The PRISM (Pliocene Palaeoclimate) Reconstruction: Time for a Paradigm Shift

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Summary: Global palaeoclimate reconstructions have been invaluable to our understanding of the causes and effects of climate change, but single-temperature representations of the oceanic mixed layer for data-model comparisons are outdated, and the time for a paradigm shift in marine palaeoclimate reconstruction is overdue. The new paradigm in marine palaeoclimate reconstruction stems the loss of valuable climate information and instead presents a holistic and nuanced interpretation of multi-dimensional oceanographic processes and responses. A wealth of environmental information is hidden within the U.S. Geological Survey's PRISM (**P**liocene **R**esearch, **I**nterpretation and **S**ynoptic **M**apping) marine palaeoclimate reconstruction, and we introduce here a plan to incorporate all valuable climate data into the next generation of PRISM products. Beyond the global approach and focus, we plan to incorporate regional climate dynamics with emphasis on processes, integrating multiple environmental proxies wherever available in order to better characterize the mixed layer, and developing a finer time-slice within the mid-Piacenzian Age of the Pliocene, complemented by underutilized proxies that offer snapshots into environmental conditions. The result will be a proxy-rich, temporally nested, process-oriented approach in a digital format- a relational database with GIS capabilities comprising a three-dimensional grid representing the surface layer, with a plethora of data in each cell.

Key index words: Palaeoclimatology, Palaeoceanography, Climate, Pliocene, PlioMIP

Running Header: PRISM Pliocene Paradigm

1. Introduction

Spatial marine palaeoclimate reconstructions have a rich history of aiding our understanding of the causes and effects of climate change. CLIMAP (**C**limate: **L**ong-Range **I**nvestigation, **M**apping, **a**nd **P**rediction), for example, has proven invaluable in exploring the conditions associated with the last glacial-maximum and last interglacial periods [1, 2]. The MARGO (**M**ultiproxy **A**pproach for the **R**econstruction of the **G**lacial **O**cean surface) reconstruction represents an immense advance in chronologic control and understanding of the interplay between different palaeotemperature proxies [3]. Similarly, a marine palaeotemperature distribution map has been the keystone of the PRISM palaeoclimate reconstruction since the project's inception [4].

The PRISM Project was launched two decades ago with two primary goals: (1) identify and characterize the nature and variability of climate during the mid-Piacenzian Age of the Pliocene Epoch, 3.264 - 3.025 Ma, as an indication of how the Earth might respond to future warming and (2) develop a series of integrated global-scale, quantitative datasets to be used in experiments modeling climate and environmental conditions during this warm period.

The mid-Piacenzian, about 3 million years ago, is a potential if imperfect analogue for near-future climate conditions. The global mean temperature of the Piacenzian Earth is estimated to have been approximately 2 to 3°C warmer than at present [5,6], within the range of warming estimated for the end of the 21st century [7,8], but atmospheric CO_2 concentrations were only slightly higher than the present value of ~390 ppm (Figure 1)[9]. The similarity of the mid-Piacenzian Earth to the modern one, in terms of continental positions, oceanic circulation patterns and extant biota, facilitates a comparison of environmental conditions between the two. The maximum sea level highstand was approximately 25m higher than at present [15,16] with a concomitant reduction in global ice volume, a poleward displacement of major terrestrial biomes [17] and changes in the oceanic thermal regime [18]. Thus, understanding Pliocene climate conditions is paramount to our ability to predict, adapt to, and mitigate the effects of future climate change.

Today, PRISM datasets are being used to test the ability of climate models to simulate past warmer conditions on Earth and to provide insights into the causes, mechanisms and effects of global warming [5, 6, 21-26], satisfying the second of the two project goals. These datasets are used in some cases as boundary conditions for initialization of climate model simulations and in other cases in verification mode, as "ground-truth", for experiments like those comprising the **Plio**cene **M**odel **I**ntercomparison **P**roject (PlioMIP) [27-31].

PRISM marine proxy data are often reduced to single mean annual sea surface temperature (SST) values that, while critical to modeling studies, represent an immense loss of palaeoenvironmental information – information that is necessary for a true conceptual understanding of Pliocene climate and the realization of PRISM's primary goal. It is crucial that the next generation of marine palaeoclimate reconstructions encapsulate all available climate data, including the full range of environmental information carried by an array of geological, biological and chemical proxies, with a focus on regional and process-driven climate change.

The new paradigm in marine palaeoclimate reconstruction stems the loss of valuable climate information inherent in model-dictated datasets and makes the jump from a two-dimensional global interpolation of SST to a holistic and nuanced interpretation of multi-dimensional oceanographic processes and responses linked in time and space. Researchers will have a new and better tool with which to take advantage of the ever-increasing complexity in Earth System Models. Here we summarize the wealth of environmental information within the current PRISM marine palaeoclimate database and introduce a plan to incorporate all valuable climate data into the next generation PRISM reconstruction.

2. The PRISM Reconstruction

PRISM is the most comprehensive and detailed global reconstruction of a period of warmth equivalent in magnitude to that projected by the IPCC for the end of the 21st century [32]. The PRISM reconstruction consists of a series of global-scale datasets covering sea- and land-surface conditions on a 2° latitude by 2° longitude grid (Table 1). In addition, the data exist in a fractional form on a 2°x2° grid in preferred and alternate versions for PlioMIP (Table 2). The preferred data are projected onto a land/sea grid that exhibits a 25m sea level rise. These data are used when the model land/sea mask can be changed. The alternate data are projected on a modern land sea grid for models that cannot change coastlines. The deep ocean temperature reconstruction has a spatial resolution of 4° latitude by 5° longitude with 33 depth layers.

Four generations of the PRISM marine reconstruction (PRISM0-PRISM3) have evolved from a series of studies summarizing conditions at a large number of marine and terrestrial sites, starting in the North Atlantic and extending laterally to every ocean basin and vertically to include a three-dimensional reconstruction of the global ocean thermal regime (PRISM3D). PRISM0 through PRISM2 are summarized in Dowsett [33]; the PRISM3 and PRISM3D reconstructions are documented in a series of later publications [18, 34, 35]. Collectively, PRISM0 through PRISM3D comprise the state of the PRISM reconstruction.

(a) *Chronology*

The establishment of the PRISM time interval was originally dictated by limitations in correlating spatially distant data sites. Dowsett and Poore [36] selected the interval surrounding 3.0 Ma as the basis for the reconstruction of a Pliocene warm period for several reasons. Down-core studies had established that interval as a prolonged period of warmer-than-modern climate, differing from more recent “interglacials” in the duration of the sustained warmth. Importantly, most of the fossil planktonic foraminifers encountered during this interval are extant, meaning that environmental interpretations derived from the fossil assemblages were more likely to produce reliable estimates of physical conditions than were interpretations derived from older assemblages containing greater numbers of extinct taxa [37].

This interval was long enough to be reliably identified and correlated between marine sequences independent of climatic characteristics because it was stratigraphically adjacent to a number of biostratigraphic and magnetostratigraphic events (Figure 2). Specifically, this interval occurs in the middle part of the Gauss Polarity Chron, ranging from C2An2r (Mammoth reversed polarity) to near the bottom of C2An1 (just above Kaena reversed polarity), and correlates in part to planktonic foraminiferal zones PL3 (*Sphaeroidinellopsis seminulina* Highest Occurrence Zone), PL4 (*Dentoglobigerina altispira* Highest Occurrence Zone) and PL5 (Atlantic) (*Globorotalia miocenica* Highest

Occurrence Zone) or PL5 (Indo-Pacific) (*Globorotalia pseudomiocenica* Highest Occurrence Zone) [38].

Detailed oxygen isotope stratigraphy was not initially used for inter-core correlation (e.g. [39]) or to define the PRISM interval. The identification of high-frequency isotopic variation in the Pliocene was just beginning, and there was no agreed-upon standard for correlation purposes. In any case, detailed isotopic records did not exist for many of our original sites. With the arrival of improved marine isotope chronology [40, 41], the PRISM time-slab was further constrained between the transition of marine isotope stages M2/M1 (3.264 Ma) and G21/G20 (3.025Ma). This stratigraphic position placed the PRISM reconstruction prior to the onset of high-amplitude oxygen isotope oscillations, which represents a shift toward modern conditions (i.e., Northern Hemisphere ice volume increased and glacial–interglacial variation intensified). Within the bounding positive $\delta^{18}O$ excursions that mark glacial stages M2 and G20, and excepting glacial stage KM2 at ~3.1 Ma, benthic foraminiferal oxygen isotope values in this interval are equal to or isotopically lighter than those measured today, further making this interval easily distinguishable.

Note that the Pliocene-Pleistocene boundary has been redefined by the International Union of Geological Sciences. For practical reasons PRISM continues to use the last major published time scale in which the base of the Pleistocene is equivalent to the base of the Calabrian Stage at 1.806 (1.81) Ma [42] to give historical context to the ‘mid-Pliocene warm period’. In that time scale the Pliocene Epoch consists of the Zanclean Age, followed by the Piacenzian Age, which is followed by the Gelasian Age (Figure 2). This arrangement has led many workers to refer to the PRISM interval, which correlates to the middle of the Piacenzian, as “mid-Pliocene”, “mid-Piacenzian”, and “mPWP” (mid-Piacenzian warm period), all of which are used interchangeably.

(b) *Palaeoenvironmental proxies applied to Piacenzian sequences*

The Piacenzian is well-suited for the analysis of future warming because Piacenzian sedimentary deposits containing fossil proxies of climate variables are abundant worldwide, and their ages are relatively easily determined. Therefore, by making a few assumptions concerning the stability of ocean chemistry and ecological tolerances, we can use fossils to reconstruct past environments at specific locations (Figure 3). Numerous researchers utilizing a variety of fossil groups and palaeothermometry techniques have documented and quantified global Piacenzian warmth. Traditionally, past SST has been estimated from counts of microfossils. Many Piacenzian species are extant, making palaeotemperature estimations based on modern calibrations possible. Each species lives in a well-defined range of environmental conditions (an ecological niche), and the species assemblage tells us something about those environmental conditions. The majority of reconstructed PRISM ocean temperatures are derived from planktonic foraminifera, with other micro- (diatoms, radiolaria, ostracods and dinoflagellates) and also macrofossils (mollusks, bryozoans) affording assemblage-based estimates. In addition, geochemical (Mg/Ca, oxygen isotopes, alkenone unsaturation) and sclerochronological (growth increment) approaches are being applied in palaeothermometry, expanding Piacenzian SST coverage (Figure 3).

1. Planktonic foraminiferal assemblages. Planktonic foraminifera are single-celled eukaryotic organisms that live in the near-surface marine environment and exhibit passive floating lifestyles. They secrete calcium carbonate tests ranging in size from 100µm to 1mm in length. As with most microfossils, small size and abundance greatly increase the utility of planktonic foraminifera. Like other planktonic organisms, they exhibit widespread geographic distribution making them ideal environmental and biochronological indicators [43].

Quantitative analysis of assemblages of planktonic foraminifera has been widely used to reconstruct past SST using a transfer function or nearest analogue approach. Transfer functions range from simple [44] to complex factor analytic approaches pioneered by Imbrie and Kipp [45]. This later technique formed the basis of the CLIMAP Last Glacial Maximum reconstruction [1] and has been modified and used to reconstruct palaeoclimate conditions during other time periods back to the PRISM interval [18, 46-49].

2. Ostracod assemblages. Ostracods, small (millimetric) bivalved crustaceans with carapaces composed of calcium carbonate, are commonly used to estimate palaeoenvironmental conditions in marine, brackish and lacustrine environments [50]. Used in many areas of palaeoceanography, they have particular value in studies of nearshore marine sediments where planktonic organisms are rarely preserved.

In the PRISM reconstructions, ostracods are used to determine the position of major nearshore currents and to obtain palaeotemperature estimates in the mixed ocean layer at water depths shallower than 100m, usually less than 30m [51-57]. The Mg/Ca ratio of valves of the ubiquitous genus *Krithe* have been used extensively to reconstruct deep ocean temperature at key Piacenzian transects in the Atlantic and Pacific Oceans [18, 58, 59]. Combination of these bottom water temperature estimates with benthic foraminiferal oxygen isotopes allows an estimate of the isotopic composition of seawater and therefore provides an estimate of continental ice volume and sea-level variability [60].

3. Diatom assemblages. Diatoms are unicellular eukaryotic algae that form siliceous frustules 20-200 µm in diameter or length. In marine settings, diatoms thrive in nutrient-replete environments such as coastal upwelling zones and the high-nutrient, low-chlorophyll Southern Ocean. These cosmopolitan phytoplankton are the dominant primary producers in the subarctic Pacific Ocean and south of the Antarctic Polar Front, where conditions do not favor preservation of carbonate-producing organisms [61]. Marine diatoms occupy a wide range of ecological niches; some species inhabit warm, stable open waters while others live in and around sea ice. Core-top diatom assemblages can be related to physical characteristics in the overlying water column such as SST, sea ice concentration, and annual sea ice duration, making the fossil record of these organisms a multifaceted tool for palaeoclimate reconstruction [62-64].

