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# AstroComb(v.1.0): Non-linear, Multi-channel, Probabilistic Cyclostratigraphic Analysis

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**Abstract**

We present a new algorithm for constructing floating astronomical timescales with explicit uncertainty estimates from sedimentary sequences. The method integrates probabilistic spectral analysis with inverse geochronological modeling, applied to ultra-high-resolution, multiproxy datasets such as core scanning X-Ray Fluorescence (XRF) elemental records. Our framework does not smooth data or impose layer-to-layer dependency, allowing sedimentation rates to vary abruptly at short stratigraphic length scales. By detecting and statistically constraining Milankovitch cycles preserved in stratigraphic signals, the algorithm seeks a floating age-depth model that can be anchored to astronomical tie points, where available. The resulting timescales enable precise, uncertainty-bounded timing of biostratigraphic zones, geochemical events, and depositional cycles. This approach advances astrochronology by combining cycle detection with formal stratigraphic modelling, while preserving fine-scale depositional variability, offering a reproducible and statistically rigorous framework for dating deep-time records.

## 1 Introduction

Stratigraphic records from sedimentary basins are powerful archives of past environmental variability, recording both long-term geological trends and short-term changes in Earth's climate system. Identifying and decoding these Milankovitch cycles provides an essential tool for reconstructing past timescales — a methodology known as astrochronology.

Traditional astrochronologic approaches typically rely on matching repetitive spectral features in stratigraphic depth-series data to a target set of orbital frequencies, either through spectral filtering (Hays et al. (1976); Weedon (2003); Meyers et al. (2008, 2001)), or tuning

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against numerical astronomical solutions (`TimeOpt`: Meyers (2015), `TimeOptMCMC`: Meyers and Malinverno (2018); `AstroGeoFit`: Hoang et al. (2025)) or evolutionary spectral correlation (`eCOCO`: Li et al. (2018), `eTimeOpt`: Meyers (2019)).

Despite sedimentation is a punctuated process (Kemp and Sexton (2014)) over shorter timescales, these cyclostratigraphic methods often assume continuous, smoothly varying sedimentation rates or enforce strict stationarity in cycle expression over longer time scales; e.g. precession period. As a result, current age-depth models likely oversimplify the stratigraphic record, particularly in cases where sedimentation is punctuated by hiatuses, erosion, rapid deposition events, authigenic sediment, diagenetic chemical alteration or lithologic transitions. In reality, sediment accumulation in marine basins is controlled by a complex interplay of sediment supply, accommodation space, bottom water conditions, and diagenesis — all of which can introduce non-uniformity in the sedimentation rate at fine scales.

The continuity-assumption becomes problematic especially over shorter stratigraphic thickness representing shorter time scales. For example, the approximately 500 million year-old Cambrian Alum Shale Formation of Scandinavia has been slowly-deposited, and the shortest Milankovitch periods (19 kyrs) are covered by only 2–12 cm of stratigraphy (Sørensen et al. (2020); Zhao et al. (2022)). Here, we advocate that spectral matching to target periodicities must be done probabilistically, and astrochronological models must accommodate uncertainty in the depositional response to the forcing signal. Fortunately, these shales consists of finely laminated mud (grain size $\approx 2\,\mu m$) and high-resolution elemental datasets can be obtained at sub-millimeter resolution using Core Scanning X-Ray Fluorescence (CS-XRF) spectroscopy providing opportunities and challenges for refining astrochronological timescales including rigorous error propagation that requires more sophisticated analytical tools.

In response to these challenges, we present a probabilistic method to infer instantaneous sedimentation rates directly from multi-channel geochemical time series data (e.g. elemental abundances or ratios) by fitting Milankovitch cycles in a locally adaptive manner. Rather than assuming a constant or globally smoothed rate model, our approach treats sedimentation as a piecewise continuous process, allowing for abrupt or non-linear changes across the stratigraphic column. The core innovation is to invert a forward model of spectral signal generation — simulating how Milankovitch frequencies are expressed across stratigraphic depth under varying sedimentation rates — to obtain the probability distribution of the sedimentation rate at each depth, conditioned on observed multi-channel data and a target astronomical signal.

This framework is implemented in a newly developed algorithm, `AstroComb`, which builds upon and extends the concepts behind earlier astrochronological tools, such as `TimeOptMCMC` (Meyers and Malinverno (2018) and `eCOCO` Li et al. (2018)), while incorporating uncertainty quantification adapted to high-speed computation on large, multi-channel data sets. `AstroComb` applies a windowed, sliding inversion across the stratigraphy, yielding a depth-resolved series of sedimentation rates and posterior uncertainties. `AstroComb` allows discontinuities in sedimentation rate where supported by the data — for example, in the presence of condensed layers, stratigraphic breaks, or sharp facies transitions — which may be essential for reconstructing realistic depositional histories. Furthermore, `AstroComb` provides a measure of the information content of the data at all depths, indicating the uncertainty/reliability of the sedimentation rate estimates. Importantly, `AstroComb` calculates the full probability

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distribution of sedimentation rates based on multi-channel input data, which is essential input for sub-precession cycle refinement of age-depth relationships using geochemically-informed sedimentation rates as exercised with `ProBE4T` (Fernandes et al. (2026)).

