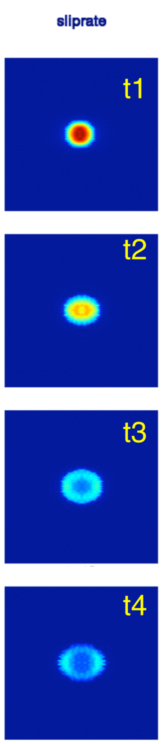
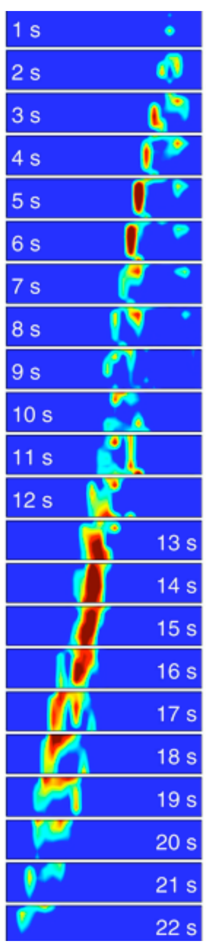
Conditions required to start an earthquake?

upper crust property: ______
fault friction: _______
shear stress on fault exceeds: _______
(at a point? over an area?) ________



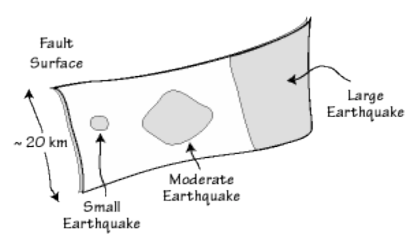
Madariaga,
Wald and Heaton 1994

vs.



We now know what it takes to <u>start</u> an earthquake.

What does it take to make a large earthquake?



They all start
small at the
hypocenter...

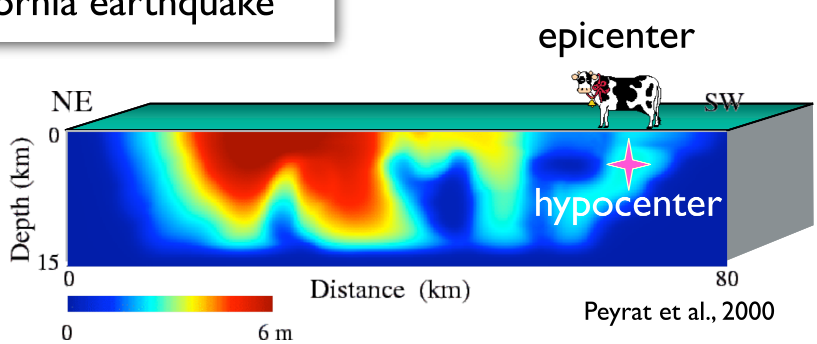
Animation of the Landers earthquake rupture

http://www.edcenter.sdsu.edu/ssc/3d/landers/landers-final-sm.mov

created by Jeff Sale and used with permission.
total time fault was slipping: about 20 seconds
(Tohoku M9 took about three minutes!)

What happens along the fault during a large magnitude earthquake?

1994 M = 7.4 Landers, California earthquake



Peyrat et al., 2000

- rupture begins at the hypocenter and travels away ('unilateral' = one-way, 'bilateral' = both ways)
- maximum slip is **not** usually at the hypocenter
- rupture propagates away from the hypocenter at **about 2-3 km / sec** (slower near the surface).

Approximate! Scaling of earthquake properties with magnitude

M_w	Moment M_o	Length	Mean Slip	Area	Duration *of slip*
4	10^{15} N m	1000 m	2 cm	1 km^2	0.2 s
5	3.0×10^{16} N m	3000 m	10 cm	9 km^2	0.4 s
6	1.1×10^{18} N m	10 km	40 cm	100	5 s
7	3.5×10^{19} N m	80 km	1 m	1000	30 s
8	1.1×10^{21} N m	300 km	6 m	6000	150 s
9	3.5×10^{22} N m	800 km	20 m	6×10^4 km^2	300 s

$$\log M_o = 1.5(M_w + 6.0333)$$

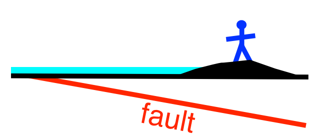
$$M_w = \log M_o/1.5 - 6.0333$$

$$M_o = AsG$$

Slip and slip speed animation for the 2011 M 9.0 Tohoku, Japan earthquake

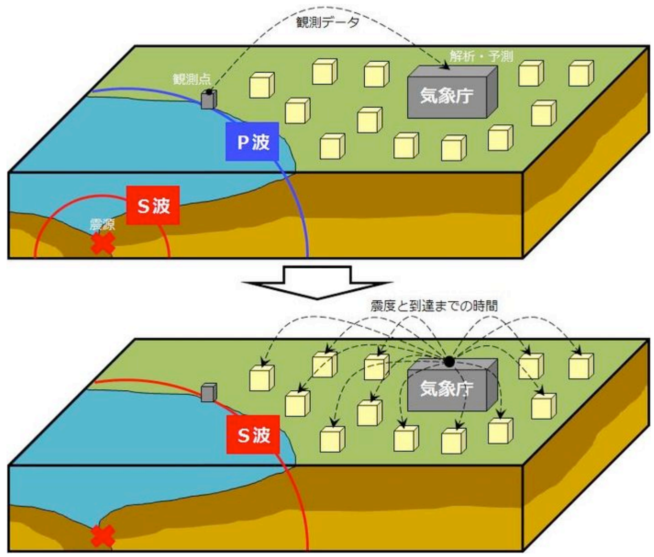
http://www.youtube.com/watch?v=A_dWf9Lr9qE

The fault is almost horizontal, so we can look from above at the slip moving along it.



