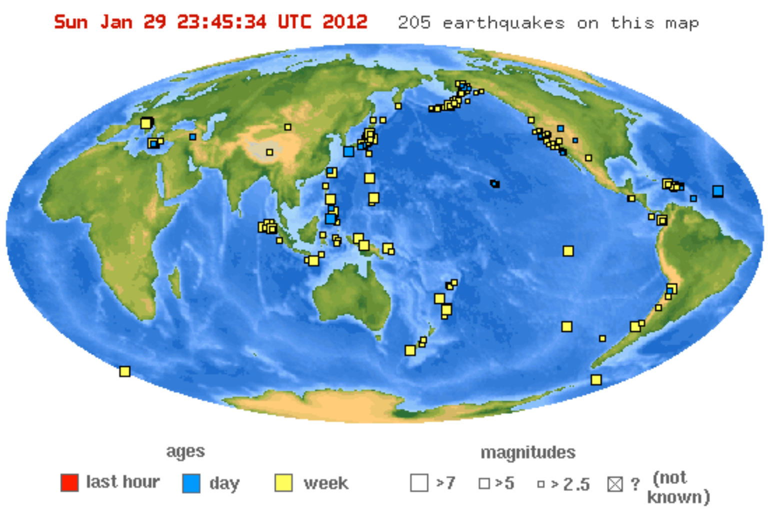
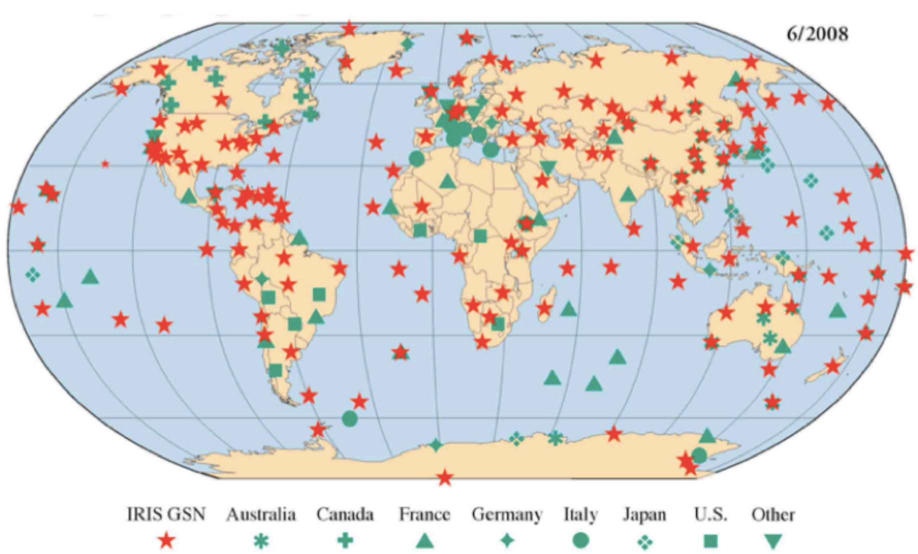
Locating Earthquakes



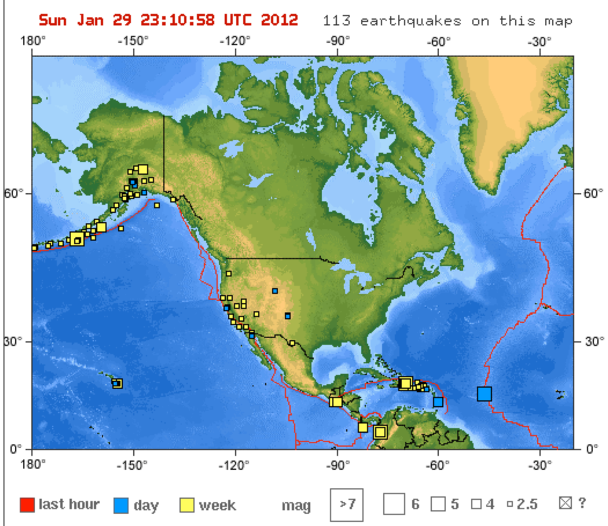
How can we quickly estimate earthquake location (2 ways)?
What can complicate these estimates?
How are such estimates made *in the real world*?

Global Seismic Network



- About 150 stations - mostly broadband and 3 components
- Detects M4 and larger events worldwide
- Partly funded to aid in nuclear test ban verification

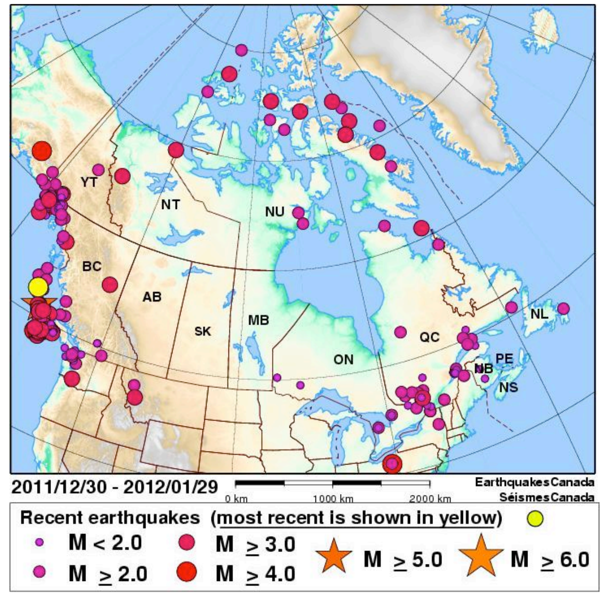
USA quakes this past week



from Advanced National Seismic System (ANSS) (almost 100 broadband seismometers [backbone array] plus several locally run networks).

http://earthquake.usgs.gov/earthquakes/recenteqsww/Maps/region/N_America.php

Canada quakes this past month



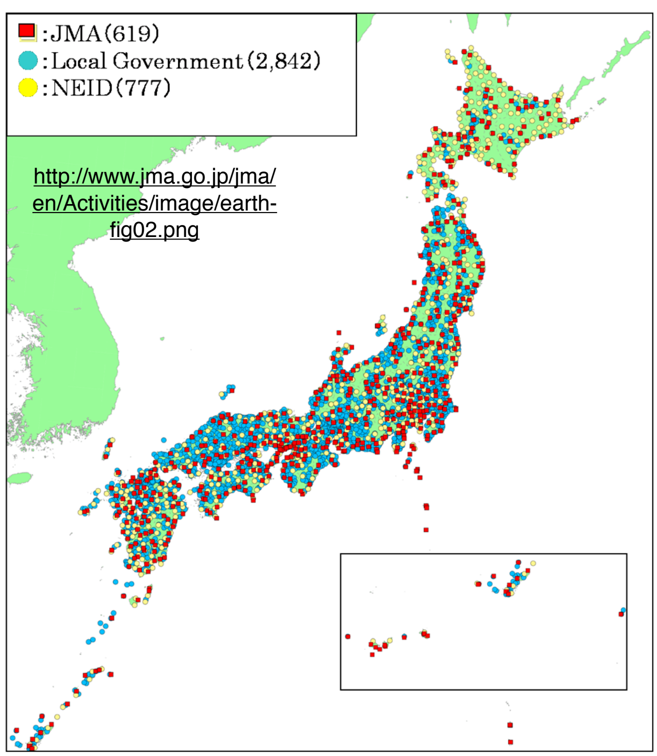
from Canada National Seismograph Network (CNSN) (100 seismographs of various types, plus 60 accelerometers)

http://earthquakescanada.nrcan.gc.ca/index-eng.php

Japan

each dot is a seismometer!

