The Geological Orrery:
Mapping the Chaotic History of the Solar System using Earth's Geological Record

Scott Kelly / NASA

Paul E. Olsen

SIAM: DS, MS162
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The Newark Basin Coring Project team

The Colorado Plateau Coring Project team

NSF, ICDP, Lamont Climate Center

A Philosopher Lecturing on the Orrery

Wright of Derby: 1765

The late 20th century *Digital Orrery*

A piece of the *Geological Orrery*

Problem:
To what degree is the Solar System Stable?

Numerical solutions for Solar System gravitational behavior are chaotic limiting their usefulness for predicting the long-term behavior of the Solar System and our ability to test physical theories and develop paleoclimate models.

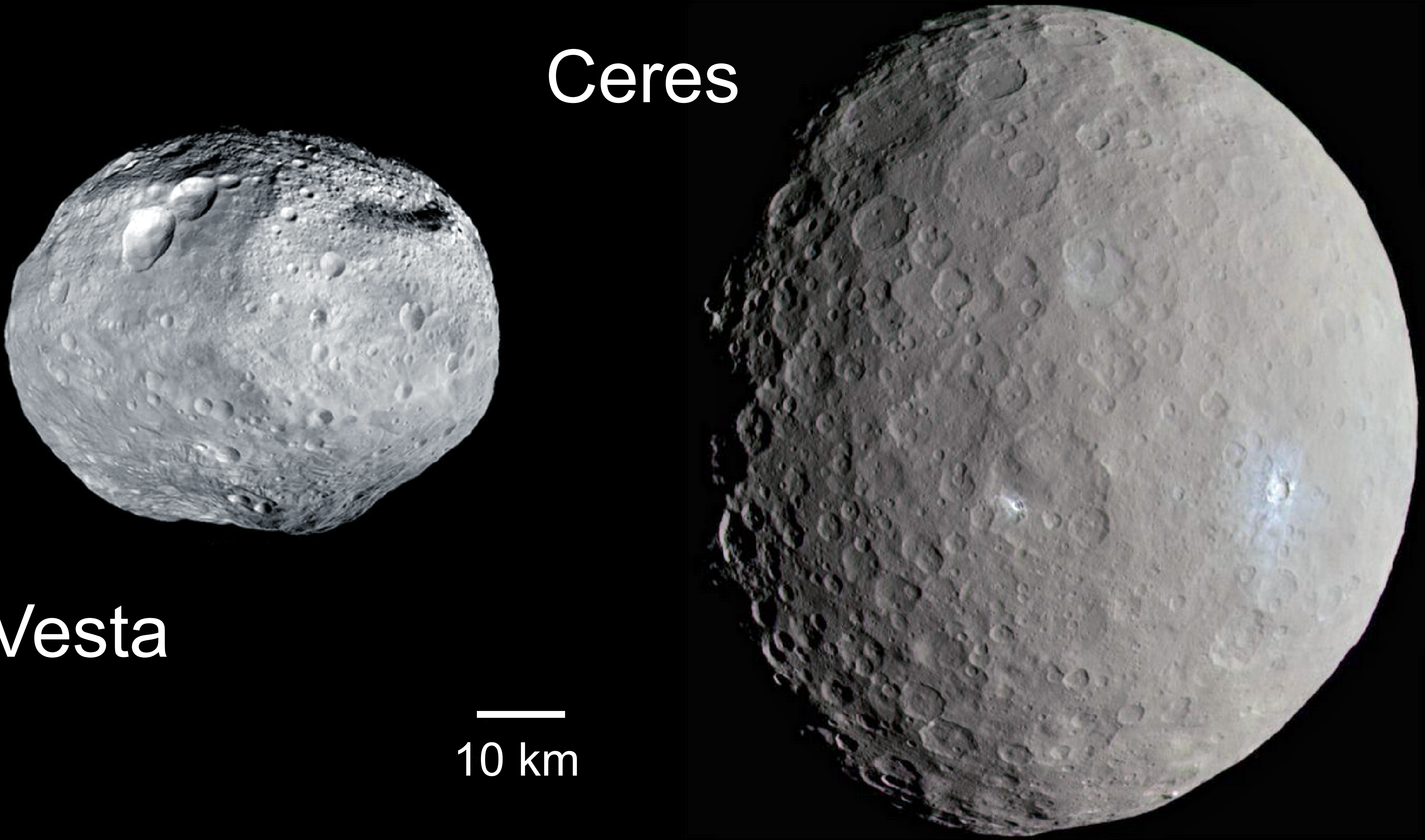
Solar System Solutions

Lyapunov time (1/exponent)

Inner planets: 1-5 Million years

Inner Solar System : 5 Million years

Initial errors expand at $d(T) \approx d_0 10^{T/10}$


Ceres
Vesta
10 km

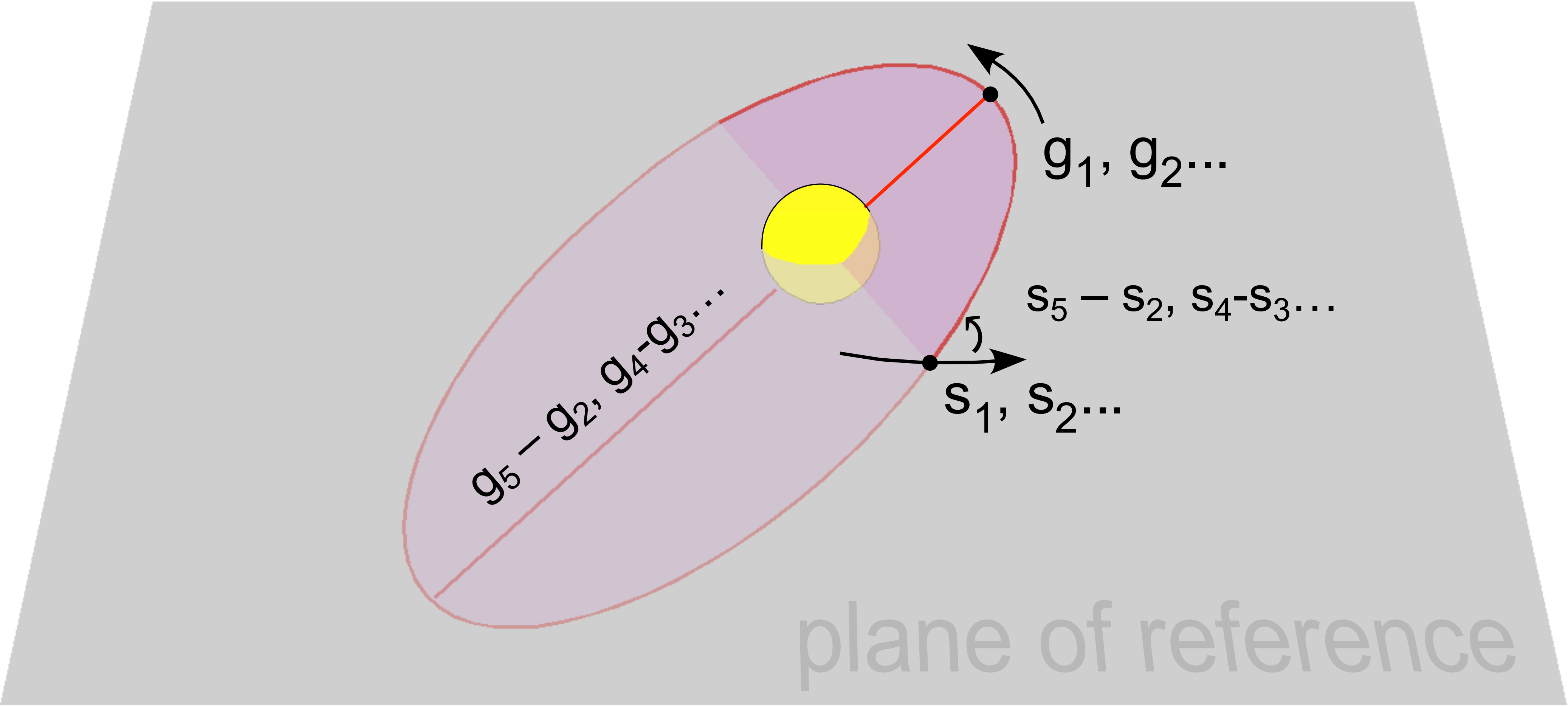
Main Sources of Uncertainty in the Orbital Solution (from Laskar 1999, 2004)

Time of validity of the numerical solutions	T_{V}
Uncertainty on the masses and initial conditions	38 m.y.
Contribution of the main Galilean satellites	35 m.y.
Uncertainty in the Earth–Moon system evolution	40 m.y.
Effect of the main asteroids	32 m.y.
Mass loss of the Sun	50 m.y.
Uncertainty of 2 x 10^{-7} on the J_2 of the Sun	26 m.y.
g_4-g_3 resonance	30 m.y.

Earth's orbital eccentricity is not actually a direct orbital element determined in solutions or in quantitative descriptions of planetary motion.

Instead the orbital elements are described as secular fundamental frequencies termed g_1, g_2 …; $s_{1,}$ s_2 … linear differences of which in the form of $g_i – g_j$ give us the frequencies of eccentricity (and inclination).

