Revisiting the 1960 Chilean Earthquake

-For the 50th Anniversary -

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In collaboration with Luis Rivera, and with help from Stewart Smith, and Frank Press.

1960 Chilean Earthquake (M_w=9.5)

Believed to be the largest in the last century.

cf. 1964 Alaskan Earthquake, M_w=9.2
2004 Sumatra-Andaman Is. Earthquake, M_w=9.2
1952 Kamchatka Earthquake, M_w=9.0

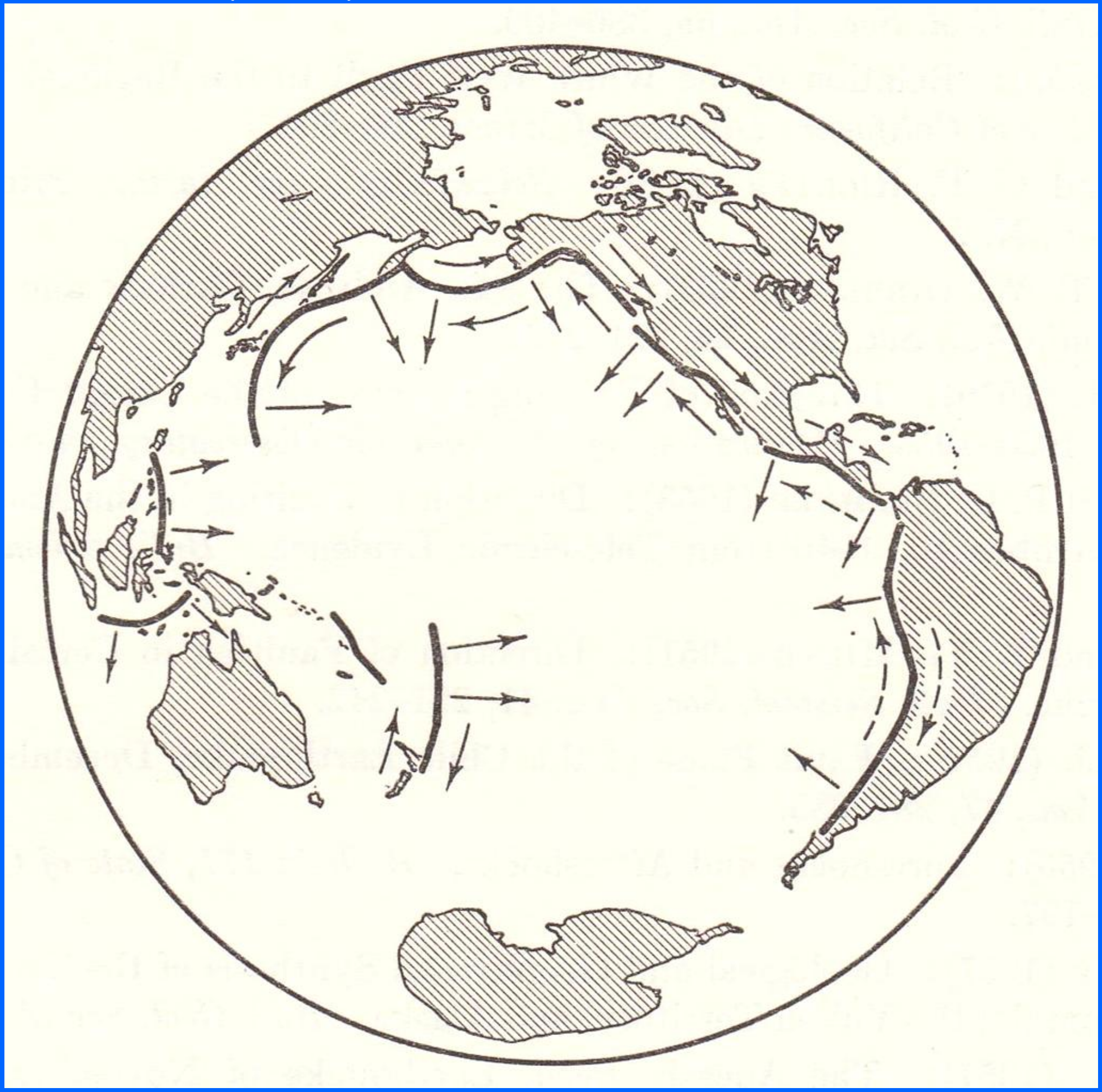
Is it really the largest ?

Is something special ?

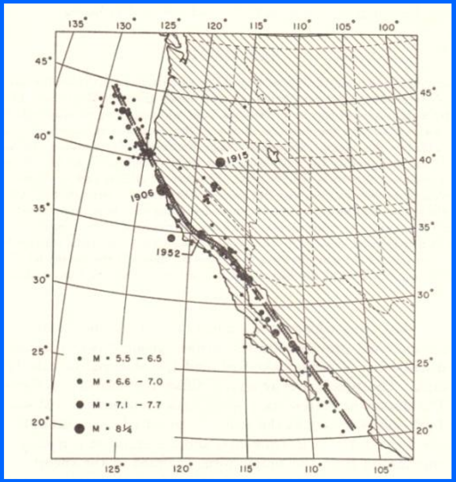
What have we learnt from it?

Background, e.g., Benioff's Idea

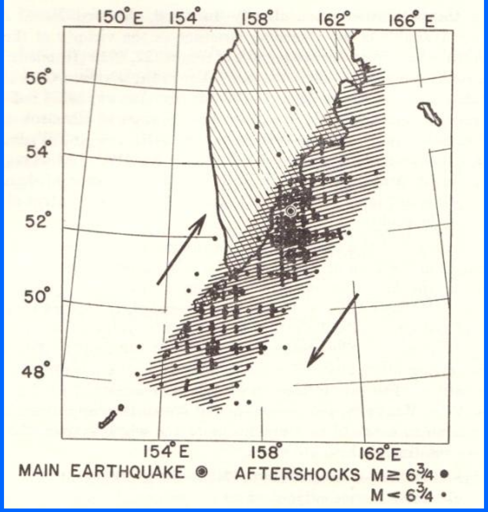
Dextral (right-lateral) Rotation of the Pacific
Benioff (1958)



San Andreas

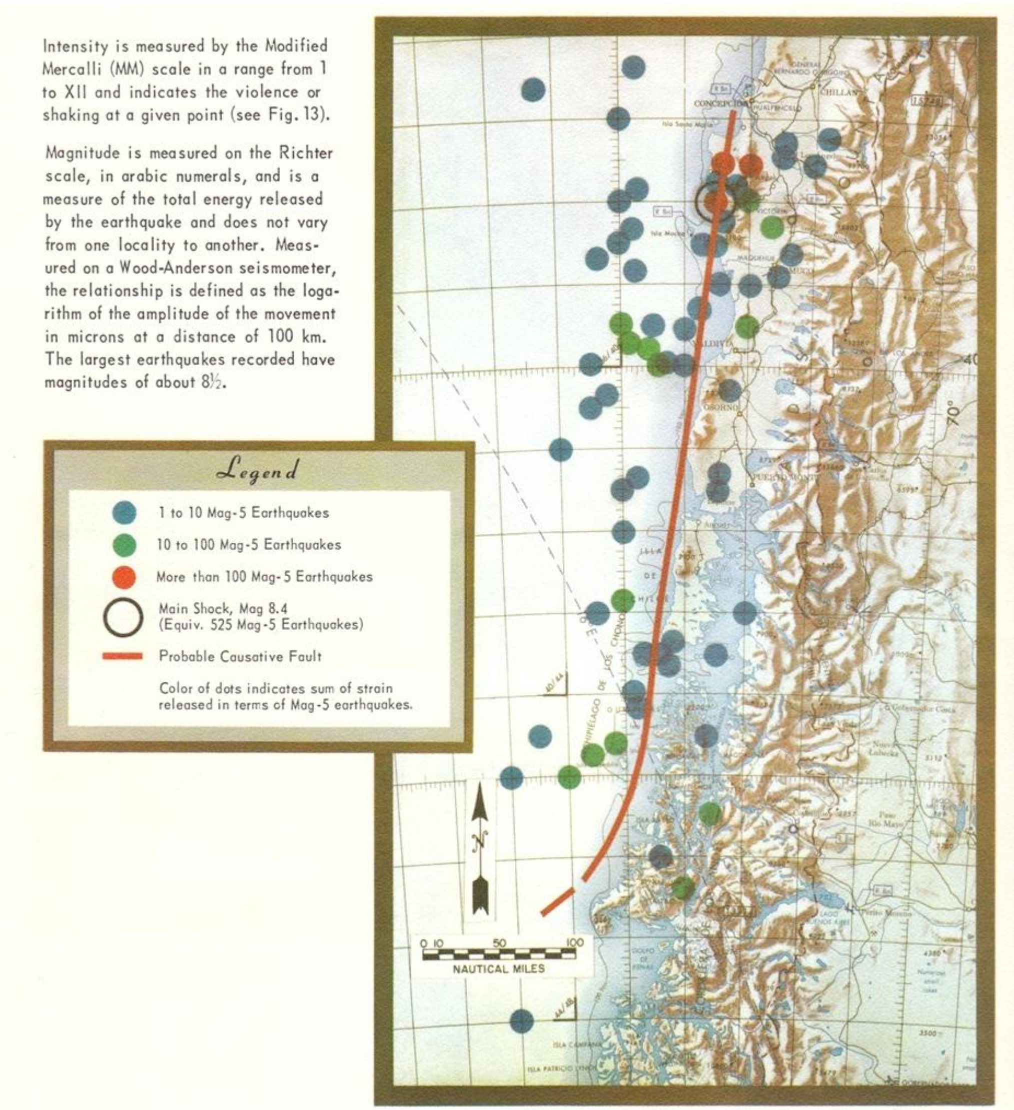


Kamchatka
Hodgson's (1956) mechanism



Japan, Right-lateral
(Median Tectonic line)

Aftershocks immediately after the 1960 earthquake



200 km

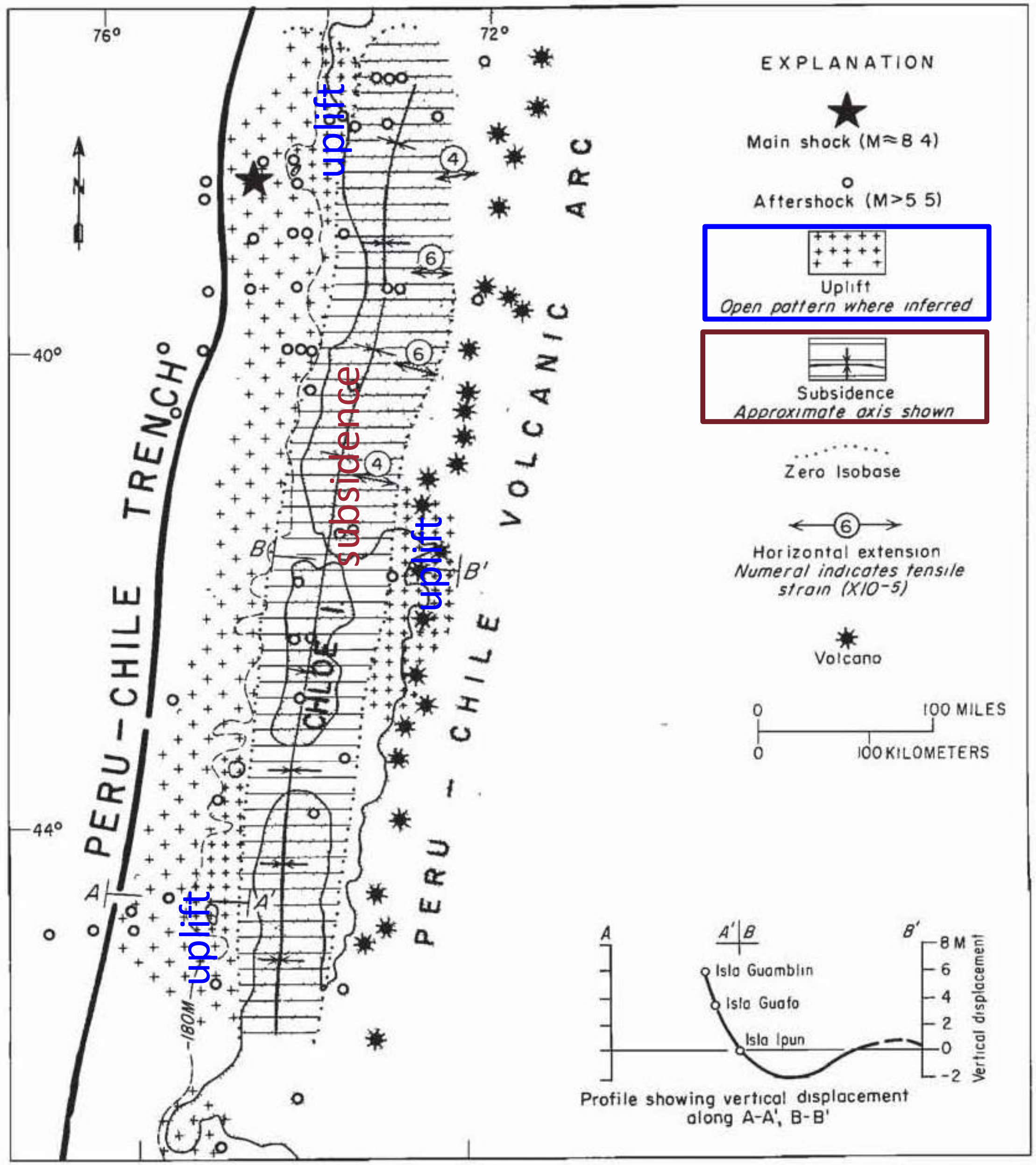
Saint-Amand, 1961

Static (uplift, subsidence, strain etc)

Plafker and Savage (1970)

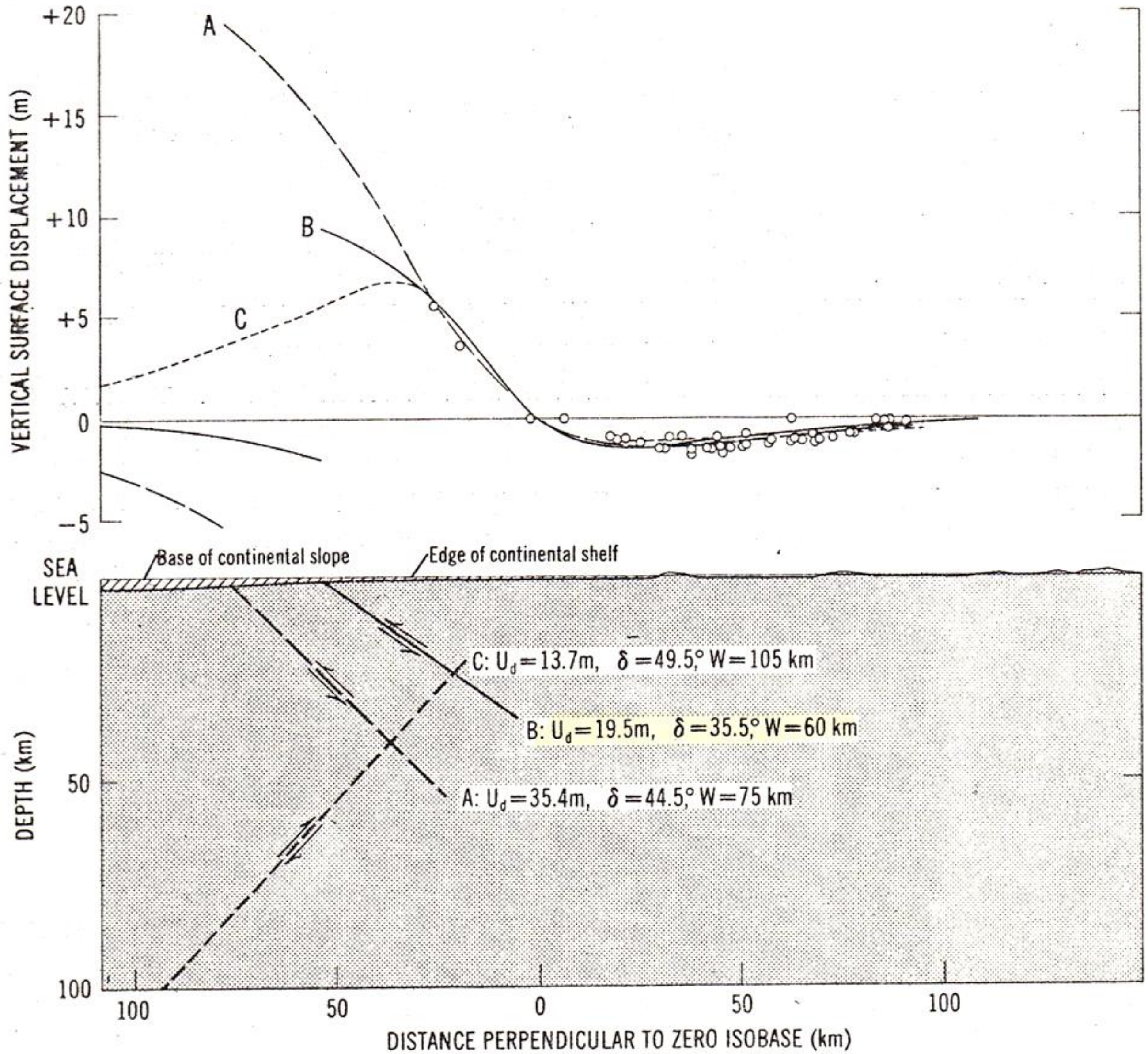
Vertical Displacement (subsidence and uplift)

Plafker and Savage (1970)
Plafker (1972)