Here, we apply `AstroComb` to the Fågeltofta-2 core through the later Cambrian Alum Shale Formation. The core comprises a thick, continuous succession of laminated, organic-rich, black mudrocks with high pyrite content and strong enrichments in redox sensitive elements (Dahl et al. (2019)). The Alum shale was deposited extremely slowly ($\sim$ 1–6 mm/ky, Nielsen et al. (2018)) on the Baltoscandian passive margin. Using high-resolution XRF data from over 90,000 measurements across 18 m of stratigraphy at 0.2 mm intervals, previous cyclostratigraphic analyses have confirmed such slow sedimentation rates (Sørensen et al. (2020); Zhao et al. (2022)), which we here show are also consistent with `AstroComb` results presented here. Further, the `AstroComb` results reveal abrupt variation in sedimentation rates, potentially identifying intervals of slow background accumulation interspersed with short-duration accumulation events. Potentially, chemical oscillations allow for improved dating of stratigraphic intervals, duration of event, and lithologic transitions within the core — with implications for rates of paleoenvironmental change and refinement of the geological time-scale.

`AstroComb` is designed to leverage high-resolution multi-element core data for astrochronology in a quantitative probabilistic manner. The algorithm aligns a range of astronomical periods with recurring signals in the stratigraphy, and extends the capabilities of previous toolboxes by incorporating multichannel geochemical data and uncertainty quantification through inverse modeling at each analysis step. Each channel represent elemental abundance (in peak area or concentrations), best fit mineral abundance (in weight percent) or ratios between XRF peaks areas (e.g. Al/RhCoh, normalized peak area signals).

The overarching goal is to detect Milankovitch signals and construct floating astronomical timescales, while explicitly accounting for uncertainties. The approach is built on four main components, which constitute the workflow of `AstroComb`:

- A probabilistic inversion framework to recover, not only the best-fit sedimentation rate at any given stratigraphic point in an elemental time series, but also uncertainties and a measure of information content.
- A generalizable methodology that can be applied to any cyclic geochemical or paleoenvironmental signal,
- A demonstration of how variable sedimentation rates manifest in the spectral expression of Milankovitch cycles
- An application to a ~500 Ma Cambrian core verifies the preservation of astronomical signals and evaluate sedimentation rates and their probability distributions (uncertainty) from the information content.

By integrating multi-element signal processing, spectral modeling, and inversion theory, our approach extends the methodological framework of astrochronology into previously unexplored domains. It enables the simultaneous analysis of multiple signals and accommodates probabilistic age–depth models that can be non-smooth, and discontinuous—reflecting the inherent complexity of real-world sedimentary systems.

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# 2 Theory and Methods

## 2.1 Overview

The goal of this study is to reconstruct a *locally varying sedimentation rate profile* from multiple geochemical depth series, under the assumption that certain stratigraphic signals (e.g., elemental variability) reflect astronomical forcing. We achieve this by inverting a forward model of signal distortion under varying sedimentation, using a formulation rooted in probabilistic inversion.

This method builds upon the principles of astrochronology—particularly the spectral identification of Milankovitch-band periodicities in sedimentary records—but extends them to allow for *instantaneous, non-stationary sedimentation rates*. `AstroComb` performs a sliding-window probabilistic fit of observed geochemical spectra to a predefined target astronomical spectrum, yielding a sedimentation rate that optimally "stretches" or "compresses" the time axis at each position to recover astronomical frequencies. The fit is performed in frequency domain, which allows multi-channel (e.g. multiple elements) that will not be obscured if displaced by a phase-lag.

We begin by formalizing the relationship between sedimentation rate and spectral distortion, then describe the inversion procedure and implementation of `AstroComb`. Finally – as an example – we discuss its application to the Alum Shale data and compare to previous results (Sørensen et al. (2020)).

## 2.2 Forward Model of Spectral Distortion

Let $d(z)$ be a geochemical depth series (e.g., Al concentrations), where $z$ is stratigraphic depth. If sediment accumulated at a locally constant rate $r(z) = \frac{dz}{dt}$, then in the time domain, the corresponding series is $d(t)$. However, in practice we only observe the signal in the depth domain.

Let $k$ be a frequency in the depth domain (wave number in cycles per mm) and $f$ its time-domain counterpart (cycles per kyr). The transformation between the two is:

$$k = \frac{f}{r} \tag{1}$$

Thus, a fixed astronomical frequency $f$ will appear in the stratigraphic record as a peak at $k$, depending on the local sedimentation rate. Variations in $r(z)$ distort the signal, shifting, splitting, or smearing spectral peaks. Our objective is to recover $r(z)$ such that the observed power spectrum matches that predicted from astronomical forcing (see Figure 1).

## 2.3 Target Astronomical Spectrum

Because no closed form orbital solution exists beyond about 50 Ma (Laskar et al. (2011, 2004)), we adopt theoretical periods constructed from studies of deep-time orbital mechanics (Farhat et al. (2022); Waltham (2015)). For the later Cambrian $\sim$ 497 Ma, the target includes:

- Long eccentricity: 405 kyr

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- Short eccentricity: 99 ky
- Obliquity: 32.4 kyr
- Precession: 19.5 kyr

We encode these as 4 sinusoids with known periods. We do not define their expected spectral power ratios based on orbital modulation transfer, since the Earth's climate and environmental response to the Milankovitch forcing modifies these ratios in an unknown way.