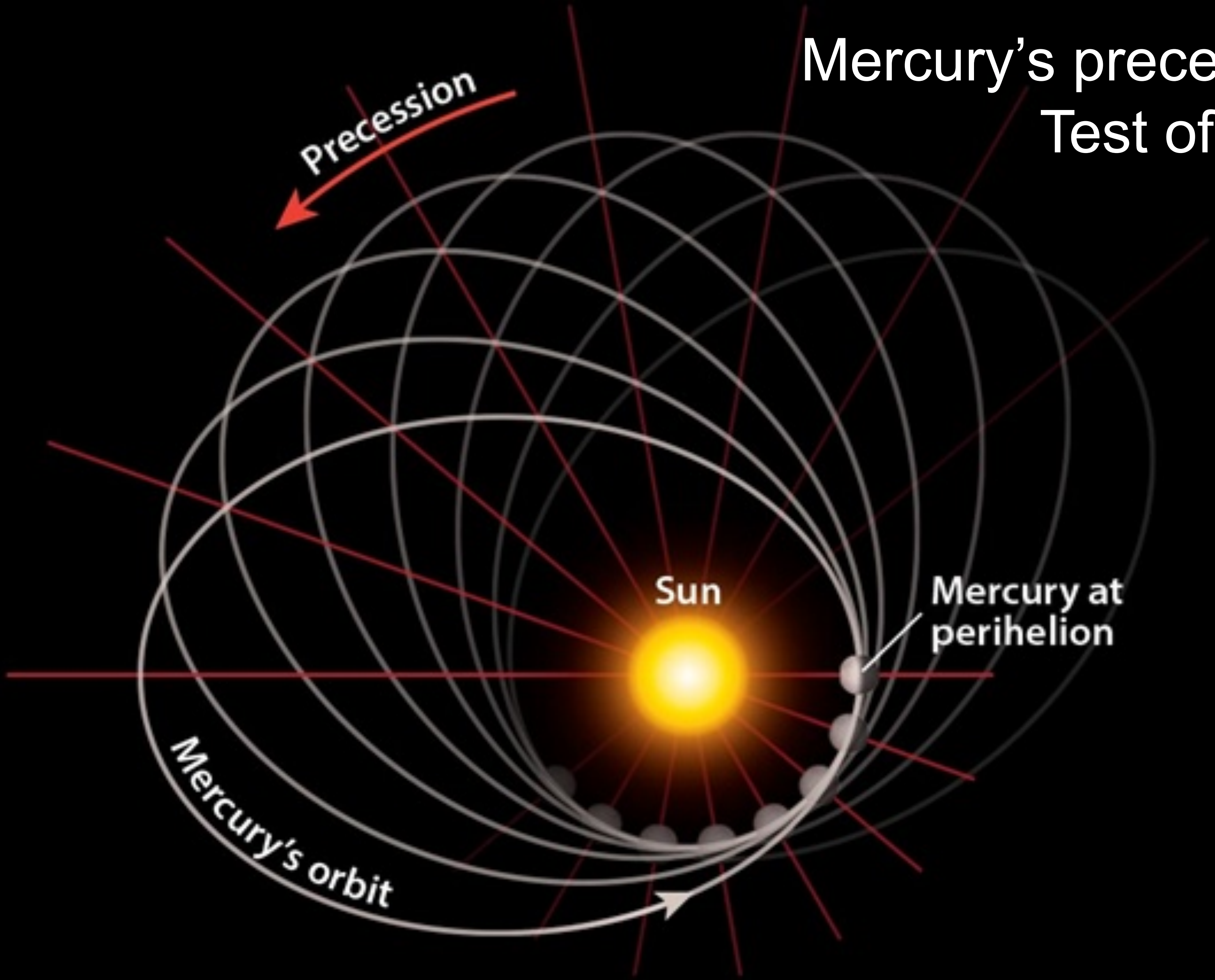
Secular Fundamental Frequencies



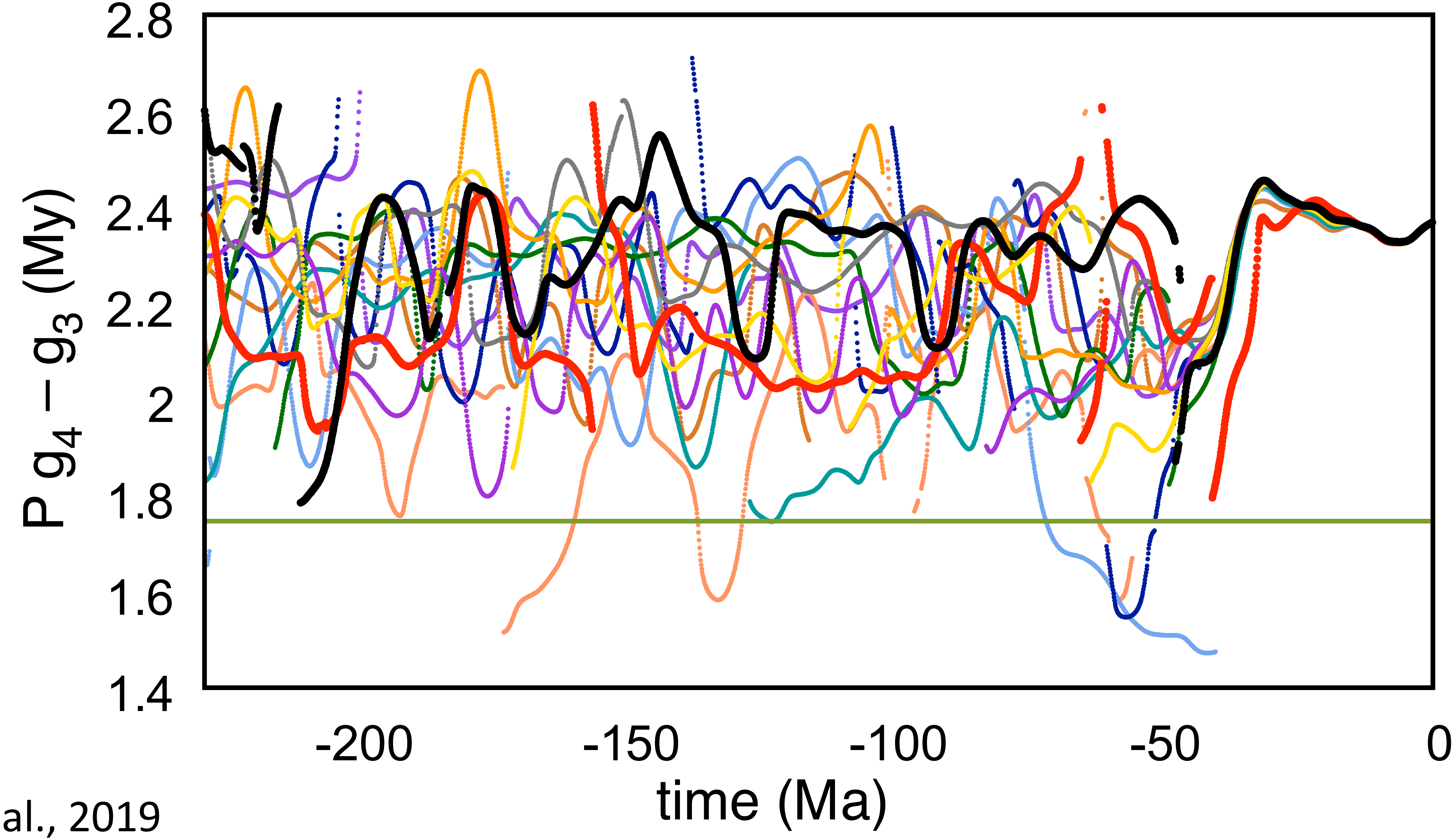
$g_5 - g_2, g_4 - g_3$… = grand eccentricity cycles (e.g., present 2.4 Myr cycle)

$s_5 - s_2, s_4 - s_3$… = grand obliquity cycles (e.g., present 1.2 Myr cycle)

Mercury’s precession of perihelion
Test of General Relativity



Nearly 2° / yr
43” deviation
From Newtonian



Olsen et al., 2019

But celestial mechanical interactions leave a record on the Earth in the sedimentary record of climate.

The sedimentary record can be used like an Orrery that can empirically map the long term behavior of the Solar System

Three Experiments Comprising the Geological Orrery Proof-of-Concept.

Experiment 1: Testing the prevalence of Milankovitch Cycles in the Triassic Tropics – The Newark Basin Coring Project (NBCP: 1989-1994).

Experiment 2

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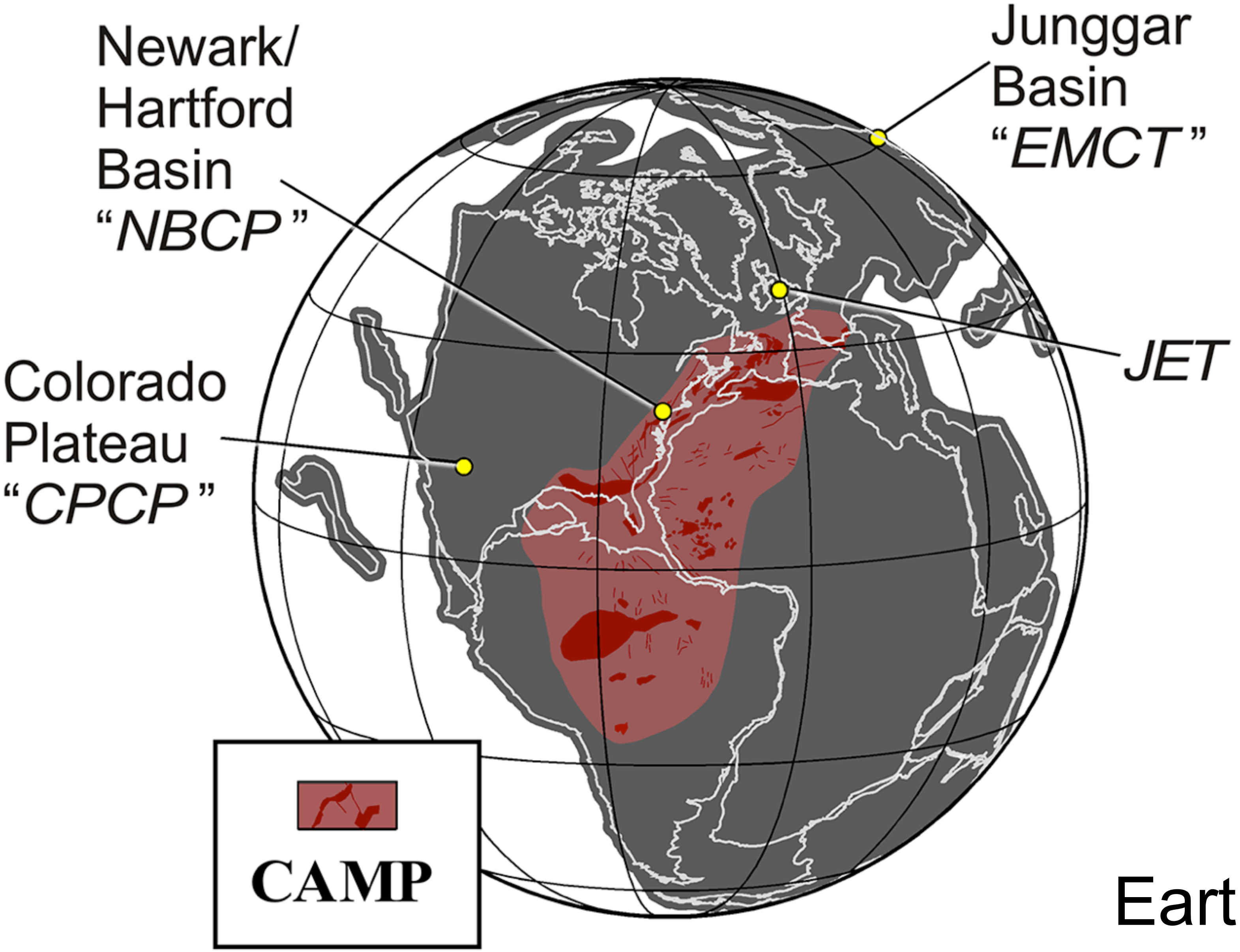
Experiment 3

Constraining mode of the Mars-Earth obliquity cycle in the low and high latitudes – The Early Mesozoic Climatic Transect (EMCT – 2020?).

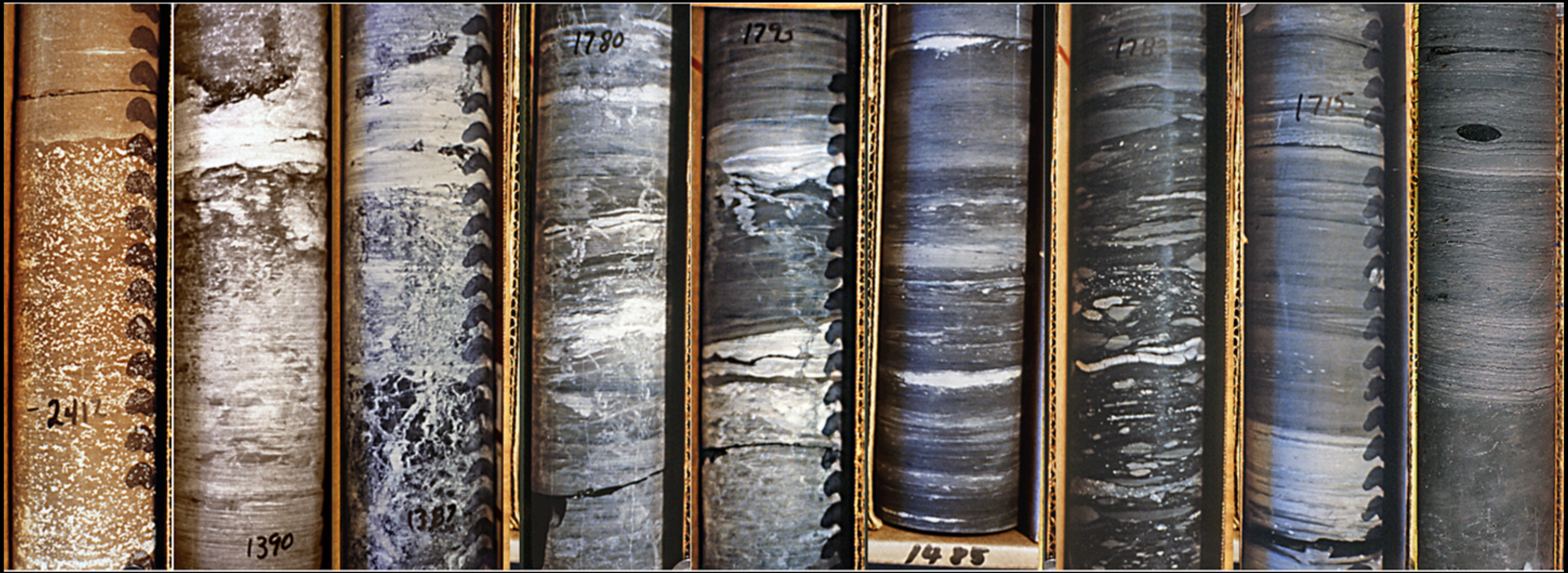

Newark/
Hartford
Basin
"*NBCP*"
Junggar
Basin
"*EMCT*"
Colorado
Plateau
"*CPCP*"
JET
CAMP

