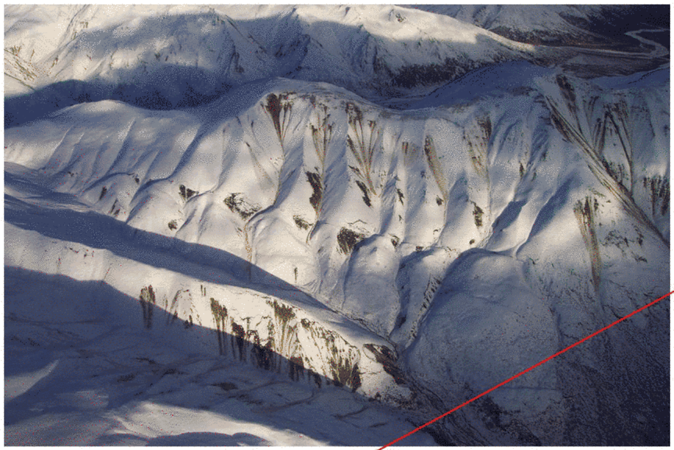
Morgan Hill 1984 Magnitude 6.2 Earthquake



S-wave arrival Unexplained pulse

- Consistent with high energy concentrations in barrier focusing mechanism

2002 Denali Fault Earthquake

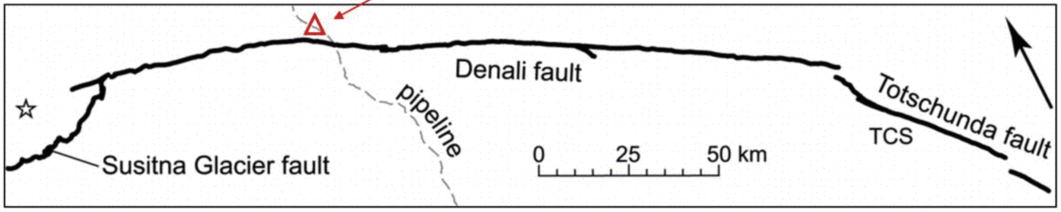


courtesy USGS

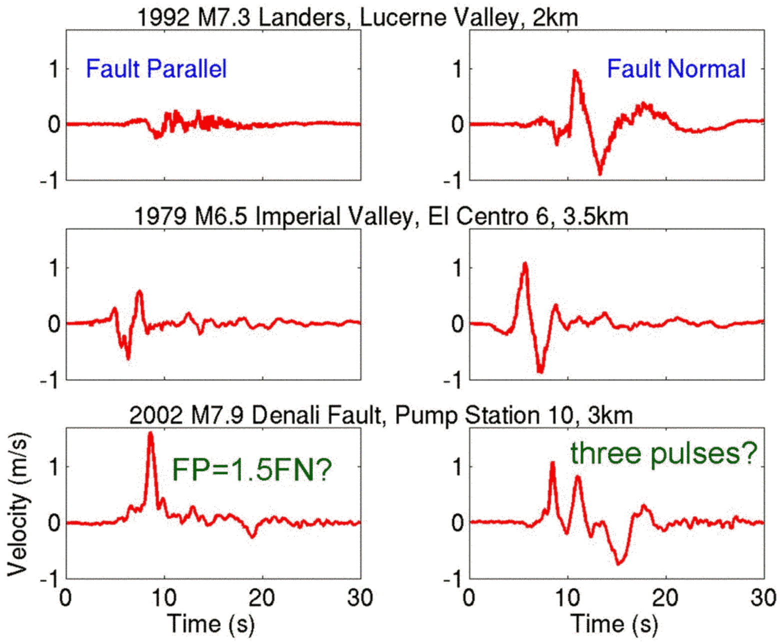
(Dunham and Archuleta)

Pump Station 10 (PS10)

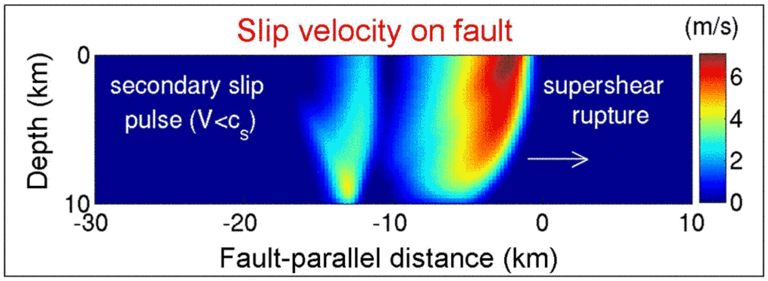
3km N of fault

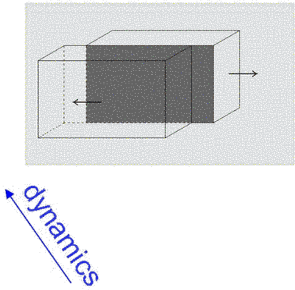


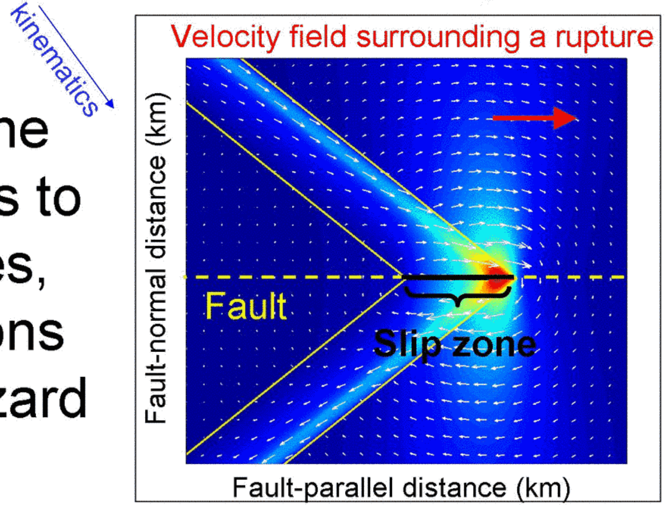
A Puzzle in the Seismograms



PS10 data processing by Ellsworth et al. [2004]

