Tipping Points in the Climate System: Automatic Detection of Abrupt Transitions in Paleoclimate Records

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Abstract

Bifurcations and tipping points (TPs) are an important part of the Earth system's behavior. These critical points represent thresholds at which small changes in the system's parameters or in the forcing abruptly switch the system from one state or type of behavior to another. Current concern with TPs is largely due to the potential contribution of anthropogenic forcing to one or more climatic subsystems undergoing such abrupt, and possibly irreversible, transitions. Paleorecords of past climate have been shown to contain abrupt transitions, or "jumps," which may represent former instances of tipping. Robustly identifying and describing such transitions is essential to properly understanding the underlying bifurcation mechanisms. Doing so may provide valuable information for identifying critical TPs in current and future climate evolution.Here we present a robust methodology for detecting abrupt transitions in proxy records that is applied to a set of ice core, speleothem, and marine sediment records of the last climate cycle and the Holocene. This methodology is based on the nonparametric Kolmogorov-Smirnov (KS) test for the equality, or not, of the probability distributions associated with two samples drawn from a time series, before and after any potential jump. The KS test is augmented by several other criteria and it is evaluated against other jump detection algorithms, aiming to establish a "gold standard" for abrupt-transition detection. This objective approach to identifying climate TPs will allow us to construct better nonlinear and stochastic models of bifurcations in the Earth's climate and its interactions with ecosystems within the TiPES (Tipping Points in the Earth System) EU-funded project.

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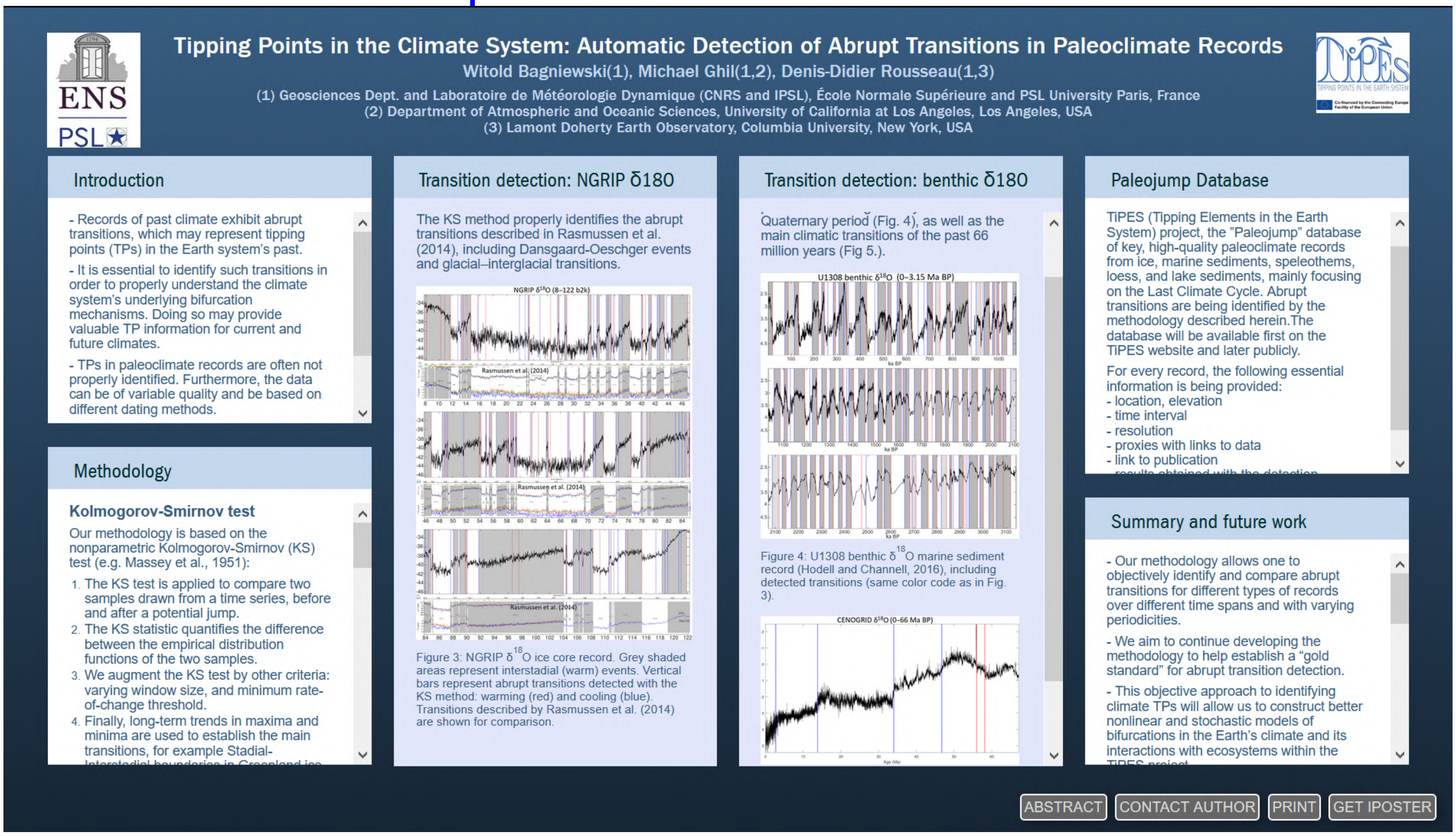

