The Geological Orrery: Using Earth's Geological Record to Map the Chaotic Evolution of the Solar System

Paul E. Olsen &
Dennis V. Kent
April, 29, 2015
in honor of
Jacques Laskar

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

1) What is the Geological Orrery?

2) Astronomical solutions chaotic. Geological record allows tests of astronomical solutions (NBCP – CPCP)

3) Need obliquity from high latitudes

4) The Geological Orrery Program

1) What is the Geological Orrery?

2) Astronomical solutions chaotic. Geological record allows tests of astronomical solutions (NBCP – CPCP)

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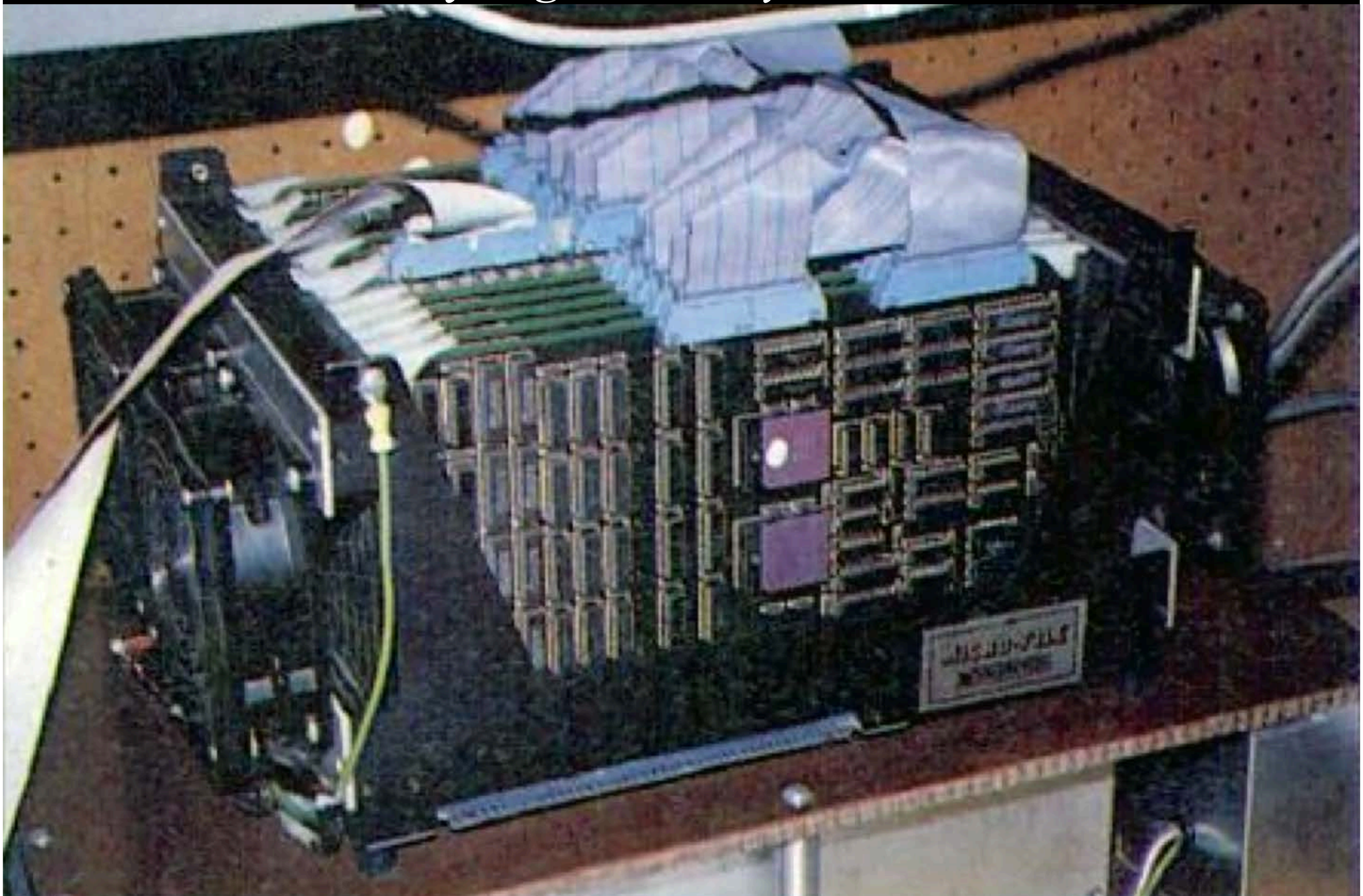
An 18^{th} century *Orrery*

The late 20th century *Digital Orrery*



Applegate et al. (1985); Sussman & Wisdom (1988, 1992)


A piece of the *Geological Orrery*

1) What is the Geological Orrery?

2) Astronomical solutions chaotic.
   Geological record allows tests of
   astronomical solutions (NBCP – CPCP)

3) Need obliquity from high latitudes

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What we would like

- Continuous record through deep time over hundreds of millions of years
- Resolvable orbital parameters at appropriate time scales, including precession and obliquity modulators (g_4-g_3 and s_4-s_3) from low *and* high latitudes.
- So that both the drift in secular frequencies and the major transitions in resonances can be recognized

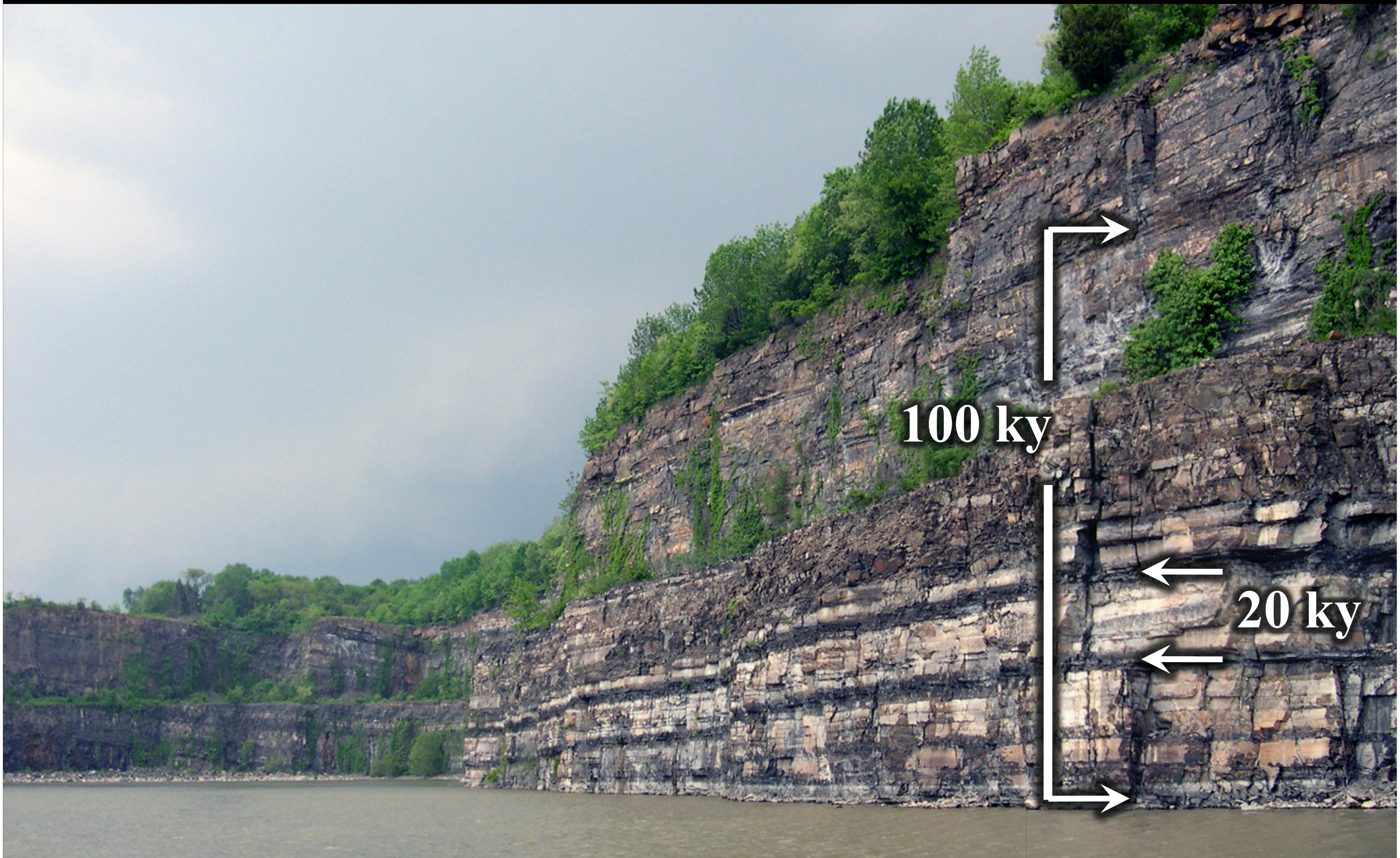
Example:

From the Newark Basin Coring Project (NBCP)

to the Colorado Plateau Coring Project (CPCP)

Newark Basin Coring Project (NBCP)

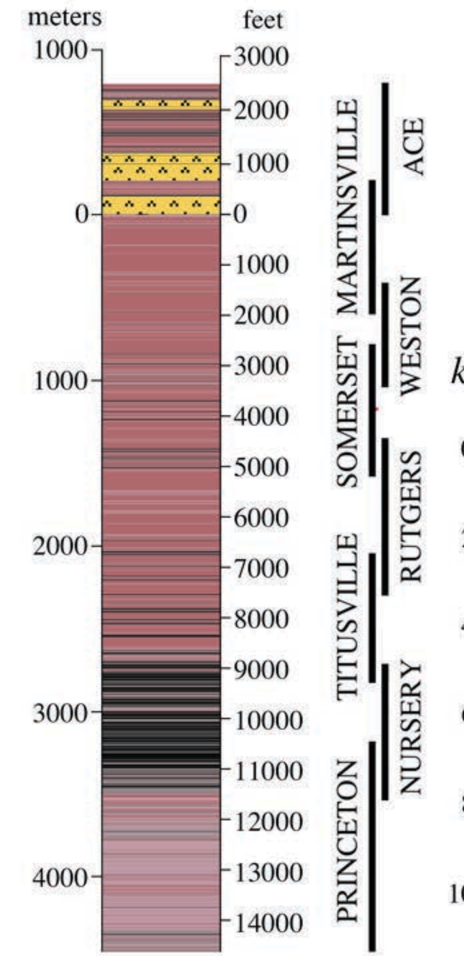
5° N: Lacustrine Cycles, Newark Basin

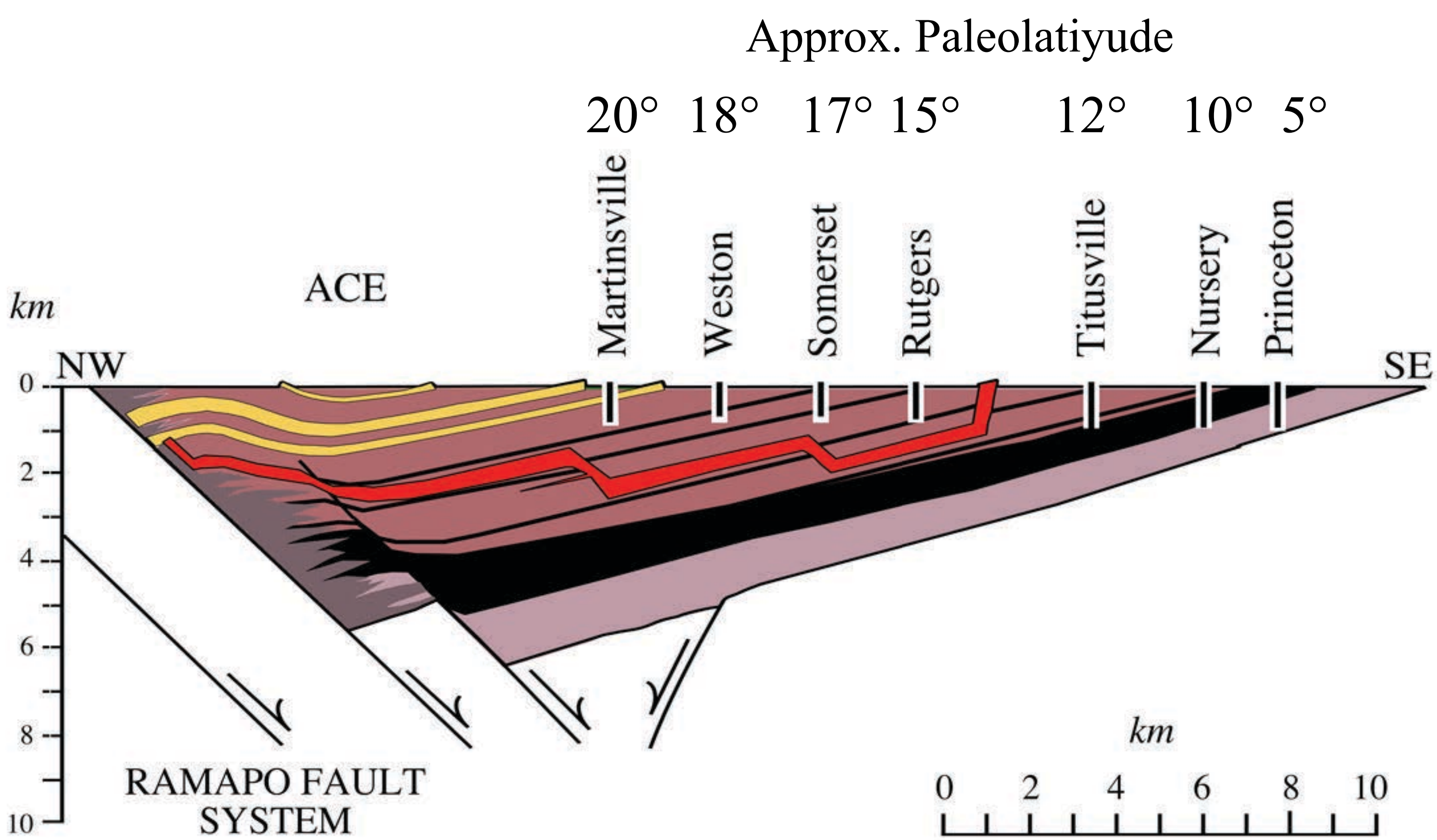


Late Triassic, Lockatong Formation, Eureka, PA


20 ky

Newark Basin Coring Project (NBCP)





