Deep Moonquakes, Isolated Deep Earthquakes, and Deep Earthquakes NOT in Subduction Zones

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Motivated by the question:

What is the physical mechanism of deep earthquakes?

A Very Brief History of the Deep Earthquake Question

Before 1925: Q: What is the depth of normal earthquakes? A: 0 – 1000 km
Wadati [1927]: Some EQ are crustal; some deeper than about 400 km

Jeffreys [1928]: isostasy shows 100 km or more is NOT possible
Griffith [1924]: fracture = microcracks [but cracks close up by ~100 km]

1930's – DEQ: Implosive phase transitions? BUT focal mechanisms are DC
1947 - AGU Pres. Leason Adams in EOS: No viable DEQ mechanism known
What is the physical mechanism of deep earthquakes?
This is one of his 6 "outstanding problems in geophysics"

Then: 1950-1990

- 'Dehydration embrittlement'; H20 dehydrating minerals keeps cracks open
- Transformational faulting– phase change fills cracks w fine-grained material
- Shear/thermal instability – stress-induced runaway melting

1990-2018:
Q: Which mechanism is responsible? Or…
Q: How many mechanisms are responsible?

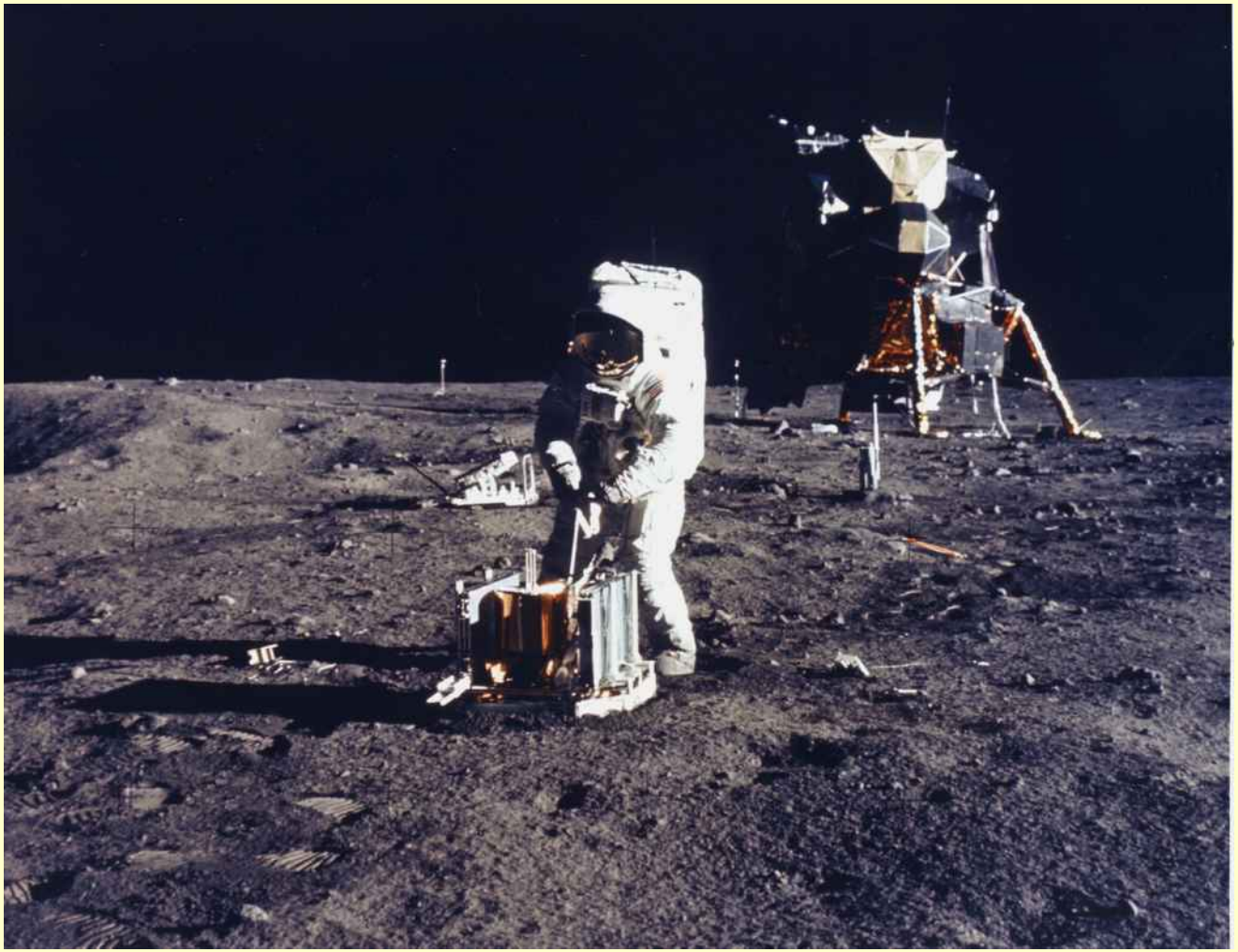
Ordinary brittle fracture isn't possible at pressures/temperatures where intermediate/deep earthquakes occur because open cracks can't form

The most popular mechanisms to explain intermediate/deep earthquakes are:

- Dehydration embrittlement (60-300 km)
- "Transformational faulting" (350-700 km)
- Thermally induced shear instabilities

Today's objective: To call attention to some 'unusual' deep earthquakes, and to encourage considering whether these provide clues to "the" mechanism at work, or whether additional mechanisms are required.

