Earthquakes
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In our lab on plate tectonics, one of the main datasets we drew on was earthquake epicenter locations and depths. We saw that both correlate strongly (though not exclusively) with plate boundary locations, and inferred that most seismicity is associated somehow with plate motions. Today we'll examine the details of that connection, and in the process will draw on our discussions of rheology and rock deformation.

Why do EQs happen?
- Pre- plate tectonics, it was recognized that EQs were associated with slip on faults, but the ultimate reason for fault motion was not understood. Now we know that most large EQs are associated with relative plate motions.
- How is plate motion accommodated?
  - At surface, crust behaves brittlely
  - At depth, crust behaves ductilely (recall brittle-ductile transition). Deformation is still localized, but occurs as creep rather than frictional sliding.
  - B-D transition in continental crust ~ 15 km, so most EQs are shallower than this. But not all – where might deeper EQs occur? Subduction zones, where cold crust behaves brittlely to greater depth.
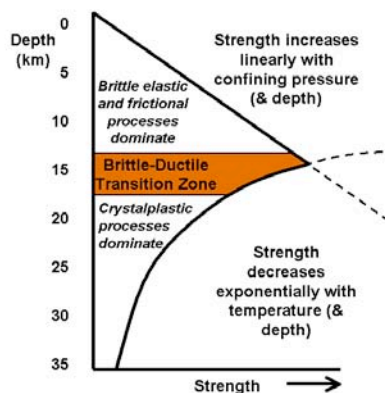
- Most relative plate motion at surface accommodated on faults
  - Almost always multiple faults
  - But with a distribution in which most motion occurs on a few big faults, with the rest spread across a larger number of smaller faults.
  - This means that, in a time-averaged sense, the major faults must accommodate cm/yr of offset. Ex) Relative motion between Pacific & NA plates ~ 50mm/yr. Time-averaged offset on SAF ~35mm/yr.
- So why don't faults just glide along smoothly and happily at a few cm/yr?
  - Sometimes they do and sometimes they don't: creeping section of SAF, bounded by "locked" sections. [PPT: SAF map] What's the difference?
 - Faults are rough --> friction

- Static and dynamic friction forces can differ. The first-order explanation is that creeping faults have $f_d > f_s$, whereas faults that exhibit stick-slip behavior have $f_d < f_s$. [DEMO: friction block attached to spring]
- What would make $f_d > f_s$, such that faults creep? A big research question. Probably lowering of static friction due to reduced normal stress or increased fluid pressure.