Comment on rupture propagation speed versus slip speed

Japan's earthquake early warning system



They locate the hypocenter and time <u>using P waves only</u> and the alarm goes out. S waves and surface waves are more damaging but are slower, so a warning can be given before they arrive. Figure: Japan Meteorological Agency.

Japan's earthquake early warning system: Tohoku

Notes	Update number	Time since first P-wave detection (sec)	Estimated magnitude	Estimated maximum shaking intensity (JMA scale)	Lat	Lon	Depth (km)	Origin time
1st assessment of the event, 5.4 sec after 1st P-wave detection	1	**5.4**	**4.3**	**1**	38.2	142.7	10	14:46:19
	2	**6.5**	**5.9**	**3**	38.2	142.7	10	14:46:19
	3	**7.5**	**6.8**	**4**	38.2	142.7	10	14:46:19
Earthquake warning issued	**4**	**8.6**	**7.2**	**5-lower**	38.2	142.7	10	14:46:19
	5	**9.6**	**6.3**	**4**	38.2	142.7	10	14:46:19
	6	**10.7**	**6.6**	**4**	38.2	142.7	10	14:46:19
	7	**11.0**	**6.6**	**4**	38.2	142.7	10	14:46:19
	8	**15.9**	**7.2**	**4**	38.1	142.9	10	14:46:17
	9	**22.2**	**7.6**	**5-lower**	38.1	142.9	10	14:46:16
	10	**30.0**	**7.7**	**5-lower**	38.1	142.9	10	14:46:16
	11	**45.0**	**7.7**	**5-lower**	38.1	142.9	10	14:46:16
	12	**65.1**	**7.9**	**5-upper**	38.1	142.9	10	14:46:17
	13	**85.0**	**8.0**	**5-upper**	38.1	142.9	10	14:46:17
	14	**105.0**	**8.1**	**6-lower**	38.1	142.9	10	14:46:17
	15	**116.8**	**8.1**	**6-lower**	38.1	142.9	10	14:46:17

Table notes. The first P-wave detection was at 14:46:40.2. All times are JST on March 11, 2011.

<u>http://seismo.berkeley.edu/~rallen/research/WarningsInJapan/</u>
(thanks to Simon Peacock)

