The imprint of climate in phylogenetic trees: a global analysis on the diversification of Tetrapod families

Théo Pannetier

Study carried out in the *Phylogénie et Évolution Moléculaires* at the ISEM,

under the supervision of Fabien Condamine

Drivers of diversity :

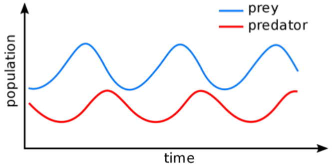
Two concurrent hypothesis

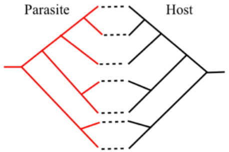
Benton 2009 – Science

Red Queen

Diversification process driven by biotic factors

→ Effects through biotic interactions

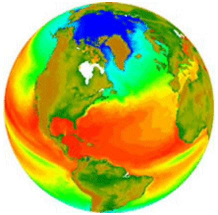




Court Jester

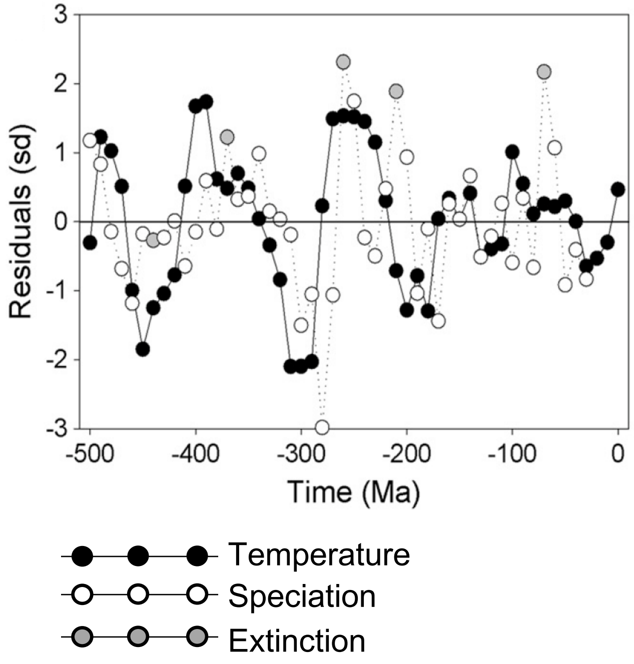
Diversification process driven by abiotic factors

→ Effects through the environment



Temperature → Climate

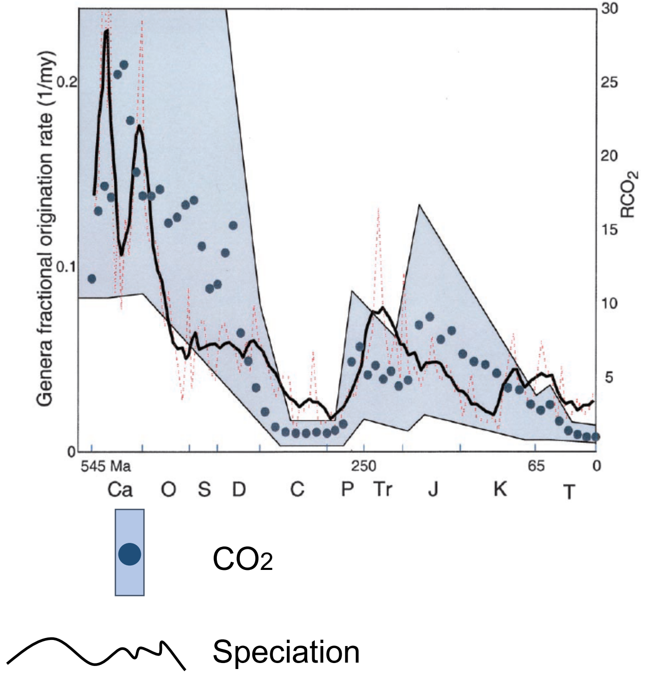
Biodiversity tracks temperature over time



Mayhew et al. 2012 – PNAS

CO_2 → Climate

Documenting a significant relationship between macroevolutionary origination rates and Phanerozoic pCO_2 levels



Cornette et al. 2002 – PNAS

Temperature → Climate

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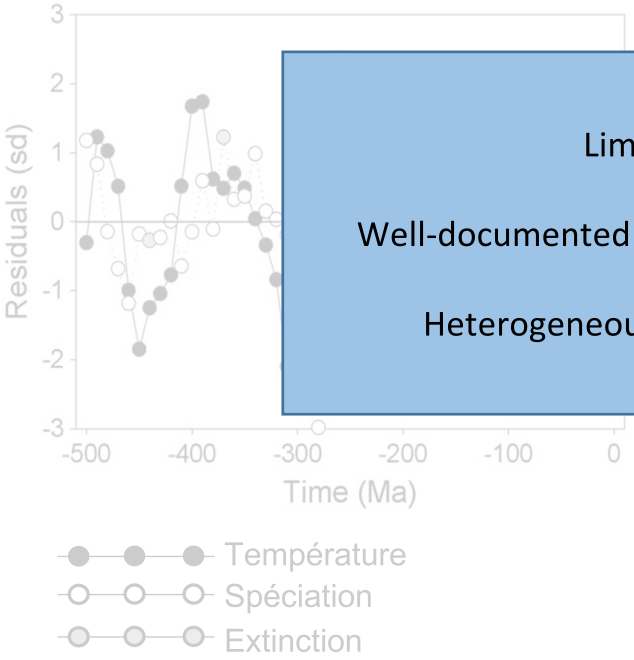

Mayhew et al. 2012 – PNAS

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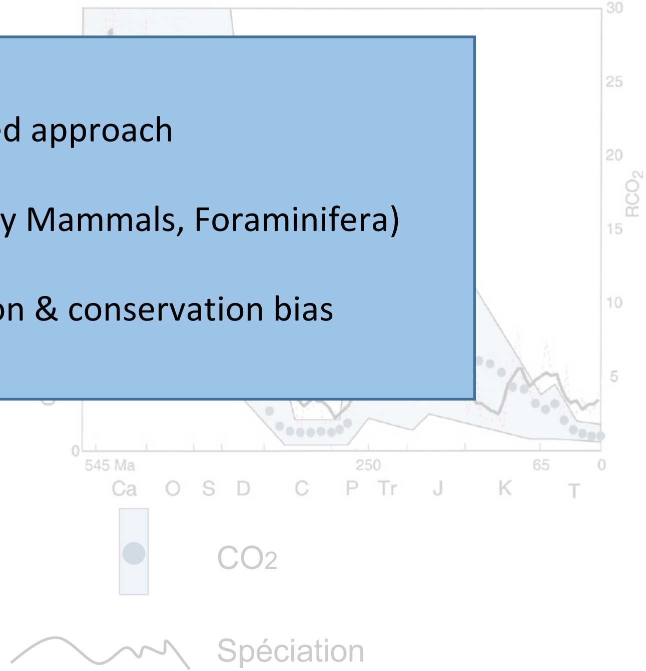


Cornette et al. 2002 – PNAS

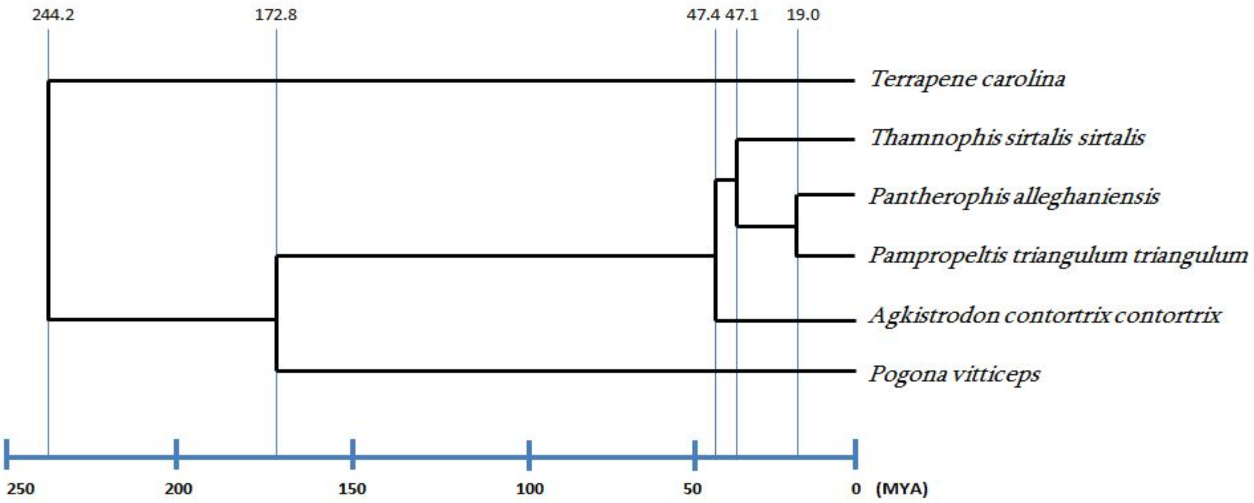
Limits to the fossil-based approach

Well-documented groups only (Tertiary Mammals, Foraminifera)

Heterogeneous record, observation & conservation bias

Another source of information available : molecular phylogenies

Diversification = Speciation (λ) – Extinction (μ)



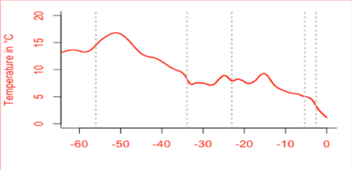
Diversification rate can be inferred from branch lengths

Nee et al. 1994 – PTRSB
Stadler 2013 – J. Evol. Biol.
Morlon 2014 – Ecol. Lett.

3. A phylogeny-based approach of diversification

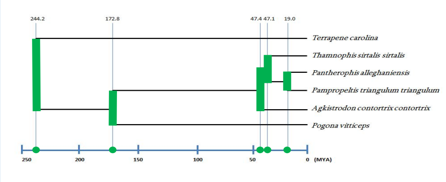
?

Temperature

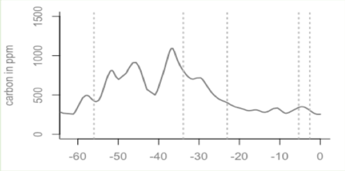


λ

Diversification

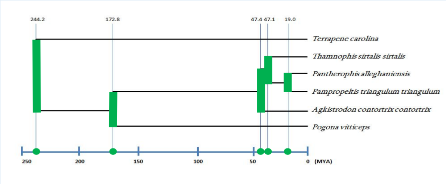


CO_2



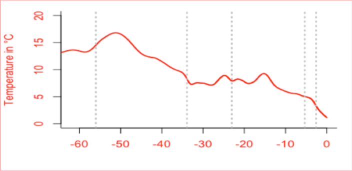
λ

Diversification



3. A phylogeny-based approach of diversification

Temperature

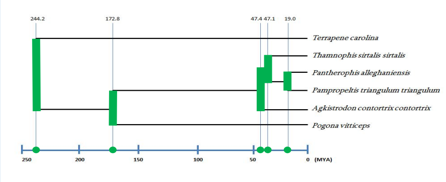


λ

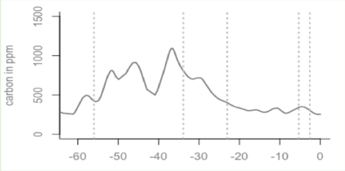
$\mu = 0$

?