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TIPPING POINTS IN THE EARTH SYSTEM

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INTRODUCTION

- Records of past climate exhibit abrupt transitions, which may represent tipping points (TPs) in the Earth system's past.

- It is essential to identify such transitions in order to properly understand the climate system's underlying bifurcation mechanisms. Doing so may provide valuable TP information for current and future climates.

- TPs in paleoclimate records are often not properly identified. Furthermore, the data can be of variable quality and be based on different dating methods.

- Here, we present a methodology for automatically detecting abrupt transitions in paleoclimatic proxy records of many types and timescales.

METHODOLOGY

Kolmogorov-Smirnov test

Our methodology is based on the nonparametric Kolmogorov-Smirnov (KS) test (e.g. Massey et al., 1951):

1. The KS test is applied to compare two samples drawn from a time series, before and after a potential jump.
2. The KS statistic quantifies the difference between the empirical distribution functions of the two samples.
3. We augment the KS test by other criteria: varying window size, and minimum rate-of-change threshold.
4. Finally, long-term trends in maxima and minima are used to establish the main transitions, for example Stadial-Interstadial boundaries in Greenland ice cores.

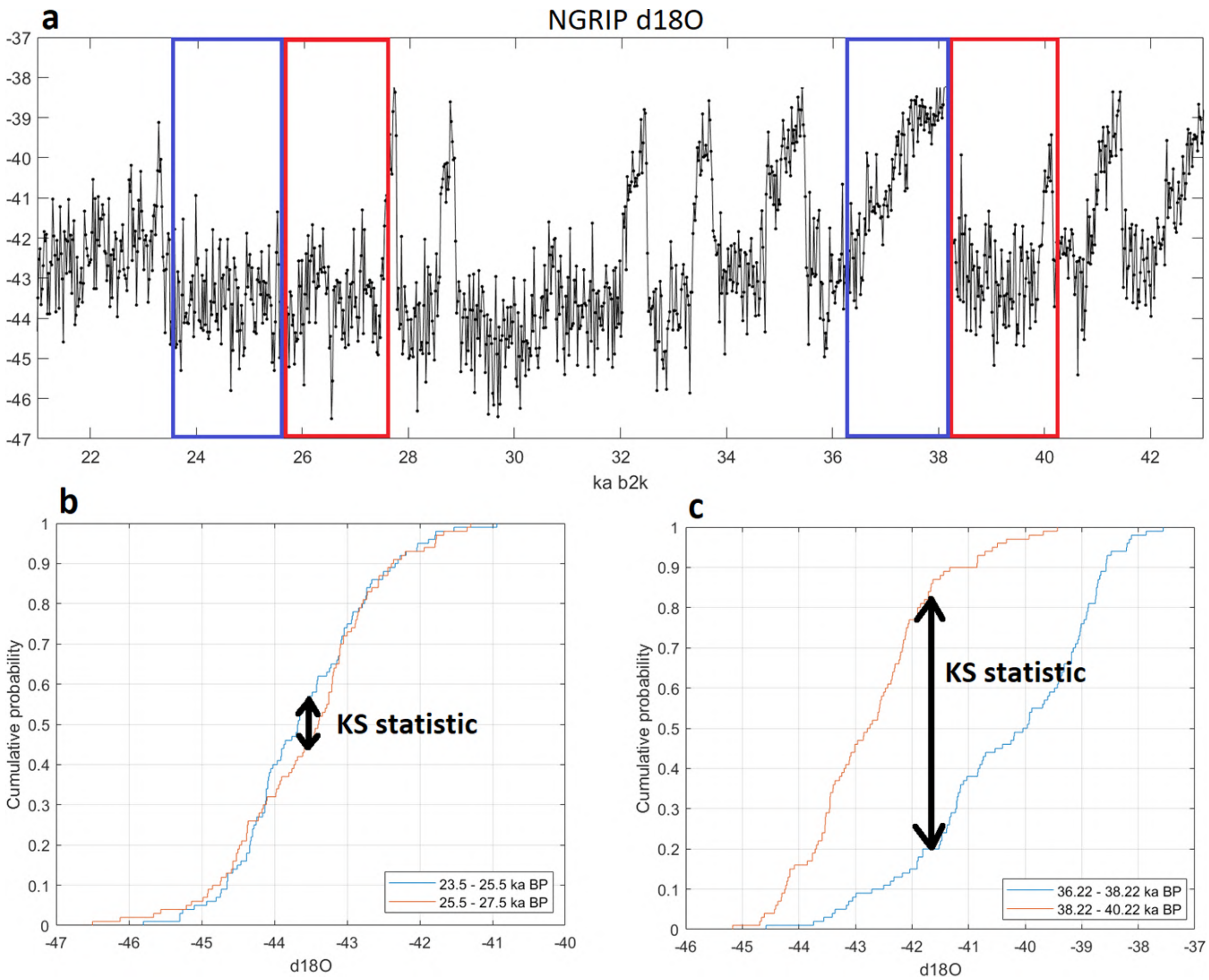

Figure 1. (a) Snapshot of the NGRIP $\delta^{18}O$ record (21–43 ka b2k). Red and blue rectangles correspond to the sample windows used for evaluating the KS statistic. (b, c) Empirical distribution functions of the "blue" and "red" samples. The length of the black arrow is equal to the KS statistic.

Receiver operating characteristic

We use the receiver operating characteristic (ROC) analysis to compare the diagnostic ability of different classifiers used in our methodology and to optimize the KS method's parameters. The area under the curve in Fig. 2 quantifies the skill of a classifier.

The ROC's “ground truth” is based on the boundaries in Ramussen et al. (2014), resulting in the “True positive” and “False positive” values on the axes.

