Astrochronology of the Cenozoic Era: A Critical Review*

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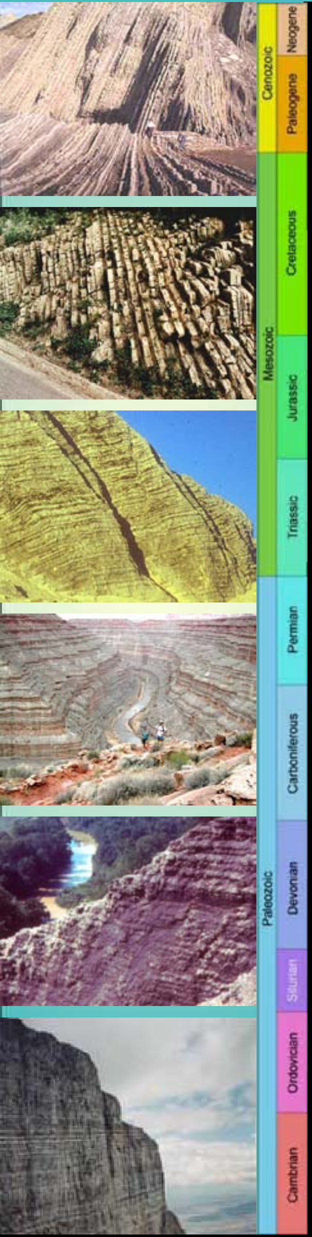
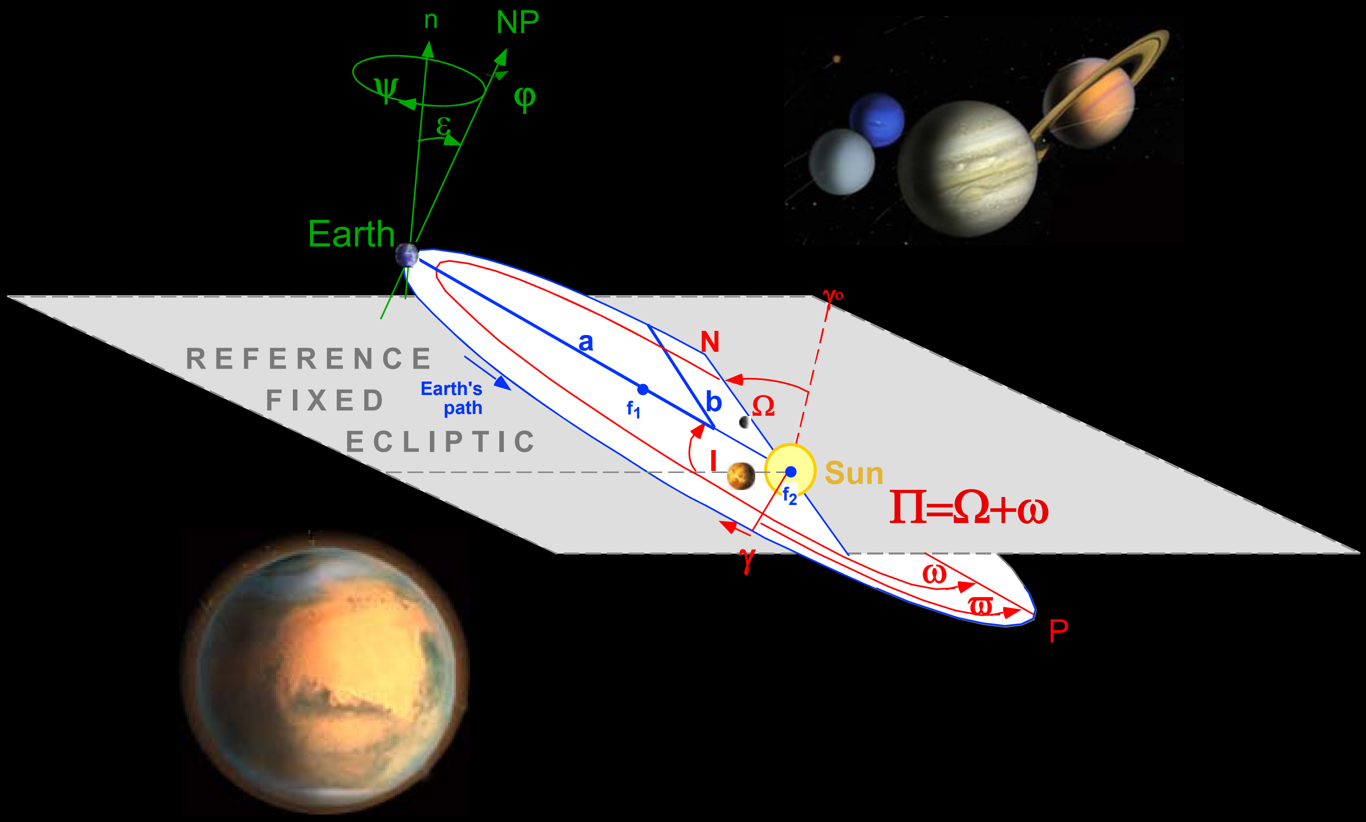
Abstract

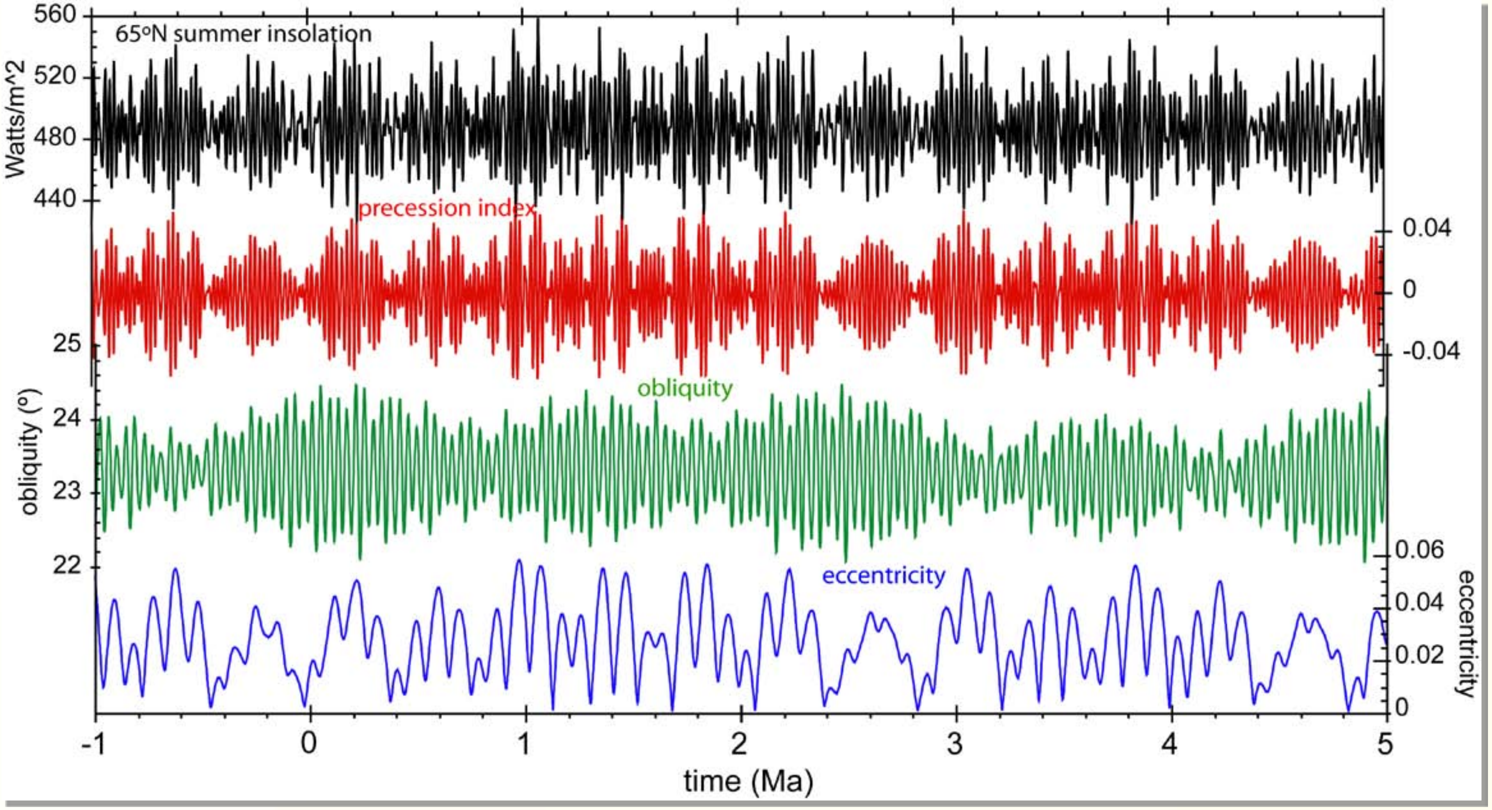
The global stratigraphic record of Milankovitch cyclicity within oceanic sediments has been compiled for almost 100% of the Cenozoic Era. This cycle stratigraphy record provides a continuous "Astronomical Time Scale (ATS)" for the Era that includes integration with magnetic stratigraphy, biostratigraphy, and geochronology from formations in the western Equatorial Atlantic Ocean and Mediterranean Sea. This ATS has been correlated to a high-precision model of the Earth's astronomical parameters, the nominal La2004 astronomical model (Laskar et al., 2004), thereby placing numerical ages on each major cycle and calibrated event. The building of this ATS took place over many years, including the landmark "Astronomically Tuned Neogene Time Scale (ATNTS)" with a resolving power finer than ~20,000 years through the majority of the Neogene Period that was implemented in the Geologic Time Scale 2004 (GTS2004) (Lourens et al., 2004). Since 2004, additional astrochronologic scales developed from extended cyclic sedimentary sequences drilled by the Ocean Drilling Program have closed gaps in the early Neogene and extended the scaling to the base of the Paleogene Period. The only significant remaining gap is an 11 million year interval spanning the Early Eocene Climatic Optimum (42 to 53 Ma), which is the focus of IODP Expeditions 320-321 in the equatorial Pacific (during the time of this AAPG meeting). Despite this gap, the early Paleogene ATS is anchored in absolute time by using recalibrated Ar-Ar ages for the base-Cenozoic that are tied to longer-term 405-kyr astronomical cycles. In early 2008, the pan-European Earthtime-EU Project initiated activities to further improve the Cenozoic ATS. This involves, among other things, fine-scale ATS inter-calibration with high-precision radioisotope dating, and advanced modeling of geodynamic variables (e.g., tidal dissipation) that are used in the astronomical solution. The community goal of a robust ATS with calibrated ages for all biologic, magnetic, and geochemical events through the entire Cenozoic is nearing fruition.