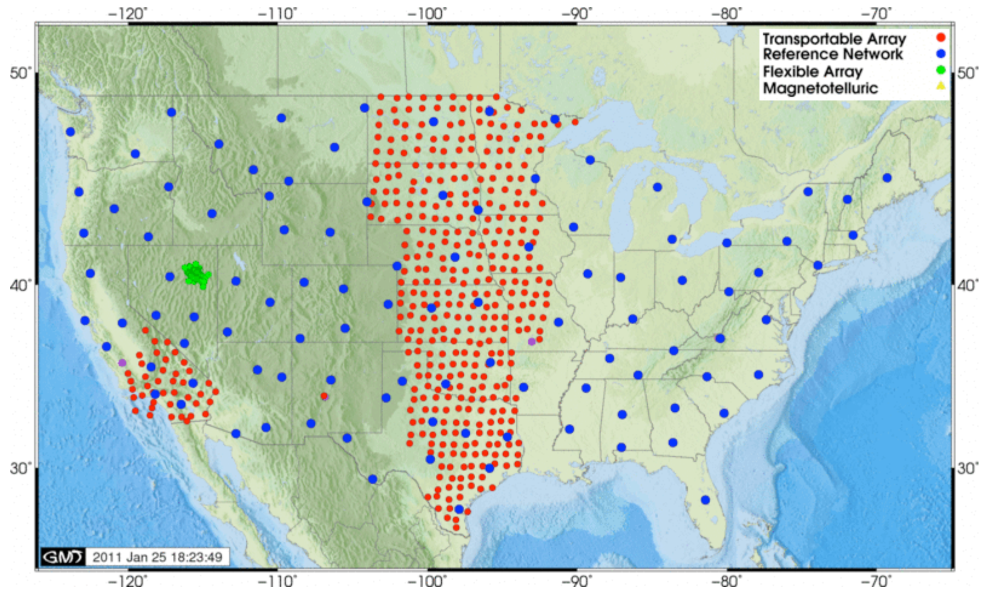
red dots: seismometers in boreholes, operated by JMA (“Hi-Net”)



http://www.jma.go.jp/jma/en/Activities/image/earth-fig02.png

US Earthscope Project

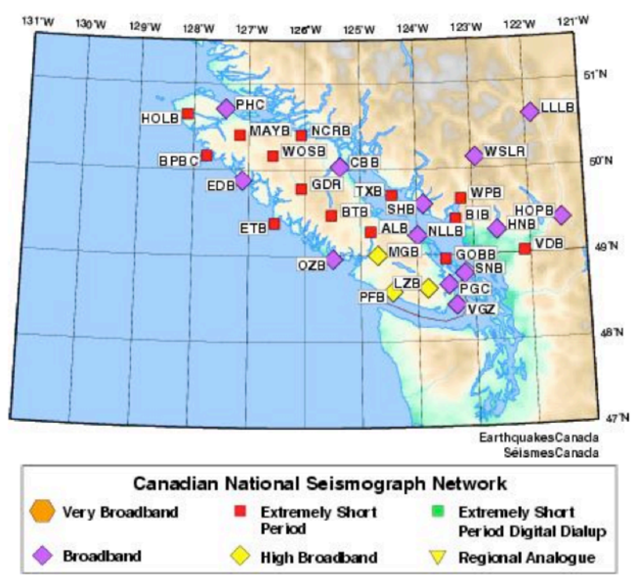
- reference network (permanent)
- transportable array (marching across the lower 48, 2-year deployments) (*coming soon to Quebec!* If they have any sense it'll go to Alaska via BC...)
- flexible arrays (instruments for local, temporary seismic arrays)



CANADIAN NATIONAL SEISMOGRAPH NETWORK (B.C.)

> G.S.C. operates ~30 seismographs in SW B.C.

> note concentration on V.I. and lower mainland



Locating earthquakes using seismometer networks

Recall: Seismic wave speed depends on:

1) incompressibility (K) ← resistance to volume change

2) rigidity (μ) ← resistance to distortion or bending (=0 for fluids)

3) density (ρ) ← mass per cubic meter

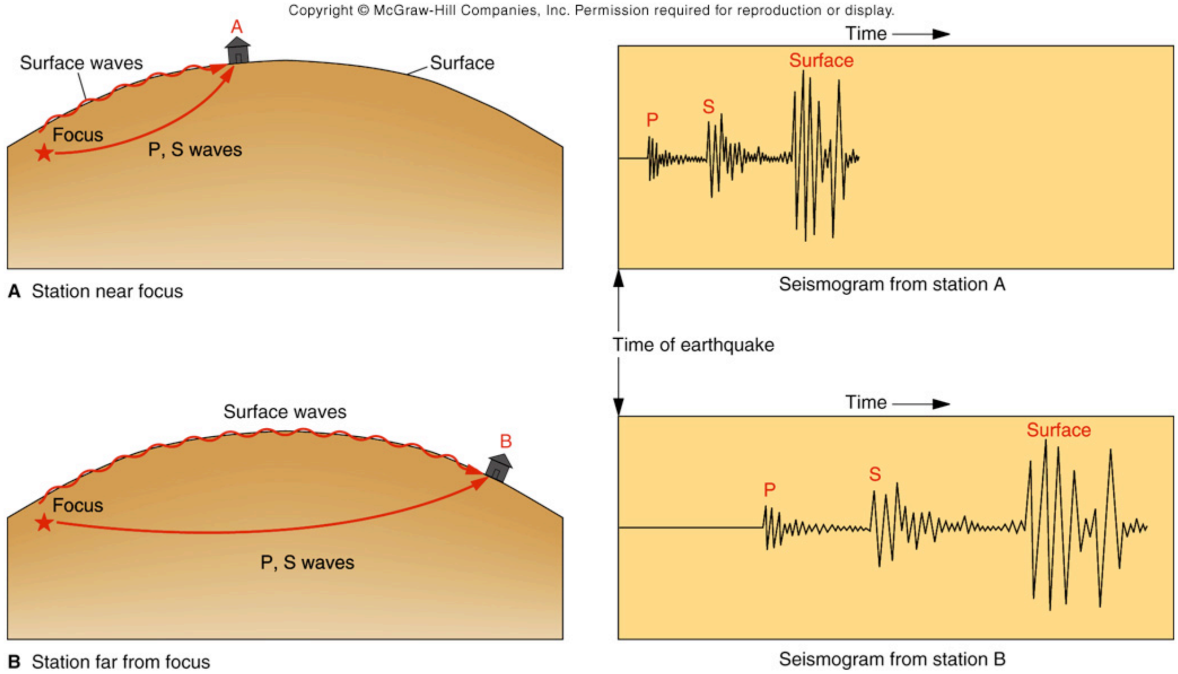
P Waves

$$V_p = \sqrt{\frac{K + \frac{4}{3}\mu}{\rho}}$$

S Waves

$$V_s = \sqrt{\frac{\mu}{\rho}}$$

Locating Earthquakes (1): s-p lag time

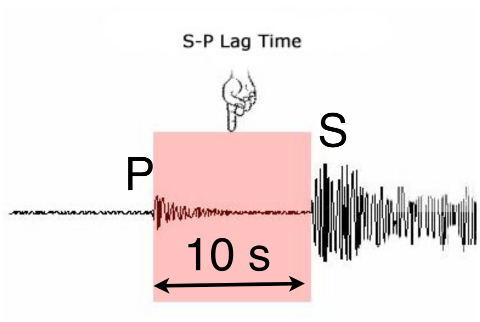


How far was the earthquake from my seismograph?

$t_s = \color{red}{D} / v_s$. $t_p = \color{red}{D} / v_p$.

