Earth Science Applications of Space Based Geodesy

DES-7355

Tu-Th 9:40-11:05

Seminar Room in 3892 Central Ave. (Long building)

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http://www.ceri.memphis.edu/people/smalley/ESCI7355/ESCI_7355_Applications_of_Space_Based_Geodesy.html

Class 12

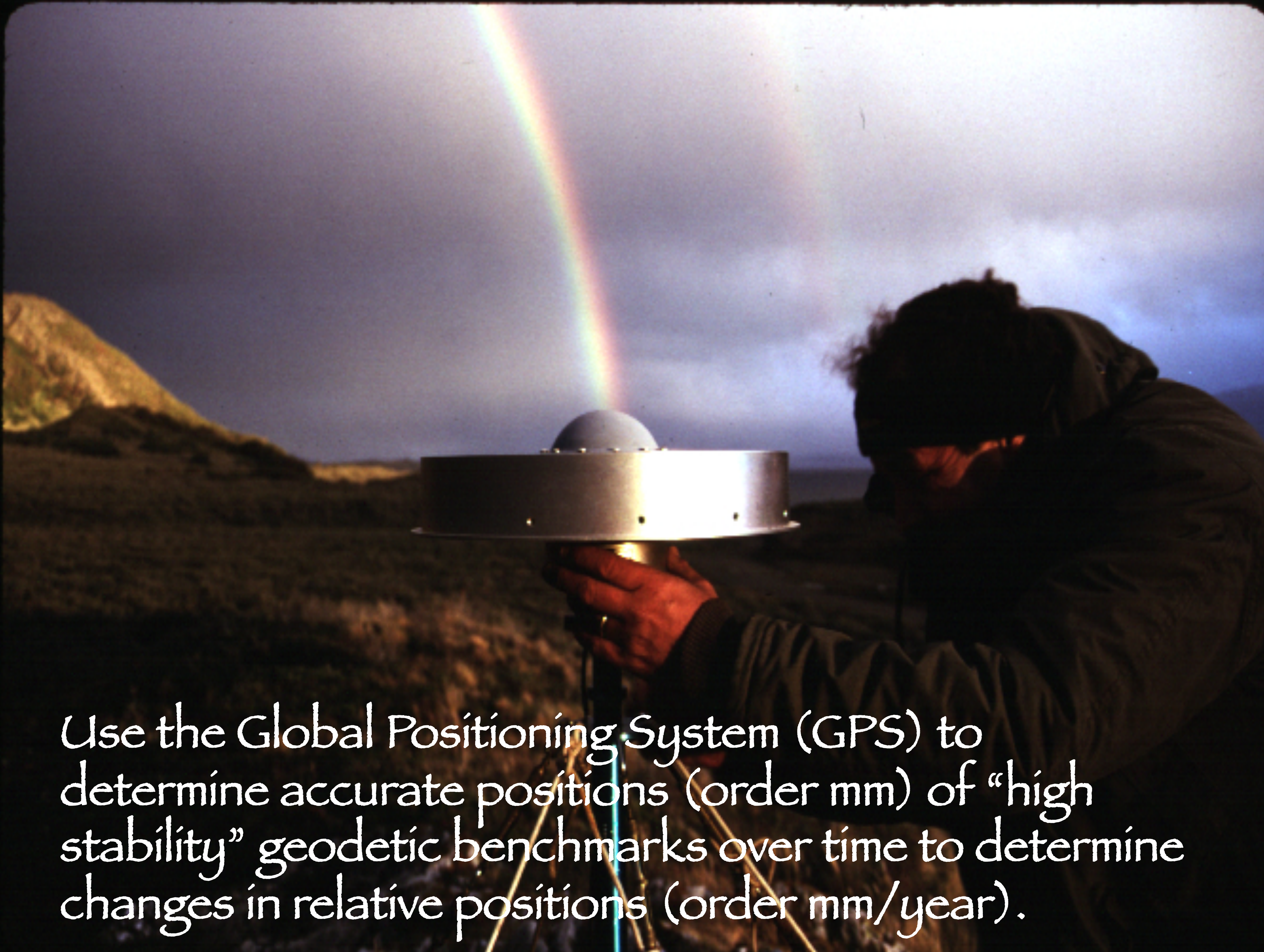
(incomplete)

look at

Applications of GPS

in Earth Sciences

carpincho
or
capybara


Use the Global Positioning System (GPS) to determine accurate positions (order mm) of "high stability" geodetic benchmarks over time to determine changes in relative positions (order mm/year).

Principal tenet/Central assumption of plate tectonics:

plate (interiors) are rigid

-Observation –

Plates move with respect to one another

-Secondary tenet/assumption –

Interaction limited to (narrow) plate boundary zones where deformation is allowed

Plate motions --- NUVEL vs GPS

NUVEL – geologic

Spreading rate and orientation (Myr ave)
Transform fault orientation (no rate info, Myr ave)
Earthquake Focal mechanism (problem with slip partitioning, 30 yr ave - actual)

GPS – non-geologic

Measures relative movement (20 yr ave – actual)
Can't test (yet) plate stability assumption

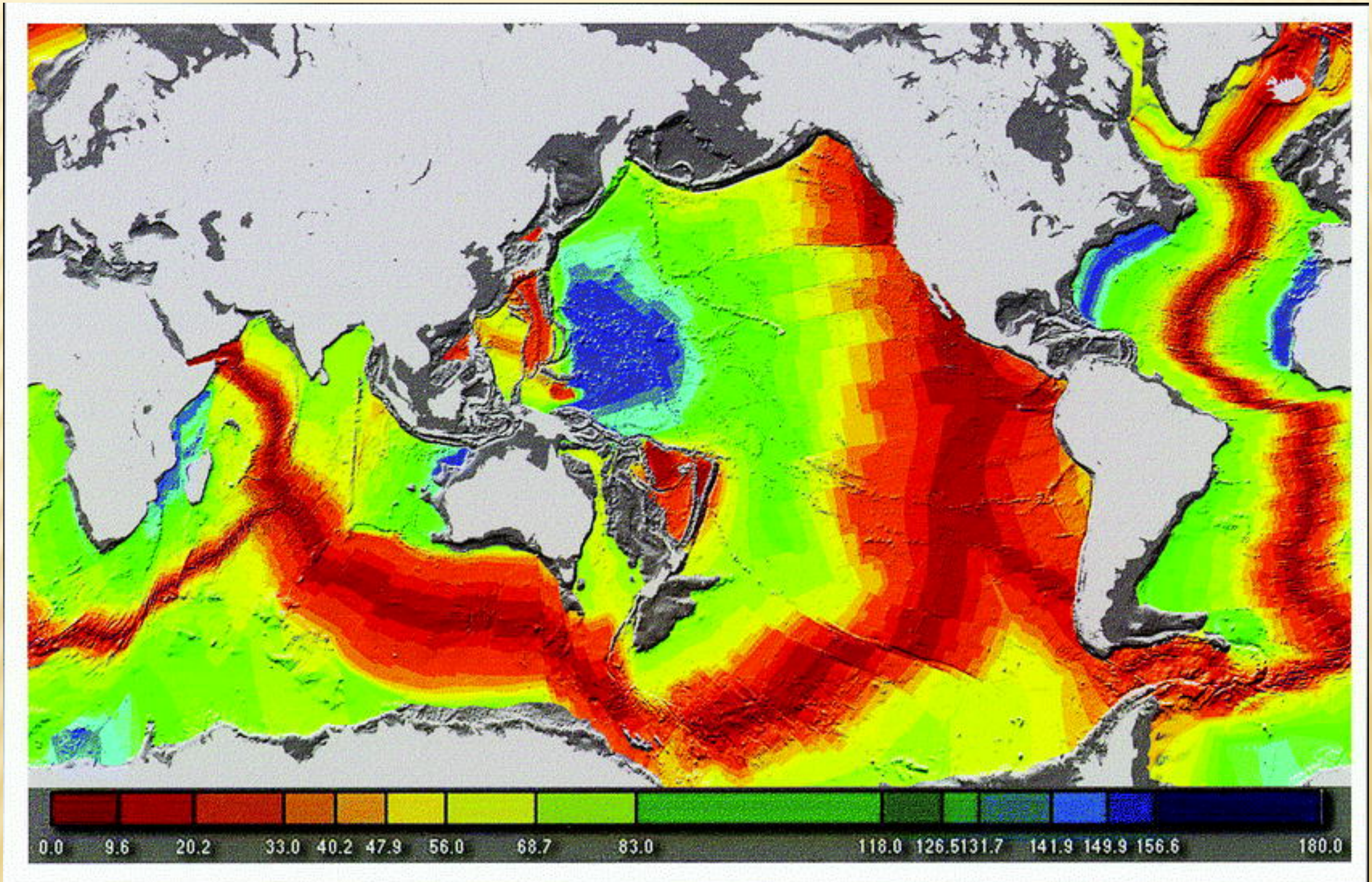
Strain rates in

stable plate interiors -

bounded between

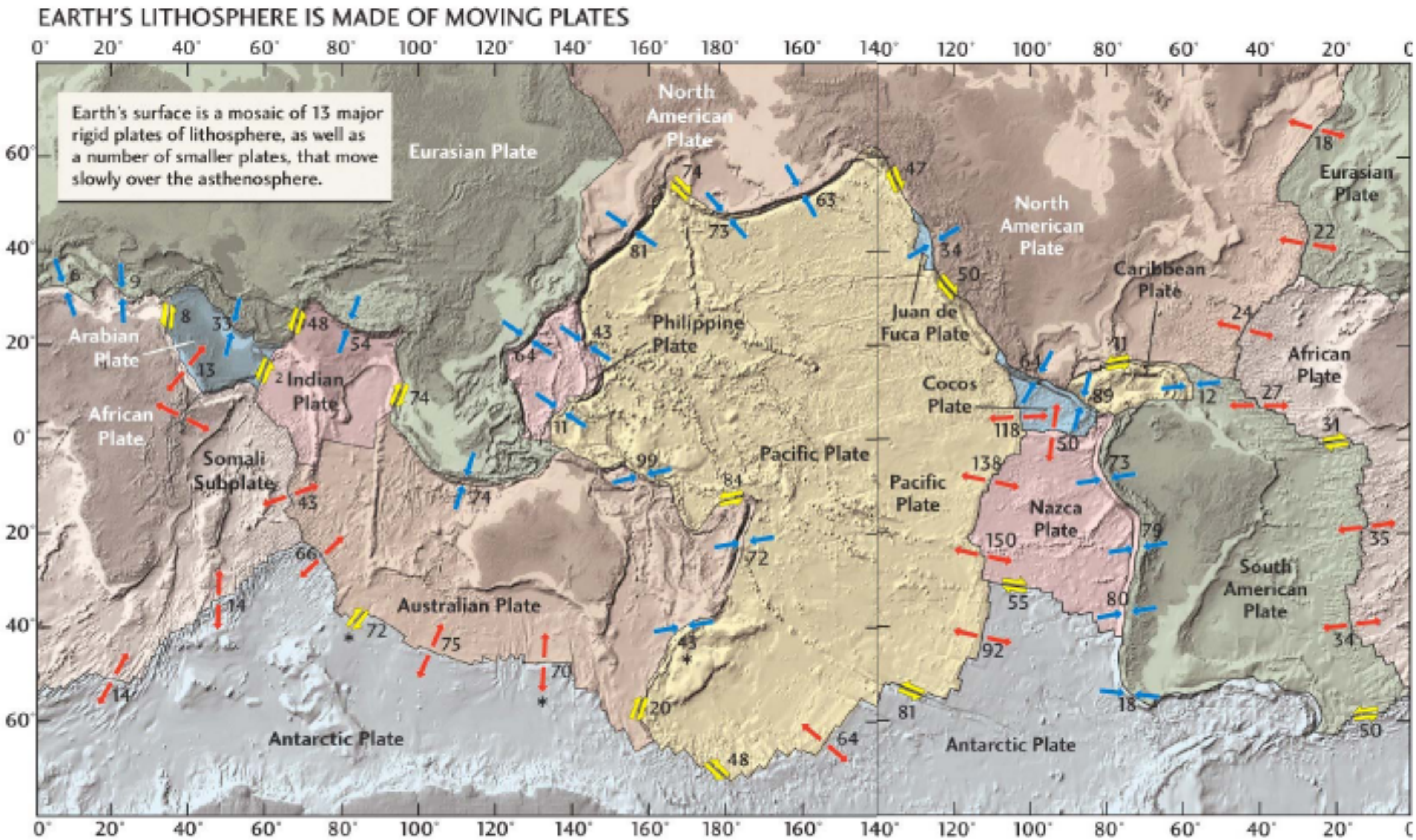
10^{-12} -10^{-11} year and 10^{-10} year.

THE PLATE TECTONIC APPROXIMATION: Plate Nonrigidity, Diffuse Plate Boundaries, and Global Plate Reconstructions
Richard G. Gordon
Annual Review of Earth and Planetary Sciences
Vol. 26: 615-642 (Volume publication date May 1998)
(doi:10.1146/annurev.earth.26.1.615)



Unpublished 2003 compilation provided by R.D. Müller

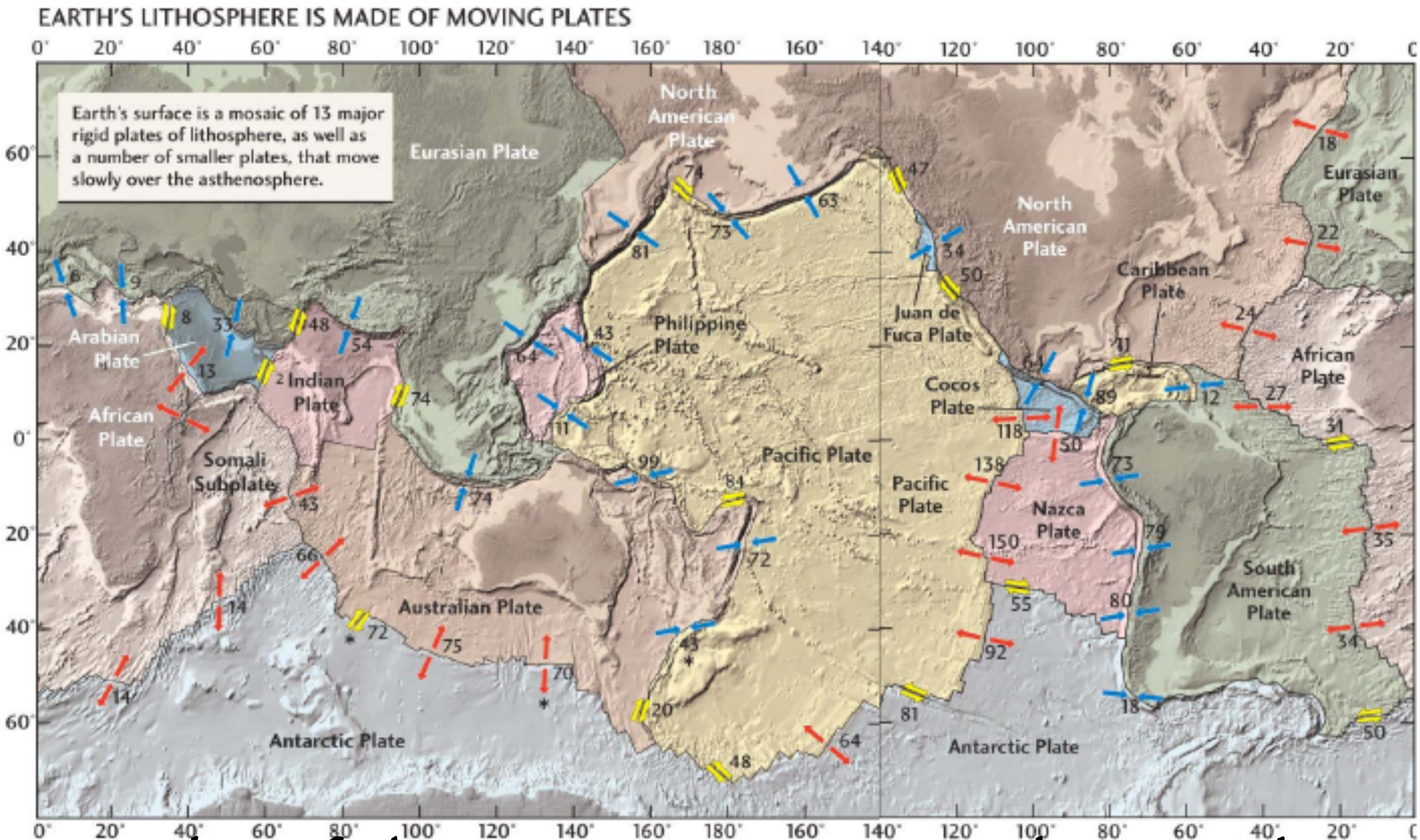
NUVEL picture



Relative velocities across boundaries

http://owlnet.rice.edu/~esci101, looks like NUVEL

NUVEL picture



A number of plates missing (e.g. Scotia) because don't have spreading boundaries

First big contribution of space based geodesy

Motion of plates

(note –

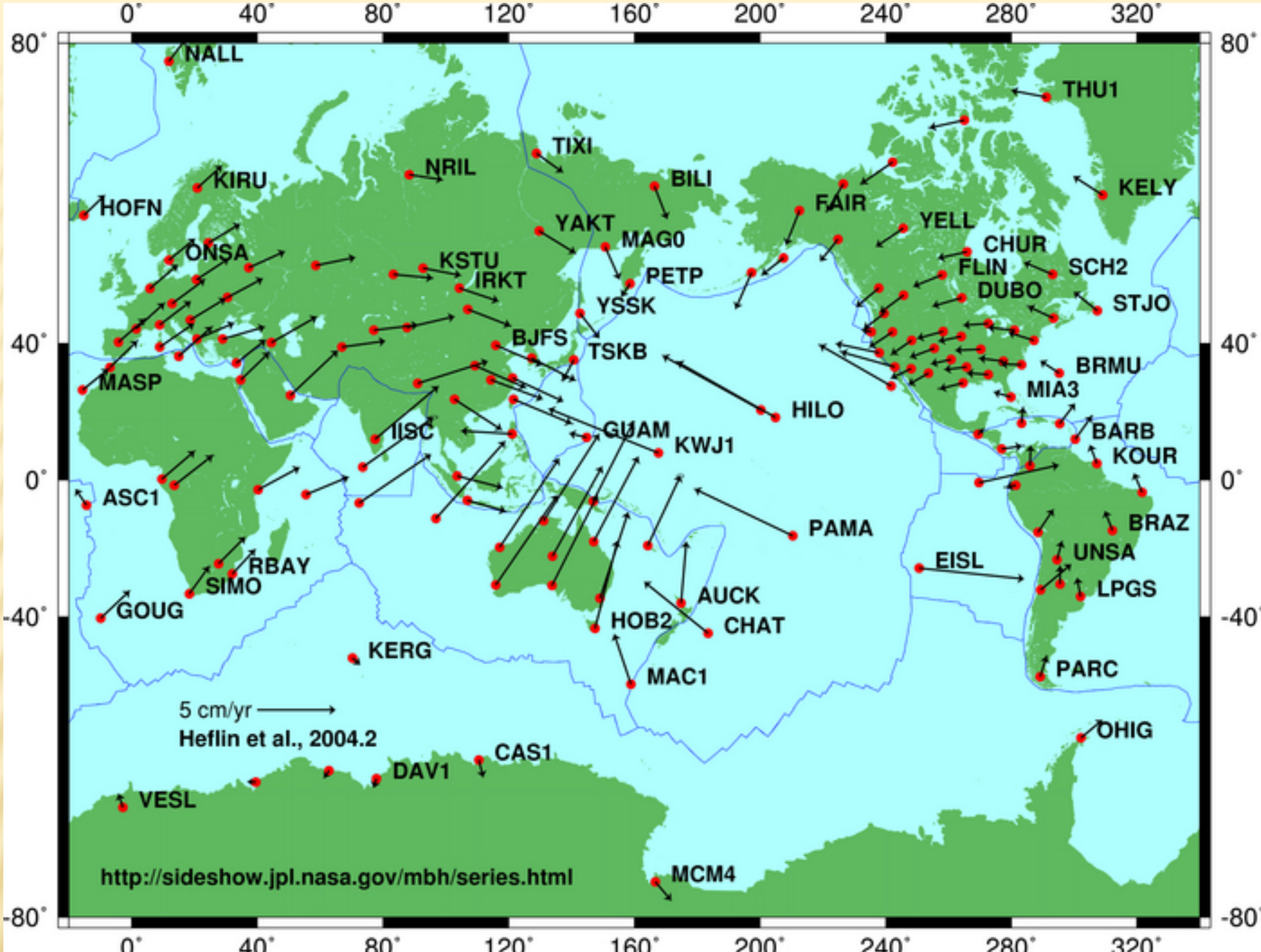
plates

- have to be "pre-defined"

– are not part of how velocities of sites are computed,

-selected based on "rigidity" at level of GPS precision

Also VLBI, SLR, DORIS – space based, not limited to GPS - results)

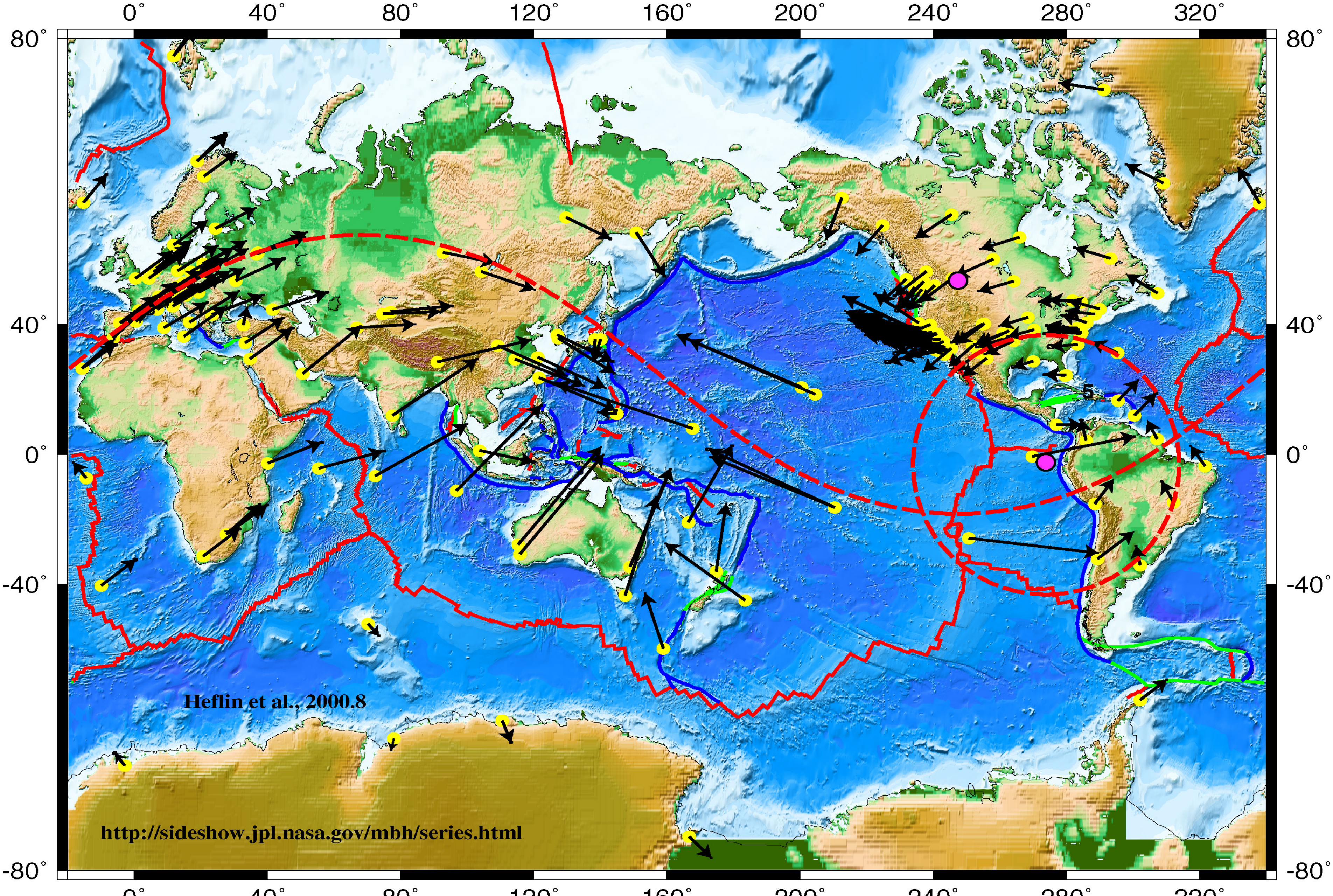


GPS picture – now motion with respect to some "absolute reference frame (ITRF), does not know about "plates" two distinct reference systems:

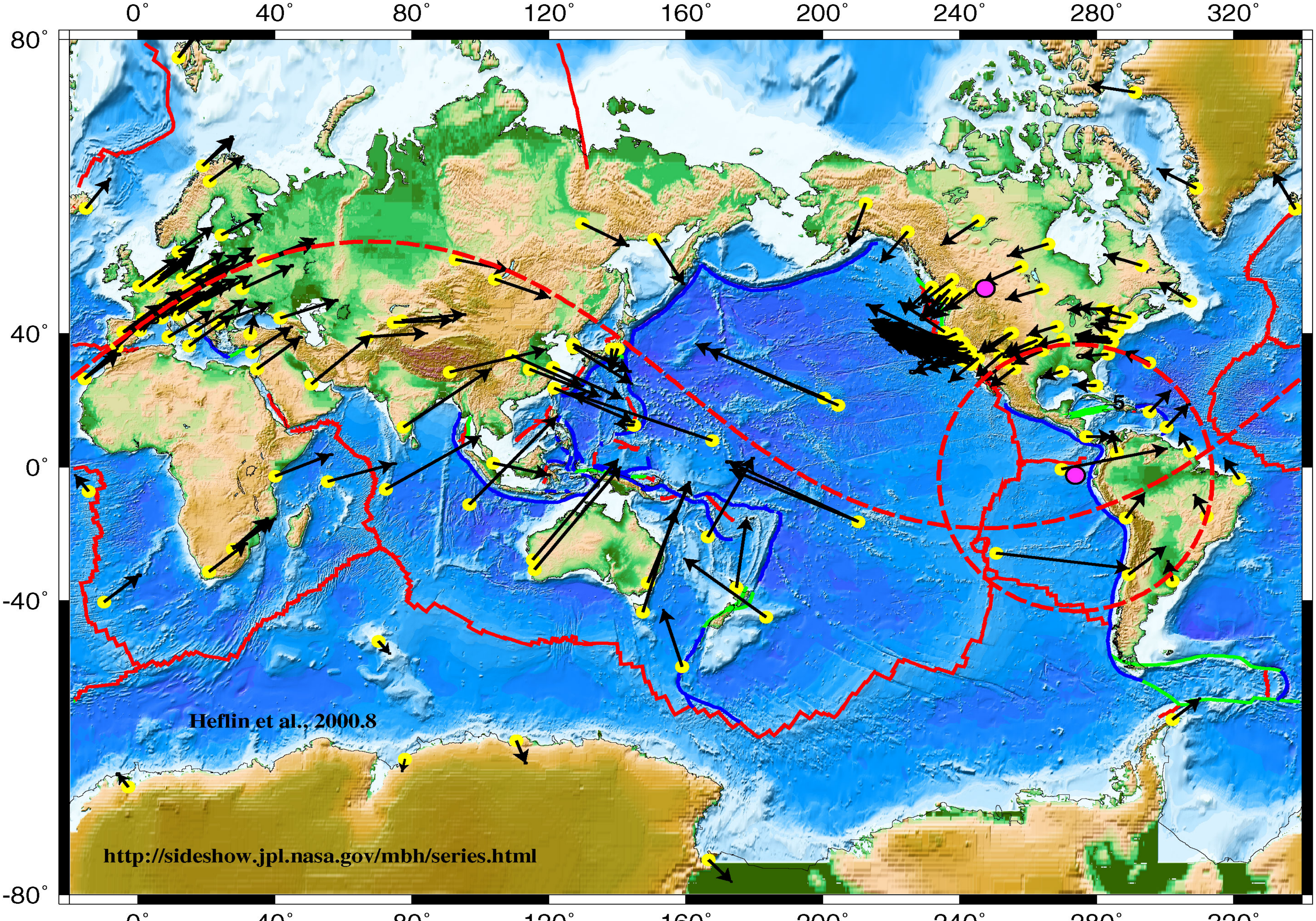
1. space-fixed (quasi) inertial system
(Conventional Inertial System CIS)
(Astronomy, VLBI in this system)
ITRF

2. Earth-fixed terrestrial system
(Conventional Terrestrial System CTS)

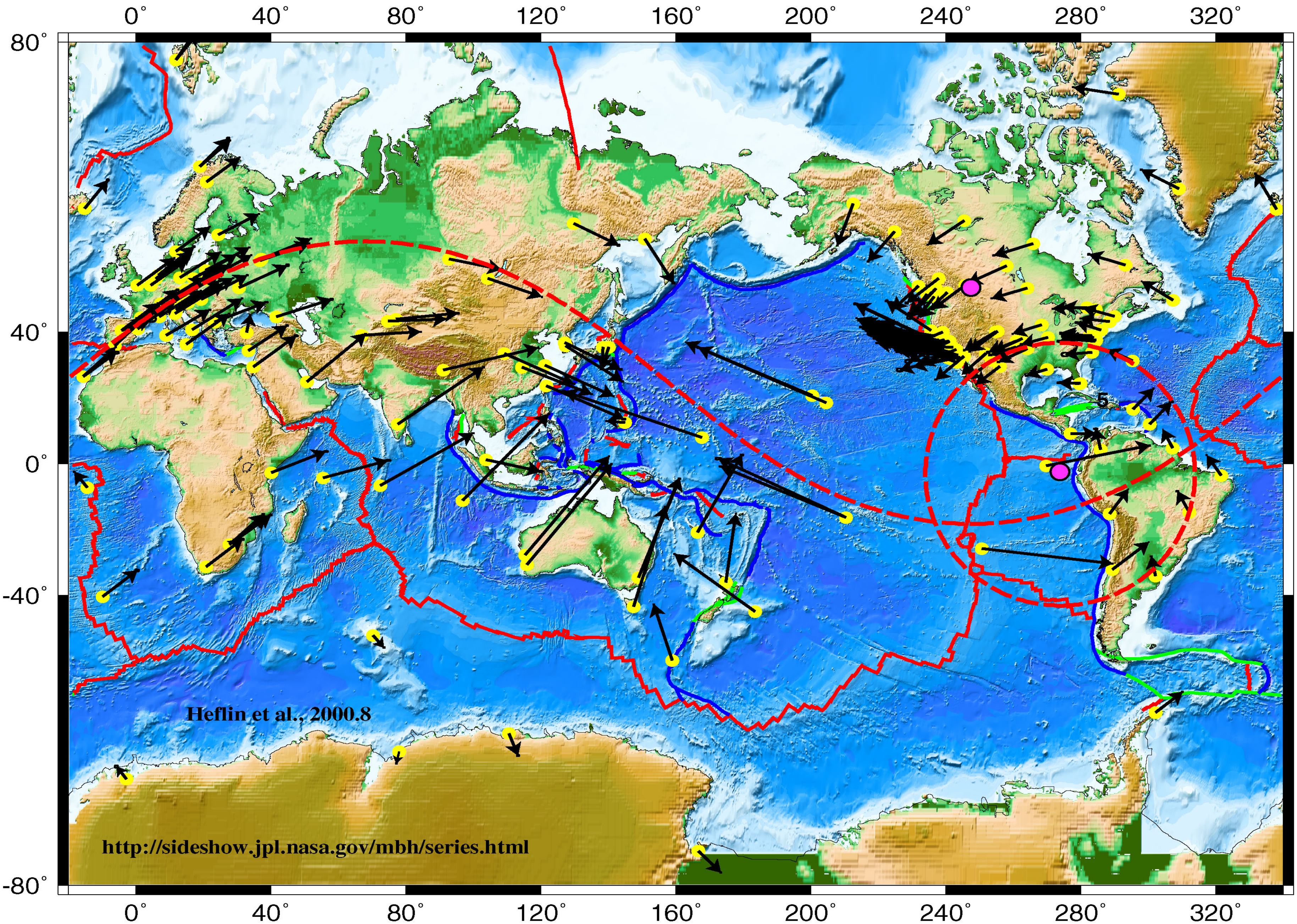
Both systems use center of earth and earth rotation in definition and realization



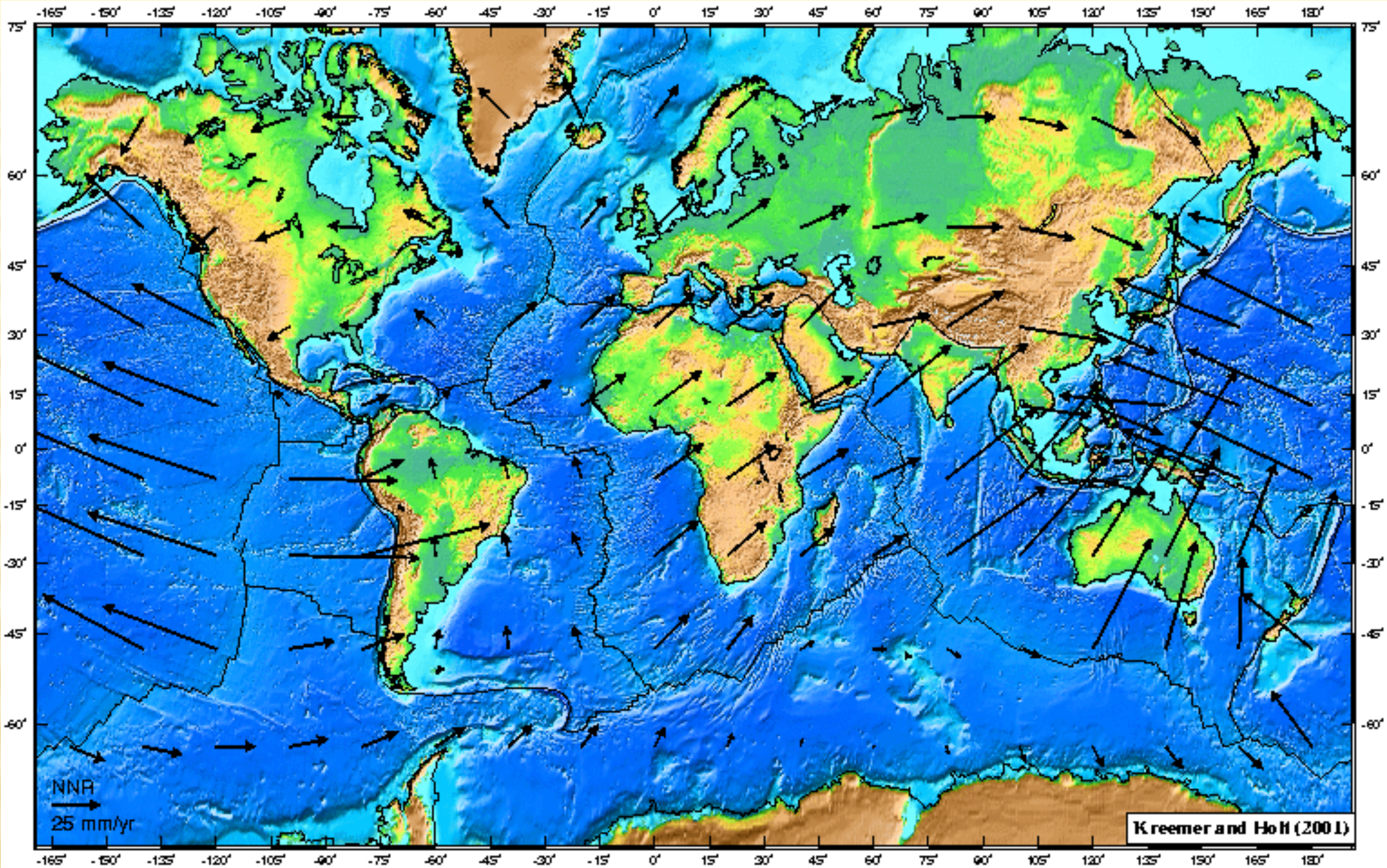
Velocities of IGS global tracking GPS sites in ITRF.



Small "circles" for European and N. American poles.



Velocities are tangent to small circles (look like windshield wiper streaks).



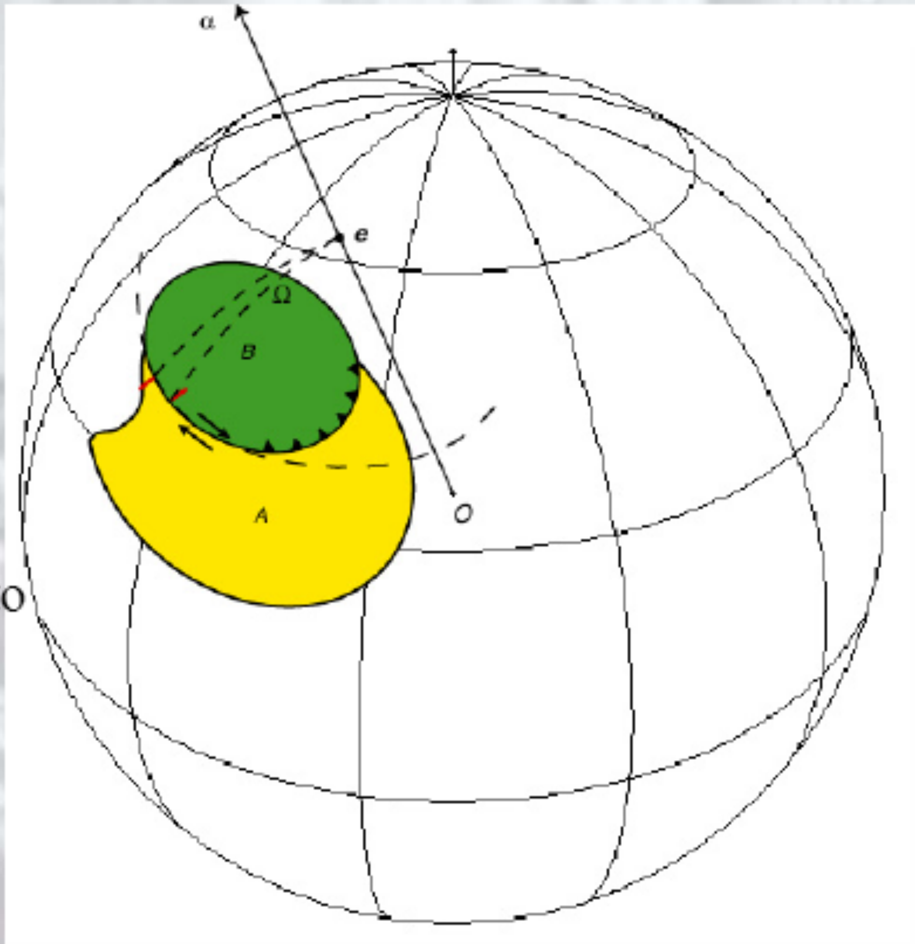
Gridded view of plate velocities in ITRF

(approximates NUVEL, but does not "look like" NUVEL because NUVEL shows relative motions)

Rotation of N. America about Euler pole.

Plate translation on a sphere

- Transcurrent and transform tectonic boundaries allow direct calculation of finite rotations by a combination of geological data and kinematic methods
- The strike-slip fault is modelled as a small circle arc about axis α
- The corresponding Euler pole ***e*** is calculated by fitting the modelled arc to plate boundary data
- The rotation angle Ω is determined geologically, through the identification of displaced markers (red lines)
- Finally, the timing of displacement is estimated stratigraphically or by other indirect methods



Sketch map illustrating the method of computation of finite rotations associated to strike-slip boundaries

Solving for Euler poles

Forward problem

Given rotation pole, R, for movement of spherical shell on surface of sphere

We can find the velocity of a point, X, on that shell from

$$\vec{V} = \vec{R} \times \vec{X}$$

(review)

We can write this in matrix form

(in Cartesian coordinates)

as

$$\vec{V} = \vec{R} \times \vec{X}$$

$$\vec{V} = \Omega\vec{X}$$

Where Ω is the rotation matrix

$$\Omega = \begin{pmatrix} 0 & -r_z & r_y \\ r_z & 0 & -r_x \\ -r_y & r_x & 0 \end{pmatrix}$$

(note – this is for infinitesimal, not finite rotations)

So – now we solve this

$$\vec{V} = \Omega\vec{X}$$

Hopefully with more data than is absolutely necessary using Least Squares

(this is the remark you find in most papers –

Now we solve this by Least Squares)

But

known   known

$$\vec{V} = \Omega \vec{X}$$

And

we want to find

$$\vec{V} = \boxed{\Omega}\vec{X}$$

This is how we would set the problem up if we know V and *Ω* and wanted to find X

So we have to recast the expression to put the knowns and unknowns into the correct functional relationship.

Start by multiplying it out

$$\begin{pmatrix} V_x \\ V_y \\ V_z \end{pmatrix} = \begin{pmatrix} 0 & -r_z & r_y \\ r_z & 0 & -r_x \\ -r_y & r_x & 0 \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}$$

$$V_x = -r_z Y + r_y Z$$

$$V_y = r_z X - r_x Z$$

$$V_Z = -r_y X + r_x Y$$

Now rearrange into the form

$$\vec{b} = A\vec{x}$$

Where $\underline{b}$ and A are known

$$V_x = -r_z Y + r_y Z$$

$$V_y = r_z X - r_x Z$$

$$V_Z = -r_y X + r_x Y$$

obtaining the following

$$\begin{pmatrix} V_x \\ V_y \\ V_z \end{pmatrix} = \begin{pmatrix} 0 & Z & -Y \\ -Z & 0 & X \\ Y & -X & 0 \end{pmatrix} \begin{pmatrix} r_x \\ r_y \\ r_z \end{pmatrix}$$

$$\begin{pmatrix} V_x \\ V_y \\ V_z \end{pmatrix} = \begin{pmatrix} 0 & Z & -Y \\ -Z & 0 & X \\ Y & -X & 0 \end{pmatrix} \begin{pmatrix} r_x \\ r_y \\ r_z \end{pmatrix}$$

$$\vec{V} = X\vec{R}$$

So now we have a form that expresses the relationship between the two vectors

$\underline{V}$ and $\underline{R}$

With the "funny" matrix X.

$$\begin{pmatrix} V_x \\ V_y \\ V_z \end{pmatrix} = \begin{pmatrix} 0 & Z & -Y \\ -Z & 0 & X \\ Y & -X & 0 \end{pmatrix} \begin{pmatrix} r_x \\ r_y \\ r_z \end{pmatrix}$$

$$\vec{V} = X\vec{R}$$

We have

3 equations and
3 unknowns

So we should be able to solve this
(unfortunately not!)

$$\begin{pmatrix} V_x \\ V_y \\ V_z \end{pmatrix} = \begin{pmatrix} 0 & Z & -Y \\ -Z & 0 & X \\ Y & -X & 0 \end{pmatrix} \begin{pmatrix} r_x \\ r_y \\ r_z \end{pmatrix}$$

$$\vec{V} = X\vec{R}$$

You can see this two ways

1 - The matrix is singular (the determinant is zero)

2 - Geometrically, the velocity vector is tangent to a small circle about the rotation pole –
There are an infinite number of small circles (defined by a rotation pole) to which a single vector is tangent

$$\begin{pmatrix} V_x \\ V_y \\ V_z \end{pmatrix} = \begin{pmatrix} 0 & Z & -Y \\ -Z & 0 & X \\ Y & -X & 0 \end{pmatrix} \begin{pmatrix} r_x \\ r_y \\ r_z \end{pmatrix}$$

$$\vec{V} = X\vec{R}$$

So there are an infinite number of solutions to this expression.

Can we fix this by adding a second data point?
(another $\underline{X}$, where $\underline{V}$ is known)

Yes – or we would not have asked!

Following the lead from before in terms of the relationship between V and R we can write

$$\begin{pmatrix} V_{x_1} \\ V_{y_1} \\ V_{z_1} \\ V_{x_2} \\ V_{y_2} \\ V_{z_2} \end{pmatrix} = \begin{pmatrix} 0 & Z_1 & -Y_1 \\ -Z_1 & 0 & X_1 \\ Y_1 & -X_1 & 0 \\ 0 & Z_2 & -Y_2 \\ -Z_2 & 0 & X_2 \\ Y_2 & -X_2 & 0 \end{pmatrix} \begin{pmatrix} r_x \\ r_y \\ r_z \end{pmatrix}$$

$$\vec{V} = X\vec{R}$$

Where V is now the "funny" thing on the left.