Earth’s Orbital Parameters

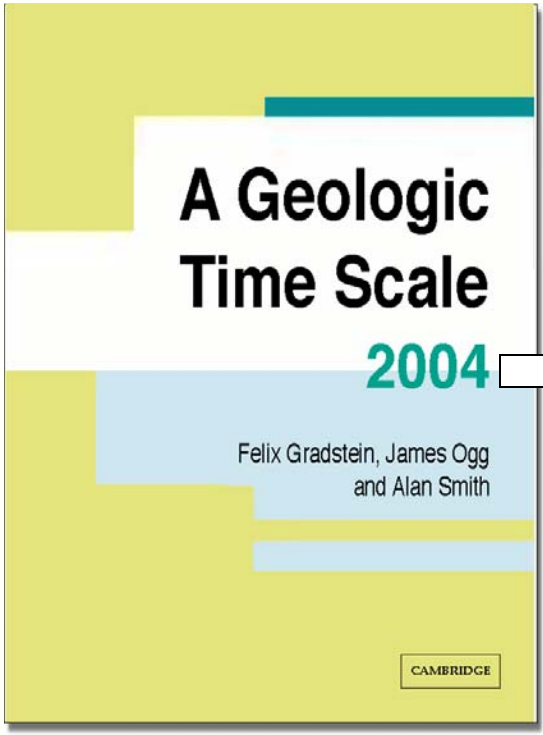


Earth's orbital parameters and insolation



Opening remarks
Cenozoic overview
Eocene Green River
K/T boundary
-BREAK -
Cretaceous ATS
Jurassic ATS
Solar System Roadmap
Late Paleozoic ATS
Mars Cyclostratigraphy

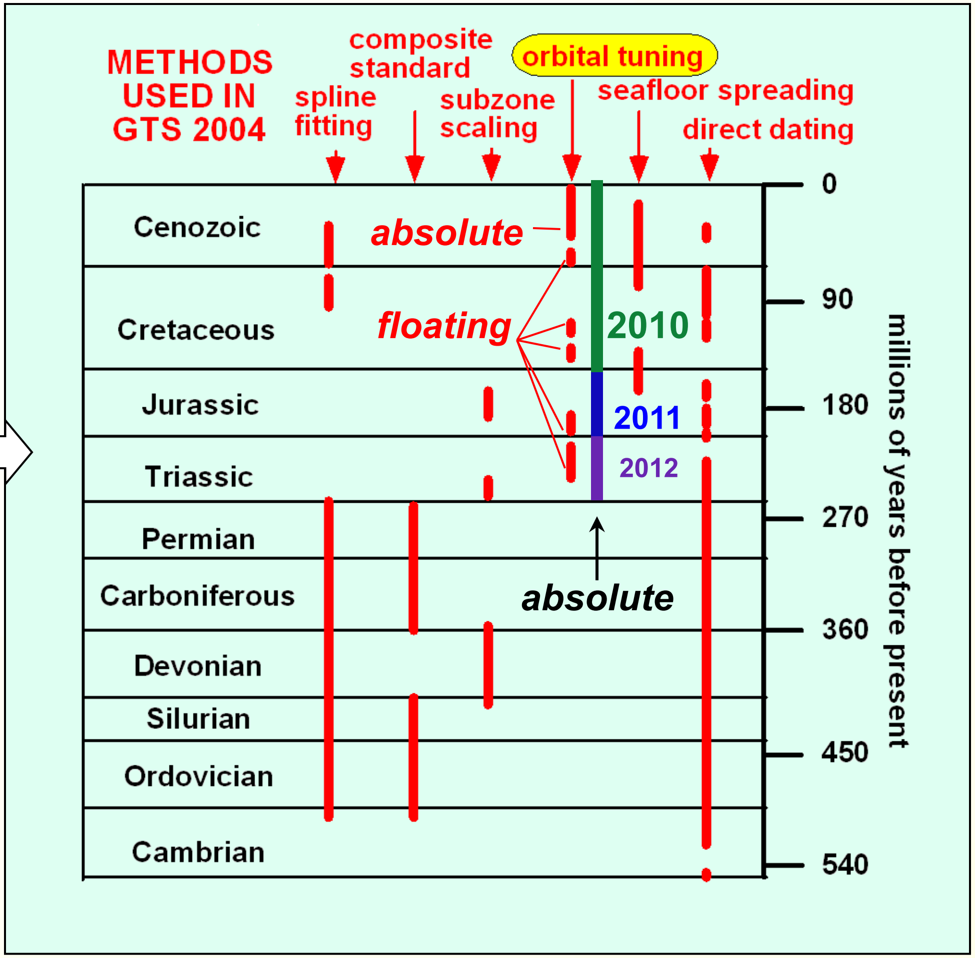
ATS and the GTS



A Geologic Time Scale 2004

Felix Gradstein, James Ogg and Alan Smith

CAMBRIDGE



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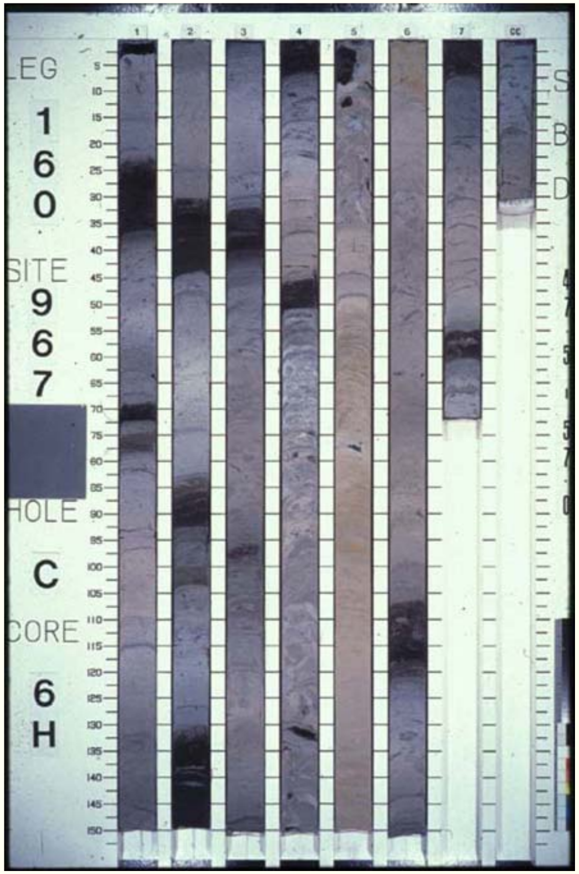
Late Miocene, Gibliscemi, Sicily



Late Pliocene, ODP Leg 160

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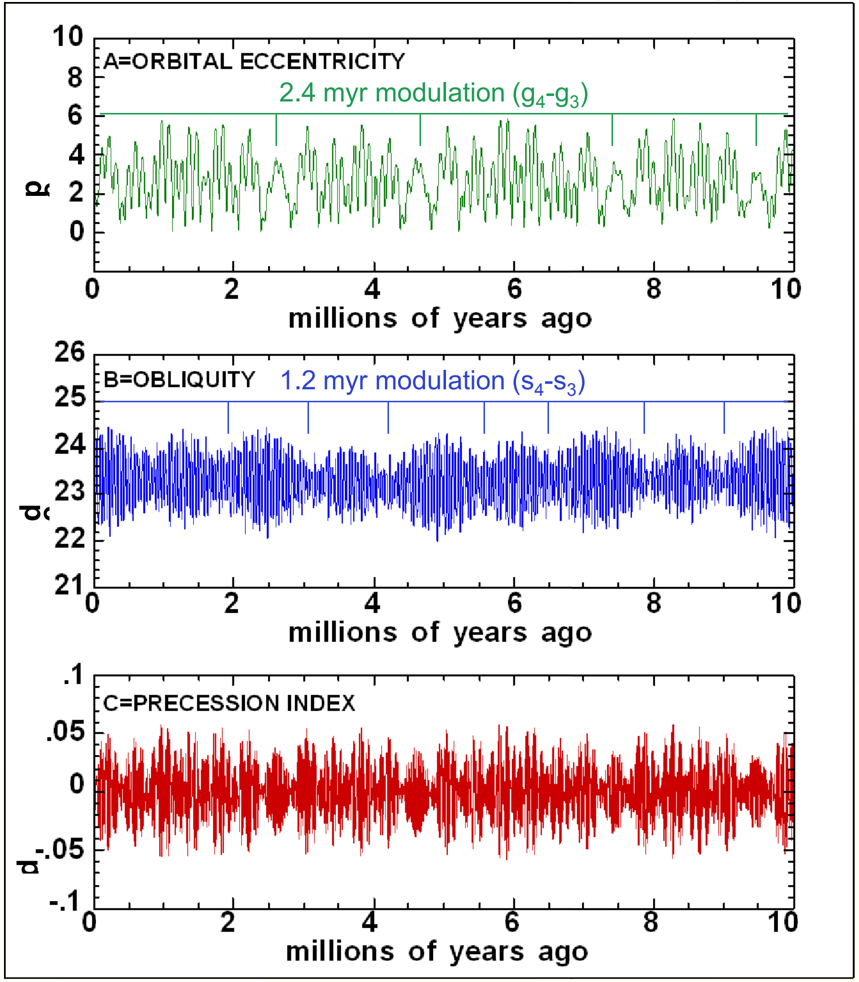
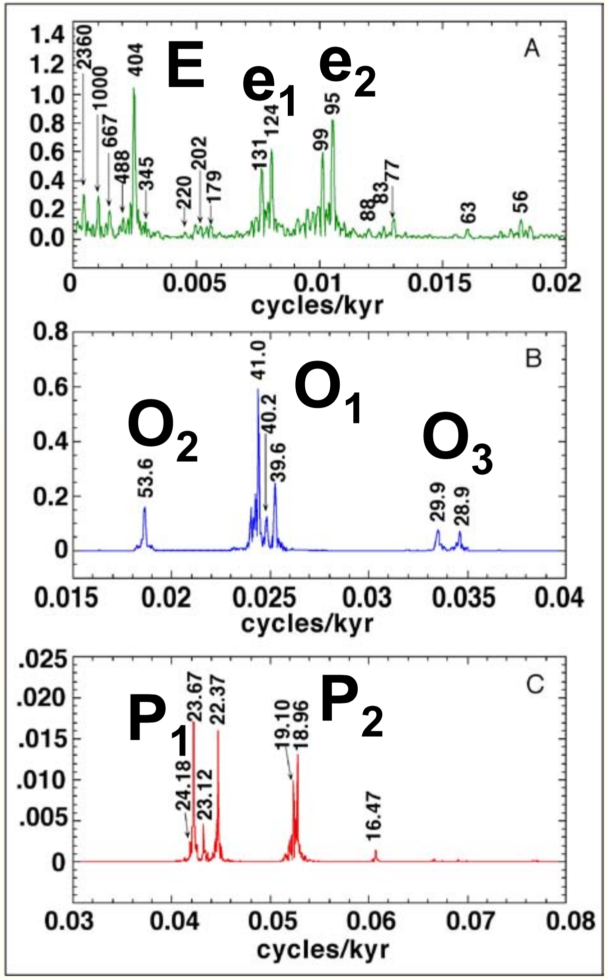