Diversification



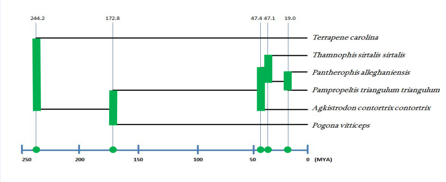
CO_2



λ

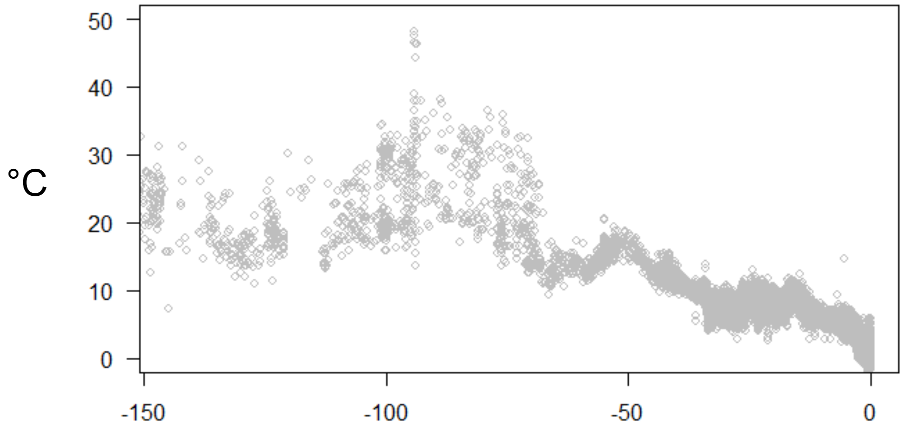
$\mu = 0$

Diversification

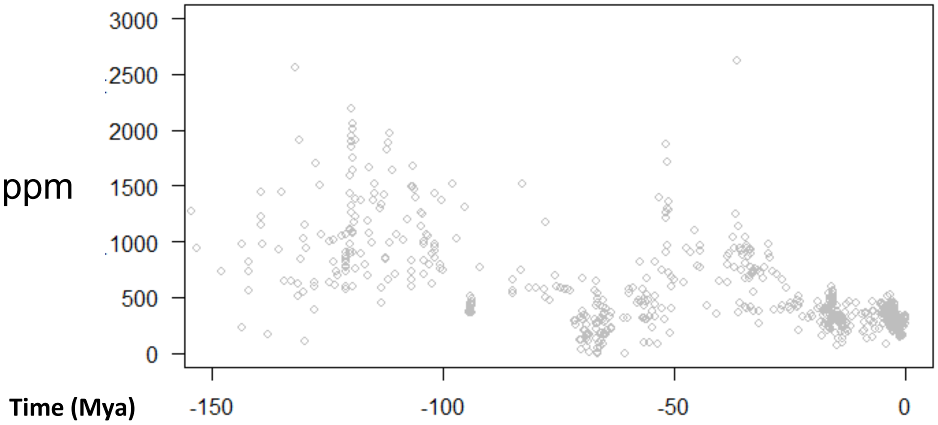


Climatic data obtained from two datasets covering the whole 500 Mya

Global temperature



Atmospheric CO_2



Zachos et al. 2008 – Nature
Prokoph et al. 2008 – Earth-Sci. Rev.
Cramer et al. 2011 – J. Geophys. Res.

Foster et al. 2017 – Nat. Comm.

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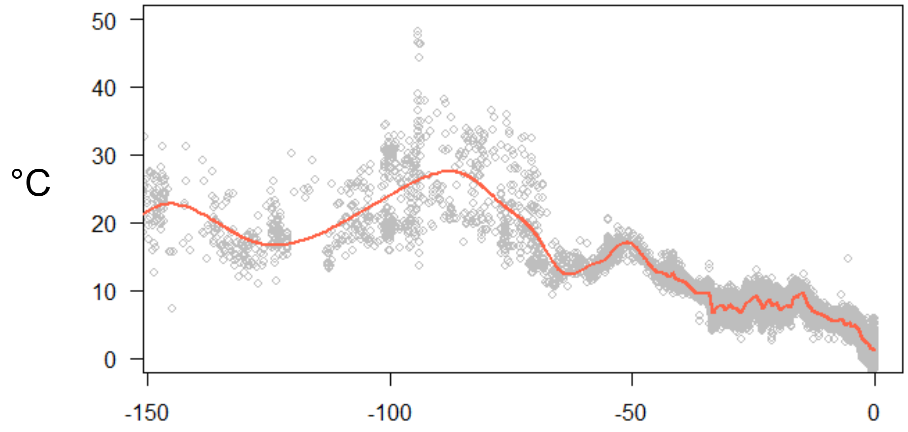

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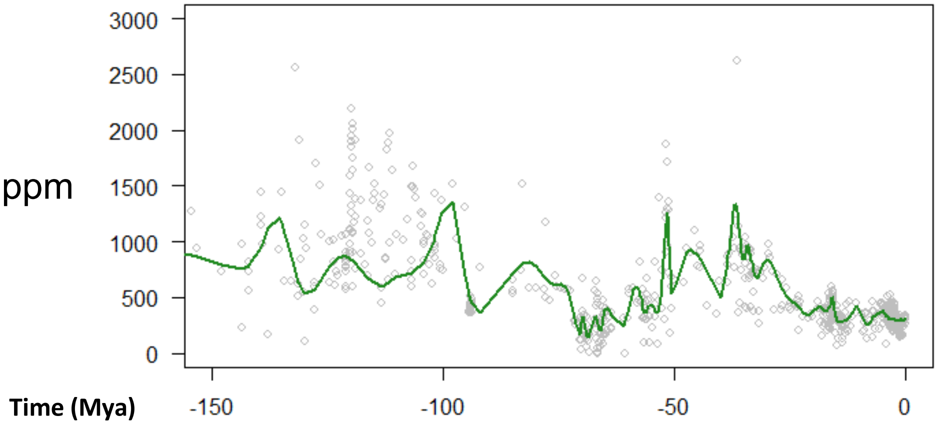


Discrete data points → *Continuous curve*

Zachos et al. 2008 – Nature
Prokoph et al. 2008 – Earth-Sci. Rev.
Cramer et al. 2011 – J. Geophys. Res.

Foster et al. 2017 – Nat. Comm.

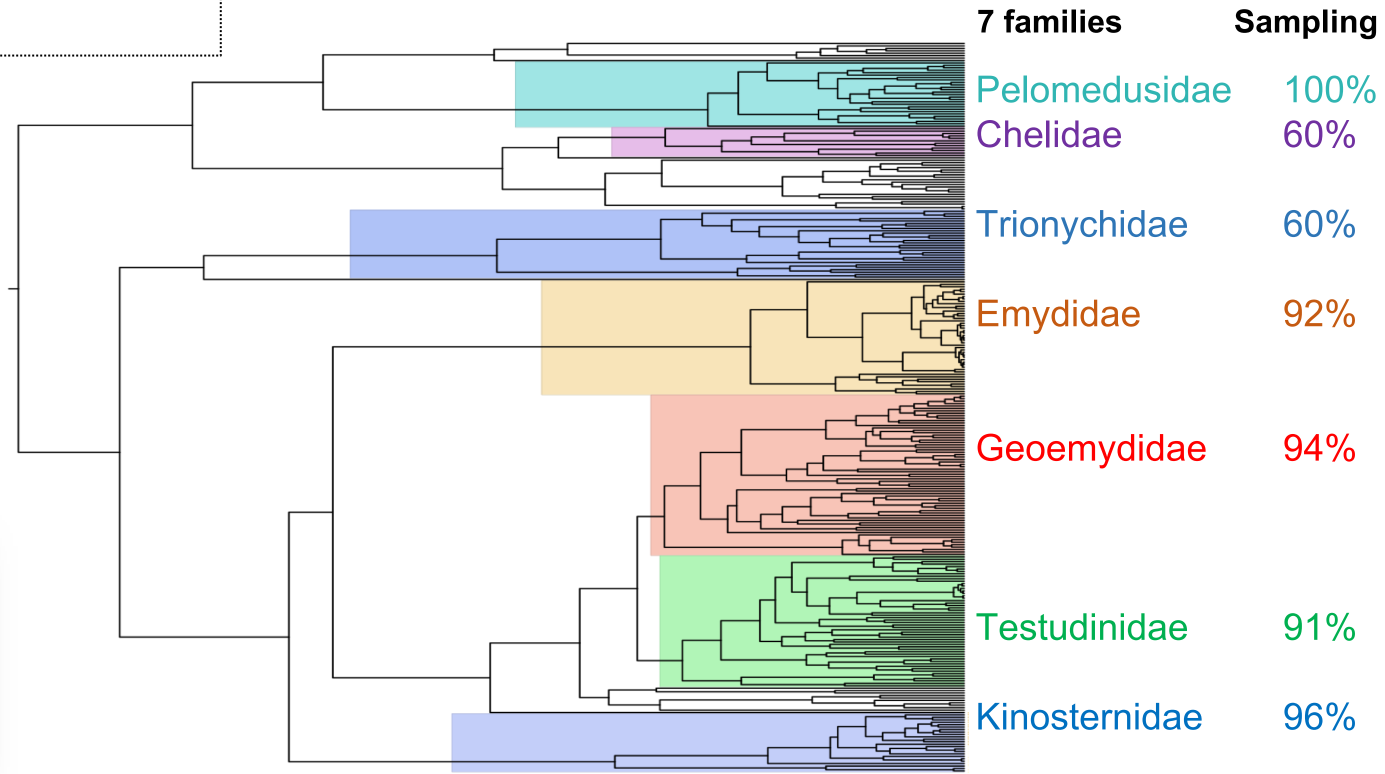
Dated phylogenies for the six main clades of Tetrapods

Clade	Number of species	Taxon sampling	Authors	Number of families
Crocodylia	25	**100%**	Oaks (2011)	**1**
Aves	11 000	**99%**	Jetz et al. (2012)	**129**
Testudines	330	**91%**	Rodrigues & Diniz-Filho (2016)	**7**
Mammalia	5 500	**99%**	Bininda-Emonds et al. (2007)	**66**
Squamates	10 500	**41%**	Zheng & Wiens (2016)	**14**
Amphibia	7 700	**37%**	Pyron (2014)	**15**

Exemple with Testudine phylogeny (turtles & tortoises)

Criterions for inclusion in the sample:
1) At least 10 spp
2) At least 60 % of the taxa