Geometrically

Given two points we now have

Two tangents to the same small circle

And

(assuming they are not incompatible – i.e contradictory resulting in no solution.)

we can find a single (actually there is a 180° ambiguity)

Euler pole

For n data points we obtain

$$\begin{pmatrix} V_{x_1} \\ V_{y_1} \\ V_{z_1} \\ V_{x_2} \\ V_{y_2} \\ V_{z_2} \\ \vdots \\ V_{x_n} \\ V_{y_n} \\ V_{z_n} \end{pmatrix} = \begin{pmatrix} 0 & Z_1 & -Y_1 \\ -Z_1 & 0 & X_1 \\ Y_1 & -X_1 & 0 \\ 0 & Z_2 & -Y_2 \\ -Z_2 & 0 & X_2 \\ Y_2 & -X_2 & 0 \\ & \vdots & \\ 0 & Z_n & -Y_n \\ -Z_n & 0 & X_n \\ Y_n & -X_n & 0 \end{pmatrix} \begin{pmatrix} r_x \\ r_y \\ r_z \end{pmatrix}$$

$$\vec{V} = X\vec{R}$$

Which we can solve by Least Squares

We actually saw this earlier when we developed the Least Squares method and wrote $\underline{y}=m\underline{x}+b$ as

$$\begin{pmatrix} y_1 \\ y_2 \\ y_3 \\ \vdots \\ y_N \end{pmatrix} = \begin{pmatrix} x_1 & 1 \\ x_2 & 1 \\ x_3 & 1 \\ \vdots & \vdots \\ x_N & 1 \end{pmatrix} \begin{pmatrix} m \\ b \end{pmatrix}$$

$$\vec{y} = G\vec{m}$$

Where

$\underline{y}$ is the data vector (known)

$\underline{m}$ is the model vector (unknown parameters, what we want)

G is the "model" (known)

Pretend leftmost thing is "regular" vector and solve same way as linear least squares

$$\begin{pmatrix} V_{x_1} \\ V_{y_1} \\ V_{z_1} \\ V_{x_2} \\ V_{y_2} \\ V_{z_2} \\ \vdots \\ V_{x_n} \\ V_{y_n} \\ V_{z_n} \end{pmatrix} = \begin{pmatrix} 0 & Z_1 & -Y_1 \\ -Z_1 & 0 & X_1 \\ Y_1 & -X_1 & 0 \\ 0 & Z_2 & -Y_2 \\ -Z_2 & 0 & X_2 \\ Y_2 & -X_2 & 0 \\ & \vdots & \\ 0 & Z_n & -Y_n \\ -Z_n & 0 & X_n \\ Y_n & -X_n & 0 \end{pmatrix} \begin{pmatrix} r_x \\ r_y \\ r_z \end{pmatrix}$$

$$\begin{pmatrix} y_1 \\ y_2 \\ y_3 \\ \vdots \\ y_N \end{pmatrix} = \begin{pmatrix} x_1 & 1 \\ x_2 & 1 \\ x_3 & 1 \\ \vdots & \vdots \\ x_N & 1 \end{pmatrix} \begin{pmatrix} m \\ b \end{pmatrix}$$

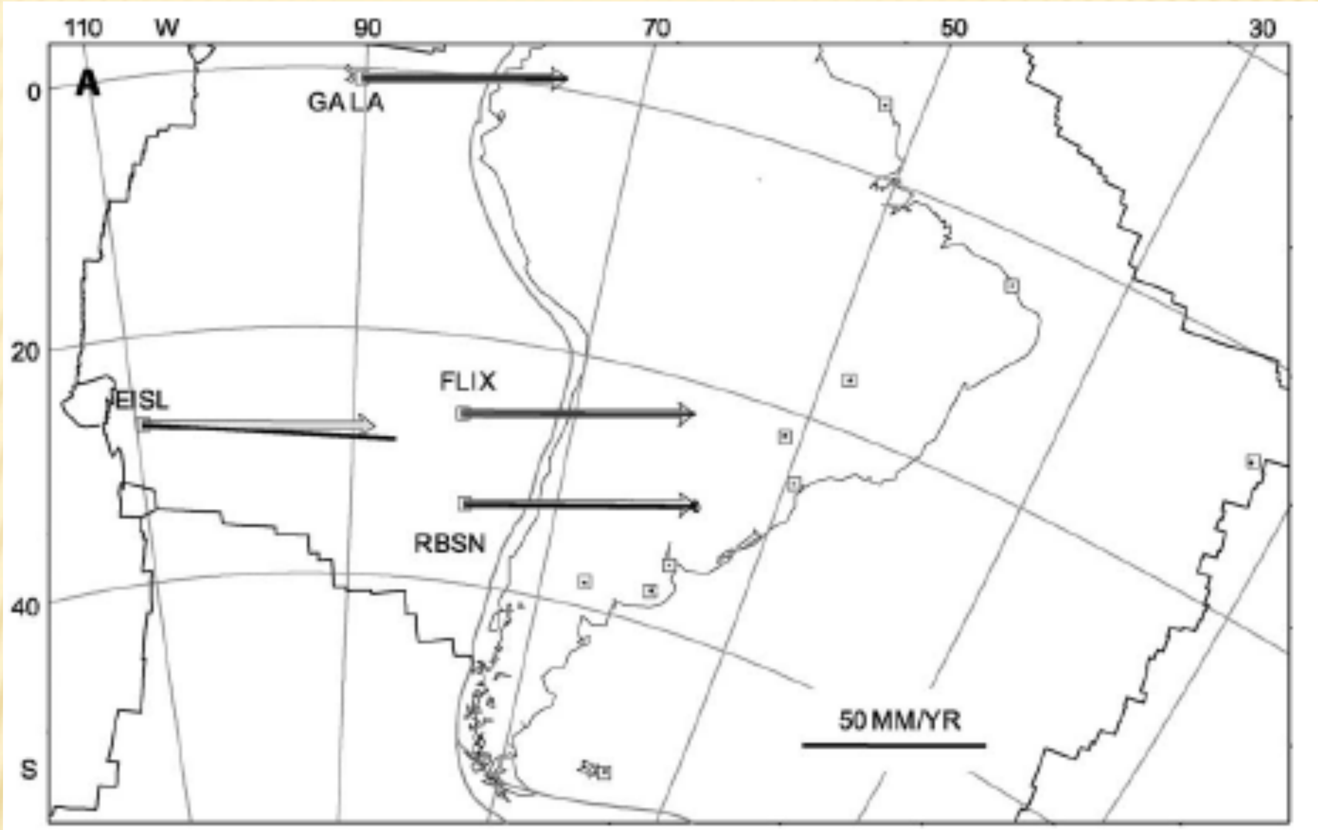
$$\vec{y} = G\vec{m}$$

$$\vec{V} = X\vec{R}$$

$$\vec{R} = \left(X^T X\right)^{-1} X^T \vec{V}$$

$$\vec{m} = \left(G^T G\right)^{-1} G^T \vec{d}$$

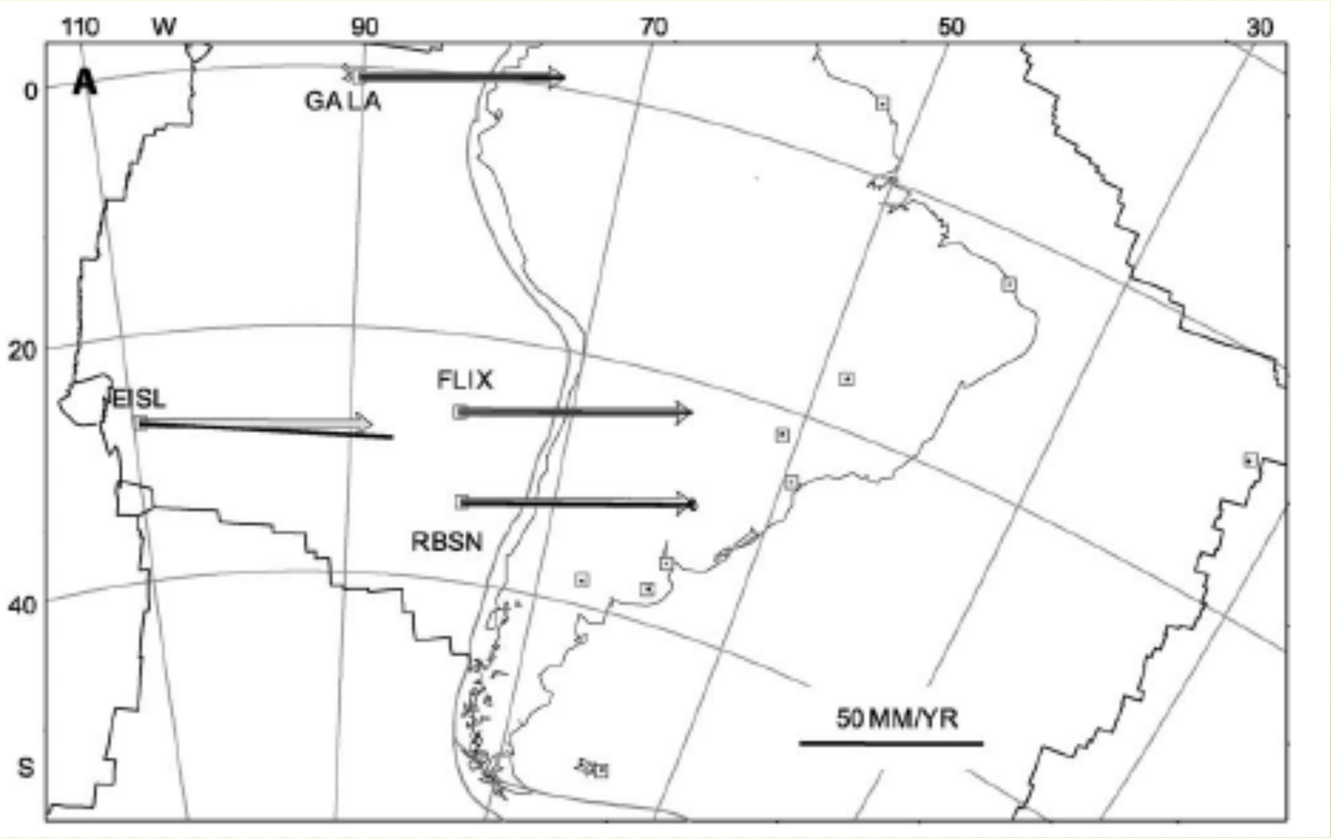
Example: Nazca-South America Euler pole



Data plotted in South America reference frame (points on South America plate have zero – or near zero – velocities.)

Kendrick et al, 2003

Example: Nazca-South America Euler pole (relative)

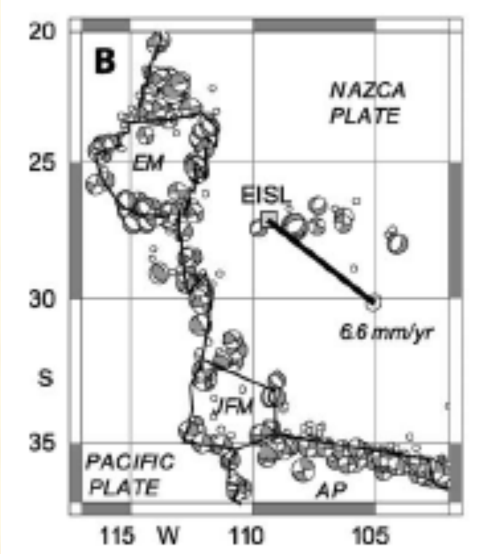


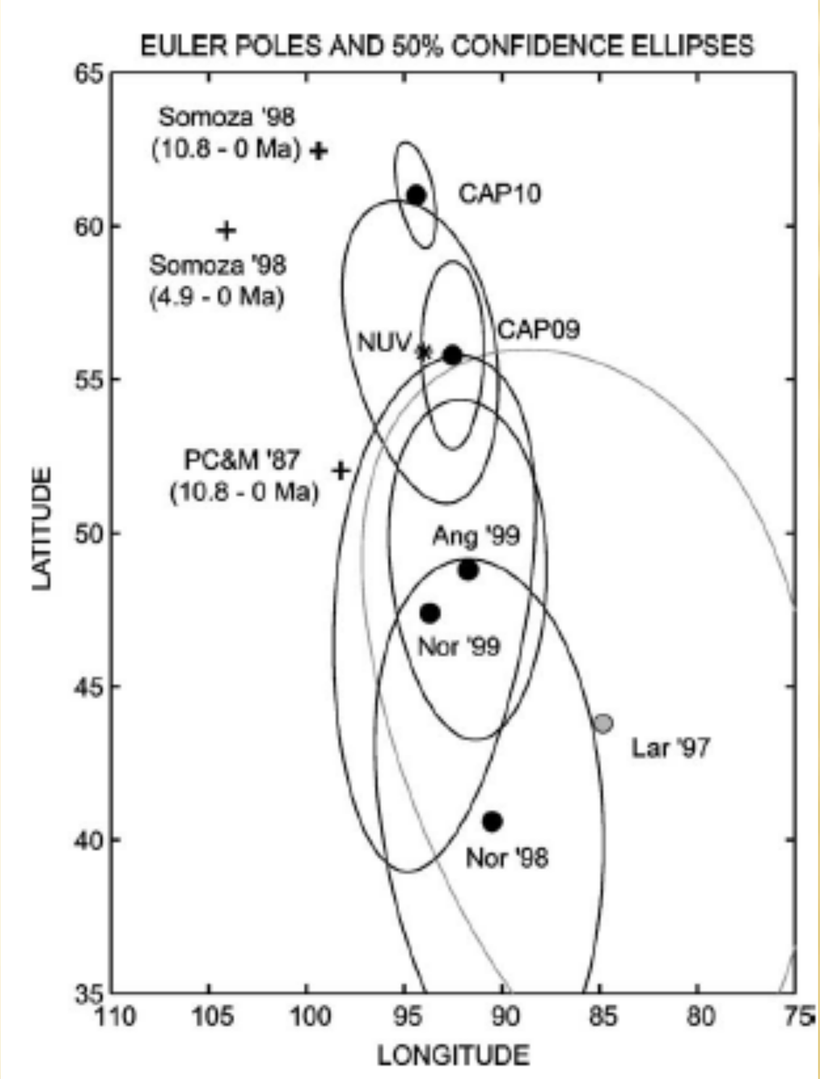
Also plotted in
Oblique Mercator projection
about Nazca-South America Euler pole

Kendrick et al, 2003

Question – is Easter Island on "stable" Nazca Plate

We think not.





Only 4 points total on Nazca Plate (no other islands!)

Galapagos and Easter Island part of IGS (continuous)

FLIX and RBSN campaign

Kendrick et al, 2003

Complications to simple model in plate interiors

Horizontal deformations associated with post glacial rebound

$$\vec{V} = \Omega\vec{X} + \gamma\vec{V}_{pgr}$$

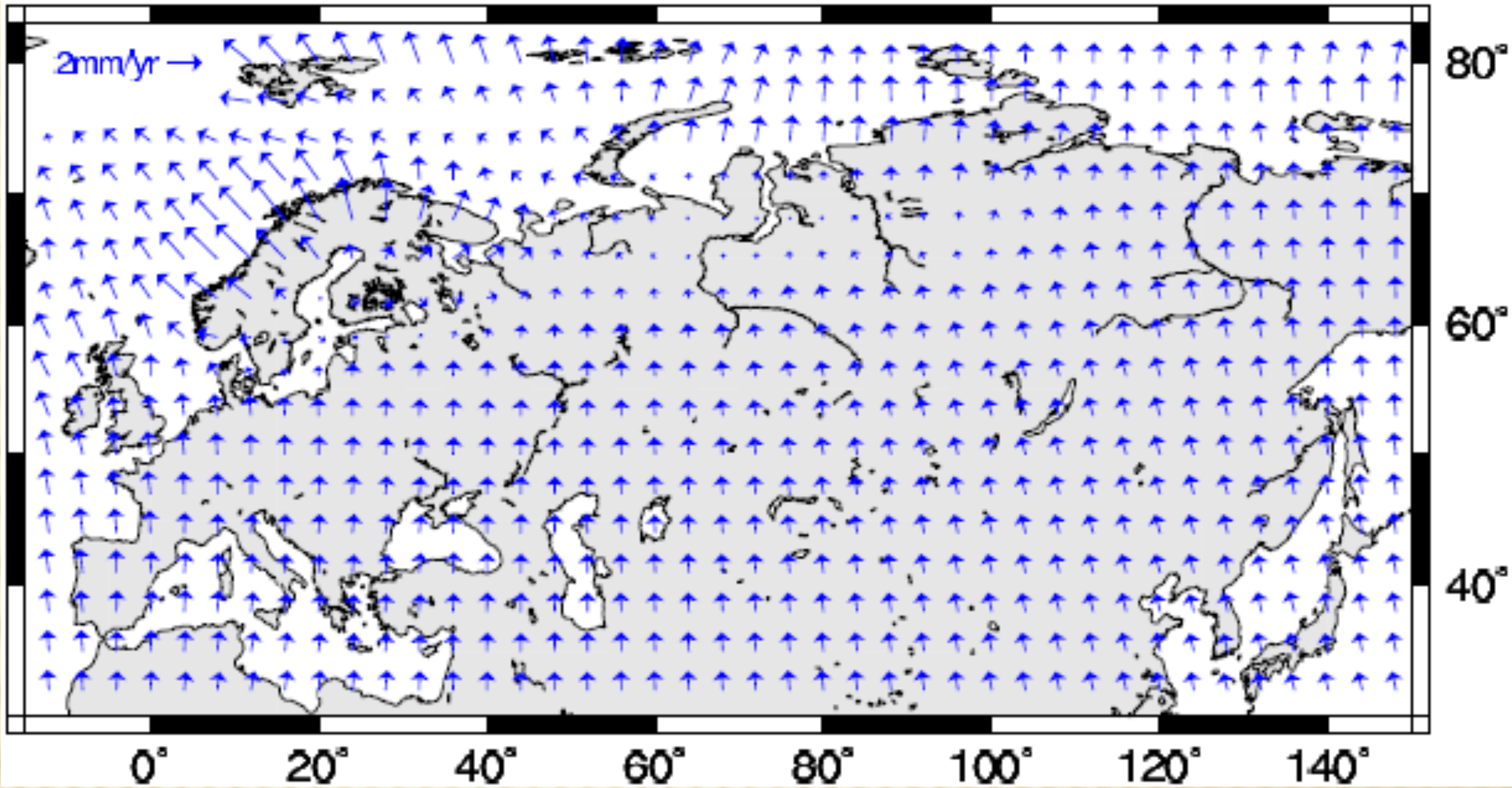
(problem for N. America and Eurasia)

Other effects

Other causes horizontal movement/deformation (tectonics, changes in EOP?)

Most vertical movements – tidal, atmospheric, etc. , as in case of PGR - have some “cross talk” to horizontal

$$\vec{V} = \Omega \vec{X} + \sum_i \vec{V}_i^{\text{geologic effects}}$$



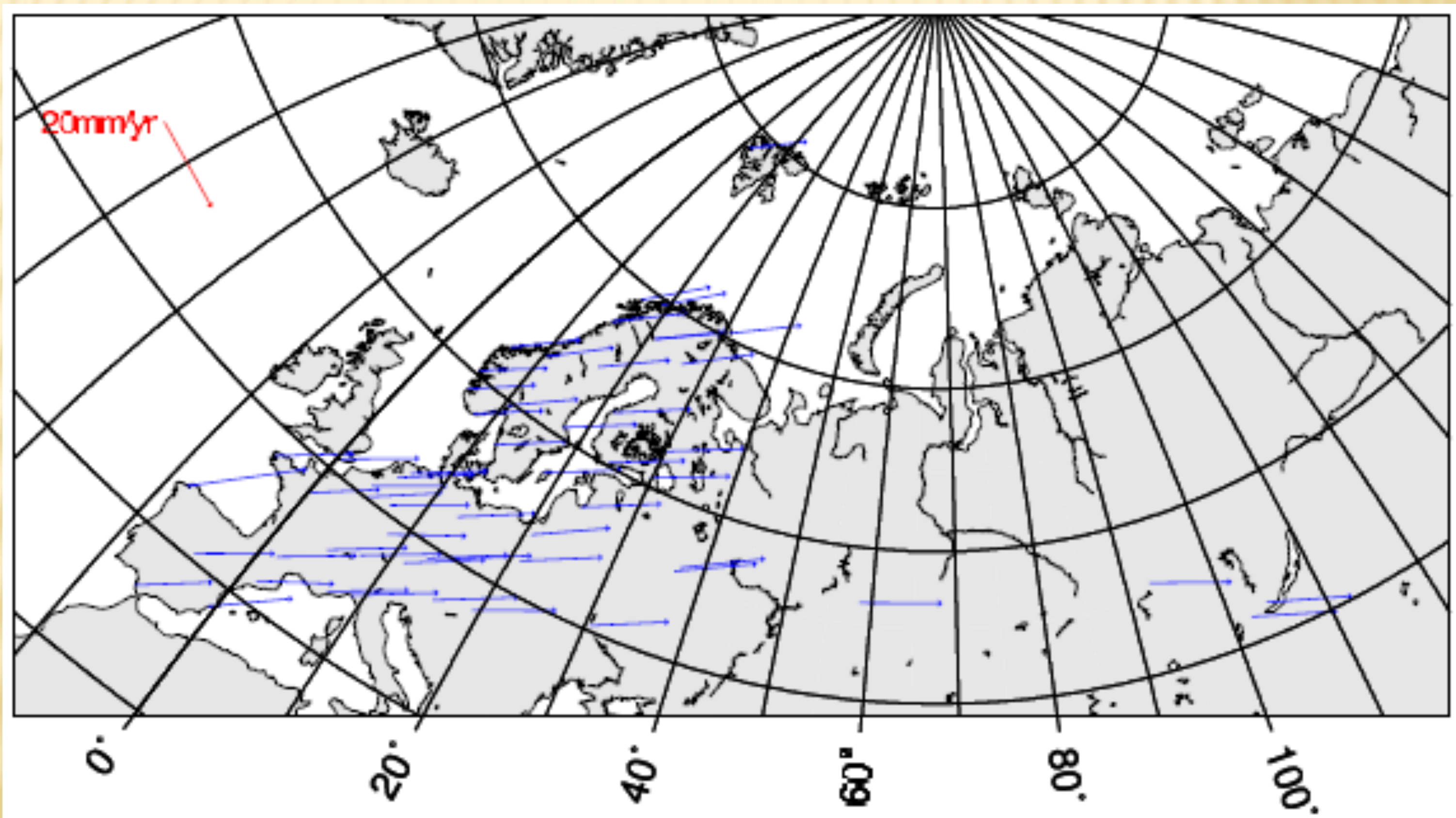
Predicted horizontal velocities in northern Eurasia from PGR

(No velocity scale! Largest are order 3 mm/yr away from center of ice load, figure does not seem to agree with discussion in paper)

http://www.epncb.oma.be/papers/euref02/platerotation.pdf International Association of Geodesy / Section I – Positioning; Subcommission for Europe (EUREF) , Publication No. 12 , Report on the Symposium of the IAG Subcommission for Europe (EUREF) held in Ponta Delgada 5-8 June 2002.

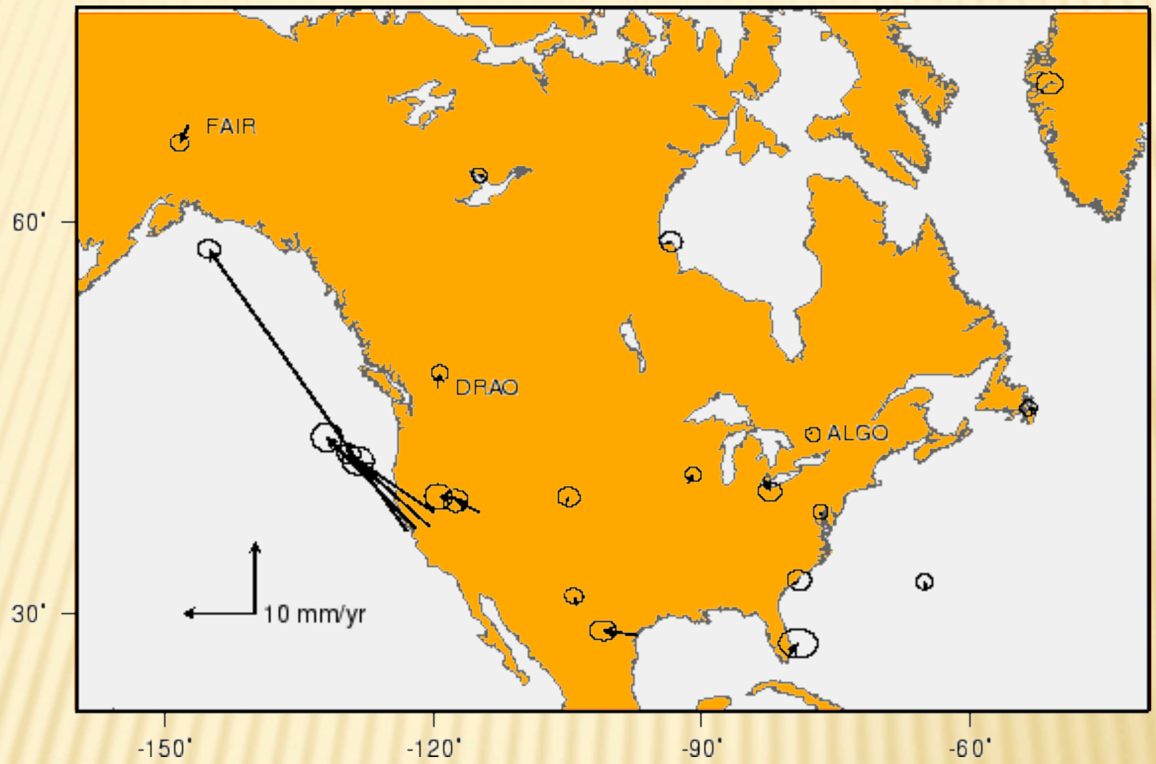
Results for Eurasia

Site velocities plotted in oblique Mercator projection (should be horizontal)



http://www.epncb.oma.be/papers/euref02/platerotation.pdf International Association of Geodesy / Section I – Positioning; Subcommission for Europe (EUREF) , Publication No. 12 , Report on the Symposium of the IAG Subcommission for Europe (EUREF) held in Ponta Delgada 5-8 June 2002.