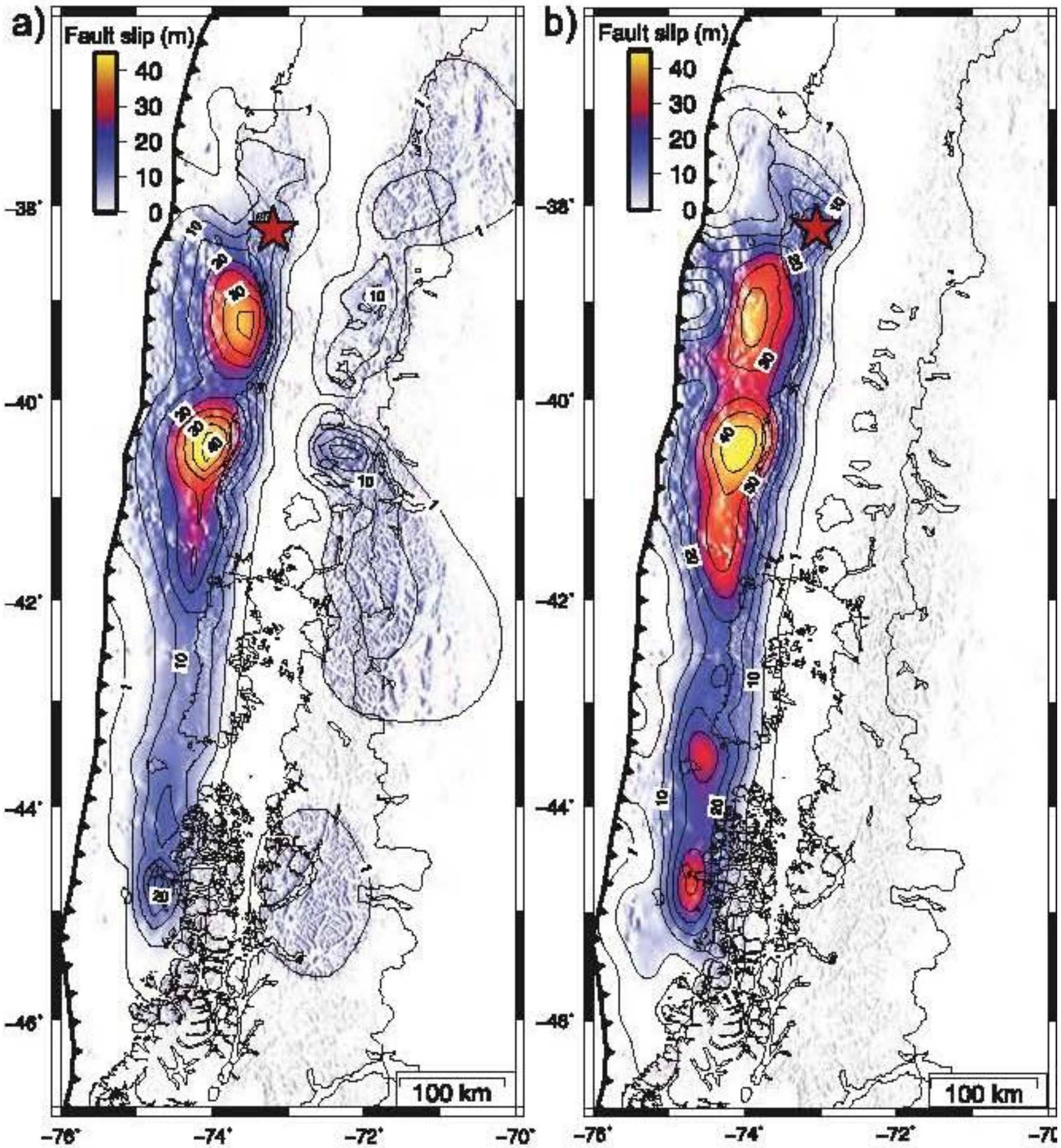


Plafker and Savage (1970) Uplift-Subsidence data and Models

→ Model B



M_w=9.26



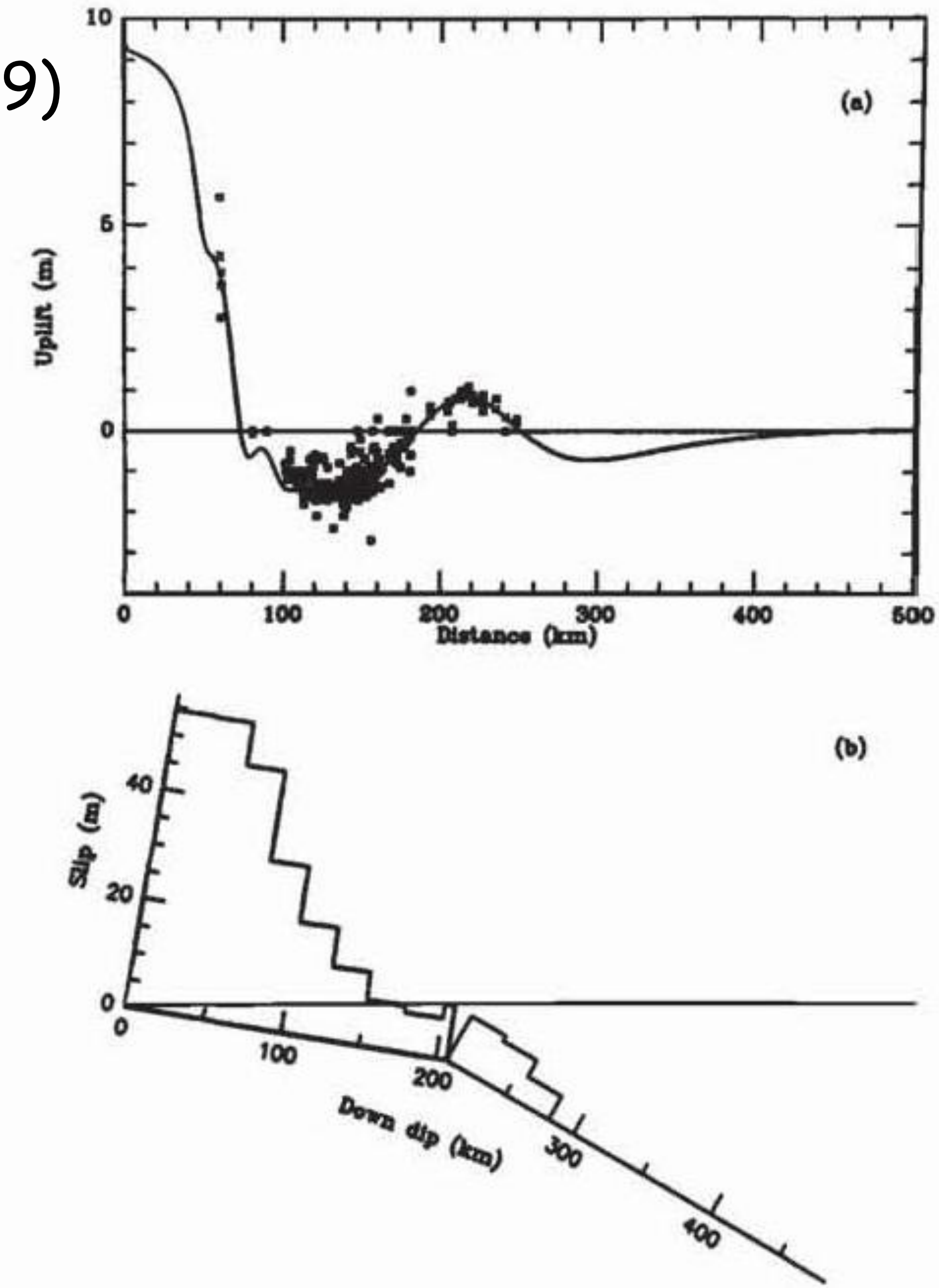
Barrientos and Ward (1990)

Moreno et al. (2009)

Linde and Silver (1989)

deep slip

→ Larger M_w (=9.45)

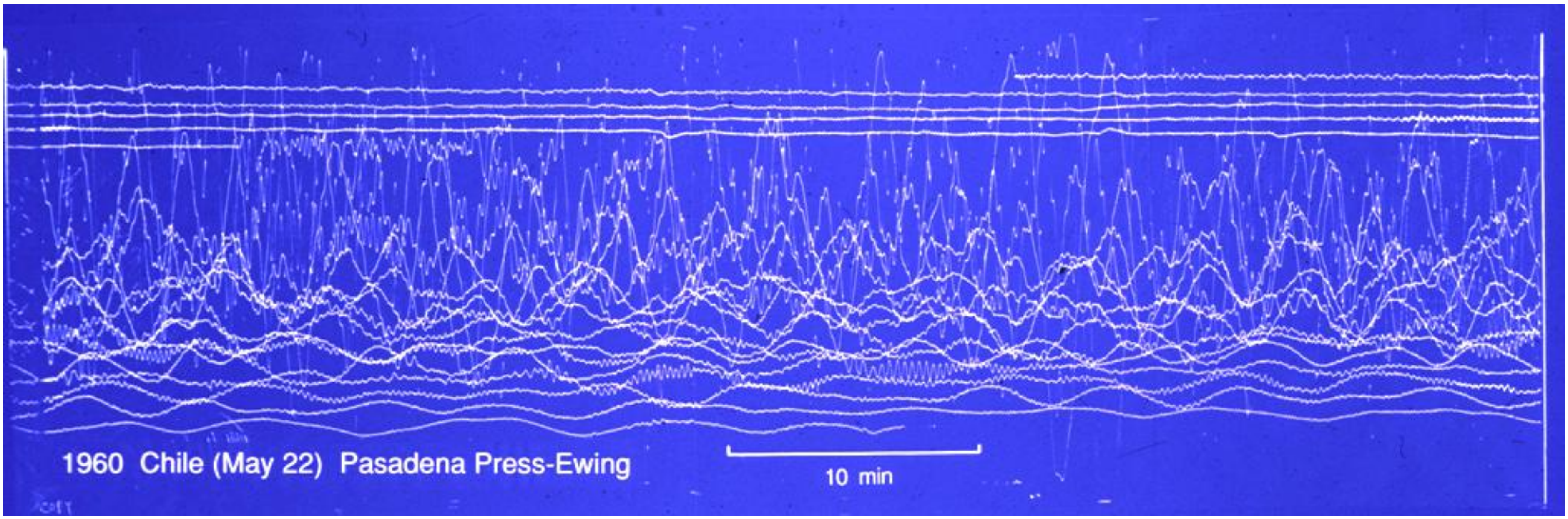


Seismology

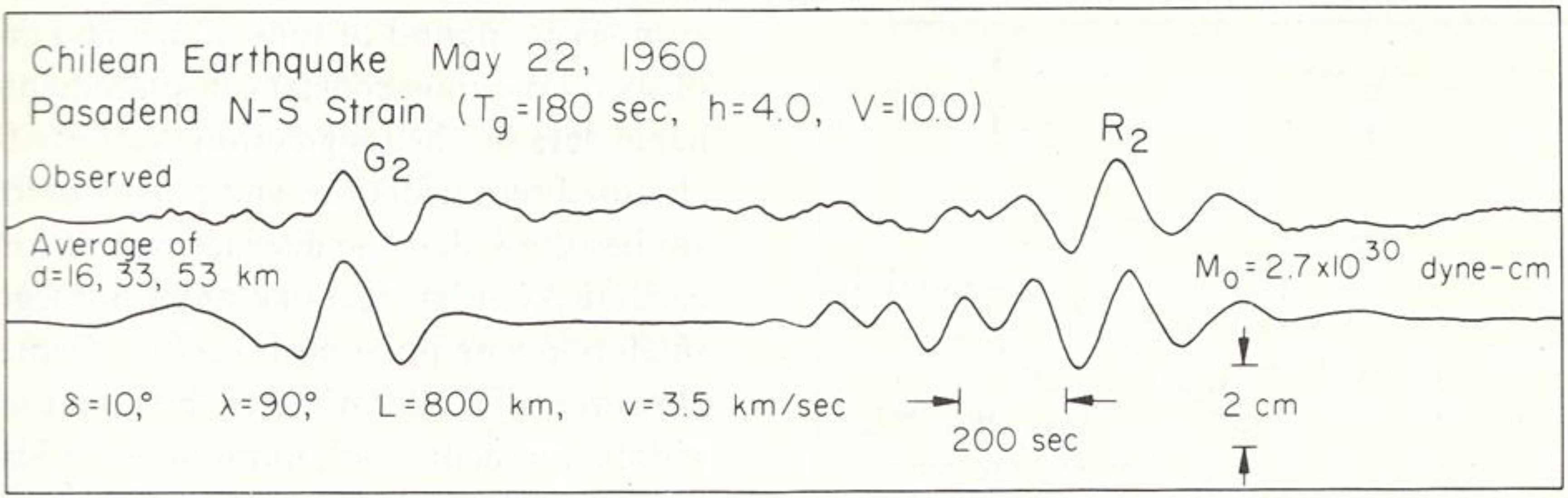
Normal mode
Surface waves

One-day seismogram of the 1960 Chilean earthquake (M_w=9.5)

1960 Chile, PAS Δ=83°, Θ=135°



Interpretation of Pasadena strain record (Kanamori and Cipar, 1974)



