Using hierarchical dynamic time warping to synchronize age-uncertain (proxy) time series

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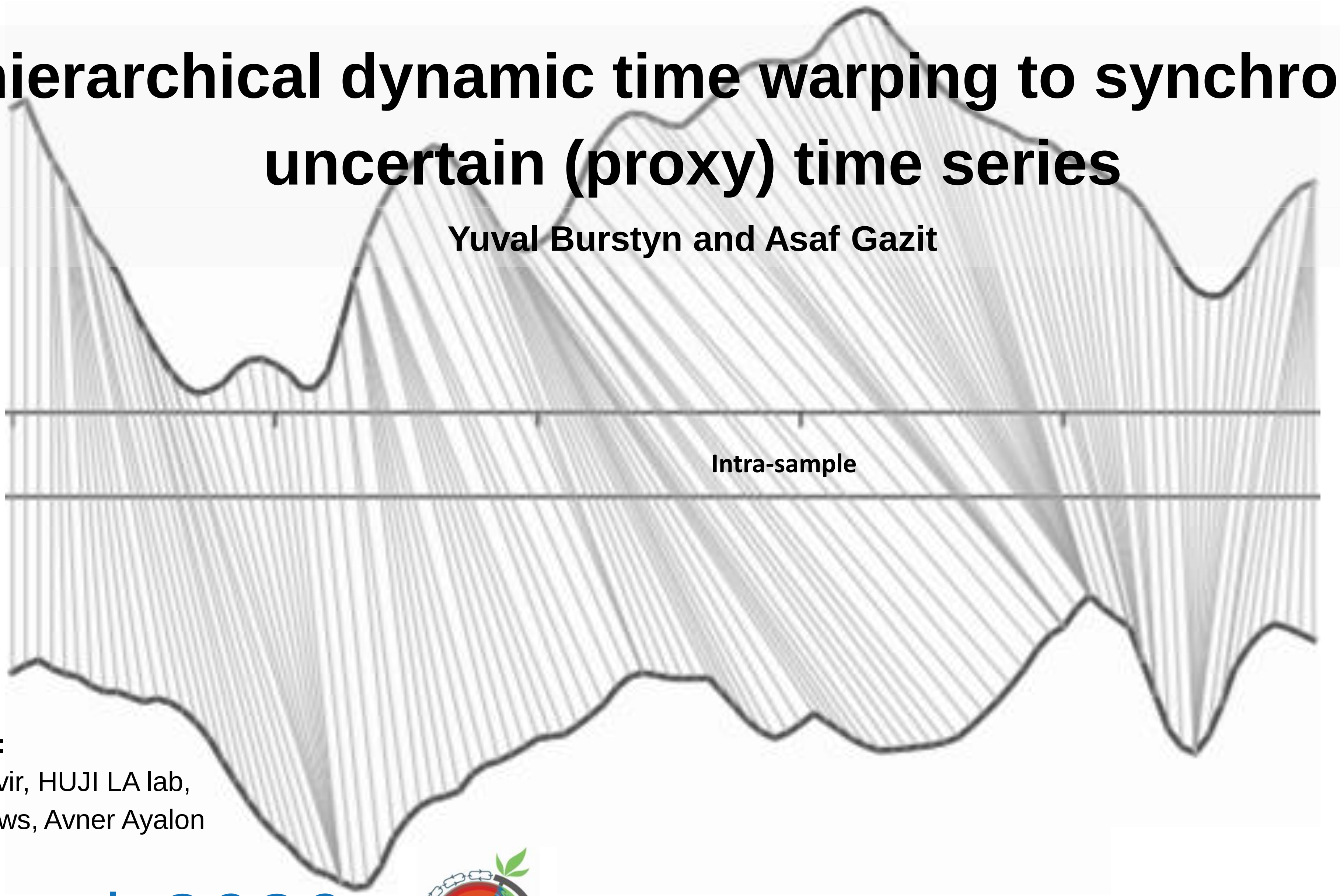

