Paleoceanography and Paleoclimatology

RESEARCH ARTICLE
10.1029/2021PA004236

Special Section: Cenozoic Evolution of Mountains, Monsoons, and the Biosphere

Key Points:
- A high-resolution, continuous benthic foraminiferal oxygen isotope record is presented using sediments of IODP Site U1427 (Exp. 346).
- MIS 24-17 are characterized by the glacial near-isolation of the Japan Sea, while for stages 39-25 an improved connection is suggested.
- Presenting a new core-top Mg/Ca-temperature calibration for *Uvigerina spp.* from the Japan Sea and revised age model for IODP Site U1427.

Supporting Information: Supporting Information may be found in the online version of this article.

Correspondence to: S. Felder, s.felder1@ncl.ac.uk; sonja.felder@ewetel.net

Citation: Felder, S., Sagawa, T., Greaves, M., Leng, M. J., Ikehara, K., Kimoto, K., et al. (2022). Paleoceanography of the Japan Sea across the mid-Pleistocene transition: Insights from IODP Exp. 346, Site U1427. *Paleoceanography and Paleoclimatology*, 37, e2021PA004236. https://doi.org/10.1029/2021PA004236

Received 4 FEB 2021
Accepted 9 NOV 2021

Author Contributions:
Formal analysis: Thomas Wagner
Resources: Thomas Wagner
Supervision: Thomas Wagner

© 2021. The Authors. This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

Abstract
Large-scale atmospheric circulation patterns, such as the East Asian monsoon, have been proposed as possible feedbacks of the mid-Pleistocene transition (MPT). Marine sediments of the Japan Sea (JS) record variations in the East Asian monsoon over long timescales and may be crucial for understanding of the MPT. To interpret these sediments correctly an understanding of the JS paleoceanography is necessary. So far, the JS paleoceanography has been extrapolated across the MPT from studies of the most recent glacial-interglacial cycles. These suggest a good connection and unrestricted water-mass exchange with the open ocean during interglacial sea-level highstands, while during glacial sea-level lowstands the JS is nearly isolated. Glacial isolation often results in poor carbonate preservation and unusually low oxygen isotope (δ¹⁸O) ratios from low-saline/low-δ¹⁸O waters accumulating in the basin. Using the sediments of Integrated Ocean Drilling Program (IODP) Site U1427, a shallow-water site in the southern JS, we present a continuous foraminiferal δ¹⁸O record encompassing the MPT. This record shows the JS-typical low glacial δ¹⁸O values in the late phase of the MPT, across Marine Isotope Stages (MIS) 24-17, while earlier MPT glacial, across MIS 39-25, are characterized by high δ¹⁸O values. We propose that high glacial δ¹⁸O values are the result of an improved connection between the shallow, southern JS and adjacent ocean during early MPT glacialis. The impact of this paleoceanographic mode, if continued to deep-water sites, would make the interpretation of dark/light sediment layers as glacial/interglacial deposits uncertain.

1. Introduction
1.1. The Mid-Pleistocene Transition and the East Asian Monsoon

The Quaternary period is characterized by glacial-interglacial variability that has been linked to Earth's orbital cyclicity (e.g., Hays et al., 1976; Ruddiman, 2001). During the early part of the Quaternary, glacial-interglacial cycles varied at a frequency of 41,000 years (41 ka), but approximately half-way through the Quaternary, during the mid-Pleistocene, the glacial-interglacial cycle shifted to quasi 100,000 years (100 ka) cycles (e.g., Lisiecki & Raymo, 2005; Zachos et al., 2001). The transition period between 41 ka and 100 ka is centred at ~1200 to 600 ka and often referred to as the mid-Pleistocene transition (MPT). After the MPT, glacialis became more intense, producing larger ice-sheets that decayed more rapidly at glacial terminations (e.g., Lisiecki & Raymo, 2005; Pisia & Moore, 1981; Shackleton & Opdyke, 1976) and greater sea-level variations, as inferred from global, open ocean sea-level reconstructions (e.g., Bintanja et al., 2005; Berends et al., 2019; Elderfield et al., 2012; Rohling et al., 2014). Before the MPT (~2.700–1200 ka), global eustatic sea-level fluctuations were small, having an average glacial sea-level drop of ~60 to ~80 m, compared to the larger sea-level falls of the last ~900 ka, when glacial sea-levels were up to 120 m higher than present (cf. Sosdian & Rosenthal, 2009). Crucially, the MPT occurred in the absence of changes in orbital/Milankovitch forcing, implying the mechanisms for the emergence of the 100 ka cycles are internal to the Earth's climate system. Proposed forcing mechanisms include changes in ice-sheet dynamics (e.g., Chalk et al., 2017; Clark et al., 2006; Imbrie et al., 1993; Raymo...
et al., 1997) and feedback mechanisms associated with changes in the carbon cycle, including atmospheric CO$_2$ drawdown and ocean carbon storage (e.g., Chalk et al., 2017; DeMenocal, 1995; Farmer, Goldstein, et al., 2019; Hönisch et al., 2009; Higgins et al., 2015; Hasenfratz et al., 2019; Kender et al., 2018; Lear et al., 2016; Martín-García et al., 2011; Pena & Goldstein, 2014; Ruddiman, 2003, 2004; Sosdian et al., 2018; Shackleton, 2000). Large-scale atmospheric circulation patterns, such as the East Asian monsoon, have also been suggested as possible important influences, acting as fast conveyers of climate signals and triggers between ocean basins and across continents (Clark et al., 1999; Kubota et al., 2010; Porter & An, 1995; Tada, 2004; Tada et al., 2015a).

Records of past East Asian monsoon variations, particularly of the East Asian summer monsoon, which is characterized by its precipitation, can be found in continental archives, such as speleothems of Chinese caves, and lake and/or loess-paleosol sequences on the Chinese Loess Plateau (Cheng et al., 2016; Ruddiman, 2001; Wang et al., 2001; Wang et al., 2008). These are, however, not ideal archives to trace the monsoon across the MPT, for example, as they do not encompass the MPT (longest Chinese speleothem record ~640 ka, longest lake record ~20 ka), can contain gaps/hiatuses (e.g., lakes that do not record when dried out, erosion of loess deposits), and there is debate about whether they record the monsoon precipitation intensity or rather atmospheric circulation changes (Cheng et al., 2016; Clemens et al., 2010; Lu et al., 2006; Maher & Thompson, 2012; Obreht et al., 2019; Wang et al., 2001; Wang et al., 2008; Zhang et al., 2018). Marine records of East Asian summer monsoon variations may be more reliable as they record regional precipitation changes through freshwater runoff and they may also be more complete (Clemens et al., 2018).

1.2. Influences of Variations in Glacio-Eustatic Sea-Level and the East Asian Summer Monsoon on Japan Sea Paleocceanography

The Japan Sea (JS) palaeoceanography is sensitive to variations in glacio-eustatic sea-level due to its shallow sills connecting it with the open ocean, all being shallower than 130 m at present (Lee & Choi, 2015; Oba et al., 1991; Tada, 1994; Tada et al., 1999; Figure 1). The main inflow to the JS is the Tsushima Warm Current (TWC), which enters through the Tsushima Strait (TSS) in the south (Figure 1). It is estimated that during sea-level lowstands of the most recent glacial, around −134 to −120 m (Lambeck et al., 2014; Sosdian & Rosenthal, 2009), most of the TSS sill (present water depth ∼130 m) had dried up and there was negligible inflow (Matsui et al., 1998; Tada et al., 1999), leaving the JS nearly isolated (Ingle, 1975; Matsui et al., 1998; Oba et al., 1991; Saavedra-Pellitero et al., 2019; Tada, 1994; Tada et al., 1999; Watanabe et al., 2007).

In addition to the glacio-eustatic influences, the JS is also characterized by variations in the East Asian summer monsoon precipitation. Part of the monsoon precipitation from the East Asian hinterland enters through two of the world's largest rivers, the Yangtze and Yellow Rivers (e.g., Zhang et al., 2016), both of which drain onto the East China Sea shelf (Figure 1). Here the freshwater mixes with ocean waters, reducing sea-water salinities and increasing water nutrient contents, and forming the East China Sea Coastal Water (ECSCW). A branch of the ECSCW is directed into the JS, where it joins the Tsushima Warm Current (Figure 1), and its warm, nutrient-enriched waters prime marine productivity (e.g., Oba et al., 1991; Saavedra-Pellitero et al., 2019; Tada et al., 1999).