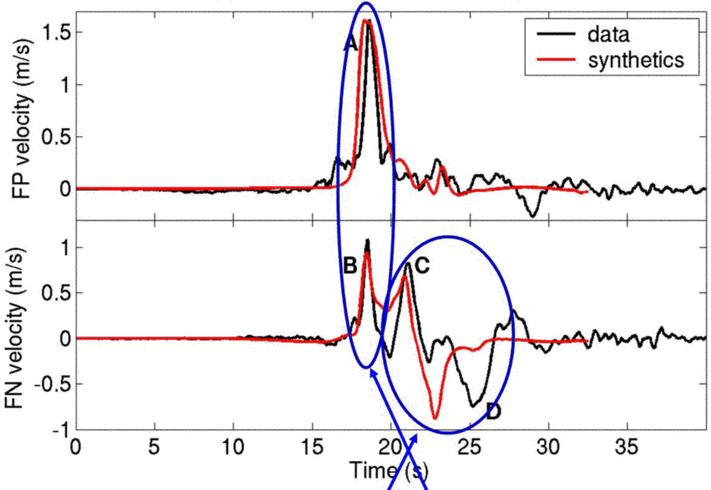




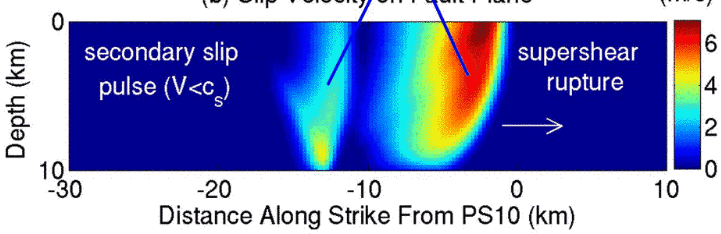


Connecting the source process to seismic waves, with implications for seismic hazard

(a) Data and Synthetic Seismograms



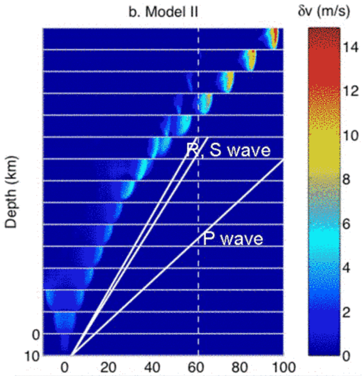
(b) Slip Velocity on Fault Plane

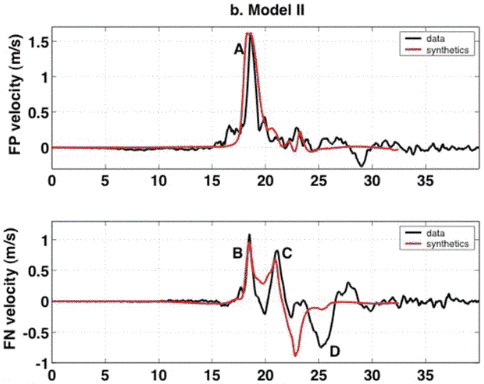


Dunham and Archuleta [2005]

A Model of Denali Earthquake (M 7.9, Nov. 2001)

Dunham and Archuleta



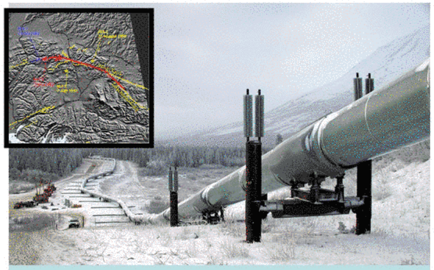


Fault Parallel

Dominated by supershear

Fault Normal

Supershear + subshear

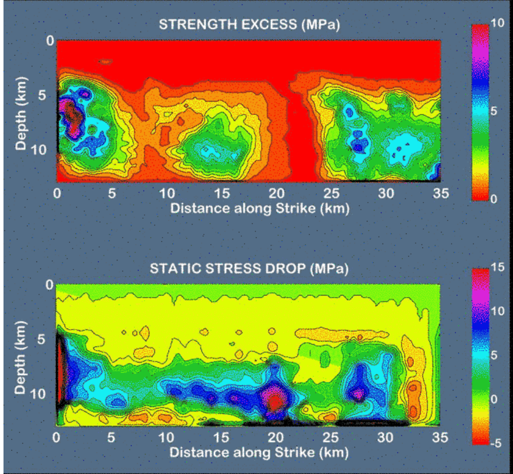


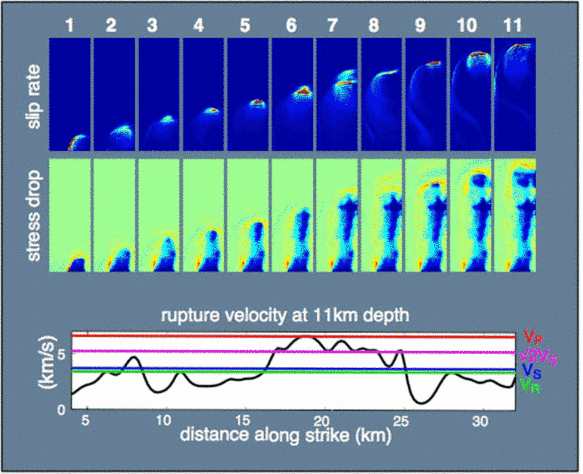
Rob Kayen, Nick Sitar, Gary Carver, Brian Collins, Robb Moss

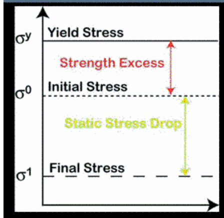
Feedback between instantaneous stress state and rupture front which produces a new stress state

- Models are non-unique; two models fit equally well
- Variation in rupture velocity produces high frequency ground motion; values of rupture velocity drastically alter the ground motion
- Modeling can produce a suite of ground motion; how are statistics of the ground motion related to statistics of the physical variables controlling the rupture?

Uncertainty in Earthquake Modeling







Initial parameters determined by low frequency inversion of recorded ground motion. Uncertainty in the inversion allows different representation of the rupture. Including the uncertainty in the physical process, which governs the radiated elastic waves, has not been solved.