Because diatoms, made of silica, are often abundant in settings where foraminifera and other calcium carbonate organisms are not preserved, they fill important gaps in the PRISM reconstruction. North Pacific SST estimates from five PRISM sites are derived from ratios of subtropical to cold-water diatom species [65, 66]. In the Southern Ocean, diatom assemblages constrain summer SST at 18 PRISM sites, and are further employed to track the seasonal extent of sea ice and the position of the Antarctic Polar Front in the mid-Piacenzian [67-70]

4. Magnesium to calcium ratios. Foraminifer tests and ostracod shells, composed of calcium carbonate but containing within them a small amount of magnesium, are considered to be secreted in equilibrium with seawater at the time of formation. The uptake of Mg into the foraminiferal test or ostracod shell is temperature dependent, hence the ratio of magnesium to calcium in a fossil shell can be converted to water temperature using calibration equations formulated through both laboratory culturing and plankton tow experiments (e.g., 71-80). Mg/Ca ratios are higher for calcite precipitated in warmer water.

With the knowledge that different species of planktonic foraminifera live at different depths and reach maximum abundance at different times of the year (e.g. 76, 79, 80), these geochemical analyses can provide a wealth of information on the composition and structure of the water column. When coupled with benthic foraminifera and ostracods, which provide information from bottom waters, detailed palaeoenvironmental and palaeoclimatic reconstructions become possible.

5. Alkenone unsaturation indices. Alkenones are long-chained *di*-, *tri*- and *tetra*-unsaturated ethyl and methyl ketones synthesized by a small group of algae that dwell near the surface of the ocean [81, 82]. The $U_{37}^{k'}$ index has been linearly calibrated to ocean near surface temperature [83-85] and can be used to estimate mean annual SST. In general, organic molecules are extracted from sediment samples and analyzed using a gas chromatograph. Peak areas of C37:2 and C37:3 alkenones are used to calculate the alkenone unsaturation ($U_{37}^{k'}$) index. PRISM $U_{37}^{k'}$ SST estimates are obtained using the

Prahl et al. [83] calibration curve. Reproducibility of analyses is better than 0.005 $U_{37}^{k'}$ units, which corresponds to a temperature uncertainty of 0.28 °C.

Alkenones provide SST estimates in all but the warmest environments because the carbon chains become fully saturated at ~28°C. The temperatures recorded are most closely linked to mean annual temperature in modern calibrations, but are likely describing the season or seasons of the algal bloom. This gives us additional information regarding palaeoproductivity.

6. Mollusks and sclerochronology. Mollusks provide age control and semi-quantitative temperature estimates for shallow marine Piacenzian successions via temperature-diagnostic taxa [86-94]. Studies of Pliocene marine environmental conditions reconstructed from ontogenetic profiles of oxygen isotopic composition ($\delta^{18}O$) have been gradually emerging [95-98] and this approach has recently been supplemented by the use of evidence from microgrowth increments [99-101]. These applications of ontogenetic time-series data from mineralised tissue (sclerochronology) allow for reconstruction of annual seafloor temperature range, absolute seafloor temperatures, reconstructed surface water temperature and by inference, sea ice extent [99-101]. In addition, carbon isotope ($\delta^{13}C$) profiles may provide an indication of seasonal phytoplankton dynamics.

7. Bryozoa. Zooid size in cheilostome bryozoa was established as a method of determining mean annual range in temperature (MART) by Okamura and Bishop [102]. Knowles et al. [103] demonstrated that the combined use of the MART technique and oxygen isotopic analysis could provide a robust means of reconstructing shallow bottom water temperatures. These techniques have been successfully applied to Pliocene marginal marine successions in Antarctica, Europe, Central America and the east coast of North America [98, 104, 105].

8. Other proxies. Many other proxies provide estimates of surface conditions, both temperature and other parameters, although few of these have been used consistently in the PRISM reconstructions. Among important SST indicators are dinoflagellate transfer functions (e.g. [106, 107]) and the TEX_{86} SST proxy [108]. Both provide a means for obtaining temperature estimates in environments and regions where other proxies discussed above are not as useful. Also, stable isotopes of carbon and oxygen are used in a variety of ways in addition to the above in PRISM work as in almost any marine palaeoclimate reconstruction.

3. New Challenges to the Old Paradigm

The overarching goal of the PRISM Project is to identify and characterize the nature and variability of the mid-Piacenzian climate. With the increasing amount and variety of palaeoenvironmental data, however, the biggest challenge of the traditional climate reconstruction format has become its inherent limitation in communicating both the nature and variability of climate. The result is the loss of information regarding temperature variability within the time interval and within the mixed layer with depth and season. The one site-one numerical value philosophy that was at one time optimistic is now unnecessarily restrictive. In addition, the incorporation of a wealth of data from multiple proxies has made it difficult and inappropriate to standardize temperature calibrations and to calculate error.

(a) *Information Loss*

1. Variability within the Time-Slab. To date, PRISM has approached mid-Piacenzian climate reconstruction through a time-*slab*, not a time-*slice* (i.e. a single time plane) approach. At most marine sites, the palaeoenvironment during this interval is represented by 20 to 30 samples. Based upon the marine isotopic record and all temperature time series analyzed by the PRISM group, there is a high degree of variability within this interval that is not communicated in the digital reconstructions [23]. Dowsett and Poore [36] introduced a warm peak averaging (WPA) technique to establish an estimate of the mean *warm phase of climate* at each site and to avoid problems associated with peak-to-peak correlations between cores. Figure 2 illustrates the various individual warm peak temperature estimates obtained from a factor analytic transfer function applied to the planktonic foraminiferal assemblages at ODP Hole 625B. In this example, these values are used to characterize the mean interglacial winter state (the reported WPA value) as well as the variability of SST within the time-slab. The amount of variability within the time-slab is no longer acceptable to properly evaluate climate model simulations.

2. Mixed Layer Characterization. The existing PRISM marine reconstruction incorporates multiple proxies wherever possible, but the multi-proxy approach to palaeotemperature estimation is complicated in that each proxy records a different aspect of mixed layer conditions. For example, assemblage-based SST estimates provide cold and warm season temperatures that correspond to a range of annual surface conditions, Mg/Ca-derived temperature estimates reflect conditions at the preferred calcification depth and season of the individual foraminifer species studied, and alkenone-derived SST estimates are linked to the timing of plankton blooms that vary with latitude. Although differences among SST estimates from these proxies are expected because each proxy defines the temperature of the water column at a specific depth and/or season, PRISM has calculated and reported a single mean annual temperature estimate for each site, in order to integrate estimates from the multiple proxies.

Atmospheric general circulation models require monthly SST data and proxy information on seasonality. Traditionally, winter and summer WPA SST values from PRISM localities have been contoured to provide global maps of winter (cold season) and summer (warm season) SST, and the remaining 10 months of the year have been derived by fitting a sine curve to the winter and summer data (Figure 4). The result is a distortion of the annual cycle of temperature for many regions [109] and a loss of important information regarding seasonality that is included in the proxy data. The next phase of PRISM seeks to recapture the suite of information provided by the diverse proxies, giving a much more complete and robust estimate of palaeoenvironmental conditions both seasonally and with depth.

(b) *Competing Temperature Calibrations*

Efforts to integrate various palaeontologically-based proxies (e.g. CLIMAP) have always been limited by disagreement between modern calibration climatologies (e.g., Goddard Institute for Space Sciences [GISS], and the Advanced Very High Resolution Radiometer [AVHRR]). Initially, PRISM SSTs were calibrated by the "best available data" for each faunal/floral proxy method and region. The PRISM2 reconstruction rectified these differences by recalibrating all faunal/floral proxies to the modern SST analysis of

Reynolds and Smith [110]. Today, PRISM integrates faunal and floral assemblage data, Mg/Ca palaeothermometry of selected species of planktonic foraminifera, and the $U_{37}^{k'}$ unsaturation index. These proxies are primarily based upon core-top material and calibrated to overhead surface climatologies. While PRISM3 faunal estimates are calibrated using Reynolds and Smith [110] both alkenones and Mg/Ca palaeothermometers are calibrated to Levitus and Boyer [111]. These data sets integrate different periods in the late 20th century (1950 to 1979 [with satellite data from 1982 to 1993], and 1900 to 1992, respectively), and a comparison of the two shows differences approaching ±1.5 °C [109]. These differences arise due to the varying mean position of surface circulation features at different times during the last century. Differences between calibration climatologies are one potential source of disagreement between proxy estimates, and PRISM analyses of surface conditions must recognize and correct for the potential variability imposed by calibration choice.

(c) *Unquantifiable Error*

It has become common practice to hindcast past climate conditions using numerical models and to verify those efforts using palaeoenvironmental reconstructions. The confidence we place on the palaeo-observations then becomes paramount to the understanding of model strengths and weaknesses. While some elements of palaeoclimate studies rich in multiple proxies lend themselves to error analysis (e.g. laboratory measurements, transfer function communality values), some do not. The stationarity of environmental tolerances, for example, or the age control of a sample, are inherently non-quantifiable and are therefore not available for inclusion in a conventional error analysis.

There are presently 112 marine localities in the PRISM reconstruction with 96 providing surface temperature estimates (Figure 5). As an initial attempt to define the quality of PRISM estimates, the λ-confidence metric was created [112]. The λ metric takes into account the confidence in age control of the samples, number of samples at each locality, the sample quality (which has specific ranges for faunal, floral, alkenone and Mg/Ca proxies), the method chosen to estimate SST, and the performance of that method. The λ metric has a range of values associated with low to very high confidence, and the distribution of PRISM localities associated with various levels of λ can be found in Figure 5.

4. Toward a New Paradigm in Palaeoclimate Reconstruction

Studying palaeo-proxies at the community or ecosystem level is not a new idea. Plant biologists, for example, have always looked holistically at the assemblage to determine a range of environmental conditions including temperature, precipitation, and seasonality. Even within PRISM, palynologists work to describe the complete environment, and the PRISM vegetation reconstructions reflect this. The PRISM SST dataset, on the other hand, came about because the tools to provide quantitative estimates of temperature were available, and atmospheric general circulation models required prescribed Pliocene temperatures. As a result, the current PRISM monthly SST reconstruction was developed to prescribe surface temperature in atmosphere-only climate model experiments and to initialize fully coupled ocean-atmosphere climate model experiments. Confidence-assessed PRISM mean annual SST verification data are the standard used to compare the ensemble of 8 fully-coupled models that contribute to the suite of PlioMIP experiments aimed at providing a palaeo-perspective for the IPCC AR5 [27, 28, 112].

With these requirements met, we can focus a new holistic eye on our proxy data. We can discard the idea of estimating a single value because the environments the proxies describe are *inherently non-quantifiable* in these terms; they are sensitive to many variables in addition to temperature, including the way in which the multiple proxies themselves interact. This is where a database of alternative proxy signal-carriers will allow windows into the actual process linked to the overall high-resolution record.

(a) *Incorporating Additional Complexity*

The PRISM reconstruction incorporates data from multiple independent proxies whenever possible. Fine-scale comparison of faunal estimates, Mg/Ca, and alkenone-based estimates usually shows differences that may be attributable to (1) problems with any and/or all of the techniques; (2) differences owing to deviation in sampling strategies; and (3) complexities arising from what each proxy is actually monitoring (e.g. depth or season of estimate) and how these compare in time-averaged samples [113]. This last point is important and worthy of additional consideration. If all other aspects of the proxy methods are working well, small differences between proxy estimates suggest different signal carriers are unique and heretofore underutilized sources of information. The different proxies, therefore, may be used in conjunction to provide a holistic understanding of the palaeoenvironment.

One example of the utility of looking at all proxies simultaneously is illustrated by an analysis of the mid-Piacenzian at ODP Site 609 [114]. In that study, analysis of components of the foraminifer assemblage, along with alkenones and Mg/Ca palaeothermometry using multiple taxa, indicated that the mid-Piacenzian interval was not as warm as the transfer function suggested. Instead, there was an increase in productivity and potential change in the seasons of maximum production of some key taxa relative to present day. This not only corrected an anomalously high SST value but also provided a more complete picture of palaeoceanographic conditions in the region. Possibly most important is the realization that independently, the performance of each proxy method was sound. Transfer function communalities were extremely high suggesting the Pliocene assemblage was described by the core-top factor analysis with little loss of information. The fauna was abundant and well preserved. Alkenone analyses showed well-defined peaks and were, along with the Mg/Ca analyses, reproduced on replicate samples with a high degree of precision. Averaging the different proxy estimates would have been a mistake as it would have ignored the additional information recorded by the multiple proxies. Instead, recognition of possible subtle changes in the timing of production of elements of the fauna allowed for an intricate and admittedly subjective reconstruction of surface and subsurface, seasonal and mean annual, conditions during the mid-Piacenzian at that location.

Other recent work in the marine palaeoclimate community is leading toward multi-dimensionality and understanding processes in both the temporal and spatial domains. The notion of a "permanent El Niño" comes about from this next step in integration of proxies. Rickaby and Halloran [115], using the modern seasonal temperature profile as a guide to depth habitat of different species of planktonic foraminifera, were able to reconstruct the depth of the thermocline in the eastern and western equatorial Pacific and concluded that the warm Pliocene was characterized by a

La Niña state. Wara et al. [116] analyzed higher resolution data from the same sites in the equatorial Pacific and reached the opposite conclusion that a permanent El Niño state existed during the warm Pliocene. These opposing conclusions, while interesting, are not germane to our argument. However, the implicit influence of methodology illustrated in these attempts to monitor surface temperature and temperature at depth using depth stratification of planktonic foraminifera species (assuming those preferences did not change over time) is crucial.