## 2.4 Computing the Likelihood of a Sedimentation Rate

For a given depth interval (window) centered at $z_0$, we obtain power spectra $\mathbf{D}_{obs}$ of multiple, observed signals ($\mathbf{D}_{obs}$ is a matrix of spectra with a spectrum of one channel in each column). For each trial sedimentation rate $r$, we convert the target time-domain frequencies $f$ to expected depth-domain frequencies (wave numbers) $k = f/r$ and compute *synthetic spectra*

$$\mathbf{G}(r, \mathbf{a}) = \sum_{m=1}^{M} a_m \mathbf{w}\left(\frac{f_m}{r}\right) \tag{2}$$

where $\mathbf{G}(r, \mathbf{a})$ is a matrix of computed data spectra (a copy of the spectrum in each column), $f_m$ is the $m$'th Milankovitch frequency (assumed known), and $\mathbf{w}(\frac{f_m}{r})$ is the shape of a spectral line, centered at $\frac{f_m}{r}$. The shape $\mathbf{w}$ can be computed as the discrete Fourier transform of a discretized delta function with the same length as the window.

From the synthetic spectra $\mathbf{G}(r, \mathbf{a})$ and the matrix of observation spectra $\mathbf{D}_{obs}$ we can now calculate the likelihood as the probability of data, given the sedimentation rate $r$ and the spectral peak amplitudes $\mathbf{a}$:

$$L(r, \mathbf{a}) = P\left(\mathbf{D}_{obs} | (r, \mathbf{a})\right). \tag{3}$$

Our computation of the likelihood is done as follows:

1. As prior information about the data uncertainties, we mimic the 'manual' process of spectral line identification by defining a probability that there is a potential Milankovic peak at a given wavenumber $k$ in the spectrum. Between user-defined lower and upper bounds $a$ (the lower limit for being identified as a "peak") and $b$ (the value above which we are sure that we have found a potential peak), the probability increases from a user defined, small positive number $p_a$ at the lower limit to $p_b = 1 - p_a$ at the upper limit. Typical values are $a = \langle F \rangle + \sigma_F$ and $b = \langle F \rangle + 3\sigma_F$, where $\langle F \rangle$ is a local mean of the spectrum around the considered wavenumber $k$, and $\sigma_F$ is the local standard deviation of the spectrum. A typical value of the threshold probability $p_a$ is 0.01. The probability is chosen as a smooth, monotonically increasing sigmoid function $p(x)$ satisfying

$$p(a) = p_a, \qquad p_b(b) = 1 - p_a, \tag{4}$$

with the constraints

$$b > a, \qquad 0 < p_a < 0.5. \tag{5}$$

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We adopt the logistic sigmoid form

$$p(x) = \frac{1}{1 + \exp\big(-k(x - x_0)\big)} \tag{6}$$

with

$$x_0 = \frac{a + b}{2}. \tag{7}$$

2. For each layer (which is $\Delta z = 0.2$ mm thick in the Fågeltofta-2 core example), we evaluate the likelihood in a grid of sedimentation rates $r$ with typical grid spacing $\Delta r = 0.02$ mm/ky. Each possible choice corresponds to given locations of the Milankovic cycles in the spectrum, and for each location at $k_i$ with spectral amplitude $a_i$, we evaluate the probability $p(k_i, a_i)$. Finally, the likelihood of the considered sedimentation rate $\mathbf{r}$ is computed as the product

$$L(\mathbf{r}) = \prod_{i=1}^{I_M} p(k_i, a_i), \tag{8}$$

where $I_M$ is the number of Milankovic cycles considered. When several records of, e.g., basic elements concentrations are used in the calculation, the combined likelihood for all records is computed as the product of the individual likelihoods.

## 2.5 The Posterior Probabilities of Sedimentation Rates

If prior information about $(r, \mathbf{a})$ is encoded by a probability density $\rho(r, \mathbf{a})$ we can - in a Bayesian formulation - express the complete, probabilistic solution as a *posterior* probability density

$$p(r, \mathbf{a}) = C \cdot L(r, \mathbf{a})\, \rho(r, \mathbf{a}). \tag{9}$$

where $C$ is a proportionality constant. In the example below, where data from Fågeltofta-2 is analyzed, the prior assigns constant values to all sedimentation rates within user-defined boundaries of 1.0 mm/ky $< r <$ 10.0 mm/ky.

From the marginal sedimentation rate distribution

$$p(r) = \int p(r, \mathbf{a})\ da \tag{10}$$

at each stratigraphic position, we can now compute a floating geological time, $t$, and its uncertainties as a function of depth, $z$. If the absolute time, $t_0$, is known at a given depth $z_0$, and the sedimentation rate in layer $n$ is $r_n$, the time at $z_0 + N\Delta z$ is

$$t(z_0 + N\Delta z) = t_0 + \Delta z \sum_{n=1}^{N} \frac{1}{r_n}\ . \tag{11}$$

From the posterior probability densities of the sedimentation rates $r_n$, and hence $\Delta z / r_n$, we can now calculate the uncertainties of the times. From the variances of the distributions of $\Delta z / r_n$ for all layers $n$, we can obtain the variance of $t(z_0 + N\Delta z)$ by a simple summation:

$$Var(t(z_0 + N\Delta z)) = \sum_{n=1}^{N} Var\left(\frac{\Delta z}{r_n}\right)\ . \tag{12}$$

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Working with variances, instead of the full probability distributions for the inverse sedimentation rates, saves computer storage and time when processing large data sets. Furthermore, due to the central limit theorem, the distribution of the sum of random time increments will converge to a Gaussian distribution when the number of layers increases, making the variance an adequate description of the uncertainty.

