Geophysics and Astronomy in dialogue

Cyclostratigraphy as a bridge between orbital cycles, climate, and life on Earth

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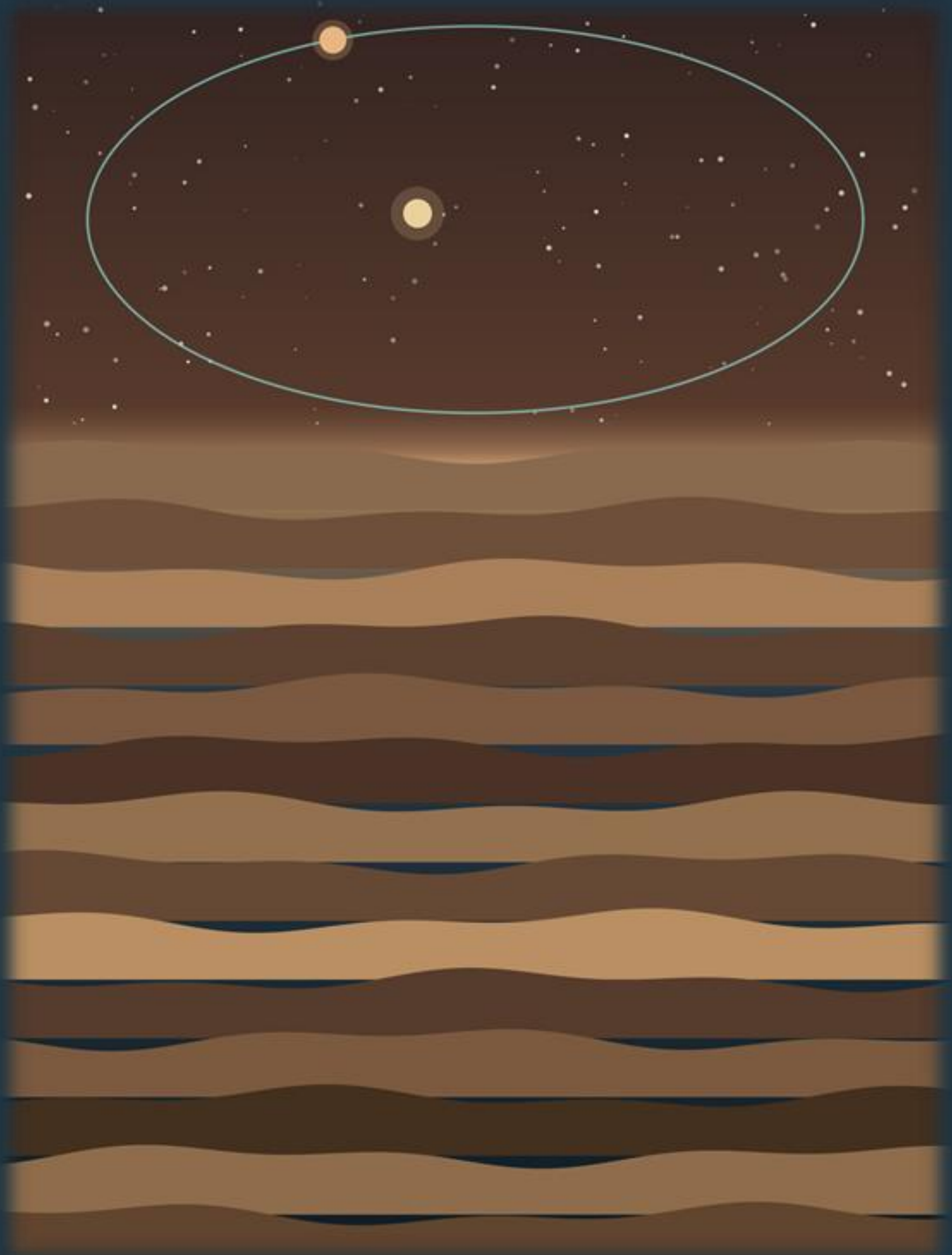
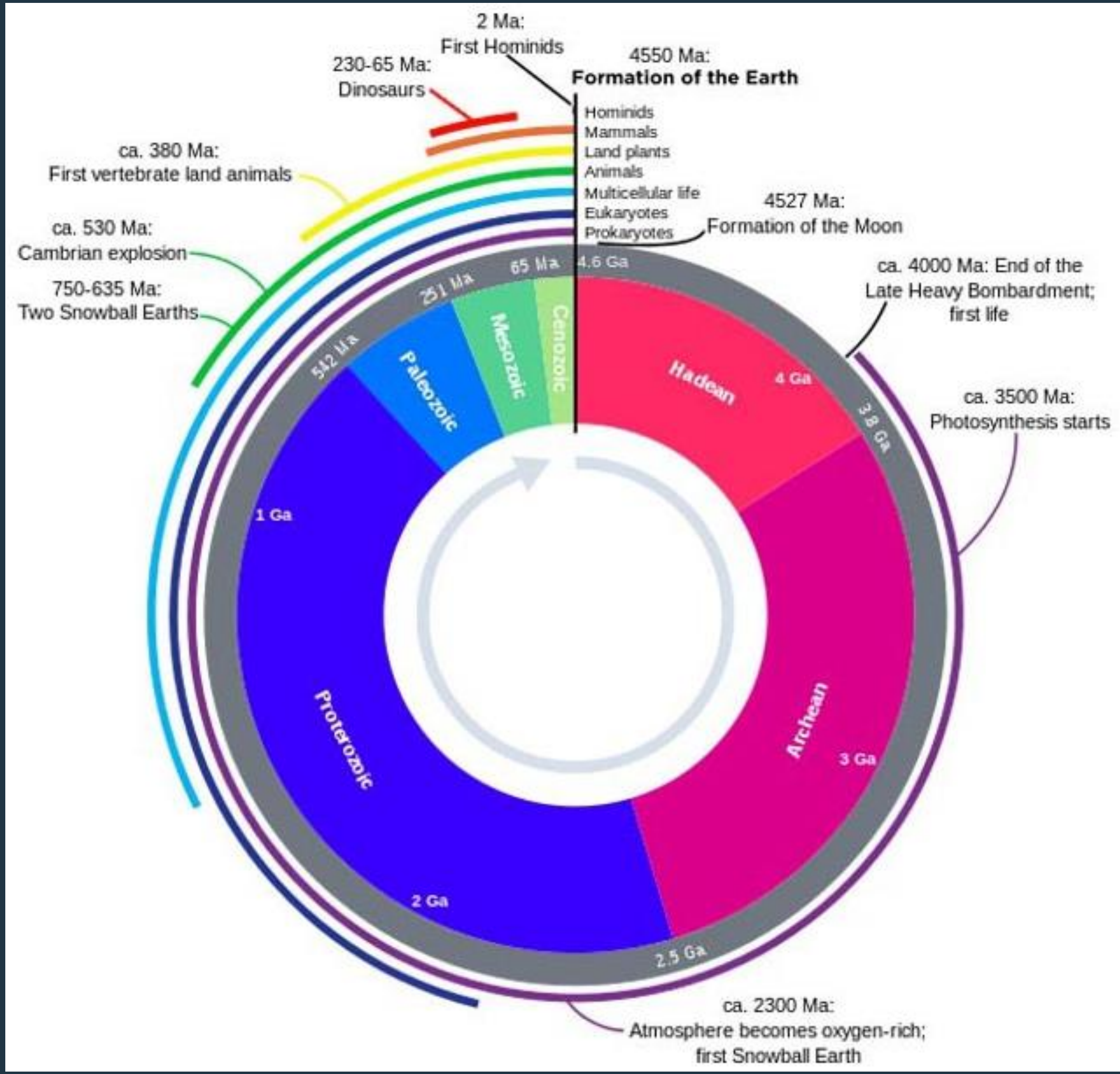


A journey through deep time



From ancient Earth to the present

From the Paleoproterozoic (2.5 Ga) to the Aptian (125 Ma), always asking: how much time does this rock represent?

One method, many ages

Astronomical cycles and magnetic polarity connect every example, whatever the age of the rock.

From Earth to other worlds

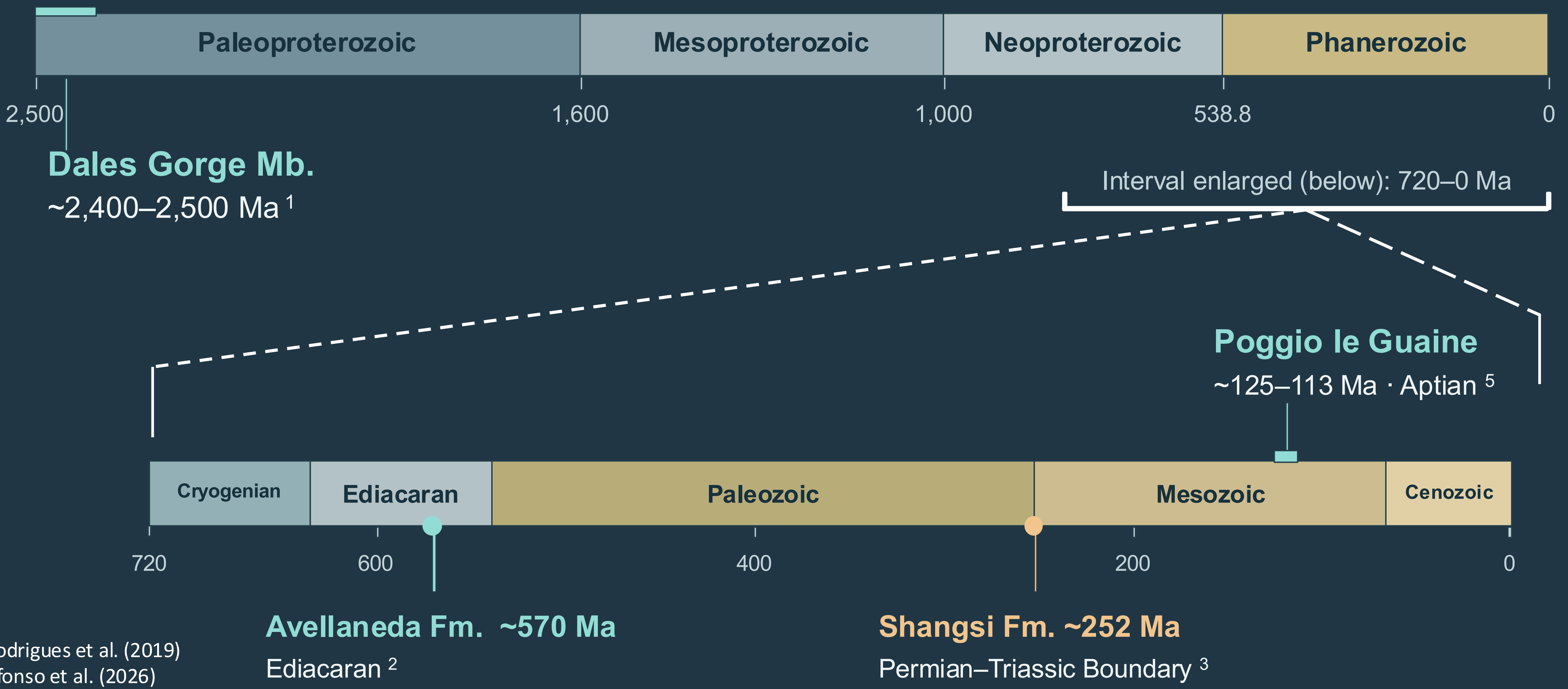
Mars: testing the limits.

Where are we? A look at the Geological Time Scale

International Commission on Stratigraphy (2023), International Chronostratigraphic Chart.

Last 2.5 Ga

Hierarchy: Eon > Era > Period > Epoch > Age.
Paleoproterozoic (Era); Ediacaran, Permian, Triassic (Periods); Aptian (Age).



[1] Rodrigues et al. (2019)
[2] Afonso et al. (2026)
[3] Wu et al. (2013)

How can rocks test an astronomical prediction?

ASTRONOMY

Calculated variations in solar radiation

→

GEOLOGICAL RECORD

Traces of past environmental change

Monte Gibliscemi, Sicily

A repeating pattern alone
does not identify an orbital cycle.

What does the material record, and when did it accumulate?

1941 Milankovitch’s synthesis

1976 A test using ocean sediments

1976 The establishment of modern cyclostratigraphy and its link to climate research

10 December 1976, Volume 194, Number 4270 SCIENCE

Variations in the Earth's Orbit: Pacemaker of the Ice Ages

For 500,000 years, major climatic changes have followed variations in obliquity and precession.

J. D. Hays, John Imbrie, N. J. Shackleton

For more than a century the cause of fluctuations in the Pleistocene ice sheets has remained an intriguing and unsolved scientific mystery. Interest in this problem has generated a number of possible explanations (*1, 2*). One group of theories invokes factors external to the climate system, including variations in the output of the sun, or the amount of solar energy reaching the earth caused by changing concentrations of interstellar dust (*3*); the seasonal and latitudinal distribution of incoming radiation caused by changes in the earth's orbital geometry (*4*); the volcanic dust content of the atmo-

hypothesis has been formulated so as to predict the frequencies of major Pleistocene glacial fluctuations. Thus it is the only explanation that can be tested geologically by determining what these frequencies are. Our main purpose here is to make such a test.

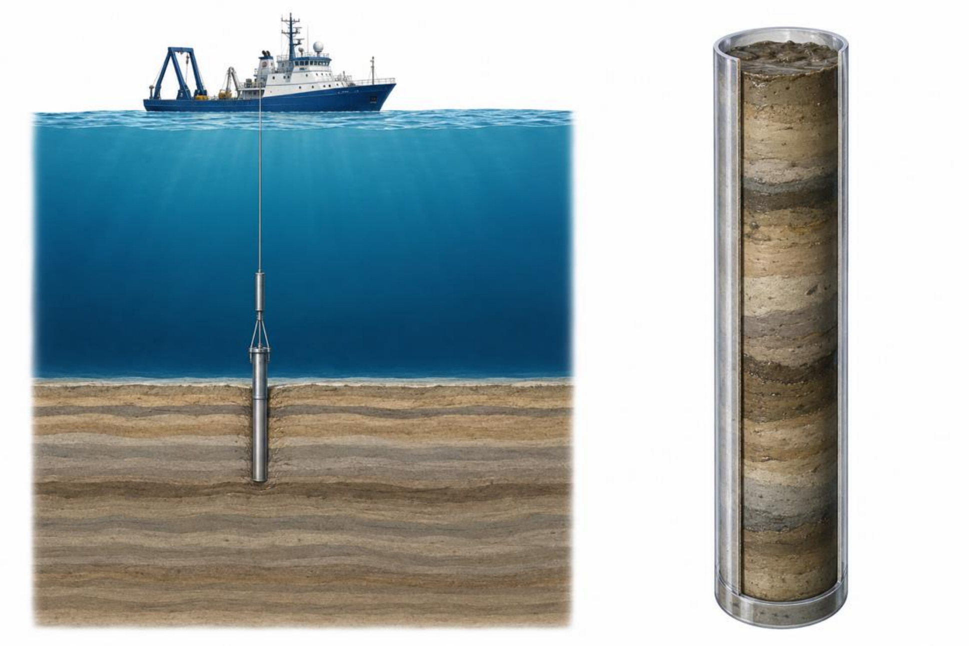
Previous work has provided strong suggestive evidence that orbital changes induced climatic change (*13–20*). However, two primary obstacles have led to continuing controversy. The first is the uncertainty in identifying which aspects of the radiation budget are critical to climatic change. Depending on the lati-

the last interglacial on the basis of these curves have ranged from 80,000 to 180,000 years ago (*22*).

The second and more critical problem in testing the orbital theory has been the uncertainty of geological chronology. Until recently the inaccuracy of dating methods limited the interval over which a meaningful test could be made to the last 150,000 years. Hence the most convincing arguments advanced in support of the orbital theory to date have been based on the ages of 80,000, 105,000, and 125,000 years obtained for coral terraces first on Barbados (*15*) and later on New Guinea (*23*) and Hawaii (*24*). These structures record episodes of high sea level (and therefore low ice volume) at times predicted by the Milankovitch theory. Unfortunately, dates for older terraces are too uncertain to yield a definitive test (*25*).