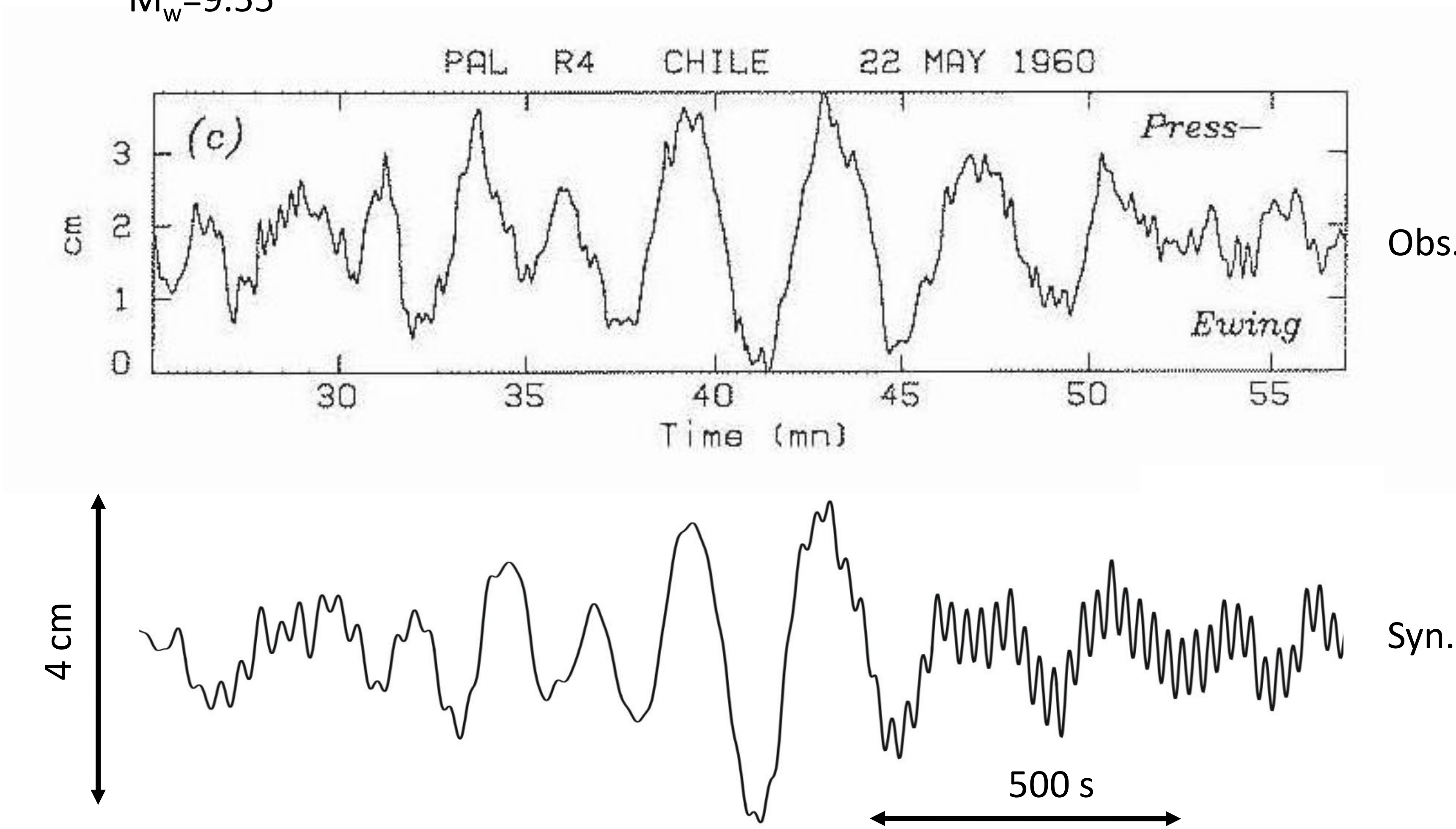
→ M_w=9.55

Uncertainties: dip angle, source finiteness, instrument response

→ M_w=9.35

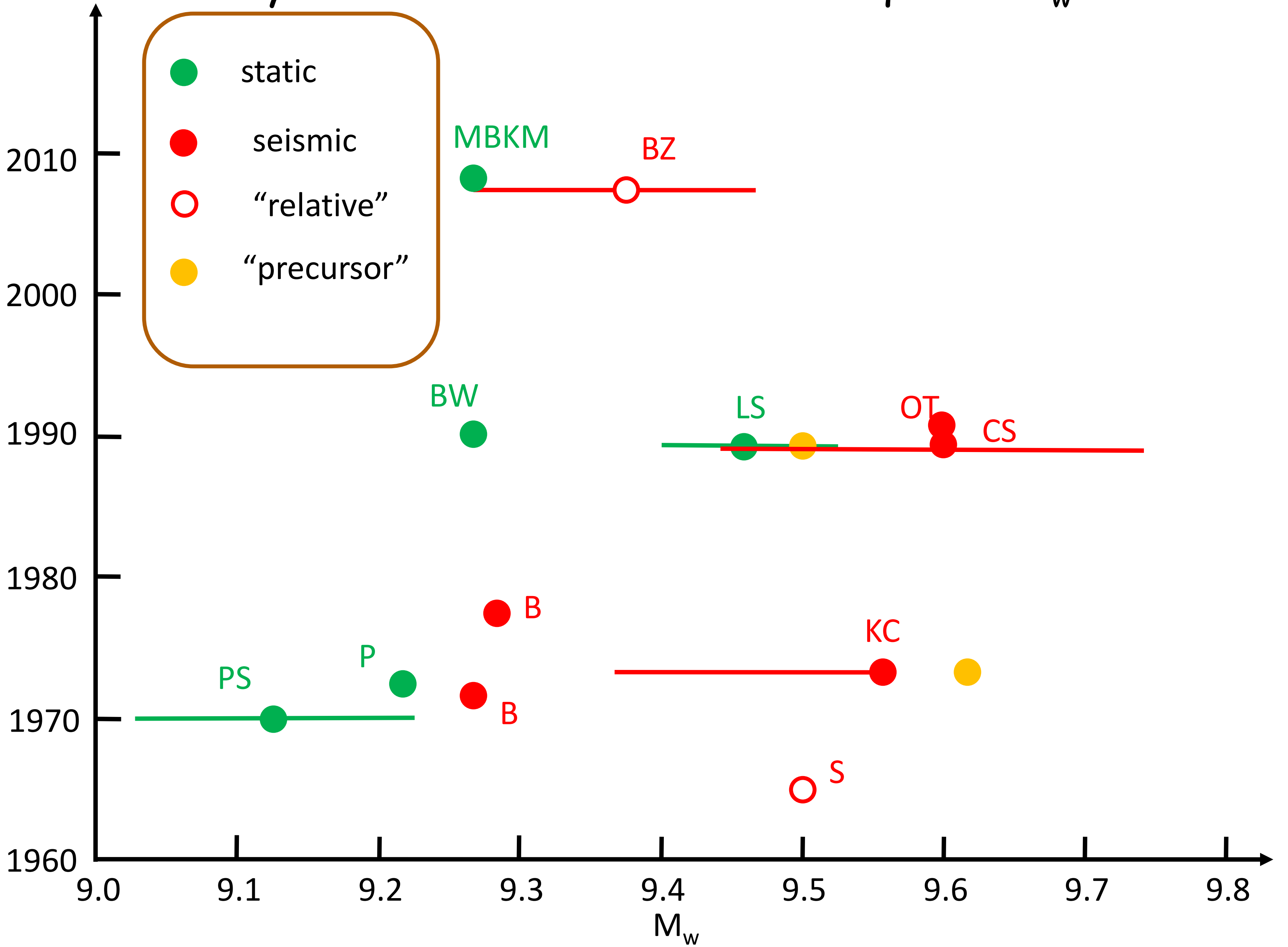
1960 Chile, Palisade R4

M_w=9.55

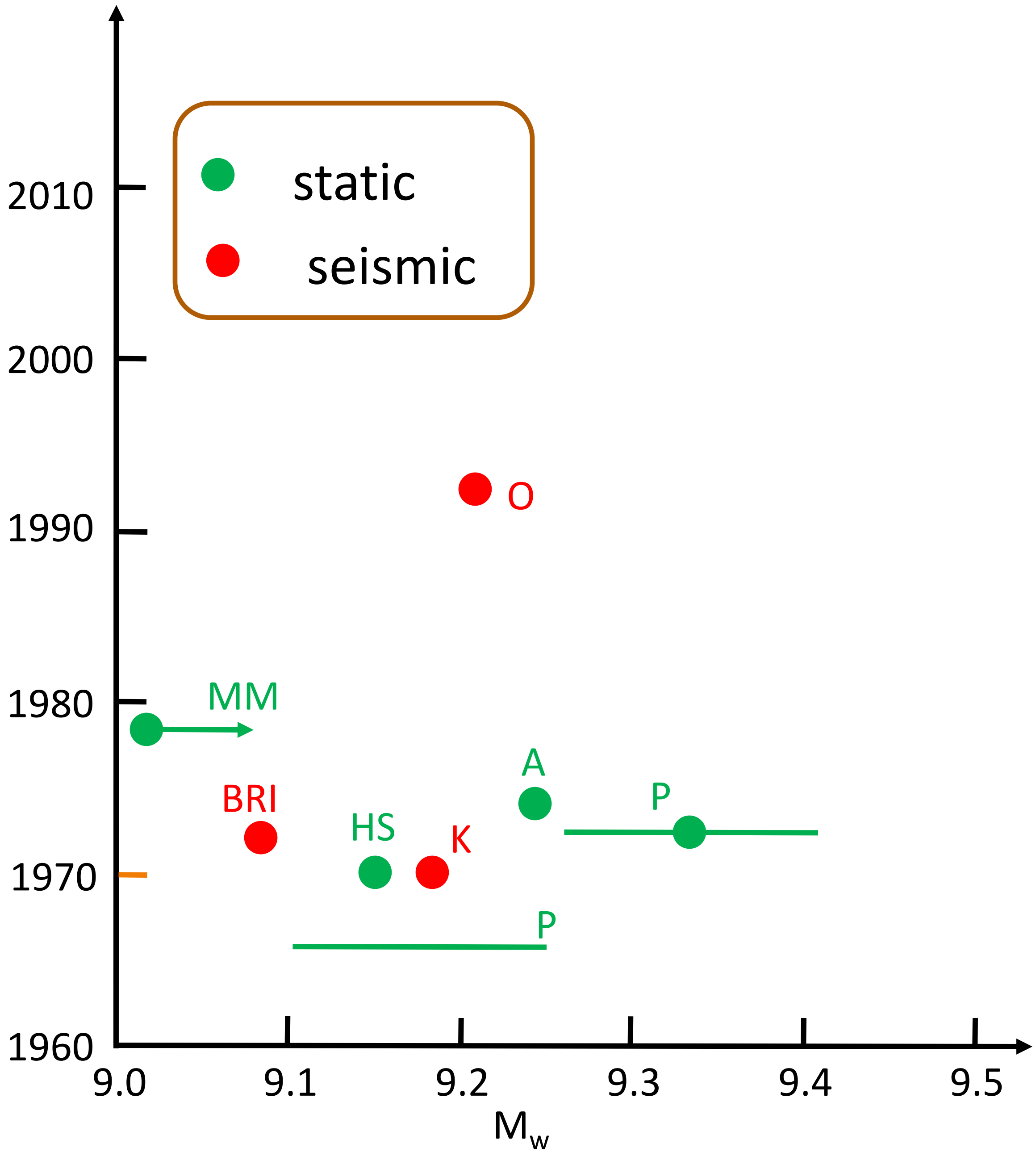


Synthetic HK M_0=2.7x10^{23} N-m sf=l80

History of the 1960 Chilean Earthquake M_w estimates



History of the 1964 Alaskan Earthquake M_w estimates



An important record is the strain seismogram recorded at Isabella, California.

This record is of historical importance because it provided the first observations of the Earth's free oscillations.

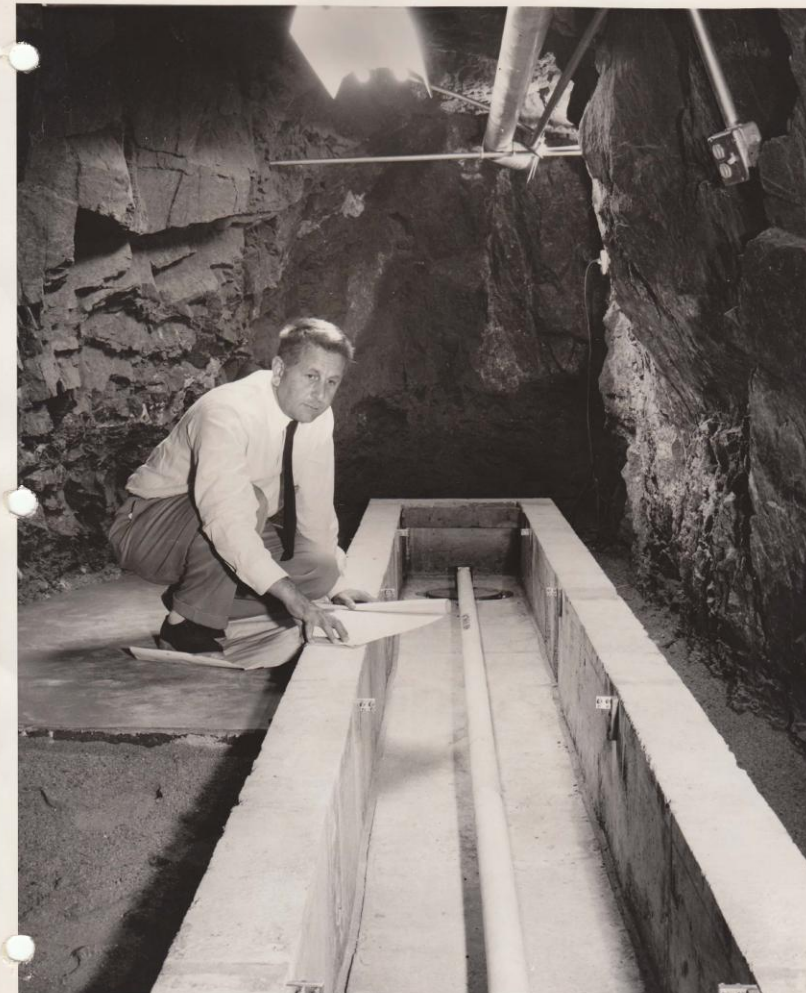
Bullen (An Introduction to the Theory of Seismology, 1963)

Then in 1960 at the Helsinki meeting of the I.A.S.P.E.I., there occurred one of the most dramatic scientific sessions this author has witnessed.

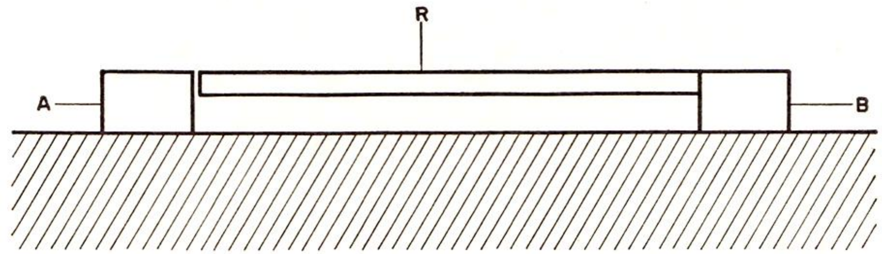
Press announced that Benioff had once again observed long-period waves ....

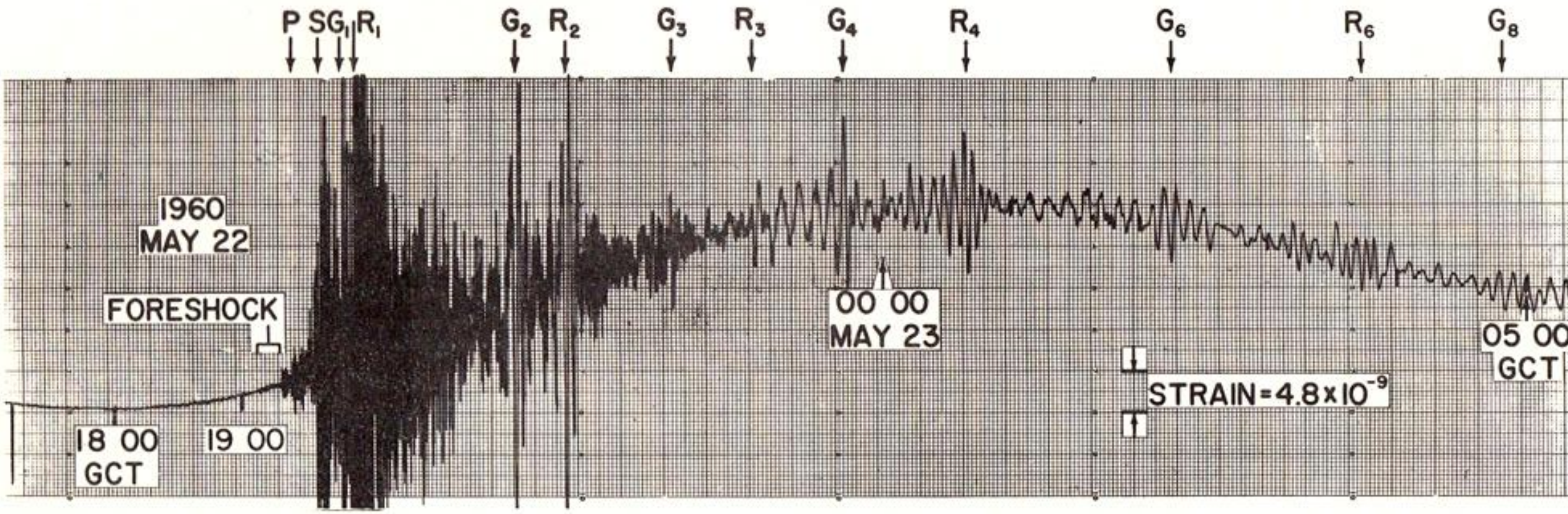
Slichter announced ....

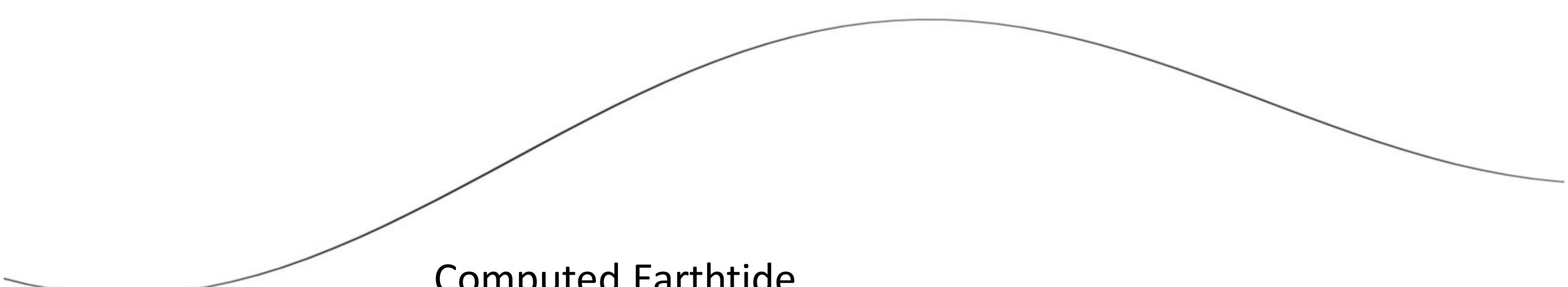
Lamont result ......



1960 Chilean Earthquake, Isabella Benioff Strain Record

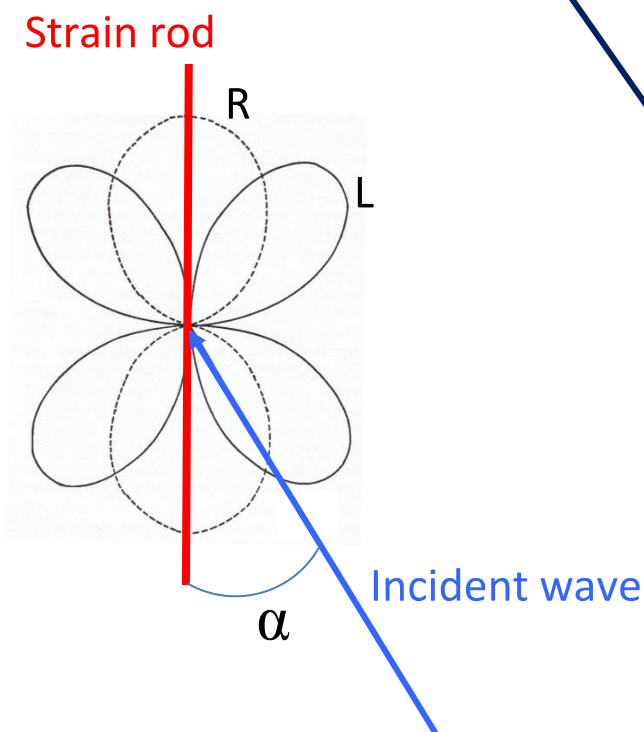


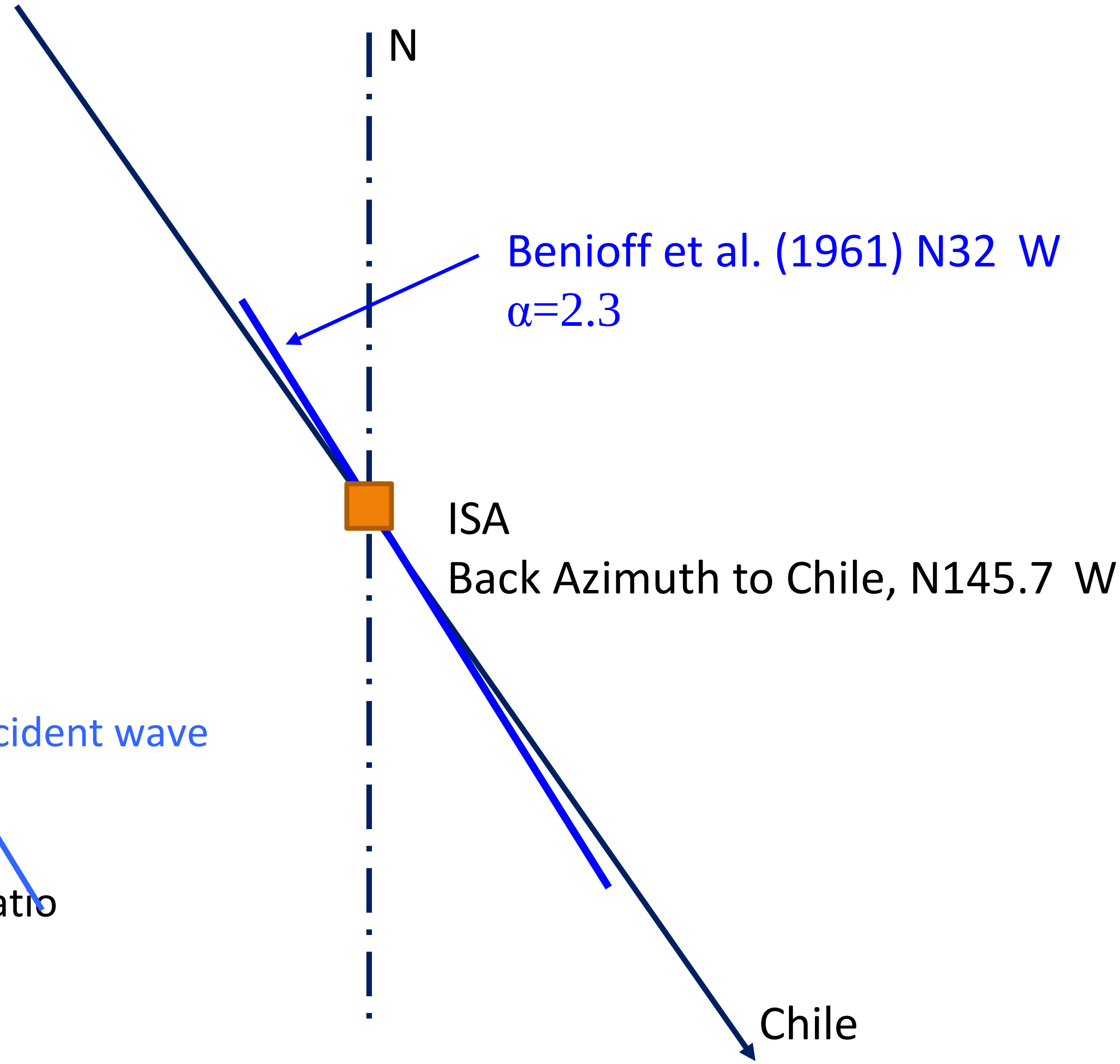




Computed Earthtide

Angle (α) between the ISA strain rod and the great circle to Chile



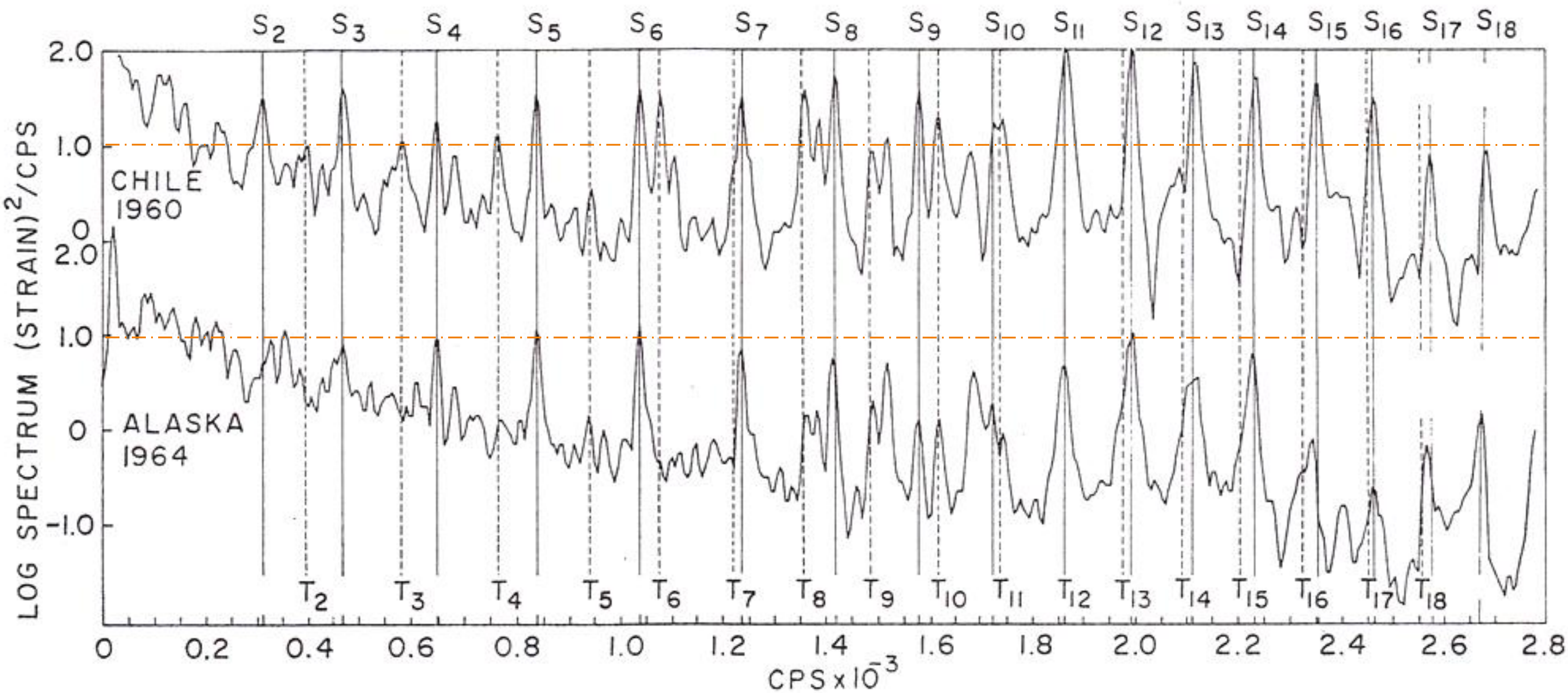


L(G) to R sensitivity ratio

$$= \frac{\sin(2\alpha)}{\cos^2 \alpha}$$

Normal-mode spectrum (from 7.5 min to 54 min) of the 1960 Chilean and the 1964 Alaskan earthquakes recorded with the ISA strainmeter.