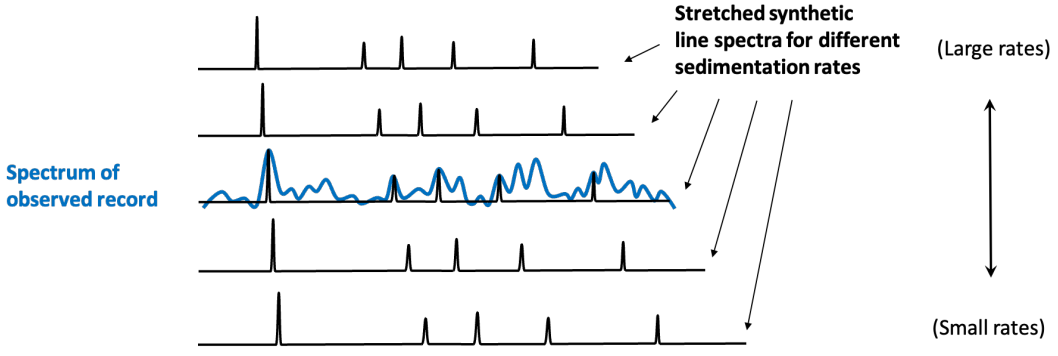


Figure 1: Schematic overview of the likelihood calculation for fitting Milankovitch cycles in elemental profiles. The spectrum of the observed geochemical signal (e.g., Al content) is compared against a theoretical line spectrum, composed of known astronomical frequencies, and stretched according to the sedimentation rate. The likelihood of each assumed sedimentation rate is computed from the probabilities that amplitudes at line locations are significant peaks. This process yields probability distributions of sedimentation rates as a function of depth, and allows an age–depth model consistent with Milankovitch forcing to be computed.

## 2.6 The AstroComb Algorithm

AstroComb implements the above approach through the following steps:

1. **Preprocessing**: Detrend and normalise the depth series, optionally re-sample or smooth.
2. **Sliding Window**: For each depth window (e.g., 2–4 m interval), compute the local power spectrum.
3. **Spectral Inversion**: Fit the observed spectrum to the target astronomical model and estimate the posterior probability distribution of the sedimentation rate.
4. **Output**: Store the sedimentation rate $r(z)$ and its posterior probability distribution for the window.

Every step in our calculation is accompanied by an uncertainty estimate. For each position of the sliding data window, the total noise on the signal (measurement noise on the data from the XRF scanner, and "geological noise" defined as signal that is not measurement noise or Milankovic signal) is automatically estimated by the algorithm (see the likelihood calculation above).

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# 3 Results

To illustrate the application of the multichannel, probabilistic Milankovitch period detector, `AstroComb`, we analysed high-resolution XRF data from a ∼20-meter long interval of the Fågeltofta-2 drill core through the Alum Shale Formation in southern Sweden. Given that the XRF measurements were collected with a sampling resolution of 0.0002 meters and captured the concentrations of at least 22 elements, incl. $Al_2O_3$, $SiO_2$, S, $K_2O$, CaO, $TiO_2$, V, MnO, $Fe_2O_3$, Ni, Cu, Zn, Ge, As, Rb, Sr, Y, Zr, Mo, Ba, Hf, and U, this extensive elemental dataset formed the basis for the spectral analysis. Figure 2 shows a subset (the top 40 mm) of the data from ∼19 m of core, yielding ∼90,000 measurements.

We simultaneously searched for 4 canonical Milankovitch periods applicable to the late Cambrian area at 494 Ma based on Waltham (2015), grouped as follows:

- **Precession** (in ky): 19.5
- **Obliquity** (in ky): 32.4
- **Eccentricity** (in ky): 405, 99

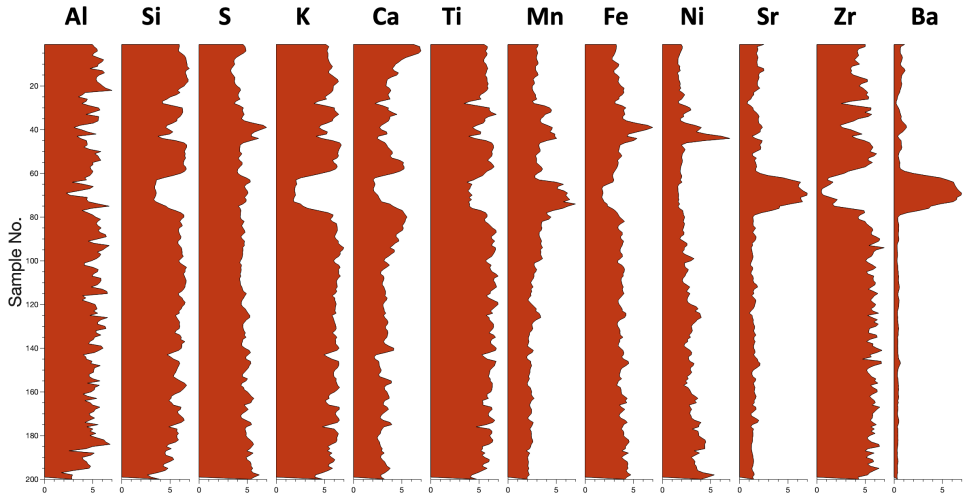


Figure 2: A selection of concentration profiles of the Fågeltofta Alum Shale core, measured via XRF core scanning at 0.2 mm resolution. The dataset spans approximately 19 meters of stratigraphy and comprises ∼ 90,000 individual measurements. Several profiles show well-developed quasi-periodic oscillations, which serve as the primary proxy for detecting orbitally forced sedimentary cycles in the subsequent astrochronological analysis.