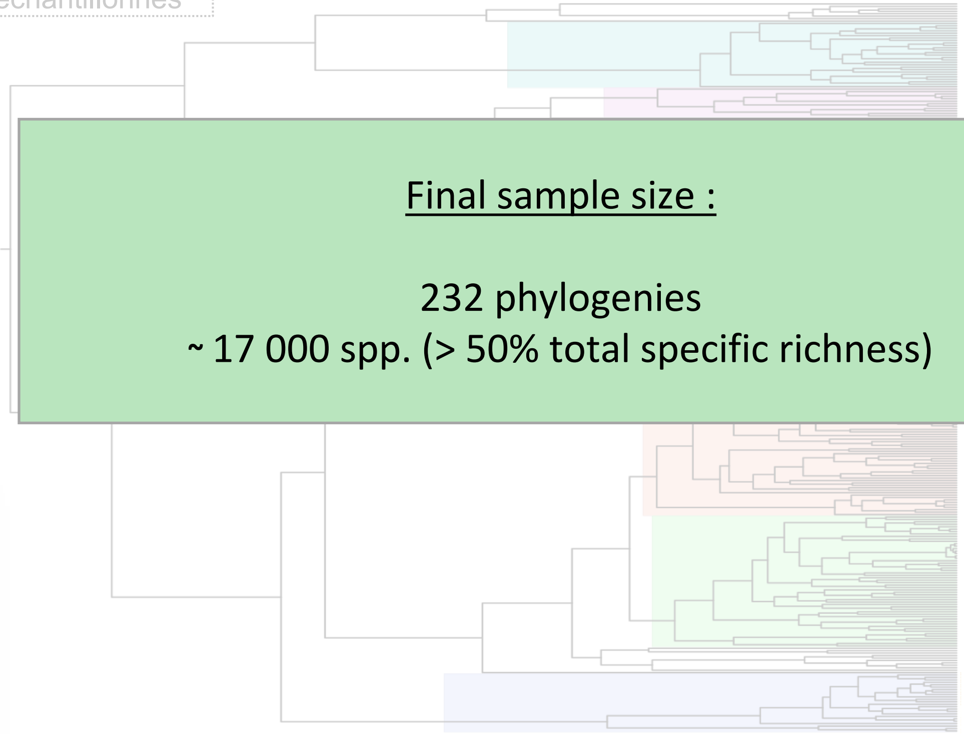
Testudines



Trionychidae

Exemple avec la phylogénie des Testudines (tortues)

Extraction des familles avec :
1) Au moins 10 espèces
2) Au moins 60% des taxons échantillonnés



Trionychidae

Final sample size :

232 phylogenies
~ 17 000 spp. (> 50% total specific richness)

Four speciation models were tested on each phylogeny

Model	Equation	Description
Constant model	$\lambda(t) = \lambda$	Speciation rate constant & independent
Time-dependent model	$\lambda(t) = \lambda \times e^{\alpha t}$	Speciation rate increases/decreases through time
Temperature-dependent model	$\lambda(t) = \lambda \times e^{\alpha T°(t)}$	Speciation rate is function of temperature
CO_2 -dependent model	$\lambda(t) = \lambda \times e^{\alpha CO_2(t)}$	Speciation rate is function of a CO2

Four speciation models were tested on each phylogeny

Constant model
$\lambda(t) = \lambda$

Time-dependent model
$\lambda(t) = \lambda \times e^{\alpha t}$

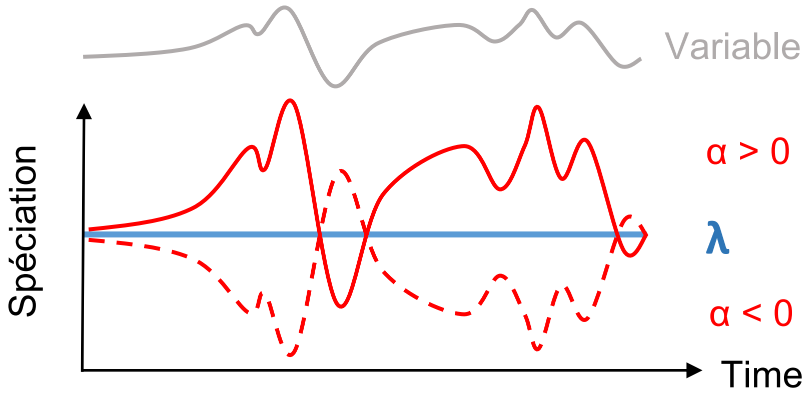
Temperature-dependent model
$\lambda(t) = \lambda \times e^{\alpha\, T°(t)}$

CO_2 -dependent model
$\lambda(t) = \lambda \times e^{\alpha\, CO_2(t)}$

Two parameters :

λ « background » speciation rate

α strength and sense of the dependency



Quatre types de modèles de spéciation testés sur chaque phylogénie

Modèle constant

$\lambda(t) = \lambda$

Modèle te

$\lambda(t$

Modèle temp

Température $\lambda(t) = \lambda \times e^{\alpha\, T°(t)}$

Modèle CO_2 -dépendant

CO_2 $\lambda(t) = \lambda \times e^{\alpha\, CO_2(t)}$

Deux paramètres:

λ correspond à un taux de spéciation sous-jacent

le signe de

tée

Variable

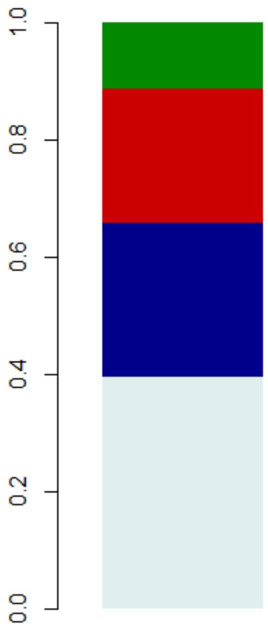
Parameter optimisation → **Maximum likelihood**

Model selection → **AIC**

Results of model selection

Overall results for the 232 families

N = 232



CO_2-dependent model
26 families – 11%

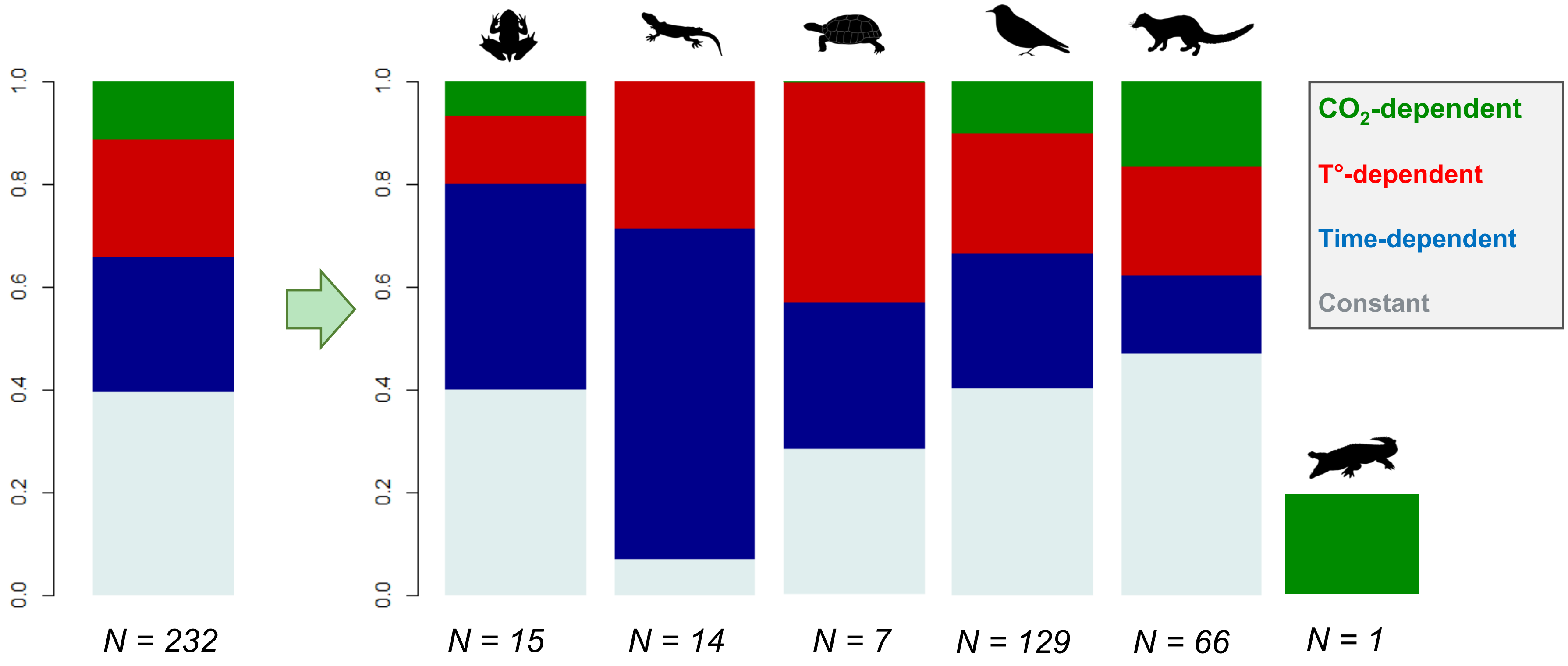
Temperature-dependent model
53 families – 23%

Time-dependent model
62 families – 27%

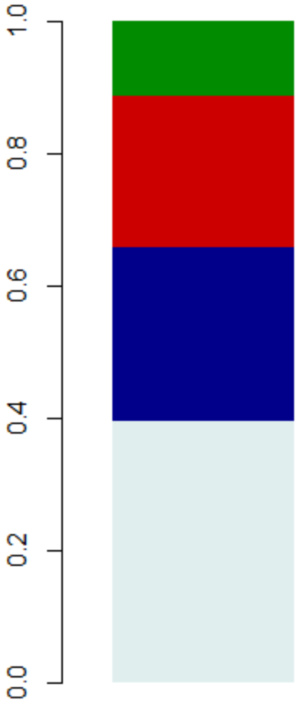
Constant model
91 families – 39%

Results of model selection

Overall results for the 232 families



DISCUSSION



34% of families: speciation rate variations best explained by climatic variations (CO_2 & temperature)

1 - Signal of climate : rule or exception ?

