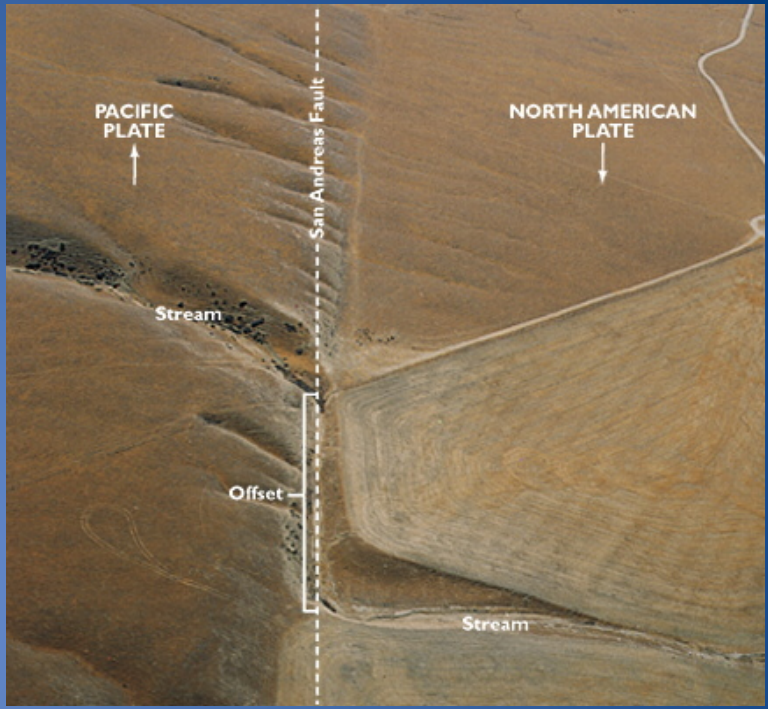
The Weertmans and the San Andreas Fault: How a dislocation solution became a key tool in earthquake science



Seth Stein & James Neely
Earth & Planetary Sciences, Northwestern

Weertman, J., and J. R. Weertman, *Elementary Dislocation Theory*, 213 pp., Macmillan, New York, 1964.

SAN FRANCISCO EARTHQUAKE
April 18, 1906

3000 deaths
28,000 buildings destroyed (most by fire)
$10B damage

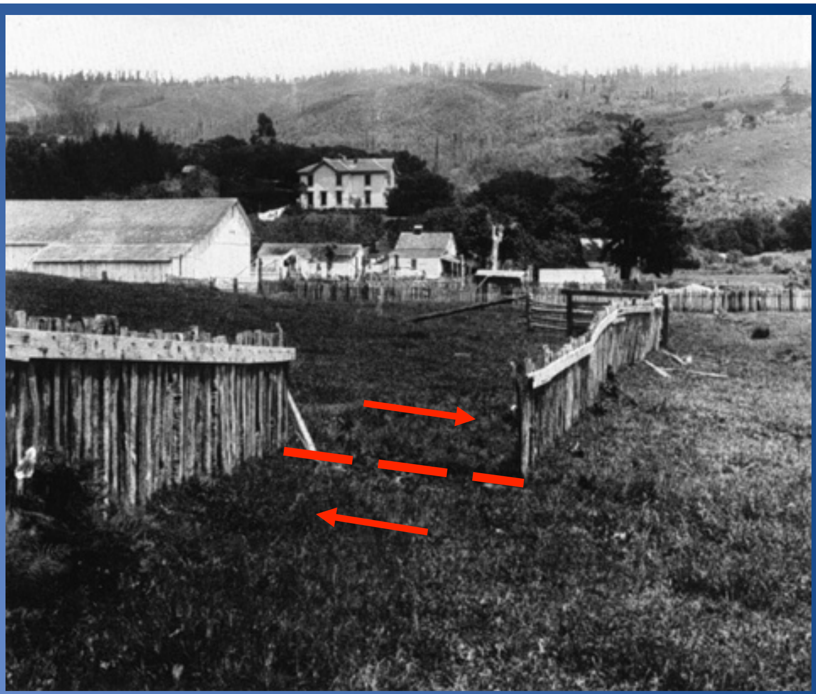
"The whole street was undulating as if the waves of the ocean were coming toward me."

"I saw the whole city enveloped in a pile of dust caused by falling buildings."

"Inside of twelve hours half the heart of the city was gone"

Average 4m of motion
West side moved north

Motion along hundreds of km of San Andreas Fault

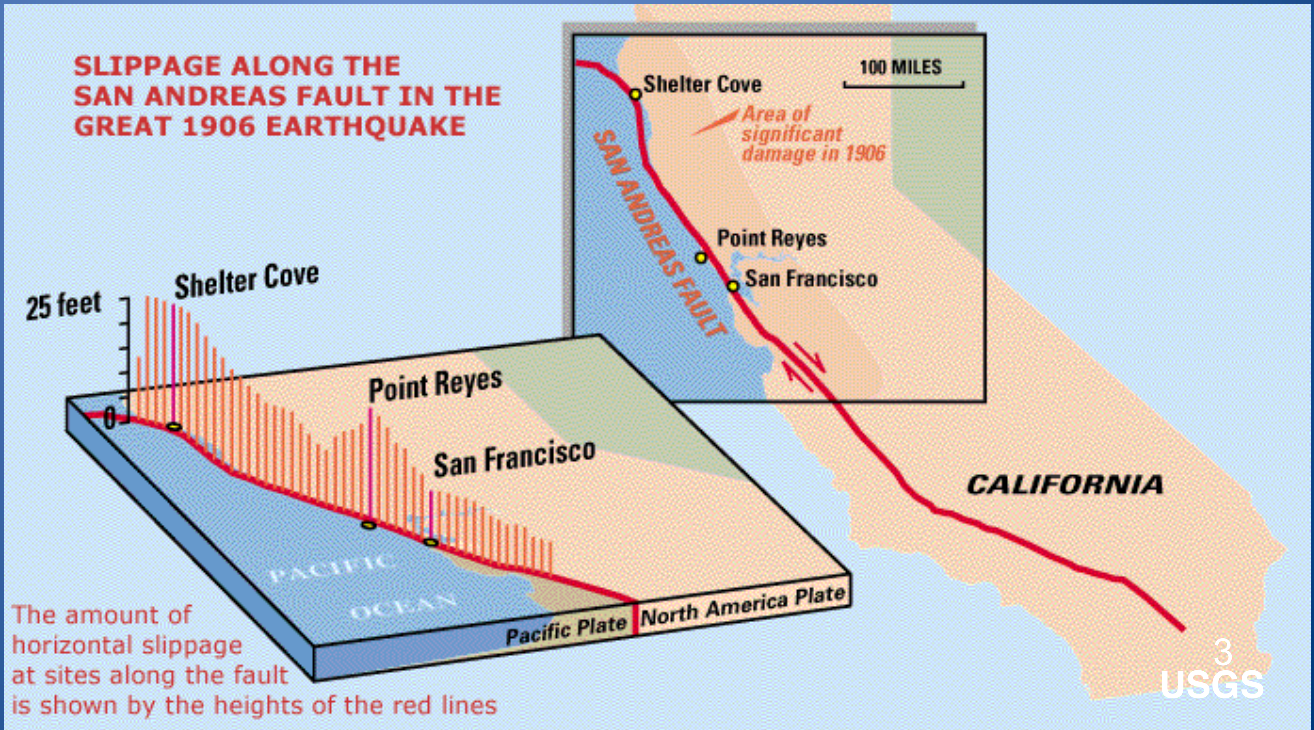


Questions arose:

What is the fault?

Why does the ground move?

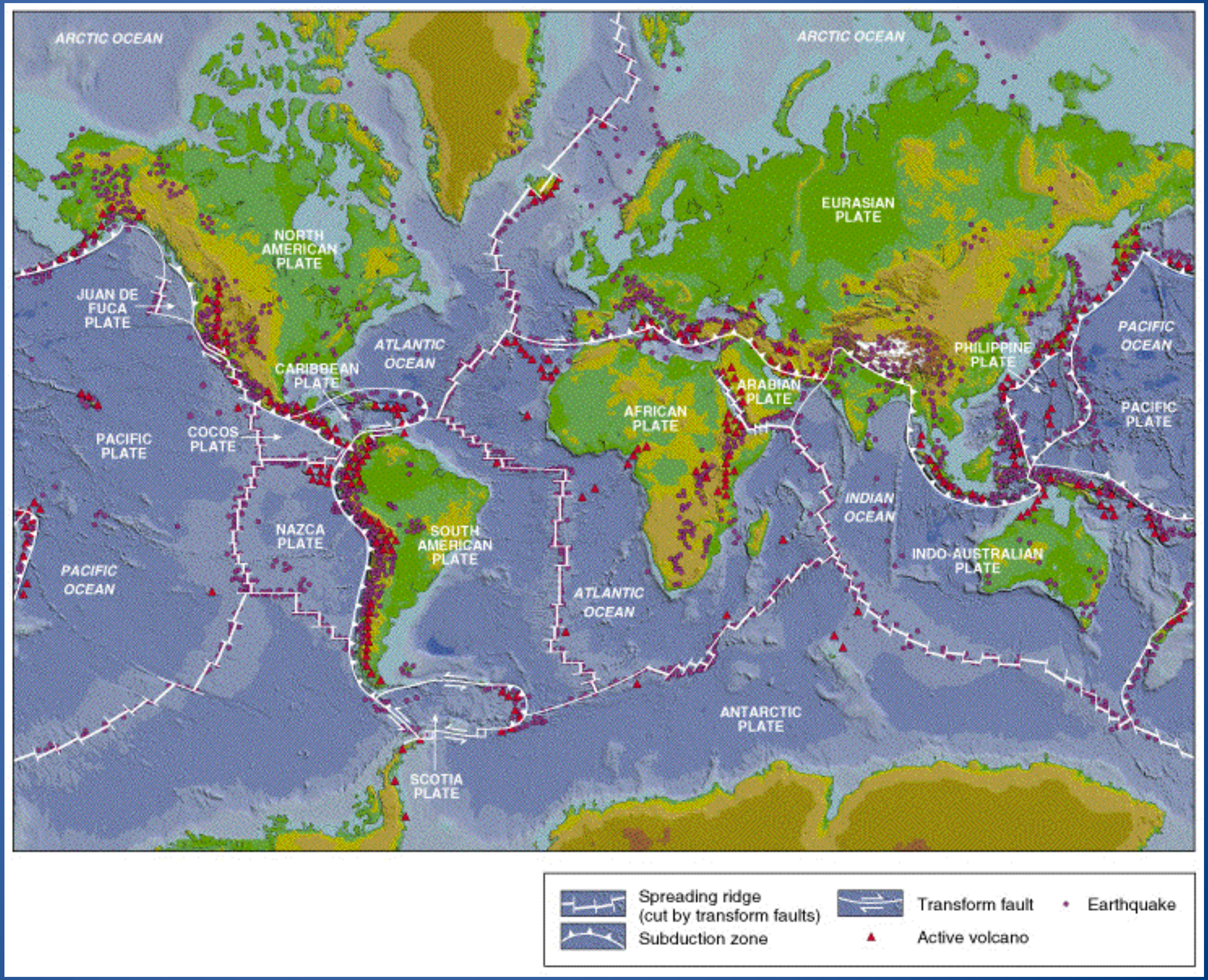
Will another quake happen and when?