We selected Al as the primary input because of its robustness as a proxy for detrital input and its strong spectral structure in preliminary analysis (Sørensen et al. (2020); Zhao et al. (2022)). The depth series was detrended with a linear function. AstroComb was run using a window length of 3.3 m, stepped every 0.2 mm.

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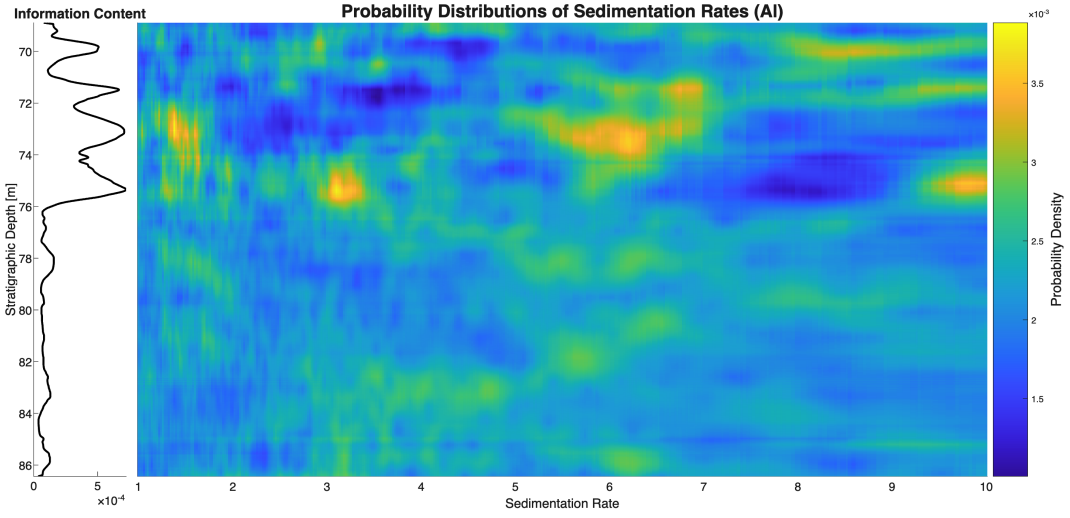


Figure 3: Sedimentation rate probability distribution for the Fågeltofta-2 core. The information content about Milankovic cycles contained in the XRF data is shown (green curve) as quantified by the Kullback-Leibler measure.

The bulk sedimentation rate was *a priori* found within a range of realistic sedimentation rates from 1.0 to 10.0 mm/ky. As output, we show the a posteriori probability distribution of the sedimentation rates versus stratigraphic depth (figure 3), and selected spectral fits for each 2 m in the core (figure 4). Also, we introduce the Kullback-Leibler information measure at each depth $z$ showing how much Milankovic information is present in the data as a function of depth. This is obtained from:

$$\mathcal{I} = \int_R P_z(r) \ln\left(\frac{P_z(r)}{U(r)}\right) dr \tag{13}$$

where $P_z(r)$ is the calculated probability distribution of $r$ at depth $z$, $R$ is the range of sedimentation rates, and $U(r)$ is a uniform (non-informative) distribution. Figure 3 shows that Milankovic cycles information is present in the core, and that the sedimentation rates vary also within information-dense intervals.

From the estimated sedimentation rates, a Milankovitch timescale and its uncertainty was derived (Figure 5), using the age of 496.595 Ma, consistent with Sørensen et al. (2020), at a stratigraphic depth of 86.005 m as a reference. This timescale enables the estimation of relative geological ages across the core, and allows depth-indexed chemical data to be analysed in the temporal domain, significantly enhancing our ability to interpret environmental transitions over geological timescales.

To demonstrate AstroComb's capability of multi-channel analysis of several basic elements records to obtain improved resolution of the Milankovic cycles, we simultaneously ran the algorithm on the S, Al and Mn records. The result, which is given in figure 6, shows that

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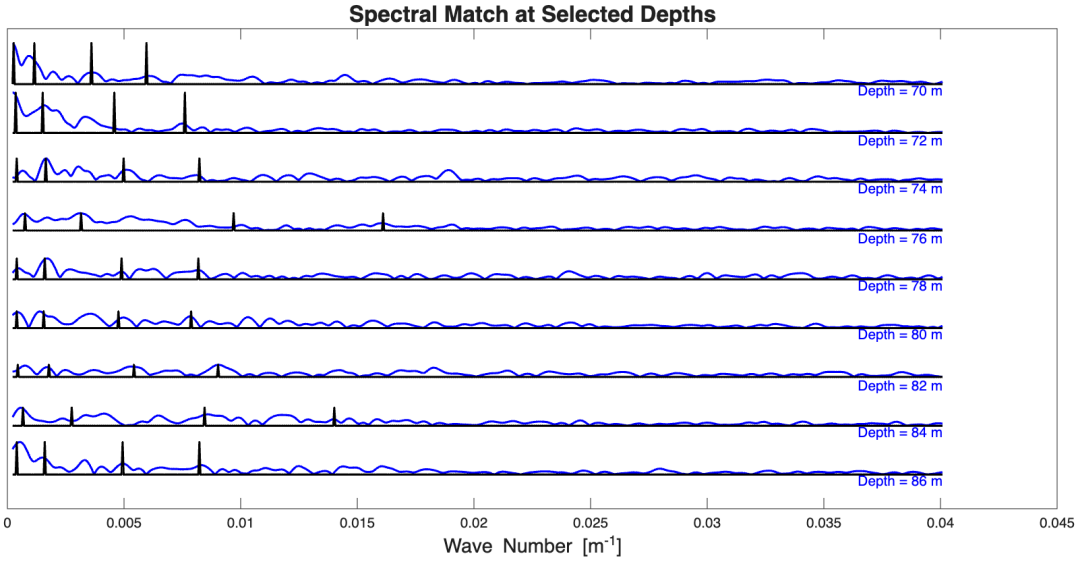