Signal found in the 6 main clades of living tetrapods

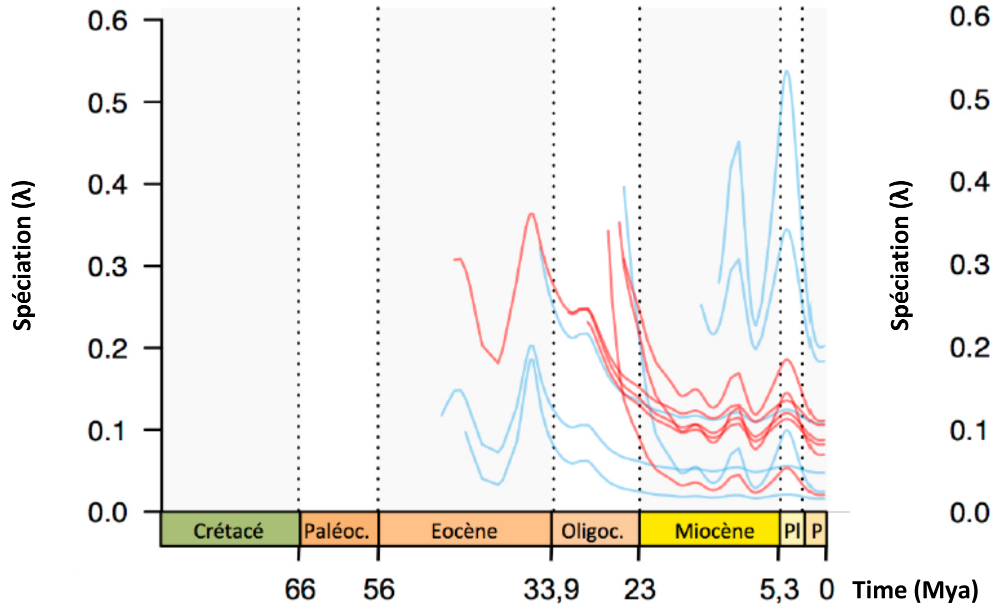
RESULTS

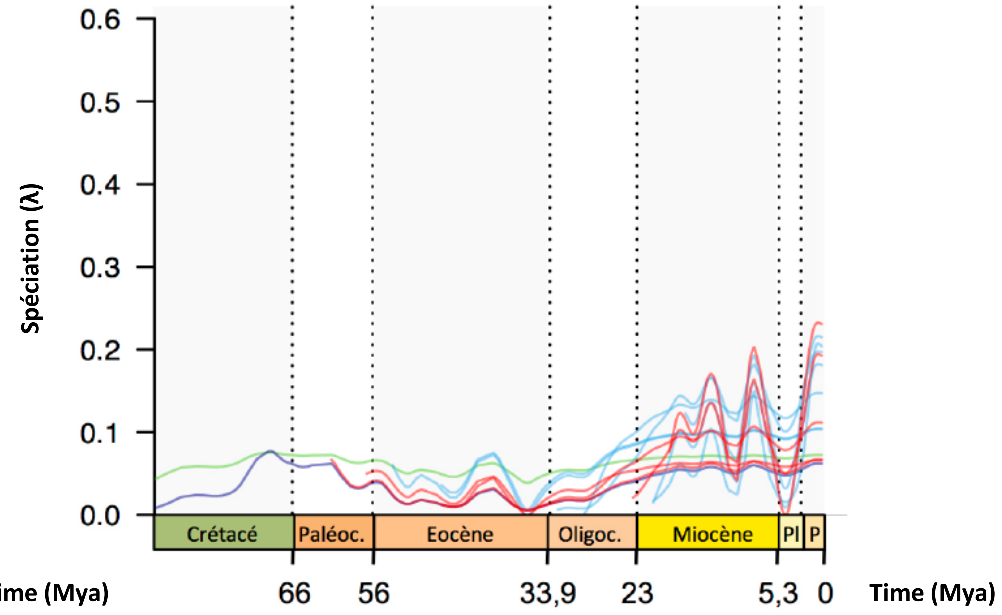
CO_2-dependent speciation

Positive correlation α > 0

Negative correlation α < 0

48 % | **52 %**





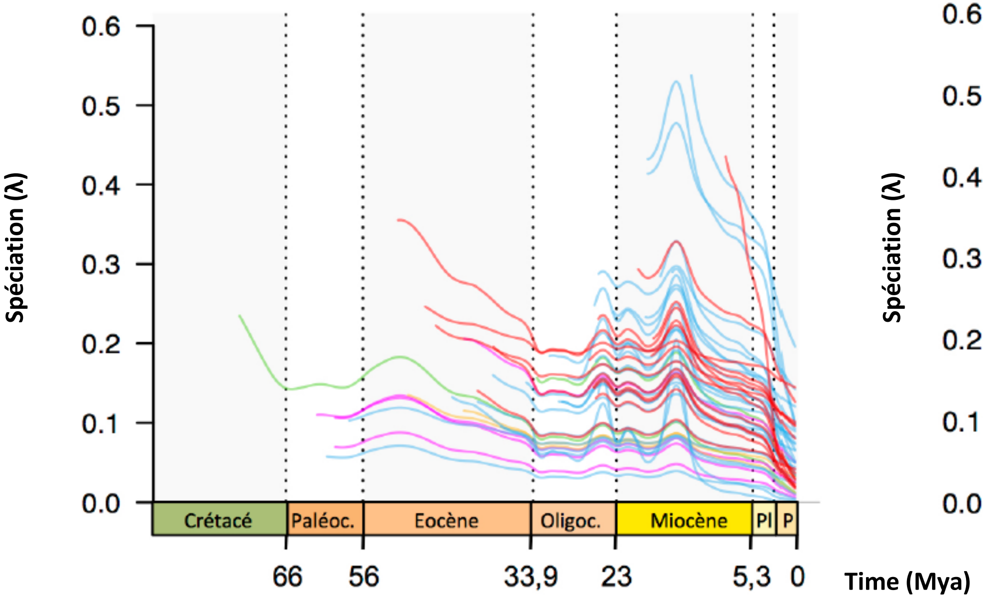
Temperature-dependent speciation

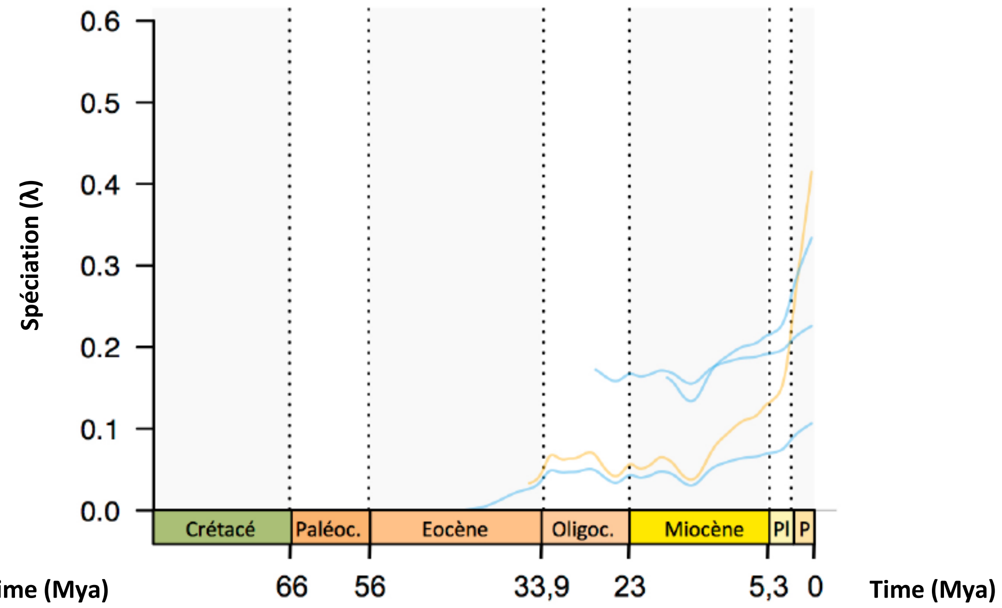
Positive correlation α > 0

Negative correlation α < 0

92 %

8 %





2 - Do warm climates promote or inhibit speciation ?

Positive correlation

Negative correlation

Speciation rate increases as temperature increases

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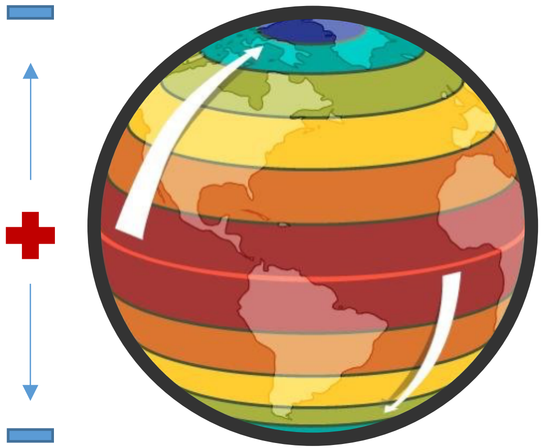
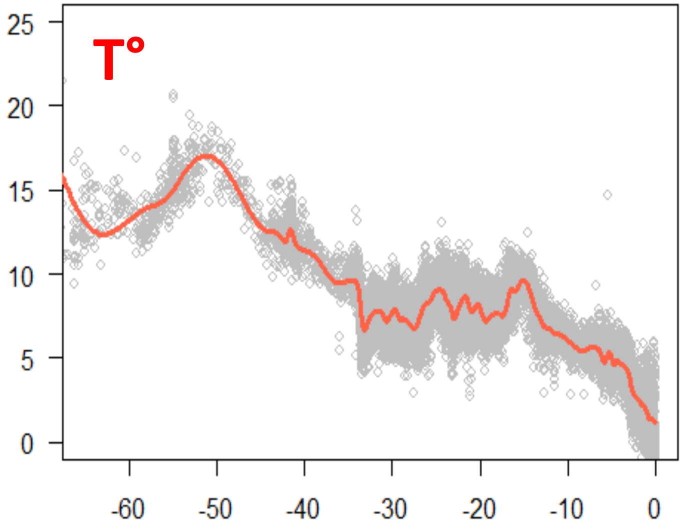
Speciation rate increases as temperature increases

Latitudinal gradient of diversity

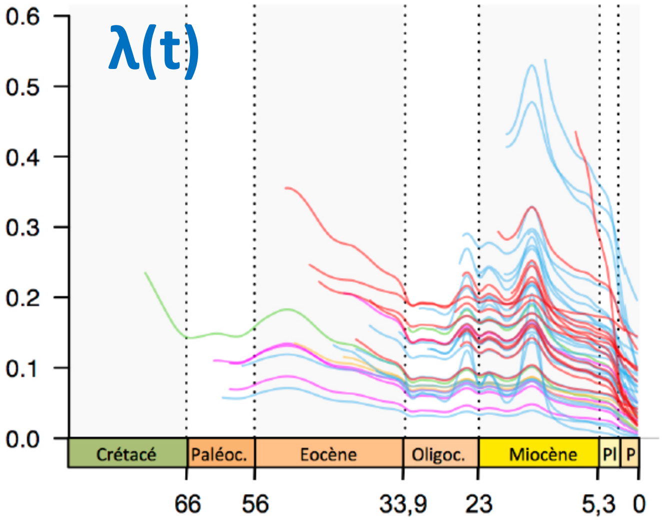


Speciation rate increases as temperature increases

Global cooling
over the Cenozoic



Speciation slowdown



Speciation slowdown often inferred from phylogenies

Phillimore & Price 2008 – PLoS Biol.
Glor 2010 – AREES
Rabosky 2013 – AREES
Moen & Morlon 2014 – TREE

Some hypotheses

Diversity-dependent speciation
Etienne et al. 2012 Proc. R. Soc. B

As niches fill over time there are less opportunities for speciation

Protracted speciation
Rosindell et al. 2010 – Ecol. Lett.

Underestimated speciation at present due to ongoing speciation events

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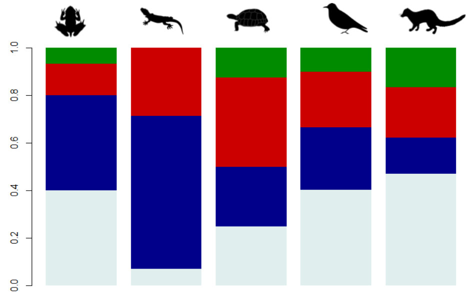
T°-dependent speciation ?