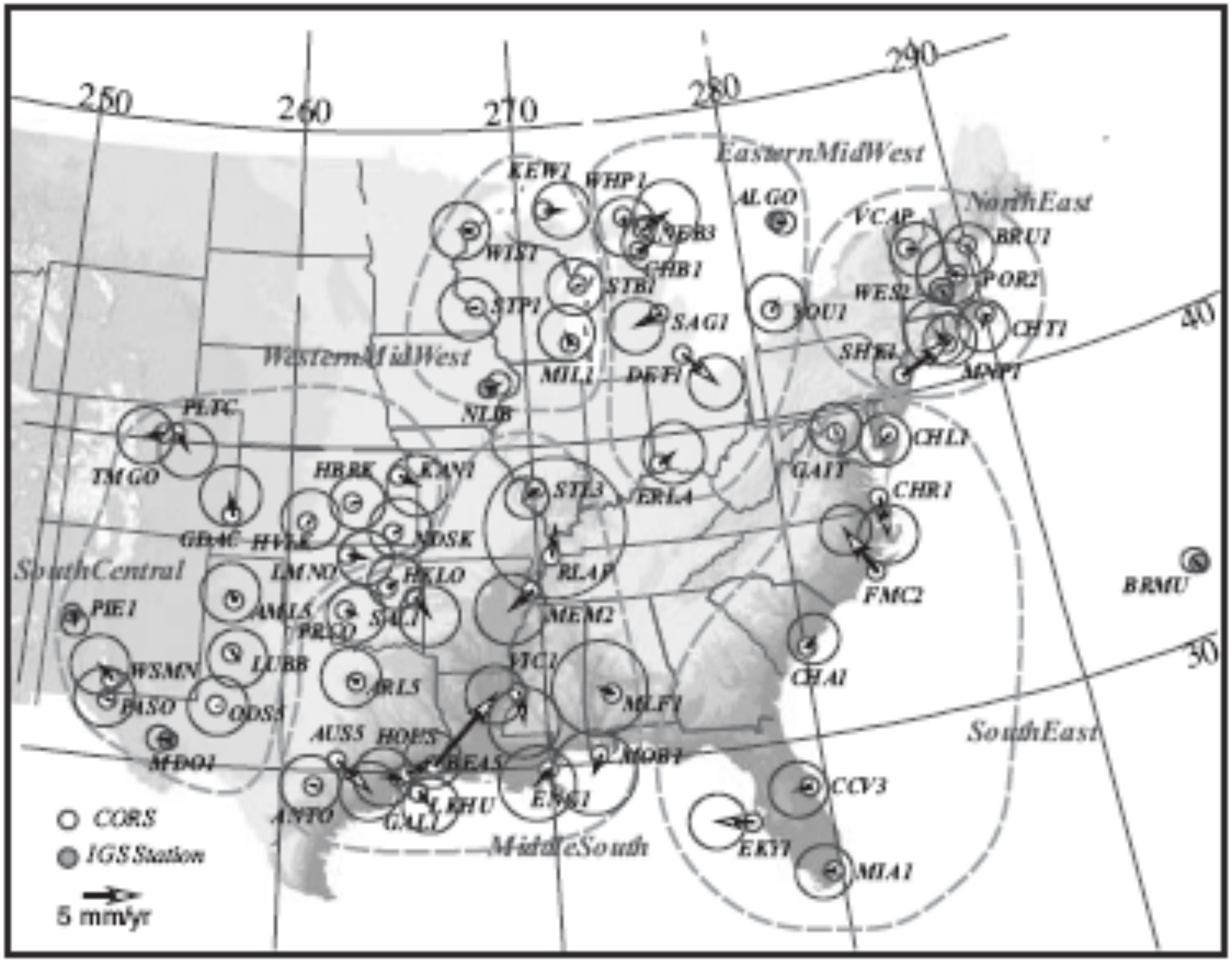
For North America



Stable North America Reference Frame (SNARF)

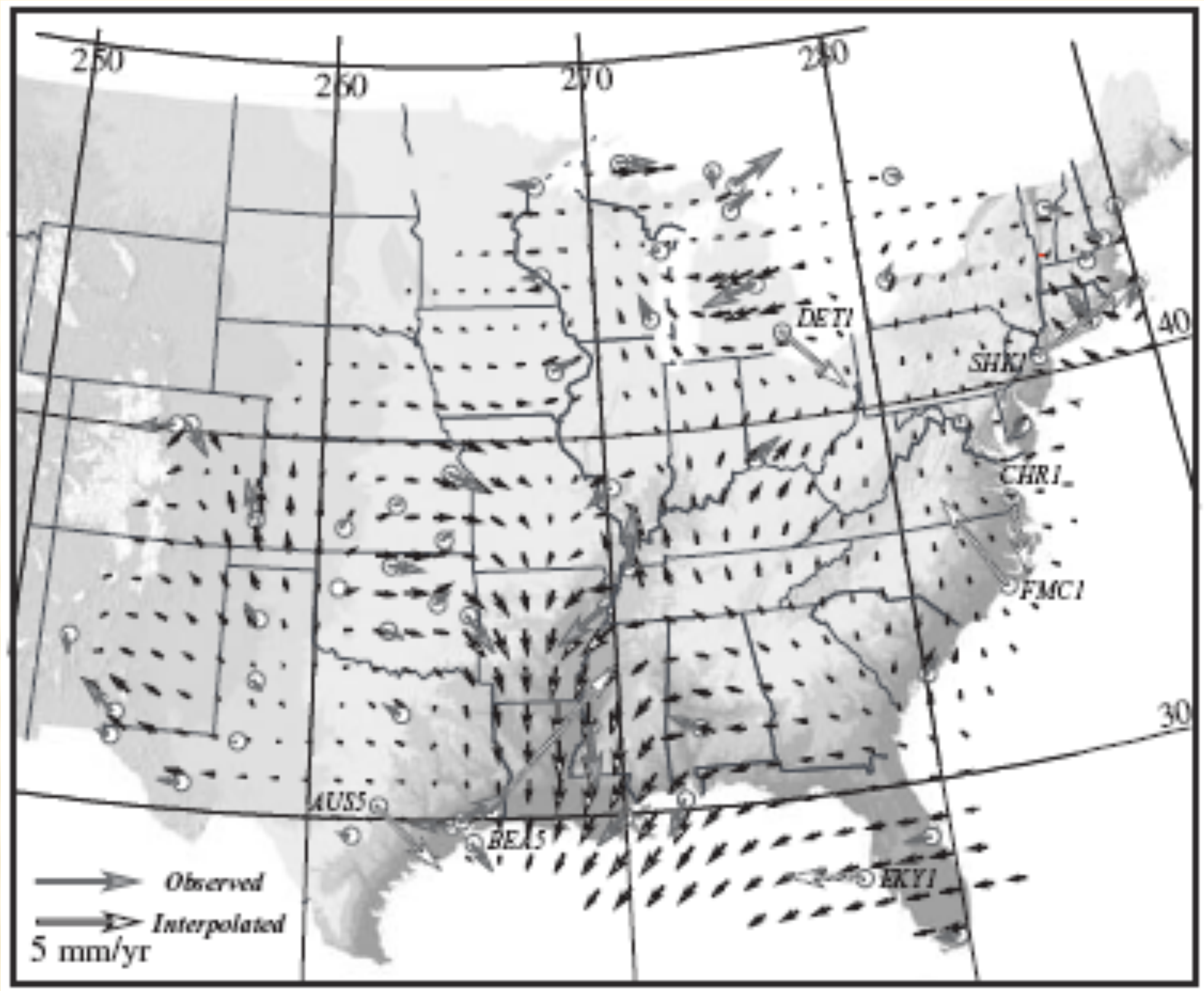
Over 300 continuous GPS sites available in Central and Eastern US (and N. America)

(unfortunately most are garbage)



Analysis of CORS plus other continuous GPS data for intraplate deformation

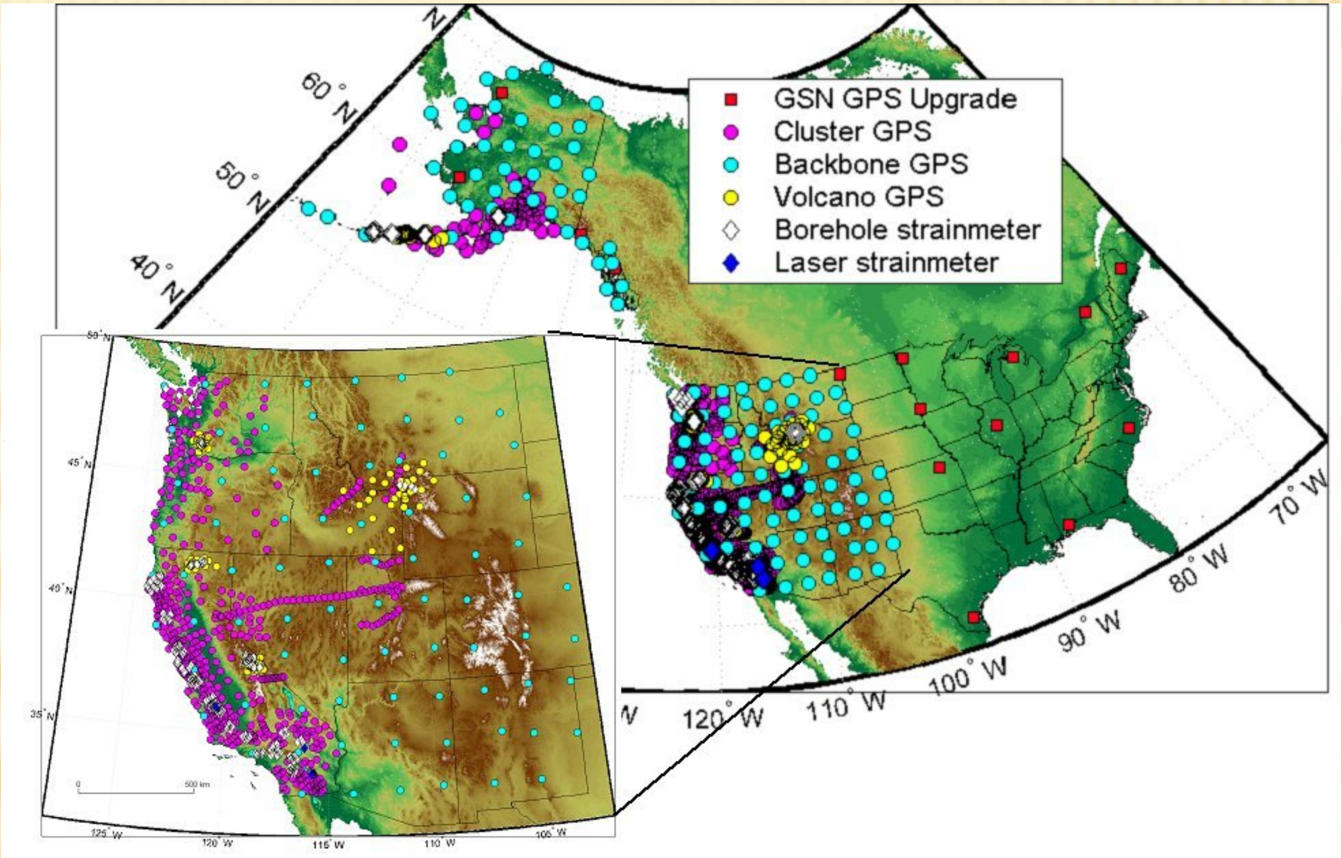
Gan and Prescott, GRL, 2001



Contoured (interpolated) velocity field
(ready for tectonic interpretation!)

Gan and Prescott, GRL, 2001

PBO Needs



- What are PBO reference frame needs?
- How can we meet those needs?

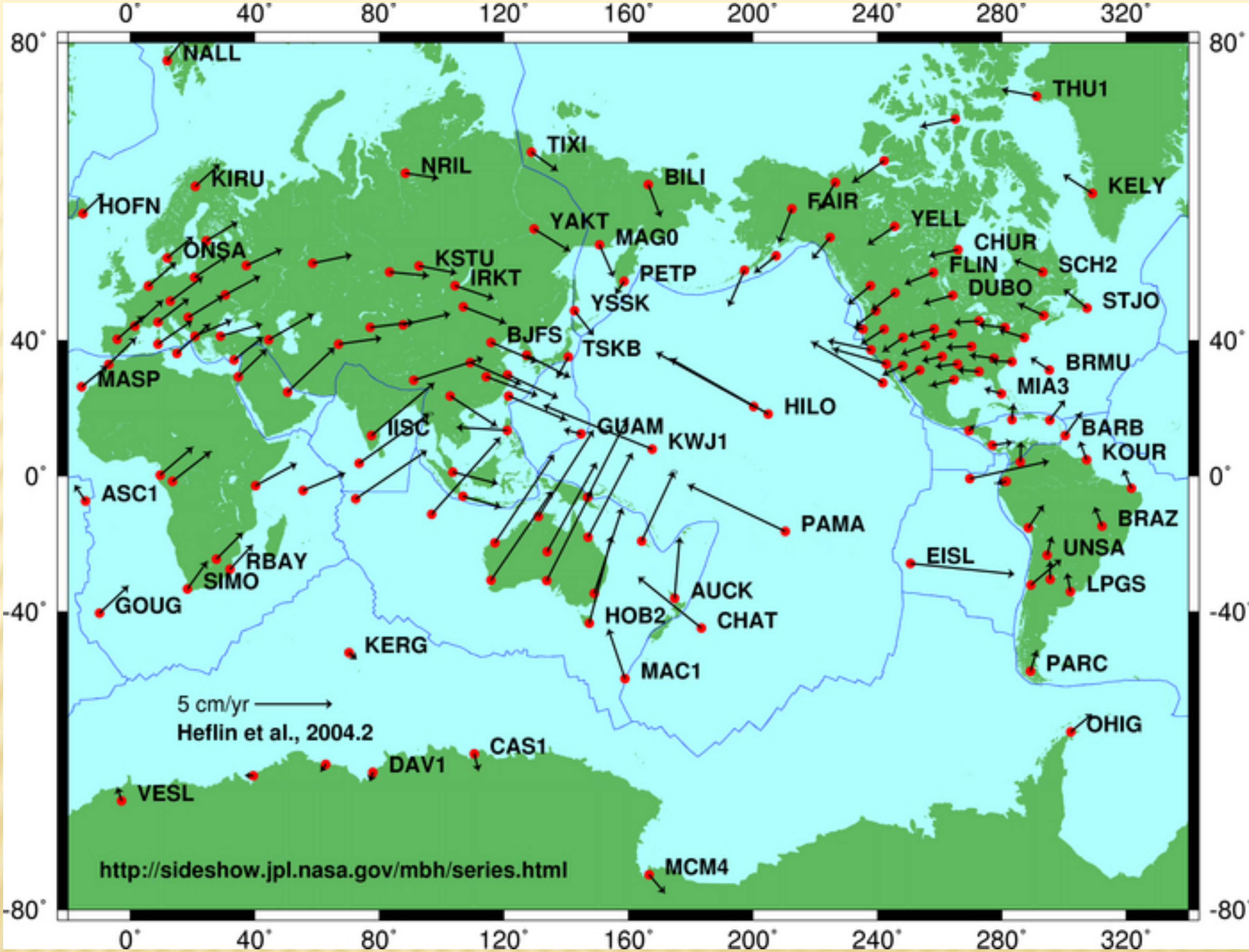
NUVEL-1A & GPS differences

Rotation rates of

- India, Arabian and Nubian plates wrt Eurasia are 30, 13 and 50% slower
- Nazca-South America 17% slower
- Caribbean-North America 76% faster

than NUVEL-1A

Kreemer, 2003



GPS picture – Scotia Plate missing (also missing from NUVEL-1, "included, but not constrained in NUVEL-1A)

More things to do with GPS

Deformation in plate boundary zones

(other main assumption of plate tectonics)

Narrowness of plate boundaries

contradicted by many observations,

in both continents and oceans.

Some diffuse plate boundaries exceed dimensions of 1000 km on a side.

Diffuse plate boundaries cover 15% of Earth's surface.

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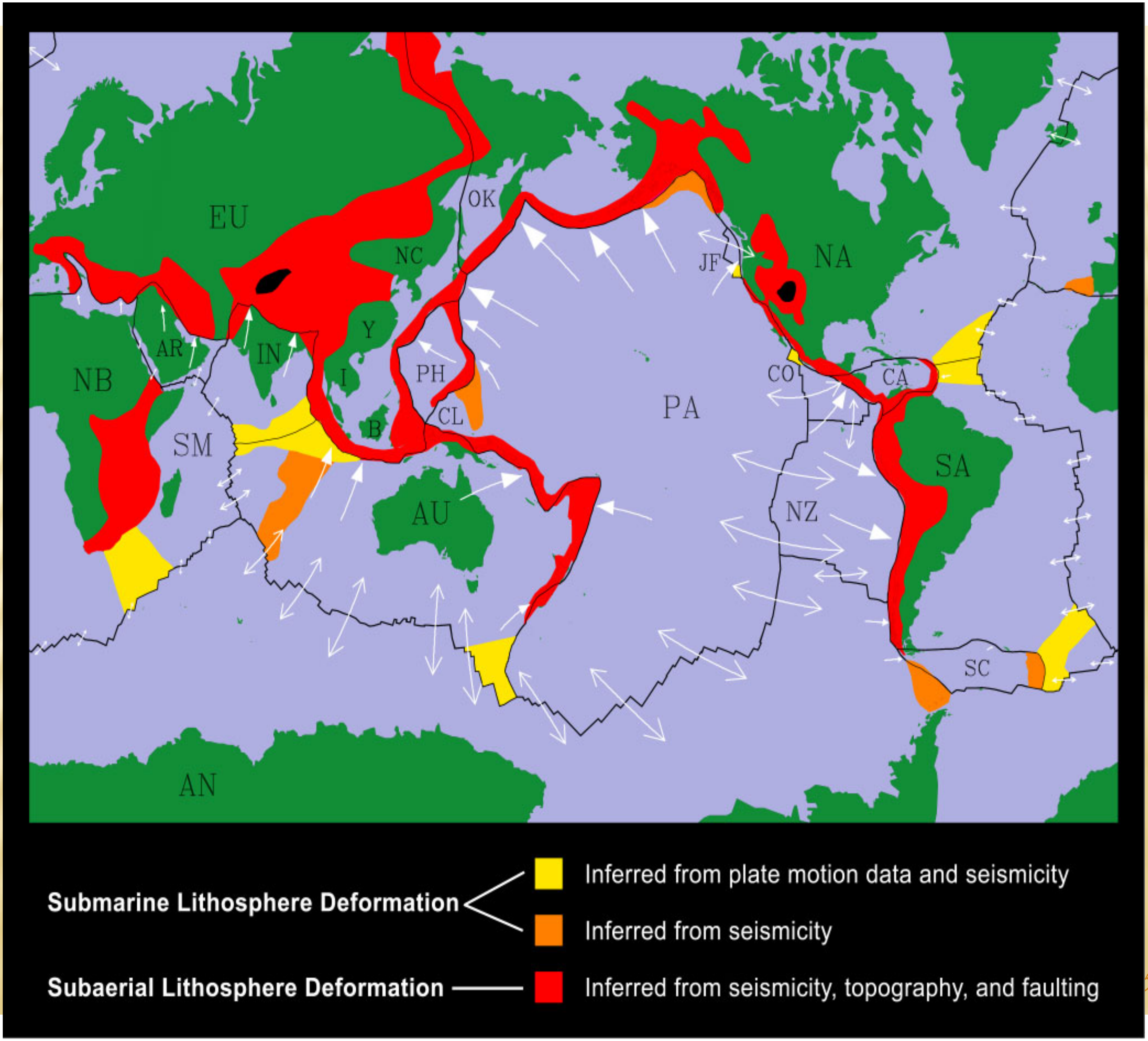
(doi:10.1146/annurev.earth.26.1.615)

T. Shoberg and P. Stoddard, after R. Gordon and S. Stein, 1992



Diffuse plate boundaries

Maximum speed (relative) across diffuse plate boundaries
2 to 15 mm/year

Strain rates in diffuse plate boundaries as high as 10^{-8} year

25 times higher than upper bound on strain rates of stable plate interiors

600 times lower than lowest strain rates across typical narrow plate boundaries.

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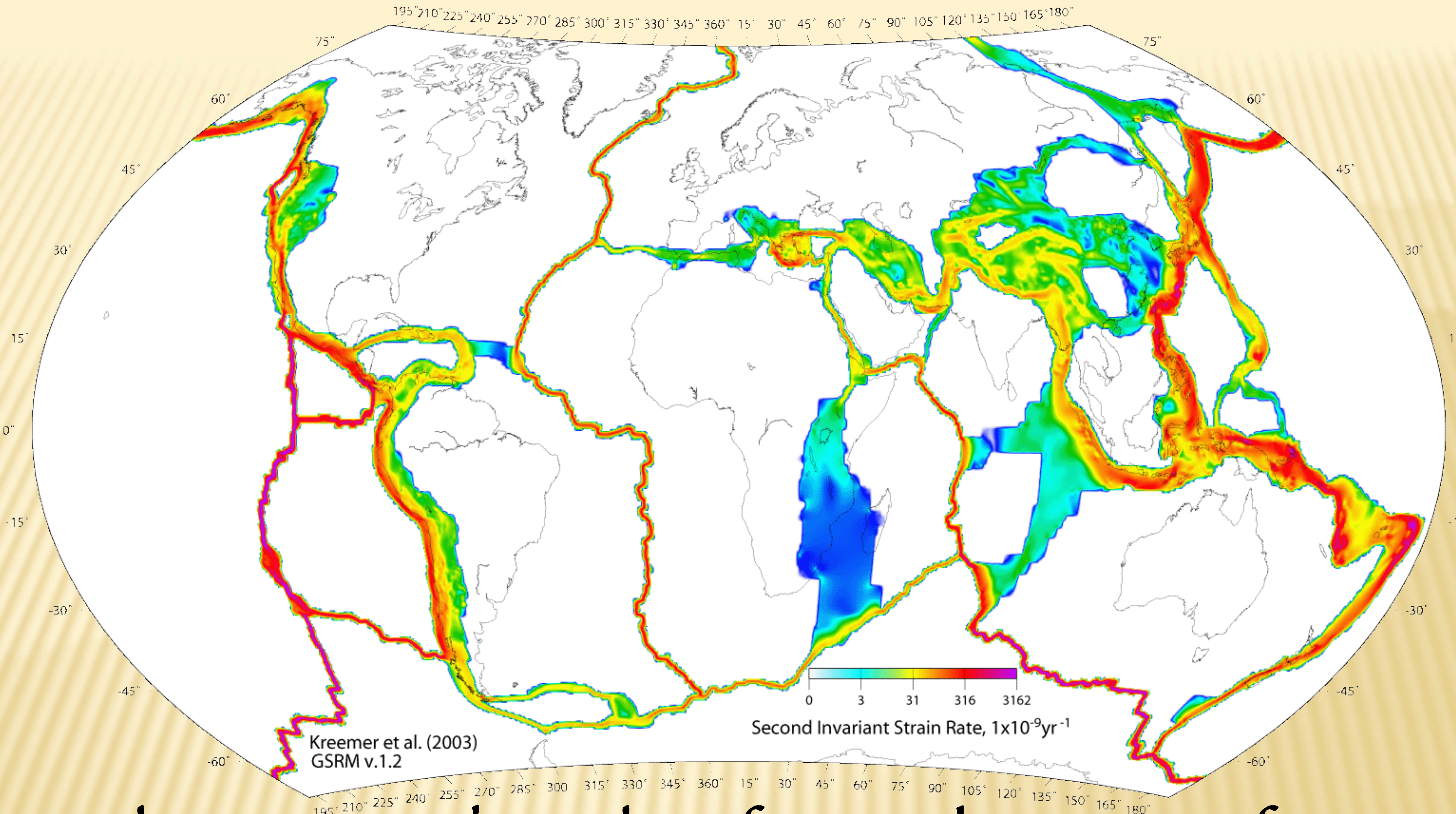


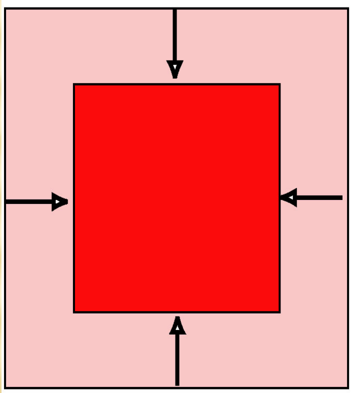
"Color topographic" plot of second invariant of strain rate tensor. Quantified version of previous figure.

