Evaluation of Paleocene-Eocene Thermal Maximum Carbon Isotope Record Completeness—An Illustration of the Potential of Dynamic Time Warping in Aligning Paleo-Proxy Records

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Abstract Variations in sedimentation rate, bioturbation, winnowing, and dissolution modify the deep-sea sedimentary record, complicating the apparent relationship between stratigraphic depth and time of a geochemical proxy record and confounding the extraction of a clear picture of past climates and environments. Dynamic time warping (DTW) is used to align time series with similar patterns. Here we explore the use of DTW to identify gaps in proxy records of the Paleocene-Eocene thermal maximum (PETM), aligning bulk sediment carbonate isotope records ($\delta^{13}C$) from various deep-sea sediment core sections spanning the event. Alignment of PETM $\delta^{13}C$ records from the Walvis Ridge, South Atlantic transect of ODP Leg 208 (Sites 1262, 1263, and 1265) was similar to previously published manually established alignments and consistent with the expectation that shallower sites have more complete records. The $\delta^{13}C$ record from a Southern Ocean site (Maud Rise; ODP Site 690) was then aligned to ODP Site 1263, the most complete Walvis Ridge site. This alignment identifies a gap in Site 690, indicating that peak excursion $\delta^{13}C$ values were not recorded. We conclude that DTW provides an objective way to align climate proxy records and rectify data loss associated with unconformities and other types of distortions, leading to a more complete understanding of the geologic record of past episodes of biotic and environmental change.

1. Introduction

Geochemical proxies provide invaluable records of past environmental conditions. Skeletal and organic materials from planktic and benthic marine organisms are primary sources of geochemical proxies and ideally are deposited and buried in stratigraphic order at a constant sedimentation rate, and without subsequent modification of their chemical, mineralogical, and isotopic composition or physical mixing of materials. In reality, a host of factors including variations in sedimentation rate, winnowing, seafloor dissolution, bioturbation, nondeposition, and other processes during early burial often generate gaps and distortion in the sedimentary record. Winnowing involves the removal, transportation, and redeposition of sediments caused by flowing water, while seafloor dissolution of carbonates occurs when the carbonate ion concentration and pH of the deep ocean declines (e.g., Hönisch et al., 2012) or as a result of oxidation of organic matter during burial. Bioturbation involves the mixing of sediments by organisms at the ocean floor, causing older sediment to be brought up to the surface and newly deposited sediment to be buried deeper. All of these processes complicate the apparent relationship between depth in the sediment column and time of deposition for geochemical proxies, erasing information and impeding the correlation of records from different locations.