I. **Moonquakes**: Apollo astronauts emplaced 4 lunar seismographs that recorded seismic signals from 1969-1977

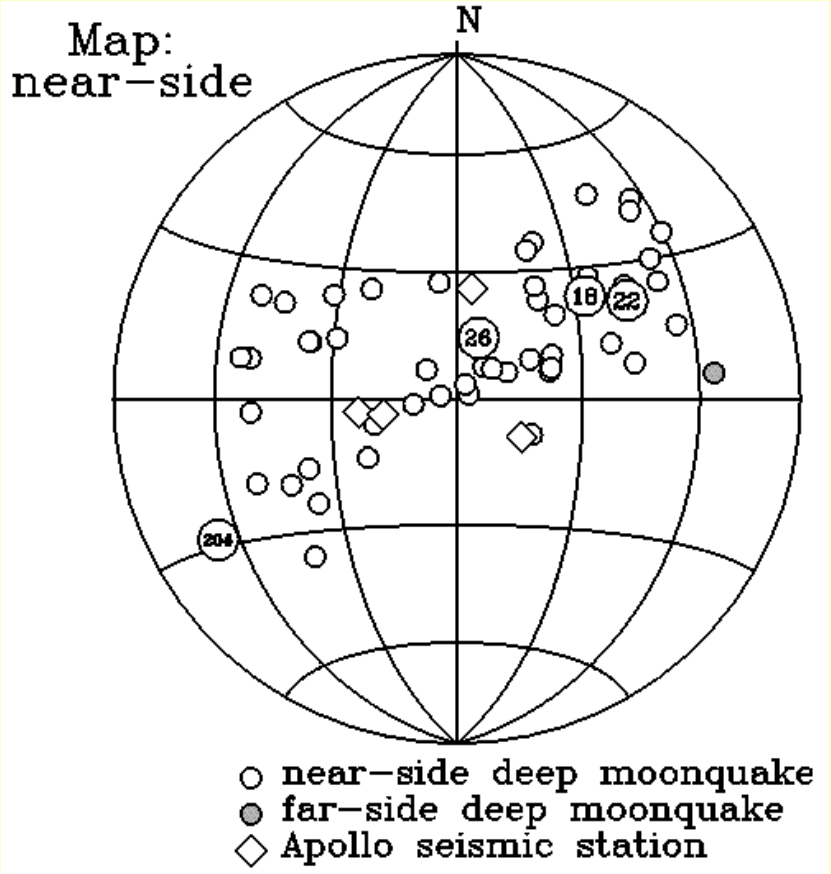


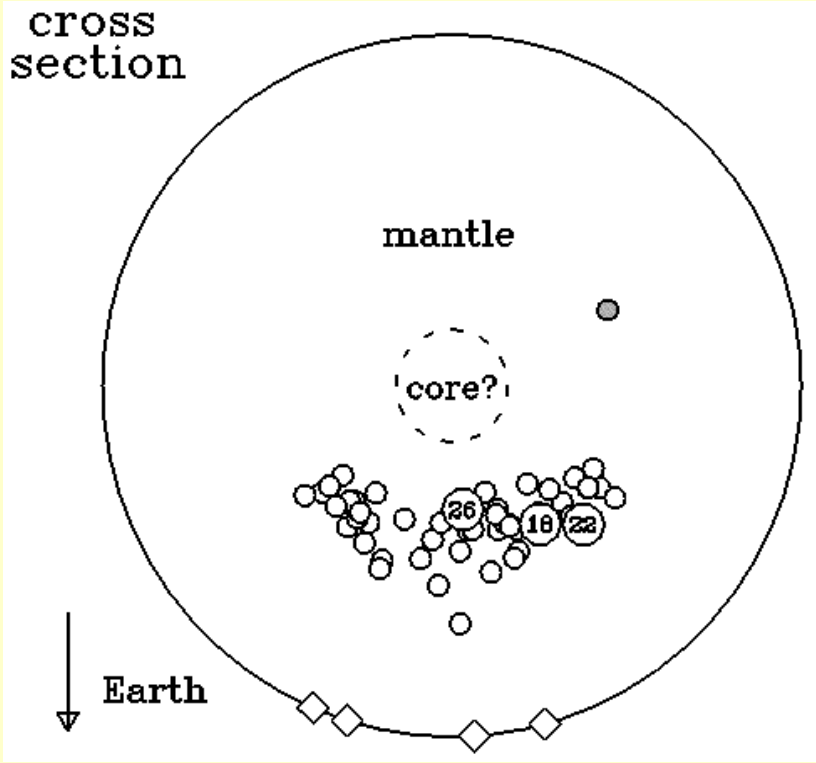
Scientists knew Moon would be dead… and thus network would record only:

- Meteoroids
- Manmade impacts
- Thermal moonquakes

But…

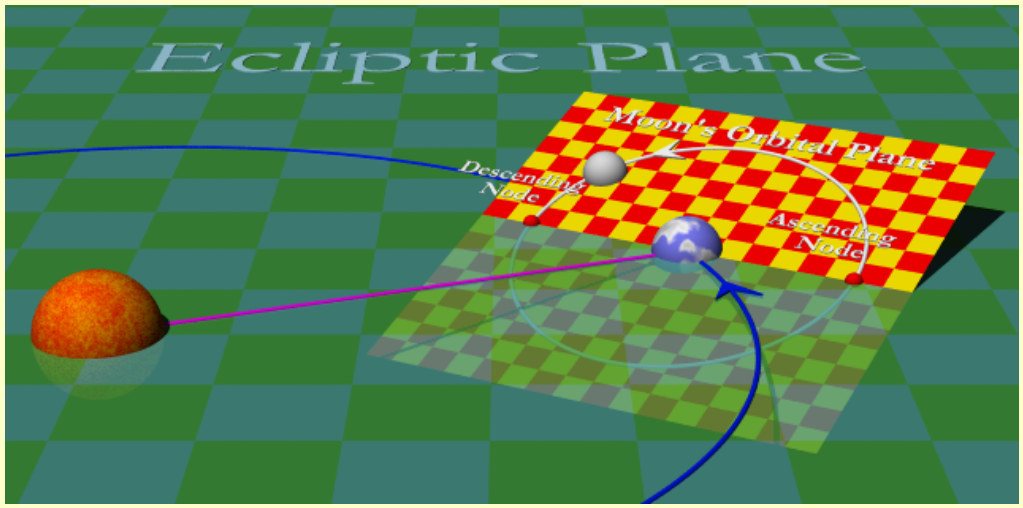
WHAT WE KNOW ABOUT DMQ:





- majority have depths of 700-1200 km
- more than 7000 DMQ have been identified
- 'nests' have ~2-300 DMQ each
- spatial extent of individual nests < ~2 km

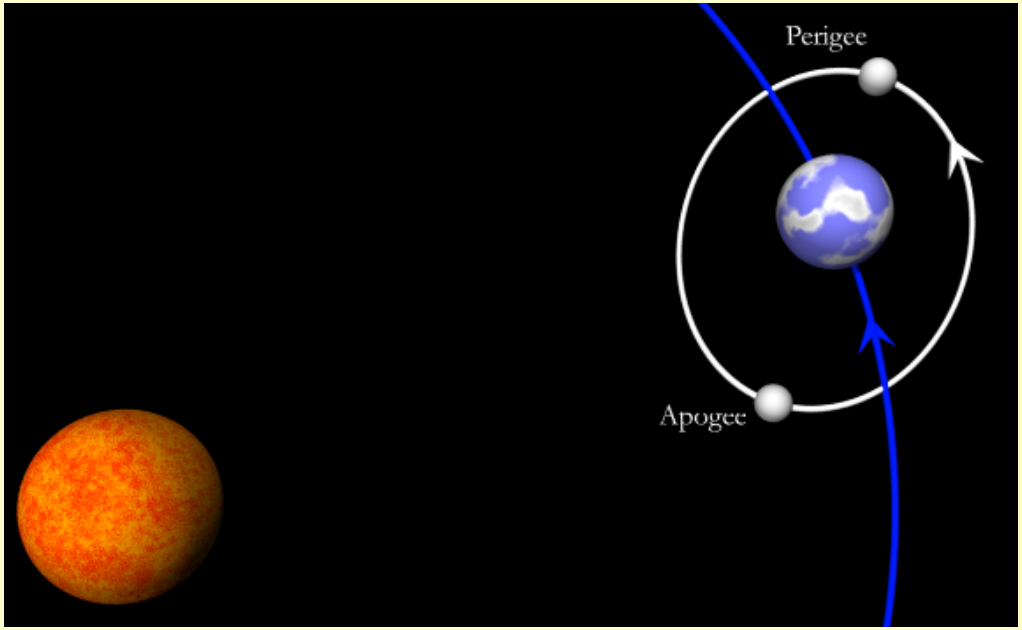
different ‘months’ and libration



Draconic month:

Man-in-the-Moon nods “yes”

