The Abdus Salam
International Centre
for Theoretical Physics

2464-11

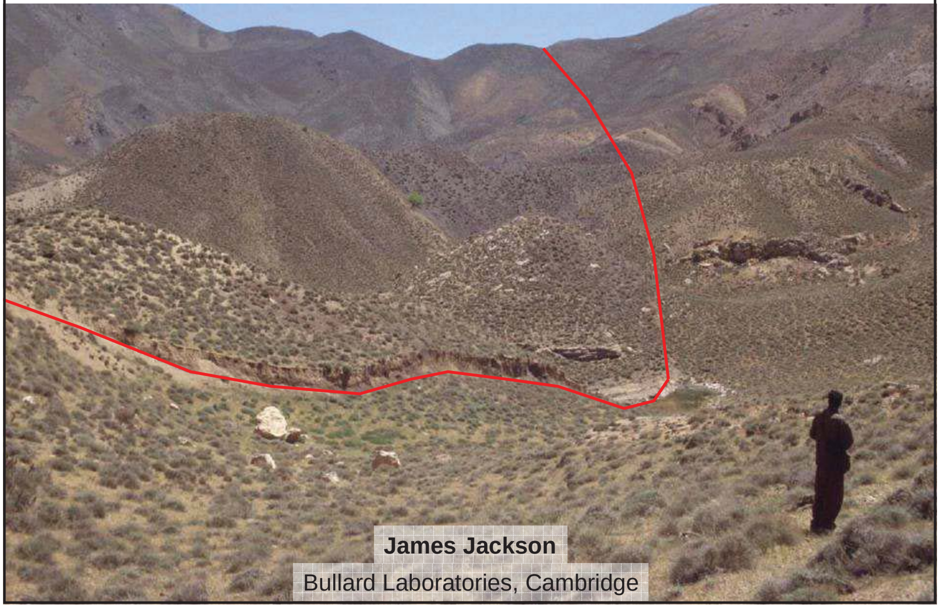
Earthquake Tectonics and Hazards on the Continents

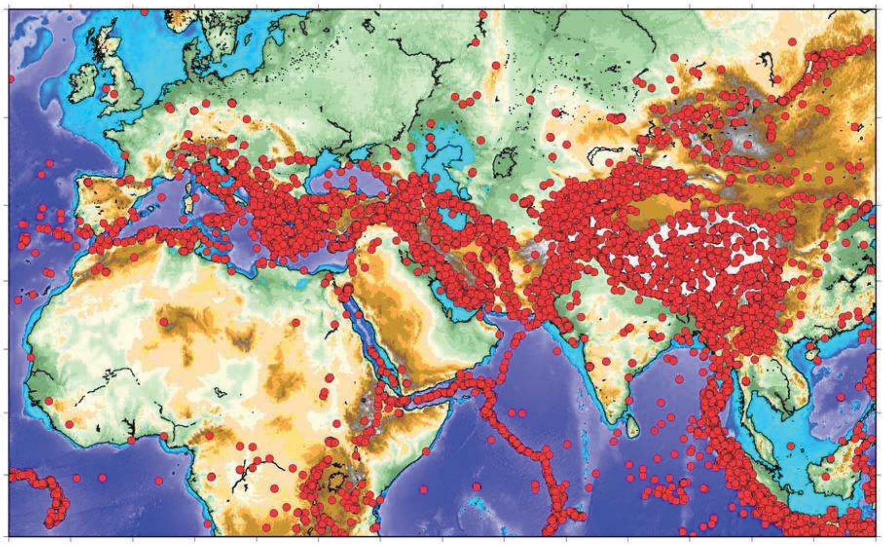
17 - 28 June 2013

Earthquake source parameters; simple seismology; what to believe.

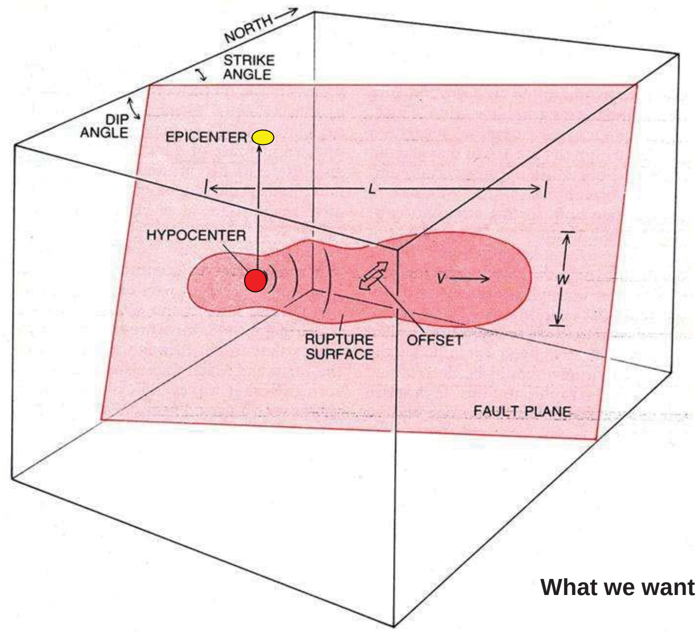
J. Jackson
University of Cambridge
UK

Earthquake source seismology





Each earthquake is a fault moving.
What can seismology tell us about that fault?