It is important to note that neither of these studies nor derivatives used quantitative analysis of the faunal assemblages. The addition of planktonic foraminiferal-based mean annual temperature estimates at Site 847 in the eastern equatorial Pacific shows remarkable agreement between proxies (26.9° C) representing faunal-, alkenone- and Mg/Ca-based temperature anomalies of 2.8°, 2.5° and 2.5° C respectively. All three proxies indicate mean annual temperature at or very near the surface. However, the faunal assemblage data also provide cold and warm season temperatures of 25.7° C and 28.5° C, respectively, and suggest high nutrient conditions. That indicates a mean annual range of temperature (MART) of only 2.8° C, approximately half of the present day 4.8° C MART. Existing δ^{18}O and Mg/Ca analyses of *Globorotalia tumida* specimens argue for a shallower thermocline that, like the faunal assemblages, indicates higher nutrient concentrations.

A similar analysis can be done at a site further south in the upwelling region off Peru (ODP 1237). There faunal-, alkenone- and Mg/Ca-based temperature anomalies of 4.4°, 3.8° and 1.7° C, respectively, suggest general agreement in mean annual surface water warming of approximately 4.0° C with a lesser warming at depth based upon

Mg/Ca-based estimates from shallow (*Globigerinoides ruber* and *Globigerinoides sacculifer*) and intermediate depth (*Globigerina bulloides*) signal carriers. The integration of these different proxies suggests a structure of the upper water column not unlike that of the present day but offset toward warmer conditions. Present day MART values (7.0 °C) are similar to those reconstructed for the Pliocene (6.5°C).

The potential exists to add bryozoan MART data and isotopic series from selected mollusks from coeval marine deposits along coastal Peru (Pisco Basin) and Chile (Mejillones Peninisula and the Coquimbo region [117]). These signal carriers/proxies would provide temporally instantaneous point estimates of seasonality, structure and range of the annual cycle of surface temperature along with traditional palaeontological analysis of assemblages.

(b) *Maturing to a Regional and/or Process Viewpoint*

Both the Antarctic/Southern Ocean system and the Arctic/North Atlantic provide powerful examples of the way in which a regionally focused, multi-proxy effort might be advanced by the new PRISM paradigm. Breakthroughs in drilling methods by ANDRILL (**AN**tarctic **DRILL**ing Project) have allowed access to marine successions deep under the ice shelves that provide proximal and nearly continuous records of dynamic ice sheet conditions [118]. Multiple proxy data from ANDRILL are being incorporated into PRISM, providing a unique high-resolution framework into which bryozoan- and mollusk-derived palaeoclimate records of seasonal variability from the Antarctic Peninsula [100, 105] can be incorporated. These short-term, seasonally-resolved data will help provide a new understanding of temporal and spatial variability of the Antarctic cryosphere and its concomitant effects on the global climate system.

It has long been realized that the Arctic and high latitude North Atlantic are critical regions as early warning flags of future climate change. The extent and temporal duration of sea-ice and the surface temperature conditions impact the overturning circulation and path and strength of the Gulf Stream/North Atlantic Drift. This is also the region of greatest disagreement in mean climate state conditions between climate models and proxy data [109, 112]. A wealth of marine microfossil data suggests a North Atlantic warm anomaly in the Pliocene increasing with latitude from the Caribbean to the Arctic [13, 114]. Plant macrofossils from bordering regions are in general agreement [120-122]. Additional data - biomarkers, other multivariate floral analyses, dinoflagellates, marine invertebrate data from macrofossil assemblages, bryozoan MART data and isotopic analyses of mollusks - from the borderlands of the Atlantic and North Sea [94, 99, 101, 104, 123-126] provide a more robust understanding of regionally warmer conditions punctuated by pulses of warmth extending to the Arctic. These pulses of warmth entering the Arctic are well documented for more recent intervals (this century and other times during the last millennium) [127-129]. The different approaches and temporal acuity of the various proxies should lead to a generalized spatial reconstruction with windows documenting high-resolution (perhaps seasonal) variability.

Upwelling regions provide another example of the new PRISM focus. Upwelling sites in the PRISM dataset include DSDP and ODP Sites 532 in the Benguela Current upwelling system, Sites 36, 1014 and 1021 in the California Current upwelling system, Sites 677 and 1237 in the Peru Current upwelling system, and Sites 659, 661 and 958 in the Canary Current upwelling system. To date, most of these sites have been studied for their input to the global SST dataset [34, 130] but not for their contribution to a better understanding of Piacenzian upwelling dynamics. While these sites show Piacenzian SST estimates that are warmer than modern, most of these sites register significantly cooler mean annual Piacenzian SST than the overall global PRISM reconstruction because upwelling zones are usually cooler than other locations at the same latitude. Some sites, however, particularly in the California Current upwelling system, are characterized by temperatures warmer than the global average and warmer still than the North Pacific locations of the same latitude [131, 132]. Together, these sites suggest a commonality among Piacenzian upwelling regions, arguing for a system-wide phenomenon of warmer, nutrient-rich upwelling zones.

The process or processes responsible for changes in upwelling temperature and nutrient richness is under consideration. The warm upwelling zone Piacenzian SSTs are presumably due to either a deeper thermocline or appreciably warmer water at depth. A link between thermocline depth and latitudinal extent of the subpolar oceans has been established at ODP Sites 882 in the sub-Arctic Pacific and 1090 in the sub-Antarctic Atlantic [133], pointing to a deeper Piacenzian thermocline when warmer temperatures spread poleward. In addition, ODP Site 1082 in the Benguela upwelling system off southwest Africa experienced weaker upwelling activity from a different source region during the Piacenzian [134], indicating atmospheric and oceanic circulation patterns unlike those today. These studies in conjunction with existing PRISM sites serve as a starting point for a high-resolution, multi-dimensional, process-oriented upwelling reconstruction.

(c) *Developing a Finer Chronology*

The dynamics of most oceanographic processes take place on time scales that cannot be adequately sampled in the palaeoceanographic domain due to limitations imposed by sediment accumulation rates and bioturbation. Thus our best deep-sea records are still time-averaged. However, orbital configurations associated with defined peaks (or narrow time-slices) can be derived using astronomical solutions [135], and the number of orbitally-tuned deep-sea records is increasing rapidly. The next PRISM iteration will produce a confidence-assessed [112] mid-Piacenzian global SST reconstruction representing a single warm *interglacial* peak, MIS KM5c, rather than an average of warm peaks. The designation of KM5c within the PRISM time-slab will reduce uncertainty in the experimental design of Pliocene climate model experiments by dictating insolation forcing at the top of the atmosphere. Previous Pliocene climate model simulations have used a modern orbital configuration to represent the entirety of the ~250kyr PRISM time-slab interval. This narrowed window will also provide a target for more temporally focused assessments of sea level change and of terrestrial vegetation from well-dated coastal marine sites.

Even this two-order of magnitude increase in stratigraphic resolution is not without problems. The time-slab approach used an average of warm phases within a 250kyr interval. The time-*slice* assumes temporal synchrony between KM5c at all localities, not allowing for regional differences in phasing between surface conditions and the bottom water oxygen isotope signal. One potential solution would be to run a number of closely spaced simulations within a chosen temporal window. In such a scenario, any simulation within the target window that matched mean annual SST at a particular locality would be considered a match of the model to the data. However, this approach relies on the *ad hoc* assumption that correlation problems are the cause of non-agreement between data and models. Alternatively, short time series extending beyond a reasonable estimated phase difference could be analyzed for both magnitude and variability of change. This in turn becomes less of a time-slice and more of a refined time-slab. Despite potential problems, a time-slice reconstruction is the next logical step in Pliocene palaeoclimatology. The palaeoceanographic community will continue to generate high-resolution analyses using a variety of SST proxies. Through careful evaluation, integration of multiple proxies at a new refined stratigraphic focus, and implementation of innovative techniques, data-model comparisons will take on a new level of sophistication.

The majority of PRISM proxy material comes from deep-sea sedimentary deposits with relatively constant accumulation rates over time, but under the new paradigm, many additional proxies from ephemeral or transient deposits will be incorporated. A fundamentally important component of the new paradigm is, in addition to enhancing high-resolution deep sea records, to include a wide variety of short-lived, seasonally-resolved proxies in telescoped regional and process reconstructions.

The stratigraphic analysis of single shell beds suggests in some instances extremely short duration of accumulation, perhaps ranging from a single storm deposit to an episode of deposition that may have only lasted several decades. Mollusks within such a deposit can represent between one year and, in some instances, over a century of growth. Annual-increment records from modern examples of such longevous taxa (e.g. the bivalve *Arctica islandica*) have been successfully cross-matched to yield composite chronologies that may be many centuries in length [136]. Such records can in their own right provide information on climate (e.g. air temperature [136]) and climate variability (e.g. fluctuations in winter North Atlantic Oscillation index; [137]). Alternatively, lengthy growth records can be microsampled and investigated isotopically to yield long-term continuous information on seasonal climate [138]. It should be possible to acquire such climate data from Pliocene shells, providing a resolution not previously attained.

How does one reconcile an orbitally-tuned deep sea record with a storm bed deposit representing one or more discrete events? Correlating mollusk shells, for example, from the Yorktown Formation (Atlantic Coastal Plain of Virginia and North Carolina) to offshore DSDP Site 603 is like comparing apples and oranges. However, there is an argument to be made regarding the length of time represented by a bed within the Yorktown Formation (perhaps a single storm deposit) compared to the age estimate of the entire Yorktown sedimentary package (~3.5 to 3.0 Ma). We can analyze proxies at Site 603 representing peak warmth compared to pre-industrial conditions, and then probe mid-Pliocene storm deposits onshore and compare a population of coeval mollusk shells representing 30 years of growth and know what the seasonal signal was like in ~40m of water. This nested proxy concept will be very important if the palaeoceanographic community can accumulate enough data within a relational database with GIS capabilities. A network of multiple windows into deep-time will be priceless for understanding three-dimensional processes through time.

(d) *Developing a Digital Environmental Representation*

As the new paradigm of palaeoenvironmental reconstructions evolves, so must its digital representation. How do we represent our proxy-rich, temporally nested, process-oriented approach (Figure 6) in a digital format? How do we link together disparate pieces of data? We foresee a relational database with GIS capabilities comprising a three-dimensional grid representing the surface layer, with sliding scales for temperature, salinity, productivity, and other environmental parameters in each cell where we have data (Figure 7). Because we do not know what questions will be asked in the future, we want to include all data (acknowledging chronological resolution problems). Meanwhile, we are moving toward a finer timescale (the KM5c time-slice) for questions that are being asked now. In addition, all PRISM data sets are being moved to a standard 0.5° latitude by 0.5° longitude spatial grid. In early experiments, we are using the existing PRISM SST reconstruction as the surface of the digital framework, adding innovative data and proxies that will allow us to weigh in on a number of different questions and problems regarding palaeoclimate and its fundamental relation to future climate.

5. Conclusions

The time for a paradigm shift in palaeoclimate reconstruction is overdue. With better understanding of climate dynamics, the demand for a global surface temperature field is being replaced by a need for more specific regional and process-oriented environmental information. Too often under the one site-one value system, disagreement of apparently good proxy-estimates has remained unaddressed when a systematic series of conceptual tests could have led to an understanding of the disagreement as an indication of a process. To ignore the differences and compare a two-dimensional reconstruction to model results is (1) presupposing that models are inherently correct and (2) discarding what is the potential key to a heretofore unachieved understanding of the deep-time environment. The next phase of PRISM is uniquely poised to provide palaeoenvironmental data for the most recent warm interval analogous to the near future because it holds within it a wealth of information and data (see Figure 6) that can be integrated to produce a more holistic picture of the Pliocene.

A new paradigm in marine palaeoclimate reconstruction is necessary and will be accomplished by 1) moving away from a global approach and focusing instead on regional climate dynamics with emphasis on processes, 2) integrating multiple environmental proxies wherever available, recognizing the more complete picture of the water column they provide, and 3) developing a finer time-slice of synchronous signature complemented by environmental snapshots within the time-slice (Figure 6).

There have traditionally been two ways to accomplish marine palaeoclimate reconstruction: time-series and time-slice. Both are perfectly valid approaches with very different assumptions and the ability to answer very different types of questions. What we envision here is a highly resolved time-slice approach incorporating nested regional and even local time-series of varying lengths. Thus, the next PRISM geospatial reconstruction will be constrained by orbital chronology -a series of time-slices integrated with time-series (Figure 7). For example, the oxygen isotope record at a site in the North Pacific will be a cornerstone for studies of the evolution of climate through the Pliocene in that region, while a bivalve from the Pinecrest Beds in Florida will provide magnitude of temperature change and a direct measure of seasonality over months to a few years. It is only with the full integration of these very different approaches that we can hope to truly understand the nature and variability of climate during this most recent episode of global warmth.

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7. References

1 CLIMAP. 1981 *Seasonal reconstructions of the earth's surface at the Last Glacial Maximum*. Map and Chart Series MC-36. Boulder, CO: Geological Society of America.