Earth @ 201.6

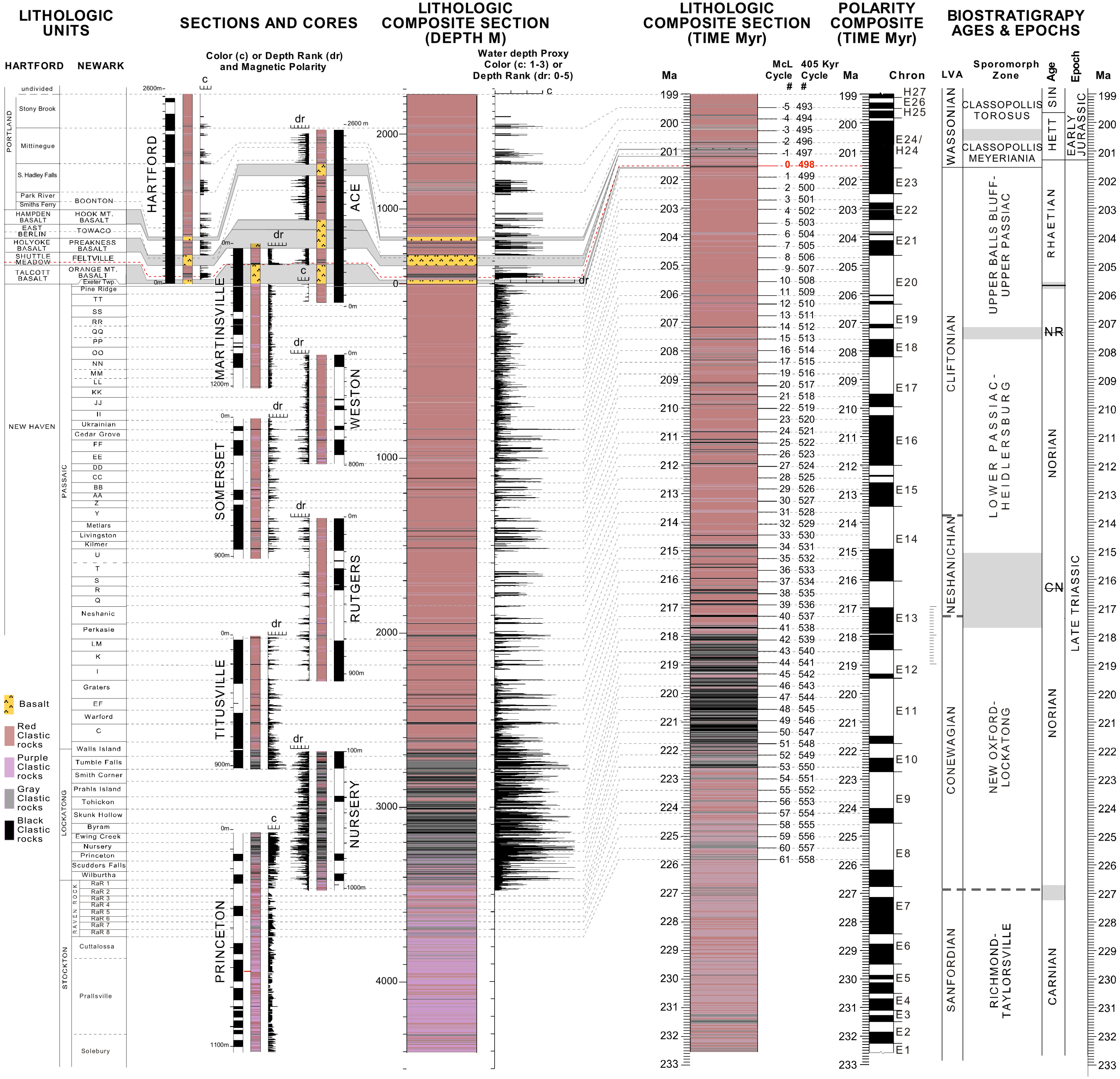
5° N: Lacustrine Cycles, Newark Basin

Late Triassic, Lockatong Formation, Eureka, PA

“Depth Rank” Proxy of Lake Depth



Examples of Facies in Cores

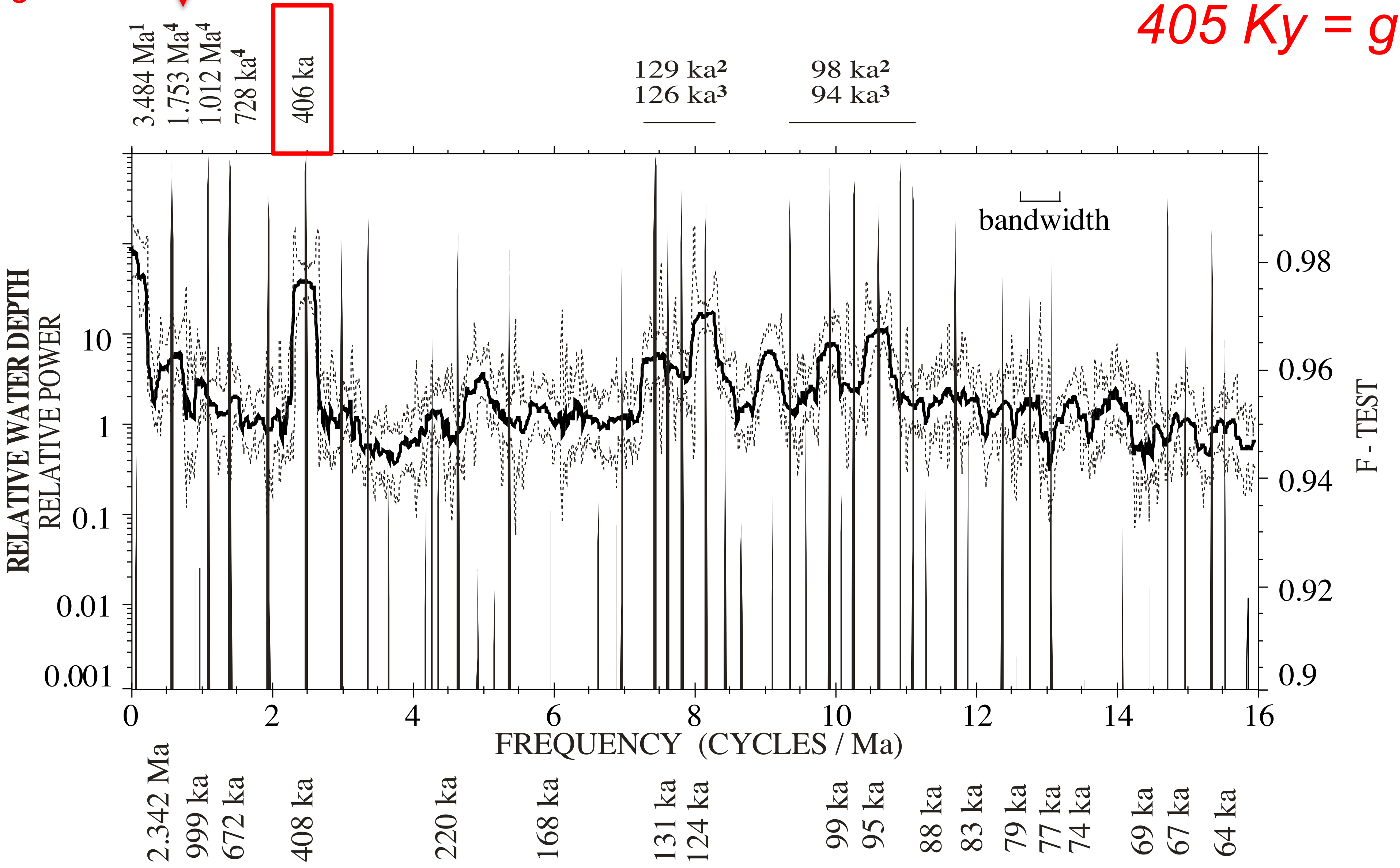


Kent et al. 2017

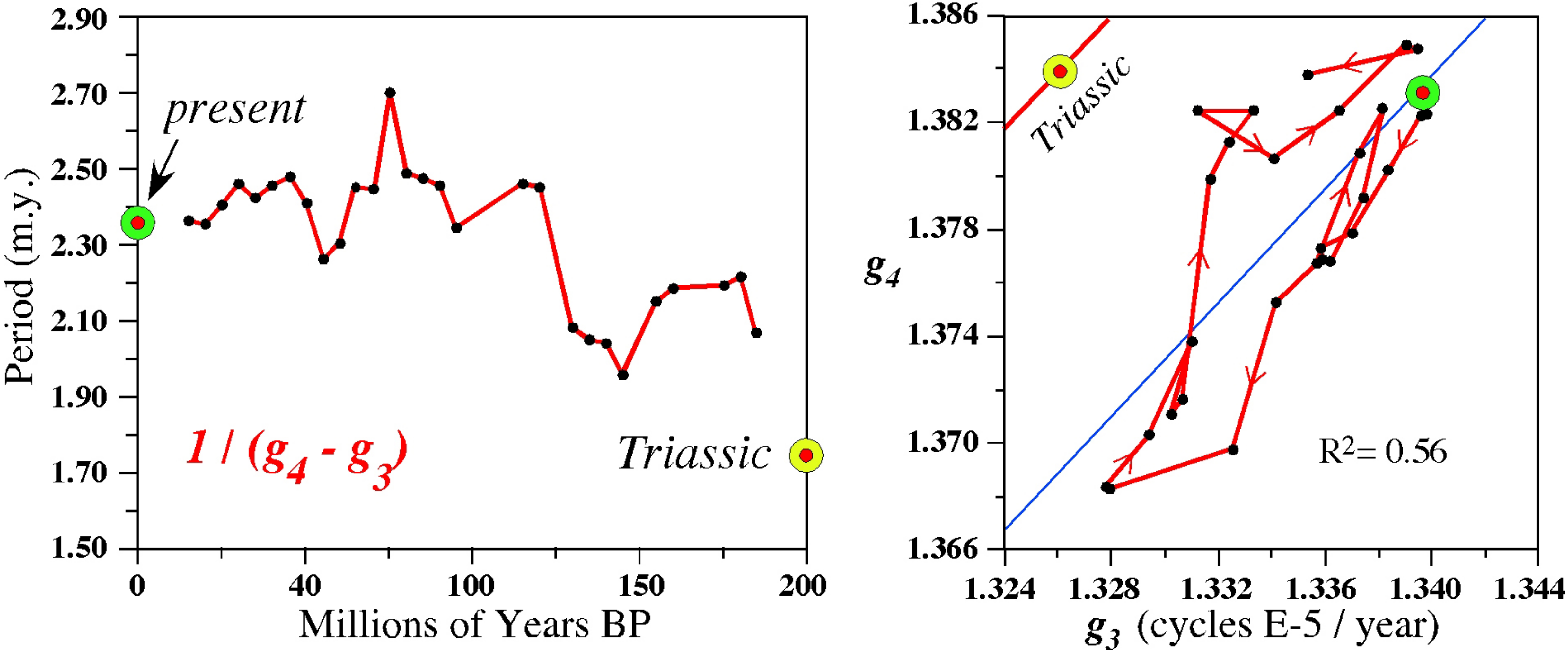
1.75 Myr
$g_4 - g_3$?

