New evidence for “far-field” Holocene sea level oscillations and links to global climate records

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A B S T R A C T

Rising sea level in the coming century is of significant concern, yet predicting relative sea level change in response to eustatic sea level variability is complex. Potential analogues are provided by the recent geological past but, until recently, many sea level reconstructions have been limited to millennial scale interpretations due to age uncertainties and paucity in proxy derived records. Here we present a sea level history for the tectonically stable “far-field” Great Barrier Reef, Australia, derived from 94 high precision uranium–thorium dates of sub-fossil coral microatolls. Our results provide evidence for at least two periods of relative sea level instability during the Holocene. These sea level oscillations are broadly synchronous with Indo-Pacific negative sea surface temperature anomalies, rapid global cooling events and glacial advances. We propose that the pace and magnitude of these oscillations are suggestive of eustatic/thermometric processes operating in conjunction with regional climatic controls.

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1. Introduction

Over the coming century sea-level uncertainty will be one of the greatest challenges of projected global climate change (Milne et al., 2009; Haigh et al., 2014). Not only are millions of people living in coastal communities at threat of being displaced due to potential sea-level rise, but the vulnerabilities of coastal and intertidal ecosystems are still relatively ambiguous (Hamlyn et al., 2014). At local to regional scales the immediate and future impacts of sea-level rise will be governed largely by the rate of sea-level change and adaptation thresholds (Hamlyn et al., 2014), however understanding the spatial heterogeneity of relative sea level (RSL) response to eustatic sea-level rise is complex (Milne et al., 2009). The Holocene offers potential analogues for understanding future sea-level variability, with geographically divergent RSL histories responding to global melt water following the end of the Last Glacial Maximum (Clark et al., 1978; Pirazzoli and Pluet, 1991; Lambeck et al., 2014). Where the transition from the Last Glacial Maximum to the early Holocene (∼18,000–8000 yr before present; yr BP) is characterized by a relatively globally coherent rapid sea-level rise of ∼125 m due to melting of substantial northern hemisphere ice sheets, the mid-Holocene presents more complex and geographically divergent RSL histories as a result of glacio-hydro-isostatic and water redistribution processes over sub-millennial to millennial timescales (Clark et al., 1978; Pirazzoli and Pluet, 1991; Mitrovica and Milne, 2002; Lambeck et al., 2014). Yet whether sea level has oscillated significantly at centennial timescales in response to climate perturbations during the Holocene is controversial (Fairbridge, 1961; Chappell, 1983; Baker et al., 2005; Woodroffe and Horton, 2005; Sloss et al., 2007; Woodroffe et al., 2012; Lewis et al., 2013; Lambeck et al., 2014). Therefore, precisely dated geological indicators in tectonically stable “far-field” regions offer the best potential to develop RSL histories that may shed light on global eustatic sea-level history.

The intraplate position of Australia (tectonic stability) and its location in the far-field makes it an ideal site for paleo-sea level investigations (Lambeck and Nakada, 1990; Lambeck, 2002). Geo-physical models of glacio-hydro-isostatic RSL response place the Australian East Coast within Zone IV of the of post-glacial melt response (Clark et al., 1978). This zone is characterised by a mid-Holocene RSL highstand, representing the cessation of northern hemisphere ice melt (glacio-eustasy), followed by a RSL regression to present levels where ocean mass redistribution and hydro-isostasy dominate the signal (Clark et al., 1978). In agreement with this model Chappell (1983) used coral microatoll data from the Great Barrier Reef (GBR) to demonstrate a mid-Holocene highstand of 1.0–1.5 m above modern levels by ∼6000 yr BP (where present is defined as before 1950), followed by a linear (smooth fall) RSL
regression to modern levels (Chappell, 1983). However, reports of an oscillating or stepped sea-level signal both relative to Australia (Fairbridge, 1961; Baker et al., 2001, 2005; Lewis et al., 2008) and elsewhere globally (Hamanaka et al., 2012) are numerous. Unfortunately, until recent advances in both the accuracy and precision of radiometric dating, understanding sub-centennial sea-level variability has not been realistically possible (Lewis et al., 2008; Lambeck et al., 2014).