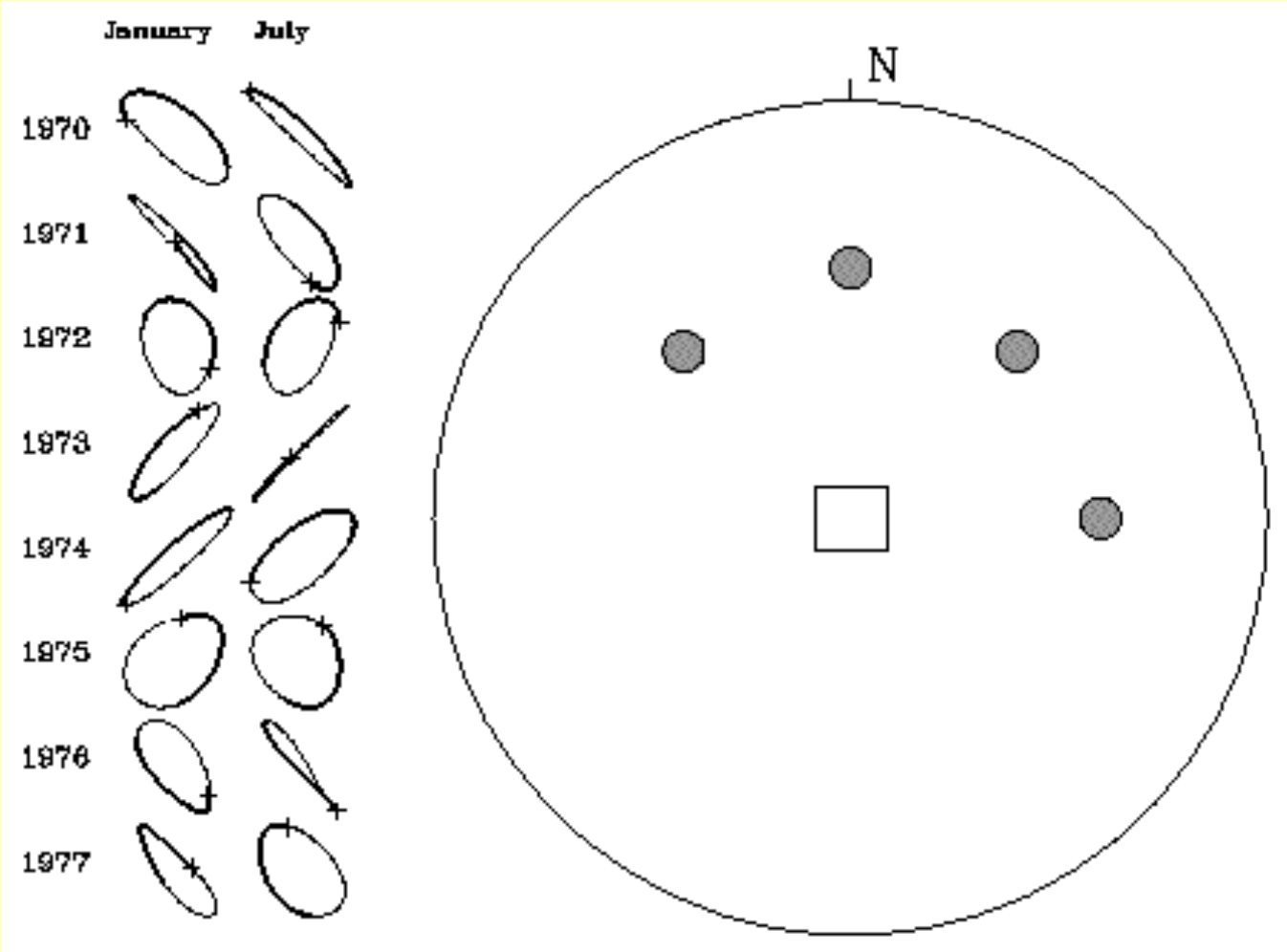
(up and down ±7°)



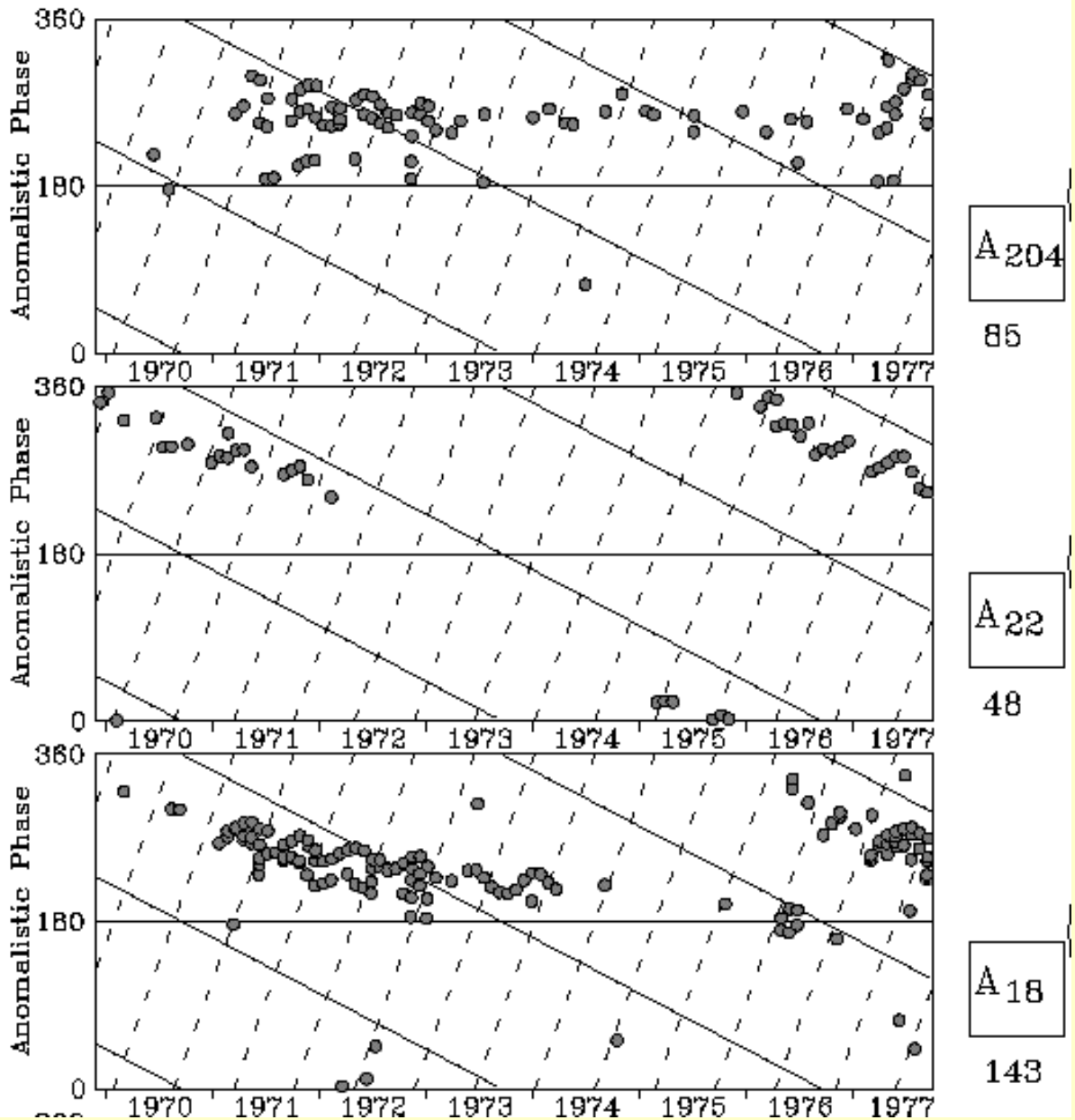
Anomalistic month:

Man-in-the-Moon nods “no”

(side to side ±8°) and tidal potential changes by ±20%



Motion of subearth point (libration) affects DMQ nests differently depending on location



WHAT WE KNOW ABOUT DMQ:

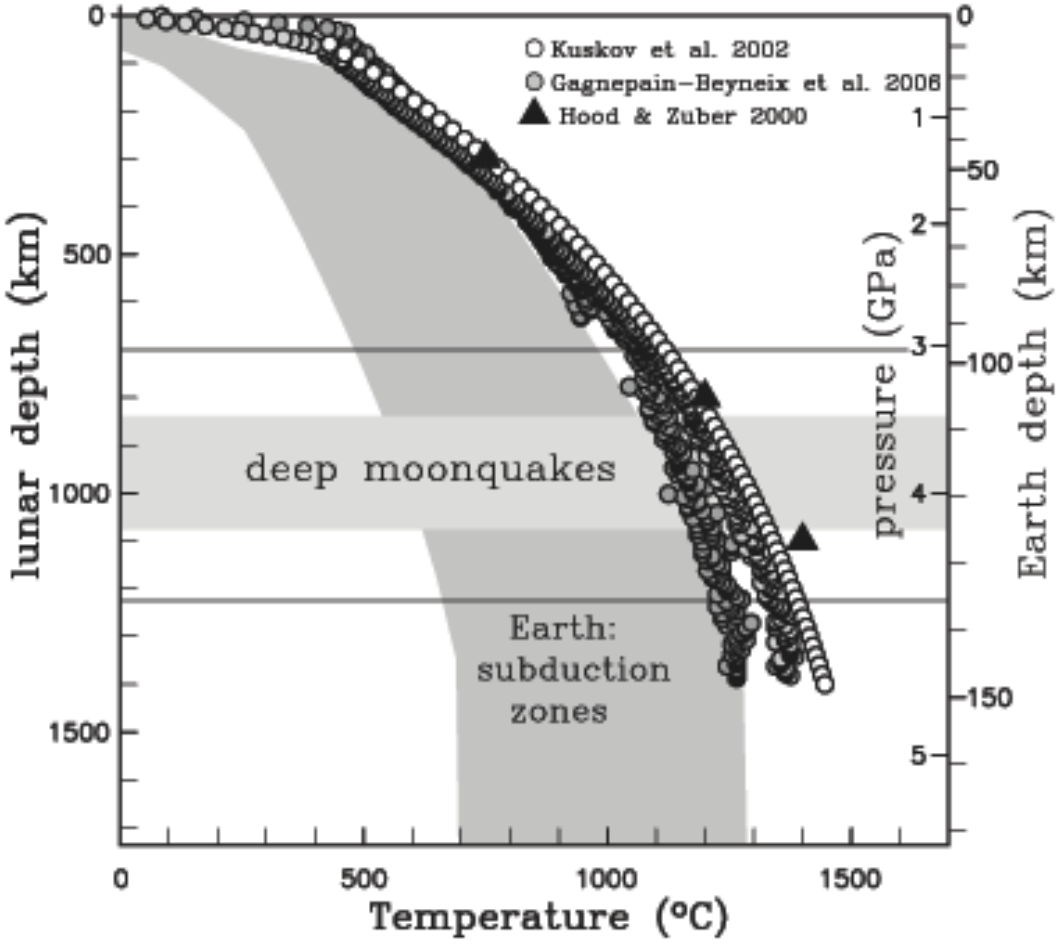
Tides control DMQ:

Some correlate with anomalistic month (27.55 d) (Moon's distance from Earth)

Some correlate strongly with draconic month (27.21 d) (Moon above and below Earth's orbital plane)

Some show distinct patterns, not obviously draconic or anomalistic

Deep Moonquakes and Deep Earthquakes



Where deep moonquakes occur, P-T conditions on Moon are roughly similar to Earth at 110-125 km depth

- **no subduction on Moon**

- **conventional wisdom says lunar interior is dry (no water)**

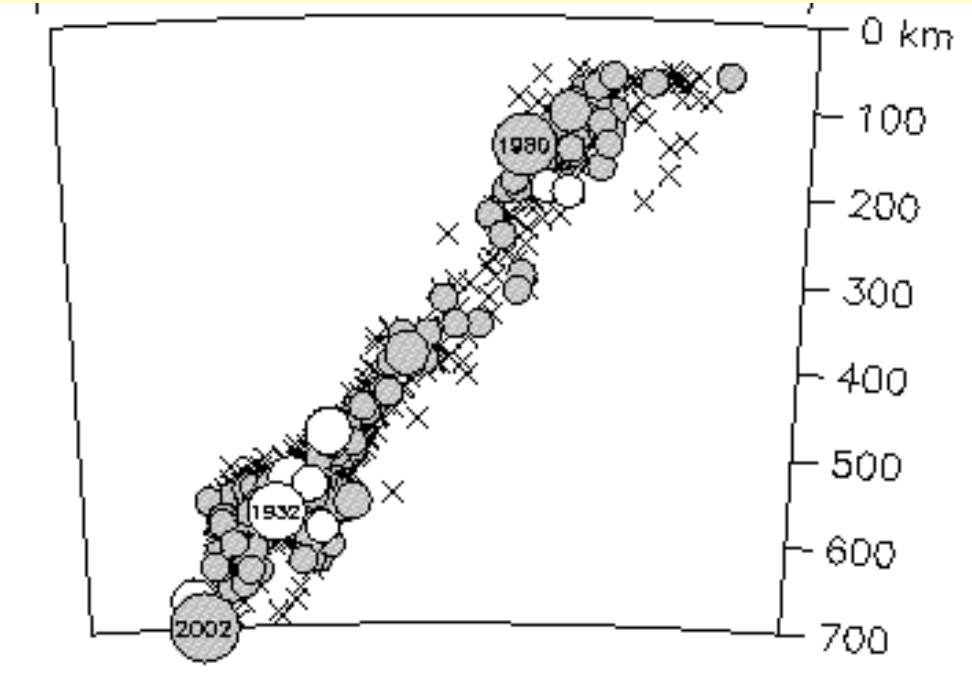
- **dehydration embrittlement, transformational faulting, both unlikely**

- **is conventional wisdom wrong or is another physical mechanism at work?**

?? Ockham's Razor ??