Smith (1966)

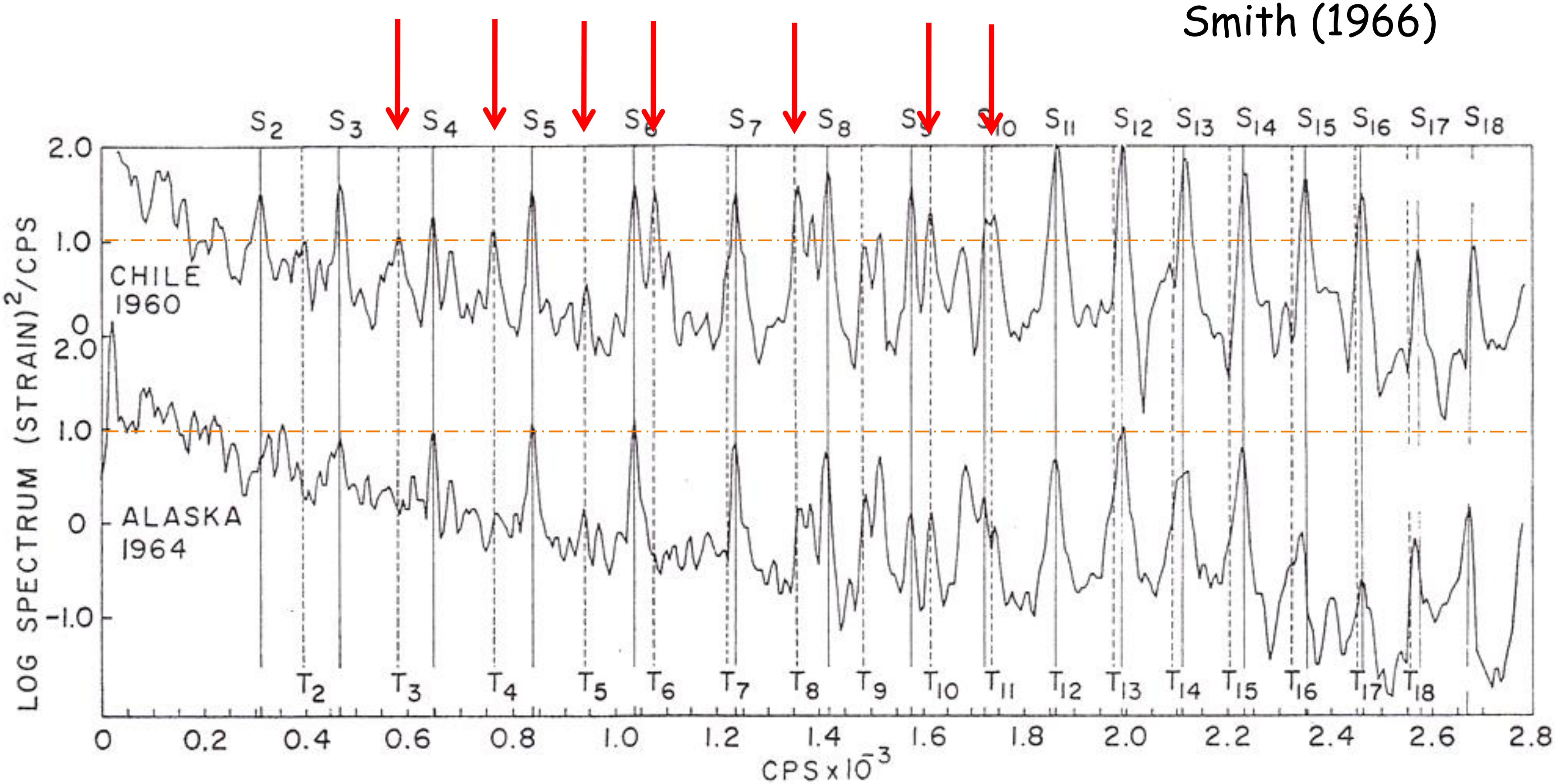


54 min

7.5 min

Toroidal Modes on the ISA Spectrum (Red)

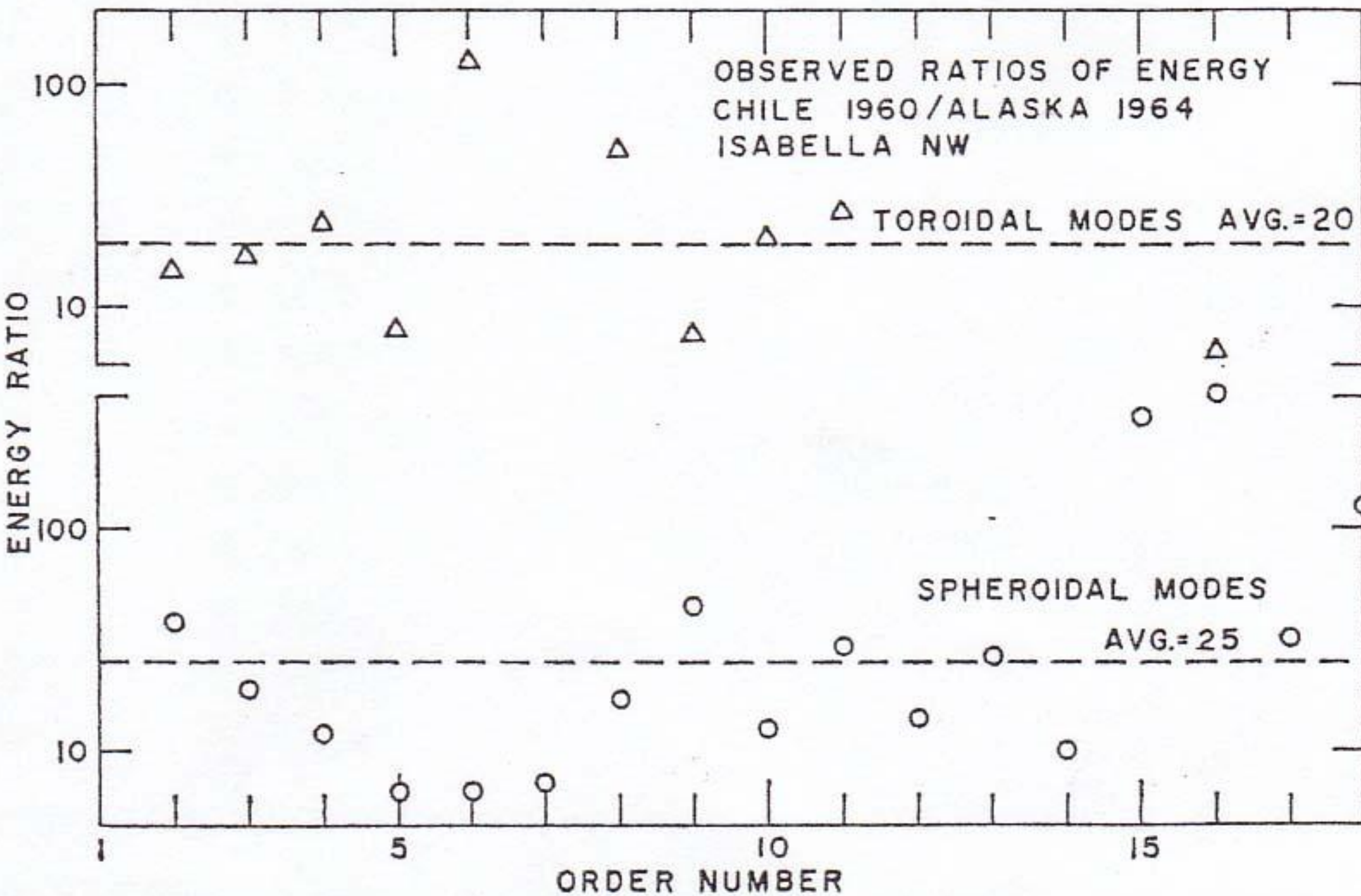
Smith (1966)



54 min

7.5 min

Observed Mode Energy Ratio of Chile to Alaska earthquakes, Smith(1966)



Normal mode spectral amplitudes of the 1960 Chilean earthquake are about 2 to 5 times larger than those of the 1964 Alaskan earthquake.

This does not necessarily mean that the Chilean earthquake is correspondingly larger (in M_0) than the Alaskan earthquake.

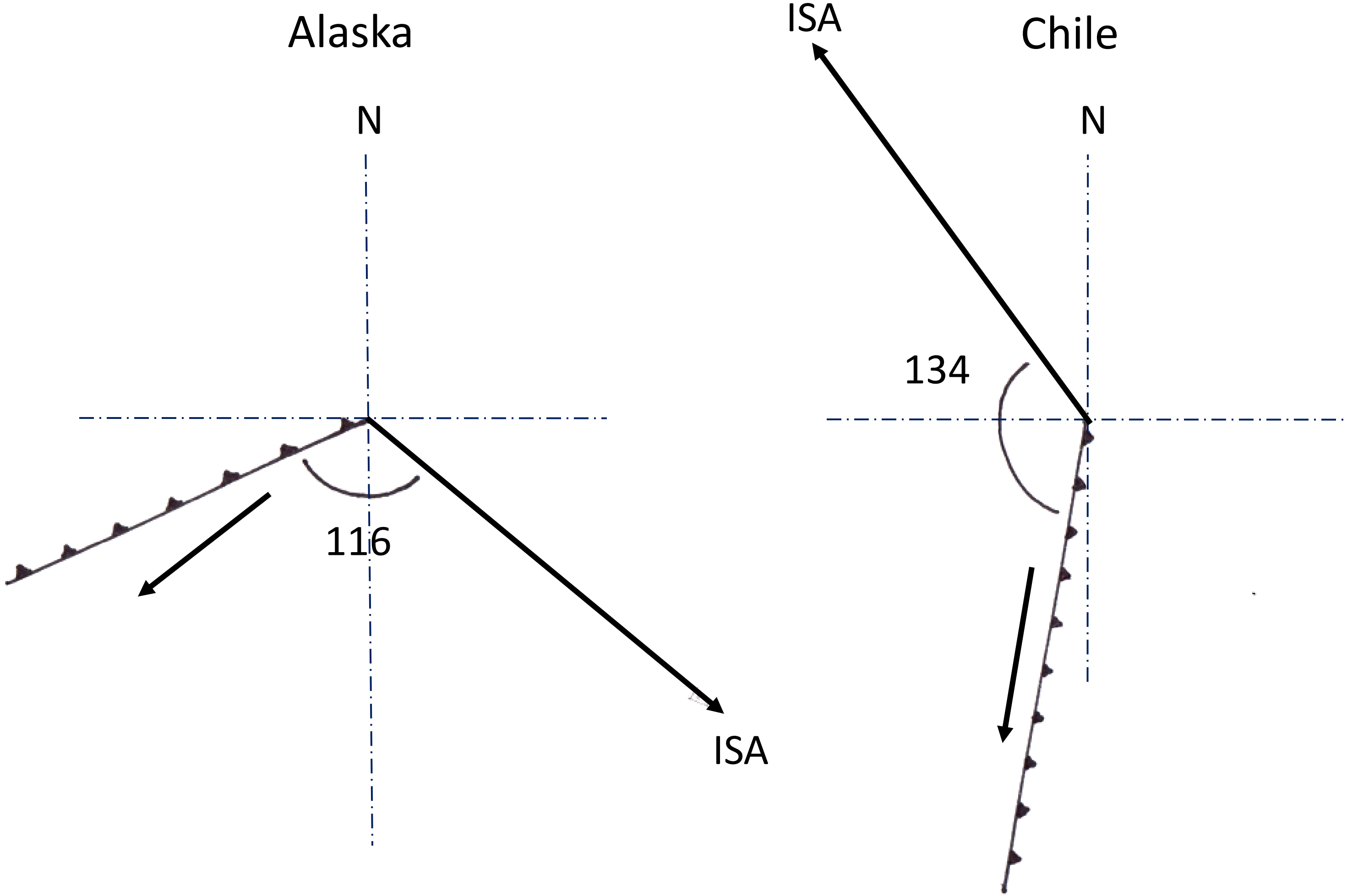
$$\frac{\text{observed amp}_{\text{Chile}}}{\text{observed amp}_{\text{Alaska}}} = \left(\frac{M_{0\text{Chile}}}{M_{0\text{Alaska}}} \right) \frac{\text{Excitation}_{\text{unit}M_0\ \text{Chile}}}{\text{Excitation}_{\text{unit}M_0\ \text{Alaska}}}$$

Determined in 1966

Unknown in 1966

Can be computed now

Rupture-Station Geometry



Computation of Strain Spectrum

$$e_{\theta\theta} = \frac{\partial u_\theta}{R\partial\theta} + \frac{u_R}{R}$$

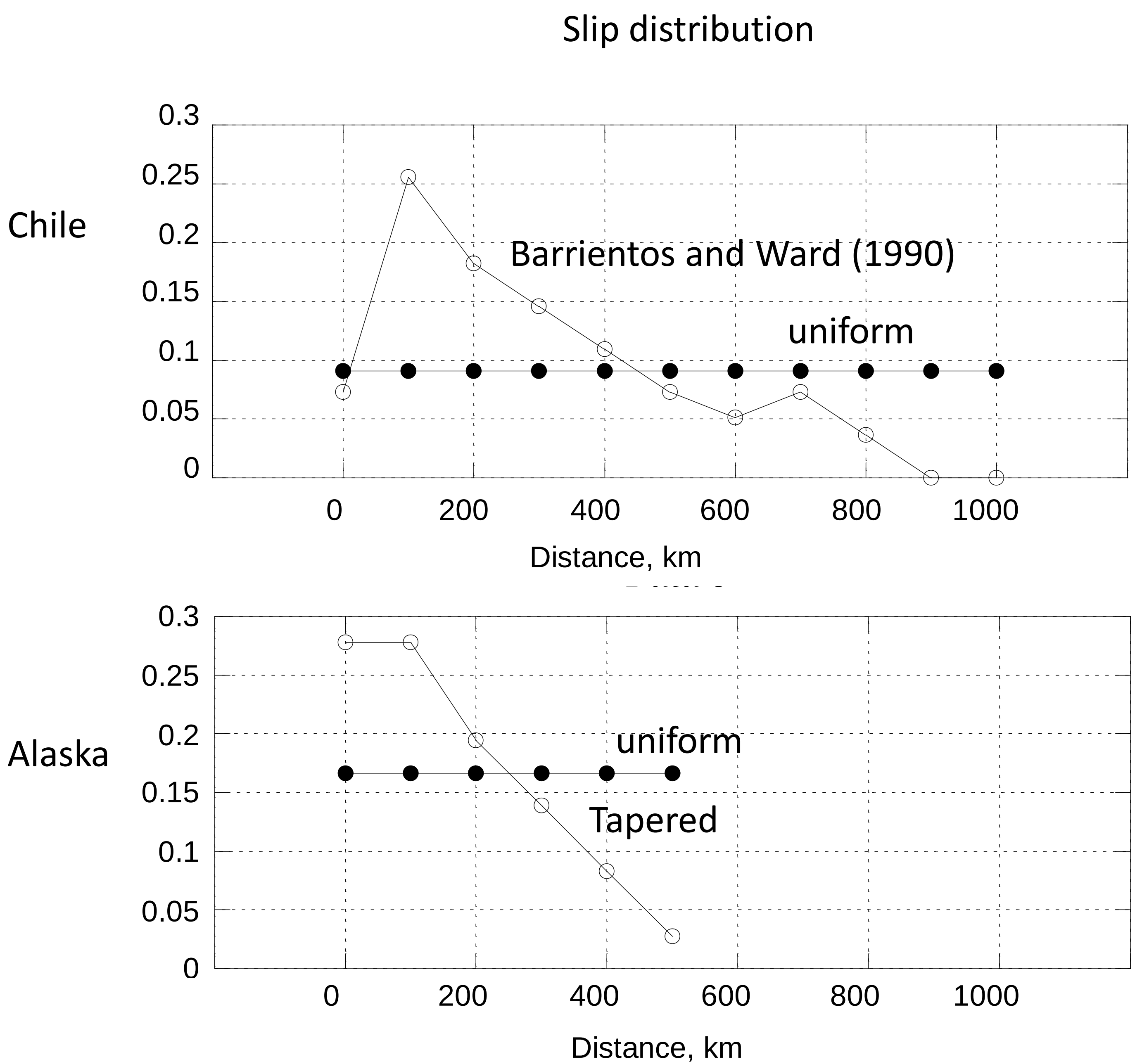
From 285 min to 8139 min (about 5.45 days)