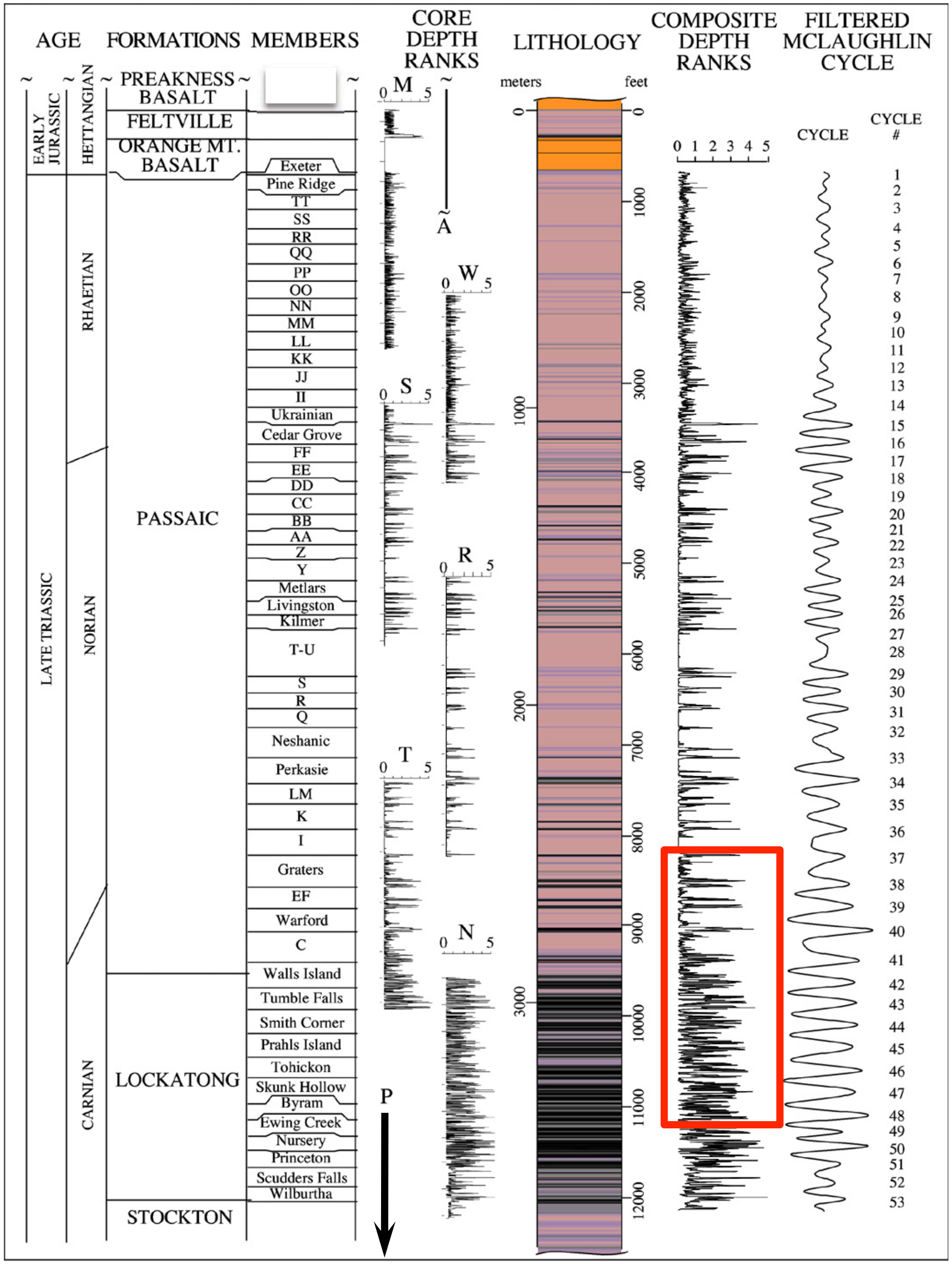
1989 - 1994

“Depth Rank” Proxy of Lake Depth

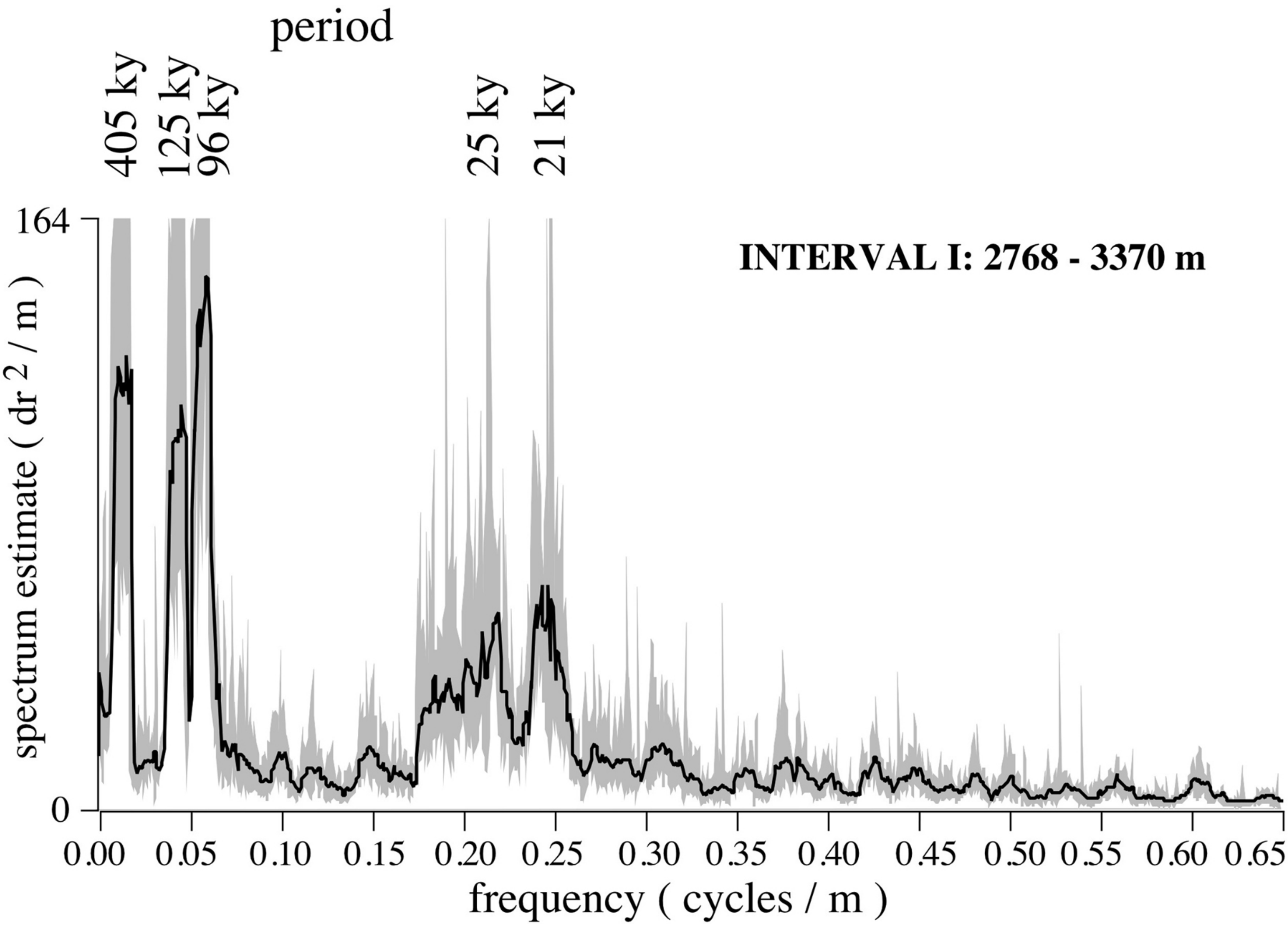
0 0.5 1 1.5 2 2.5 3 4 5

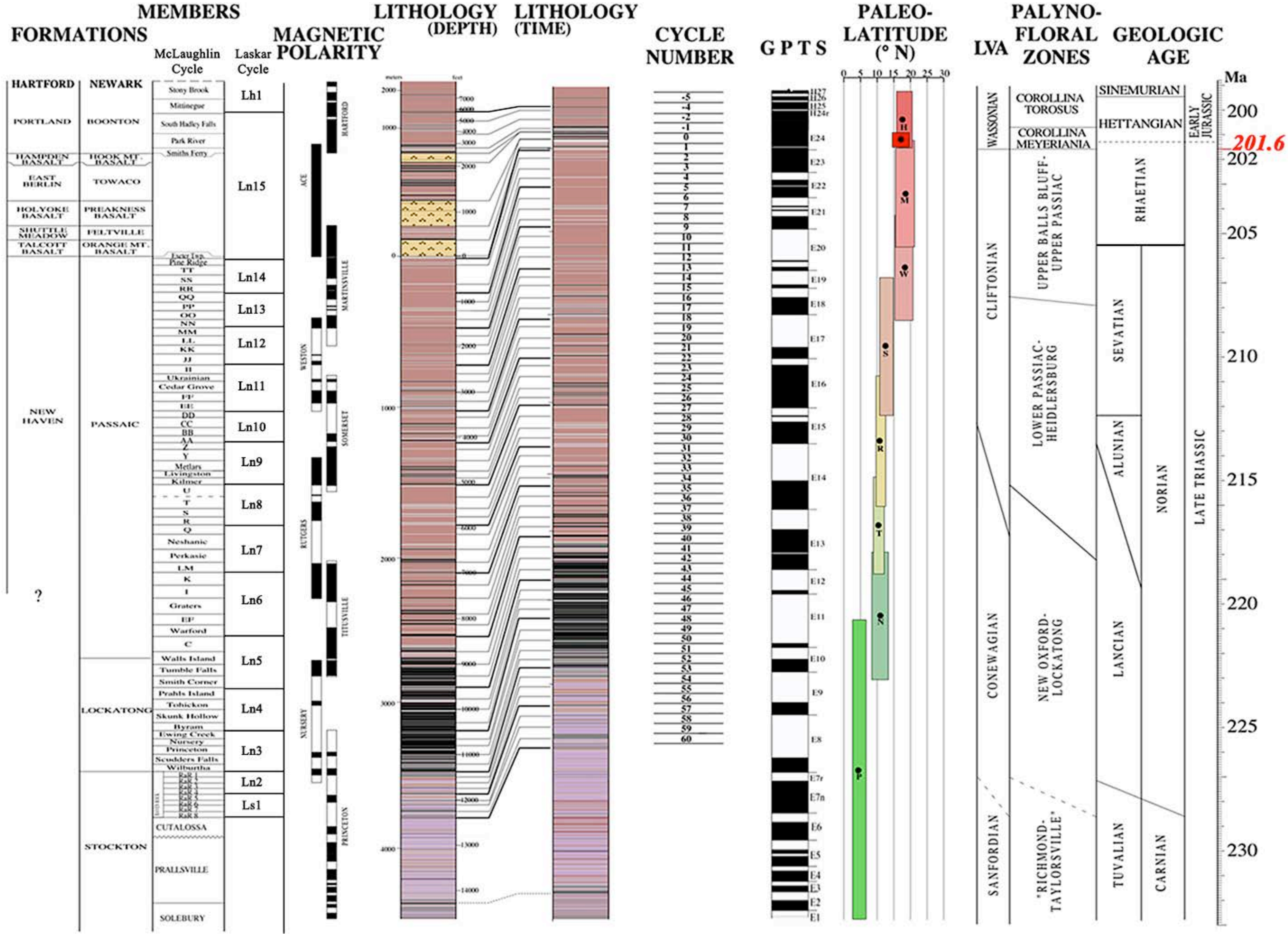
Dry Lake Deep Lake

Examples of Facies in Cores

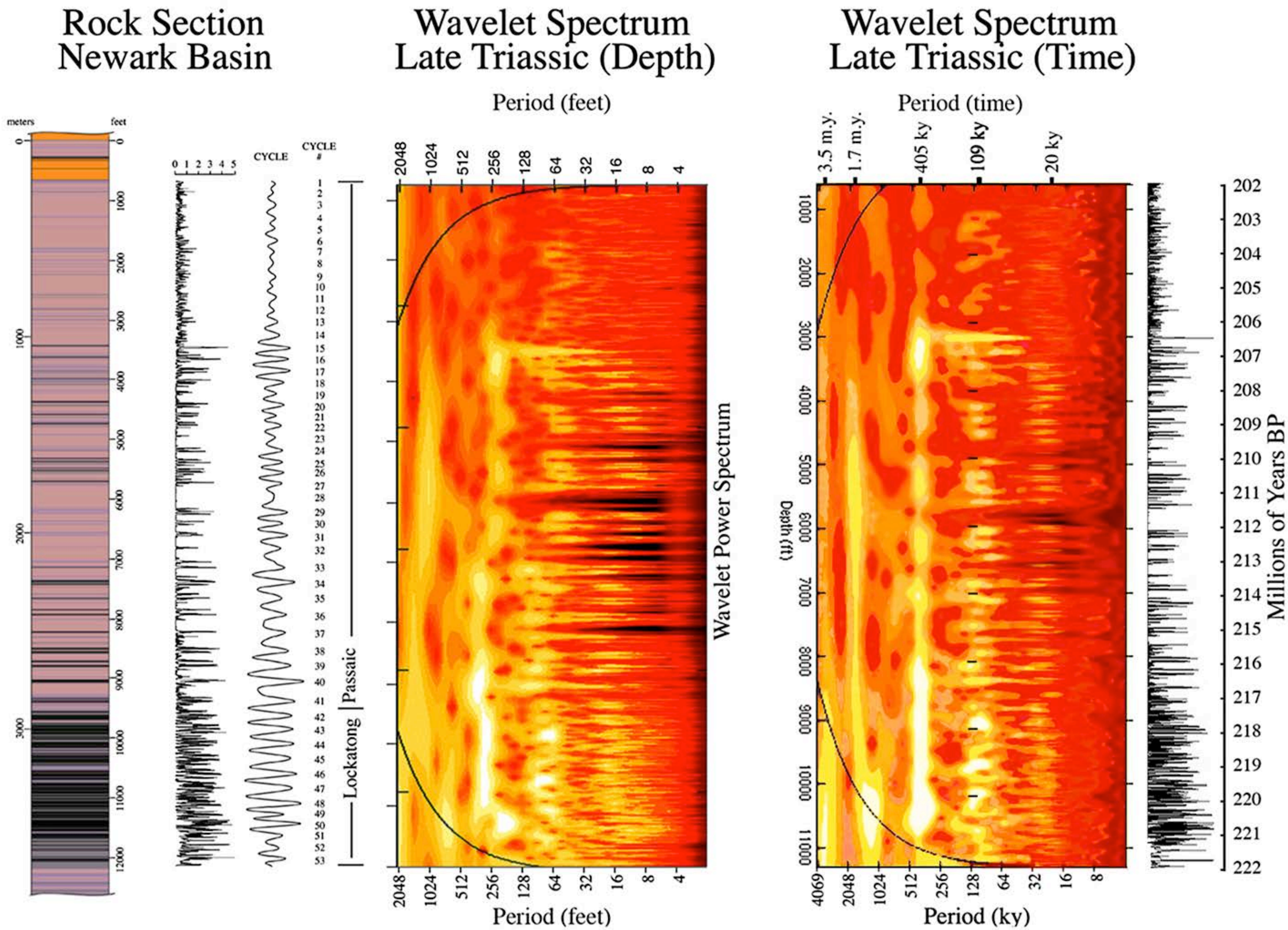

AGE
FORMATIONS
MEMBERS
CORE DEPTH RANKS
LITHOLOGY
COMPOSITE DEPTH RANKS
FILTERED MCLAUGHLIN CYCLE
EARLY JURASSIC
HETTANGIAN
RHAETIAN
NORIAN
CARNIAN
LATE TRIASSIC
PREAKNESS BASALT
FELTVILLE
ORANGE MT. BASALT
PASSAIC
LOCKATONG
STOCKTON
Exeter
Pine Ridge
TT
SS
RR
QQ
PP
OO
NN
MM
LL
KK
JJ
II
Ukrainian
Cedar Grove
FF
EE
DD
CC
BB
AA
Z
Y
Metlars
Livingston
Kilmer
T-U
S
R
Q
Neshanic
Perkasie
LM
K
I
Graters
EF
Warford
C
Walls Island
Tumble Falls
Smith Corner
Prahls Island
Tohickon
Skunk Hollow
Byram
Ewing Creek
Nursery
Princeton
Scudders Falls
Wilburtha
M
A
W
S
R
T
N
P
meters
feet
CYCLE
CYCLE #

MTM Power Spectrum of Depth Ranks

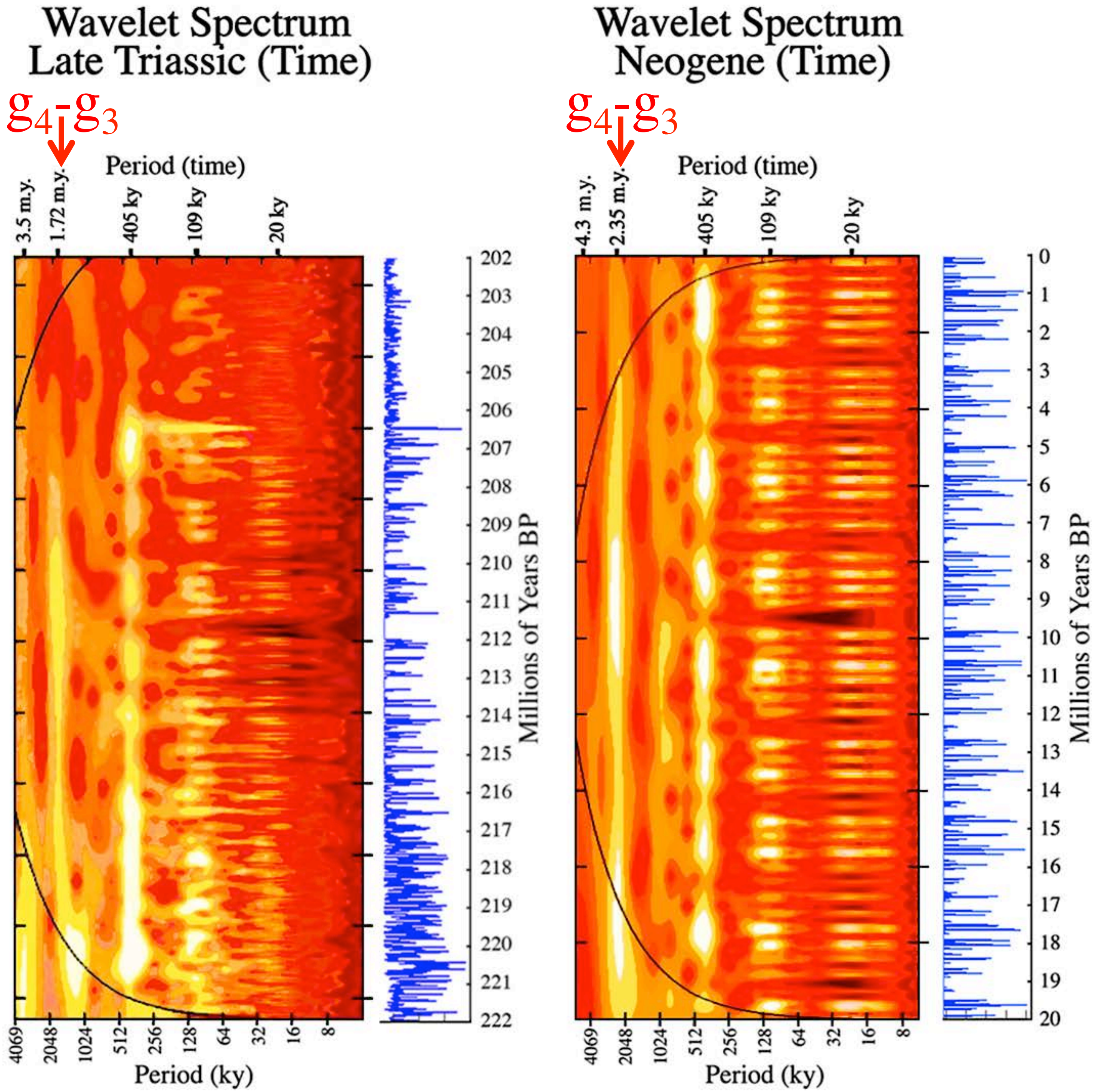




FORMATIONS
MEMBERS
McLaughlin Cycle
Laskar Cycle
MAGNETIC POLARITY
LITHOLOGY (DEPTH)
LITHOLOGY (TIME)
CYCLE NUMBER
G P T S
PALEO-LATITUDE (° N)
LVA
PALYNO-FLORAL ZONES
GEOLOGIC AGE
Ma
HARTFORD
NEWARK
PORTLAND
BOONTON
HAMPDEN BASALT
HOOK MT. BASALT
EAST BERLIN
TOWACO
HOLYOKE BASALT
PREAKNESS BASALT
SHUTTLE MEADOW
FELTVILLE
TALCOTT BASALT
ORANGE MT. BASALT
NEW HAVEN
PASSAIC
LOCKATONG
STOCKTON
CUTALOSSA
PRALLSVILLE
SOLEBURY
Stony Brook
Mittinegue
South Hadley Falls
Park River
Smiths Ferry
Pine Ridge
Ukrainian
Cedar Grove
Metlars
Livingston
Kilmer
Neshanic
Perkasie
Graters
Warford
Walls Island
Tumble Falls
Smith Corner
Prahls Island
Tohickon
Skunk Hollow
Byram
Ewing Creek
Nursery
Princeton
Scudders Falls
Wilburtha
Lh1
Ln15
Ln14
Ln13
Ln12
Ln11
Ln10
Ln9
Ln8
Ln7
Ln6
Ln5
Ln4
Ln3
Ln2
Ls1
HARTFORD
ACE
MARTINSVILLE
WESTON
SOMERSET
RUTGERS
TITUSVILLE
NURSERY
PRINCETON
COROLLINA TOROSUS
COROLLINA MEYERIANIA
UPPER BALLS BLUFF-UPPER PASSIAC
LOWER PASSIAC-HEIDLERSBURG
NEW OXFORD-LOCKATONG
"RICHMOND-TAYLORSVILLE"
WASSONIAN
CLIFTONIAN
CONEWAGIAN
SANFORDIAN
SINEMURIAN
HETTANGIAN
EARLY JURASSIC
RHAETIAN
SEVATIAN
ALUNIAN
LANCIAN
TUVALIAN
NORIAN
CARNIAN
LATE TRIASSIC
201.6