Kinematic Inversions - Background

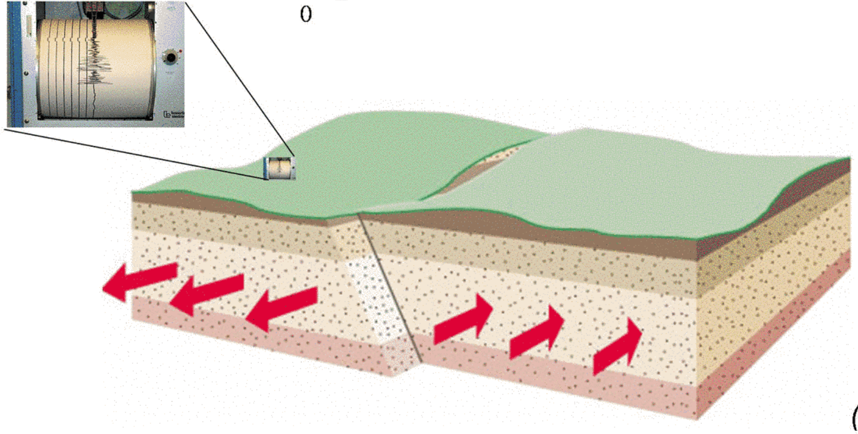
Fully dynamical inversions of seismograms are not computationally practical. How can we incorporate insights from dynamics into kinematics, which make assumptions about the slip, and estimate uncertainty in the results?

displacements in the medium

slip on the fault

Green's function

$$u_i(\dot{x},t)=\int_0^t\int_{\Sigma}\Delta u_j(\dot{\xi},t)G_{ij}(\dot{x}-\dot{\xi},t-\tau)d\xi d\tau$$



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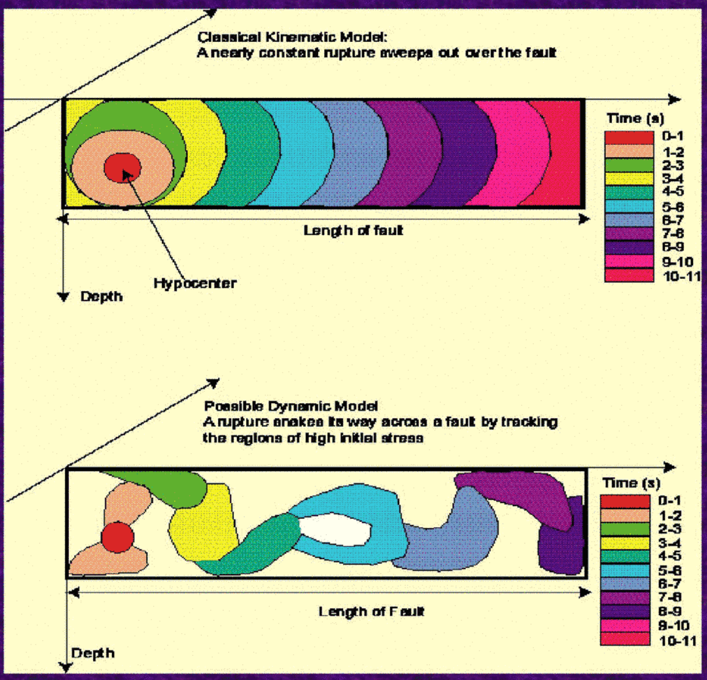
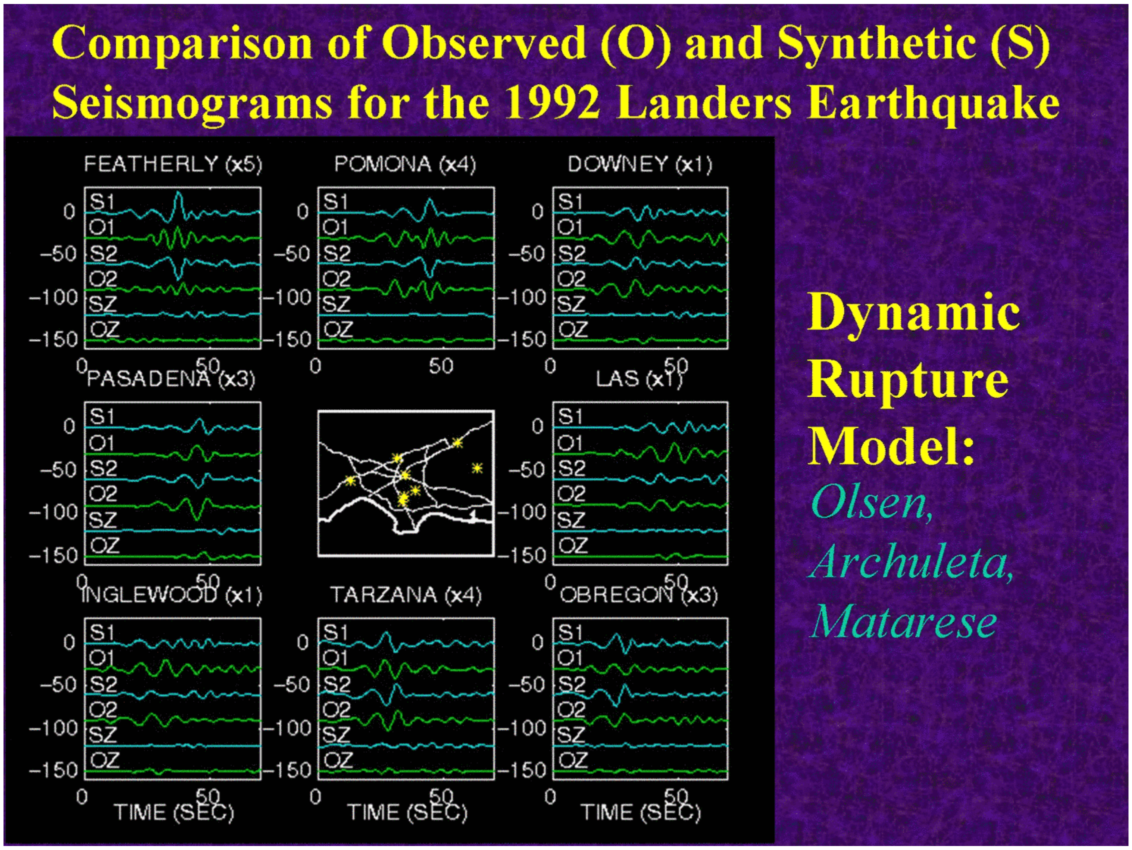
Dynamic simulations suggest greater complexity





