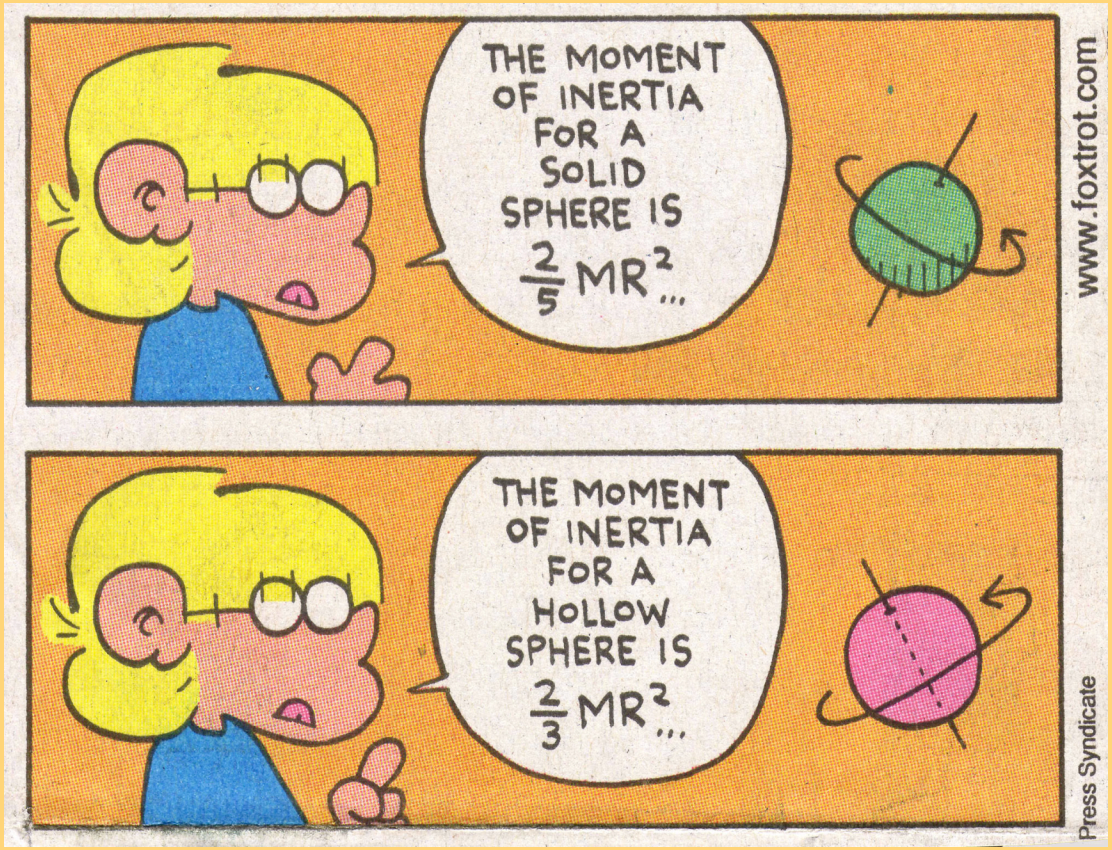
Geological and geophysical constraints on the orbital evolution of the Moon

Bruce Runnegar, Per Jögi & Paul Davis
University of California, Los Angeles

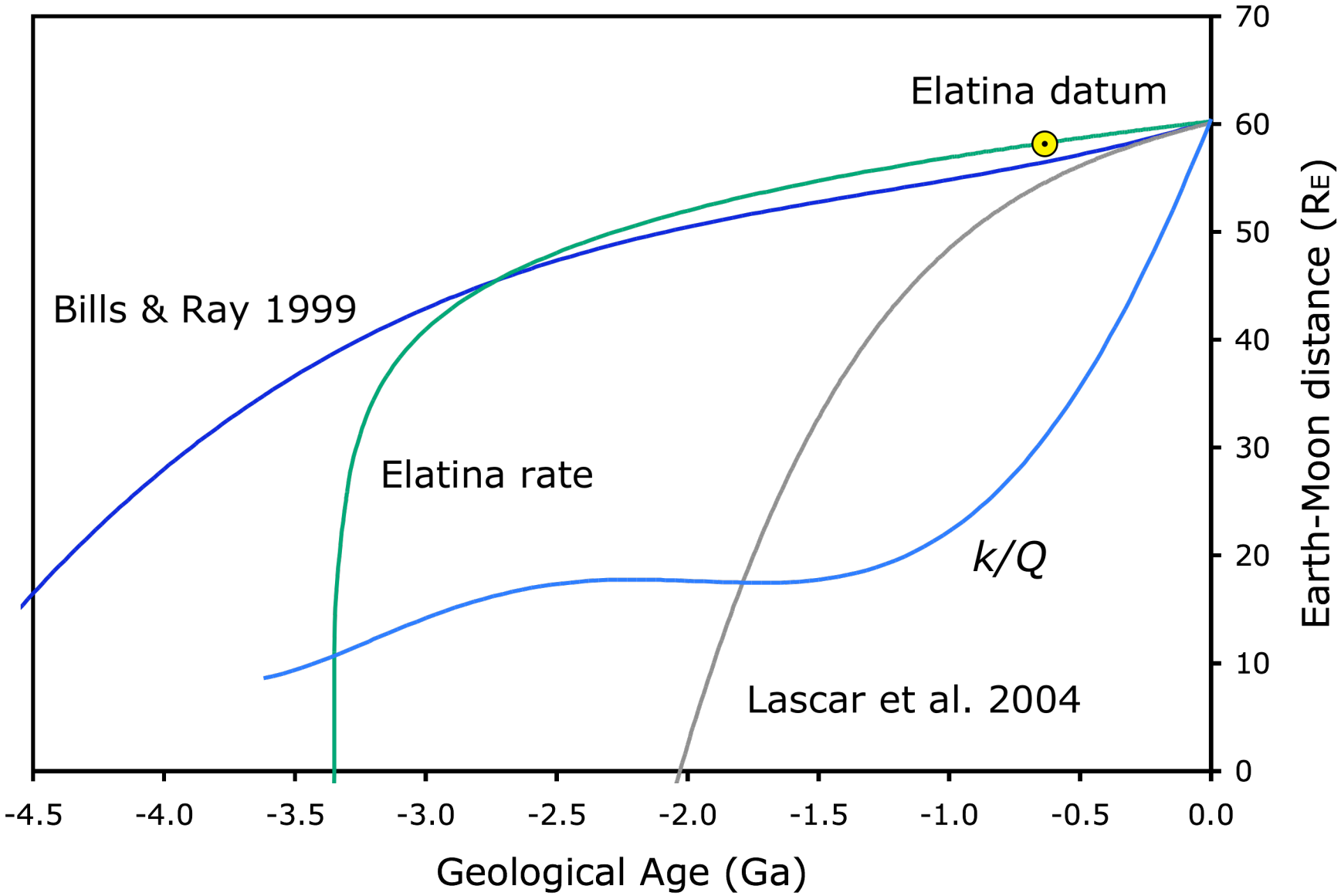
Problem

- Current rate of lunar recession (3.82 cm/year) is too fast
- Models of ocean tidal dissipation bypass paleotidal constraints
- Models may be oversimplified
- Paleotidal data is of variable quality and difficult to interpret
- Some physics has been ignored
- Can we do better?