Accurate correlation of proxy records is important, but also difficult, particularly during episodes of rapid environmental change for which generating and aligning new records is greatest. A preeminent example involves records from the Paleocene-Eocene thermal maximum (PETM), $56.01 \pm 0.05$ million years ago (Zeebe & Lourens, 2019). During the PETM, $^{13}C$-depleted (“isotopically light”) carbon was rapidly injected into the ocean and atmosphere, as indicated by a negative carbon isotope excursion (CIE) of 3.5–4.5‰ over $<20$ Kyr (Bralower et al., 1997; Kennett & Stott, 1991), leading to an abrupt global warming of $5–8 \, ^{\circ}C$.
(Kennett & Stott, 1991; McInerney & Wing, 2011; Zachos et al., 2006) and a gradual recovery for a total event duration of 120 to 220 Kyr (Farley & Eltgroth, 2003; McInerney & Wing, 2011; Röhl et al., 2007). The CO₂ sequestered in the ocean during the event lowered the pH and carbonate ion concentration in seawater, and the resulting post depositional dissolution of carbonate mineral particles erased proxy information at some deep-sea sites (e.g., Bralower, Meissner, et al., 2014; Ridgwell, 2007a; Zachos et al., 2005). Attaining an accurate interpretation of the PETM is important because it provides a potential analog for the impacts of greenhouse gas driven global climate warming today (e.g., Dickens et al., 1997) and may tell us about the strength of feedbacks between carbon cycling and a warming climate (e.g., Gutjahr et al., 2017). Previous attempts to piece together proxy records of the PETM at high resolution have primarily employed correlation using carbon isotope stratigraphy and astrochronology (Röhl et al., 2007). Two classic deep-sea locations, Ocean Drilling Program (ODP) Site 690 (Maud Rise) and ODP Leg 208 (Walvis Ridge) transect, both in the South Atlantic (Figure 1), are considered to provide relatively complete records of the event. However, dissolution near the base of the CIE in the Leg 208 records scales in severity as a function of paleo-ocean depth, making it challenging to estimate rates and extent of environmental change in this critical interval. Zachos et al. (2005) correlated bulk sediment carbon isotope (δ¹³C) records from the Leg 208 sites using visual matching of features in the δ¹³C records, supplemented by records of Fe content, magnetic susceptibility, and nannofossil biostratigraphy. They also aligned the Leg 208 records to the Site 690 δ¹³C record to determine age, using an astronomical age model developed for Site 690 (Röhl et al., 2007). These correlations and the associated chronology have provided an influential framework for understanding the deep-sea response to the PETM carbon injection and interpretation of the nature of the event as a whole. However, despite its general success and widespread use, the method used by Zachos et al. (2005) to align the carbon isotope records is subjective, involving the recognition of breaks in slope and inflection points in the δ¹³C records. Dynamic time warping (DTW) provides the means for correlating these sites in an objective fashion. DTW, and similar dynamic programming tools, (Giorgino, 2009) are ideally suited for aligning records that have distortions and gaps. They have been applied in a variety of fields, including voice recognition (Levinson et al., 1983; Sakoe & Chiba, 1978), computational biology (Durbin et al., 1998; Webb et al., 2002; Zhu et al., 1998), and to a limited extent, paleoceanography and paleoclimatology (Lin et al., 2014). Alignments are accomplished by stretching or compressing the depth (or time) axis on the “candidate” record (typically the one considered to be less complete and more distorted) to find the statistically strongest correlation with the more complete or “target” record (Berndt & Clifford, 1994). The aligned candidate record is then presented on the target’s depth (or time) axis. These techniques have also previously been
applied in the geosciences for the alignment of oxygen isotope records (Lisiecki & Lisiecki, 2002) and magnetic susceptibility logs (Hladil et al., 2010). Most recently, Hay et al. (2019) used DTW to create an array of possible alignments of Early Cambrian carbonate δ¹³C records that were both statistically significant and geologically plausible, leading to better constraints on the timing of animal diversification. Hidden Markov models (HMMs) have also been used in the alignment of oxygen isotope records with the capability of finding uncertainties in the alignment (Lin et al., 2014). This particular method has the advantage of less dependence on user-derived parameters, deriving uncertainty from the estimation of sedimentation rates.

In this study, we applied the Hay et al. (2019) script “dtw.m” for its use of generalized fitting parameters, allowing us to avoid the (over) use of subjective tie points while assessing a new method for record alignment. We applied this tool to the same bulk δ¹³C records of the PETM from ODP Sites 1262, 1263, 1265, and 690 used in Zachos et al. (2005). We show that DTW reproduces the general features of the alignments of Zachos et al. (2005) but provides an objective way to align proxy records. The technique also identifies potential gaps and sedimentation-rate variations that were not detected in the Zachos et al. (2005) alignments, showing its potential in stratigraphic correlation of complex records.