Quake starts at 14:46:19

20 s

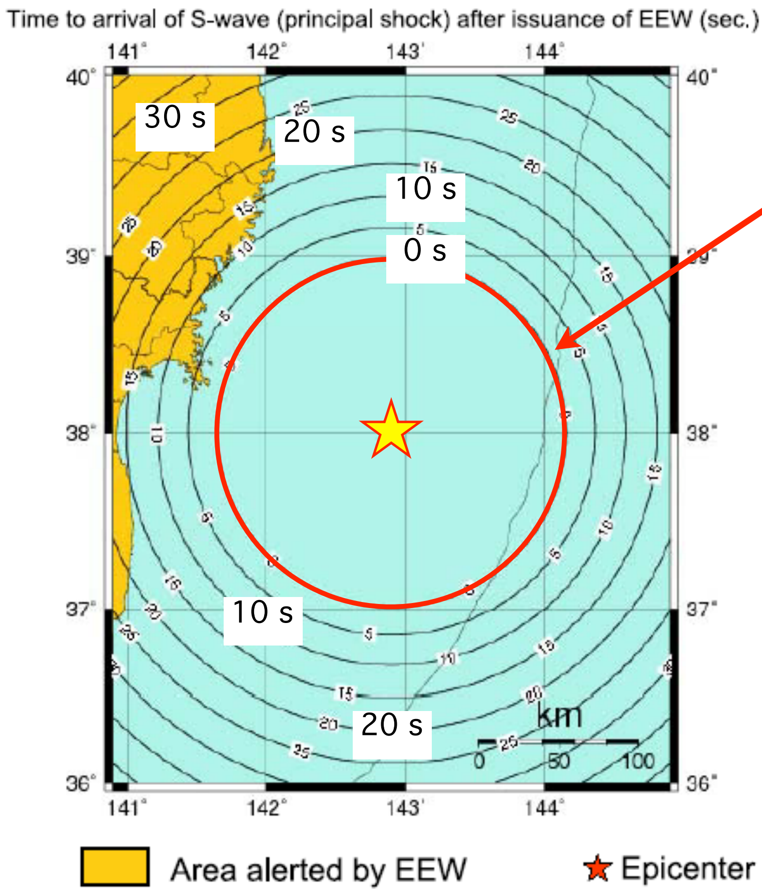
P wave detected at 14:46:40

5.4 s

Quake located by computer 14:46:45

3.2s

Warning on TV, computers and phones 14:46:49

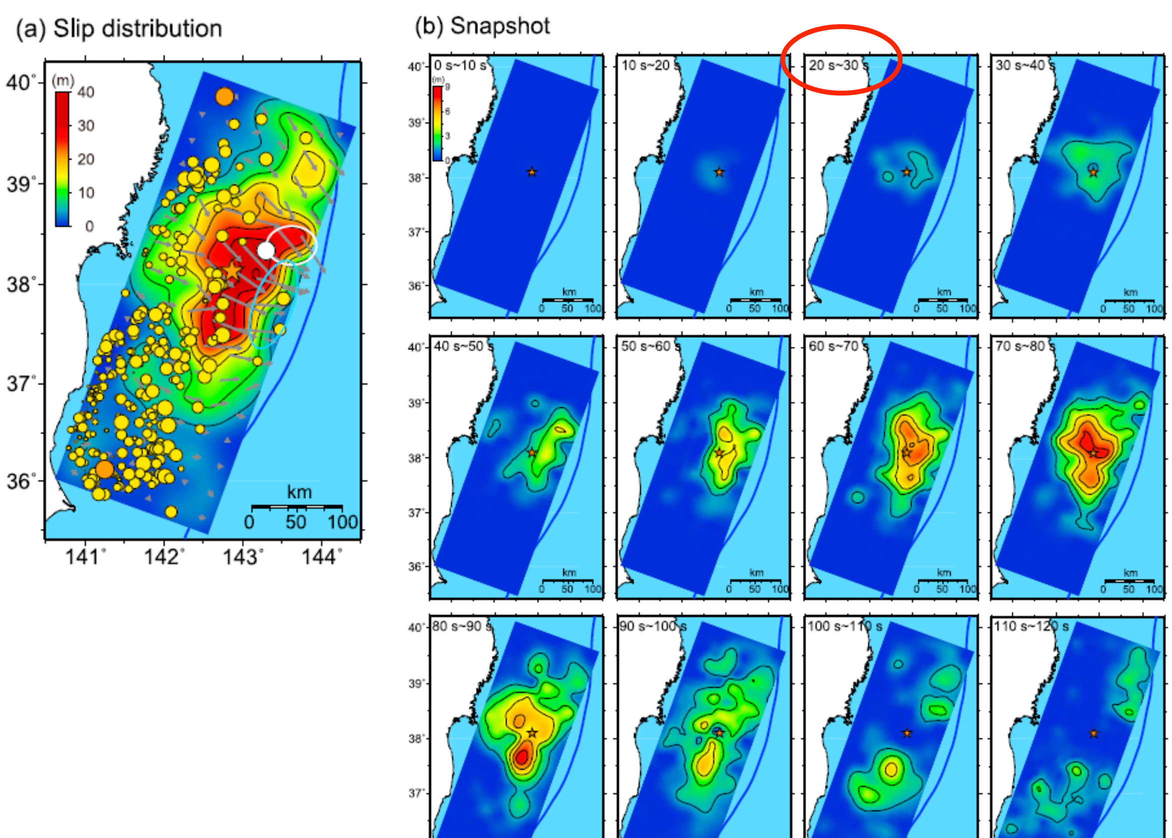


At the time of the warning, the S wave had made it this far

Warning times after the alarm sounded are shown here

About 30 seconds of warning in Tokyo, less in most places where shaking was violent

It took minutes to break the fault - so JMA had no idea how big this quake would eventually become

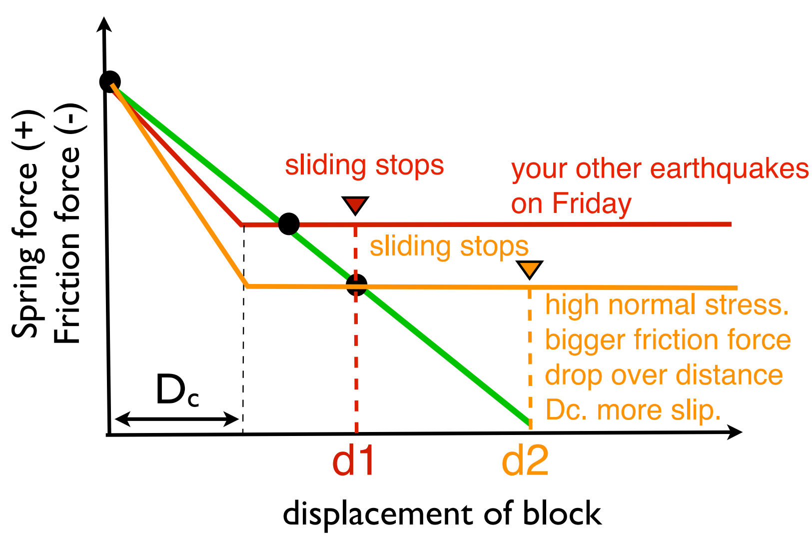


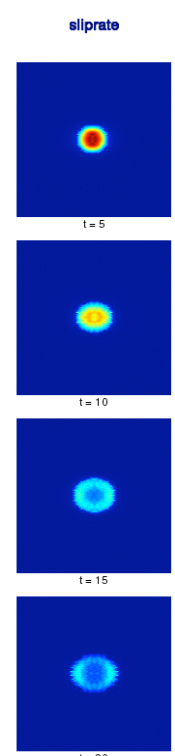
Yokota et al. (2011)

Magnitude estimates keep going up as this live broadcast proceeds...

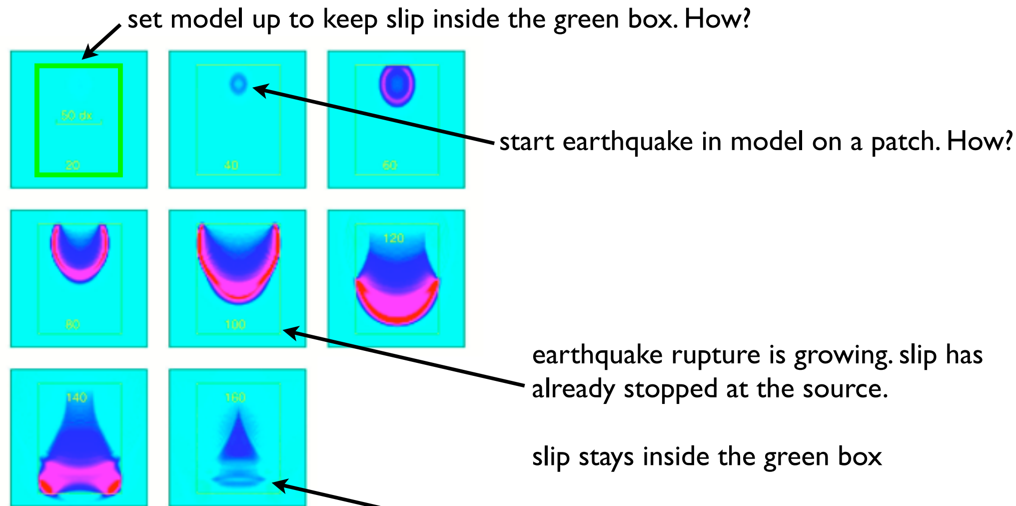
http://www.youtube.com/watch?v=6C_rOVIbbvc&feature=related