More climatic information is provided by the continuous records from deep-sea cores, especially the oxygen isotope record obtained by Emiliani (*26*). However, the quasi-periodic nature of both the isotopic and insolation curves, and the uncertain chronology of the older geologic records, have combined to render plausible different astronomical interpretations of the same geologic data (*13, 14, 17, 27*).

- 500 kyr of isotope and faunal records (deep-marine environment);
- Record: deep-sea sediment cores from the southern Indian Ocean;
- Age control from C-14 dating and volcanic ash layers;
- Result: cyclicity in ice volume and ocean temperature;
- Use of Milankovitch's calculations to refine the ages of Pleistocene glacial events

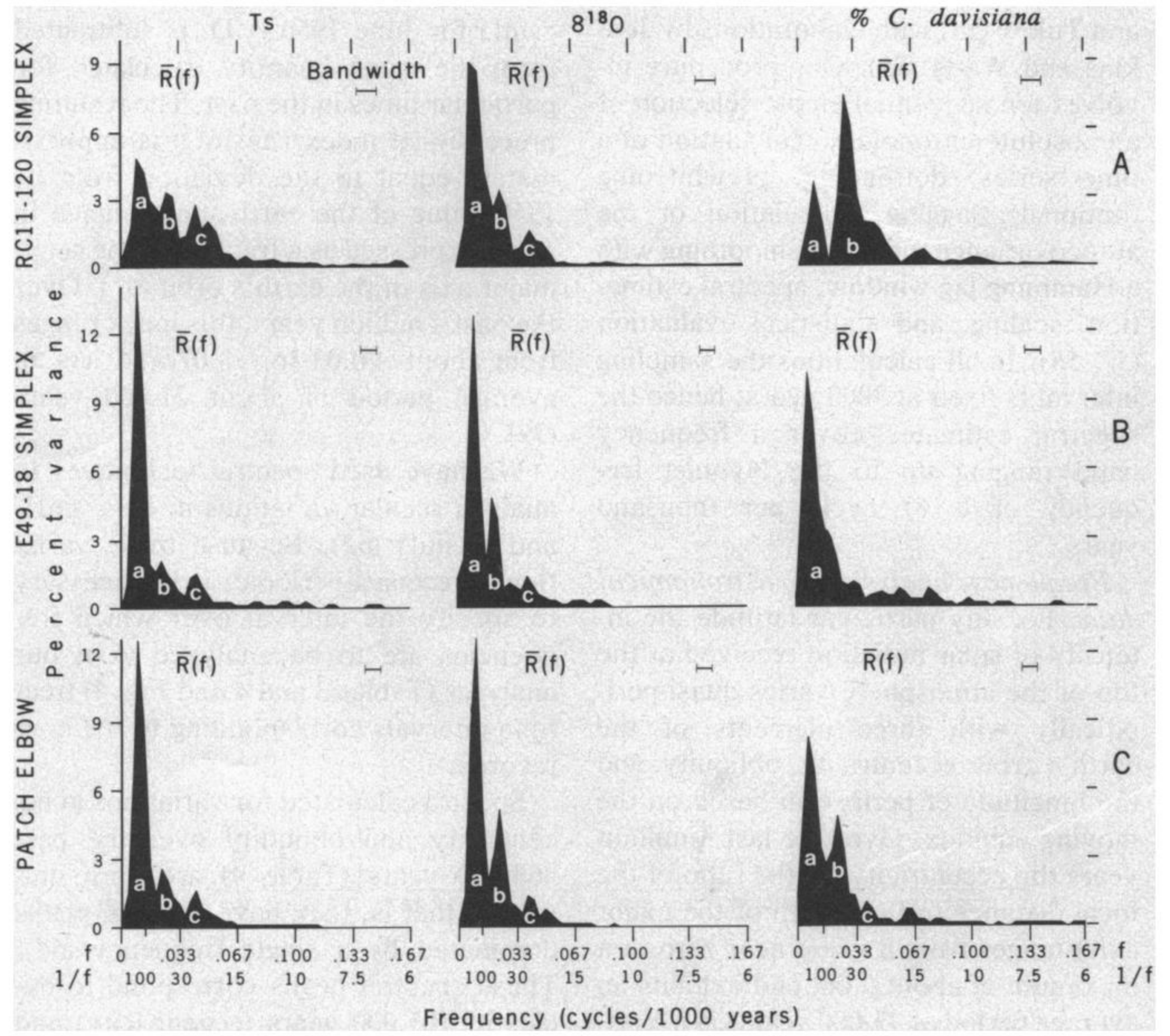


A sequence through time

In an undisturbed sequence, deeper sediments are generally older.

Hays et al. investigated whether these changes recurred at the expected orbital periods.

Hays et al. (1976): rhythms in the climate record



How to read the figure

Horizontal: frequency; 1/f gives the period in thousands of years.
Vertical: concentration of variability at each frequency.

What the peaks mean

b and c: rhythms near the obliquity and precession bands, around 41 and 19–23 thousand years.
a: a strong rhythm near 100 thousand years.

The scientific conclusion

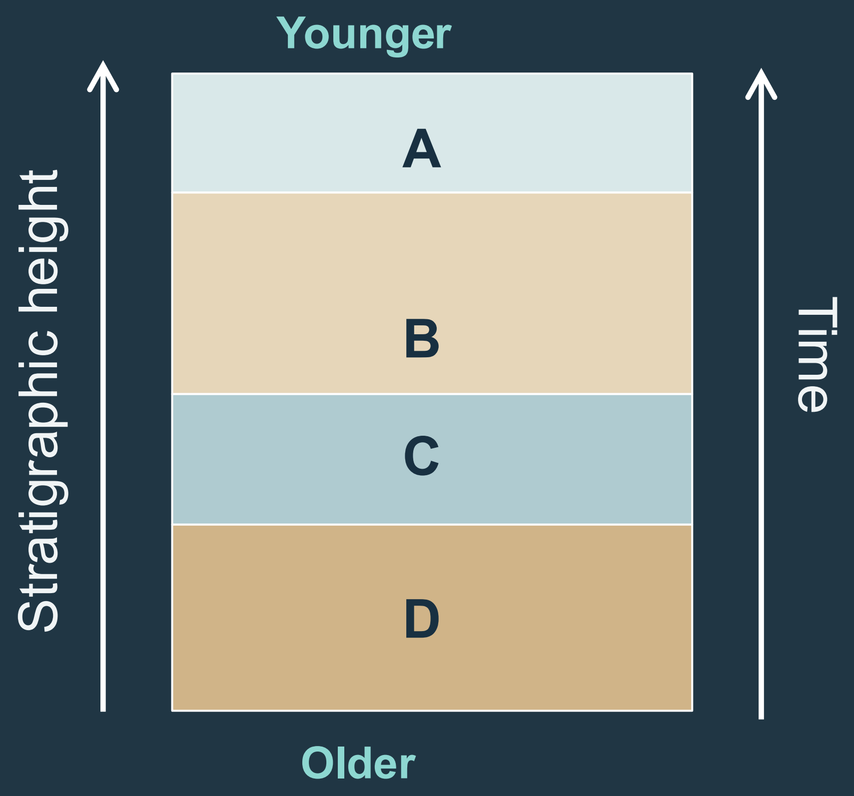
The comparison supported orbital pacing. The strong 100-thousand-year response still required a physical explanation.

Hays et al. (1976), Science. DOI: 10.1126/science.194.4270.1121

Depth, duration, and geological time

Depth establishes order. An age model adds durations and rates.

SEDIMENTARY SEQUENCE



Conceptual sequence; no measured data.
Assumes that stratigraphic order is preserved.
Letters indicate sampled levels.

TEMPORAL INTERPRETATION

D preceded C, which preceded B; B preceded A.

The ages of these levels indicate how much time separates them.

Equal thicknesses may represent different durations.

WHY THIS MATTERS

Order of events

Did the environmental change precede the biological response?

Duration and rate

Was the transition rapid or gradual? Which mechanisms are consistent with its duration?

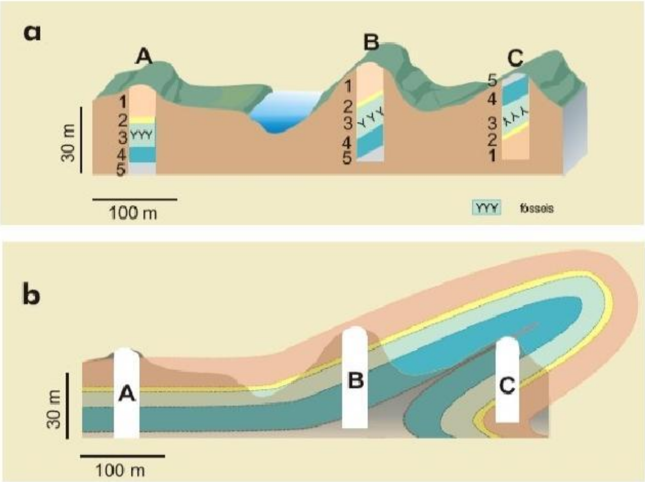
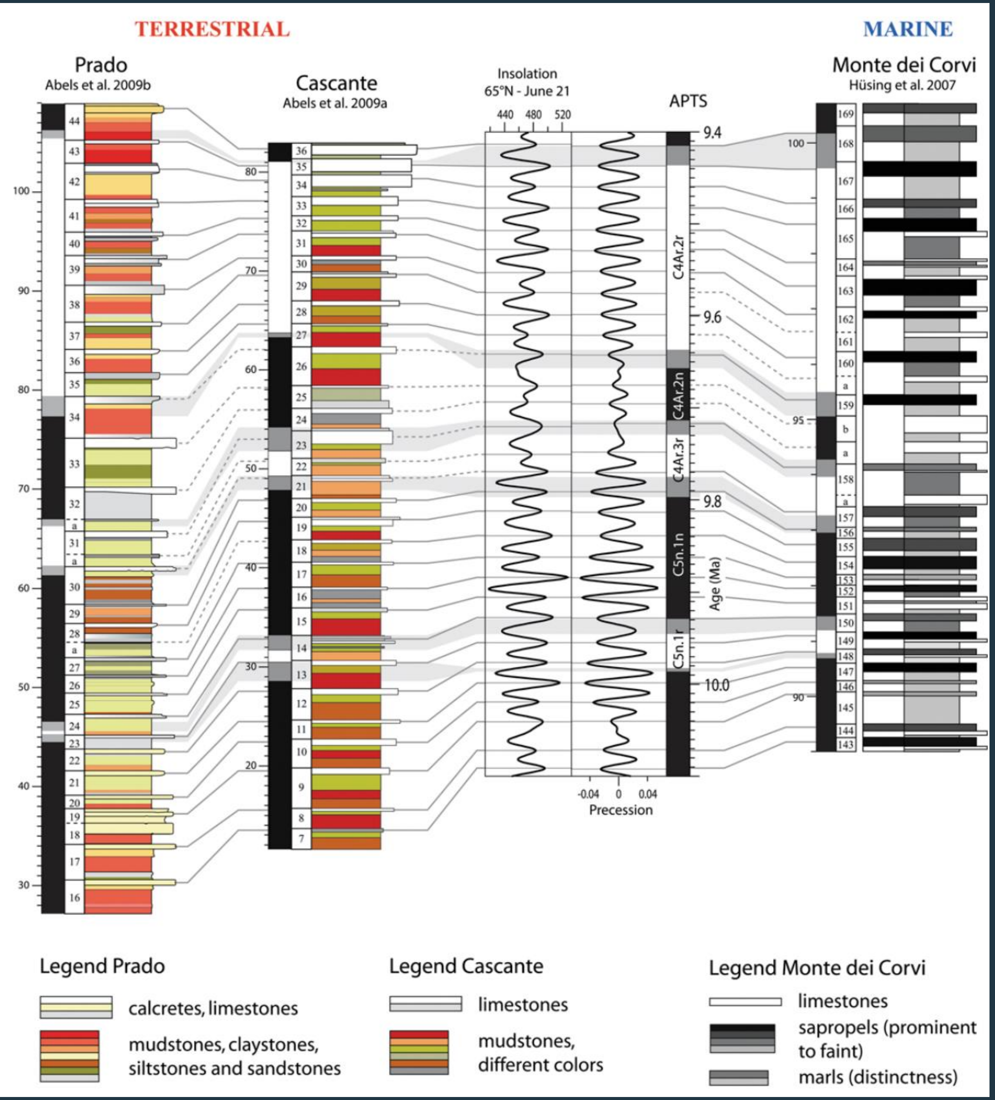


Fig. 15.5 Utilização dos princípios de Steno no campo. Uma geóloga investiga afloramentos A, B e C; em a) Pelos princípios de superposição e de horizontalidade original (e apoiada pela observação dos corais fósseis preservados em posição de vida), ela interpreta como normal (não perturbado) o arranjo das camadas 1 a 5 no afloramento A, sendo a camada 1 a mais nova e a camada 5, a mais velha. Pelos princípios de continuidade lateral e de superposição, ela infere que a mesma seqüência também se estende até B e C, apresentando-se, porém, pelo princípio de horizontalidade original, ligeiramente dobrada em B e invertida em C. b) Com base nessas conclusões, a geóloga apresenta sua interpretação final sob a forma de um perfil geológico.

Fonte: Decifrando a Terra / TEIXEIRA, TOLEDO, FAIRCHILD e TAIOLI - São Paulo: Oficina de Textos, 2000.

The Chevron folds, North Cornwall, United Kingdom (Source: Geology In.)

Our contribution: calibrating geological time



How do we place rocks from different environments on the same timescale?

Different records

Prado and Cascante: continental settings.
Monte dei Corvi: a marine setting.

Magnetic polarity

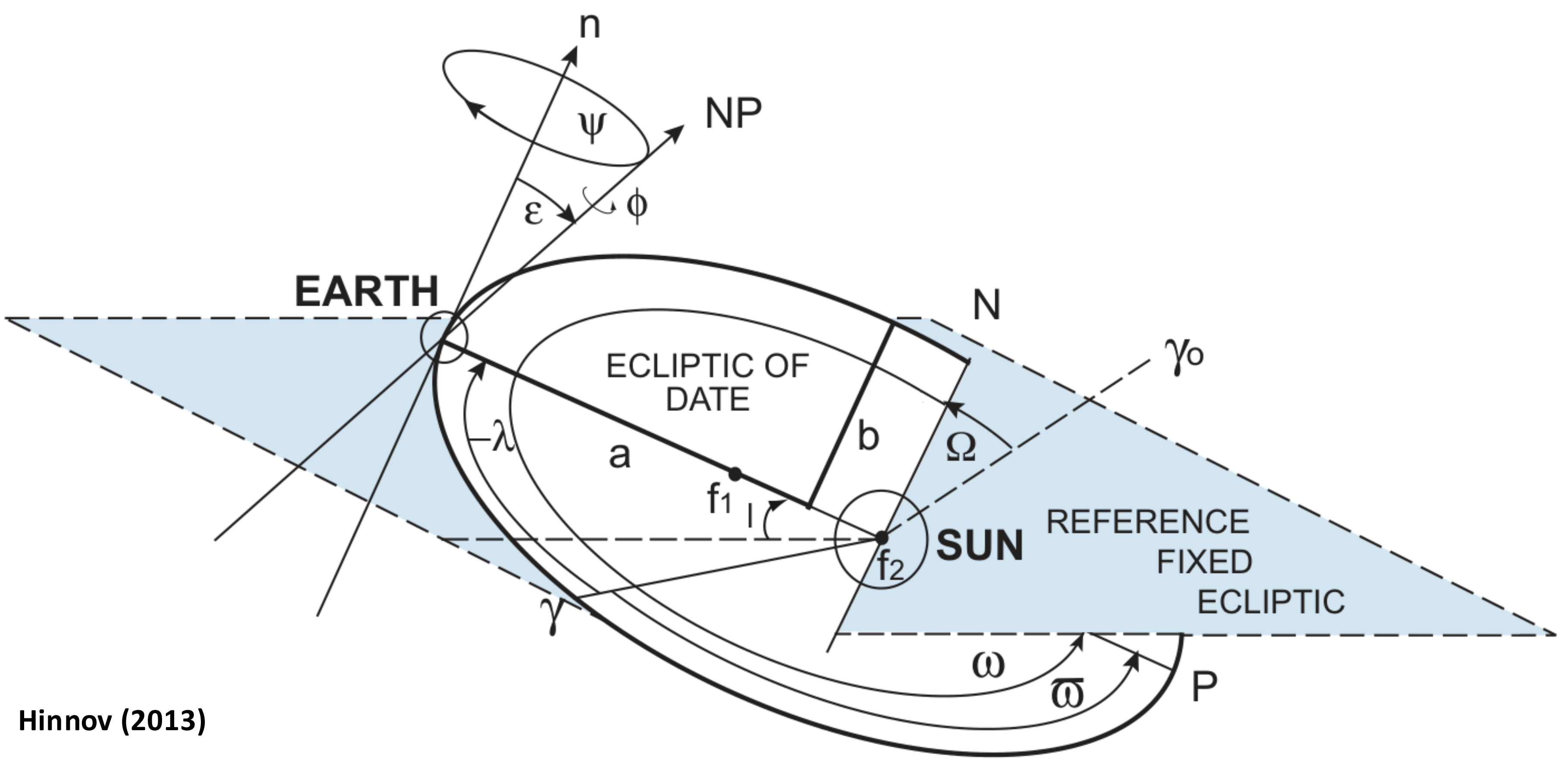
Polarity sequences help correlate the records.