As a result of the (near) isolation of the JS and the input of low saline waters (ECSCW, precipitation over the basin, river runoff from surrounding landmasses) during glacial, the water column becomes stratified. This stratification can lead the bottom waters at >500 m water depth to become corrosive to carbonates, resulting in widespread carbonate dissolution (e.g., Dunbar et al., 1992; Ikehara, 1991; Ikehara et al., 1994; Kido et al., 2007; Oba et al., 1991; Tada, 1994; Tada et al., 1992).

The poor carbonate preservation causes incomplete microfossil and foraminifera-based oxygen isotope records, δ$^{18}$O, resulting in difficulties and hindering the establishment of robust geochronologies for JS sediments (Dunbar et al., 1992; Oba et al., 1991; Tada, 1994). Furthermore, the accumulation of low-saline and, more crucially, low-δ$^{18}$O waters can imprint on δ$^{18}$O records, leading to unusually low glacial δ$^{18}$O values and making records challenging and often counterintuitive to interpret (Oba et al., 1991; Saavedra-Pellitero et al., 2019; Sagawa et al., 2018; Tada, 1994; Tada et al., 1992; Tada et al., 1999). During the Last Glacial maximum, for example, the input of large amounts of monsoon runoff/freshwater evened out glacial temperature drops in foraminiferal δ$^{18}$O records of the JS (Oba et al., 1991; Oba & Irino, 2012).

Detailed studies of the connection between the JS palaeoceanography and variations in monsoon precipitation, i.e., relative contributions of ECSCW to the TWC, exist for the sediments of ODP Site 797 (~2,860 m water
Tada et al. (1999) analyzed metre to sub-metre scale sediment color alterations—dark (interstadial) and light (stadial)—at ODP Site 797, encompassing the last ~200 ka (MIS 1-7). It is suggested that at sea-level stands greater than ~90 m below present (TSS sill water depth <40 m), the JS was isolated from the open ocean and the excess of precipitation over evaporation resulted in a stratified water column and low marine productivity (Tada et al., 1999). At sea-level stands of −90 to −60 m (TSS sill depth 40 to 70 m), the JS was semi-isolated, i.e., not isolated enough to form a persistent low-salinity surface layer and with slightly enhanced marine productivity. Instead, water mass stratification varies with ECSCW contributions to the TWC, as a consequence of variations in the East Asian summer monsoon (Tada et al., 1999). At intermediate sea-levels of −60 to −20 m (TSS sill 70 to 100 m), inflow via the TSS is significant, and marine productivity, deep water oxygenation/water mass stratification and organic matter preservation vary with the monsoon, i.e., the ECSCW contribution to the TWC (Tada et al., 1999). For example, at times of enhanced monsoon precipitation the ECSCW contribution to the TWC is enhanced, leading to increased marine productivity and a stronger water mass stratification due to the low-saline, high-nutrient composition of ECSCW. In contrast, at times of weaker monsoon at intermediate sea-levels, the contribution of ECSCW to the TWC is reduced, leading to reduced marine productivity and likely a better mixed water column. The oscillations in marine productivity, associated with sea-level and ECSCW contributions at intermediate sea-levels (−90 to −20 m), have recently been corroborated by a coccolithophore assemblage study of a shallow water site in the JS, Site U1427 (Saavedra-Pellitero et al., 2019, Figure 1). At sea-levels of ~20 to +10 m, inflow via the TSS is high and the relative contribution of ECSCW is...
reduced, resulting in improved deep-water ventilation and high marine carbonate productivity (Saavedra-Pellitero et al., 2019; Tada et al., 1999).

This sensitivity of the JS paleoceanography to glacio-eustatic sea-level variations suggests its sediments might have recorded the intensity increase in glacial-interglacial cycles and associated sea-level fluctuations that occurred across the MPT (e.g., Berends et al., 2019; Bintanja et al., 2005; Elderfield et al., 2012; Rohling et al., 2014). A detailed study of the JS paleoceanography and its potential response to the increased fluctuations across the MPT has, however, not yet been carried out. In part, this information has not been generated because the MPT is often condensed into just ∼10 to 50 m of sediments at deep-water sites (see e.g., Expedition reports and associated studies for ODP Legs 127/128 by Ingle et al., 1990, or Tamaki et al., 1992, and for IODP Exp. 346 by Tada et al., 2013, 2015a) but it is also influenced by issues of dating JS sediments.

1.3. This Study

Recently recovered sediments from a shallow-water site in the southern JS, IODP Site U1427 (~330 m water depth, Figure 1), have good carbonate preservation throughout the cored interval, including across the MPT (e.g., Tada et al., 2015b). Due to constant, high sedimentation rates, the sediments record the MPT in high resolution across approximately 250 m of sediment cores (Gallagher et al., 2018; Irino et al., 2018; Saavedra-Pellitero et al., 2019; Sagawa et al., 2018; Tada et al., 2015b).

The palaeo-water depth across the MPT is difficult to estimate. On the one hand, removing the sediment column deposited since the MPT and compensating for porosity/compaction implies that palaeo-water depth could have been much greater than at present. On the other hand, while this approach may be applicable to passive margin settings, the tectonics in the JS, including Site U1427, are more complex. It has been shown that in the southwestern JS, near U1427, relatively complex tectonic activities are taking place (e.g., Itoh et al., 2002; Ismail-Zadeh et al., 2013; Okuno et al., 2014), and the overall structure, with horst and graben features that form the marginal terrace on which U1427 is located (Figure 1), are the result of extensional tectonics in a back-arc basin. Therefore, the vertical tectonic movement of the site was more likely one of subsidence, although there is recent strike-slip reactivation of the faults (op. cit.). While high resolution tectonic reconstructions for the MPT are not available, a general assumption of a net subsidence of the Site U1427 location would mean that the downward tectonic movement counteracted sediment accumulation. Lithological features, such as the absence of dark/light sediment lamination, also indicate that the sediments encompassing the MPT at Site U1427 remained at shallow water depths of less than 500 m (Ikehara et al., 1994; Oba et al., 1991; Tada et al., 1999; Tada et al., 2018).

Recent studies on the sediments enabled the production of a high-resolution, benthic foraminifera-based δ¹⁸O record, encompassing the last ~850 ka (MIS 1-21; Figure S4a in Supporting Information S1; Sagawa et al., 2018). This record shows relatively lower δ¹⁸O values during glacials (when resolved), while interglacials are characterized by higher δ¹⁸O values (Sagawa et al., 2018). While much work has been done on the upper 250 m of sediment cores, little work has yet been done on the sediments that encompass the MPT (Black et al., 2018; Gallagher et al., 2018; Miller & Dickens, 2017; Peterson & Schimmenti, 2020; Saavedra-Pellitero et al., 2019; Sagawa et al., 2018). The aim of this study is therefore twofold. First, we generate an orbital-scale geochronology for the JS encompassing the MPT, based on a foraminiferal δ¹⁸O record from Site U1427 sediment cores. Using this age model, we examine the paleoceanographic changes that have occurred in response to increasing amplitudes of glacial sea-level fluctuations. This information can be used to disentangle eustatic sea-level from monsoon signals and pave the way for detailed studies of the East Asian summer monsoon history on these sediments, to investigate its potential role during the MPT.

The foraminiferal δ¹⁸O record presented in this study is affected by global ice volume/sea-level changes, as well as salinity influences and possibly sea-level-induced temperature changes given its shallow setting and likely tectonic history (see above). Therefore, low glacial δ¹⁸O values could be induced by a sea-level drop (for example, from 330 m water depth at present to between ~134 to ~120 m, similar to the last glacial maximum; Lambeck et al., 2014; Sosdian & Rosenthal, 2009; Tada et al., 2015b), resulting in a shallower water depth and possibly a relative increase in bottom water temperatures. In contrast, interglacials place the site at greater water depths and likely lower bottom water temperatures, which would increase δ¹⁸O values. It may therefore be difficult to decipher glacial from interglacials based on δ¹⁸O-based temperature estimates only.
To disentangle the local freshwater from the global ice volume/temperature signal in the JS δ¹⁸O records, an additional proxy for either temperature or salinity is needed, such as Mg/Ca ratios (e.g., Elderfield et al., 2012; Elderfield & Ganssen, 2000; Nürnberg, 1995; Raymo et al., 2018; Rosenthal, 2007; Rosenthal et al., 1997; Sosdian & Rosenthal, 2009). Potential effects of environmental variables other than temperature on the Mg/Ca ratio of even diagenetically unaffected, well-preserved benthic foraminifera like the ones used here (such as morphotypes, regional differences, water carbonate saturation) are possible. However, *Uvigerina-*based core top calibrations have proven Mg/Ca ratios to be one of the most robust palaeo-temperature proxies available, especially if a region-specific calibration is applied (e.g., Strípe et al., 2021, and references therein). Furthermore, the combination of Mg/Ca and δ¹⁸O of foraminiferal carbonate records enables reconstructing the palaeo-seawater δ¹⁸O, which has not previously been shown for the JS (see Text S4 in Supporting Information S1).

