Tectonic Reorganizations and Multistability of the Mantle-Plate System

Ilyas Jaah[1], Nicolas Coltice[1], Alexandre Janin[2,3], Nicolas Flament[4]

[1]Géoazur, Université Côte d'Azur, Nice, France
[2]Laboratoire de Géologie–CNRS UMR 8538, École normale supérieure–PSL University, Paris, France
[3]Department of Earth and Environmental Sciences, Boston College, Chestnut Hill, MA, USA
[4]School of Environmental Futures, School of Science, University of Wollongong, Northfields Avenue, NSW 2522, Australia

This presentation participates in OSPP
EGU
Outstanding Student & PhD candidate Presentation contest

Geo AZUR
TERRE - OCÉAN - ESPACE

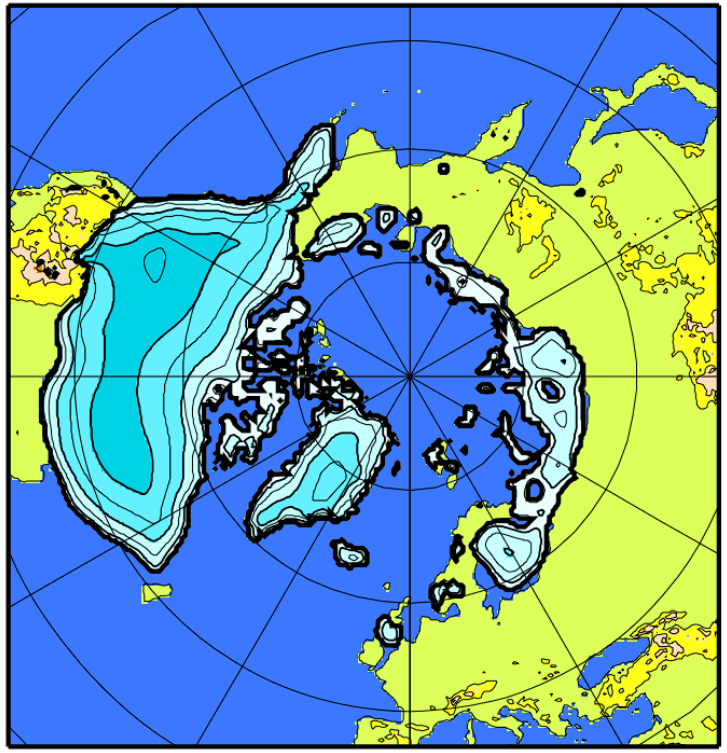
erc
European Research Council
Established by the European Commission

Laboratoire de Géologie de l'ENS

COLLEGIUM BOSTONIENSE FUND. MDCCCLXIII

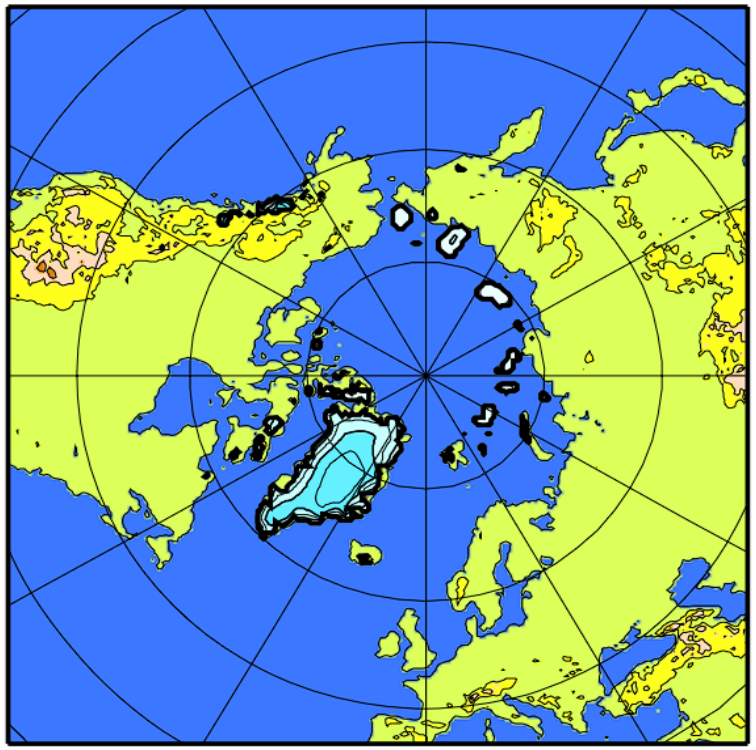
The Climate, a Multistable System

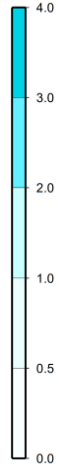
57 kyr BP



Abrupt Transition

Present day

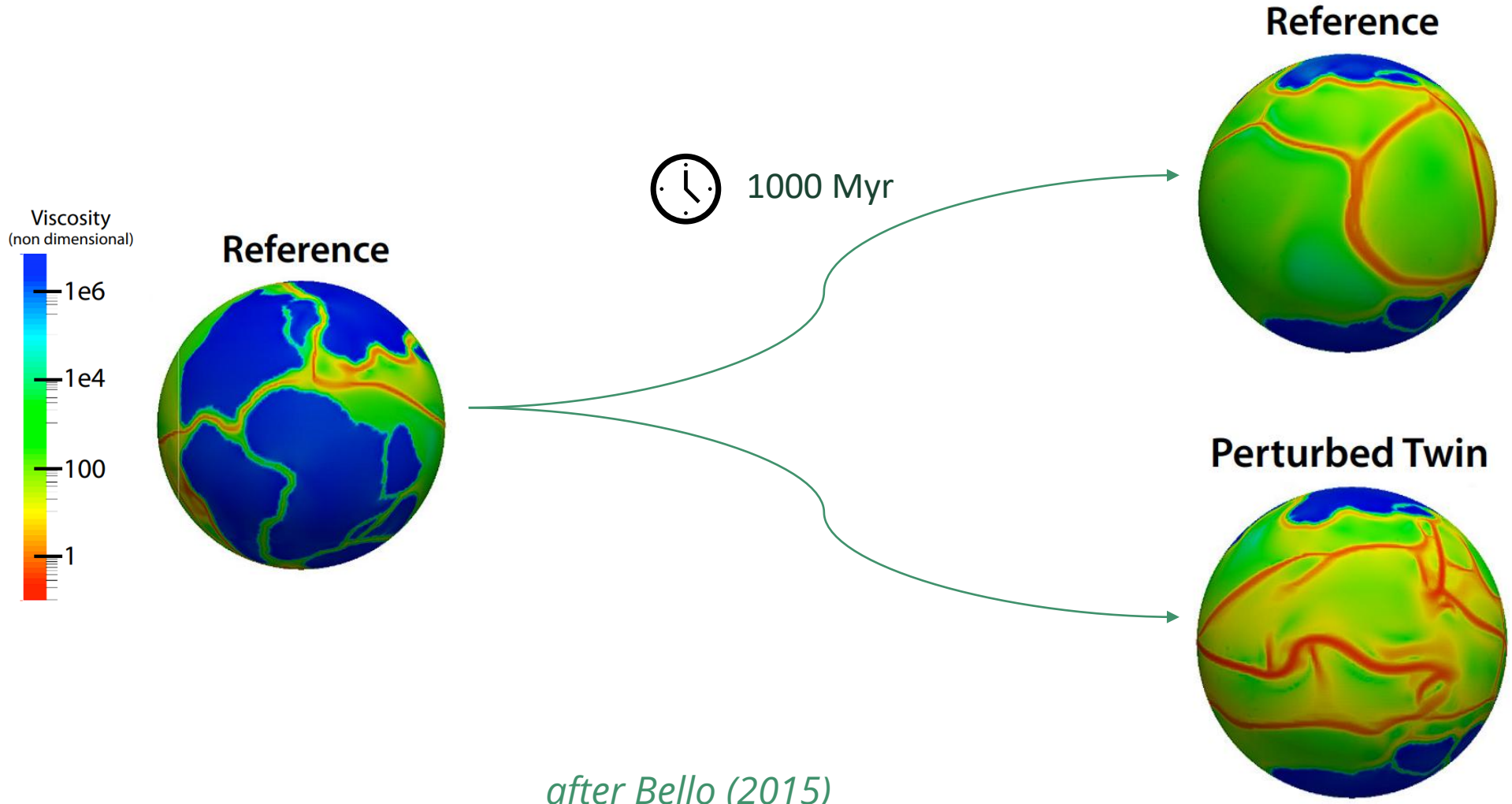




Ice thickness (km)

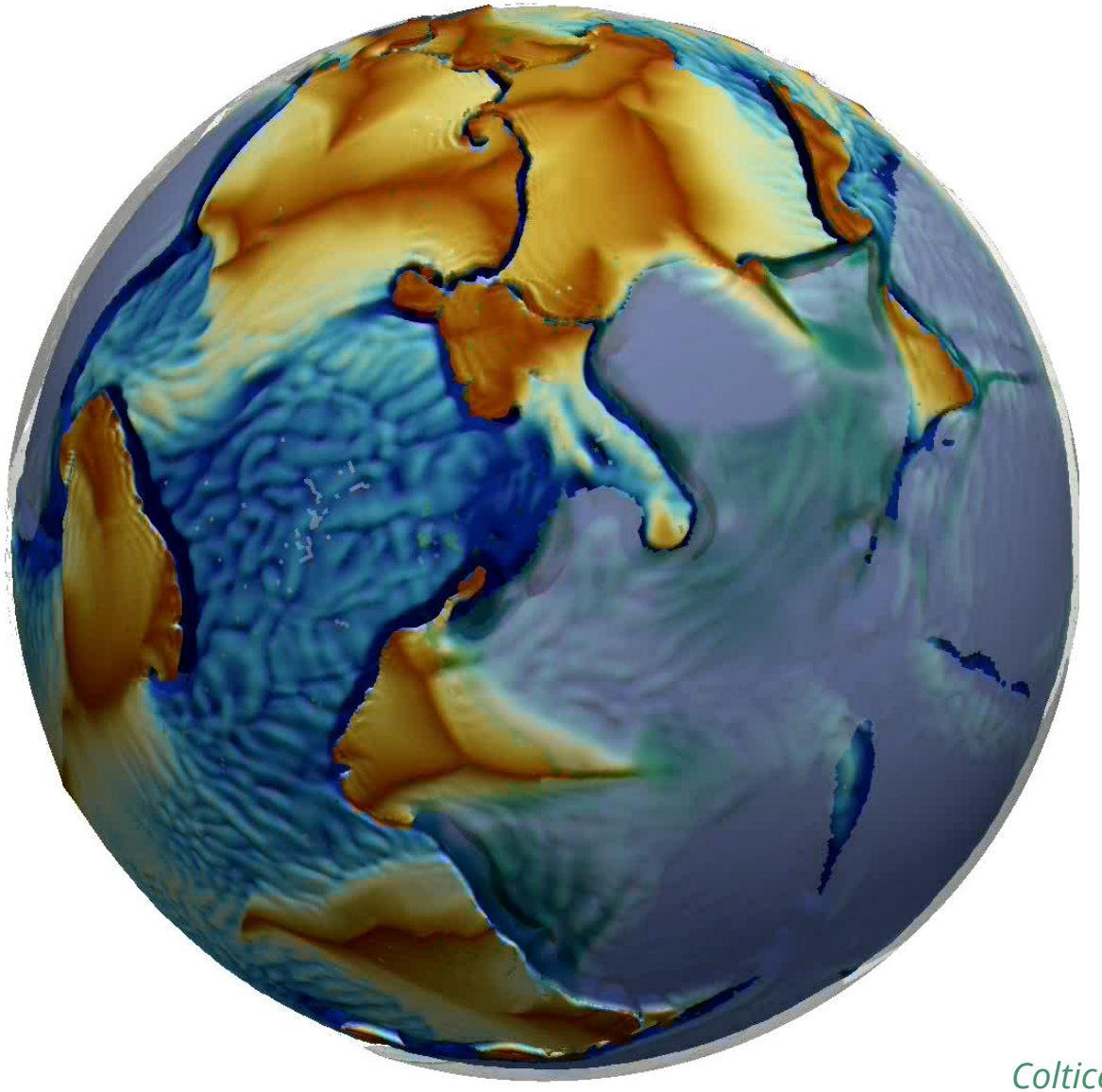
Charbit et al., 2007

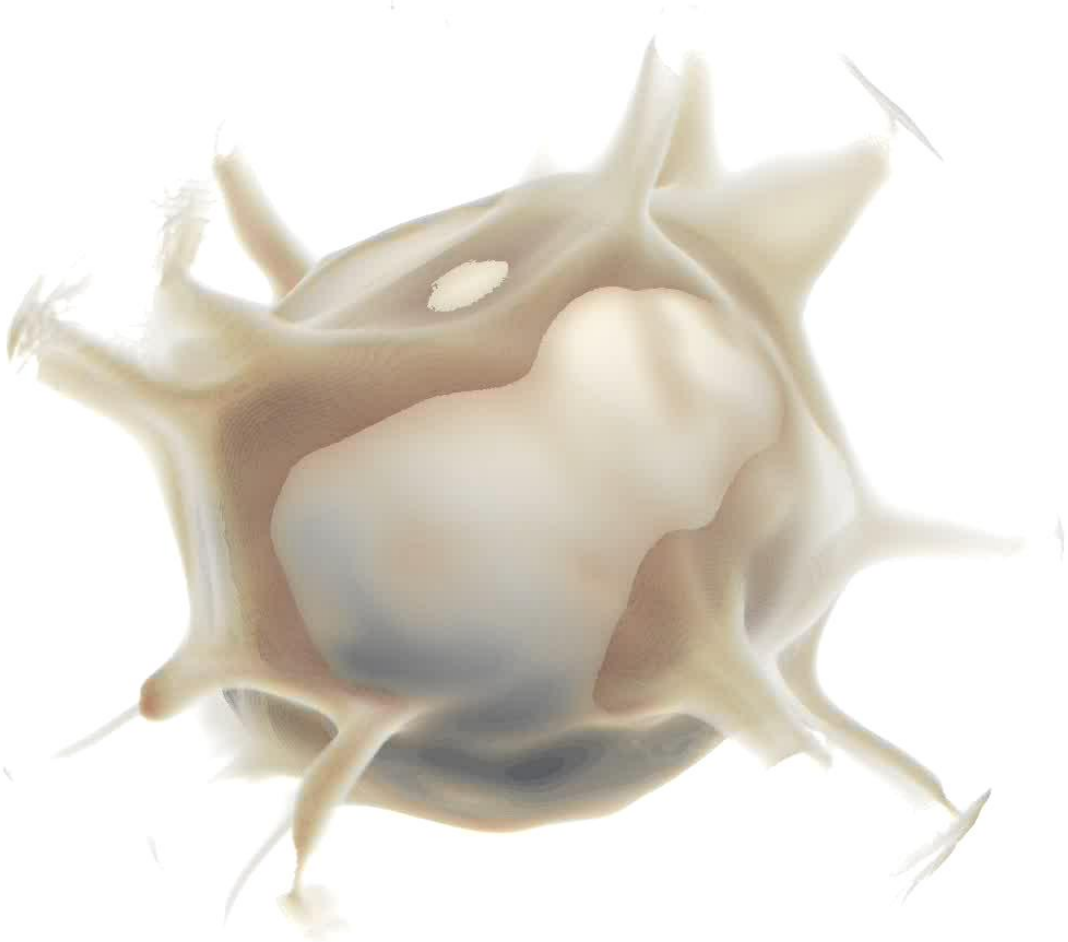
Mantle Convection is a Chaotic System



after Bello (2015)