For Chile K&C (1974) ϕ_s=10°, δ=10°, λ=90°, d=35 km

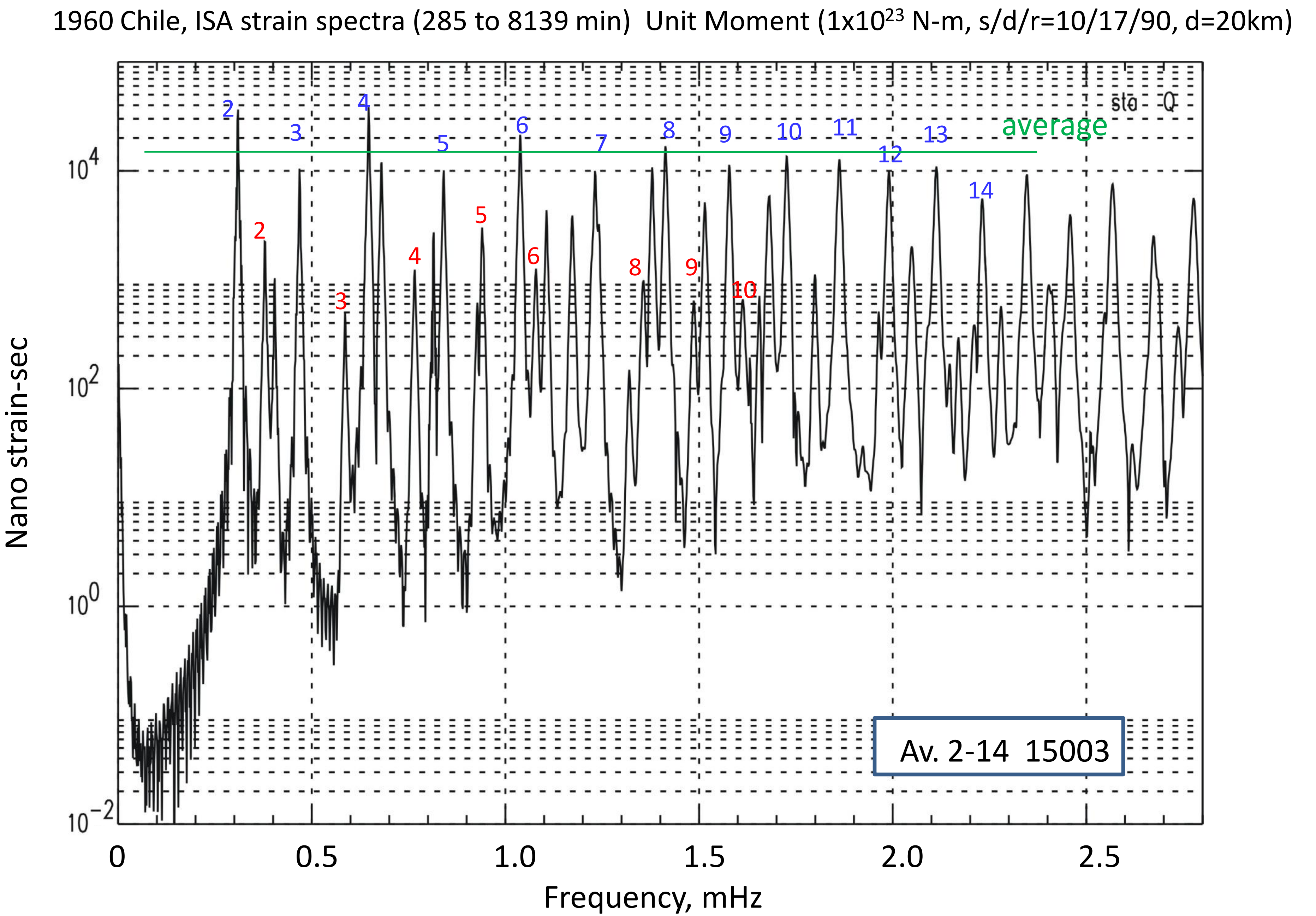
modified ϕ_s=10°, δ=17°, λ=90°, d=20 km

For Alaska K (1970) ϕ_s=246°, δ=20°, λ=90°, d=75 km

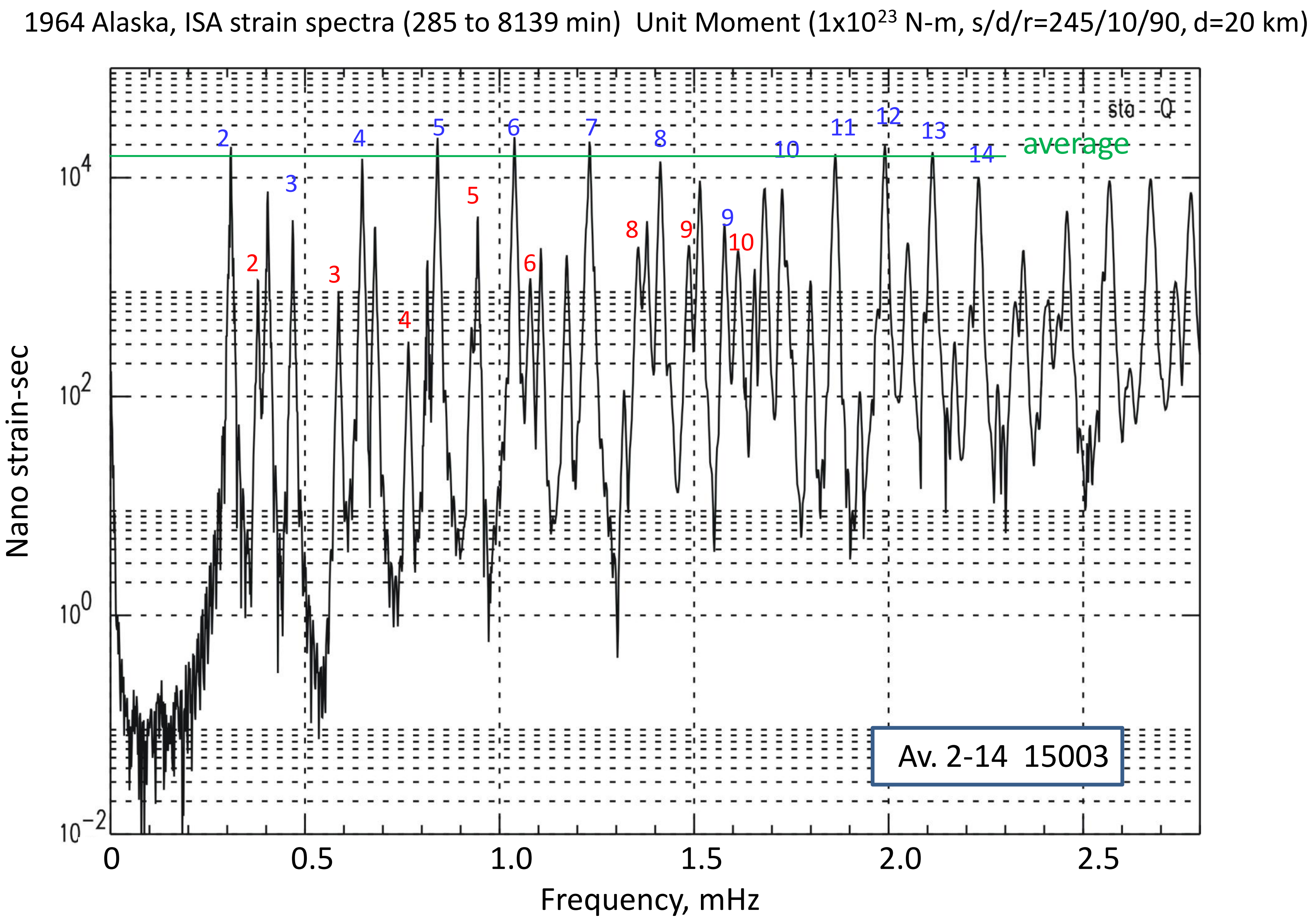
modified ϕ_s=246°, δ=10°, λ=90°, d=20 km


Slip distribution
Chile
Barrientos and Ward (1990)
uniform
0.3
0.25
0.2
0.15
0.1
0.05
0
0
200
400
600
800
1000
Distance, km
Alaska
uniform
Tapered
0.3
0.25
0.2
0.15
0.1
0.05
0
0
200
400
600
800
1000
Distance, km

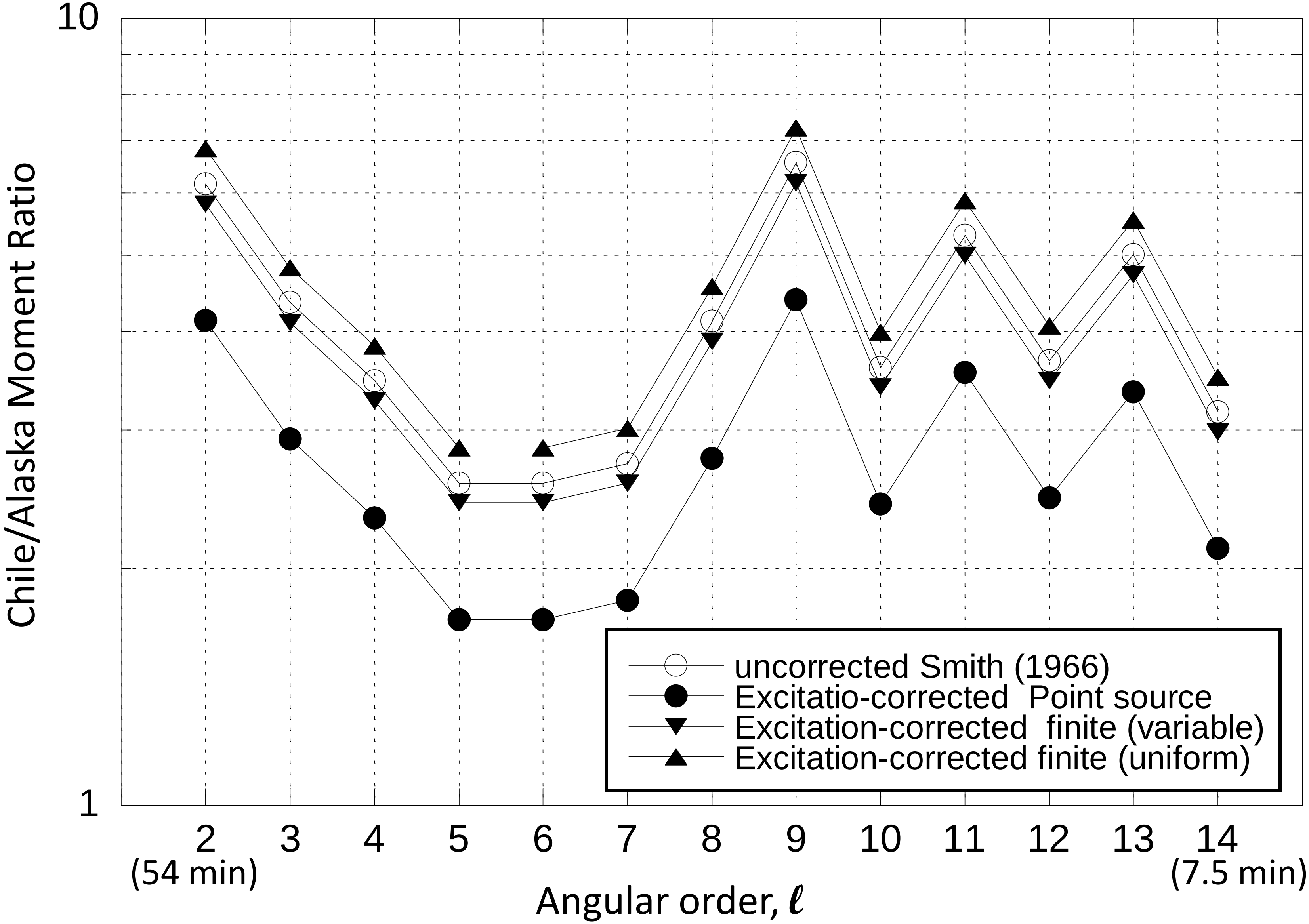
Finite source (B-W)



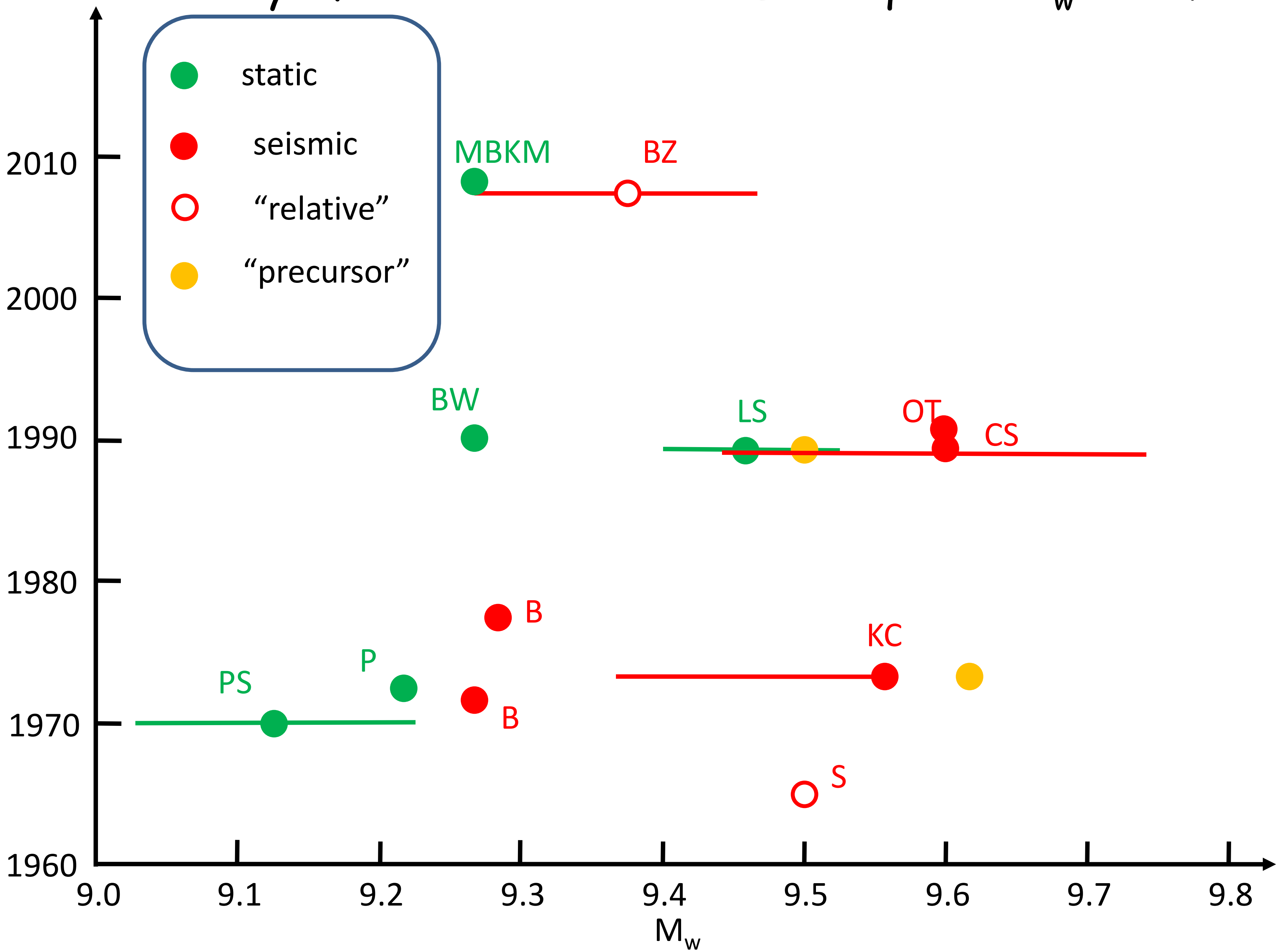
Finite source(Tapered)



Chile/Alaska Moment Ratio



History of the 1960 Chilean Earthquake M_w estimates

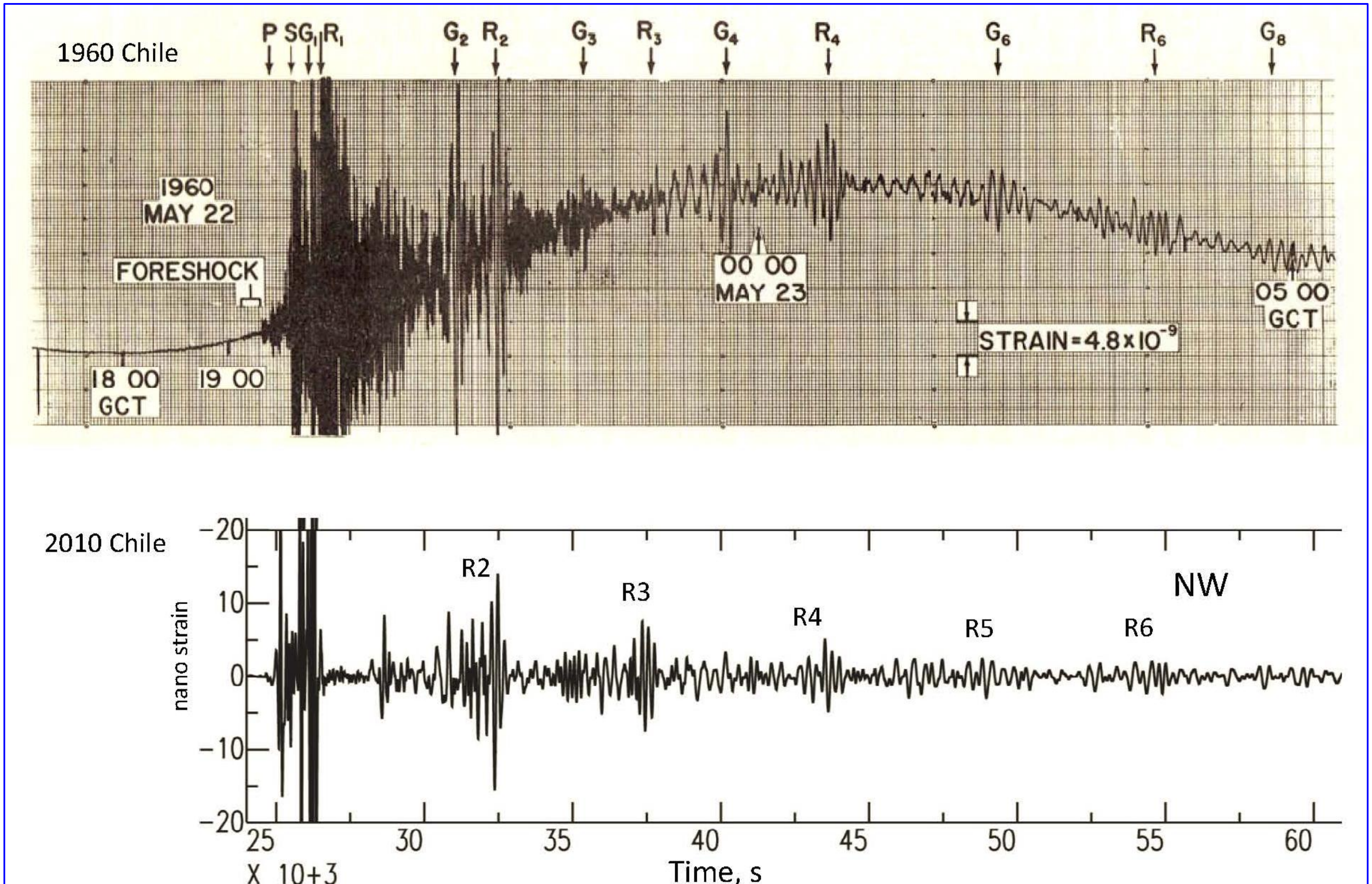


Revisiting the Toroidal modes

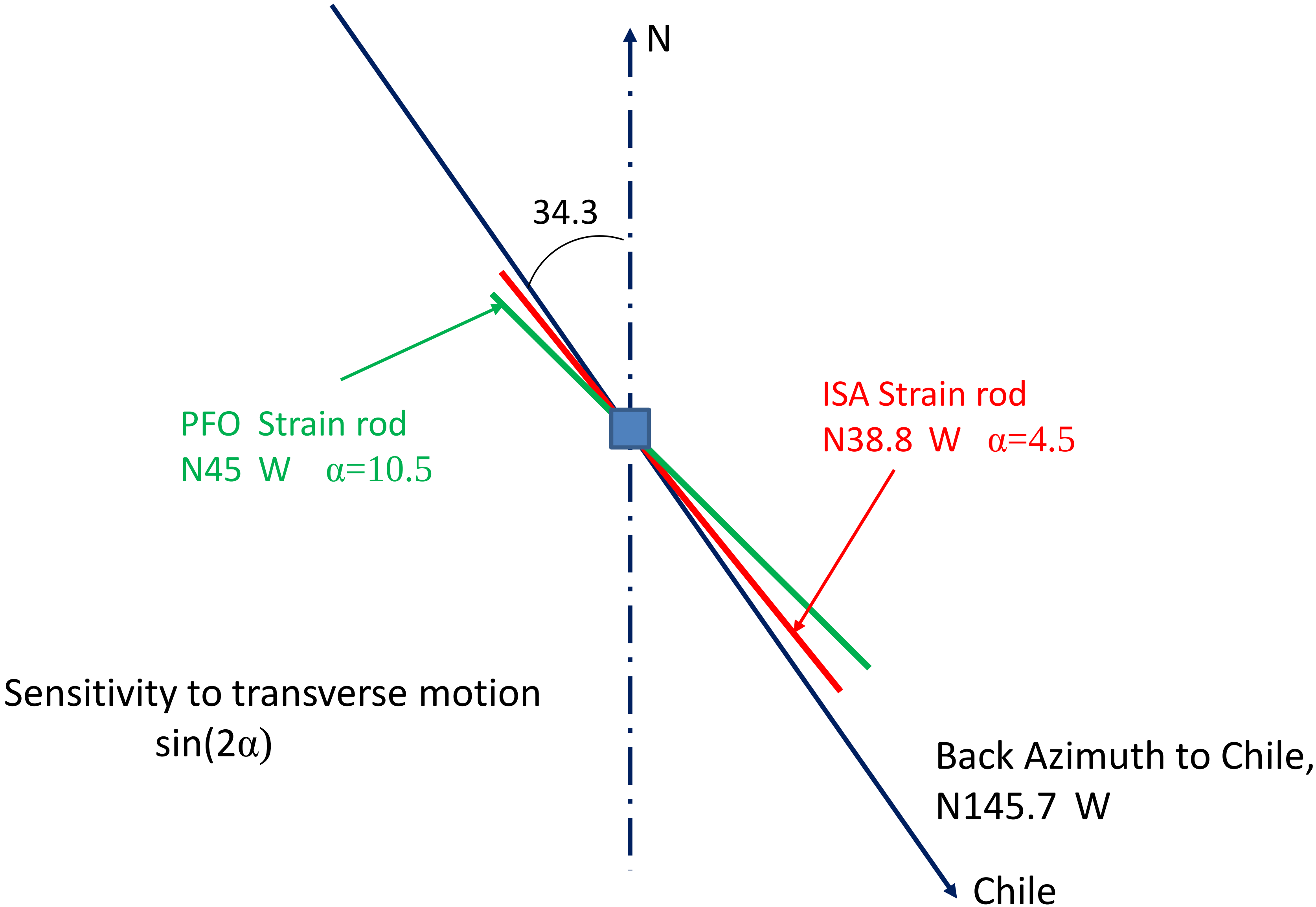
Comparison of the 1960 Chile (Valdivia) and the 2010 Chile (Maule) Earthquakes

Top: The strainmeter record of the 1960 earthquake at ISA (NW component). This is one of the most important historical records in seismology from which the first observation of the Earth's free oscillations was made.
Bottom: The strainmeter record of the 2010 earthquake at PFO (NW component).