2. Data

Bulk sediment δ¹³C and wt. % CaCO₃ records from Walvis Ridge (Southeast Atlantic) and Maud Rise (Southern Ocean sector of the South Atlantic) were used in the alignments. The Walvis Ridge bulk δ¹³C records were generated using samples obtained during ODP Leg 208, which recovered pelagic carbonate ooze and claystones spanning the Paleocene–Eocene (PETM) boundary (Zachos et al., 2004). Advanced piston coring recovered multiple, vertically offset holes at five sites (1262, 1263, 1265, 1266, and 1267) between 1,400 and 3,500 m paleowater depth. These sites were considered relatively stratigraphically complete and undisturbed across the upper Paleocene and lowermost Eocene (Zachos et al., 2004).

The bulk carbonate δ¹³C records from Leg 208 Sites 1263, 1262, and 1265, and the wt. % CaCO₃ record for Sites 1262 and 1265, were obtained at sampling intervals ranging from 1 to 5 cm (available at: https://doi.pangaea.de/10.1594/PANGAEA.772042; Zachos et al., 2005; Figure 2). At these sites, sediments change abruptly from light gray nannofossil ooze to a grayish brown ash-bearing clay at the onset of the PETM before gradually transitioning back into light gray nannofossil ooze during the peak and recovery of the event. The thickness of the clay layer generally increases with ocean depth, from 6 cm at the shallowest site (1263) to 35 cm in the deepest site (1262) (Zachos et al., 2005; Figure 2). This relationship is consistent with the expectation that during an ocean acidification event, the deepest sites would be exposed to corrosive waters the longest, with dissolution not only of newly arriving carbonate sediment but also “burn down” into the preexisting latest Paleocene sediments. Site 1265 is a notable exception to this trend. The wt. % CaCO₃ record from Site 1265 does not decrease to 0 wt. %, and the clay layer is the thinnest (even though Site 1265 was in deeper water than Site 1263). However, because the other sites show thick clay layers, it is likely that either uppermost Paleocene carbonate was bioturbated into the basal PETM, or the earliest part of the event may be missing in this section (Zachos et al., 2004).

Sediments from Maud Rise were collected during ODP Leg 113 (Barker & Kennett, 1988) at Site 690 where the PETM isotope excursion was first identified by Kennett and Stott (1991). Site 690 records were some of the first used to determine the duration of the PETM through both orbital chronology (Röhl et al., 2000) and ³He measurements (Farley & Eltgroth, 2003). The PETM paleowater depth of this site was approximately 2,100 m. Unlike the Leg 208 records, Site 690 maintains a relatively high CaCO₃ content throughout the PETM (Farley & Eltgroth, 2003; Figure 2). There is no clay layer and little visual evidence of significant dissolution. Bulk carbonate δ¹³C data from Site 690 were obtained from Bains et al. (1999), who sampled the working half of the core at 5 cm intervals (Figure 2). The wt. % CaCO₃ record for Site 690 was from the archive half of the core at varying intervals ranging from 1 to 10 cm (Farley & Eltgroth, 2003). The data are available at https://doi.pangaea.de/10.1594/PANGAEA.723912.

3. Methods

In DTW, alignments are performed between two records at a time: a target record and a candidate record. The target record is presumed to be a relatively complete and continuous record (depth series) of the
interval of interest. The candidate record is a depth series from another site covering a similar time interval. The candidate record is initially considered as less complete.

The squared difference is calculated between each value in the candidate and target records, using either raw or normalized values of the time series. For the alignment between Site 690 and Site 1263, the records were first standardized to a mean of 0 and a standard deviation of 1 to accommodate the possibility that the true magnitude of the excursion at these two sites differed. In contrast, within the two Walvis Ridge transect records, this standardization was not performed because the sites were in close proximity to each other, and the CIE is expected to originally have had the same magnitude (the supply of settling CaCO₃ to the sites was the same). An example array of squared differences—here between Sites 1262 and 1263—is shown in Figure 3. There are “N” number of data points in the candidate series and “M” number of data points in the target series; “n” refers to the column number, and “m” refers to the row number in the matrix.