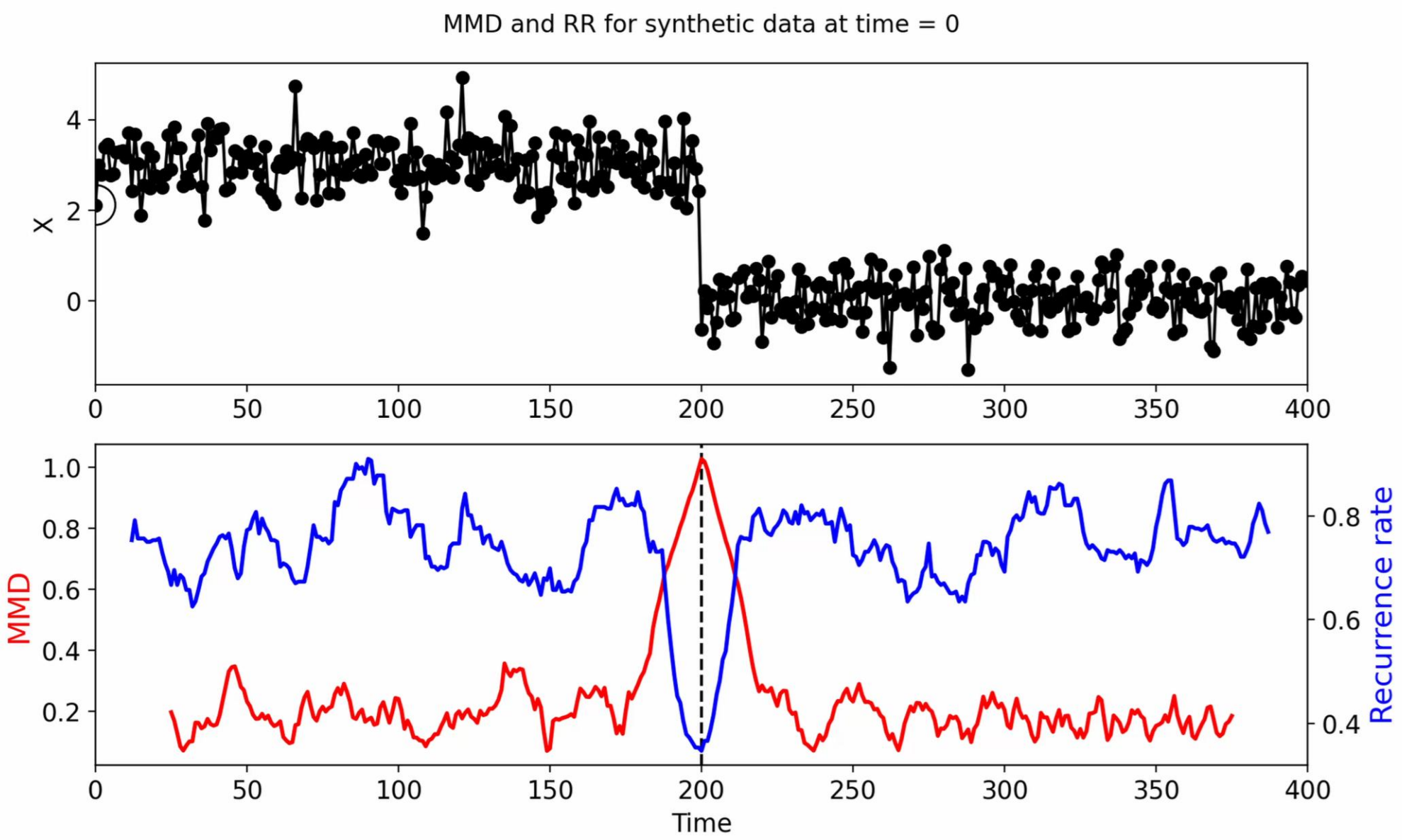
Earth-like mantle convection model



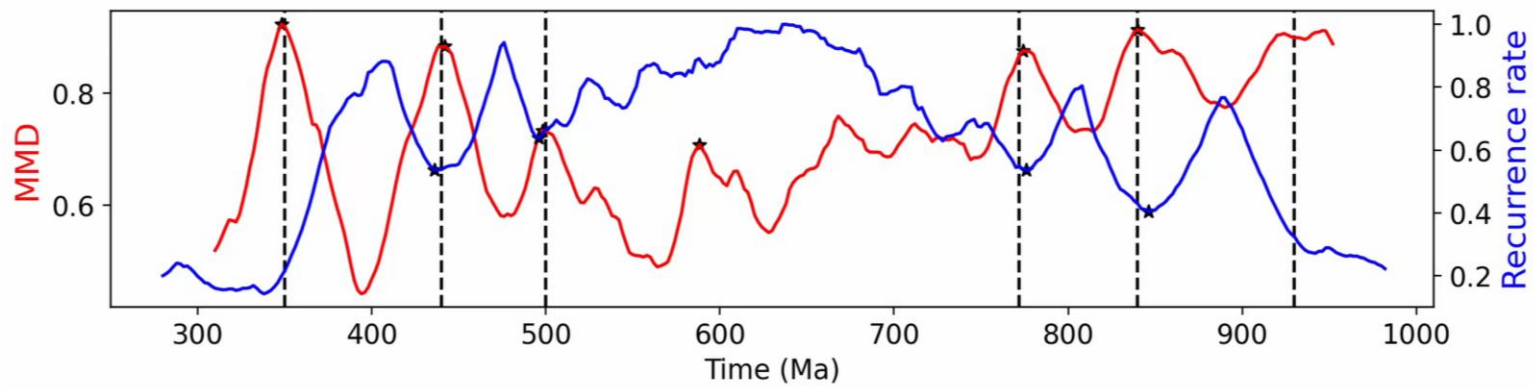


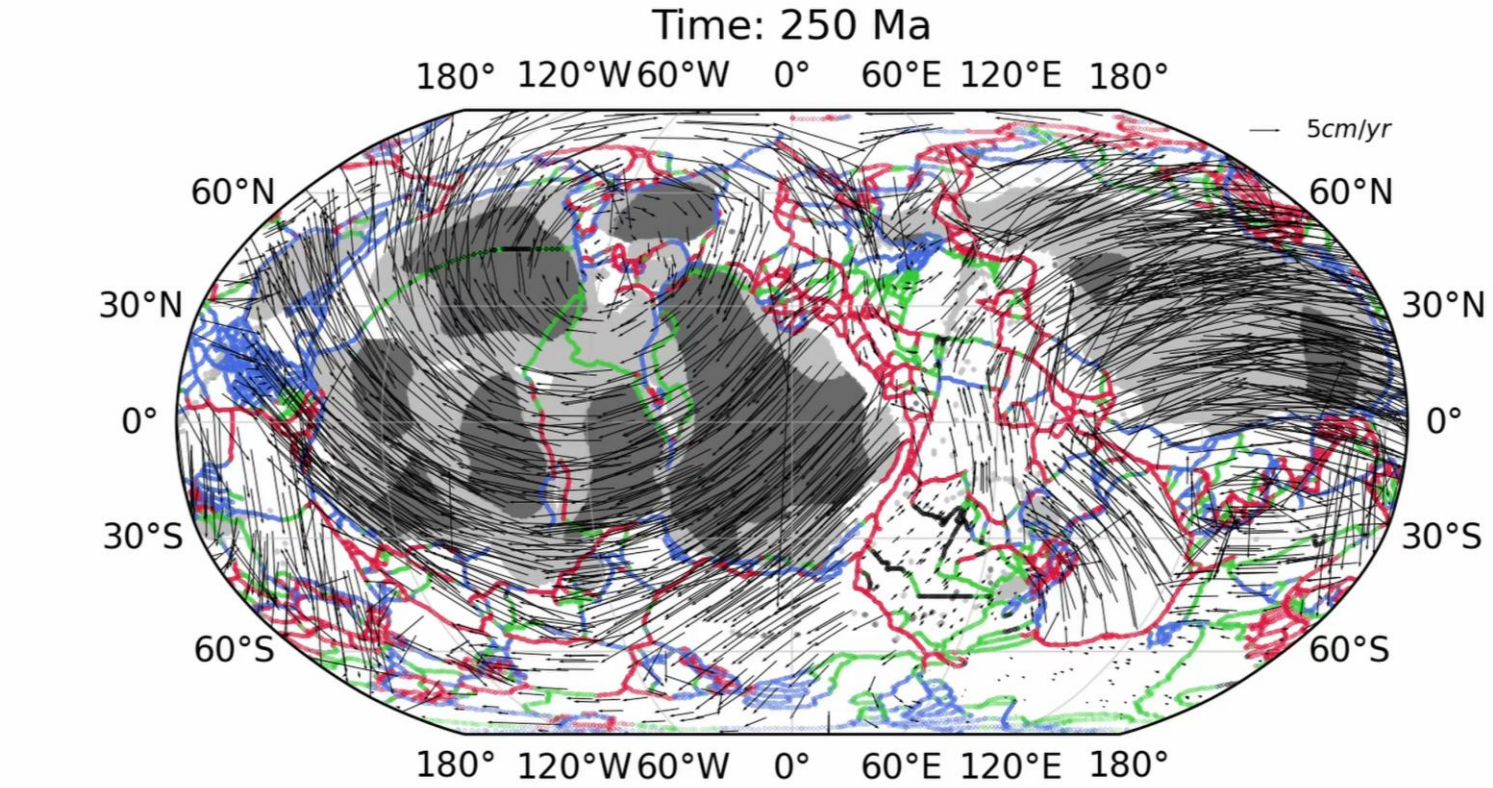
Coltice et al. (2019)

Transition Identification



Geodynamic Abrupt Transitions





Tectonic Reorganizations and Multistability of the Mantle-Plate System

Ilyas Jaah[1], Nicolas Coltice[1], Alexandre Janin[2,3], Nicolas Flament[4]

[1]Géoazur, Université Côte d'Azur, Nice, France
[2]Laboratoire de Géologie–CNRS UMR 8538, École normale supérieure–PSL University, Paris, France
[3]Department of Earth and Environmental Sciences, Boston College, Chestnut Hill, MA, USA
[4]School of Environmental Futures, School of Science, University of Wollongong, Northfields Avenue, NSW 2522, Australia

This presentation participates in OSPP
EGU
Outstanding Student & PhD candidate Presentation contest

Come find me at **PICO 3.3** !

Géo AZUR
TERRE · OCÉAN · ESPACE

erc
European Research Council
Established by the European Commission

Laboratoire de Géologie de l'ENS

COLLEGIUM BOSTONIENSE · FUND. MDCCCLXIII ·

This presentation participates in OSPP

Outstanding Student & PhD candidate Presentation contest

Tectonic Reorganizations and Multistability of the Mantle-Plate System

Ilyas Jaah (Ilyas.Jaah@geoazur.unice.fr)[1],

Nicolas Coltice[1], Alexandre Janin[2,3], Nicolas Flament[4]

[1]Géoazur, Université Côte d'Azur, Nice, France
[2]Laboratoire de Géologie–CNRS UMR 8538, École normale supérieure–PSL University, Paris, France
[3]Department of Earth and Environmental Sciences, Boston College, Chestnut Hill, MA, USA
[4]School of Environmental Futures, School of Science, University of Wollongong, Northfields Avenue, NSW 2522, Australia

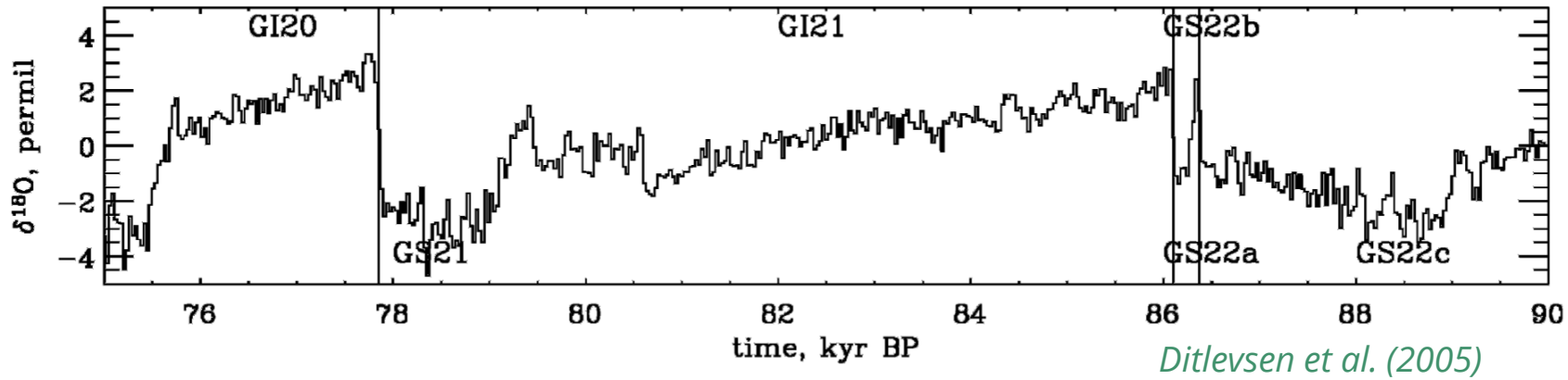
European Research Council
Established by the European Commission