II. Isolated Deep Earthquakes

Researchers usually study deep earthquakes in areas where clusters of numerous deep quakes occur, as in Tonga or Japan Wadati-Benioff zones



2/3 of all quakes h>300 km are in Tonga

Alternate approach:

Focus on other categories of deep earthquake phenomena

e.g.:
Isolated deep earthquakes

Hypothesis: Lithosphere warms as it subducts, and thus at great depths very large earthquakes aren't possible because smaller volumes of cold material are available to accommodate seismic rupture

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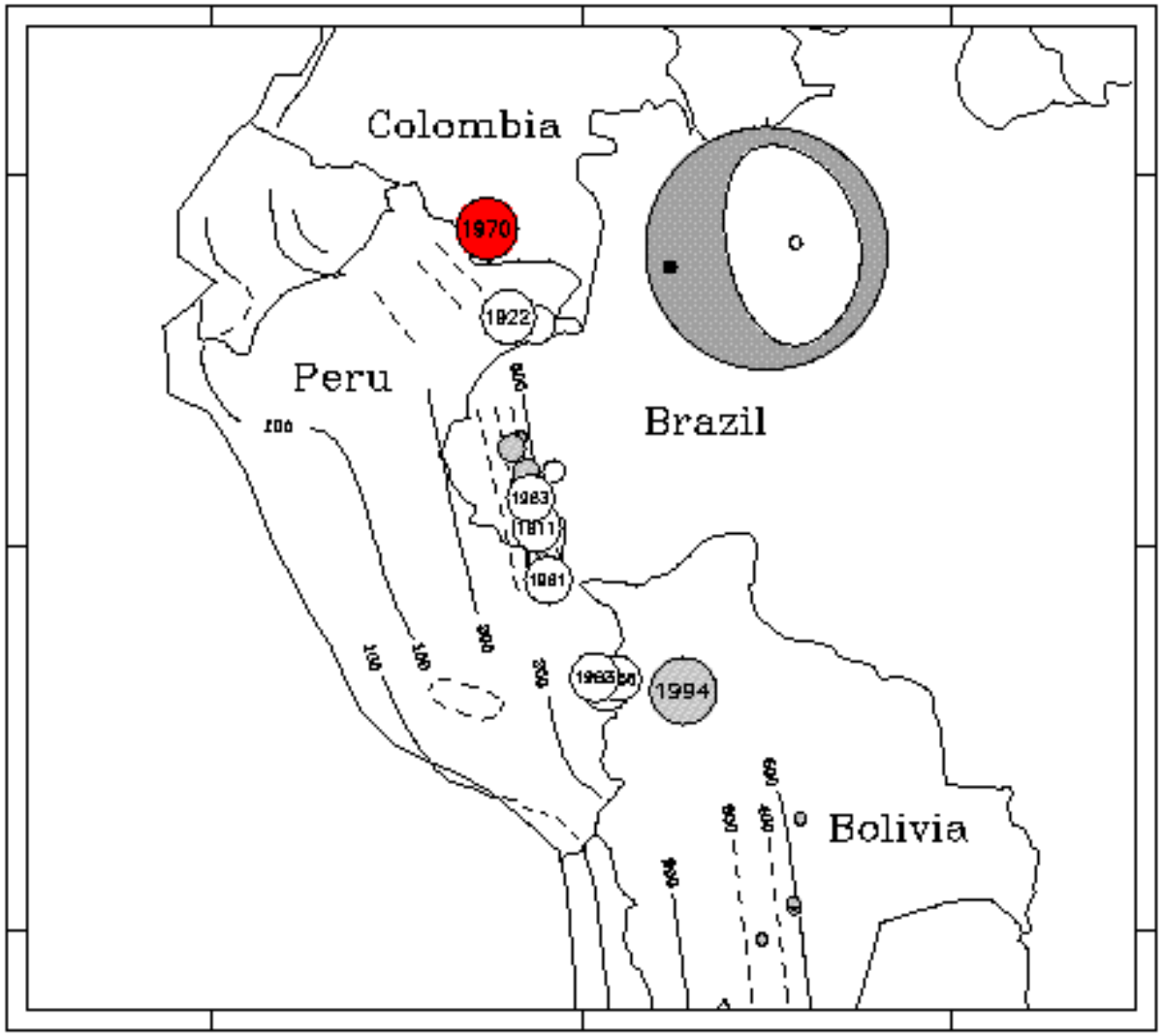
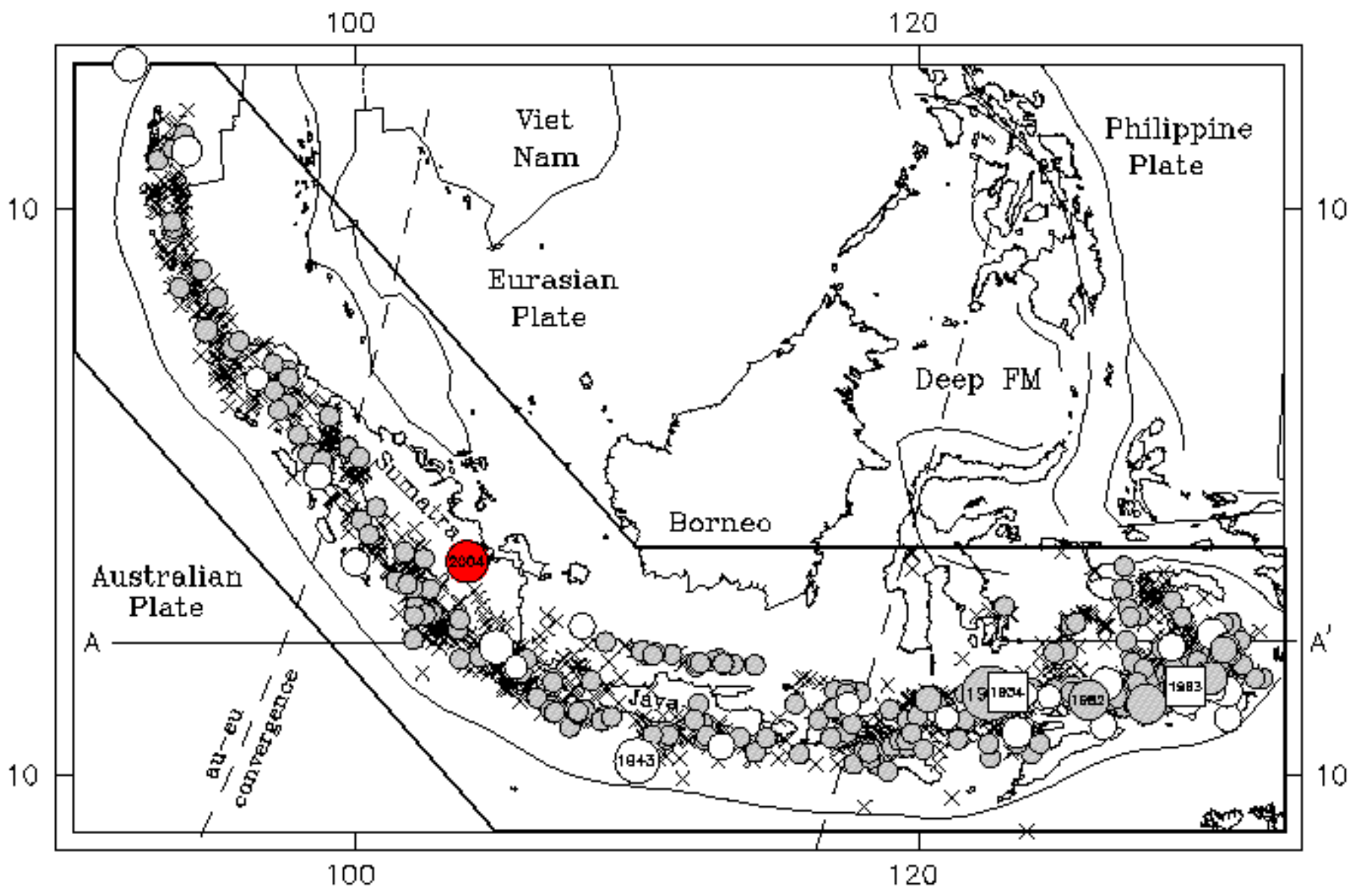
Fact: Some of the very largest deep earthquakes occur at depths exceeding 600 km and are highly isolated, far apart from nearby activity