MTM Spectrum entire pre-basalt NBCP lacustrine record (22 Myr) (Olsen & Kent, 1999)

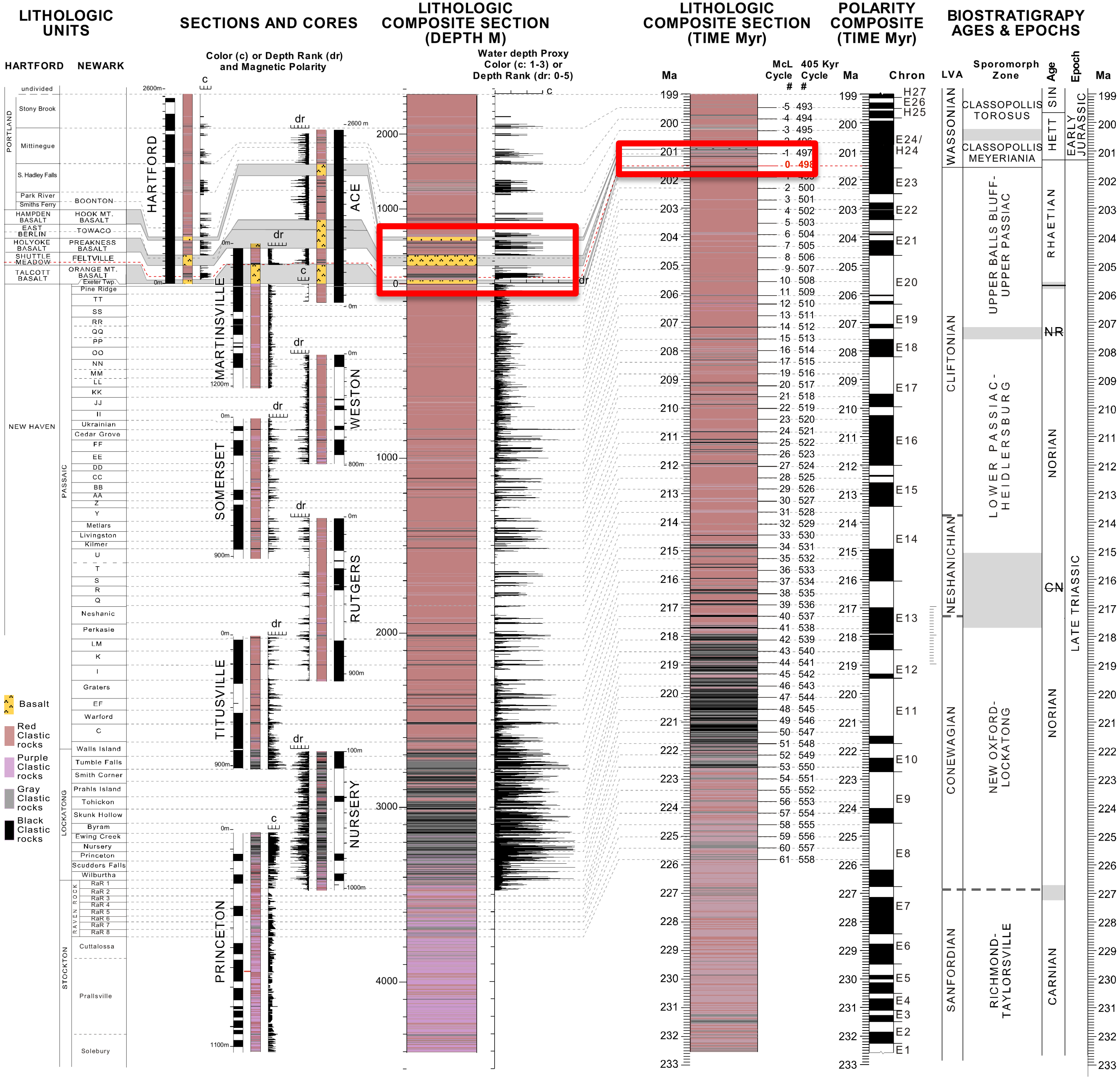
405 Ky = $g_2 - g_5$



Chaotic Diffusion of $g_4 - g_3$

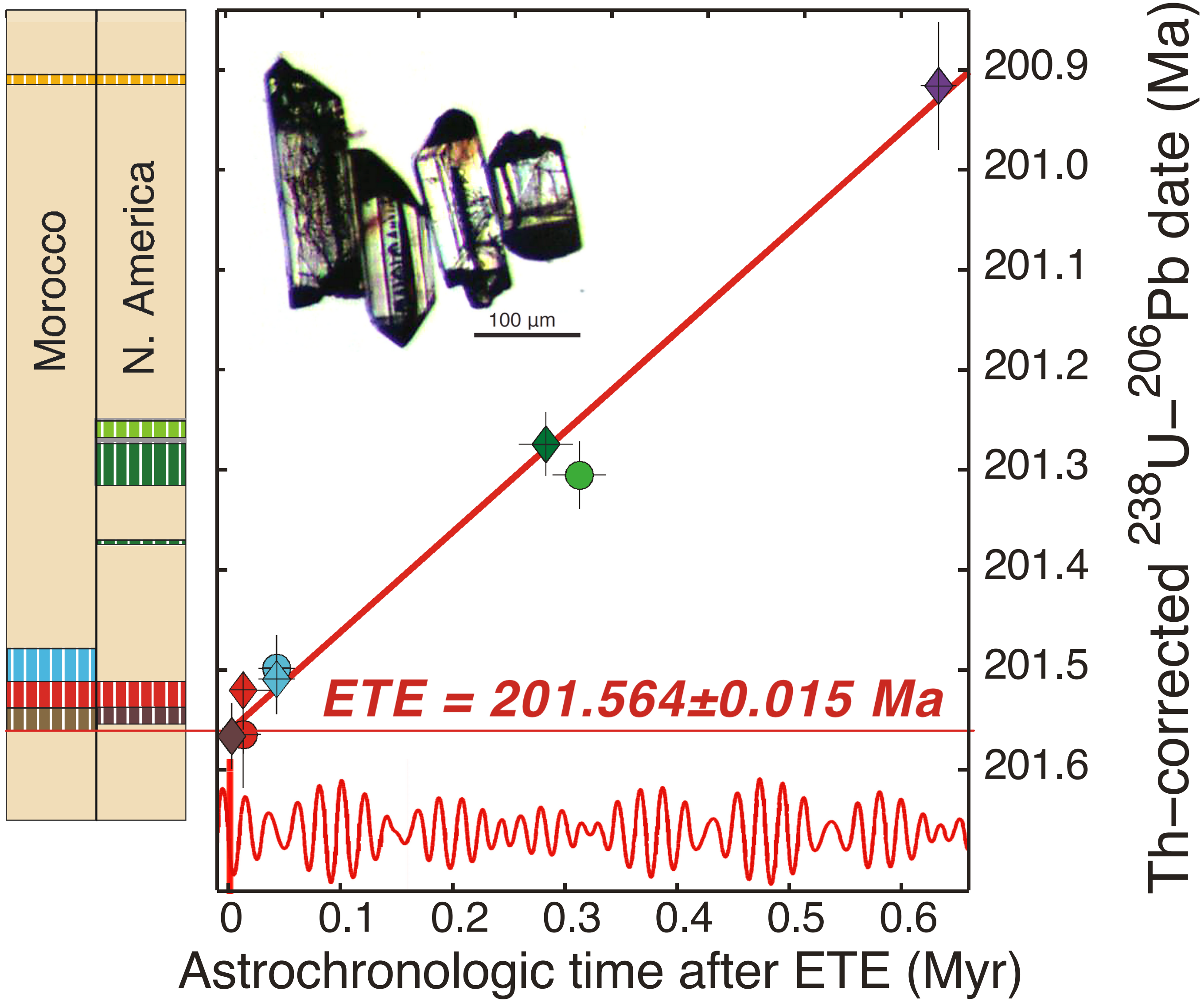


Data from Laskar, 1999

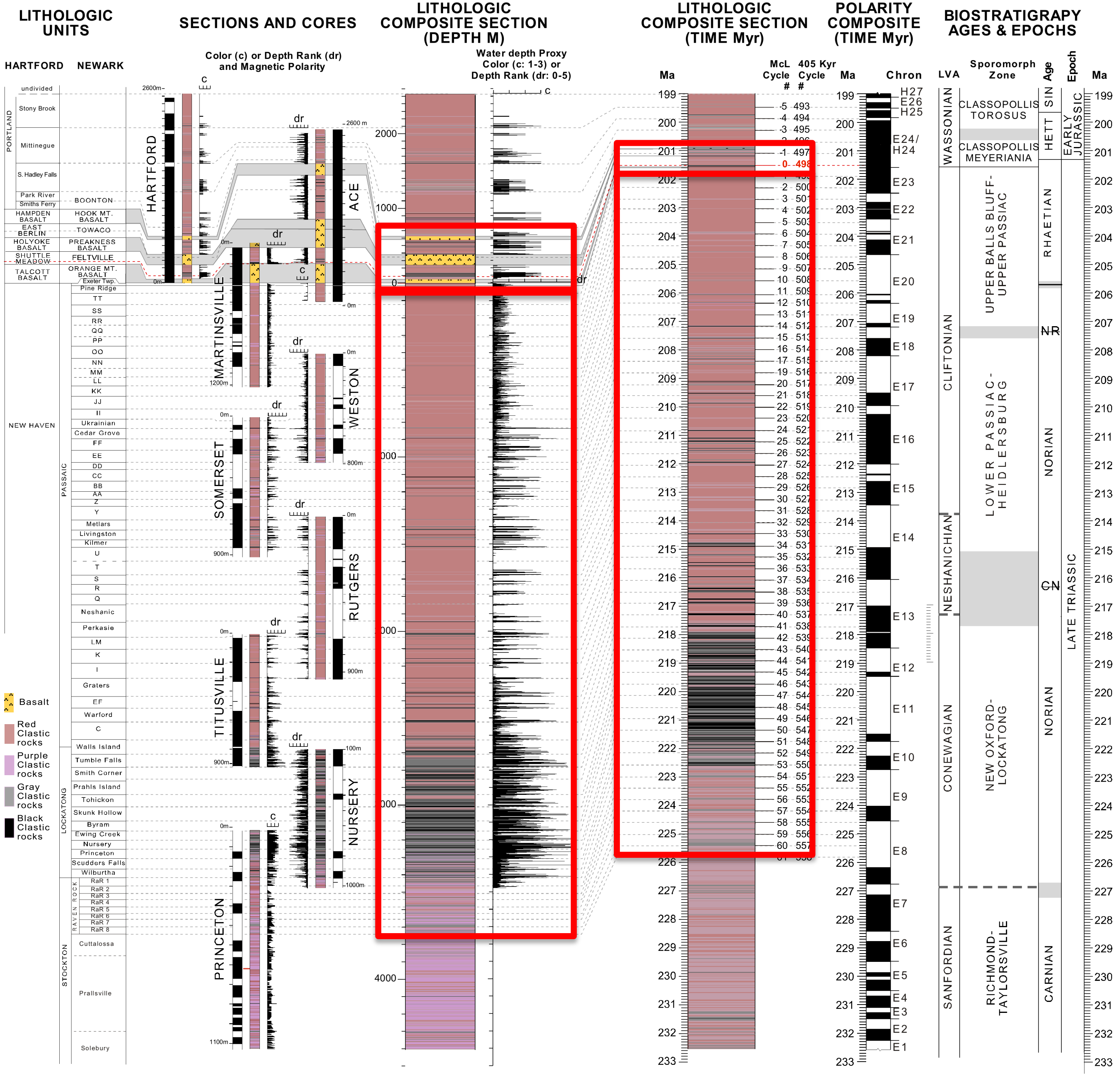


Kent et al. 2017

CAMP Lavas



Blackburn et al., 2013



Kent et al. 2017

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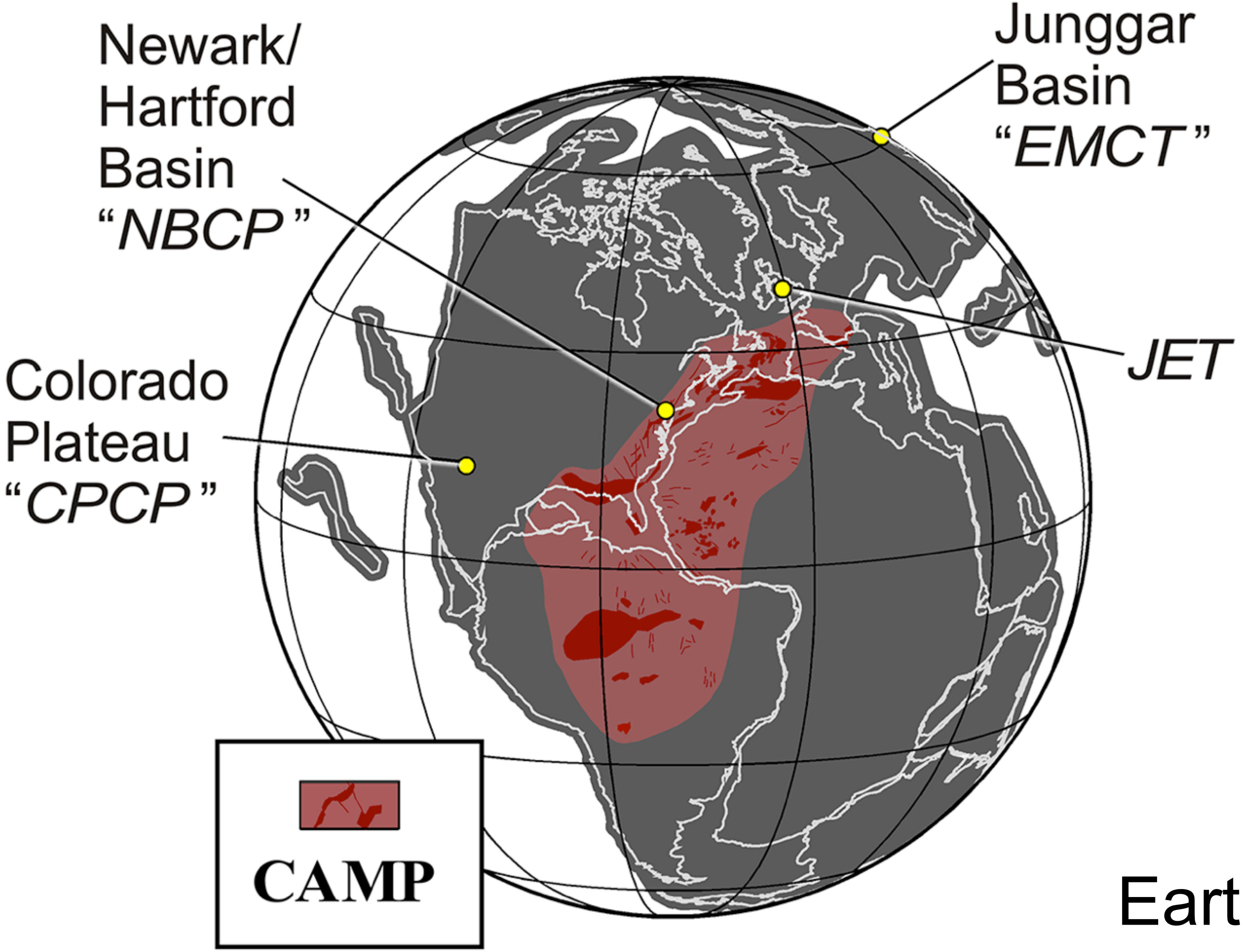
Newark/