Astronomical cycles

Tuning adds ages and durations to the correlation framework.

Hilgen et al. (2015)

Orbital geometry and seasonal insolation



Hinnov (2013)

Axial precession and climatic precession are distinct quantities.

Eccentricity

Shape of the orbit

Obliquity

Axial tilt relative to the orbital normal

Climatic precession

Position of the seasons relative to perihelion

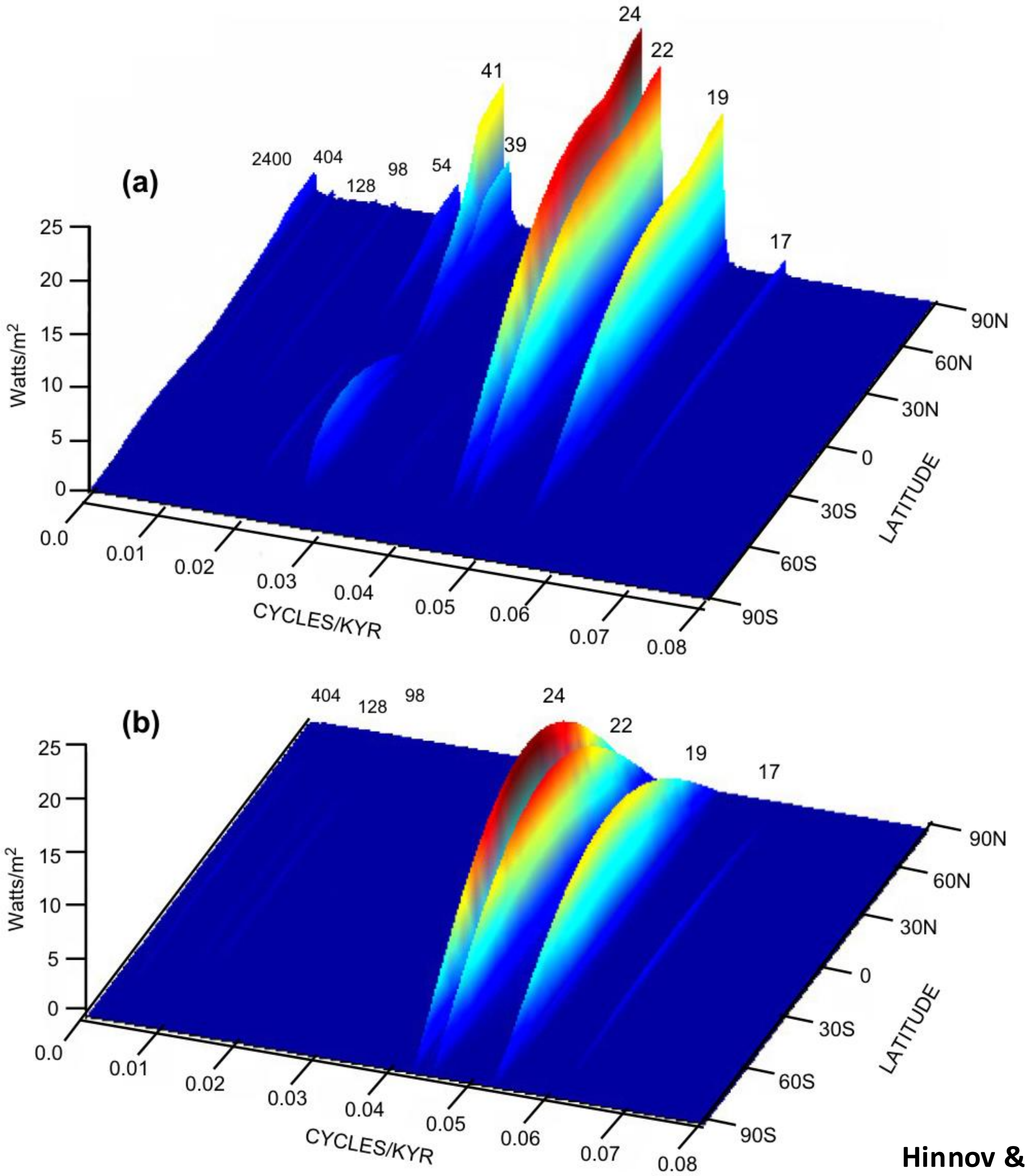
Characteristic periods in the recent past

Approximate bands in the recent past: Hays et al. (1976); Laskar et al. (2004); Hinnov (2013).

Quantity	Approximate bands	Climatic relevance
Eccentricity	~100 and 405 thousand years	Distance contrast and modulation of climatic precession
Obliquity	~41 thousand years	Seasonal distribution of sunlight across latitudes
Climatic precession	~19–23 thousand years	Seasonal position relative to perihelion

Period bands provide predictions for the geological test.

These periods are not universal constants throughout geological time.



Hinnov & Hilgen (2012)

Which insolation signal reaches the record?

Reading the surface

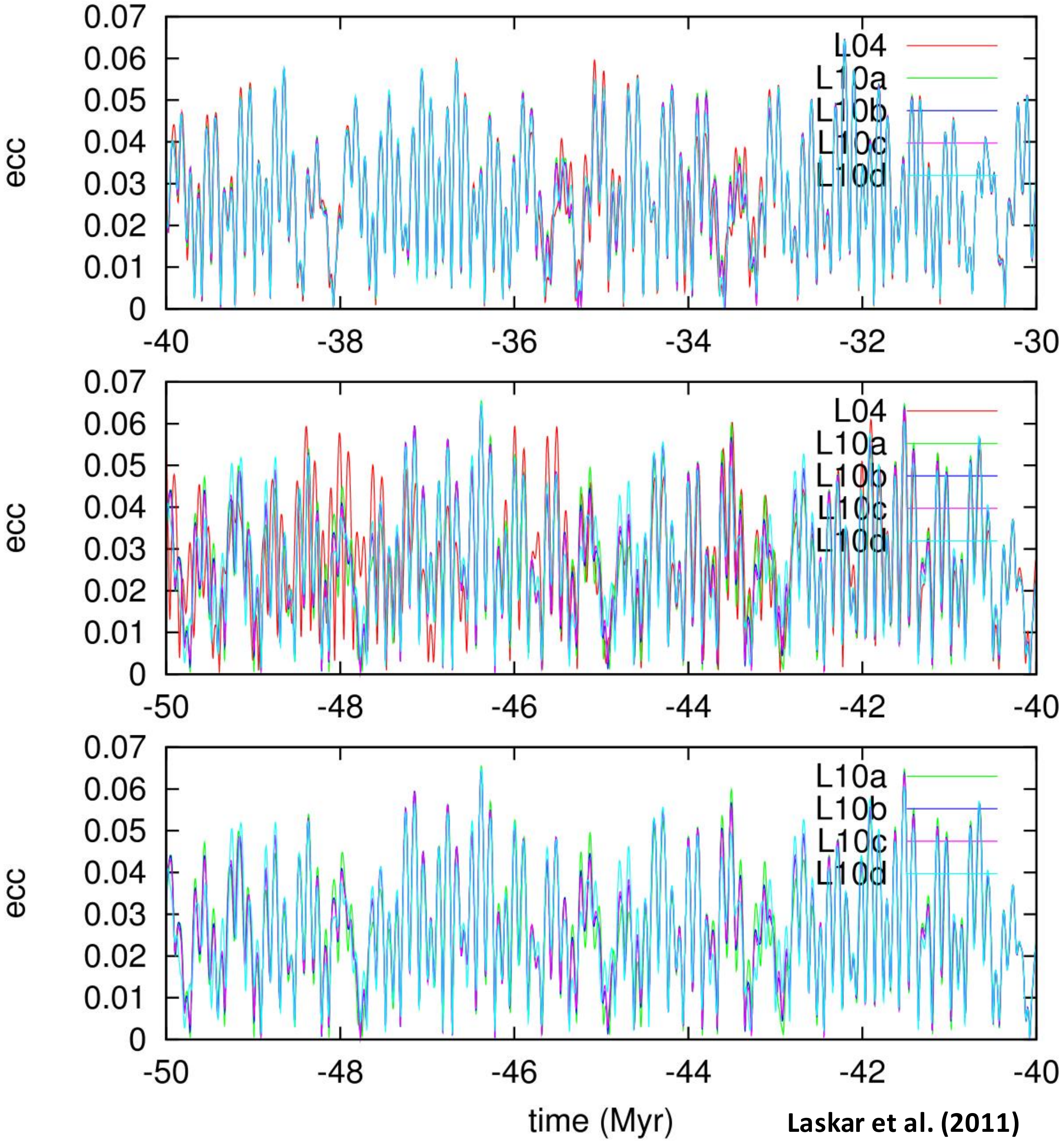
Frequency × latitude. Height represents spectral amplitude.

Solstice and equinox (NH)

Panels (a) and (b) compare June 21 and March 21.

Choosing the target

Which latitude and season influence the sedimentary process?



Laskar et al. (2011)

The reach of an astronomical solution

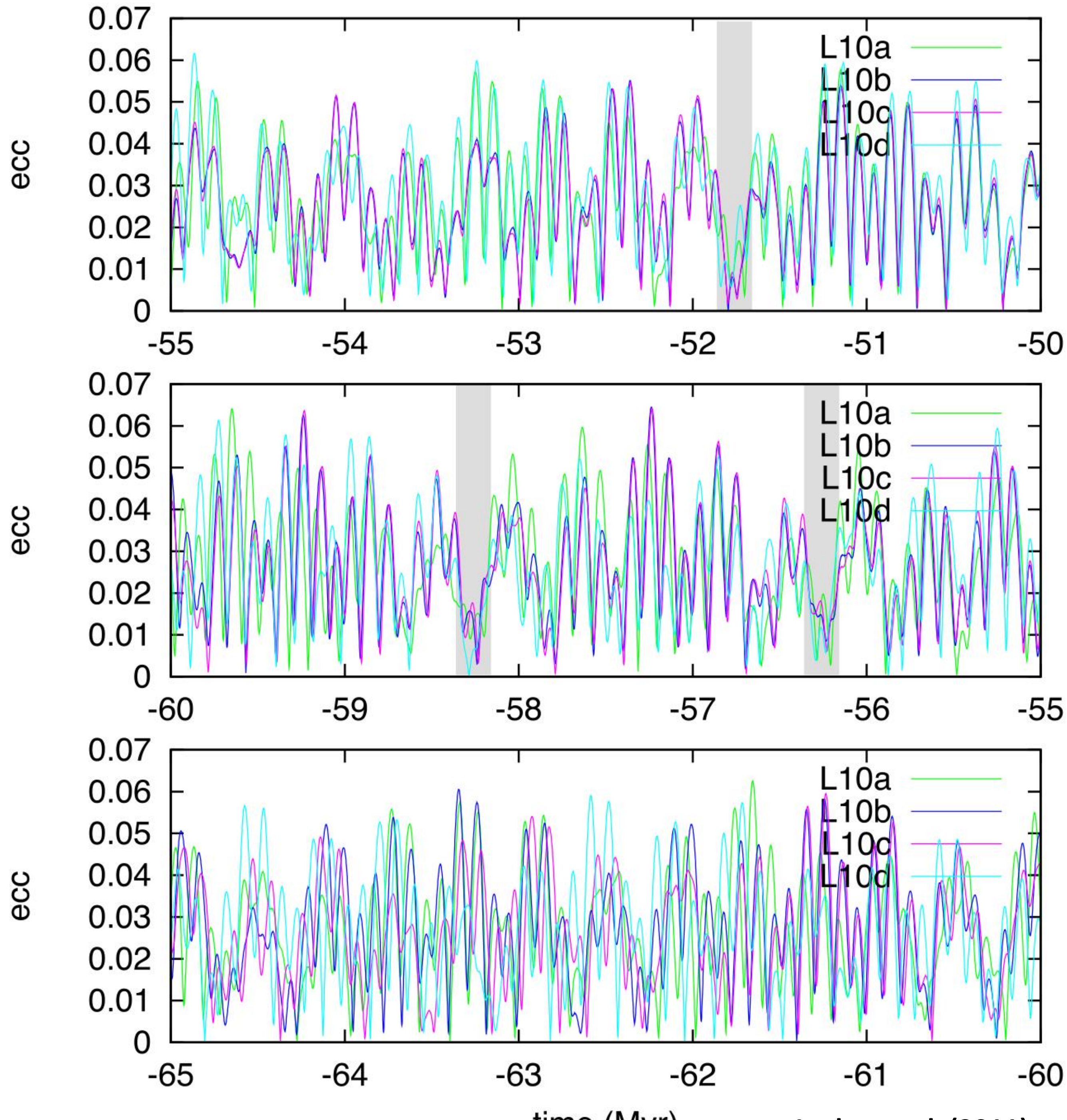
The same quantity

Earth's eccentricity in different orbital solutions.

A useful comparison

Where do the solutions agree, and which features remain robust?

Integration length alone does not establish predictive accuracy.