Laboratoire de Géologie de l'ENS

Why ? — How ? — Results — Summary

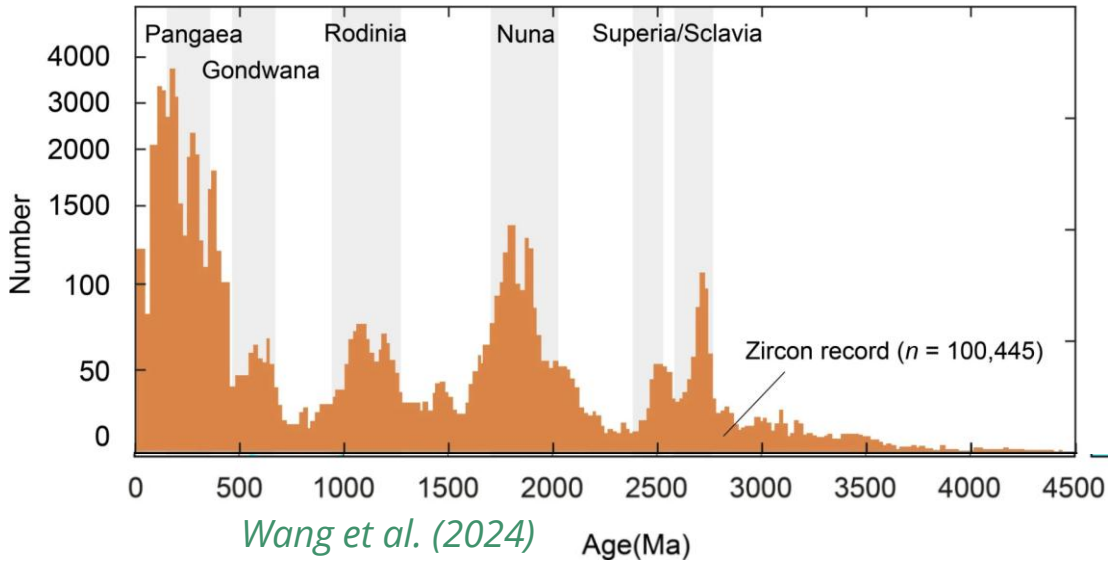
Background

$\delta^{18}O$ record from ice cores from the GRIP



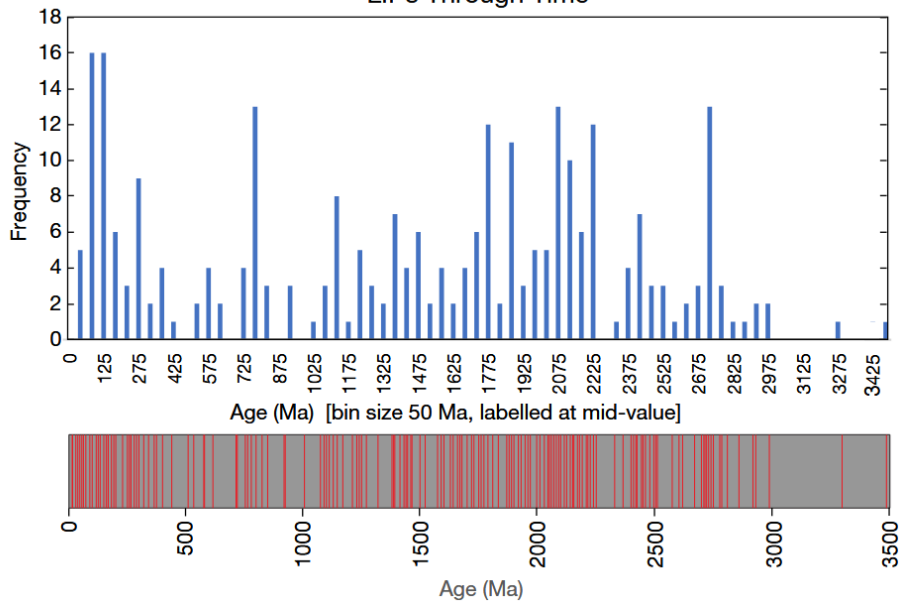
Ditlevsen et al. (2005)

Age frequency distribution of detritical zircons



Wang et al. (2024)

LIPs Through Time

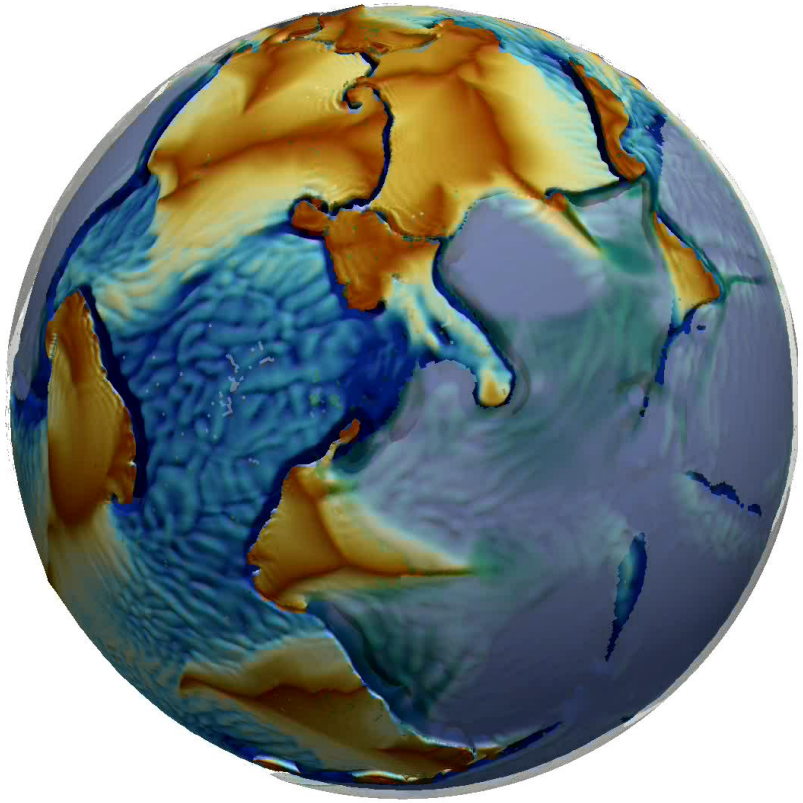


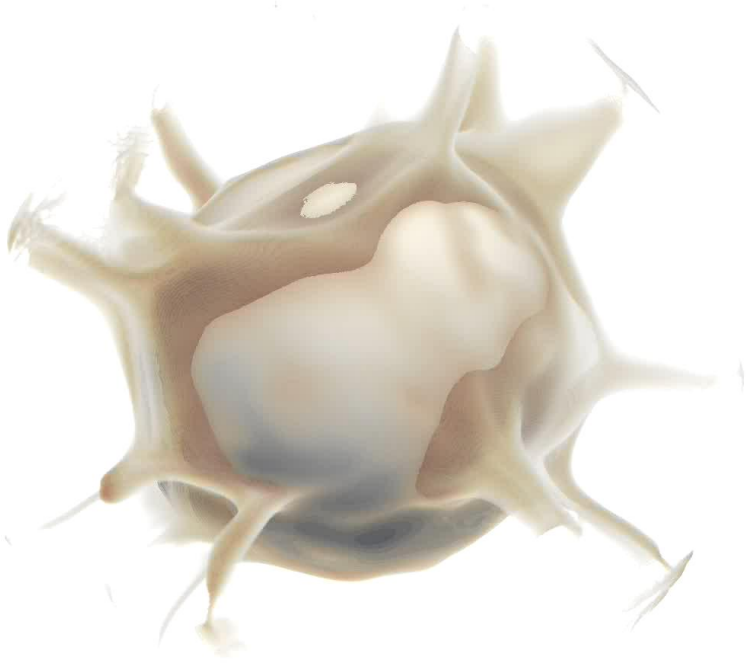
Ernst (2021)

Questions

- **Can we detect abrupt transitions between different states of mantle convection and plate tectonics ?**
- **Does these changes concern the lithosphere or the whole mantle ?**
- **Are tectonic changes fluctuations or global changes in dynamics ?**

Model and Data Extraction

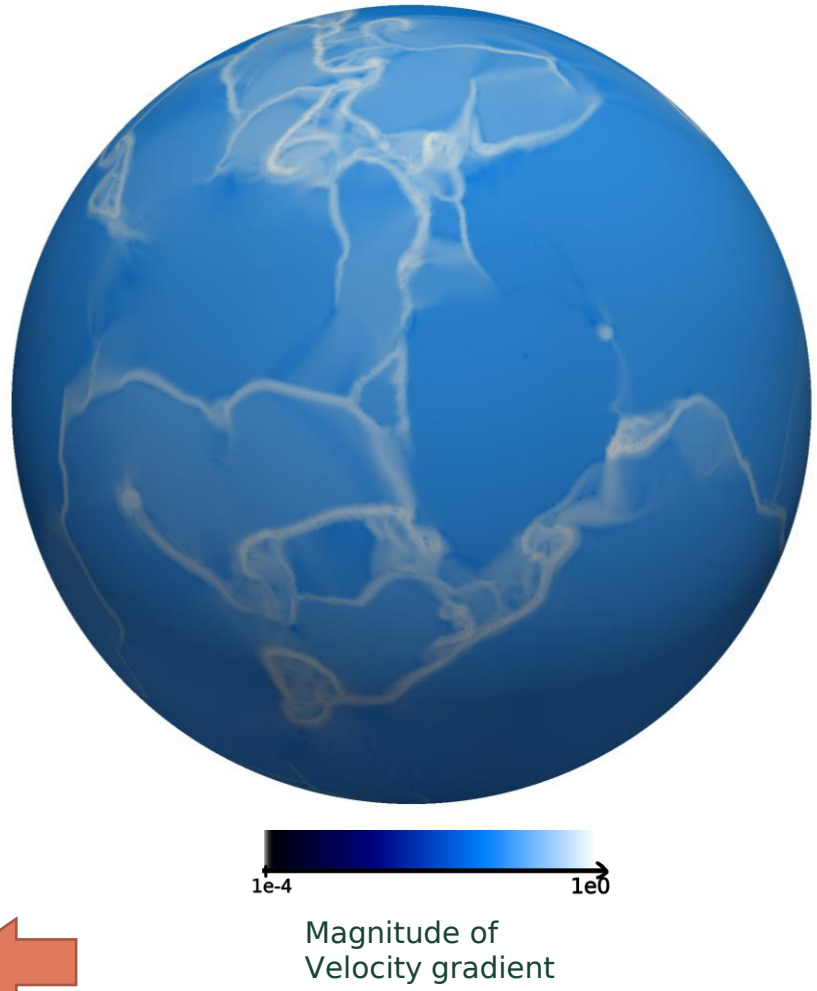




- Data extracted from Coltice et al. (2019)
- Mantle convection model with non-linear rheology producing plate-like behaviour
- Reproduces major features of Earth's tectonics

Coltice et al. (2019)

Detection of tectonic plates and boundaries

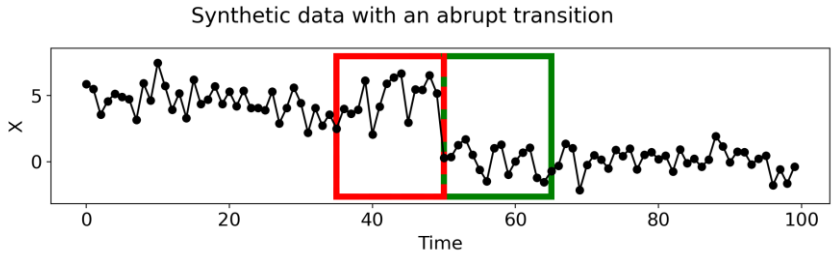


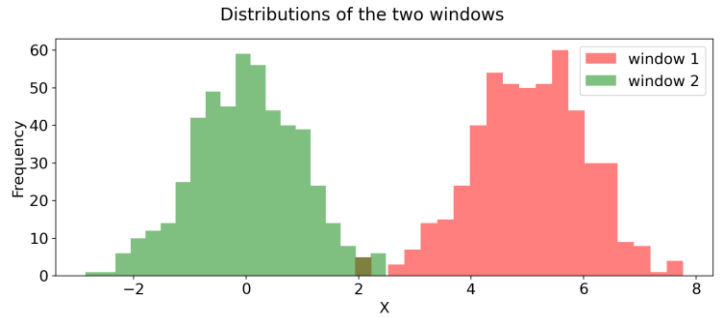
- Topological analysis of the magnitude of the velocity gradient
- Equivalent to watershed decomposition

Janin et al. (2025)

Transition Detection

Maximum Mean Discrepancy : Distances between distribution



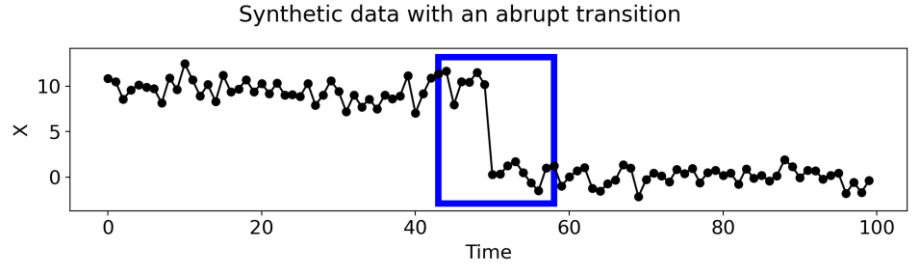


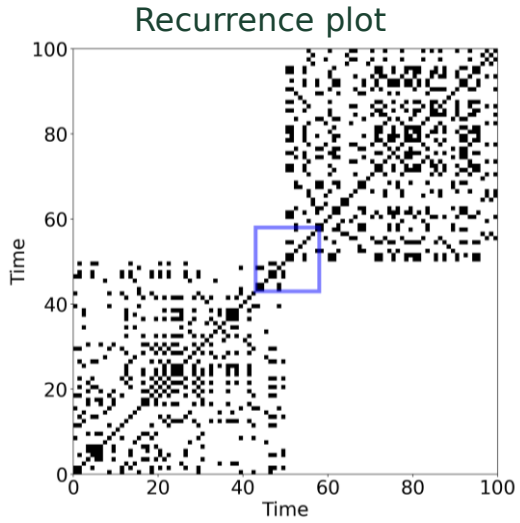
$$MMD^2(X,Y) = \frac{1}{m(m-1)} \sum_i \sum_{j \neq i} k(\mathbf{x_i}, \mathbf{x_j}) - 2\frac{1}{m.m} \sum_i \sum_j k(\mathbf{x_i}, \mathbf{y_j}) + \frac{1}{m(m-1)} \sum_i \sum_{j \neq i} k(\mathbf{y_i}, \mathbf{y_j})$$

$$k(\mathbf{x_i}, \mathbf{x_j}) = \exp\left(\frac{-\|\mathbf{x_i} - \mathbf{x_j}\|^2}{2\sigma^2}\right)$$