What controls when an EQ happens (i.e., when faults suddenly unlock)?
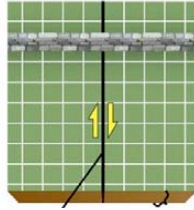
- As plates move WRT one another, rocks deform elastically.
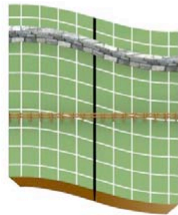
- This elastic deformation must be caused by the buildup of stress (recall Hooke's law). Eventually, this stress will exceed the frictional strength of a fault within the plate boundary zone, and the fault will begin to slip.
- Slip occurs along a finite section of the fault, releasing the energy stored in the elastic strain.
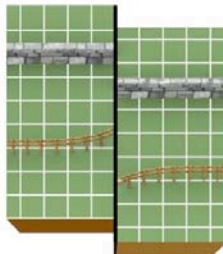
- This hypothesized cycle of repeated buildup of stress, accumulation of distributed elastic strain, and rapid release of the energy stored in that elastic strain, has been labeled the EQ cycle.
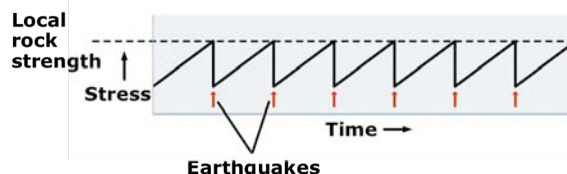
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- o Does it really work this way? Obviously, not exactly: if it did, we'd be able to predict EQs.
- o There are some places that are close: we know that some faults repeatedly cause EQs with a characteristic size and recurrence interval. Ex) SAF near Parkfield, site of drilling project.
- o This is how most probabilistic attempts at EQ hazard forecasting work. [PPT: USGS "forecast" for SF Bay Area]
- o But in reality, there are several factors that prevent us from predicting EQs this way:
  - Change in rate of stress accumulation (variations in plate motion) – add a curved line to the sketch
  - Incomplete stress release
  - Change in fault strength (rock WX, water pressure, "damage" due to previous EQs)
  - Changes in stress state due to nearby EQs
  - The actual EQ time series often looks like this:
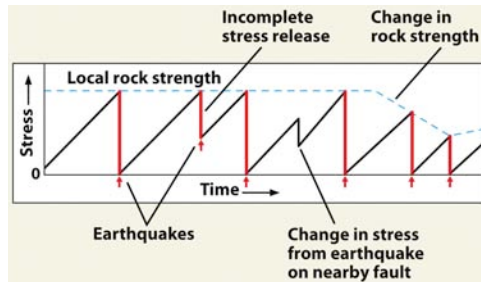
What happens during an EQ?
- Fault rupture nucleates at a point (focus or hypocenter). These are the first seismic waves emitted.
- Rupture propagates outward along the fault surface at a few km/s (~ speed of sound in rock), continuing to emit seismic waves. (Note, though, that the majority of the energy released usually goes into frictionally generated heat.)
- In large EQs, rupture propagation lasts seconds to over a minute, rupture length can be 100s of km, and total slip can be meters.
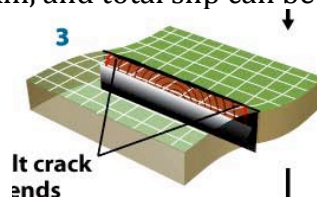
- Rupture stops when stress drops below fault strength, or when it encounters material that behaves ductilely rather than brittlely.
- Why doesn't rupture stop propagating immediately after it starts, dropping stress back just below the fault strength? Again, the first-order answer is because $f_d < f_s$. Otherwise it would be a creeping fault.
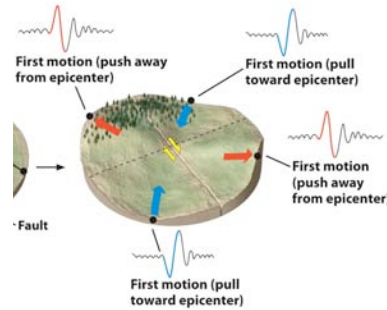
What happens after an EQ?

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- Aftershocks
  - Smaller than mainshock
  - Sections on fault that didn't slip, or didn't completely relieve stress, or where stress increased.
  - How can an EQ increase stress? Release of elastic strain alters stress on surrounding faults (example later). There is evidence that this can trigger large nearby EQs in addition to small aftershocks
- Seismic waves propagate…we'll discuss this shortly.