USGS

1960’s discovery of Plate Tectonics: Earth's outer shell made up of ~15 major rigid plates ~ 100 km thick that move relative to each other at speeds of a few cm/yr

Deformation occurs at their boundaries, giving rise to earthquakes, mountain building, volcanism, and other spectacular phenomena.



San Andreas Fault is boundary between Pacific and North America plates

It's a strike-slip fault!

This Dynamic Earth:
The Story of Plate Tectonics, USGS

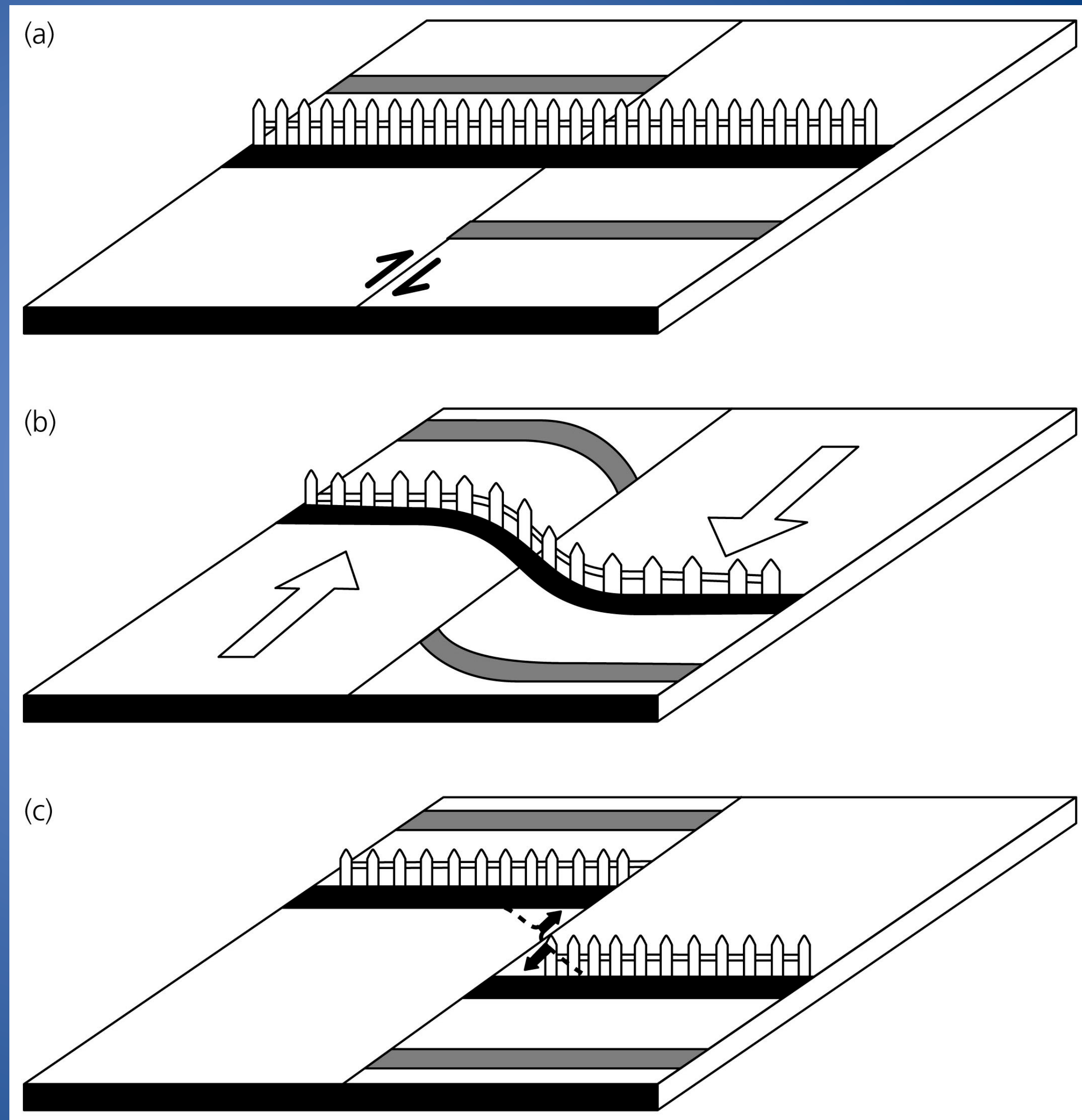
Scott Cronk (YouTube)

ELASTIC REBOUND OR SEISMIC CYCLE MODEL

Materials at distance on opposite sides of the fault move relative to each other, but friction on the fault "locks" it and prevents slip

Eventually strain accumulated is more than the rocks on the fault can withstand, and the fault slips in an earthquake

Earthquake releases strain



Long term slip rate and earthquake recurrence on the San Andreas

Wallace Creek is offset by 130 m

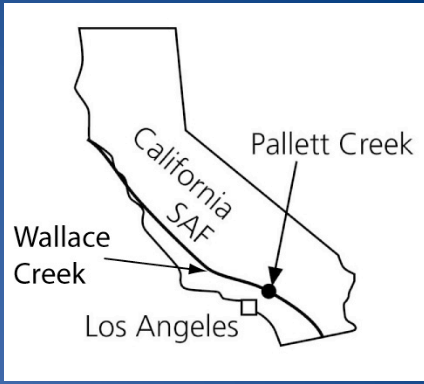
Offset developed over 3700 years

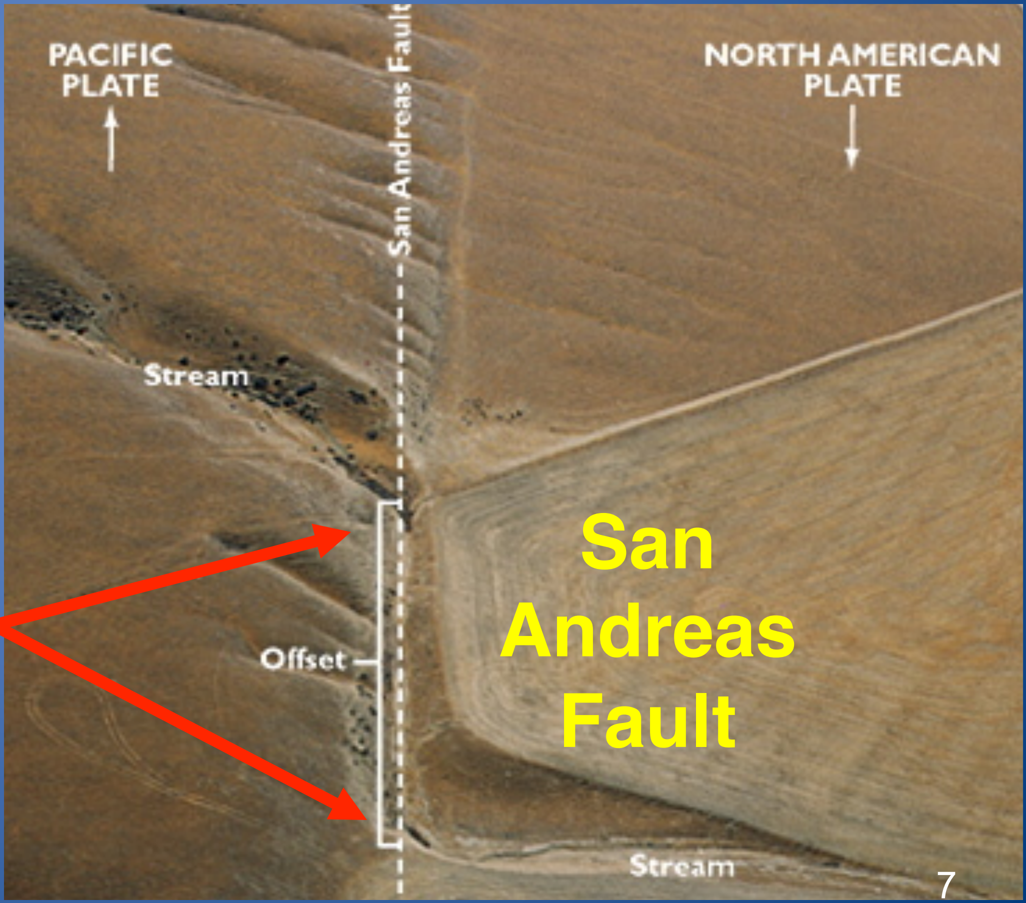
130 m / 3700 yr = 35 mm/yr

Large earthquakes with ~4 m slip should often on average ~ 115 years apart

1906 + 115 = 2021

Robert Wallace
NU Geology
BA 1938



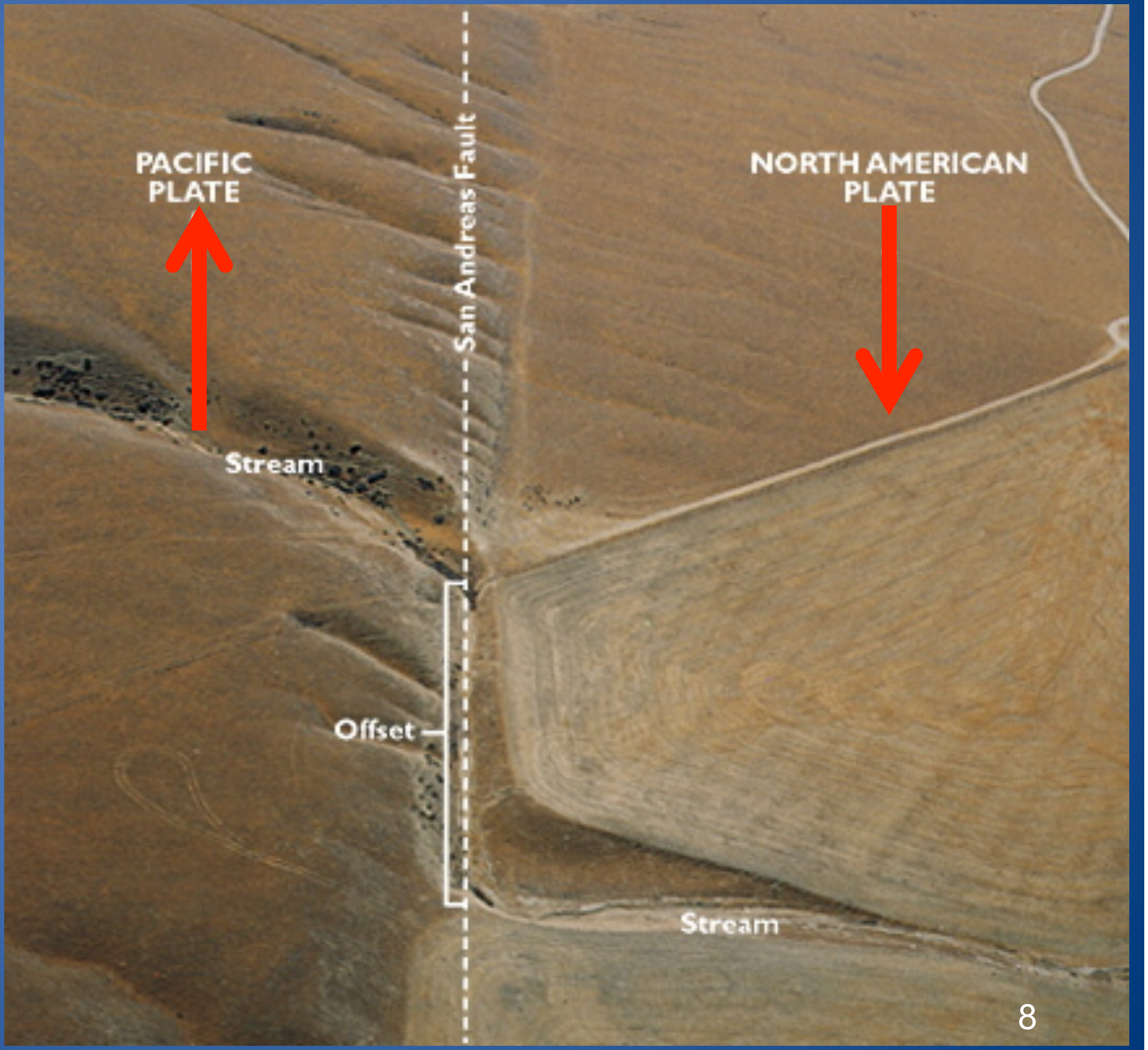


Over thousands of years have had 35 mm/yr motion between Pacific and North America

How fast is the motion *today*, which is storing strain that will be released in the next big earthquake?