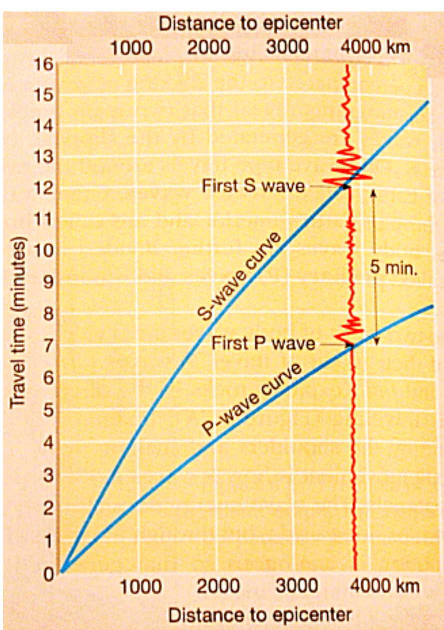
Subtract P-wave travel time (“t_p”) from S-wave travel time (“t_s”) to get S-P lag time (“t_s - t_p”).

$$\text{S-P lag time} = D \left\{ 1/v_s - 1/v_p \right\}$$



S-P lag time = 10 seconds

How far away was the earthquake?



$$\text{S-P lag time} = D \left\{ 1/v_s - 1/v_p \right\}$$

rearrange:

$$D = \frac{\text{S-P lag time}}{\left\{ 1/v_s - 1/v_p \right\}}$$

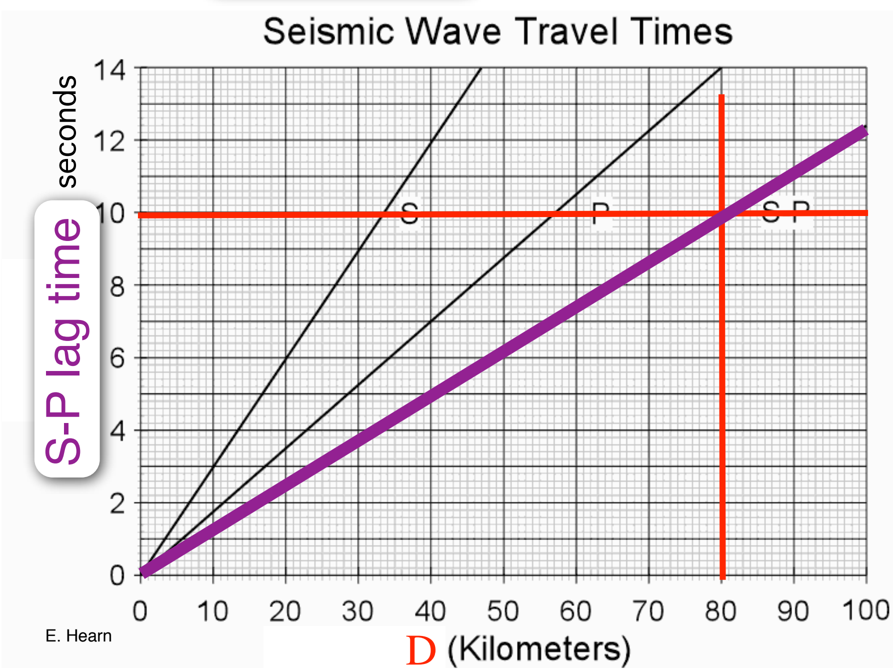
Vp ~ 6.7km/s
Vs ~ 3.8km/s
ts - tp = 5 minutes
= 300 sec

$$D = \frac{t_s - t_p}{\frac{1}{v_s} - \frac{1}{v_p}}$$

What if the quake is nearby? Then D is small - so t_s-t_p must also be small.

Even simpler...

S-P lag time = $D\left\{1/v_s - 1/v_p\right\}$



Just read D off this graph.

slope of the purple line is:

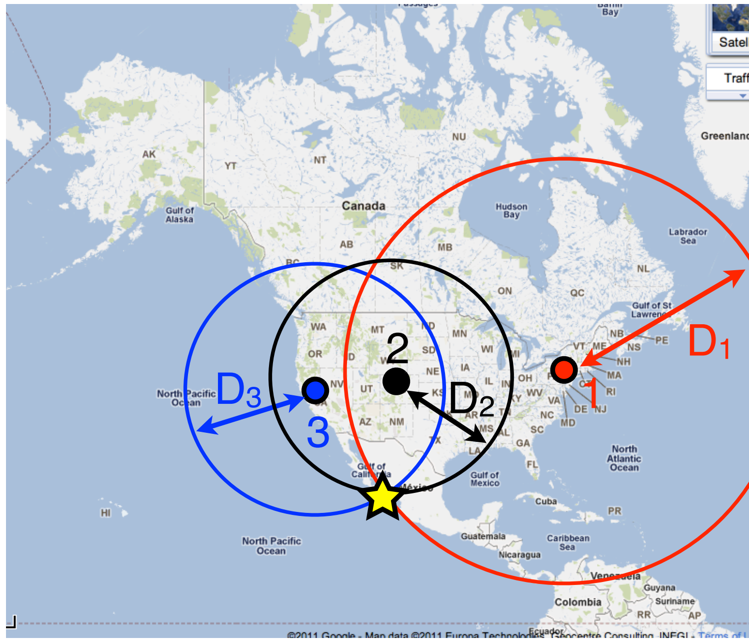
$\{1/v_s - 1/v_p\}$

What did you need to know to find D?

This graph assumes that V_p = 5800 m/s and V_s = 3300 m/s (in the crust).

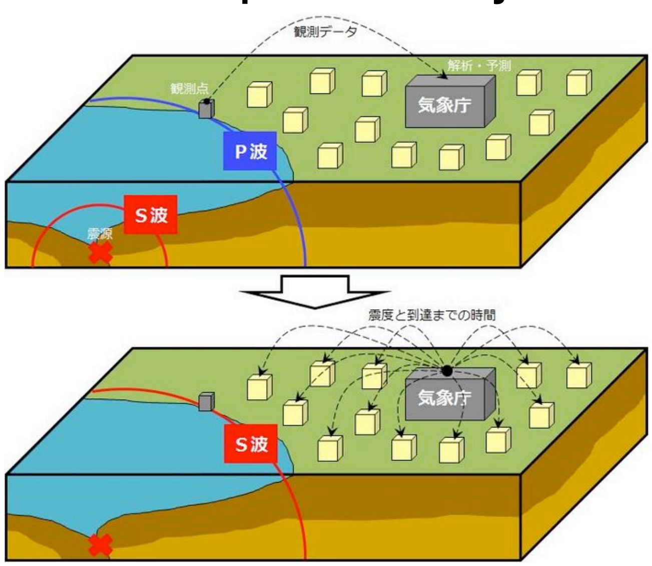
Where was the earthquake?

- calculate distance "D" to quake at 3 seismographs (D_1, D_2, and D_3)
- draw a circle of radius D around each seismograph location (e.g., D_1 for station 1)
- epicenter is where the three circles intersect ☆



Possible problem: seismographs are in a line

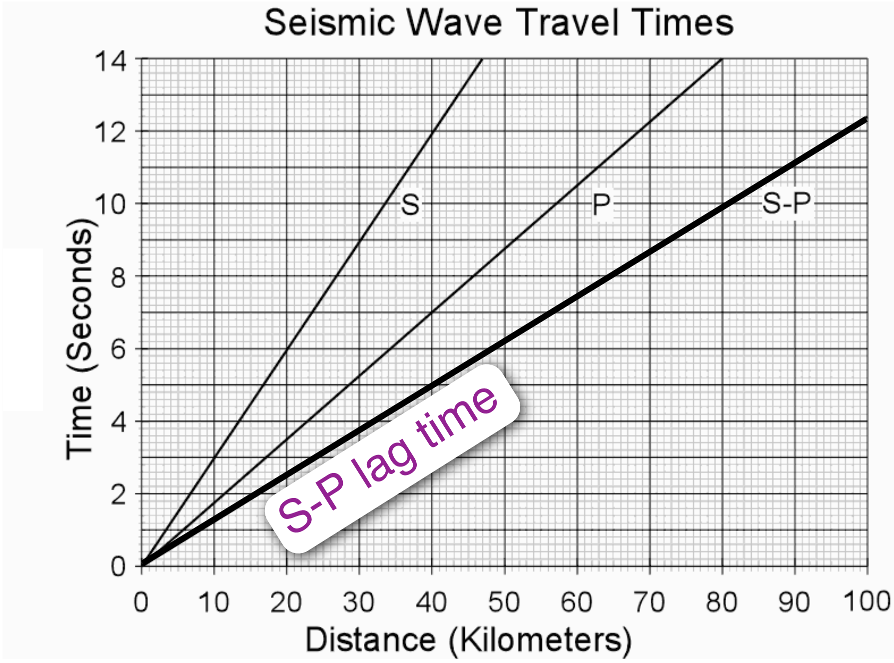
Japan's earthquake early warning system



The alarm goes out when P-waves are detected by seismometers near the epicenter. S and surface waves are slower but cause more damage. Warning time = difference between P and S wave arrival times (seconds to minutes).