Large normal stress gives the most slip at a particular spot



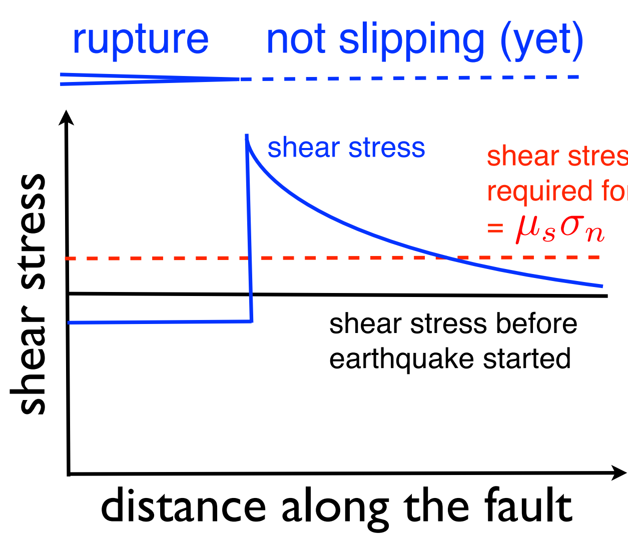


In a large earthquake, the slipping patch grows: the rupture propagates into previously unbroken parts of the fault



from a numerical model
Madariaga et al.

Good conditions for rupture propagation



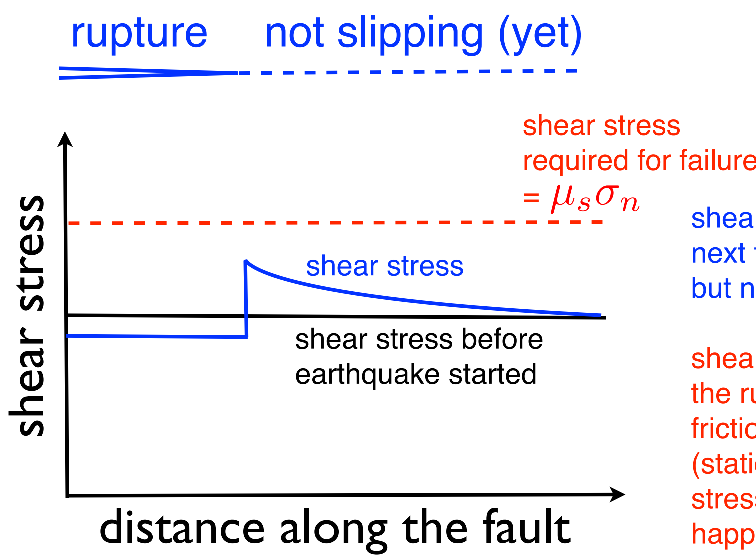
shear stress on unbroken fault next to the rupture increases!

the shear stress increase is proportional to the earthquake stress drop* times (1/ the square root of distance to the rupture tip)

neighboring parts of the fault can be driven to failure by this domino effect if they are already close to failure

*biggest for high normal stress and velocity weakening (big frictional force drop with slipping)

Bad conditions for rupture propagation



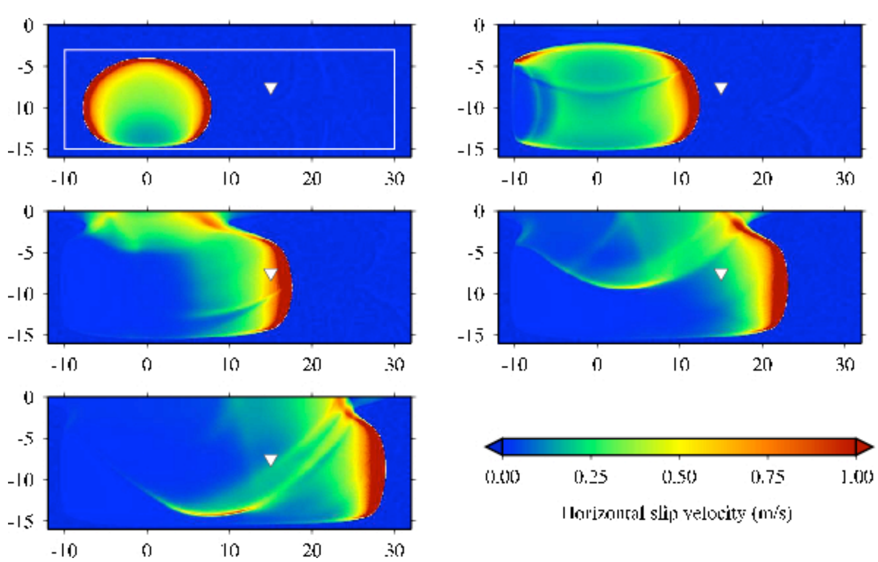
shear stress on unbroken fault next to the rupture increases - but not enough

shear stress is too low ahead of the rupture tip to overcome frictional strength of the fault (static friction times normal stress). This is what usually happens.