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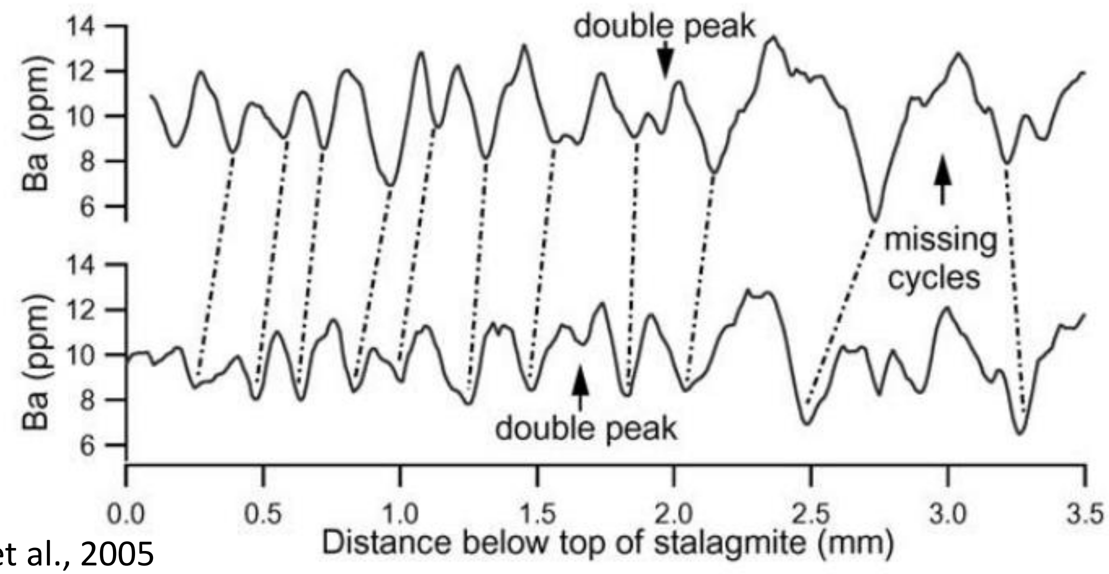
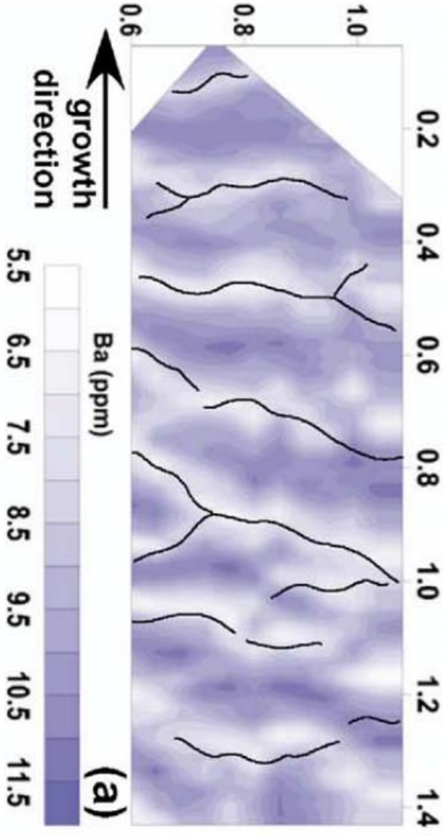
Motivation

High resolution measurements of annually layered geological samples (using Laser Ablation, Ion-microprobe, optical, fluorescence microscopy) generally display a heterogenous 2-dimensional structure (Treble et al., 2005).

The structure can be divided to **local** features which require correlation (matching peaks, stacking cycles) and **non-local** features, which for our purpose is simply 'noise' (missing peaks, double peaks in the example).



Treble et al., 2005



Treble et al., 2005

Motivation

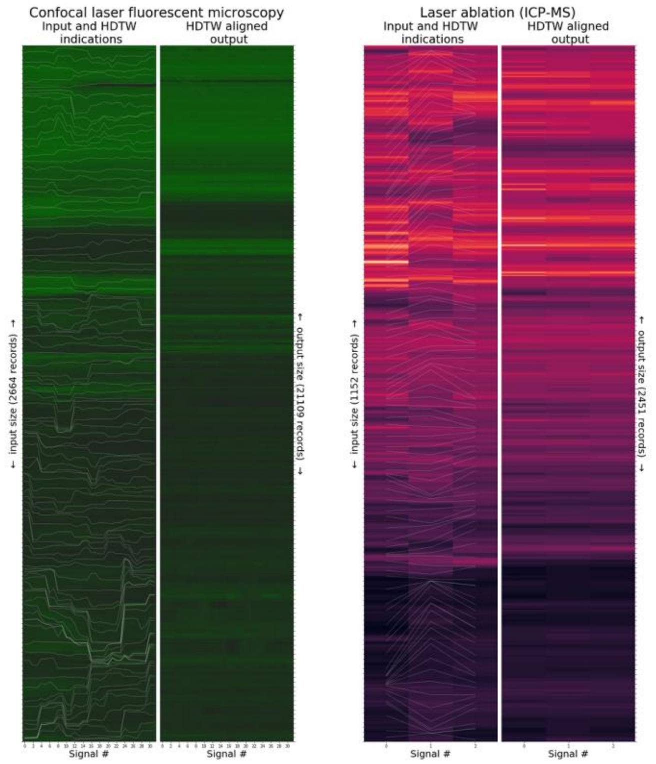
We set out to correlate multiple trace element traverses and con-focal laser microscope fluorescence images for sub-annual analysis of Soreq Cave samples.