→ Transitions should correspond to MMD maxima

Recurrence Rate : Recurrence in the variables



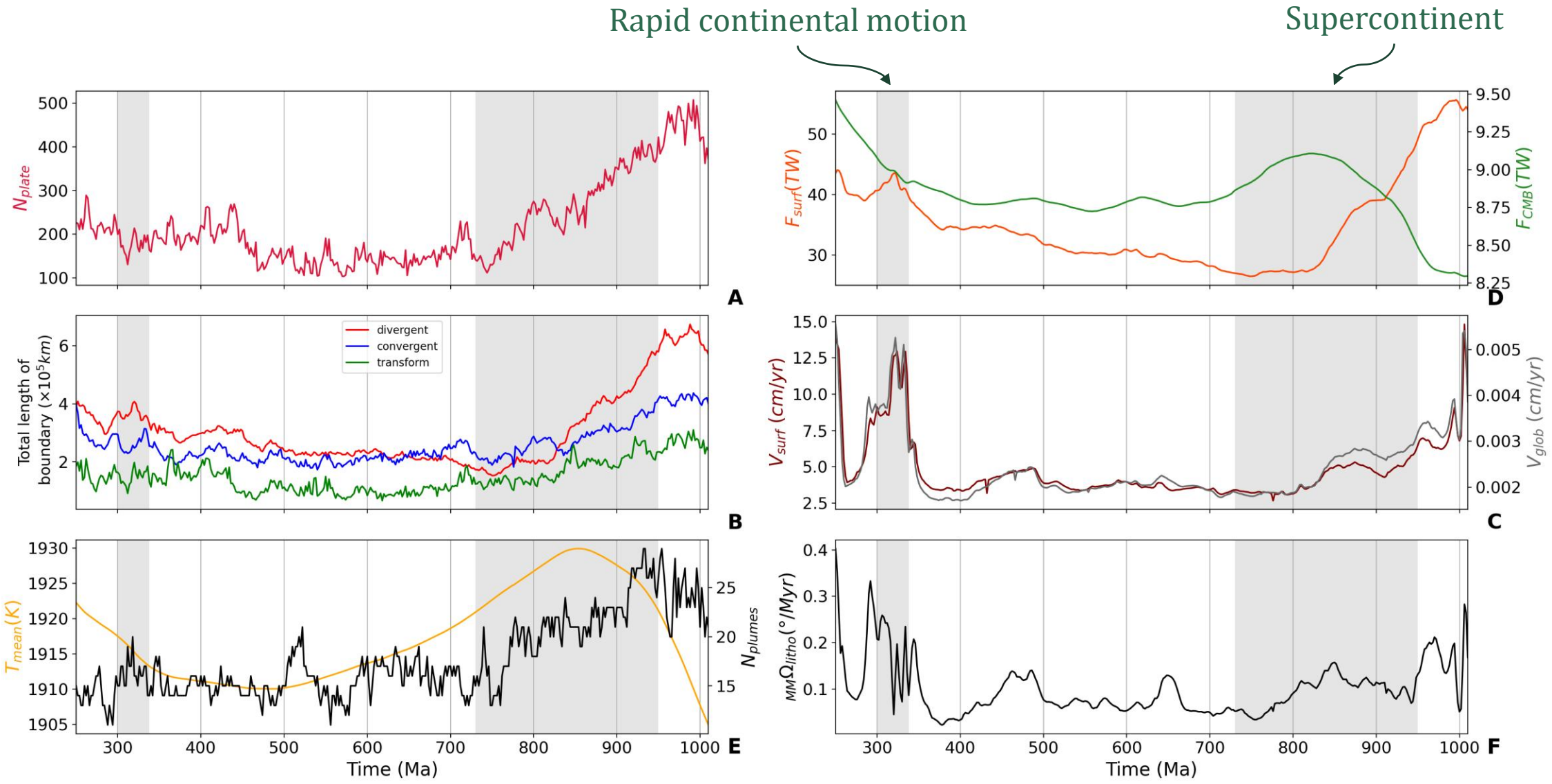


$$R(i,j) = \begin{cases} 1 & \text{if} \quad \|\vec{x}(i) - \vec{x}(j)\| \leq \varepsilon \\ 0 & \text{otherwise,} \end{cases}$$

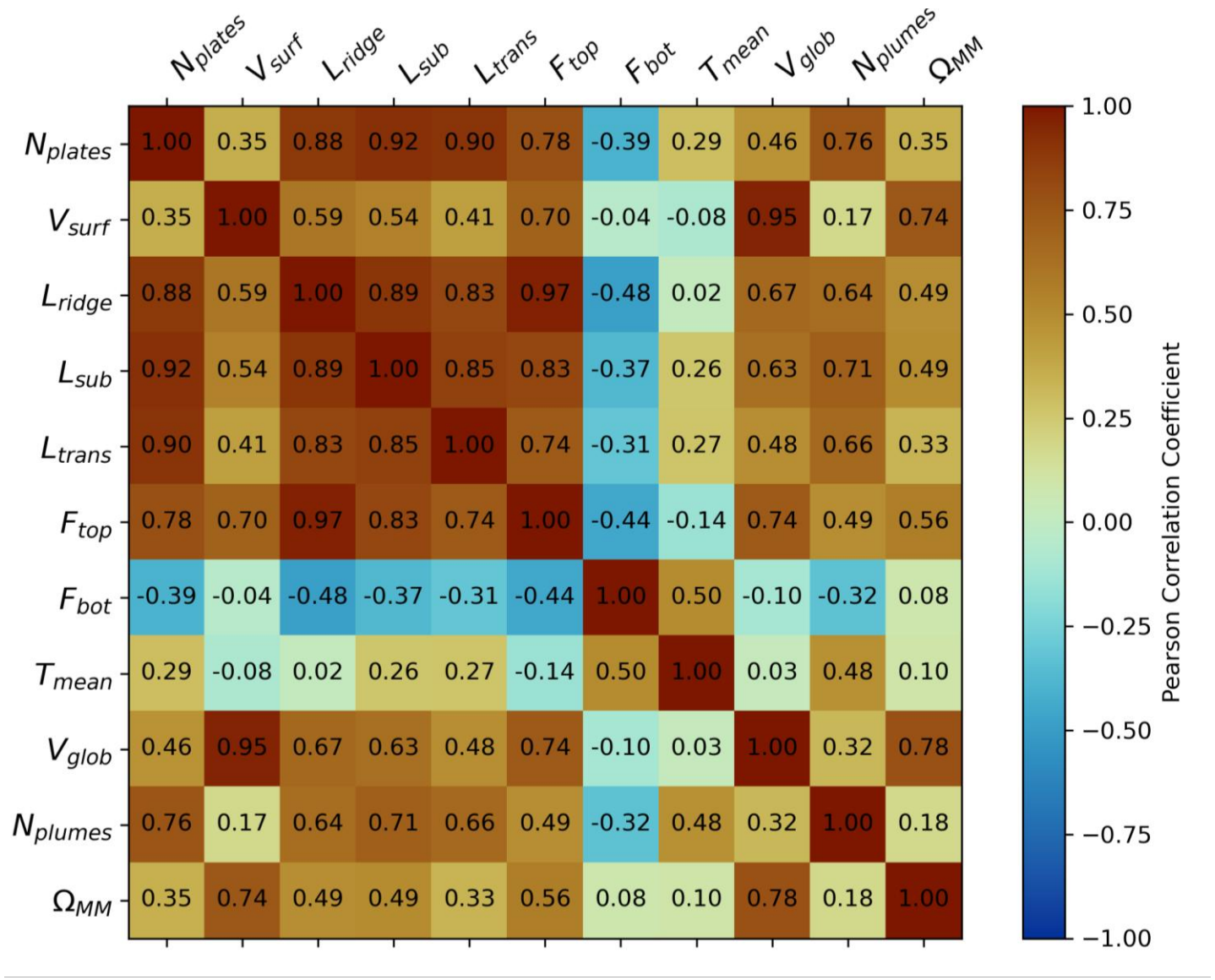
$$\mathrm{RR} = \frac{1}{N^2} \sum_{i,j=1}^{N} R(i,j).$$

→ Transitions should correspond to RR minima

Dataset


Rapid continental motion
Supercontinent
N_{plate}
A
divergent
convergent
transform
Total length of boundary ($\times 10^5 km$)
B
$T_{mean}(K)$
N_{plumes}
E
Time (Ma)
$F_{surf}(TW)$
$F_{CMB}(TW)$
D
V_{surf} (cm/yr)
V_{glob} (cm/yr)
C
$mm\Omega_{litho}$(°/Myr)
F
Time (Ma)

Correlations

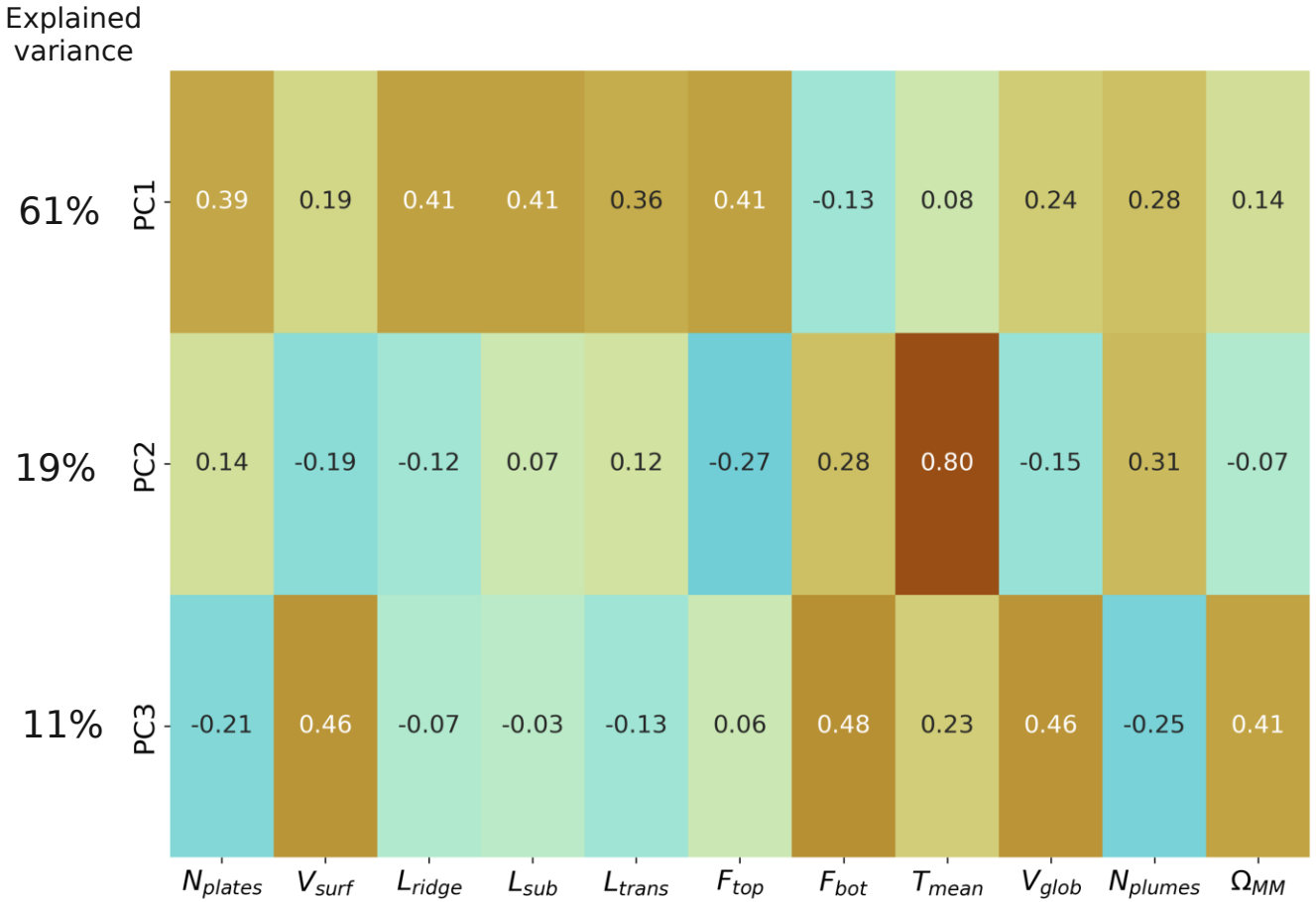


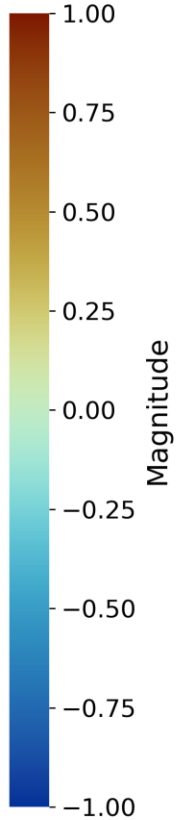
- Surface variables are highly correlated, except for velocity
- LNR correlated mostly correlated with velocity

→ Difficult to get information on mantle variables like the temperature of the mantle from surface variables

Principal Components

First 3 PC represent ~90% of variance of dataset





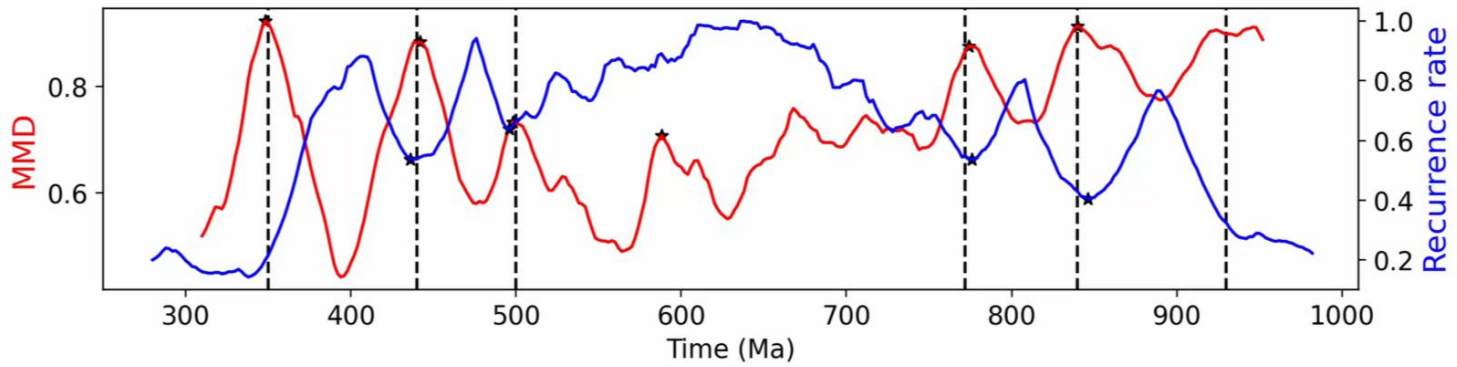
→ Surface/fragmentation

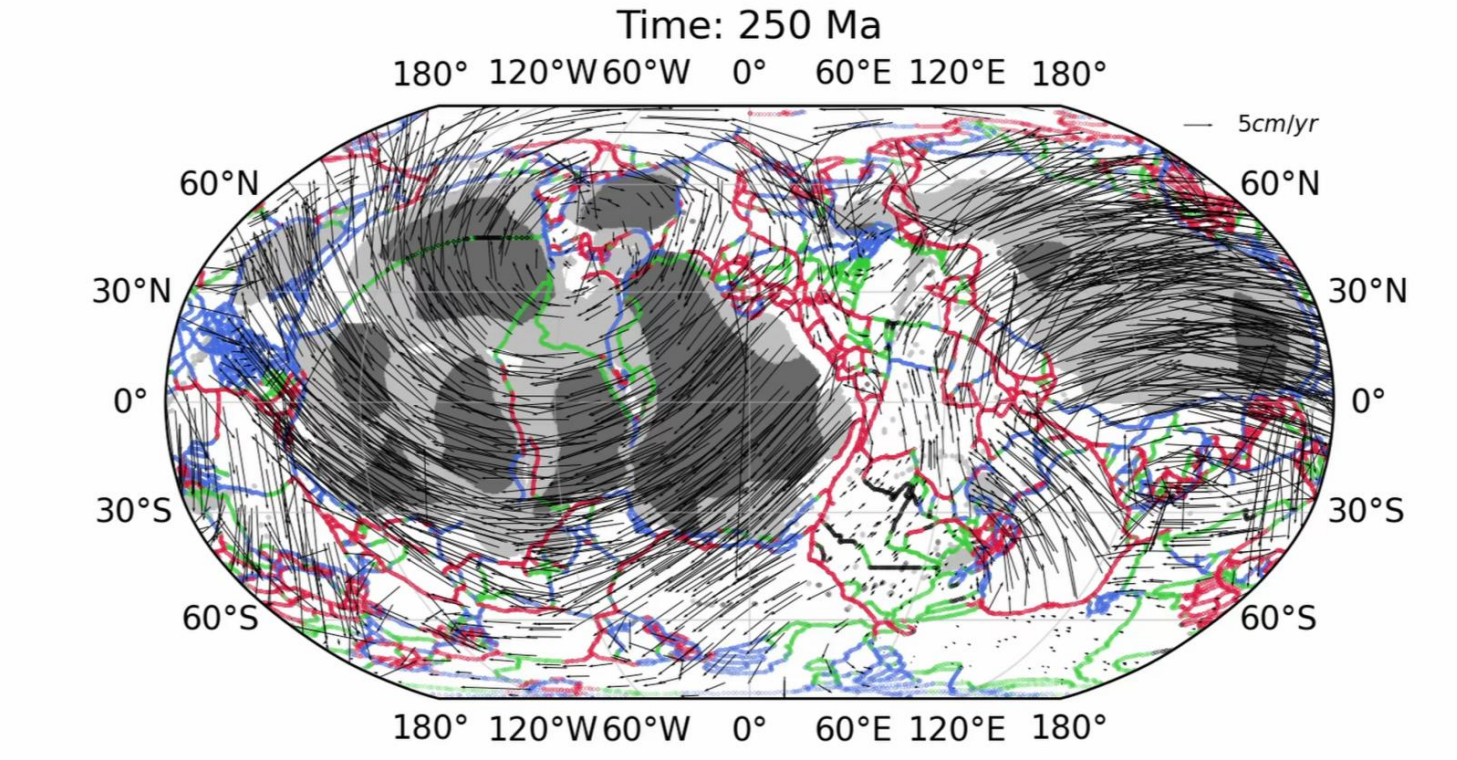
→ Mantle Temperature

→ Kinematics

→ Again, difficult to get information on mantle variables like the temperature of the mantle from surface variables