Speciation has decreased as a result of global cooling

CONCLUSIONS

Good proportion of Tetrapod phylogenies best explained by climate-dependent models of speciation



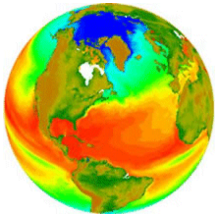
Link found in each of the 6 clades

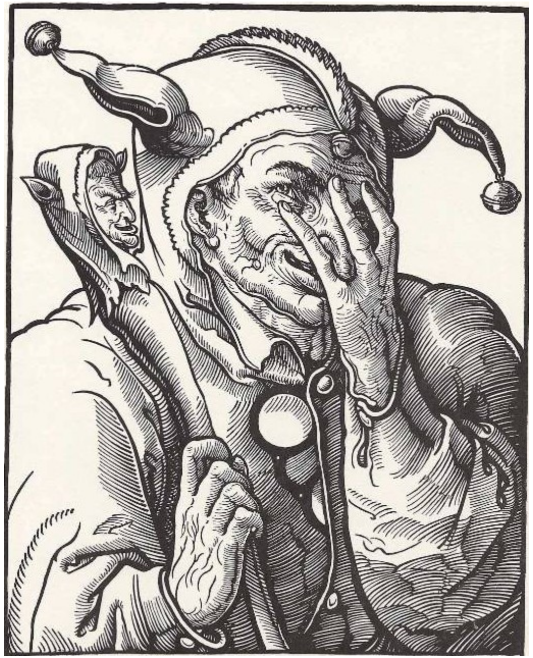
Families of animals with diverse habitats and ecologies

Support for a role of **climate as a driver** of diversification

→ What lies behind the observed correlation ?

→ Importance relative to other factors ?

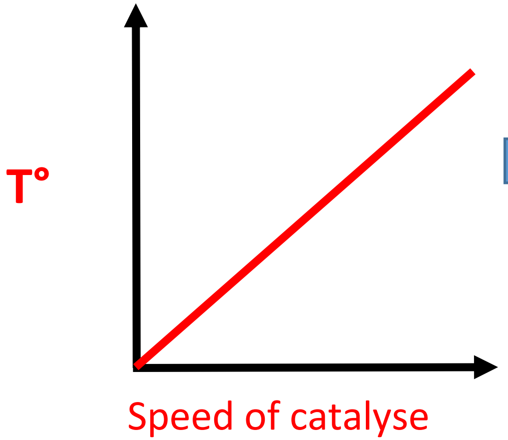




Thank you for listening !

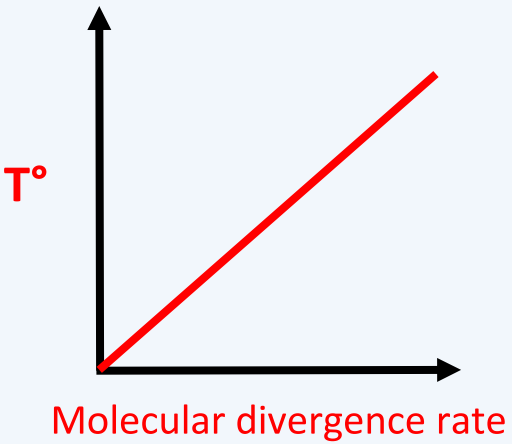
Hypothesis for a causation ?

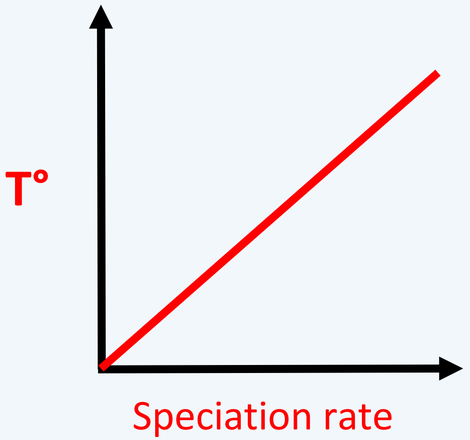
Metabolic theory



Kinetic effects of temperature on rates of genetic divergence and speciation

Andrew P. Allen*†, James F. Gillooly‡, Van M. Savage§, and James H. Brown†¶





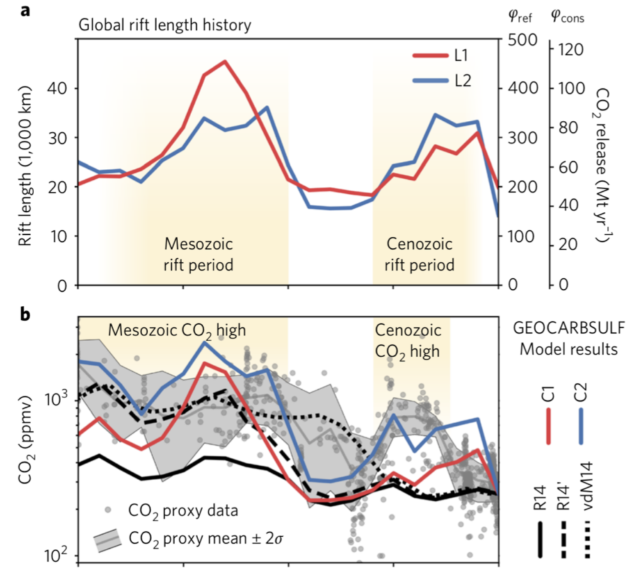
Brown et al. 2004 – Ecology

Allen et al. 2006 – PNAS

Hypothesis for a correlation ?

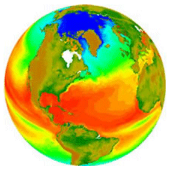
Potential links between continental rifting, CO_2 degassing and climate change through time

Sascha Brune[1,2*], Simon E. Williams[3] and R. Dietmar Müller[3,4]



Resources

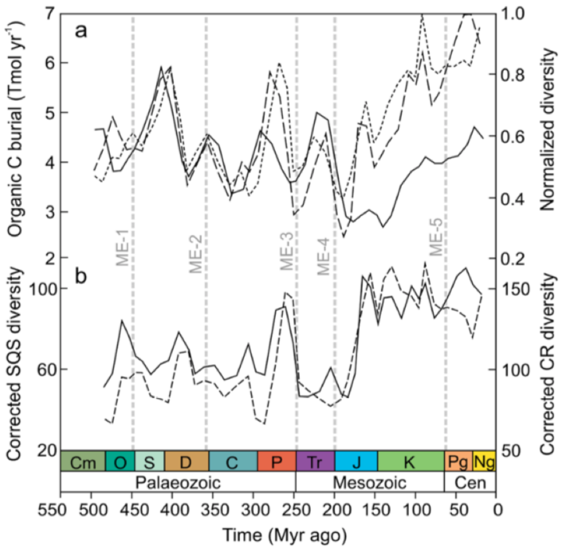
Tectonics



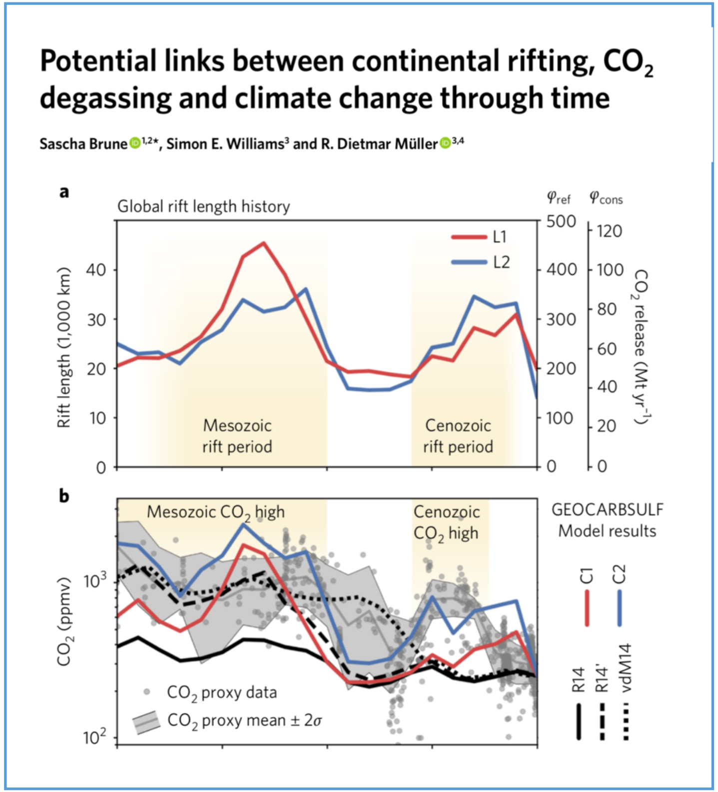
CO^2

Trophic and tectonic limits to the global increase of marine invertebrate diversity

Pedro Cermeño[1], Michael J. Benton[2], Óscar Paz[1] & Christian Vérard[3]

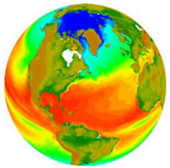


Hypothesis for a correlation ?