How do we describe EQ size, sense of slip and stress release, etc?
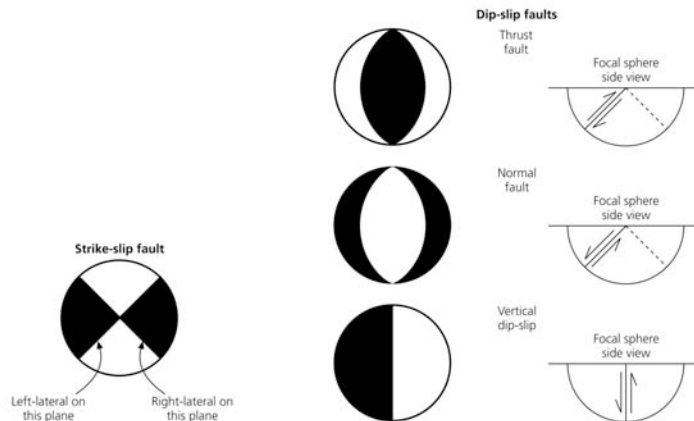- Size
  - Richter Scale (1930s)
    - Log_{10} scale of amplitude of surface ground motion (each Richter unit is 10x the ground motion)
    - Each Richter unit corresponds to a $\sim$32x ($=10^{1.5}$) increase in energy
    - Mostly obsolete
  - Moment Magnitude
    - Seismic moment, M_o
      - Proportional to rupture area A, displacement D, and shear modulus (aka rigidity) μ: $M_o = \mu AD$. Rigidity has units of stress (typically tens of GPa for rocks), so moment has units of force*displacement, or work.
      - M_o is determined from modeling of seismograms
    - Moment magnitude, $M_w = \frac{2}{3} \log_{10} M_o - 10.73$
      - The w subscript stands for work
      - M_o is in dyne cm ($= 10^{-7}$ J)
      - Constants chosen so M_w values correspond approximately to old Richter scale. As with Richter, each M_w unit corresponds to $10^{1.5}$ x more energy
      - Ex) Solve for M_o to get expression for relative energy release: $M_o = 10^{3/2(Mw + 10.73)}$. So ratio of M_o for two quakes is $10^{3/2(Mw1 - Mw2)}$.
        - For Japan 2011 (M_w9.0) vs. Haiti 2010 (M_w7.0), the ratio is $10^{3/2*2}=1000$
        - For Chile 1960 (M_w9.5) vs. Japan 2011 (M_w9.0) the ratio is $10^{3/2*0.5}=5.6$
    - Use of logarithmic scales is efficient for science, bad for PR (M9.5 doesn't sound that much worse than a M7)
  - Mercalli intensity
    - Written in Roman numeral
    - Qualitative measure of severity based on observed effects on humans & structures
    - Source of estimates of EQ location & magnitude prior to seismometers

- Sense of slip
  - Slip on a *finite* rupture creates zones of compression and zones of dilatation
  - This pattern will dictate the sense of first motion at seismic stations in the different zones.
  - The fault displacement in an EQ is constrained by examining the seismograms (including, but not limited to, first arrivals) at multiple stations, and determining the best-fit solution ("focal mechanism solution")

First motion (push away from epicenter)
First motion (pull toward epicenter)
First motion (push away from epicenter)
Fault
First motion (pull toward epicenter)

  - To describe the pattern of energy radiated during an EQ (which is a tensor called the "moment tensor solution"), we use stereonets ("beachballs")
    - Take the intersection of the fault with a *lower* hemispherical surface centered on the focus
    - Mark the quadrants of compression (colored) and dilatation
    - Project the result onto a horizontal plane

Dip-slip faults
Thrust fault
Focal sphere side view
Normal fault
Focal sphere side view
Vertical dip-slip
Focal sphere side view
Strike-slip fault
Left-lateral on this plane
Right-lateral on this plane

    - Note that there is an ambiguity in the sense of slip. This is not just a limitation of the stereonet; it is a real limitation of our ability to determine the fault motion.
- Examples from recent quakes:
  - Sumatra 2004
    - $M_w = 9.0$
    - [PPT: Moment tensor]

- - - Dimensions: ~200km in dip dir, 1500 km in strike dir (about the size of California), max ~20m slip
  - o Haiti 2010
    - ▪ M_w = 7.0
    - ▪ [PPT: Moment tensor]
    - ▪ Dimensions: ~15km x 40 km, max ~5 m / avg 2m slip
    - ▪ Enriquillo fault last ruptured on October 18 and November 21, 1751, and June 3, 1770
    - ▪ [PPT: Stress change on nearby Septentrional fault]
  - o Japan 2011
    - ▪ M_w = 9.0
    - ▪ [PPT: Tectonic context]
    - ▪ [PPT: Moment tensor + depth profile]
    - ▪ [PPT: Finite fault model]. Yes, up to 18 m of slip!
    - ▪ Dimensions: ~150km x 500 km, max ~18 m slip
  - o Chile 1960
    - ▪ M_w = 9.5 (largest EQ recorded w/modern instruments)
    - ▪ Dimensions: 1000 km along strike, max ~40m slip
    - ▪ Mw8.2 foreshock(!) 25 hrs before main shock, aftershocks as large as Mw7.9!