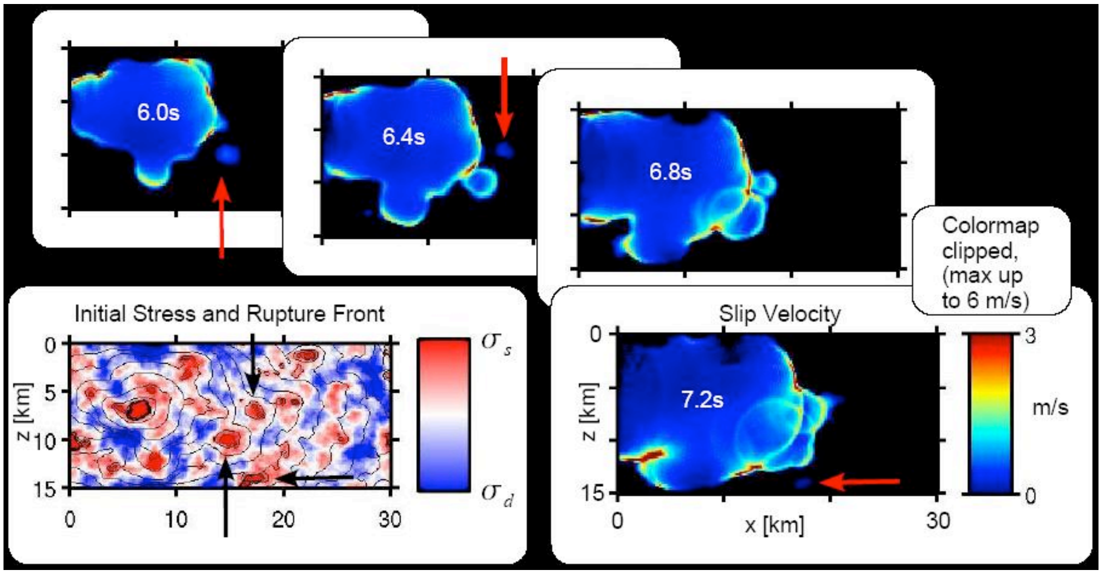
Stress drop is too small AND adjacent part of fault is not close to Coulomb failure stress.

Neighboring parts of the fault can be driven to failure by this domino effect if they are already close to failure

Two ways for a part of the fault to be close to failure - high stress or low friction



Stress is heterogeneous on real faults

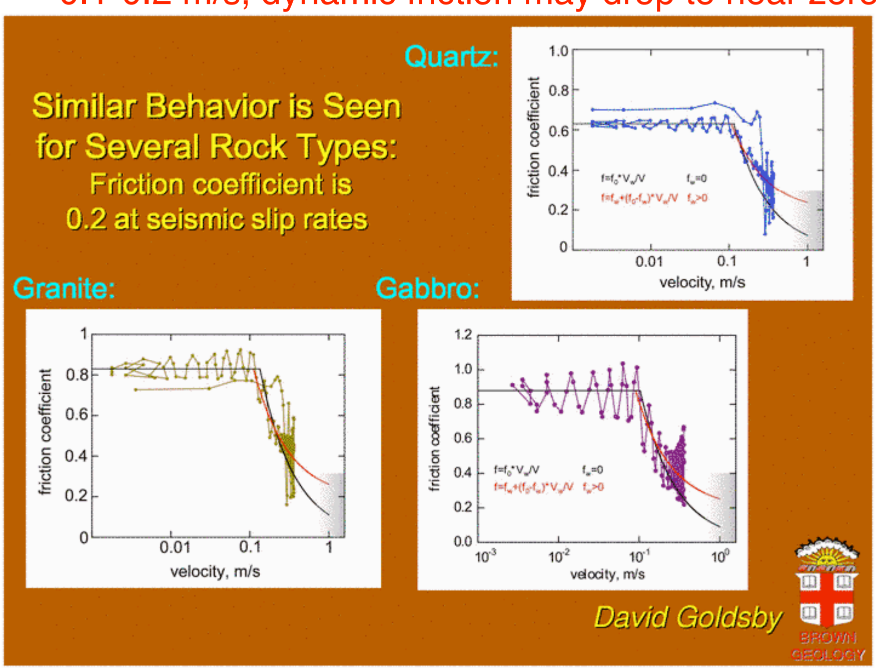


Rupture propagation model from J. Ampuero et al.

stopping the rupture: low stress, high friction, OR velocity-strengthening friction

Once a large earthquake is underway, "extreme weakening" of the fault can happen

Lab experiments show that if slip speed gets up to about 0.1-0.2 m/s, dynamic friction may drop to near zero

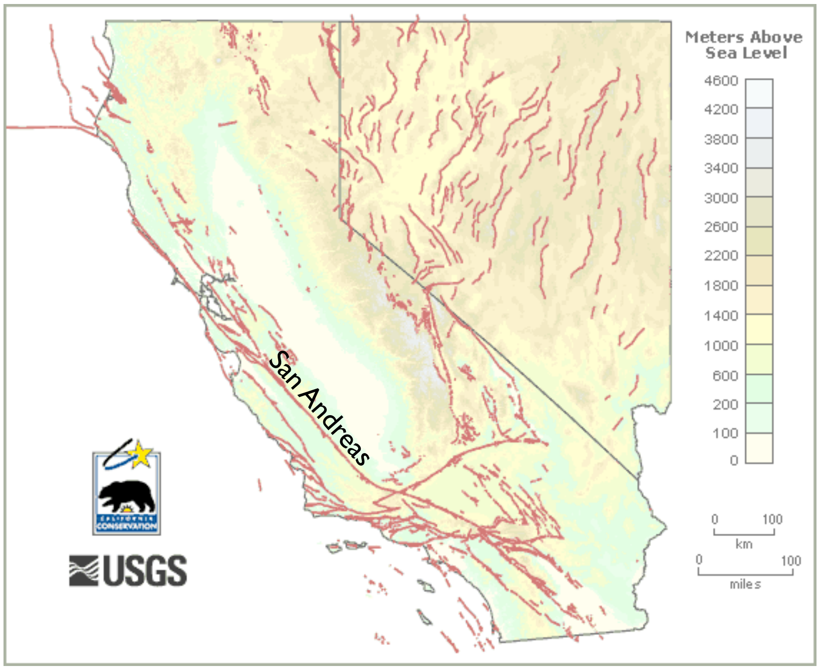


the quake has already begun at this point, but this frictional strength drop will encourage the earthquake to keep going.