Rock Section
Newark Basin
Wavelet Spectrum
Late Triassic (Depth)
Wavelet Spectrum
Late Triassic (Time)
meters
feet
CYCLE
CYCLE #
Lockatong | Passaic
Period (feet)
Wavelet Power Spectrum
Period (time)
3.5 m.y.
1.7 m.y.
405 ky
109 ky
20 ky
Depth (ft)
Period (ky)
Millions of Years BP



Wavelet Spectrum
Late Triassic (Time)
g_4-g_3
Period (time)
3.5 m.y.
1.72 m.y.
405 ky
109 ky
20 ky
4069
2048
1024
512
256
128
64
32
16
8
Period (ky)
202
203
204
205
206
207
208
209
210
211
212
213
214
215
216
217
218
219
220
221
222
Millions of Years BP
Wavelet Spectrum
Neogene (Time)
g_4-g_3
Period (time)
4.3 m.y.
2.35 m.y.
405 ky
109 ky
20 ky
4069
2048
1024
512
256
128
64
32
16
8
Period (ky)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
Millions of Years BP

How reproducable

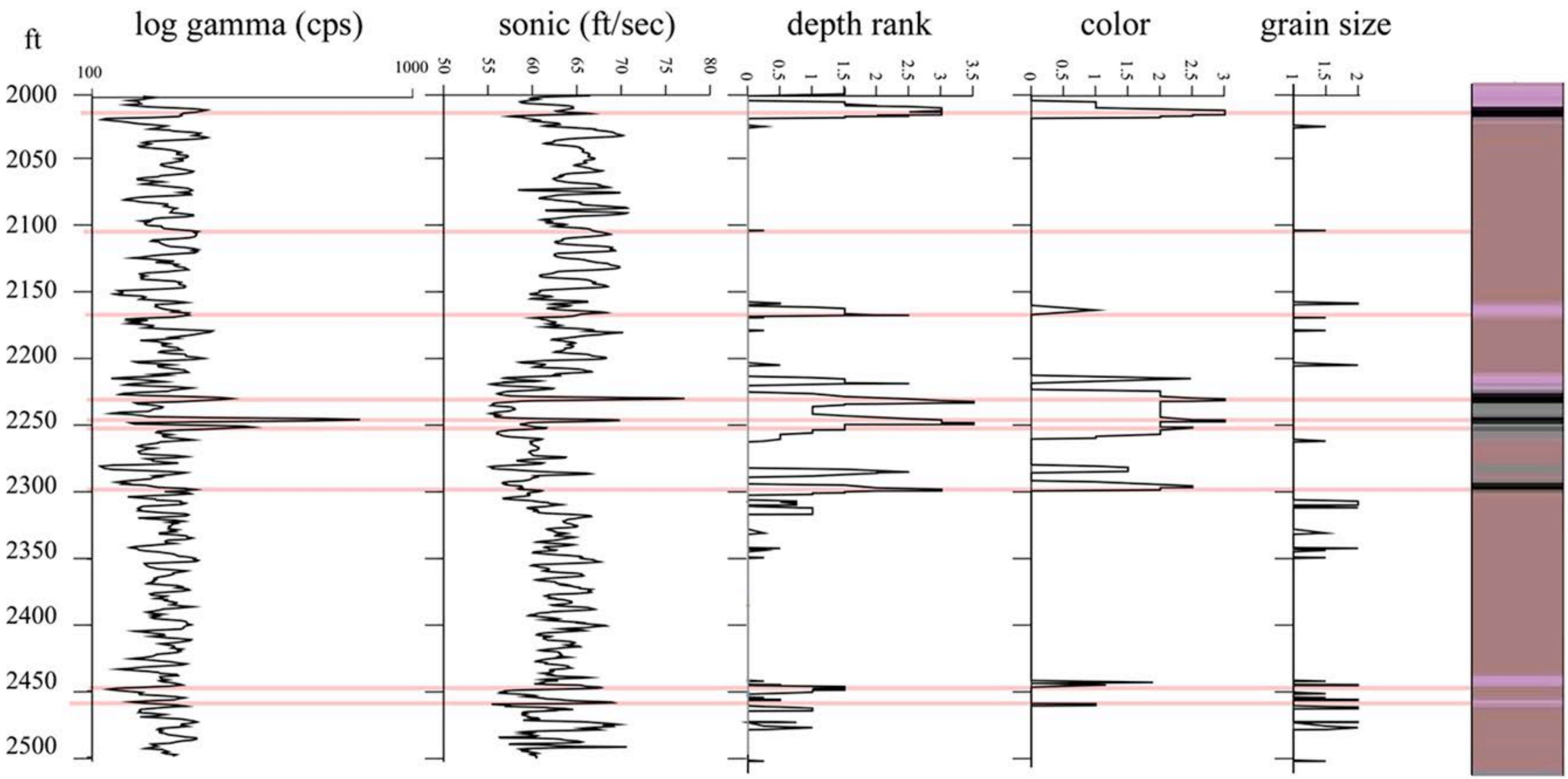
Signal in different proxies

Completeness

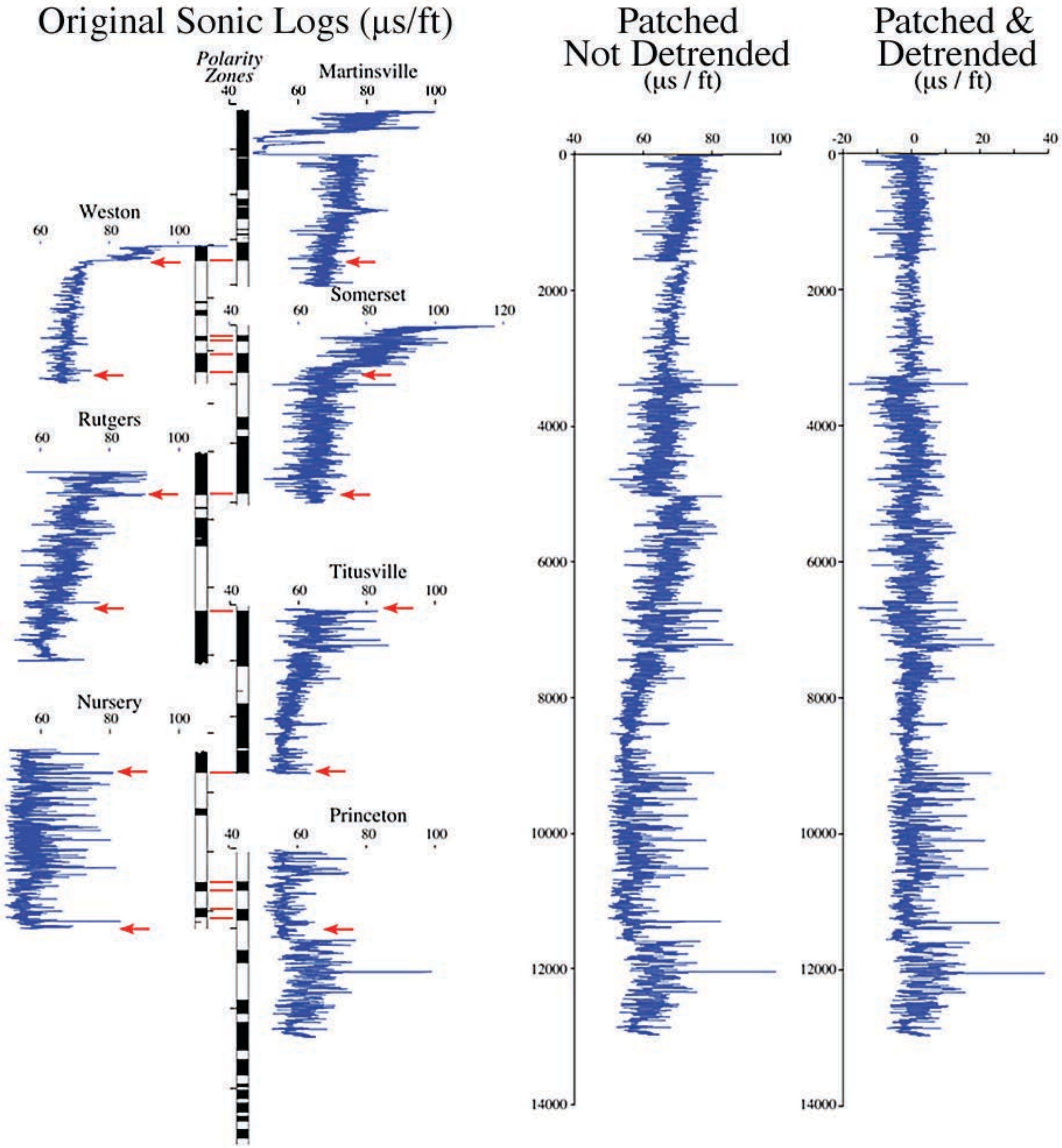
Astrochronology

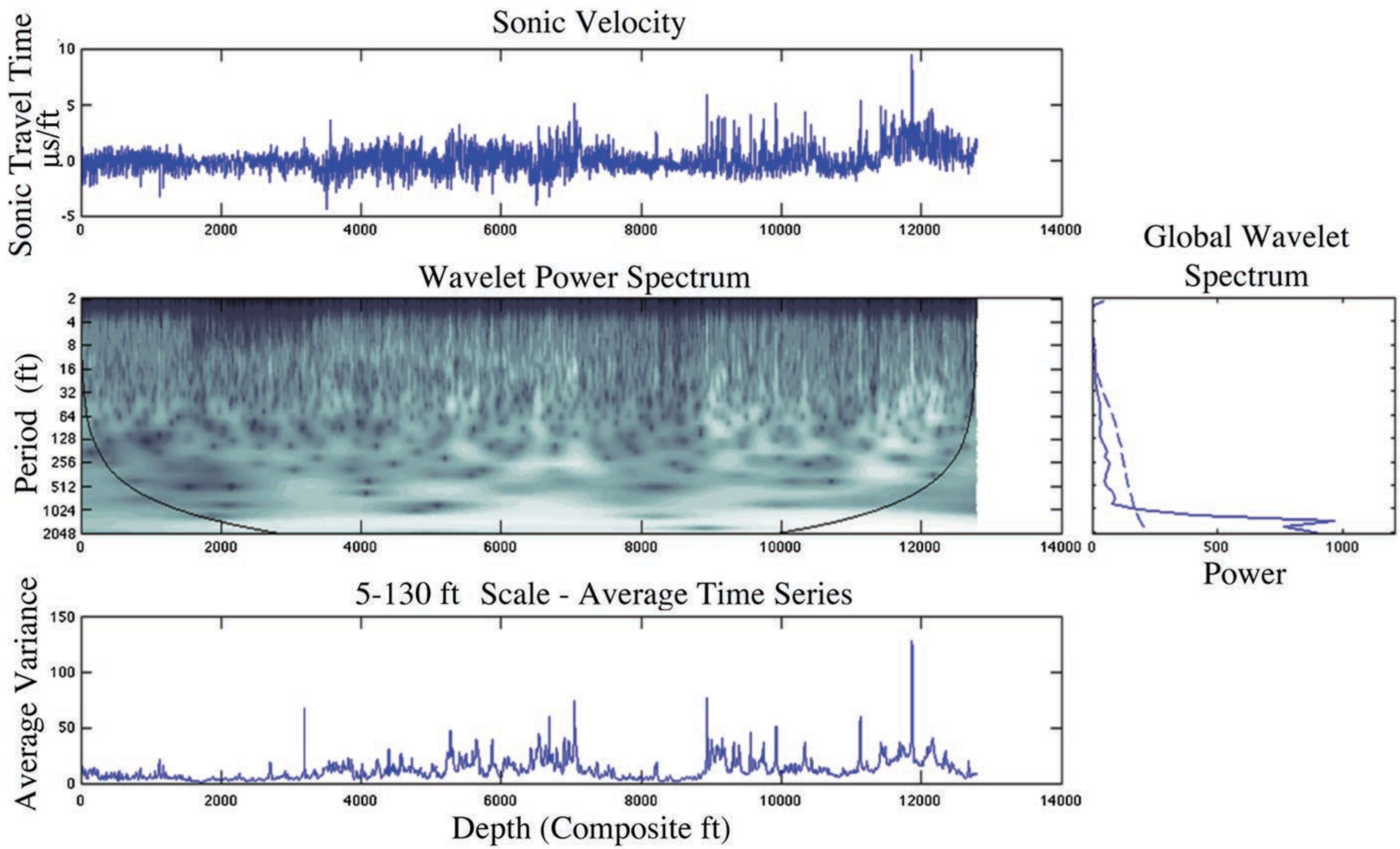
Mars-Earth, g_4-g_3 signal

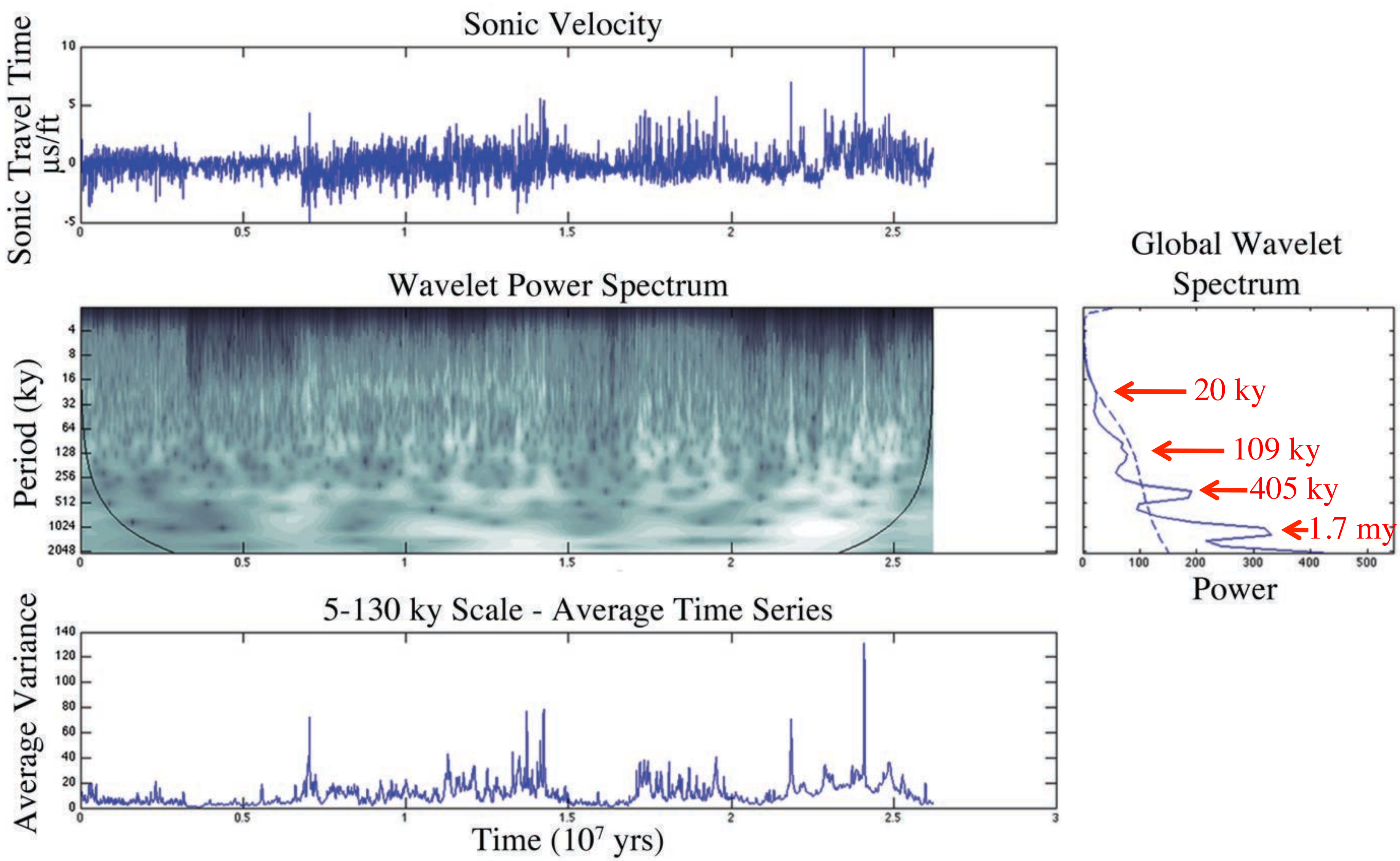
Down hole Logs and Core Properties



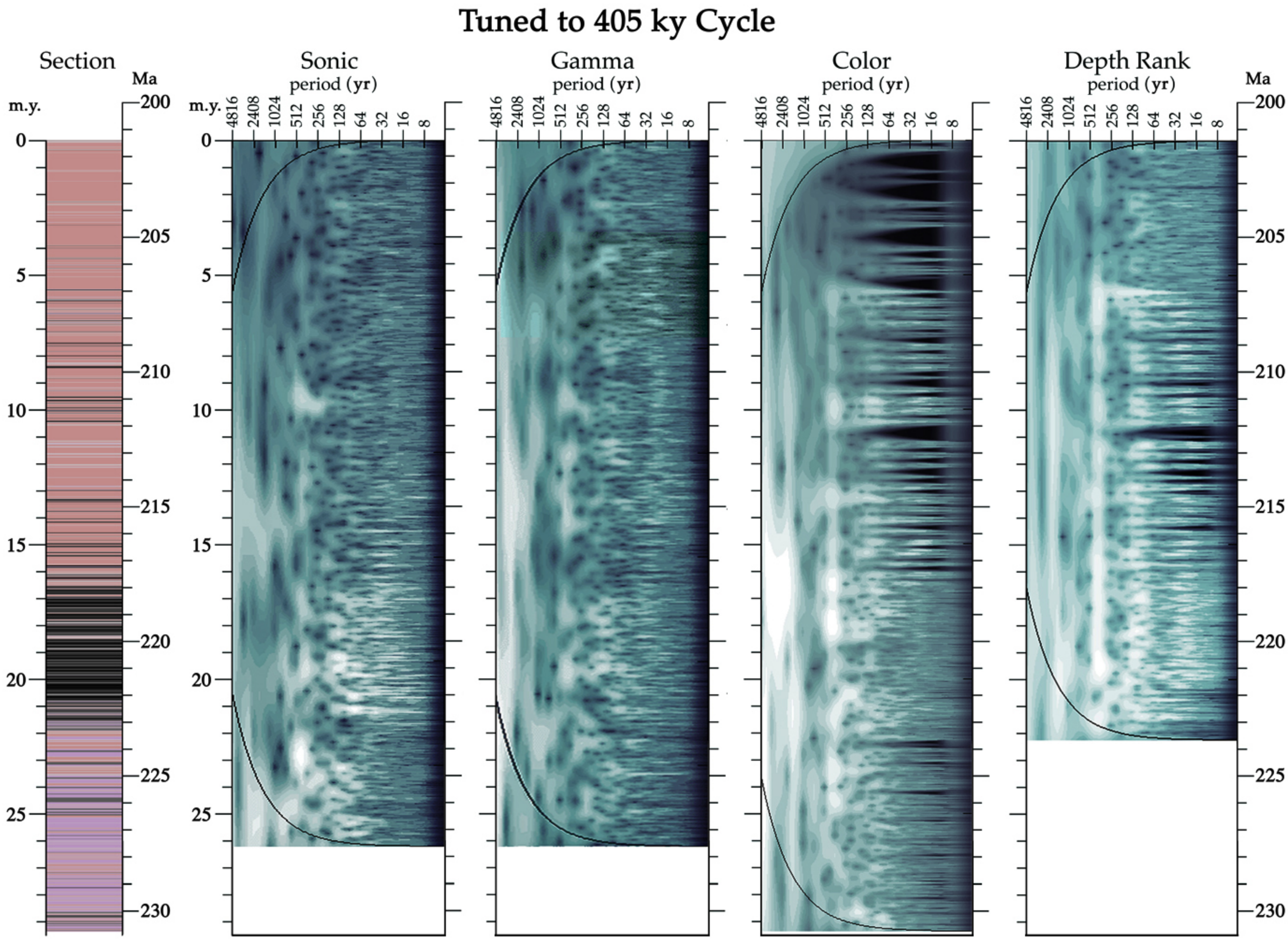
NEWARK BASIN COMPOSITE SONIC LOGS




Sonic Velocity
Sonic Travel Time
µs/ft
Wavelet Power Spectrum
Period (ft)
Global Wavelet Spectrum
Power
5-130 ft Scale - Average Time Series
Average Variance
Depth (Composite ft)