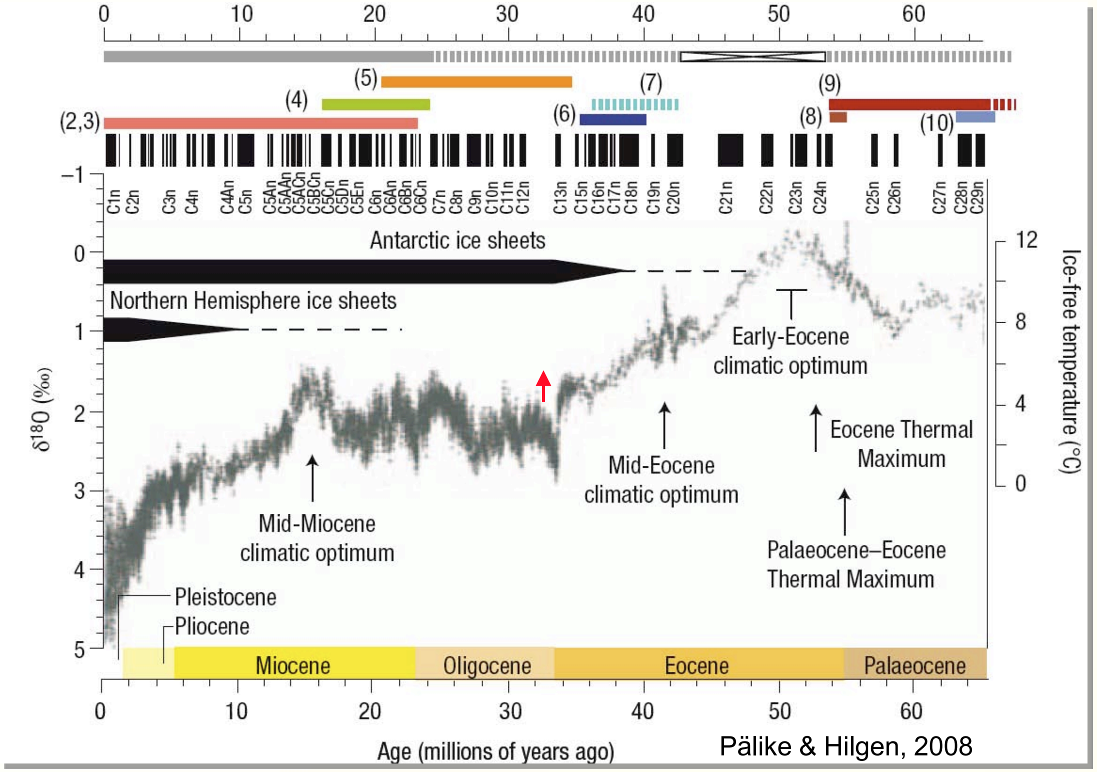


Solar constant | Earth-Sun Distance ρ | Geographic latitude θ | Solar declination δ | Hour angle H

INSOLATION: $W = S_0 \rho^{-2} (\sin\theta\sin\delta + \cos\theta\cos\delta\cos H)$

- **cyclostratigraphy**

Cenozoic coverage



Pälike & Hilgen, 2008

The data

- stable isotopes (O and C) (forams)
- $CaCO_3$, Fe, Ti/Al, Si (marine seds.)
- magnetic susceptibility
- lithofacies (e.g., sapropels)

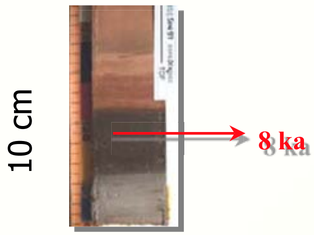
NEOGENE

• Pleistocene

Age model based on sapropel tuning to summer insolation with 3-kyr lag between maximum summer insolation and sapropel midpoint--based on radiocarbon age of Sapropel S1. ***-Lourens et al. 2004***

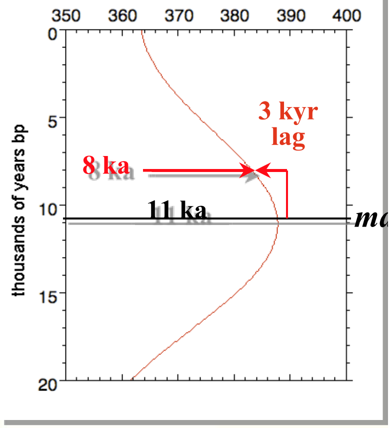
CALIBRATION:

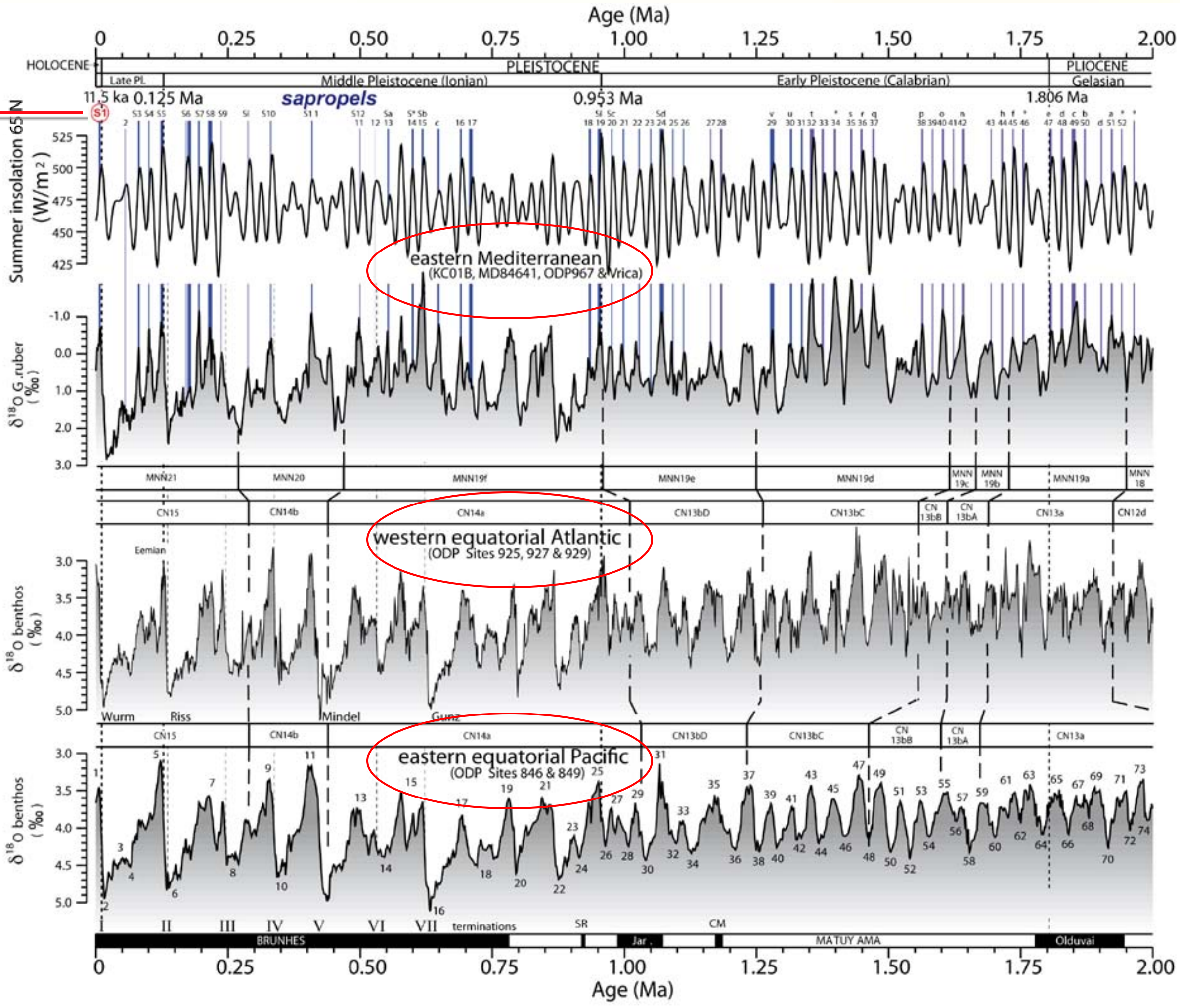
Holocene
SAPROPEL S1



Radiocarbon date: 8 ka

La2004 Summer Insolation 65°N





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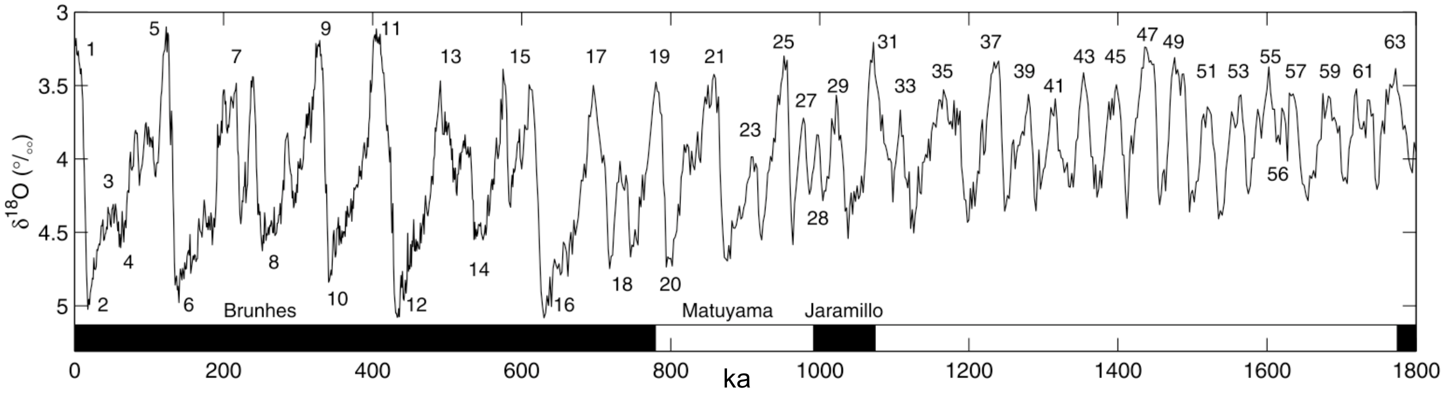
Age model from a stack of 57 globally distributed benthic δ18O records tuned to a nonlinear (5 to 15 kyr lagged) ice model driven by 21 June insolation at 65ºN, based on La93(1,1), except 0-135 Ka which is calibrated to GRIP and U/Th dating of Termination II.

Lisiecki & Raymo, 2005



Model comparison

REVERSAL	MIS	LOURENS ET AL.	LISIECKI & RAYMO	Difference (myr)
Brunhes (b)	19	0.781	0.78	0.001
Jaramillo (t)	28	0.988	0.991	-0.003
Jaramillo (b)	31	1.072	1.075	-0.003
Olduvai (t)	63	1.778	1.781	-0.003

Agree to within 3 kyrs
(Lisiecki older)

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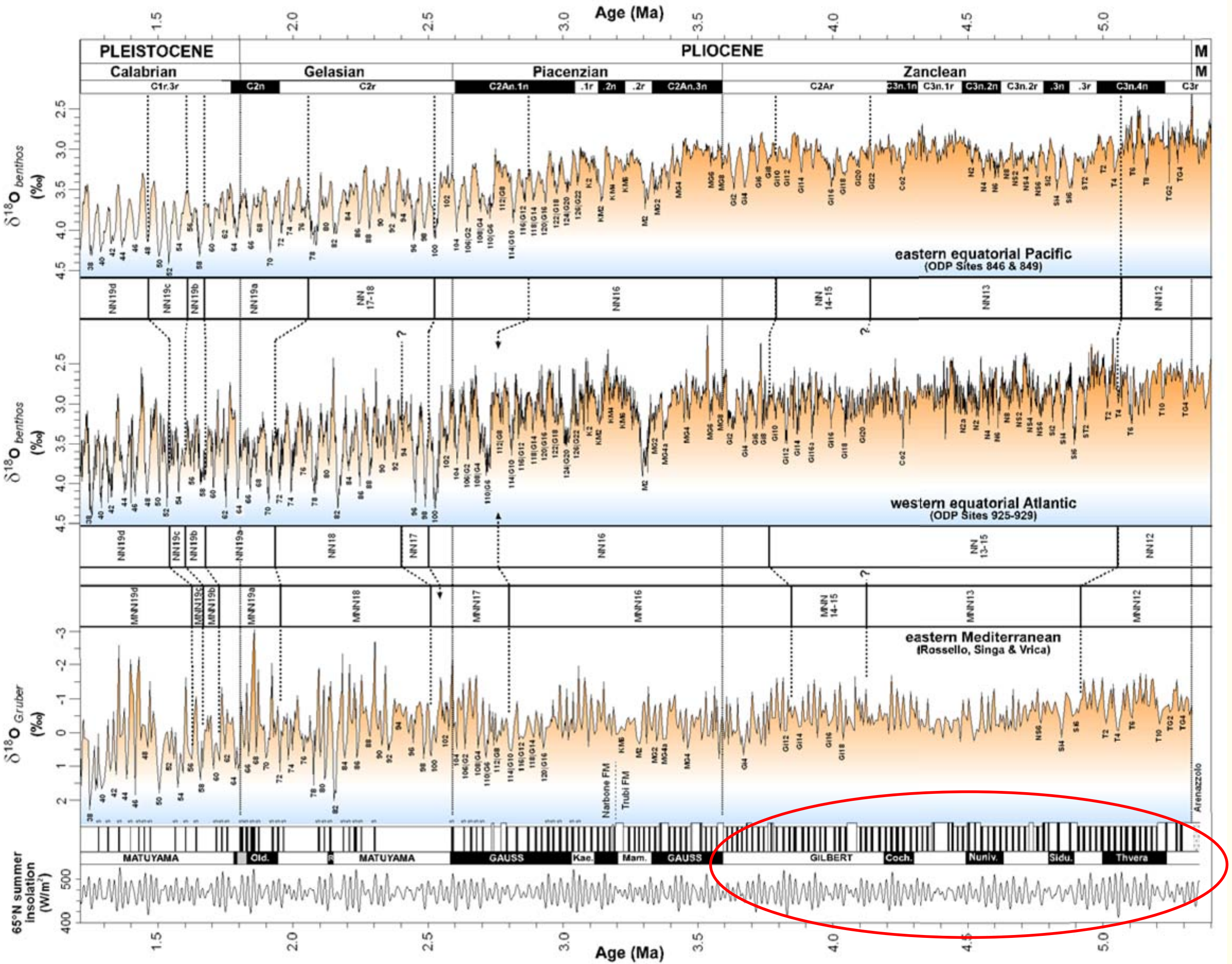
Lourens et al. 2004



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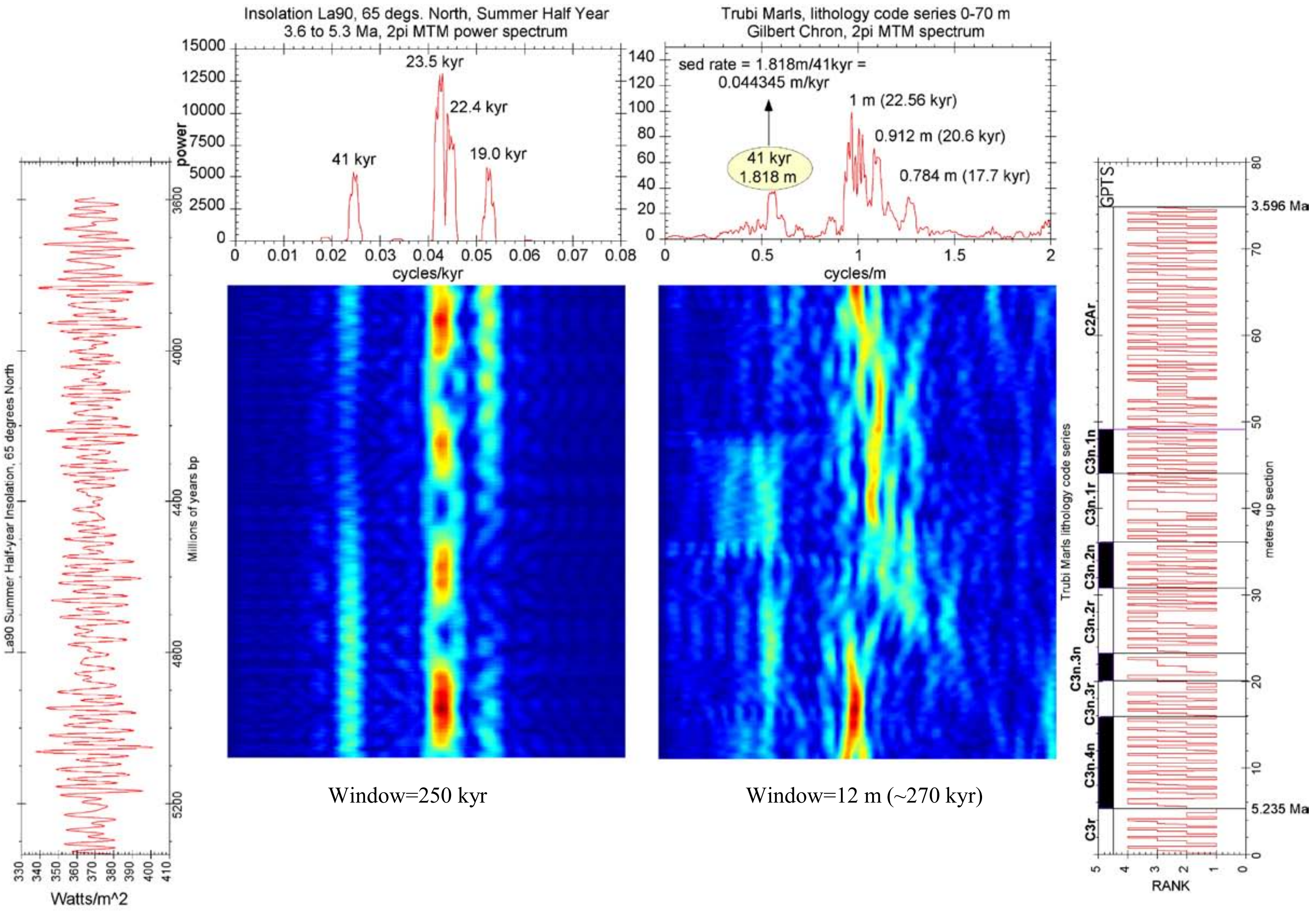
Untuned Trubi Marls v. insolation