Spain	630 km	29 Mar 1954	Mw 7.9
Colombia	623 km	31 Jul 1970	Mw 8.1
Tonga-K	699 km	19 Aug 2002	Mw 7.7
Indonesia	601 km	25 Jul 2004	Mw 7.3
Bonin	681 km	30 May 2015	Mw 7.9

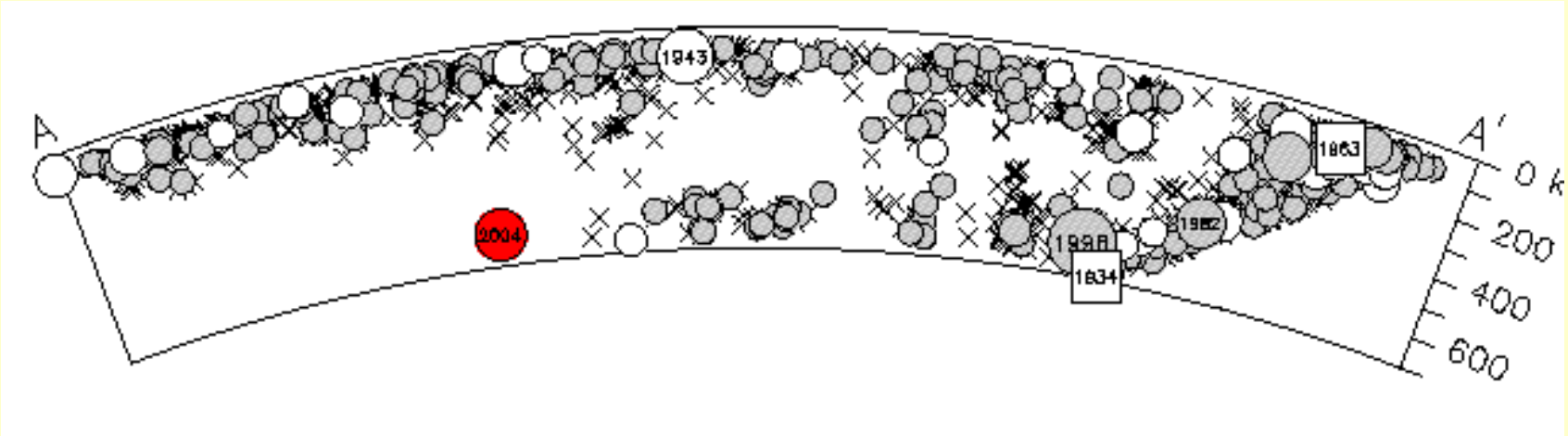


Colombia 623 km 31 July 1970:

- Mw 8.1
- No foreshocks
- No aftershocks
- No earthquakes whatsover within 200 km in entire ISC or ISS catalogs

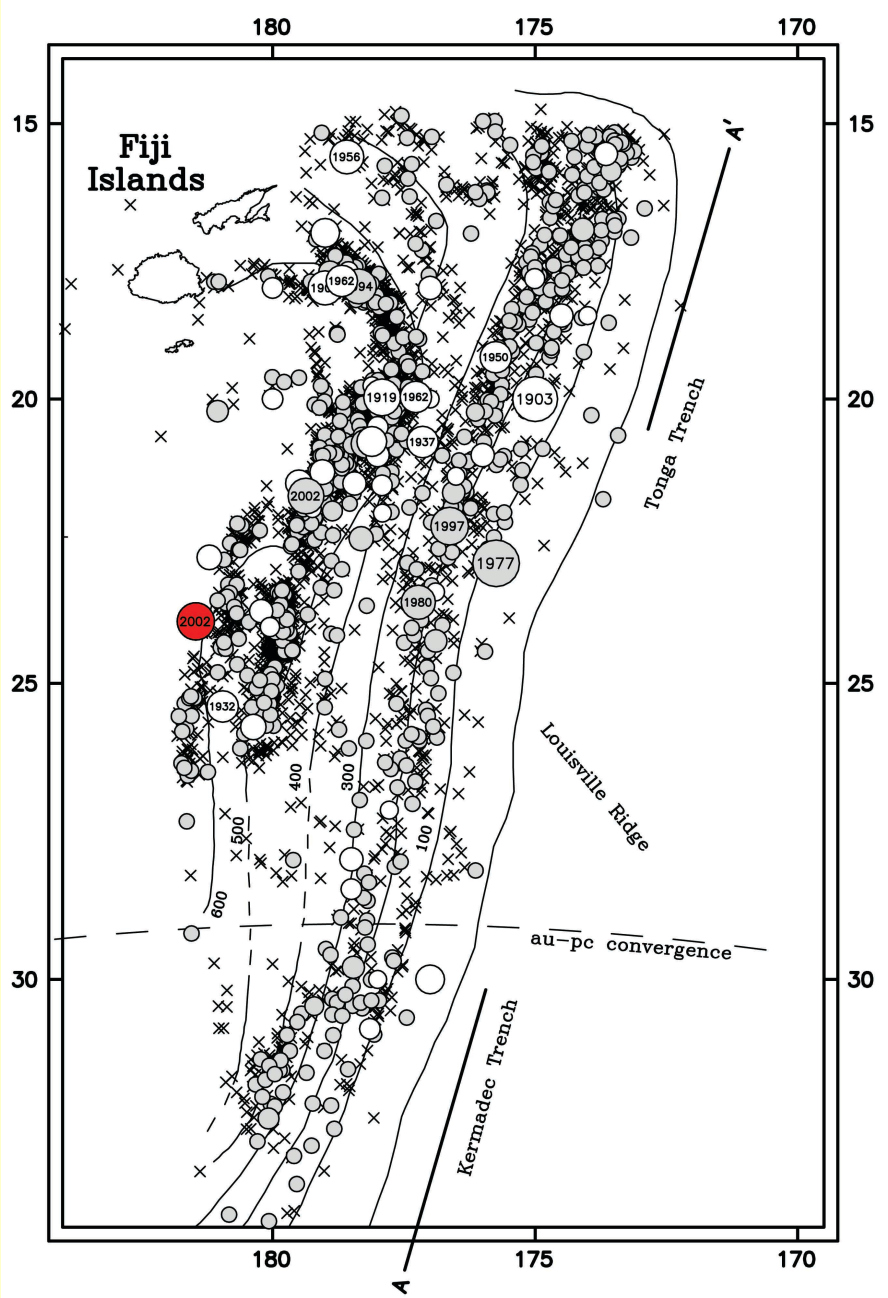


Indonesia 2004: Mw 7.3 601 km



Indonesia 2004 July 25: Mw 7.3 601 km depth

Only earthquake within 100 km was M3.9 at 624 km, one day later.