Comparison of Observed (O) and Synthetic (S) Seismograms for the 1992 Landers Earthquake

Dynamic Rupture Model: *Olsen, Archuleta, Matarese*

Kinematic Inversions - Background

displacements in the medium

slip on the fault

Green's function

$$u_i(\dot{x},t) = \int_0^t \int_\Sigma \Delta u_j(\dot{\xi},t) G_{ij}(\dot{x}-\dot{\xi},t-\tau)\, d\dot{\xi}\, d\tau$$

What we know (at least in some places on the surface)

What we want to know

What we sort-of know

To find Δu, we discretize the problem:

$$Ax = f$$

Seismograms

Medium response
(Green's function)

Slip on fault

We need to invert A and find x.

Penrose's Generalized Inverse (GI):

Among all solutions satisfying *minimum* $\| Ax - f \|$,
there exists a unique solution $\tilde{x}$ which satisfies *minimum* $\| x \|$.
The generalized inverse of A, $\tilde{A}$, satisfies $\tilde{x} = \tilde{A} f$.

$\tilde{x}$ is the least-squares solution.

$$Ax = f$$

Seismograms

Medium response
(Green's function)

Slip on fault

We can find $\tilde{A}$ with the Singular Value Decomposition:

$A = U \Lambda V^T$, where U and V are orthogonal and Λ is diagonal with elements λ_{ii}

$\tilde{A} = V \Lambda^{-1} U^T$ where $(\Lambda^{-1})_{ii} = \begin{cases} \lambda_{ii}^{-1} & for\ \lambda_{ii} > 0 \\ 0 & for\ \lambda_{ii} = 0 \end{cases}$

Recall that our solution $\tilde{x} = \tilde{A} f = \tilde{A}(Ax) = (\tilde{A}A)x$.

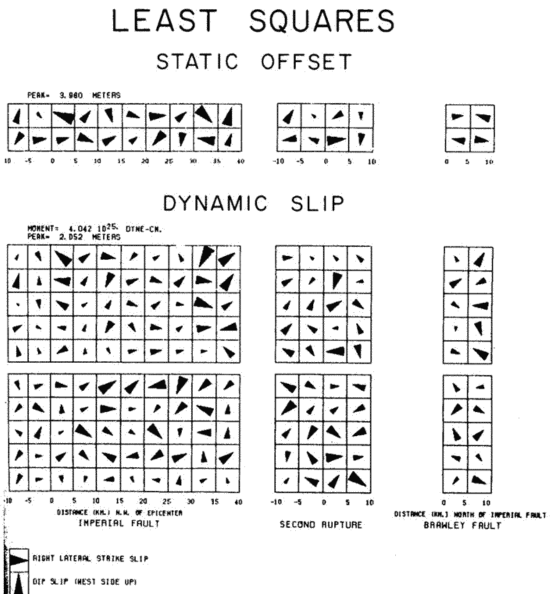
true solution

$R = \tilde{A}A$ is the **resolution matrix**.

Least Squares Fit for Imperial Valley Earthquake

Olson and Apsel, 1982

- Solution very unstable
- Backslips common
- Large variations in rake, even between neighboring cells



G. 4. Slip on the Imperial and Brawley faults obtained by least-squares inversion without stabili- n. Triangles have an area proportional to the displacement and point in the direction of slip; the define the scales for static and dynamic displacements. The static offset (*top*) is shown for the two ntal rows of 5-km square cells which make up the fault surface. The two groups of boxes (*bottom*) in the dynamic slip for the two rows of cells (*top*). Each triangle in the dynamic slip corresponds to f the s_{jk} vectors in equation (2-5). The vector sum of the five sequential slips plotted vertically m) equals the static offset in the corresponding cell above. Zero time for the dynamic slip is the required by a wave front moving at 90 per cent of the shear wave velocity to travel from the enter to the cell.

Adding constraints to inversion to get more physical rupture

Extend notion of GI to include inequality constraints:

Among all solutions satisfying $Gx > h$ and *minimum* $\|Ax - f\|$, there exists a unique solution $\tilde{x}_c$ which satisfies *minimum* $\|x\|$. The constrained generalized inverse of A, $\tilde{A}_c$, satisfies $\tilde{x}_c = \tilde{A}_c f$.

Possible constraints:
No backslip, constant rupture velocity, total moment

Alternative method of *Hartzell and Heaton (1983)* – weight a strict constraint (tradeoff between constraint and misfit)

$$\begin{bmatrix} A \\ \lambda F \end{bmatrix} \boldsymbol{x} = \begin{bmatrix} f \\ \lambda d \end{bmatrix},$$ where $Fx=d$ is a set of linear constraints and λ is a scalar weight.

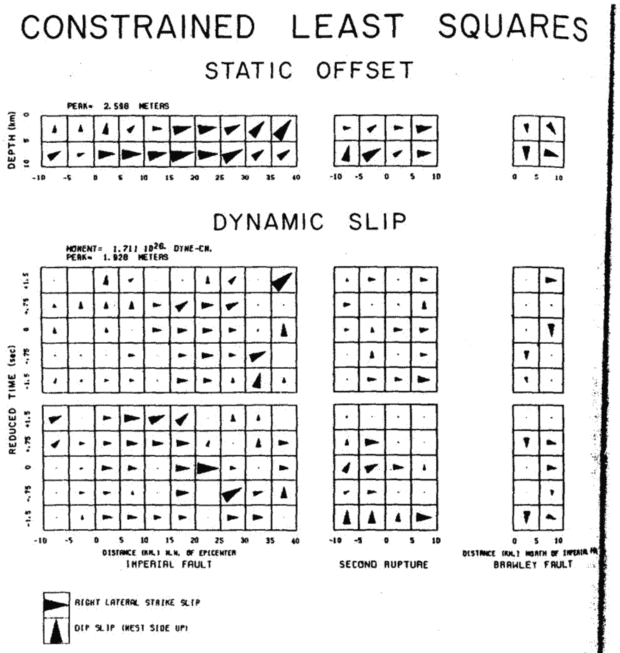


FIG. 6. Slip on the Imperial and Brawley faults obtained by constrained least-squares inversion without stabilization (analogous to the unconstrained solution shown in Figure 4). In this solution, the slip is constrained to be: right-lateral; west side up on the Imperial fault; and west side down on the Brawley fault. As a result of the constraints, the dynamic slip (*bottom*) does not reverse direction, and the static offsets (*top*) in adjacent cells are not in opposing directions (compare with Figures 4 and 5).