2 CLIMAP. 1984 The last interglacial ocean. *Quaternary Research* **21**(2), 123-224.

3 Kucera, M., Rosell-Melè, A., Schneider, R., Waelbroeck, C. & Weinelt, M. 2005 Multiproxy approach for the reconstruction of the glacial ocean surface (MARGO). *Q. Sci. Rev.* **24**, 813-819. (10.1016/j.quascirev.2004.07.017)

4 Dowsett, H., Thompson, R., Barron, J., Cronin, T., Fleming, F., Ishman, S., Poore, R., Willard, D. & Holtz Jr, T. 1994 Joint investigations of the middle Pliocene climate I: PRISM paleoenvironmental reconstructions. *Glob. Planet. Change* **9**, 169-195. (10.1016/0921-8181(94)90015-9)

5 Chandler, M. A., Rind, D. & Thompson, R. 1994 Joint investigations of the middle Pliocene climate II: GISS GCM Northern Hemisphere results. *Glob. Planet. Change* **9**, 197-219. (10.1016/0921-8181(94)90016-7)

6 Lunt, D. J., Haywood, A. M., Schmidt, G. A., Salzmann, U., Valdes, P. J. & Dowsett, H. J. 2010 Earth system sensitivity inferred from Pliocene modelling and data. *Nat. Geosci.* **3**, 60-64. (10.1038/ngeo706)

7 IPCC. 2007 *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds. S. Soloman, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor & H. L. Miller). Cambridge, UK: Cambridge University Press.

8 Allison, I., *et al.* 2009 The Copenhagen Diagnosis, 2009: Updating the World on the Latest Climate Science. *The University of New South Wales Climate Change Research Centre (CCRC), Sydney, Australia.*

9 Pagani, M., Liu, Z., LaRiviere, J. & Ravelo, A. C. 2010 High Earth-system climate sensitivity determined from Pliocene carbon dioxide. *Nat. Geosci.* **3**(1), 27-30.

10 Petit, J. *et al.*1999 Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. *Nature* **399**(6735), 429-436.

11 Siegenthaler, U. *et al*. 2005 Stable carbon cycle climate relationship during the Late Pleistocene. *Science* **310**(5752), 1313-1317.

12 Luthi, D. *et al*. 2008 High-resolution carbon dioxide concentration record 650,000-800,000 years before present. *Nature* **453**(7193), 379-382.

13 Hönisch, B., N. G. Hemming, D. Archer, M. Siddall & J. F. McManus. 2009 Atmospheric carbon dioxide concentration across the Mid-Pleistocene transition. *Science* **324**(5934), 1551-1554.

14 Bartoli, G., B. Hönisch, & R.E. Zeebe. 2011 Atmospheric CO_2 decline during the Pliocene intensification of Northern Hemisphere glaciations. *Paleoceanography* **26**(4), PA4213.

15 Dowsett, H., Robinson, M., Haywood, A., Salzmann, U., Hill, D., Sohl, L., Chandler, M., Williams, M., Foley, K. & Stoll, D. 2010 The PRISM3D paleoenvironmental reconstruction. *Stratigraphy* **7**, 123-139.

16 Miller, K. G., Wright, J. D., Browning, J. V., Kulpecz, A., Kominz, M., Naish, T. R., Cramer, B. S., Rosenthal, Y., Peltier, R. & Sosdian, S. 2012 The high tide of the warm Pliocene: Implications of global sea level for Antarctic deglaciation. *Geology* 27.

17 Salzmann, U., Haywood, A. M., Lunt, D. J., Valdes, P. J. & Hill, D. J. 2008 A new global biome reconstruction

and data-model comparison for the Middle Pliocene. *Glob. Ecol. Biogeogr.* **17**, 432-447. (10.1111/j.1466-8238.2008.00381.x)

18 Dowsett, H. J., Robinson, M. M. & Foley, K. M. 2009 Pliocene three-dimensional global ocean temperature reconstruction. *Clim. Past* **5**, 769-783. (10.5194/cp-5-769-2009)

19 Dowsett, H. J., Cronin, T. M., Poore, R. Z., Thompson, R. S., Whatley, R. C. & Wood, A. M. 1992 Micropaleontological evidence for increased meridional heat transport in the North Atlantic Ocean during the Pliocene. *Science* **258**, 1133-1135. (10.1126/science.258.5085.1133)

20 Sloan, L. C., Crowley, T. J. & Pollard, D. 1996 Modeling of middle Pliocene climate with the NCAR GENESIS general circulation model. *Mar. Micropaleontol.* **27**, 51-61. (10.1016/0377-8398(95)00063-1)

21 Haywood, A. M., Valdes, P. J. & Sellwood, B. W. 2002 Magnitude of climate variability during middle Pliocene warmth: a palaeoclimate modelling study. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **188**, 1-24. (10.1016/S0031-0182(02)00506-0)

22 Haywood, A. & Valdes, P. 2004 Modelling Pliocene warmth: contribution of atmosphere, oceans and cryosphere. *Earth Planet. Sci. Lett.* **218**, 363-377. (10.1016/S0012-821X(03)00685-X)

23 Dowsett, H. J., Chandler, M. A., Cronin, T. M. & Dwyer, G. S. 2005 Middle Pliocene sea surface temperature variability. *Paleoceanography* **20**, 1-8. (10.1029/2005PA001133)

24 Jiang, D., Wang, H., Ding, Z., Lang, X. & Drange, H. 2005 Modeling the middle Pliocene climate with a global atmospheric general circulation model. *J. Geophys. Res.* **110**, 107. (10.1029/2004JD005639)

25 Haywood, A. M., Valdes, P. J., Hill, D. J. & Williams, M. 2007 The mid-Pliocene warm period: a test-bed for integrating data and models In *Deep time perspectives on climate change: marrying the signal from computer models & biological proxies* (ed. M. Williams, A. M. Haywood, J. Gregory & D. N. Schmidt), pp. 443-457. London, UK: Geological Society of London and The Micropalaeontological Society

26 Lunt, D., Valdes, P., Haywood, A. & Rutt, I. 2008 Closure of the Panama Seaway during the Pliocene: implications for climate and Northern Hemisphere glaciation. *Clim. Dyn.* **30**, 1-18. (10.1007/s00382-007-0265-6)

27 Haywood, A. M.*, et al.* 2010 Pliocene Model Intercomparison Project (PlioMIP): experimental design and boundary conditions (Experiment 1). *Geosci. Model Dev.* **3**, 227-242. (10.5194/gmd-3-227-2010)

28 Haywood, A., Dowsett, H., Robinson, M., Stoll, D., Dolan, A., Lunt, D., Otto-Bliesner, B. & Chandler, M. 2011 Pliocene Model Intercomparison Project (PlioMIP): experimental design and boundary conditions (Experiment 2). *Geosci. Model Dev.* **4**, 571-577. (10.5194/gmdd-4-445-2011)

29 Chan, W.-L., Abe-Ouchi, A. & Ohgaito, R. 2011 Simulating the mid-Pliocene climate with the MIROC general circulation model: experimental design and initial results. *Geosci. Model Dev.* **4**, 1035-1049.

30 Koenig, S. J., DeConto, R. & Pollard, D. 2011 Pliocene Model Intercomparison Project: implementation strategy and mid-Pliocene Global climatology using GENESIS v3.0 GCM. *Geosci. Model Dev.* **4**, 2577-2603.

31 Yan, Q., Zhang, Z., Wang, H., Gao, Y. & Zheng, W. 2012 Set-up and preliminary results of mid-Pliocene climate simulations with CAM3.1. *Geosci. Model Dev.* **4**, 3339-3361.

32 Jansen, E.*, et al.* 2007 Paleoclimate. In *Climate change 2007: The Physical Science Basis. Contribution of*

Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (eds S. Solomon, M. Qin, Z. Manning, M. Chen, K. B. Marquis, M. T. Averyt & H. L. Miller). Cambridge, UK: Cambridge University Press.

33 Dowsett, H. J. 2007 The PRISM palaeoclimate reconstruction and Pliocene sea-surface temperature. In *Deep-time perspectives on climate change: marrying the signal from computer models and biological proxies* (eds M. Williams, A. M. Haywood, J. Gregory & D. N. Schmidt), 459-480. London, UK: Micropalaeontological Society (Special Publication), Geological Society of London.

34 Dowsett, H. J. & Robinson, M. M. 2009 Mid-Pliocene equatorial Pacific sea surface temperature reconstruction: a multi-proxy perspective. *Phil. Trans. R. Soc. A* **367**, 109-125. (10.1098/rsta.2008.0206)

35 Dowsett, H. J., Robinson, M. M., Stoll, D. K. & Foley, K. M. 2010 Mid-Piacenzian mean annual sea surface temperature analysis for data-model comparisons. *Stratigraphy* **7**, 189-198.

36 Dowsett, H. J. & Poore, R. Z. 1991 Pliocene sea surface temperatures of the North Atlantic Ocean at 3.0 Ma. *Q. Sci. Rev.* **10**, 189-204. (10.1016/0277-3791(91)90018-P)

37 Kucera, M. & Schonfeld, J. 2007 The origin of modern oceanic formainiferal faunas and Neogene climate change. In *Deep-Time Perspectives on Climate Change: Marrying the Signal from Computer Models and Biological Proxies*, pp. 409-425. London: The Micropalaeontological Society

38 Wade, B. S., Pearson, P. N., Berggren, W. A. & Pälike, H. 2011 Review and revision of Cenozoic tropical planktonic foraminiferal biostratigraphy and calibration to the geomagnetic polarity and astronomical time scale. *Earth Sci. Rev.* **104**, 111-142. (10.1016/j.earscirev.2010.09.003)

39 Sarnthein, M. & Tiedemann, R. 1989 Toward a high-resolution stable isotope stratigraphy of the last 3.4 million years: sites 658 and 659 off northwest Africa *Proc. ODP, Sci. Results* **108**, 167-185. (10.2973/odp.proc.sr.108.159.1989)

40 Shackleton, N. J., Crowhurst, S., Hagelberg, T., Pisias, N. G. & Schneider, D. A. 1995 A new Late Neogene time scale: application to Leg 138 sites *Proc. ODP, Sci. Results* **138**, 73-101.

41 Lisiecki, L. E. & Raymo, M. E. 2005 A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}O$ records. *Paleoceanography* **20**. (10.1029/2004PA001071)

42 Gradstein, F. M., Ogg, J. O. & Smith, A. G. (ed.) 2004 *A Geologic Time Scale* Cambridge, UK: Cambridge University Press.

43 Dowsett, H. J. 2009 Foraminifera. In *Encyclopedia of Paleoclimatology and Ancient Environments* (ed. V. Gornitz), pp. 338-339: Springer.

44 Ericson, D. B. & Wollin, G. 1956 Correlation of six cores from the equatorial Atlantic and the Caribbean. *Deep Sea Res.* **3**, 104-125.

45 Imbrie, J. & Kipp, N. G. 1971 A New Micropaleontological method for paleoclimatology: Application to a Late Pleistocene Caribbean core. In *The Late Cenozoic Glacial Ages* (ed. K. K. Turekian), pp. 71-181. New Haven, CT: Yale University Press.

46 Thunell, R. C. 1979 Pliocene - Pleistocene paleotemperature and paleosalinity history of the Mediterranean Sea: Results from DSDP Sites 125 and 132. *Mar. Micropaleontol.* **4**, 173-187. (10.1016/0377-8398(79)90013-6)

47 Dowsett, H. J. & Poore, R. Z. 1990 A new planktic foraminifer transfer function for estimating pliocene--Holocene paleoceanographic conditions in the North Atlantic. *Mar. Micropaleontol.* **16**, 1-23. (10.1016/0377-8398(90)90026-I)

48 Dowsett, H. J. 1991 The development of a long-range foraminifer transfer function and application to Late Pleistocene North Atlantic climatic extremes. *Paleoceanography* **6**, 259-273. (10.1029/90PA02541)

49 Thunell, R., Rio, D., Sprovieri, R. & Vergnaud-Grazzini, C. 1991 An Overview of the Post-Messinian Paleoenvironmental History of the Western Mediterranean. *Paleoceanography* **6**, 143-164. (10.1029/90pa02339)

50 Cronin, T. M. 2009 Ostracodes. In *Encyclopedia of Paleoclimatology and Ancient Environments* (ed. V. Gornitz): Springer Verlag.

51 Cronin, T. M. & Dowsett, H. J. 1990 A quantitative micropaleontologic method for shallow marine peleoclimatology: Application to Pliocene deposits of the western North Atlantic Ocean. *Mar. Micropaleontol.* **16**, 117-147. (10.1016/0377-8398(90)90032-H)

52 Cronin, T. M. 1991 Pliocene shallow water paleoceanography of the North Atlantic Ocean based on marine ostracodes. *Q. Sci. Rev.* **10**, 175-188. (10.1016/0277-3791(91)90017-O)

53 Cronin, T. M. 1991 Late Neogene Marine Ostracoda from Tjörnes, Iceland. *J. Paleontol.* **65**, 767-794.

54 Cronin, T. M., Whatley, R., Wood, A., Tsukagoshi, A., Ikeya, N., Brouwers, E. M. & Briggs, W. M., Jr. 1993 Microfaunal evidence for elevated Pliocene temperatures in the Arctic Ocean. *Paleoceanography* **8**, 161-173. (10.1029/93PA00060)

55 Cronin, T. M., Kitamura, A., Ikeya, N., Watanabe, M. & Kamiya, T. 1994 Late Pliocene climate change 3.4-2.3 Ma: paleoceanographic record from the Yabuta Formation, Sea of Japan. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **108**, 437-455. (10.1016/0031-0182(94)90245-3)

56 Ikeya, N. & Cronin, T. M. 1993 Quantitative analysis of Ostracoda and water masses around Japan: Application to Pliocene and Pleistocene paleoceanography. *Micropaleontology* **39**, 263-281.