Window=250 kyr

Window=12 m (~270 kyr)

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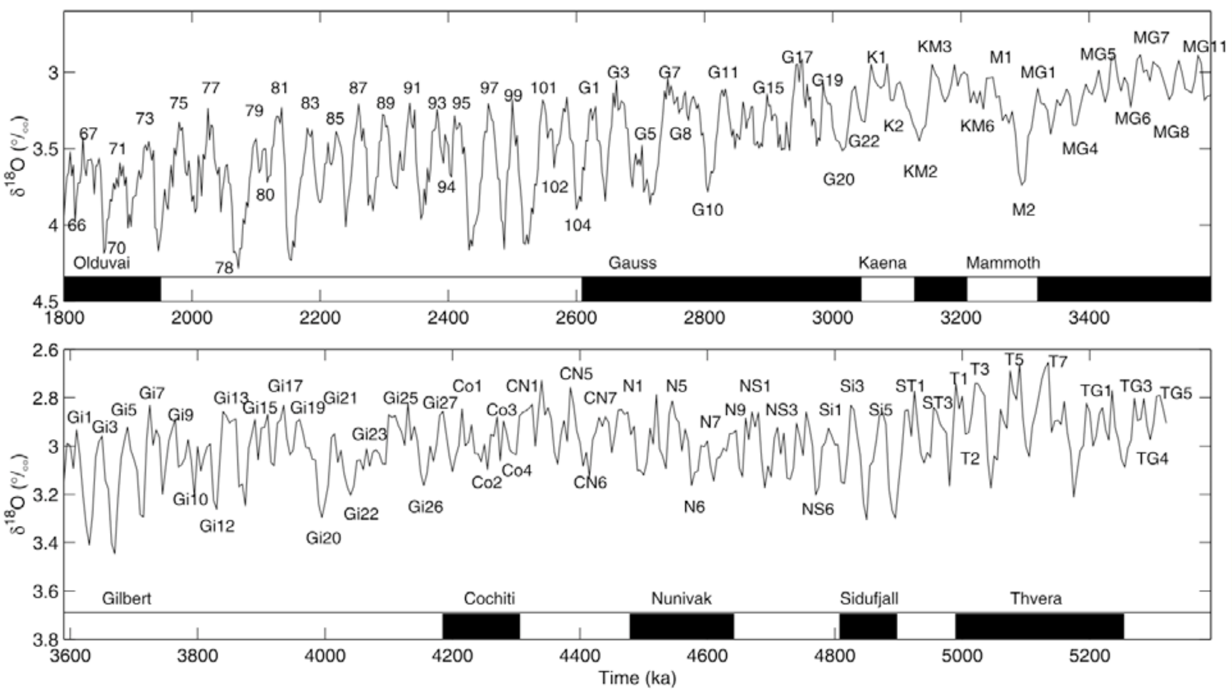
Lisiecki & Raymo 2005



Model comparison

REVERSAL	MIS	LOURENS ET AL.	LISIECKI & RAYMO	Difference (myr)
Olduvai (b)	74	1.945	1.968	-0.023
Matuyama/Gauss	G2	2.581	2.608	-0.027
Kaena (t)	G22	3.032	3.045	-0.013
Kaena (b)	KM2	3.116	3.127	-0.011
Mammoth (t)	KM6	3.207	3.21	-0.003
Mammoth (b)	MG1	3.33	3.319	0.011
Gauss/Gilbert	MG12	3.596	3.588	0.008
Cochiti (t)	Gi27	4.187	4.184	0.003
Cochiti (b)	Co4	4.3	4.306	-0.006
Nunivak (t)	N1	4.493	4.478	0.015
Nunivak (b)	N9	4.631	4.642	-0.011
Sidufall (t)	Si2	4.799	4.807	-0.008
Sidufall (b)	Si6	4.896	4.898	-0.002
Thvera (t)	T1	4.997	4.989	0.008
Thvera (b)	TG2	5.235	5.254	-0.019

**Avg. difference
-5 kyr
(Lisiecki older)**

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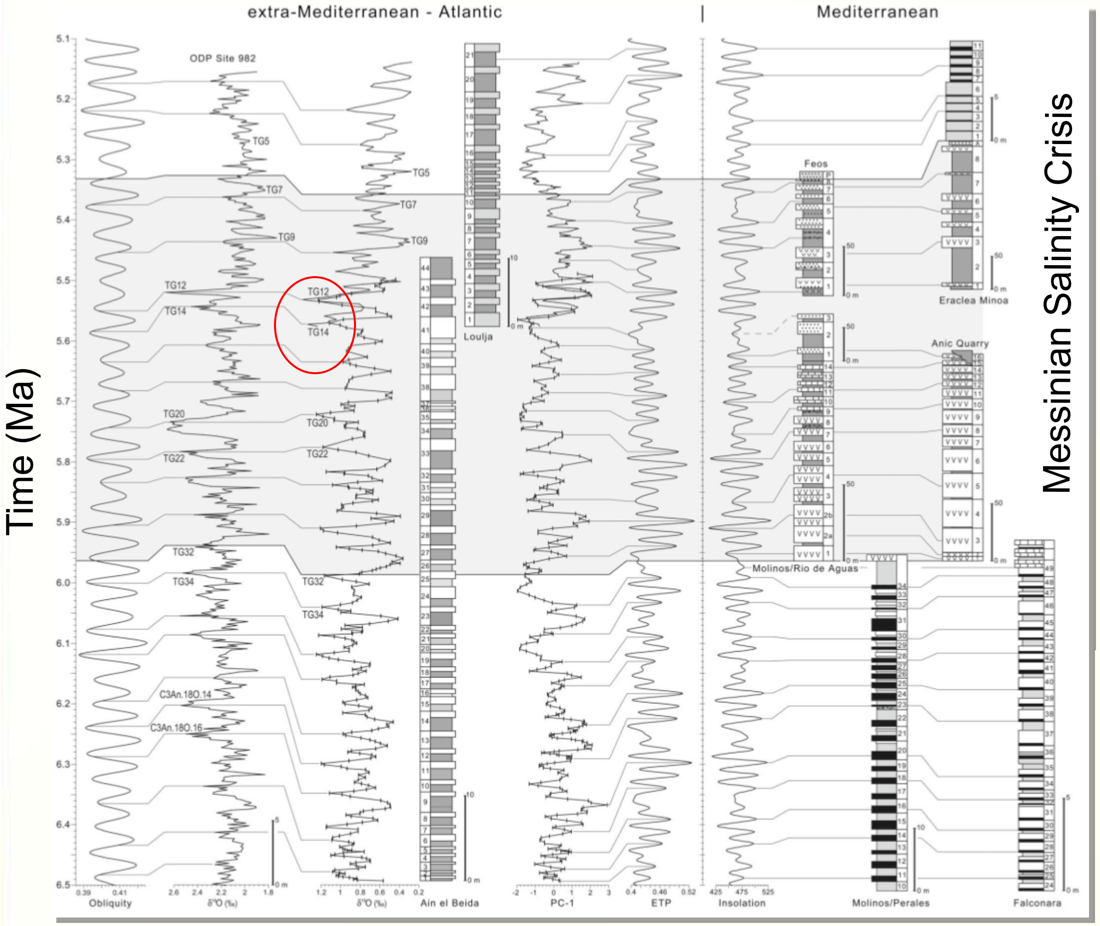
Messinian: 7.25-5.33 Ma



Stronger obliquity forcing

Stronger precession forcing

Hilgen et al. 2007

- onset of MSC 5.96 Ma (not related to glacio-eustatic sealevel lowering)
- main desiccation phase coincides with twin peak glacials TG12-14
- evaporite cycles controlled by precession-forced climate.

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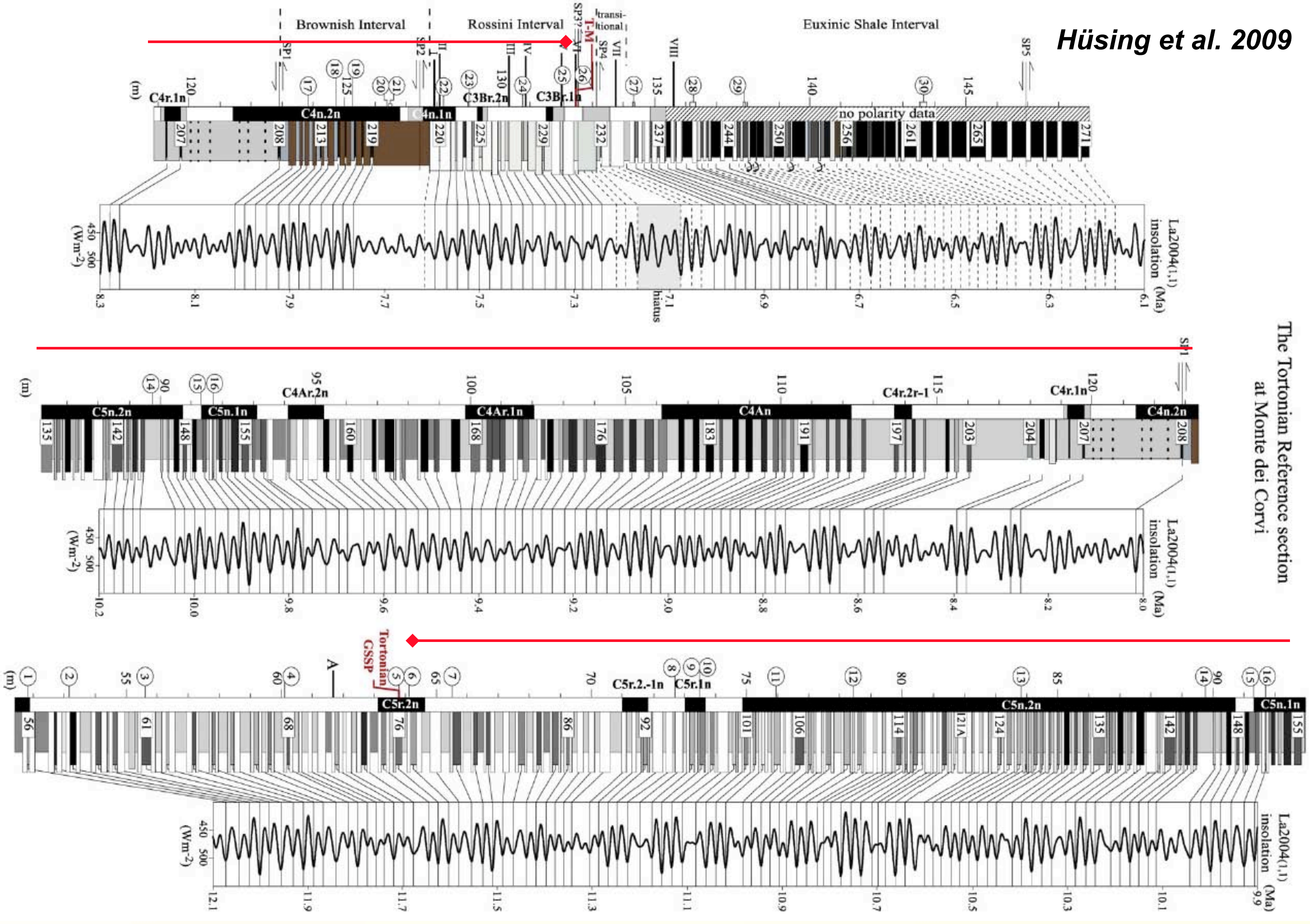
Tortonian:11.61-7.25 Ma