Sonic Velocity
Sonic Travel Time µs/ft
Wavelet Power Spectrum
Period (ky)
Global Wavelet Spectrum
20 ky
109 ky
405 ky
1.7 my
Power
5-130 ky Scale - Average Time Series
Average Variance
Time (10⁷ yrs)



Tuned to 405 ky Cycle
Section
Sonic
Gamma
Color
Depth Rank
period (yr)
m.y.
Ma
4816
2408
1024
512
256
128
64
32
16
8
0
5
10
15
20
25
200
205
210
215
220
225
230

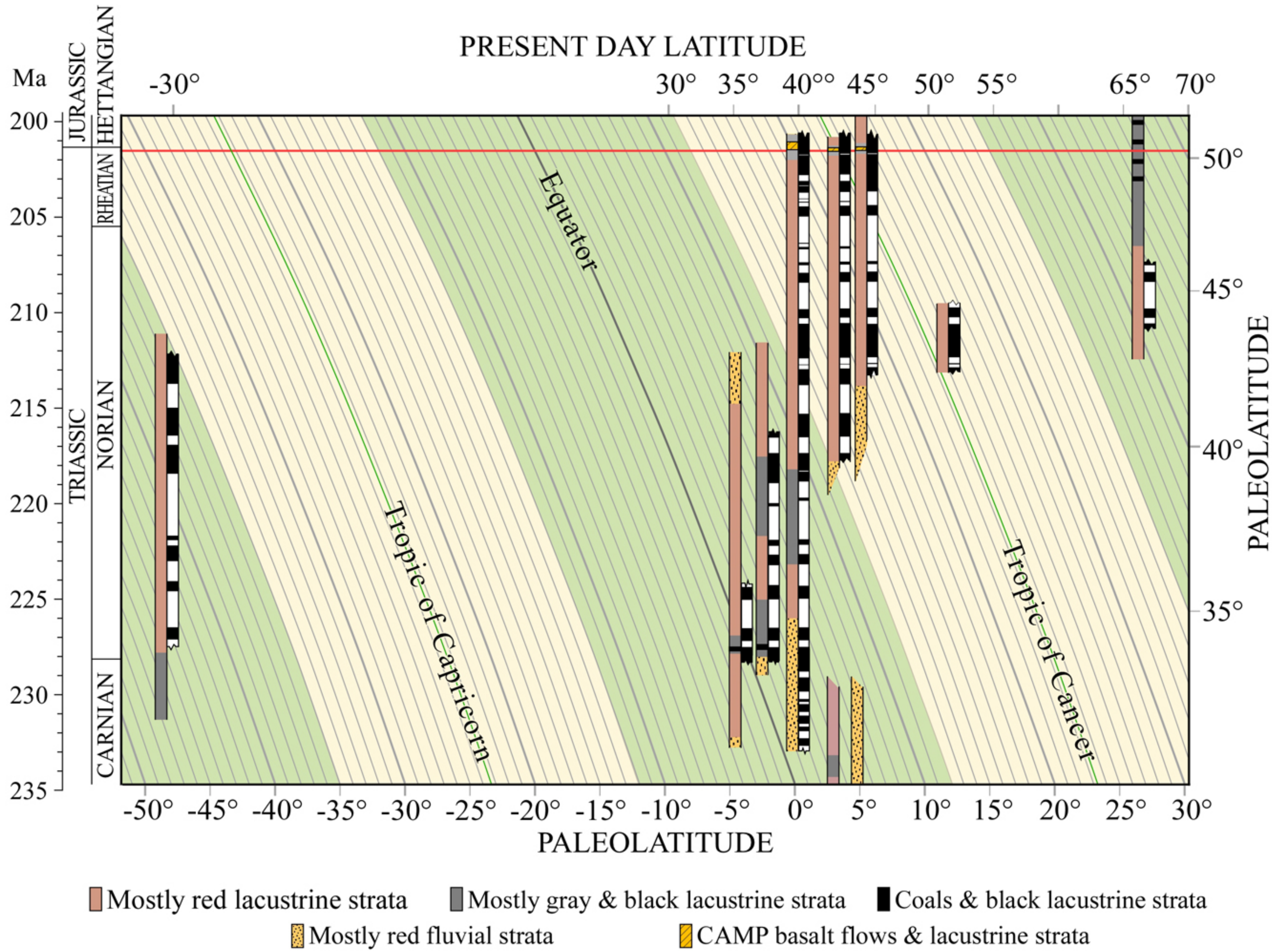
How reproducable

Signal in different proxies

Completeness

Astrochronology

Mars-Earth, g_4-g_3 signal



PRESENT DAY LATITUDE
Ma
JURASSIC
HETTANGIAN
RHEATIAN
NORIAN
TRIASSIC
CARNIAN
-30°
30°
35°
40°°
45°
50°
55°
65°
70°
200
205
210
215
220
225
230
235
Equator
Tropic of Capricorn
Tropic of Cancer
50°
45°
40°
35°
PALEOLATITUDE
-50°
-45°
-40°
-35°
-30°
-25°
-20°
-15°
-10°
-5°
0°
5°
10°
15°
20°
25°
30°
PALEOLATITUDE
Mostly red lacustrine strata
Mostly gray & black lacustrine strata
Coals & black lacustrine strata
Mostly red fluvial strata
CAMP basalt flows & lacustrine strata