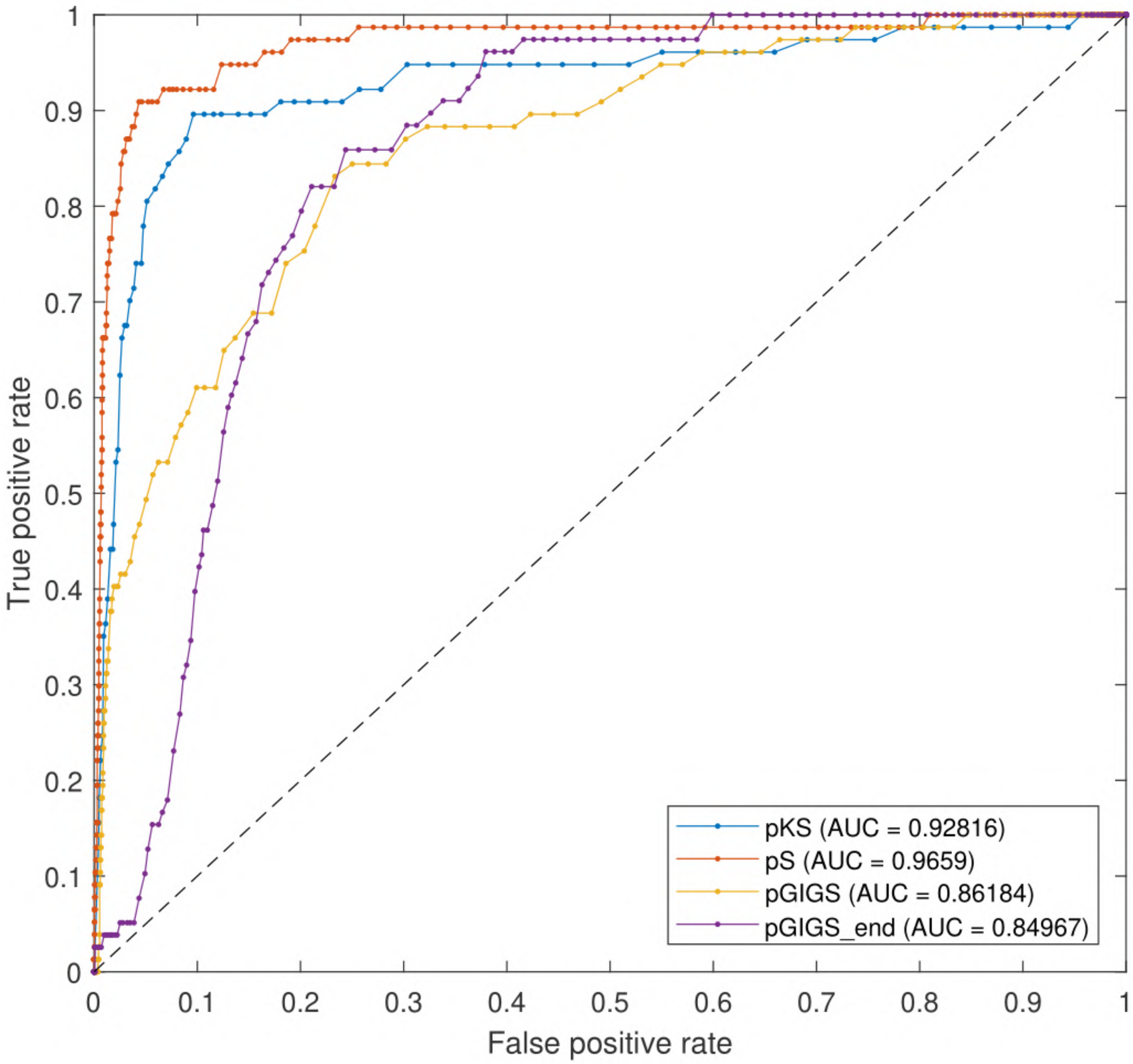

Figure 2: ROC curves obtained with different classifiers used in our methodology. Every point corresponds to a different parameter value.

TRANSITION DETECTION: NGRIP $\delta^{18}O$

The KS method properly identifies the abrupt transitions described in Rasmussen et al. (2014), including Dansgaard-Oeschger events and glacial–interglacial transitions.