Main issues with samples from water limited environments include:

- Noisy seasonal signals – system is sensitive to individual storms, there is no clear multi-annual pattern to predict rainfall amount and storm distribution
- Missing/unclear annual cycles (possible dry years)
- Highly site-specific hydrology, not unique to these environments but emphasized by the large variability in annual recharge

The nature of such environments makes is very difficult to correlate segments. Unclear annual cycles make it almost impossible to differentiate local/non-local features in the time-series.

This work

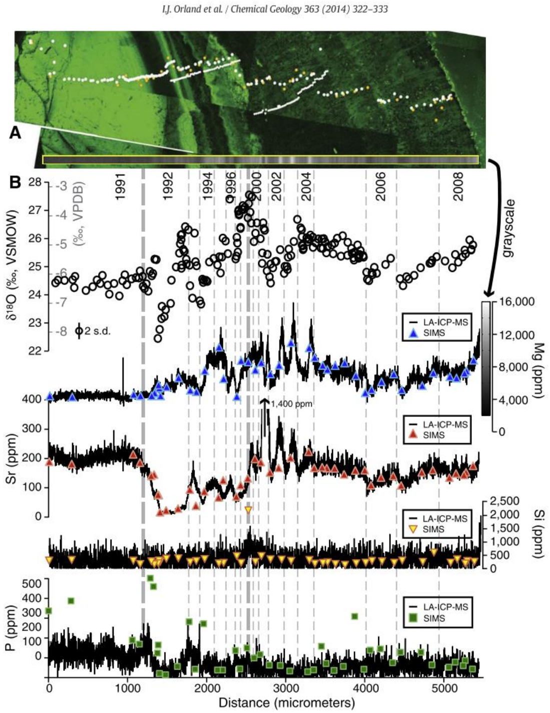


Time series correlation – We've all done it!

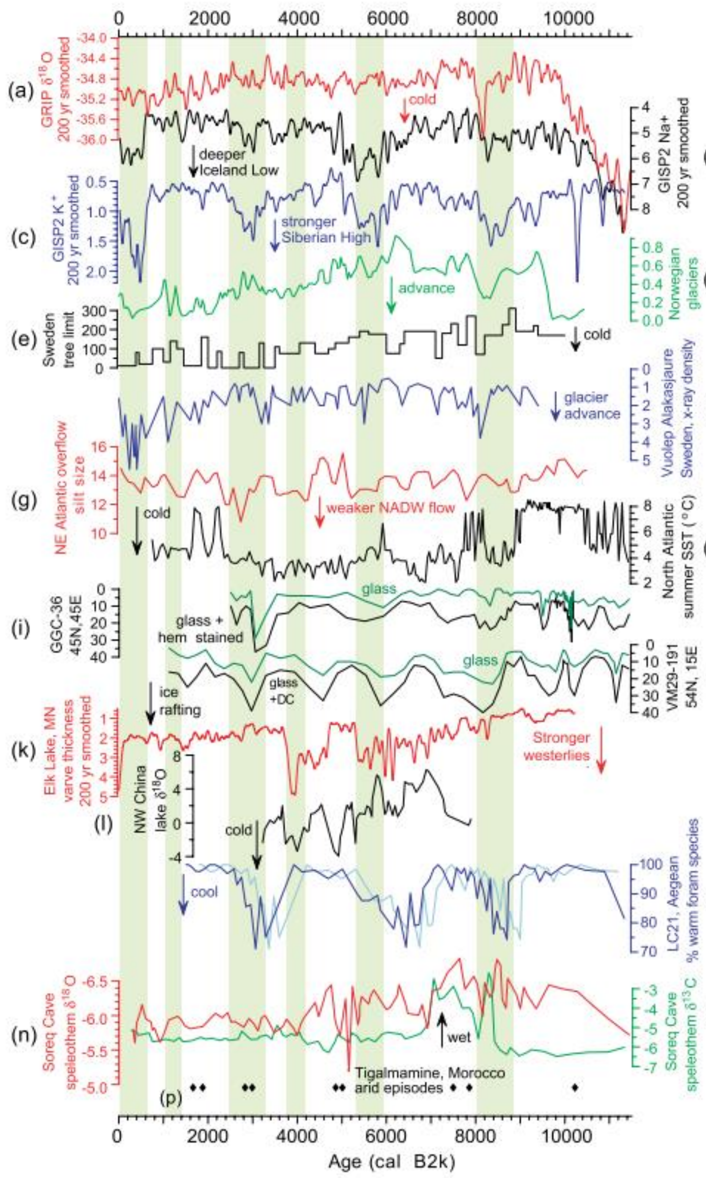
That's what we do in paleo-research…

- Matching similar or different record types from different regions for coherence studies
- "Pasting" an age model for un-dated records
- Different proxies measured in the same record
  (lead-lag times, kinetics…)
- This applies to lower temporal resolution records also!