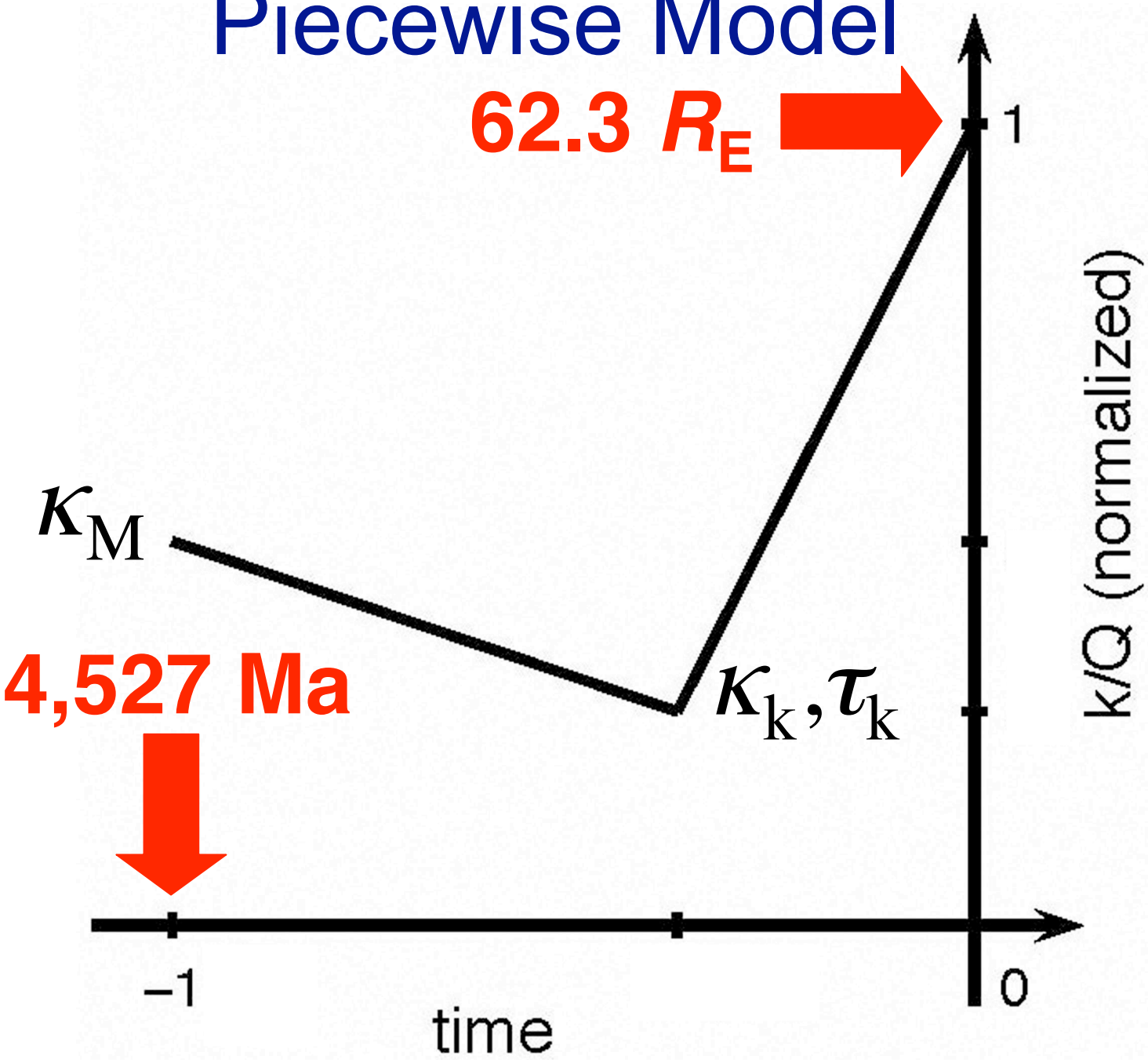
Part 1: Theory



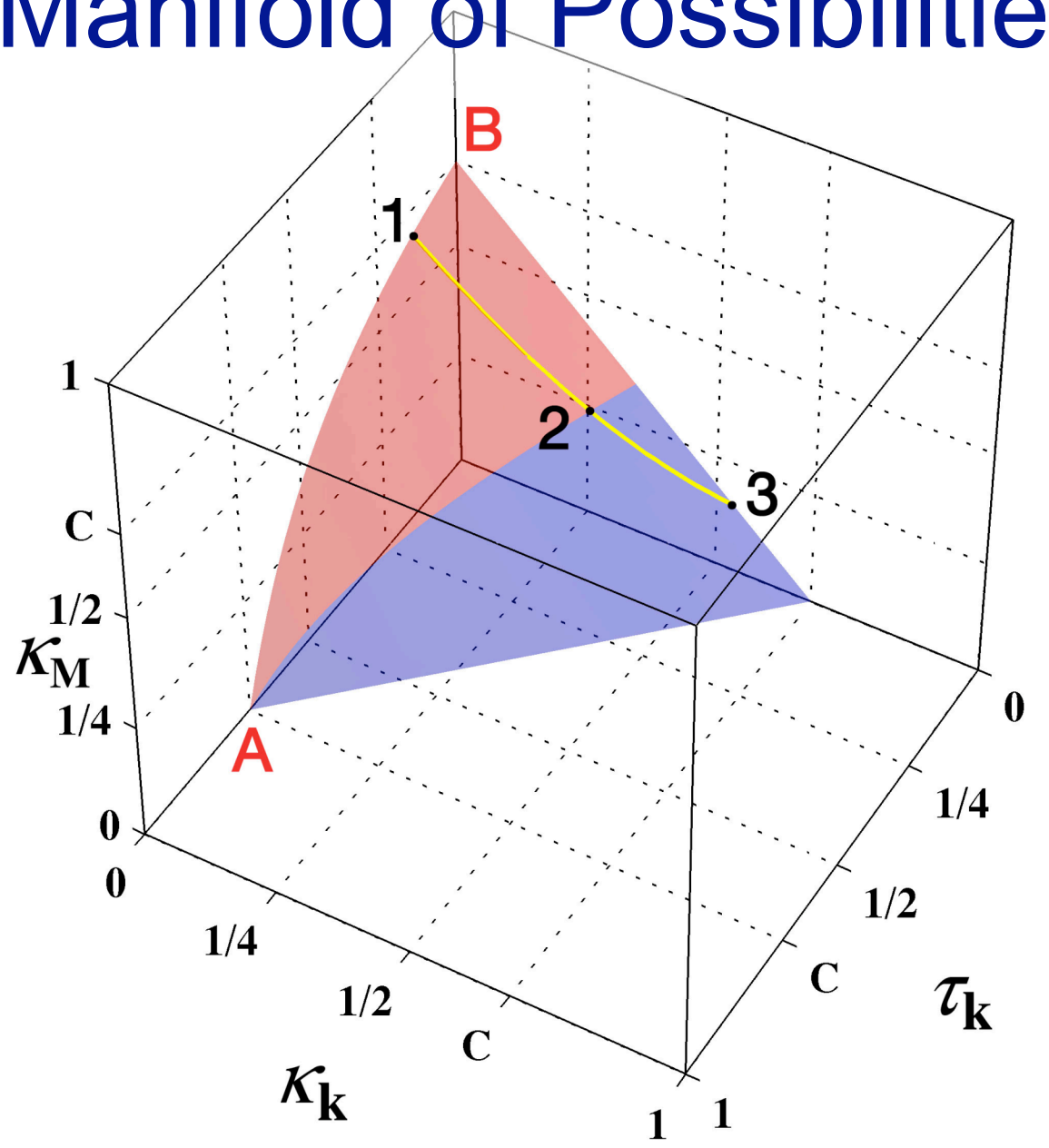
Three (inadequate) extrapolations



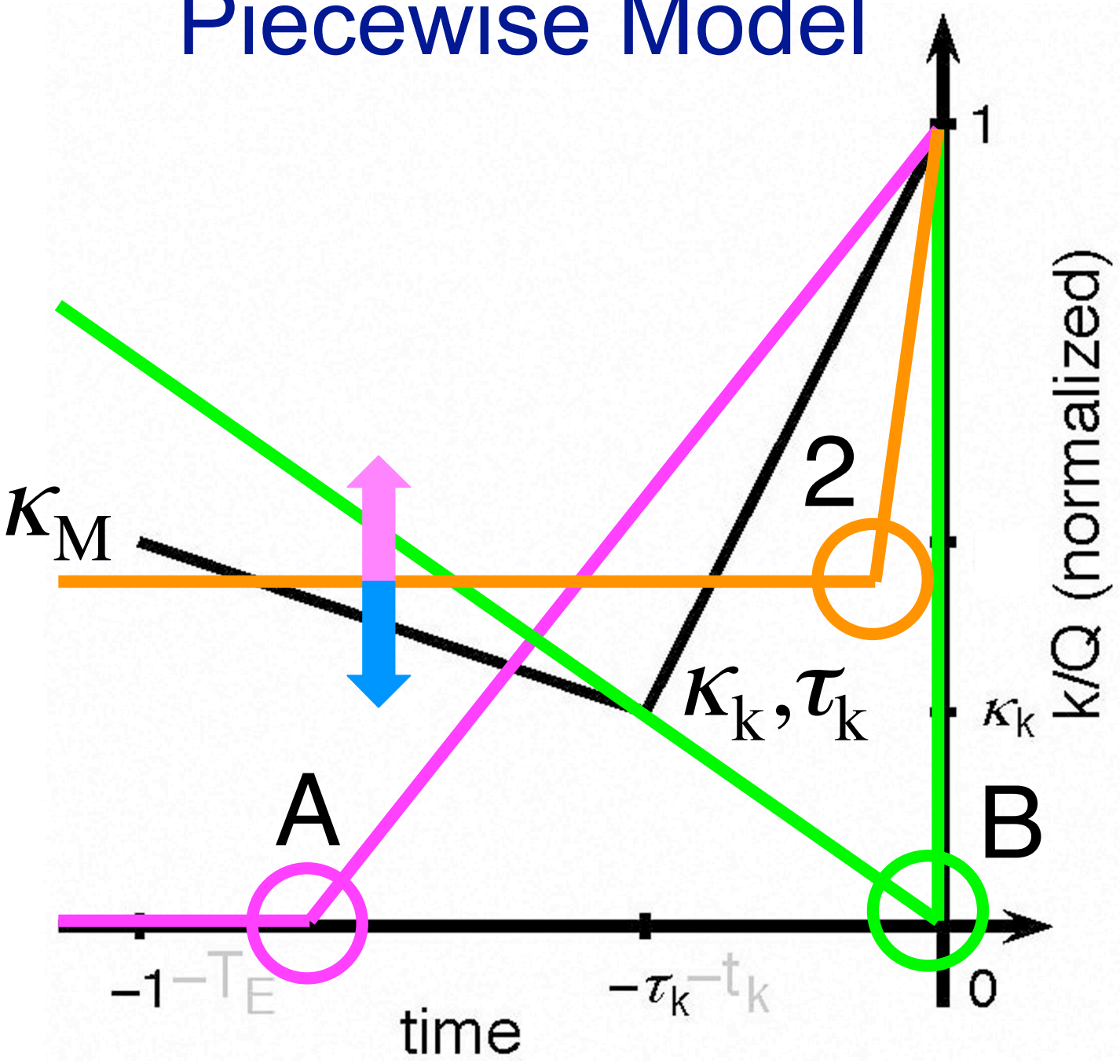
Piecewise Model

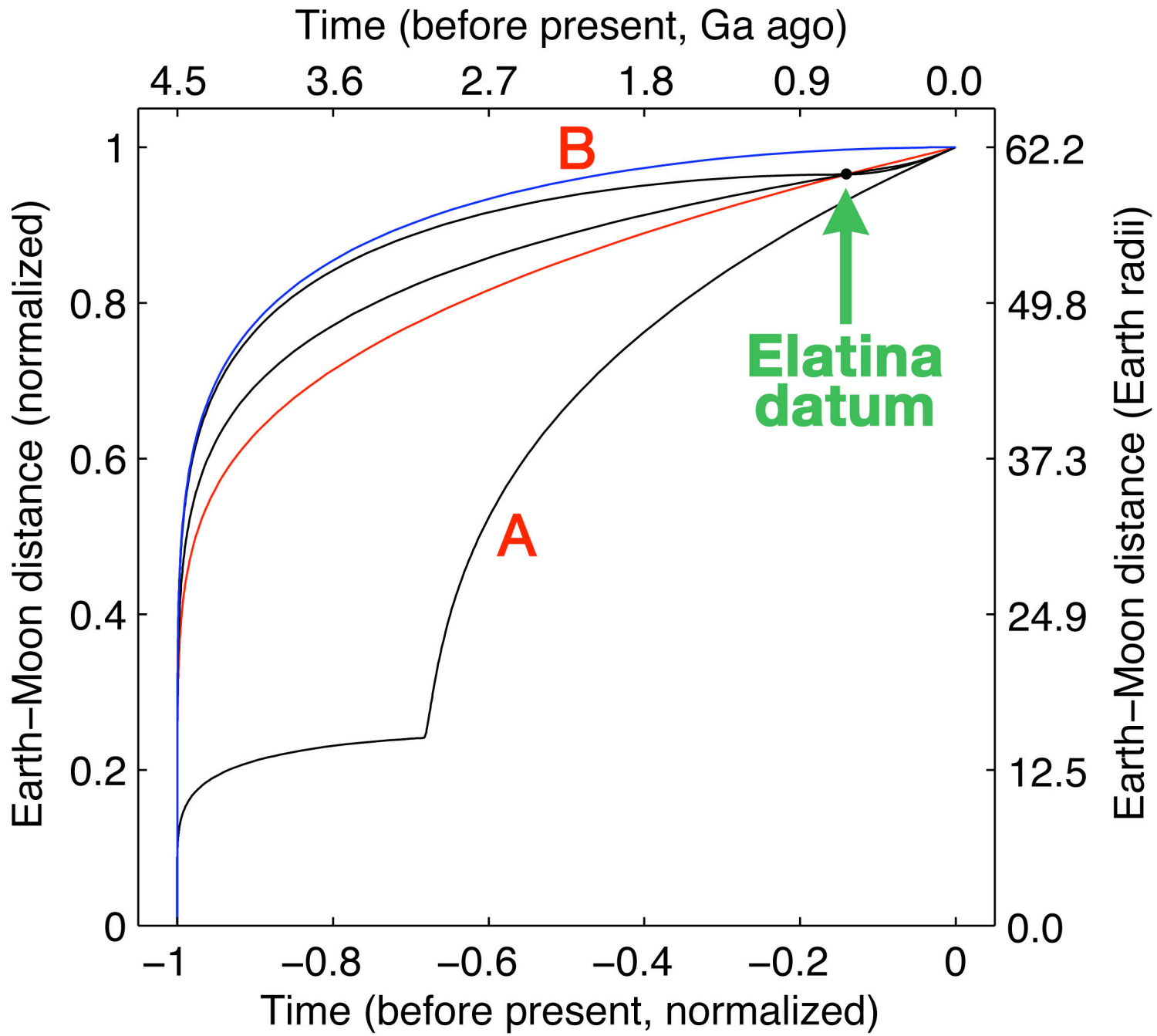


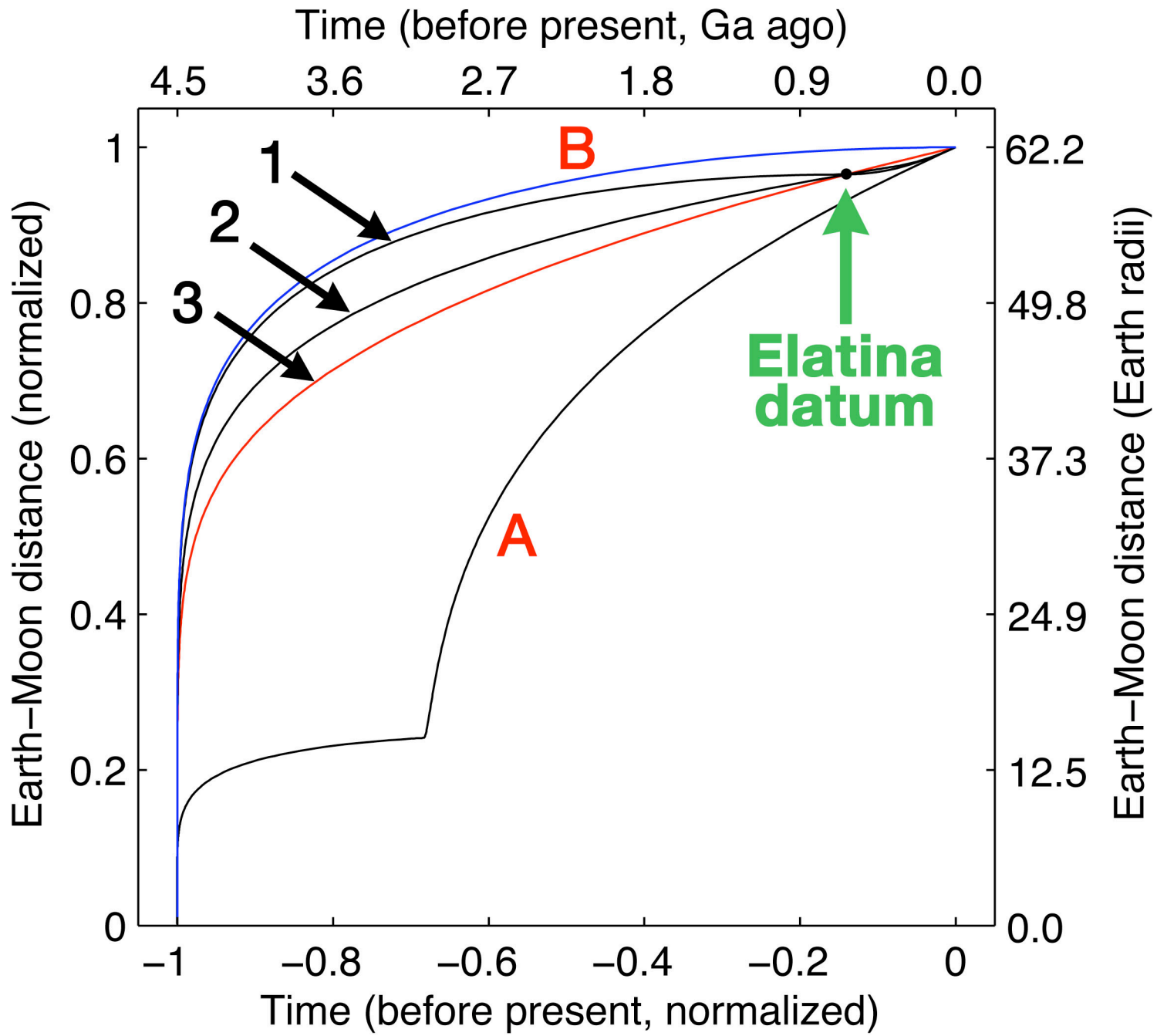