Here we aim to refine Holocene “far field” sea level based on 94 new high-precision U–Th dates of coral microatolls (Porites spp.) in conjunction with elevation surveys from the Great Barrier Reef (GBR), Australia. We combine our results with previously published U–Th dated microatoll data from the southern GBR (Leonard et al., 2016) to assess possible synchronicity of RSL oscillations across ~10 degrees of latitude (Fig. 1; Fig. SM.2; Materials and Methods). Coral microatolls, especially Porites spp., are considered one of the most reliable palaeo-sea level indicators as the upper flat surface of the colony is constrained by the air–sea interface (Murray-Wallace and Woodroffe, 2014), with modern microatoll elevations lying generally within a vertical range of ~10 cm of mean low water spring (MLWS) tide level on the GBR (Chappell et al., 1983). We therefore report all elevations relative to modern site specific MLWS level with U–Th ages reported as years before present (yr BP), where present is defined as 1950.

2. Materials and methods

2.1. Sample collection and elevation surveys

As part of a multi-faceted project conducted under the National Environmental Research Program (NERP), numerous islands and coral reefs of the inshore GBR (11°S to 23°S) were visited between 2012 and 2014. Reef flats were visited at the lowest tides possible to enable sampling of fossil Porites sp. microatolls for RSL reconstructions. Corals were deemed to be in situ based on the orientation of coralite growth direction and relationship to the surrounding substrate (i.e. relative position of other fossil microatolls and other fossil reef features).

Using only a single type of sea-level indicator that is well constrained to a predictable level – mean low water spring (MLWS) tide – reduces the uncertainty of interpretation among sites, and negates the need for elevation interpolation required when a variety of sea-level indicators are used. As current hydro-and-glacio-isostatic models for the region are based on a limited number of previously published sea-level records that are geographically and chronologically discontinuous, we present our age-elevation data separated into four latitudinal zones ranging between 11°5′–20°5′ (<25 km from the mainland) based on relative location of sites to each other, and width of the continental shelf. No correction has been applied for glacial isostatic adjustment (GIA), as, although this would affect the absolute RSL elevation, it has little effect on the relative position of microatolls to each other within one region.

Elevations of microatolls were taken using a Magnus-Proshot 4.7 Laser Level and Apache Lightning 2 receiver and referenced against a timed-still tide level and, where possible, modern living counterparts. The elevation was taken from the centre of each microatoll along with the coral surface diameter and GPS location (Table A1). Elevations were calculated using the nearest tide gauge data from Maritime Safety Queensland (MSQ), time adjusted and reduced to elevation relative to present mean low water spring tide (MLWS; semi-diurnal tides) or mean lowest low water (MLLW; diurnal tides) as given by the Australian Bureau of Meteorology (http://www.bom.gov.au/australia/tides). Tidal range data for each site relative to MSL is provided in Table A2. Although elevation errors between each sample within sites is minimal and a function of the laser level accuracy (~0.001 m/30 m), we acknowledge the uncertainties of deriving absolute elevations from timed-still tide levels. We assigned a vertical error term to measurements of ±18 cm for Haggerstone Island and a conservative error term of ±15 cm for the remaining sites based on the propagation of tidal error correction and tide tie points of the living population of microatolls at sites compared to modern MLWS/MLLW levels. Our previous dating experience indicated that the centre of the microatolls generally had lower detrital inclusions and micro-borings than the edges, which greatly improves the uranium–thorium (U–Th) age accuracy. Therefore, samples of each microatoll were collected for dating from the centre of each colony using a hammer and chisel. Sometimes the centre of the colony was more bio-eroded than the edge, or the exact centre unclear. In this case samples were taken from the edge (E – in Table A1).