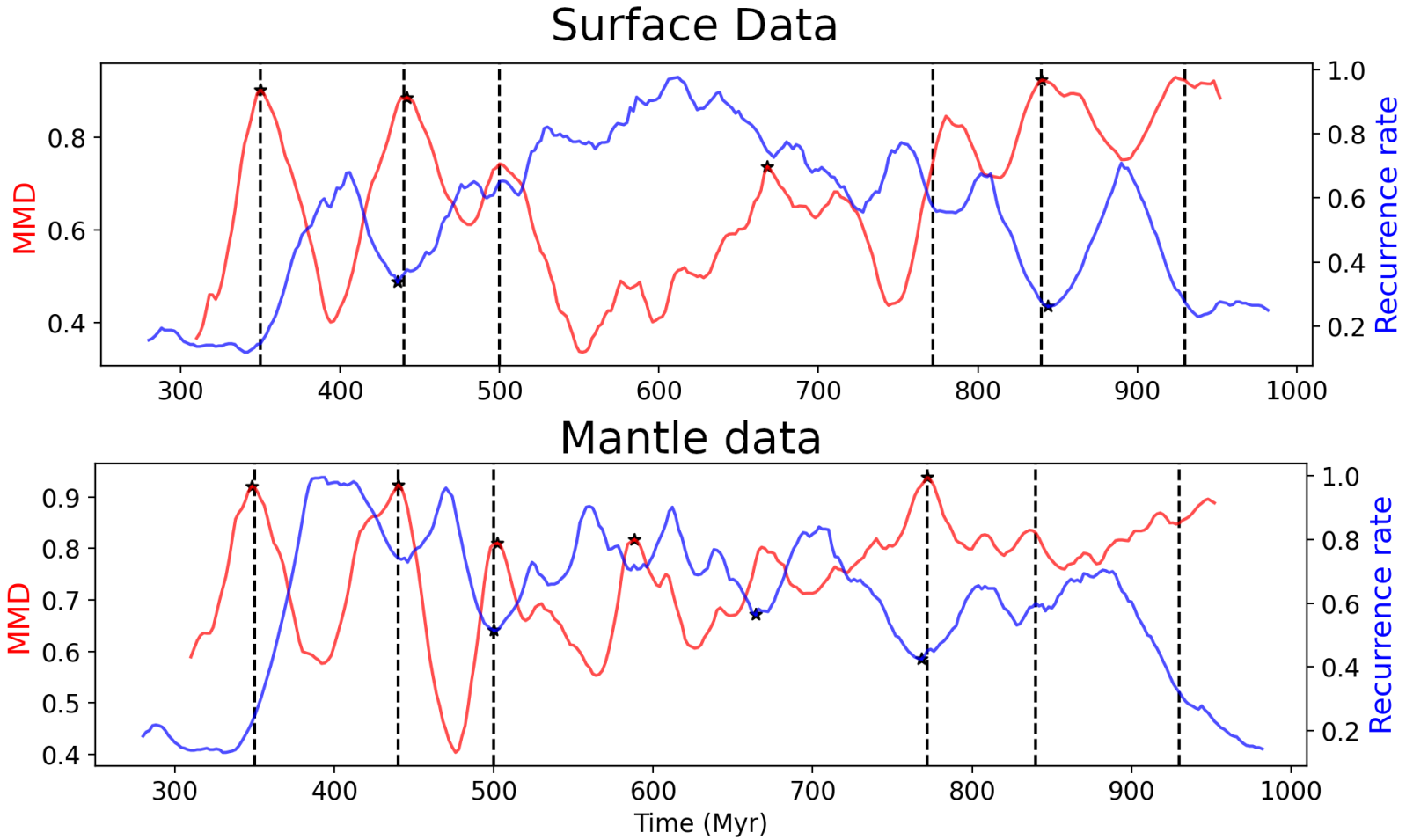
Identified Transitions





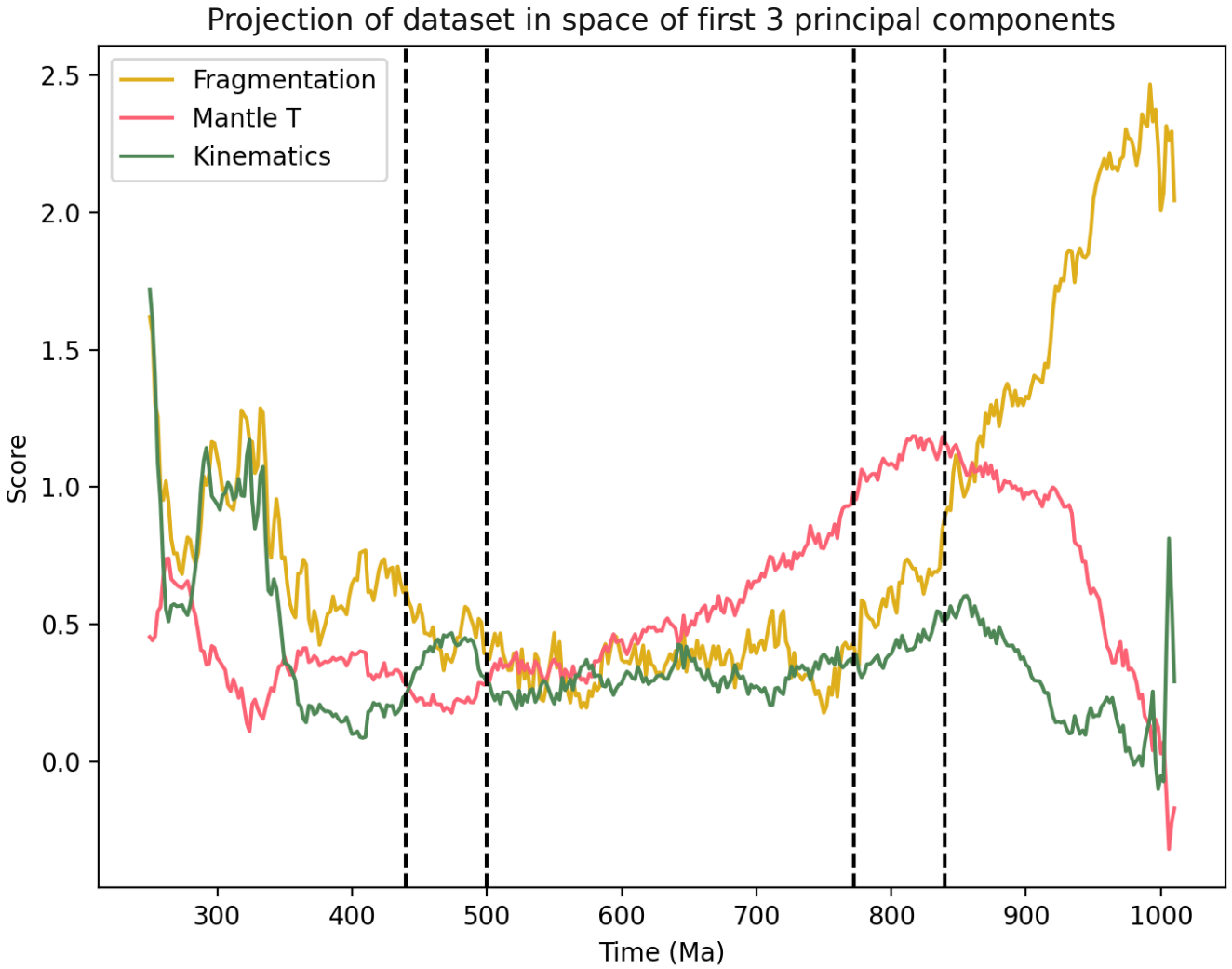
- 6 transitions over 760Myr
- Transitions are synchronous with major events like tectonic reorganisations or supercontinent breakup
- Continental breakups are associated to abrupt transitions, not continental collisions

Some Transitions concern the whole model, some only the surface



- 1 transition is not identified in the mantle
- Breakups are always identified for both dataset

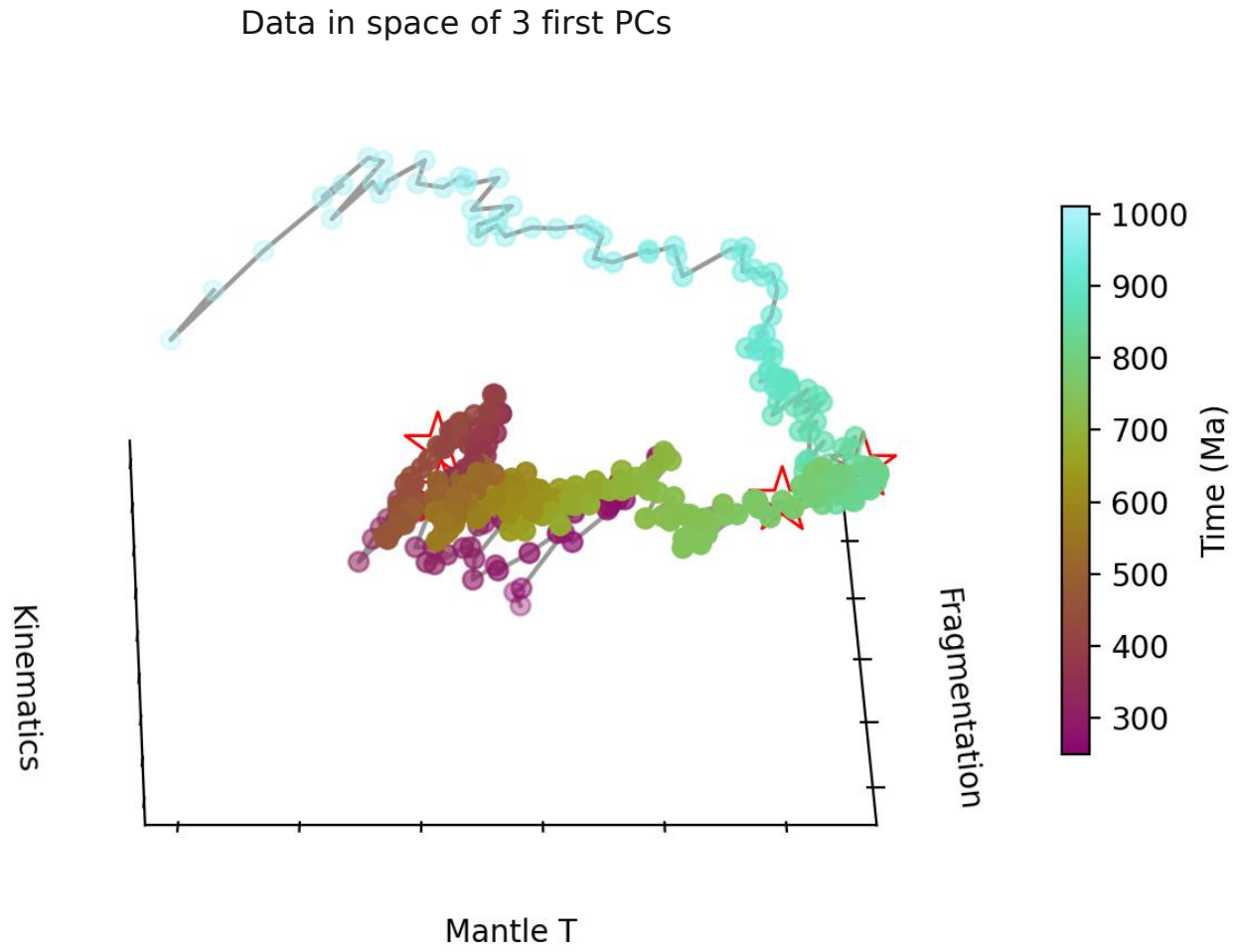
Principal Components Space



- Transitions are associated with shifts in one or more PC

→ Transitions are changes in fragmentation and/or mantle T and/or kinematics of the system

Principal Components Space



- Analogous to phase space
- No orbit, one potentially stable region
- Suggests that transitions are not fluctuations but fluctuations on longer timescales could exist
- Most transitions occur outside of ‘stable’ zone

Summary

We extracted global geodynamic data from an Earth-like mantle convection model and detected several abrupt transitions for this model

For the Earth :

- Hard to get information from the mantle temperature from kinematics and fragmentation
- Rapid transitions exist, they are characterized by changes in fragmentation and/or mantle T and/or kinematics
- Breakups are associated with abrupt transitions, not collisions
- Those transitions are either shifts from a distinct convective state to another or fluctuations on very long timescales