Manifold of Possibilities



Piecewise Model

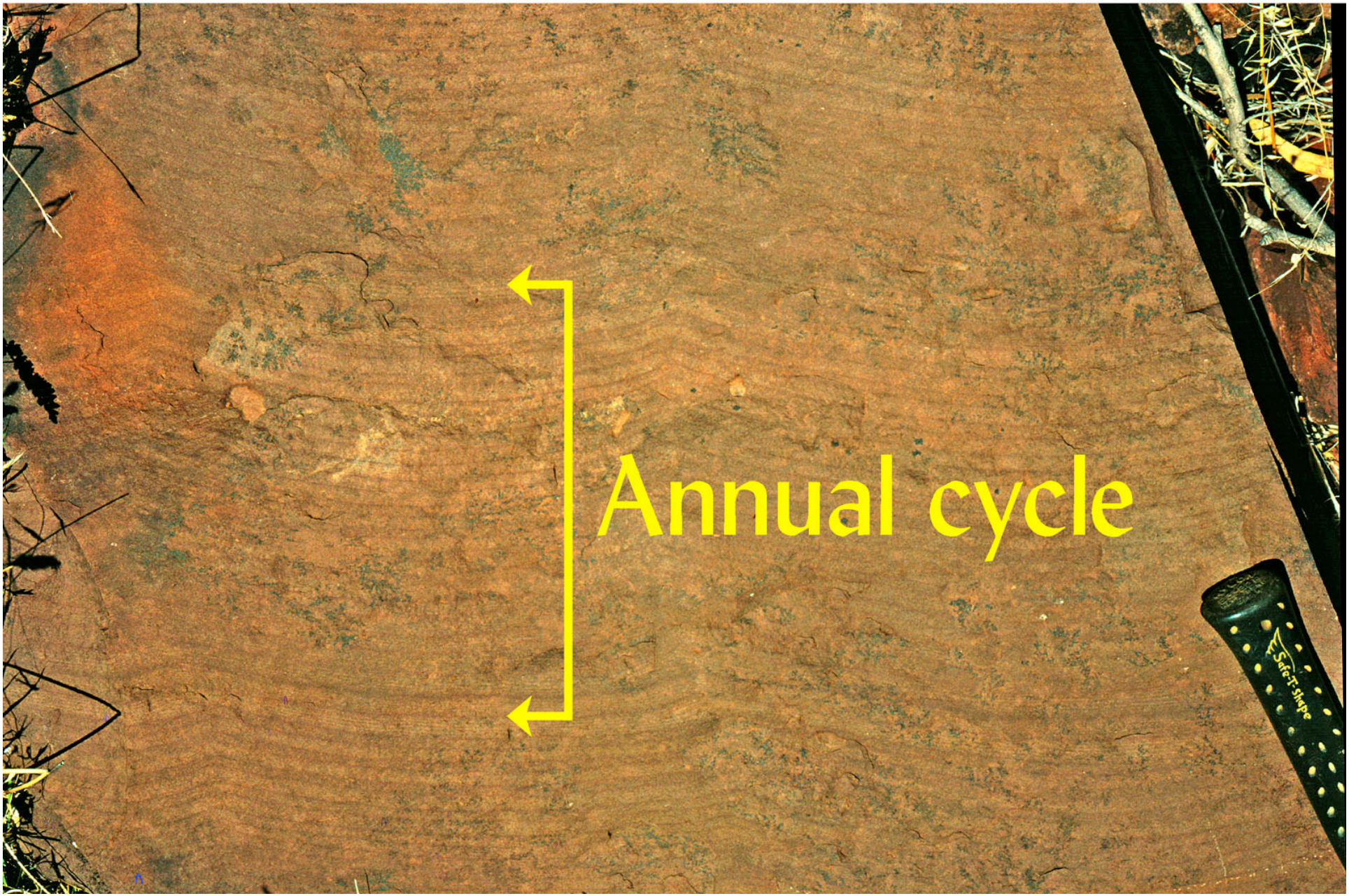



Time (before present, Ga ago)
4.5
3.6
2.7
1.8
0.9
0.0
B
A
Elatina
datum
Earth–Moon distance (normalized)
1
0.8
0.6
0.4
0.2
0
Earth–Moon distance (Earth radii)
62.2
49.8
37.3
24.9
12.5
0.0
–1
–0.8
–0.6
–0.4
–0.2
0
Time (before present, normalized)


Time (before present, Ga ago)
4.5
3.6
2.7
1.8
0.9
0.0
1
0.8
0.6
0.4
0.2
0
Earth–Moon distance (normalized)
62.2
49.8
37.3
24.9
12.5
0.0
Earth–Moon distance (Earth radii)
1
2
3
B
A
Elatina
datum
–1
–0.8
–0.6
–0.4
–0.2
0
Time (before present, normalized)