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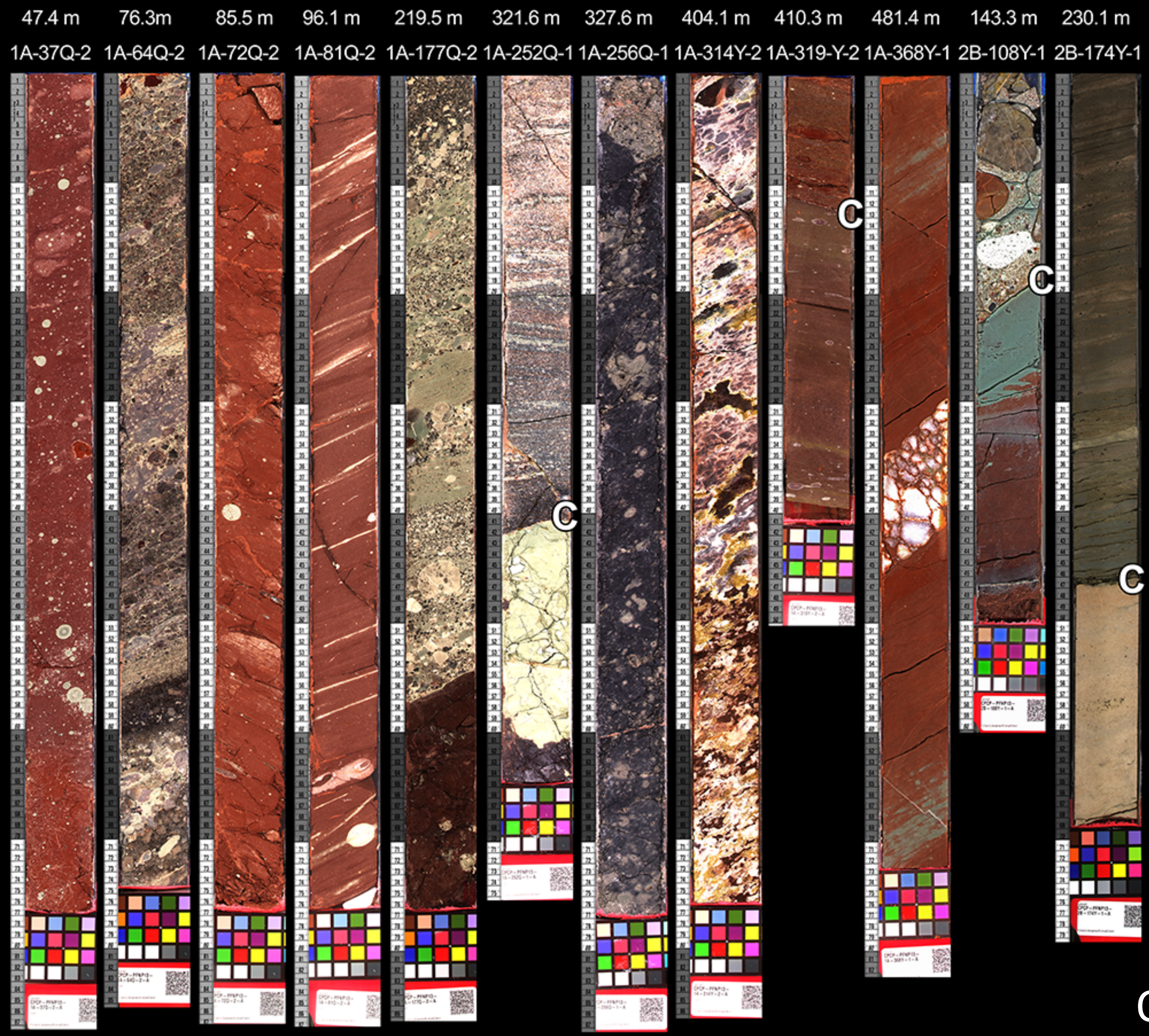
Earth @ 201.6

Chinle Formation – Petrified Forest National Park, AZ

CPCP : Phase I, Petrified Forest Core

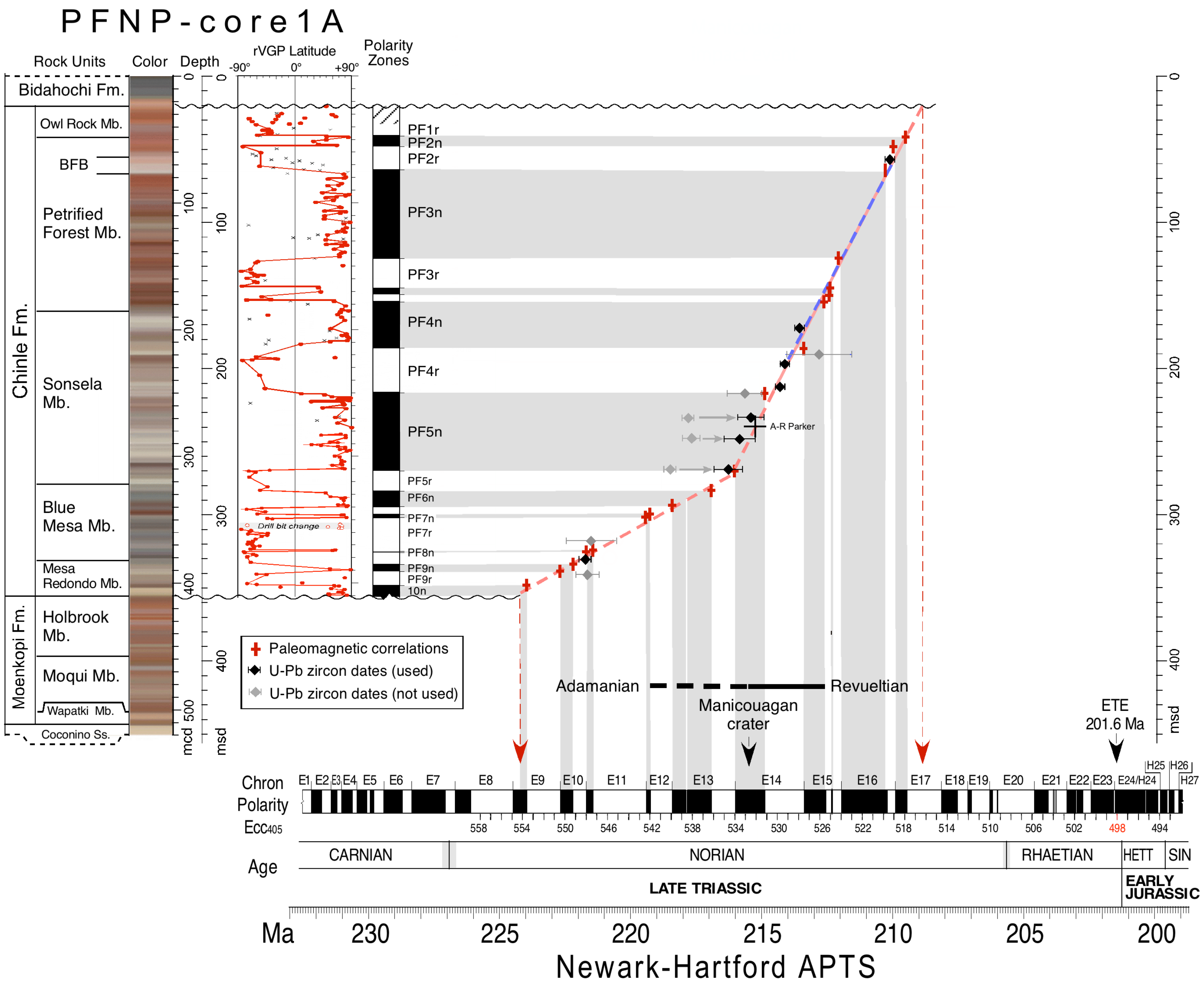
November 2013

Olsen et al. 2018a



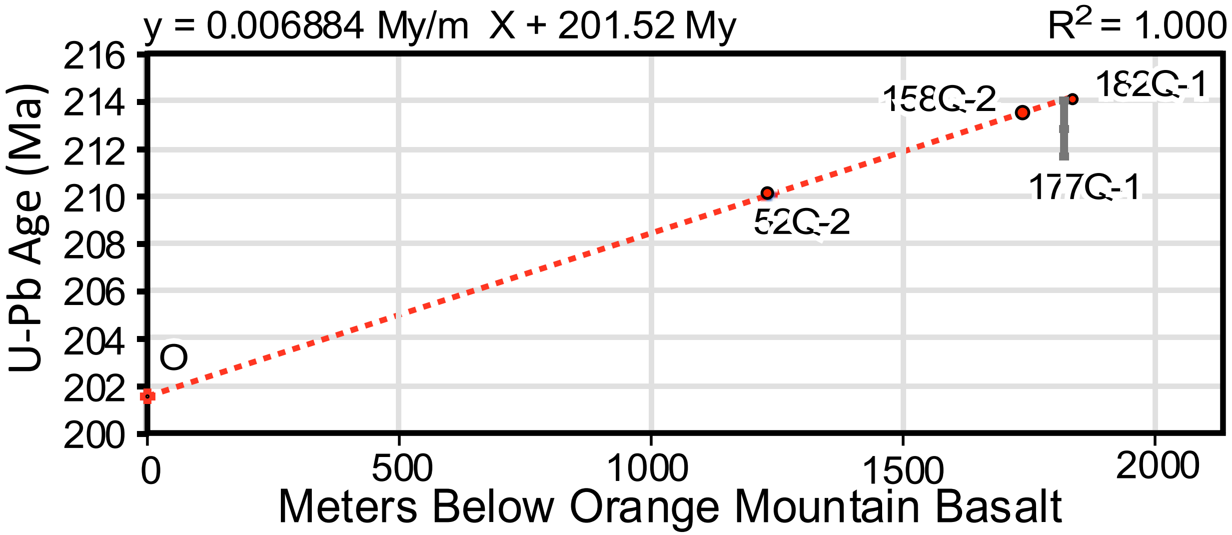
Olsen et al. 2018a

CPCP Chinle Core: Independent Paleomagnetic and U-Pb Dating

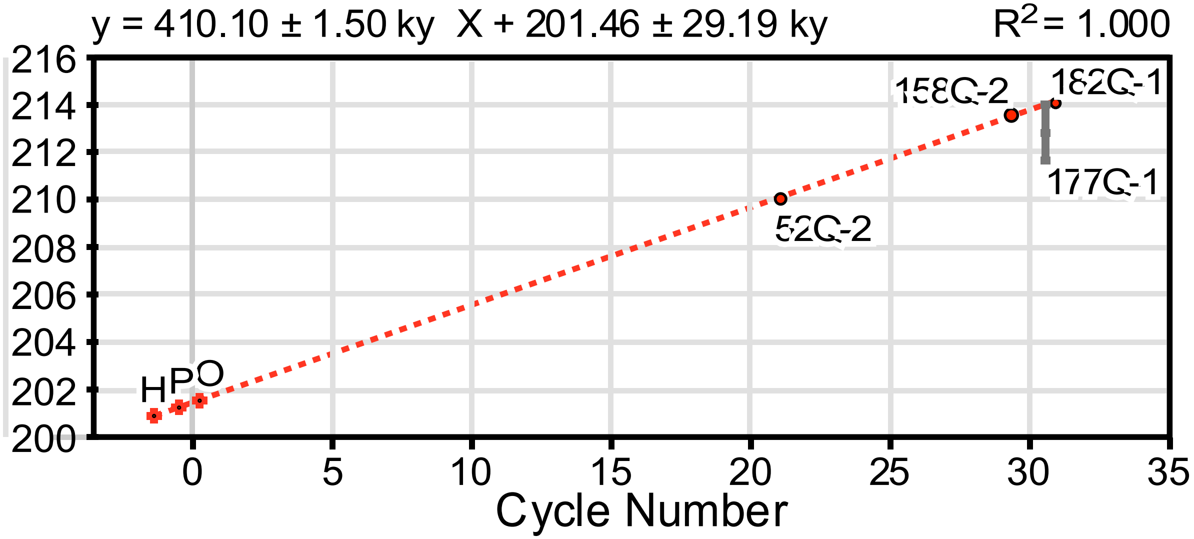


Data from Kent et al., and Rasmussen et al.