Intra-sample



Inter-sample



Mayewski et al., 2004

Time series correlation

The basics – the two main tricks are:

- Identifying and characterizing remarkable features (tie points) – highly user biased, but a domain specific “privilege” (Uniformitarianism, ‘hard’ multi-proxy data)

- Mathematical (e.g. correlation)– more objective, still requires some domain specific optimization (parameterization, border conditions etc.)

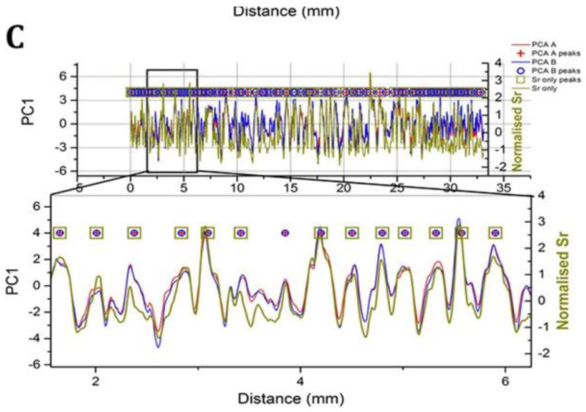


Figure 3. A comparison between peaks identified using three difference PCA experiments (PCA A, B and Sr only) for stalagmites YD-S2 (**A**), LAB-S1 (**B**), and MND-S1 (**C**). Only the PC1 time series output from one transect is shown for clarity. All methods locate similar, in phase peaks, although the output from Sr only tends to be smoother and have fewer peaks.

Nagra et al., 2017

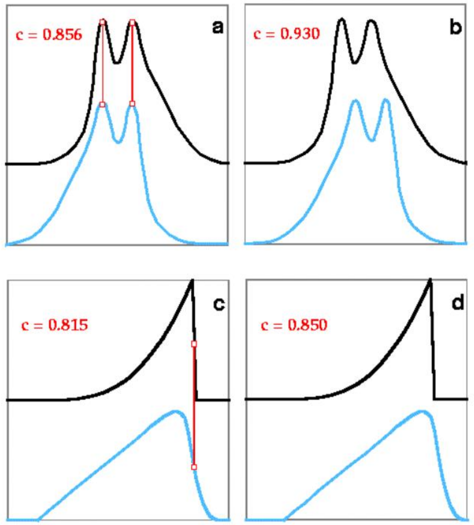
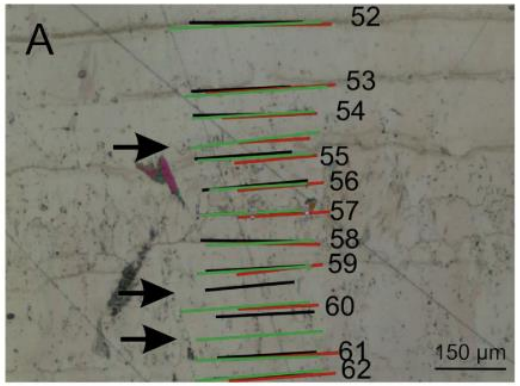


Fig. 1. The two different methods for stratigraphic correlation. Here, the lower (blue) curve is shifted so as to optimize a) visual alignment of maxima or b) the correlation coefficient c. Though the correlation coefficient is larger in b) (0.930 versus 0.856), it can be argued that a) is better, for the events are simultaneous. Similarly, though the correlation coefficient is larger in d) than in c), the transitions are simultaneous in c) while they are slightly offset in d).