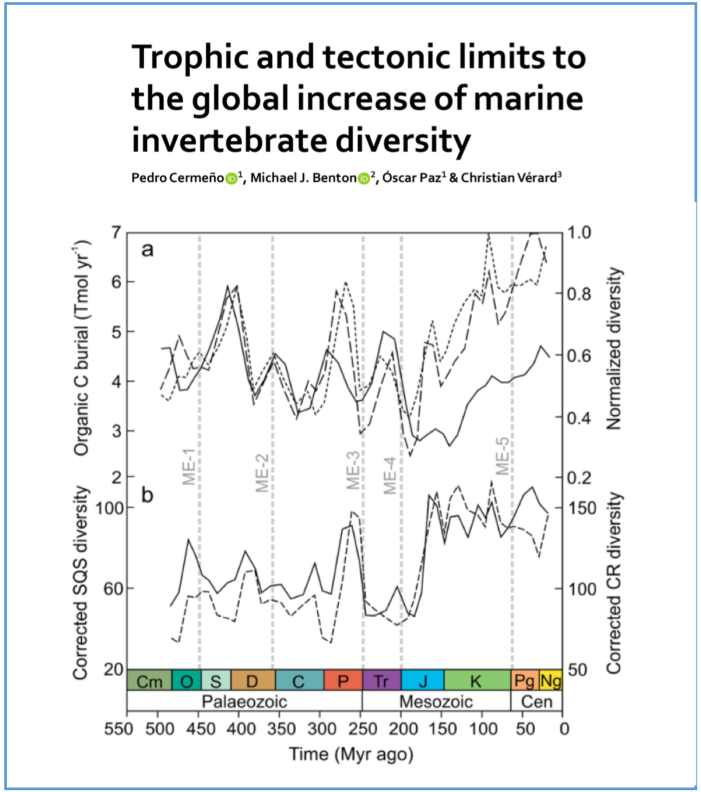


Resources

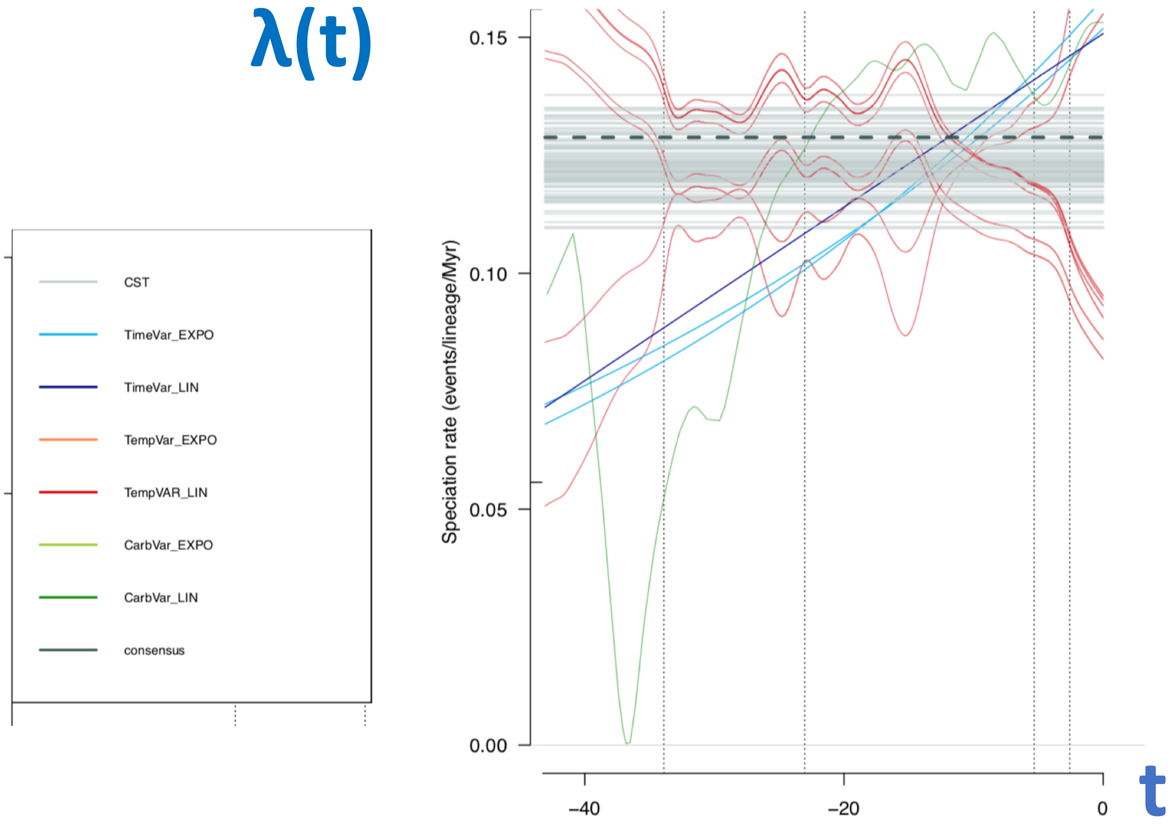
Tectonics



CO^2



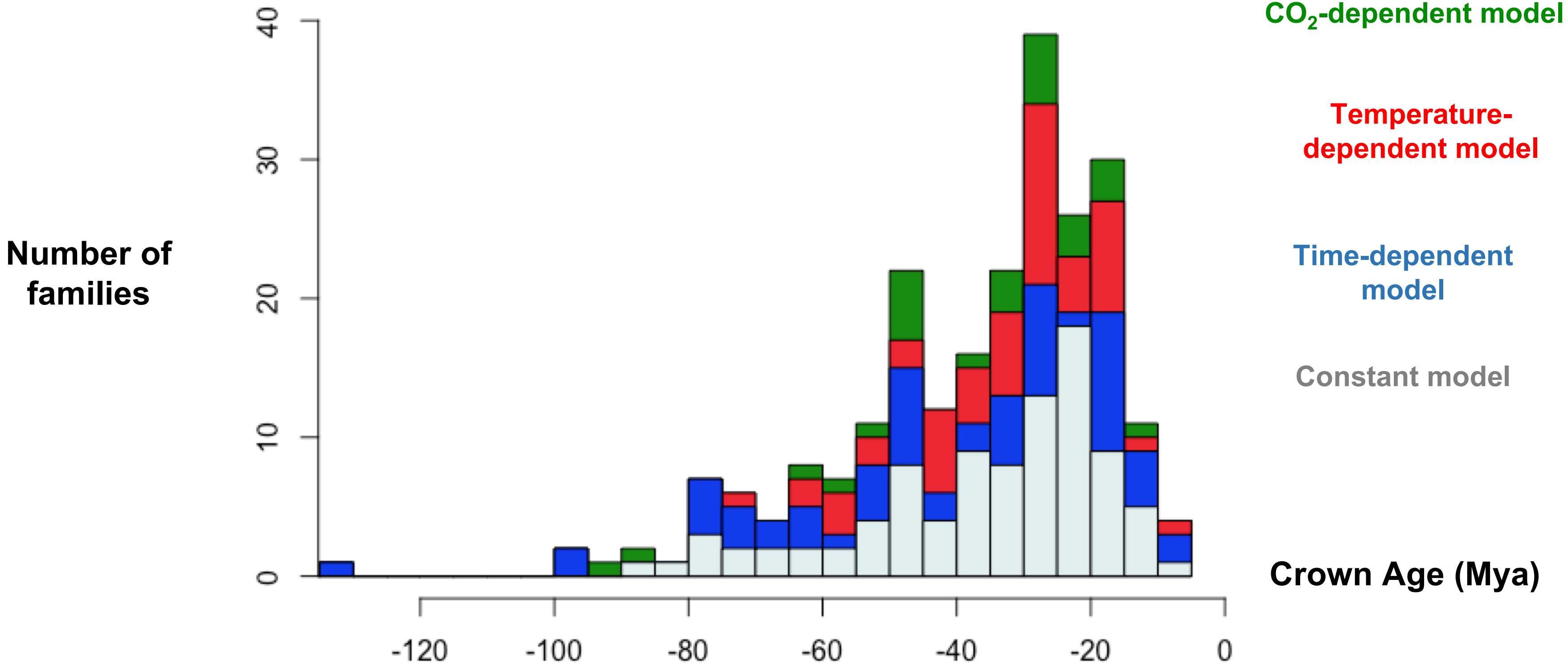
Strigidae



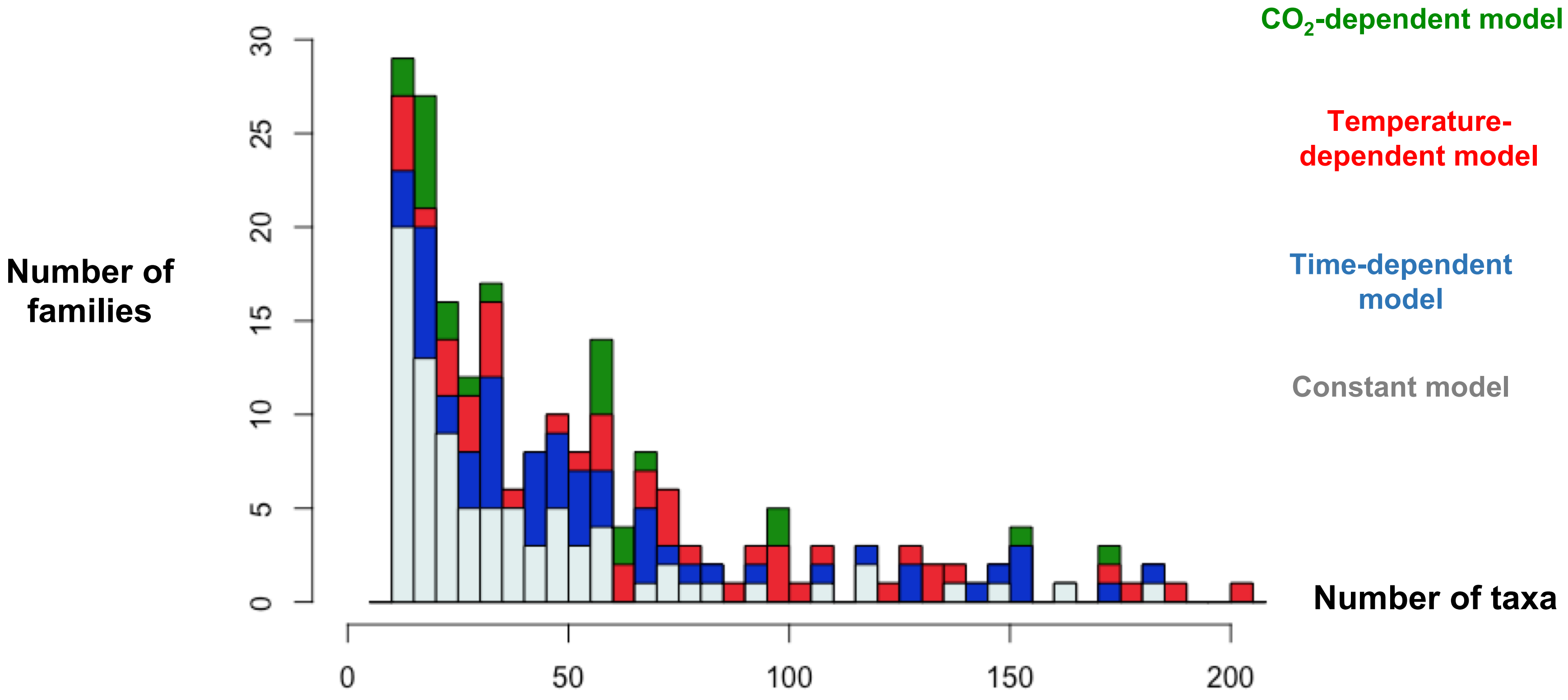
Best models selected for 100 post probability trees from Jetz et al. 2012