Shows how fast the deforming regions are straining. (Red fastest, blue slowest)

Mechanical work: Work=Force•distance

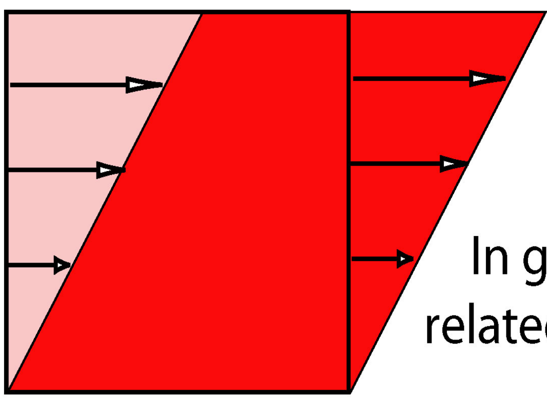
In an elastic medium it takes work to deform (change the shape of) a body: the force to create a deformation (change in distances) is a function of the deformation .

Work is therfore a function of the deformation (strain) squared.



Work related to volume change - first invarient of strain tensor - trace. Work is a function of the first invarient squared.

In general this deformation and work is not related to failure.



Work related to change in shape - second invarient - sum of cofactors. (individual terms are strain squared)

In general it is this deformation and work that is directly related to failure. (Von-Mises yield criterion).

Determining

Strain or strain rate from

Displacement or velocity field

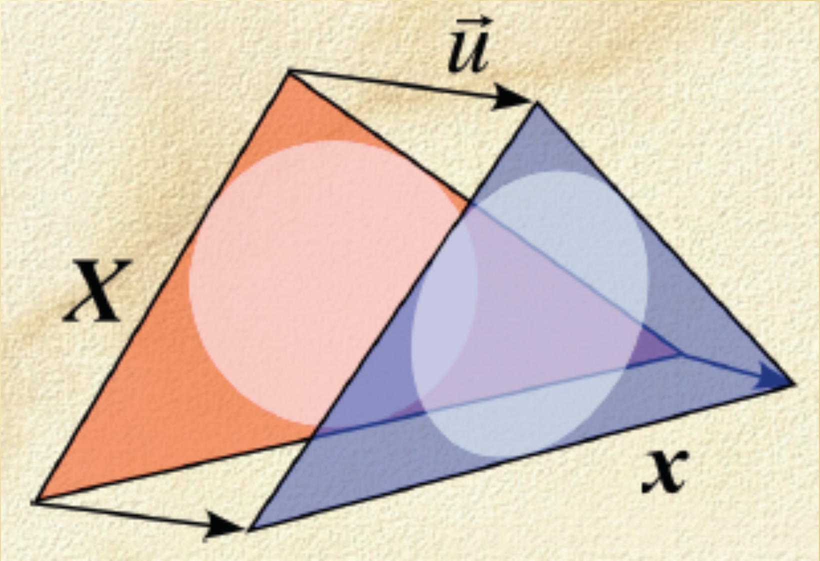
$$u_i = t_i + \frac{\partial u_i}{\partial X_j} X_j = t_i + D_{ij} X_j = t_i + \left(E_{ij} + W_{ij}\right) X_j$$

Deformation tensor

$$E_{ij} = \frac{1}{2}\left(D_{ij} + D_{ji}\right)$$

$$W_{ij} = \frac{1}{2}\left(D_{ij} - D_{ji}\right)$$

Strain (symmetric) and Rotation (anti-symmetris) tensors



Write it out

$$u_i = t_i + D_{ij} X_j$$

Deformation tensor not symmetric, have to keep d_{xy} and d_{yx}.

$$\begin{pmatrix} u_x \\ u_y \end{pmatrix} = \begin{pmatrix} t_x \\ t_y \end{pmatrix} + \begin{pmatrix} d_{xx} & d_{xy} \\ d_{yx} & d_{yy} \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$

Again – this is "wrong way around"

We know

$\underline{u}$ and $\underline{x}$

and want

$\underline{t}$ and d_{ij}.

$$u_i = t_i + D_{ij} X_j$$

$$\begin{pmatrix} u_x \\ u_y \end{pmatrix} = \begin{pmatrix} t_x \\ t_y \end{pmatrix} + \begin{pmatrix} d_{xx} & d_{xy} \\ d_{yx} & d_{yy} \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$

So rearrange it

$$\begin{pmatrix} u_x \\ u_y \end{pmatrix} = \begin{pmatrix} 1 & 0 & x & y & 0 & 0 \\ 0 & 1 & 0 & 0 & x & y \end{pmatrix} \begin{pmatrix} t_x \\ t_y \\ d_{xx} \\ d_{xy} \\ d_{yx} \\ d_{yy} \end{pmatrix}$$

Now we have 6 unknowns and 2 equations

So we need at least 3 data points
That will give us 6 data

$$
\begin{pmatrix} u_{x_1} \\ u_{y_1} \\ u_{x_2} \\ u_{y_2} \\ u_{x_3} \\ u_{y_3} \\ \vdots \\ u_{x_n} \\ u_{y_n} \end{pmatrix}
=
\begin{pmatrix}
1 & 0 & x_1 & y_1 & 0 & 0 \\
0 & 1 & 0 & 0 & x_1 & y_1 \\
1 & 0 & x_2 & y_2 & 0 & 0 \\
0 & 1 & 0 & 0 & x_2 & y_2 \\
1 & 0 & x_3 & y_3 & 0 & 0 \\
0 & 1 & 0 & 0 & x_3 & y_3 \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
1 & 0 & x_n & y_n & 0 & 0 \\
0 & 1 & 0 & 0 & x_n & y_n
\end{pmatrix}
\begin{pmatrix} t_x \\ t_y \\ d_{xx} \\ d_{xy} \\ d_{yx} \\ d_{yy} \end{pmatrix}
$$

And again – the more the merrier – do least squares.

For strain rate

Take time derivative of all terms.

But be careful

Strain rate tensor

is NOT

time derivative of strain tensor.

Spatial (Eulerian) and Material (Lagrangian) Coordinates

and the

Material Derivative

Spatial description picks out a particular location in space, x.

Material description picks out a particular piece of continuum material, X.

So we can write

$$x = x(A,t) \qquad\qquad x(A,0) = A$$

x is the position now (at time t) of the section that was initially (at time zero) located at A.

$$A = A(x,t) \qquad\qquad A(A,0) = A$$

A was the initial position of the particle now at x

This gives by definition

$$x\left[A(x,t),t\right] = x \qquad\qquad A\left[x(A,t),t\right] = A$$

We can therefore write

$$f\left[x(A,t),t\right] = F(A,t) \qquad f(x,t) = F\left[A(x,t),t\right]$$

Next consider the derivative (use chain rule)

$$\frac{\partial}{\partial A}F(A,t) = f\left[x(A,t),t\right] = \left.\frac{\partial f}{\partial x}\right|_A \frac{\partial x}{\partial A}$$

$$\frac{\partial}{\partial t}F(A,t) = f\left[x(A,t),t\right] = \left.\frac{\partial f}{\partial x}\right|_A \frac{\partial x}{\partial t} + \left.\frac{\partial f}{\partial t}\right|_A$$

Define Material Derivative

$$\frac{\partial}{\partial t}F(A,t) = f\left[x(A,t),t\right] = \left.\frac{\partial f}{\partial x}\right|_A \frac{\partial x}{\partial t} + \left.\frac{\partial f}{\partial t}\right|_A$$

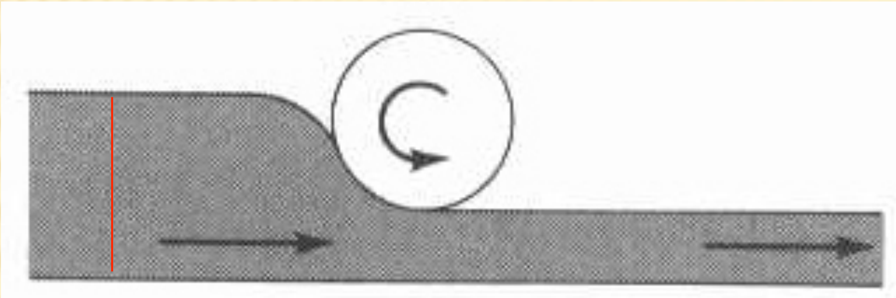
$$\frac{DF(A,t)}{Dt} = \left.\frac{\partial F(A,t)}{\partial t}\right|_{A=A(x,t)}$$

$$\frac{Df(A,t)}{Dt} = \frac{\partial f(x,t)}{\partial t} + v(x,t)\frac{\partial f(x,t)}{\partial x}$$

Vector version

$$\frac{D\vec{f}}{Dt} = \frac{\partial \vec{f}(x,t)}{\partial t} + \vec{v}(x,t)\bullet\nabla\vec{f}(x,t)$$

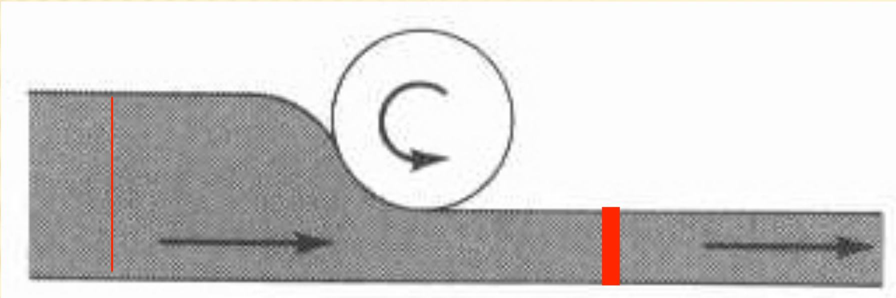
Example



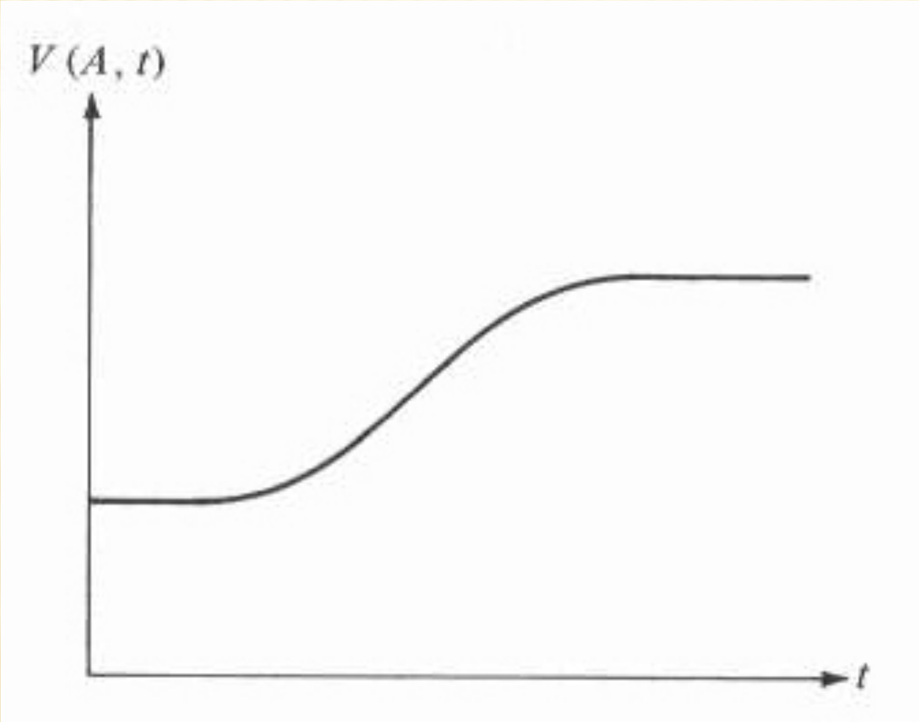
A

Consider bar steadily moving through a roller that thins it

Examine velocity as a function of time of cross section A



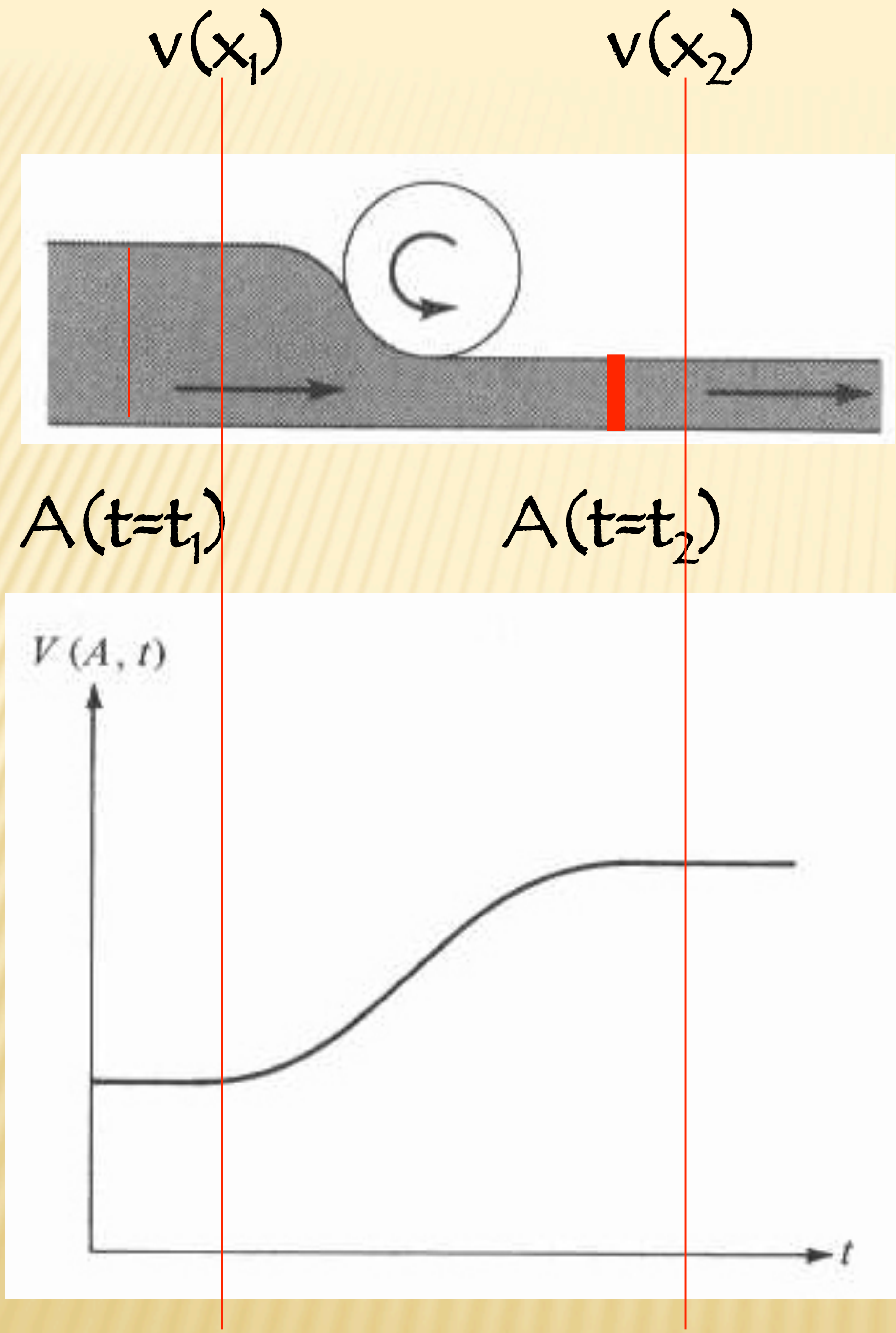
$A(t=t_1)$ $A(t=t_2)$



Velocity will be constant until it reaches the roller

At which point it will speed up (and get a little fatter, but ignore that as second order)

After passing through the roller, its velocity will again be constant



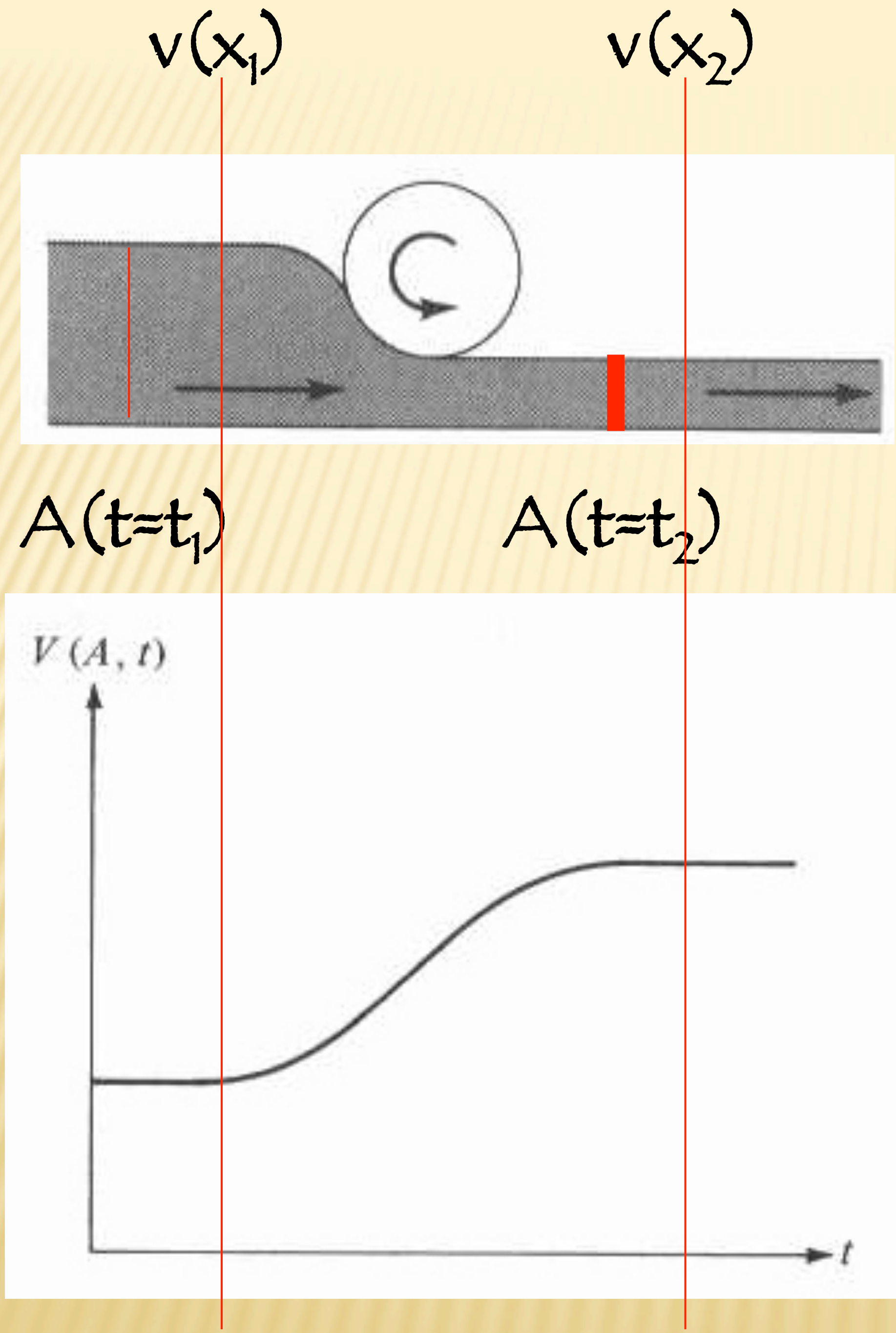
If one looks at a particular position, x, however the velocity is constant in time.

So for any fixed point in space

$$\frac{\partial v(x,t)}{\partial t} = 0$$

So the acceleration seems to be zero

(which we know it is not)



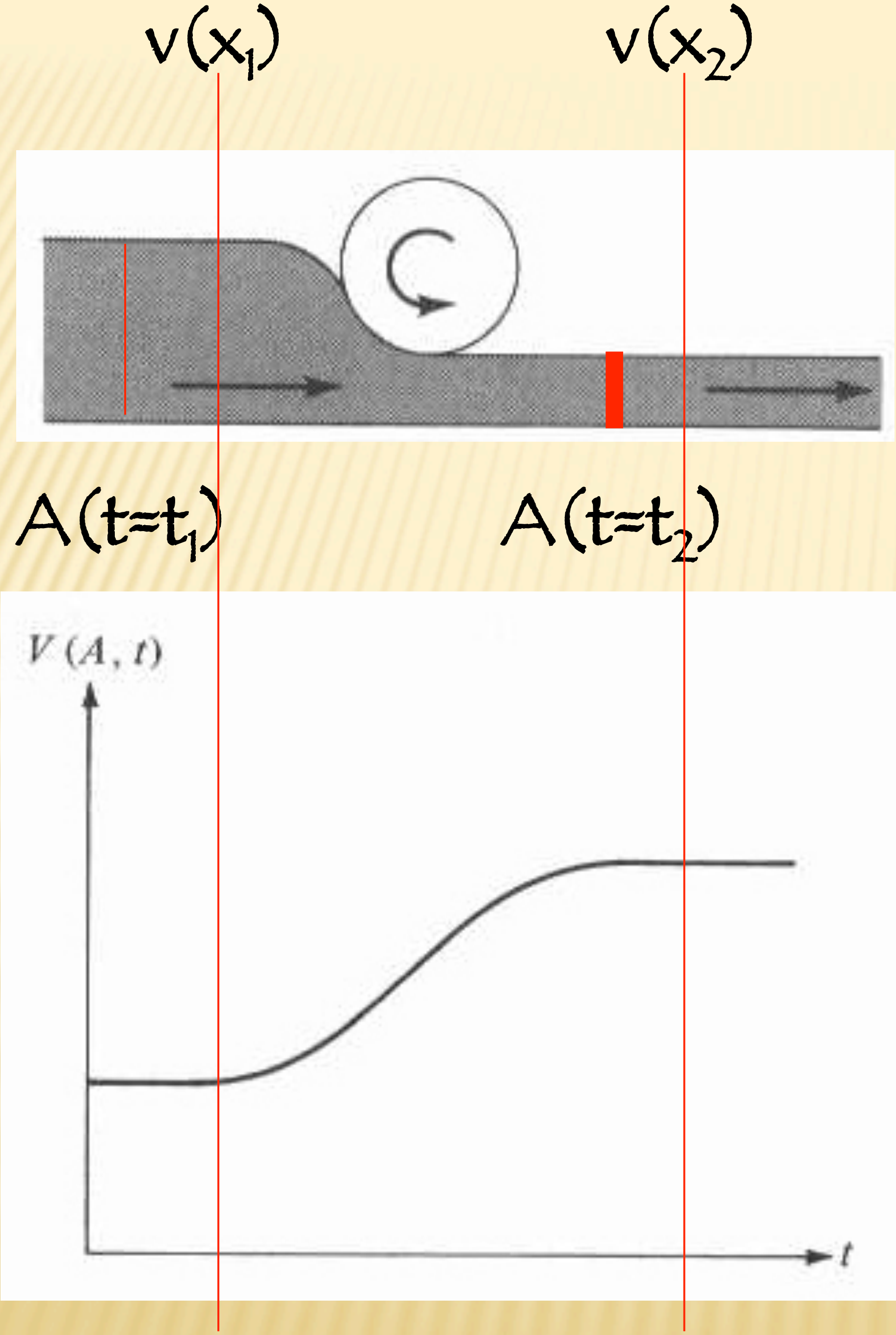
The problem is that we need to compute the time rate of change of the

material

which is moving through space

and deforming

(not rigid body)