Laskar et al. (2011)

Phase agreement and broader orbital structure

Individual cycles diverge

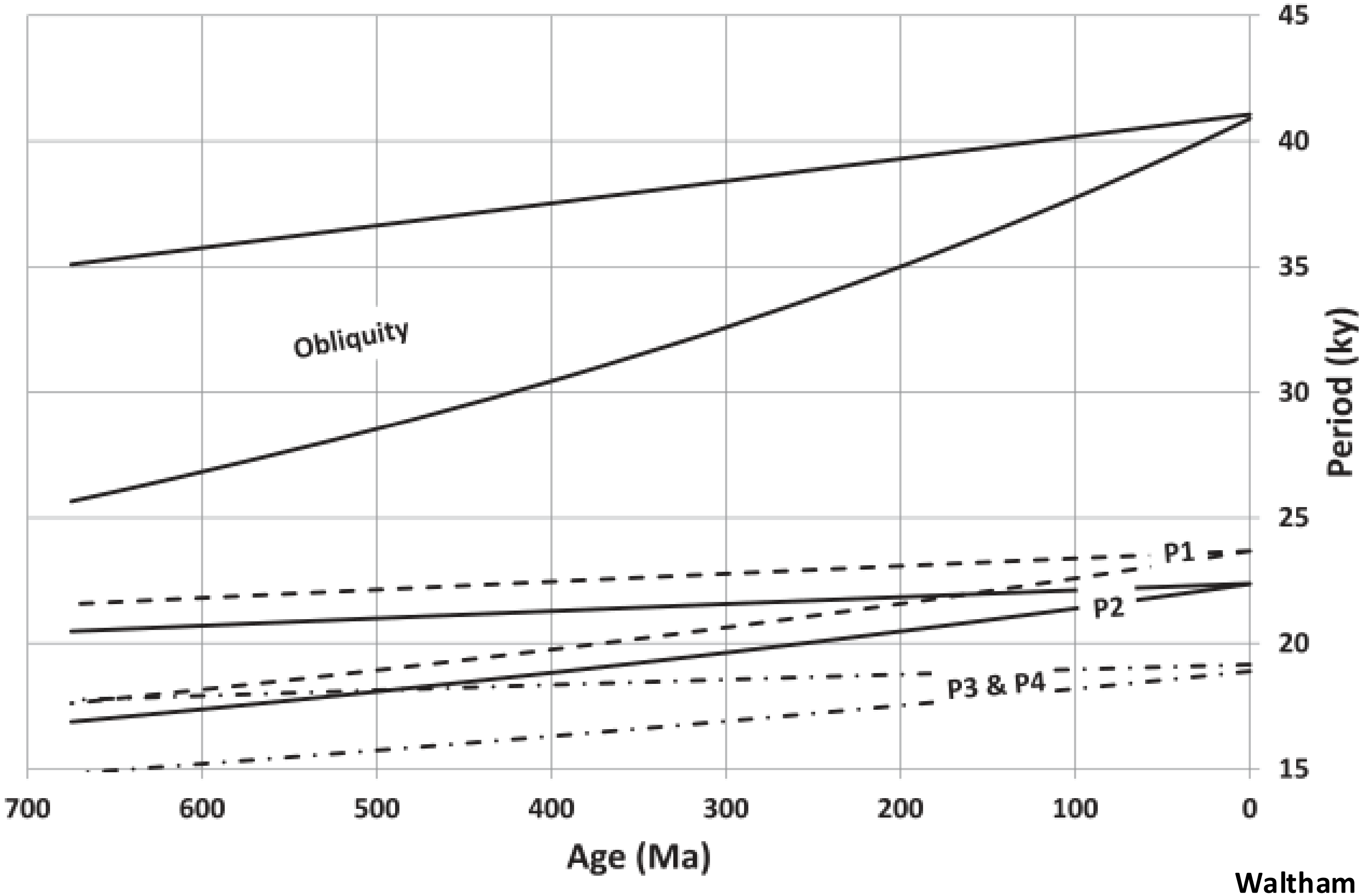
A unique phase match becomes harder to justify.

Some features persist

The original gray bands mark minima shared by the variants.

Shared features indicate agreement within this family of models.

The Earth–Moon system in deep time



Waltham (2015)

Earth–Moon evolution

Rotation and lunar recession alter the expected periods.

Model ranges

The curves bound plausible periods under the model's assumptions.

Geological constraints

Independent ages help test the assignment of periods.

Insolation and the sedimentary recording process

Insolation → **Climate response** → **Deposited material** → **Preserved sequence** → **Measured series**

Response

Feedbacks and local processes shape the climate response.

Preservation

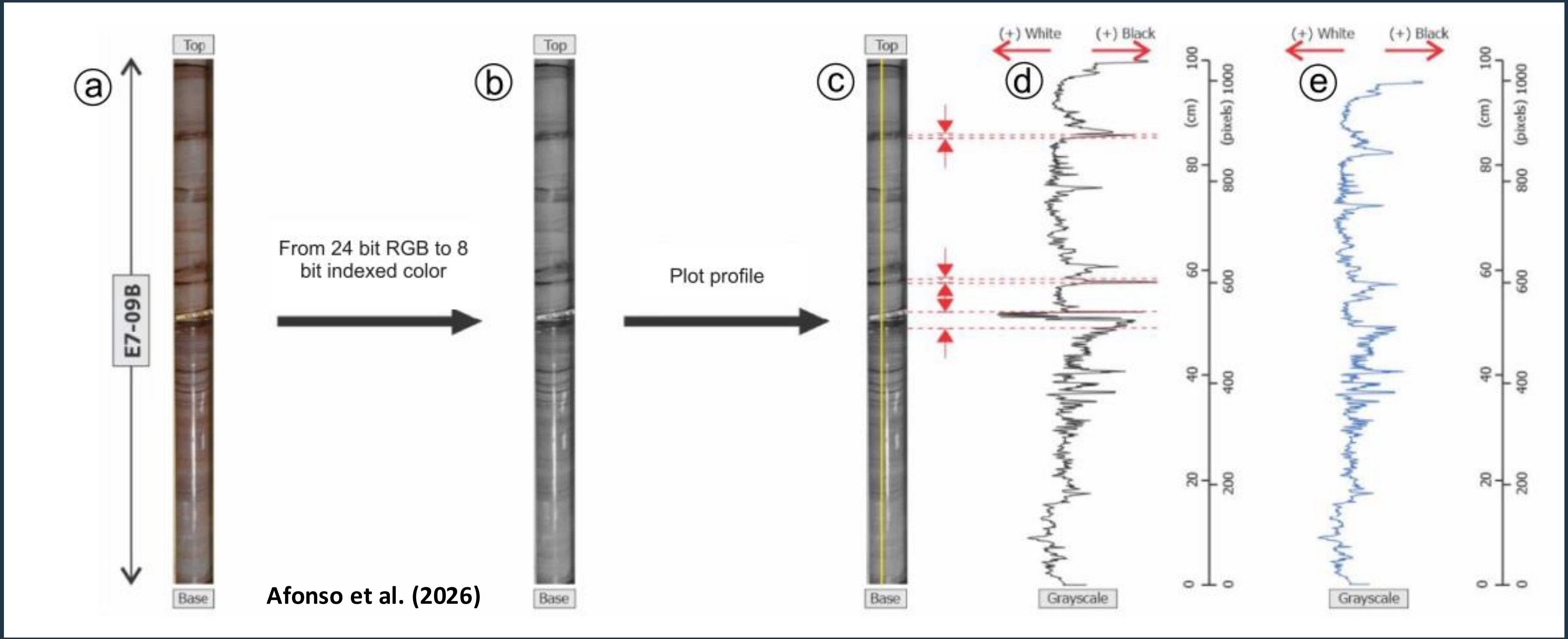
Burial, alteration, and mixing can change what is preserved.

Observation

Sampling and chronology determine the series we test.

Each stage can modify the signal preserved in the record.

Measuring sediment signals



The measured quantity

Image brightness along the core provides a continuous record of color variation.

The physical interpretation

Color must be linked to composition and preservation before it can serve as an environmental indicator.

Combining environmental measurements

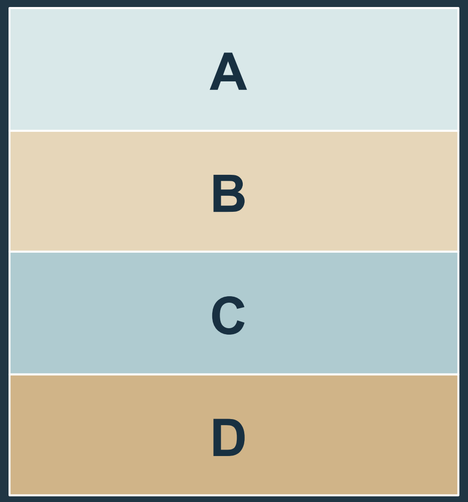
Measurement	Environmental information	What to check
Shell $\delta^{18}O$	Ocean conditions and continental ice	Water composition, temperature, and preservation
Magnetic susceptibility	Changes in magnetic material	Mineralogy, sediment supply, and alteration
Fossil assemblages	Organisms and environmental associations	Ecology, transport, and preservation

Different sensitivities can strengthen the interpretation of mechanisms.

Measurements from the same core may share chronological uncertainty.

What the record preserves

Preserved order

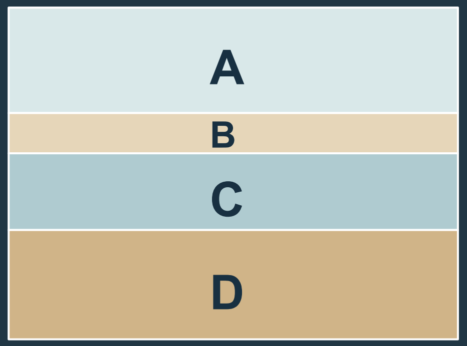


Younger at the top

Missing interval

Hiatus or removal

Compacted sequence

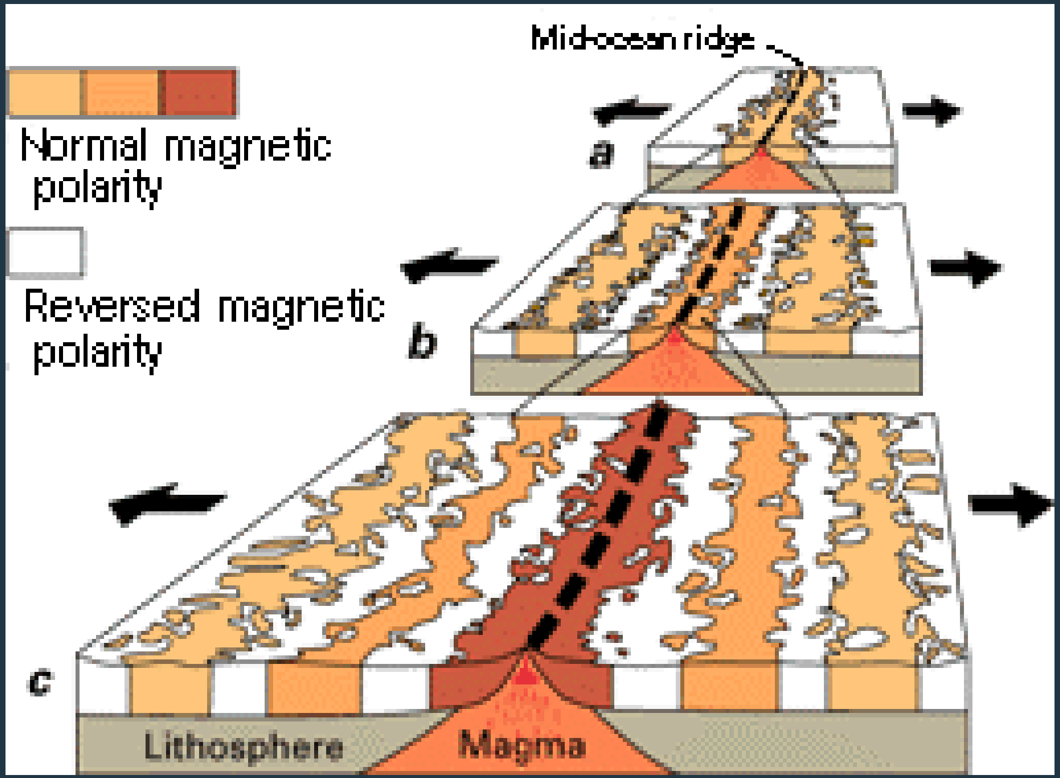


Unequal shortening; order preserved

Equal steps in depth may represent different durations.

Magnetic polarity provides another sequence for correlation.

Rocks preserve changes in magnetic polarity



Original educational illustration: USGS, Magnetic Polarity. Oceanic crust example

Normal and reversed polarity

The large-scale field direction alternates between approximately opposite states.

A geological record

Cooling lavas and burial of sediments can preserve remanent magnetization.

Reversals occur at irregular intervals.

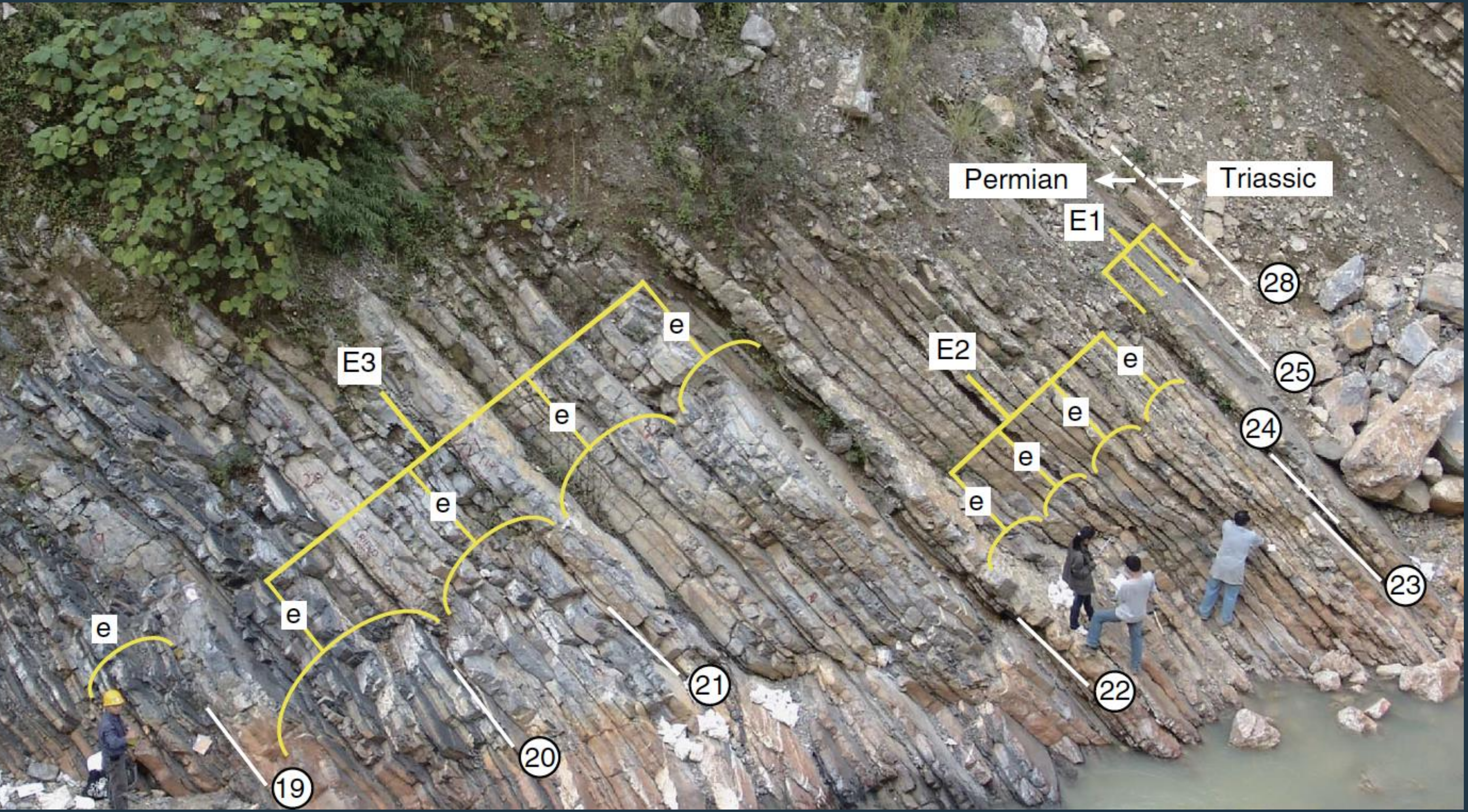
Calibrating the geomagnetic polarity timescale

Evidence	Contribution to the chronology
Magnetic directions	Locate reversals and correlate polarity sequences.
Astronomical cycles	Estimate durations and assign ages within an explicit model.
Independent age constraints	Anchor or test numerical ages and interval durations.

Astronomical ages can calibrate polarity boundaries.

These boundaries can date other records. Calibration history determines whether a test is independent.