How reproducable

Signal in different proxies

Completeness

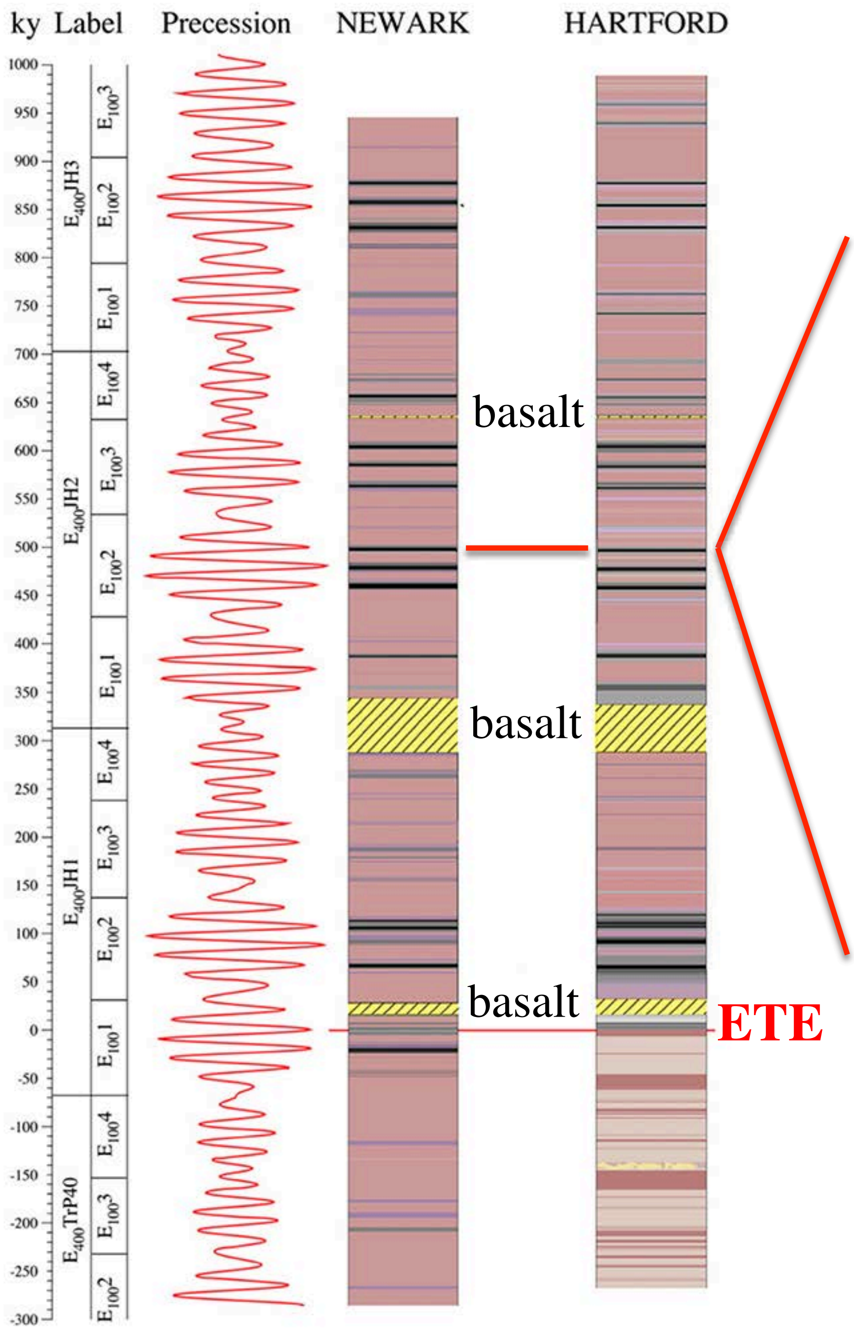
Astrochronology

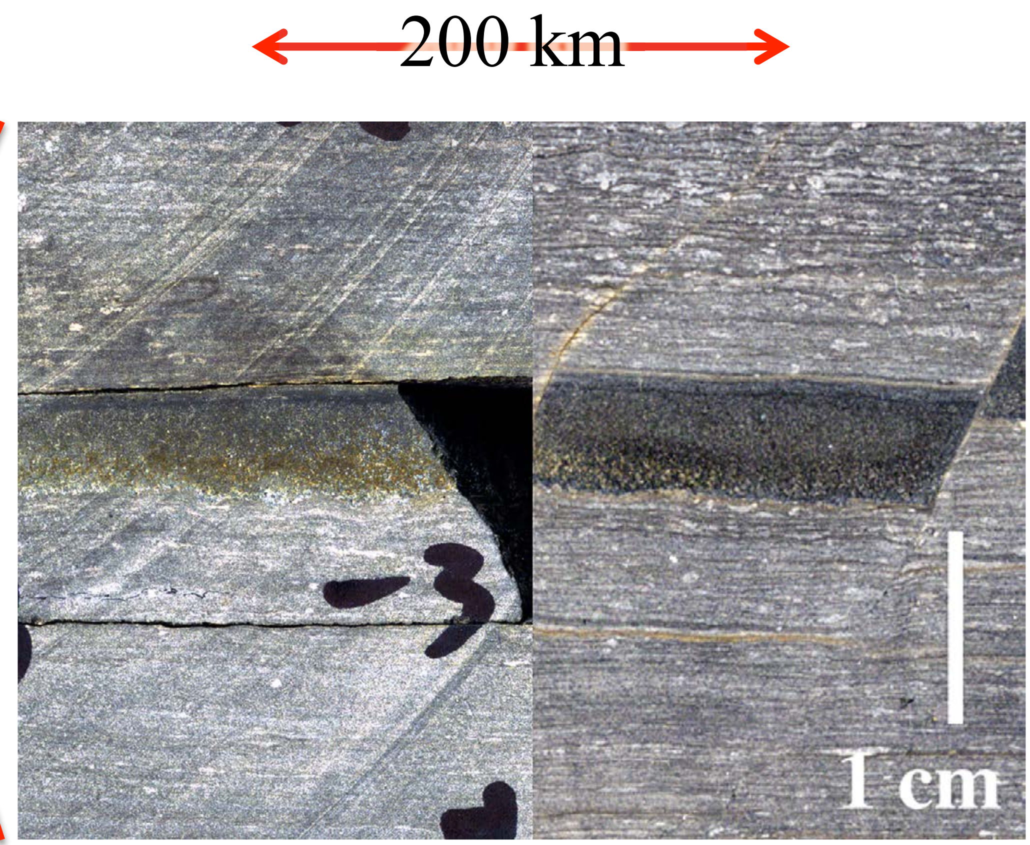
Mars-Earth, g_4-g_3 signal

21° Paleolatitude, Hartford Basin

East Berlin Formation

20°-21° N: Newark and Hartford Basins, Eastern US

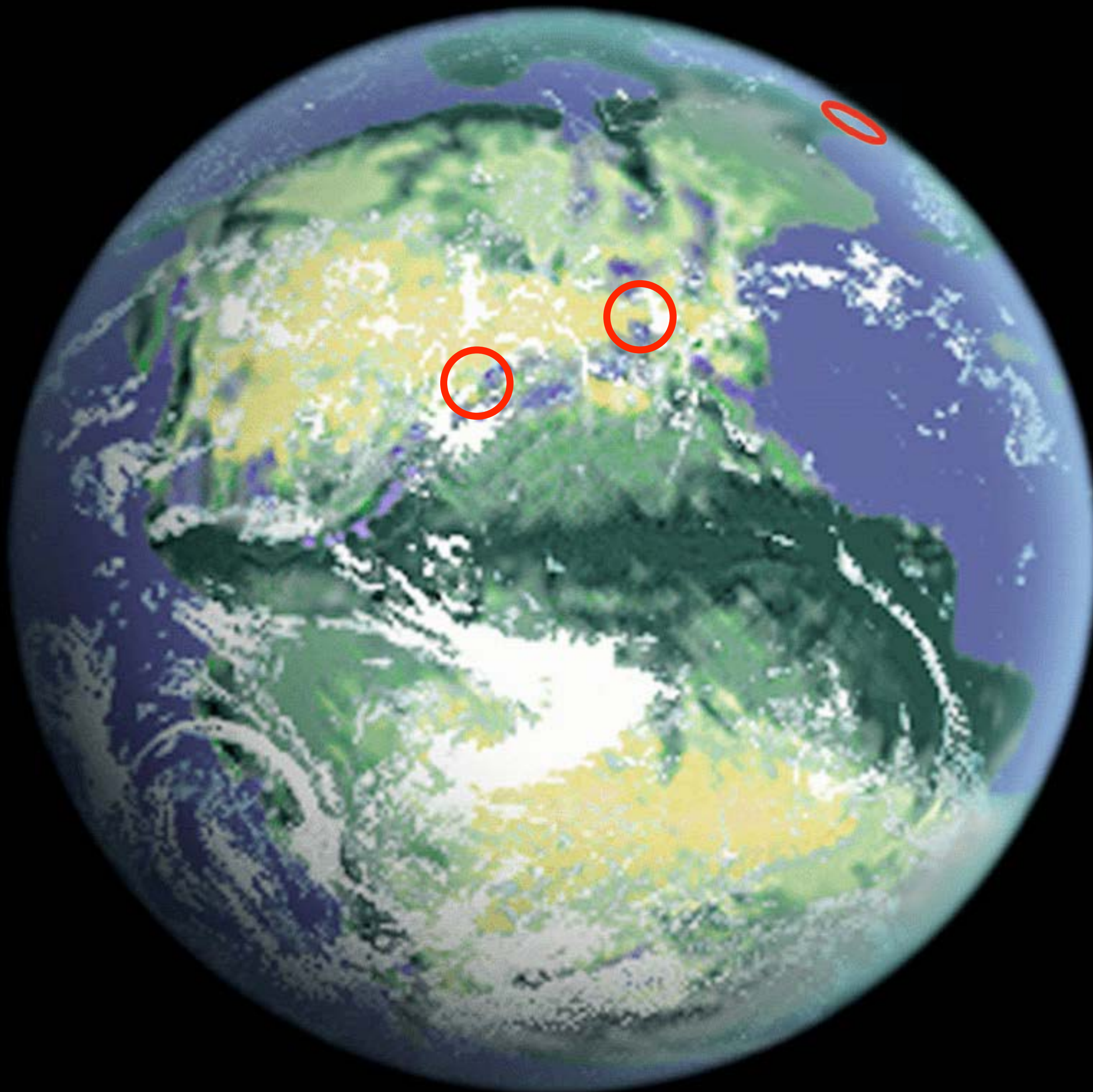




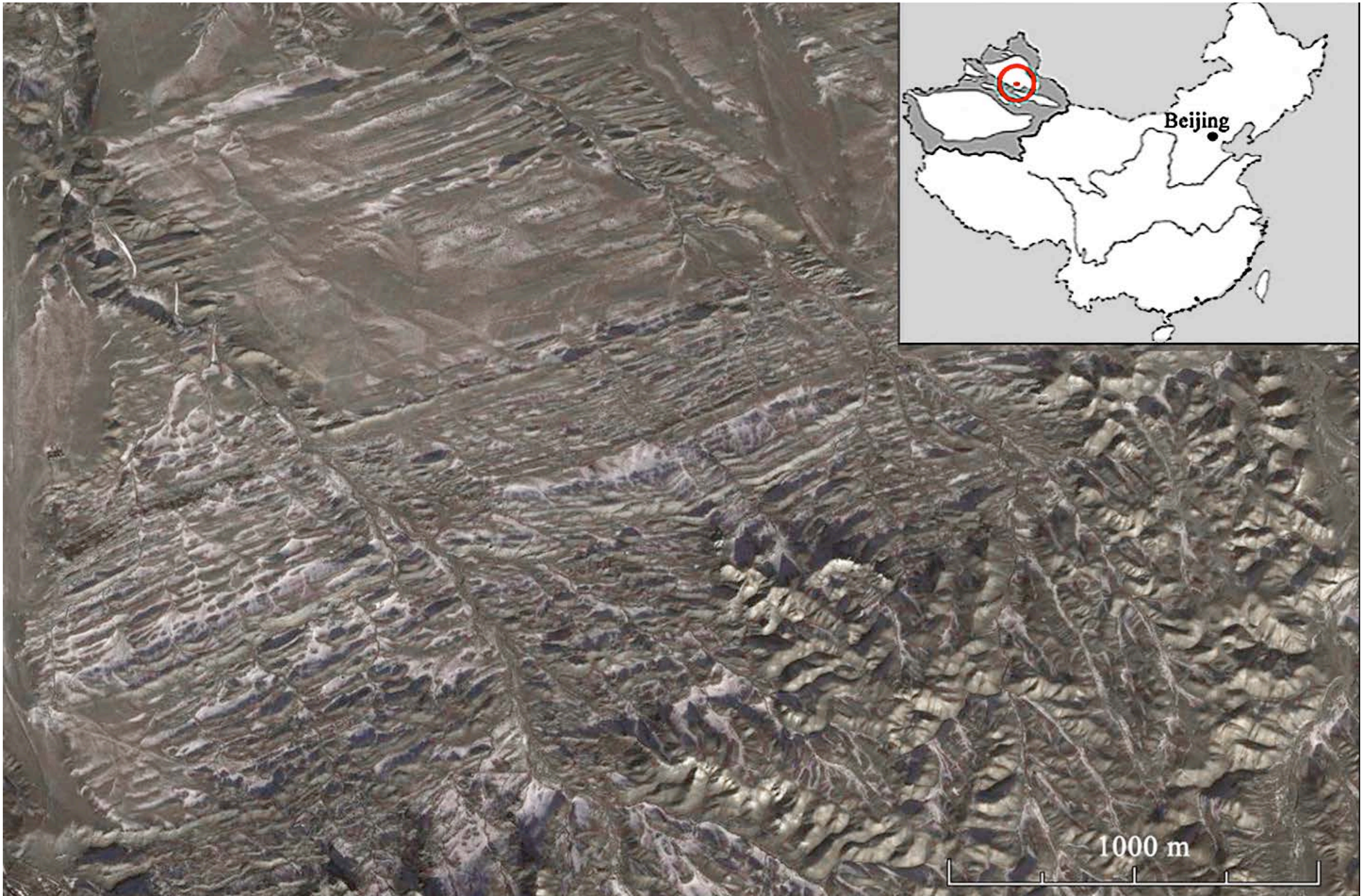
Towaco Fm. C-128 Core
Newark Basin

East Berlin Fm., Stevens
Hartford Basin

NBCP, Bristol Channel, & Junggar

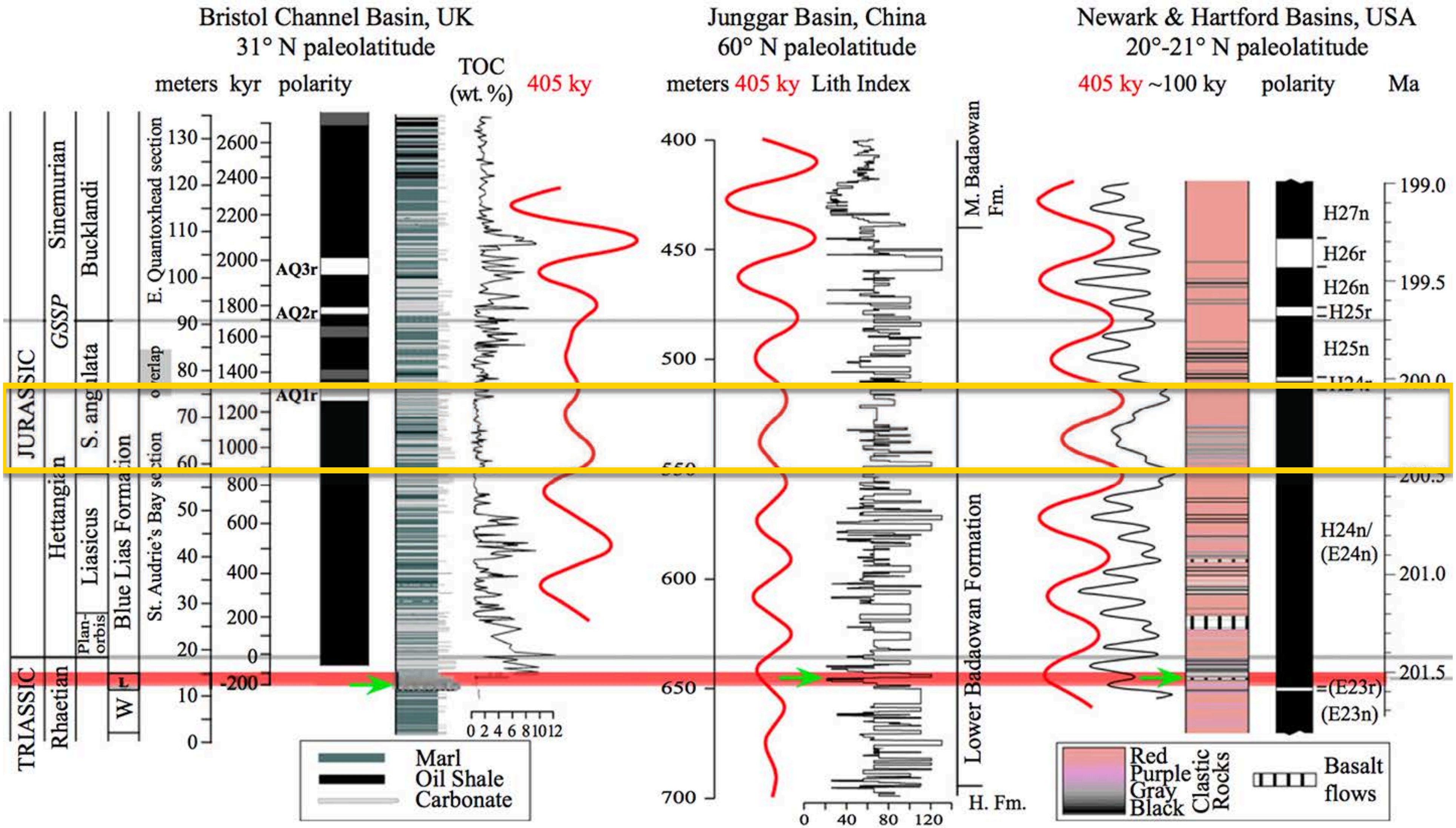


31° N: Late Triassic-Early Jurassic Marine Blue Lias Fm.,
Bristol Channel, St. Audrie’s Bay, Somerset, England



60° N: Triassic-Jurassic Badaowan and Haojiagou Formations,
Junggar Basin, Ürümqui, Western China

Match of Independent Astrochronologies



How reproducable

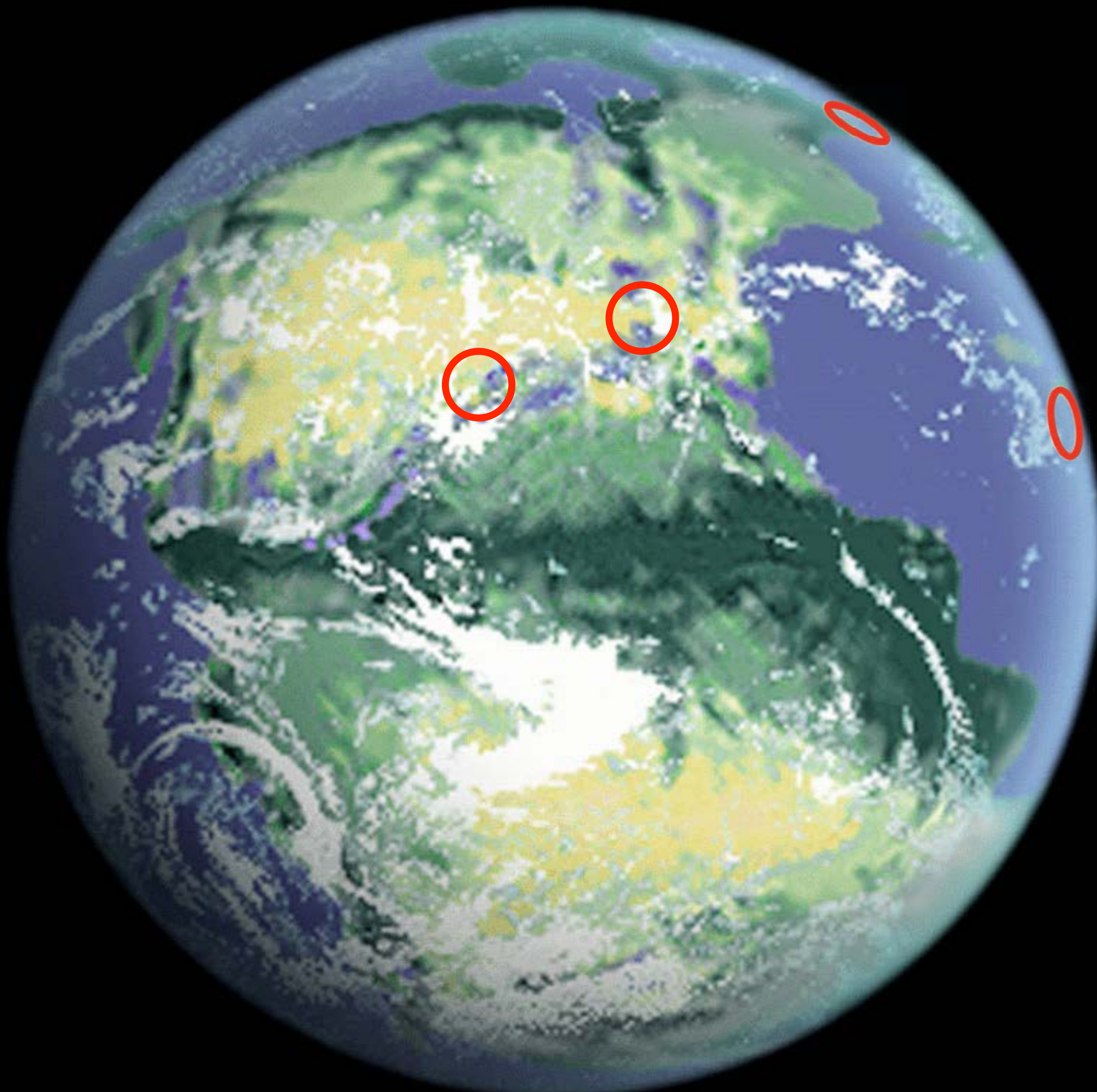
Signal in different proxies

Completeness

Astrochronology

Mars-Earth, g_4-g_3

NBCP, Bristol Channel, Junggar, & Panthalassa



Equatorial Pelagic Radiolarian Ribbon Chert, Inuyama, Japan

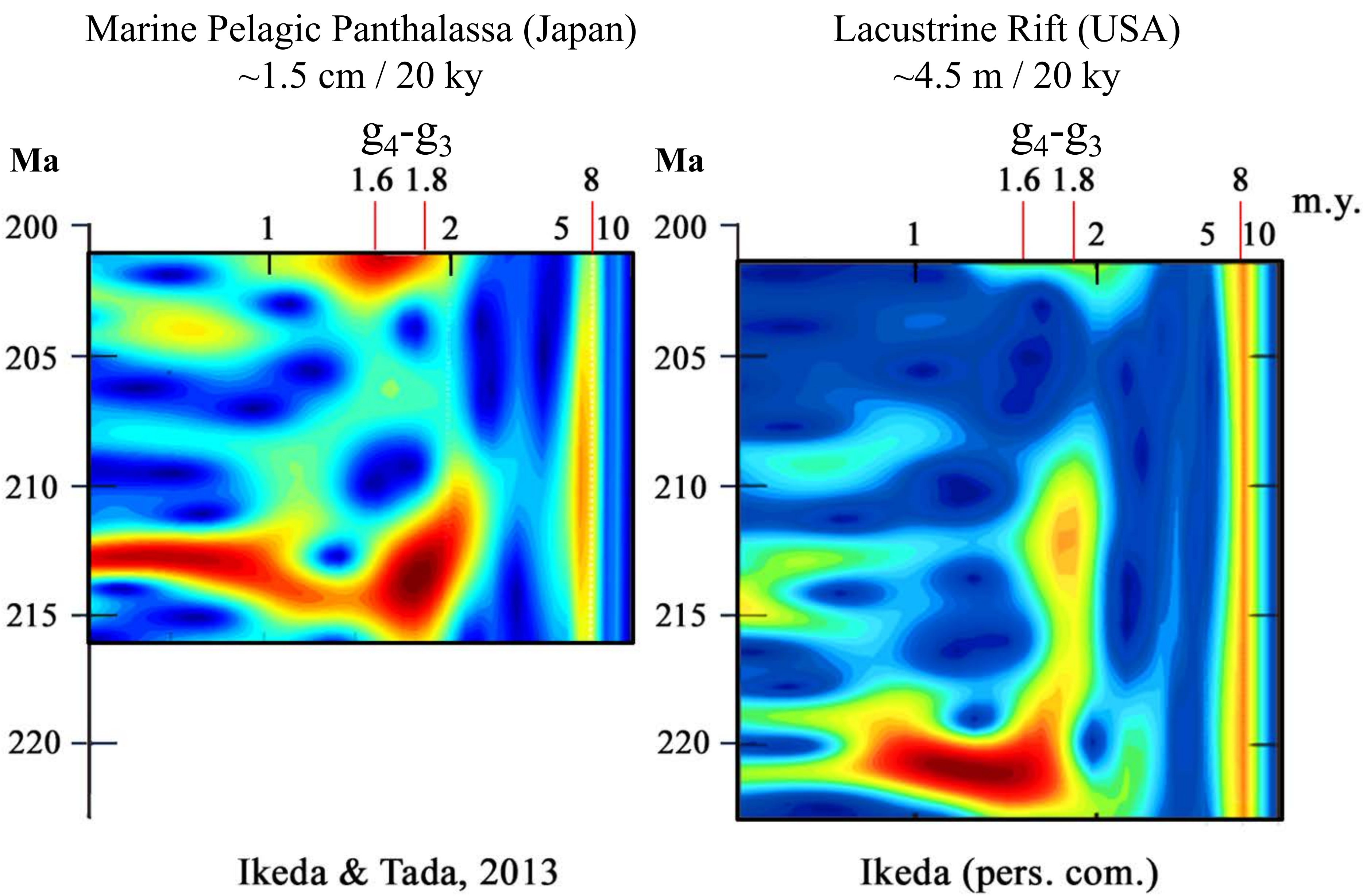
~1.7 m.y.

405 ky

~100 ky

Courtesy Masayuki Ikeda

Testing Eccentricity Modulators

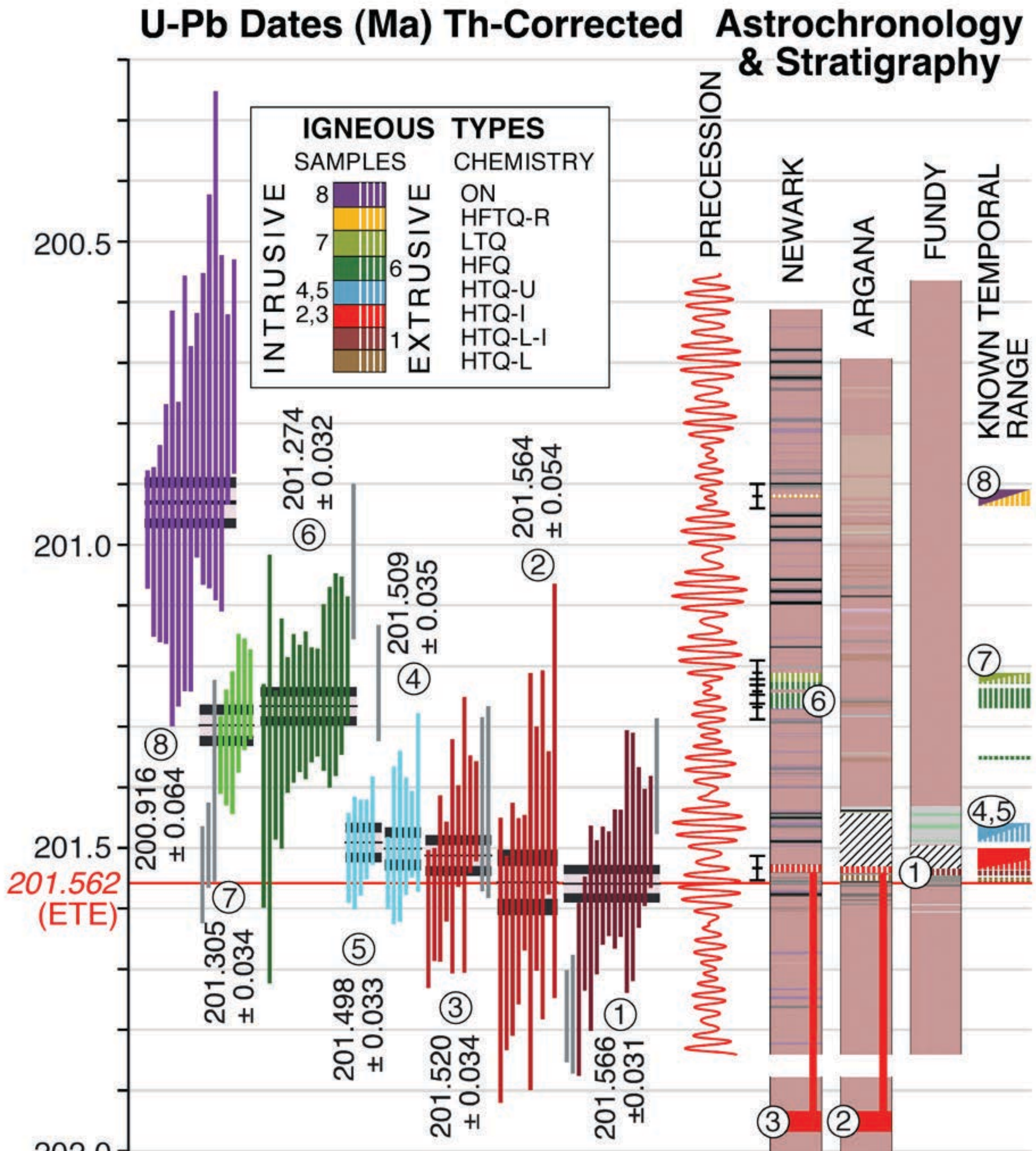


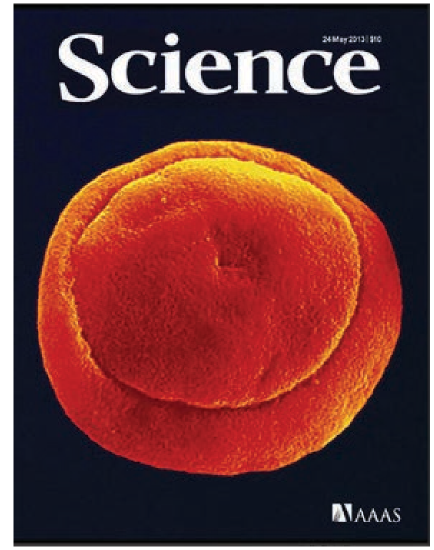
S-Transform Spectra

How accurate?