Crucial parameter for estimating earthquake hazard

San Andreas Fault – Wallace Creek, California



VOL. 78, NO. 5 JOURNAL OF GEOPHYSICAL RESEARCH FEBRUARY 10, 1973

Geodetic Determination of Relative Plate Motion in Central California

J. C. SAVAGE AND R. O. BURFORD

Weertmans' solution:

$$v = \frac{b}{\pi} arctan \left(\frac{x}{D}\right)$$

$v = observed\ surface\ velocity$

$x = distance\ to\ fault$

$b = plate\ velocity$

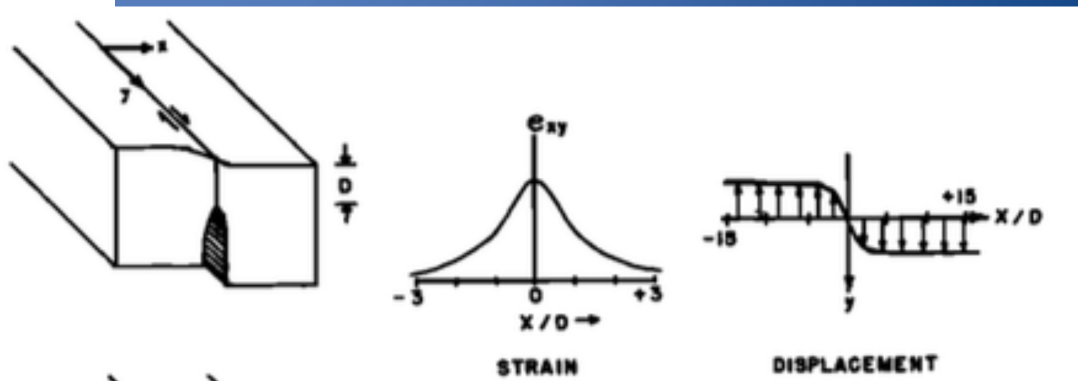
$D = locking\ depth$

upper part of Figure 2. For simplicity we assume that slip on the fault is zero down to depth D but is an amount b everywhere below that depth. Then, in the coordinate system shown in Figure 2, the strike slip displacement v and the tensor shear strain e_{xy} on the free surface are given from the simple screw dislocation model [*Weertman and Weertman*, 1964] by

$$v = (b/\pi) \arctan (x/D) \qquad (1)$$
$$e_{xy} = (bD/2\pi)(x^2 + D^2)^{-1}$$

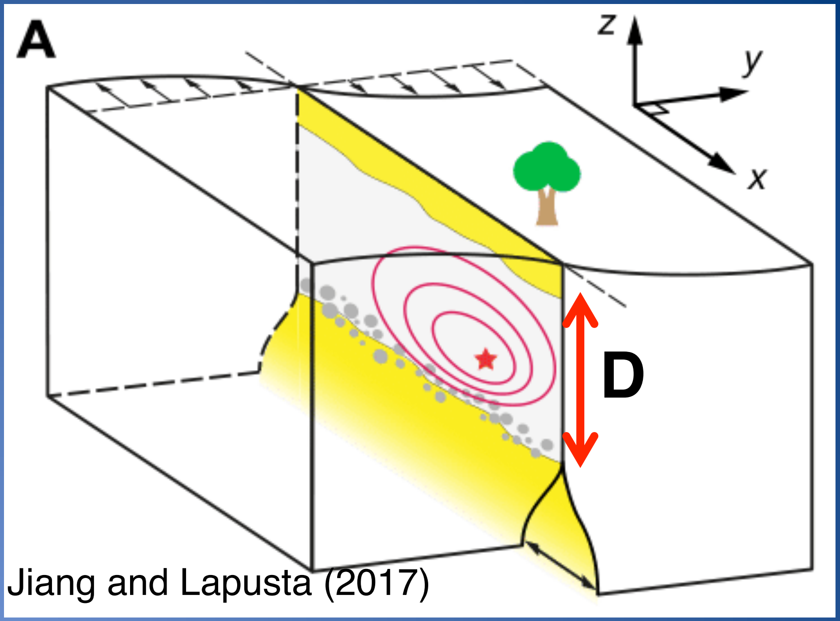
Both quantities are plotted as functions of x/D on the right-hand side of Figure 2. Most of the

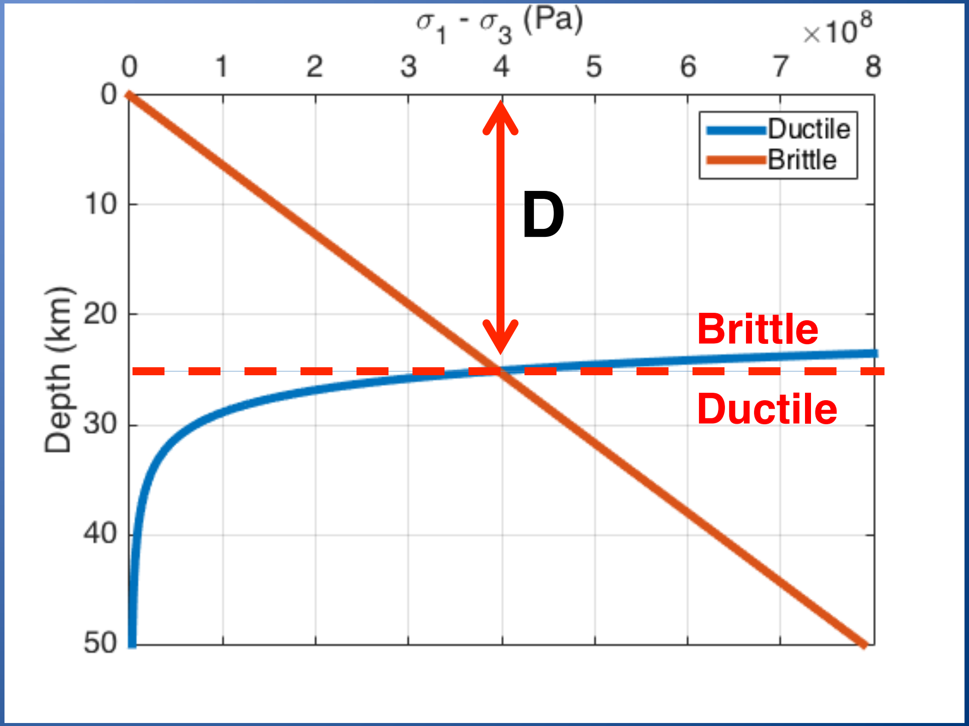
Can provide insight into size and frequency of earthquakes



Locking depth is depth to which rock is strong enough to accumulate elastic strain that will be released in future earthquakes, and thus affects their magnitude

Depends on rock properties, temperature and pressure, pore pressure, and strain rate





VOL. 78, NO. 5 JOURNAL OF GEOPHYSICAL RESEARCH FEBRUARY 10, 1973

Geodetic Determination of Relative Plate Motion in Central California

Geodetic determination of relative plate motion in central California

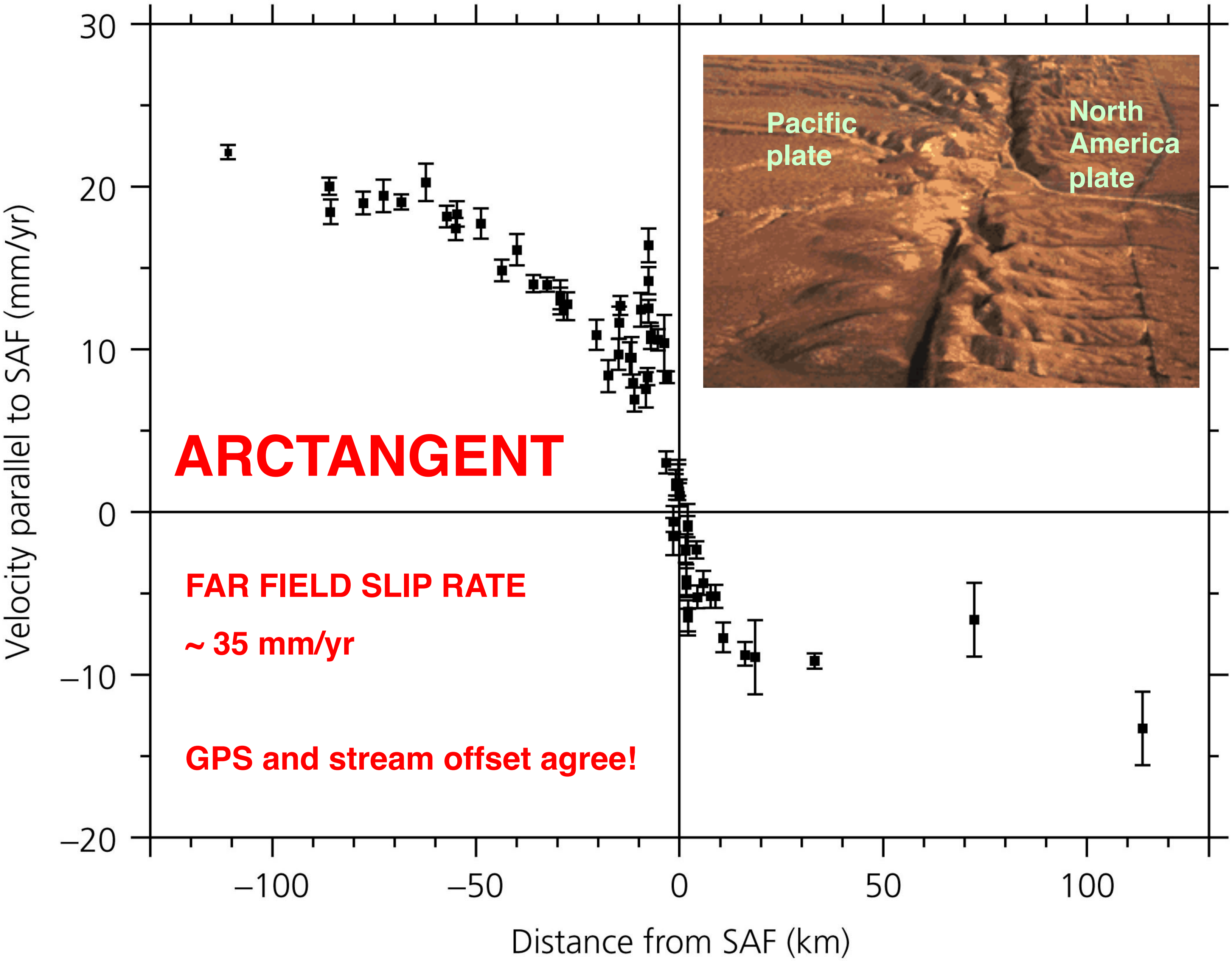
JC Savage, RO Burford - Journal of Geophysical Research, 1973 - Wiley Online Library