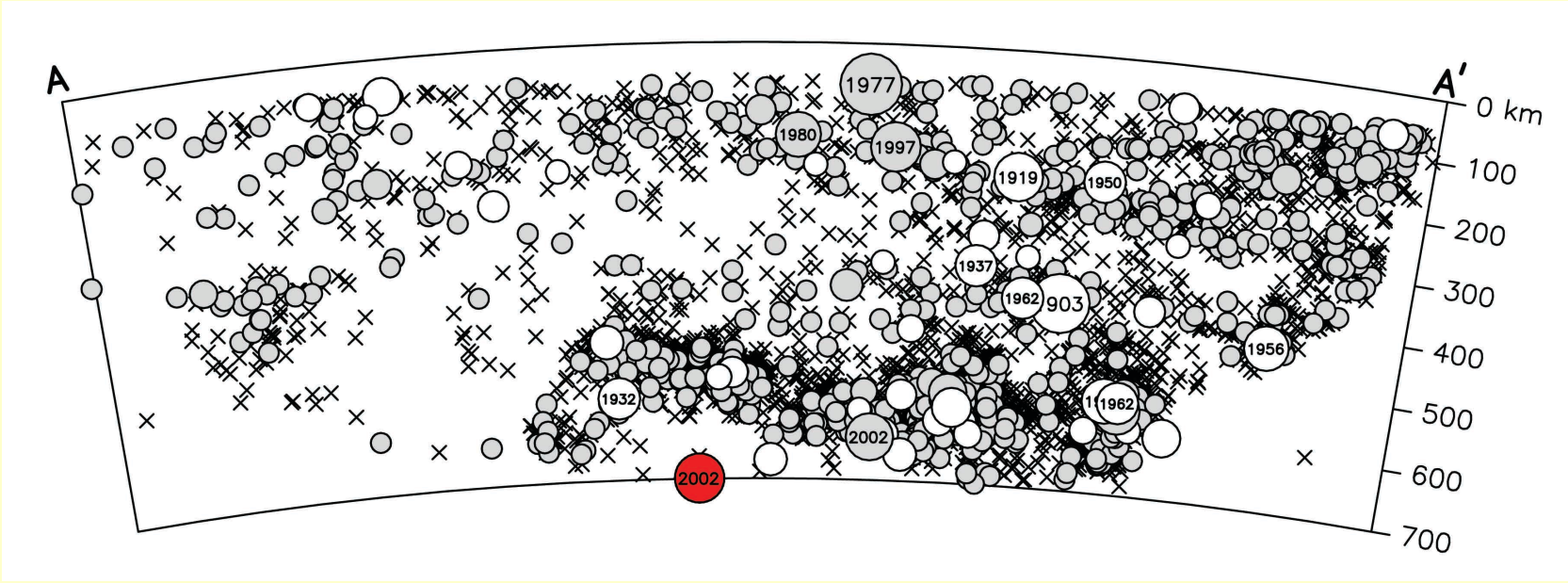
Tonga 2002 August 19
Mw7.7 699 km

deepest quake worldwide in entire CMT catalog

In Tonga-Kermadec, largest quake in CMT catalog beneath 200 km depth

had one foreshock…
one aftershock…

Occurred 7 min after Mw7.6 at 631 km depth, 290 km to N



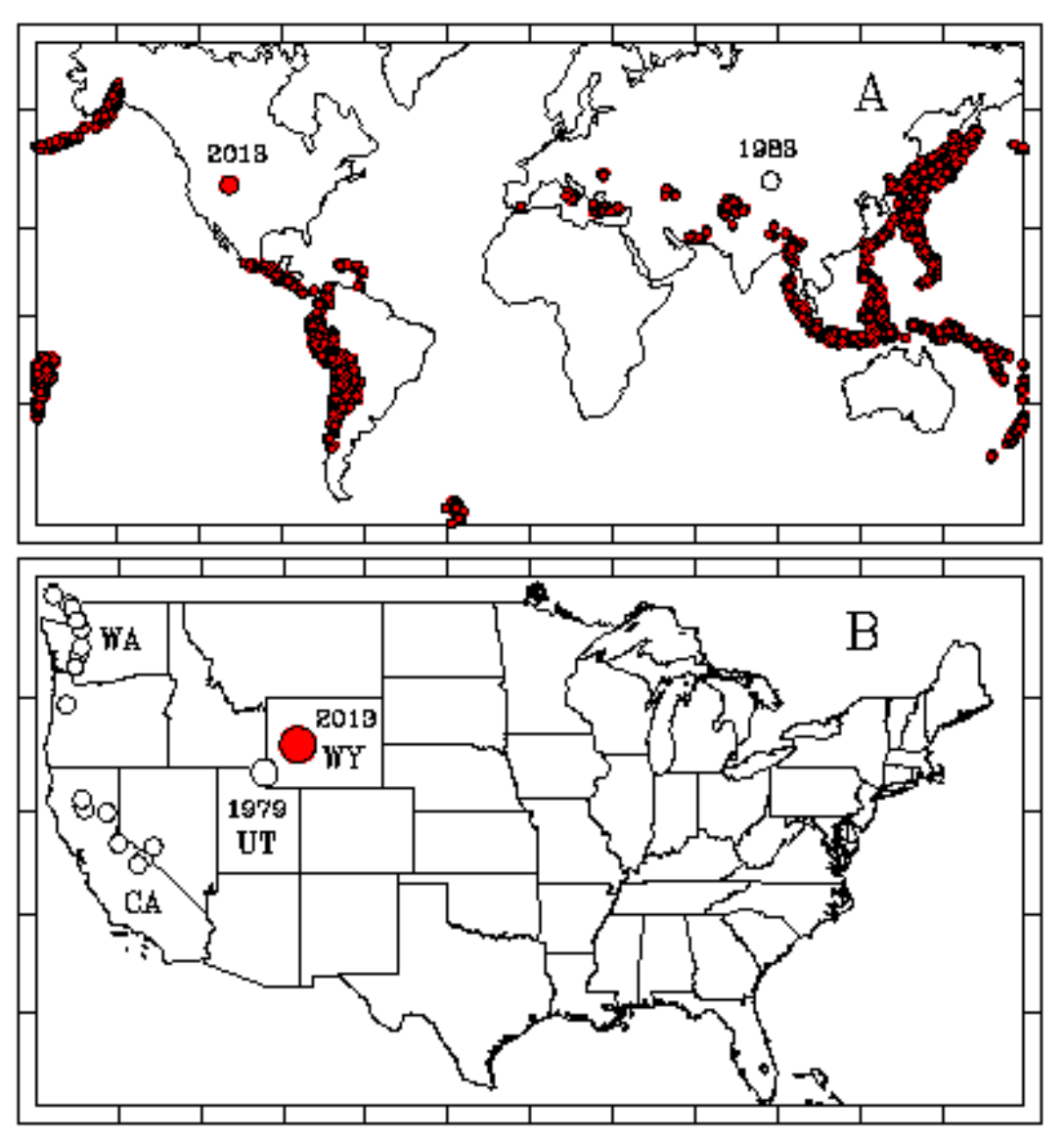
Tonga 2002 August 19 Mw7.7: 699 km

deepest quake worldwide in entire CMT catalog;
had one foreshock, one aftershock

Isolated!