– – – Consensus tree

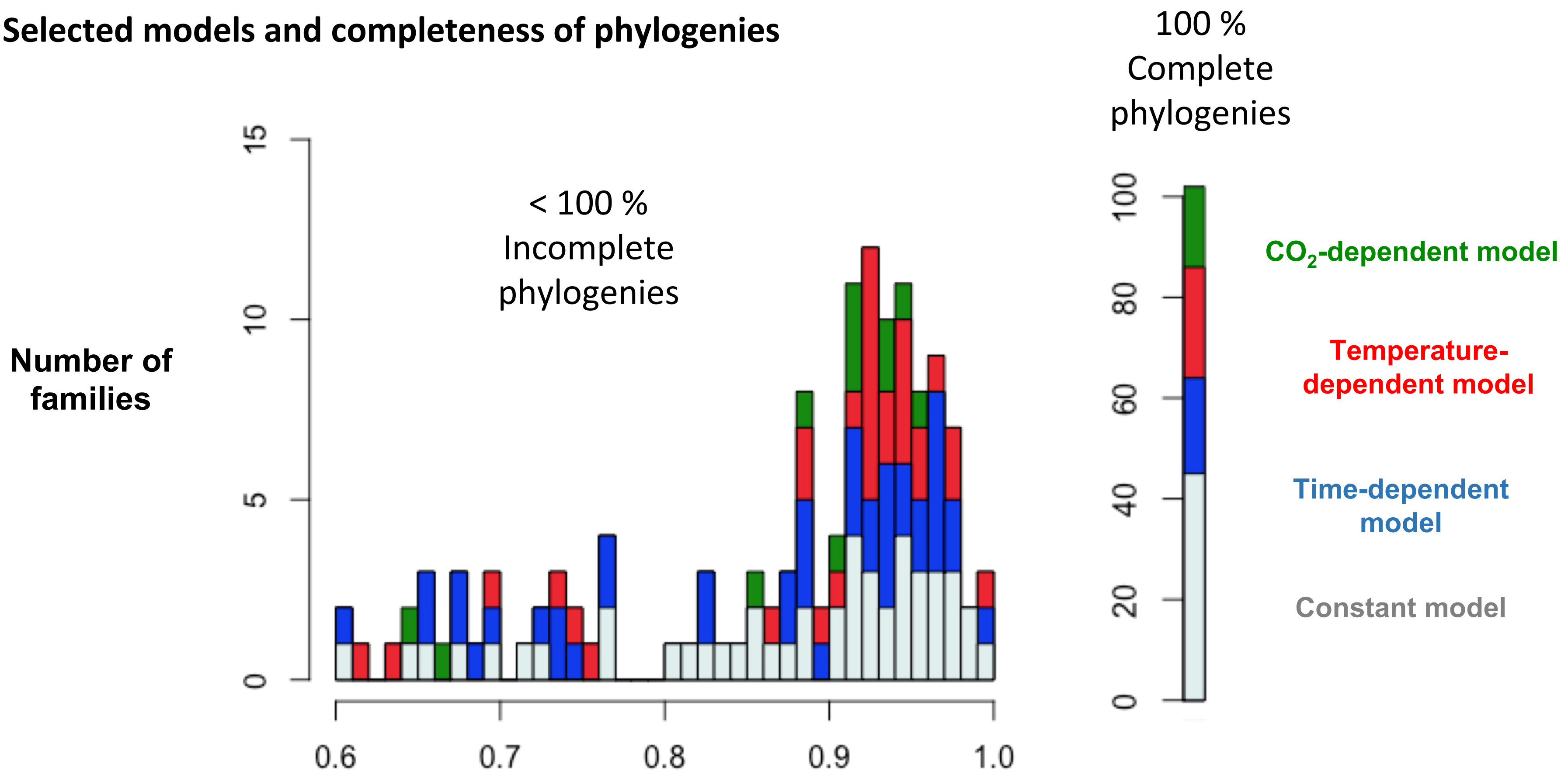
Selected models and age of phylogenies



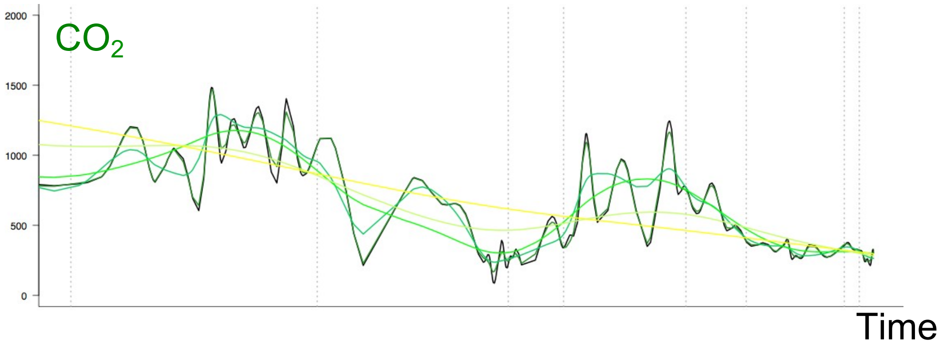
Selected models and size of phylogenies

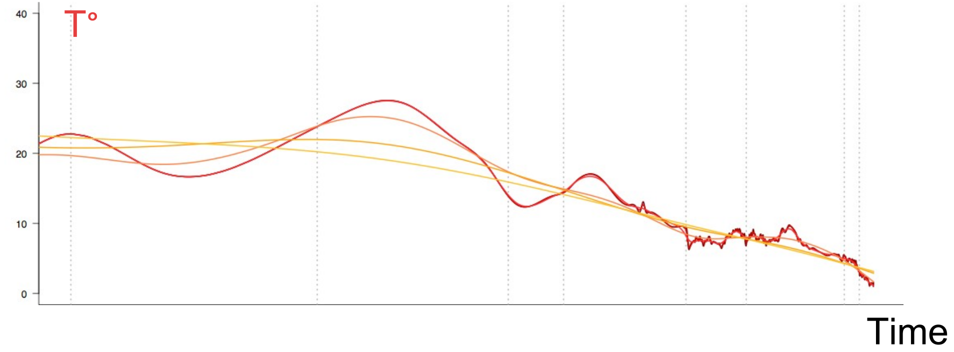


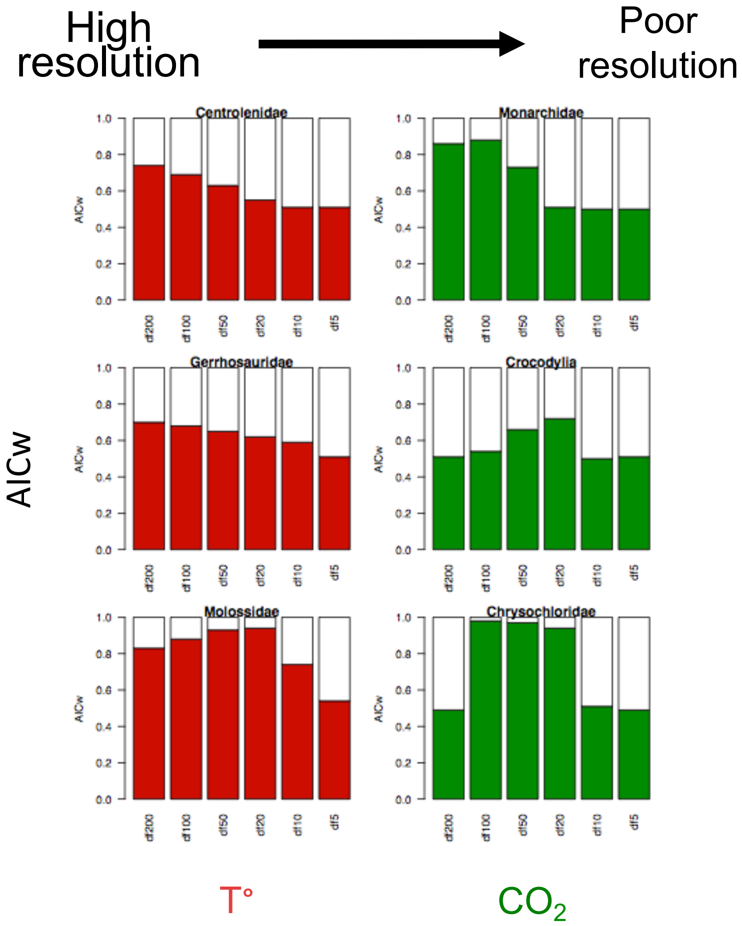
Selected models and completeness of phylogenies