2. Materials and Methods

2.1. Site U1427

IODP Site U1427, located in the southern JS in a shallow water depth of ~330 m, was drilled during IODP Expedition 346 (“Asian monsoon”), which gathered sediment cores from the JS and East China Sea (Tada et al., 2015a, 2015b). Sediments are light colored (olive gray to grayish green), homogenous/heavily bioturbated silty clays with intercalated ash layers and without light/dark color alternations present in the sediment of deeper-water JS sites, where they represent millennial-scale changes (Tada et al., 2015a, 2015b). Shipboard analyses show a correlation between the sediment color (documented by the reflectance index, b*) and the relative contributions of biogenic material and clays. Clays show a higher bulk sediment density and high values in the Natural Gamma Ray (NGR) log, a result of dense packing and higher contents of Potassium and Thorium, as well as low b* values, while biogenic material shows relatively lower density and NGR with higher b* values (Tada et al., 2015b). Variations in these data coincide with orbital cyclicity, as a result of the inflow of nutrient-rich waters via the TSS (Figure 1), where increased inflow during interglacials primes marine productivity, leading to high b* values, thus making the b* index a useful tool to help identify glacial and interglacials in the sediments. This approach was applied to the upper ~350 m of cored sediments, where it, combined with an *Uvigerina* spp.-based δ¹⁸O record, enabled the identification of MIS 1–21 (Figure S4a in Supporting Information S1; Sagawa et al., 2018).

The depth scale applied in this study is “m U1427_Patched_CCSF-D(_rev20170310)” as shown in Irino et al. (2018), and as used by other publications on the upper ~250 m sediment cores of Site U1427 (Black et al., 2018; Gallagher et al., 2018; Miller & Dickens, 2017; Peterson & Schimmenti, 2020; Saavedra-Pellitero et al., 2019; Sagawa et al., 2018). The depth scale constructed by Irino et al. (2018) is applicable to the full splice interval, that is the upper 430.337 m CCSF-A, and for the non-splice interval below 11.755 m were added to CCSF-A depths to obtain the “Patched”-equivalent depth scale. This depths scale is referred to as “m CCSF-D_Patched” throughout this study.

2.2. Foraminiferal δ¹⁸O Record

A benthic foraminiferal δ¹⁸O record based on the genus *Uvigerina* spp. was generated, using the well-preserved shells of Site U1427 (Figure 2; see Text S2 in Supporting Information S1). Sediment samples were washed over a 63 μm mesh using deionized water (DI), dried at 50°C and dry-sieved on 150 μm mesh. Well-preserved *Uvigerina* spp. shells were isolated from the >150 μm fraction and cleaned using DI and agitation in an ultrasonic bath to remove contaminants. The rigor of the cleaning step was checked under a light microscope. For each analysis 50 to 100 μg of uncleaned calcite was used, which approximated to about 10 to 30 *Uvigerina* spp. shells, all in good preservation state, i.e., showing little sign of diagenetic overgrowths.

2.3. Foraminiferal Mg/Ca Ratios

Samples were selected from two intervals, 300–395 m and 460–525 m CCSF-D_Patched, to confirm the interpretation of the δ¹⁸O record. For each analysis ~300 μg of uncleaned calcite was used, which approximated to about 10 to 30 *Uvigerina* spp. shells, all in good preservation state, i.e., showing little sign of diagenetic overgrowths.
The shells were cleaned using the Mg-/oxidative cleaning protocol after Barker et al. (2003) and analyzed on an Agilent inductively coupled plasma-optical emission spectrophotometer (ICP-OES) at the Godwin Laboratory for Palaeoclimate Research (Cambridge, UK), applying an intensity ratio calibration after De Villers et al. (2002). For quality control two reference solutions were analyzed, an in-house standard (Soln R3) and an international, external standard (JCt-1), which both show a precision (r.s.d.) of below 0.5%. The accuracy of Mg/Ca determinations has been established by interlaboratory studies (Greaves et al., 2008; Rosenthal et al., 2004) and was confirmed here by replicate analyses of standard JCt-1 where mean Mg/Ca of 1.266 mmol/mol (six replicates with standard deviation 0.005 and r.s.d. 0.40%) was obtained for JCt-1, in agreement with published results (Hathorne et al., 2013). A set of contaminant-indicating elements (Al, Ba, Fe, K, Mn, Na, Si, Ti, Zn) were determined simultaneously during each analytical run to monitor cleaning efficiency and diagenesis (c.f. Barker et al., 2003). Reproducibility between samples was tested on seven duplicates, split before cleaning, which show r.s.d. below 5%.

### 2.4. Temperature Estimates Based on Mg/Ca Ratios

A newly established Mg/Ca-temperature calibration based on *Uvigerina akitaensis* from the JS was used to calculate palaeo-water temperatures (Text S3 in Supporting Information S1). This new calibration extends the calibration range to lower temperatures, in a temperature range where few other calibrations for *Uvigerina* spp. are available (Elderfield et al., 2010; Roberts et al., 2016; Skinner et al., 2020). Besides being more comprehensive at low temperatures, this new calibration is based on the same genus (*Uvigerina*) and the same location (Japan Sea) and is hence being tuned to the regional setting of Site U1427, reducing local water mass effects (such as carbonate ion saturation, e.g., Elderfield et al., 2006; Martin et al., 2002) and increasing confidence in the calculated temperatures.

The newly established calibration is based on *Uvigerina akitaensis* from 16 core-top samples across a water depth-temperature transect at constant salinity in the JS (see, Text S3 and Figure S3 in Supporting Information S1) following the equation:

![Figure 2](image-url)  
*Figure 2*. Age-depth relationship (Figure 2a) and calculated sedimentation rates (Figure 2b) encompassing ~250 to 550 m CCSF-D_Patched of Site U1427. Black dots in Figure 2a represent age tie points as listed in Table S1 (Supporting Information S1), with red bars indicating their respective uncertainties in depth and age where available (c.f. Tada et al., 2015b; Sagawa et al., 2018).
Temperature (°C) = \left( \frac{\text{Mg}}{\text{Ca}} - 0.637 \right) / 0.089

(see Text S3 in Supporting Information S1, Equation 2 is reprinted here for reference). The *Uvigerina akitaeensis* shells were cleaned using the Cd-cleaning/reductive protocol by Boyle and Keigwin (1985) (Text S3 in Supporting Information S1), while in this study the *Uvigerina* spp. shells were cleaned using the Mg-oxidative cleaning protocol after Barker et al. (2003) (see Section 2.3). This difference in cleaning protocols leads to Mg-offsets that need to be corrected for (Barker et al., 2003; Elderfield et al., 2012; Pang et al., 2020; Rosenthal et al., 2004). Elderfield et al. (2010) estimate the Mg-offset between these two cleaning protocols in *Uvigerina* spp. to be 0.2 mmol/mol, which was applied to the Mg values in this study to calculate palaeo-temperatures using the above equation. Omitting the Mg-correction would shift the down-core temperature range from between ~0.4 and 8.7°C (see Section 3.2, Figure 4) to between ~2.7 and 10.9°C (without correction).

### 3. Results

#### 3.1. Age-Depth Relationship for Site U1427 Across the MPT

A shipboard age-depth relationship for Site U1427 was established using seven biostratigraphic tie points and one palaeomagnetic boundary between 250 and 550 m CCSF-D_Patched (Tada et al., 2015b). Recently, two well-dated tephra layers as well as 13 occurrences of warm-water species (indicating the interglacial inflow of the TWC) and low b*δ18O intervals (indicating glacial maxima) were identified in the sediment cores (see, Text S1–S4 and Table S1 in Supporting Information S1) (Sagawa et al., 2018). Based on the combination of all available chronological markers, sedimentation rates across the MPT were calculated to have varied between ~10 and 75 cm/ka, on average ~50 cm/ka, with the investigated interval spanning from ~680 to 1256 ka (Figure 2).