Calibration of sapropels to 65ºN summer insolation, Monte dei Corvi Beach, Italy.



Hüsing et al. 2009

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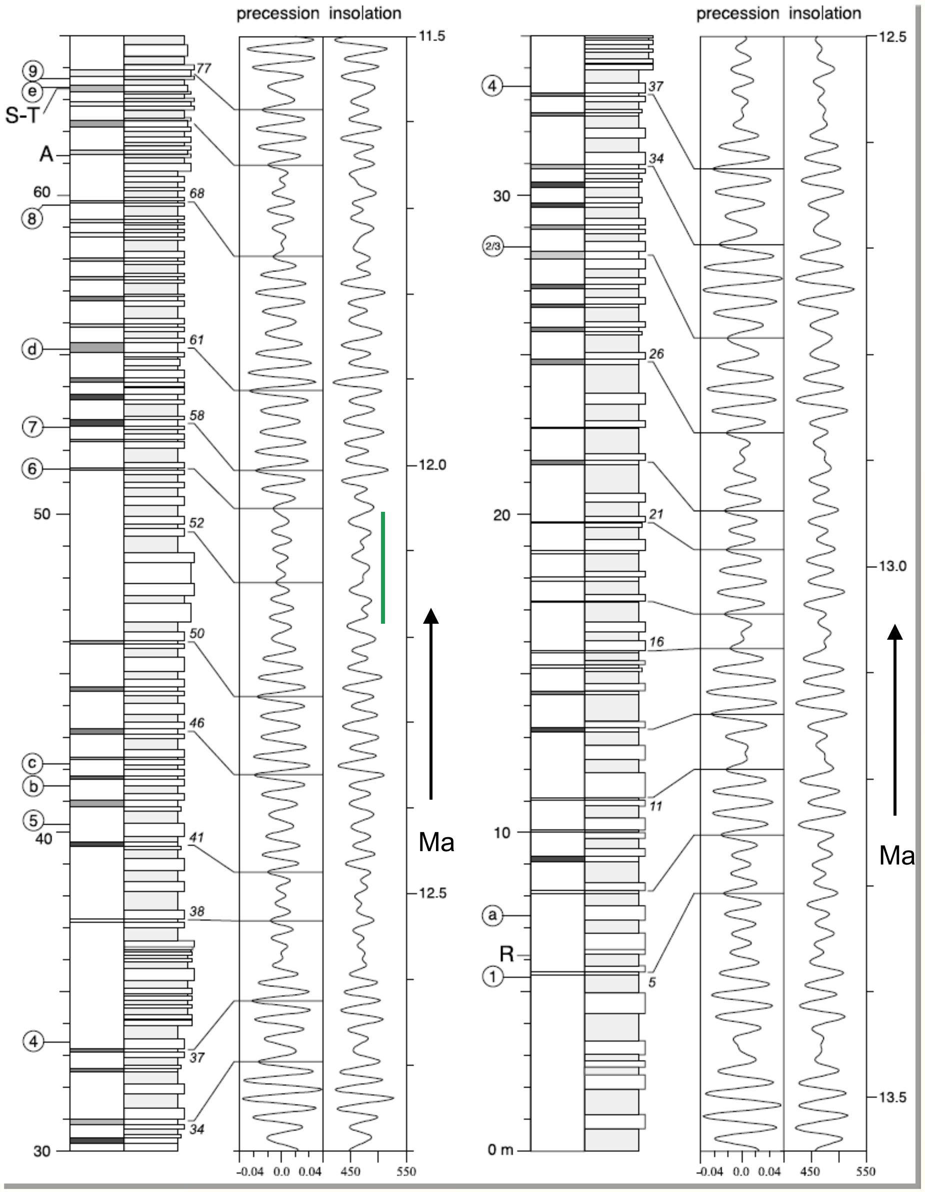

• Miocene

Serravaillian: 13.65-11.61 Ma

Hilgen et al. 2003

- Individual sapropels are correlated to precession and 65ºN insolation.
- Clusters correspond to short and long eccentricity.
- Interval with near-absence of sapropels corresponds to a2.4-myr minimum in eccentricity (see green line).
- Tuned ages are 250-400 kyr older than argon-dated (in 1997) ash beds.

NOTES:
R=Respighi ash bed (Ar-dated: 12.85±0.15 Ma)
A=Ancona ash bed (Ar-dated: 11.4 ±0.25 Ma)
Circled numbers, letters = bioevents

Monte di Corvi Beach, Italy
(lower half of section)

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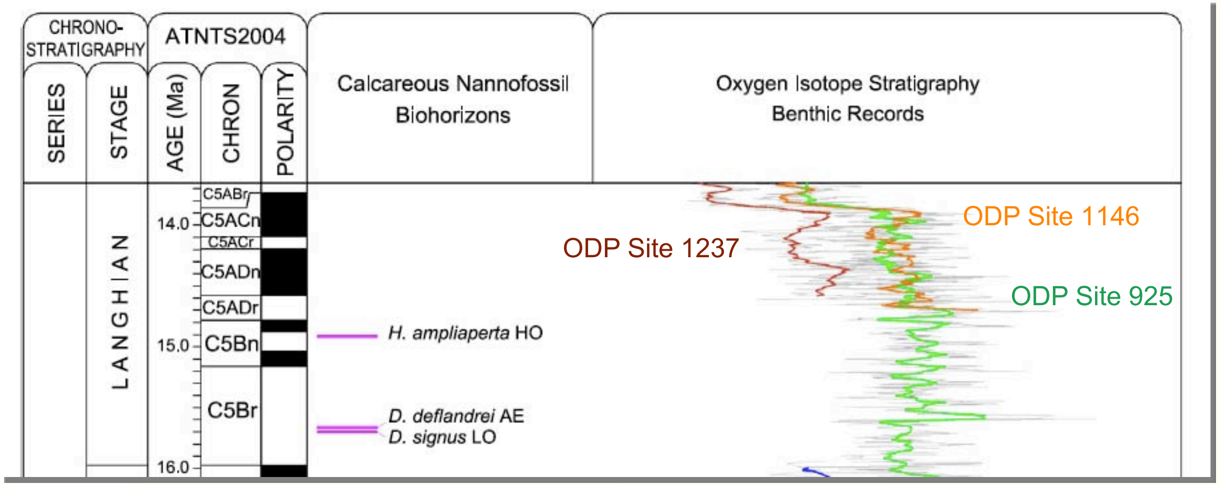
Langhian: 15.97-13.65 Ma

Raffi et al. 2006



Green curve from Shackleton, 2001 (abstract), reported in Raffi et al. 2006.
Burgundy and orange curves from Holbourn et al., 2007

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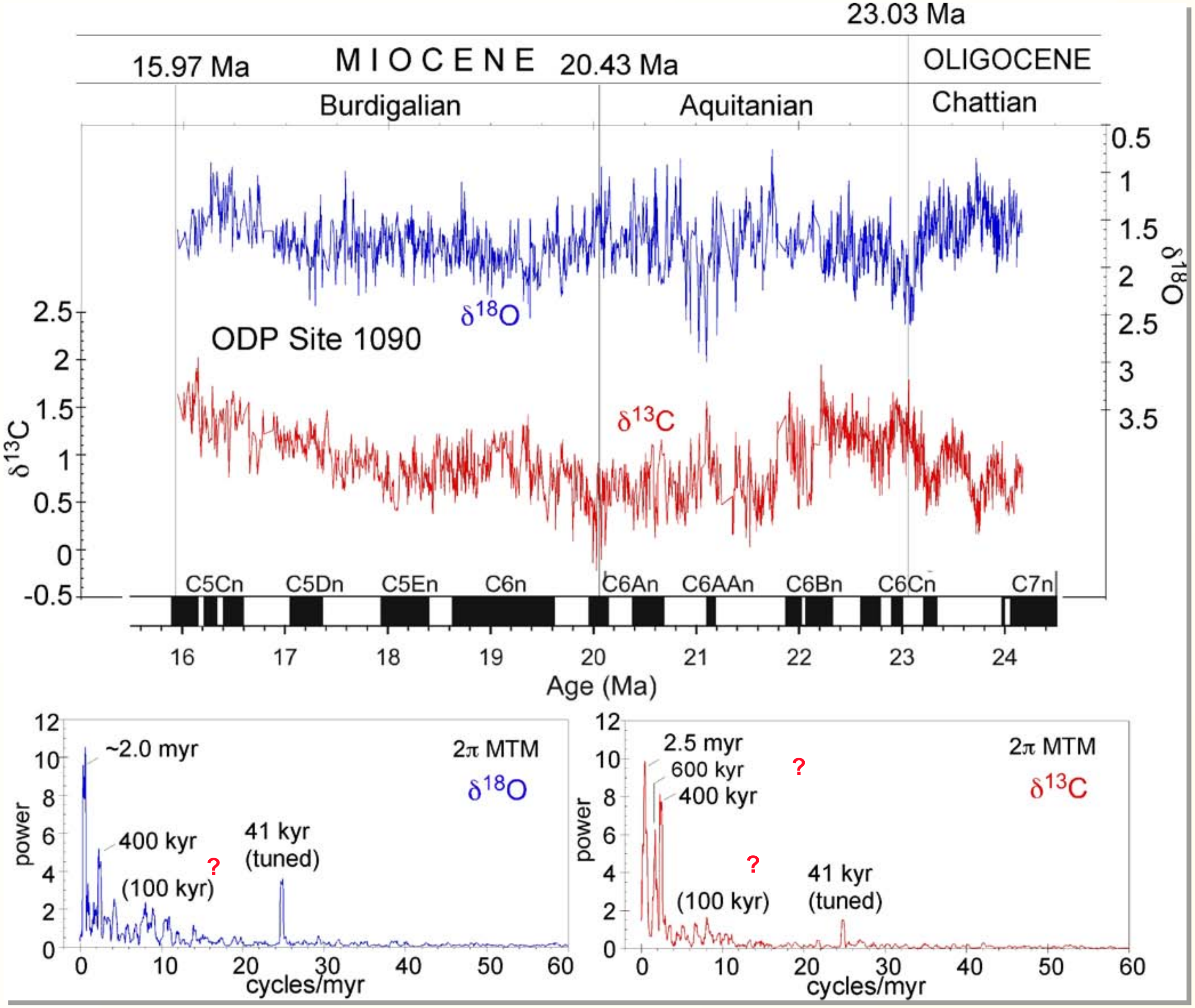
Benthic stable isotope data from ODP Site 1090. ***Billups et al. 2004***