Constrained Least Squares Fit for Imperial Valley

Olson and Apsel, 1982

Stabilizing the solution

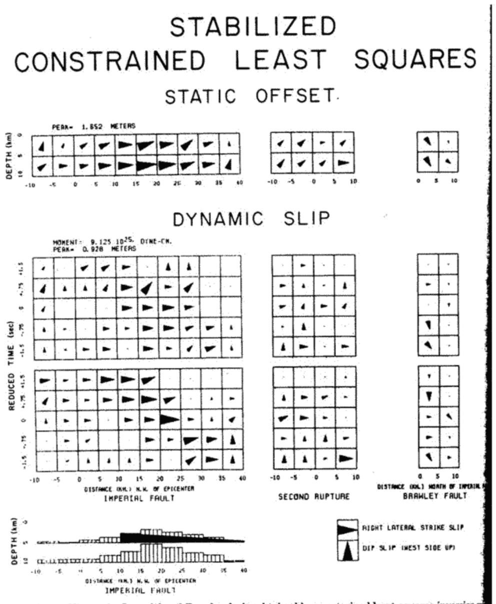


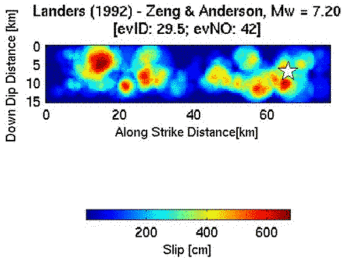
FIG. 7. Slip on the Imperial and Brawley faults obtained by constrained least-squares inversion w stabilization (analogous to the unstabilized solution in Figure 6). The seismic moment is much smal than in Figure 6. Also, a noticeable trend with a horizontal phase velocity between 4.0 and 5.0 km/sec emerged in the dynamic slip of the bottom row of cells on the Imperial fault. The strike-slip compone of offset on the Imperial fault is shown in the *lower left* superimposed upon a *shaded schematic* of observed surface offset.

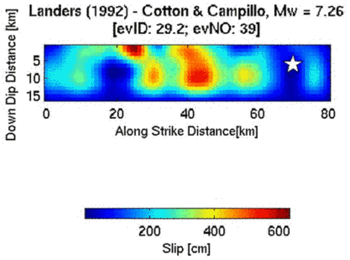
Olson and Apsel, 1982

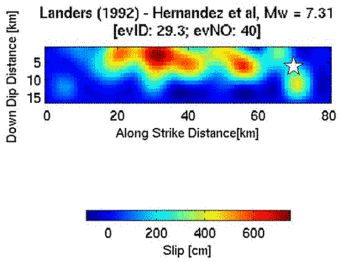
Treat small singular values as zero – so that they do not participate in solution (since GI sets the null space component of *A* to zero)

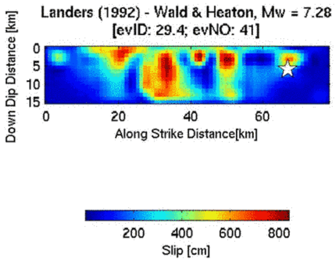
Preferred solution is more physical, but has larger misfit

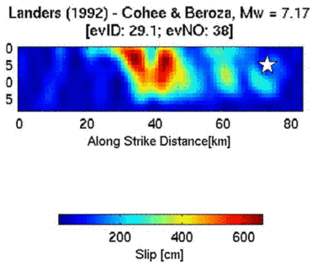
Different Slip Models of the 1992 Landers earthquake











Database of Finite Source Models
http://www.seismo.ethz.ch/staff/martin/research/srcmod/srcmod.html

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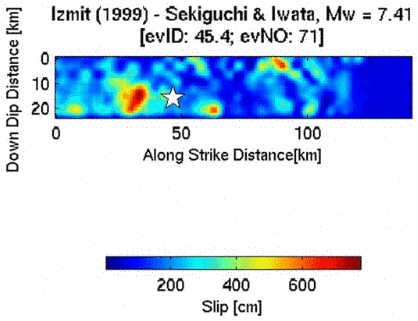
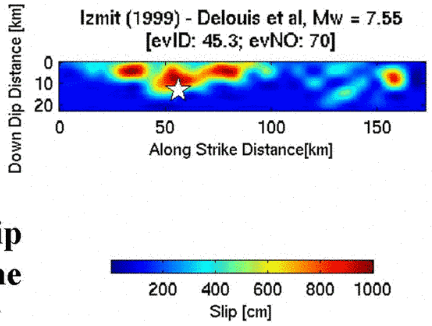
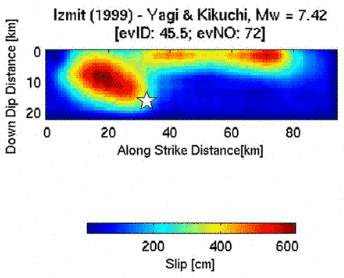
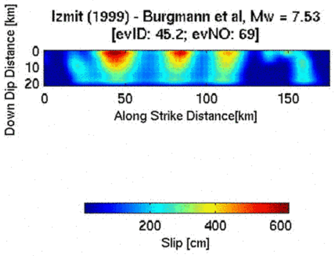
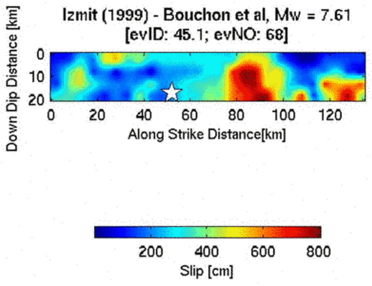
Different Slip Models of the 1999 Izmit earthquake