Paillard, 1996



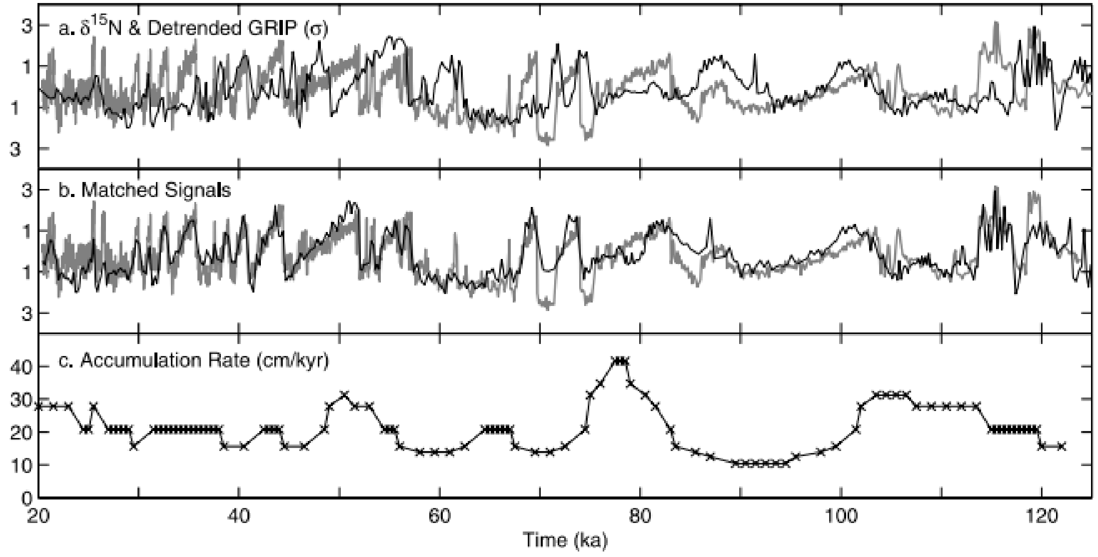
Riechelmann et al., 2019

Methodology

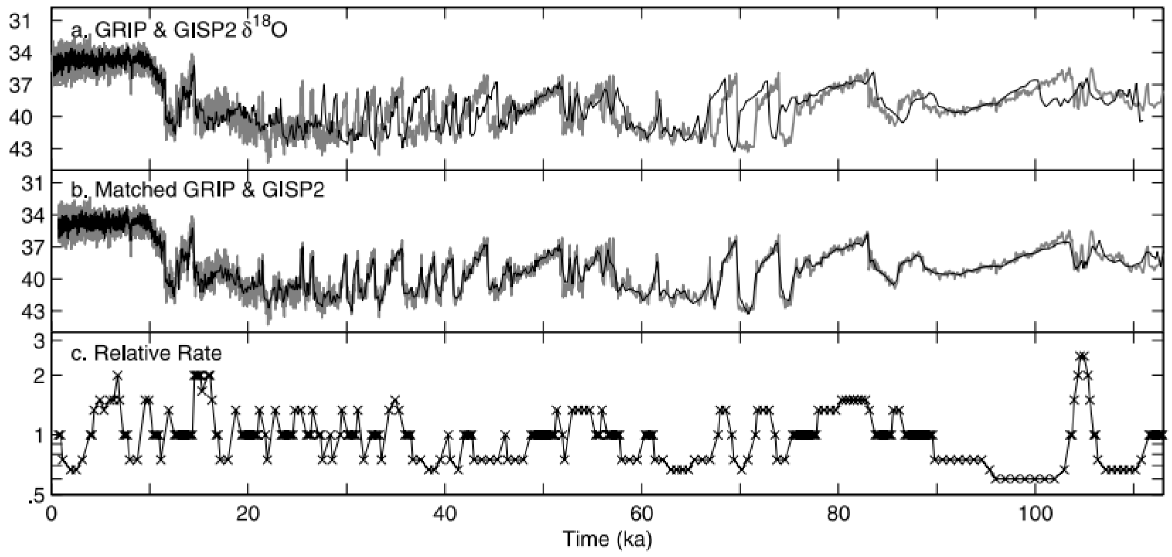
DTW – dynamic time warping has been previously used to correlate stratigraphic records, borehole data, ice-cores and ice cores proxies.

Generally, two time-series are 'synched' using this process.

$\delta^{15}N$ vs $\delta^{18}O$(GRIP)



GRIP vs GISP ($\delta^{18}O$)



Lisiecki, L. E., and P. A. (2002)

Methodology - HDTW

In order to sync more than 2 traverses and account for the locality effects (features) evident in speleothem lamina we borrowed a hierarchical approach to traverse aggregation from Vaughan and Gabrys (2016)

We implemented a slight modification to the aggregation approach in order to allow for differentiation between unique features after the aggregation processes.

The methodology could not be expended on here but will be available in Burstyn and Gazit (in prep).