Geodetic data along the San Andreas fault between Parkfield and San Francisco, California (latitudes 36° N and 38° N, respectively), have been re-examined to estimate the current relative movement between the American and Pacific plates across the San Andreas fault …

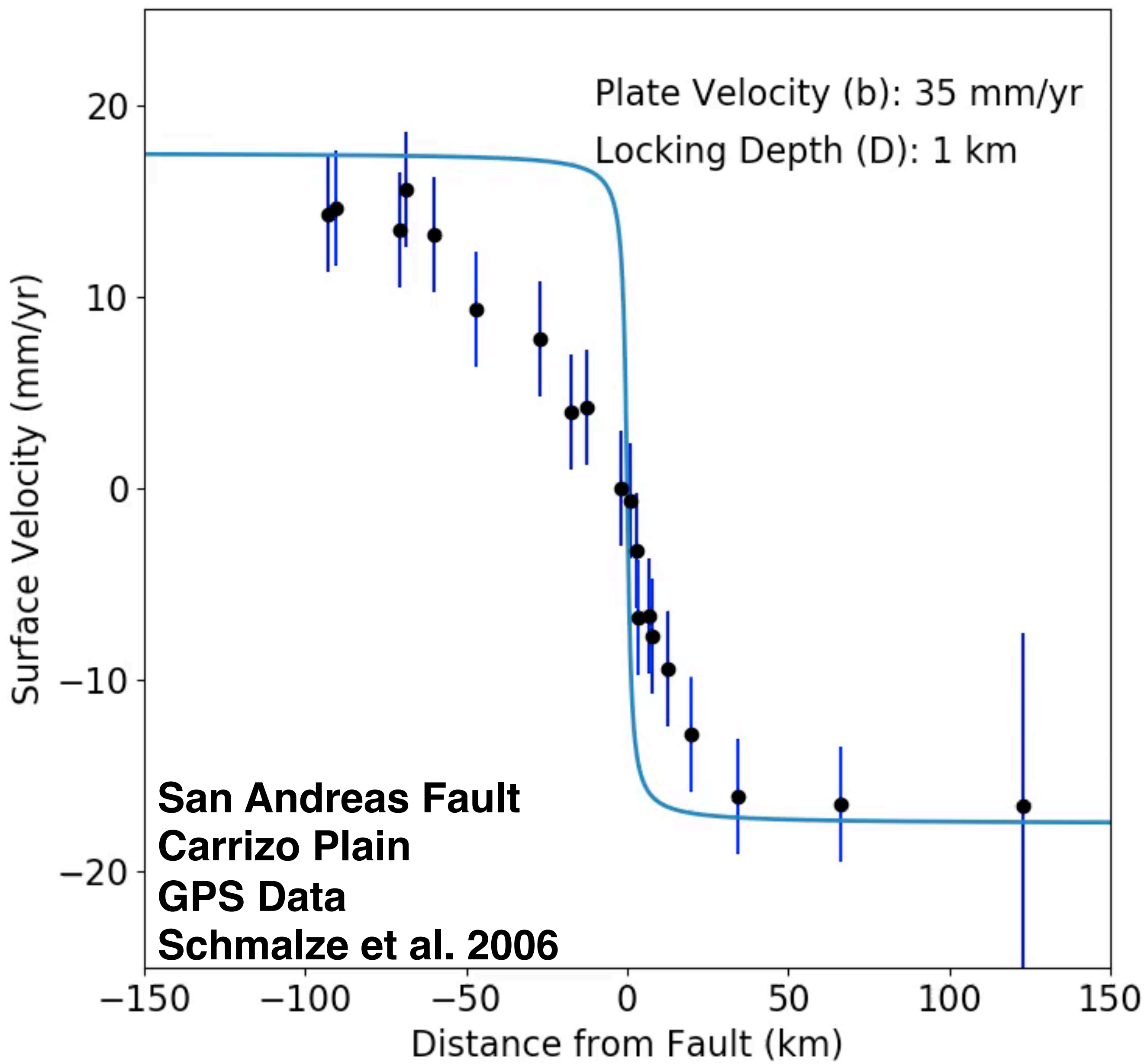
Savage & Burford is heavily cited and their method applied worldwide

Geologists don’t have copies of *Elementary Dislocation Theory,* but we have GPS

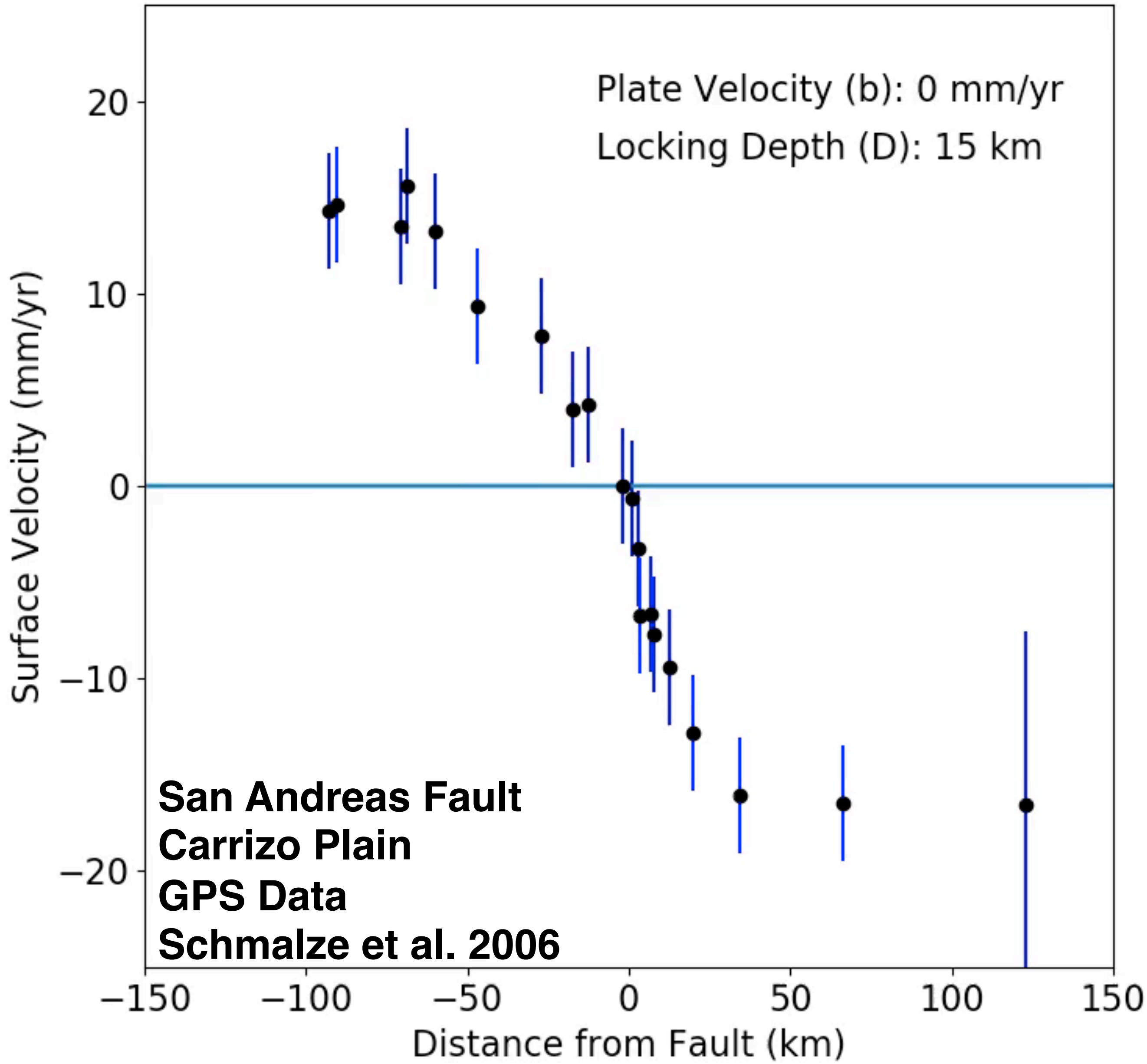
Figure 4.5-13: Fault-parallel horizontal interseismic motion across the San Andreas fault.