Part 2: Observations

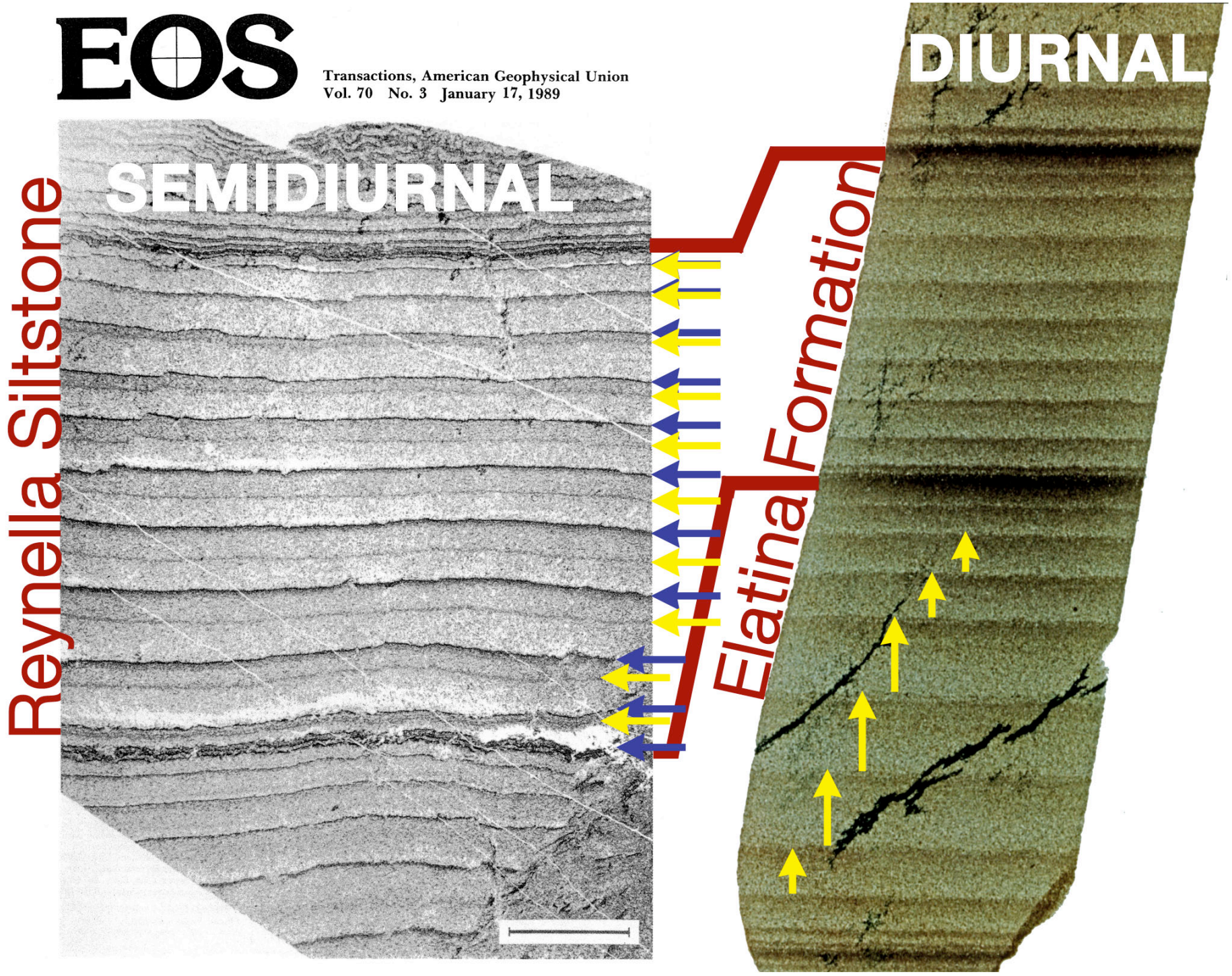
Elatina Tidalites, Pichi Richi, SA



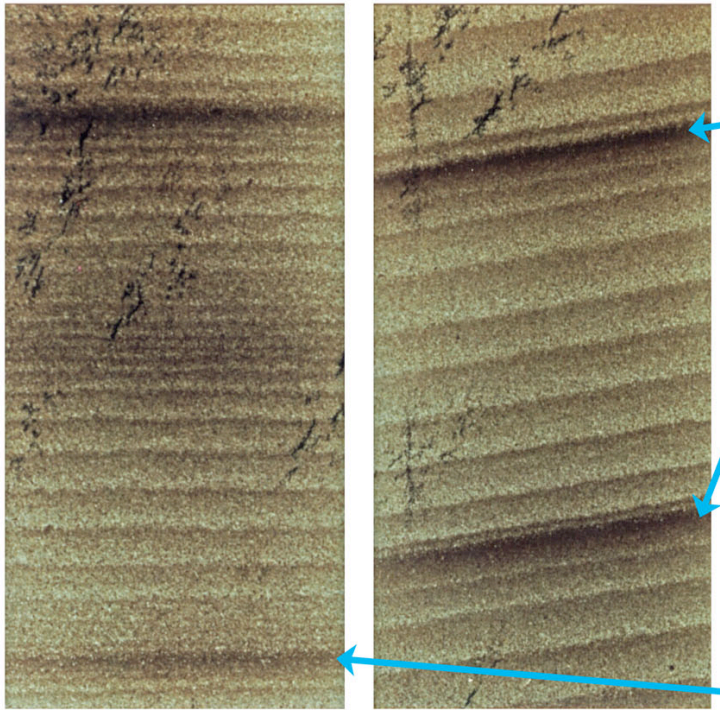
Elatina Datum (G.E. Williams, USA)

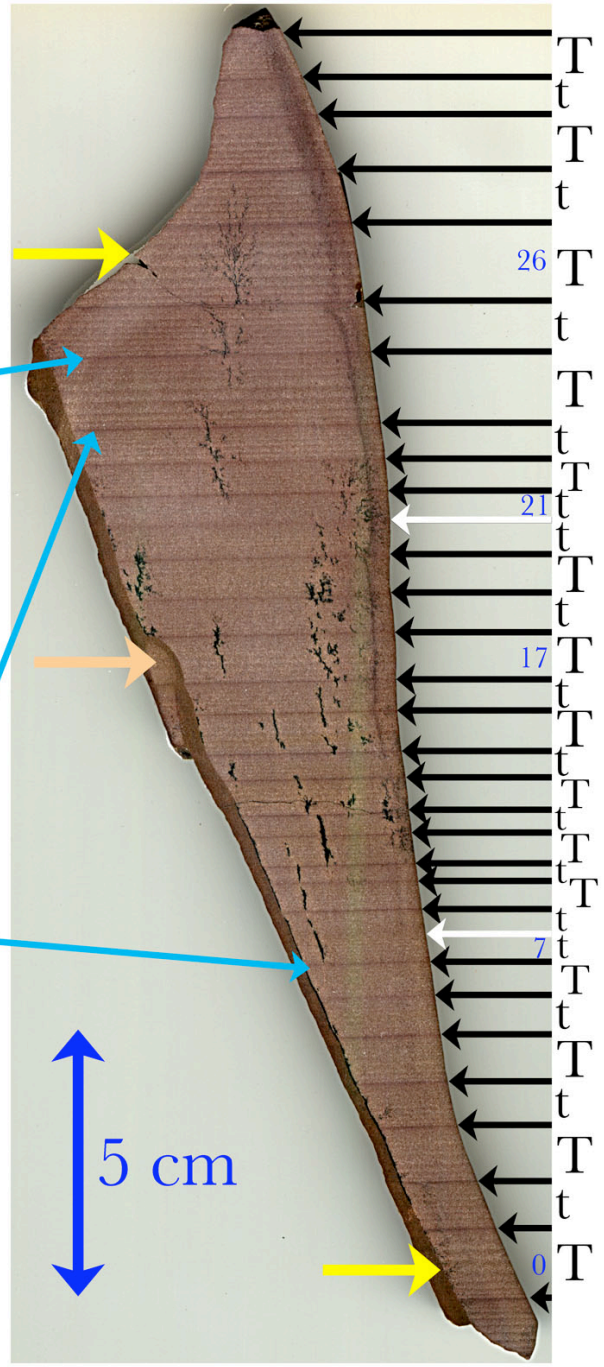
1. The 635 Myr-old **Elatina rhythmites**, South Australia, were originally considered to be **annual varves** recording the **solar cycle**.
2. George Williams subsequently disproved his own hypothesis by showing that the rhythmites are really **diurnal tidal laminae**.
3. The **Reynella siltstone**, ~300 km to the south, layers attributable to **semidiurnal tides**), but only in short sequences.
4. The absence of evidence for **semidurnal tides** in the Elatina rhythmites seems at odds with the idea that the **lamina sets** represent the **synodic lunar cycle**.