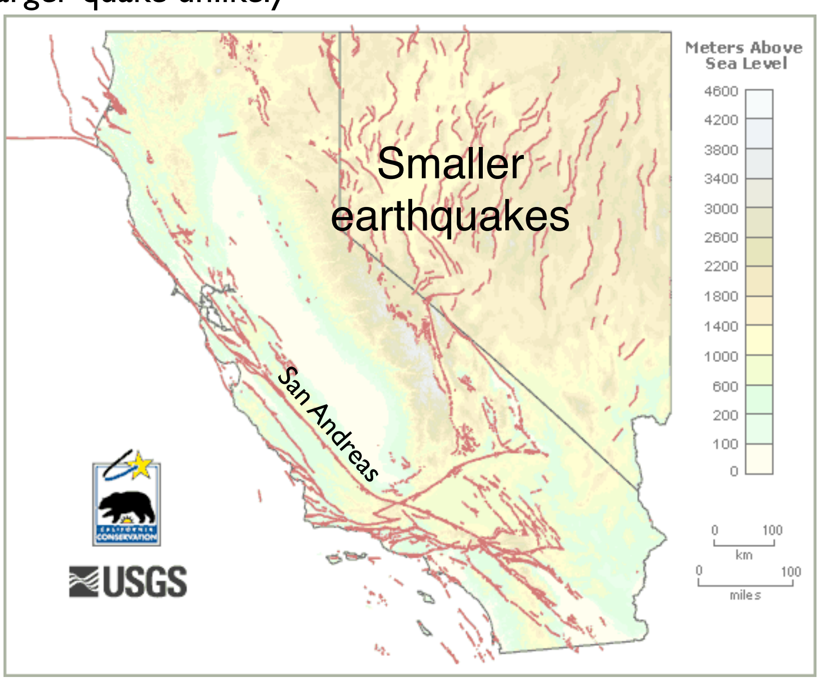
Reason for this extreme friction drip at high sliding speed is under debate.

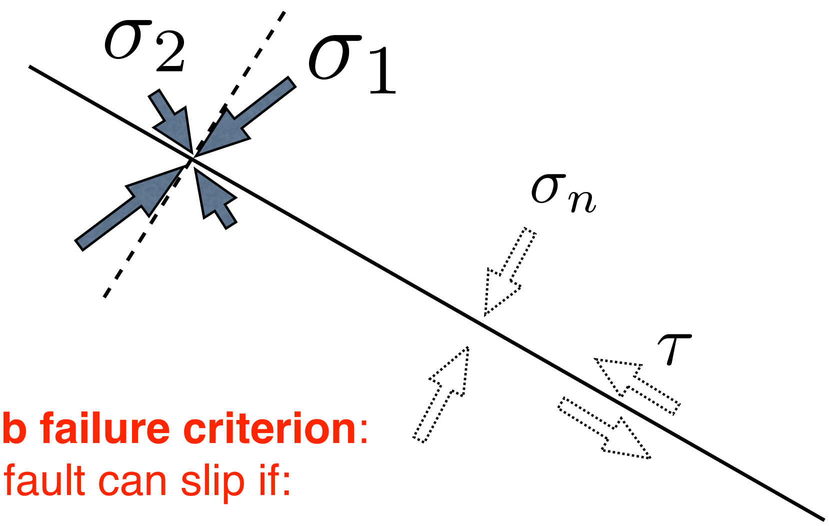
• Long, continuous fault (no need to jump from segment to segment)
• Shear stress near the Coulomb threshold along this fault
• Large normal stress and velocity weakening friction --> big frictional force drop and large "kick" to adjacent parts of the fault

Large earthquakes



• Segmented faults (rupture must jump from segment to segment, which costs energy)
• Shear stress or Coulomb failure stress heterogeneous
• Weak stress drop and small "kick" to adjacent parts of the fault make larger quake unlikely





Coulomb failure criterion:

The fault can slip if:

$$\tau = \mu\sigma_n$$

What if shear stress varies along the fault?
What if effective normal stress varies along the fault?
What if BOTH vary along the fault (eek)?

- Segmented (discontinuous) faults - rupture must jump from segment to segment, which takes energy **OR** long continuous fault
- Heterogeneous fault frictional strength and shear stress (so whole fault NOT close to Coulomb failure threshold) **OR** whole fault close to Coulomb failure.
- Small stress drop and small "kick" to adjacent parts of the fault (due to low σ_n x a-b) **OR** large stress drop and "kick" to adjacent parts of the fault (high σ_n x a-b).

Variations in frictional strength $\mu\sigma_n$
and in velocity weakening (a-b)σ_n
may be due to variations in σ_n caused by pore fluid pressure

Consider the effect of water on the fault.

Effect of water on fault friction (that is, strength) and fault stability

Consider liquefaction of saturated sand

Grains are not touching. This is a fluid with grains floating in it.