In the Hay et al. (2019) DTW script, two “penalty” factors can be applied to the difference matrix “d”: the edge parameter (edge) and the diagonal parameter (g). Edge reflects the presumed extent to which the two data series span the same epoch, and g controls the amount of allowable change in relative sedimentation rates. We explored a range of g (0.6–1.3) and edge (0.1–2) parameter values (Supporting Information Section S1). We found that for these time series, optimal fits were not improved by applying penalty factors, and we accordingly set the g and edge parameters equal to the default values of 1; that is, we did not apply penalties. Alignments with alternate g and edge parameter values are shown in the Section S1.

The minimum cumulative distance path (or warping path) “w” is the path through the “d” matrix that corresponds to the lowest total sum of “d”; the value of each grid point that the warping path is drawn through is added, and the path is chosen that minimizes this overall sum.
The path begins at the top right corner in the matrix (Figure 3). Because the data are referenced to depth, the diagonal dashed line corresponds to an alignment path with a constant relative sedimentation rate between the two records. This dynamic alignment programming method has been employed in other studies (Clark, 1985; Lisiecki & Lisiecki, 2002; Sakoe & Chiba, 1978).

Two objective criteria are used to evaluate how well the warped candidate record is aligned to the target records: the cross-correlation and the overlap. The cross-correlation evaluates the similarity between the aligned and target series by calculating their dot product at zero lag. Computation of the cross-correlation requires using only the target and aligned data that are assigned to the same depths (within a prescribed depth increment). Therefore, to measure a cross-correlation, some data points may have to be omitted from each of the data series. The overlap is the number of data points in the aligned record that were evaluated in the cross-correlation divided by the total number of data points in the original candidate record. Data points are omitted from the cross-correlation calculation for multiple reasons. For example, in the aligned records, there are often multiple data points that have been assigned to the same depth. To calculate the cross-correlation in such a circumstance, the data must be averaged to obtain one corresponding carbon isotope value for that depth. This results in a lower overlap value, because only one data point is calculated in the cross-correlation although it represents multiple data points. Both a high overlap and high cross-correlation indicate a good alignment with a good choice of the target series. A low overlap with a high cross-correlation indicates that the assigned target may be less complete than the candidate record, and a low cross-correlation regardless of overlap always indicates a poor alignment. For this reason, the “best alignment” maximizes both cross-correlation and overlap.

The statistical significance of these Walvis Ridge transect and Site 690 alignments was evaluated by assessing the distribution of cross-correlation values produced by alignments of synthetic (random) candidate records (Site 1262, Site 1265, and Site 690) to the Site 1263 target record. One hundred thousand synthetic random-walk sequences were created using a Monte Carlo method (Haam & Huybers, 2010; Hay et al., 2019). Each of these synthetic

| Target record | Candidate record | Cross-correlation | Overlap | g | Edge |
|---------------|------------------|-------------------|---------|---|------|
| Site 1263     | Site 690         | 0.97              | 0.56    | 1 | 1    |
| Site 690      | Site 1263        | 0.97              | 0.45    | 1 | 1    |
| Site 1263     | Site 1265        | 0.99              | 0.67    | 1 | 1    |
| Site 1265     | Site 1263        | 0.99              | 0.56    | 1 | 1    |
| Site 1263     | Site 1262        | 0.94              | 0.50    | 1 | 1    |
| Site 1262     | Site 1263        | 0.93              | 0.46    | 1 | 1    |
sequences had the same number of data points as the candidate records. Each sequence was aligned to Site 1263 yielding a distribution of 100,000 cross-correlation values. The cross-correlation of the alignment of the actual candidate record to Site 1263 was compared to this distribution. The p-value is the proportion of cross-correlation values that are equal or higher in the distribution of alignments of synthetic sequences to Site 1263. A low p-value of 0.004 for the cross-correlation output from the alignment of Site 690 to Site 1263, for example, indicates that there is a 0.4% chance that a synthetic sequence could produce an equal or higher cross-correlation alignment; therefore, the alignment is significant.