SUPPLEMENTS



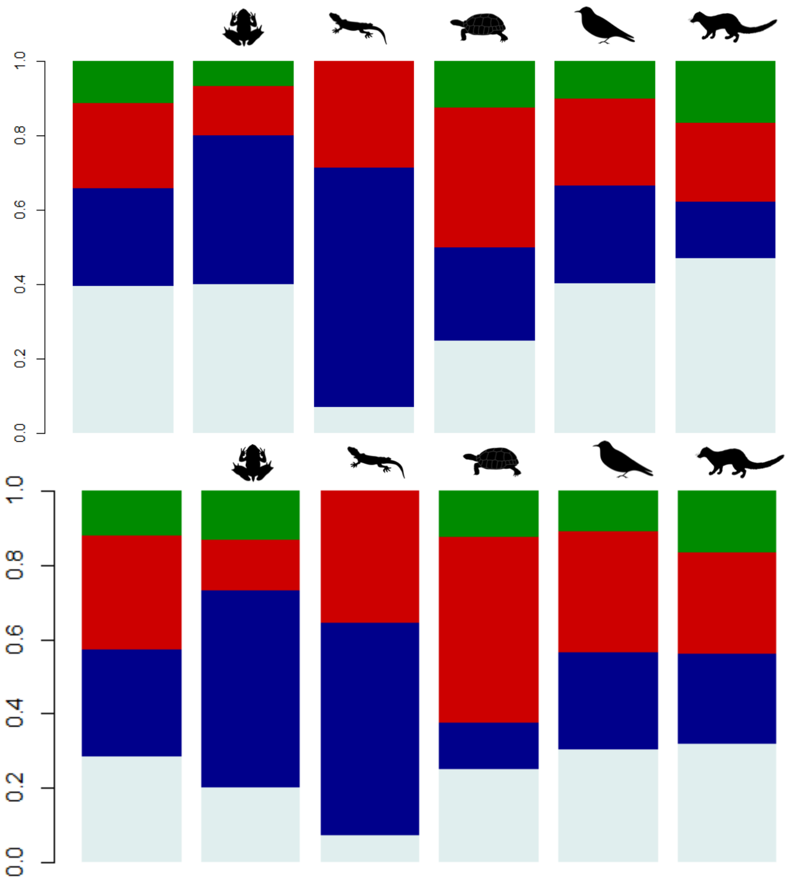




SUPPLEMENTS

Speciation only

Speciation + Extinction



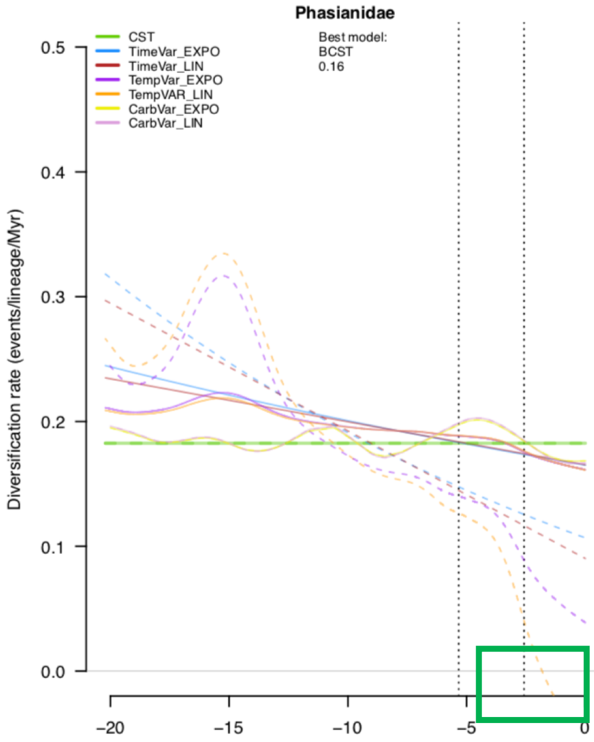
Spéciation CO_2-dépendante

Spéciation Température-dépendante

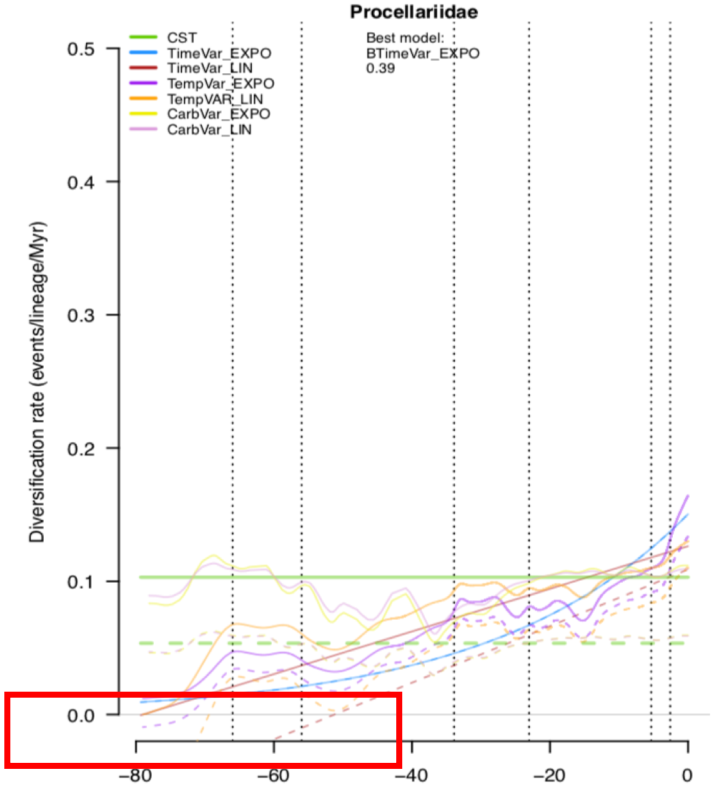
Spéciation Temps-dépendante

Spéciation constante

Negative diversification (extinction > speciation)

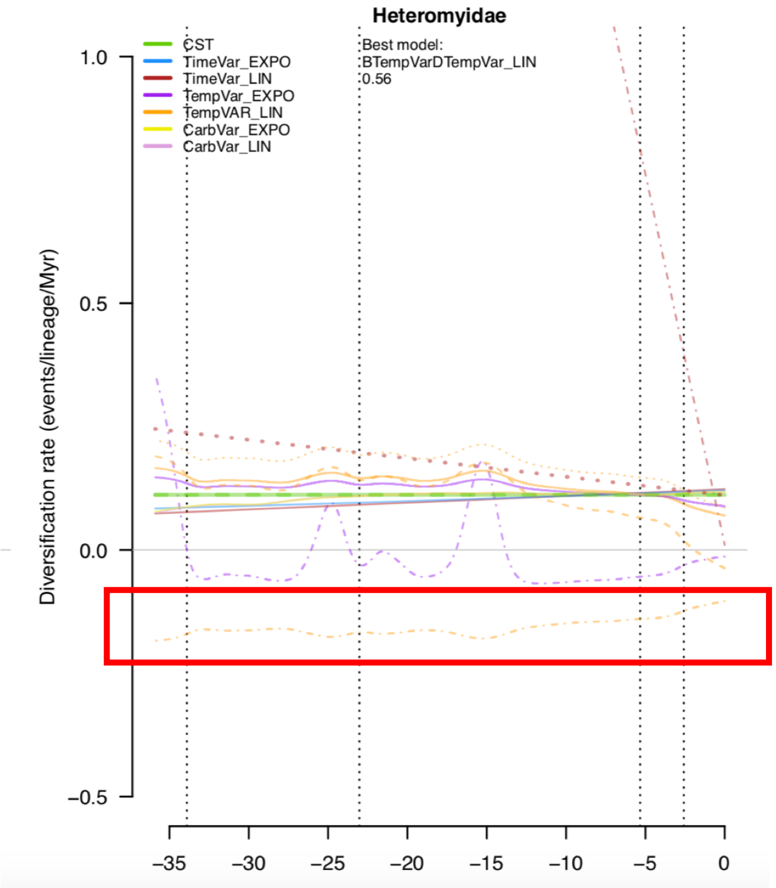


Clade loses diversity at present



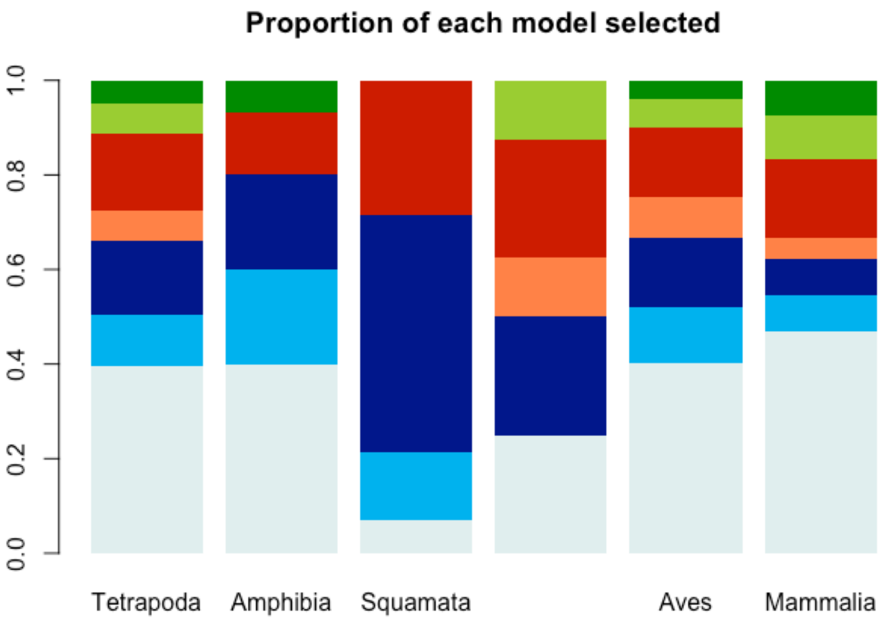
Clade should go extinct

SUPPLEMENTS



Support for a model with negative diversification over all the history of the clade !

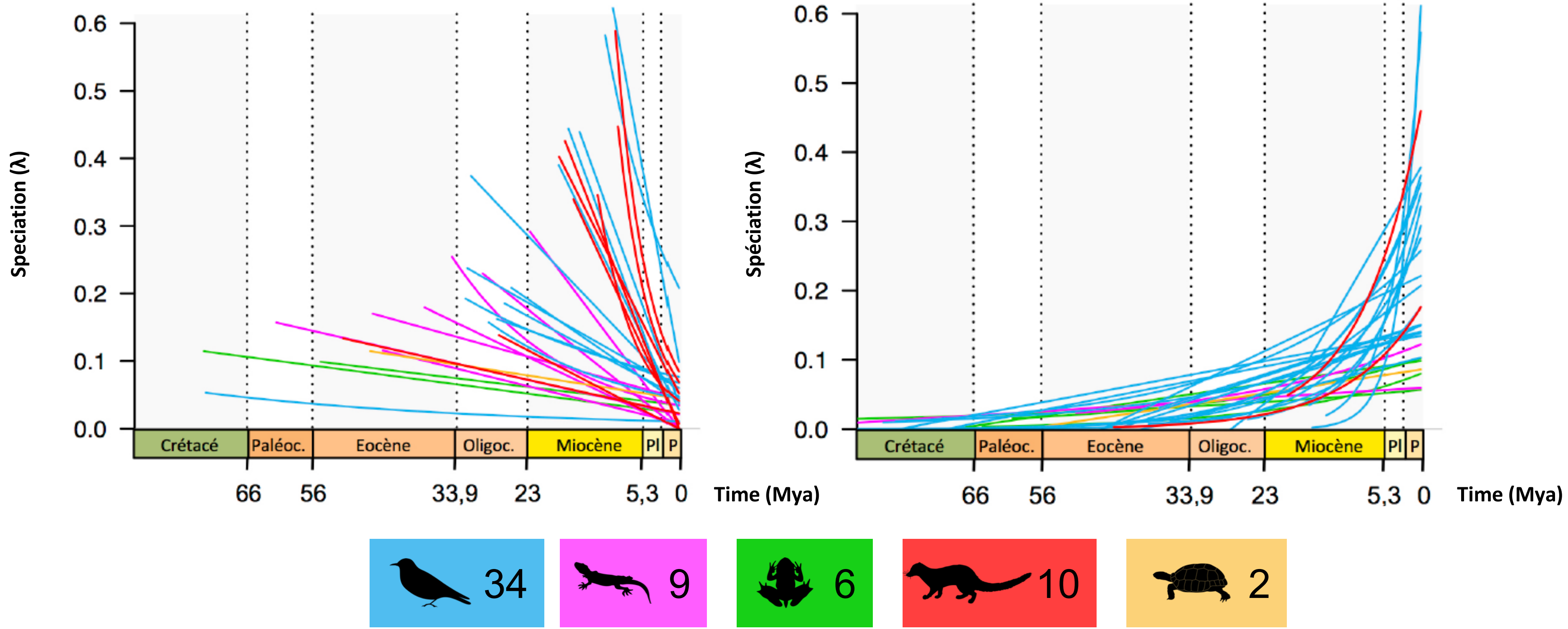
Deep shade → exponential model
Light shade → linear model



SUPPLEMENTS

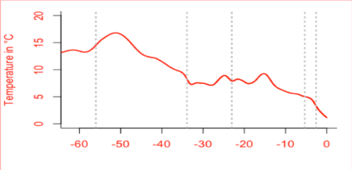
Positive correlation α > 0 | Negative correlation α < 0

49 % | **51 %**



3. A phylogeny-based approach of diversification

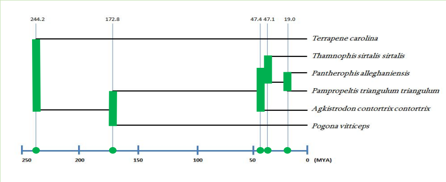
Climatic variations



λ

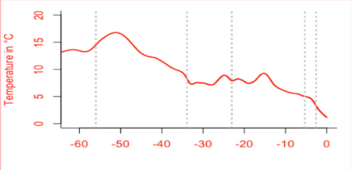
?

Diversification



Hypothesis tested on Tetrapod families

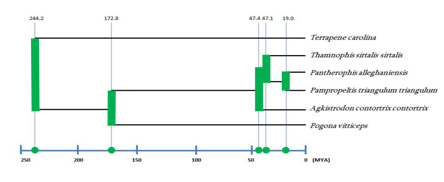
Climatic variations



λ

?

Diversification



Main questions

1) Signal of climate : rule or exception ?

2) Do warm/cold climates promote or inhibit speciation ?