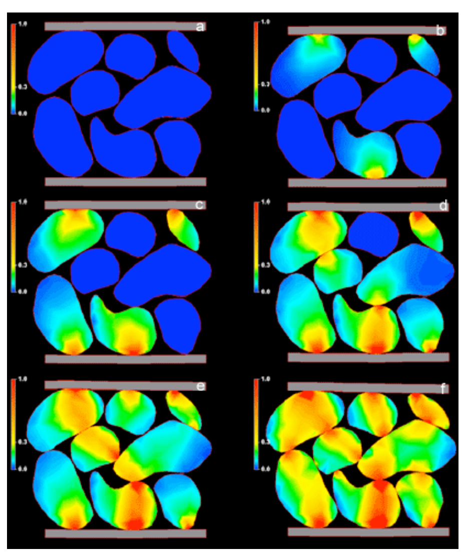


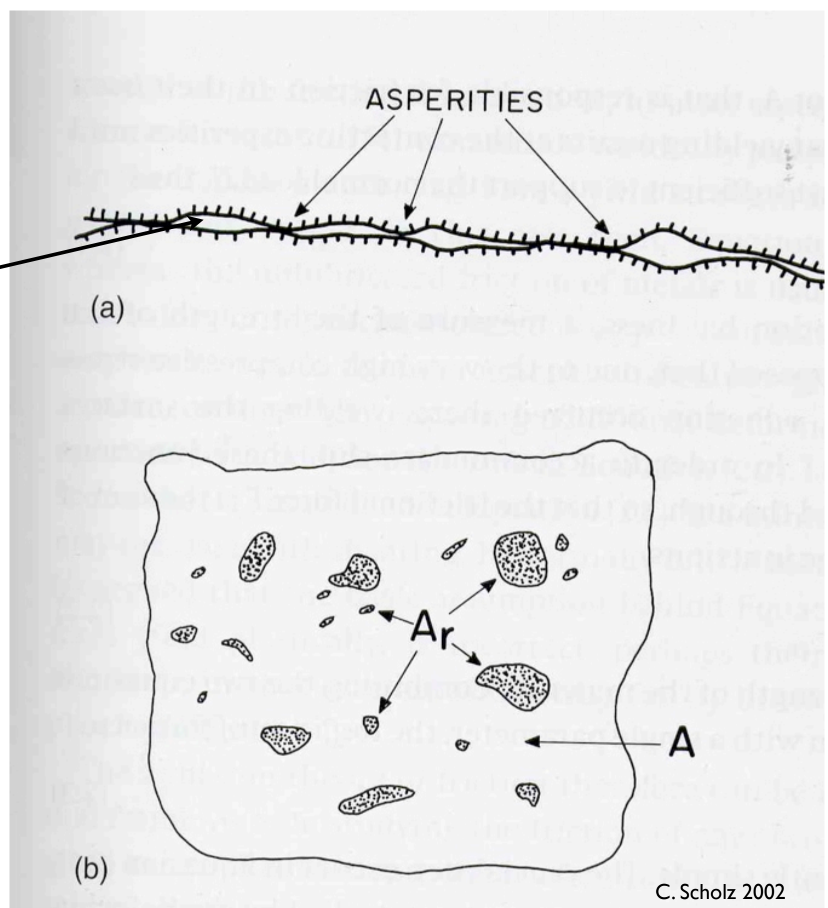
Image from Stanford University Rock Physics Lab

Grains are touching and are supporting the load (stressed parts of grains are red).

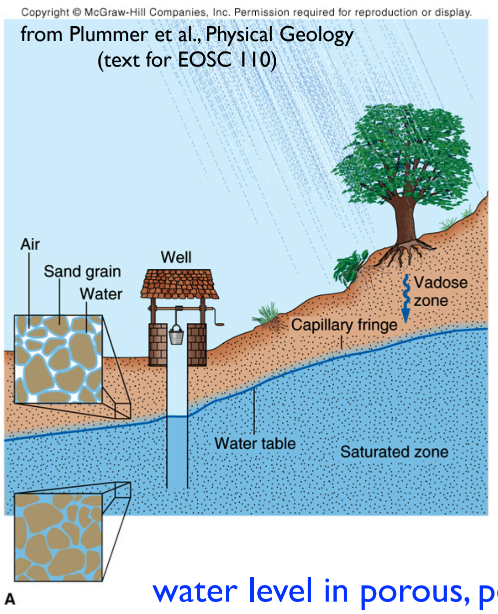
B

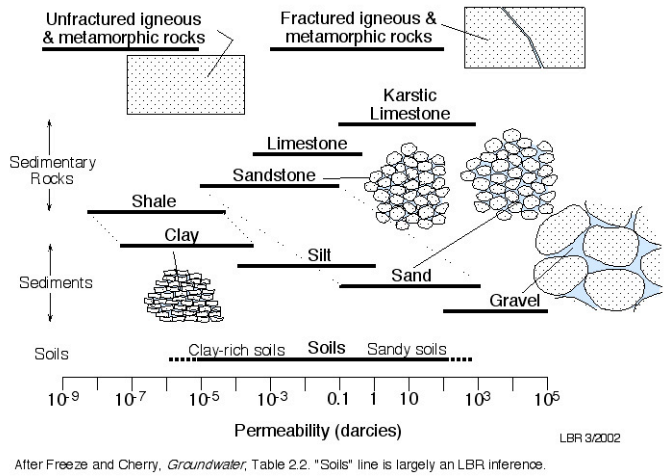
Photo by National Geophysical Data Center

just add water at high pressure. what will happen?