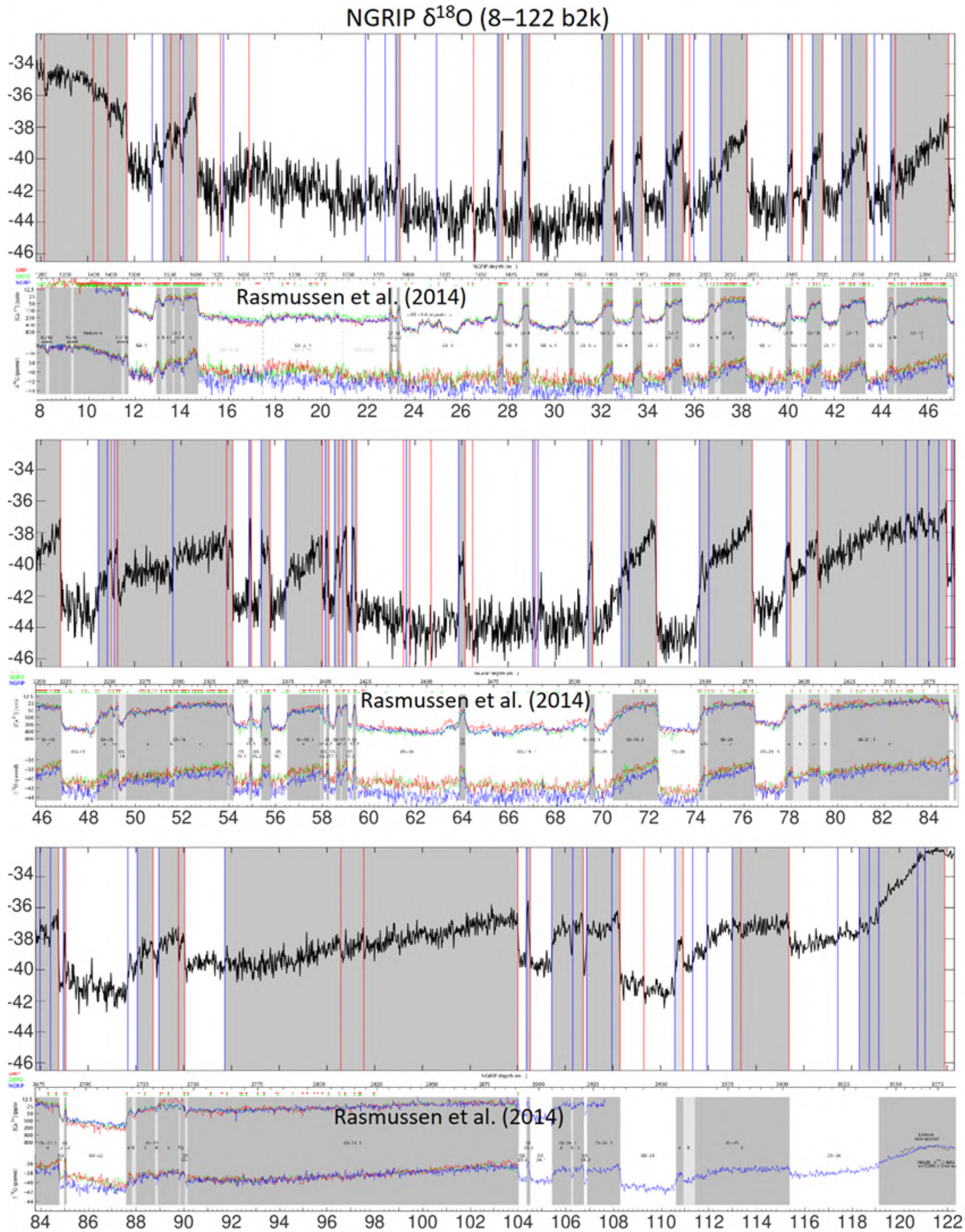

Figure 3: NGRIP $\delta^{18}O$ ice core record. Grey shaded areas represent interstadial (warm) events. Vertical bars represent abrupt transitions detected with the KS method: warming (red) and cooling (blue). Transitions described by Rasmussen et al. (2014) are shown for comparison.

TRANSITION DETECTION: BENTHIC $\delta^{18}O$

We applied the KS method successfully to other types of records with different timescales and nonlinear trends. We find precise dates for glacial cycles of the Quaternary period (Fig. 4), as well as the main climatic transitions of the past 66 million years (Fig 5).