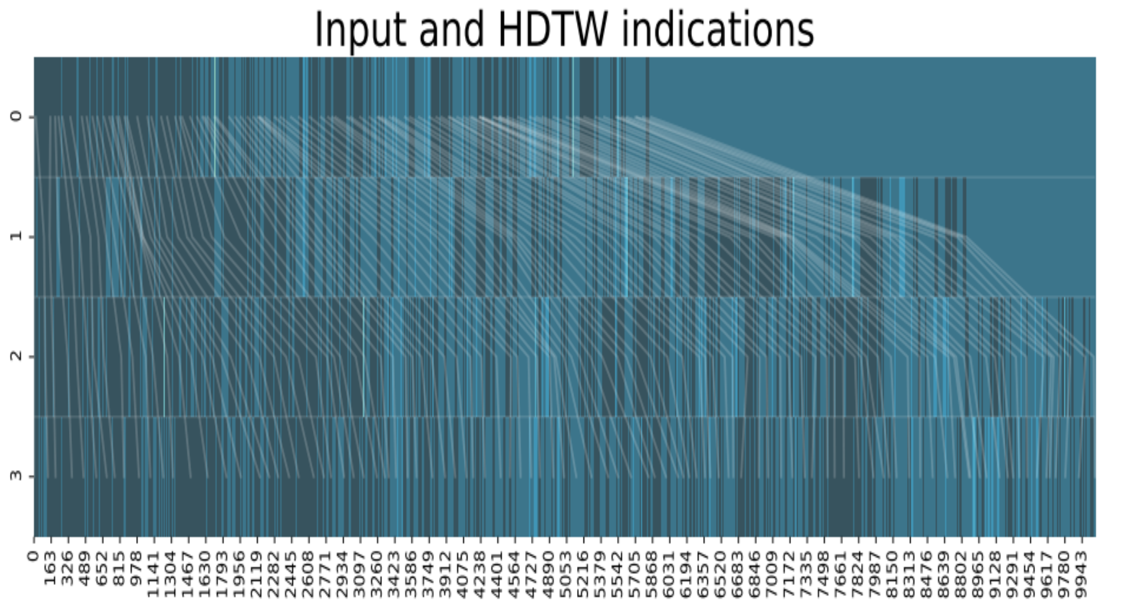
Results – Forced Resolution Experiment

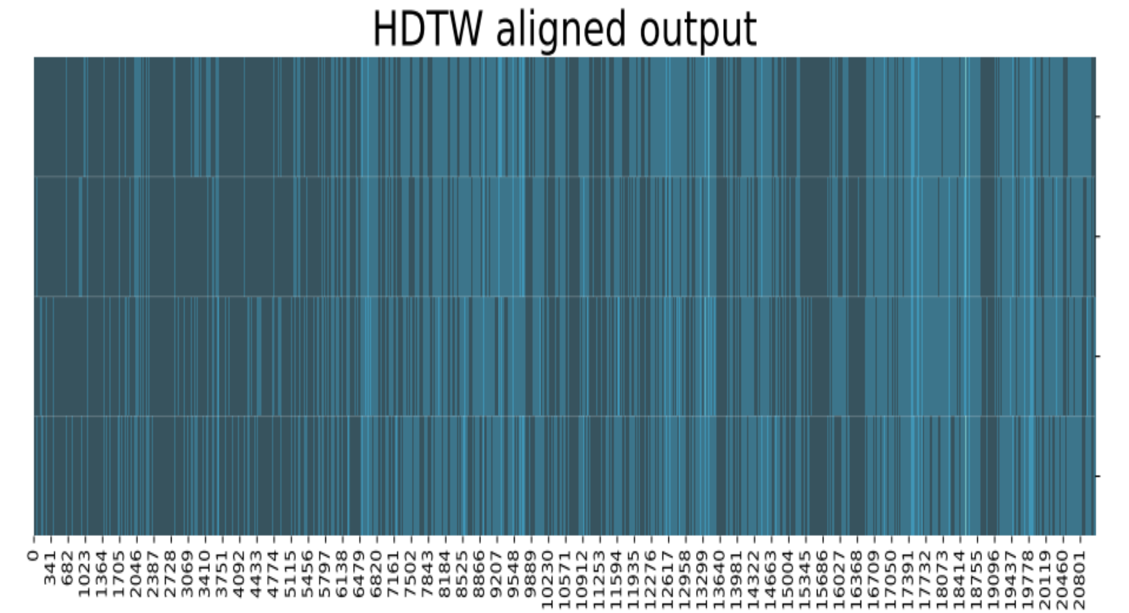
Three LA traverses measured in Soreq flowstone sample (~160 years of growth) with different scan speeds – 4/3/2 µm/s (each line spaced ~200 µm from the next)