Any questions ? Contact me : **Ilyas.Jaah@geoazur.unice.fr**

Methods : Model details

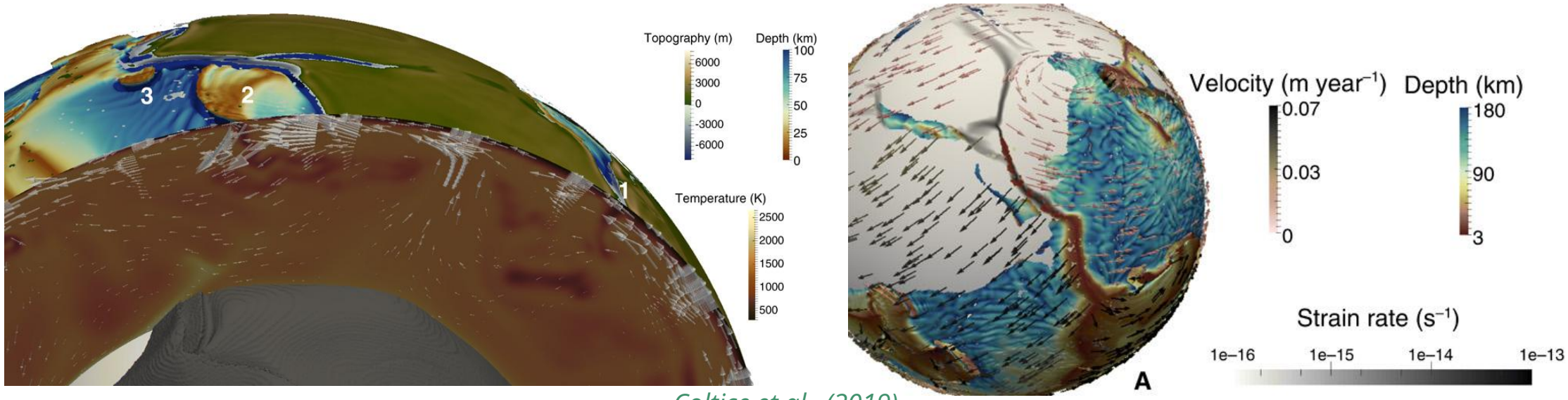
Code StagYY

Free-slip top and bottom boundaries

Lateral viscosity variation

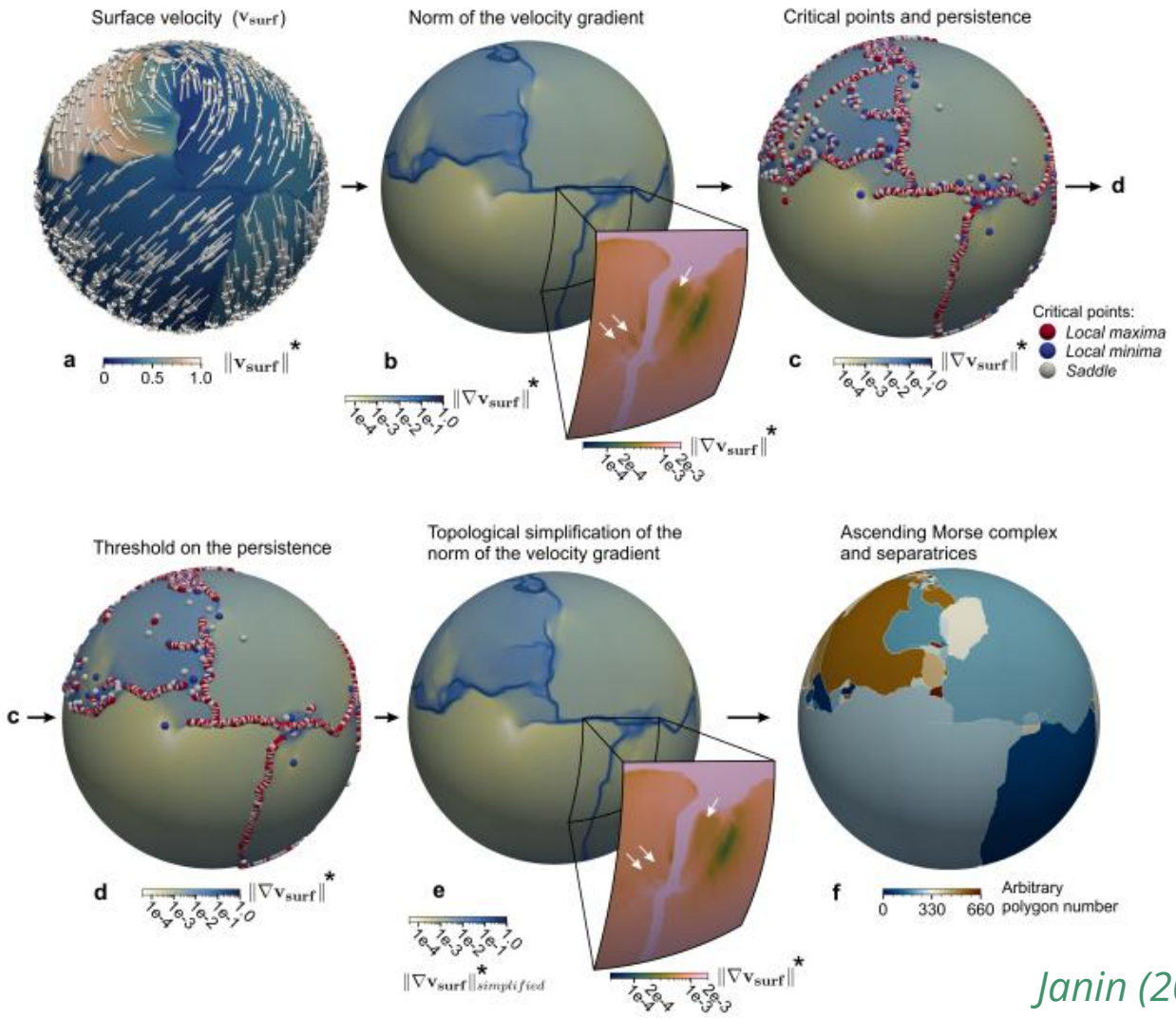
Chemical heterogeneities : Continents (less dense, more viscous) and LLSVP (denser, more viscous)

Initial condition : we fix the continents and solve the flow for the rest of the model until steady-state, then the model starts



Coltice et al., (2019)

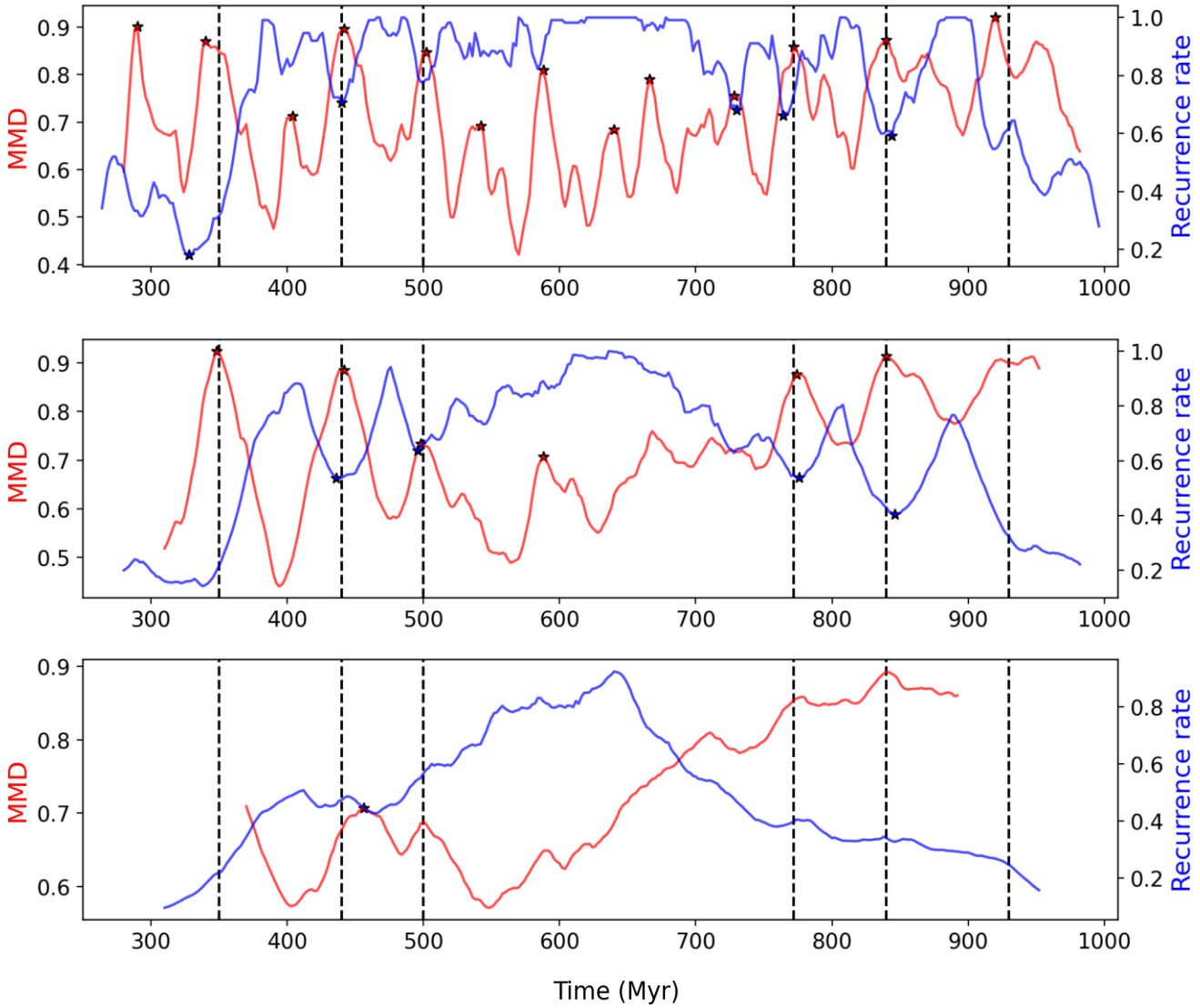
Methods : Tessellation



- Developped by Alexandre Janin
- Analysis of norm of velocity gradient
- Computation of critical points and persistence ~significance of critical points
- Threshold on persistence
- Computation of ascending Morse complex ~equivalent to watershed decomposition

Janin (2022)