Figure: Japan Meteorological Agency.

http://www.youtube.com/watch?v=A_8ZkBXVvMw



If a hypocenter is 100 km away, how much warning time can there be after the P wave is detected?

Japan's earthquake early warning system

Do you think they use s-p lag time?

Alternate approach (more commonly used): just use wave arrival times from many stations and solve for hypocenter location and time.
This requires data from at least 4 seismometers.
(in Japan, this is NOT a problem!)

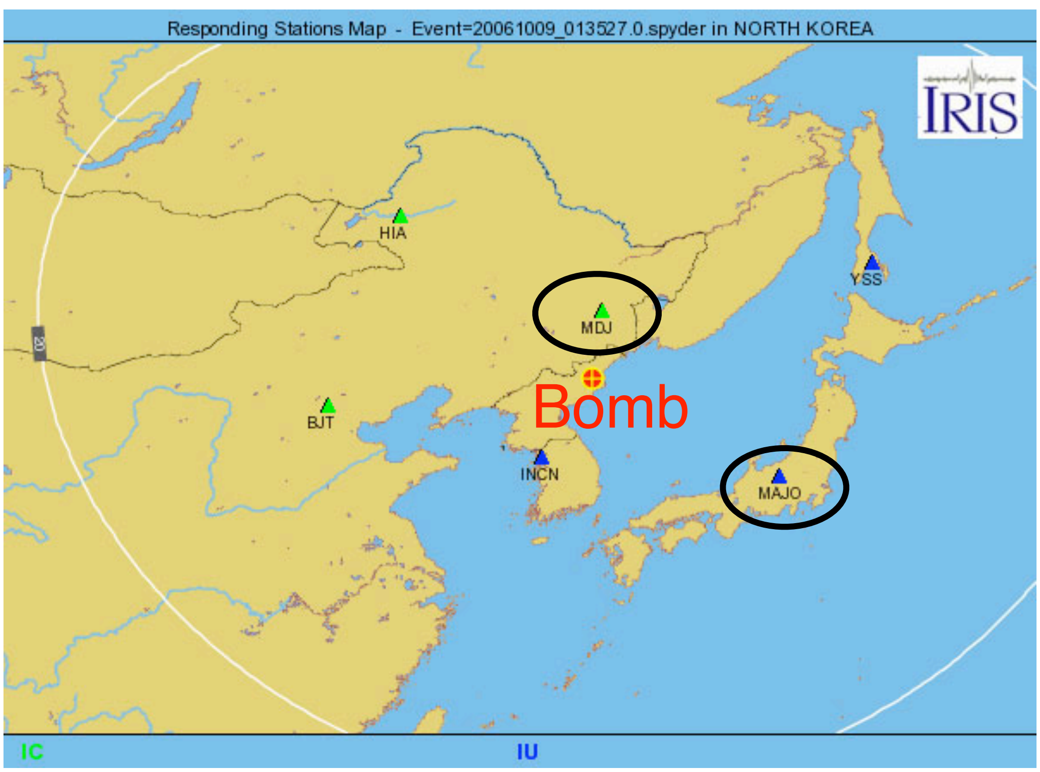
In reality:

(1) seismic velocities vary (especially with depth)

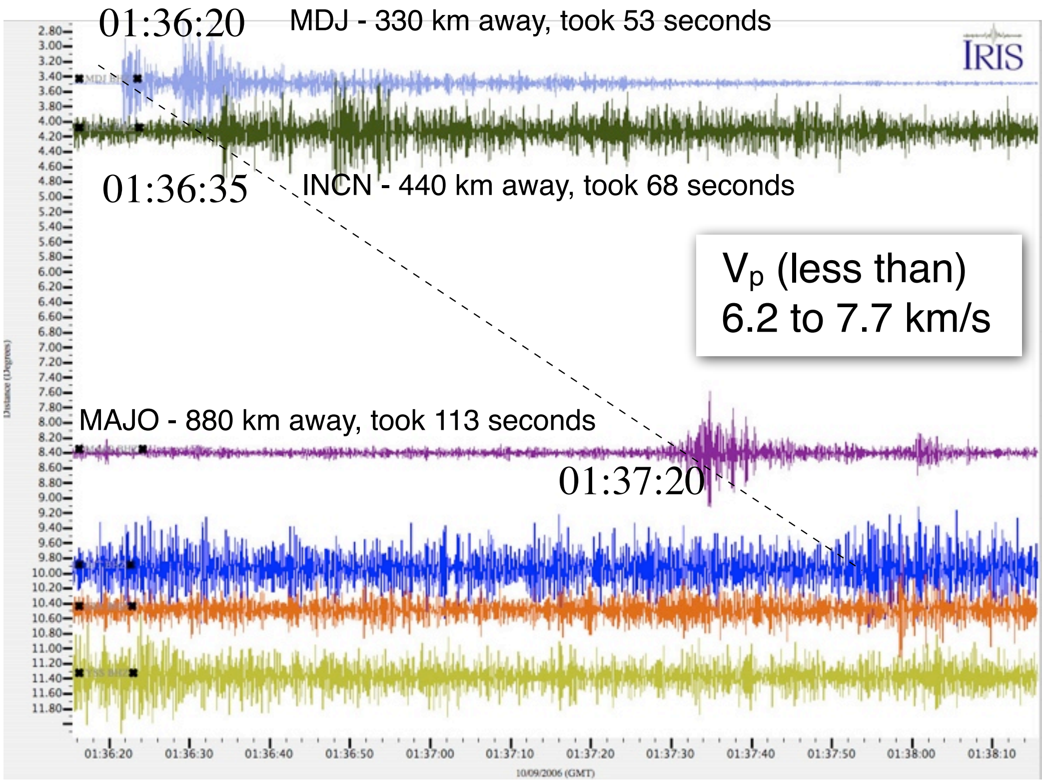
(2) location of earthquakes is automated and data from many seismometers are used, not just three)or four)

2006 Bomb Test in North Korea

2006/10/09 01:35:27.0



North Korea Bomb Test P Wave arrivals



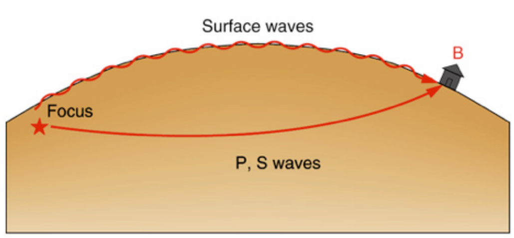
V_p (less than)
6.2 to 7.7 km/s

The further away, the faster the average seismic wave velocity (within about 100° of the epicentre)

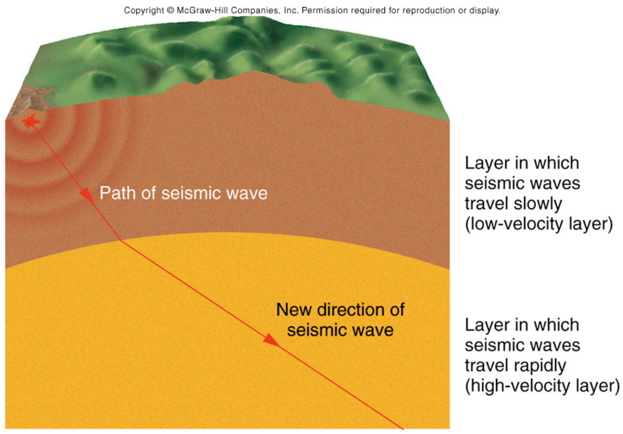
This is due to increase in K and μ with depth: due to high pressure (affects K and μ more than ρ)

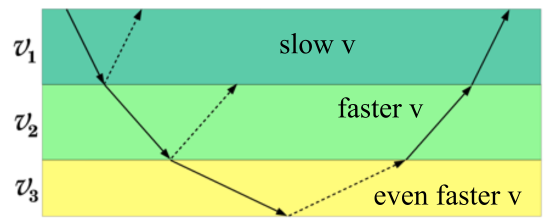
Waves that have traveled a long distance have spent more time deep in the Earth (where they travel faster).

Gradual increase in wave velocity with depth causes continuous refraction, resulting in curved travel paths.