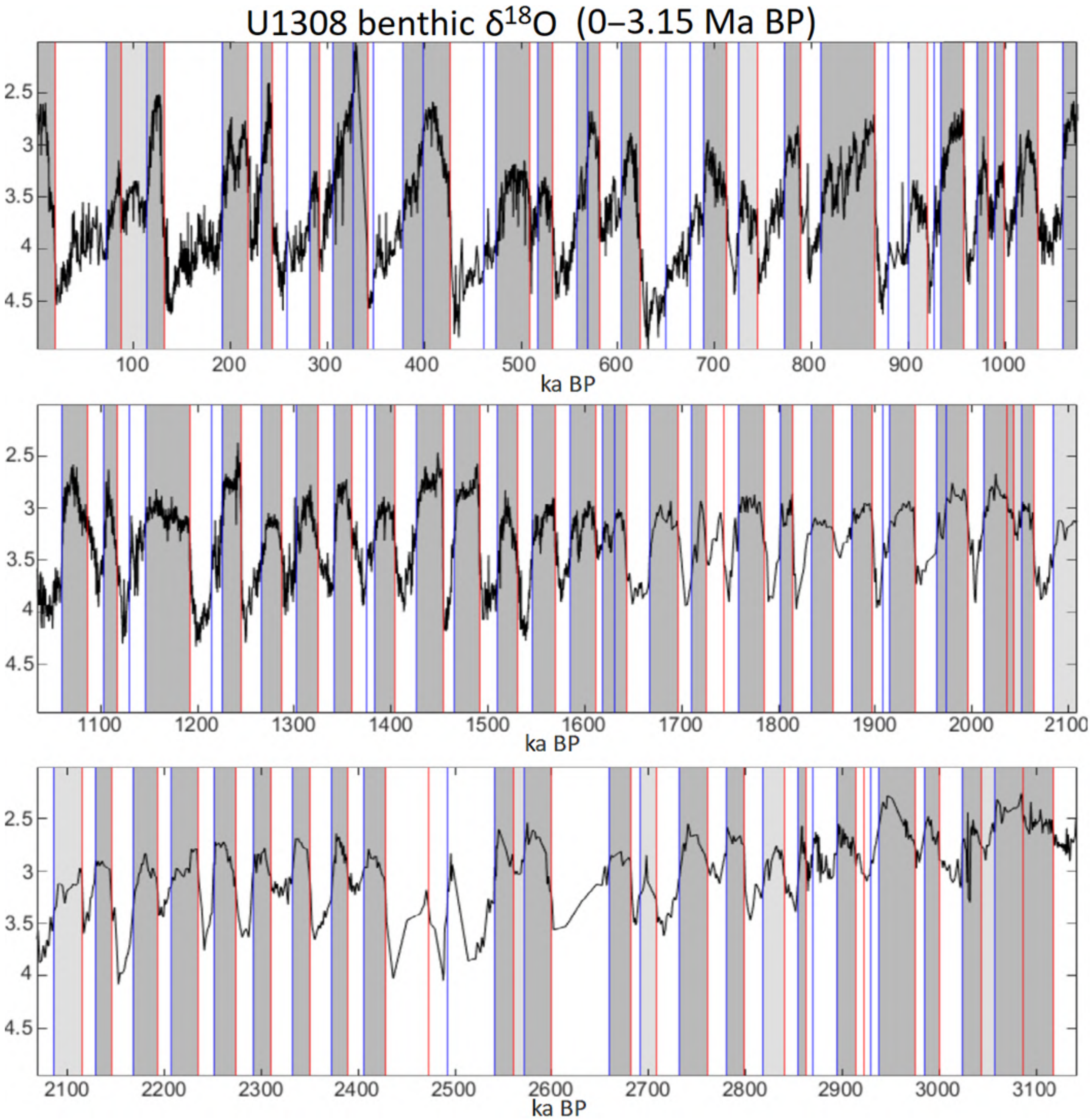

Figure 4: U1308 benthic $\delta^{18}O$ marine sediment record (Hodell and Channell, 2016), including detected transitions (same color code as in Fig. 3).