We know acceleration is not zero.

$$\frac{Df(A,t)}{Dt} = \frac{\partial f(x,t)}{\partial t} + v(x,t)\frac{\partial f(x,t)}{\partial x}$$

Term gives acceleration as one

<u>follows the material</u>

through space

(have to consider same material at t_1 and t_2)

Various names for this derivative

Substantive derivative

Lagrangian derivative

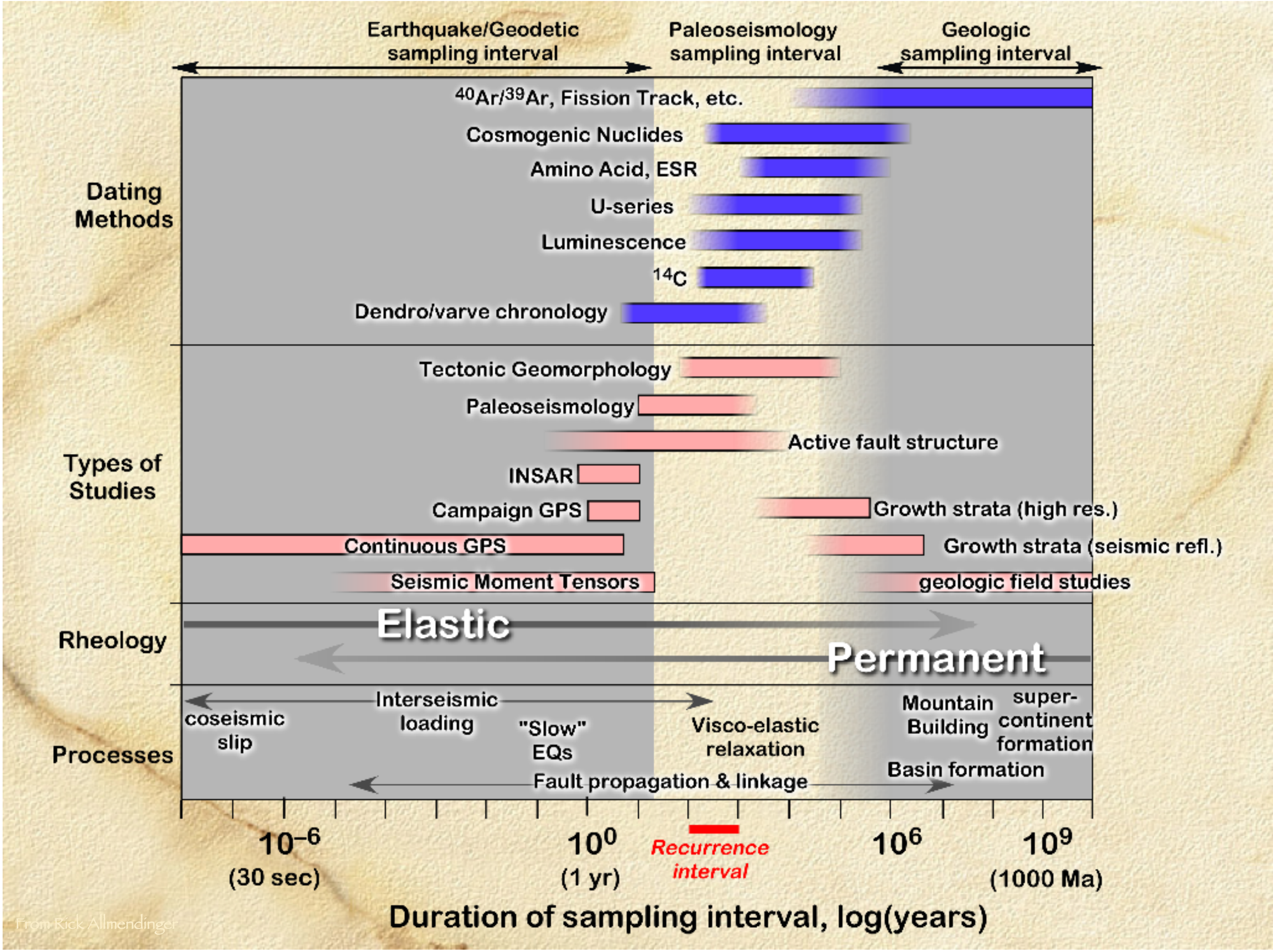
Material derivative

Advective derivative

Total derivative

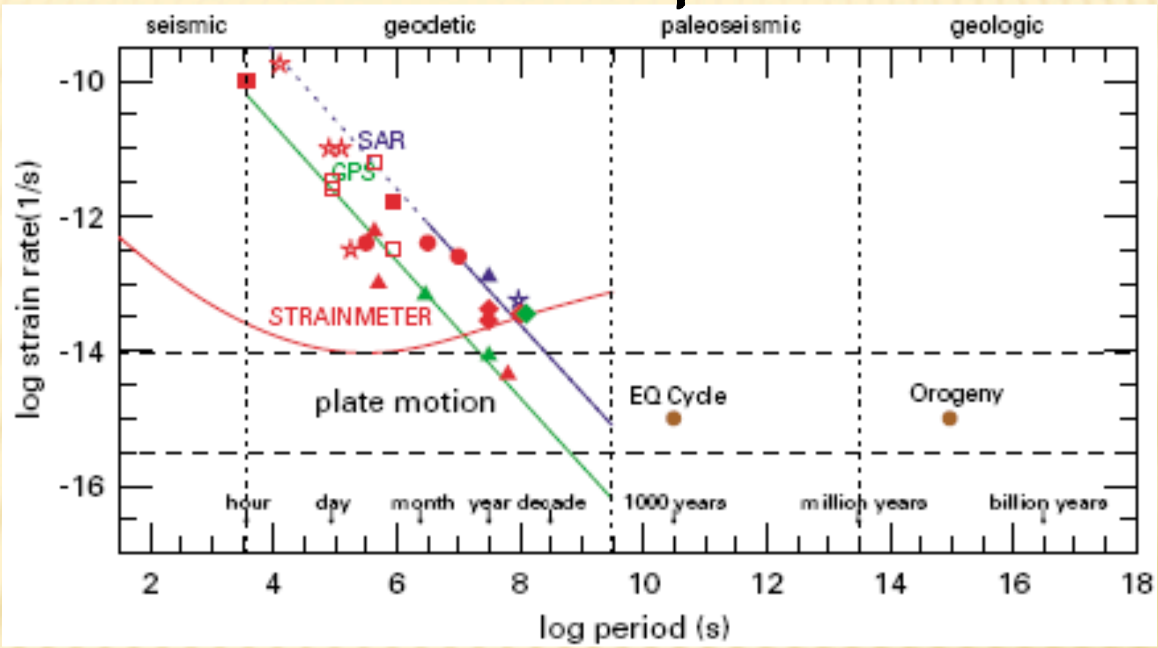
GPS and deformation

Now we examine <u>relative</u> movement between sites



Earthquake/Geodetic sampling interval
Paleoseismology sampling interval
Geologic sampling interval
Dating Methods
40Ar/39Ar, Fission Track, etc.
Cosmogenic Nuclides
Amino Acid, ESR
U-series
Luminescence
14C
Dendro/varve chronology
Types of Studies
Tectonic Geomorphology
Paleoseismology
Active fault structure
INSAR
Campaign GPS
Growth strata (high res.)
Continuous GPS
Growth strata (seismic refl.)
Seismic Moment Tensors
geologic field studies
Rheology
Elastic
Permanent
Processes
coseismic slip
Interseismic loading
"Slow" EQs
Visco-elastic relaxation
Mountain Building
super-continent formation
Basin formation
Fault propagation & linkage
10−6
(30 sec)
100
(1 yr)
Recurrence interval
106
109
(1000 Ma)
Duration of sampling interval, log(years)
From Rick Allmendinger

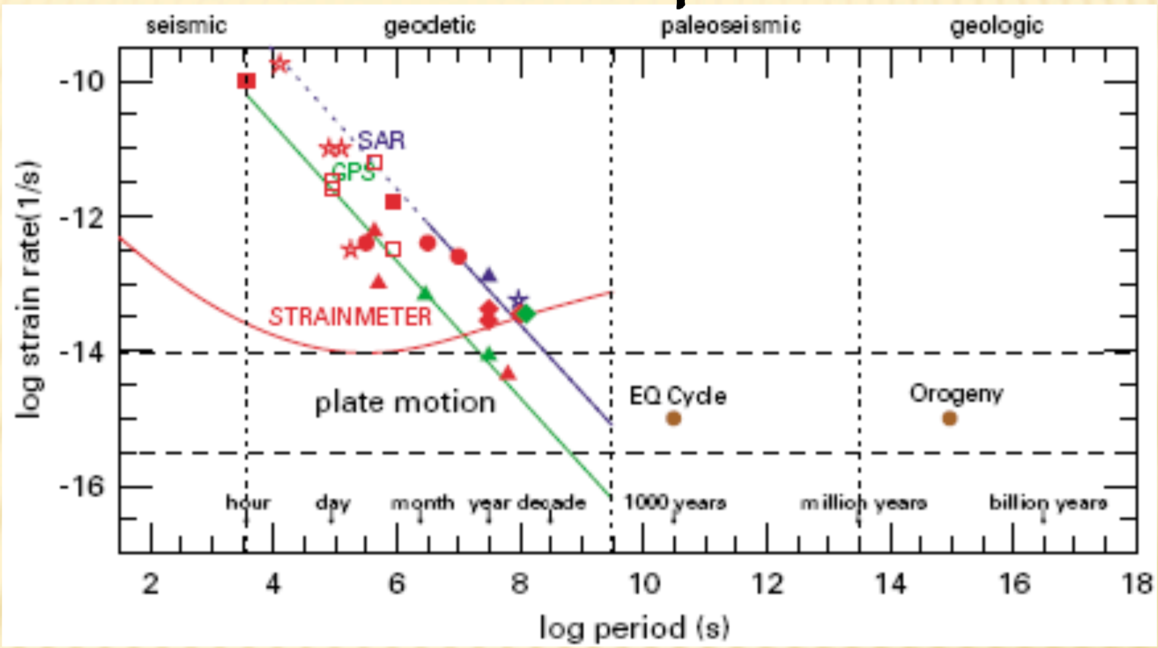
Strain-rate sensitivity thresholds (schematic) as functions of period



GPS and INSAR detection thresholds for 10-km baselines, assuming 2-mm and 2-cm displacement resolution for GPS and INSAR, respectively (horizontal only).

http://www.iris.iris.edu/USArray/EllenMaterial/assets/es_proj_plan_lo.pdf, http://www.iris.edu/news/IRISnewsletter/EE.Fall98.web/plate.html

Strain-rate sensitivity thresholds (schematic) as functions of period



Post-seismic deformation (triangles), slow earthquakes (squares), long-term aseismic deformation (diamonds), preseismic transients (circles), and volcanic strain transients (stars).

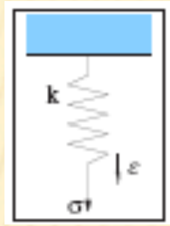
http://www.iris.iris.edu/USArray/EllenMaterial/assets/es_proj_plan_lo.pdf, http://www.iris.edu/news/IRISnewsletter/EE.Fall98.web/plate.html

Study deformation at two levels

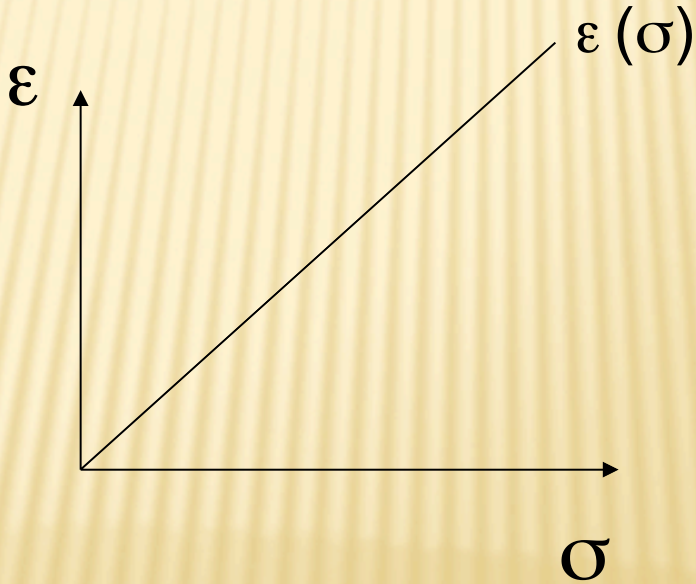
-Kinematics –
describe motions
(Have to do this first)

-Dynamics –
relate motions (kinematics) to forces (physics)
(Do through rheology/constitutive relationship/model.
Phenomenological, no first principle prediction)

Simple rheological models

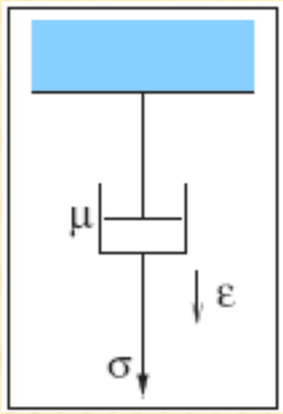


elastic $\sigma = K\varepsilon$



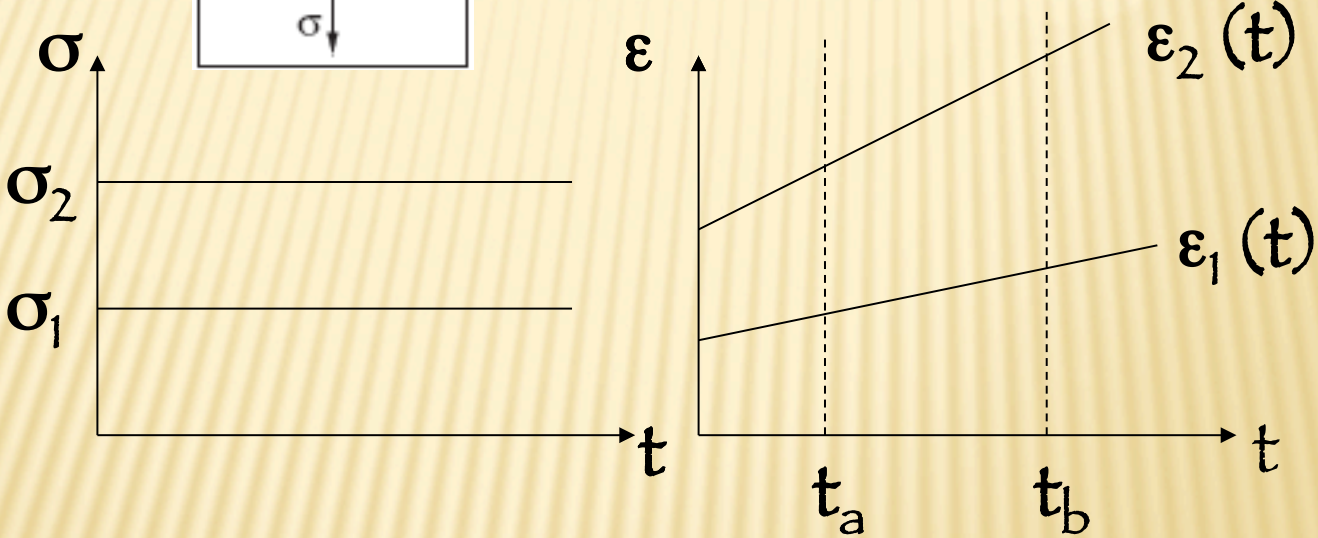
http://hcgl.eng.ohio-state.edu/~ce552/3rdMat06_handout.pdf

Simple rheological models



viscous

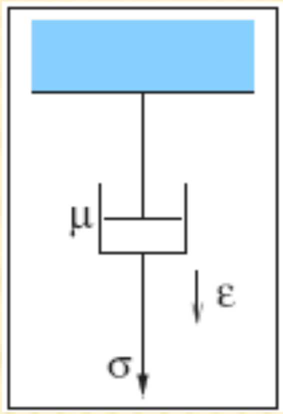
$$\sigma = \mu \frac{d\varepsilon}{dt} = \mu\dot{\varepsilon}$$



Apply constant stress, σ, to a viscoelastic material recorded deformation (strain, ε) as a function of time. ε increases with time.

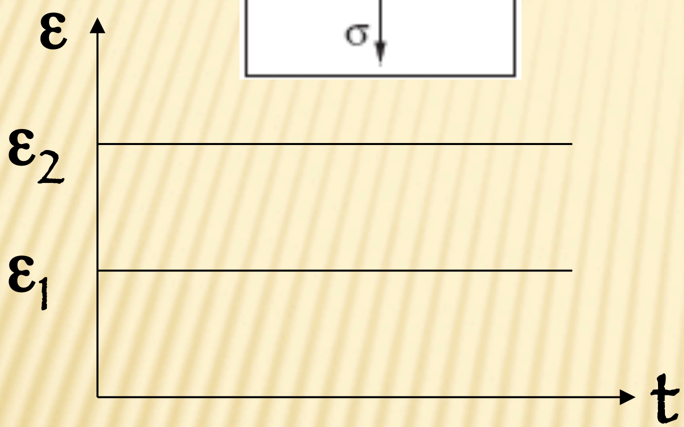
http://hcgl.eng.ohio-state.edu/~ce552/3rdMat06_handout.pdf

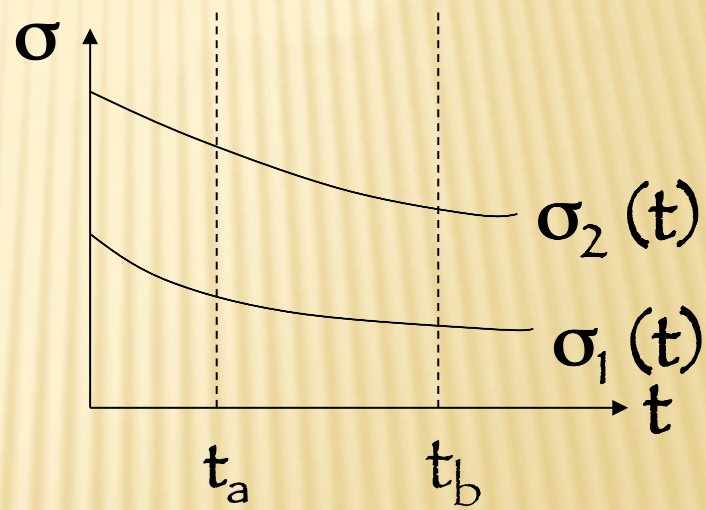
Simple rheological models



viscous

$$\sigma = \mu \frac{d\varepsilon}{dt} = \mu \dot{\varepsilon}$$



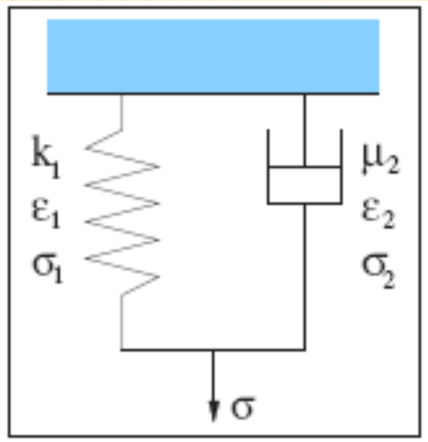


Maintain constant strain, record load stress needed.
Decreases with time.
Called relaxation.

http://hcgl.eng.ohio-state.edu/~ce552/3rdMat06_handout.pdf

viscoelastic

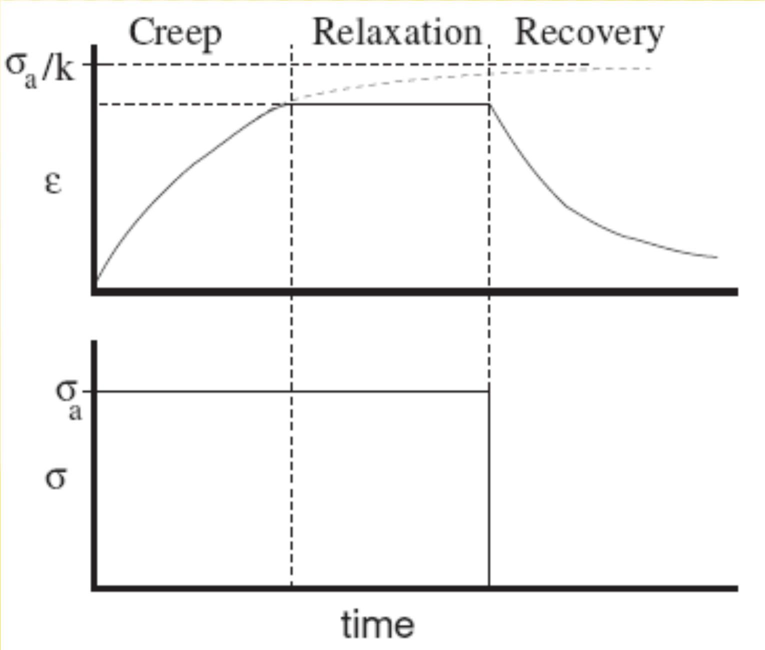
Kelvin rheology



$$\sigma = \sigma_1 + \sigma_2$$

$$\varepsilon = \varepsilon_1 = \varepsilon_2$$

$$\sigma = K\varepsilon + \mu\dot{\varepsilon}$$

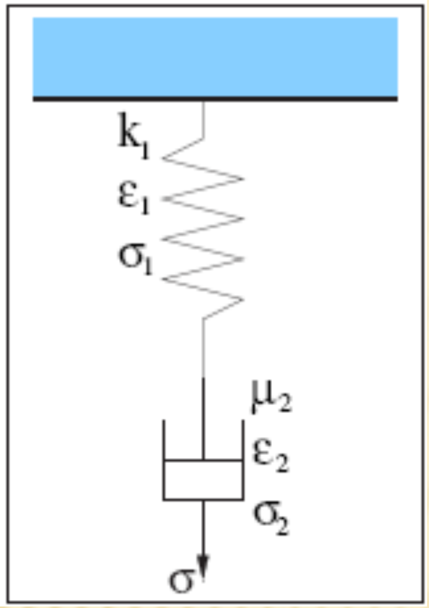


Handles creep and recovery fairly well

Does not account for relaxation

http://hcgl.eng.ohio-state.edu/~ce552/3rdMat06_handout.pdf

viscoelastic



Maxwell rheology

$$\sigma = \sigma_1 = \sigma_2$$

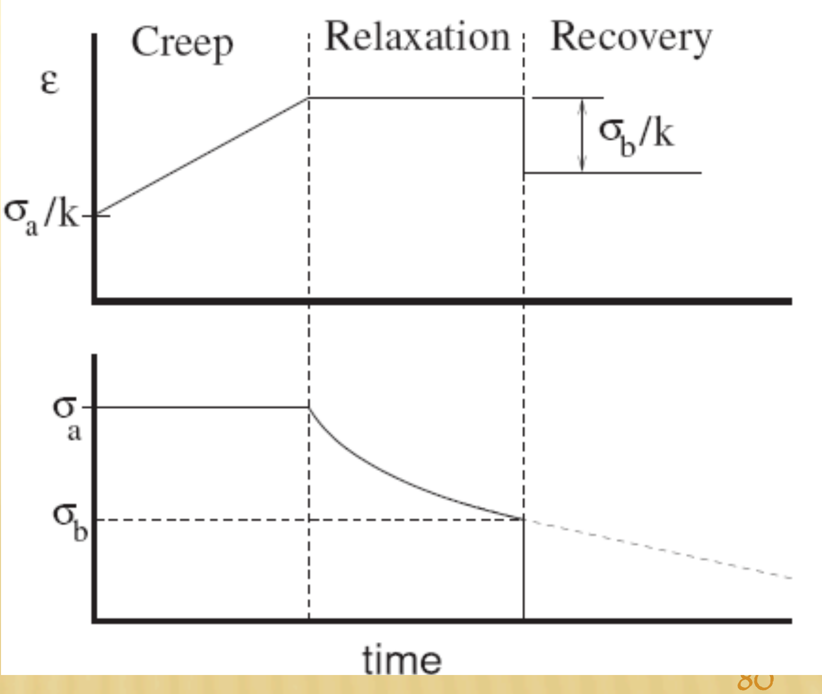
$$\varepsilon = \varepsilon_1 + \varepsilon_2$$

$$\dot{\varepsilon} = \frac{\sigma}{\mu} + \frac{\dot{\sigma}}{k}$$

Handles creep badly (unbounded)