#### 3.2. Coherence Between b*, Foraminiferal δ18O and Marine Isotope Stages

The newly generated *Uvigerina* spp.-based δ18O record presented in this study, encompasses the MPT (Figure 3). Combining this δ18O record with the revised age-depth relationship (Figure 2 and Text S1 in Supporting Information S1) and the sediment color reflectance index, b* (Figure 3a), enabled the identification of most marine isotope stages encompassing MIS 17-39 through comparison with the LR04-stack (Figure 3b). Across MIS 17-24 glacials are associated with low b* and low δ18O values, corroborating with previous studies from the JS, including the upper ~350 m CCSF-D_Patched of sediment cores at Site U1427 (Figure S4 in Supporting Information S1; Sagawa et al., 2018), while in sediments older than MIS 25 the relationship between b*, δ18O and glacial-interglacial cycles is less clear. Often glacial b* and δ18O run opposite, i.e., showing low b* and relatively high δ18O, with prominent examples being MIS 26, 36 and 38 (Figure 3a).

The identification of the early-MPT high δ18O glacials (older than MIS 25) is supported by lower Mg/Ca temperature estimates (Figures 4b and 4c; Text S3 in Supporting Information S1). The Mg/Ca record varies between ~0.8 and 1.6 mmol/mol (Figure 4b) and covers the intervals ~300–395 m (MIS 19-27) and ~460–525 m CCSF-D_Patched (MIS 35-39), where b* and δ18O show pronounced contrasting relationships (Figure 3a/4a). Temperature estimates (based on the newly generated Mg/Ca-temperature calibration for JS *Uvigerina akitaeensis*, see Text S3 in Supporting Information S1) across MIS 25 to 39 show relatively higher temperatures during suggested interglacials and relatively lower temperatures during suggested glacials, ranging overall between ~0.4 and 8.7°C (Figure 4c). While the absolute temperatures might need to be treated carefully (see Text S3 in Supporting Information S1), their relative changes confirm the identification of glacial/interglacial, hence confirming the switch in the expression of glacialia in δ18O across the MPT. Some deviations from this trend, such as low temperatures during the onset of interglacials MIS 37 and 21 are observed but, taken together, the foraminiferal carbonate-based Mg/Ca ratios and δ18O suggest persistent high glacial δ18O values across most glacials of MIS 39-25, often reaching values similar to those of open ocean sites, and lower glacial δ18O values between MIS 24-17 (see Figure 3). This trend continues upwards to the most recent glacial sediments (Figure S4a in Supporting Information S1; Sagawa et al., 2018).
4. Discussion

4.1. What Caused the Shift in the Relationship of δ¹⁸O With Glacial-Interglacial Cycles Across the MPT?

The relationship of δ¹⁸O with glacial-interglacial cycles appears to change across the MPT, and the persistent and relatively high glacial δ¹⁸O values across MIS 39-25 suggest an improved water mass exchange with the open
ocean, defying the impact of low saline/low δ¹⁸O waters accumulating around Site U1427. While this effect may be related to the increased amplitudes of glacial sea-level fluctuations across the MPT, we also tested other potential causes of the shift by analyzing the foraminifera shells used for diagenetic alterations and regional variations in precipitation and tectonics across the MPT, which are summarized here.

Diagenesis of foraminifera shells can alter their δ¹⁸O values, leading to deviations from the original signal. We combined high-resolution microscopy with semi-quantitative chemical composition of the shells but found little indication for diagenetic alterations (Text S2 in Supporting Information S1). Furthermore, diagenesis should have had a neglectable effect on the δ¹⁸O record due to using benthic foraminifera, which calcify their shells in a similar environment in which diagenesis takes place (c.f. Edgar et al., 2015; Sexton & Wilson, 2009), and due to the fine-grained lithology (predominantly silty clays; Tada et al., 2015b) with continuously high sedimentation rates of up to 75 cm/ka (Figure 2, Table S1 in Supporting Information S1).

Changes in the amount of freshwater input to the JS, influenced by variations in the East Asian summer monsoon, could also have caused the glacial δ¹⁸O shift. Reduced precipitation (as the result of a weaker monsoon), would have reduced the amount of low saline/low δ¹⁸O water runoff and input into the JS, leading to a weakened imprint on the δ¹⁸O records at Site U1427, and consequently higher glacial δ¹⁸O values. However, for MIS 39-25 monsoon proxy records suggest relatively higher glacial precipitation than during MIS 24-17. For example, pollen, spore and vegetation records from southern and central Japan indicate regional climate became warmer and wetter from ~MIS 38 onwards, as inferred from the expansion of broadleaved-tree dominated temperate warm forests (Fujiki & Ozawa, 2008; Kitaba et al., 2012). From MIS 24, plants indicative of cooler and, more importantly, dryer conditions start to dominate during glacials (Kitaba et al., 2012). Similarly, mineralogical and facies studies of deposits on the Chinese Loess Plateau, controlled by variations in the monsoon and leading to pedogenesis and the deposition of paleosol at times of strong East Asian summer monsoon precipitation and loess layers at times of relatively weaker summer monsoon and stronger winter monsoon winds, revealed a significant precipitation increase starting around 1200 ka (~MIS 36), affecting glacials more significantly than interglacials (An et al., 1990; Han et al., 2012; Meng et al., 2018; Peng et al., 2020). Most intriguingly, precipitation is suggested to have been at a similarly low level (~30 mm/a) during MIS 38 and 22 (Peng et al., 2020), two glacials with distinctively different δ¹⁸O characterization (Figure 4a). These variabilities in precipitation and freshwater input across the MPT are also indicated by the δ¹⁸O values of the surrounding seawater (Text S4 and Figure S4c in Supporting Information S1), a record not been shown before for the JS.

These findings imply that processes other than preservation state/diagenesis and/or regional precipitation must have been involved to explain the shift in glacial δ¹⁸O, most likely a change in the palaeoceanography of the shallow, southern JS. The shift from high-δ¹⁸O (open ocean-like) glacials across MIS 39-25 to low-δ¹⁸O (restricted JS) glacials from MIS 24 onwards could have been caused by local tectonic uplift movements. Although the study site is located in a tectonically very active region with volcanic events having taken place in southern Japan and the Japanese Isles across the MPT, no local uplift events could be identified (Itaki, 2016; Kitamura & Kawagoe, 2006; Yoon, 1997). The biggest tectonic events around the TSS are related to the opening of the JS, starting in the late Oligocene, with stress field changes (extensional to compressional) during the mid-Miocene and, although minor movements (minor faulting) took place after the mid-Miocene, the TSS area has been tectonically stable since the mid-Miocene, which is supported by modern seismological activity (Clarringbould et al., 2019; Fabbri et al., 1996; Ishikawa & Tagami, 1991; Katsura & Nagano, 1976; Son et al., 2015). Although there is a possibility of sill depth changes related to deposition/erosion in the TSS, no large (tectonically induced) sill depth change is expected.

There is strong evidence for increased glacio-eustatic sea-level fluctuations that might have led to an improved glacial connection between the JS and the open ocean across MIS 39-25 and a more restricted JS palaeoceanography across MIS 24-17. Before MIS 25, global eustatic sea-level fluctuations over glacial-interglacial cycles were smaller (on average, glacial sea-level dropped by ~60 to ~80 m between ~2,700 and 1200 ka) than since MIS 22, i.e., during the glacials of the last ~900 ka, where sea-levels dropped to as much as ~120m ± 32 m below present (c.f. Sosdian & Rosenthal, 2009). While sea-level curves based on foraminiferal δ¹⁸O are not available for the JS because of the widespread glacial carbonate dissolution (see above), they exist for other sites. For example, global sea-level curves modeled from the LR04-stack cover the last ~1100 ka (Bintanja et al., 2005) and, using inverse sea-level modeling, the last 3,600 ka (Berends et al., 2019). Other sea-level curves that encompass MIS 39-17 have been produced from records of Gibraltar in the Mediterranean Sea (Rohling et al., 2014) and from the
Figure 4. Benthic foraminiferal δ¹⁸O (a) (replotted for reference), Mg/Ca ratios (b) and Mg/Ca-derived temperatures (c) of Site U1427, with b* index (gray) in the background. On the left, glacial intrusions of warm-water species are indicated by green stars (based on Itaki et al., 2018; Kitamura et al., 2001; Tada et al., 2015b), age-tie points by triangles (Tada et al., 2015b; Sagawa et al., 2018) and marine isotope stages by numbers. Compared with TSS sill level stands (calculated from global sea-level reconstructions based on Bintanja et al., 2005; Berends et al., 2019; Elderfield et al., 2012 and Rohling et al., 2014. Yellow area indicating TSS sill stands at which the JS is nearly isolated) (d), JS water depth estimates (based on lithological studies of the Omma Formation in Kanazawa City; Kitamura, 2016) (e) and a precipitation/monsoon intensity reconstruction from the Chinese Loess plateau (Peng et al., 2020) (f).
South West Pacific near New Zealand (Elderfield et al., 2012). Using these sea-level reconstructions, palaeo-water levels over the TSS sill (hereafter referred to as sill depths) were estimated by deducting past sea-level stands from the modern TSS sill depth of 130 m (e.g. Oba et al., 1991). The resulting palaeo-sill depths are shown in Figure 4d. All but the Bintanja et al. (2005) curves suggest relatively stable interglacial sill depths/sea-levels, while glacial sill depths were greater across MIS 39-25 than across MIS 24-17, when the TSS sill regularly became as shallow as 50 to 20 m (Figure 4d).