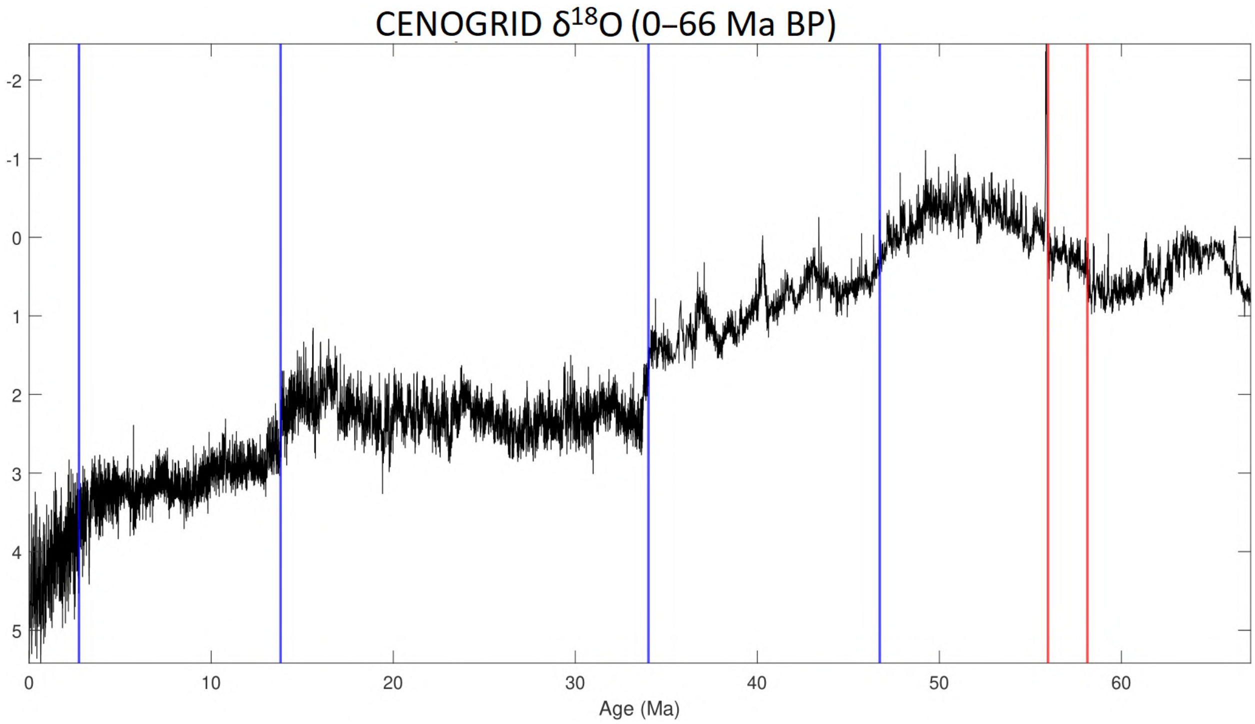

Figure 5: CENOGRID benthic $\delta^{18}O$ marine sediment stack (Westerhold et al., 2020), including the main transitions found with the KS method: 58.1 Ma, 56 Ma, 46.7 Ma, 34 Ma, 13.8 Ma, and 2.7 Ma (same color code than in Fig. 3).

PALEOJUMP DATABASE

We are building, within the EU-funded TiPES (Tipping Elements in the Earth System) project, the ”Paleojump” database of key, high-quality paleoclimate records from ice, marine sediments, speleothems, loess, and lake sediments, mainly focusing on the Last Climate Cycle. Abrupt transitions are being identified by the methodology described herein.The database will be available first on the TiPES website and later publicly.

For every record, the following essential information is being provided:
- location, elevation
- time interval
- resolution
- proxies with links to data
- link to publication
- results obtained with the detection method

SUMMARY AND FUTURE WORK

- Our methodology allows one to objectively identify and compare abrupt transitions for different types of records over different time spans and with varying periodicities.

- We aim to continue developing the methodology to help establish a “gold standard” for abrupt transition detection.

- This objective approach to identifying climate TPs will allow us to construct better nonlinear and stochastic models of bifurcations in the Earth’s climate and its interactions with ecosystems within the TiPES project.

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ABSTRACT

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