Handles recovery badly (elastic only, instantaneous)

Accounts for relaxation fairly well



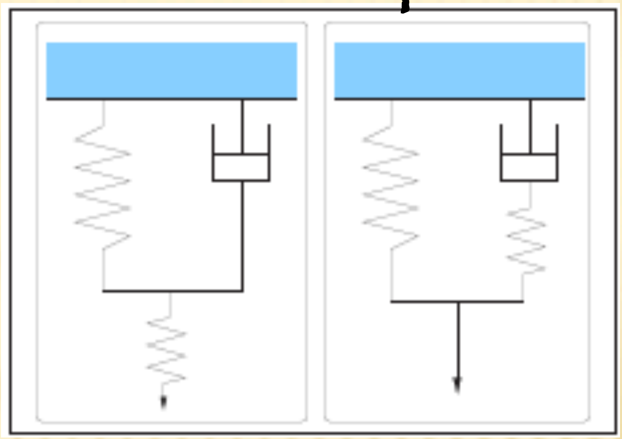
http://hcgl.eng.ohio-state.edu/~ce552/3rdMat06_handout.pdf

viscoelastic

Standard linear/Zener

(not unique)

Spring in series with Kelvin



Spring in parallel with Maxwell

Stress – equal among components in series

Total strain – sum all components in series

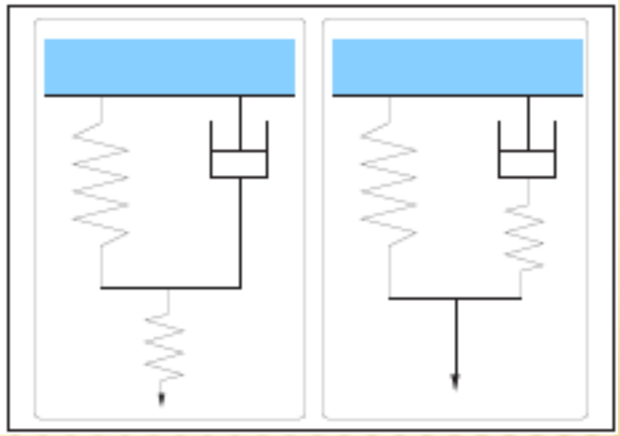
Strain – equal among components in parallel

Total stress – total of all components in parallel

http://hcgl.eng.ohio-state.edu/~ce552/3rdMat06_handout.pdf

www.mse.mtu.edu/~wangh/my4600/chapter4.ppt

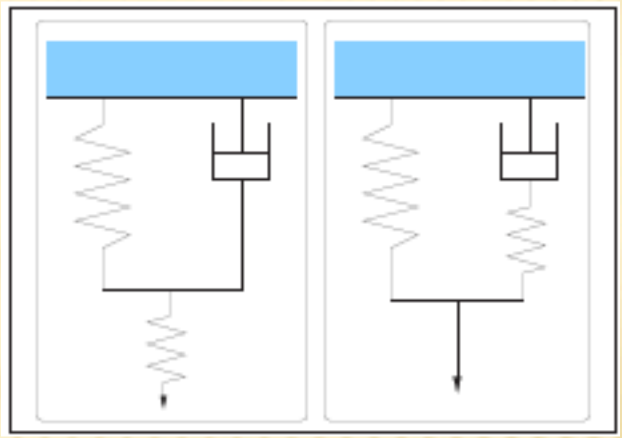
viscoelastic
Standard linear/Zener



Instantaneous elastic strain when stress applied
Strain creeps towards limit under constant stress
Stress relaxes towards limit under constant strain
Instantaneous elastic recovery when strain removed
Followed by gradual recovery to zero strain

http://hcgl.eng.ohio-state.edu/~ce552/3rdMat06_handout.pdf
www.mse.mtu.edu/~wangh/my4600/chapter4.ppt

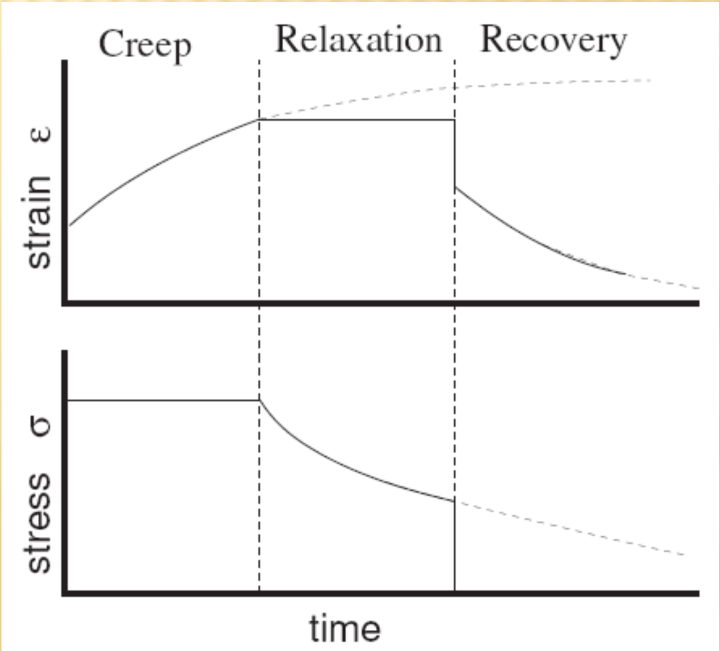
viscoelastic
Standard linear/Zener



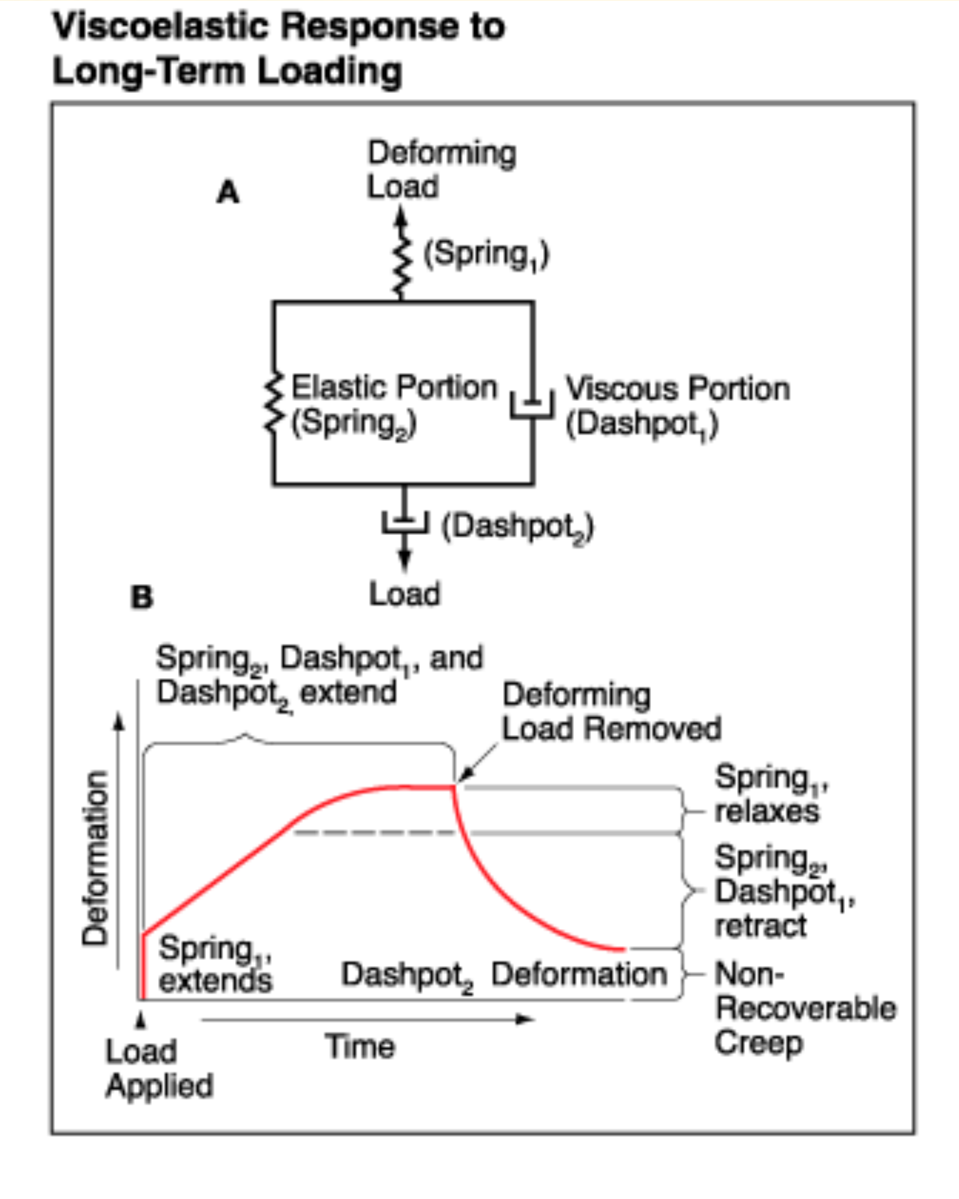
Two time constants

- Creep/recovery under constant stress

- Relaxation under constant strain



http://hcgl.eng.ohio-state.edu/~ce552/3rdMat06_handout.pdf
www.mse.mtu.edu/~wangh/my4600/chapter4.ppt



Can make arbitrarily complicated to match many deformation/ strain/time relationships

http://www.dow.com/styron/design/guide/modeling.htm

Three types faults and plate boundaries

- Faults -

Strike-slip
Thrust
Normal

- Plate Boundary -

Strike-slip
Convergent
Divergent

How to model

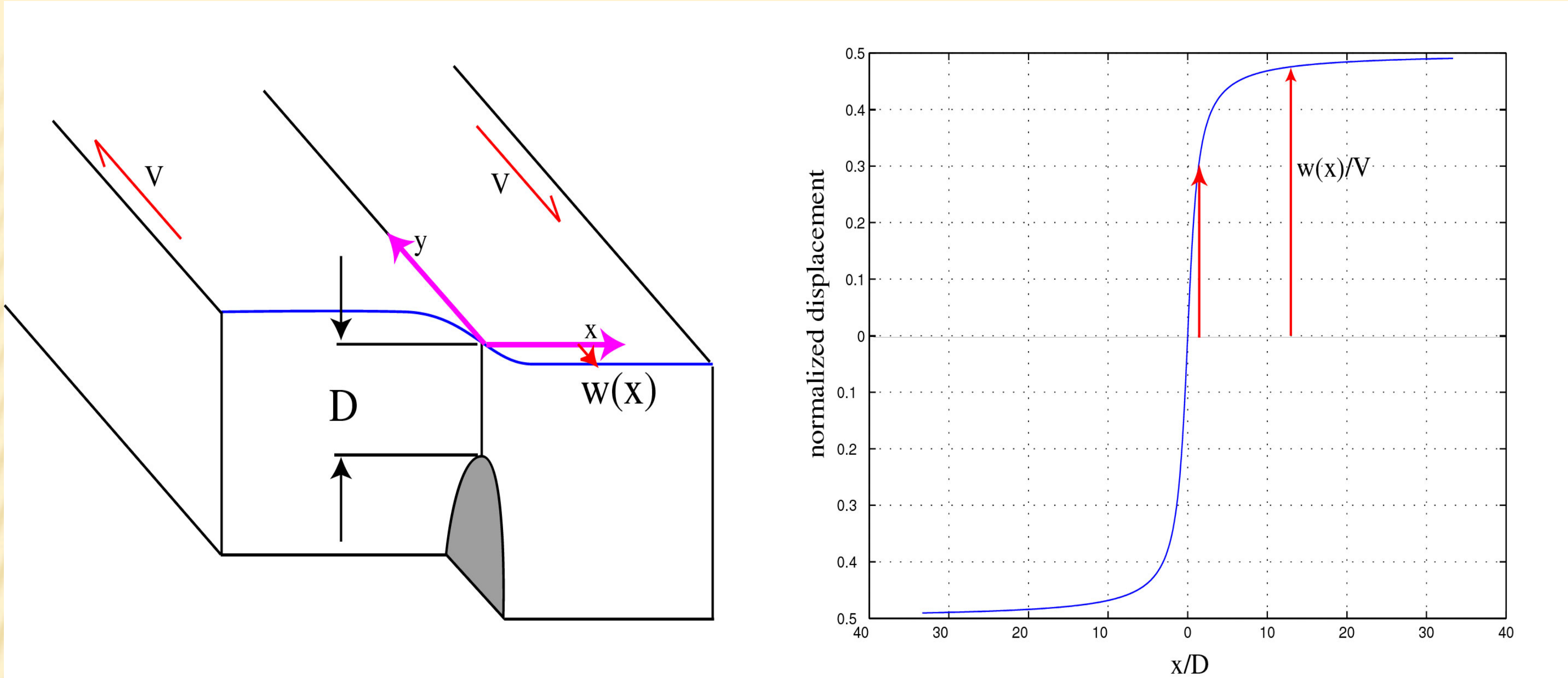
Elastic

Viscoelastic

Half space

Layers

Inhomogeneous

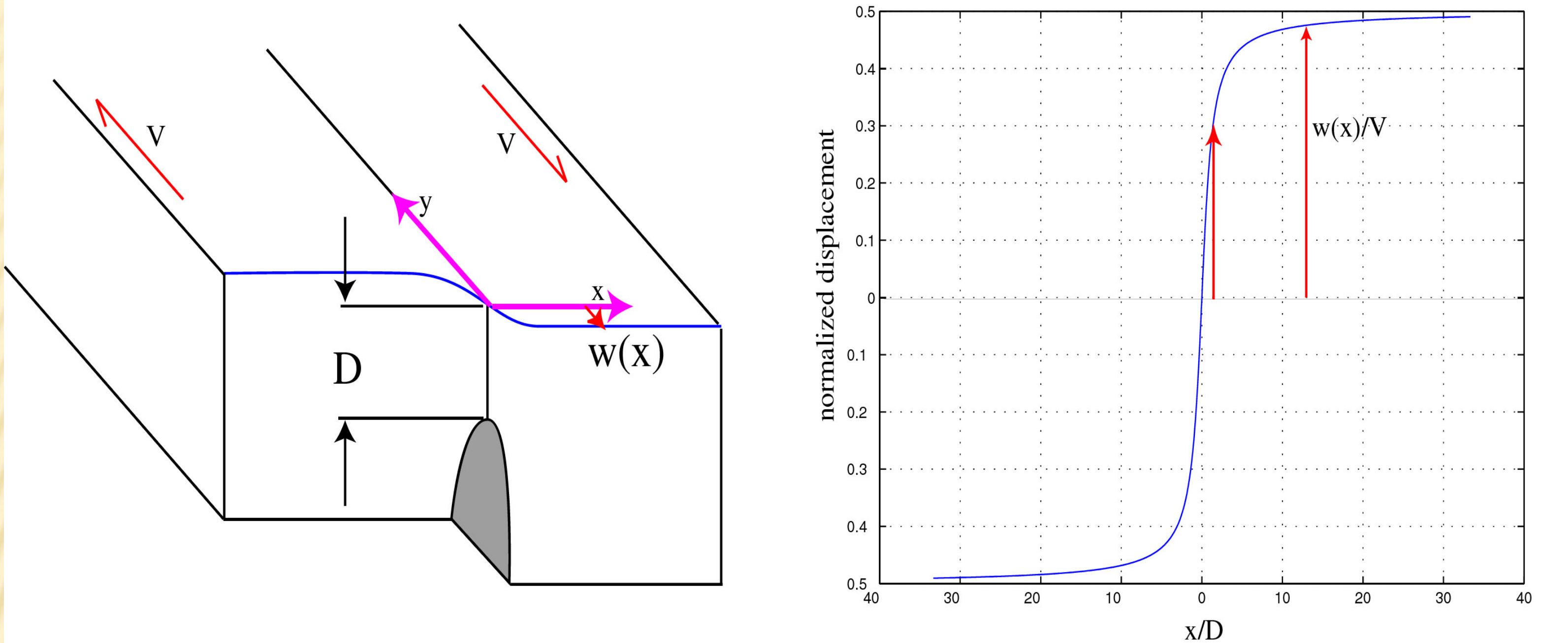


$$w(x)=(V/\pi)\mathrm{atan}(x/D)$$

2-D model for strain across strike-slip fault in elastic half space.

Fault is locked from surface to depth *D*, then free to infinity.

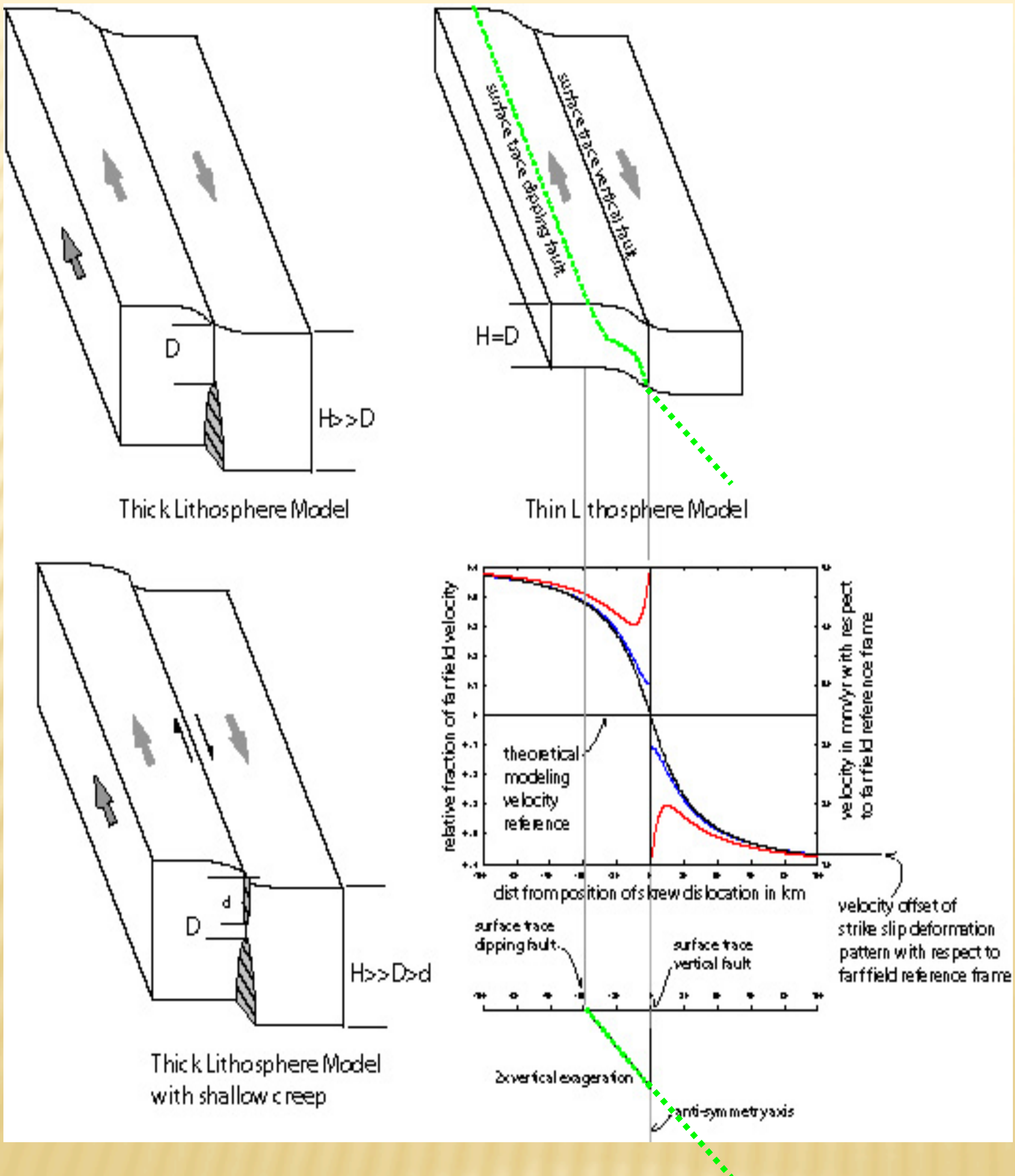
Far-field displacement, *V*, applied.



w(x)=(V/π)atan(x/D)

w(x) is the equilibrium displacement parallel to *y* at position x.

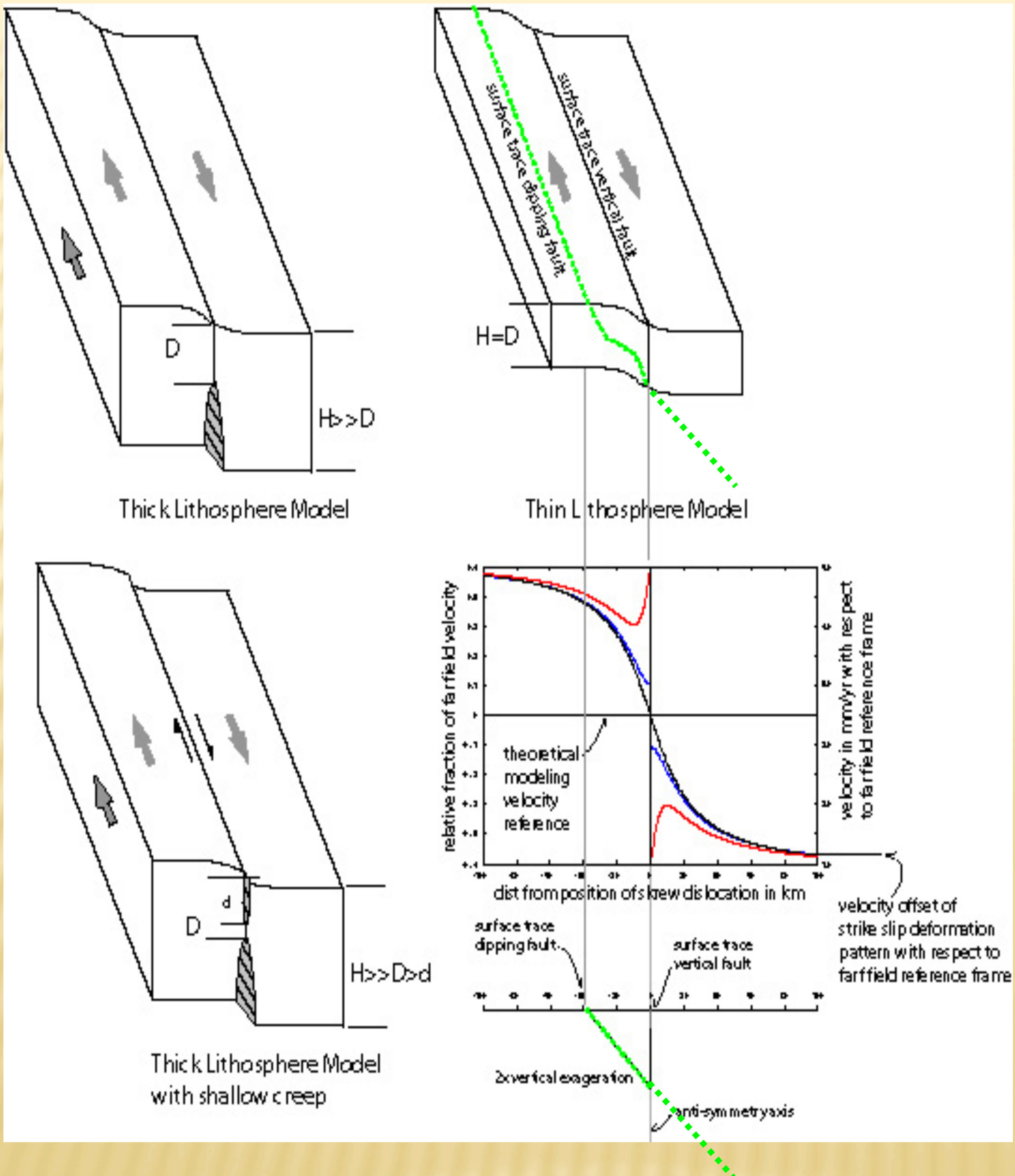
|w| is *50%* max at *x/D=.93; 63%* at *x/D=1.47 & 90%* at *x/D=6.3*



Effect of fault dip.