The Permian–Triassic transition in outcrop



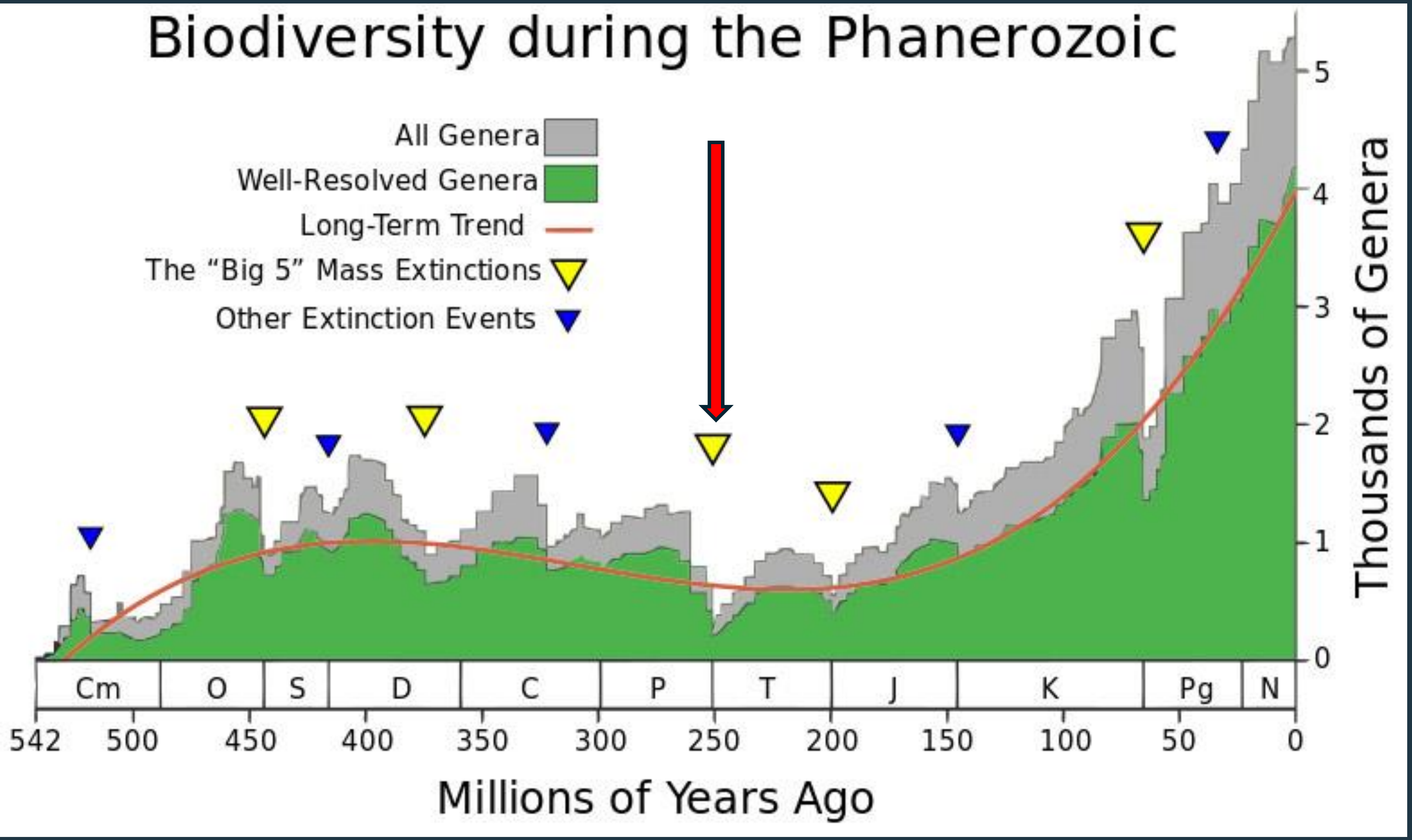
Wu et al. (2013)

~252 million years ago

The largest mass extinction of the Phanerozoic

A chronology to test the order and pace of change

Why the Permian–Triassic boundary?



From Sepkoski & Raup (University of Chicago)

~ 252 Ma

Paleozoic–Mesozoic era transition

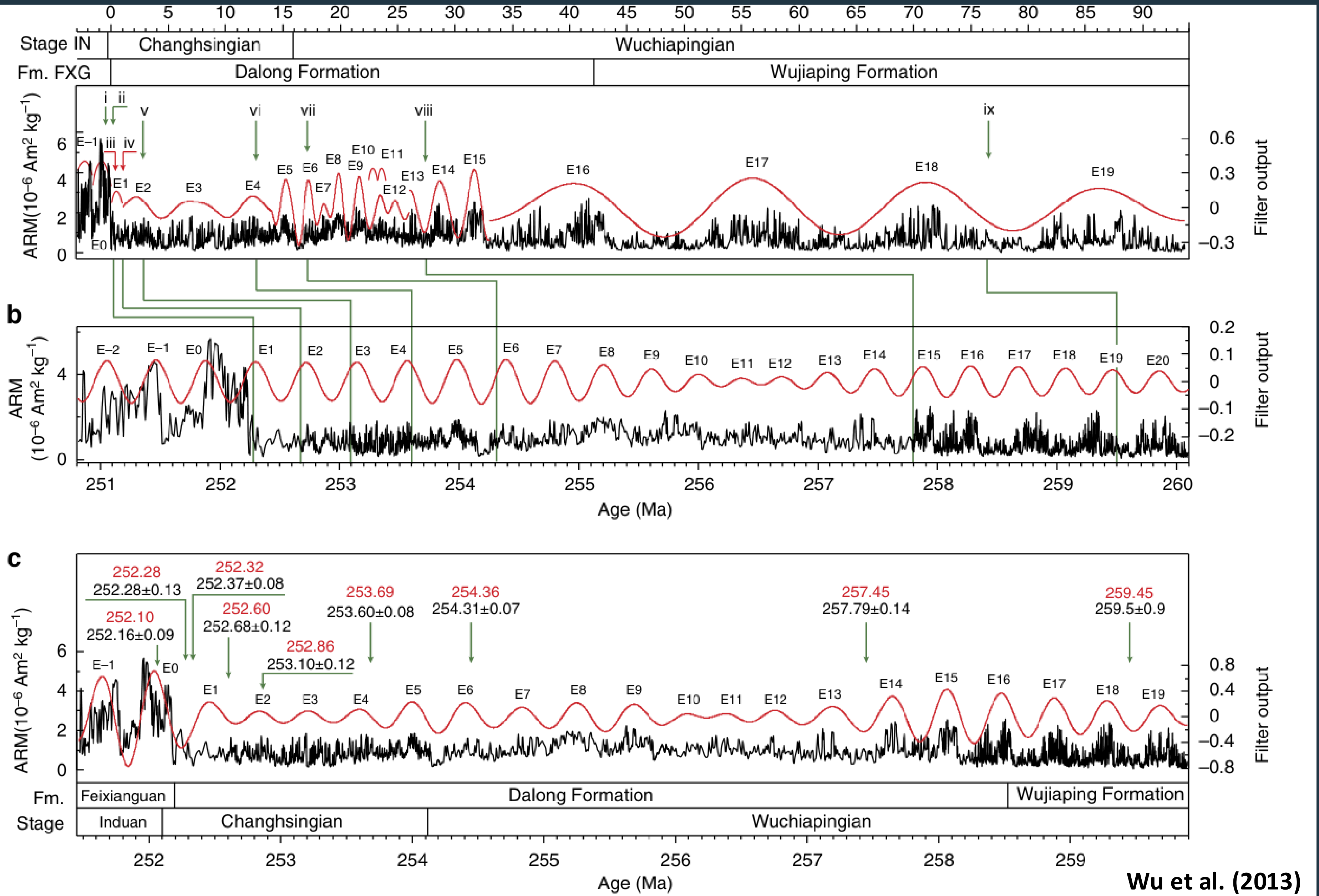
Largest mass extinction of the Phanerozoic

An estimated >80% of marine species disappeared, causing an extreme loss of biodiversity.

Intense Siberian Traps magmatism: the main trigger, through massive greenhouse gas emissions.

The crisis involved intense global warming, ocean acidification, and oxygen loss, making vast marine areas inhospitable to life

Testing the chronology with U–Pb ages



Wu et al. (2013)

(a) Depth

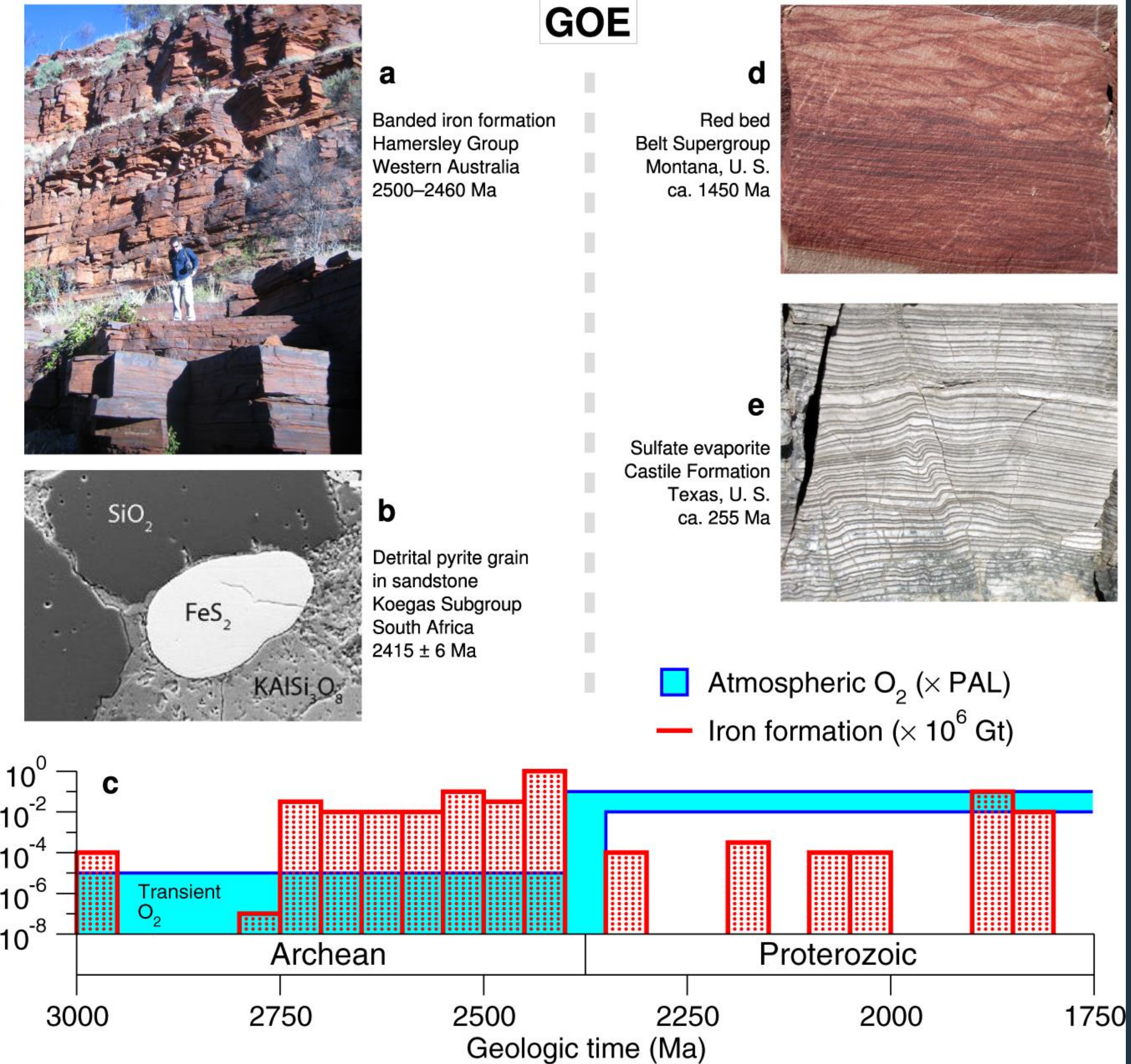
Magnetic measurements span the Shangsi succession.

(b) U–Pb chronology

Radioisotopic ages constrain the conversion to time.

(c) Orbital tuning

Tuned ages are compared with the U–Pb constraints.



Why study the Paleoproterozoic?

2.5–1.6 billion years

The Great Oxidation Event transforms chemical conditions at Earth's surface.

The geological archive

Rocks and minerals record changes in the oceans, atmosphere, and conditions for life.

Olejarz et al. (2021)

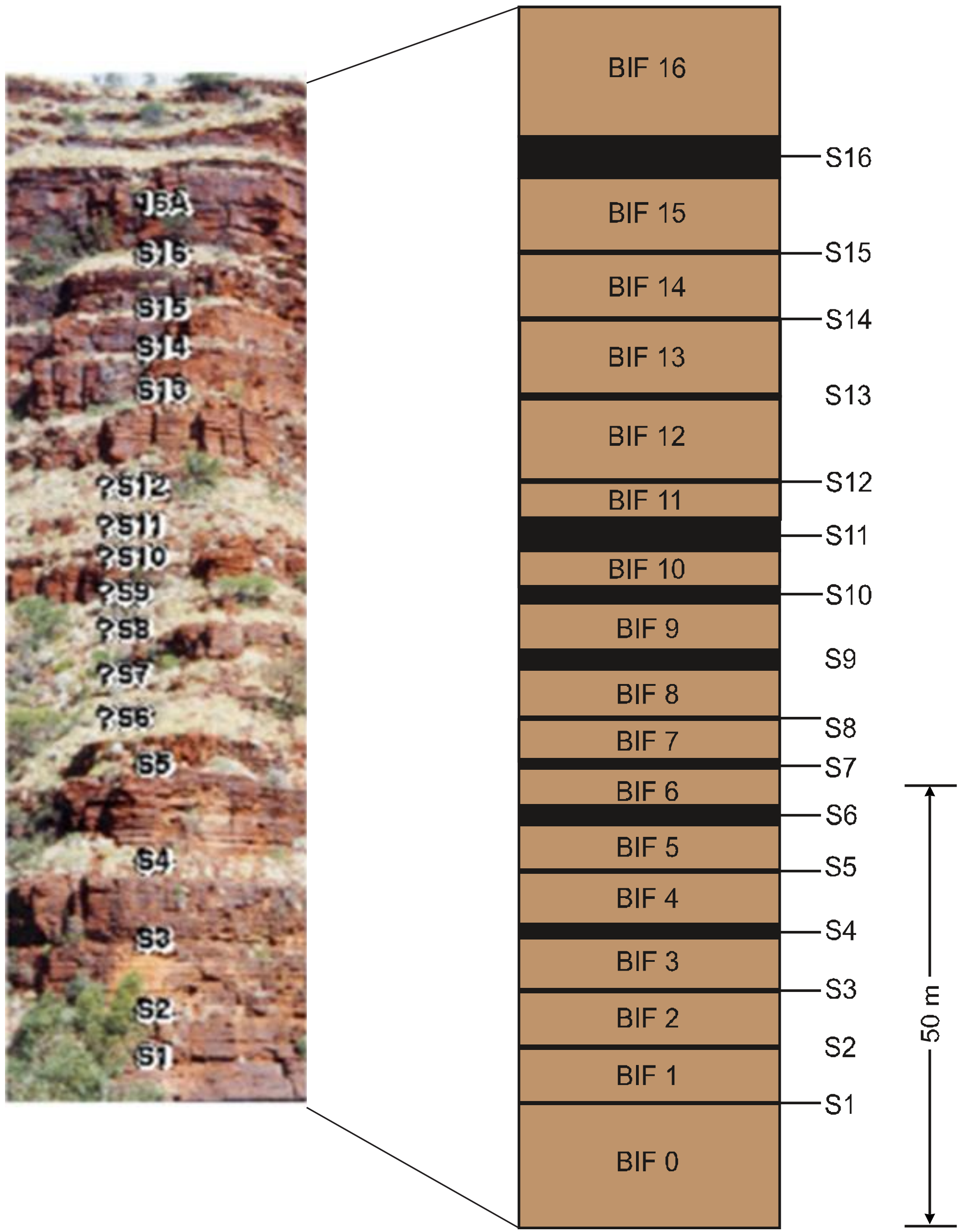
What are BIFs?