Impact of window size on MMD and RR



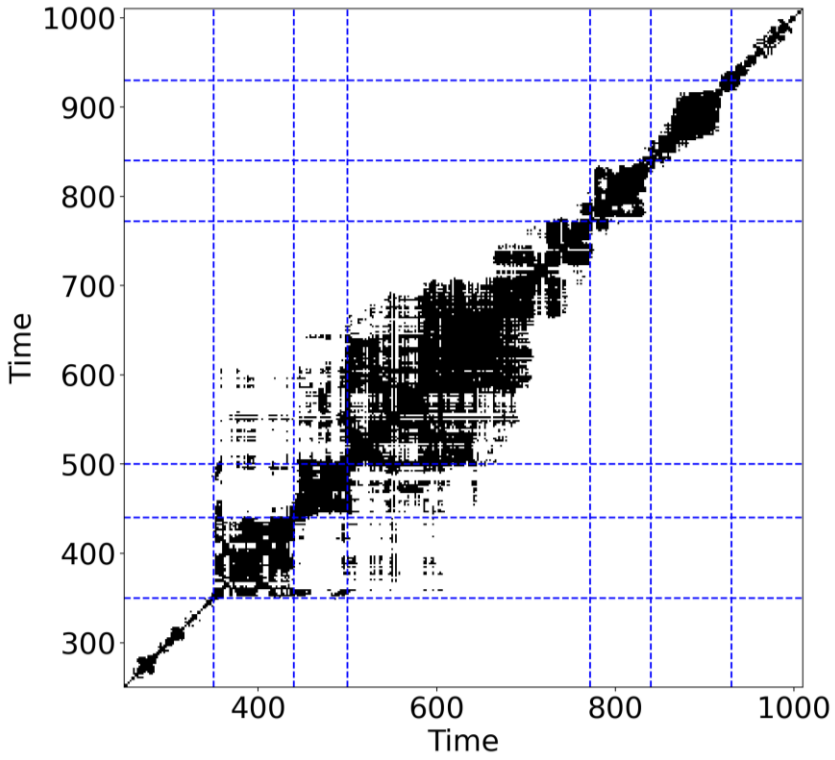
W = 30Myr, 15 points

W = 60Myr, 30 points

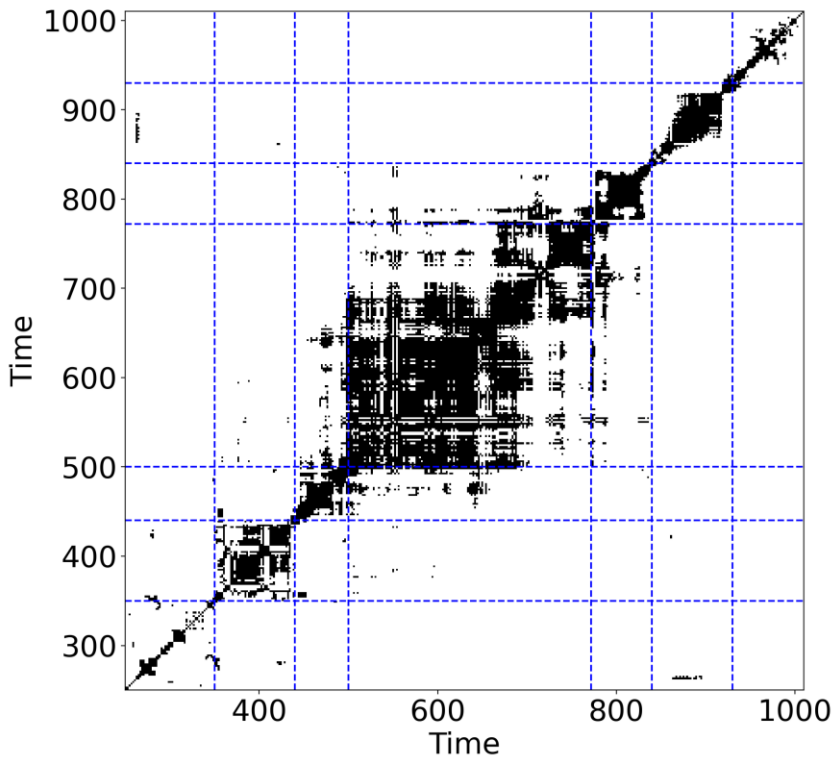
W = 120Myr, 60 points

Recurrence Plots of the Dataset

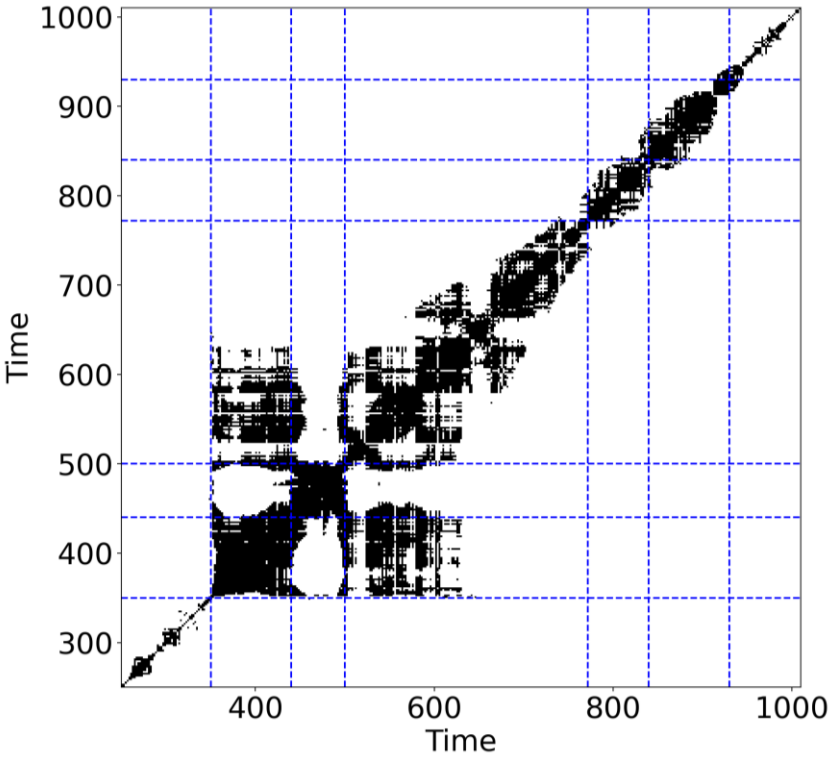
Recurrence plot for all the data



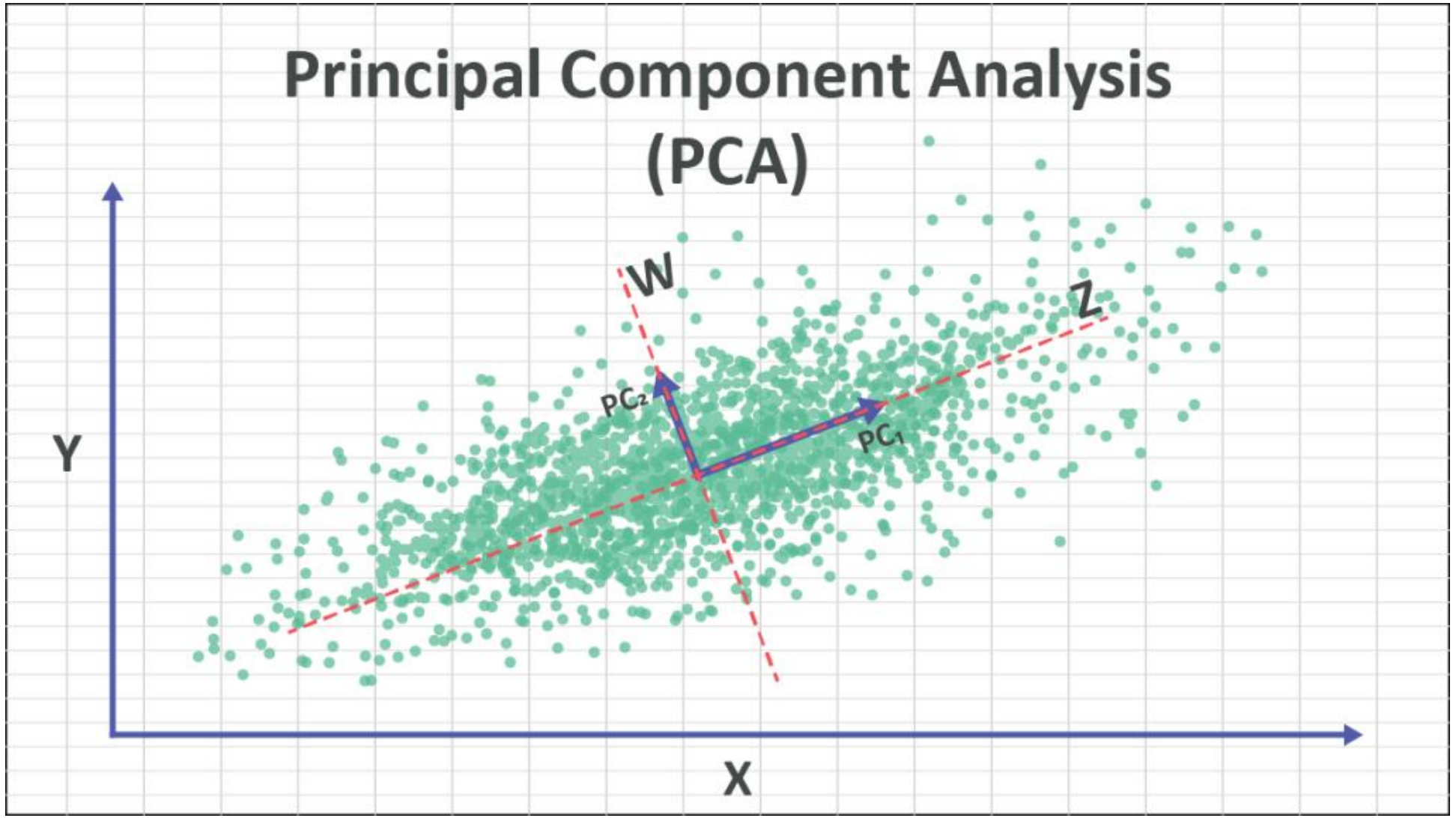
Recurrence plot for the surface



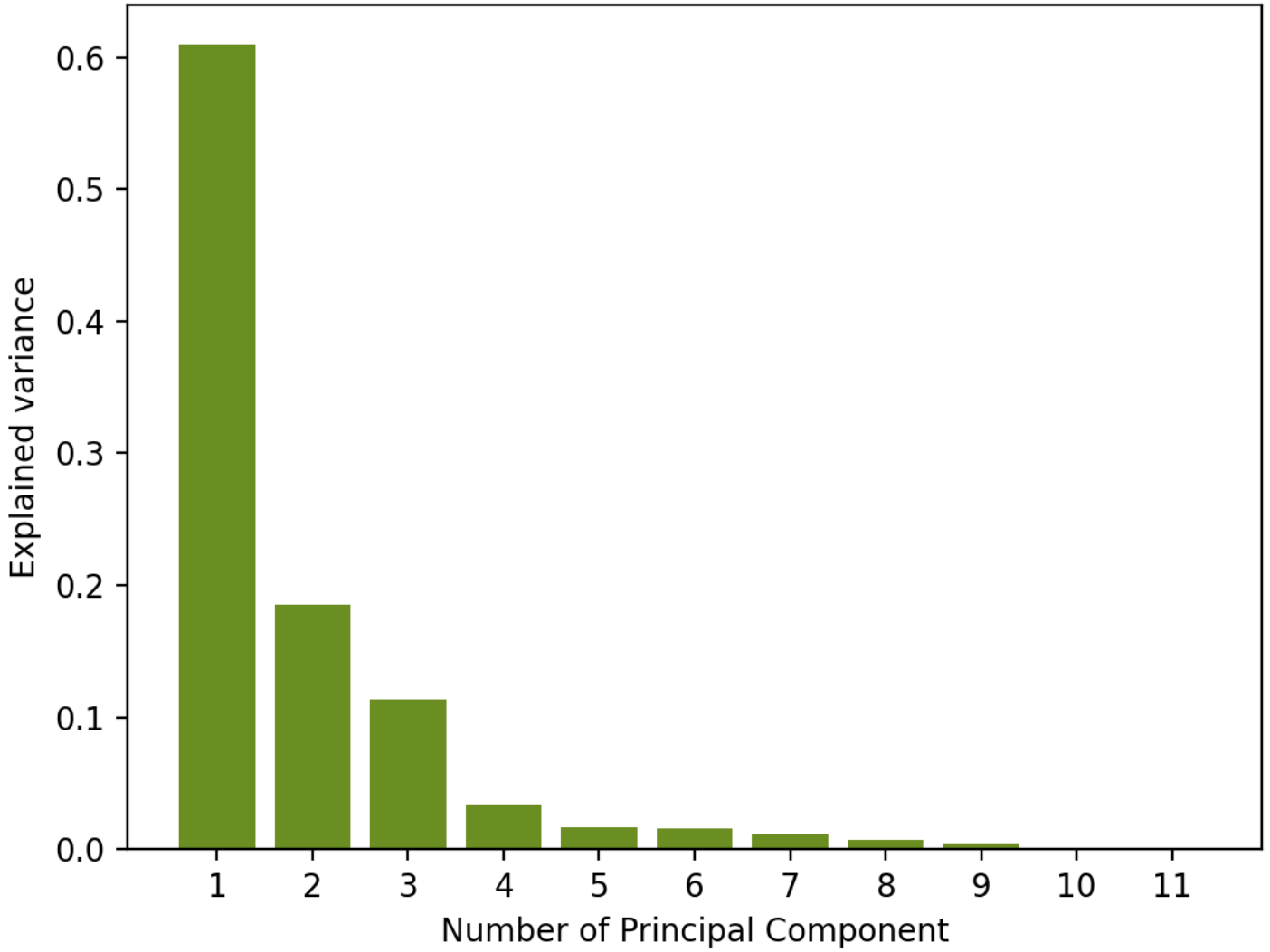
Recurrence plot for the mantle



Methods : PCA, how it works

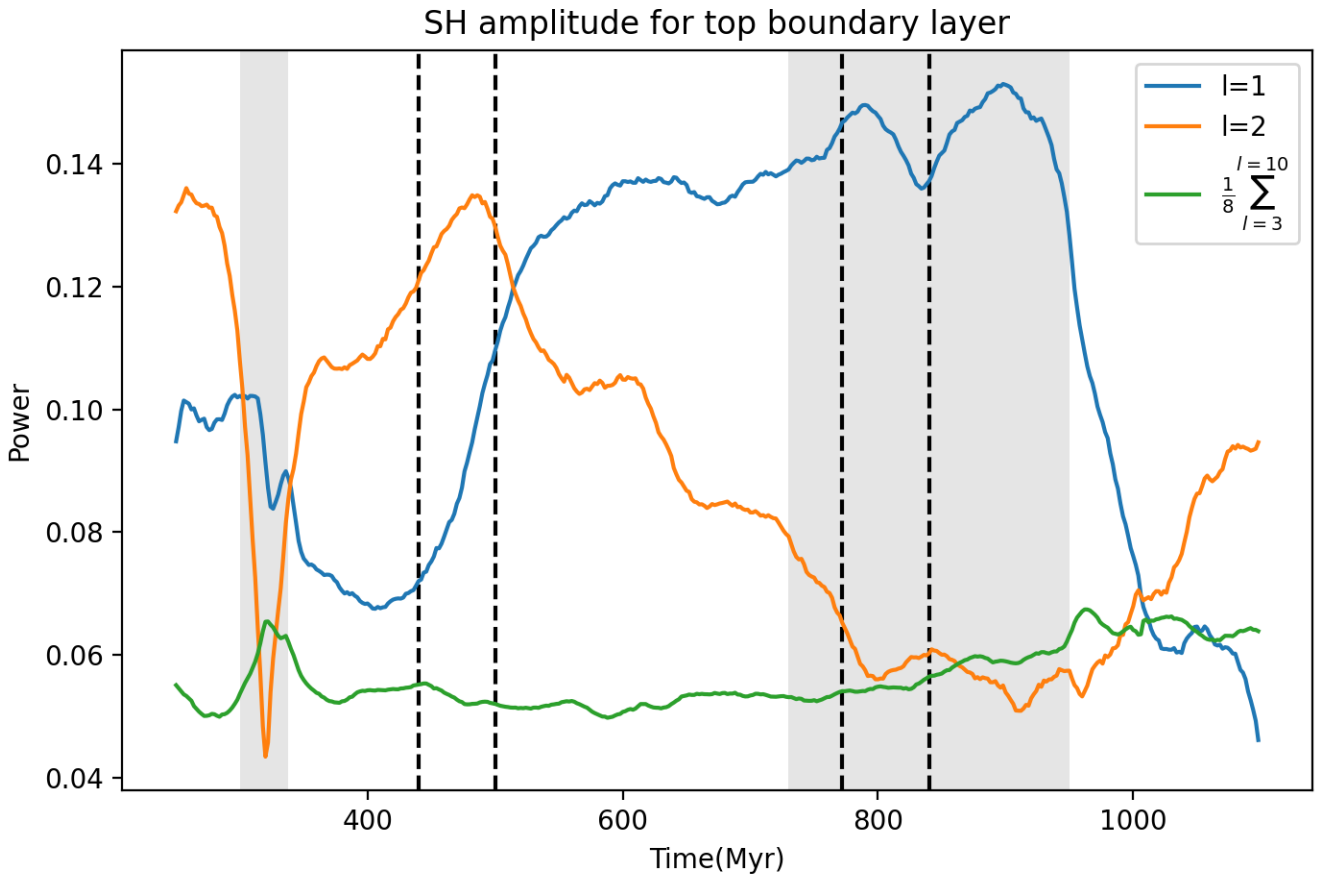


Variance of Principal Components



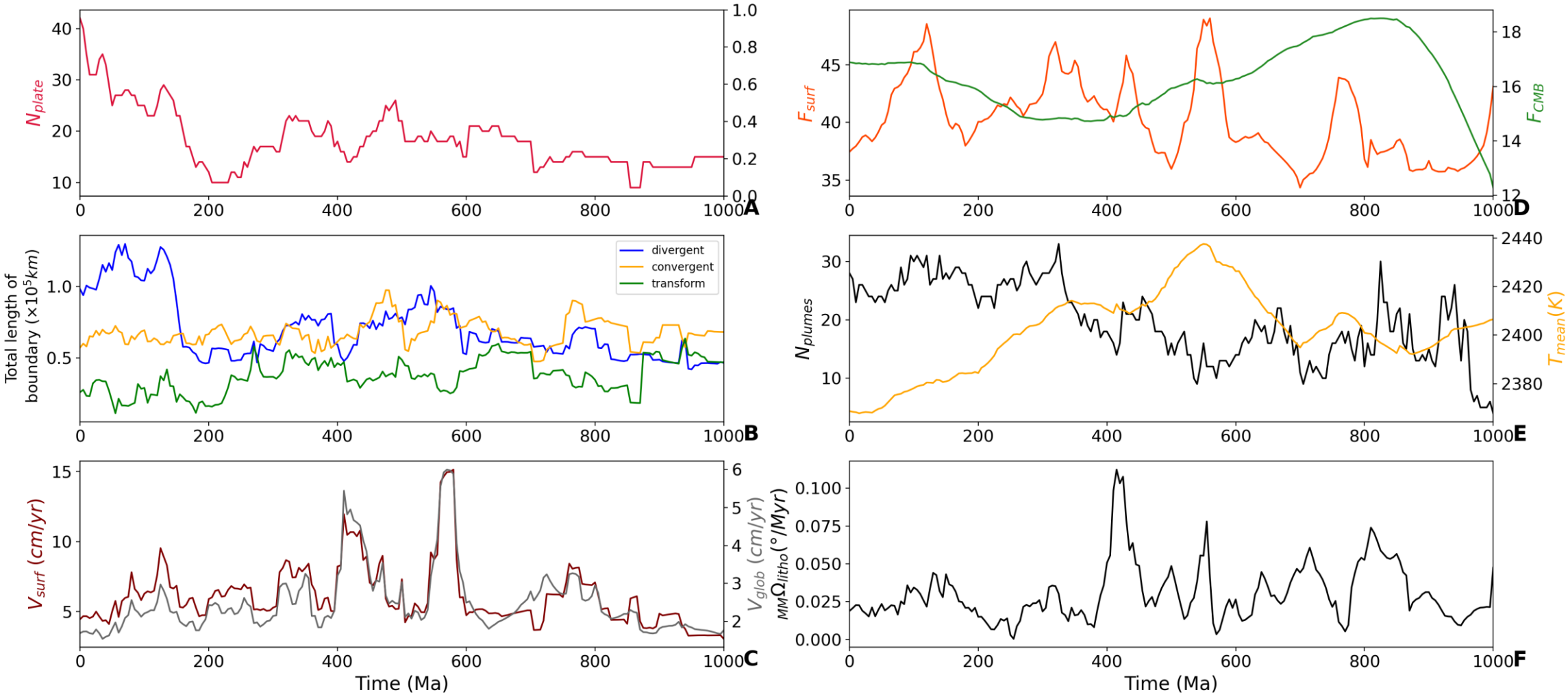
First PC : 61%
Second PC : 19%
Third PC : 11%