U-Pb Age Model of Accumulation Rate



Period of Newark Expression of “405 kyr cycle”

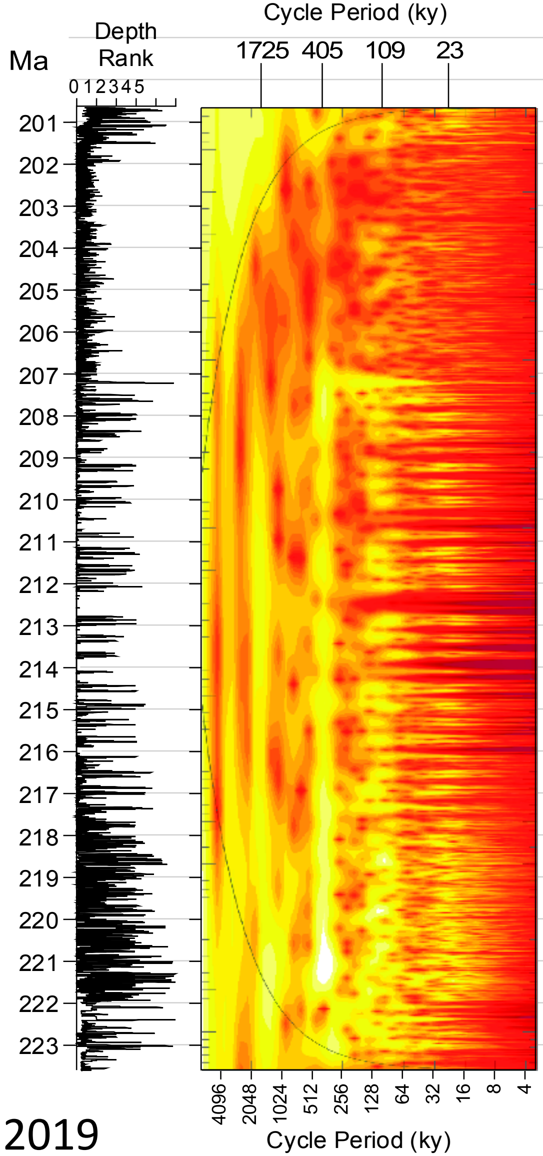


Olsen et al., 2019

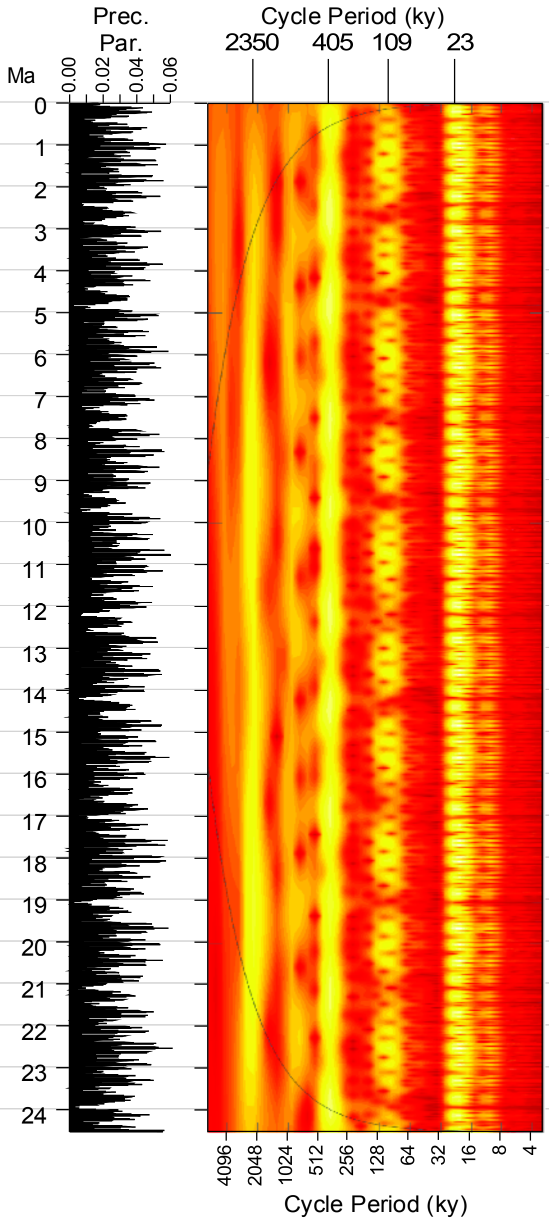
These two approaches validate the age model, the use of the 405 Kyr cycle for tuning, and show there cannot be significant gaps.

Wavelet Spectra Triassic, 0-24 Ma Solution, $\delta^{18}O$

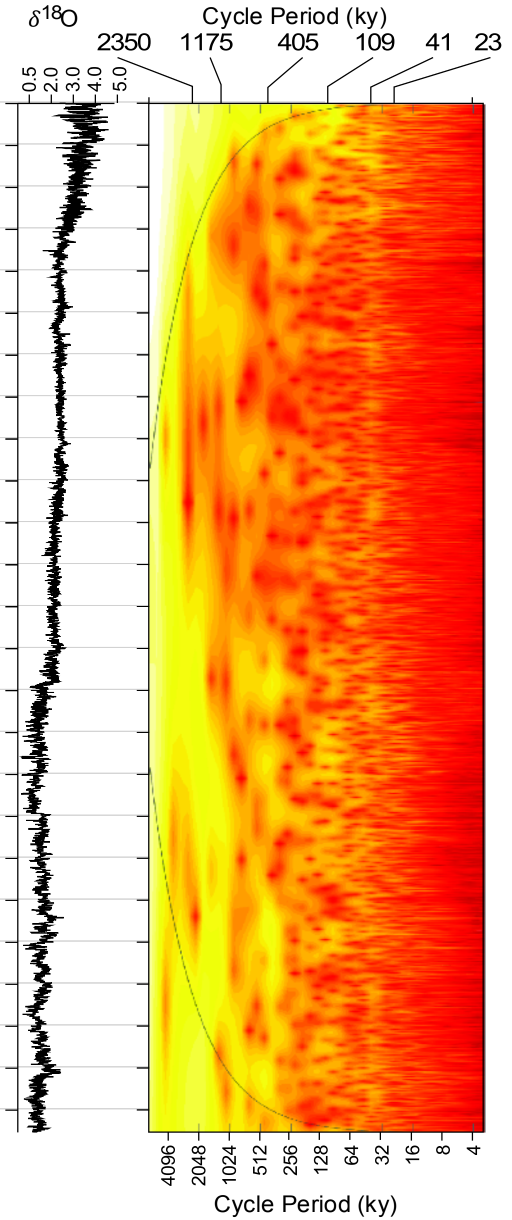
TRIASSIC-JURASSIC
NEWARK-HARTFORD
LAKE DEPTH