Burdigalian: 20.43-15.97 Ma
Aquitanian: 23.03-20.43 Ma



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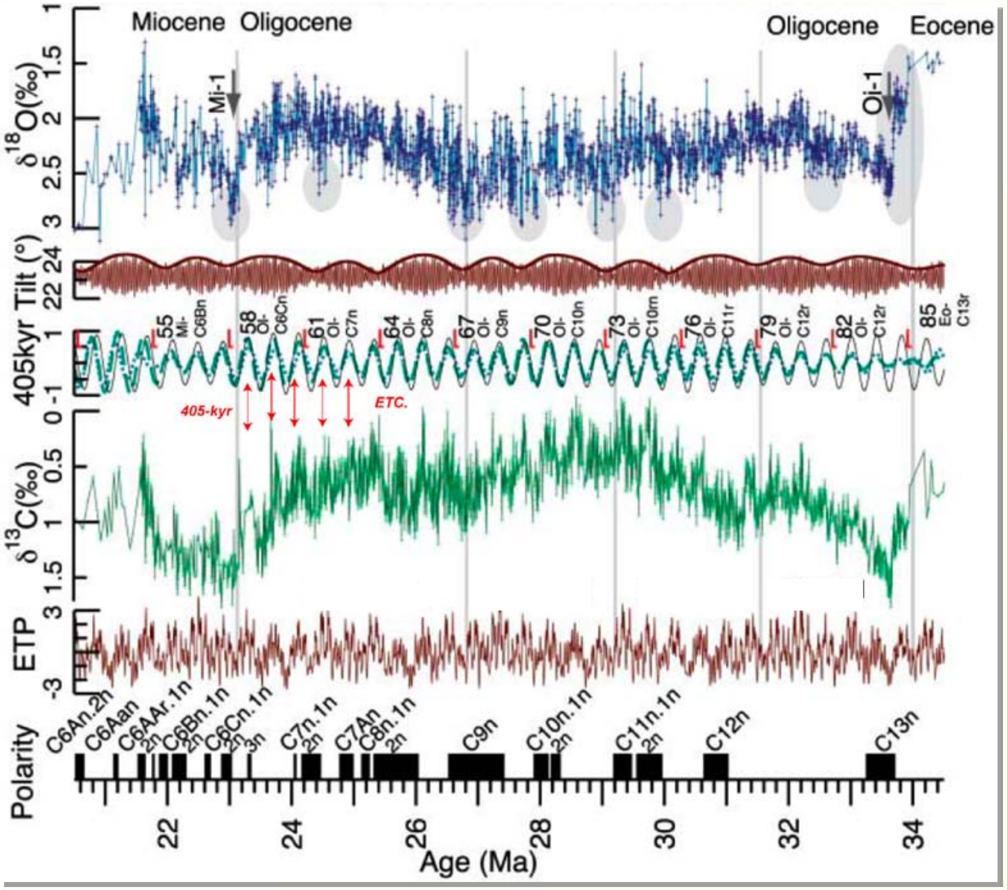
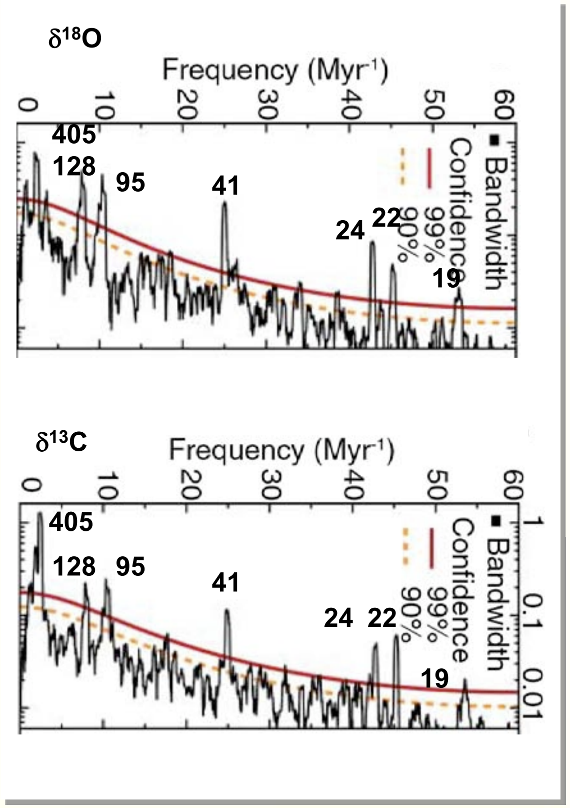
Benthic stable isotope data from ODP Leg 199, Site 1218. ***Pälike et al. 2006***





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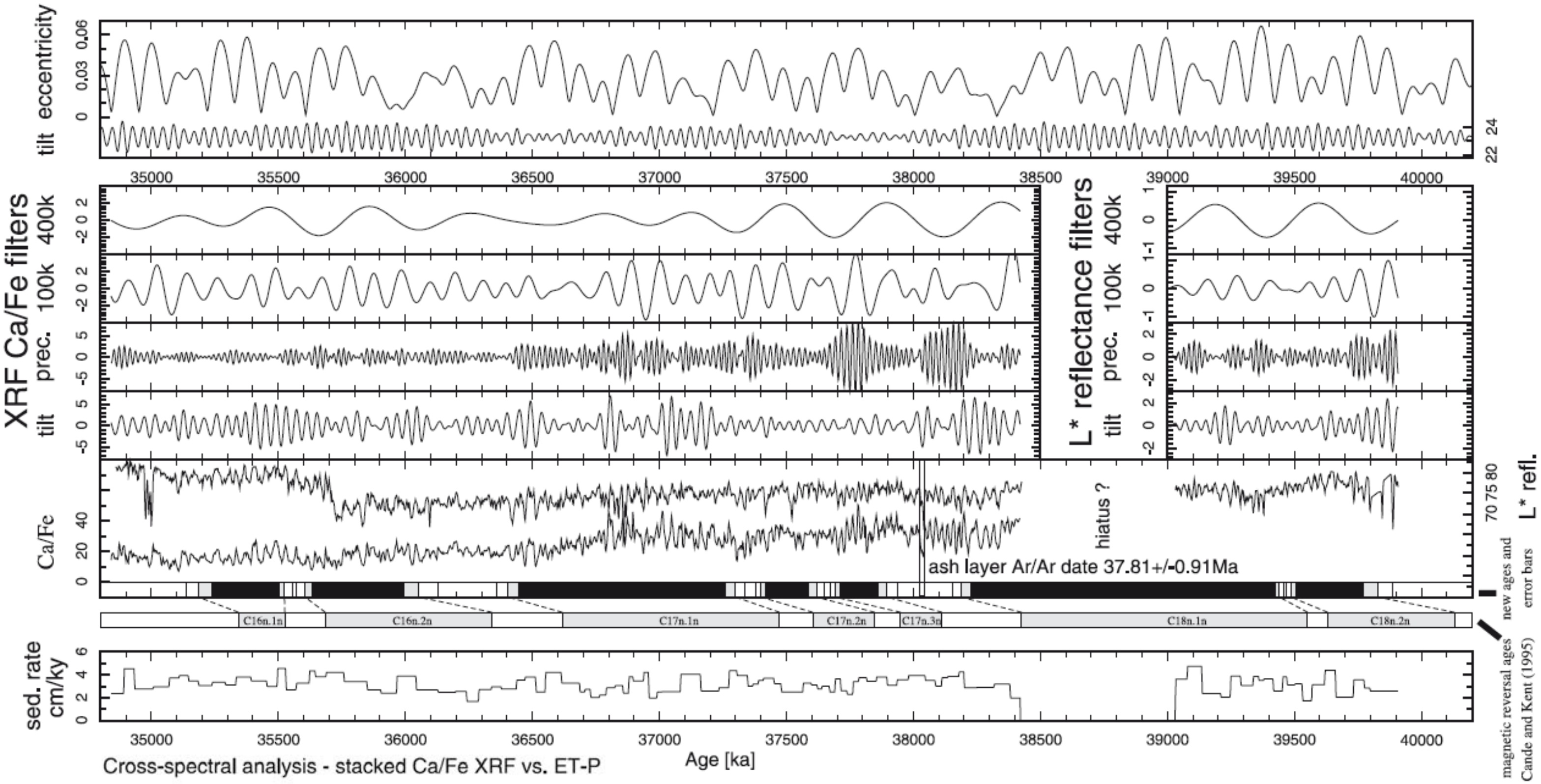
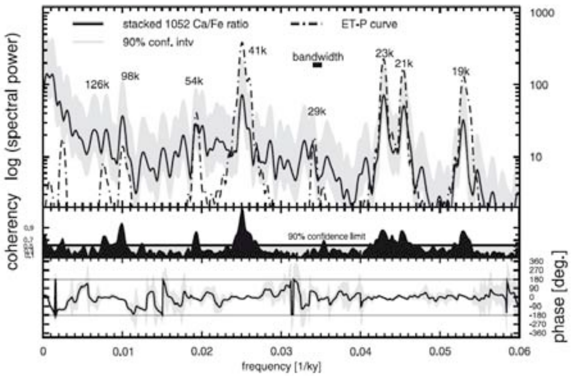


Cross-spectral analysis - stacked Ca/Fe XRF vs. ET-P



Late Eocene:

Leg 171B, Site 1052 (Blake Nose, Atlantic Margin, northern Florida).