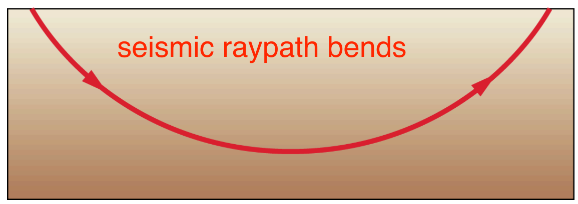


Recall refraction from last week

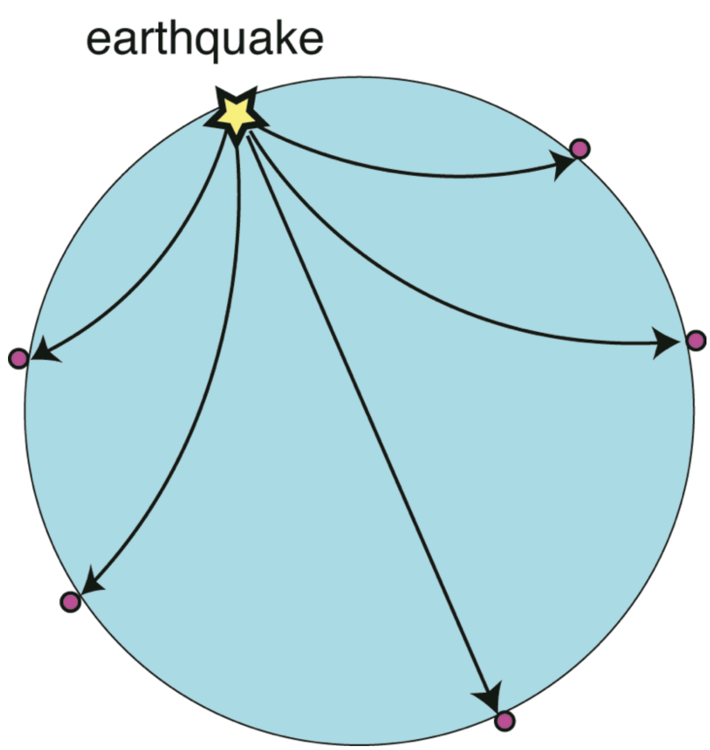




Velocity gradually increasing with depth

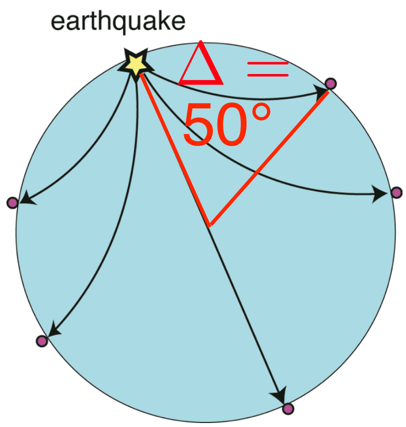


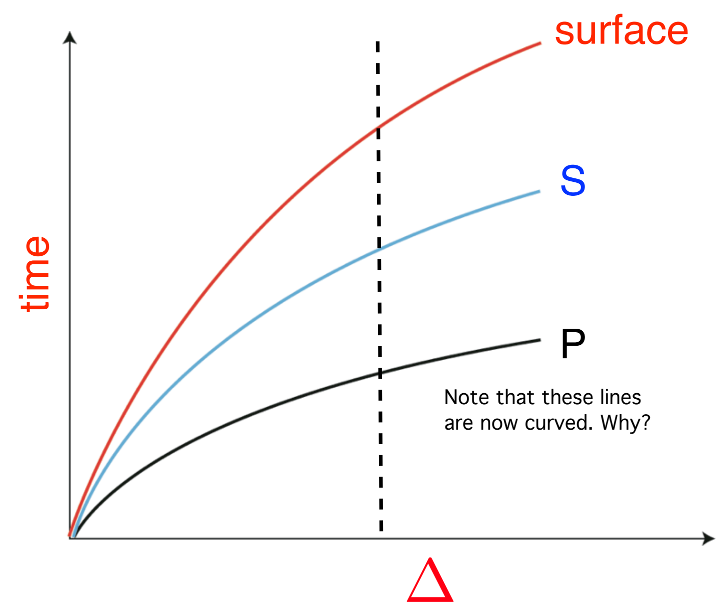
Simplest assumption: imagine that the Earth's interior is uniform material (but compressed at depth)



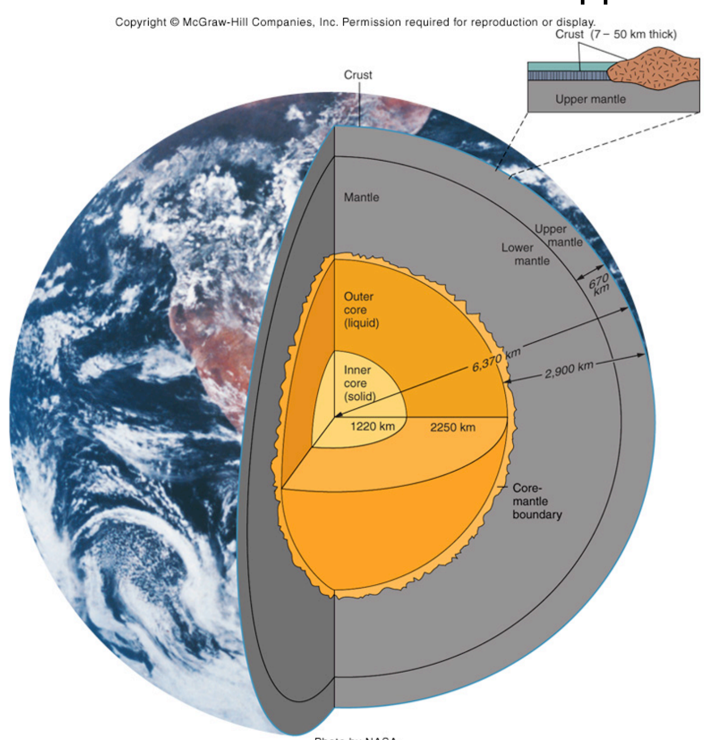
- P wave, S wave, and surface waves would arrive at all stations
- we would compute their arrival times at different seismometers assuming a gradual increase in velocity due to pressure
- this would work perfectly

we could make a plot of P, S, and surface wave arrival time with distance " Δ "

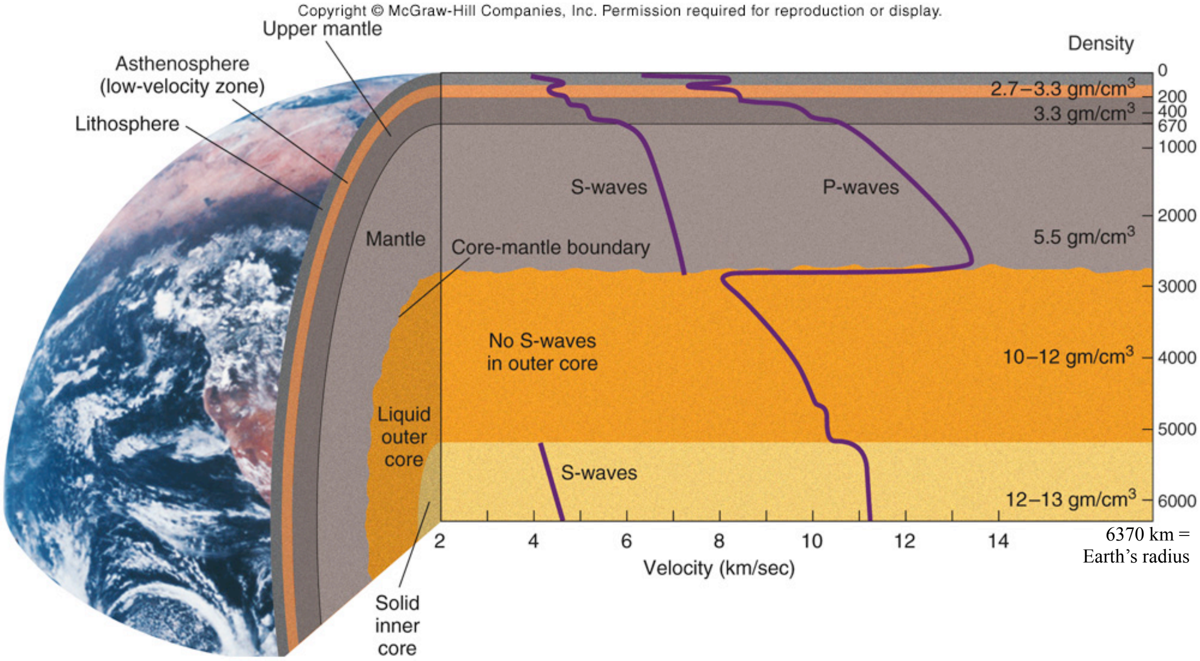




But the Earth is layered. At layer interfaces (where there is a big contrast in P and S wave velocity), both refraction and reflection happen.