PRECESSION

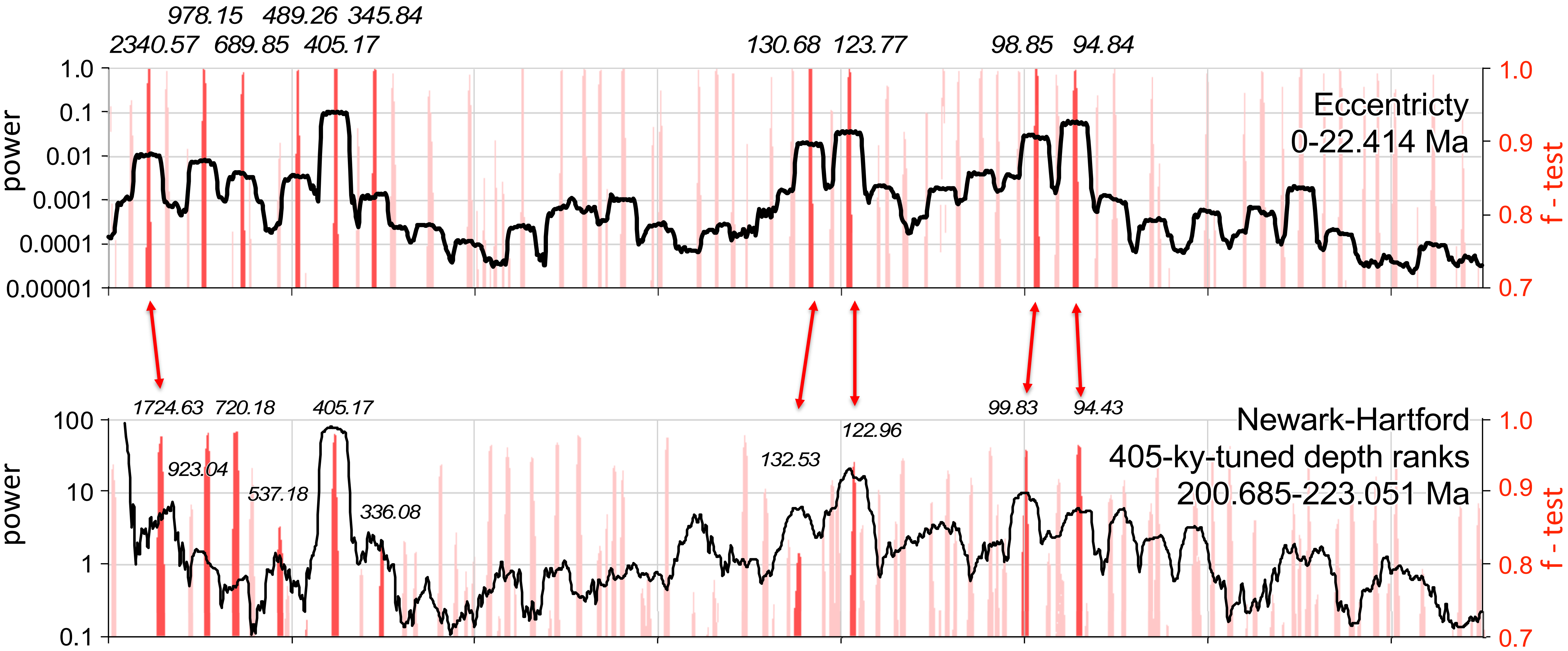


NEOGENE-QUATERNARY’
$\delta^{18}O$ MEGASPLICE



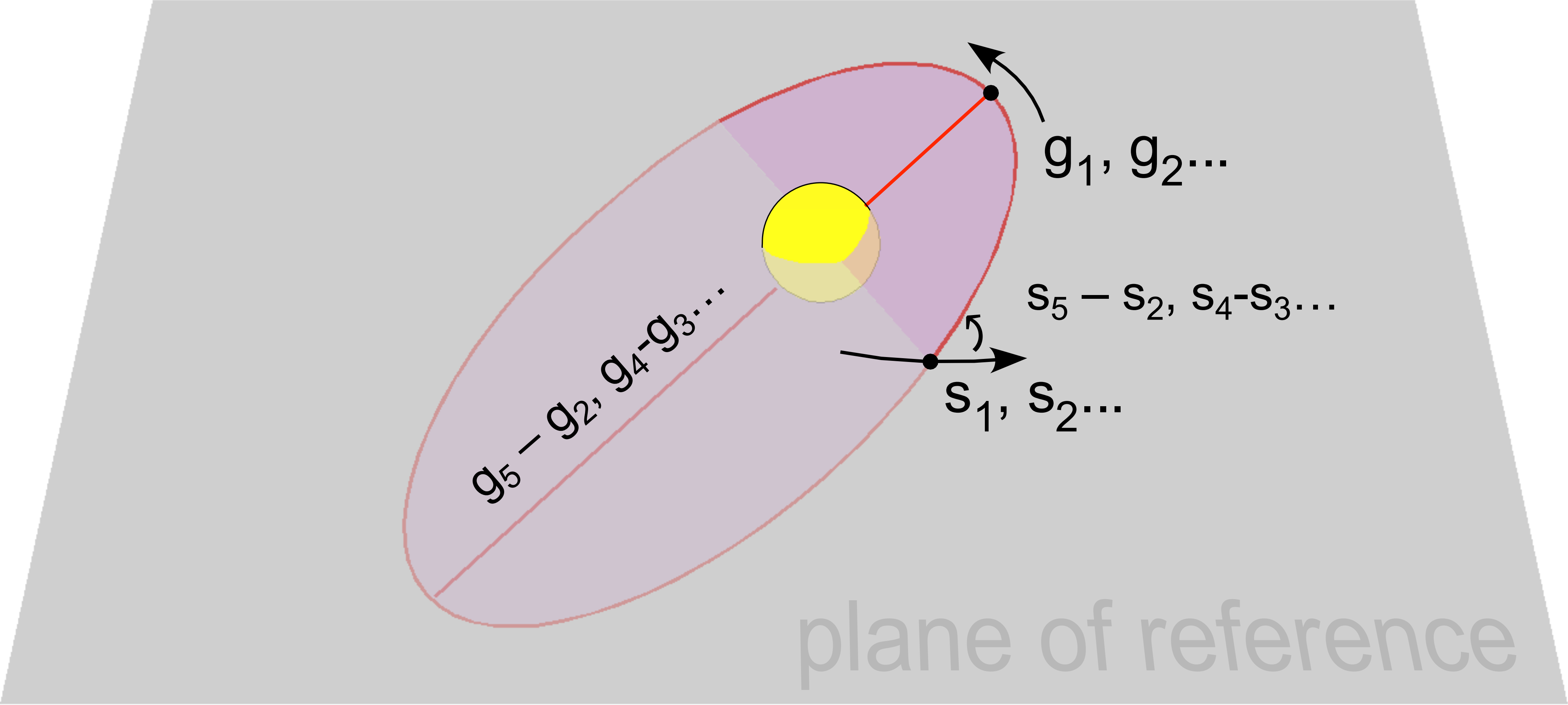
Olsen et al., 2019

Comparison of Spectra



Olsen et al., 2019

Secular Fundamental Frequencies



$g_5 - g_2, g_4 - g_3$… = grand eccentricity cycles (e.g., present 2.4 Myr cycle)

$s_5 - s_2, s_4 - s_3$… = grand obliquity cycles (e.g., present 1.2 Myr cycle)

Calculating the Secular Fundamental Frequencies of the Precession of Perihelion

Planet	Precession of Perihelion	MTM (“/yr)	FA (“/yr)	MTM-FA residual (“/yr)	La2010 (“/yr)	Newark-La2010 residual ('/yr)
Jupiter	g_5	4.257482	4.257482		4.257482	
Mercury	g_1	5.662	5.661	0.001	5.590	0.072
Venus	g_2	7.456	7.458	-0.002	7.453	0.004
Earth	g_3	17.24	17.246	-0.006	17.368	-0.125
Mars	g_4	17.982	17.973	0.009	17.916	0.061

Olsen et al., 2019

Consistency Check using Overdetermined Eccentricity Values

calculated

observed

FA RESULTS

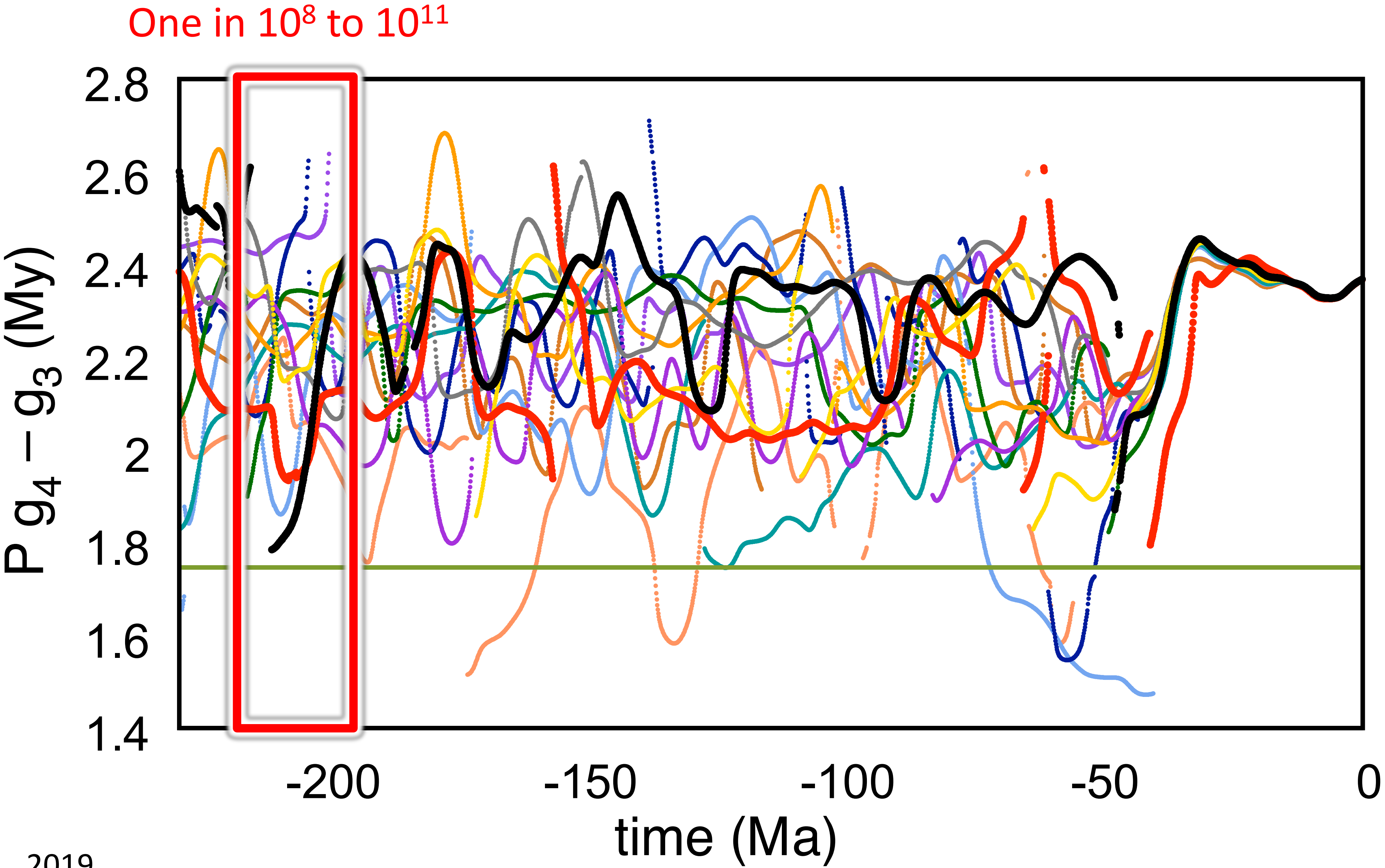
MTM RESULTS		g3-g2 132.17		g4-g2 123.08		g3-g5 99.78		g4-g5 94.49			FA RESULTS
g3-g2	132.53			**1789.60**	1747.65	**407.16**	404.97	**331.44**	330.08	132.17	g3-g2
g4-g2	122.96	**1702.81**	1724.63			**527.08**	527.56	**406.78**	404.97	123.08	g4-g2
g3-g5	99.83	**404.60**	405.17	**530.70**	537.18			**1782.27**	1747.65	99.78	g3-g5
g4-g5	94.43	**328.47**	336.53	**406.98**	405.17	**1745.73**	1724.63			94.49	g4-g5
		132.53 g3-g2		122.96 g4-g2		99.83 g3-g5		94.43 g4-g5			

MTM RESULTS

Average MTM g_4-g_3 = 1724.27 (0.02 %)

Average MTM g_2-g_5 = 405.79 (0.15 %)