Figure 4: Spectral match at selected stratigraphic depths in the Fågeltofta-2 core. For every 2 m, the spectral lines corresponding to the best Milankovic match are plotted together with spectra of data observed in windows centered at the depth.

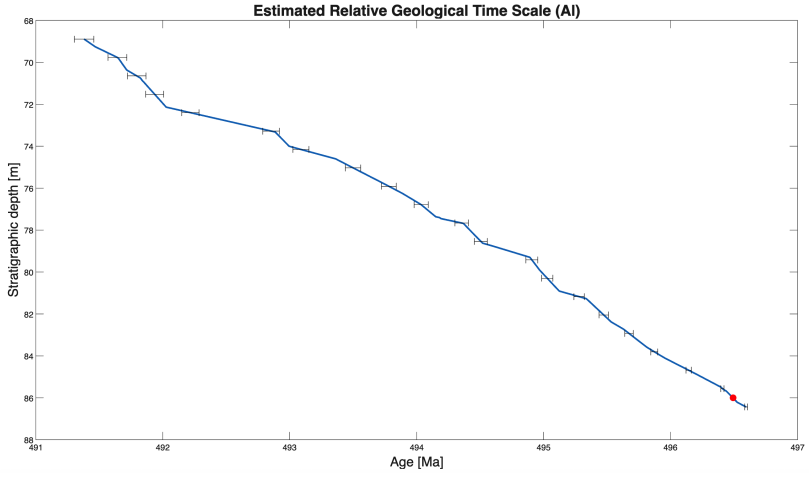


Figure 5: Estimated geological timescale and its uncertainty (standard deviations), based on probabilistic estimation of instantaneous sedimentation rates from the Al record in the Fågeltofta-2 core. The timescale is anchored at 86.005 m, corresponding to 496,595 ky (Sørensen et al. (2020)). This is marked on the graph.

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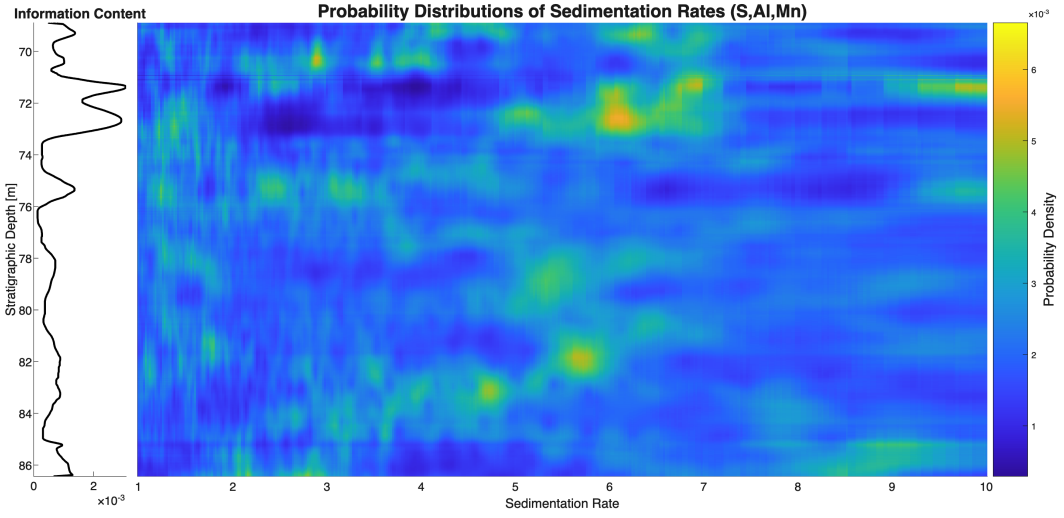


Figure 6: Probabilistic analysis of sedimentation rates in the Fågeltofta-2 core, based on simultaneous processing of S, Al, and Mn. Comparing to figure 3 it is clear that this multi-channel analysis has provided a higher resolution with more distinct peaks in the probability densities.

the resolution has improved, compared to the single-channel result in figure 3. High probabilies have increased, and low probabilities have decreased. The overall picture is generally the same, but several secondary peaks, indicating possible alternative solutions, are reduced or have disappeared. The corresponding relative time scale is shown in figure 7. The overall picture is similar to figure 5, but there is more detail, and the total time span is somewhat increased.

The results support the use of high-resolution XRF data coupled with probabilistic spectral inversion as a powerful tool for extracting geochronological information from ancient sedimentary archives.