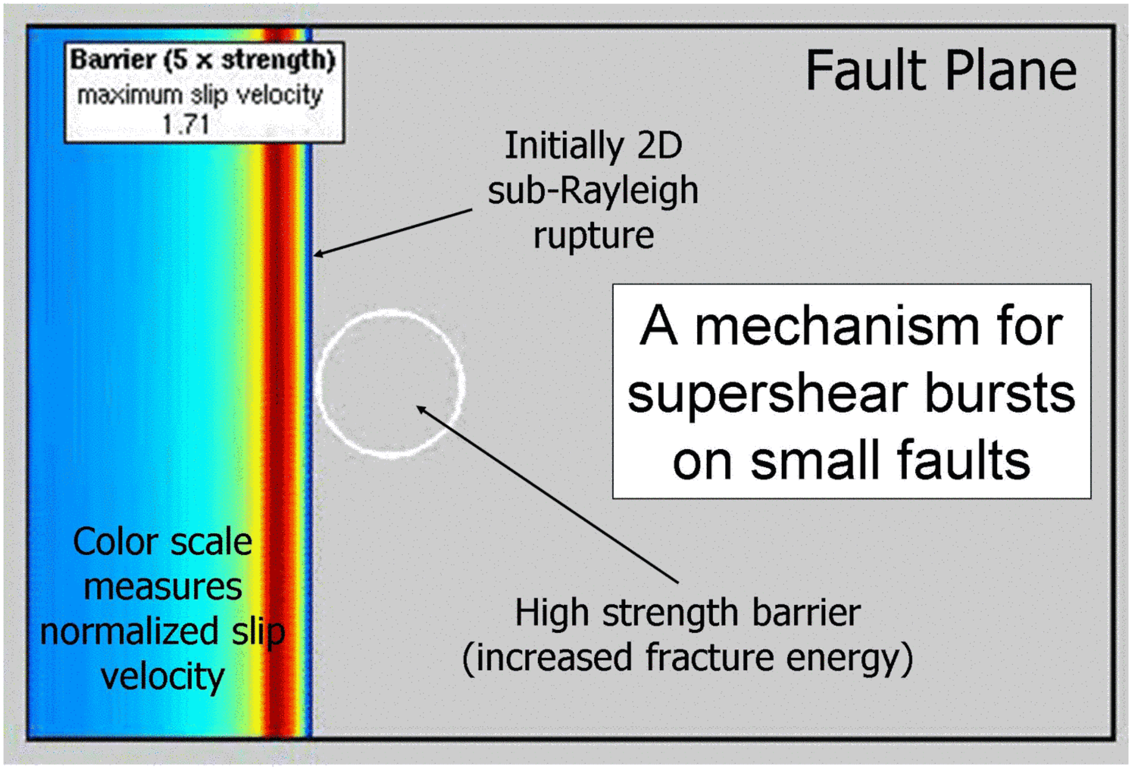




Database of Finite Source Models
http://www.seismo.ethz.ch/staff/martin/research/srcmod/srcmod.html

Current problems with kinematic inversions

- Often only one model is given
- No sense of “error” in the result
- Which parts of the result are best-constrained?
- How much of the answer is dependent on the constraints?
- Why do different inversions have such different slip models?

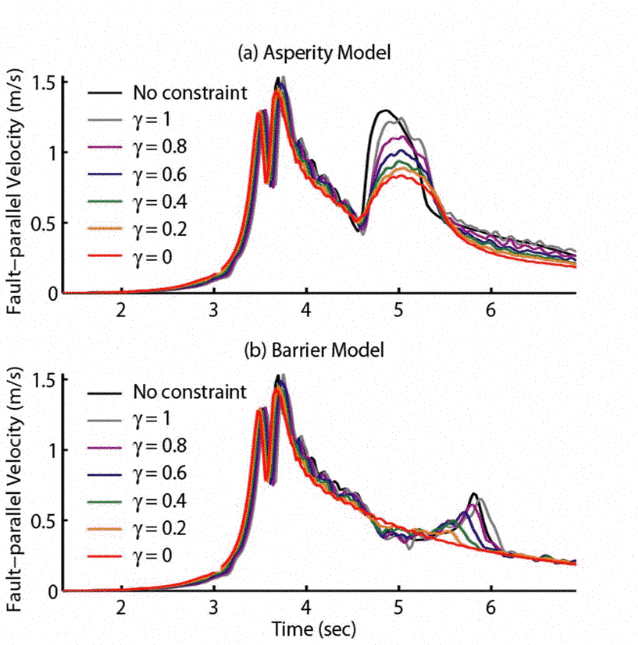


A mechanism for supershear bursts on small faults

Dunham et al. [2003]

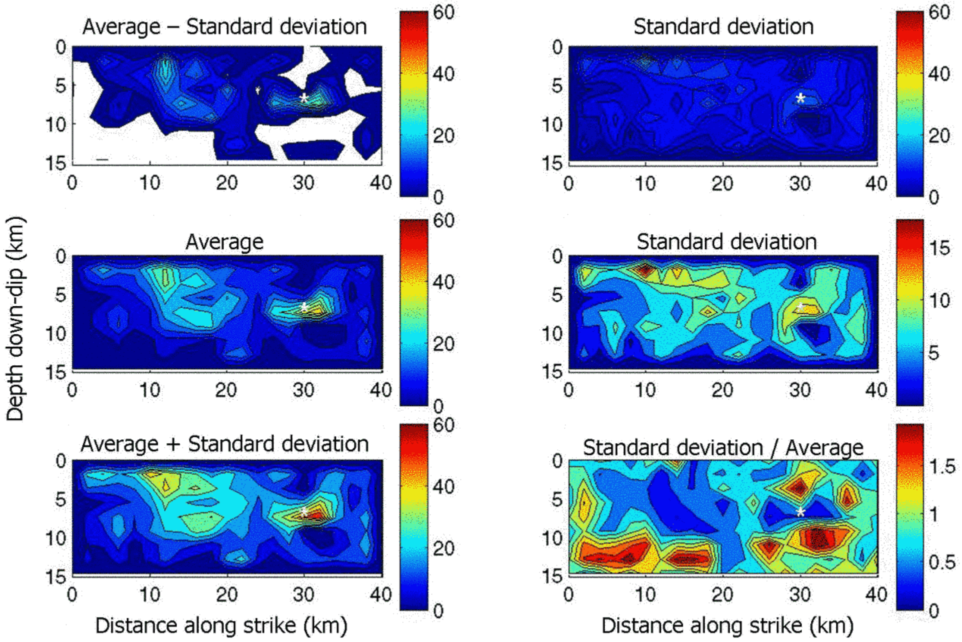
The Effect of a Rupture Velocity Constraint

(Page, Dunham, Carlson)



Forward Problem: incrementally adding dynamic effects to kinematic simulations.