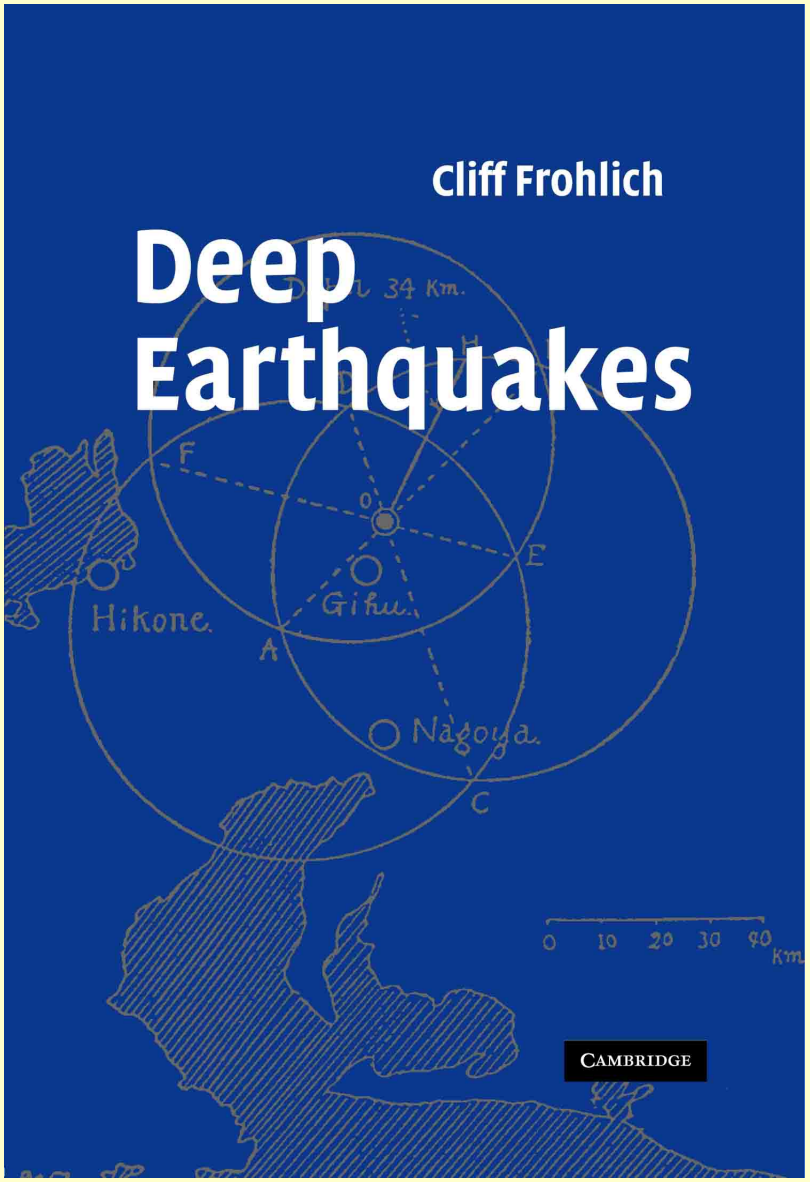
Question: Can we identify other likely locations where future large isolated deep earthquakes will occur?

III. A Deep Earthquake in Wyoming



Red circles:
Well-recorded earthquakes in GCMT catalog with depths > 60 km

Wyoming
21 Sep 2013
Depth 75 km
Mw 4.8



2006 wager concerning whether any deep earthquakes will occur outside of 28 regions identified in book:

"Prior to 2015, if there are one or more such well-located earthquakes having a believable focal depth exceeding 60 km, Cliff owes Scott Davis's family a fine dinner, prepared in the cuisine most characteristic of the region where the largest such event occurred."

Questions

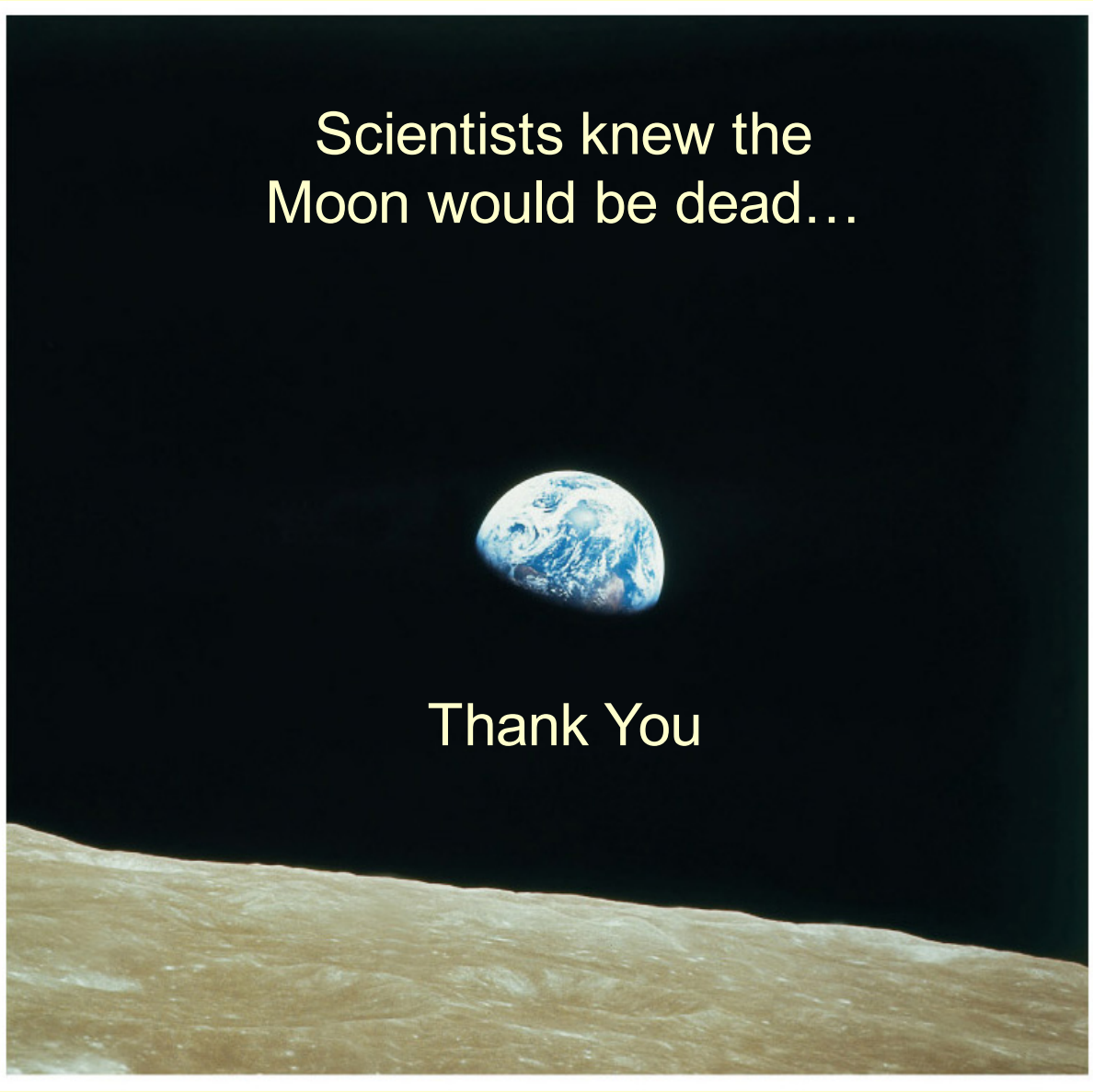
What is the physical mechanism of deep earthquakes?

How many distinct physical mechanisms are at work?

Is more than one physical mechanism active?

Are more than two physical mechanisms active?

To study trees, mostly we visit the forest…


Scientists knew the
Moon would be dead…
Thank You