The fourth line is the pre-clean line from the 4 µm/s traverse

PC1 calculated for each traverse using trace-elements - Mg, Sr, U, Ba

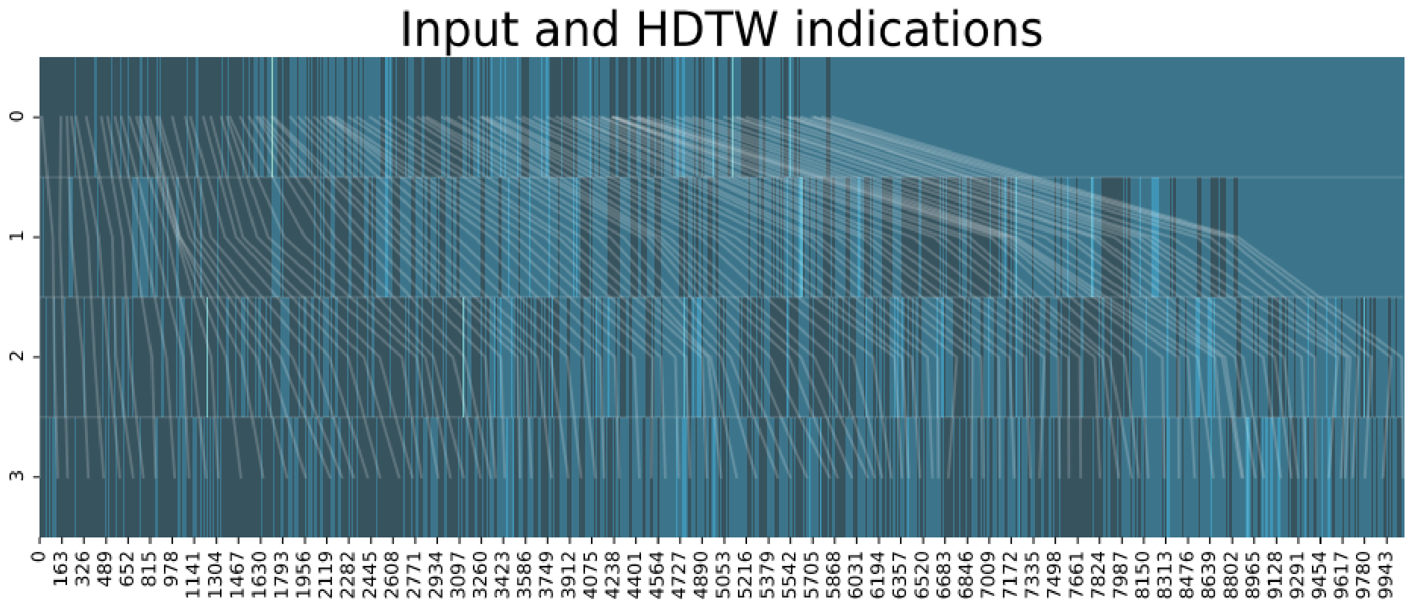
No additional alignments were made.

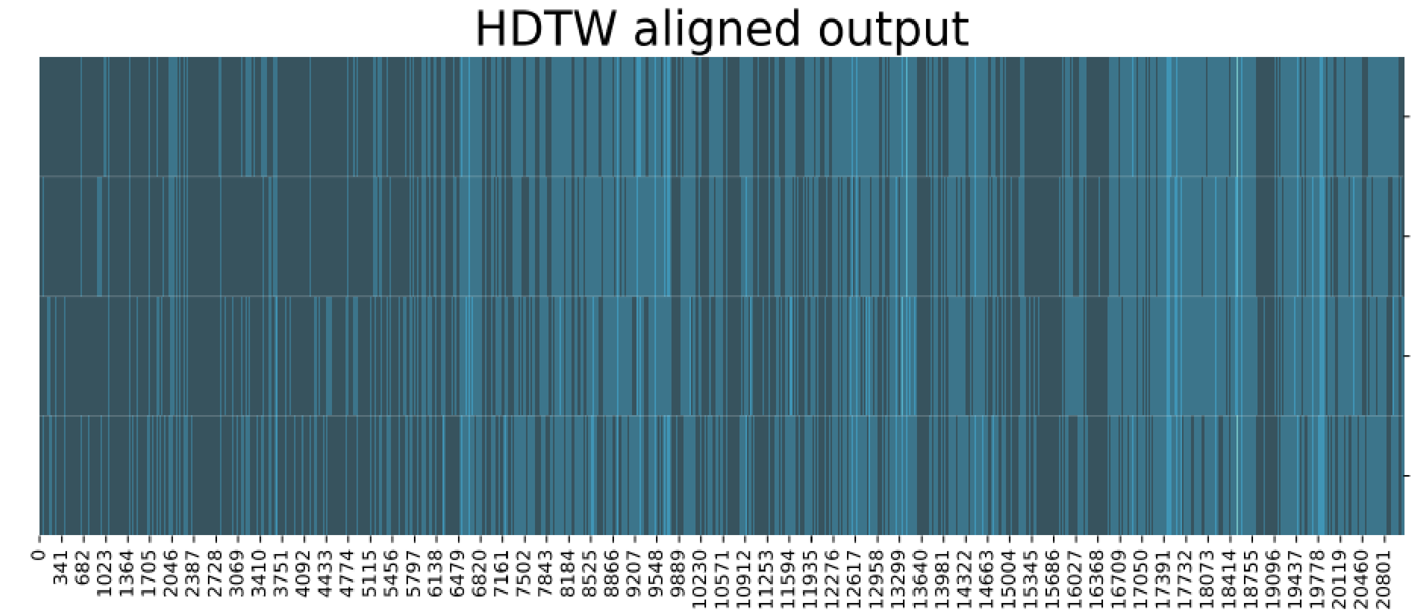




Results – Forced Resolution Experiment

- HDTW managed to spatially sync the depth profiles of all traverses (top)
- The local effects can be visually identified between all traverses (bottom)
- Aggregation can now be made manually or by any statistical method most appropriate for the research question
- Caution – keep in mind that for this case some of the local effects are caused by a forced difference in resolution