Results : Thermal heterogeneity spectrum

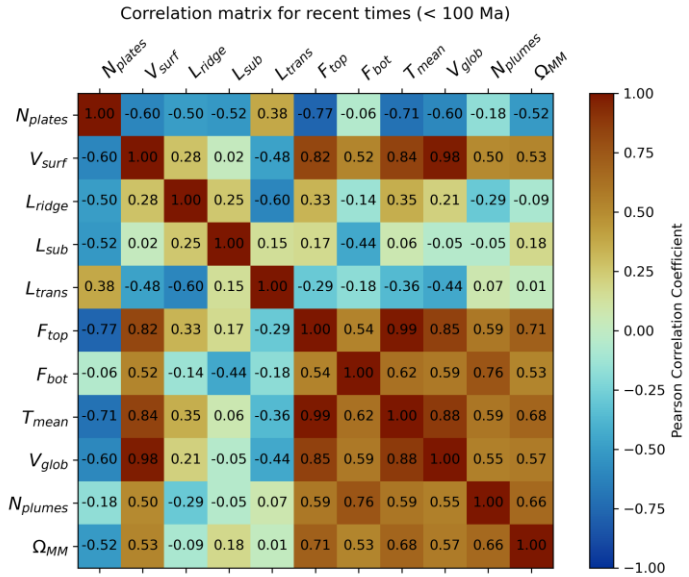


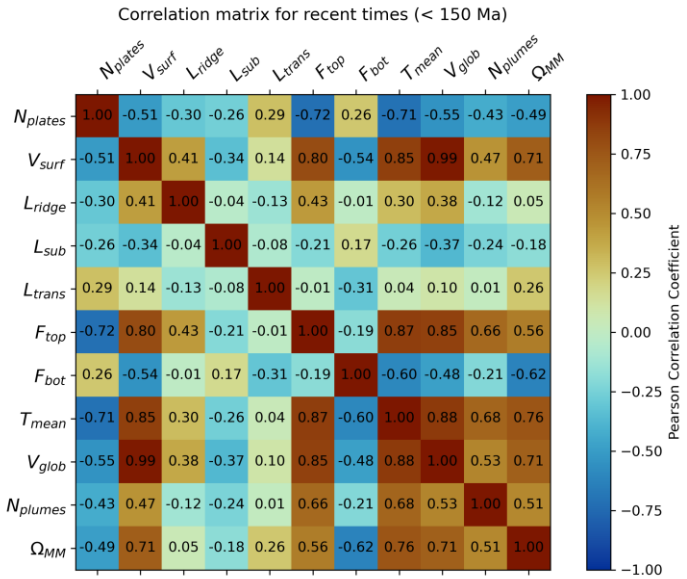
- Supercontinent cycle : degree 1 to form supercontinent, degree 2 to disperse
- Some transitions are synchronous with changes in long wavelength of convection

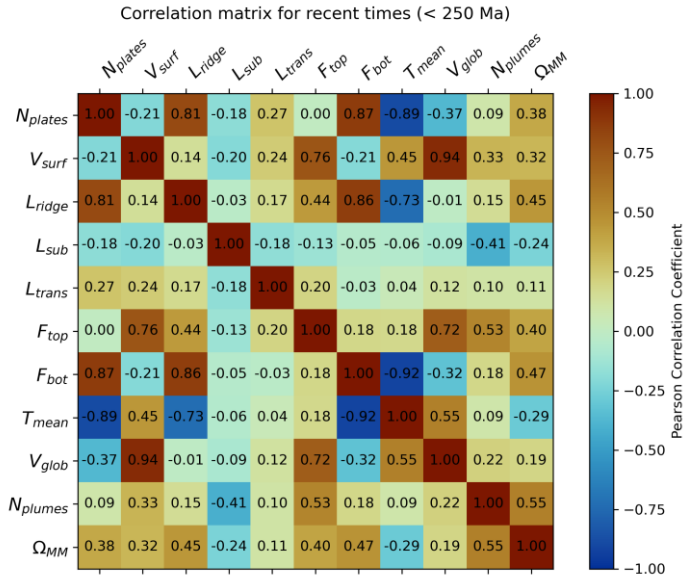
Test on Kinematically Constrained Flow Model

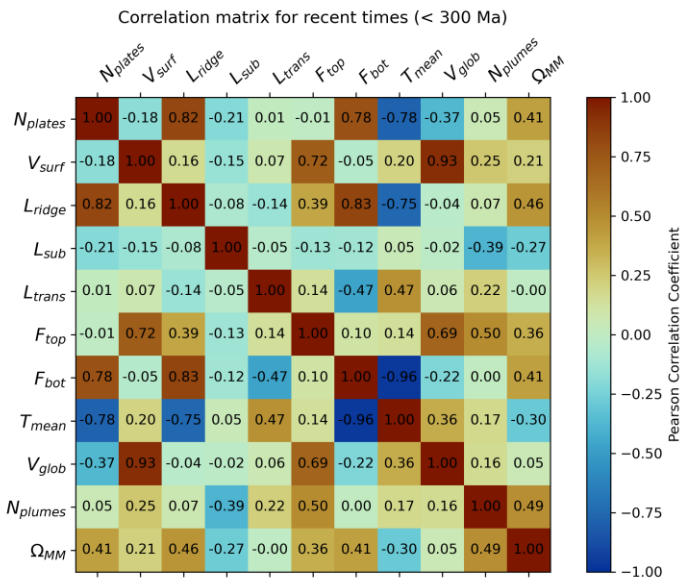


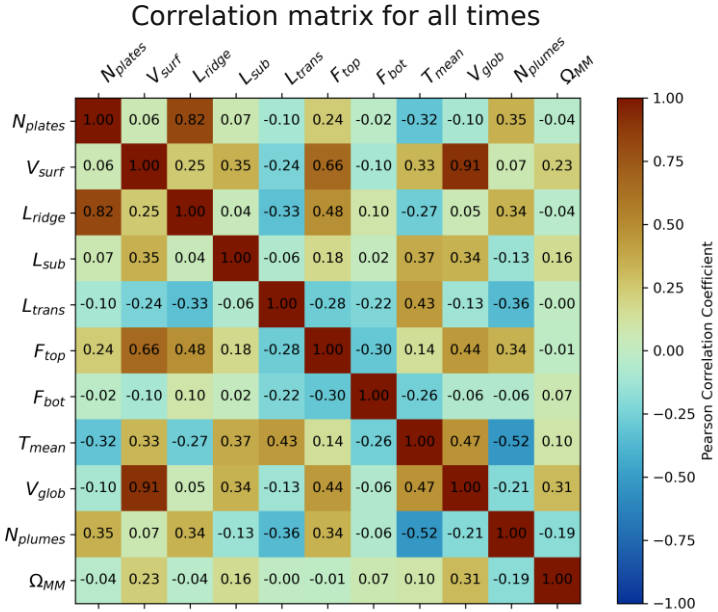
Test on Kinematically Constrained Flow Model



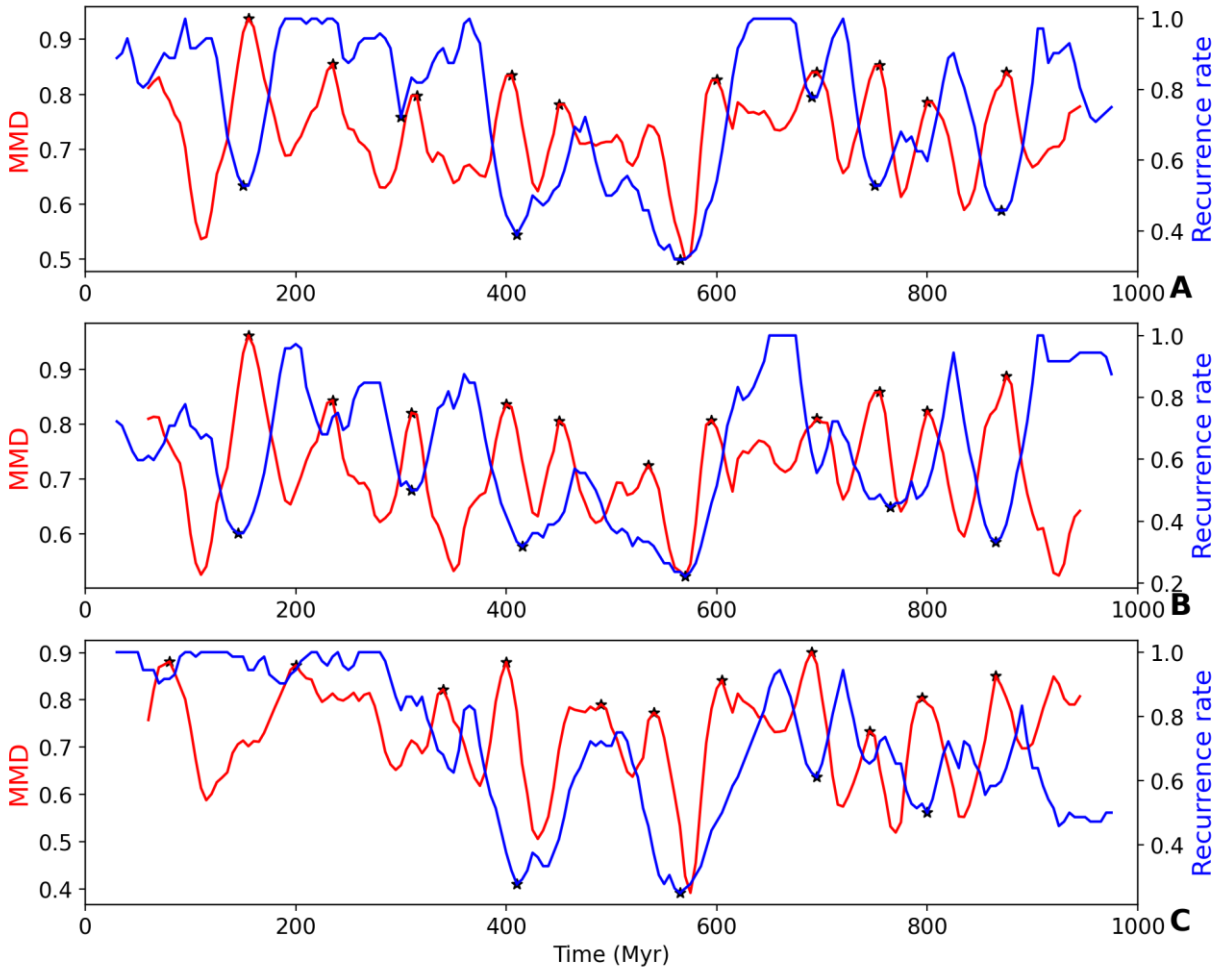




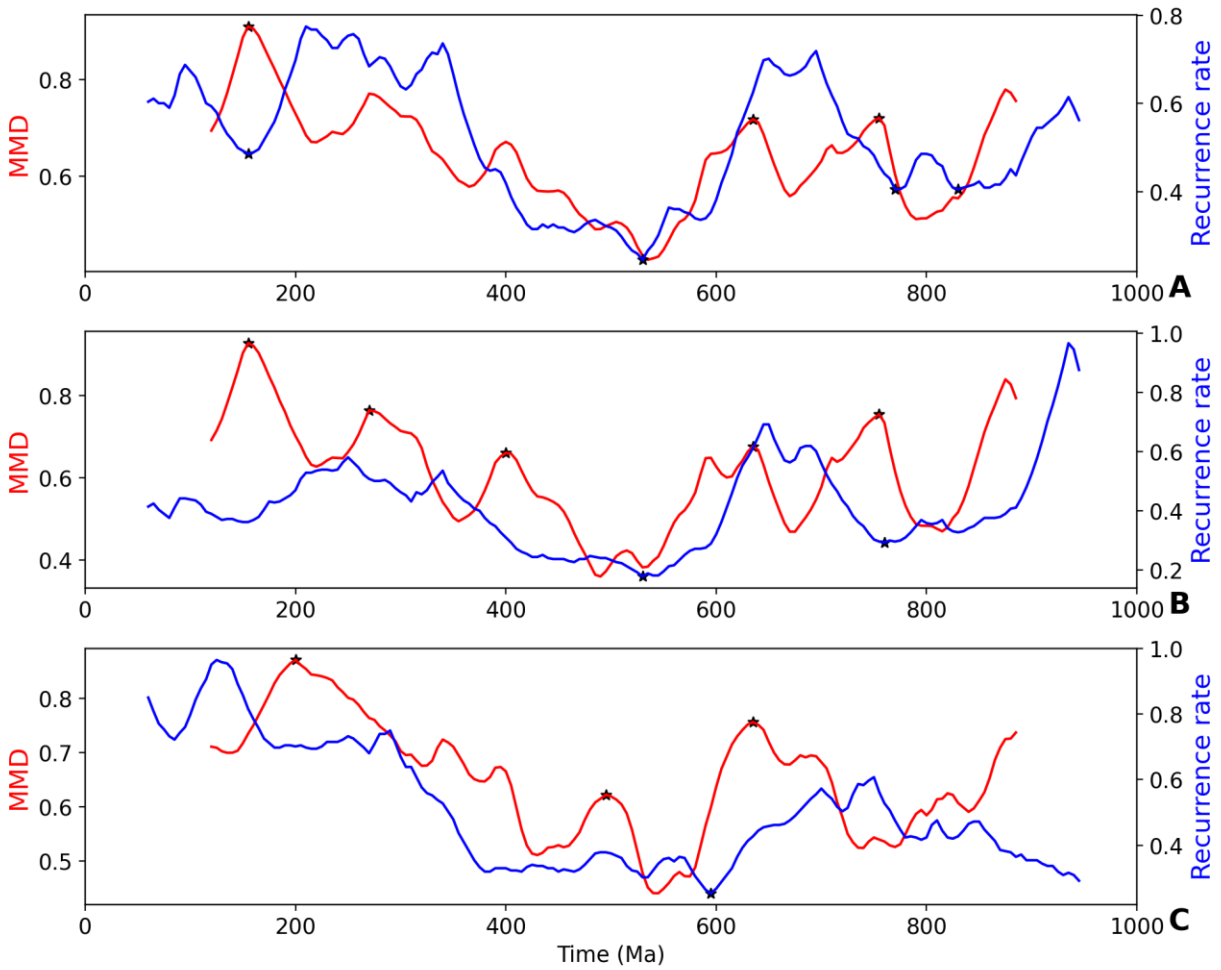




Test on Kinematically Constrained Flow Model



W = 60Myr, 12 points



W = 120Myr, 24 points