2.2. U–Th dating

Samples were prepared for U–Th dating at the Radiogenic Isotope Facility, The University of Queensland, using a pre-cleaning treatment described by Leonard et al. (2016). Crushed and ultracleaned samples were picked manually under a binocular microscope to allow the best aragonite to be selected for dating (i.e. lacking any detritus, alteration or cements). Picked samples were then weighed (15–50 mg), spiked with a 231U–229Th mixed tracer and dissolved in pre-cleaned Teflon beakers with 15.8 N quartz-double-distilled HNO3. Additionally, 6–10 drops of 30% H2O2 was added to the dissolved sample solutions to remove any remaining organics and to ensure complete homogenisation of the spike-sample solution. The Teflon beakers were capped, and the solution heated to 90°C on a hotplate overnight to ensure complete digestion. The solution was then dried down completely on a hotplate set at 90°C. Following complete drying, samples were re-dissolved using 0.7 ml of 7 N HNO3 and passed through pre-conditioned Bio-Rad AG1X8 anion resin ion-exchange columns to separate U
from Th. Quadrupole ICP-MS pre-screening of the collected U and Th solutions was conducted, and where necessary, U and Th solutions were remixed in appropriate proportions to maximize the signal. After thorough mixing of the U–Th solution, samples were centrifuged at 3500 rpm for 10 min and then measured fully automatically using a Cetac ASX110 auto-sampler on a Nu Plasma multi-collector inductively coupled plasma mass spectrometer (MC ICP-MS) as described in Clark et al. (2014). Sample ages were calculated using the decay constants of Cheng et al. (2000) using Isoplott/Ex software (Ludwig, 2003), and corrected for initial detrital $^{230}$Th using a two-component mixing correction scheme (Clark et al., 2014).

2.3. Statistical analysis

Relative sea level microatoll data from this study, as well as U–Th microatoll data obtained from the Keppel Islands by Leonard et al. (2016), were combined to derive a single sea-level record for the GBR. The mode of RSL fall to present levels was tested by applying linear and Gaussian models (two–four terms employed) to the data points with 95% confidence in Matlab®. The significance of the normality of the residuals from the models was assessed using the correlation coefficient of the probability in PAST statistical programme.

3. Results

Microatoll age elevation data from the present study (Fig. A3; Table A1), combined with previously reported U–Th microatoll data from the Keppel Islands (Fig. 2A; Leonard et al., 2016), show that continental island reef flats had developed by 7000–6500 yr BP on the inshore GBR. In the far north and northern GBR microatolls are found at least 0.5 ± 0.15 m above modern MLWS from ~7000–5500 yr BP (Fig. 2A; Fig. A3). After 5500 yr BP emergent reef flat growth ceases abruptly, with evidence that Holocene MLWS has lowered to close to modern levels between 5200–5000 yr BP at Fitzroy Island (~0.2 m) and Hayman Island (~0.0 m; Fig. 2A).

Comparatively, data from Stone Island (central GBR) indicates a rising RSL from 6900 to 6600 yr BP, at an average rate of ~1.4 mm yr$^{-1}$ (Fig. 2A). This rate of RSL rise is similar to a contemporaneous record from the Keppel Islands of ~0.5–1.1 mm yr$^{-1}$ between ~6900 and 6200 yr BP (Leonard et al., 2016) suggesting that either: a) the timing of the RSL highstand is latitudinally displaced due to a lag in water mass redistribution; or more likely b) hydro-isostatic adjustment occurred on this wider section of the continental shelf in the early mid-Holocene, with regional variation possibly related to the NE–SW structural linement boundaries across the shelf (Kleypas and Hopley, 1992; Dechnik et al., 2017).

At Alexandra Reef, a mainland fringing reef, substantial microatoll development at ~0.5 ±0.15 m above present did not commence until after 5000 yr BP (Fig. 2A; Fig. A3B). This later initiation was likely the result of turbid conditions due to reworking of coastal pre-transgressive sediments being unfavourable for substantial coral growth (Larcombe and Woolfe, 1999). A rapid RSL lowering of ~0.3 to ~0.5 m occurs at this site at ~4600 yr BP, persisting for at least 400 yr. Whilst there is overlap of microatoll U–Th dates at the time of the transition from higher to lower RSL this can be explained by both our sampling strategy and the individual coral morphologies at this site (see Fig. A1). This RSL lowstand is also supported by evidence on the leeward reef flat of Gooree Island, where microatolls occur close to the elevation of their modern counterparts (~+0.08 m) between 4300 and 4000 yr BP and at Fitzroy Island, where microatolls were found to be below their modern counterparts at 4400 yr BP (Fig. 2A). Emergent reef
flat shut down in the Keppel Islands is also synchronous with this lowstand period (Fig. 2A; Fig. A.3E). After 4000 yr BP RSL appears to have risen 0.2–0.3 m to 2800 yr BP (Leonard et al., 2016), after which only a limited number of samples are currently available for interpretation.