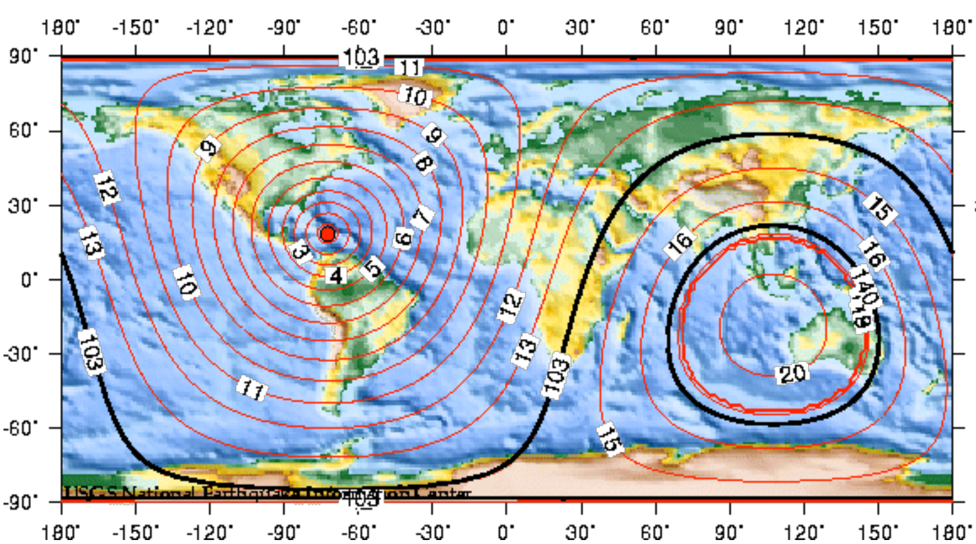
P wave velocities drop suddenly at 2900 km depth, and S waves cannot pass through this layer (the liquid outer core)



Theoretical P-Wave Travel Times

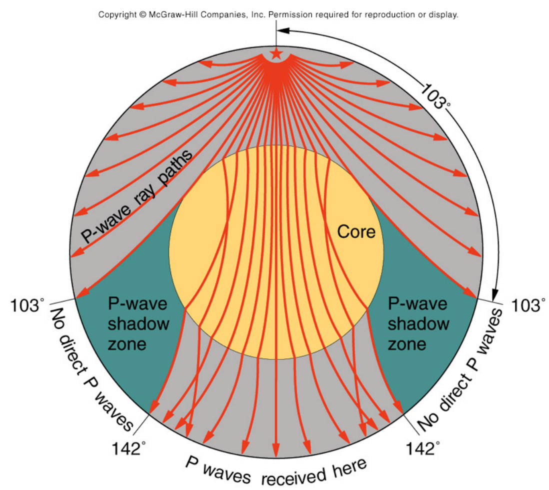
Magnitude 7.0 HAITI REGION

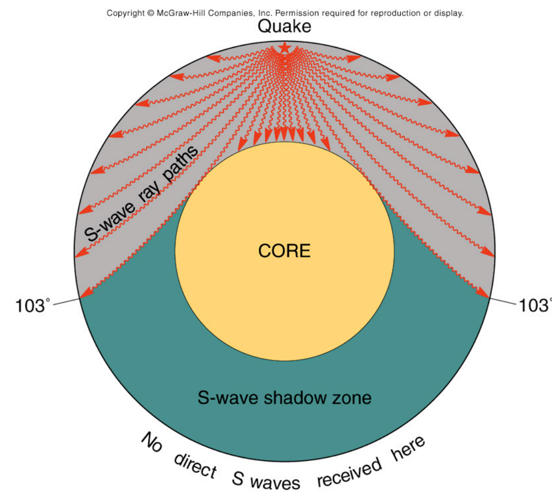
Tuesday, January 12, 2010 at 21:53:10 UTC



What are the red contours? The black ones?

Where on Earth (relative to the epicenter) can one use just the difference between the direct P and S wave arrival times to compute distance to the quake?



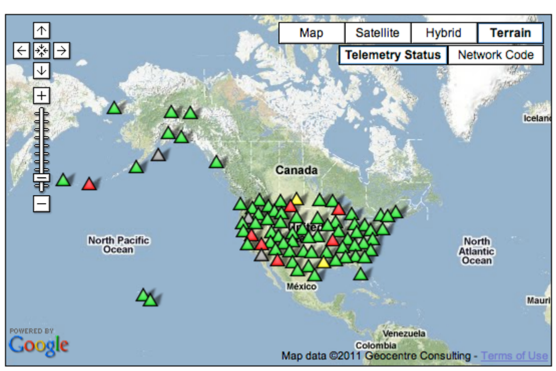


Other possible problem: heterogeneous Earth materials

In reality:

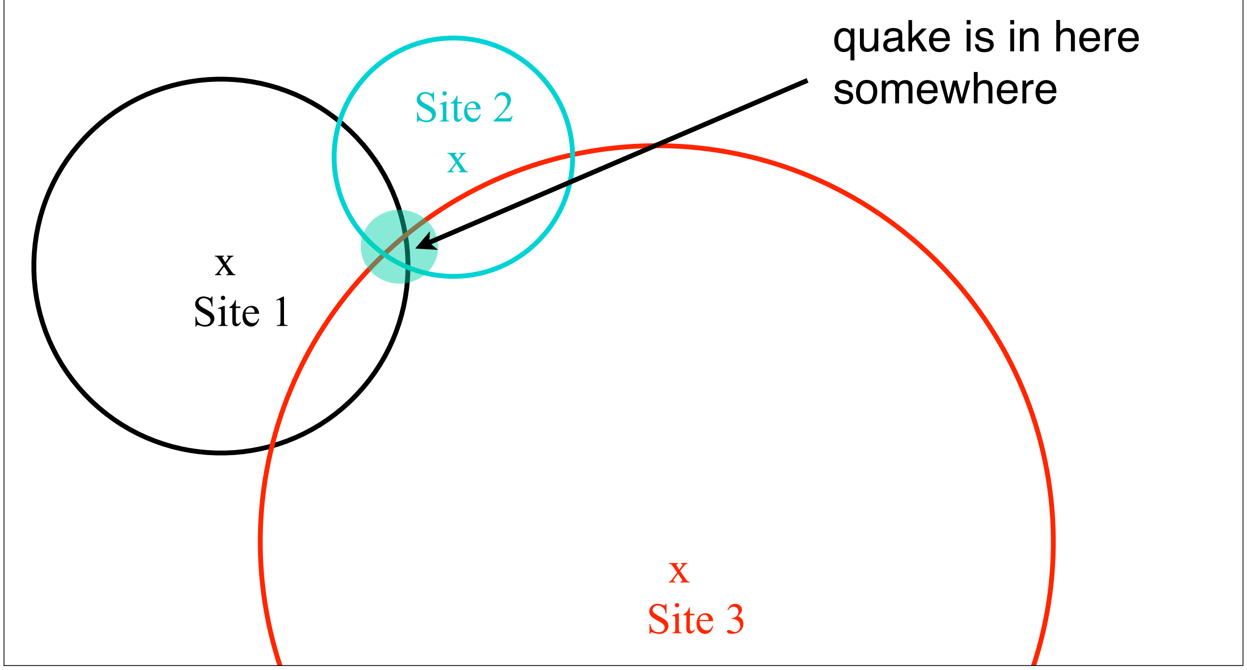
(1) seismic velocities vary (especially with depth)