4. Results

Table 1 reports statistics on the carbon isotope alignments between the warped and candidate records. For all of the alignments, the overlap values are higher when Site 1263 is the target record. Figures 4–6 show the alignments of Site 1262, Site 1265, and Site 690 to the target record, Site 1263. Also shown are data obtained from Zachos et al. (2005) that show how the alignment from their study correspond with our alignments. A composite of all the deep-sea δ¹³C alignments was created (Figure 7); the y-axis is on an age scale, obtained from a Site 1263 age model from Röhl et al. (2007). CaCO₃ records align as a consequence of the δ¹³C DTW alignment (Figure 8). Further analysis of how age models can be applied to the alignments is discussed in the Section S3.

Each of these alignments produced p-values less than or equal to 0.057, indicating high confidence that the alignments are significant. The distribution of cross-correlations produced by alignment of the synthetic records to the target record are shown in the Section S2.

5. Discussion

The good agreement between Site 1263 and Site 1265 alignments (Figure 4) was expected because Site 1263 and Site 1265 are in close proximity and at comparable water depth (1400 m paleowater depth for Site 1,263 and 1,850 m paleowater depth for Site 1265; Abels et al., 2016; Zachos et al., 2004) and hence are expected to have experienced a similar degree of distortion due to changing carbonate preservation across the event. Site 1263 and Site 1262 (Figure 5) have lower cross-correlation values and overlap because Site 1263 and Site 1262 sediments were deposited at significantly different paleowater depths (1,400 m paleowater depth for Site 1263 and 3,600 m paleowater depth for Site 1262) (Zachos et al., 2005). Site 1263 and Site 690 have high cross-correlation but moderately low overlap values.

The overlap values within the excursion interval are consistently higher when Site 1263 is the target record (Table 1). This is expected among the Leg 208 records, where Site 1263 is the most complete record, but unexpected when aligned with Site 690, given that the wt. % CaCO₃ records (Figure 2) would indicate that Site 1263 underwent more dissolution than Site 690. However, the Site 690 excursion interval does reveal lower carbonate contents than the preexcursion values, a reduction from 90 wt. % CaCO₃ to 60 wt. % (Figure 2). If this reduction in carbonate content was driven by dissolution alone, it would represent an additional (compared to prior to the event) 80% loss in the fraction of CaCO₃ delivered to the seafloor that is preserved. Moderate bioturbation could be masking even more severe dissolution (Bralower, Kelly, et al., 2014).
The alignments also suggest a gap in Site 690 from Site 1263-aligned depths of 335.13 mcd to 335.29 mcd (169.96–170.01 mbsf in the original 690 record; Figure 6), which, if real, indicates that the minimum bulk δ13C excursion values might not have been recorded at Site 690 (Bains et al., 1999, Figure 2). Core photos from Site 690 do not show any obvious change in sedimentology that would make this gap readily identifiable (see Figure S13). Importantly, the identified gap lies stratigraphically above (later in time than) most of the major events identified from isotope, sedimentological, and micropaleontological data sets. Key environmental and biotic events, summarized by Bralower, Meissner, et al. (2014), cluster between 170.8 and 170.6 mbsf, almost half a meter deeper than the DTW-identified gap. The first evidence of chemical erosion occurs at 170.788 mbsf, indicated by decreasing wt. % CaCO3, while an increase in foraminiferal fragmentation at 170.6 mbsf suggests enhanced deep water dissolution. CaCO3 content had also begun to recover and was nearly at preevent levels by ~170 mbsf. Based on the cyclostratigraphic age model for ODP Site 690, this gap lies within the third precession cycle following the PETM onset (see Figure S13). The gap though does occur at the nadir of the bulk CIE and also marks the beginning of a significant stepwise reduction in Fe content (Figure S13). McCarren et al. (2008) similarly concluded that minimum δ13C excursion values were not recorded at Site 690 by benthic foraminifera and attributed this to ecological absence. They also concluded that the Site 1263 record is truncated by dissolution; it has a lower magnitude CIE (3‰ in the bulk record) than terrestrial carbon isotope records (up to 5 to 6‰) (McCarren et al., 2008).