Linear and Gaussian models of the microatoll data from the present study, combined with previously published data from the Keppel Islands (Leonard et al., 2016), indicate that significance in the normality of residuals \( p = 0.05, n = 130; \) Filliben, 1975) is only achieved with an increase in terms for a Gaussian model of the RSL data (Fig. 3; Table A.3; adjusted \( r \)-squared 0.36) compared with lower Gaussian functions (Fig. A.4) or a linear model of RSL regression (Fig. 3; Table A.3; adjusted \( r \)-squared 0.15). Both the linear and lower term Gaussian functions overestimate microatoll RSL height from 5500–5000 yr BP and 4500–4000 yr BP (negative residuals) and under estimate RSL from 5000–4500 yr BP (Fig. 3; Fig. A.4), supporting an oscillatory mode of RSL for the GBR.

4. Discussion

4.1. Rapid sea level lowering events

In agreement with geophysical models our data indicates a RSL regression from a mid-Holocene highstand to present levels, largely attributable to ocean syphoning (Chappell, 1983; Mitrovica and Milne, 2002). However, the timing of the highstand on the GBR occurs \( \sim 1000–2000 \) yr earlier than predicted by earlier geophysical models (Fig. 1; Clark et al., 1978; Nakada and Lambeck, 1989). This temporal offset is a function of the initial modelling parameters used by Nakada and Lambeck (1989) which were based on evidence derived from radiocarbon age-elevation data (Chappell, 1983) which, when recalibrated to account for both global and local marine reservoir effects, would be shifted considerably closer to \( \sim 6500–7000 \) yr BP (Lewis et al., 2008). The timing of the highstand at \( \sim 7000 \) yr BP is therefore in agreement with previous data from the GBR (Chappell, 1983; Lewis et al., 2008) and the Australian East Coast (Sloss et al., 2007), although we find no evidence of RSL \( > 1 \) m of present in the mid-Holocene. This may be a result of the microatoll samples delineating a MLWS tide level instead of mean sea level (MSL), so that higher values cannot be discounted. Lewis et al. (2008) reported a systematic \( \sim 0.5 \) m elevation offset between microatoll RSL reconstructions and those obtained from fixed biological indicators, likely due to site-specific environmental conditions (e.g. wave energy).

More notable, however, is that the relative elevations of the microatolls surveyed in the present study suggest that the post highstand regression was punctuated by rapid sea level lowering events at 5500 and 4600 yr BP, with a third possible lowstand after \( \sim 2800 \) yr BP (Fig. 1). The RSL lowering event at 5500 yr BP in the central GBR and the Keppel Islands of at least \( \sim 0.4 \) m (Leonard et al., 2016) coincides with significant reductions in reef flat progradation (Smithers et al., 2006; Perry and Smithers, 2011), as well as a sudden reef “turn-off” in Moreton Bay by 5600 yr BP (Fig. A.3E; Lybolt et al., 2011; Leonard et al., 2013). The second RSL level lowering event of \( \sim 0.2–0.4 \) m at 4600 yr BP agrees well with the oscillation proposed by Lewis et al. (2008) for the Australian East Coast (Fig. A.3E), and is also synchronous with reef flat “turn-off” in the Keppel Islands (Leonard et al., 2016) and a significant reef initiation “hiatus” in the southern and northern GBR (Perry and Smithers, 2011). Despite variability in the response of individual reefs, the configuration of the combined RSL signal and synchronic-

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**Fig. 3.** Linear and Gaussian models of relative sea level (RSL) on the Great Barrier Reef, Australia, based on U–Th dated coral microatoll age elevation. Probability plots show the normal distribution of the model residuals. Elevation is in metres (m) relative to present mean low water spring tide (MLWS). U–Th ages are given in years before present (yr BP) where present is defined as 1950. Gaussian 4 represents number of terms included in the analysis. Dotted blue lines are 95% confidence bounds, red dashed squares indicate predictive tendency of the residuals of the models indicating poor fit to the data. The correlation coefficient of normal distribution of the residuals is only significant \( p = 0.05 \) for the Gaussian model.
ity of re-initiation at some sites between these lowstand periods suggests a return to higher levels.