Paleo-sea-level reconstructions from the JS are limited to lithological and micropalaeontological assemblage studies on the shallow-water deposits of the Omna Formation in outcrops near Kanazawa City, ~200 km east of Site U1427 (e.g., Hoiles et al., 2012; Kitamura, 1991; Kitamura et al., 2001; Kitamura & Kawagoe, 2006; Kitamura & Kimoto, 2006; Kitamura, 2016). Their lithofacies inventory also suggests higher glacial sea-levels in the JS before MIS 25 (Figure 4e, op. cit.). In detail, the Omna Formation lithofacies suggests inflow via the TSS during each interglacial since MIS 56 (~1700 ka) and that sediments were deposited in a fairly constant water depth of 30 to 100 m during MIS 39–27, while sediments younger than that were deposited under more variable sea-levels (Kitamura, 2016). For example, during MIS 27–23 water depth at the Omna Formation outcrops fell from ~100 m to between just 5 to 30 m, followed by aerial exposure of the area and the formation of a back marsh environment with trees and mammal footprints during MIS 22, before the return to around 30 to 100 m water depth during MIS 21 and return of marine molluscs (Kitamura, 2016) (Figure 4e). These findings of higher glacial sea-levels, both globally and in the JS, during MIS 39–25 and lower levels across MIS 24–17 suggest the long-term glacio-eustatic sea-level development across the MPT is a most likely cause for the switch in glacial modes from high, open ocean-like glacials. We differentiate three modes across the MPT, which are summarized here.

In order to determine the TSS sill depth at which the system switches glacial modes from high, open ocean-like to low, JS-specific δ¹⁸O values, individual glacials must be studied in detail. For example, the glacial of MIS 26 shows high δ¹⁸O values, indicating a good water mass exchange with the open ocean, while MIS 24 shows reduced δ¹⁸O values, indicating a freshwater imprint on the record and, hence, restricted water mass exchange (Figure 4a). During MIS 26 the TSS sill depth was around 100 to 75 m (i.e., sea-level drop of ~30 to ~55 m) and around 80 to 60 m (sea-level drop of ~50 to ~70 m) during MIS 24 (Figure 4d). Therefore, at TSS sill stands of greater than 100 m, i.e. sea-level of less than ~30 m below present, the δ¹⁸O record is unaffected by the input of low saline/low δ¹⁸O waters due to unrestricted water mass exchange between the JS and the open ocean (mode 1 in Figure 5a). Palaeoceanographic mode 1 prevails during interglacials across MIS 39-17 and encompasses mode 4 in Tada et al. (1999) and mode 3 in Saavedra-Pellitero et al. (2019). At intermediate TSS sill stands between 100 and ~60 m, i.e. sea-level is about ~30 to ~70 m below present, water mass exchange with the open ocean is restricted and the varying contributions of ECSCW (low saline/low δ¹⁸O, warm, nutrient-rich) has a strong influence on freshwater imprints on δ¹⁸O; this is proposed mode 2 (Figure 5b). The influence of varying ECSCW contributions to the TWC can be demonstrated by comparing, for example, the interglacial MIS 23 and the glacials 38, 36 and 30. During MIS 23 TSS sill stands are around 80 to 90 m and δ¹⁸O is low (Figures 4a and 4d), indicating restricted inflow via the TSS and relatively high contributions of ECSCW to the TWC, as can also be inferred from high fluxes in marine productivity proxies as a result of the enhanced nutrient input by the ECSCW (Felder et al., 2021) and a relatively high precipitation on the Chinese Loess Plateau (Figure 4f). In contrast, during MIS 38 TSS sill levels were at times shallower than during MIS 23, dropping to as little as ~60 m, but δ¹⁸O is consistently high, suggesting a relatively good water mass exchange with the open ocean and reduced contributions of ECSCW, as can also be inferred from relatively lower marine productivity (Felder et al., 2021) and much lower precipitation on the Chinese Loess Plateau (Figures 4a–4d, 4f).

The glacial of MIS 30 and 36 are other another examples of the sensitivity of mode 2 to variations in the East Asian summer monsoon are the glacials of MIS 36 and 30. MIS 36 begins and ends with relatively high δ¹⁸O
Figure 5. Paleoceanographic modes for the shallow, southern Japan Sea across the MPT with TSS sill depths (top row), showing mode 1 (a), the stages of mode 2 (b) and mode 3 (c). Below are schematic illustrations of the circulation in the southern Japan Sea during each stage. Base map of the top row from Tada et al. (2013), with palaeo-shorelines redrawn from Saavedra-Pellitero et al. (2019) (using mode 1 sea-level at −100 m and mode 3 sea-level at −20 m below present), from Tada et al. (2013) for central to north Honshu, Hokkaido and Sakhalin (mode 2) and from Park and Chia (2006) for southern Japan Sea, East China Sea and TSS area (mode 2 sea-level at −75 m below present). Vertical lines in bottom row indicate drill sites, horizontal lines in b and c indicate stratified water column. TSS, Tsushima strait; TWC, Tsushima warm current; CSCW, East China Sea coastal water.
and lower δ¹⁸O values in its mid-section, while MIS 30 has overall low δ¹⁸O values (Figure 4a). During MIS 36, the reduced δ¹⁸O values are likely associated with a period of increased monsoon precipitation affecting the δ¹⁸O record and, although a direct proxy for freshwater input/monsoon variations (such as diatom assemblages) is not available, the enhanced contributions of nutrient-rich ECSCW can also be inferred from enhanced marine productivity (Felder et al., 2021) and high precipitation over the Chinese Loess Plateau (Figure 4f). During MIS 30, the low δ¹⁸O values may be the result of a combination of enhanced monsoon precipitation (Figure 4f) and potentially a sea-level/sill level that would have reduced the exchange of water masses with open ocean (Figure 4d, yellow area). Comparing the proposed mode 2 with previous studies, it encompasses modes 2 and 3 of Tada et al. (1999) and mode 2 of Saavedra-Pellitero et al. (2019). Mode 2 dominates during glacials of MIS 39-25, strongly suggesting a consistent glacial connection/water mass exchange between the open ocean and the shallow southern JS during the early stages of the MPT. Further evidence for the glacial inflow via the TSS comes from numerous micropalaeontological studies highlighting the (intermittent) presence of warm-water species, having originated from the East China Sea and having been identified in outcrops and marine sediments from the JS across glacials of MIS 39-25. For example, micropalaeontological studies on the Omma Formation describe the occasional glacial occurrence of the warm water foraminifera Globigerinoides ruber (d’Orbigny, 1839) in sediments equivalent in time to MIS 38, 36 and 34 (Hoiles et al., 2012; Kitamura et al., 2001). Globigerinoides ruber have also been identified at Site U1427 in sediments depths corresponding to MIS 38 and 39 (Tada et al., 2015b). Furthermore, radiolarian assemblages contain warm water species at depths corresponding to MIS 34, 32, 28 and potentially further glacials, although these depths cannot be dated with great certainty based on the data provided (Itaki et al., 2018). While these studies indicate the occasional inflow of warm waters via the TSS, the continuous δ¹⁸O record of Site U1427 suggests a persistent glacial inflow or water mass exchange across MIS 39-25.