57 Wood, A. M., Whatley, R. C., Cronin, T. M. & Holtz, T. 1993 Pliocene palaeotemperature reconstruction for the southern North Sea Based on Ostracoda. *Q. Sci. Rev.* **12**, 747-767. (10.1016/0277-3791(93)90015-E)

58 Cronin, T. M., Dowsett, H. J., Dwyer, G. S., Baker, P. A. & Chandler, M. A. 2005 Mid-Pliocene deep-sea bottom-water temperatures based on ostracode Mg/Ca ratios. *Mar. Micropaleontol.* **54**, 249-261. (10.1016/j.marmicro.2004.12.003)

59 Dowsett, H. J., Robinson, M. M., Dwyer, G. S., Chandler, M. A. & Cronin, T. M. 2006 PRISM 3 DOT1 Atlantic Basin Reconstruction. *U.S. Geological Survey Data Series 189*.

60 Dwyer, G. S. & Chandler, M. A. 2009 Mid-Pliocene sea level and continental ice volume based on coupled benthic Mg/Ca palaeotemperatures and oxygen isotopes. *Phil. Trans. R. Soc. A* **367**, 157-168. (10.1098/rsta.2008.0222)

61 Cortese, G., Gersonde, R., Hillenbrand, C.-D. & Kuhn, G. 2004 Opal sedimentation shifts in the World Ocean over the last 15 Myr. *Earth Planet. Sci. Lett.* **224**, 509-527. (10.1016/j.epsl.2004.05.035)

62 Armand, L. K., Crosta, X., Romero, O. & Pichon, J.-J. 2005 The biogeography of major diatom taxa in Southern Ocean sediments: 1. Sea ice related species. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **223**, 93-126.

63 Crosta, X., Romero, O. E., Armand, L. K. & Pichon, J.-J. 2005 The biogeography of major diatom taxa in Southern Ocean surface sediments: 2. Open-ocean related species. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **223**, 66-92.

64 Romero, O., Armand, L. K., Crosta, X. & Pichon, J. J. 2005 The biogeography of major diatom taxa in Southern Ocean sediments: 3. Tropical/Subtropical species. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **223**, 49-65.

65 Barron, J. A. 1992 Pliocene paleoclimatic interpretation of DSDP Site 580 (NW Pacific) using diatoms. *Mar. Micropaleontol.* **20**, 23-44. (10.1016/0377-8398(92)90007-7)

66 Barron, J. A. 1995 High resolution diatom paleoclimatology of the middle part of the Pliocene of the Northwest Pacific *Proc. ODP, Sci. Results* **145**, 43-53. (10.2973/odp.proc.sr.145.102.1995)

67 Barron, J. A., Cronin, T. M., Dowsett, H. J., Fleming, R. F., Holtz, T., Ishman, S. E., Poore, R. Z., Thompson, R. S. & Willard, D. A. 1995 Middle Pliocene paleoenvironments of the Northern Hemisphere. In *Paleoclimate and Evolution with Emphasis on Human Origins* (ed. E. S. Vrba, G. H. Denton, T. C. Partridge & L. H. Burckle), pp. 197-212. New Haven, CT: Yale University Press.

68 Barron, J. A. 1996 Diatom constraints on the position of the Antarctic Polar Front in the middle part of the Pliocene. *Mar. Micropaleontol.* **27**, 195-213.

69 Dowsett, H. J., Barron, J. & Poore, H. R. 1996 Middle Pliocene sea surface temperatures: a global reconstruction *Mar. Micropaleontol.* **27**, 13-25. (10.1016/0377-8398(95)00050-X)

70 Riesselman, C. R. & Dunbar, R. B. in press Diatom evidence for the onset of Pliocene cooling from AND-1B, McMurdo Sound, Antarctica. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* (10.1016/j.palaeo.2012.10.014)

71 Dwyer G. S., Cronin T. M., Baker P. A., Raymo M. E., Buzas J. S., & Correge T. 1995 North Atlantic deepwater temperature change during Late Pliocene and Late Quaternary climatic cycles. *Science* 270, 1347–1351.

72 Nürnberg D. 1995 Magnesium in tests of *Neogloboquadrina pachyderma* sinistral from high Northern and Southern latitudes. *J. Foraminiferal Res*. 25(4), 350–368.

73 Nürnberg D., Bijma J., & Hemleben C. 1996a Assessing the reliability of magnesium in foraminiferal calcite as a proxy for water mass temperatures. *Geochim. Cosmochim. Acta* 60(5), 803–814.

74 Nürnberg D., Bijma J., & Hemleben C. 1996b Erratum: assessing the reliability of magnesium in foraminiferal calcite as a proxy for water mass temperatures. *Geochim. Cosmochim. Acta* 60(13), 2483–2484.

75 Mashiotta T. A., Lea D. W., & Spero H. J. 1999 Glacial-interglacial changes in Subantarctic sea surface temperature and δ^{18}O-water using foraminiferal Mg. *Earth Planet. Sci. Lett*. 170(4), 417–432.

76 Elderfield H. & Ganssen G. 2000 Past temperature and d18O of surface ocean waters inferred from foraminiferal Mg/Ca ratios. *Nature* 405, 442–445.

77 Lea D. W., Pak D. K., & Spero H. J. 2000 Climate impact of Late Quaternary equatorial Pacific sea surface temperature variations. *Science* 289(5486), 1719–1724.

78 Lear C. H., Elderfield H., & Wilson P. A. 2000) Cenozoic deep-sea temperatures and global ice volumes from Mg/Ca in benthic foraminiferal calcite. *Science* 287, 269–272.

79 Dekens, P. S., D. W. Lea, D. K. Pak, & H. J. Spero, Core top calibration of Mg/Ca in tropical foraminifera: Refining paleotemperature estimation, *Geochem. Geophys. Geosyst*., 3(4), 10.1029/2001GC000200, 2002.

80 Anand, P., H. Elderfield, & M. H. Conte (2003), Calibration of Mg/Ca thermometry in planktonic foraminifera from a sediment trap time series, *Paleoceanography*, 18(2), 1050, doi:10.1029/2002PA000846.

81 Volkman, J. K., Eglinton, G., Corner, E. D. & Forsberg, T. 1980 Long-chain alkenes and alkenones in the marine coccolithophorid *Emiliania huxleyi*. *Phytochemistry* **19**, 2619-2622. (10.1016/S0031-9422(00)83930-8)

82 Conte, M. H., Volkman, J. K. & Eglinton, G. 1994 Lipid biomarkers of the Haptophyta. In *The Haptophyte Algae* (ed. J. C. Green & B. S. C. Leadbeater), pp. 351–377. Oxford: Clarendon Press.

83 Prahl, F. G., Muehlhausen, L. A. & Zahnle, D. L. 1988 Further evaluation of long-chain alkenones as indicators of paleoceanographic conditions. *Geochim. Cosmochim. Acta* **52**, 2303-2310. (10.1016/0016-7037(88)90132-9)

84 Müller, P. J., Kirst, G., Ruhland, G., von Storch, I. & Rosell-Melè, A. 1998 Calibration of the alkenone paleotemperature index U37K' based on core-tops from the eastern South Atlantic and the global ocean (60°N-60°S). *Geochimica et Cosmochimica Acta* **62**, 1757-1772. (10.1016/S0016-7037(98)00097-0)

85 Conte, M. H., Sicre, M.-A., Ruhlemann, C., Weber, J. C., Schulte, S., Schulz-Bull, D. & Blanz, T. 2006 Global temperature calibration of the alkenone unsaturation index (U^{k}_{37}) in surface waters and comparison with surface sediments. *Geochem. Geophys. Geosys.* **7**, 22. (10.1029/2005GC001054)

86 Raffi, S., Stanley, S. M. & Marasti, R. 1985 Biogeographic Patterns and Plio-Pleistocene Extinction of Bivalvia in the Mediterranean and Southern North Sea. *Paleobiology* **11**, 368-388.

87 Ward, L. W. & Blackwelder, B. W. 1987 Late Pliocene and Early Pleistocene Mollusca from the James City and Chowan River Formations at Lee Creek Mine In *Geology and Paleontology of the Lee Creek Lake, North Carolina, II*, vol. 61 (ed. C. E. Ray), pp. 113-283: Smithsonian Contributions to Paleobiology.

88 Ward, L. W. & Huddlestun, P. F. 1988 Age and stratigraphic correlation of the Raysor Formation, late Pliocene, South Carolina *Tulane Studies in Geology and Paleontology* **21**, 59-75.

89 Ward, L. W., Bailey, R. H. & Carter, J. G. 1991 Pliocene and early Pleistocene stratigraphy, depositional history, and molluscan paleobiogeography of the coastal plain. In *The geology of the Carolinas: Carolina Geological Society fiftieth anniversary volume* (ed. J. W. Horton & V. A. Zullo), pp. 274-289. Knoxville, TN University of Tennessee Press.

90 Fyles, J. G., Marincovich, L., Matthews, J. V. & Barendregt, R. W. 1991 Unique mollusc find in the Beaufort Formation (Pliocene) on Meighen Island, Arctic Canada *Geologic Survey of Canada, Current Research, Part B* **91-1B**, 105-112.

91 Gladenkov, Y. B., Barinov, K. B., Basilian, A. E. & Cronin, T. M. 1991 Stratigraphy and paleoceanography of Pliocene deposits of Karaginsky Island, eastern Kamchatka, U.S.S.R. *Q. Sci. Rev.* **10**, 239-245. (10.1016/0277-3791(91)90022-M)

92 Allmon, W. D., Rosenberg, G., Portell, R. W. & Schindler, K. 1996 Diversity of Pliocene-Recent mollusks in the western Atlantic: extinction, origination, and environmental change In *Evolution and environment in tropical America* (ed. J. B. C. Jackson, A. F. Budd & A. G. Coates), pp. 217-302. Chicago, IL: University of Chicago Press.

93 Marquet, R. 2004 Ecology and evolution of Pliocene bivalves from the Antwerp Basin. *Bulletin de l'Institut Royal des Sciences Naturelles de Belgique* **74**, 205-212.

94 Long, P. E. & Zalasiewicz, J. A. 2011 The molluscan fauna of the Coralline Crag (Pliocene, Zanclean) at Raydon Hall, Suffolk, UK: Palaeoecological significance reassessed. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **309**, 53-72. (10.1016/j.palaeo.2011.05.039)

95 Krantz, D. E. 1990 Mollusk-Isotope Records of Plio-Pleistocene Marine Paleoclimate, U.S. Middle Atlantic Coastal Plain. *PALAIOS* **5**, 317-335. (10.2307/3514888)

96 Jones, D. S. & Allmon, W. D. 1995 Records of upwelling, seasonality and growth in stable-isotope profiles of Pliocene mollusk shells from Florida. *Lethaia* **28**, 61-74. (10.1111/j.1502-3931.1995.tb01593.x)

97 Goewert, A. E. & Surge, D. 2008 Seasonality and growth patterns using isotope sclerochronology in shells of the Pliocene scallop *Chesapecten madisonius*. *GeoMar. Lett.* **28**, 327-338.

98 Williams, M., Haywood, A. M., Harper, E. M., Johnson, A. L. A., Knowles, T., Leng, M. J., Lunt, D. J., Okamura, B., Taylor, P. D. & Zalasiewics, J. 2009 Pliocene climate and seasonality in North Atlantic shelf seas. *Phil. Trans. R. Soc. A* **367**, 85-108. (10.1098/rsta.2008.0224)

99 Johnson, A. L. A., Hickson, J. A., Bird, A., Schöne, B. R., Balson, P. S., Heaton, T. H. E. & Williams, M. 2009 Comparative sclerochronology of modern and mid-Pliocene (c. 3.5 Ma) *Aequipecten opercularis* (Mollusca, Bivalvia): an insight into past and future climate change in the north-east Atlantic region. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **284**, 164-179. (10.1016/j.palaeo.2009.09.022)

100 Williams, M.*, et al.* 2010 Sea ice extent and seasonality for the Early Pliocene northern Weddell Sea. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **292**, 306-318. (10.1016/j.palaeo.2010.04.003)

101 Valentine, A., Johnson, A. L. A., Leng, M. J., Sloane, H. J. & Balson, P. S. 2011 Isotopic evidence of cool winter conditions in the mid-Piacenzian (Pliocene) of the southern North Sea Basin. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **309**, 9-16. (10.1016/j.palaeo.2011.05.015)

102 Okamura, B. & Bishop, J. D. D. 1988 Zooid size in cheilostome bryozoans as an indicator of relative palaeotemperature. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **66**, 145-152. (10.1016/0031-0182(88)90197-6)

103 Knowles, T., Leng, M., Williams, M., Taylor, P., Sloane, H. & Okamura, B. 2010 Interpreting seawater temperature range using oxygen isotopes and zooid size variation in *Pentapora foliacea* (Bryozoa). *Mar. Bio.* **157**, 1171-1180. (10.1007/s00227-010-1397-5)

104 Knowles, T., Taylor, P. D., Williams, M., Haywood, A. M. & Okamura, B. 2009 Pliocene seasonality across the North Atlantic inferred from cheilostome bryozoans. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **277**, 226-235. (10.1016/j.palaeo.2009.04.006)

105 Clark, N., Williams, M., Okamura, B., Smellie, J., Nelson, A., Knowles, T., Taylor, P., Leng, M., Zalasiewicz, J. & Haywood, A. 2010 Early Pliocene Weddell Sea seasonality determined from bryozoans. *Stratigraphy* **7**, 199-206.