Note the large even-order G waves (Love waves and toroidal modes) on the 1960 record and the almost complete absence of them on the 2010 record, suggesting significantly different mechanisms for the two earthquakes.

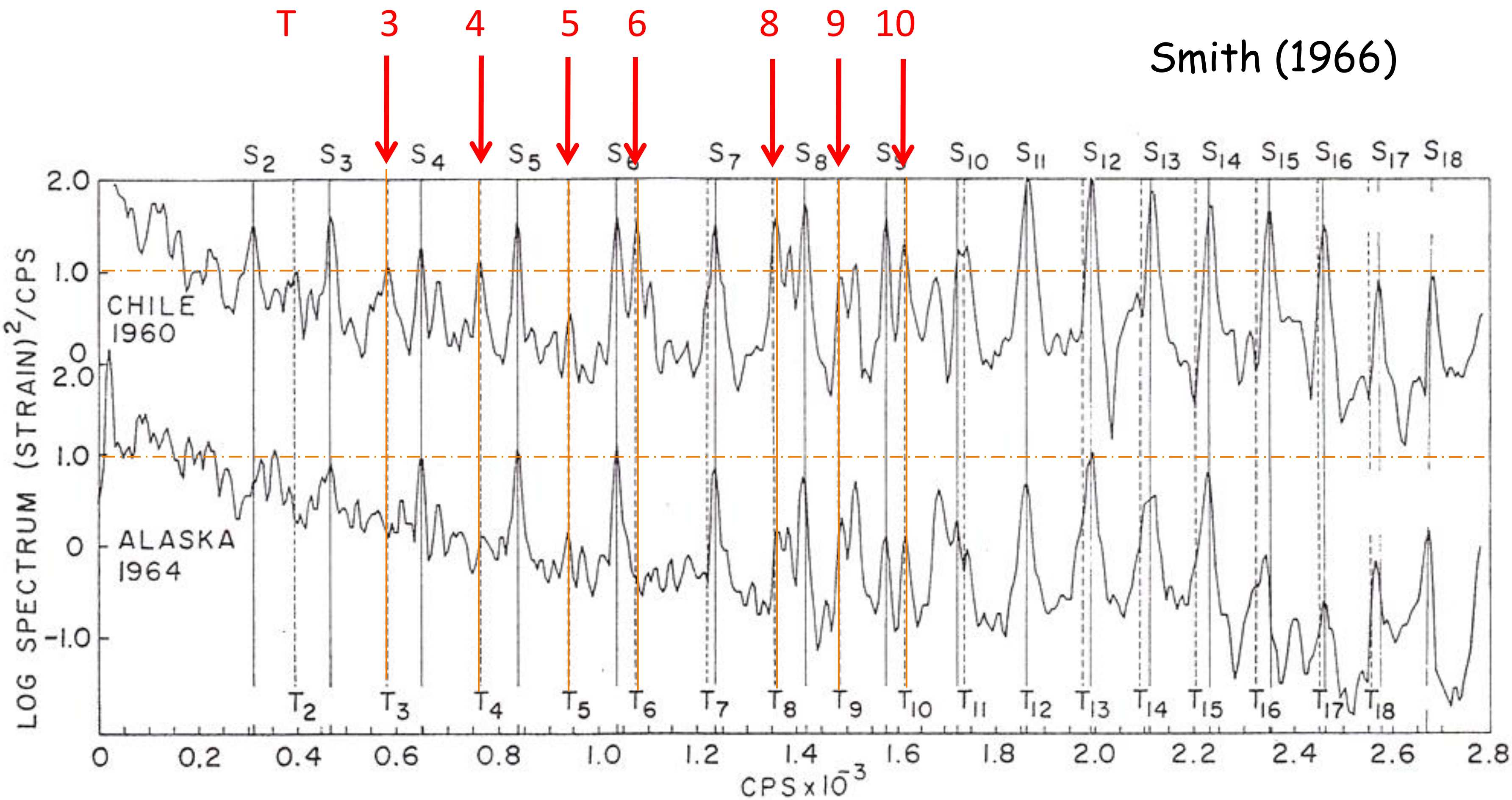


Angle (α) between strain rod and the great circle to Chile



Toroidal Modes on the ISA Spectrum (Red)

Smith (1966)



54 min

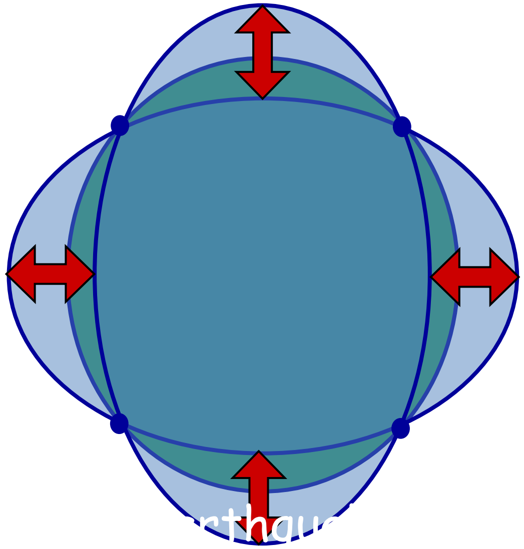
7.5 min

To increase G/R (or T/S) ratio, increasing the strike-slip component is most effective.

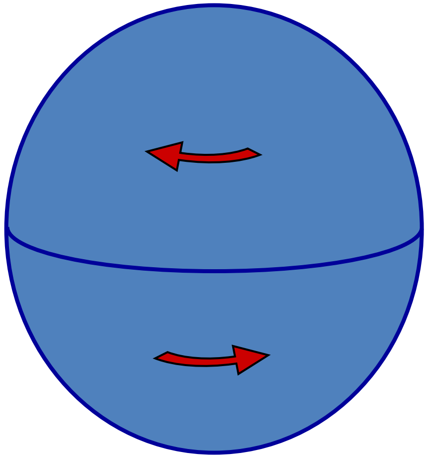
No thrust mechanism can explain the observed ratio.

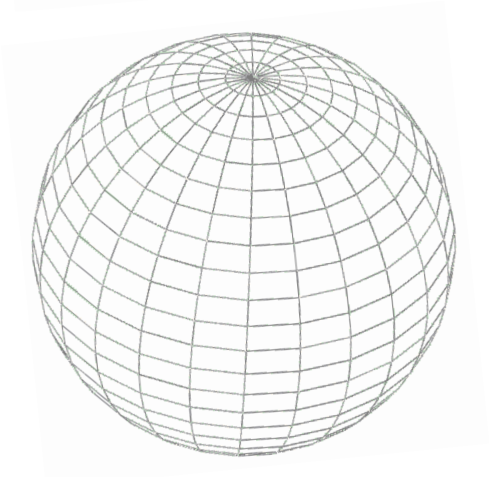
Free oscillation patterns

Spheroidal mode



Toroidal mode



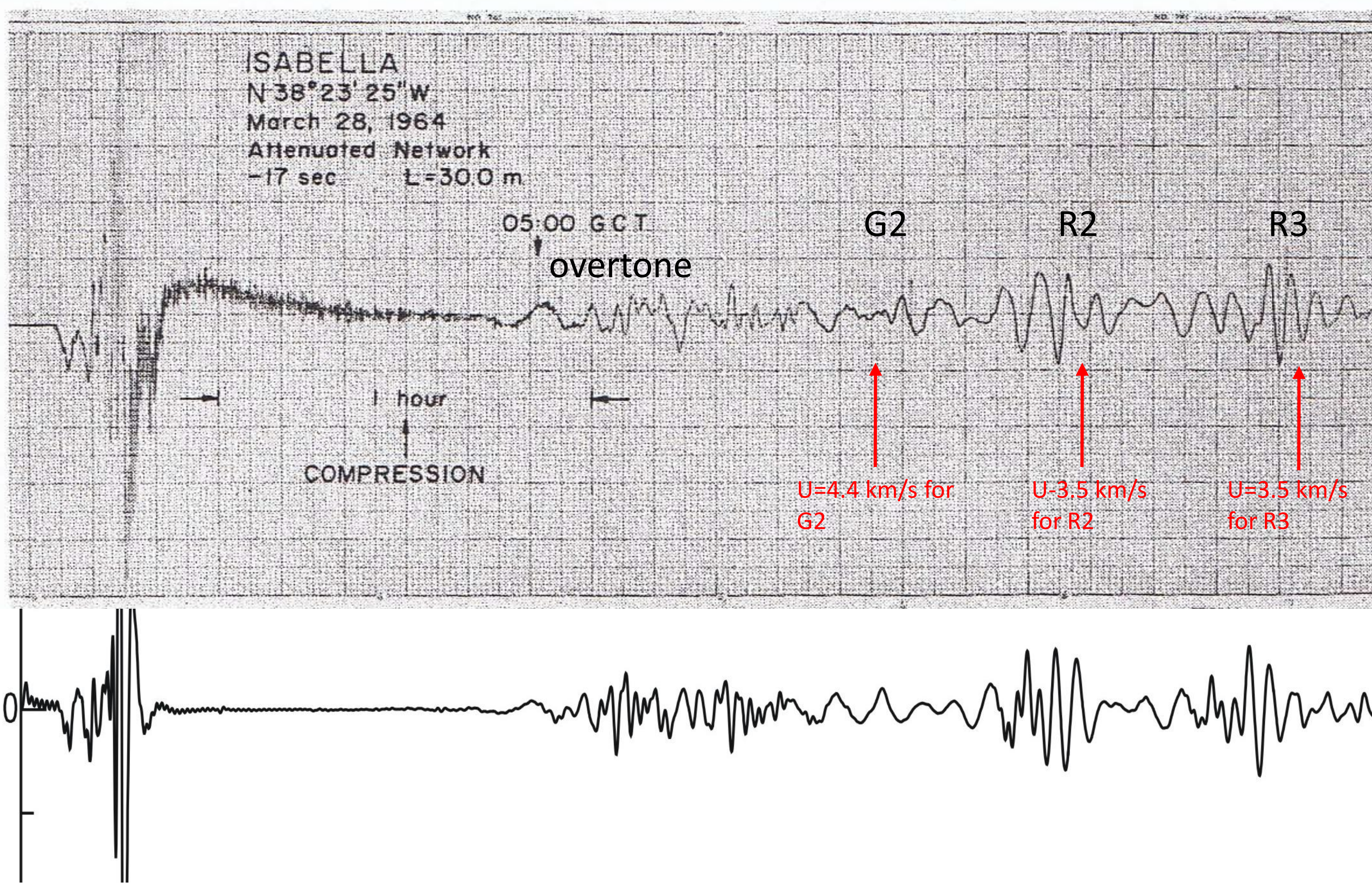


Animation from Hein Haak
http://www.knmi.nl/kenniscentrum/eigentrillingen-sumatra.html

Courtesy of Dr. Michel Van Camp

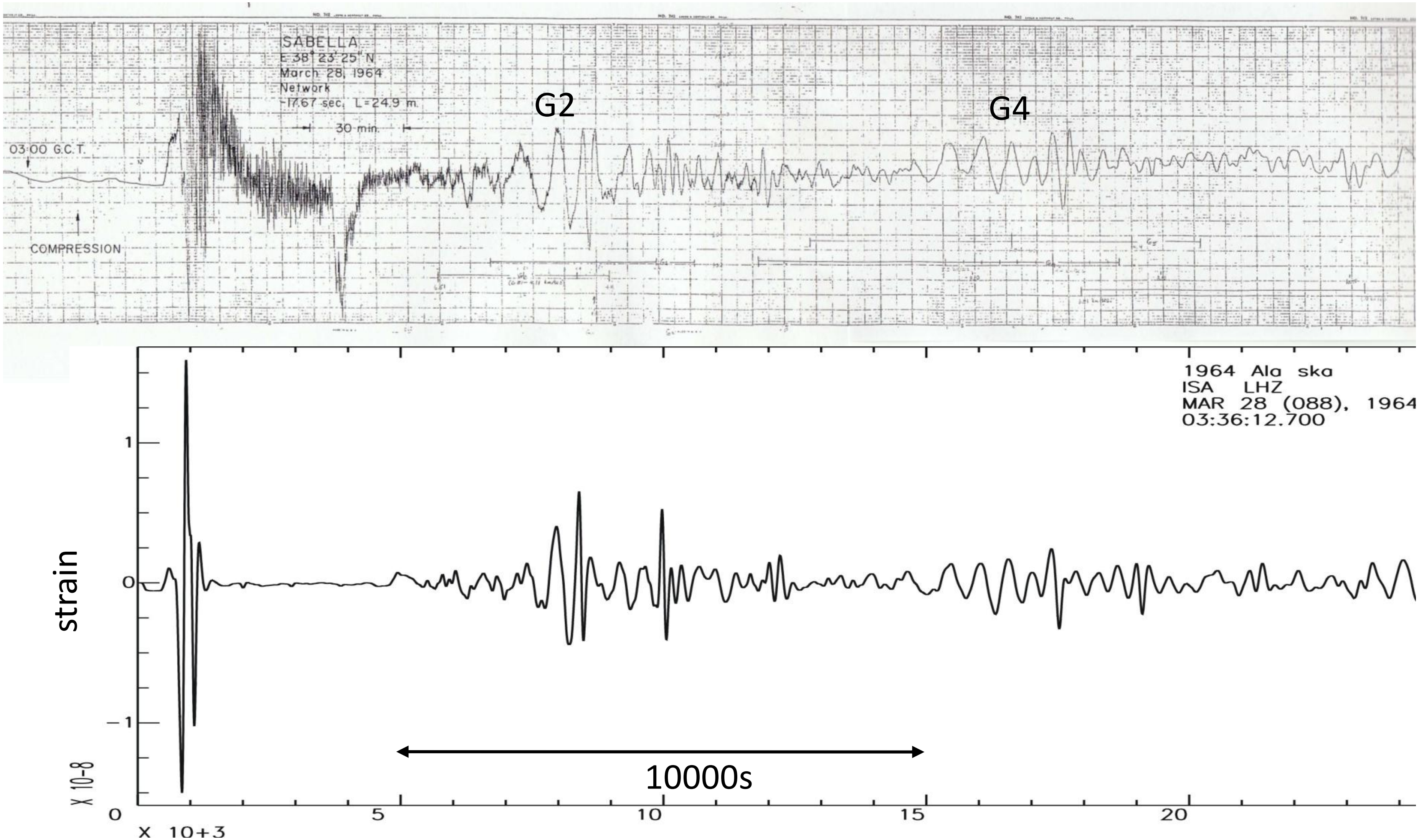
Isabella strain seismograph worked normally (i.e., no anomalous L/R ratio) for the 1964 Alaska earthquake (after) and the 1957 Mongolian earthquake (before).