The third proposed palaeoceanographic mode (mode 3) occurs at lowest TSS sill/sea-level stands of less than 60 m, i.e. sea-levels lower than −70 m below present (yellow in Figure 4d). During mode 3 water mass exchange with the open ocean is restricted and the JS becomes nearly isolated, leading to the formation of a low-saline surface layer which impacts on the δ¹⁸O record, leading to lower values (Figure 5c). This mode encompasses mode 1 in Tada et al. (1999) and Saavedra-Pellitero et al. (2019), and it persists during glacials across MIS 24-17, continuing upwards to the most recent sediments (Figure S4 in Supporting Information S1; Sagawa et al., 2018). Intriguingly, the switch from glacial sediments dominated by mode 1 to predominantly mode 3 first appears during the glacial of MIS 24 (sea-level about ∼90 to 100 m below present; cf. Bintanja et al., 2005; Elderfield et al., 2012), a time which is crucial in the MPT as the modern 100 ka frequency in glacial-interglacial climate cyclicity becomes statistically significant in marine δ¹⁸O records (e.g., Clark et al., 2006; Imbrie et al., 1992; Kitaba et al., 2011; Sosdian & Rosenthal, 2009). Previously published sea-level reconstructions suggest a significant sea-level fall of up to ∼120 m below present not before MIS 22 (Figure 3d; Berends et al., 2019; Bintanja et al., 2005; Elderfield et al., 2012; Haq et al., 1987; Lisiecki & Raymo, 2005; Rohling et al., 2014; Sosdian & Rosenthal, 2009), associated with declining temperatures and significant ice-volume increase around 900 ka (themed the “900 ka-event”; e.g., Elderfield et al., 2012; Farmer, Hönisch, et al., 2019; Hoogakker et al., 2006; Raymo et al., 1997; Rohling et al., 2014). The δ¹⁸O-mode switch at Site U1427 precedes the 900 ka-event by one glacial, demonstrating the great sensitivity of the sediments of Site U1427 to sea-level fluctuations across the MPT.

There may be consequences for dating JS deep-water sediments should the improved glacial water mass exchange, as suggested by mode 2, extend to greater water depths. The inflow via the TSS, i.e., the TWC with variable amounts of ECSCW, affects water mass stratification and the lithology at deep-water sites from the JS (see Introduction), leading to the deposition of dark and light sediment layers, which have been associated with glacials and interglacials respectively (e.g., Oba et al., 1991; Tada et al., 1999). Hypothetically, the improved glacial water mass exchange that led to higher glacial δ¹⁸O values at Site U1427, could have extended further offshore to be located above deep-water sites. Here the more saline/higher δ¹⁸O waters could avert water column stratification, to some degree, and hence improve carbonate preservation at deep-water sites, leading to lighter colors of glacial sediments. As the inflow from the south/East China Sea is, in addition, likely warmer than JS waters, warm water species could be contained in the glacial sediments. Therefore, if the effect of the glacial TWC inflow would have continued to greater water depths, it would lead to some difficulties in sediment dating, as the assumption of light sediments with warm-water microfossils indicating interglacials, may be invalid.
Acknowledgments
This study used samples provided by the Integrated Ocean Drilling Program (IODP). We would like to thank the co-chairs, Ryuji Tada and Richard W. Murray, and all IODP Expedition 346 participants, and two anonymous reviewers for their insights and tremendous efforts to improve this manuscript. This research was supported by a NERC IAPE/US Doctoral Training Partnership studentship (NE/L002990/1) and by a British Geological Survey CASE partnership (BUFI S270) and forms part of S. Felder’s PhD research (“The mid-Pleistocene climate transition in the Japan Sea: Insights of a combined palaeoceanographic and -monsoon, multi-proxy study using marine sediments of IODP Site U1427 from the shallow, southern Japan Sea”, unpublished PhD thesis, Newcastle University, UK). Analyses were also supported by the National Environmental Isotope Facility at the British Geological Survey under awards IP-16668-111, IP-1486-1114 and IP-1668-1116, and by a research grant by the European Consortium for Ocean Research Drilling (ECORD) to undertake training and analysis in the Mg/Ca determination at the Godwin Laboratory, Cambridge. This work is also partly supported by JSPS Grant JPMSX505E2900001 and by Kanazawa University SAKIGAKE project 2020. We are grateful to UK IODP for supporting S. Felder in the participation in the Expedition 346 second post cruise meeting in Melbourne, Australia, and for A. C. G. Henderson in Expedition 346 (NE/L002655/1). We would also like to thank Dr Tracy Ace, University of Leeds, for making microscope facilities available as well as Christian März and Eva for their continuous support and patience during the lead author’s PhD and the writing this manuscript. Each named author has substantially contributed to conducting the underlying research and drafting this manuscript.

5. Conclusions and Implications
This study shows that there are changes in the JS palaeoceanography across the MPT, which have not been observed previously but may have implications for the interpretation of dark/light sediment alternations from JS deep-water sites, commonly associated with interglacials and glacial periods (e.g., Obu et al., 1991; Tada et al., 1999). The δ18O record of Site U1427, encompassing MIS 39-17, shows a switch in the expression of glacial in δ18O across the MPT, associated with higher glacial sea-levels before MIS 25, globally and in the JS. An improved glacial water mass exchange between the shallow, southern JS and the open ocean is proposed as the cause of the δ18O switch, having attenuated any potential freshwater imprint on δ18O and resulting in relatively higher glacial δ18O values across MIS 39-25 than across MIS 24-17, and continuing upwards to the most recent sediments (Figure S4a in Supporting Information S1; Sagawa et al., 2018). Deviations from this trend are likely associated with enhanced monsoon precipitation, for example, lower δ18O values during the mid-section of MIS 36 (Figure 4), and demonstrate the sensitivity of the sediments of Site U1427 to orbital- and sub-orbital scale monsoon variations. In contrast to previous studies that suggest the possibility of an intermittent glacial TWC inflow during some glacial, the new proposed mode suggests inflow was possible for the duration of entire glacials across MIS 39-25. Should this mode have extended further offshore and to greater water depths, it may have significant consequences for the dating of JS deep-water sediments, as the interpretation of light layers with warm-water species present as representing interglacials, may not be valid. Crucially, the δ18O-mode switch from glacials with TWC inflow to such glacial suggesting the (near) isolation of the JS, occurs at MIS 25/24. This is one glacial-interglacial cycle earlier than the significant ice-volume increase and associated sea-level fall identified in open ocean sites (i.e., 900 ka-event; e.g., Elderfield et al., 2012). This demonstrates the great sensitivity of the sediments of Site U1427 to glacio-eustatic sea-level variations and suggests that significant events took place before the 900 ka-event, which should be considered when deciphering the mechanisms surrounding the MPT.

Conflict of Interest
The authors declare no conflicts of interest relevant to this study.

Data Availability Statement
All new data, shown in the manuscript and its supporting information, are included in the open-access data repository PANGAEA (https://doi.pangaea.de/10.1594/PANGAEA.931921).

References
An, Z., Tungsheng, L., Yanchou, L., Porter, S. C., Kukla, G., Xihao, W., et al. (1990). The long-term paleosummon variation recorded by the loess-paleosol sequences in central China. Quaternary International, 7/8, 91-95. https://doi.org/10.1016/1040-6182(90)90042-3
Barker, S., Greaves, M., & Elderfield, H. (2003). A study of cleaning procedures used for foraminiferal Mg/Ca paleothermometry. Geochemistry, Geophysics, Geosystems, 4(9), 8407. https://doi.org/10.1029/2003gc000559
Berends, C. J., de Boer, B., Dolan, A. M., Hill, D. J., & van de Wal, R. S. W. (2019). Modelling ice sheet evolution and atmospheric CO2 during the late Pliocene. Climate of the Past, 15, 1603–1619. https://doi.org/10.5194/cp-15-1603-2019
Bintanja, R., van de Wal, R. S. W., & Oerlemans, J. (2005). Modelled atmospheric temperatures and global sea levels over the past million years. Nature, 437, 125–128. https://doi.org/10.1038/nature03975
Black, H. D., Anderson, W. T., & Alvarez-Zarikian, C. A. (2018). Data report: Organic matter, carbonate, and stable isotope stratigraphy from IODP Expedition 346 Sites U1426, U1427, and U1429. In R. Tada, R. W. Murray, C. A. Alvarez Zarikian (Eds.), Proceedings of IODP expedition 346. Integrated Ocean Drilling Program. https://doi.org/10.2204/iodp.proc.346.204.2018
Boyle, E., & Keigwin, L. (1985). Comparison of Atlantic and Pacific paleochemical records for the last 215,000 years: Changes in deep ocean circulation and chemical inventories. Earth and Planetary Science Letters, 76, 135-150. https://doi.org/10.10160/0012-821x/85/00154-2
Chalk, T. B., Hain, M. P., Foster, G. F., Rohling, E. J., Sexton, P. F., Badger, M. P. S., et al. (2017). Causes of ice age intensification across the mid-Pleistocene transition. Proceedings of the National Academy of Sciences of the USA, 114(50), 13114–13119. https://doi.org/10.1073/pnas.1702143114
Cheng, H., Edwards, R. L., Sinha, A., Spötl, C., Yi, L., Chen, S., et al. (2016). The Asian monsoon over the past 640,000 years and ice age terminations. Nature, 534, 640-646. https://doi.org/10.1038/nature18591
Clark, P. U., Alley, R. B., & Pollard, D. (1999). Northern hemisphere ice-sheet influences on global climate change. Science, 286, 1104–1111. https://doi.org/10.1126/science.286.5442.1104
Chalk, T. B., Hain, M. P., Foster, G. F., Rohling, E. J., Sexton, P. F., Badger, M. P. S., et al. (2017). Causes of ice age intensification across the mid-Pleistocene transition. Proceedings of the National Academy of Sciences of the USA, 114(50), 13114–13119. https://doi.org/10.1073/pnas.1702143114
Cheng, H., Edwards, R. L., Sinha, A., Spötl, C., Yi, L., Chen, S., et al. (2016). The Asian monsoon over the past 640,000 years and ice age terminations. Nature, 534, 640-646. https://doi.org/10.1038/nature18591
Clairnbourg, J. S., Saito, H., Ishiyama, T., Van Horne, A., Kawasaki, S., & Abe, S. (2019). Cenozoic evolution of the Tsushima Strait and the Fukue Basin, southern Sea of Japan: An interplay of tectonics, palaeo-environment, and volcanism. Japan Geoscience Union Meeting. Abstract S057-12, 26th–30th May 2019.
Clark, P. U., Alley, R. B., & Pollard, D. (1999). Northern hemisphere ice-sheet influences on global climate change. Science, 286, 1104–1111. https://doi.org/10.1126/science.286.5442.1104
Boyle, E., & Keigwin, L. (1985). Comparison of Atlantic and Pacific paleochemical records for the last 215,000 years: Changes in deep ocean circulation and chemical inventories. Earth and Planetary Science Letters, 76, 135-150. https://doi.org/10.10160/0012-821x/85/00154-2
Chalk, T. B., Hain, M. P., Foster, G. F., Rohling, E. J., Sexton, P. F., Badger, M. P. S., et al. (2017). Causes of ice age intensification across the mid-Pleistocene transition. Proceedings of the National Academy of Sciences of the USA, 114(50), 13114–13119. https://doi.org/10.1073/pnas.1702143114
Cheng, H., Edwards, R. L., Sinha, A., Spötl, C., Yi, L., Chen, S., et al. (2016). The Asian monsoon over the past 640,000 years and ice age terminations. Nature, 534, 640-646. https://doi.org/10.1038/nature18591