High-resolution Ca/Fe chalk-rich series was tuned to ETP series with precession index reversed (to mimic Northern summer polarity).

Pälike et al. 2001

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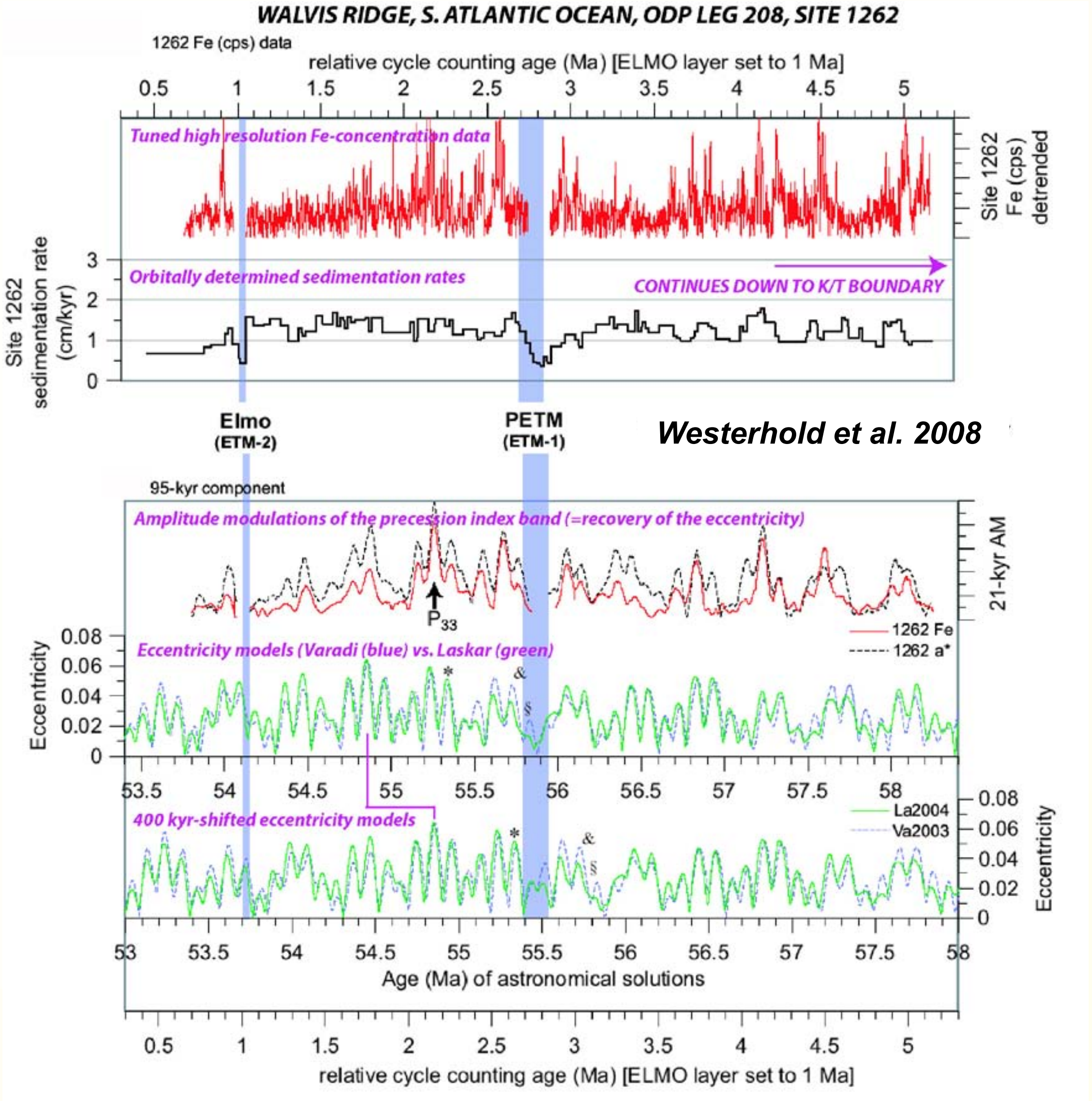
mid-Eocene incomplete

But see
M. Malchus, 2009



Westerhold et al. 2008

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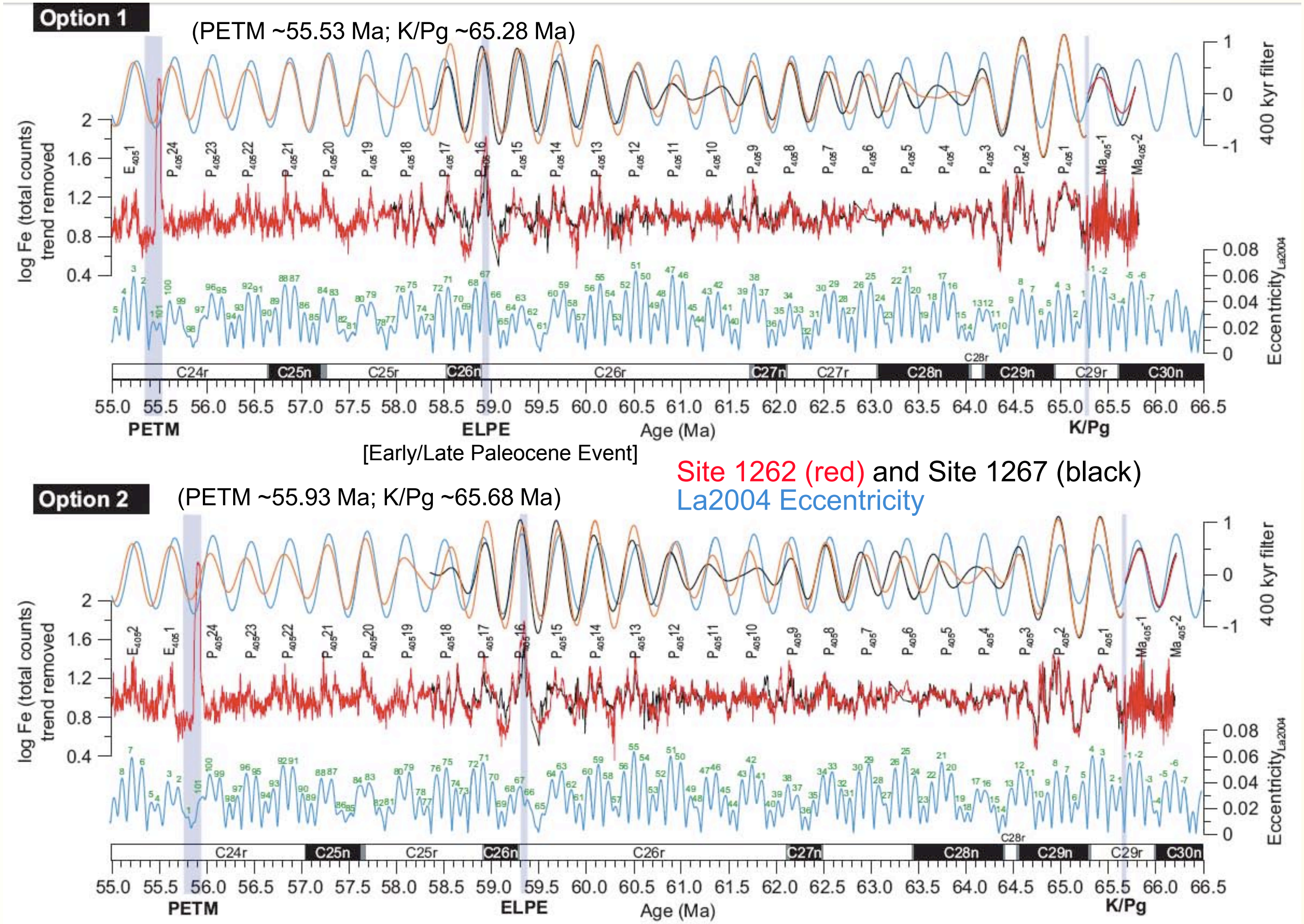
LEG 208, WALVIS RIDGE

- **Paleocene**

Westerhold et al. 2008



Independent sections from Zumaya (Spain)--Dinares-Turell et al., 2007 and **K. Kuiper, 2009**

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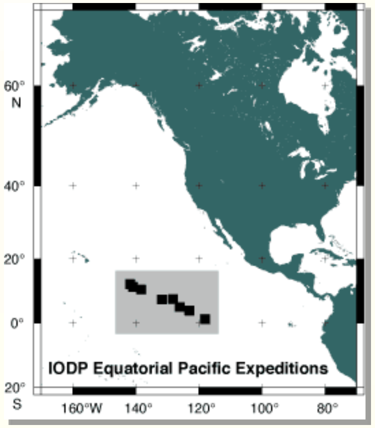
ONGOING WORK

Spring, 2009 -- IODP Expeditions 320/321: The Pacific Equatorial Age Transect (PEAT) targets the mid-Eocene from 42-53 Ma for astrochronology.



EARTHTIME-
The European Contribution

towards the next generation Geological Time Scale for the last 100 million years

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