1964 Alaska   ISA NW strain   L/R sensitivity=0.42



1964 Alaska ISA Strain NE M_0=7.5x10^{22} N-m (s/d/r=245/10/20) (Network, sf=ℓ50s)

L/R sensitivity=9.5



1957 Mongolian earthquake recorded at ISA

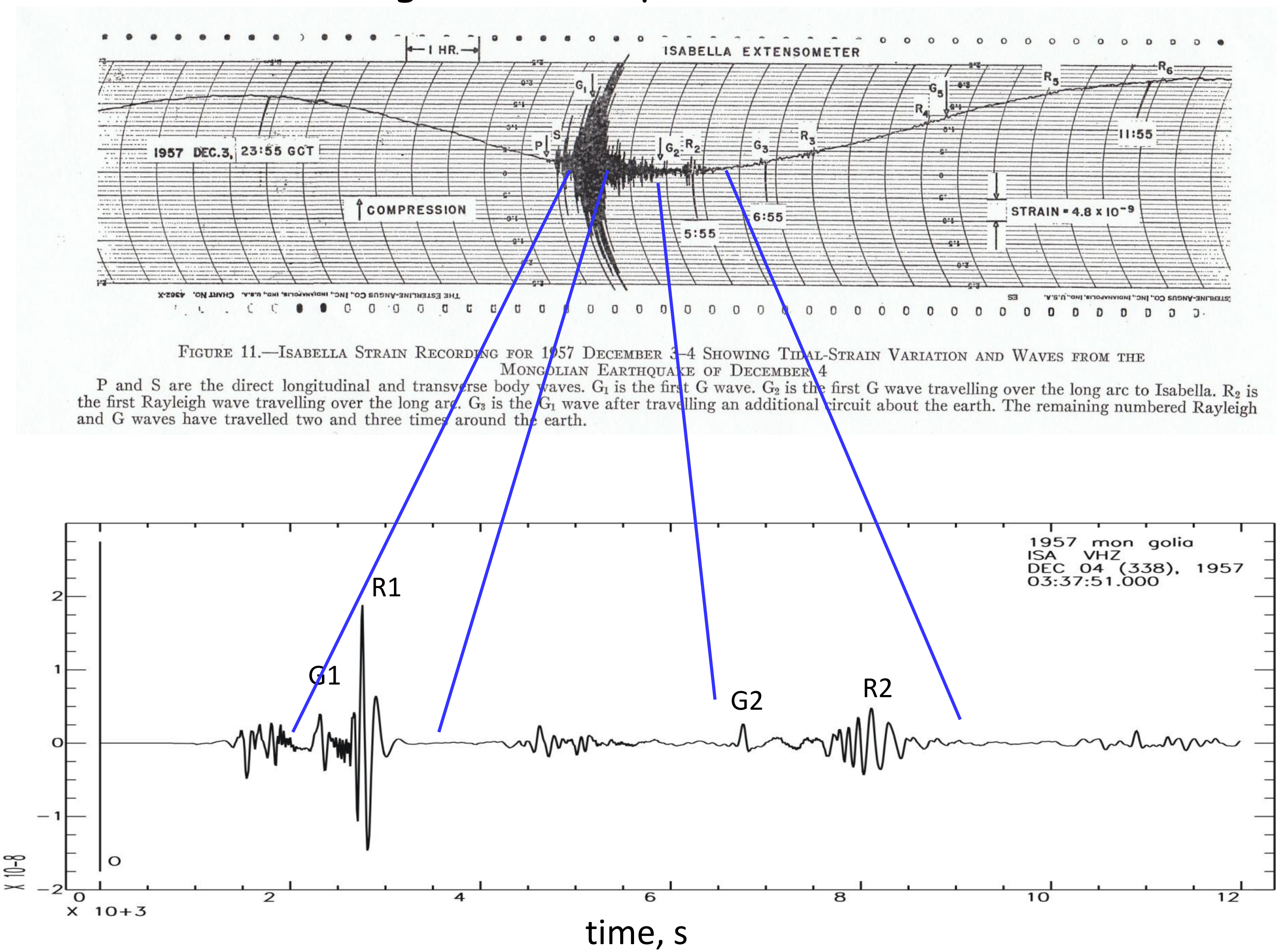


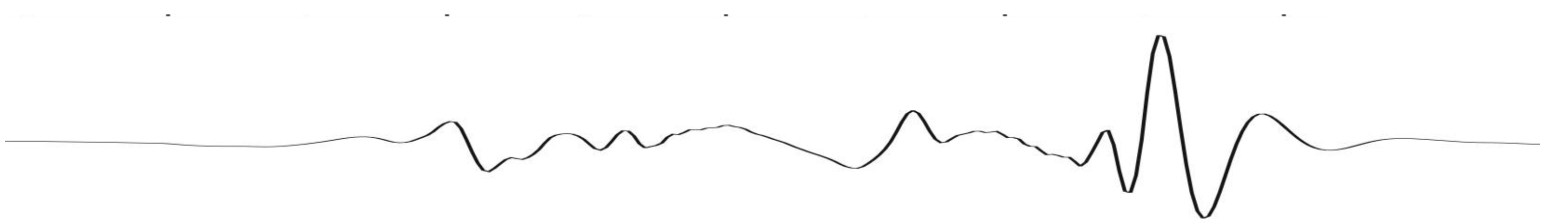
FIGURE 11.—ISABELLA STRAIN RECORDING FOR 1957 DECEMBER 3–4 SHOWING TIDAL-STRAIN VARIATION AND WAVES FROM THE MONGOLIAN EARTHQUAKE OF DECEMBER 4

P and S are the direct longitudinal and transverse body waves. G_1 is the first G wave. G_2 is the first G wave travelling over the long arc to Isabella. R_2 is the first Rayleigh wave travelling over the long arc. G_3 is the G_1 wave after travelling an additional circuit about the earth. The remaining numbered Rayleigh and G waves have travelled two and three times around the earth.

1957 Mongolian earthquake recorded at ISA
(strain meter + network + galvanometer)

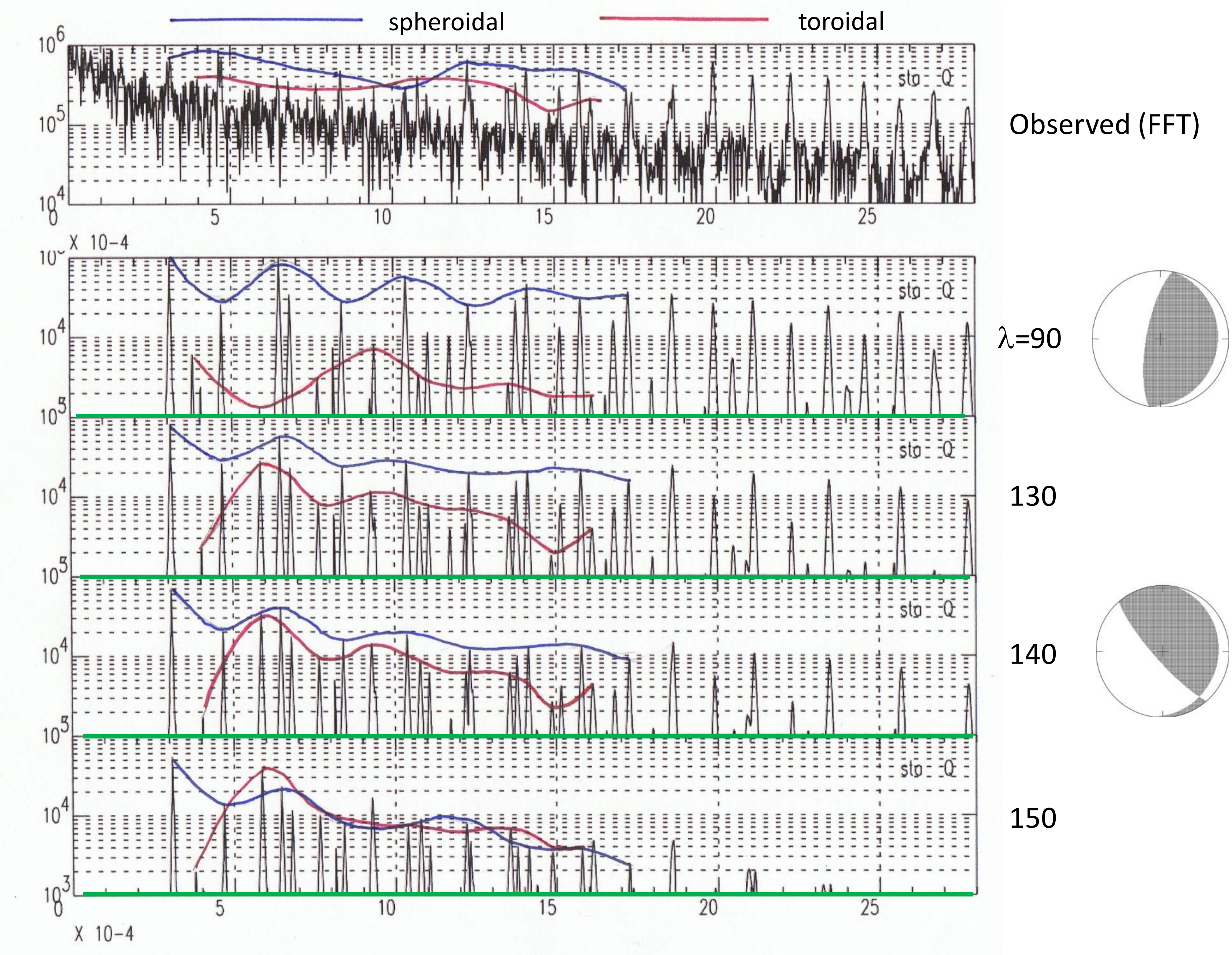
FIGURE 10.—PORTION OF ISABELLA SEISMOGRAM OF THE GREAT MONGOLIAN EARTHQUAKE OF 1957 DECEMBER 4 WRITTEN WITH GALVANOMETER OF 10-MINUTES PERIOD

S and SS are the direct and once surface-reflected shear waves. G_1 is the first G wave—a horizontally polarized surface shear wave. R_1 is the first Rayleigh wave arrival.



Integrated strain

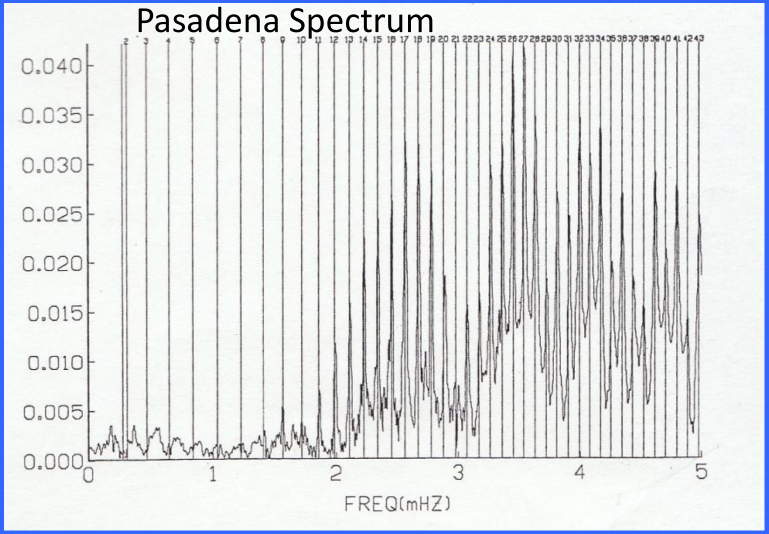
Comparison between spheroidal and toroidal mode excitation (ℓ=2 to 10)



Precursor?

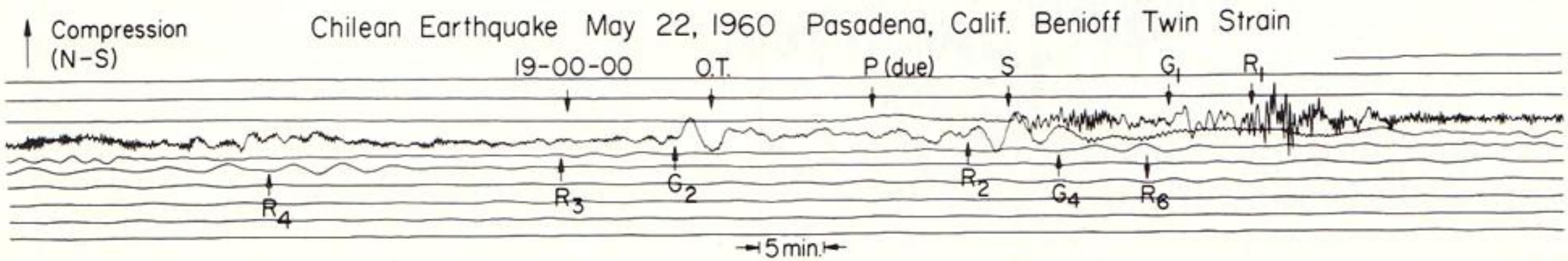
About 15 min before the mainshock.
Large (comparable to the mainshock)

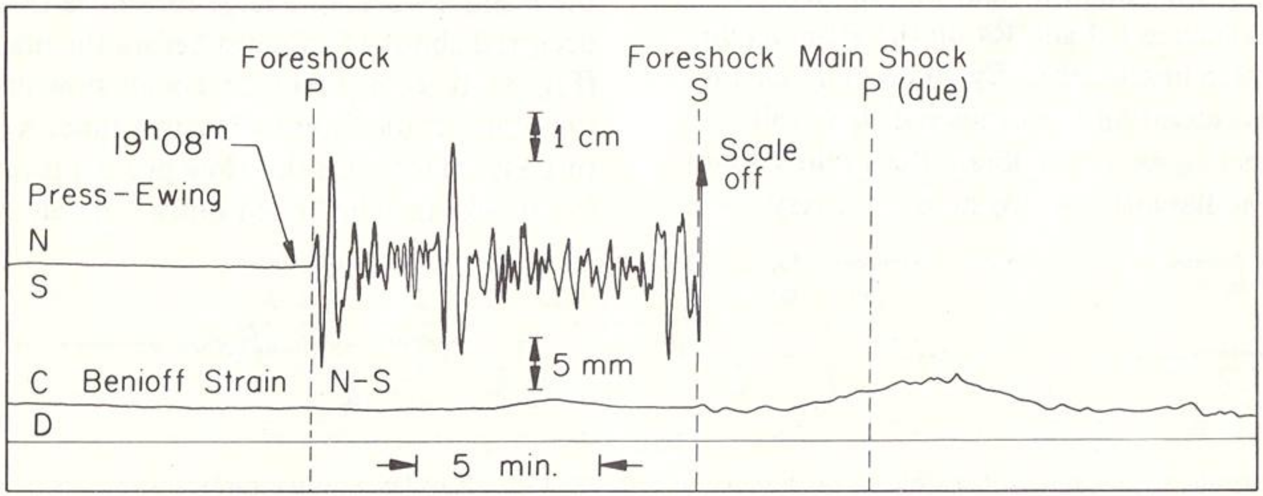
Kanamori and Cipar (1974)
Pasadena strain meter

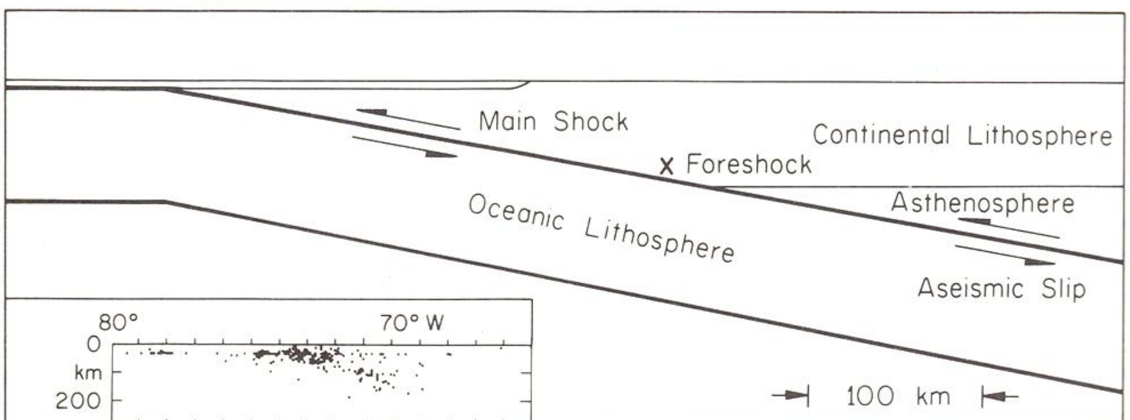


Kanamori and Anderson (1975)
Normal mode

Cifuentes and Silver (1989)
Normal mode (more complete than K&A)

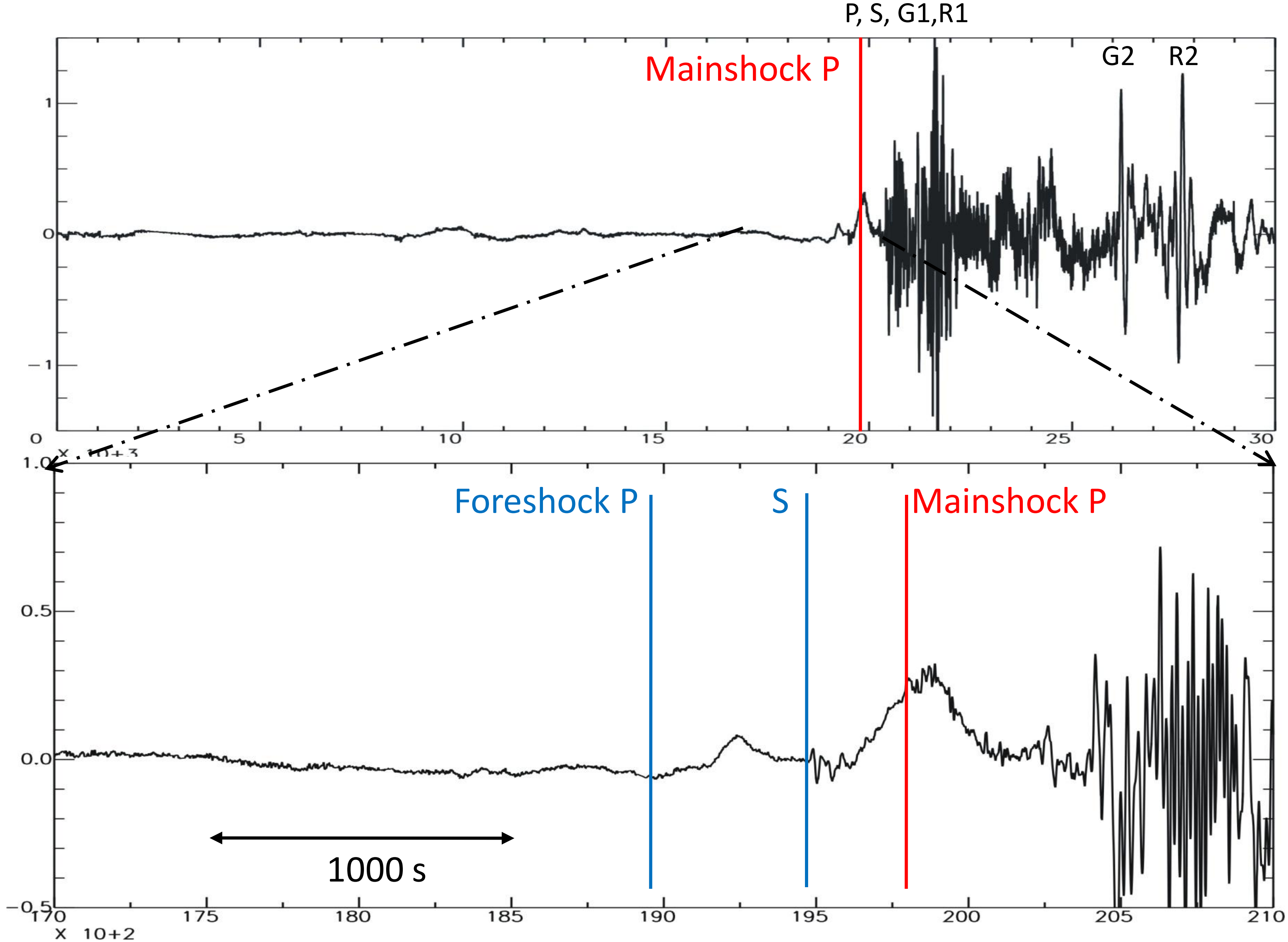




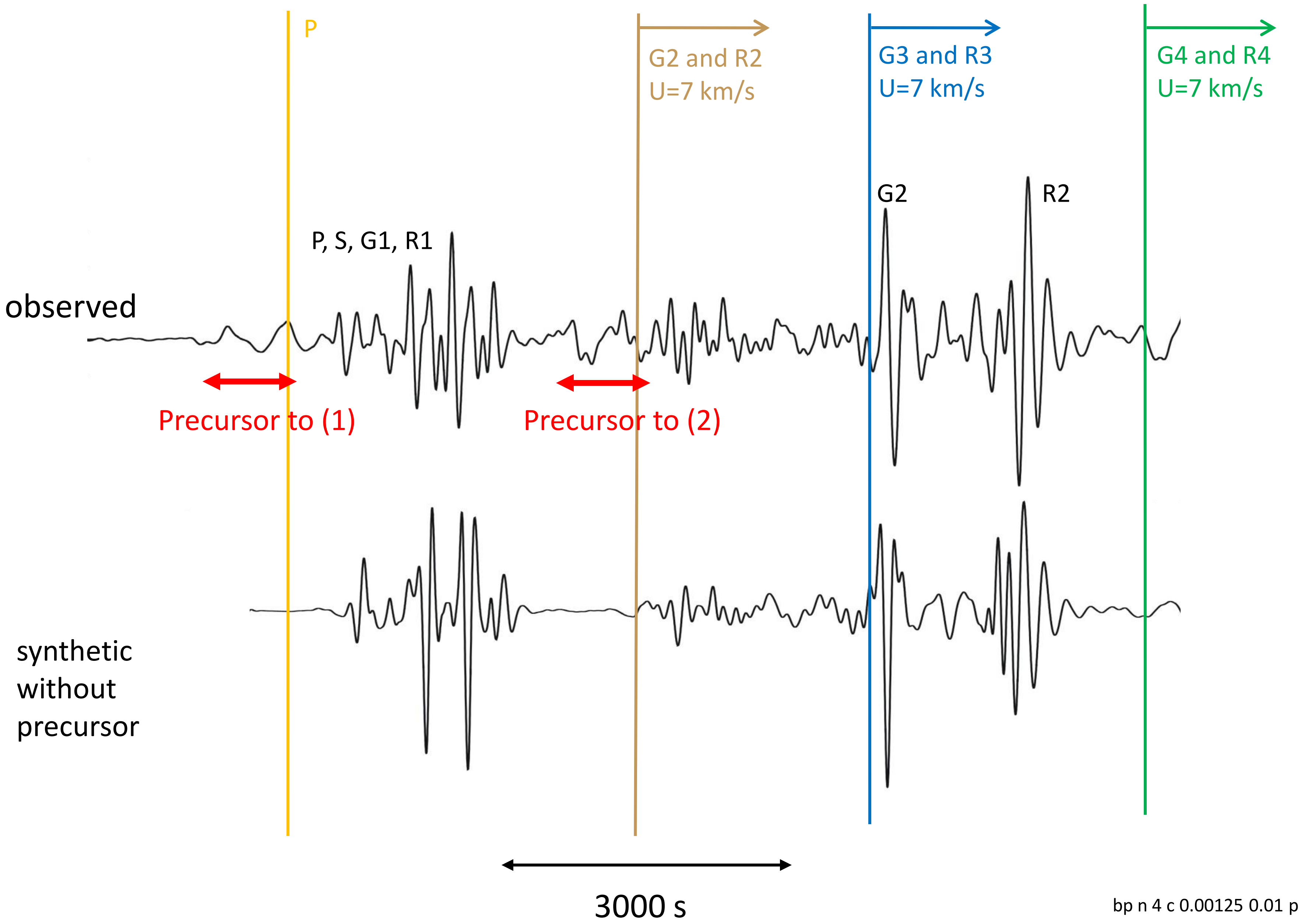


Kanamori and Cipar (1974)