Paleoceanography and Paleoclimatology 10.1029/2021PA004236
Sosdian, S., & Rosenthal, Y. (2009). Deep-sea temperature and ice volume changes across the Pliocene-Pleistocene climate transitions. *Science*, 325, 306–310. https://doi.org/10.1126/science.1169938

Sosdian, S., Rosenthal, Y., & Toggweiler, J. R. (2008). Deep Atlantic carbonate ion and CaCO3 compensation during the ice ages. *Paleoceanography and Paleoclimatology*, 33, 546–562. https://doi.org/10.1029/2007pa001331

Sturup, C. R., Allen, K. A., Sikes, E. L.,zhou, X., Rosenthal, Y., Cruz-Urbie, A. M., et al. (2021). The Mg/Ca proxy for temperature: A Uvigerina core-top study in the southwest Pacific. *Geochimica et Cosmochimica Acta*, 509, 299–312. https://doi.org/10.1016/j.gca.2021.06.015

Tada, R. (1994). Paleoceanographic evolution of the Japan Sea. *Paleogeography, Palaeoclimatology, Palaeoecology*, 108 (3–4), 487–508. https://doi.org/10.1016/0031-0182(94)90248-8

Tada, R. (2004). Onset and evolution of millennial-scale variability in the Asian Monsoon and its impact on paleoceanography of the Japan Sea. In P. D. Clift, W., Kuhnt, P., Wang, D., & Hayes (Eds.) *Continent-ocean interactions in the east Asian marginal seas*. (Vol. 149, pp. 283–298). AGU Monograph. https://doi.org/10.1029/149gm15

Tada, R., Irino, T., Ikehara, K., Karasuda, A., Sugisaki, S., Xuan, C., et al. (2018). High-resolution and high-precision correlation of dark and light layer in the Quaternary hemipelagic sediments of the Japan Sea recovered during IODP Expedition 346. *Progress in Earth and Planetary Sciences*, 5, 19. https://doi.org/10.1186/s40645-018-0167-8

Tada, R., Irino, T., Koizumi, I. (1999). Land-based linkages over orbital and millenial timescales recorded in late Quaternary sediments of the Japan Sea. *Paleoceanography*, 14(2): 236–247. https://doi.org/10.1029/99pa00016

Tada, R., Koizumi, I., Cramp, A., & Rahman, A. (1992). Correlation of dark and light layers, and the origin of their cyclicity in the Quaternary sediments from the Japan Sea. In K. A., Pisciotto, J. C., Ingle Jr, M. T., von Breymann, J., Barron, S. C., Clemens, G. R., Dickens, et al. (Eds.), *Proceedings of the Ocean Drilling Program, scientific results. Part (1)*, (Vol. 127, 128), pp. 577–601. Ocean Drilling Program. https://doi.org/10.2973/iodp.proc.sr.127128-1.160.1992

Tada, R., Murray, R. W., Alvarez Zarikian, C. A., Anderson, W. T., Jr, Bassetti, M.-A., Brace, B. J., et al. (2013) Proceedings of IODP expedition 346. Integrated Ocean Drilling Program. https://doi.org/10.2204/iodp.proc.346.2013

Tada, R., Murray, R. W., Alvarez Zarikian, C. A., Anderson, W. T., Jr, Bassetti, M.-A., Brace, B. J., et al. (2015a). Expedition summary. In R. W. Murray, C. A. Alvarez Zarikian, & the Expedition 346 scientists (Eds.) *Proceedings of the Integrated Ocean Drilling Program, scientific results, part 2*, (Vol. 127/128 pp. 1333–1348). Ocean Drilling Program.

Tada, R., Murray, R. W., Alvarez Zarikian, C. A., Anderson, W. T., Jr, Bassetti, M.-A., Brace, B. J., et al. (2015b). Site U1427 Summary. In R. Tada, R. W. Murray, C. A. Alvarez Zarikian, & the Expedition 346 scientists (Eds.) *Proceedings of the Integrated Ocean Drilling Program, scientific results*, (Vol. 346). Integrated Ocean Drilling Program. https://doi.org/10.2204/iodp.proc.346.108.2015

Taya, M., Suyehiro, K., Allan, J., Ingle, J. C., & Pisciotto, K. A. (1992). 83. Tectonic synthesis and implications of Japan Sea OD Drilling. In K. Pisciotto, K. Tama, J. Allan, M. Alexanderovich, D. A. Barnes, S. Boggs, et al. (Eds.) *Proceedings of the Ocean Drilling Program, scientific results, part 2*, (Vol. 127/128 pp. 1333–1348). Ocean Drilling Program.

Tomczak, M., & Godfrey, M. J. S. (1994) *Regional oceanography: An introduction*. Pergamon, (pp. 422).

Wang, Y., Cheng, H., Edwards, R. L., Kong, X., Shao, X., Chen, S., et al. (2008). Millennial and orbital-scale changes in the East Asian Monsoon and Yangtze River summer flooding. *Geophysical Research Letters*, 35, 11375–11382. https://doi.org/10.1029/2008gl036690

References From the Supporting Information

Benton, S., & Ezez, J. (2006). Impact of biomineralization processes on the Mg content of foraminiferal shells: A biological perspective. *Geochimica et Cosmochimica Acta*, 70, 611–625. https://doi.org/10.1016/j.gca.2005.09.015

Bryan, S. P., & Marchitto, T. M. (2008). Mg/Ca-temperature proxy in benthic foraminifera: New calibrations from the Florida Straits and a hypothesis regarding Mg/Li. *Science*, 324, 234–2348. https://doi.org/10.1126/science.1064618

Casasius, R. L. (2012). *Symbiosis in the fossil record: Eocene nummulites and pleistocene reefs of Egypt*. PhD thesis (pp. 115). University of California.

Collen, J. D., & Burgess, C. J. (1979). Calcite dissolution, overgrowth and recrystallization in the benthic foraminiferal genus *NLorotatula*. *Journal of Paleontology*, 53(6), 1343–1353.