106 de Vernal, A. & Hillaire-Marcel, C. 2000 Sea-ice cover, sea-surface salinity and halo-/thermocline structure of the northwest North Atlantic: modern versus full glacial conditions. *Q. Sci. Rev.* **19**, 65-85. (10.1016/S0277-3791(99)00055-4)

107 de Vernal, A.*, et al.* 2005 Reconstruction of sea-surface conditions at middle to high latitudes of the Northern Hemisphere during the Last Glacial Maximum (LGM) based on dinoflagellate cyst assemblages. *Q. Sci. Rev.* **24**,

897-924. (10.1016/j.quascirev.2004.06.014)

108 Schouten, S., Hopmans, E. C., Schefus, E. & Damste, S. 2002 Distributional variation in marine crenarchaeotal membrane lipids: a new tool for reconstructing ancient sea water temperatures? *Earth Planet. Sci. Lett.* **204**, 265-274.

109 Dowsett, H. J., Haywood, A. M., Valdes, P. J., Robinson, M. M., Lunt, D. J., Hill, D. J., Stoll, D. K. & Foley, K. M. 2011 Sea surface temperatures of the mid-Piacenzian Warm Period: A comparison of PRISM3 and HadCM3. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **309**, 83-91. (10.1016/j.palaeo.2011.03.016)

110 Reynolds, R. W. & Smith, T. M. 1995 A High-Resolution Global Sea Surface Temperature Climatology. *J Clim.* **8**, 1571-1583.

111 Levitus, S. & Boyer, T. P. 1994 World ocean atlas 1994: Temperature In *NOAA Atlas NESDIS* Vol. 4. Washington, DC: US Department of Commerce.

112 Dowsett, H.J., Robinson, M.M., Haywood, A.M., Hill, D.J., Dolan, A.M., Stoll, D.K., Chan, W.-L., Abe-Ouchi, A., Chandler, M.A., Rosenbloom, N.A., Otto-Bliesner, B.L., Bragg, F.J., Lunt, D.J., Foley, K.M., & Riesselman, C.R., 2012. Assessing confidence in Pliocene sea surface temperatures to evaluate predictive models, *Nature Climate Change* 2: 365-371, doi: 10.1038/NCLIMATE1455.

113 Dowsett, H. J. & Robinson, M. M. 2006 Stratigraphic framework for Pliocene paleoclimate reconstruction: The correlation conundrum. *Stratigraphy* **3**, 53-64.

114 Robinson, M. M., Dowsett, H. J., Dwyer, G. S. & Lawrence, K. T. 2008 Reevaluation of mid-Pliocene North Atlantic sea surface temperatures. *Paleoceanography* **23**. (10.1029/2008PA001608)

115 Rickaby, R. E. M. & Halloran, P. 2005 Cool La Niña During the Warmth of the Pliocene? *Science* **307**, 1948-1952. (10.1126/science.1104666)

116 Wara, M. W., Ravelo, A. C. & Delaney, M. L. 2005 Permanent El Niño-Like Conditions During the Pliocene Warm Period. *Science* **309**, 758-761. (10.1126/science.1112596)

117 Ragaini, L., Di Celma, C. & Cantalamessa, G. 2008 Warm-water mollusc assemblages from northern Chile (Mejillones Peninsula): new evidence for permanent El Niño-like conditions during Pliocene warmth? *J. Geol. Soc.* **165**, 1075-1084. (10.1144/0016-76492007-039)

118 Naish, T., *et al.* 2009 Obliquity-paced Pliocene West Antarctic ice sheet oscillations. *Nature* **458**, 322-328. (10.1038/nature07867)

119 Robinson, M. M. 2009 New quantitative evidence of extreme warmth in the Pliocene Arctic. *Stratigraphy* **6**, 265-275.

120 Willard, D. A. 1994 Palynological record from the North Atlantic region at 3 Ma: vegetational distribution during a period of global warmth. *Rev. Palaeobot. Palynol.* **83**, 275-297. (10.1016/0034-6667(94)90141-4)

121 Willard, D. A. 1996 Pliocene-Pleistocene pollen assemblages from the Yermak Plateau, Arctic Ocean, sites 910 and 911. *Proc. ODP, Sci. Results* **151**, 297-305. (10.2973/odp.proc.sr.151.115.1996)

122 Salzmann, U., Williams, M., Haywood, A. M., Johnson, A. L. A., Kender, S. & Zalasiewicz, J. 2011 Climate and environment of a Pliocene warm world. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **309**, 1-8. (10.1016/j.palaeo.2011.05.044)

123 De Schepper, S., Head, M. J. & Louwye, S. 2004 New dinoflagellate cyst and incertae sedis taxa from the Pliocene of northern Belgium, southern North Sea Basin *J. Paleontol.* **78**, 625-644. (10.1666/0022-3360(2004)078<0625:NDCAIS>2.0.CO;2)

124 De Schepper, S., Head, M. J. & Groeneveld, J. 2009 North Atlantic Current variability through marine isotope stage M2 (circa 3.3 Ma) during the mid-Pliocene. *Paleoceanography* **24**, PA4206. (10.1029/2008pa001725)

125 De Schepper, S., Fischer, E. I., Groeneveld, J., Head, M. J. & Matthiessen, J. 2011 Deciphering the palaeoecology of Late Pliocene and Early Pleistocene dinoflagellate cysts. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **309**, 17-32. (10.1016/j.palaeo.2011.04.020)

126 Naafs, B.D.A., Stein, R., Hefter, J., Khélifi, N., De Schepper, S. & Haug, G. 2010. Late Pliocene changes in the North Atlantic Current, *Earth Planet. Sci. Lett*. doi:10.1016/j.epsl.2010.08.023

127 Bjørklund, K.R., Kruglikova, S.B. & Anderson, O.R. 2012. Modern incursions of tropical Radiolaria into the Arctic Ocean. *Journal of Micropalaeontology,* **31,** 139-158.

128 Matul, A., Khusid, T., Mukhina, V., Chekhovskaya, M, & Safarova, S. 2007. Recent and Late Holocene environments on the southeastern shelf of the Laptev Sea as inferred from microfossil data. *Oceanology*, **47**(1), 80-90.

129 Bauch, H. A., Kassens, H., Erlenkeuser, H., Grootes, P. M., & Thiede, J. 1999. Depositional environment of the Laptev Sea (Arctic Siberia) during the Holocene. *Boreas* **28**, 194–204.

130 Dowsett, H. & Willard, D. 1996 Southeast Atlantic marine and terrestrial response to middle Pliocene climate change. *Mar. Micropaleontol.* **27**, 181-193. (10.1016/0377-8398(95)00059-3)

131 Dekens, P. S., Ravelo, A. C. & McCarthy, M. D. 2007 Warm upwelling regions in the Pliocene warm period. *Paleoceanography* **22**, 12. (10.1029/2006pa001394)

132 Reed-Sterrett, C., Dekens, P. S., White, L. D. & Aiello, I. W. 2010 Cooling upwelling regions along the California margin during the early Pliocene: evidence for a shoaling thermocline. *Stratigraphy* **7**, 141-150.

133 Martinez-Garcia, A., Rosell-Mele, A., McClymont, E.L., Gersonde, R., Haug, G.H., 2010. Subpolar Link to the Emergence of the Modern Equatorial Pacific Cold Tongue. Science 328, 1550-1553.

134 Etourneau, J., Martinez, P., Blanz, T., Schneider, R., 2009. Pliocene-Pleistocene variability of upwelling activity, productivity, and nutrient cycling in the Benguela region. Geology 37, 871-874.

135 Laskar, J., Robutel, P., Joutel, F., Gastineau, M., Correia, A. C. M. & Levrard, B. 2004 A long-term numerical solution for the insolation quantities of the Earth. *Astron. Astrophys.* **428**, 261-285.

136 Butler, P. G., Richardson, C. A., Scourse, J. D., Wanamaker, A. D., Shammon, T. M. & Bennell, J. D. 2010 Marine climate in the Irish Sea: analysis of a 489-year marine master chronology derived from growth increments in the shell of the clam *Arctica islandica*. *Q. Sci. Rev.* **29**, 1614-1632.

137 Schone, B. R., Oschmann, W., Rossler, J., Freyre Castro, A. D., Houk, S. D., Kröncke, I., Dreyer, W., Janssen, R., Rumohr, H. & Dunca, E. 2003 North Atlantic Oscillation dynamics recorded in shells of a long-lived bivalve mollusk. *Geology* **31**, 1037-1040.

138 Schone, B. R., Fiebig, J., Pfeiffer, M., Gle, R., Hickson, J., Johnson, A. L. A., Dreyer, W. & Oschmann, W. 2005 Climate records from a bivalved Methuselah (*Arctica islandica*, Mollusca; Iceland). *Palaeogeogr.*

Palaeoclimatol. Palaeoecol. **228**, 130-148. (10.1016/j.palaeo.2005.03.049)

Figure Captions

Figure 1. Composite record of atmospheric $p\mathrm{CO}_2$ estimates from 4.6 Ma to present. $p\mathrm{CO}_2$ Values plotted from present day to 0.8 Ma are obtained from ice core records [10-12]. $p\mathrm{CO}_2$ values from 0.8 Ma to 2.0 Ma are plotted as a black line with shaded area indicating propagated uncertainties of proxies used in calculation of $p\mathrm{CO}_2$. [13]. Values of $p\mathrm{CO}_2$ from 2.0 Ma to 4.6 Ma are plotted as a black line and a shaded area with an upper boundary calculated with correction for variation in SST, and a lower boundary calculated with correction for variation in $\delta^{11}\mathrm{B}_{sw}$ [14].

Figure 2. Pliocene stratigraphic framework and position of PRISM time-slab (shaded horizontal band) and benthic $\delta^{18}\mathrm{O}$ stack from Lisiecki and Raymo [41]. Blow up shows detail of the $\delta^{18}\mathrm{O}$ stack for the mid-Piacenzian and the new KM5c time-slice is highlighted in red. On far right is an example of warm peak average (WPA) process. WPA utilizes those warm peaks (•) in the time-slab that do not fall below a predefined communality level (•) to develop an "average interglacial" SST. Maximum and minimum warm peaks are also designated and together provide a "climatological error bar" about the WPA estimate.

Figure 3. Distribution of proxy estimates of sea surface temperature in the PRISM synthesis from (a) foraminifera, (b) alkenones, (c) foraminiferal Mg/Ca and (d) ostracods, diatoms, mollusks and radiolaria.

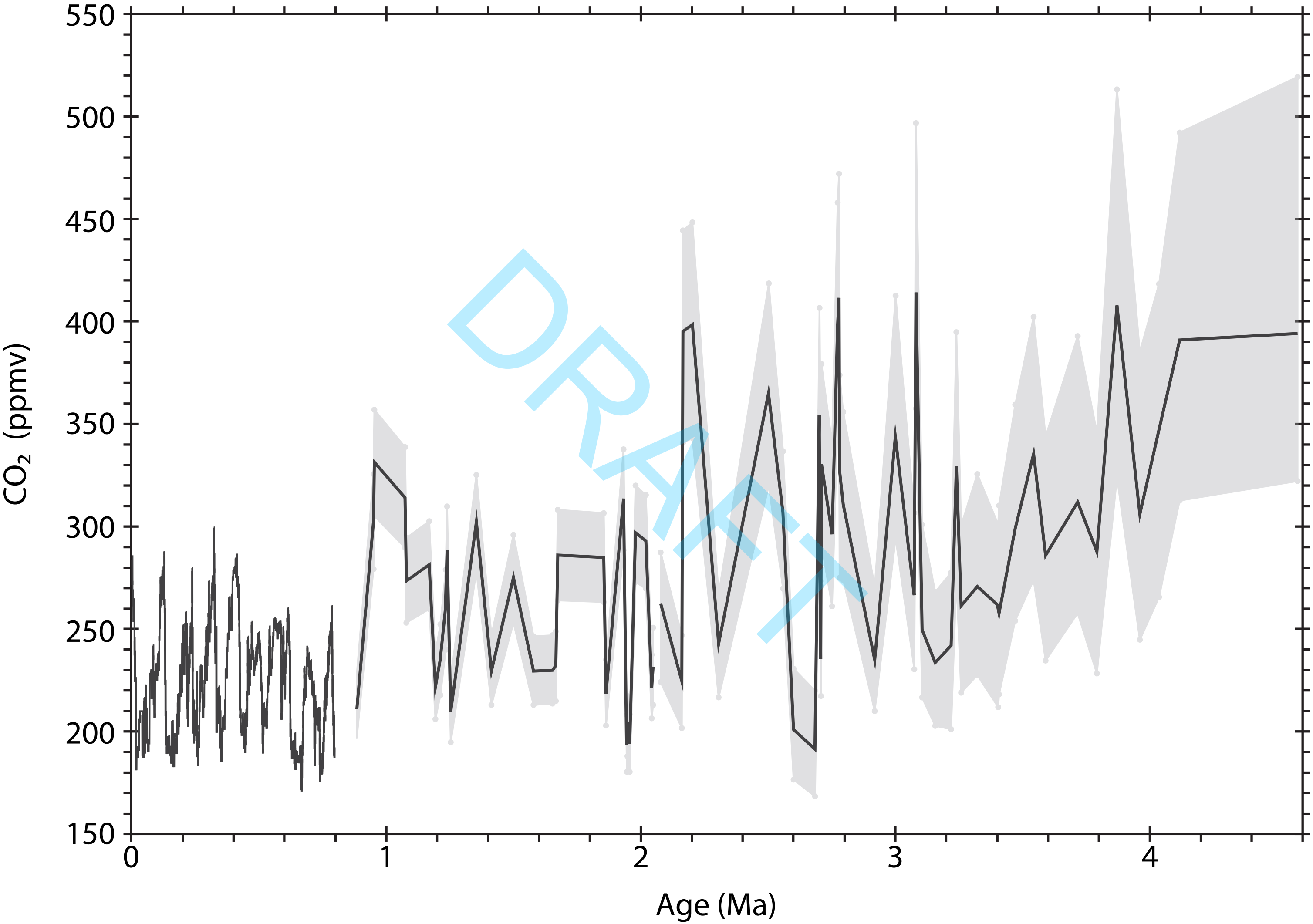
Figure 4. PRISM3 monthly SST maps. Yearly cycle is created by fitting a sine curve to the February and August estimates in each 2° latitude by 2° longitude grid cell and sampling the curve to derive the remaining 10 months of the year.