What we want to know

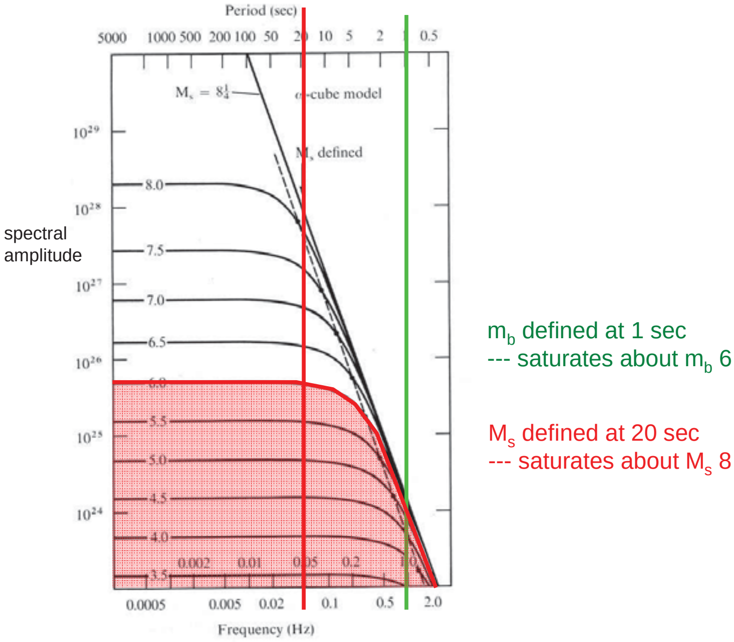
Size and magnitude

Place	*Date*	M_w	M_s	m_b	M_0 (10^{20} Nm)	A (10^3 km^2)	$\bar{u}$ (m)	L (km)	$\bar{u}/L$ ($\times 10^{-4}$)
Chile	1960.5.22	9.6	8.3		2700	160	24.0	800	0.3
Alaska	1964.3.28	9.2	8.5	6.4	820	130	21.0	650	0.3
Iran	1968.3.31	7.3	7.3	6.0	1.0	1.6	2.0	80	0.2
Landers (CA)	1992.6.28	7.3	7.5	6.2	1.0	0.7	5.0	70	0.7
Turkey	1967.7.22	7.2	7.1	6.0	0.83	1.6	1.7	40	0.4
Loma Prieta (CA)	1989.10.18	6.9	7.1	6.5	0.29	0.6	1.6	40	0.4
Algeria	1980.10.10	6.9	7.3	6.5	0.25	0.38	2.2	25	0.8
Greece	1981.2.25	6.3	6.4	5.7	0.04	0.15	1.1	15	0.7
Truckee (CA)	1966.9.12	5.9	5.9	5.4	0.0083	0.1	0.3	10	0.3
San Fernando aftershock (CA)	1971.2.10 (113134 GMT)	—	—	4.2	0.000001	0.00002	0.02	0.1	2.0

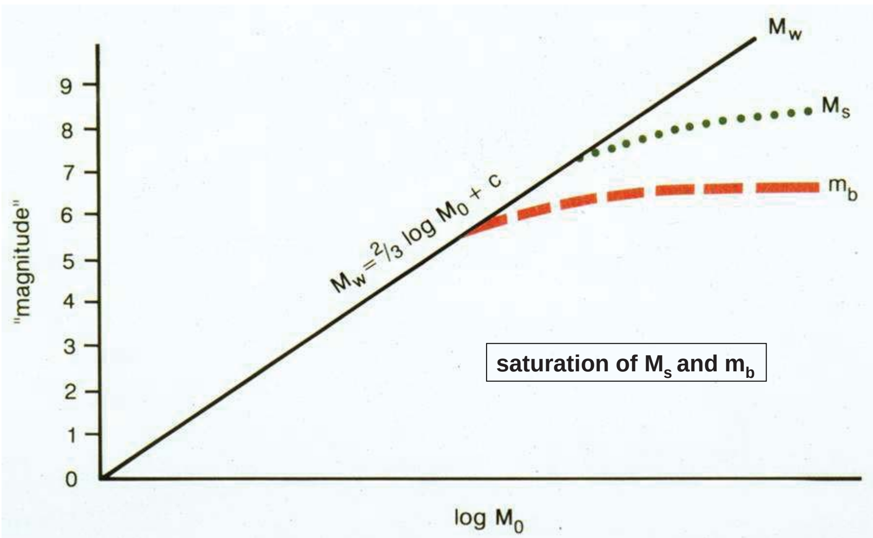
Original definition of magnitude was related to the amplitude of ground motion at **a single frequency (period):** 20 seconds for surface waves (M_s)
1 second for body waves (m_b)

Note the big range of fault lengths (L) in these earthquakes, but the small range in M_s and m_b.

M_s never exceeds about 8.5 and m_b never exceeds about 6.5. This is called **saturation**.



Period (sec)
5000 1000 500 200 100 50 20 10 5 2 1 0.5
$M_s = 8\frac{1}{4}$
ω-cube model
M_s defined
spectral
amplitude
10^{29}
10^{28}
10^{27}
10^{26}
10^{25}
10^{24}
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
0.002 0.01 0.05 0.2 1.0
0.0005 0.005 0.02 0.1 0.5 2.0
Frequency (Hz)
m_b defined at 1 sec
--- saturates about m_b 6
M_s defined at 20 sec
--- saturates about M_s 8



M_w
M_s
m_b
"magnitude"
0
1
2
3
4
5
6
7
8
9
$M_w = {}^2/_3 \log M_0 + c$
saturation of M_s and m_b
log M_0

Place	*Date*	M_w	M_s	m_b	M_0 (10^{20} Nm)	A (10^3 km^2)	$\bar{u}$ (m)	L (km)	$\bar{u}/L$ ($\times 10^{-4}$)
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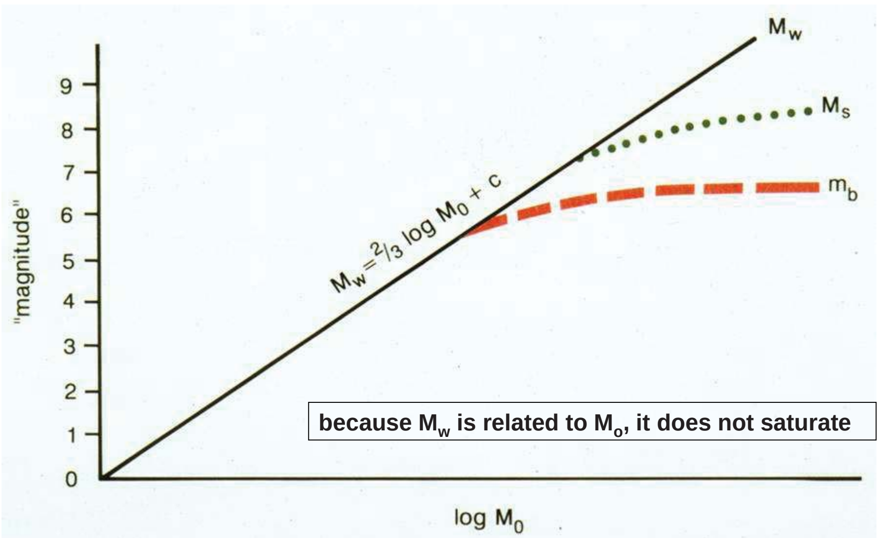
Seismic Moment $M_0 = \mu A u$

is a much better measure of size than magnitude

Moment magnitude $M_w = 2/3 \log_{10} M_0 - 6.0$

μ = rigidity modulus (about 3x10^{10} Pas)
A = fault area; u = average slip



below about M_w 6.0, M_w and m_b are approximately the same
below about M_w 7.0, M_w and M_s are approximately the same