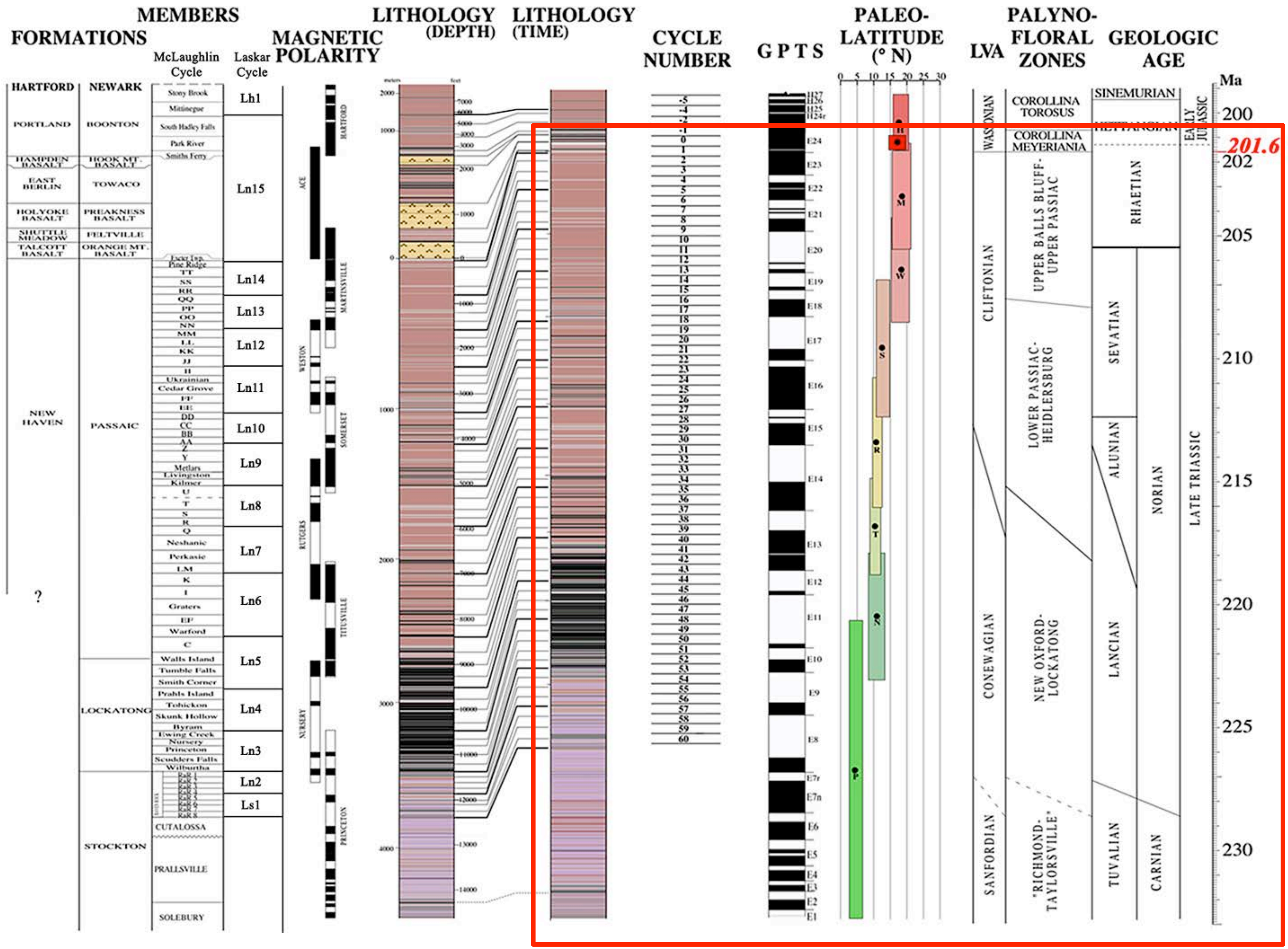
Time on small scale

On large Scale (the CPCP)

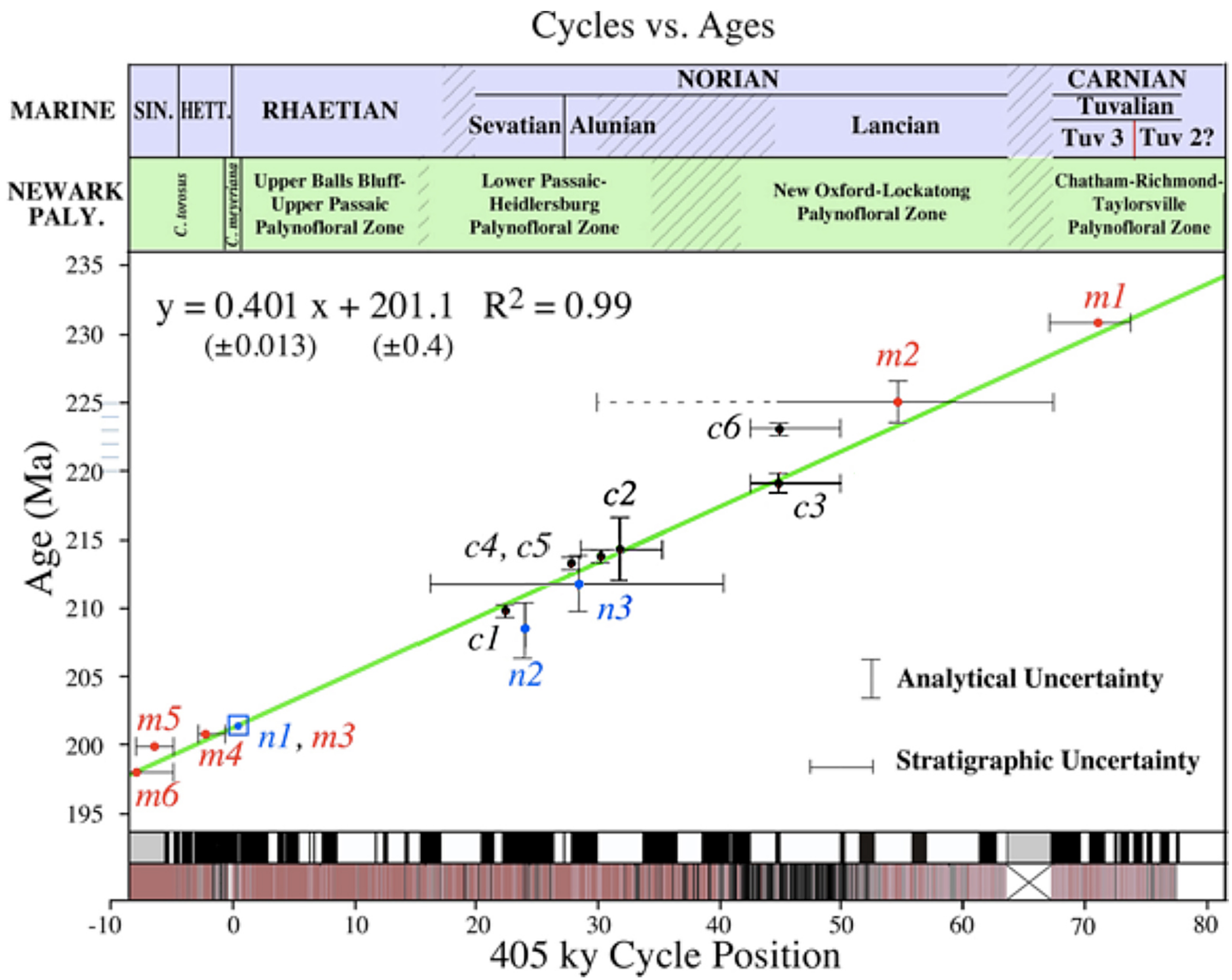




Blackburn et al., 2013

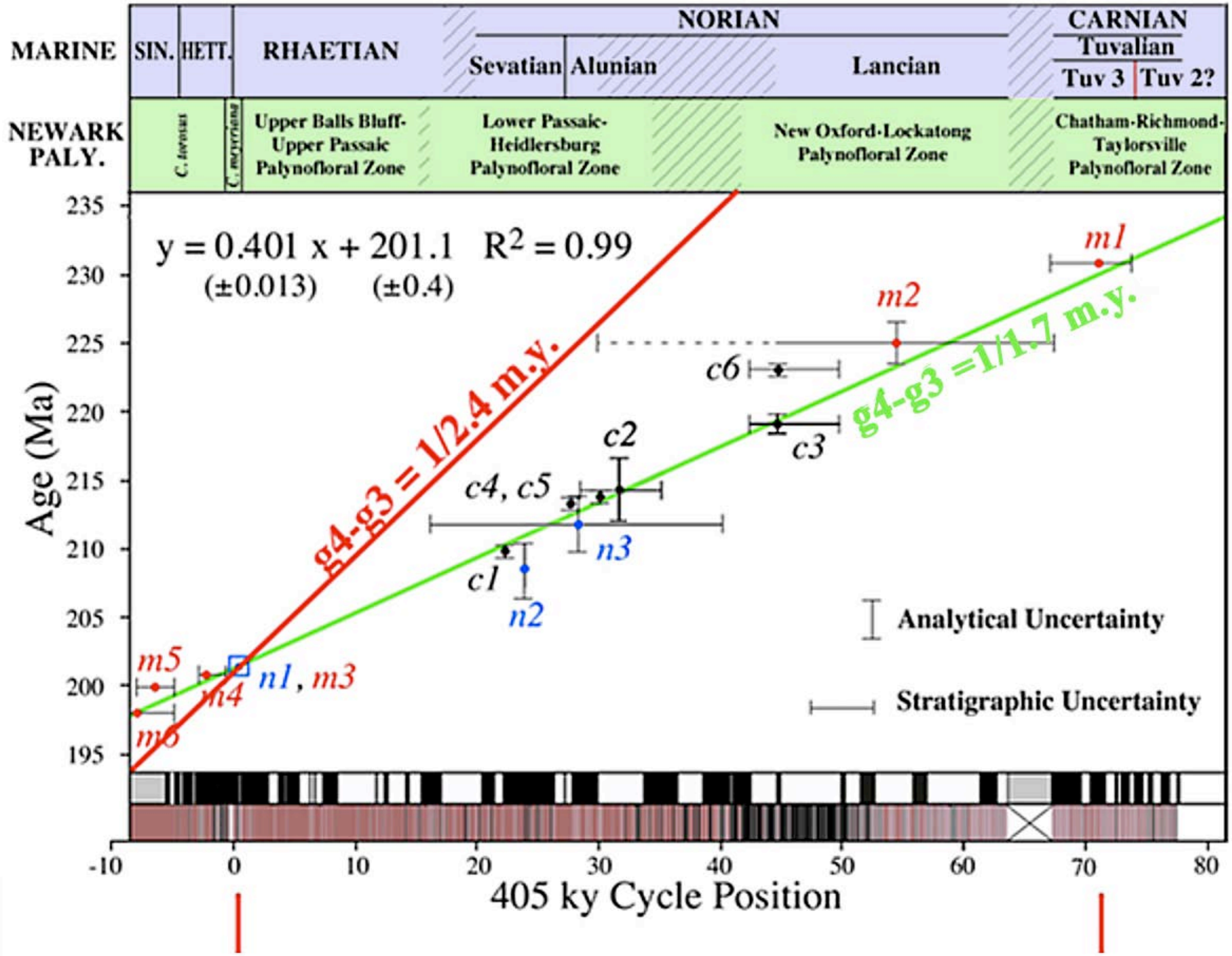


FORMATIONS
MEMBERS
McLaughlin Cycle
Laskar Cycle
MAGNETIC POLARITY
LITHOLOGY (DEPTH)
LITHOLOGY (TIME)
CYCLE NUMBER
G P T S
PALEO-LATITUDE (° N)
LVA
PALYNO-FLORAL ZONES
GEOLOGIC AGE
Ma
HARTFORD
NEWARK
PORTLAND
BOONTON
HAMPDEN BASALT
HOOK MT. BASALT
EAST BERLIN
TOWACO
HOLYOKE BASALT
PREAKNESS BASALT
SHUTTLE MEADOW
FELTVILLE
TALCOTT BASALT
ORANGE MT. BASALT
NEW HAVEN
PASSAIC
LOCKATONG
STOCKTON
Lh1
Ln15
Ln14
Ln13
Ln12
Ln11
Ln10
Ln9
Ln8
Ln7
Ln6
Ln5
Ln4
Ln3
Ln2
Ls1
CUTALOSSA
PRALLSVILLE
SOLEBURY
WASONIAN
CLIFTONIAN
CONEWAGIAN
SANFORDIAN
COROLLINA TOROSUS
COROLLINA MEYERIANIA
UPPER BALLS BLUFF-UPPER PASSAIC
LOWER PASSAIC-HEIDLERSBURG
NEW OXFORD-LOCKATONG
"RICHMOND-TAYLORSVILLE"
SINEMURIAN
HETTANGIAN
RHAETIAN
SEVATIAN
ALUNIAN
LANCIAN
TUVALIAN
NORIAN
CARNIAN
EARLY JURASSIC
LATE TRIASSIC
201.6
200
202
205
210
215
220
225
230



Cycles vs. Ages
MARINE
SIN.
HETT.
RHAETIAN
NORIAN
Sevatian
Alunian
Lancian
CARNIAN
Tuvalian
Tuv 3
Tuv 2?
NEWARK PALY.
C. torosus
C. meyeriana
Upper Balls Bluff-Upper Passaic Palynofloral Zone
Lower Passaic-Heidlersburg Palynofloral Zone
New Oxford-Lockatong Palynofloral Zone
Chatham-Richmond-Taylorsville Palynofloral Zone
y = 0.401 x + 201.1 R2 = 0.99
(±0.013) (±0.4)
Age (Ma)
405 ky Cycle Position
m1
m2
c6
c2
c3
c4, c5
n3
c1
n2
m5
m4
n1, m3
m6
Analytical Uncertainty
Stratigraphic Uncertainty

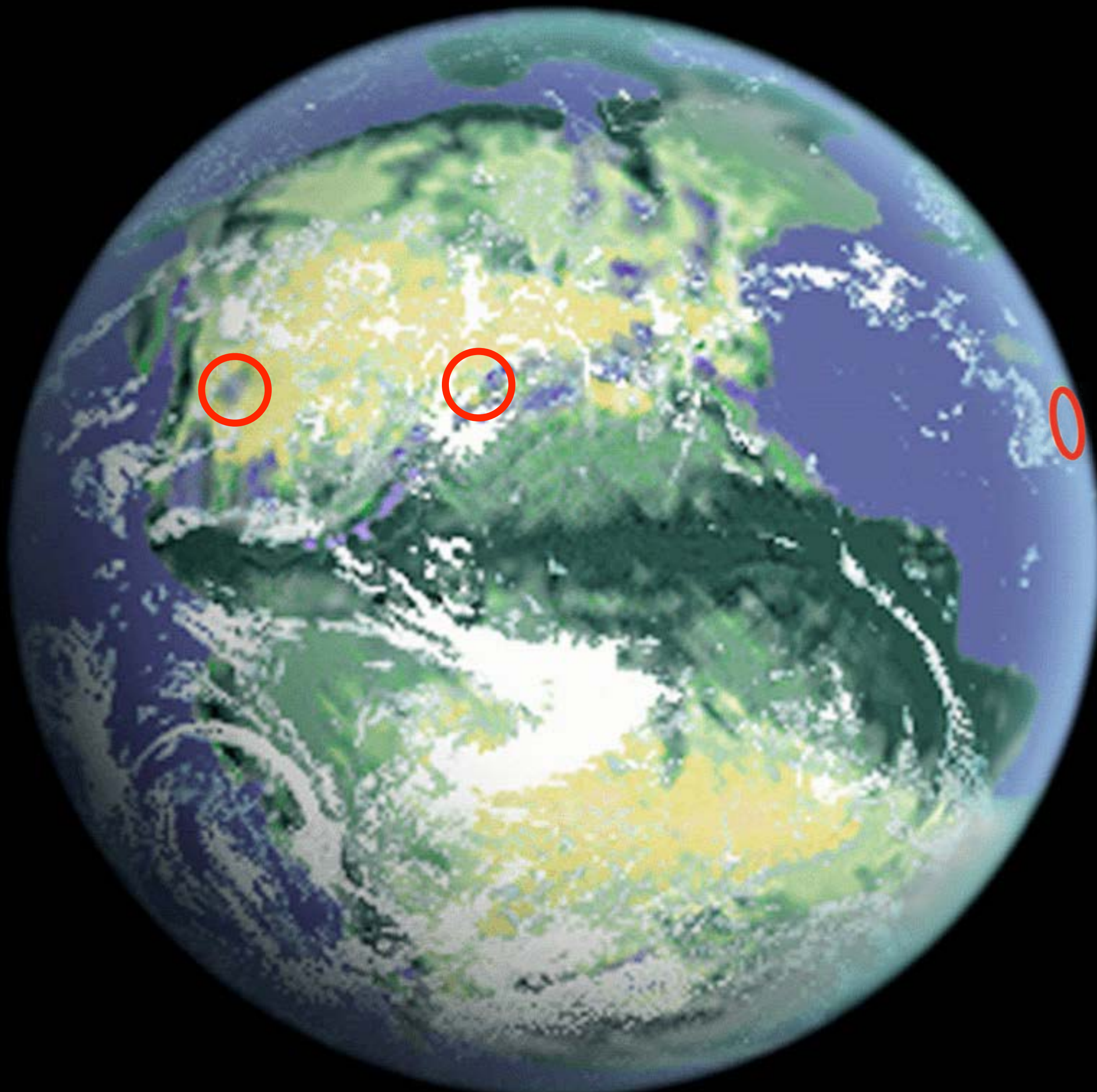
Cycles vs. Ages



$^{206}Pb/^{238}U$ age = 201.6 Ma

$^{206}Pb/^{238}U$ age = 230.9 Ma
2.4 m.y. cycle age = 241.2 Ma

NBCP & CPCP (Colorado Plateau Coring Project)