Figure 5. Mean annual SST anomalies (Pliocene minus present day) used in the PRISM3 marine reconstruction. Symbol size indicates λ confidence level and is categorized as low, medium, high or very-high [107]. Low confidence sites are not included in the PRISM reconstruction.

Figure 6. Mid-Piacenzian generalized marine environment. PRISM *archives* include (1) deep-sea cores and (2) outcrops on land. *Palaeoenvironments sampled* range from (3) shelf to (4) open-ocean and (5) deep-ocean bottom. *Signal carriers* include (a) planktonic and (b) benthic foraminifers, (c) ostracods, (d) diatoms, (e) calcareous nannoplankton, (f) radiolaria, (g) dinoflagellates, (h) picoplankton, (i) mollusks and (j) bryozoa. Fish teeth (also used as signal carriers) are not figured. Quantitative analysis of planktonic and benthic foraminifer, diatom, radiolaria and dinoflagellate assemblages provide SST, shallow bottom water temperature (SBT), productivity, salinity and sea ice distribution. Calibrated biomarker molecules derived from nanno- and picoplankton provide additional SST information. Macro invertebrate assemblages provide semi-quantitative estimates of SBT and mean annual range in temperature (MART). Oxygen isotopic analysis of mollusks allows for seasonality estimates. Mg/Ca analysis of planktonic and benthic foraminifers establishes independent SST, SBT and deep ocean temperature (DOT). Paired Mg/Ca and oxygen isotopic analyses on deep ocean benthic

foraminifers and ostracods allow for sea level and global ice volume estimates. Analysis of stable carbon isotopes on benthic foraminifers and Nd derived from fish teeth provide estimates of palaeocirculation. An increased understanding of the timing and variability of production of these signal carriers and knowledge of their environmental preferences (e.g. depth habitat) provide a means of analyzing upwelling systems and constraining circulation (shown by arrows).

Figure 7. Conceptual illustration of the potential data contained in the PRISM4D reconstruction. The Pliocene ocean is gridded into 2° latitude by 2° longitude cells. Within cells containing data there may be multiple proxies for different environmental parameters and a number of signal carriers. In the hypothetical example shown, faunal and floral data present in the cell allow for (a) assemblage based SST estimates of cold and warm seasons as well as mean annual temperature, (b) Mg/Ca and alkenone based SST estimates, (c) productivity, (d) sea-surface salinity, (e) bottom water temperature, (f) MART and (g) macro-invertebrate based seasonality. Different cells will contain different data types and the entire record is tied to age, providing the 4th dimension.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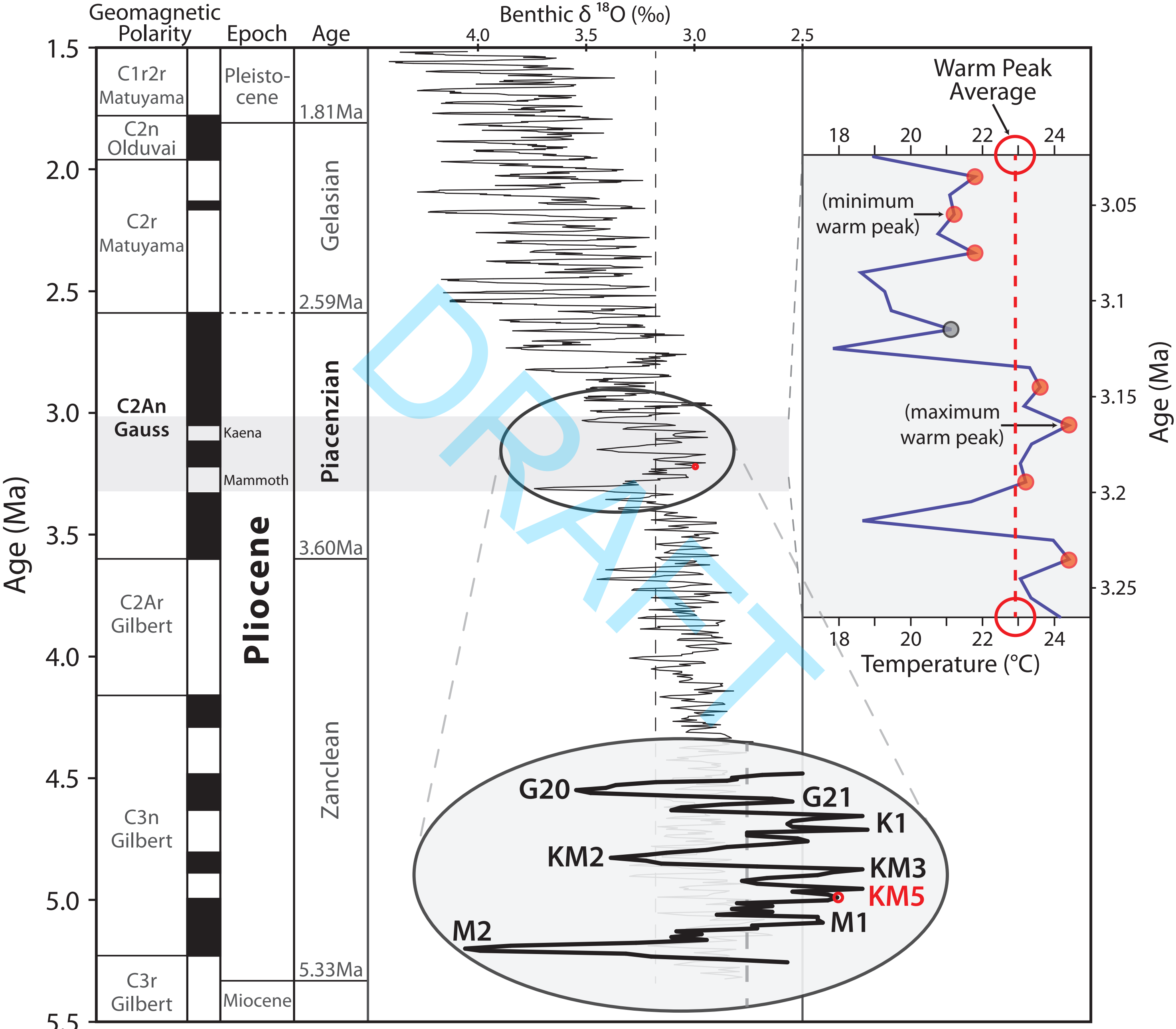
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C2An Gauss
Kaena
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C3n Gilbert
C3r Gilbert
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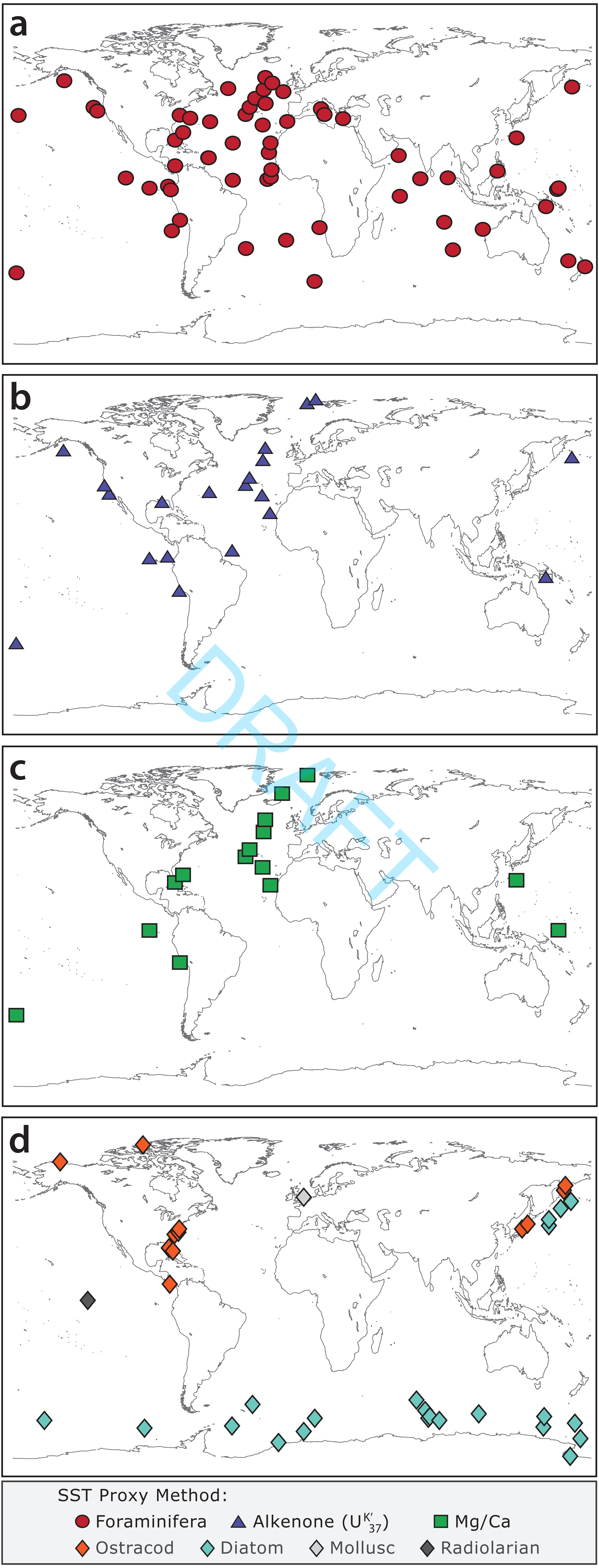
Dowsett F2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SST Proxy Method:
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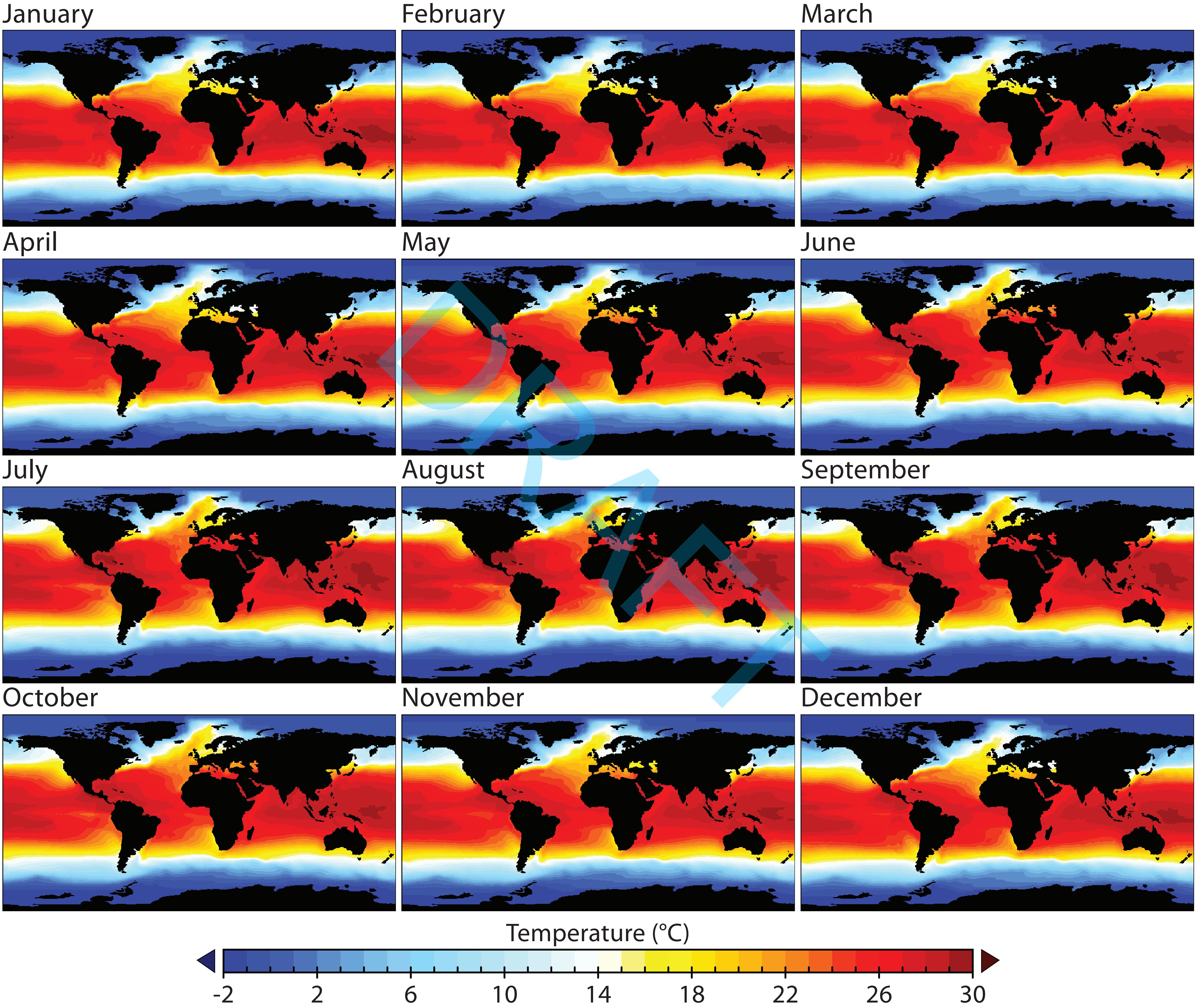
◇ Mollusc
◆ Radiolarian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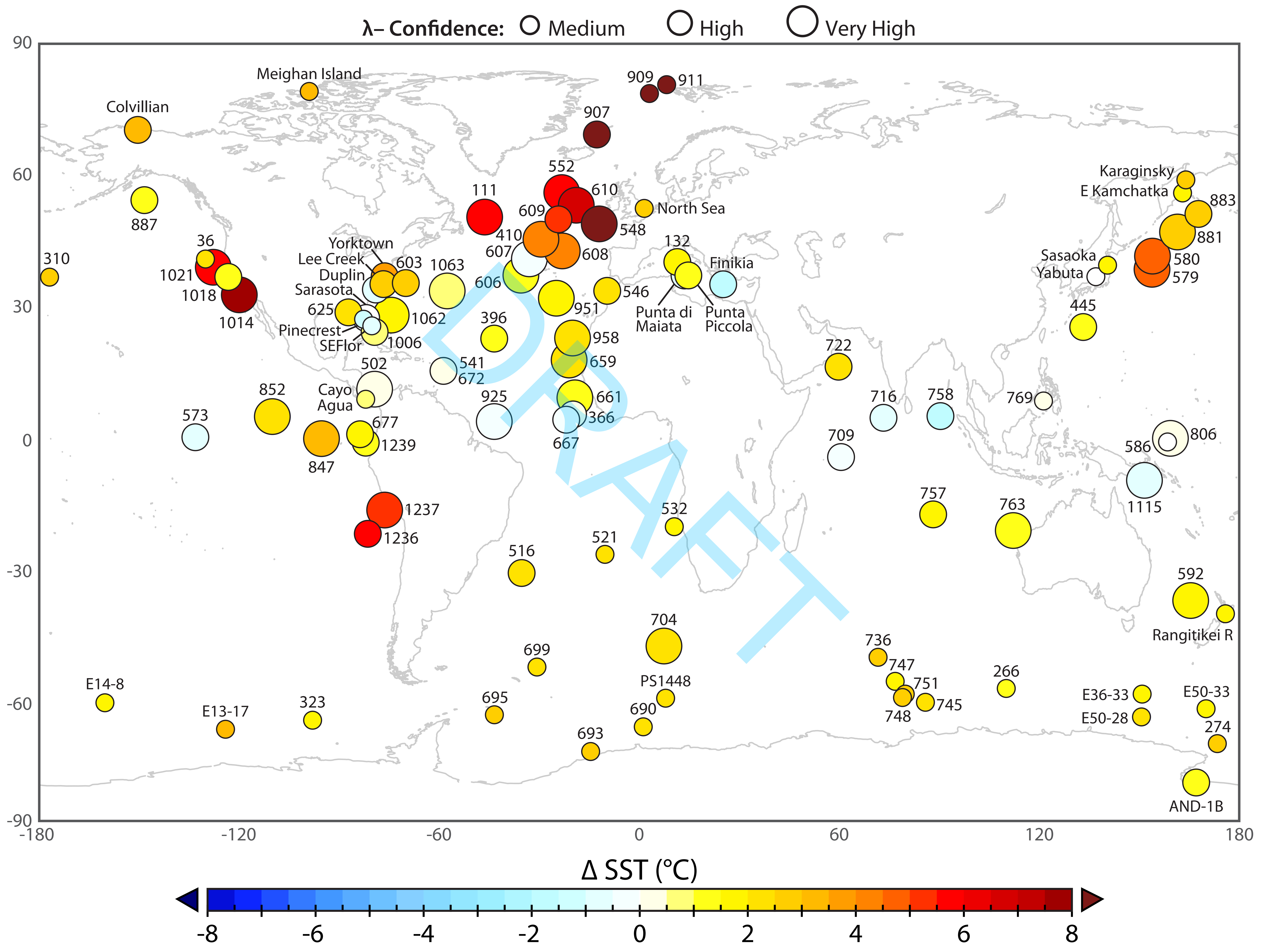
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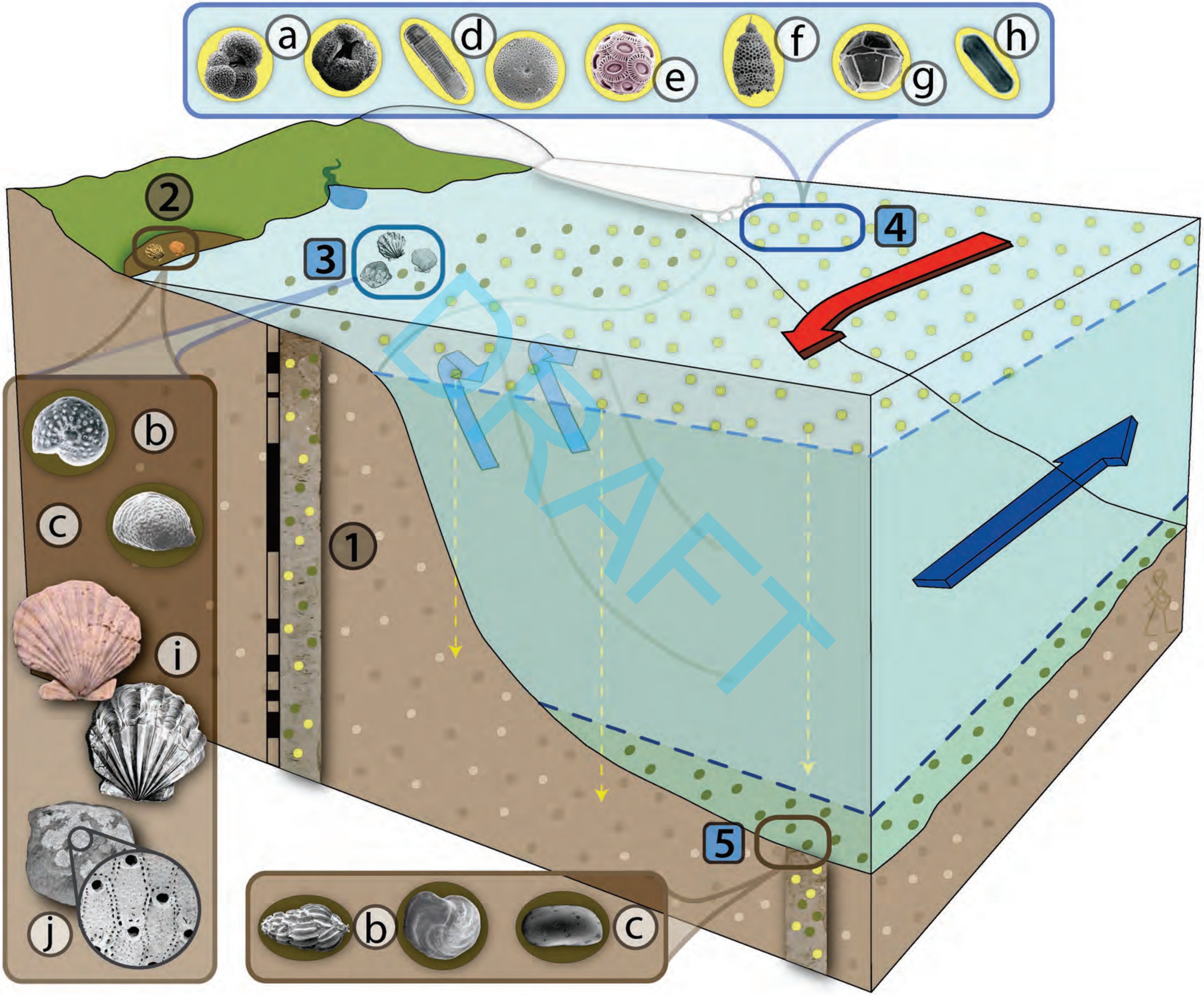
6
8