Banded iron formations

Sedimentary rocks of predominantly chemical origin

Alternating iron-rich and silica-rich bands

What produced the banding, and how much time does it represent?



TESTING TIMESCALES FOR 2.5 GA BANDED IRON FORMATIONS RHYTHMS (DALES GORGE MEMBER, HAMERSLEY BASIN, AUSTRALIA) BY USING DISTINCT CYCLOSTRATIGRAPHIC APPROACHES

PhD thesis of Pillar Rodrigues (2018)

GENERAL OBJECTIVE

Test whether the banding preserves astronomical cycles and can support a timescale for the succession.

SPECIFIC OBJECTIVES

Characterize rhythms in rock grayscale series.

Test calibration hypotheses using spectral analyses and statistical tests.

Estimate sedimentation rates and the duration of the succession.

WHAT DID WE HOPE TO CLARIFY?

Which chronologies are plausible, and how astronomy could help interpret the deposition of these iron formations.

Trendall & Blockley (1968)

From photo archives to a data series

Reconstructing the sequence

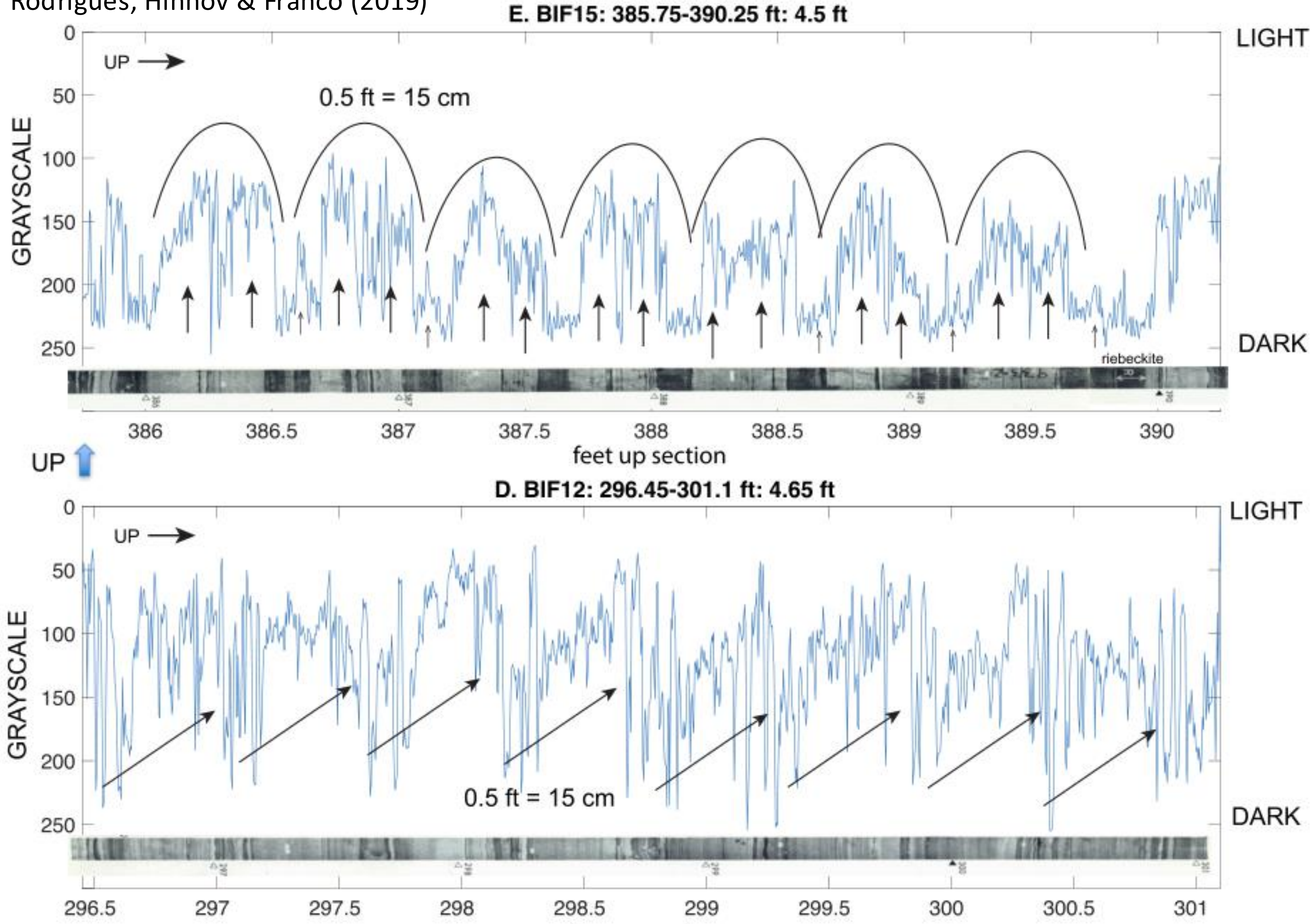
Position, orientation, and scale allow the segments to be ordered.

Measuring banding

Grayscale quantifies contrasts requiring geological interpretation.

Dales Gorge Member BIFs: ancient sedimentary rhythms at orbital scales?

Rodrigues, Hinnov & Franco (2019)



The record

Iron-rich and silica-rich materials produce light and dark bands.

The observation

Bands of similar thickness have different internal structures.

The question

What depositional history can explain these structures?

Dales Gorge Member BIFs: alternative geological clocks

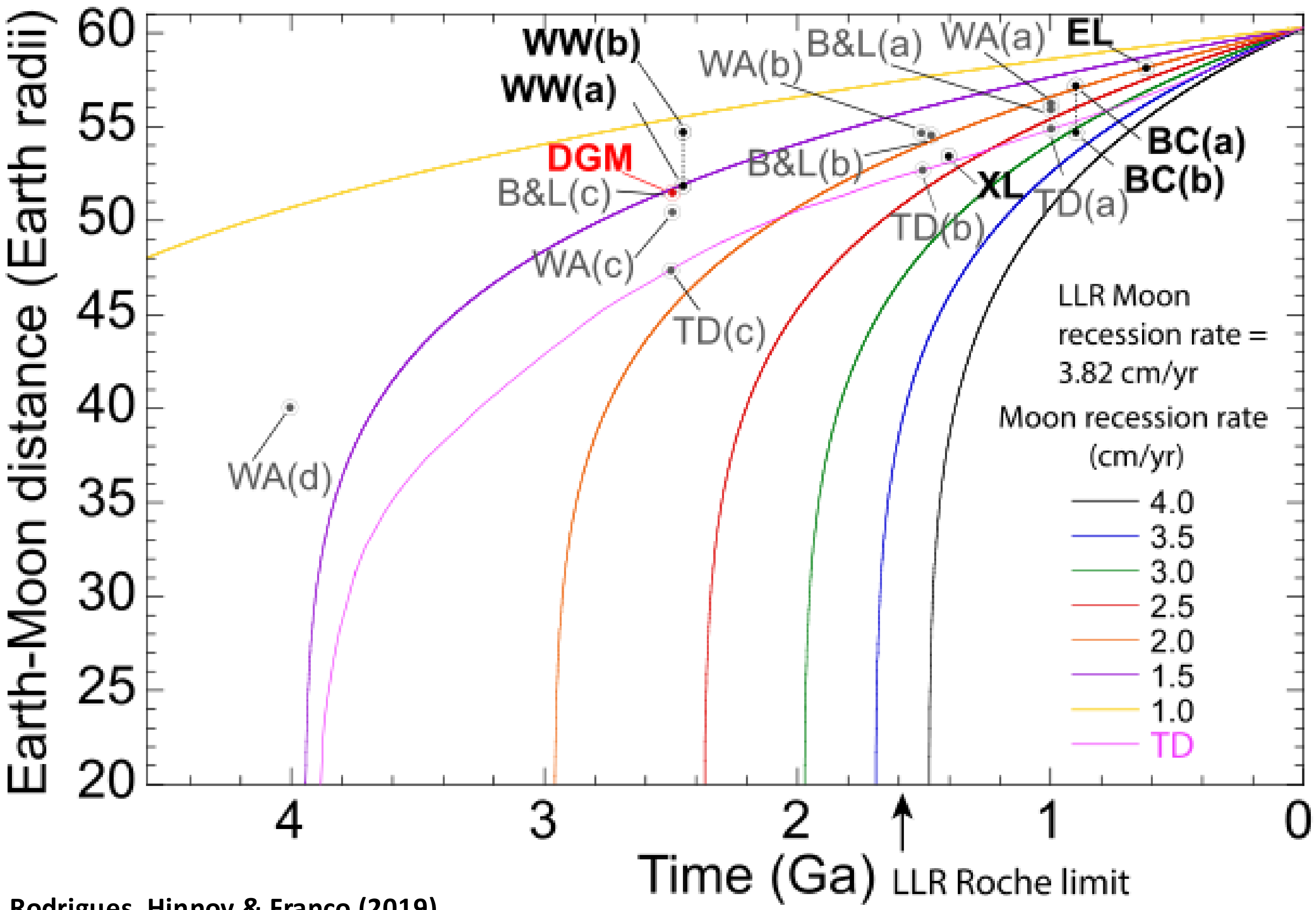
Rodrigues, Hinnov & Franco (2019)

Calibration	Main temporal assumption	DGM duration
Timescale 1	BIF–shale pairs assigned to ~405 thousand years	7.21 million years
Timescale 2	Previous zircon ages used in the calibration	60.65 million years

These are alternative models, not a confidence interval.

The independent ages available in the study did not resolve a unique chronology.

Cyclostratigraphy of the Dales Gorge Member:
constraints on Earth–Moon dynamics at 2.5 Ga



Rodrigues, Hinnov & Franco (2019)

Model curves

Different recession assumptions yield different histories.

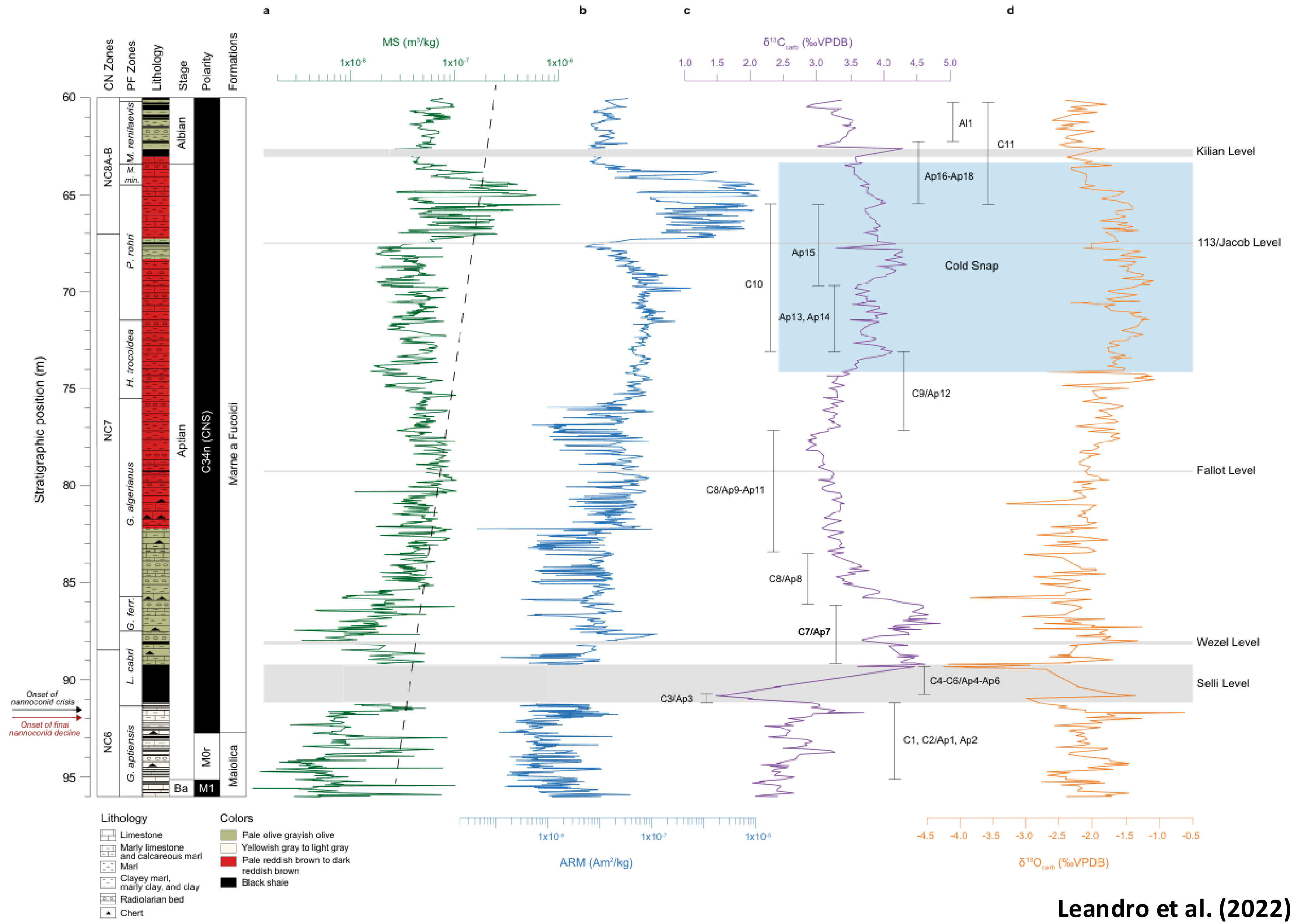
Geological constraints

Symbols compile different records and their interpretations.

The DGM estimate

The published point depends on timescale 1.

Aptian magneto-cyclostratigraphy: dating environmental change



Leandro et al. (2022)

Multiple measurements

Magnetic properties and isotopes describe different processes.

Fossil-bearing horizons

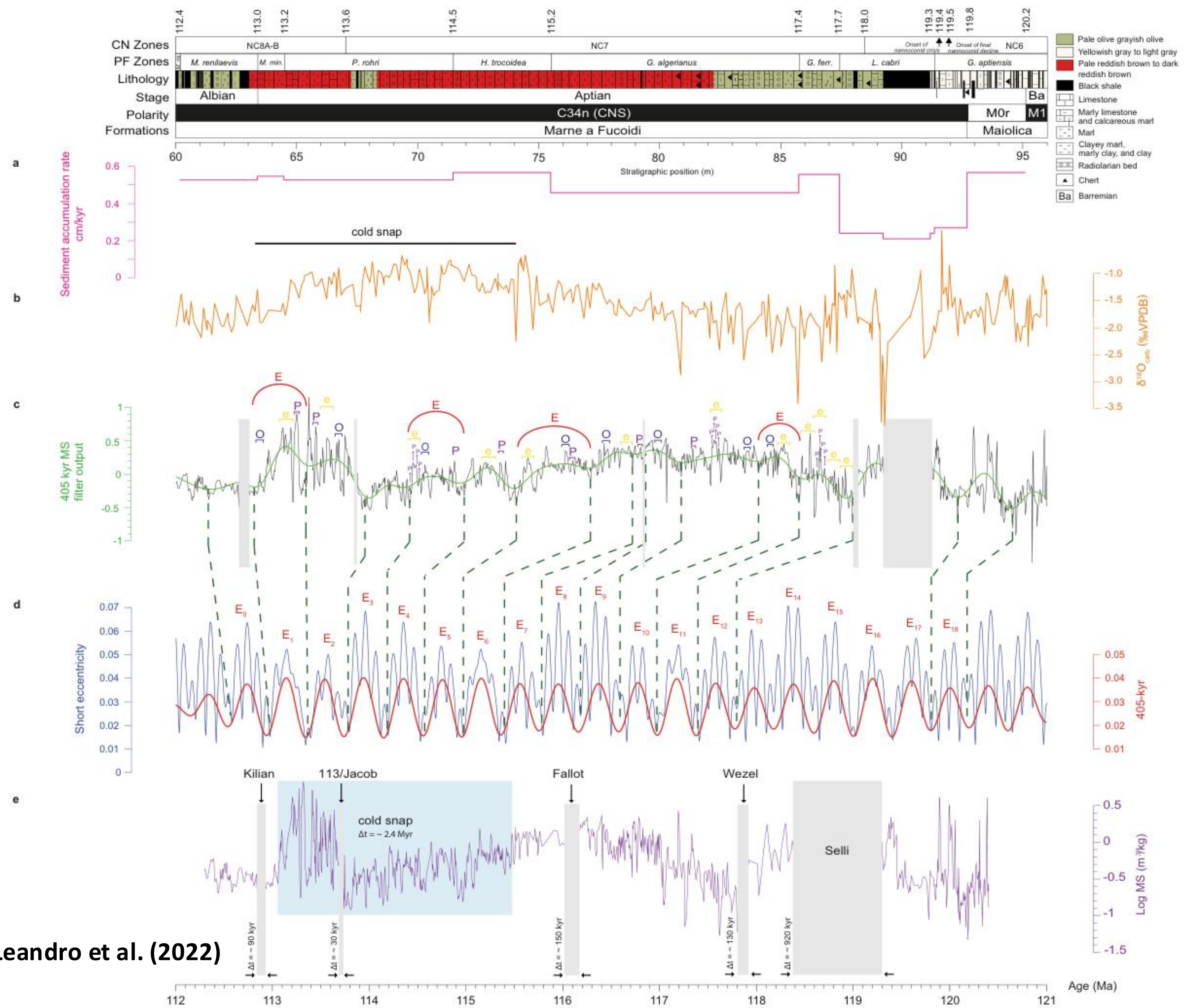
The columns on the left locate biological changes within the succession.