Comparison of our alignment to Zachos et al. (2005) reveals a general agreement for Site 1265 (Figure 4) and Site 690 alignments (Figure 6) to Site 1263. The Site 1262 alignment agrees moderately well with our alignment; however, Zachos et al. (2005) inserts a longer gap in the Site 1262 record (warped to Site 1263 at 335.65 mcd; prewarping depth of 139.98 mcd) reflecting the observed thick clay layer in which carbonate sediment is not preserved after the onset (Figure 5). Zeebe and Lourens (2019) hypothesized a similar gap in Site 1262 in creating an astronomical time scale for Site 1262. In this case, the Zachos et al. (2005) correlation, informed by additional geological data (carbonate content), may be presenting a more accurate alignment of these two records during the onset interval.

Despite the success of the specific example presented here, DTW alignment of paleo-proxy records involves a unique (as compared to more “traditional” DTW usage) set of caveats and potential pitfalls. Firstly, DTW assumes monotonicity in the target record. Reworking by large-scale geologic processes such as turbidite flows and slumping are relatively easy to identify. Furthermore, deep-sea sites selected for the development of high-resolution geochemical records are generally chosen to avoid such occurrences as far as possible. On a much smaller scale, bioturbation, the displacement of particles in the upper sediment column due to the feeding, burrowing, and locomotion activities of animals, has the potential to break the assumption of monotonicity. For bulk (isotope) records, as employed here, this may not be a particularly significant concern as the effect of bioturbation on bulk sediment composition is generally to smear out (reduce in amplitude) and introduce a lag into a signal rather than stratigraphically invert signals. However, single foraminifera-based proxy records have a much greater potential for signal artifacts to be introduced (e.g., see Turner et al., 2017) and break the assumption of monotonicity.

Figure 6. Bulk carbonate δ13C record of Site 690 aligned to Site 1263. Both records have been normalized to a mean of zero and scaled by standard deviations from that mean (positive and negative). Also shown is the alignment from Zachos et al. (2005). The statistical significance assessment of the alignment yielded a p-value of 0.004.

Figure 7. All alignments for δ13C to Site 1263. Age based on Röhl et al. (2007) Site 1263 age model.
Figure 8. All alignments for CaCO₃ to Site 1263. Age based on Röhl et al. (2007) Site 1263 age model. The DTW alignment was conducted on the \( \delta^{13}C \) records, this figure shows how CaCO₃ aligns as a consequence. Bulk carbonate CaCO₃ data from Site 690 (Farley & Eltgroth, 2003) were sampled from the archive half and bulk carbonate \( \delta^{13}C \) data from Site 690 (Bains et al., 1999) were sampled from the working half of Site 690. The archive half of the core likely sampled a burrow, which created a 7-cm offset between the PETM onset between the archive half and working half (Bralower, Kelly, et al., 2014). Therefore, Site 690 CaCO₃ depths could not be aligned accurately to the Site 690 \( \delta^{13}C \) depths, and Site 690 CaCO₃ data were not shown in this figure.

There is also the question of the extent to which any two proxy records directly reflect the same primary (e.g., global) signal. Attempting to align a pair of records, one of which is not as distorted as compared to the first but also has been significantly overprinted by a second and different signal, would obviously be problematic. For instance, in the case of a carbon isotope (\( \delta^{13}C \)) signal recorded in pelagic carbonate, a number of factors might act to cause the \( \delta^{13}C \) signal delivered to the surface sediment to diverge (and before postdepositional distortion such as by bioturbation or changing rates of dissolution have occurred) from location to location.