a
d
e
f
g
h
2
3
4
1
b
c
i
j
5
b
c

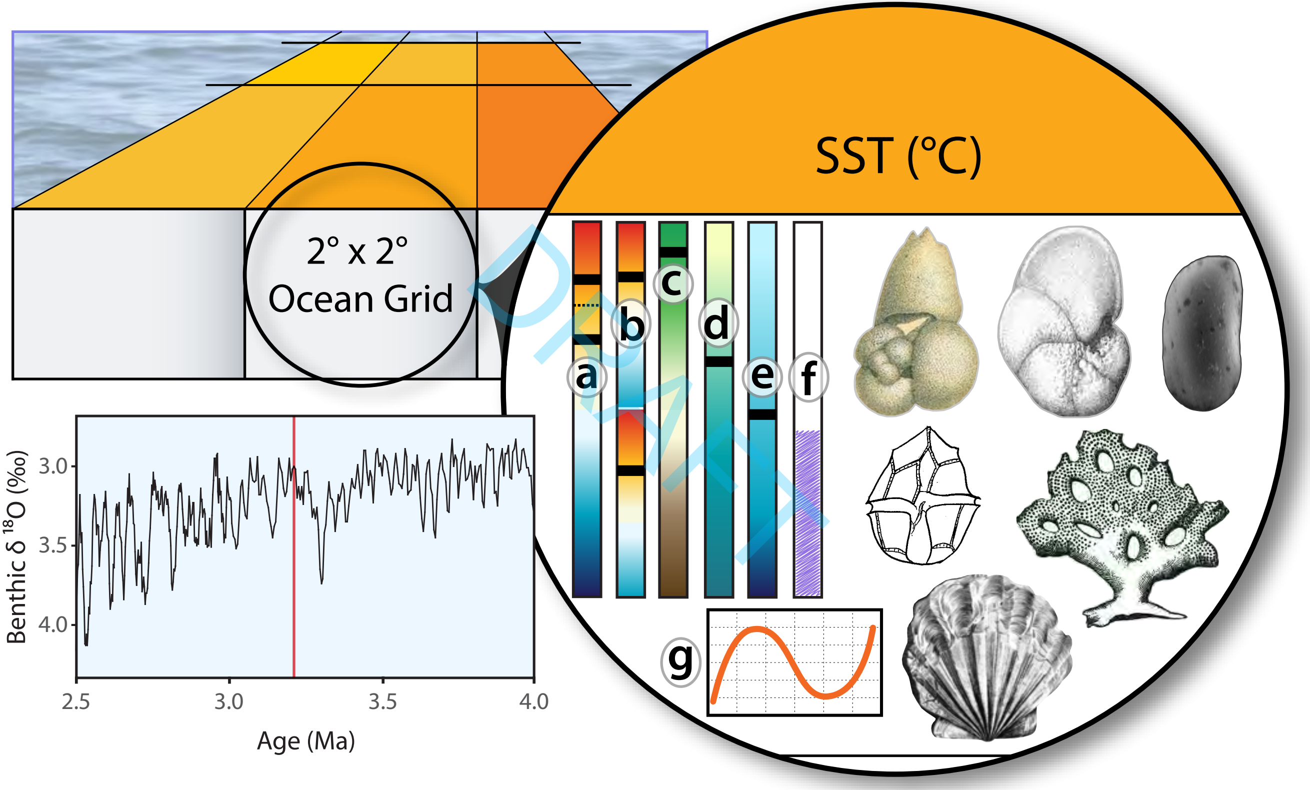

2° x 2°
Ocean Grid
SST (°C)
a
b
c
d
e
f
g
Benthic δ 18O (‰)
3.0
3.5
4.0
2.5
3.0
3.5
4.0
Age (Ma)

Table 1. PRISM3D Reconstruction

Description	Filename
Ocean	
PRISM3 12-Month Sea Surface Temperature, Sea Ice	PRISM3_SST_v1.0
PRISM3 Mean Annual SST Anomaly Validation Data Set	PRISM3_MASST_anomaly
PRISM3 Atlantic Deep Ocean Temperature, Sea Ice	atlantic_dot_v1.0
PRISM3 Global Deep Ocean Temperature, Sea Ice	global_dot_v2.0
PRISM3 Dec. 1 Sea Surface Temperature Anomaly	PRISM3_anom_dec_1_4x5
Vegetation	
PRISM3/BAS Biome Land cover, ice v1.0	BAS_P3_biome_veg_v1.0
PRISM3/BAS Megabiome Land cover, ice v1.0	BAS_P3_mbiome_veg_v1.0
Land/Sea Mask, Topography, Ice Sheets	
	land_fraction_v1.1
	topo_v1.1

Table 2. PlioMIP Boundary Conditions.

Description	Preferred	Alternate
Fractional land/sea grid	land_fraction_v1.1	land_fraction_v1.3
Topography	topo_v1.1	topo_v1.4
Vegetation	biome_veg_v1.3 mbiome_veg_v1.3	biome_veg_v1.2 mbiome_veg_v1.2
Ocean Temperature	PRISM3_SST_v1.1 global_dot_v2.0	PRISM3_SST_v1.3 global_dot_v2.0