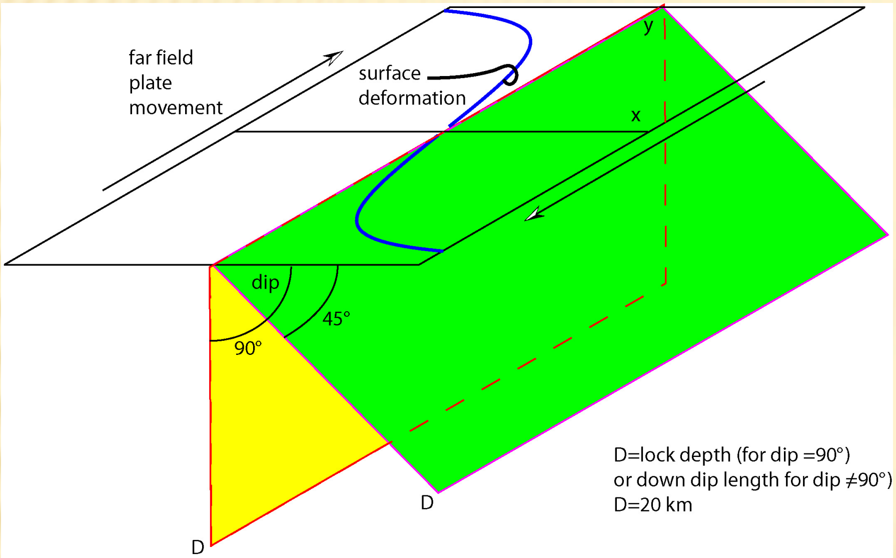
The fault is locked from the surface to a depth *D* (not a down dip length of *D*).

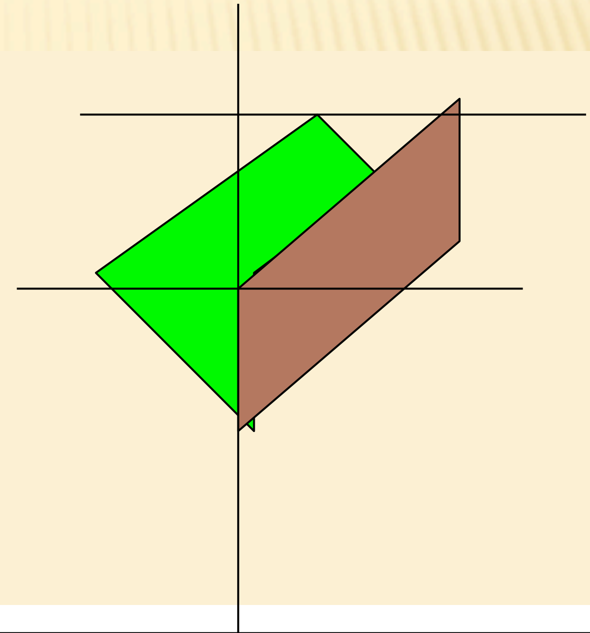
The fault is free from this depth to infinity.

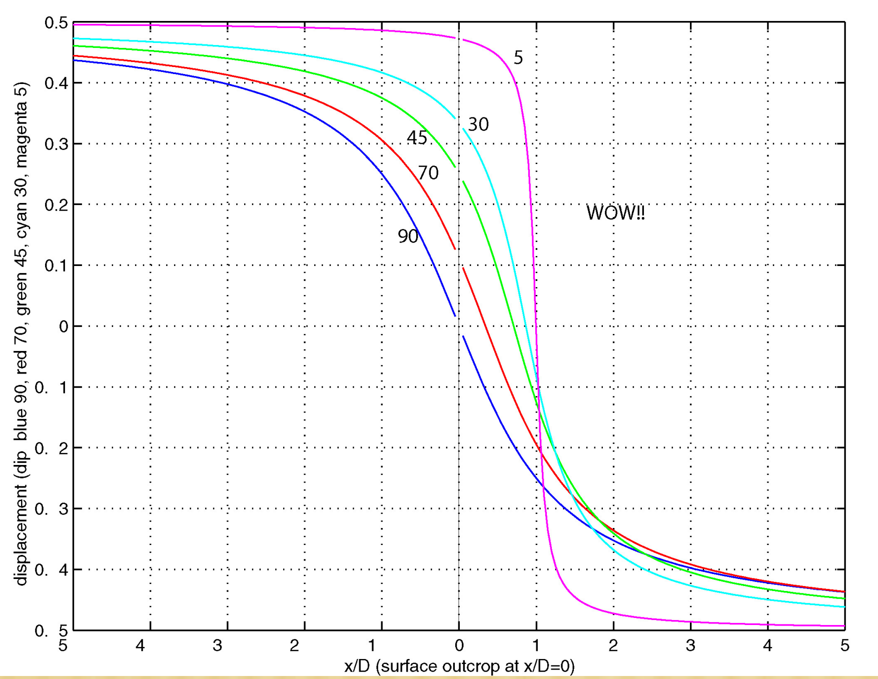


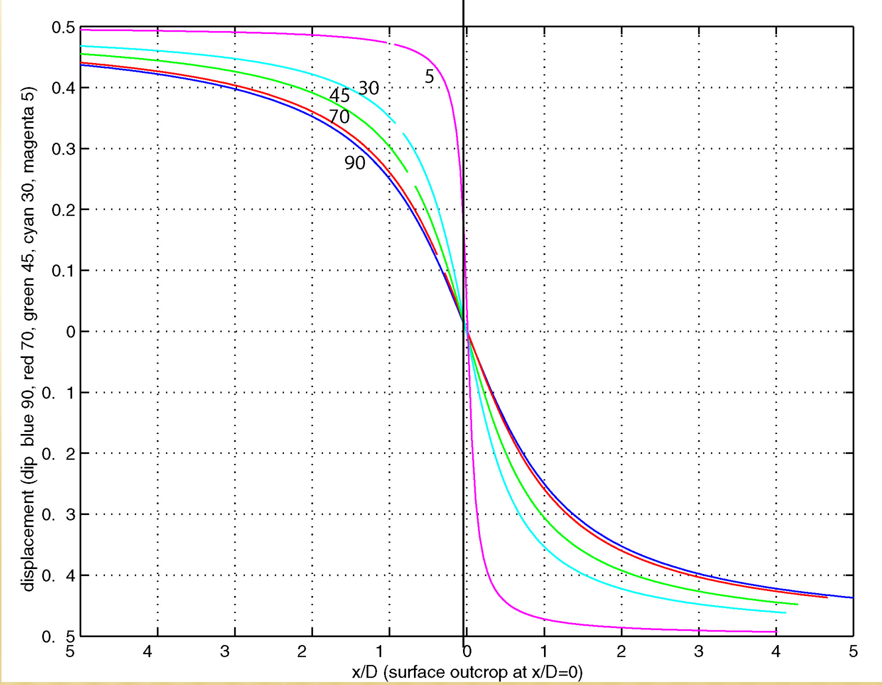
Surface deformation pattern is <u>*SAME*</u> as for vertical fault, but centered over <u>*down dip end*</u> of dipping fault.

Dip estimation from center of deformation pattern to surface trace and locking depth.

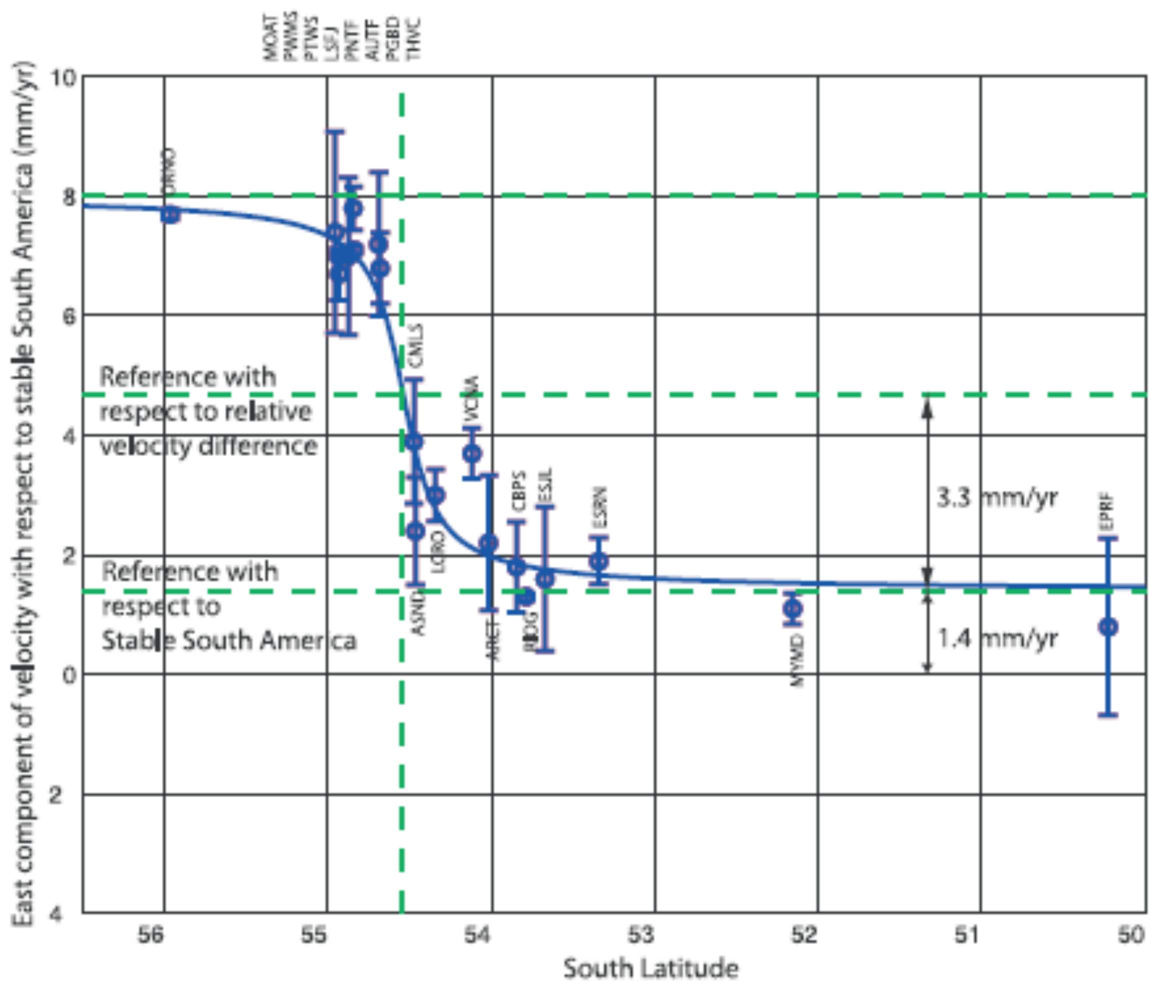

far field
plate
movement
surface
deformation
y
x
dip
45°
90°
D
D
D=lock depth (for dip =90°)
or down dip length for dip ≠90°)
D=20 km

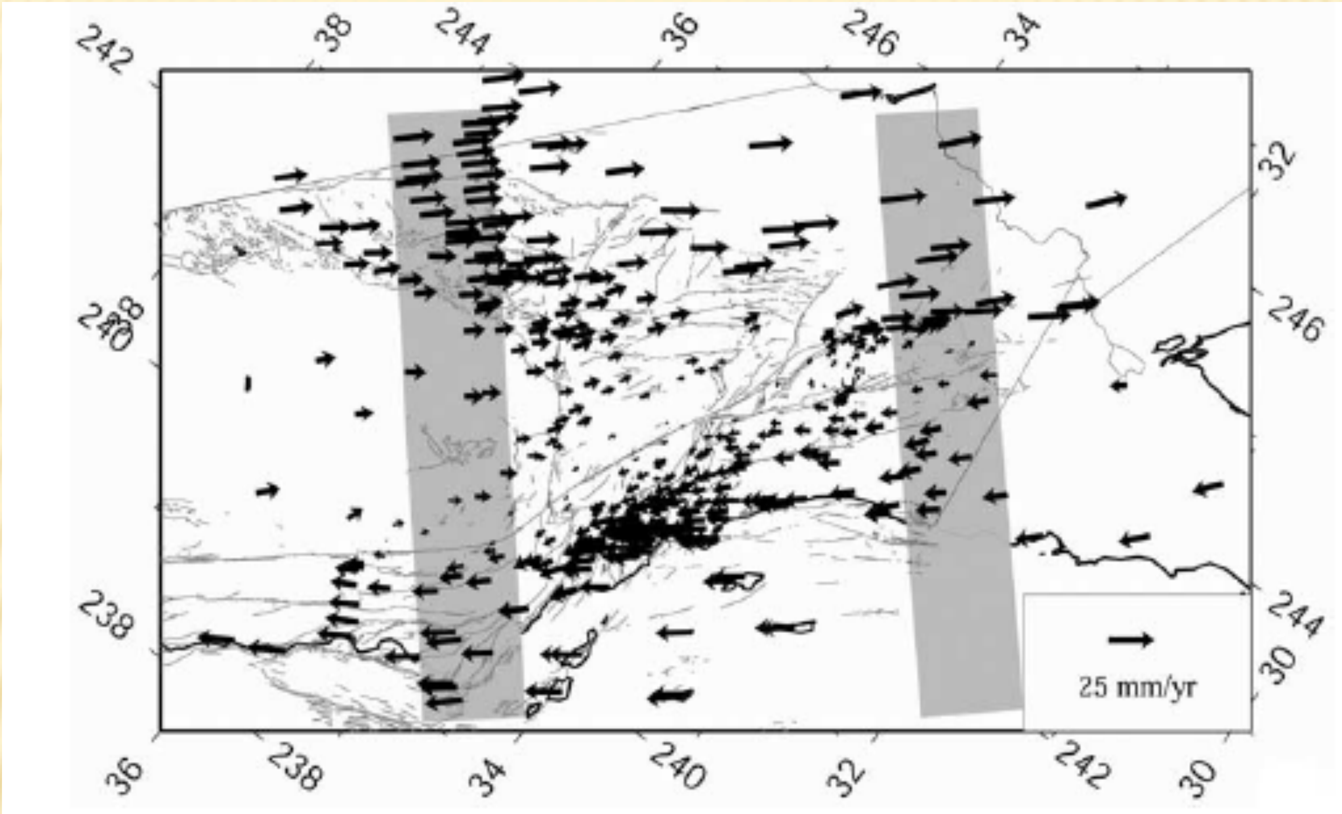



displacement (dip blue 90, red 70, green 45, cyan 30, magenta 5)
x/D (surface outcrop at x/D=0)
5
30
45
70
90
WOW!!


displacement (dip blue 90, red 70, green 45, cyan 30, magenta 5)
x/D (surface outcrop at x/D=0)
5
30
45
70
90

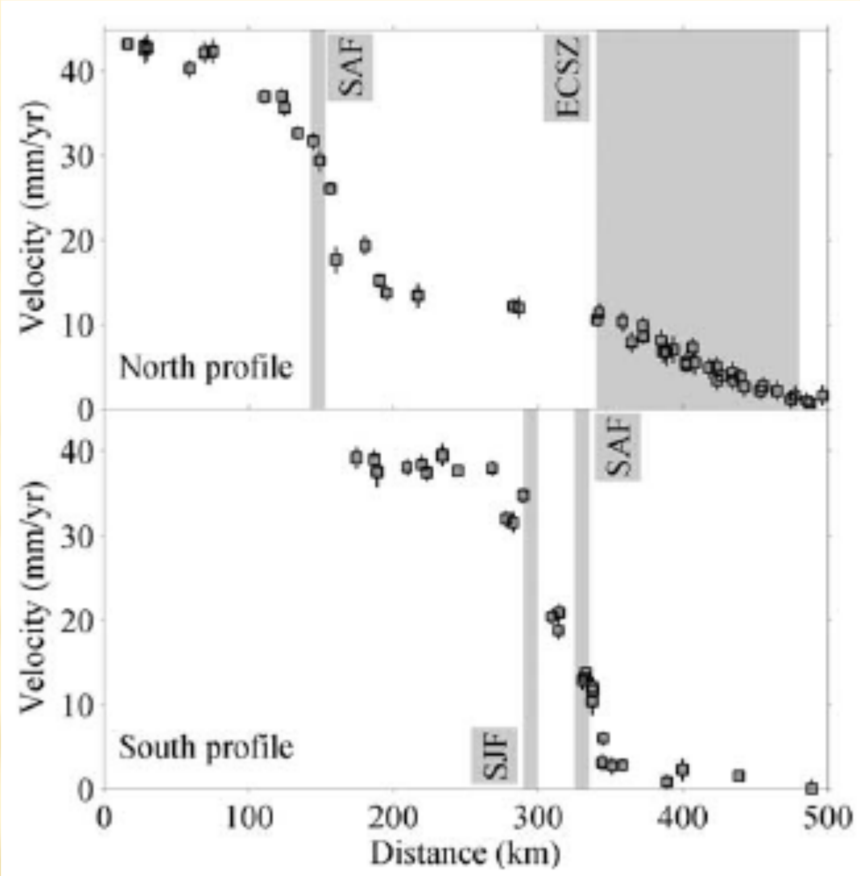

10 mm/yr
BSRN
ESJL
RIOG
CBPS
ARCT
VCNA
LCRO
ASND
CMLS
PGBD
THVC
PNTF
AUTF
LSFJ
PWMS
PTWS
MOAT
ORNO


East component of velocity with respect to stable South America (mm/yr)
South Latitude
Reference with respect to relative velocity difference
Reference with respect to Stable South America
3.3 mm/yr
1.4 mm/yr



Interseismic velocities in southern California from GPS

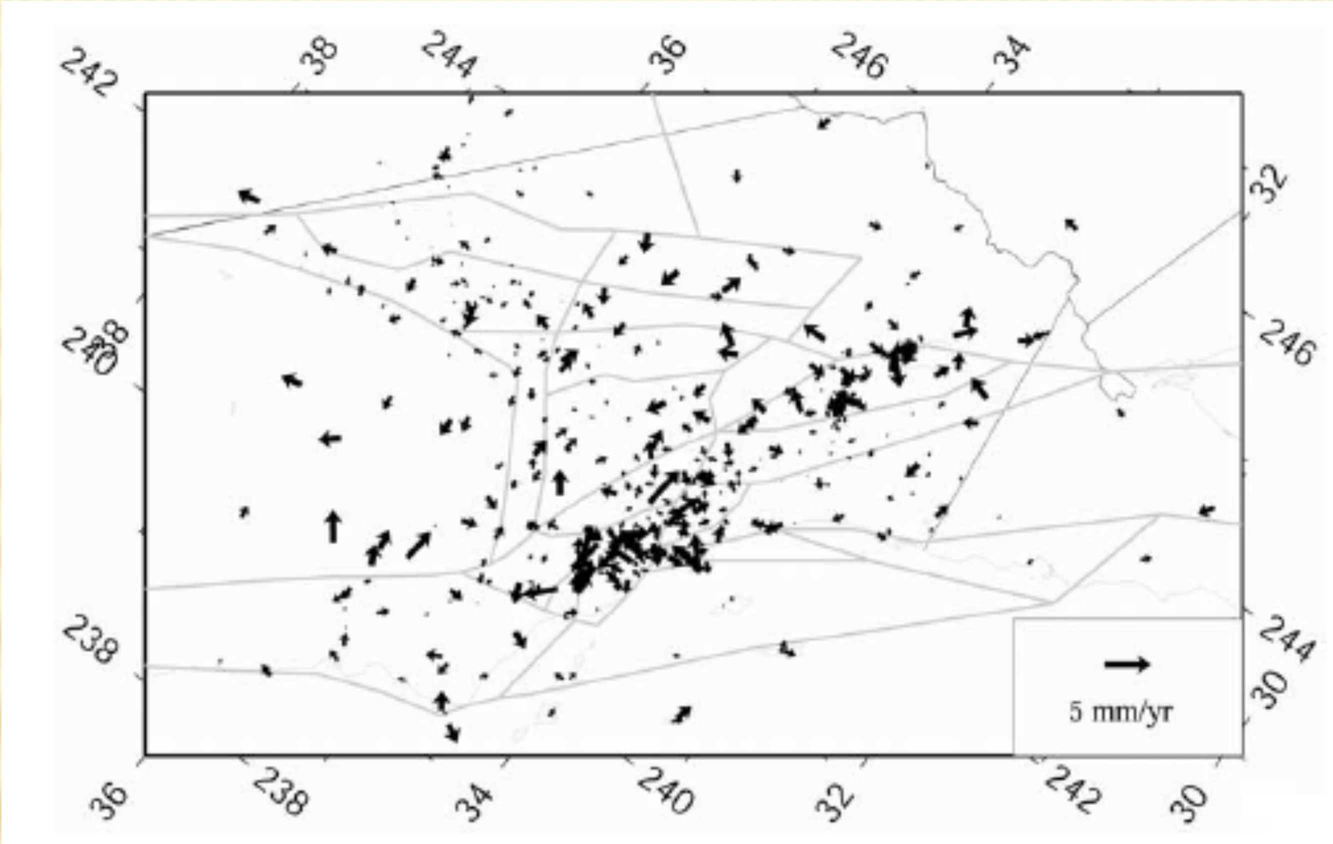
Meade and Hager, 2005



Fault parallel velocities for northern and southern "swaths".

Total change in velocity ~42mm/yr on both.

Meade and Hager, 2005



Residual (observed-model) velocities for block fault model (faults in grey)

Meade and Hager, 2005

Modeling velocities in California

$$\vec{V}(\vec{r}) = \Omega(\vec{r}) \times \vec{r} + \sum_{f=1}^{F} G \bullet s_f$$

Ω is the angular velocity vector

effect of interseismic strain accumulation is given by an elastic Green's function G

response to backslip distribution, s, on each of, f, faults.

Modeling Broadscale Deformation From Plate Motions and Elastic Strain Accumulation, Murray and Segall, USGS NEHRP report.

$$\vec{V}(\vec{r}) = \Omega(\vec{r}) \times \vec{r} + \sum_{f=1}^{F} G \bullet s_f$$

In general, the model can accommodate zones of distributed horizontal deformation if Ω varies within the zones

latter terms can account both for the Earth's sphericity and viscoelastic response of the lower crust and upper mantle.

Modeling Broadscale Deformation From Plate Motions and Elastic Strain Accumulation, Murray and Segall, USGS NEHRP report.

$$\sum_{f=1}^{F} G \bullet s_f \rightarrow -\frac{a}{\pi}\sum_{f=1}^{F} \Delta\omega_f \sin\phi_f \tan^{-1}\left(\frac{d_f}{a\left(\phi - \phi_f\right)}\right)$$

Where

a is the Earth radius

distance from each fault located at ϕ_f is $a(\phi-\phi_f)$.

Each fault has deep-slip rate

$a\Delta\omega_f\sin\phi_f$,

where $\Delta\omega_f$ is the difference in angular velocity rates on either side of the fault.

Modeling Broadscale Deformation From Plate Motions and Elastic Strain Accumulation, Murray and Segall, USGS NEHRP report.