(2) location of earthquakes is automated and data from many seismometers are used, not just three or four

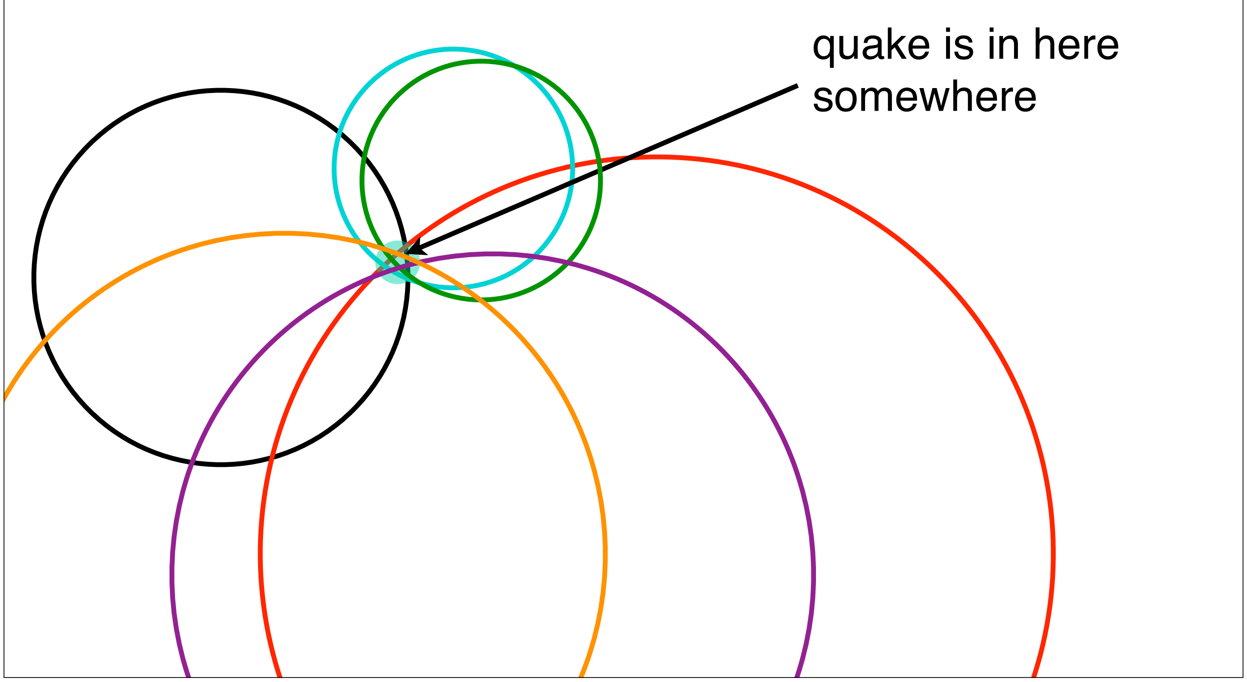


ANSS

Triangulation:
Usually what happens is that the circles don't meet exactly.



Add more stations and the error in location estimate can be reduced (find the epicentre that "best" matches ALL of the distance estimates)



How to minimize disagreement between station-epicenter distances, for all stations:

trial and error?

or: set up as an "inverse problem":

(1) guess the focus location (x,y,z) and origin time τ

REPEAT steps 2 and 3 several times:

(2) see how bad that guess is (compute "misfit" to seismometer-focus distances: summed squared residual)

(3) refine your guess of quake (x,y,z,τ)

UNTIL your estimate is pretty good (misfit is small)

"Alternate approach (more commonly used): just use wave arrival times from many stations and solve for hypocenter location and origin time. This requires data from at least 4 seismometers."

The basic data in earthquake location is

Arrival Time, t

The time of day that a wave from the earthquake arrives at a seismograph station

The next several slides are from W. Menke: http://www.ldeo.columbia.edu/users/menke/talks/

The distinction between

Arrival Time: time of day something arrives

And

Travel Time: the length of time spent traveling

Is very important in earthquake location!

Arrival Time ≠Travel Time

Q: a car arrived in town after traveling for an half an hour at sixty miles an hour. Where did it start?

A. Thirty miles away

Q: a car arrived in town at half past one, traveling at sixty miles an hour. Where and when did it start?

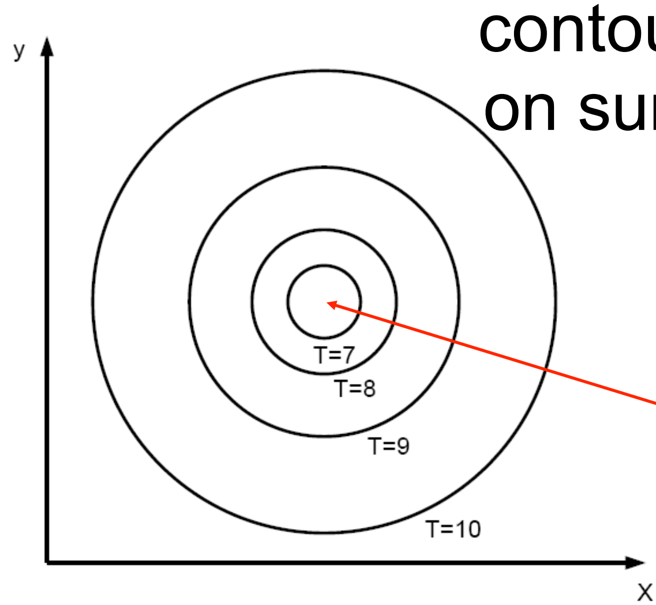
A. Are you crazy?

An earthquake location has
4 Parameters

x, y (epicenter)
z (depth)
τ (origin time)

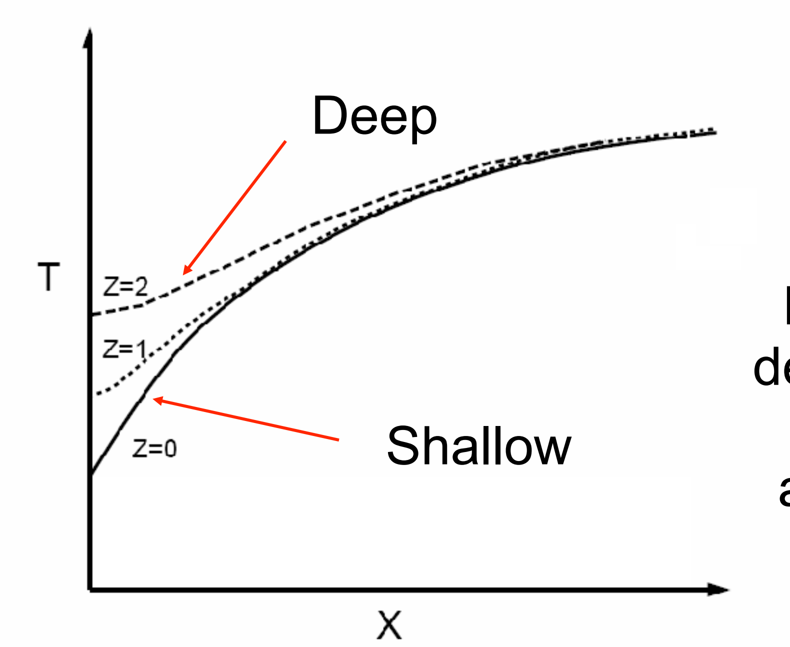
Together, (x, y, z) are called the hypocenter. The fact that origin time is an unknown adds complexity to the earthquake location problem!