Seismic waves: 2 classes
- • Body waves
  - o Compressional waves (P-waves)
    - ▪ Particle displacement parallel to propagation direction
    - ▪ Faster (P= "primary"). Typical crustal V_P ~ 6 km/s
    - ▪ $V_P = [(K + 4/3\mu)/\rho]^{1/2}$, where μ is shear modulus ("rigidity", ratio of shear stress to shear strain), K is bulk modulus ("incompressibility", ratio of pressure change to volume change), and ρ is density.
    - ▪ In liquid, μ→0, and $V_P = [K/\rho]^{1/2}$
  - o Shear waves (S-waves)
    - ▪ Particle displacement normal to propagation direction
    - ▪ Slower (S = "secondary"). Typical crustal V_S ~3-4 km/s
    - ▪ $V_S = (\mu/\rho)^{1/2}$.
    - ▪ In liquid, μ→0, and $V_S = 0$
- • Surface waves
  - o Slower than body waves (~3 km/s), but more destructive
  - o [PPT: animations of surface waves]
  - o Rayleigh waves
    - ▪ "Rolling" motion
    - ▪ Particle paths are elliptical in plane normal to surface and parallel to propagation direction
  - o Love waves
    - ▪ Sideways shaking motion

- - - Particle displacements are in the surface plane, normal to propagation direction. Essentially a horizontally polarized shear wave guided by the surface.
      - Slightly faster than Rayleigh waves
      - [PPT: Love waves in 1995 Kobe EQ]
- Why are there variations in K, μ, ρ that influence seismic wave speeds?
  - Mineral composition
  - Mineral phase (even for same elemental composition, crystal structure changes with P and T)
  - State of matter: Solid, liquid (melt), or a combination
  - Fabric: in this case, orientation of crystals
  - Stress state (you will explore this effect in your lab!)
  - These are all things that seismologists try to infer about the Earth, based on their observations of wave propagation
- Wave propagation and arrival patterns
  - Surface waves travel along the surface. What path will body waves follow through Earth's interior?
    - [Start drawing hypothetical ray paths on board] → Depends on how wave speed varies with depth, because changes in speed will cause refraction.
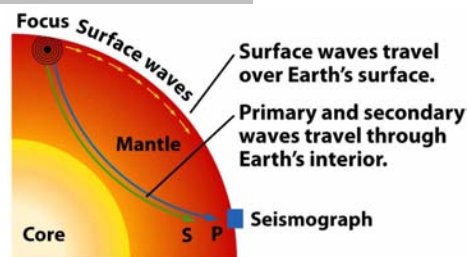
    - What controls wave speed? Moduli and density.
    - How does density vary with depth? Increases → slower speed! What kind of ray paths would this predict?
    - How do moduli vary with depth? Not as easy to intuit…you will discover this in your lab.
  - Typical seismogram:
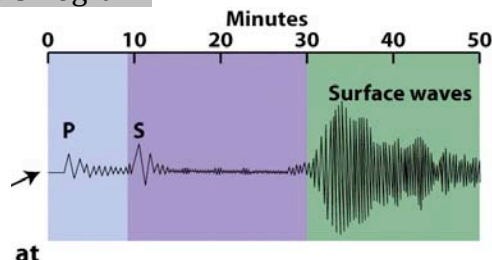
- Interior Earth structure worked out by seismologists in early 20th c.: crust, mantle, outer & inner core. How?
  - Velocity of a medium + path of wave --> travel time

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- Differences in velocity between layers cause refraction, which also influences when (or even whether or not) a wave arrives at a given location
  - Ex) Liquid outer core inferred from "shadow zone" caused by gap between wave that just misses outer core, and refraction of wave that hits it.
- Differences in velocity can also cause reflection
  - Ex) Inner core was originally suggested because there *were* actually some weak P-wave arrivals in shadow zones, which could be explained by a solid reflector inside the core. (Solid inner core was later demonstrated based on free oscillations.)

Other earthquake-related topics, time permitting
- Change in MOI due to EQs (especially when dense subducting slabs move deeper into the mantle), TPW, and length-of-day
- Earthquake hazards mitigation
  - Difference between impact of Haiti 2010 and Japan 2011 EQs
  - Use this to illustrate the difference between hazard and risk

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