EOS
Transactions, American Geophysical Union
Vol. 70 No. 3 January 17, 1989

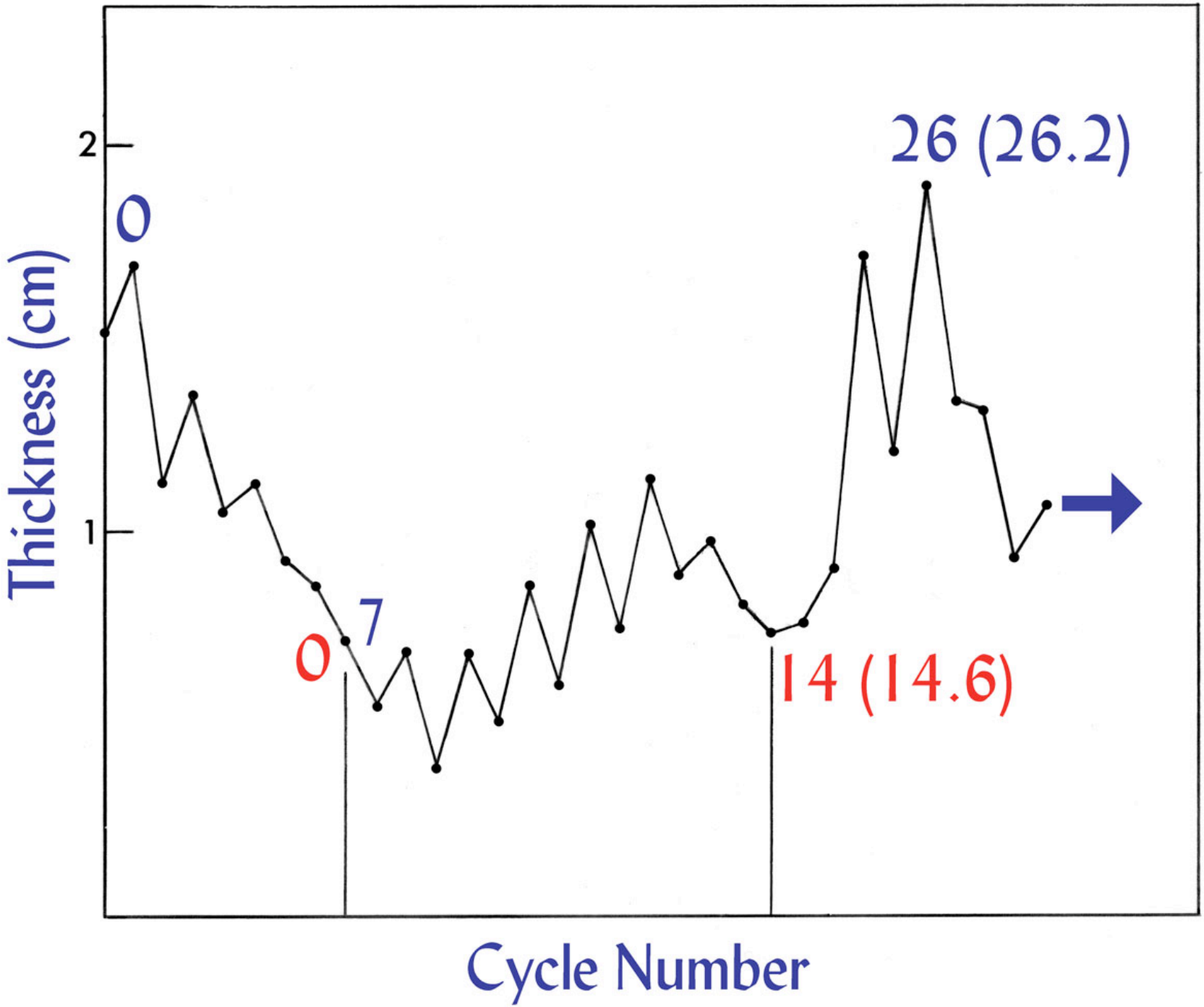


Random sample of Elatina tidalites, collected in 1986, showing one complete year of fortnightly lamina cycles

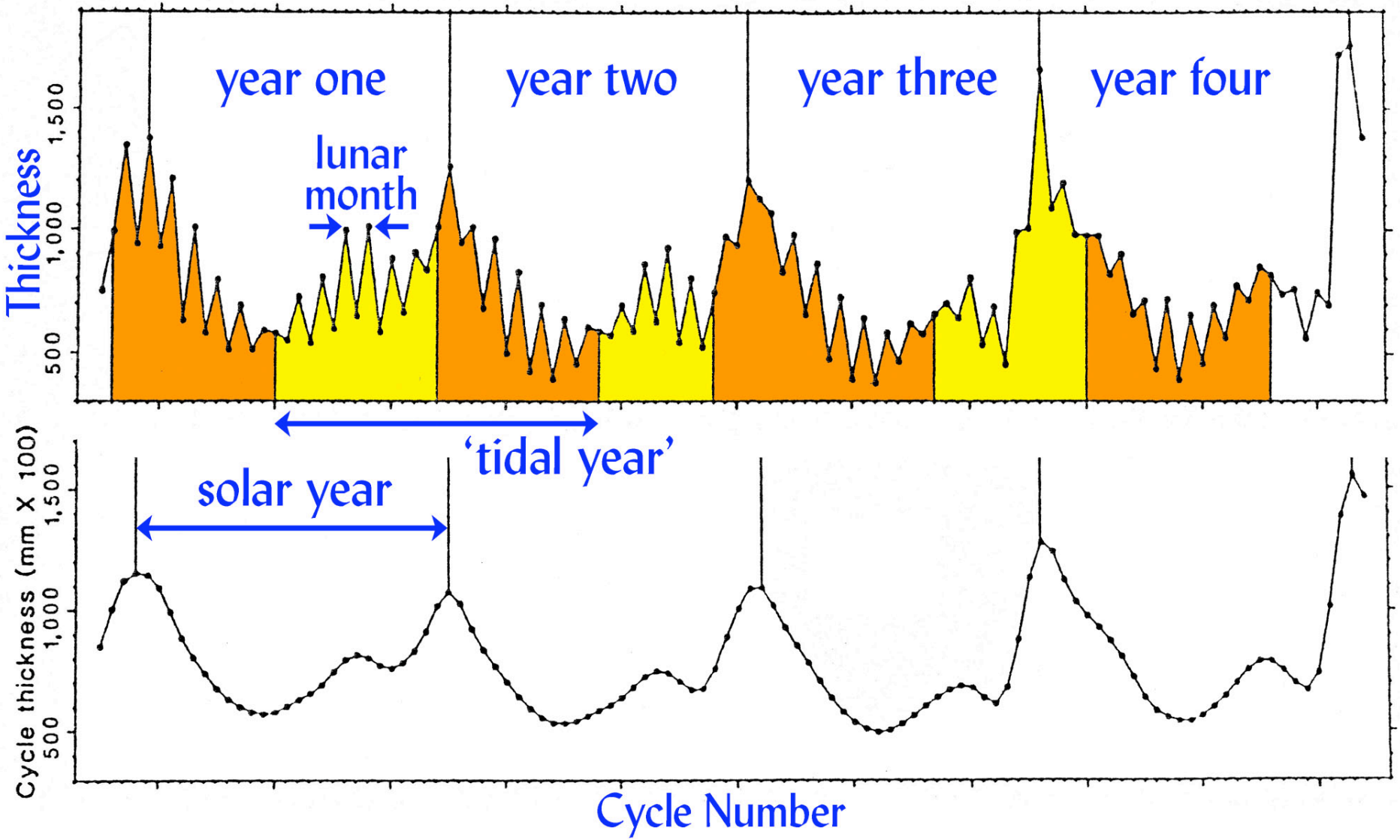




T = Thick, t = thin


Thickness (cm)
2
1
0
7
14 (14.6)
26 (26.2)
Cycle Number

Four Elatina cycles in the Elatina rhythmites after Williams & Sonett, *Nature* (1985)