Place	*Date*	M_w	M_s	m_b	M_0 (10^{20} Nm)	A (10^3 km^2)	$\bar{u}$ (m)	L (km)	$\bar{u}/L$ ($\times 10^{-4}$)
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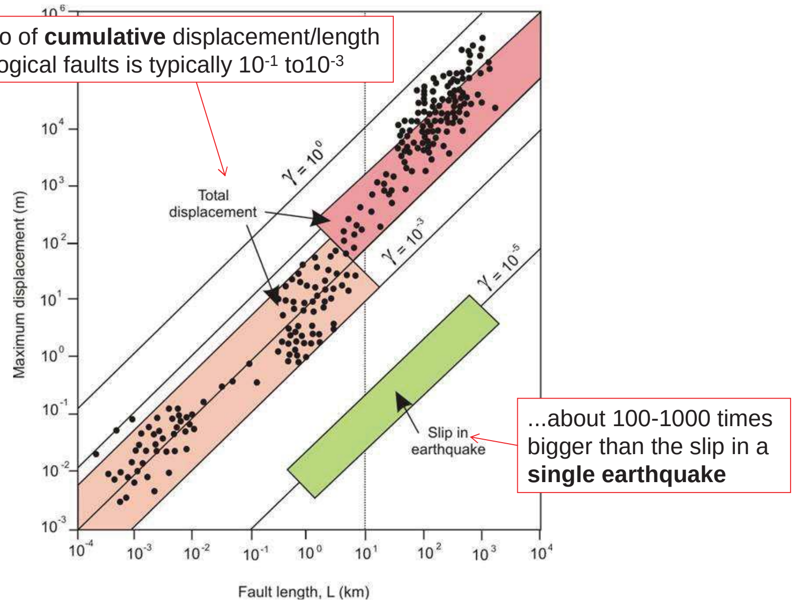
The ratio of slip/length (u/L) is approximately 5×10^{-5} for all sizes of earthquake

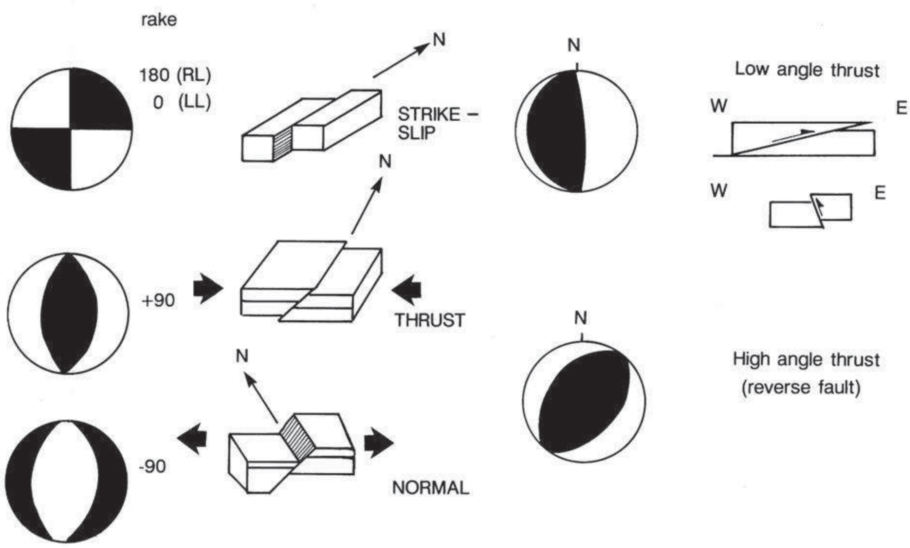
So the average stress drop in earthquakes is usually 1-10 MPa (1-10 x 10^6 Pascals)