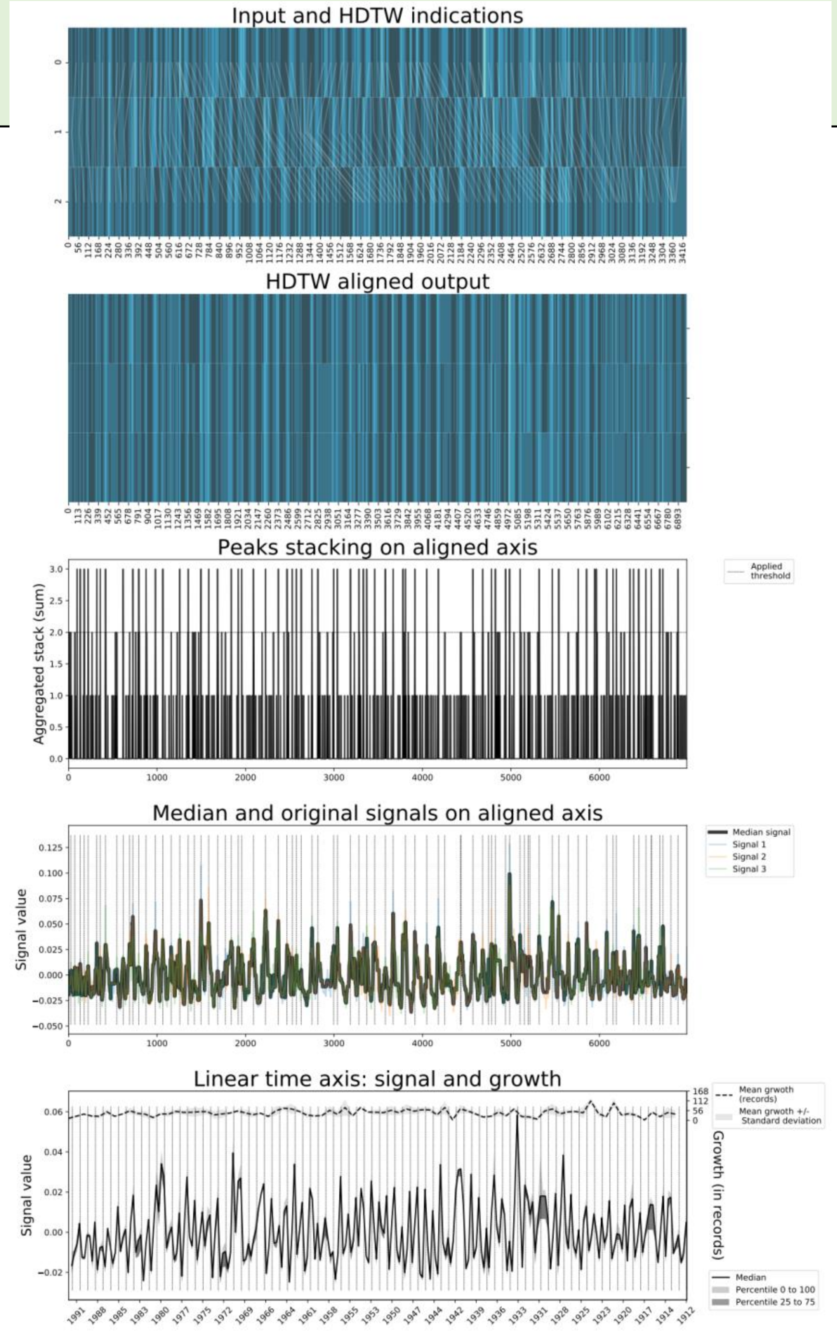




Results – a quick visit to MNDS1

- Exactly 80 years old stalagmite
- Original sample reported in Treble (2005)
- Revisited by Nagra et al. (2017)

- Here we apply HDTW on the raw data (no alignment, no resampling) (top 2 plots)
- Peaks are counted on each of the traverses after the new alignment vector is applied (middle)
- A majority vote (2 peaks of 3) is applied on the stacked peak-count matrix (middle)
- New 79 year age model is applied on PC1 (bottom)



Summary

- HDTW can successfully align time axes of similar proxies with a sample
- HDTW is shown to be compatible with existing peak-counting methodologies applied on laser-ablation trace element

- Preliminary work has also been done on fluorescence traverses in speleothmes

- HDTW is an important new tool for locating and identifying local and non-local phenomena in micron scale measurements
- HDTW can potentially be applied on multiple sample time-series (intra-sample, intra-site, multi-proxy)

Thank you

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