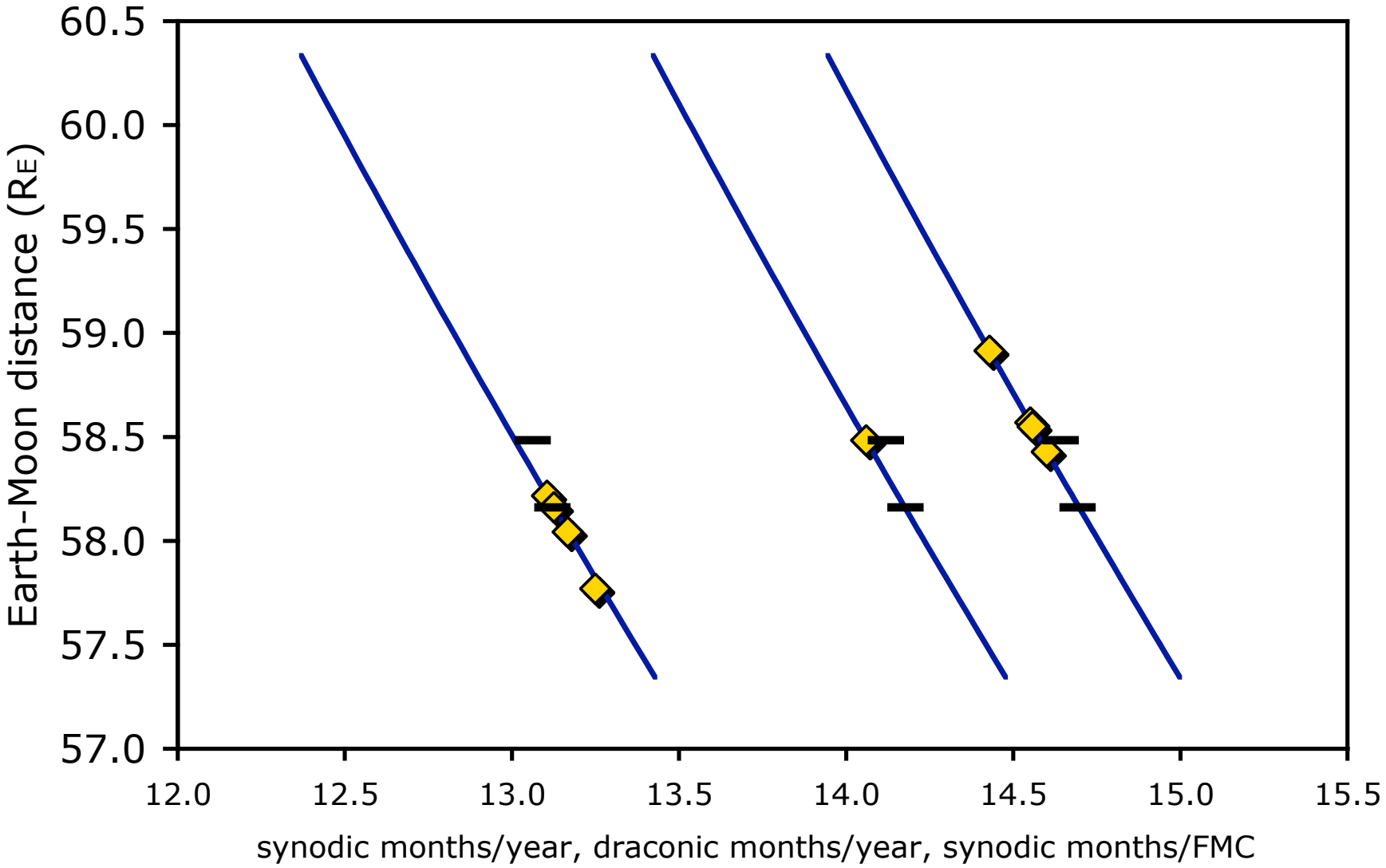
Evidence from Lamina Sets (1)

1. The **Elatina cycle**, which peaks after **~26.4** sets, has been assumed to be an **annual, non-tidal event**, perhaps due to SSTs.
2. If this is true, there are too few months/year for them to be anything except **synodic**.
3. As there is one more sidereal month than synodic month in any year, there were **(26.4/2) + 1 = 14.2 sidereal months** in the Cryogenian year.
4. Using Kepler's third law, the ratio of 14.2 synodic months (then) to 13.4 months (now) gives an Earth-Moon distance (then) of **57.9 ± 2 R_E**.

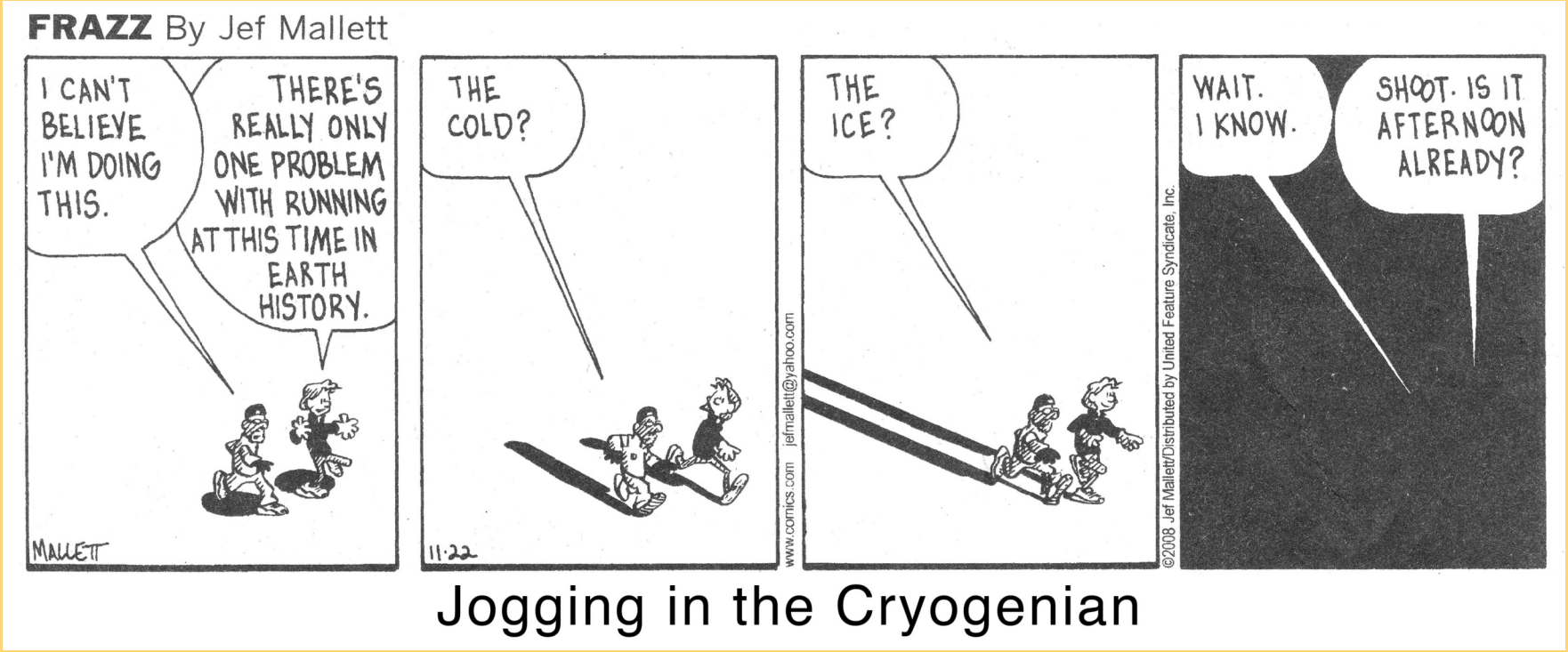
Evidence from Lamina Sets (2)

1. An **independent test** of this hypothesis is provided by the **phase reversals**.
2. The reversals, which occur, on average, every **14.6 sets**, must represent the beat between **anomalistic** and **synodic** months.
3. Today, this period is known as the **Full Moon Cycle** (~412 days).
4. By assuming that the ratio of **sidereal to synodic months** was ~1.07, versus 1.08 at present, it is possible to use Kepler's third law to estimate the Cryogenian Earth-Moon distance at **58.0 ± 2 R_E**.