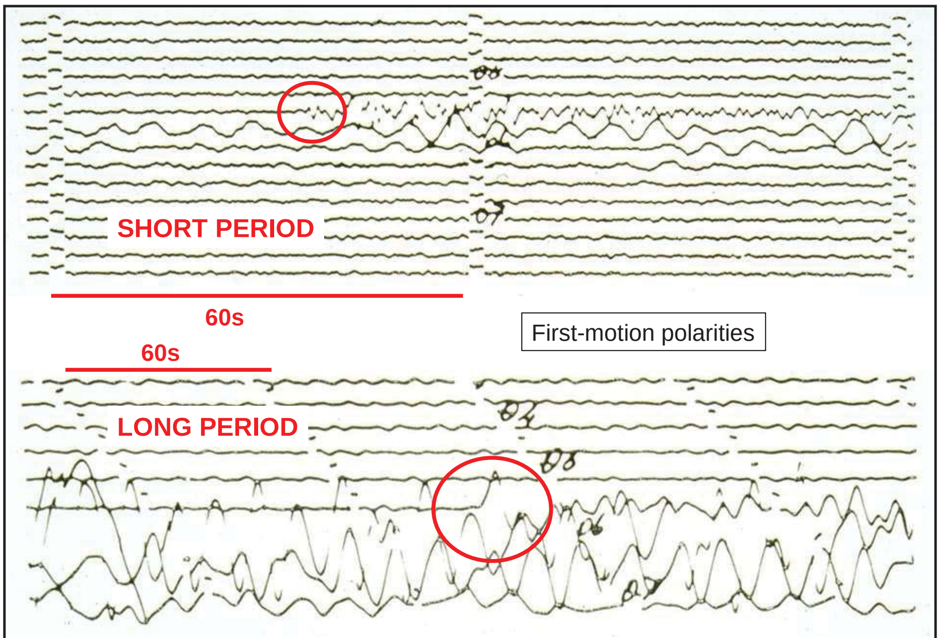


So: Faults **increase their offset by repeated slip** in earthquakes

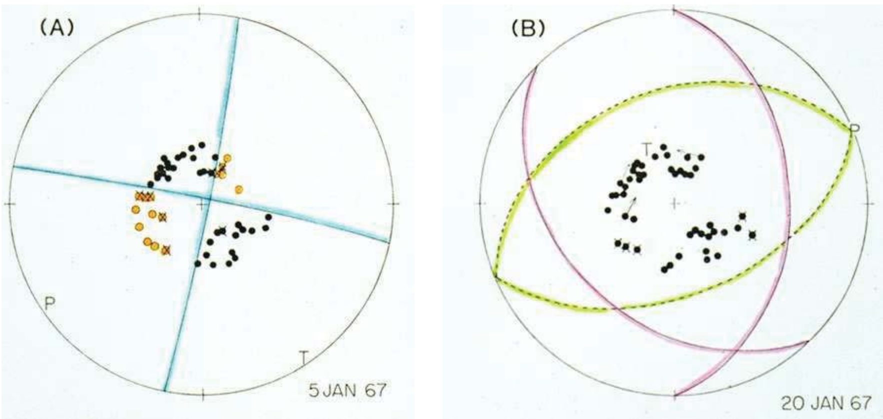
And they must **grow in length** at the same time

Fault plane solutions

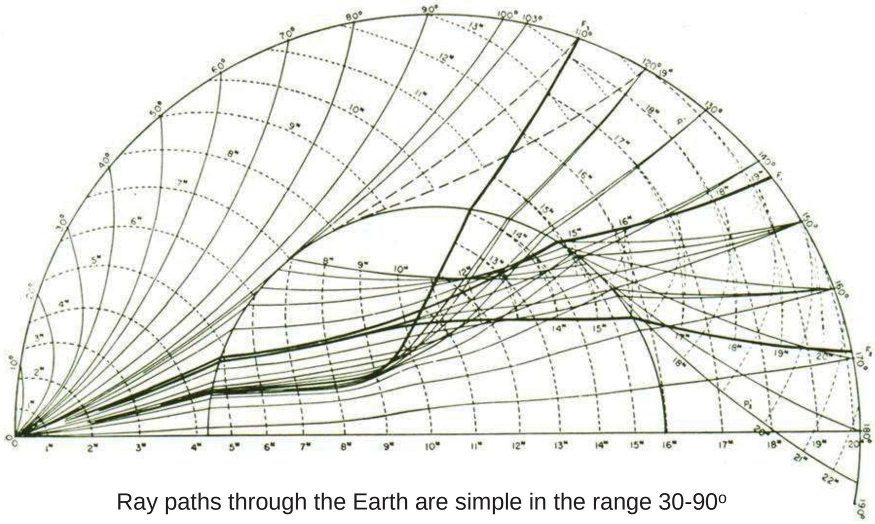




..are clearer on long-period than short-period seismograms (less noise)...

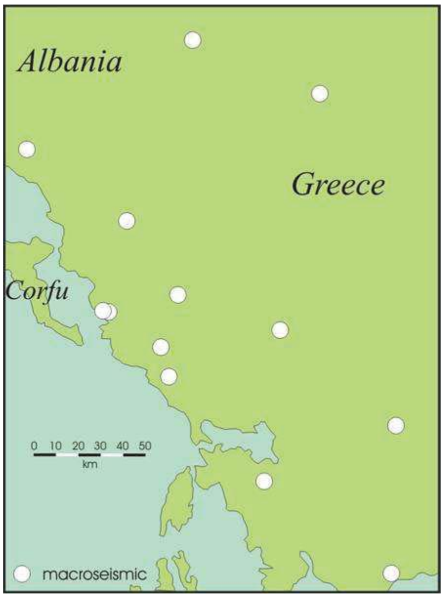


Quality depends on station distribution and focal mechanism type

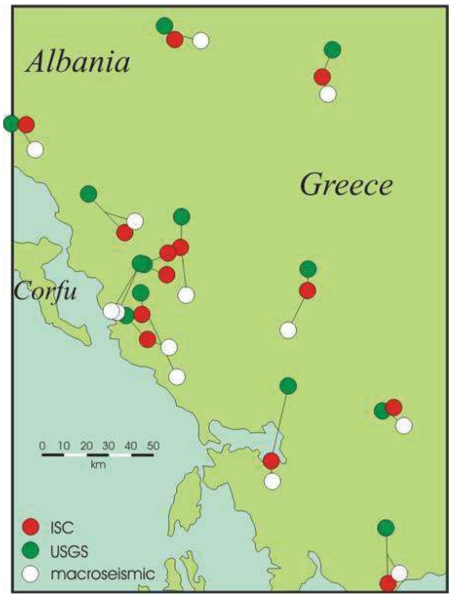


Ray paths through the Earth are simple in the range 30-90^{o}

Earthquake locations: epicentres



Earthquake locations: epicentres



Except where there are dense networks of local stations (California, Japan), routinely determined epicentres can be wrong by 20 km or more.