These effects can be divided into factors that control how the \( \delta^{13}C \) of seawater dissolved inorganic carbon (DIC) is incorporated into pelagic carbon and those that control the \( \delta^{13}C \) of DIC itself. The former group includes vital effects and for bulk carbonate records, the proportion of CaCO₃ derived from calcifying phytoplankton (e.g., coccolithophores) versus calcifying zooplankton (foraminifera) (and indeed changing assemblage composition within the phytoplankton and zooplankton communities).

Primary controls on the \( \delta^{13}C \) of DIC include biological productivity and air-sea gas exchange (including temperature) (Schmittner et al., 2013). While many of these controls might have a relatively predictable response to an environmental perturbation such as associated with the PETM CIE (e.g., using numerical models such as in Gutjahr et al., 2017), the response need not be linear, meaning, the inflection points of the primary \( \delta^{13}C \) signal at two different ocean locations might differ in time yet be forced to align under DTW. However, the spatial impact of all these factors together only imparts only a 0.6‰ total variability at the modern ocean surface (Schmittner et al., 2013), suggesting that for most paleo \( \delta^{13}C \) events of interest, the global signal component will be dominant. Similar arguments can be made for benthic records but with potential changes in deep ocean circulation patterns that lead to an overprinting of any global \( \delta^{13}C \) signal being the greatest concern.

6. Conclusions and Perspectives

We found that carrying out proxy-record alignments using DTW yielded new insights into the relative completeness of two classic PETM records from Walvis Ridge in the South Atlantic Ocean and Maud Rise in the Southern Ocean. DTW results generally agree with the Zachos et al. (2005) alignments of Site 1262 to Site 1263 and Site 1265 to Site 1263. DTW indicates that Site 1263 is more complete than Site 690 within the CIE interval; the overlap is greater when Site 1263 is the target record and Site 690 is the candidate record. The alignment of Site 690 to Site 1263 also identifies a gap in Site 690, indicating that the Site 690 bulk carbonate record may not have preserved the minimum excursion value. Dissolution may have impacted Site 690 to a greater degree than previously thought (Bralower, Meissner, et al., 2014). Alternatively, Site 690 may simply have experienced a lower magnitude CIE. We cannot confidently discriminate between these two alternatives based on our DTW results. From a more practical perspective, we found that DTW was largely able to reproduce the correlations established by expert but nonautomated and more subjective means.

However, there remain a number of uncertainties surrounding the application of DTW to deep-sea proxy records, particularly with regard to how bioturbation distorts records and the occurrence of significantly increased carbonate dissolution and hence reduced sediment rates (and even “erosion”) during the peak of past carbon release events such as the PETM and how these may affect alignment between records. We are addressing this in several lines of ongoing work.

1. Our ongoing efforts are directed at developing a multivariate application of DTW to allow simultaneous alignment of multiple proxies (e.g., XRF-derived Fe and Ca, \( \delta^{18}O \), and \( \delta^{13}C \)). We also are exploring the use of HMM-Match (Lin et al., 2014) for deep-time alignments because of its ability.
to assess uncertainty in alignments. The apparent inability of DTW to align the Site 1262 and Site 1263 records during the interval of intense dissolution at the PETM onset may be addressed through application of HMM-Match to these records, using He accumulation data to better constrain sedimentation rates.

2. We aim to employ an Earth system model that gives us the capability of creating “synthetic” (“artificial”) deep-sea proxy records that encapsulate the key distorting features of proxy records such as changes in carbonate preservation (including “erosion”) and bioturbation (Ridgwell, 2007a, 2007b) together with a background orbital variability. In being able to generate both “perfect” complete records as well as records of varying distortion and incompleteness, and for simulated events of different characteristics, we will be in a position to develop a comprehensive empirical based understanding of the specific limitations of DTW for aligning paleo-proxy records and identify the characteristic events and depositional environments in which DTW can be fully relied upon.

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