The coherence of the oscillations across an extensive latitudinal range rules out regional neotectonic activity or local reef/coastal dynamics, although local variations in the absolute level of the RSL reconstruction may be affected. The sub-centennial timescale of the oscillations also precludes hydroisostasy/ocean syphoning as the primary drivers, although these factors explain the overall regressive trend following the highstand well. We therefore consider that the oscillations detected in our record may be of eustatic, thermoclastic or regional climatic origin, or a combination of these factors.

4.2. Links to climate

At a regional scale, the most important modulating climate system at annual to decadal scales on the GBR is the El Niño Southern Oscillation (ENSO), with La Niña (El Niño) associated with increased (decreased) precipitation in the Austral summer. Although the effect of El Niño/La Niña events on sea surface height on the Australian East Coast is not well understood, in the central Pacific sea surface height can vary by as much as 0.3–0.4 m due to the varying phases of ENSO (Woodroffe and McLean, 1998).

Recent evidence also suggests that during La Niña phases low latitude glaciers advance (Francou et al., 2004) and Antarctic glacier melting is greatly reduced (Dutrieux et al., 2014), increasing the potential of terrestrial water storage in the Southern Hemisphere.

Marine based reconstructions of Holocene climate variability on the GBR are currently restricted to short time windows. Coral derived sea surface temperature (SST-Sr/Ca) reconstructions demonstrate conditions~1°C warmer than present at ~6200 (re-calibrated 14C) and 4700 yr BP, with a suggested increase in salinity range (δ18O) associated with amplified seasonal flood events, suggestive of La Niña (Gagan et al., 1998; Roche et al., 2014).

A multi-proxy terrestrial record of pluvial conditions in southern Australia also shows a La Niña like mean state of climate, inferred from rainfall maximums at ~5800–5200, ~4500 and from ~3500–2700 yr BP (Gliganic et al., 2014). These periods are also synchronous with phases of dampered El Niño events identified at Laguna Pallcacocha, Ecuador (Fig. A.5F; Moy et al., 2002) and to cooling (or contraction) of the Indo-Pacific warm pool (IPWP) in the western Pacific (Abram et al., 2009).

Coral derived Sr/Ca SST anomaly data from the Indo-Pacific (McCulloch et al., 1996; Gagan et al., 1998; Montaggioni et al., 2006; Abram et al., 2009; Duprey et al., 2012; DeLong et al., 2013; Roche et al., 2014; Sadler et al., 2016) also demonstrate warmer than present conditions ~6500 yr BP, followed by a transition to cooler temperatures by ~5500 yr BP (Fig. 2B).

At a broader scale, foraminiferal abundance and δ18O analysis of a deep sea core off the South Australian coast demonstrates distinct marine cooling events (of possibly ~2°C) at 5800, 4300 and 2700 yr BP (Fig. A.5B; Moros et al., 2009), which are aligned with cold events identified in the EPICA Dome C ice core. A period of significant SST cooling and ice expansion was also reported for the South Atlantic sector of the Southern Ocean between ~5500–4700 yr BP (Hodell et al., 2001). In the northern hemisphere, evidence from Greenland (GISP 2) suggests rapid cooling events of 1.5–2.0°C from 5600–5400 yr BP, 5000–4700 yr BP, and a stepped cooling trend from 2100–1200 yr BP (Alley, 2000).

Rapid cooling also occurs in the North Atlantic (Bond Cycles 4, 3 and 2) at 5900, 4200 and 2800 yr BP (Bond et al., 1997), which align with periods of global glacier advances (Fig. A.5; Denton and Karlén, 1973; Mayewski et al., 2004). With modelled projections of future sea-level rise suggesting a 0.2–0.6 m per +1°C (Church et al., 2013), a first order approximation of observed cooling events of ~1°C in the northern and southern hemisphere during the Holocene may reconcile the RSL oscillations on the GBR. Although marine and terrestrial palaeo-temperature reconstructions within a given study are not indicative of global mean response, the synchronicity of cooling events and the RSL oscillations described here for the GBR are noteworthy and require further investigation. If the oscillations presented here for the GBR are of eustatic/global climatic origin, then oscillations with comparable chronologies and/or magnitude should be detectable in other “far-field” locations, even if the absolute elevation of RSLs differ due to local response and the indicators used.