A question of timing

How long did the events last, and which came first?

Aptian ≈125–113 Ma (Lower Cretaceous)

The Aptian astronomical timescale



Leandro et al. (2022)

A selected component

Long eccentricity guides the authors’ tuning.

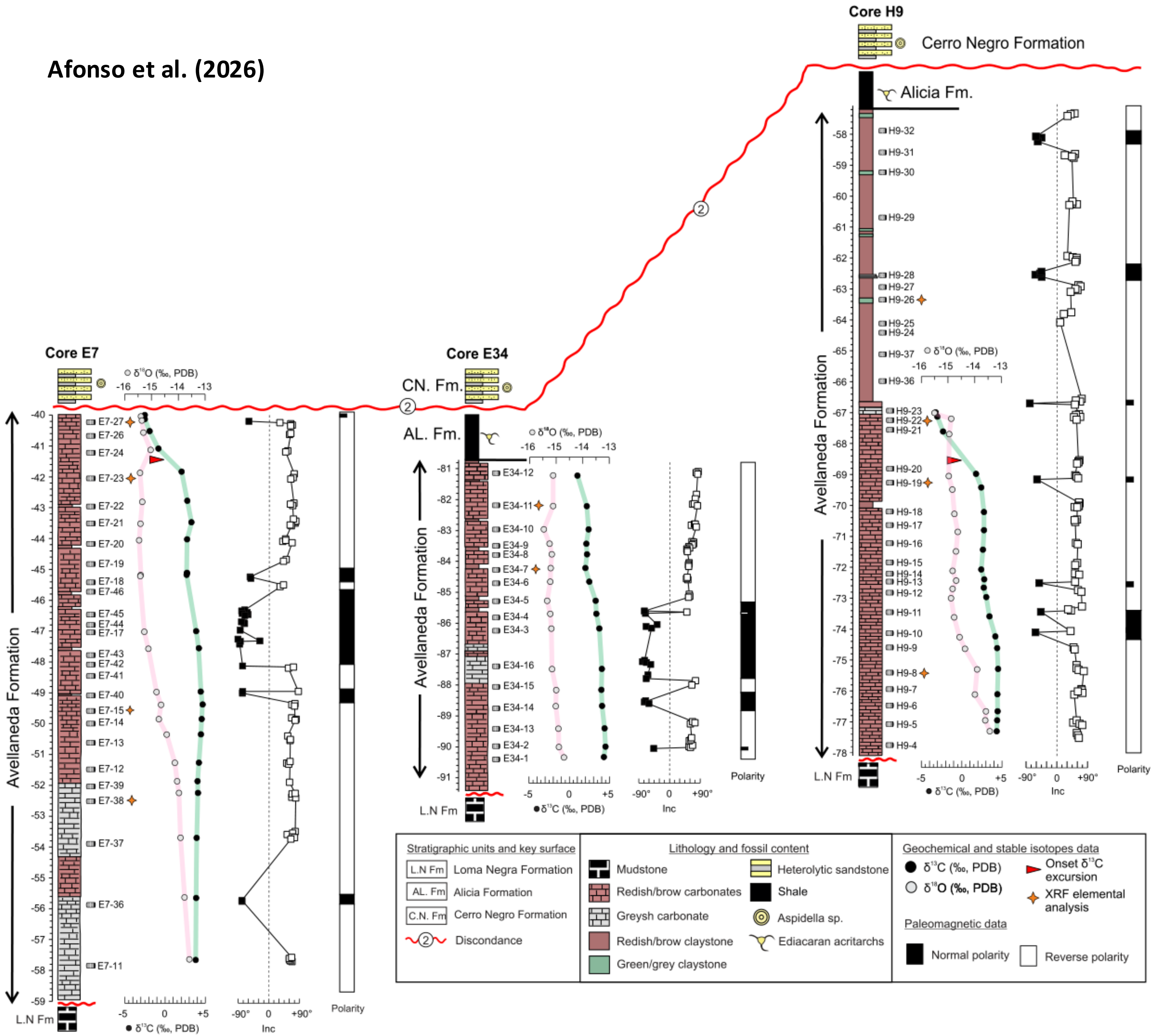
Elapsed time

Durations and accumulation rates follow from the alignment.

Absolute ages

Numerical ages also depend on the age adopted for a boundary.

Afonso et al. (2026)



Correlating the magnetic record between cores

The observations

Field directions and polarity intervals accompany the profiles.

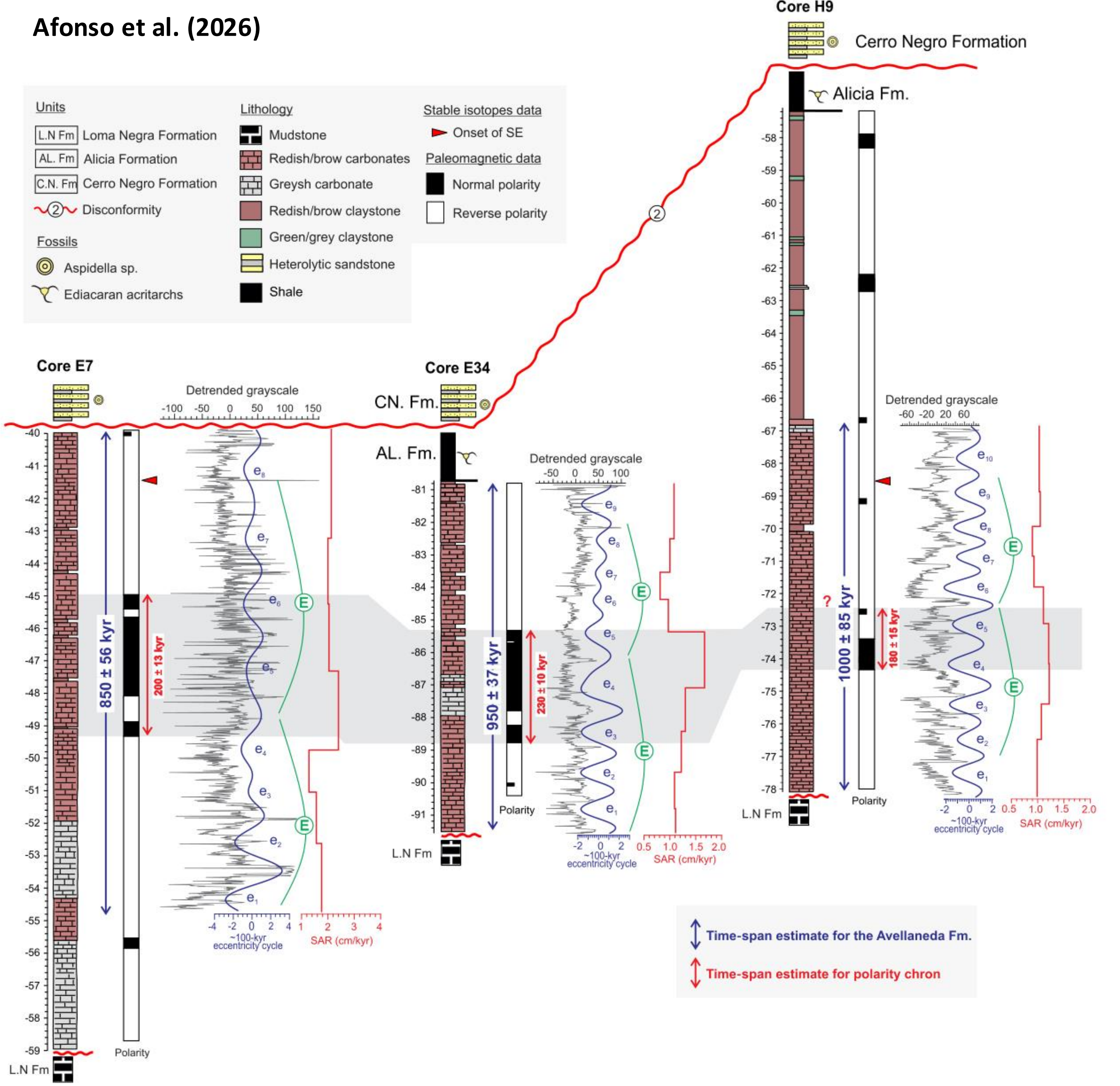
The correlation

Patterns and isotope records help identify equivalent intervals.

The next question

How much time do these intervals represent?

Afonso et al. (2026)



Avellaneda Fm. (Argentina): a calibrated reversal rate

Magnetic polarity

Black and white intervals record the polarity sequence.

Elapsed time

A ~100-thousand-year component interpreted as a floating clock.

The reported rate

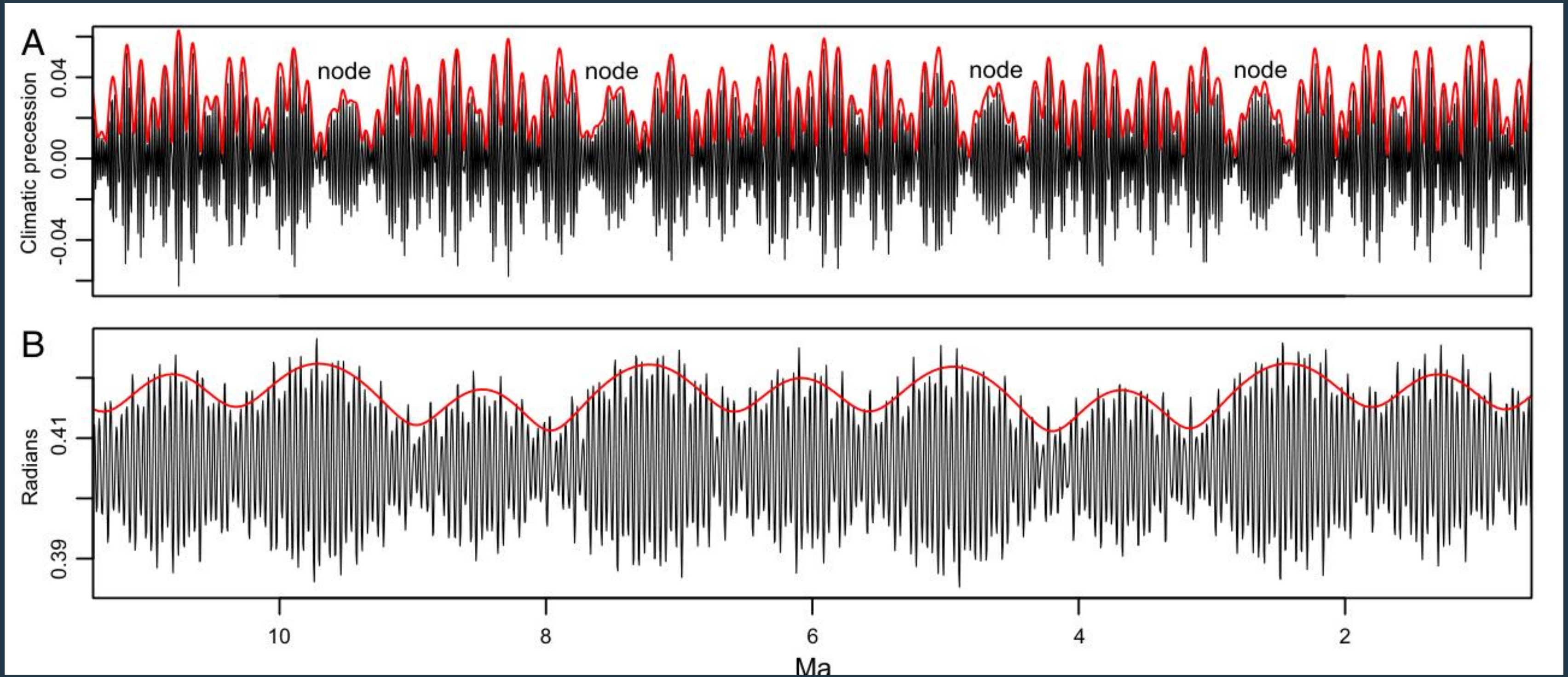
~7–11 reversals/million years, under the adopted calibration and preservation assumptions.