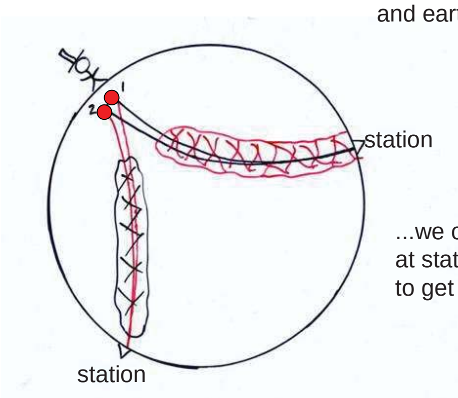
Best catalogue is the **EHB Bulletin**
http://www.isc.ac.uk/ehbbulletin/search/bulletin/

...but even this often has epicentre errors of 10 km or more where there are no close stations

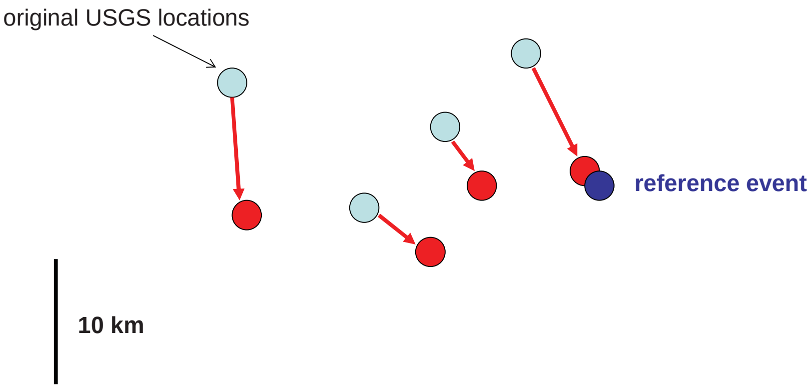
In dense local networks with station separations of <5 km, epicentre errors can be < 1 km.

Improving epicentres with relative locations

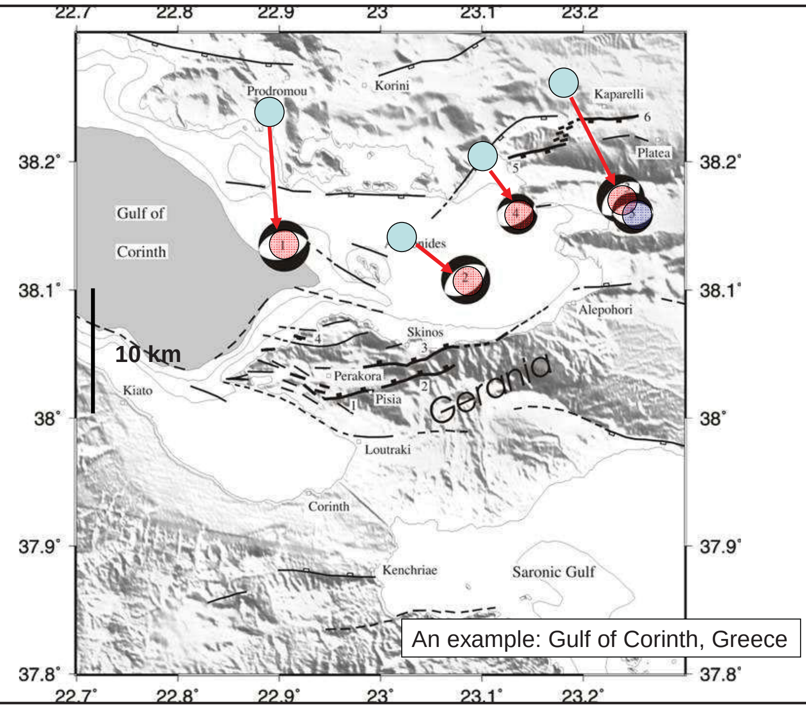
If the distance between adjacent earthquakes is small compared to distance between station and earthquake....



...we can use the difference in arrival times at stations (instead of absolute arrival times) to get the difference in location



An example: Gulf of Corinth, Greece

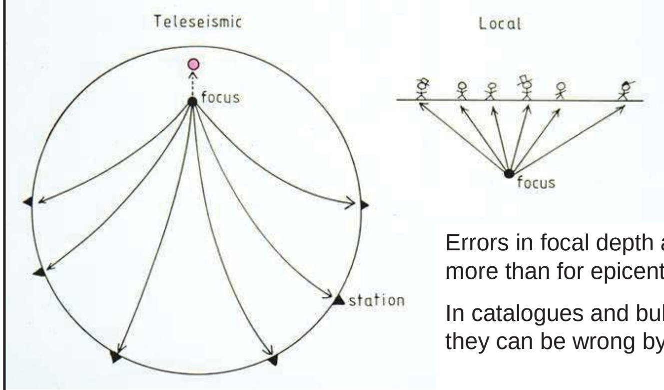


An example: Gulf of Corinth, Greece

Earthquake focal depths: a special problem

Earthquake location needs: latitude, longitude, depth, ***origin time***

Origin time and depth: an example of a ***trade-off***



Errors in focal depth are often much more than for epicentres:.

In catalogues and bulletins they can be wrong by 50 km or more.

Do not believe catalogue depths!

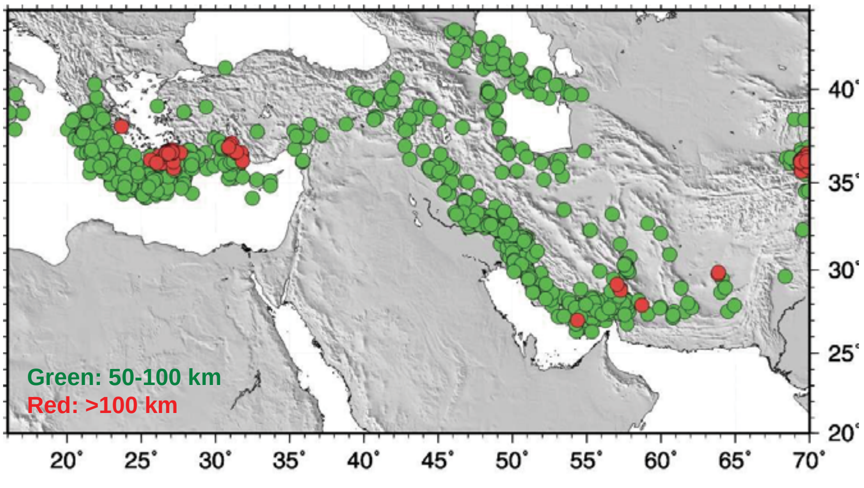
Earthquake focal depths: questions to ask

From local networks:

1. ***What is the station spacing?***
   Resolution is generally best at a depth about the same as the station spacing. For example, a network with a spacing of 30 km will have no resolution at depths shallower than about 20 km.
2. ***Are both P and S arrival times used?***
   Using S as well as P greatly helps constrain locations, as the station-hypocentre distance is about:
   (S-P time) x 8 km

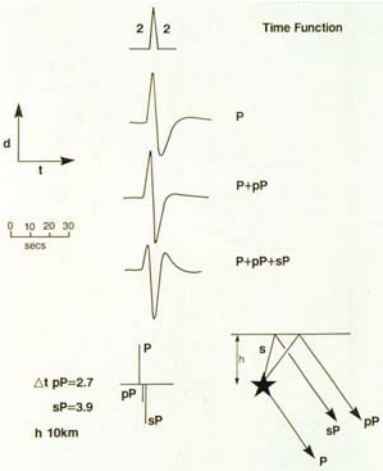
From teleseismic catalogues or bulletins:

1. ***Are the depths based on waveform analysis?***
   If not, they may be in error by several tens of km...
   (EHB Bulletin is better than that, but is still often wrong by 10 or more)

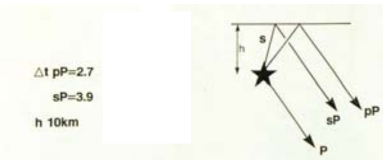


Earthquakes reported deeper than 50 km 1964-98

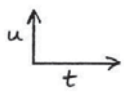
Synthetic seismograms

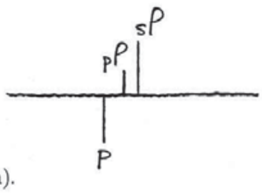


- use long periods
- then earthquake appears as a *point source* (the ***centroid***)
- use P, pP, sP (and S, sS for S waves)
- pulse *width* depends on *depth*
- pulse *shape* depends on *focal mechanism*
- pulse *amplitude* depends on *seismic moment*



So the P seismogram should look like:

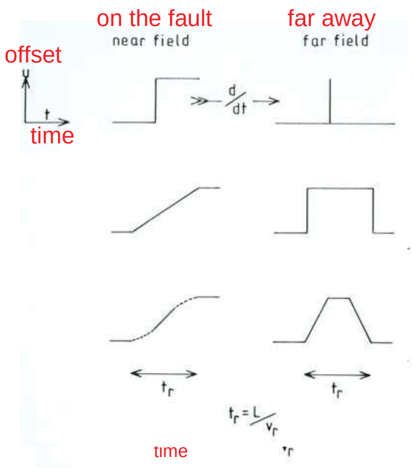




1st attempt

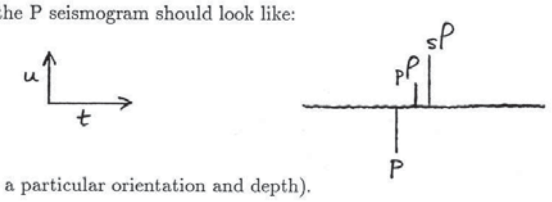
(for a particular orientation and depth).

The source time function



- STF is the time *history of slip* on the fault
- the *duration* of STF is approximately the fault *length divided by the rupture velocity*
- rupture velocity (v_r) is usually $\leq V_s$ (~2-2.5 km/s)

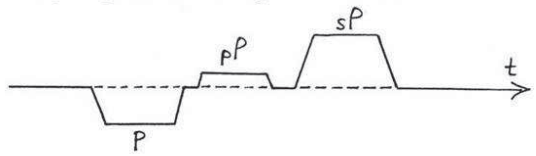
So the P seismogram should look like:



1st attempt

(for a particular orientation and depth).

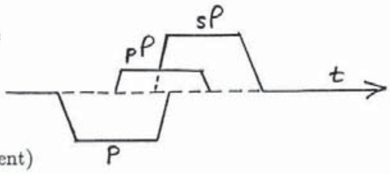
So you might expect the P seismogram to look like:



2nd attempt

but...(nothing's simple)

1. The trapezoids usually overlap in time



2. The **seismometer** (recording instrument)

turns  into 

so the three pulses interfere with each other, to produce a P waveform that looks like:

3rd attempt

for a simple, shallow (~10 km), normal faulting earthquake of magnitude ~6.

P

P + pP

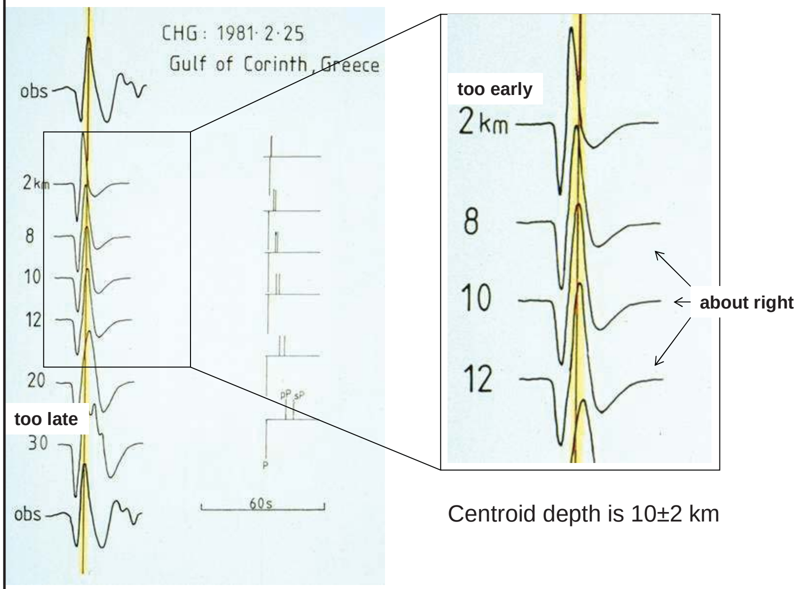
P + pP + sP

so the three pulses interfere with each other, to produce a P waveform that looks like:

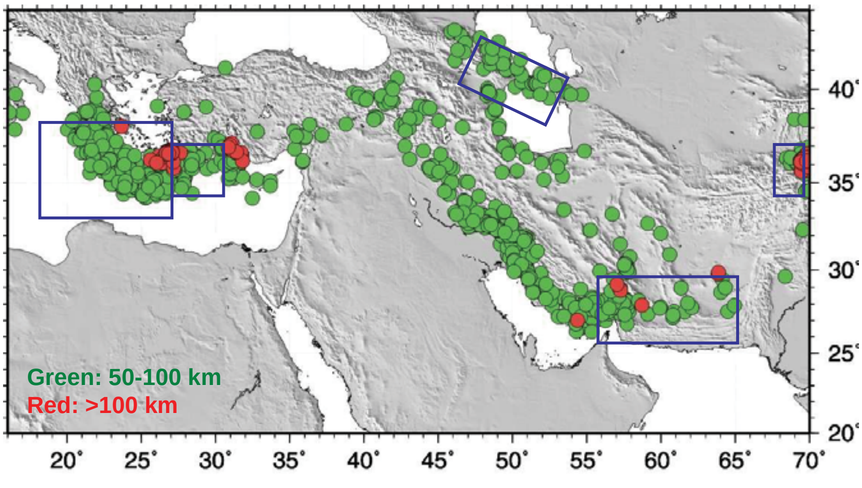
3rd attempt

for a simple, shallow (~10 km), normal faulting earthquake of magnitude ~6.

An example:



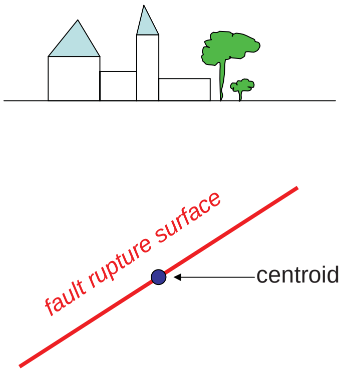
Centroid depth is 10±2 km



Earthquakes reported deeper than 50 km 1964-98

All are shallower than 25 km except in the blue boxes

What does centroid depth mean?



- The **centroid** is the *centre* of the fault rupture surface
- If the fault breaks the surface, the total fault depth is approximately *twice* the centroid depth

Waveform analysis:

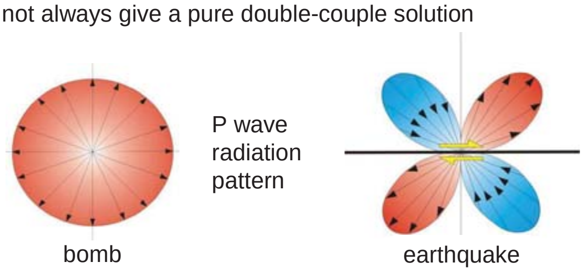
Is important for accurate estimates of earthquake source parameters

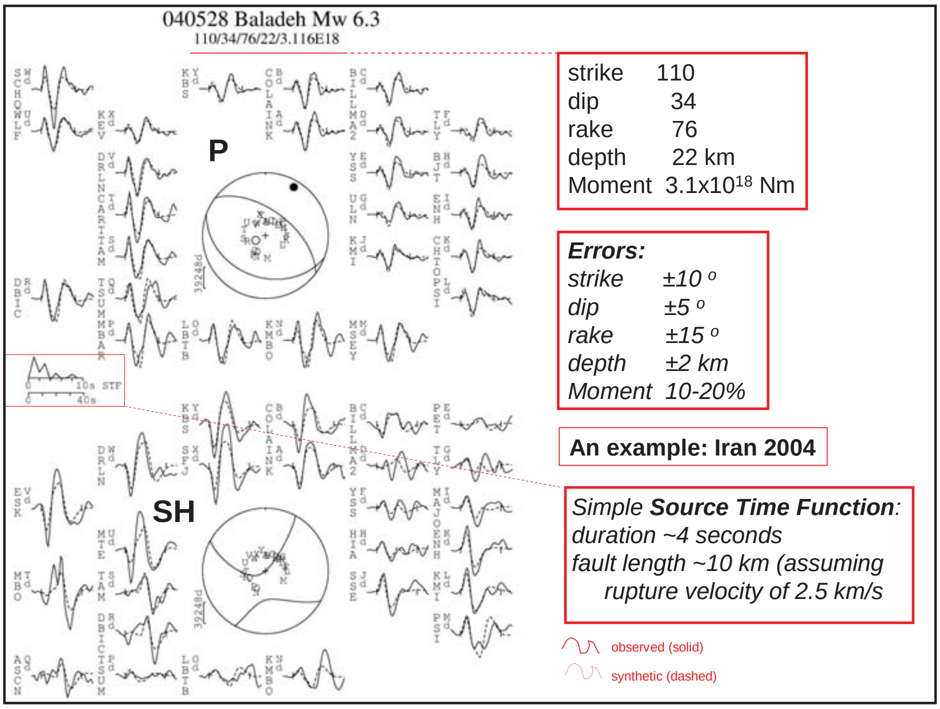
The **Global Centroid-Moment-Tensor (gCMT)** Project:
http://www.globalcmt.org/