4.3. Far-field sea level records

Mid- to late-Holocene sea level oscillations of over 1 m, as first proposed by Fairbridge (1961), have hitherto been dismissed due to the difficulty in reconciling the required ice volume or thermoclastic contribution for such substantial eustatic changes. The oscillations identified here for the GBR between 0.2–0.4 m are, however, within the bounds of modelled and hind cast response of global sea levels to relatively minor temperature changes (0.9 ± 0.8 m/0.2°C) derived from proxy evidence over the past 3000 yr (Kopp et al., 2014).

Sea level oscillations of ~0.5 m have also been inferred from both individual microatoll morphological features in Indonesia (Meltzer et al., 2017) and China (Yu et al., 2009), although both occur ~1000 yr prior to our record. In the north west Pacific at Kodakara Island, disconformities (and hiatus) in an uplifted coral reef at ~5800, ~4200 and ~3200 yr BP were reported, with the latter two events associated with sea level oscillations linked to northern hemisphere cooling (Hamanaka et al., 2012). Geomorphic evidence from the Atlantic coast of South Africa indicates a rapid sea level fall to below present after ~5500 yr BP and between 4800–4200 yr BP (Compton, 2006), consistent with the GBR record presented here, although of much larger amplitudes. Facies and faunal interpretations on the coast of Bangladesh also record a stepped RSL regression with rapid lowering from 5900–5700 yr BP, and at 5500 yr BP and a further minor regression after 4800 yr BP (Rashid et al., 2013).

Conversely, a continuous far-field RSL record from Kiritimati, derived from microatoll age-elevation data, suggested that sea level had been within of ~0.25 m of present throughout the Holocene (Woodroffe et al., 2012). However, separating the interior emergent microatoll population data from reef flat data greatly affects the continuity of this record, resulting in a RSL history that is not inconsistent with possible oscillations. The elevation of the fossil reef flat microatolls close to present sea level between 4700 and 4100 yr BP, and after 2800 yr BP on the island’s exterior, is in line with the timing of the negative sea-level oscillations proposed for the GBR. Furthermore, the most elevated (uncorrected) microatolls from the centre of the atoll occur between our lowstand periods, suggesting that populations inside the former reticulate lagoon may either have been isolated from oceanic influence or have reduced tidal flushing, leading to coral demise between 4600–4000 yr BP and 2800–2100 yr BP (within dating uncertainties). Unfortunately, the age errors (>±500 yr) of the two earliest reef flat samples between 6000–5000 yr BP make comparisons with our data difficult. Similarly, a recent analysis of global “far-field” sea level proxy data also reported no evidence of eustatic sea-level variability >0.15–0.20 m for the past 6000 yr. However, the vertical uncertainty of the proxies used in this analysis was sometimes several metres (Lambeck et al., 2014) and age error terms were up to ±700 yr (Woodroffe et al., 2012), making interpretation at timescales relevant to rapid climate change events problematic.
5. Conclusions

Supporting a model of RSL instability throughout the Holocene, our study is the first to demonstrate coherent rapid RSL oscillations represented across a large geographic range based upon measurements of coral microatoll elevations dated with high-precision U–Th techniques. Despite variation in the response of individual coral reefs to RSL lowering events on the GBR throughout the Holocene, synchronicity of responses at 5500 and 4600 yr BP and after 2800 yr BP concurs with both oscillations reported at other far-field locations, and with independently documented climate shifts. We propose that GBR RSL oscillations are likely the result of ocean-atmosphere climatic perturbations affecting SSTS, as well as sensitive mountain ice-cap and non-polar ice sheet water storage balances in both the northern and southern hemispheres.

With recent advancements in the accuracy and precision of geochronological techniques future research efforts should be concentrated on obtaining high resolution RSL data from other terminally stable far-field locations. Furthermore, reconstructing high resolution palaeoclimate records, especially in the southern hemisphere, is imperative to interpreting possible sub-centennial scale associations between Holocene climate and sea level. Establishing links between sea level and climate in the recent geological past, and refining RSL histories with regard to eustatic changes, will ultimately improve the models of future climate change scenarios that are essential for coastal planning and management.

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Appendix A. Supplementary material

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