1960 Chilean earthquake, PAS Benioff Strain (NS) 180-4-10
"Precursor"



1960 Chilean earthquake, PAS Benioff Strain (NS) 180-4-10



bp n 4 c 0.00125 0.01 p 2

Foreshock-Mainshock sequence

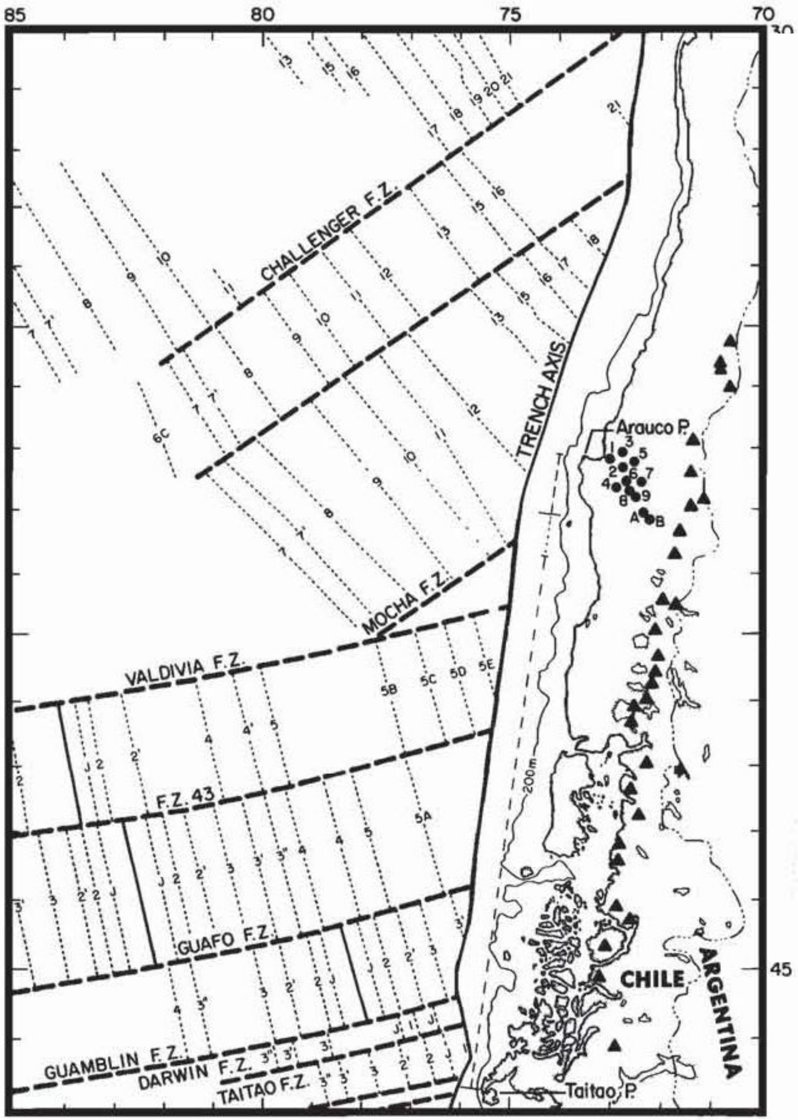


Fig. 4. Relocation of events 1–9 and events A and B. Symbols as in Figure 2.

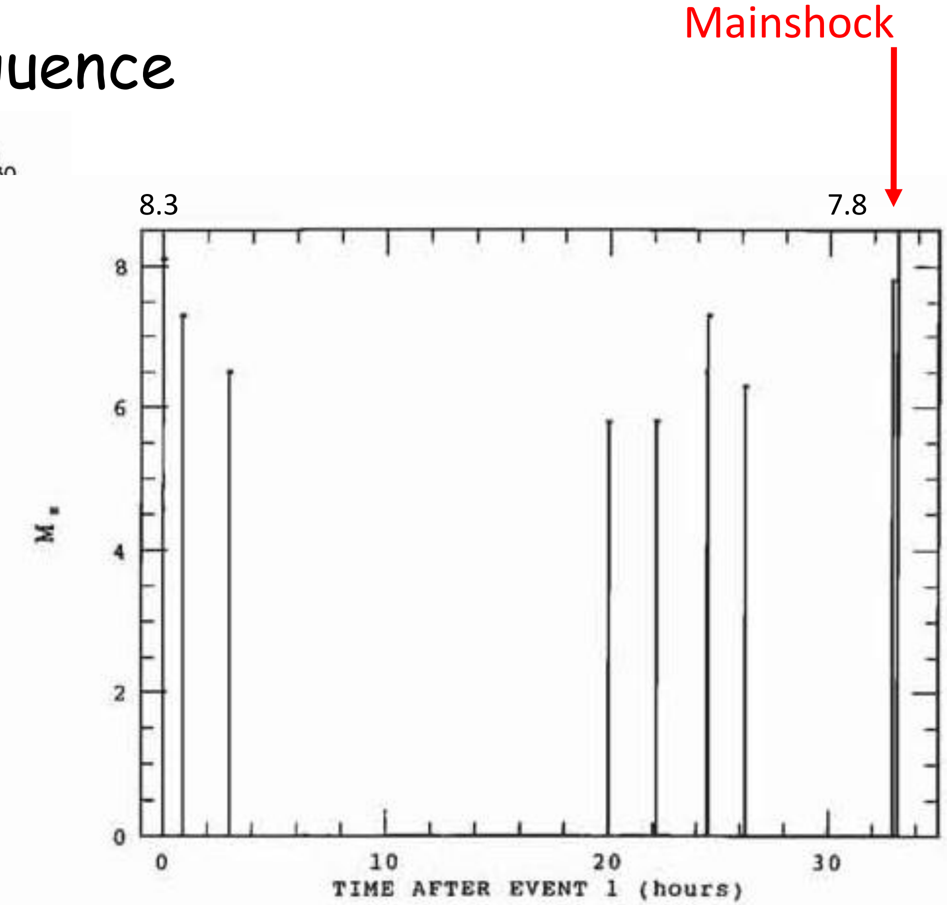
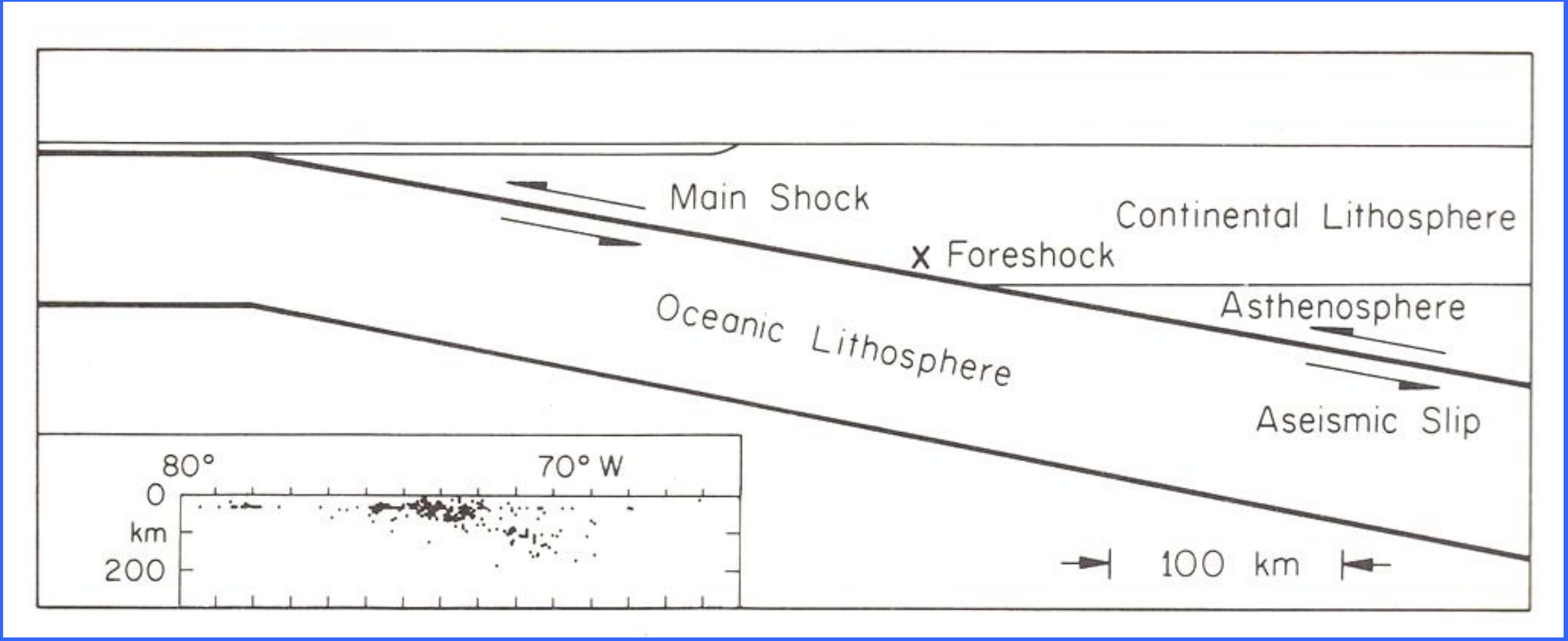


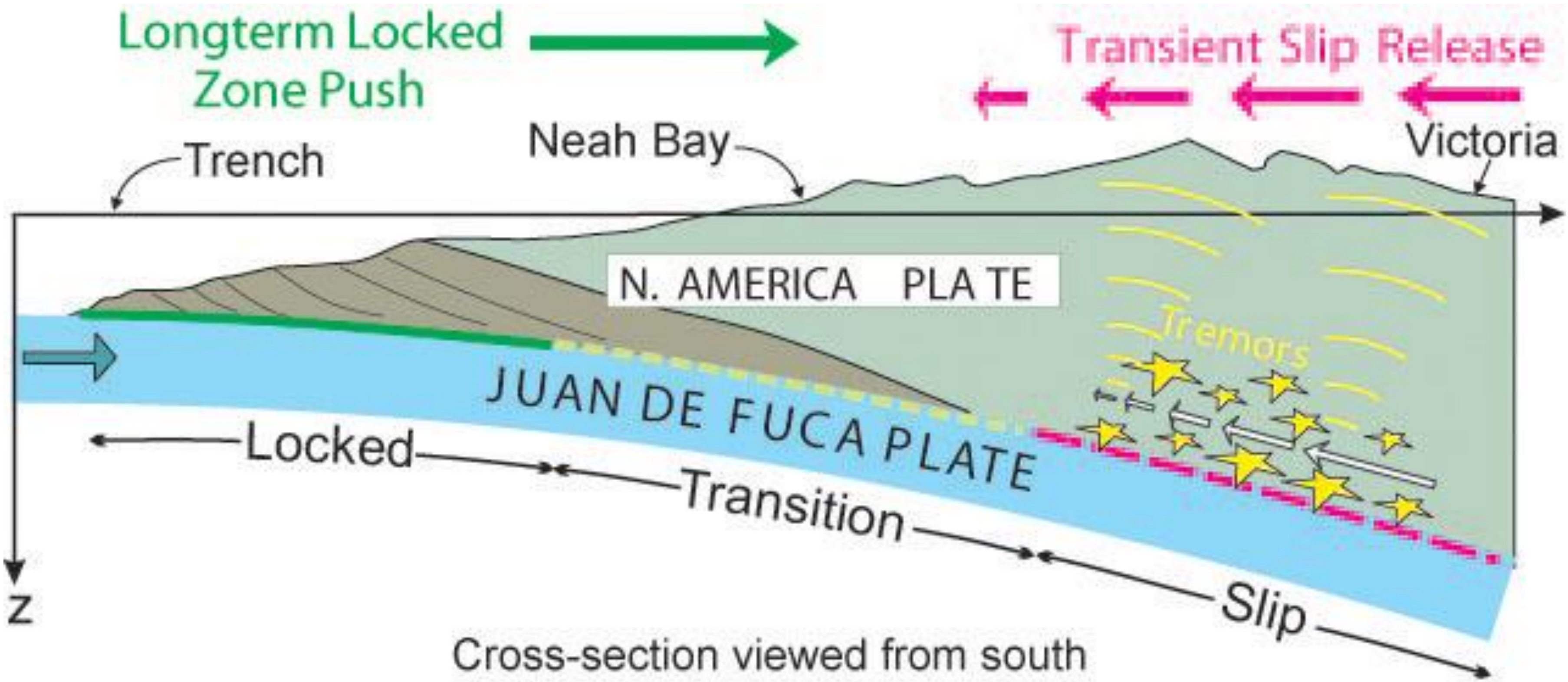
Fig. 3. Magnitude (M_s) as a function of time of foreshock sequence (events 1–9).

Cifuentes (1989)

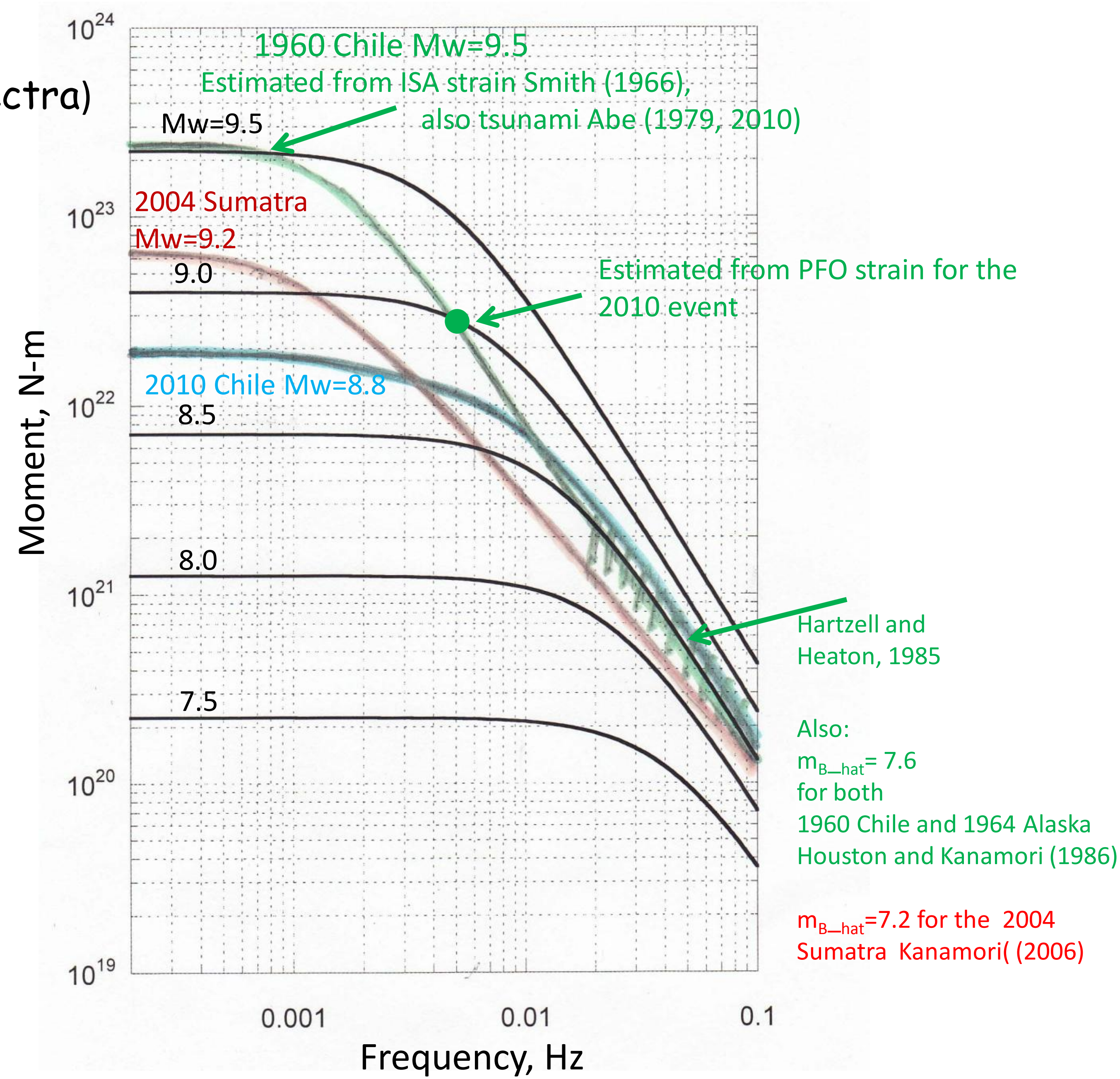
Where does the precursory deformation occur?



Cascadia Current model (Geological Survey of Canada)



Moment-rate Spectrum (with ω² reference spectra)



Conclusion

1. The 1960 Chilean earthquake is probably 2 to 5 times (in M_0) larger than the 1964 Alaska earthquake. (super-cycle event?)

2. The existence and mechanism of precursor are still inconclusive.

3. Slip or deformation may have to be invoked in somewhere other than the mega-thrust boundary. (e.g., deep slip or deformation)

4. "Super-cycle event" may involve a different deformation pattern. Most likely, half thrust and half right-lateral.

5. The super-cycle event can be different from other "average" great earthquakes. Strike slip strain is not released in every great earthquake, and only when it accumulates over several events it triggers a super-cycle event.

Caveat:

Old data are inevitably incomplete and uncertain.

End