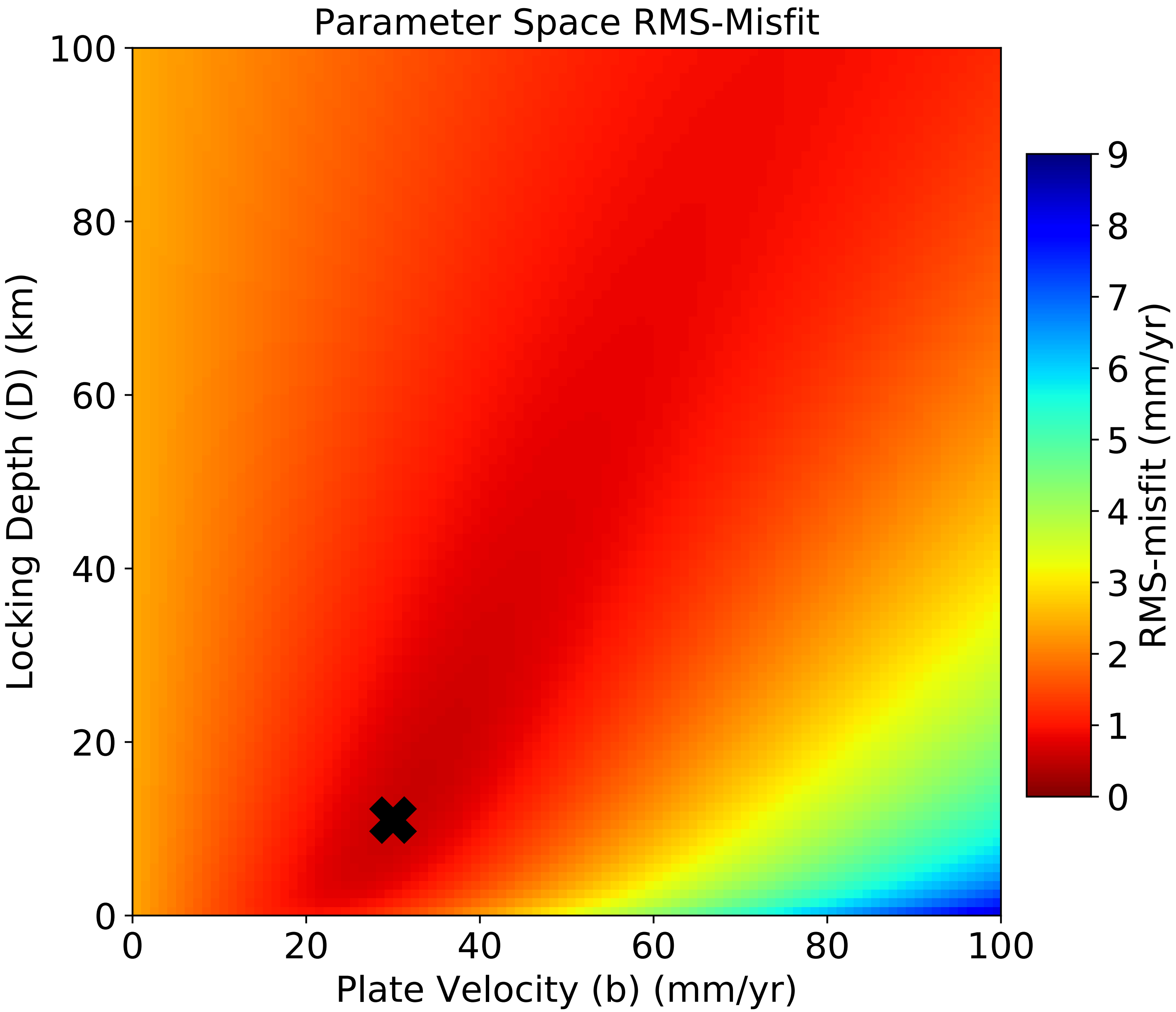


Fix Rate, Change Locking Depth

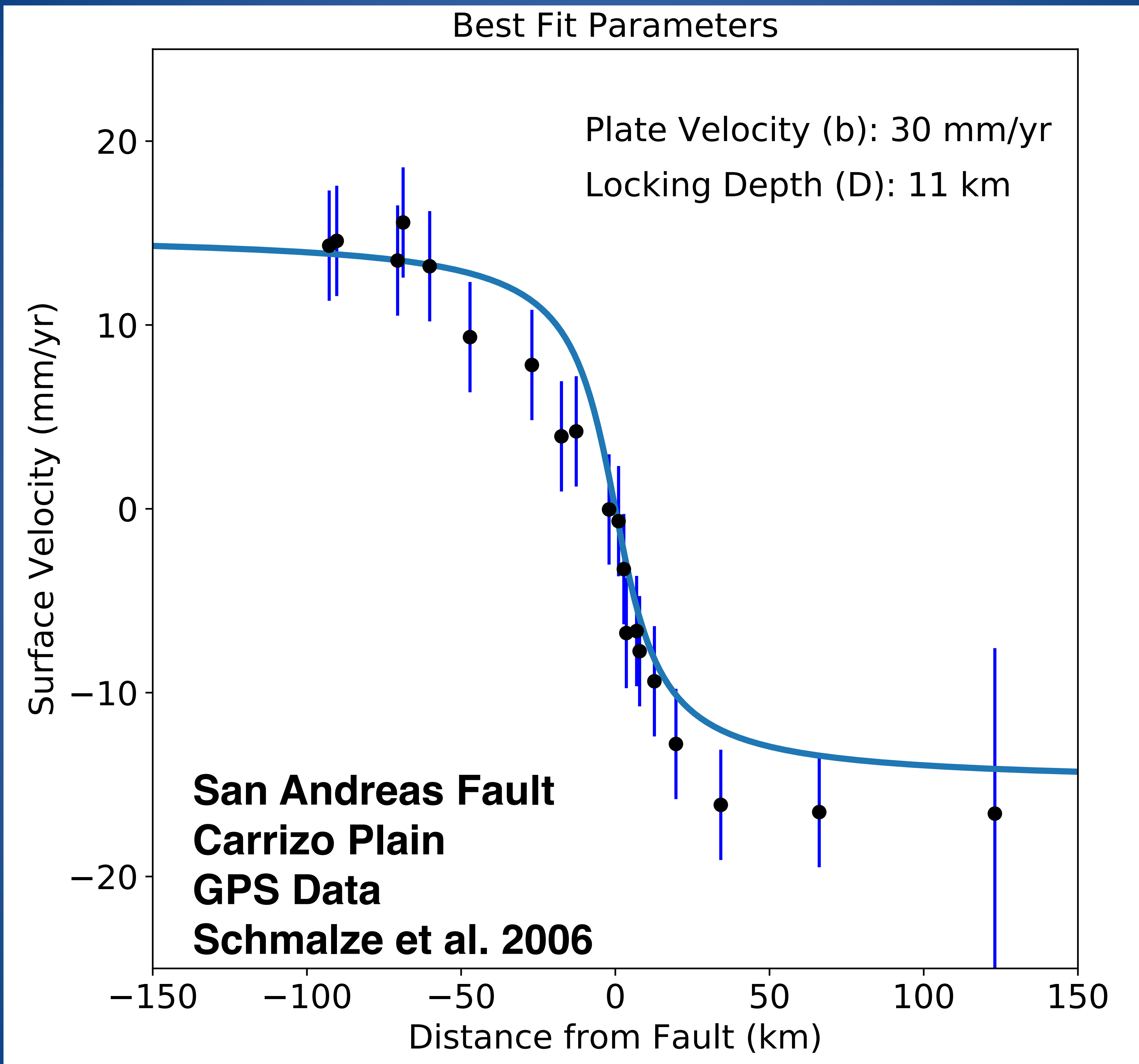


Change Rate, Fix Locking Depth



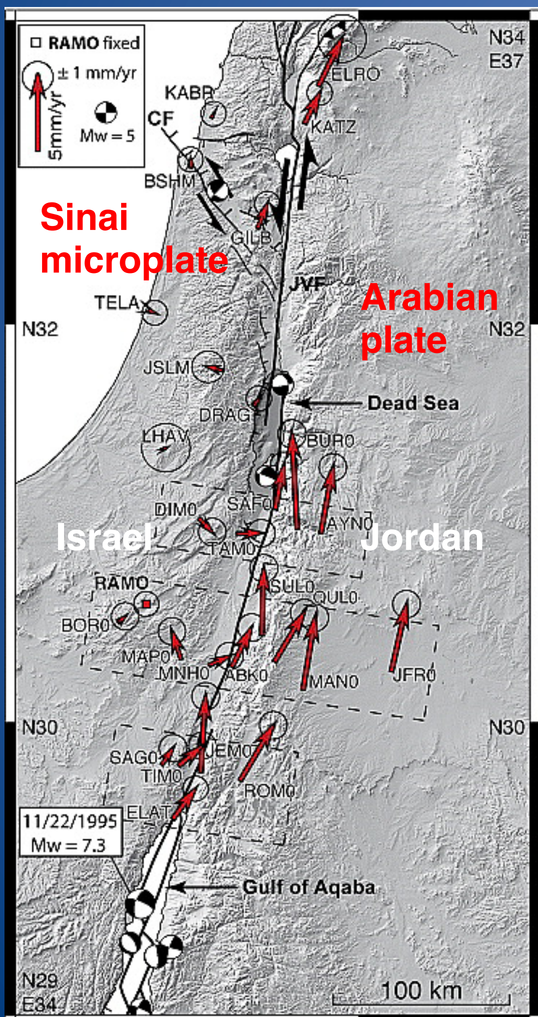


Parameter Space RMS-Misfit
Locking Depth (D) (km)
Plate Velocity (b) (mm/yr)
RMS-misfit (mm/yr)
0
20
40
60
80
100
0
1
2
3
4
5
6
7
8
9

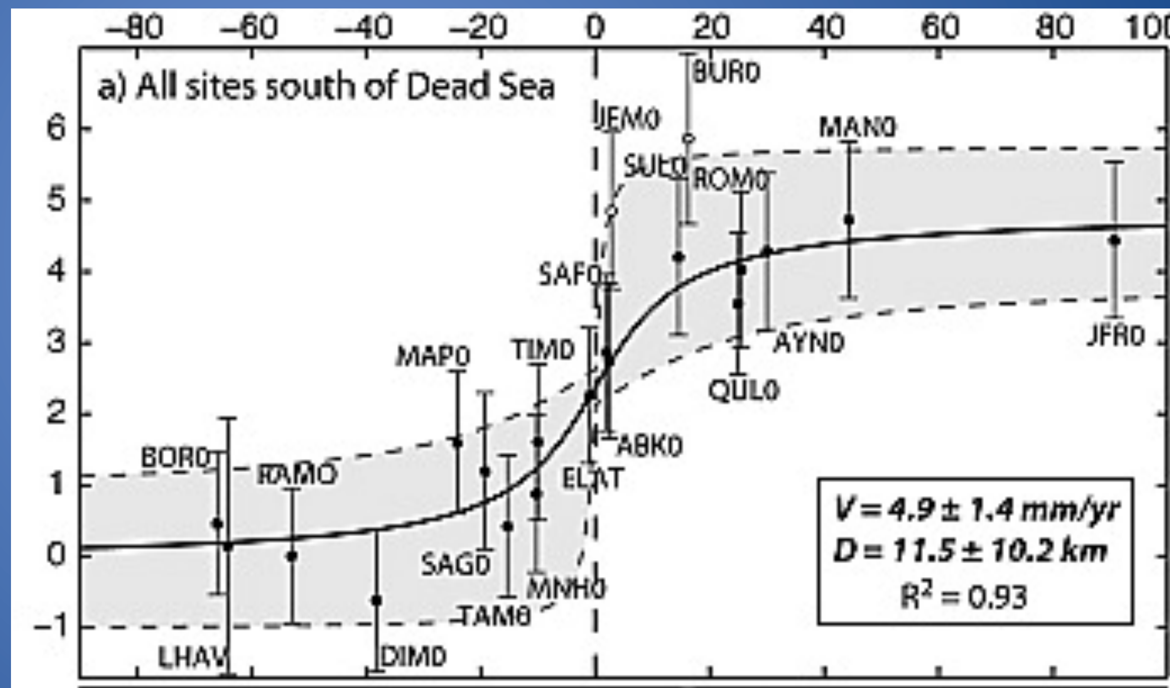

Best Fit Parameters
Plate Velocity (b): 30 mm/yr
Locking Depth (D): 11 km
San Andreas Fault
Carrizo Plain
GPS Data
Schmalze et al. 2006
Surface Velocity (mm/yr)
Distance from Fault (km)
20
10
0
−10
−20
−150
−100
−50
0
50
100
150

Slip rate and locking depth from GPS profiles across the southern Dead Sea Transform

Maryline Le Beon, Yann Klinger, Abdel Qader Amrat, Amotz Agnon, Louis Dorbath, Gidon Baer, Jean-Claude Ruegg, Olivier Charade, Omar Mayyas