CPCP : Phase I, Petrified Forest Core

Chinde Point, Petrified Forest National Park

CPCP : Phase I, Petrified Forest Core

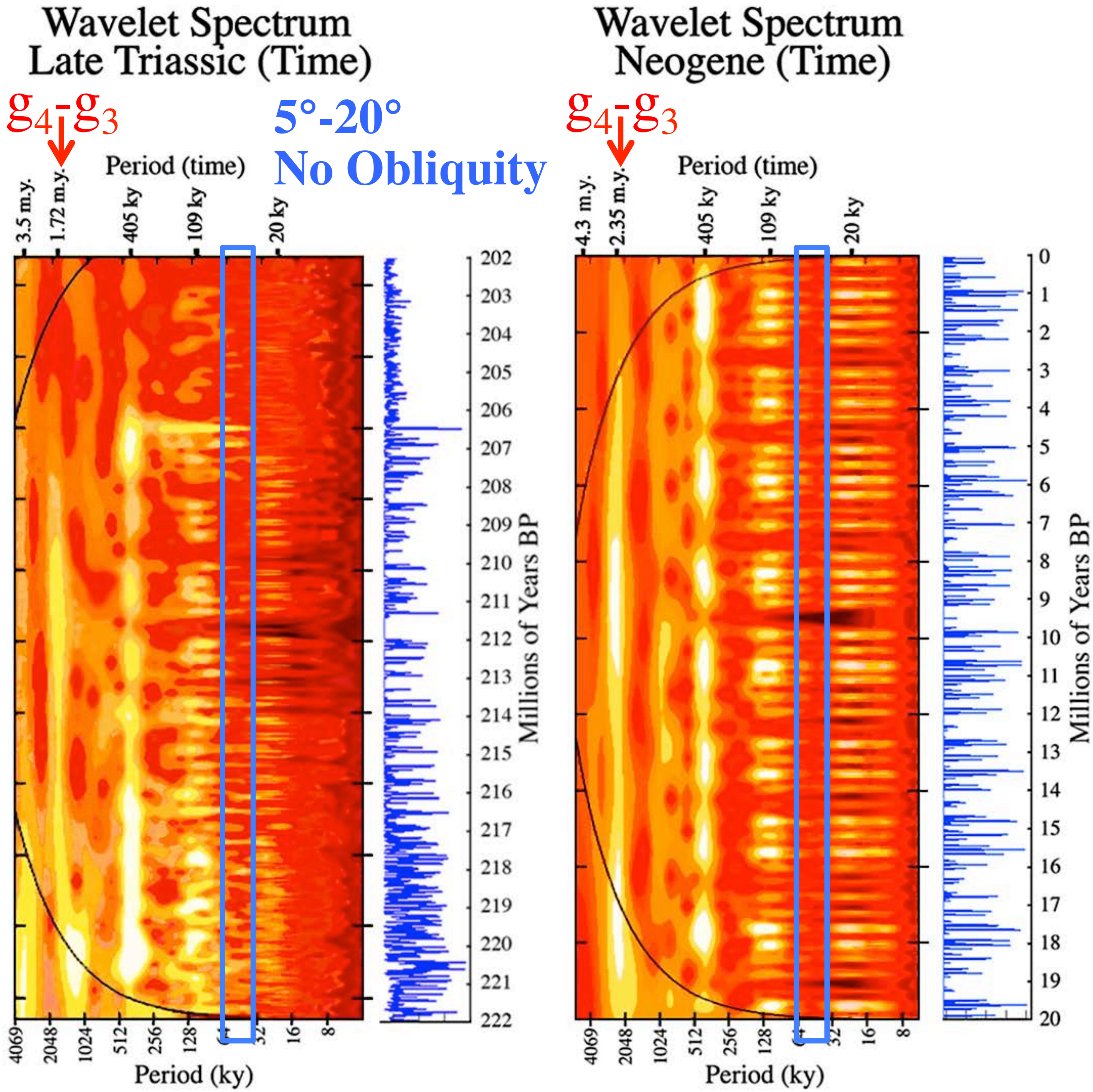
November 2013

1) Problem: Astronomical solutions chaotic. Geological record allows tests of astronomical solutions

2) Showing that it is possible to get meaningful results from deep time (NBCP – CPCP)

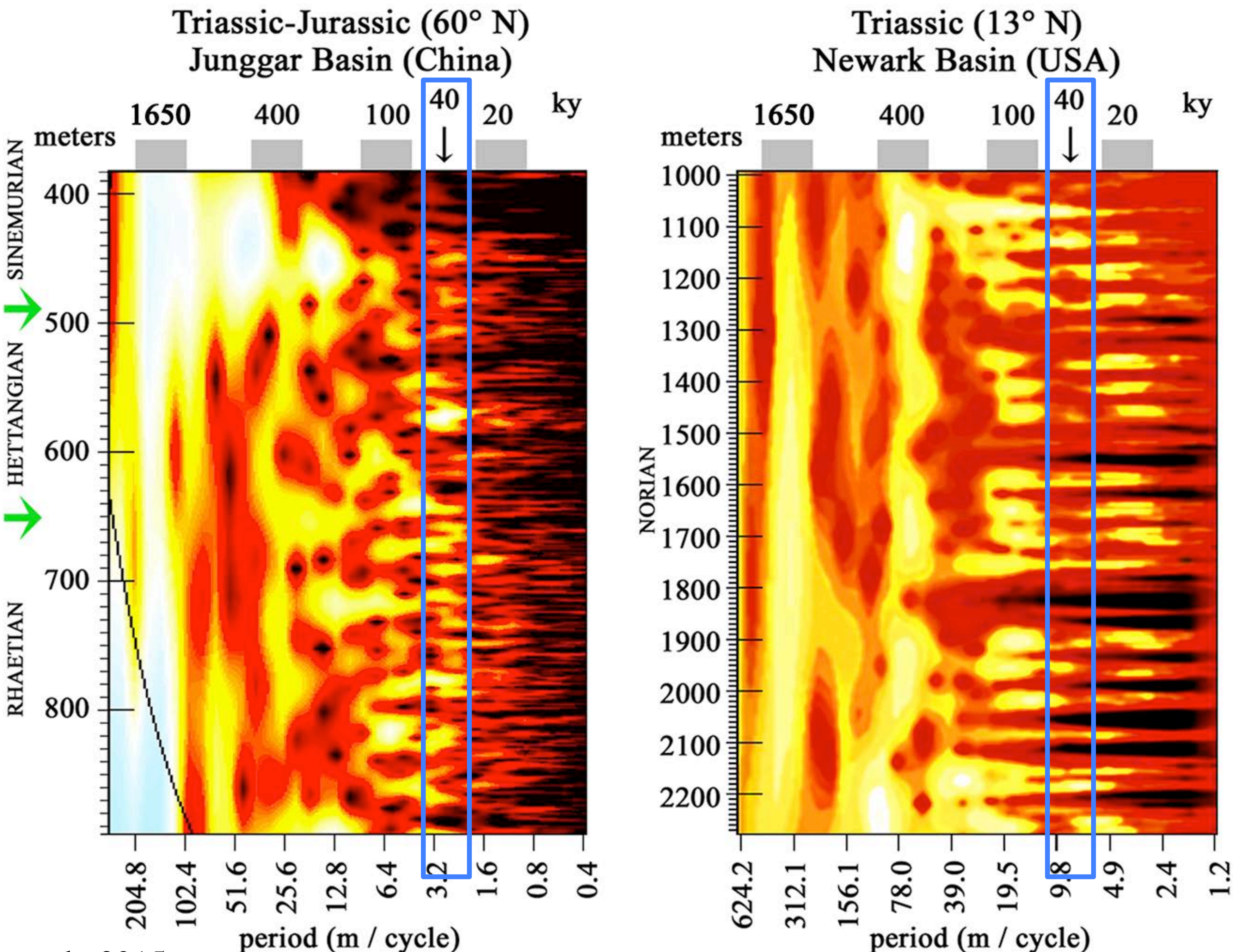
3) Recovering obliquity from high latitudes

4) The Geological Orrery Program


Wavelet Spectrum
Late Triassic (Time)
g4-g3
5°-20°
No Obliquity
Period (time)
3.5 m.y.
1.72 m.y.
405 ky
109 ky
20 ky
4069
2048
1024
512
256
128
64
32
16
8
Period (ky)
202
203
204
205
206
207
208
209
210
211
212
213
214
215
216
217
218
219
220
221
222
Millions of Years BP
Wavelet Spectrum
Neogene (Time)
g4-g3
Period (time)
4.3 m.y.
2.35 m.y.
405 ky
109 ky
20 ky
4069
2048
1024
512
256
128
64
32
16
8
Period (ky)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
Millions of Years BP

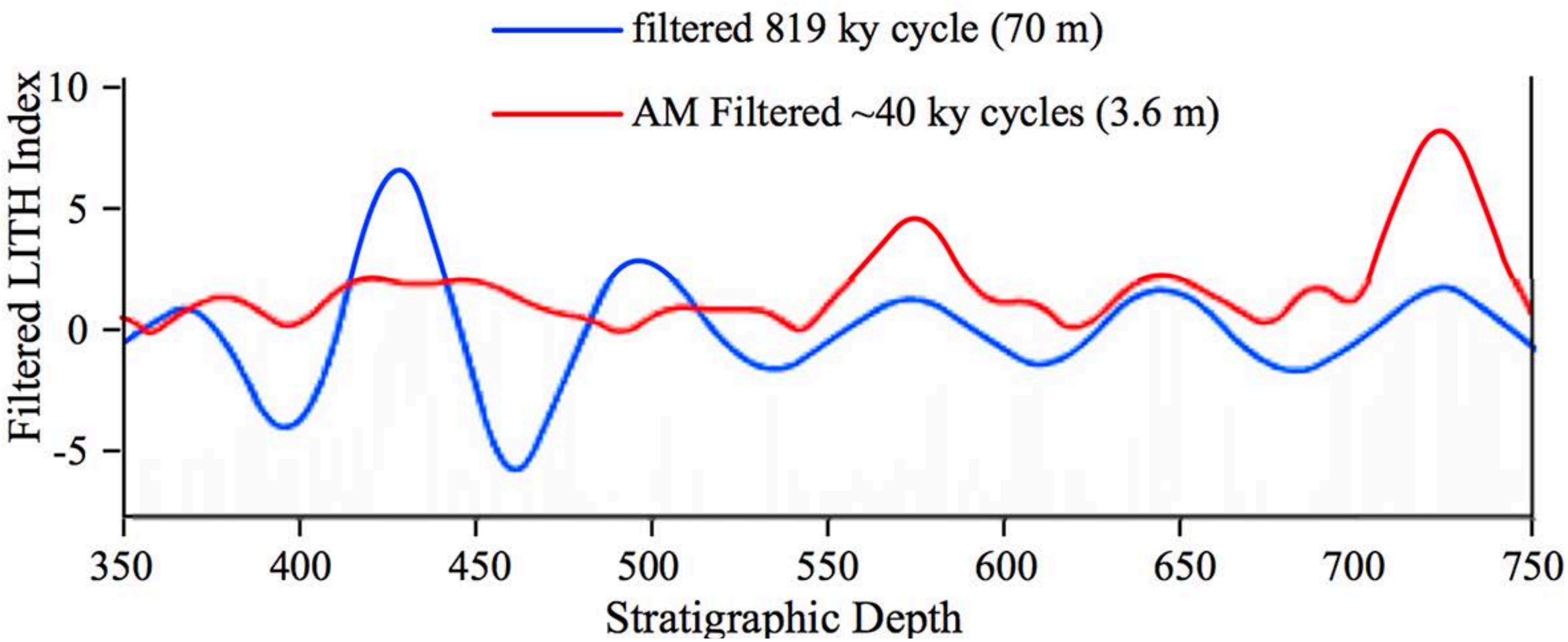
Junggar Basin, Triassic- Jurassic: 60° N

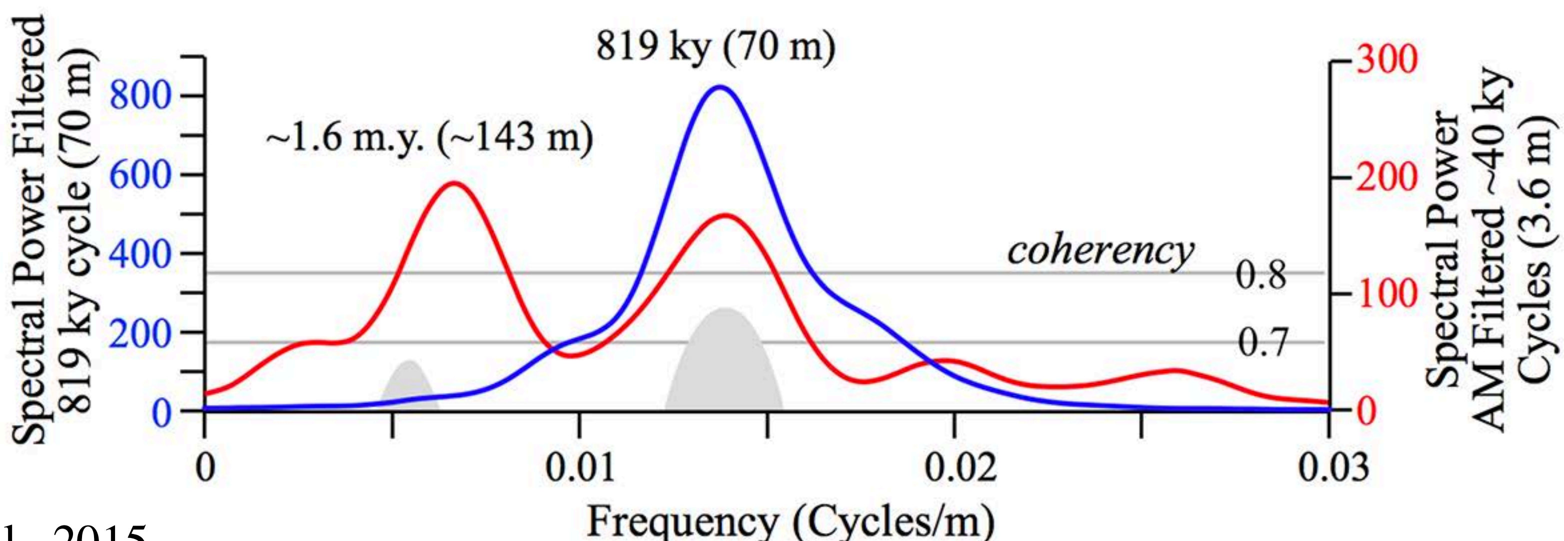
Badaowan Formation, Haojiagou Valley



Sha et al., 2015

s_4-s_3?