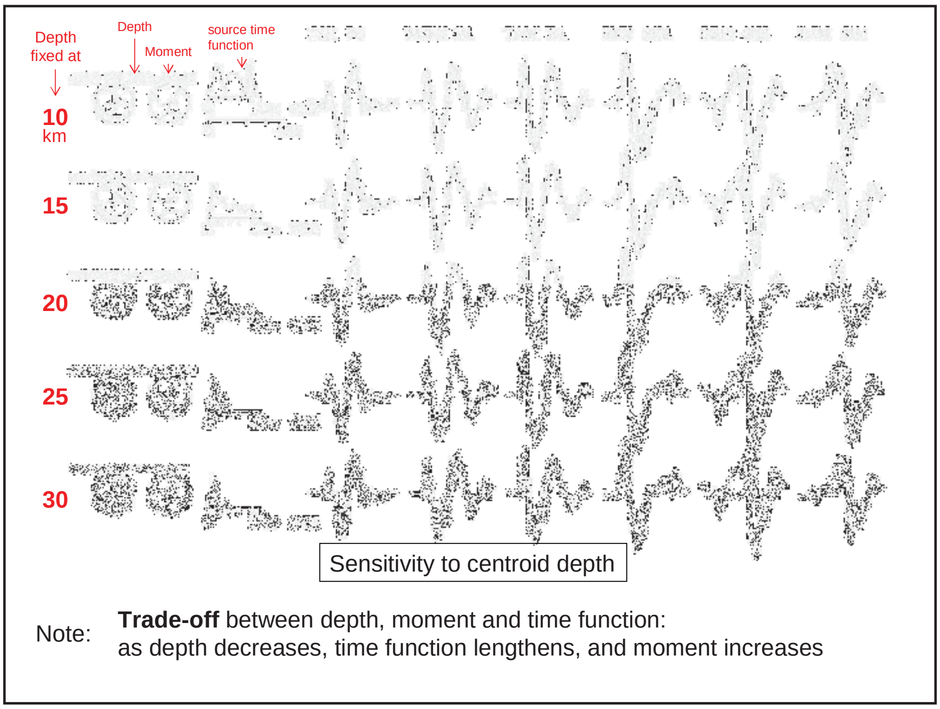
An excellent resource, routinely determining parameters for nearly all earthquakes larger than about Mw 5.2

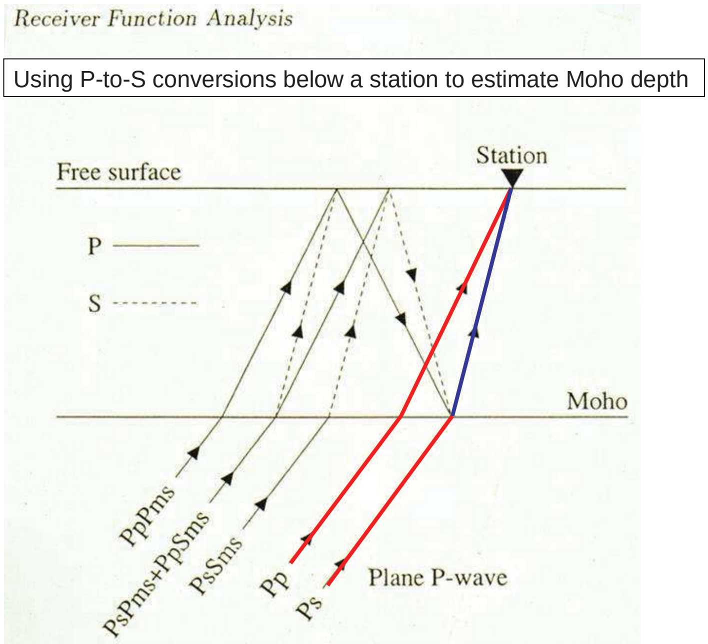
Uses relatively long periods, with body waves usually <45s. (gives poor depth resolution shallower than about 30 km)

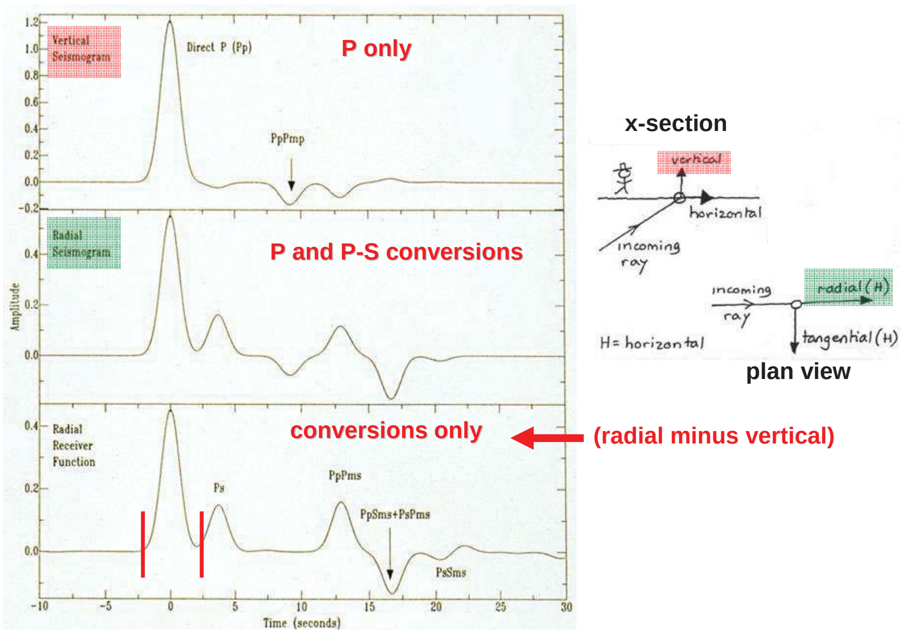
May not always give a pure double-couple solution




040528 Baladeh Mw 6.3
110/34/76/22/3.116E18
P
SH
STF
strike 110
dip 34
rake 76
depth 22 km
Moment 3.1x10^18 Nm
Errors:
strike ±10 º
dip ±5 º
rake ±15 º
depth ±2 km
Moment 10-20%
An example: Iran 2004
Simple Source Time Function:
duration ~4 seconds
fault length ~10 km (assuming
rupture velocity of 2.5 km/s
observed (solid)
synthetic (dashed)


Depth
fixed at
Depth
Moment
source time
function
10 km
15
20
25
30
Sensitivity to centroid depth
Note: Trade-off between depth, moment and time function:
as depth decreases, time function lengthens, and moment increases


Receiver Function Analysis
Using P-to-S conversions below a station to estimate Moho depth
Free surface
Station
P
S
Moho
PpPms
PsPms+PpSms
PsSms
Pp
Ps
Plane P-wave


Vertical Seismogram
Direct P (Pp)
P only
PpPmp
Radial Seismogram
P and P-S conversions
Amplitude
Radial Receiver Function
conversions only
(radial minus vertical)
Ps
PpPms
PpSms+PsPms
PsSms
Time (seconds)
x-section
vertical
horizontal
incoming ray
radial (H)
tangential (H)
H= horizontal
plan view