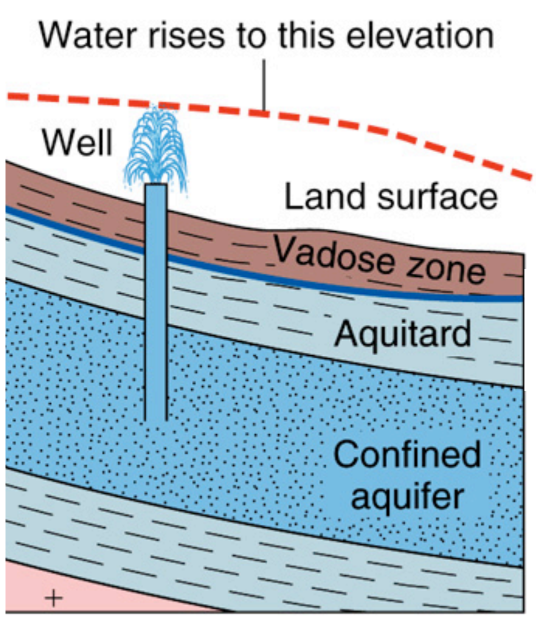
Groundwater is present throughout the upper crust





water level in porous, permeable rock = water level in well

water pressure at depth is same as for a column of water ("unconfined" shallow aquifer)



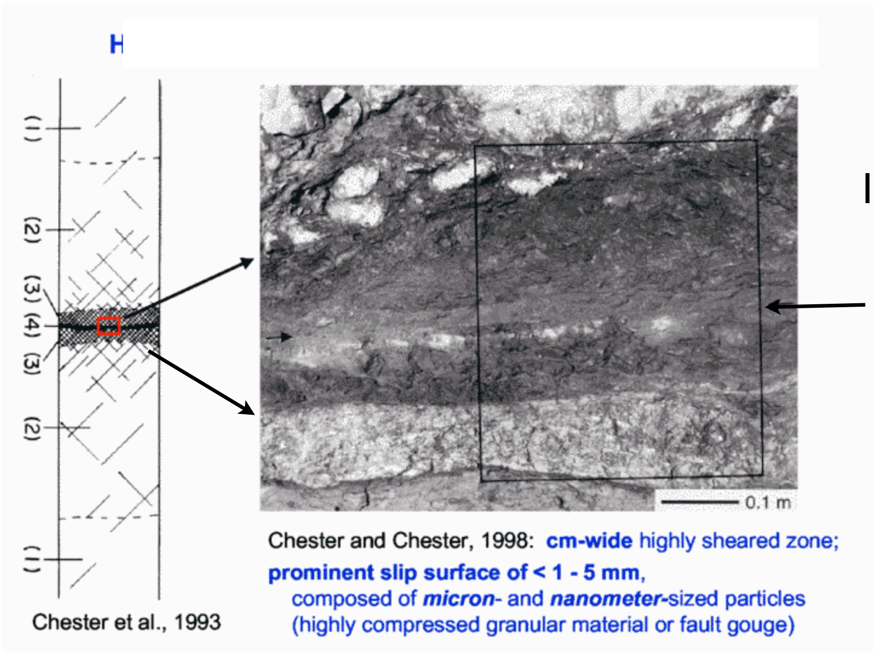
from Plummer et al., Physical Geology
(text for EOSC 110)

In some aquifers, and deeper in the crust, water in pores and cracks may become trapped.

Fluid cannot flow out faster than compaction is occurring, so water pressure goes up.

"pore fluid pressure" can approach the lithostatic pressure!

Water may become trapped inside low-permeability faults



low permeability

pore pressure may increase dramatically!

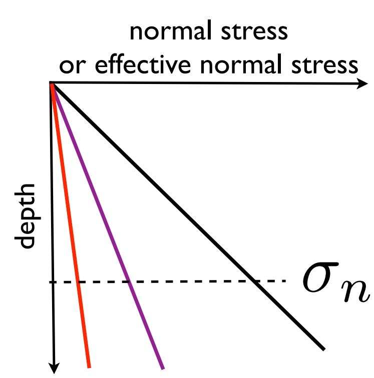
Pore pressure can dramatically reduce effective normal stress

$$|\sigma_e| = |\sigma_n| - P_p$$

At a depth of 10 km:

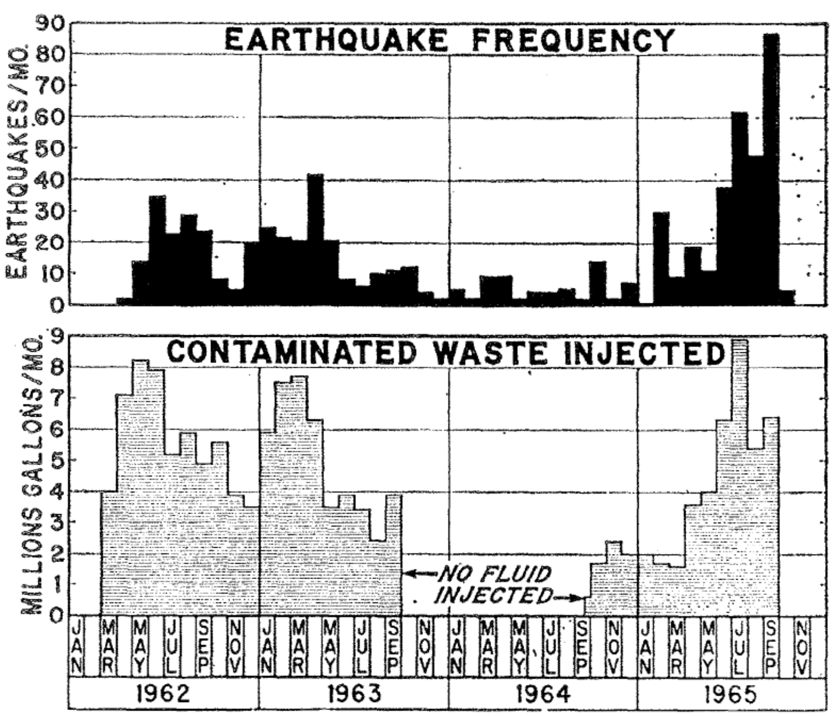
σ_e if water is not overpressured?

σ_e if pore pressure = 0.9 x lithostatic pressure?



Rocky Mt. Arsenal (US Army base) near Denver Colorado, early 1960's: 3670 m deep well was drilled and used for disposal of wastewater...

Human-triggered earthquakes: wastewater injection wells



Still happens, recently in Arkansas and Switzerland.