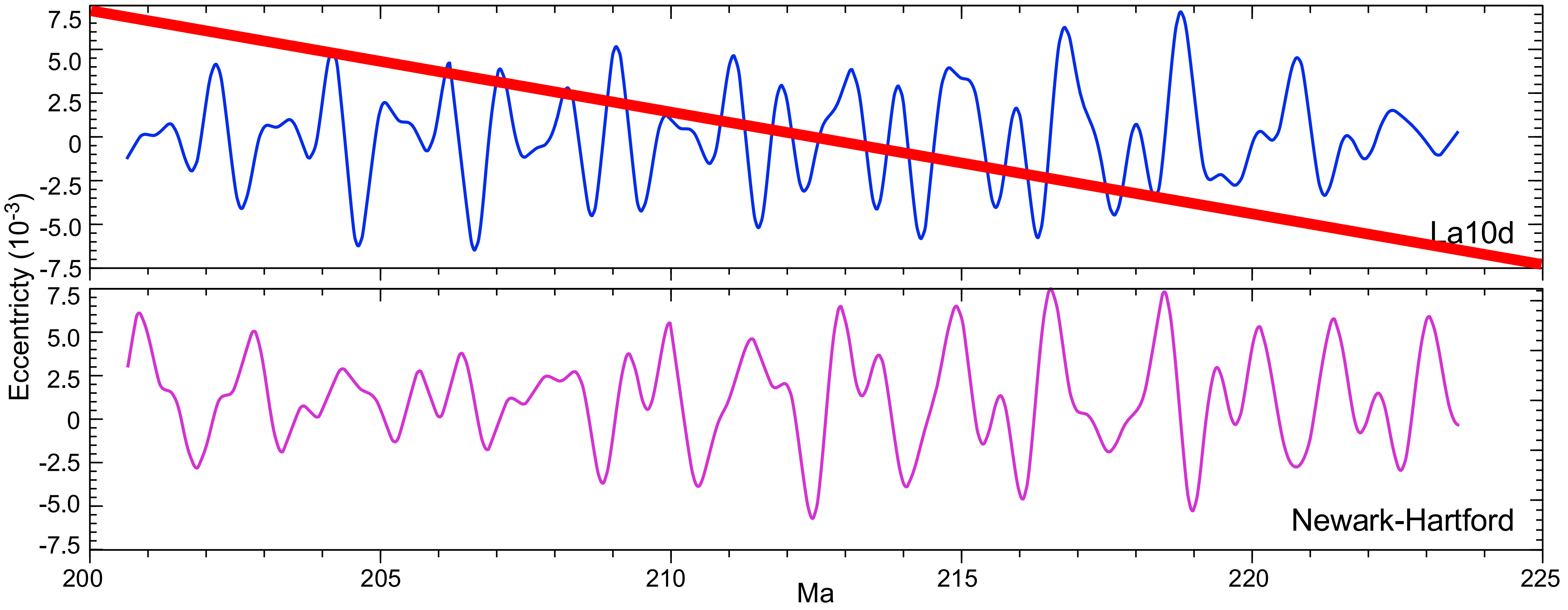
Olsen et al., 2019



Olsen et al., 2019

La10d Solution 1/ (g_4-g_3) = 1.75 Ma

Eccentricity $(g_4-g_3^*, g_1-g_5, g_1-g_2)$



Newark & Hartford Basins 1/ (g_4-g_3) = 1.75 Ma

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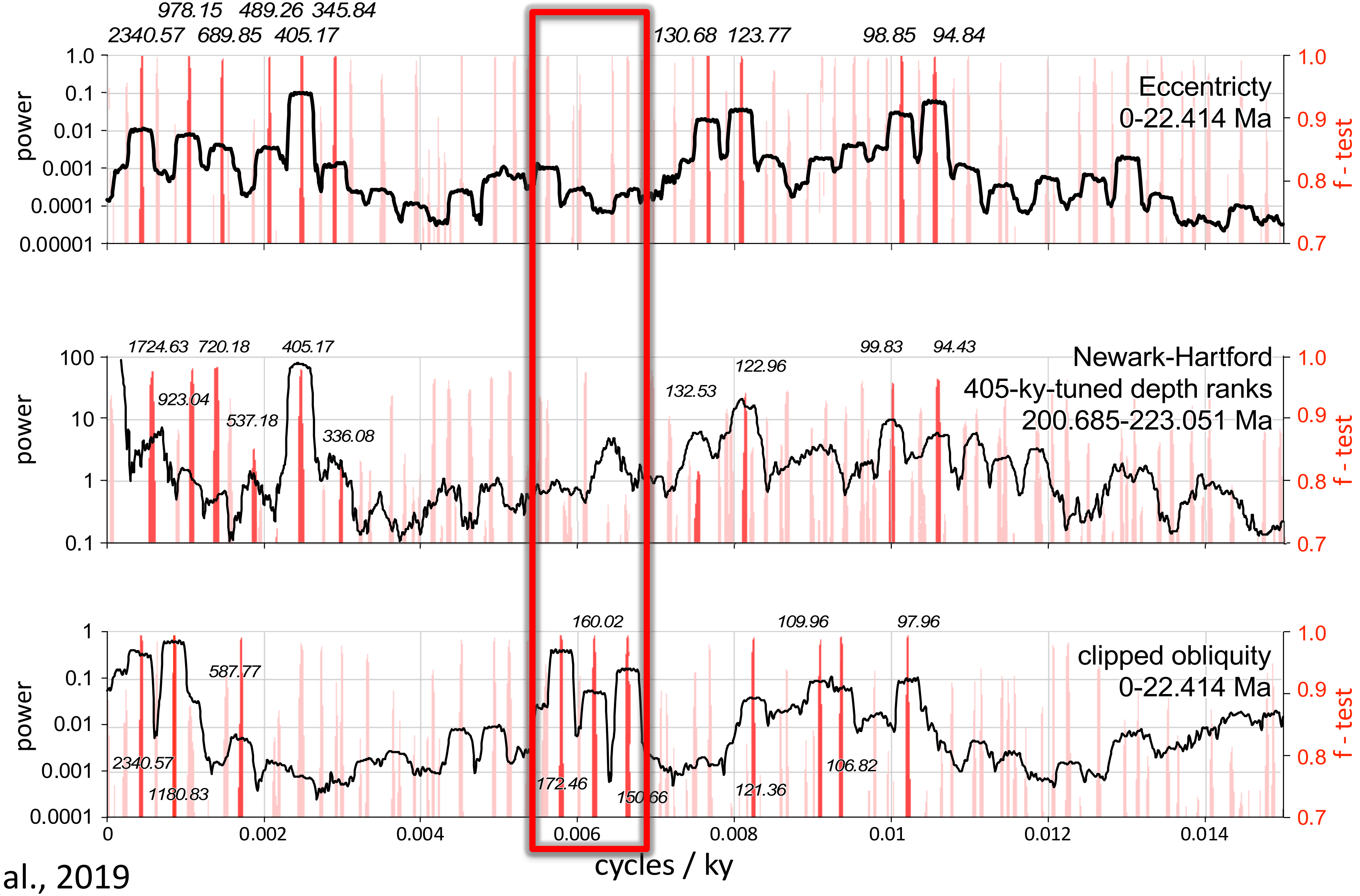
The g_4-g_3 : s_4-s_3 (Mars – Earth) Resonance

One could even dream that if the succession of the transitions from the 1:2 to the 1:1 resonance were found and dated over an interval of 200 Ma that this could be the ultimate test for the gravitational model.

J. Laskar, 1999

Comparison of Spectra

obliquity



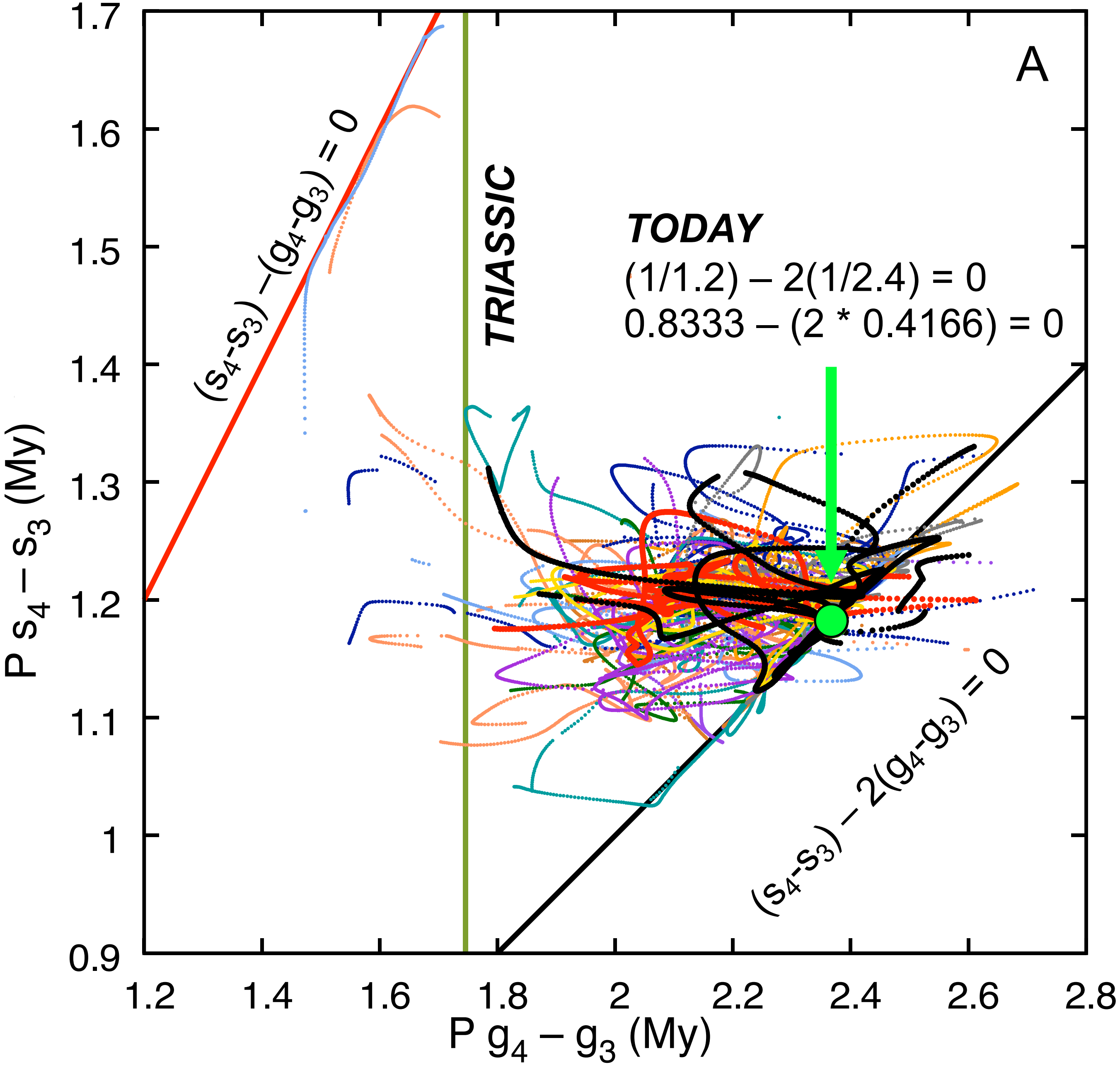
eccentricty frequencies

Tropical Triassic-Jurassic frequencies

Inclination frequencies

Olsen et al., 2019

Resonance between Mars and Earth

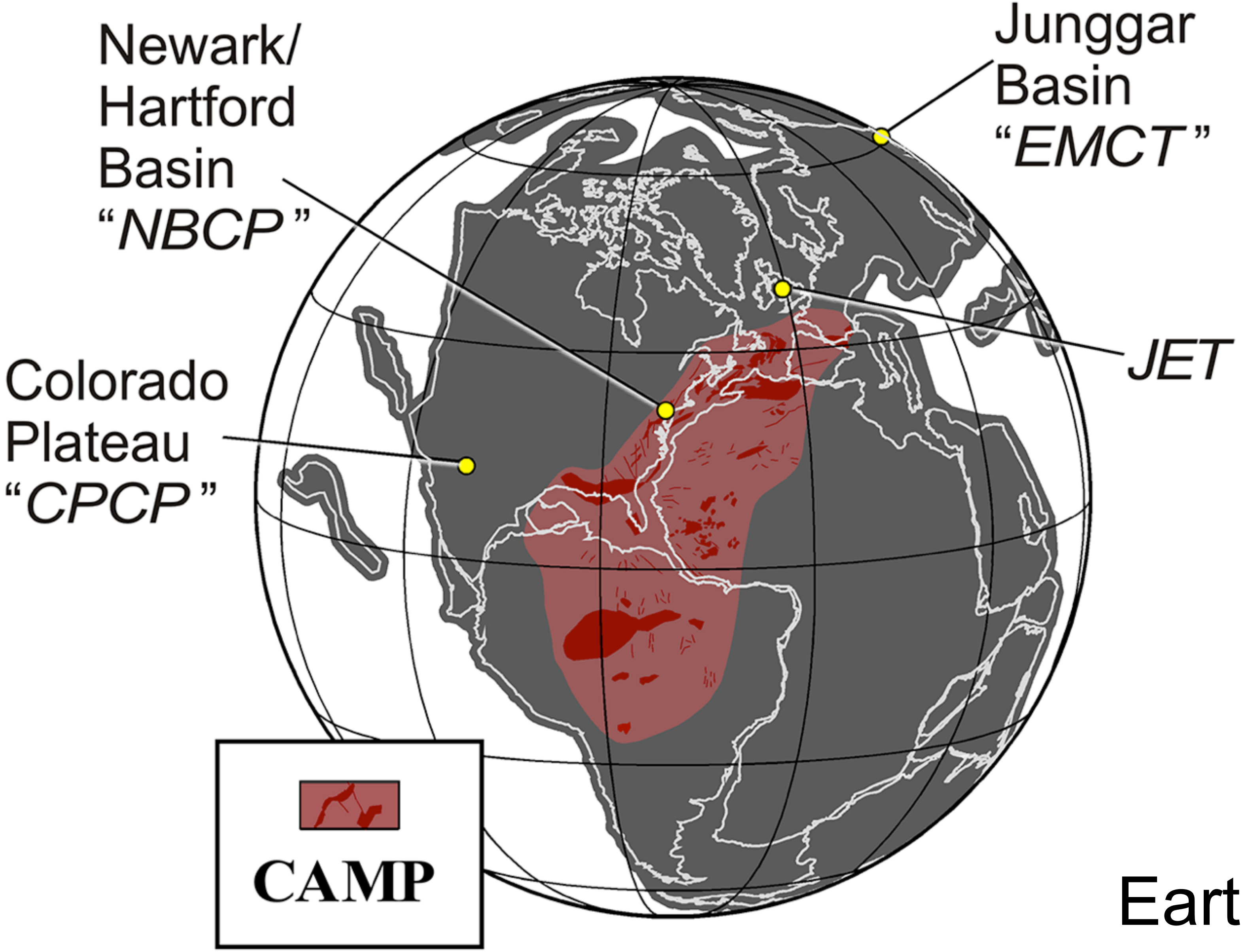


TODAY

(1/1.2) – 2(1/2.4) = 0

0.8333 – (2 * 0.4166) = 0

Olsen et al., 2019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Earth @ 201.6

EMCT / CPCP2: Recovering Triassic-Jurassic Eccentricity (g_4-g_3) and Obliquity (s_4-s_3) With Paired Triassic-Jurassic Low- and High-Latitude Sites

5°- 25° N: Phase II CPCP Chinle – Kayenta Fms

71° N: Junggar Basin, NW China

The ***Geological Orrery*** will give us

- Continuous climate record through deep time over hundreds of millions of years.

- Resolved orbital parameters including Mars – Earth, precession and obliquity cycles.

- So that both the chaotic drift in and the major transitions in resonances can be recognized.

Implications of The Geological Orrery

1. Understanding of stability of Solar System.
2. Paleoclimate target curves for any arbitrary time.
3. Time scale with a <20 ky *precision* and *accuracy*.
4. Improved precision of 10^4 to 10^{10} in celestial mechanical measurements (Laskar, 2008).
5. Targets for understanding the climate history of other planets.
6. Tuning of radiometric decay constants
7. Constraining the J2 of the sun (Laskar, 2008).
8. Calibration of the survivability of Earth-like exoplanets.
9. Tests of gravity theories (GR, r-MOND, etc.) – dissipative effects.

Scott Kelly