# 4 Discussion

Extensive tests were carried out to study the accuracy and stability of the algorithm. A severe test with artificial data with 200% noise, showing significant sedimentation rate discontinuities, was carried out. The synthetic sedimentation rate model, seen in figure 8, is characterized by layers with realistic sedimentation rates, and separated by significant discontinuities. From this model, the synthetic data were calculated (see figure 10). The 200% noise was red noise with a $1/f^2$ power spectral density, simulating a background spectrum of geological signal that cannot be explained as astronomical forcing. Figure 10 shows the posterior probability densities of sedimentation rates for all depths, computed by `AstroComb` using the synthetic data. The true result (the synthetic model) is overlain to show the fidelity

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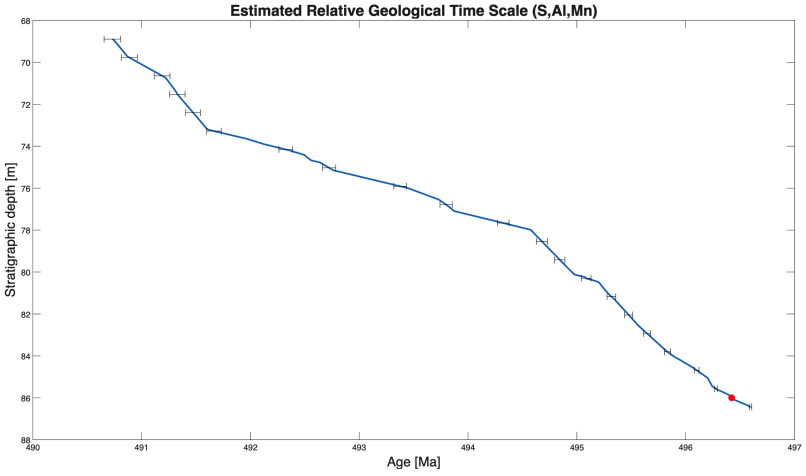


Figure 7: Relative timescale computed from the multi-channel data with records of S, Al and Mn.

of the reconstruction. Considering the very high noise level, the reconstruction of the true sedimentation rates is excellent. However, the test also illustrates how artifacts (possible, incorrect sedimentation rates) are introduced by the noise, the variability of the true model, and the non-linearity of the problem. Some of these spurious features could be interpreted as true sedimentation rates. This is a challenge, but, on the other hand, all true sedimentation rates are found by the algorithm, and the large discontinuities beteen layers of constant rates are quite well reconstructed, despite the high noise level.

This study demonstrates that the `AstroComb` method extends the spectral misfit minimization strategy in a probabilistic framework, handling uncertainty propagation and parameter tuning with statistical rigor.

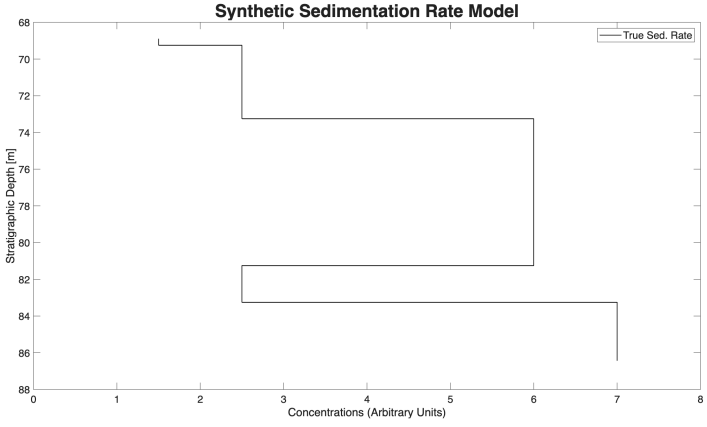


Figure 8: Synthetic sedimentation rate model used in the testing of the algorithm. The model has layers with realistic sedimentation rates, and the layers are separated by significant discontinuities.

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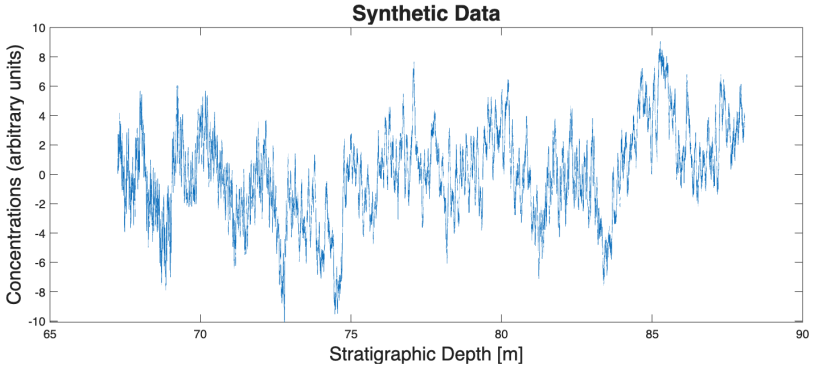


Figure 9: Synthetic data with 200% red noise used to test of the algorithm.