Suppose you contour arrival time on surface of earth



Earthquake's (x,y) is center of bulls-eye

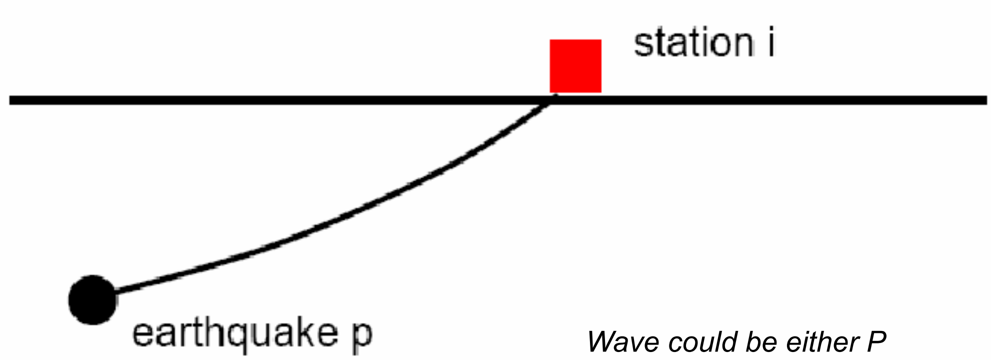
but what about its depth?



Since origin time unknown we have not marked it on time axis

Earthquake's depth related to curvature of arrival time at origin

Fundamental data: arrival time t_{pi} of waves from earthquake p to station i

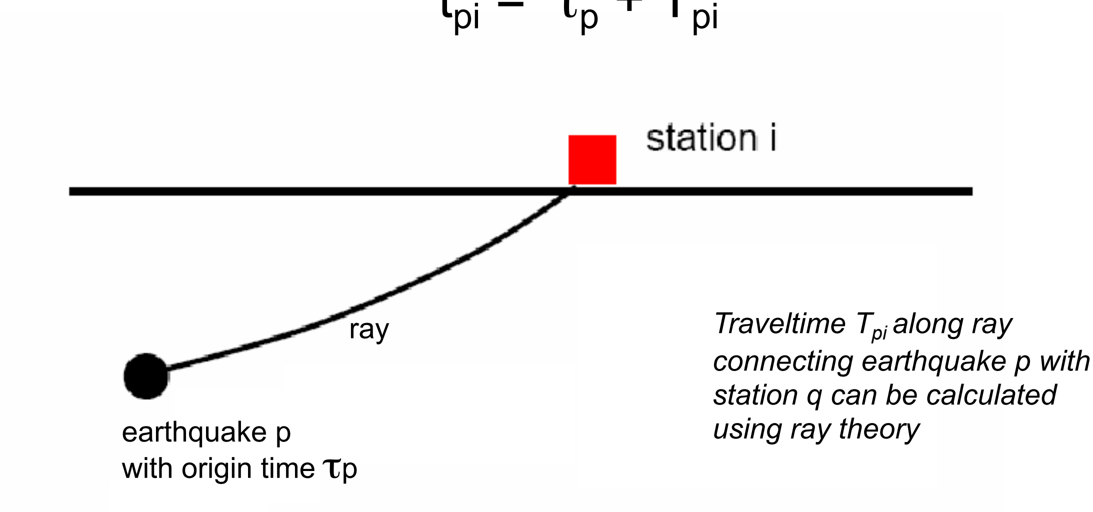


Wave could be either P wave or S wave. Both are used.

Fundamental Relationship

Arrival Time = Origin Time + Travel Time

$$t_{pi} = \tau_p + T_{pi}$$



Basic Principle

Best estimates of the hypocentral parameters and origin time are the ones that best predict the arrival times at all the stations.

Usually, "best predicts" means minimizing the least-squares prediction error, E:

$$E_p = \Sigma_i \left[t_{pi}^{observed} - t_{pi}^{predicted} \right]^2$$

where $t_{pi}^{predicted} = \tau_p^{predicted} + T_{pi}^{predicted}$

and where $T_{pi}^{predicted}$ depends on (x_p, y_p, z_p)

The mathematical problem is to find the hypocentral parameters,

$$\mathbf{x}_p^{predicted}=(x_p,\ y_p,\ z_p)^{predicted}$$

and origin time,

$$\tau_p^{predicted}$$

that give the best fit
(which is to say, minimize the error)

But the problem is that the traveltime varies in a complicated, non-linear way with the hypocentral parameters, $\mathbf{x}_p^{predicted}$

The usual solution is to use an iterative method:

Step 1: Guess a set of hypocentral parameters, $\mathbf{h}=(x_p, y_p, z_p, \tau_p) = (\mathbf{x}_p, , \tau_p)$ and use it to predict the traveltime

Step 2: Determine how much the arrival time would change if the guess were changed by a small amount, $\delta\mathbf{h} = (\delta\mathbf{x}, \delta\tau)$.

Step 3: Use that information to attempt to find a slightly different **h** that reduces the error, E.

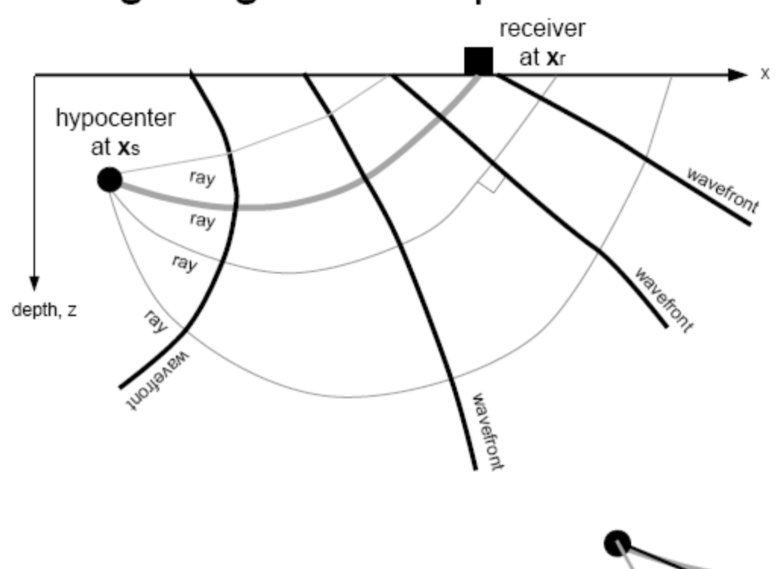
Do steps 2 and 3 over and over again, hoping that eventually the error will become acceptably small.

It turns out that Step 2 is incredibly easy.

A small change in origin time, $\delta\tau$, simply shifts the arrival times by the same amount, $\delta t = \delta\tau$.

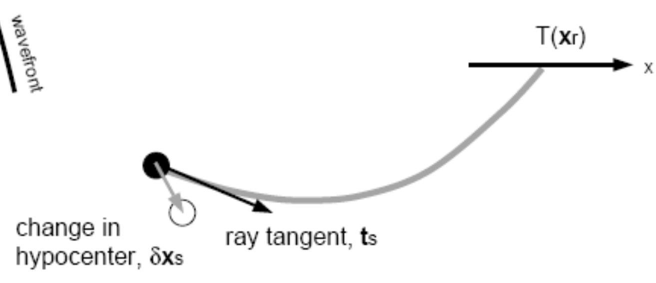
The effect of a small change in location depends on the direction of the shift. A change δx along the ray direction shifts the time by $\delta t=\delta x/v$. But a change perpendicular to the ray has no effect. This is Geiger's Principle, and illustrated in the next slide.

Earthquake Location using Geiger's Principle



How much does a small change in hypocentral location change the traveltime at a given statopn ?

Only the component of the change parallel to the ray direction matters.



change in traveltime = $\delta T = \mathbf{t}_s \bullet \delta\mathbf{x}_s / V(\mathbf{x}_s)$

Step 3 is pretty easy too. The trick is to realize that the equation that says the observed and predicted traveltimes are equal is now linear in the unknowns:

$$t_{pi}^{obs} = t_{pi}^{pre} \quad = \quad \tau_p + T_{pi}^{pre}$$

$$= \tau_p^{guess} + \delta\tau + T_{pi}^{pre}(\mathbf{x}_p^{guess}) + (\mathbf{t}/v)\bullet\delta\mathbf{x}$$

Or by moving two terms to the left:

$$t_{pi}^{obs} - T_{pi}^{pre}(\mathbf{x}_p^{guess}) - \tau_p^{guess} = \delta\tau + (\mathbf{t}/v)\bullet\delta\mathbf{x}$$

The methodology for solving a linear equation in the least-squares sense is very well known. It requires some tedious matrix algebra, so we wont discuss it here. But is routine.