A step in the right direction: Custodio et al. give several models with different data sets, which gives a sense of the result's stability



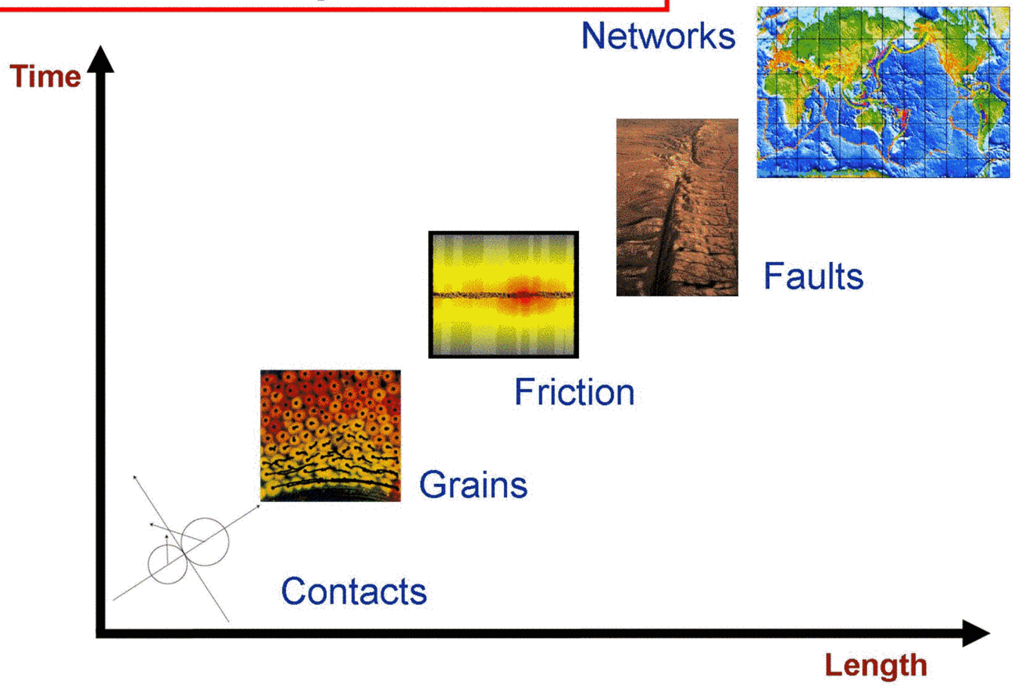
Can we do this more systematically?

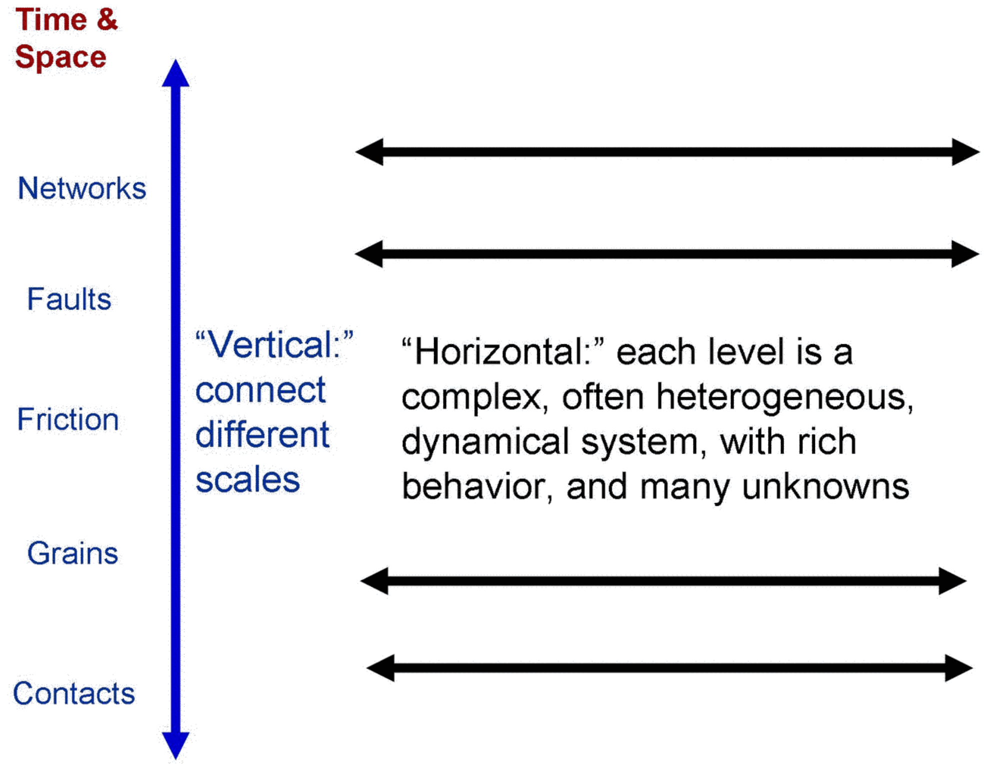
Applying control-theoretic techniques to the inverse problem

- Small singular values of A give directions of highest instability
- Extend to include analysis of sensitivities of constraints
- Effect of uncertainty in Green's function (site response, path effects, velocity structure uncertainty, etc.)
- How to weight different stations / components (which are most affected by noise in Green's function, for example)

Goal: A better measure of just how much we can resolve in kinematic inversions

Multiscale Earthquakes Problem:





Time & Space

Networks

Faults

Friction

Grains

Contacts

"Vertical:" connect different scales

"Horizontal:" each level is a complex, often heterogeneous, dynamical system, with rich behavior, and many unknowns

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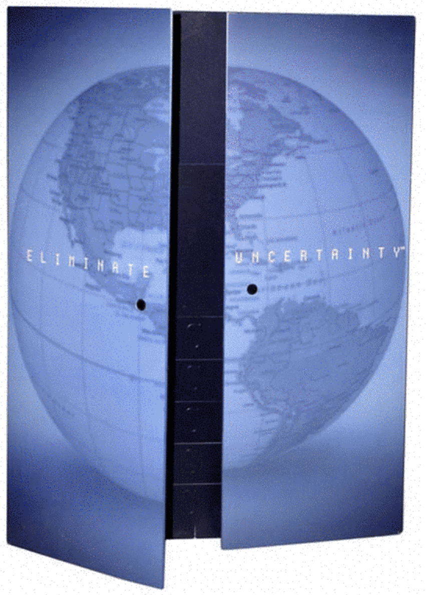


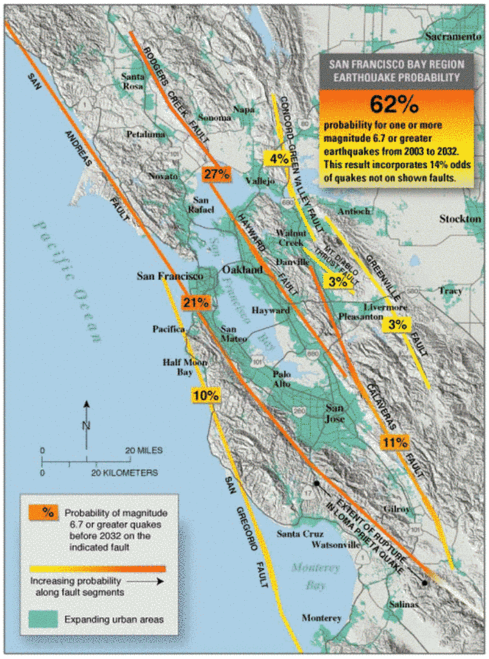
Dealing with Uncertainty in Seismic Hazard Analysis

- **Horizontal Challenge:**
  Identify the range of behavior which is physically plausible
- **Vertical Challenges:**
  Uncertainty management connecting scales, and investment of numerical resolution

Economics and policy are based on regional hazard estimates, which require:

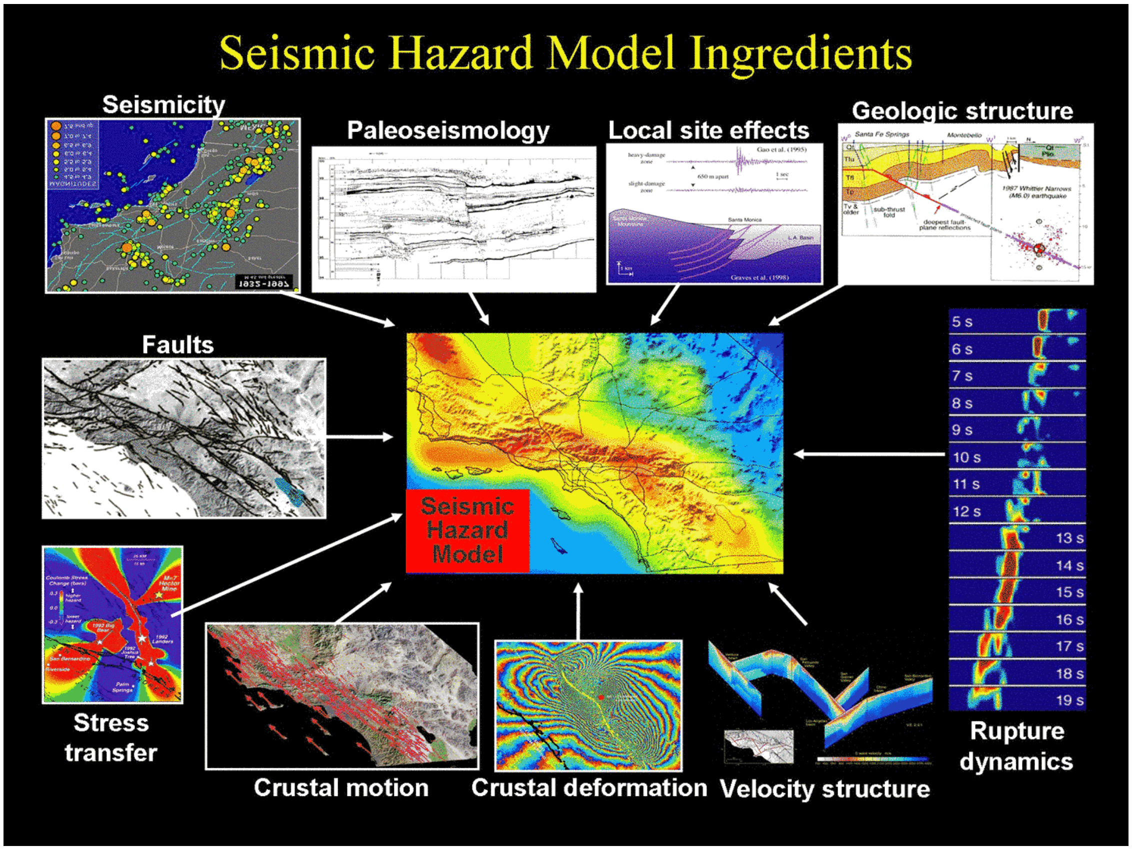
- *More rigorous statistical methodologies for assimilating data*
- *Methods to systematically incorporate physical constraints on ground motion based on dynamics*

(Morgan Page, poster session)



Working Group 2002 (WG02) Earthquake Probability Study for the San Francisco Bay Region

Seismic Hazard Model Ingredients



Seismicity

Paleoseismology

Local site effects

Geologic structure

Faults

Seismic Hazard Model

Rupture dynamics

Stress transfer

Crustal motion

Crustal deformation

Velocity structure