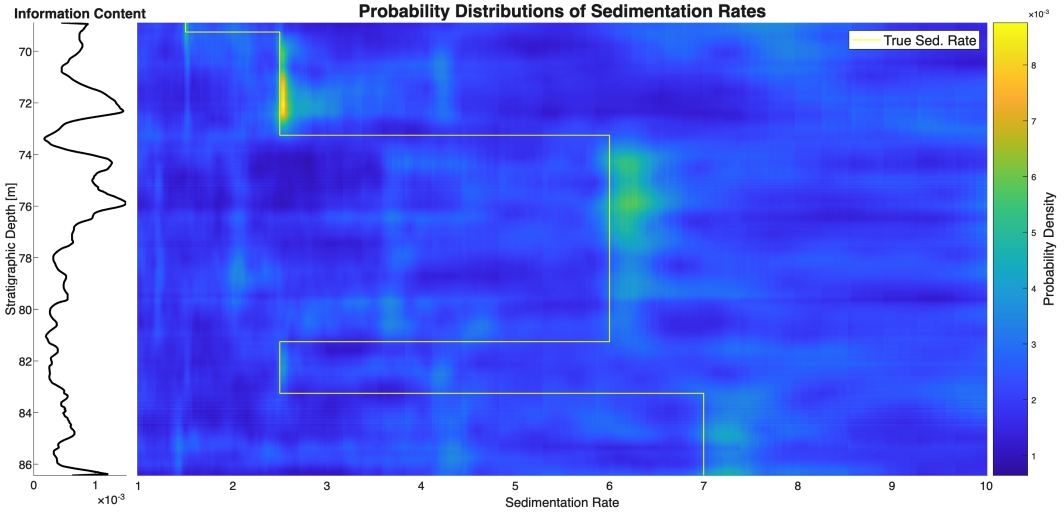


Figure 10: Probability densities of sedimentation rates, computed from the synthetic data with 200% red noise. The synthetic model is overlain to show the fidelity of the reconstruction. In view the very high noise level, the reconstruction of the true sedimentation rates is very good. However, the test also shows how artifacts are introduced by the noise, the variability of the true model, and the non-linearity of the problem.

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## 4.1 Limitations

Nonetheless, some limitations must be acknowledged. The assumed orbital target periods are model-based and cannot be empirically verified for the Cambrian. While the tuning strategy relies on the 405 kyr eccentricity cycle as a stable chronometer, potential shifts in Earth's rotational parameters due to e.g. tidal dissipation effects could introduce biases.

Our algorithm is based on the assumption that prior information about the spectral peak identification process can be provided, and that it adequately describes the way Milankovic periods are identified by human analysts. According to our synthetic tests, and the good consistency of our Fågeltofta results with results from previous studies, it works well, but it is advisable to carefully check results obtained in new cases, particularly to what extent they are compatible with other, independent knowledge about the geological scenario considered.

There are also some fundamental assumptions behind Milankovic analysis that apply to any method. Milankovic cycles are (quasi-)periodic, but not sinusoidal. This means that a hypothetical, noise-free Milankovic spectrum will, in general, contain spectral components outside the main Milankovic frequencies. These components are generally disregarded in Milankovic analysis programs, including `AstroComb`. More seriously, the Earth's sedimentary system is highly nonlinear and is therefore expected to produce additional periods that are sums and differences of the main Milankovic cycles. The amplitudes of such periods could be significant, but they are ignored by our algorithm. An additional problem with the non-linearity of the sedimentary system is that, even if we know the amplitudes of the input Milankovic signal, the output amplitudes observed in boreholes are entirely unknown. This was the background for the the way that we implemented our spectral fit algorithm.

Last, but not least, it is important to remember that Milankovic cycle identification is a *difficult* problem. The signal-to-noise ratio is generally very low, and the problem is often similar to finding a needle in a hay stack. Such problems are prone to detrimental human biases, but `AstroComb` is designed with the aim of quantifying the analysis, and casting the problem as a probabilistic inference problem, so as to avoid such biases. It generally provides several plausible solutions for the sedimentation rates at given depths, allowing the user to choose, based on geological/stratigraphic knowledge.

## 4.2 Broader Implications

The `AstroComb` algorithm has discovered abrupt changes in sedimentation rate in the Fågeltofta core, making predictions to guide sedimentologist in reconstructing pulses of sedimentation from geological archives. As sedimentation rate is a fundamental parameter characterizing a sedimentary environment and a factor that serves as a first order control on organic matter preservation, `AstroComb` may help engaging sedimentologists with a new relative chronometer. Also, we envision to use it in combination with geochemical information about sedimentation rate changes.

# 5 Conclusion

Our algorithm contributes methodologically to the field of deep-time astrochronology by offering a multi-channel, probabilistic method for estimation of astronomically constrained

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timescales. At the same time we offer critical quality control of the data, allowing the user to evaluate how much Milankovic information can actually be detected in the basic elements records. The framework established here provides a robust platform for exploring the causes and consequences of climatic, geochemical, and evolutionary change in Earth's early history.

# 6 Code and Data Availability

The current version, which is the exact version of the program used to produce the results used in this paper, as well as the input data and scripts to run the model and produce the plots for all the simulations, is available at https://doi.org/10.5281/zenodo.17966227 (Fernandes (2025)) under the licence GNU General Public License v3.0.

# 7 Author Contributions

Iris Fernandes and Klaus Mosegaard led the conceptualization of the study and the development of the methodology, including algorithm design, numerical analysis, inverse problem formulation, and the integration of uncertainty quantification. They implemented the data processing and analysis pipeline, contributed to the overall methodological design, and drafted the original manuscript. Tais W. Dahl and Aske Sørensen contributed to the theoretical framework and provided critical input on the geochemical and geological interpretation and analysis. Mohammad Youssof contributed to algorithm parameterization and optimization. Nicholas Thibault contributed with geochronological insights in the analysis.

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