Ediacaran geomagnetic reversal rates

Geological record	Approximate age	Reversals per million years	Reference
Avellaneda Formation Argentina	~570 Ma	**7–11**	Afonso et al. (2026)
Rainstorm Member, Johnnie Formation (USA)	Middle Ediacaran	**~13**	Kodama (2021)
Crown Hill Formation Canada	~560 Ma	**~10–12**	Shen et al. (2025)
Zigan Formation Southern Urals, Russia	~548 Ma	**≥20**	Bazhenov et al. (2016) Levashova et al. (2021)

Hyperactive regime: ≥10 reversals per million years

Testing a connection with biological change



Crampton et al. (2018)

Fast cycles and their envelope

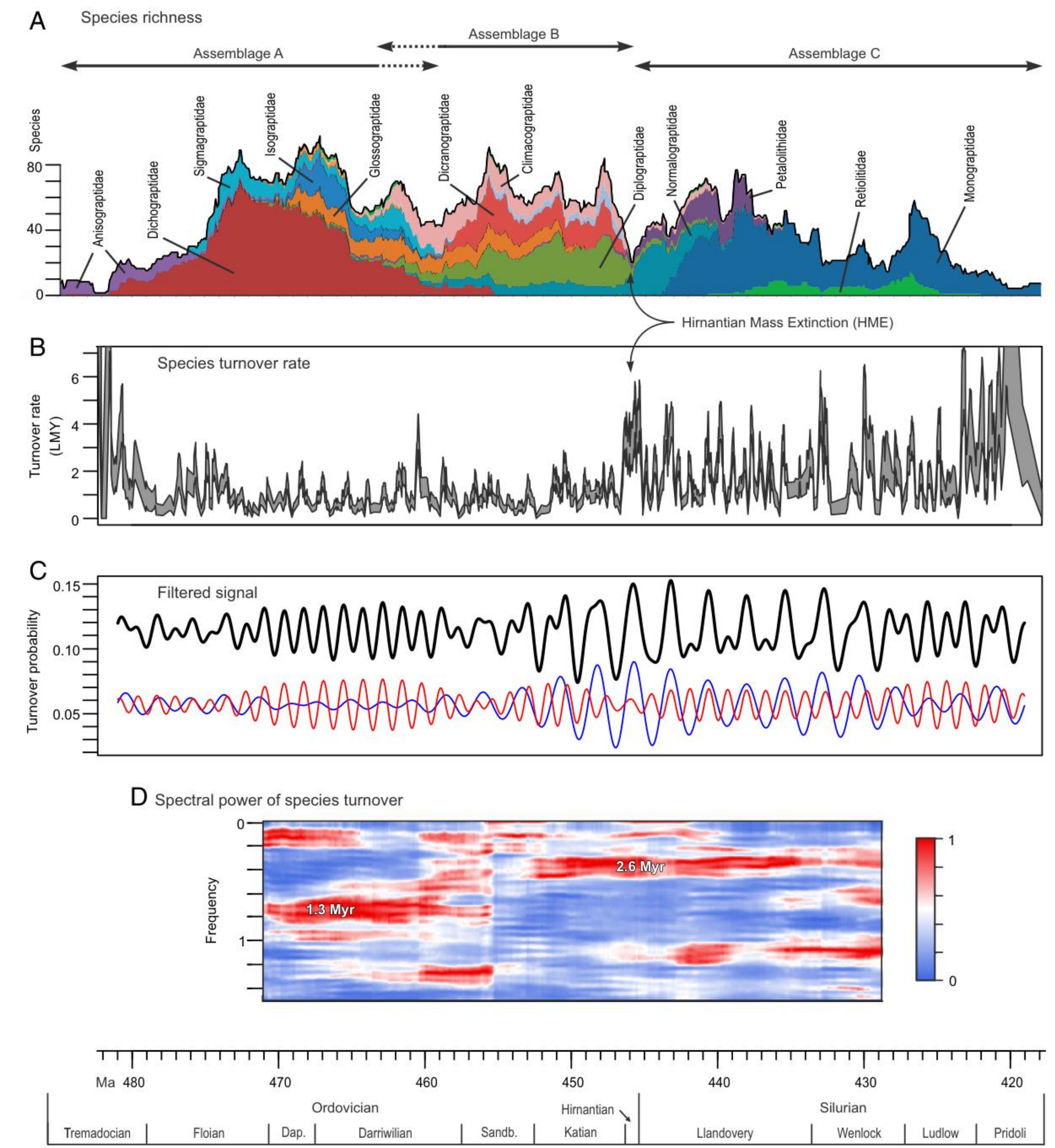
Black curves: orbital cycles.
Red curves: amplitude modulation.

The biological hypothesis

Long-term climate variations could affect marine habitats and species turnover.

The test requires biological data

Astronomical curves alone do not demonstrate an evolutionary response.



Graptoloid turnover: the biological evidence

The biological record

Graptoloids: colonial plankton. Turnover: changes in species.

Observed association

~1.3 and ~2.6 million years: 9–16% of turnover variance.

The limits

The exact orbital phase and proposed mechanism remain unresolved.

Crampton et al. (2018)

Orbital cycles and biology: what the literature shows

A hypothesis over 30 years old

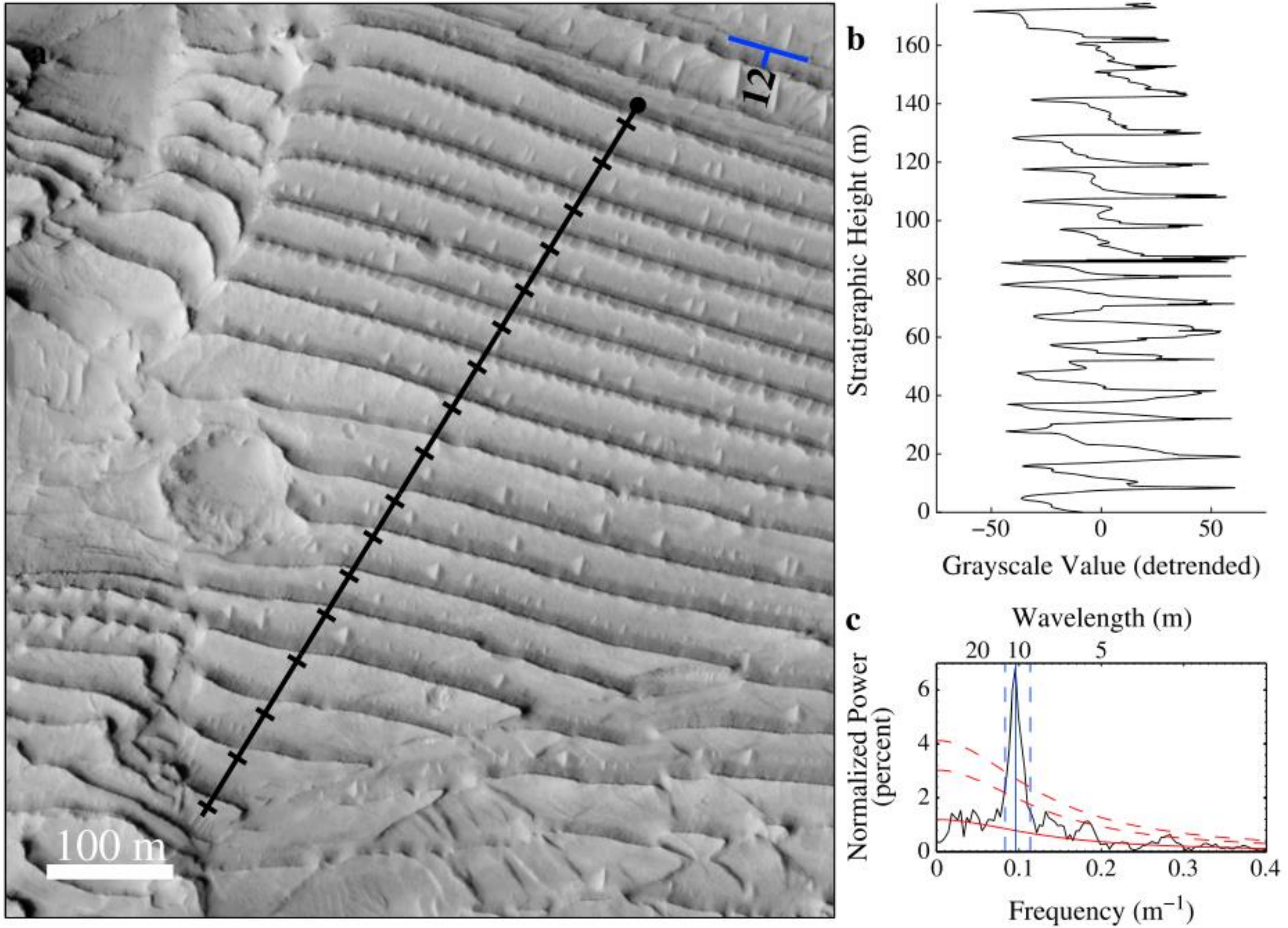
Bennett (1990): Milankovitch cycles impose climatic instability on timescales shorter than a typical species' lifespan.

Where the evidence is strongest

Crampton et al. (2018): long-period variations explain 9–16% of graptoloid turnover. Statistical association, not demonstrated causation.

What is still missing

Exact orbital phase, a plausible climate mechanism, and a biological chronology independent of the orbital hypothesis itself.



A sedimentary archive on Mars

Danielson crater

Orbital images reveal repeated sedimentary layers.

A spatial pattern

Pixels × depth scale; wavelengths in meters.

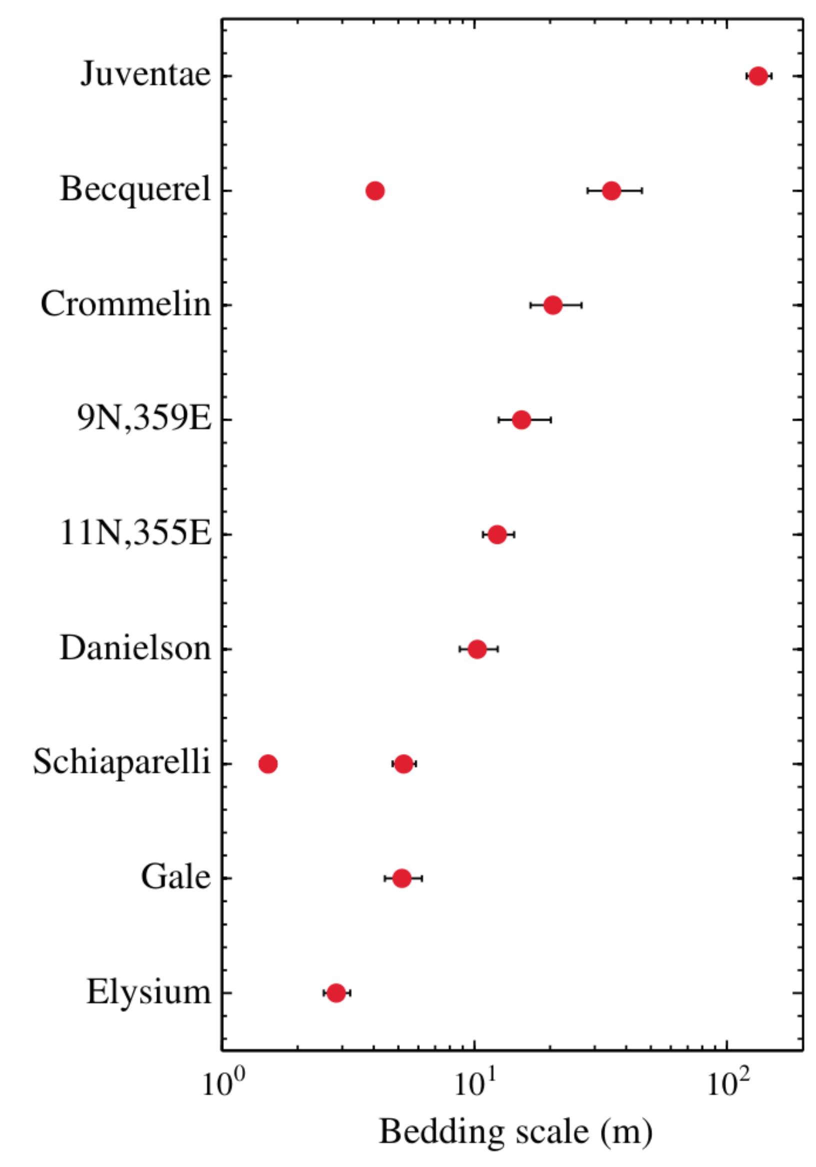
The missing clock

An orbital period requires a defensible depth–time relationship.

Lewis & Aharonson (2014)

Rhythmic sedimentary rocks on Mars

Lewis & Aharonson (2014)



Observed across low-latitude Mars

Quasiperiodic bedding occurs in several regions, including two units within Gale crater.

Recurring scales in the rock record

2–5 m and 10–15 m at multiple sites.
Juventae Chasma reaches ~130 m.

Proposed formation processes

Orbitally paced dust deposition is favored.
Groundwater-fed evaporites may contribute locally.

Limits of the orbital interpretation

Specific orbital cycles and depositional durations remain difficult to constrain at most sites.

Conclusions

What the four case studies show:

Dales Gorge Member (~2.5 billion years ago)	The orbital chronology still depends on competing assumptions. Without them, there is no unique duration for the ancient Earth–Moon system.
Permian–Triassic and Aptian	Astronomical cycles help calibrate environmental crises: the largest Phanerozoic mass extinction and a Cretaceous anoxic event, testing their durations against independent ages.
Avellaneda Fm. (~570 million years ago)	Integrating astronomical cycles and polarity turns a sequence of geomagnetic reversals into a rate estimate.

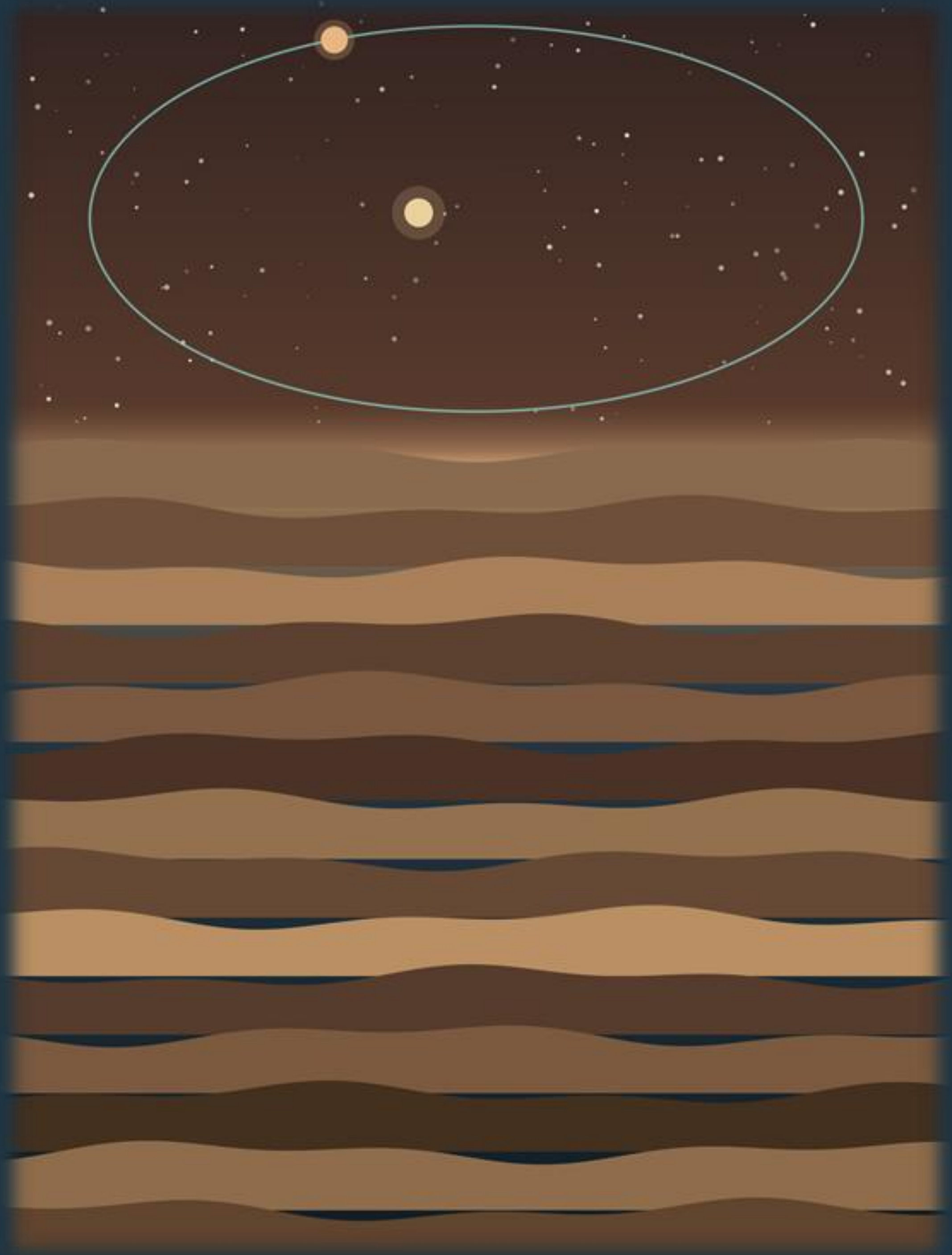
Conclusions

Orbital cycles, climate, and life: the bridge

A two-way dialogue	Astronomy provides physical expectations for orbital cycles; well-calibrated rocks test parts of that orbital and planetary history.
Climate as the link	From the climate response in Hays et al. (1976) to Aptian greenhouse conditions, climate was the physical link between orbit and rock, ultimately tested in exoplanet climate models.
The connection with life requires care	Time calibration allows environmental and biological histories to be compared, but a causal mechanism, as in the graptoloid case, still requires further evidence.

Thank you

To the audience and organizers
of VI AstrobiON



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