D’Hondt, S., & Arthur, A. (1996). Late Cretaceous oceans and the cool tropic paradox. *Science*, 271, 5257–1838. https://doi.org/10.1126/science.271.5257.1838

Edgar, K. M., Pälike, H., & Wilson, P. A. (2013). Testing the impact of diageneric on the δ18O and δ13C of benthic foraminiferal calcite from a sediment burial depth transect in the equatorial Pacific. *Paleoceanography*, 28, 468–480. https://doi.org/10.1029/2005pa20045

Emery, W. E., & Torson, R. E. (2001). *Data analysis methods in physical oceanography* (2nd ed.) Elsevier Science. https://doi.org/10.1016/B978-0-444-50756-3.X5000-X

Flügel, E. (2004). Integrated facies analysis. In E. Flügel, & author (Eds.), *Microfacies of carbonate rocks – analysis, interpretation and application* (pp. 646). Springer. https://doi.org/10.1007/978-3-662-08726-8_13

Fox, L. R., & Wade, B. S. (2013). Systematic taxonomy of early-middle Miocene planktonic foraminifera from the equatorial Pacific Ocean: Integrated ocean drilling program, site U1338. *Journal of Foraminiferal Research*, 43(4), 374–405. https://doi.org/10.2113/gsafr.43.4.374

Goyet, C., Healy, R., & Ryan, J. (2000). Global distribution of total inorganic carbon and total alkalinity below the deepest winter mixed layer depths. *Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy*, 756 ORNL/CDIAC-127, NDP-076. https://doi.org/10.3334/cdcat/ngd076
Isobe, A. (2020). Paleo-ocean destratification triggered by the subduction of the Oyashio water into the Sea of Japan after the Last Glacial Max-
imum. Paleoceanography and Paleoclimatology, 35, e2019PA003593. https://doi.org/10.1029/2019PA003593
Itaki, T., Ikekara, K., Motoyama, I., & Hasegawa, S. (2004). Abrupt ventilation changes in the Japan Sea over the last 30 ky: Evidence from
deep-dwelling radiolarians. Palaeogeography, Palaeoclimatology, Palaeoecology, 298, 263–278. https://doi.org/10.1016/j.palaeo.2004.03.010
Katz, A. (1973). The interaction of magnesium with calcite during crystal growth at 25–90 °C and one atmosphere. Geochemistry et Cosmochimica
Acta, 37, 1597–1598. https://doi.org/10.1016/0016-7037(73)90091-4
Lamb, J. L., & Miller, T. H. (1984). Stratigraphic significance of Uvigerinid foraminifers in the western hemisphere. Harold Norman Fisk Mem-
orial Papers. No. 66. Exxon Company.
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. https://doi.org/10.1126/science.287.5451.269
Lear, C. H., Rose, H., & Slowey, N. (2002). Benthic foraminifer Mg/Ca/Capaciometer: A revised core-top calibration. Geochemistry et
Cosmochimica Acta, 66(19), 3375–3387. https://doi.org/10.1016/S0016-7037(02)00941-9
Lewis, E., & Wallace, D. (1998). Program Developed for CO₂ System Calculations. ORNL/CDIAC-105. Carbon Dioxide Information Analysis
Center, Oak Ridge National Laboratory.
Marchitto, T. M., Bryan, S. P., Curry, W. B., & McCorkle, D. C. (2007). Mg/Ca temperature calibration for the benthic foraminifer Cibicidoides
pachyderma. Paleoceanography, 22, PA11203. https://doi.org/10.1029/2006PA001287
Martin, P. A., & Lea, D. W. (2002). A simple evaluation of cleaning procedures on fossil benthic foraminifer Mg/Ca. Geochimica, Geophysics,
Geosystems, 3(10), 8401. https://doi.org/10.1029/2002GC000280
Mawbey, E. M., Hendry, K. R., Greaves, M. J., Hillenbrand, C.-D., Kuhn, G., Spencer-Jones, C. L., et al. (2020). Mg/Ca Temperature calibration
of polar benthic foraminifera species for reconstruction of bottom water temperatures on the Antarctic shelf. Geochimica et Cosmochimica
Acta, 283, 54–66. https://doi.org/10.1016/j.gca.2020.05.027
Nomaki, H., Heinz, P., Nakatsuka, T., Shimanaga, M., & Kitazato, H. (2005). Species-specific ingestion of organic carbon by deep-sea ben-
thic foraminifera and meiobenthos: In situ tracer experiments. Limnology and Oceanography, 50(1), 134–146. https://doi.org/10.4319/
lo.2005.50.1.0134
Ohga, T., & Kitazato, H. (1997). Seasonal changes in benthal foraminiferal populations in response to the flux of organic matter (Sagami Bay,
Japan). Terra Nova, 9(1), 33–37. https://doi.org/10.1046/j.1365-3121.1997.doi-1.x
Oomori, T., Kaneshima, H., Maezato, Y., & Kitano, Y. (1987). Distribution coefficient of Mg²⁺ ions between calcite and solution at 10–50°C.
Marine Chemistry, 20(4), 327–336. https://doi.org/10.1016/0304-4203(87)90066-1
Pearson, P. N., & Burgess, C. (2008). Foraminifer shell preservation and diagenesis: Comparison of high latitude Eocene sites. In W. E. N. Austin,
& R. H. James (Eds.), Biogeochemical controls on palaeoceanographic proxies (Vol. 303, pp. 59–72). Geological Society of London, Special
Publications. https://doi.org/10.1144/SP303.5
Pearson, P. N., Ditchfield, P. W., Singano, J., Harcourt-Brown, K. G., Nicholas, C. J., Olsson, R. K., et al. (2020). Warm tropical sea surface
temperatures in the Late Cretaceous and Eocene epochs. Nature, 413, 481–487. https://doi.org/10.1038/35097000
Pearson, P. N., Evans, S. L., & Evans, J. (2015). Effect of diagenetic recrystallization on the stability of planktonic foraminifer tests under comp-
pression. Journal of Micropalaeontology, 34(1), 59–64. https://doi.org/10.1144/jmpaleo2013-032
Rathburn, A. E., & De Deckker, P. (1997). Magnesium and strontium compositions of Recent benthic foraminifera from the Coral Sea, Australia
and Prydz Bay, Antarctica. Marine Micropaleontology, 29(3–4), 231–248. https://doi.org/10.1016/S0377-8398(97)00028-5
Rose, H., & Doyle, E. (1993). Factors controlling the fluoride content of planktonic foraminifera: An evaluation of its palaeoceanographic
applicability. Geochimica et Cosmochimica Acta, 57, 335–346. https://doi.org/10.1016/0016-7037(93)90435-y
 Sexton, P. N., Wilson, P. A., & Pearson, P. N. (2006). Microstructural and geochemical perspectives on planktonic foraminifer preservation:
“glassy” versus “frosty”. Geochemistry, Geophysics, Geosystems, 7(12), GC01291. https://doi.org/10.1029/2006gc001291
Shackleton, N. J. (1974). Attainment of isotopic equilibrium between ocean water and the benthonic foraminifera genus Uvigerina: Isotopic
changes in the ocean during the Last Glacial. Colloques Internationaux de C.N.R.S., (pp. 203–209).<ref>
Tachikawa, K., & Elderfield, H. (2002). Microhabitat effects on Cd/Ca and δ¹⁸O of benthic foraminifera. Earth and Planetary Science Letters,
202(3–4), 607–624. https://doi.org/10.1016/S0012-821X(02)00796-3
Taylor, L. D., Lobanov, V., Ponomarev, V., Salyuk, A., Tsichchenko, P., Zhabin, I., et al. (2003). Deep convection and brine rejection in the Japan
Sea. Geophysical Research Letters, 30(4), 1159. https://doi.org/10.1029/2002GL016451
Voigt, J., Hathorne, E. C., Frank, M., & Holburn, A. (2016). Minimal influence of recrystallization on middle Miocene benthic foraminiferal
stable isotopic stratigraphy in the eastern equatorial Pacific. Paleoceanography, 31, 98–114. https://doi.org/10.1002/2015pa002822
Wilson, P. A., Norris, R. D., & Cooper, M. J. (2002). Testing the Cretaceous greenhouse hypothesis using glassy foraminiferal calcite from the
core of the Turonian tropsics on Demerara Rise. Geology, 30, 607–610. https://doi.org/10.1130/0091-7613(2002)030<0607:tnghhc>2.0.co;2
Wilson, P. A., & Opdyke, B. N. (1996). Equilibrium sea-surface temperatures for the Maastrichtian revealed through remarkable preservation
of metastable carbonate. Geology, 24, 555–558. https://doi.org/10.1130/0091-7613.1996.024<0555:esstet>2.3.co;2
Yu, J., & Elderfield, H. (2008). Mg/Ca in the benthic foraminifera Cibicidoides wuellerstorfi and Cibicidoides mundulus: Temperature versus
carbonate ion saturation. Earth and Planetary Science Letters, 276, 129–139. https://doi.org/10.1016/j.epsl.2008.09.015