Three independent estimates of R_E

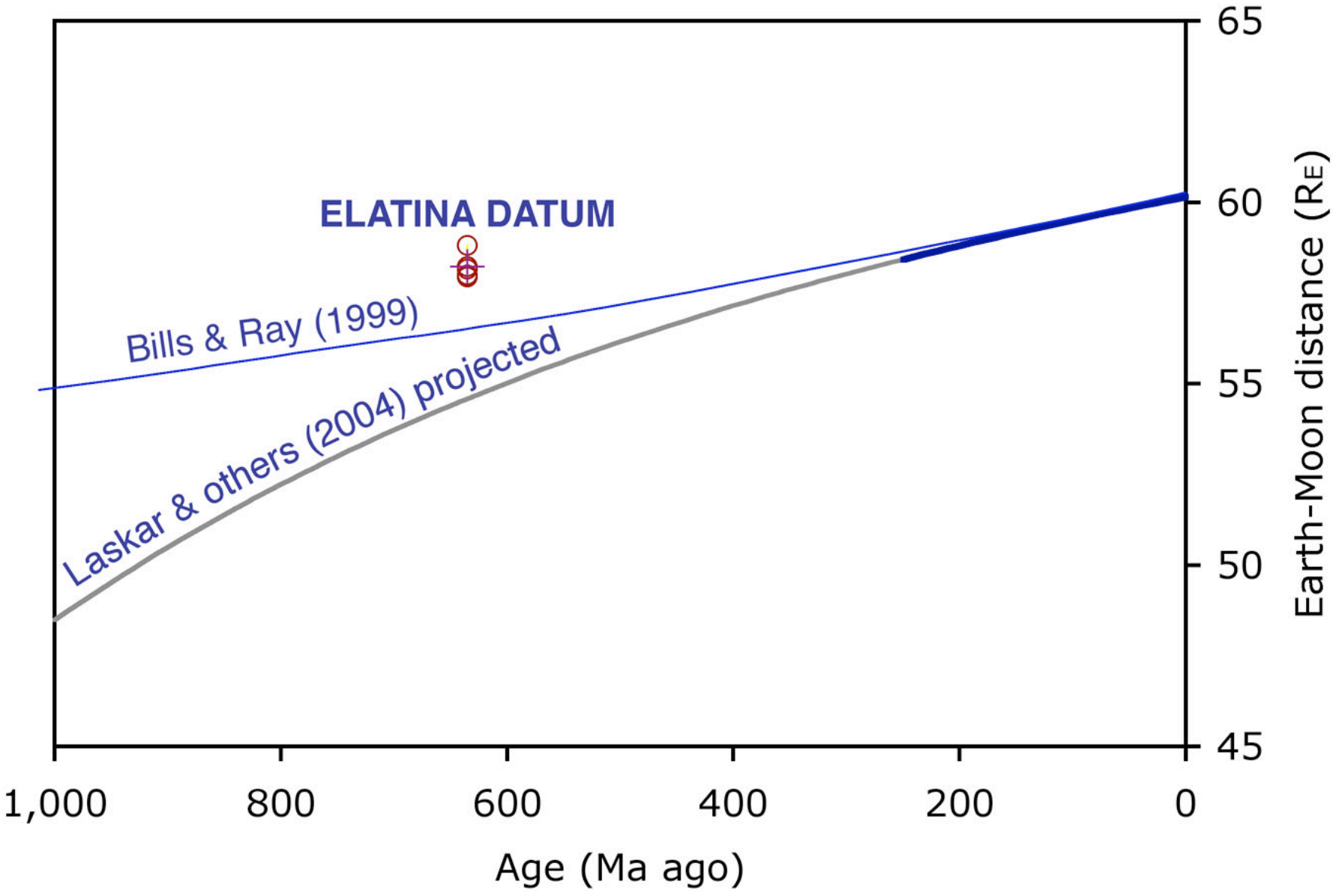


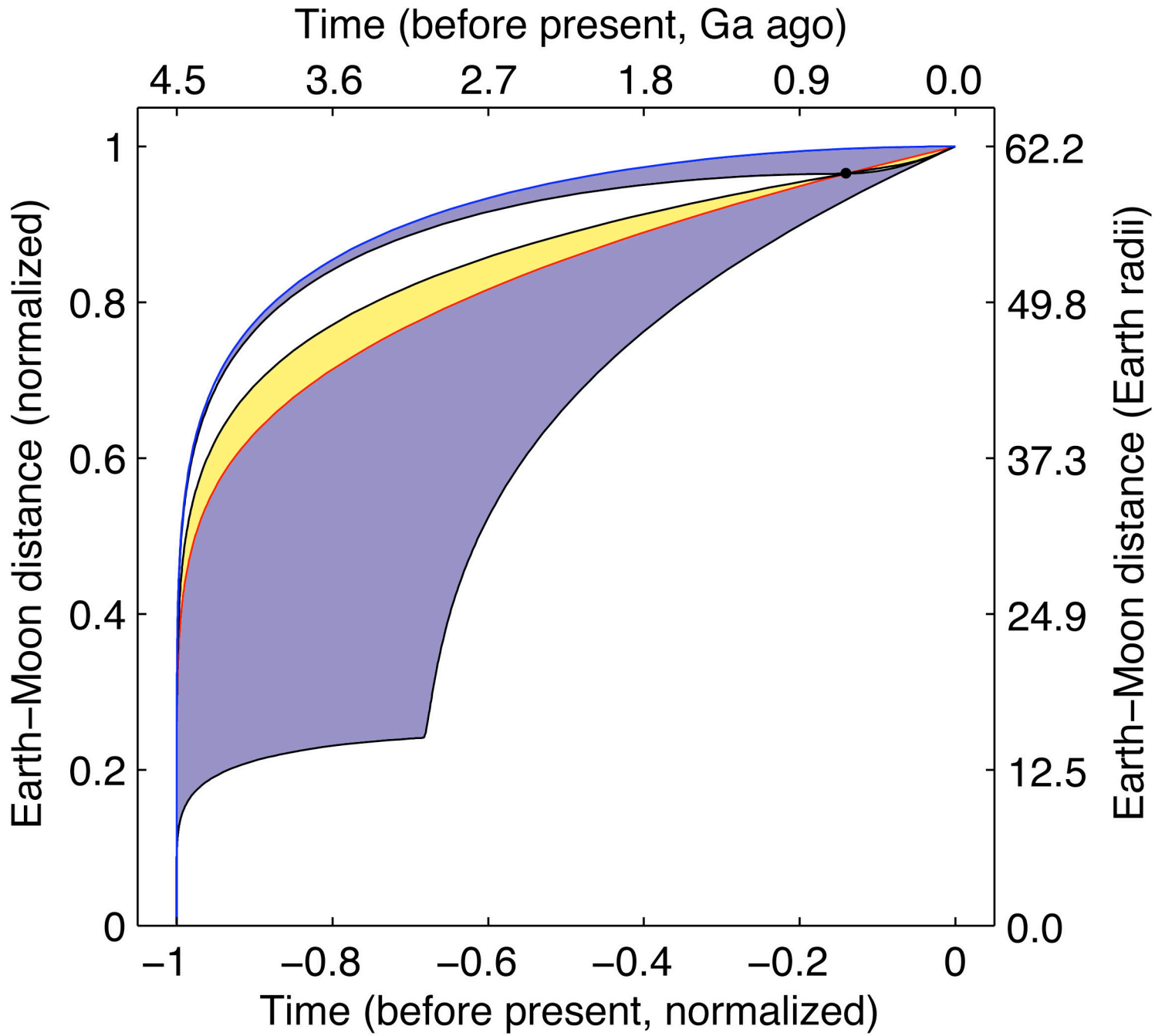
Part 3: Orbital Evolution



Jogging in the Cryogenian

Elatina Datum is confirmed




Time (before present, Ga ago)
4.5
3.6
2.7
1.8
0.9
0.0
Earth–Moon distance (normalized)
1
0.8
0.6
0.4
0.2
0
Earth–Moon distance (Earth radii)
62.2
49.8
37.3
24.9
12.5
0.0
–1
–0.8
–0.6
–0.4
–0.2
0
Time (before present, normalized)

Conclusions

1. The end-Cryogenian Earth-Moon distance is estimated to be **58 ± 2 R_E**.
2. This corresponds to a year of **403 days**.
3. George Williams' careful investigations of the Elatina rhythmites are **confirmed and strengthened** by this analysis.
4. The **Elatina datum** restricts most possible scenarios for the evolution of the lunar orbit.
5. Another equivalent data point in **deep time** (> 2.5 Ga ago) is the next obvious goal.
6. Banded iron formations (**BIFs**) may be the best bet.

Bottom Line

1. George Williams (2000) claimed **three independent estimates** of R_E:
2. The lunar nodal period (19.5 ± 0.5),
3. The number of sidereal months per year (14.1 ± 0.1),
4. And the number of sidereal days per year (401 ± 7).
5. All depend upon the assumption that the **Elatina cycle peaks are annual**.
6. Our work tests and confirms this assumption.