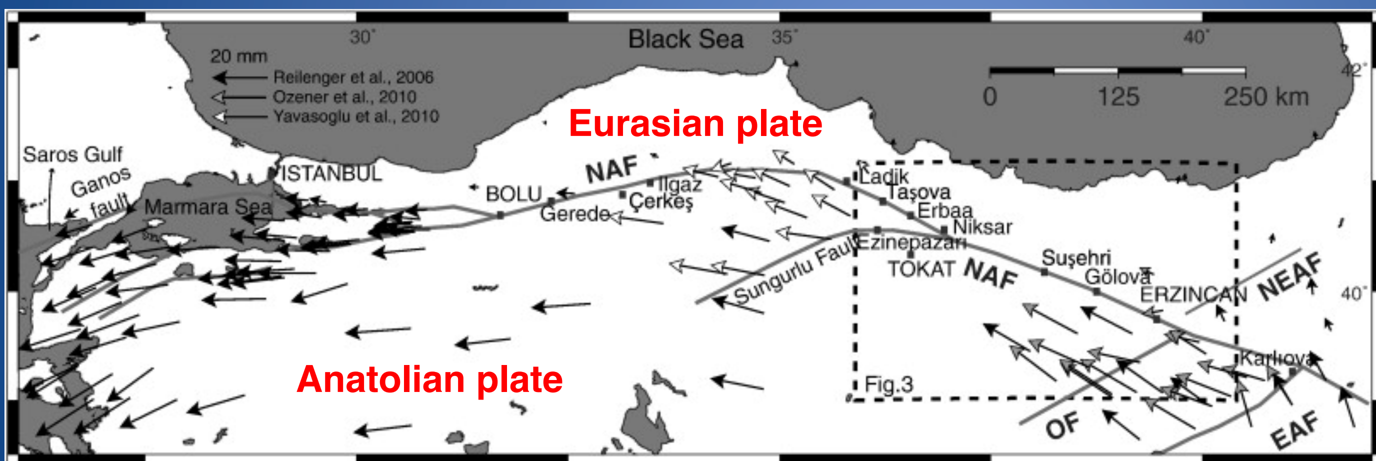
Arctangent



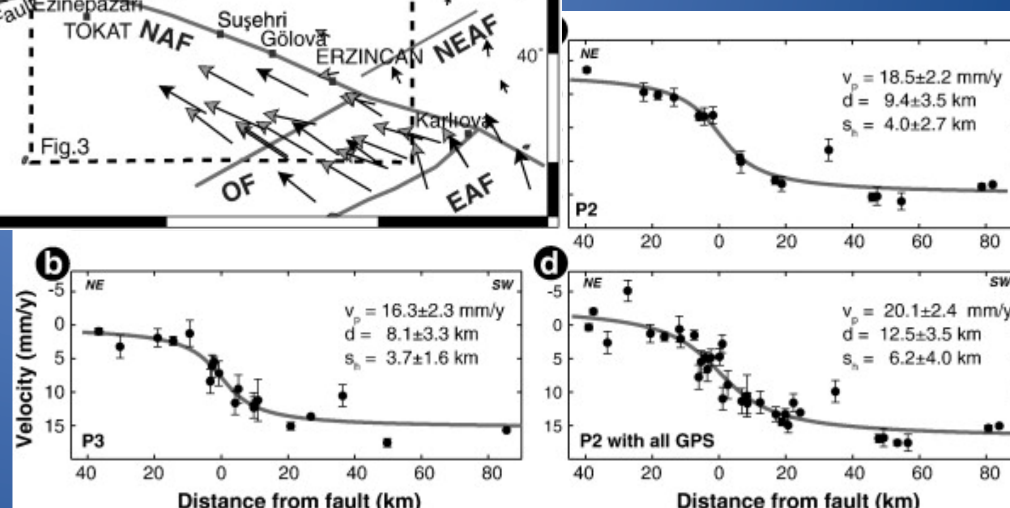
Site of many historical earthquakes since Biblical times, more expected

Crustal deformation and kinematics of the Eastern Part of the North Anatolian Fault Zone (Turkey) from GPS measurements

Orhan Tatar [a], Fatih Poyraz [b], Halil Gürsoy [a], Ziyadin Cakir [c], Semih Ergintav [d], Zafer Akpınar [a], Fikret Koçbulut [a], Fikret Sezen [a], Tarık Türk [b], Kemal Ö. Hastaoğlu [b], Ali Polat [a], B. Levent Mesci [a], Önder Gürsoy [e], İ. Ercüment Ayazlı [f], Rahşan Çakmak [d], Alpay Belgen [d], Hakan Yavaşoğlu [e]



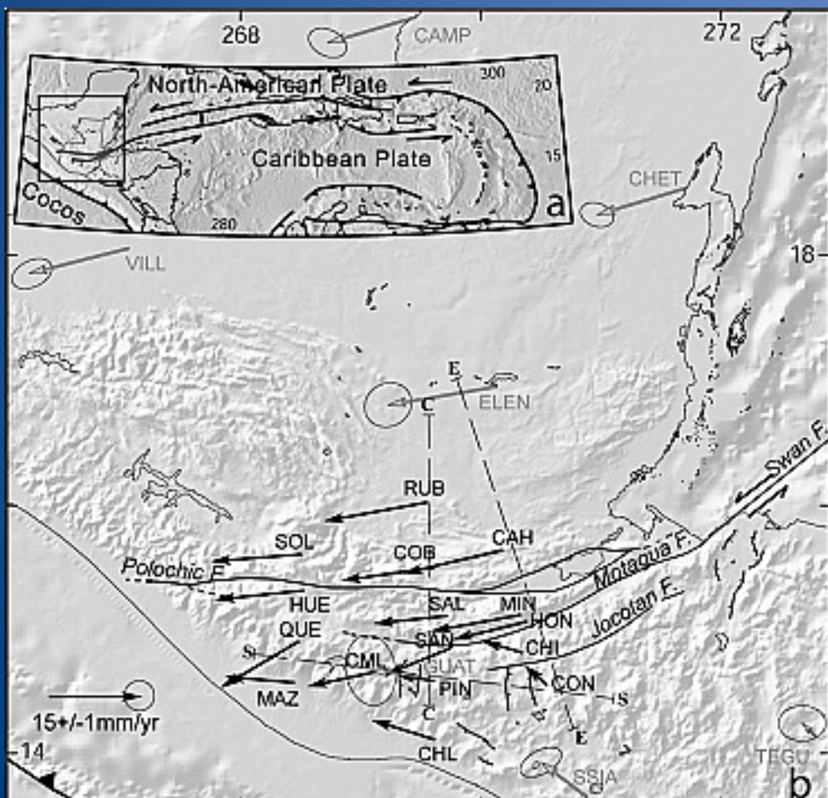
Arctangent

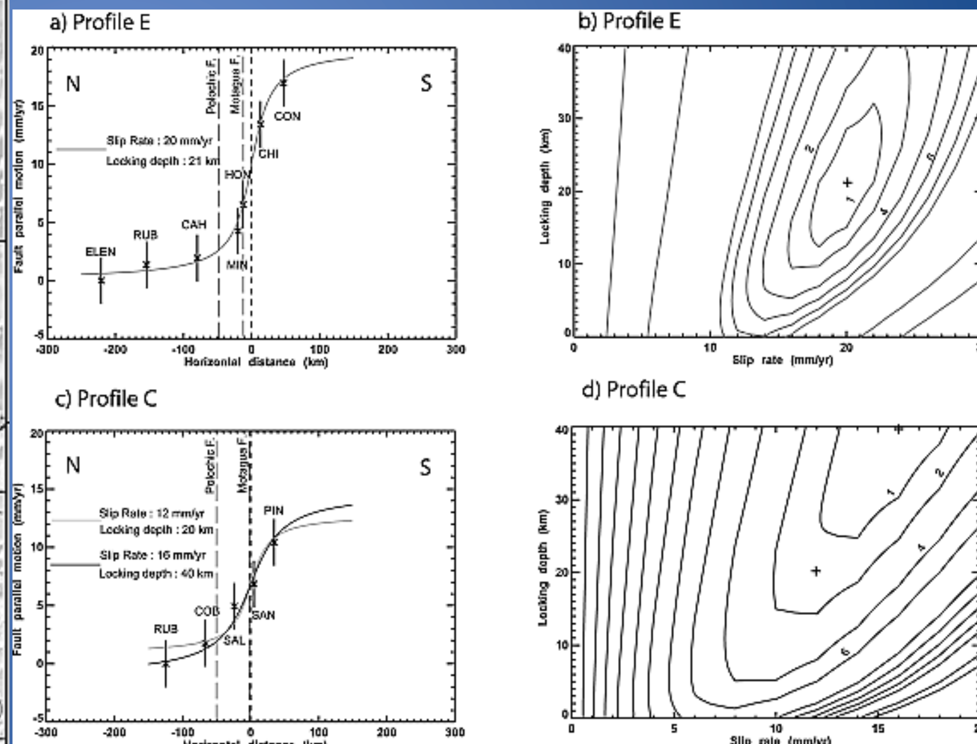


Site of 1999 Mw 7.6 Izmit earthquake, another expected soon

Kinematics of the North American–Caribbean-Cocos plates in Central America from new GPS measurements across the Polochic-Motagua fault system

H. Lyon-Caen,[1] E. Barrier,[2] C. Lasserre,[1] A. Franco,[1] I. Arzu,[3] L. Chiquin,[4] M. Chiquin,[4] T. Duquesnoy,[5] O. Flores,[6] O. Galicia,[7] J. Luna,[6] E. Molina,[8] O. Porras,[8] J. Requena,[4] V. Robles,[9] J. Romero,[10] and R. Wolf[7]