Sha et al., 2015

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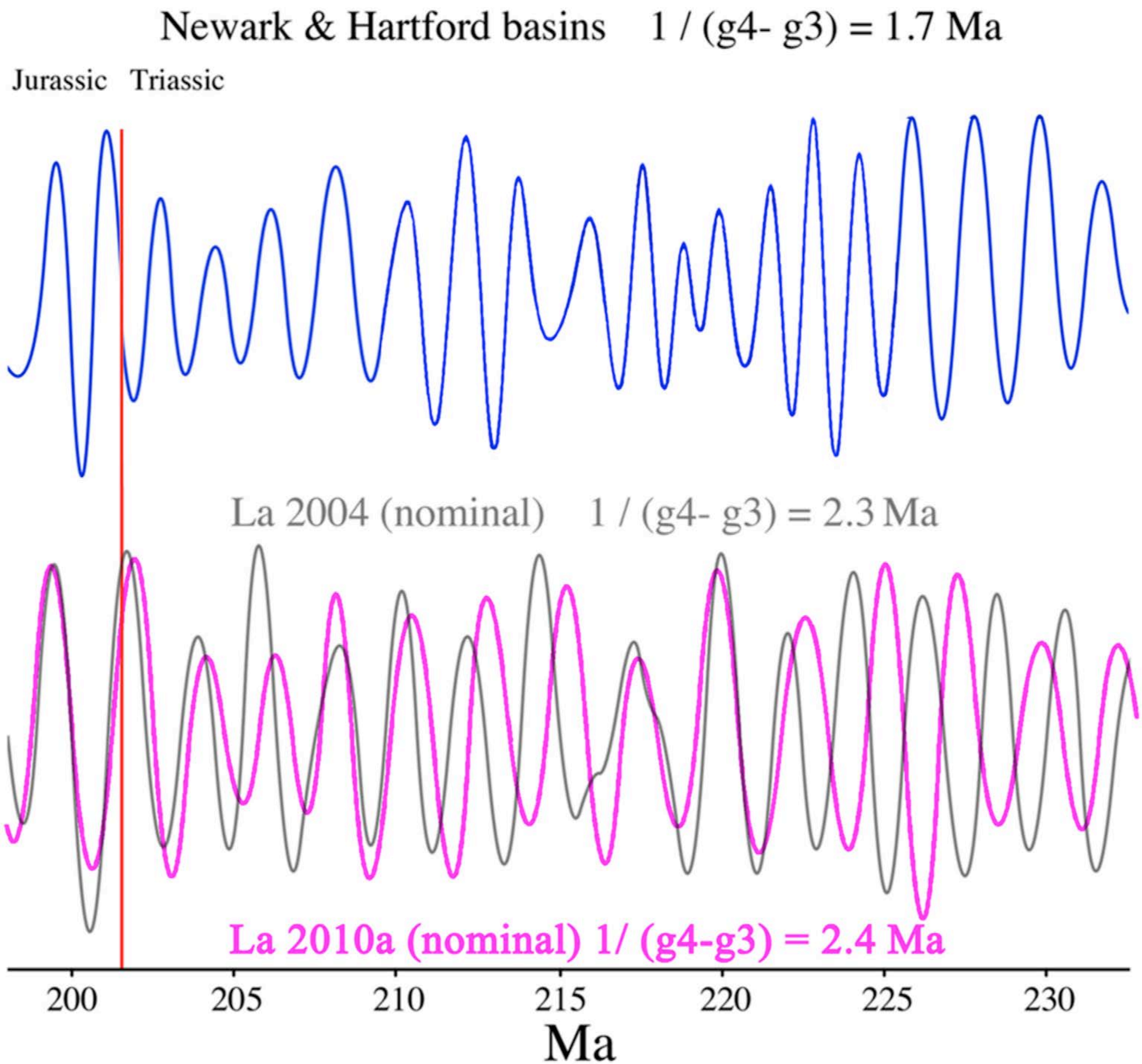
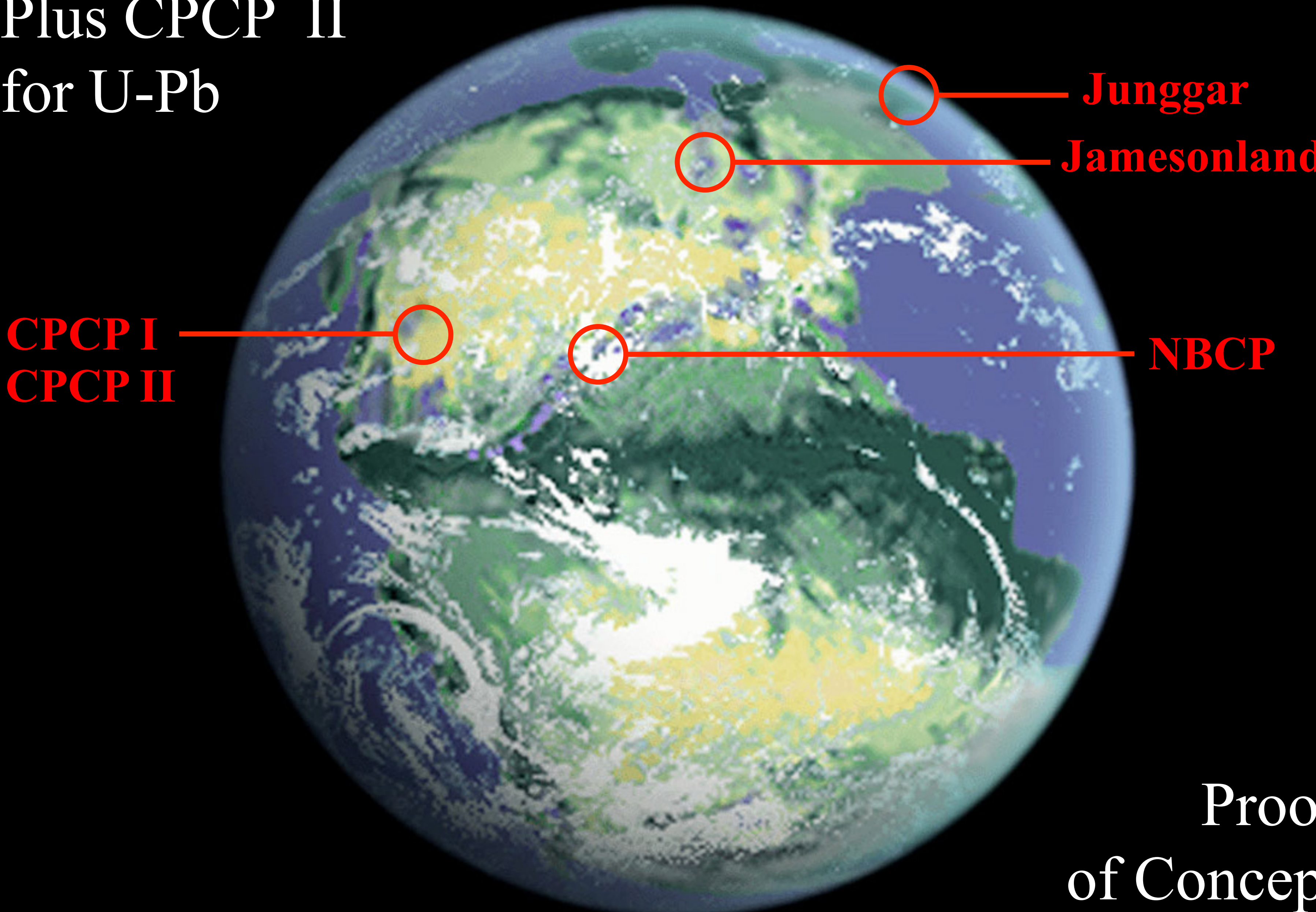


Newark & Hartford basins 1 / (g4- g3) = 1.7 Ma
Jurassic
Triassic
La 2004 (nominal) 1 / (g4- g3) = 2.3 Ma
La 2010a (nominal) 1/ (g4-g3) = 2.4 Ma
200
205
210
215
220
225
230
Ma

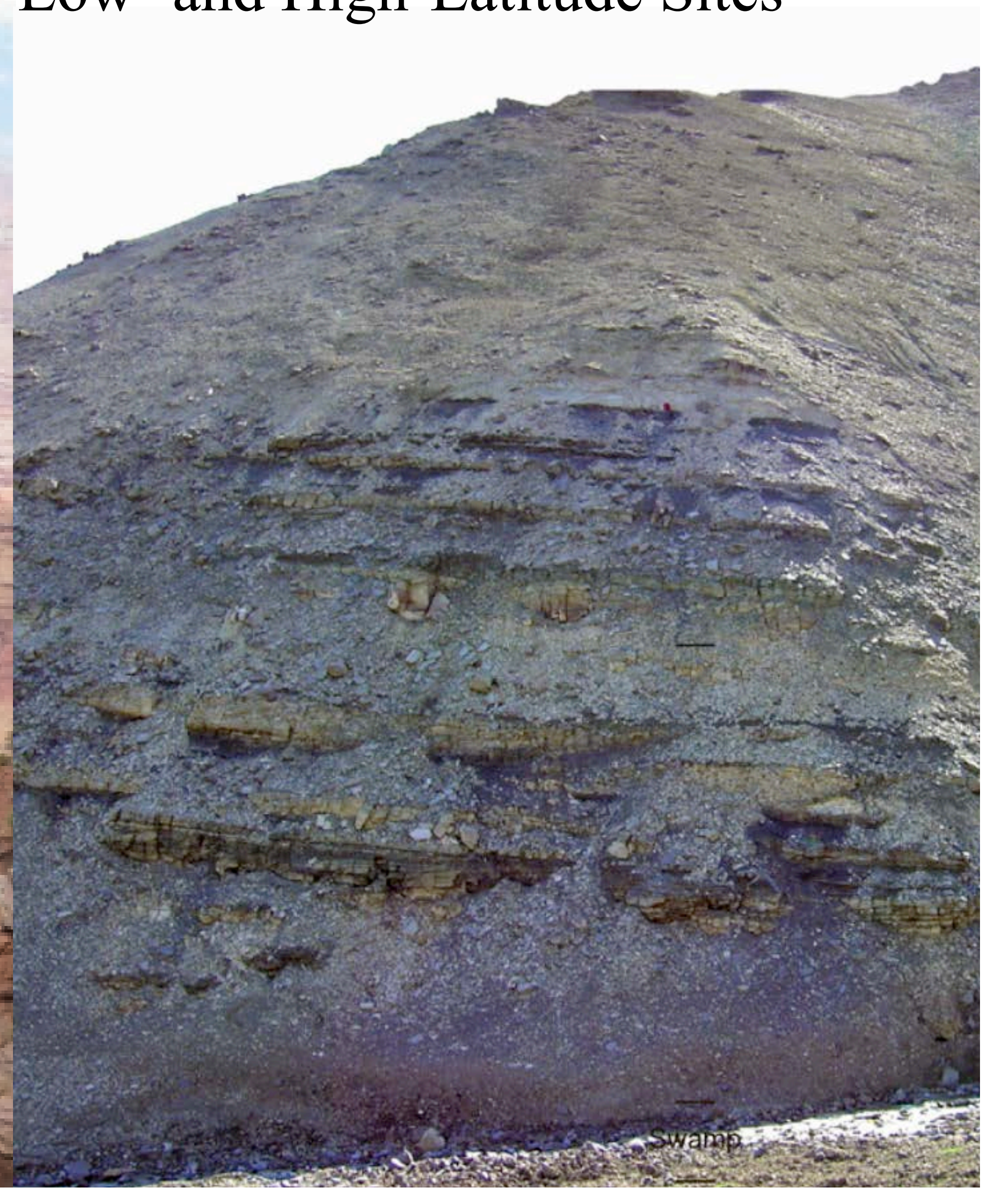
NBCP & Greenland (low latitude – high latitude pair)
Plus CPCP II
for U-Pb



Proof
of Concept

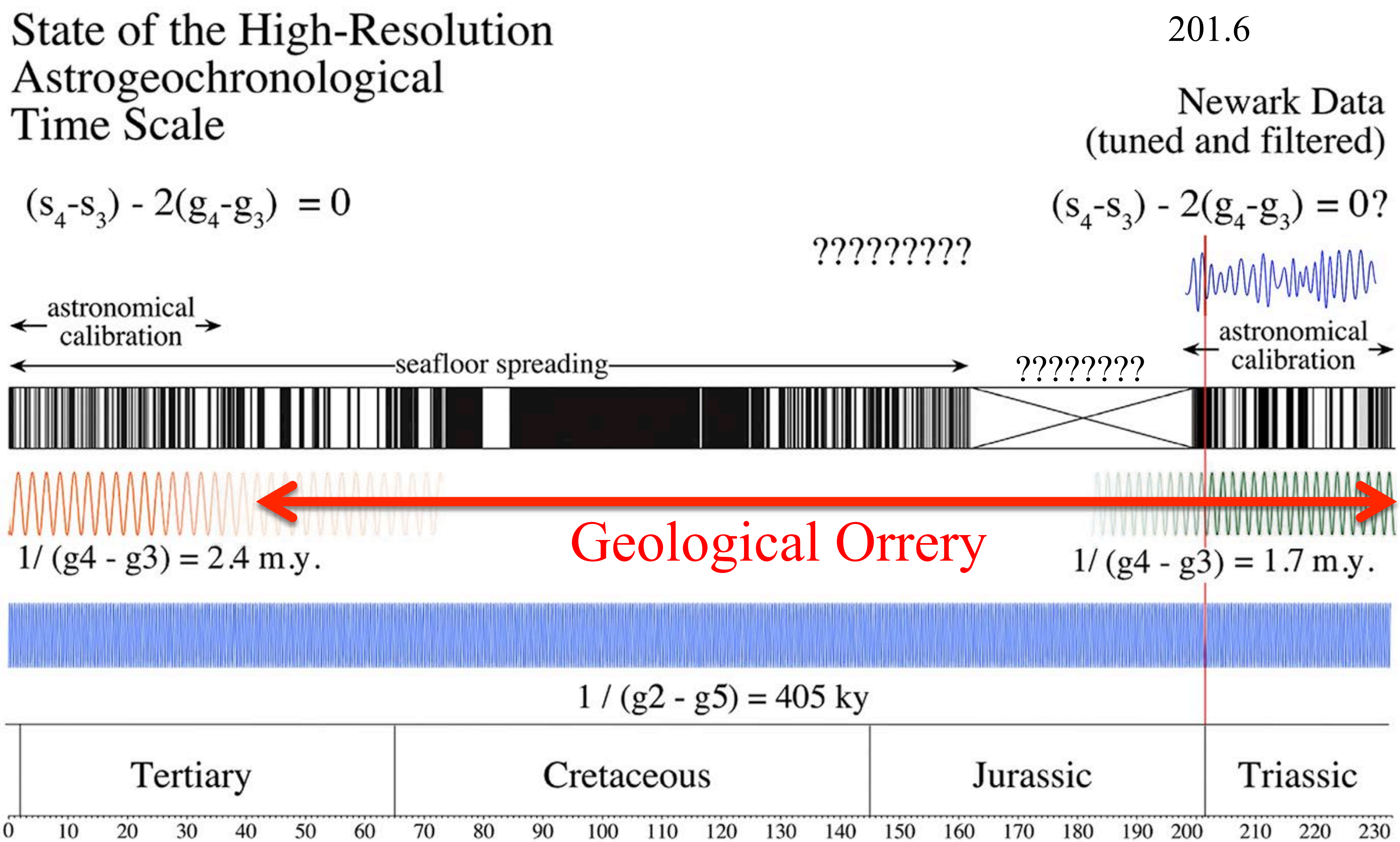
Recovering Triassic-Jurassic Eccentricity (g4-g3)and Obliquity (s4-s3) With Paired Triassic-Jurassic Low- and High-Latitude Sites

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



40°- 60° N: Jamesonland,
East Greenland


Middle Jurassic Tiaojishan Fm., Inner Mongolia



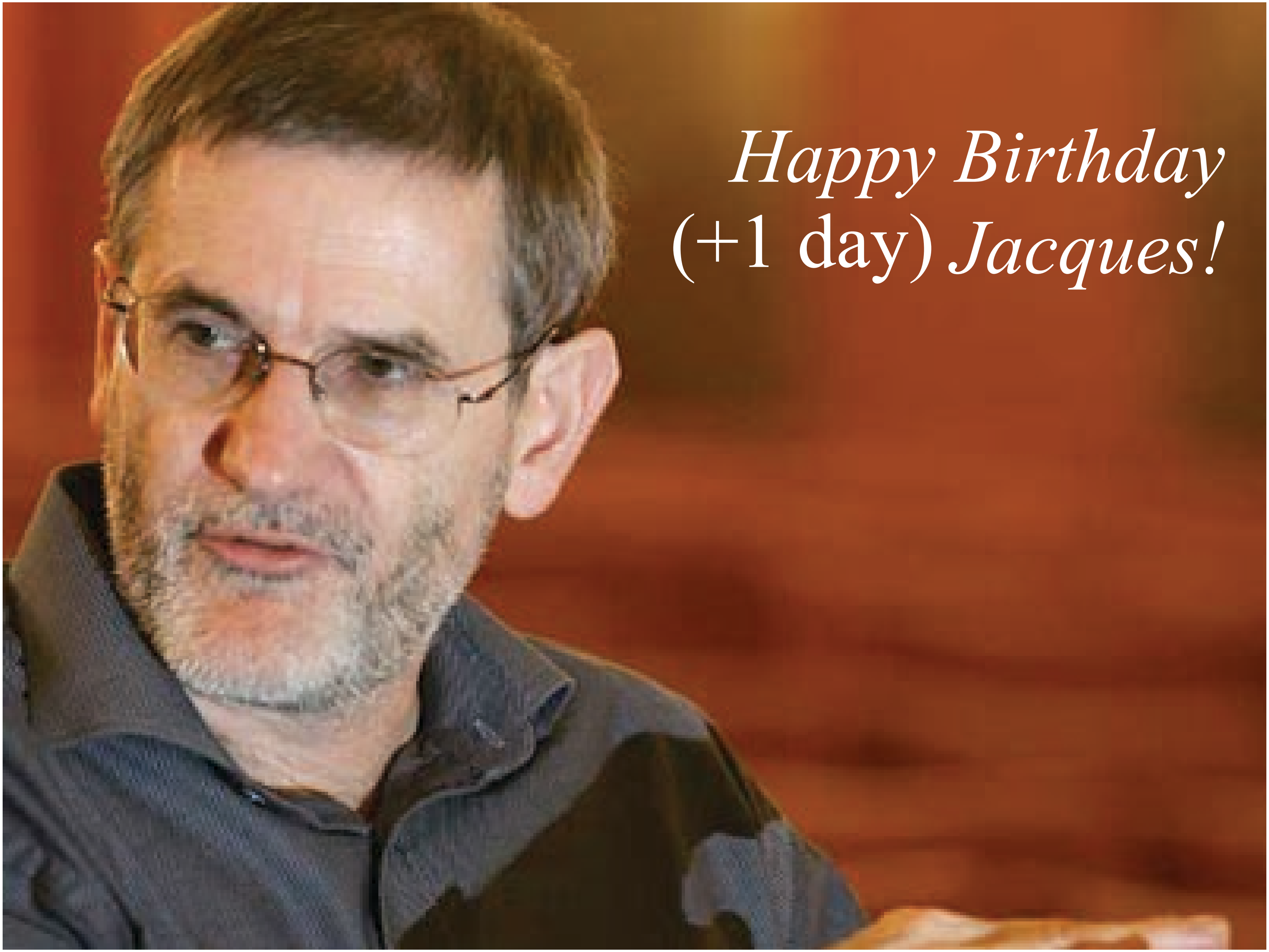
State of the High-Resolution Astrogeochronological Time Scale
201.6
Newark Data (tuned and filtered)
$(s_4-s_3) - 2(g_4-g_3) = 0$
$(s_4-s_3) - 2(g_4-g_3) = 0?$
?????????
astronomical calibration
seafloor spreading
????????
astronomical calibration
Geological Orrery
1/ (g4 - g3) = 2.4 m.y.
1/ (g4 - g3) = 1.7 m.y.
1 / (g2 - g5) = 405 ky
Tertiary
Cretaceous
Jurassic
Triassic
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220 230

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

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

- Resolvable orbital parameters at appropriate time scales, including precession and obliquity modulators (g_4-g_3 and s_4-s_3) from low *and* high latitudes.

- So that both the drift in secular frequencies and the major transitions in resonances can be recognized


Happy Birthday
(+1 day) *Jacques!*