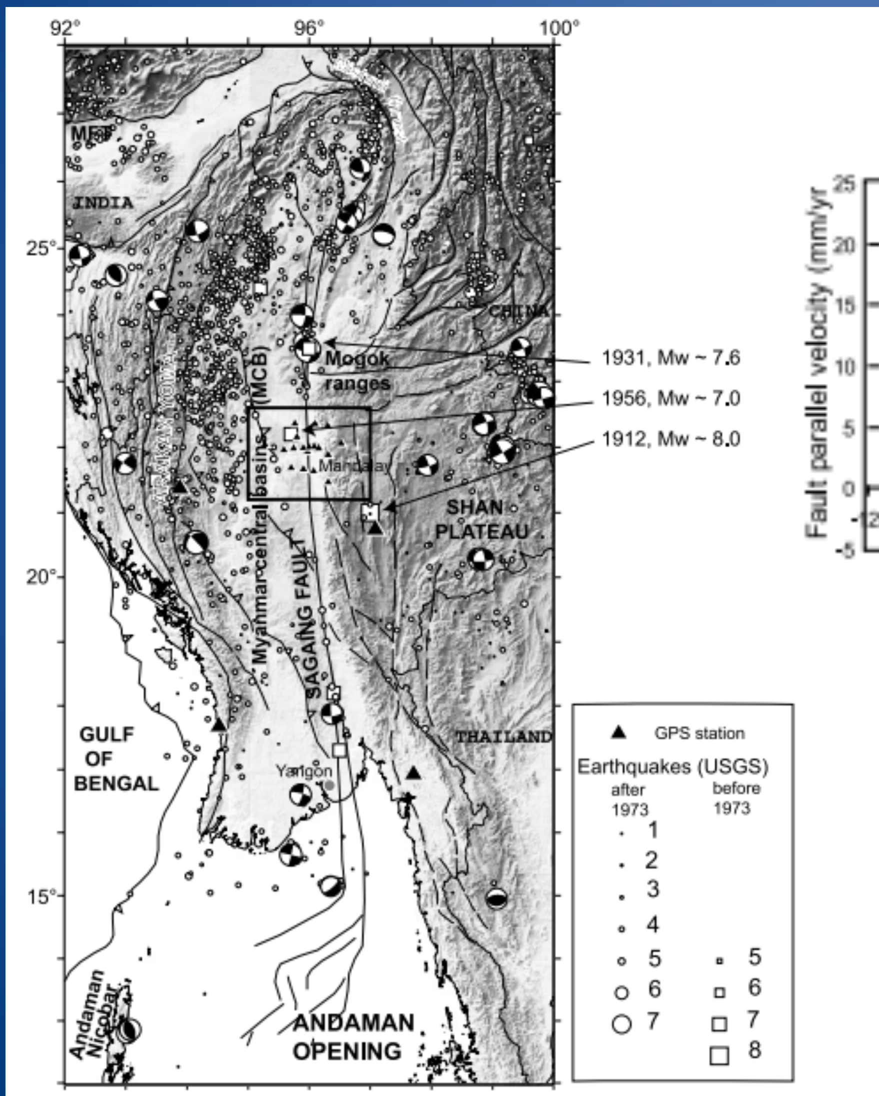


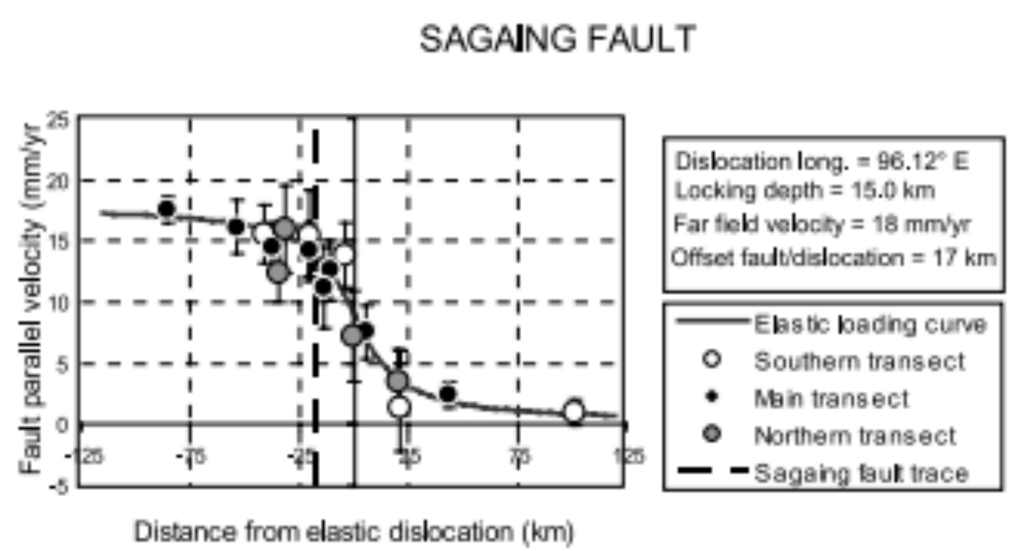
Site of 1975 Mw 7.5 Guatemala earthquake

Present-day crustal deformation around Sagaing fault, Myanmar

Christophe Vigny,[1] Anne Socquet,[1] Claude Rangin,[1] Nicolas Chamot-Rooke,[1] Manuel Pubellier,[1] Marie-Noëlle Bouin,[2] Guillaume Bertrand,[1,3] and M. Becker[4]

Received 29 May 2002; revised 7 July 2003; accepted 23 July 2003; published 19 November 2003.





Another arctangent!

Most earthquakes at plate boundaries, where motion is fast

Some from slow motion inside plates

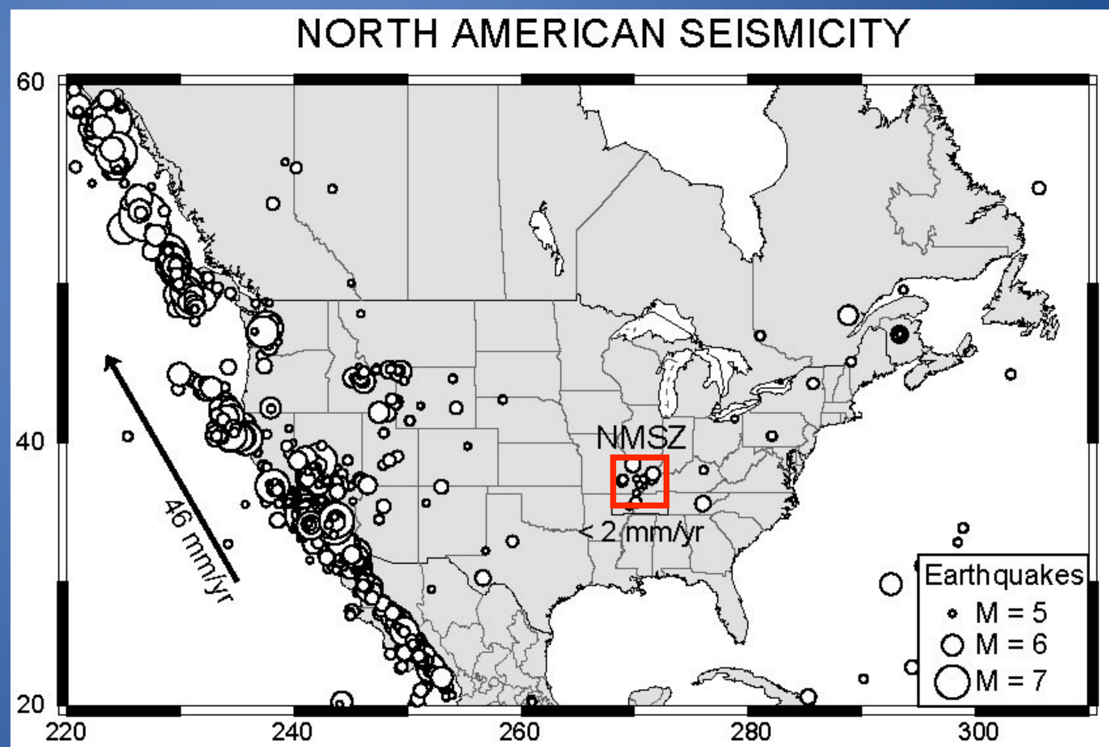
New Madrid seismic zone in central U.S.

M 7 earthquakes in 1811-12

Small earthquakes continue

Big ones might happen again

What's happening today?



New Madrid GPS surveys

Significant motion expected as strain builds up for next earthquake

Best fitting arctangent gives rate 0.2 ± 2.4 mm/year.

No significant motion!

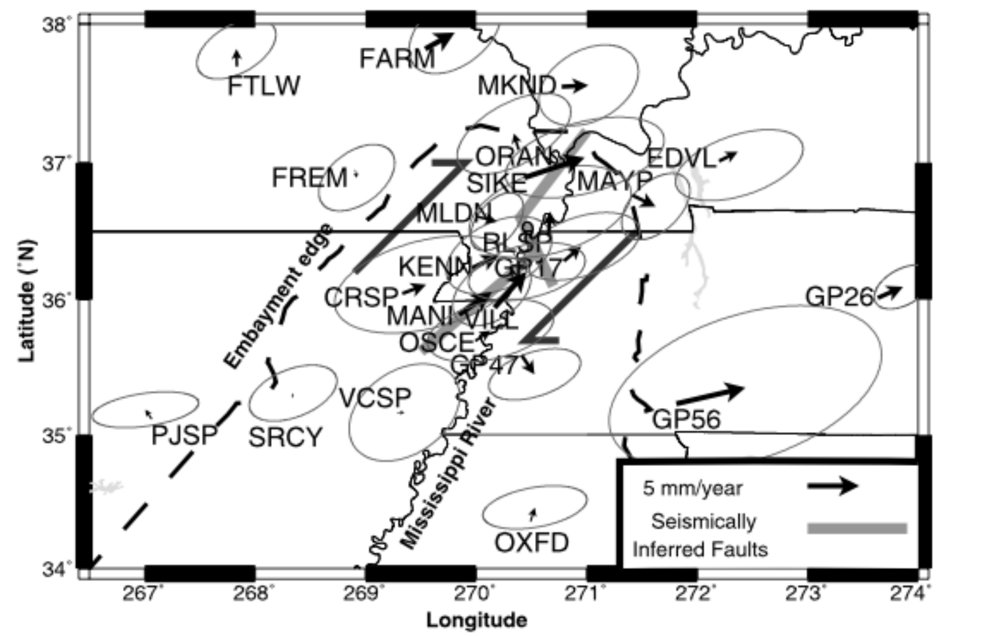
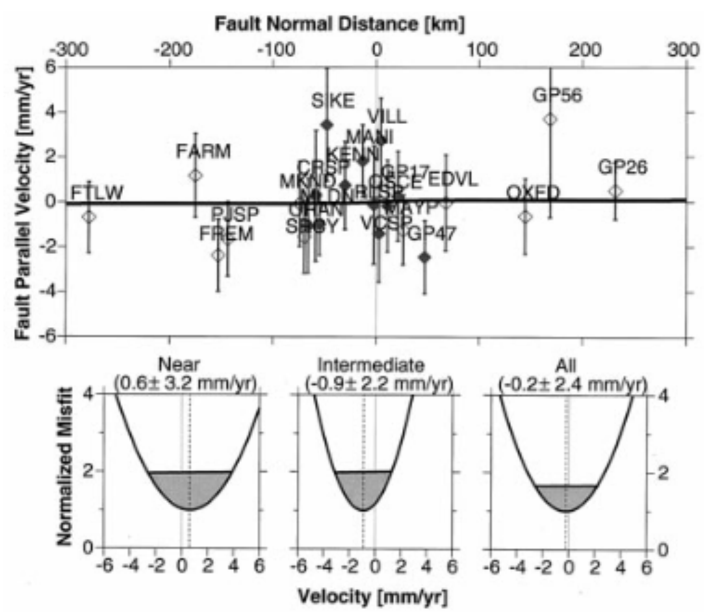


Fig. 1. Residual horizontal site velocities (1997 to 1991) for the New Madrid GPS network, after removal of the motion of the North American plate. Velocities are small, within 2σ error ellipses.

Fig. 2. (**Top**) Profile of site velocities with 1σ error bars, parallel to the approximate strike of the major strike-slip faults in the NMSZ. Solid and open symbols denote near- and intermediate-field sites. Mean velocity is removed. Also shown is a best-fitting model profile for a locked vertical strike-slip fault driven by interseismic motion. (**Bottom**) Misfit as a function of interseismic rate is shown with 2σ ranges shaded. None of the best-fitting rates differs significantly from zero.

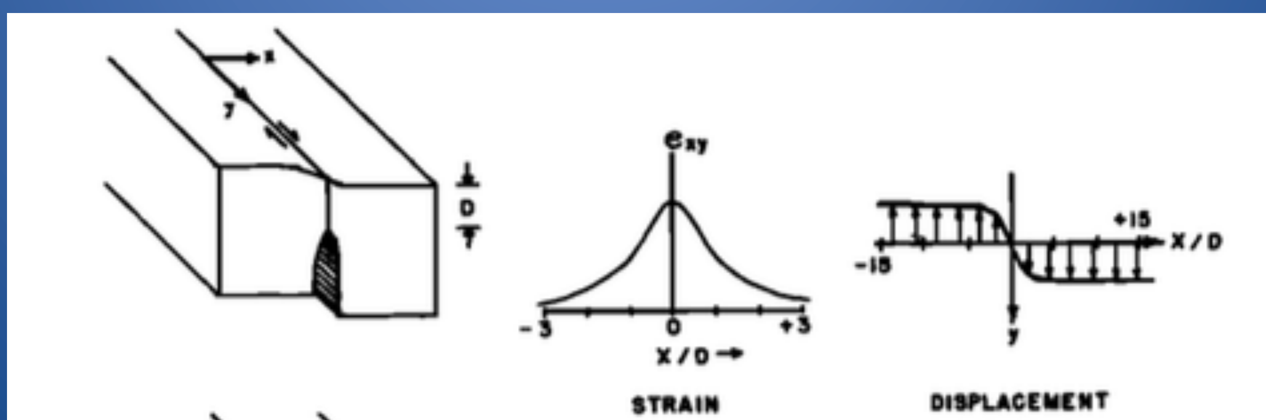


Hans & Julia Weertman's 1964 solution has become geophysicists' standard tool for inferring slip rates on strike-slip faults worldwide and making crucial inferences about plate motions and earthquake recurrence

upper part of Figure 2. For simplicity we assume that slip on the fault is zero down to depth D but is an amount b everywhere below that depth. Then, in the coordinate system shown in Figure 2, the strike slip displacement v and the tensor shear strain e_{xy} on the free surface are given from the simple screw dislocation model [*Weertman and Weertman*, 1964] by

$$v = (b/\pi)\arctan(x/D)$$
$$e_{xy} = (bD/2\pi)(x^2 + D^2)^{-1} \quad (1)$$

Both quantities are plotted as functions of x/D on the right-hand side of Figure 2. Most of the



The Weertmans also had a major role in bringing ideas about high temperature creep of rock into the geoscience community

HIGH TEMPERATURE CREEP OF ROCK AND MANTLE VISCOSITY ×10041

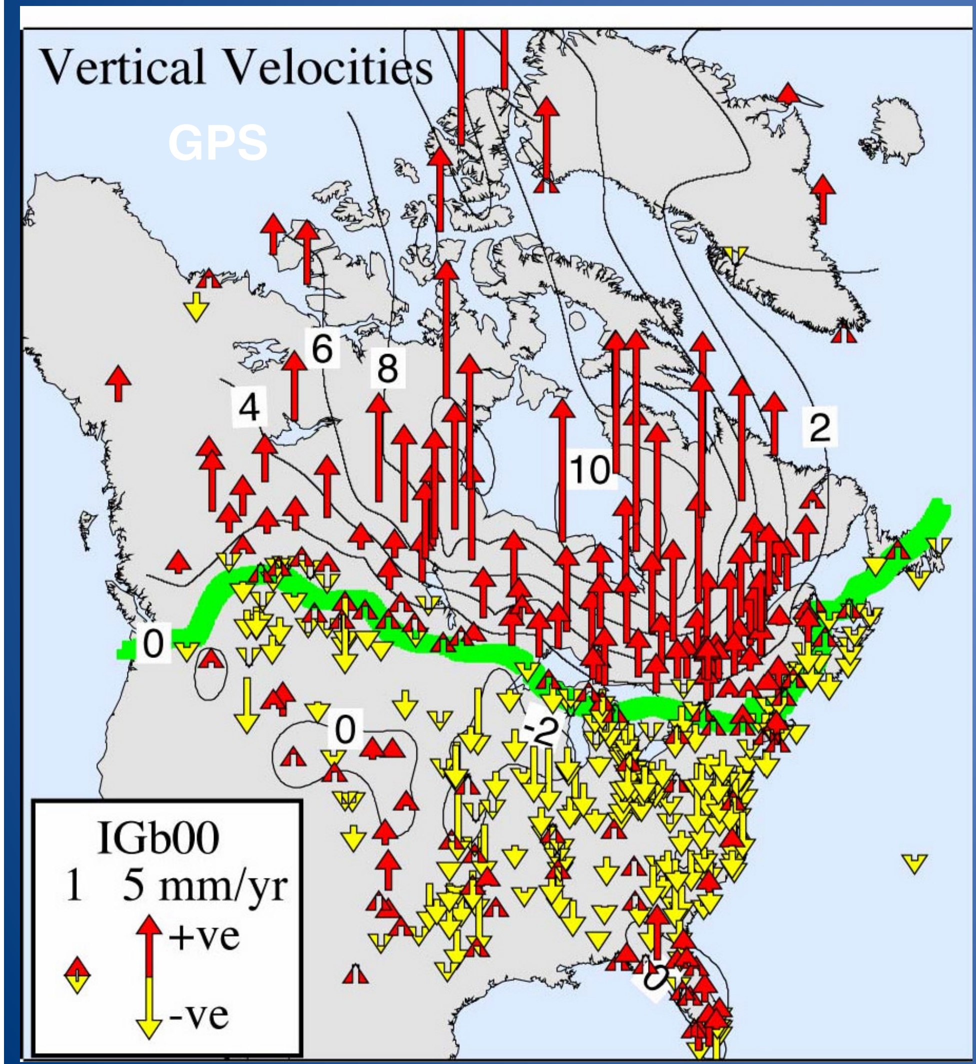
Johannes Weertman
Departments of Materials Science and Geological Sciences and Materials Research Center, Northwestern University, Evanston, Illinois 60201

Julia R. Weertman
Department of Materials Science, Northwestern University, Evanston, Illinois 60201

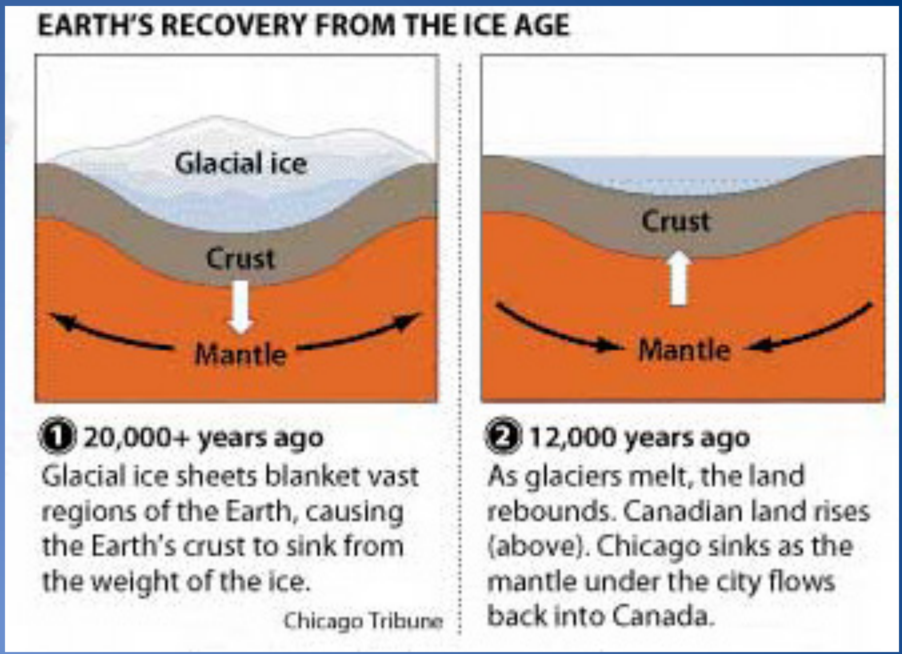
[PDF] High temperature creep of rock and mantle viscosity
J Weertman, JR Weertman, Annual Review, of Earth and - Annual Review of Earth and ..., 1975 - annualreviews.org
Some 20 years ago, the field of glaciology began a renaissance when laboratory determined creep properties of ice were used as the basis of theoretical analyses of the mechanics of glaciers, ice sheets, ice caps, and ice shelves (Lliboutry 1965, Paterson 1969) ...
Cited by 320 Related articles All 3 versions Web of Science: 233

Creep laws for the mantle of the Earth
J Weertman - Phil. Trans. R. Soc. Lond. A, 1978 - rsta.royalsocietypublishing.org
The analyses of glacial rebound data by Gathles and by Peltier and Andrews have led them to the conclusion that the flow law of the mantle of the Earth is Newtonian and that the viscosity is essentially a constant (10 22 P) throughout the mantle. In this paper it is ...
Cited by 196 Related articles All 4 versions Web of Science: 135

These are used to infer mantle viscosity from post-glacial rebound



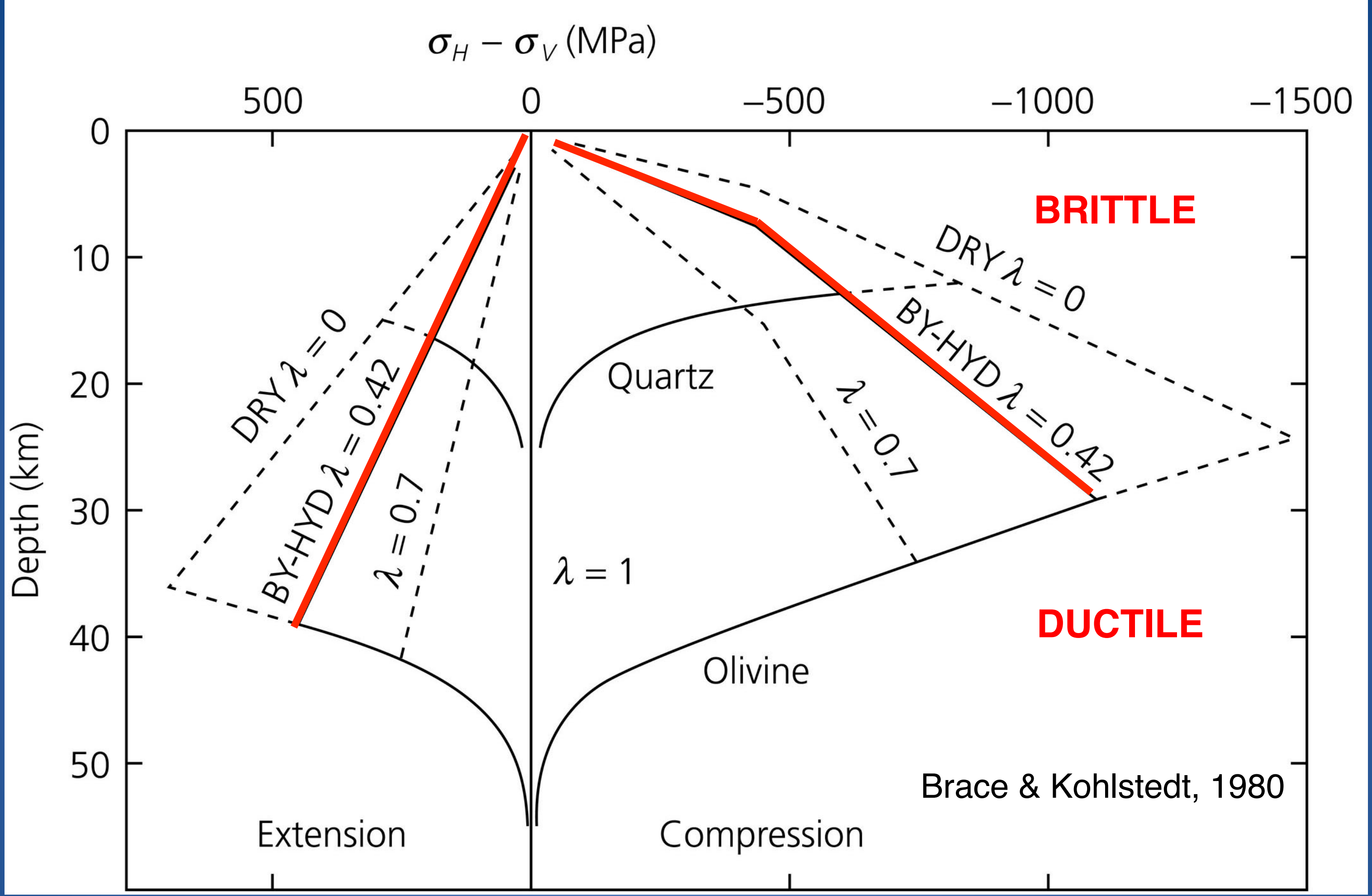
Sella et al., 2007



Canada rises & US sinks

Hinge line agrees with lake level data

Figure 5.7-14: Strength envelopes as a function of depth and material.



And to infer the strength of rocks due to increasing temperature and pressure and thus where earthquakes do and don't occur at depth

The adage “Nice guys finish last” didn’t apply to Hans and Julia Weertman – nice people and superb scientists who finished first.

We in earth science were lucky to have had them as friends.