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Response of the Great Barrier Reef to sea-level and environmental changes over the past 30,000 years

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Previous drilling through submerged fossil coral reefs has greatly improved our understanding of the general pattern of sea-level change since the Last Glacial Maximum, however, how reefs responded to these changes remains uncertain. Here we document the evolution of the Great Barrier Reef (GBR), the world's largest reef system, to major, abrupt environmental changes over the past 30 thousand years based on comprehensive sedimentological, biological and geochronological records from fossil reef cores. We show that reefs migrated seaward as sea level fell to its lowest level during the most recent glaciation (~20.5–20.7 thousand years ago (ka)), then landward as the shelf flooded and ocean temperatures increased during the subsequent deglacial period (~20–10 ka). Growth was interrupted by five reef-death events caused by subaerial exposure or sea-level rise outpacing reef growth. Around 10 ka, the reef drowned as the sea level continued to rise, flooding more of the shelf and causing a higher sediment flux. The GBR's capacity for rapid lateral migration at rates of 0.2–1.5 m yr^{-1} (and the ability to recruit locally) suggest that, as an ecosystem, the GBR has been more resilient to past sea-level and temperature fluctuations than previously thought, but it has been highly sensitive to increased sediment input over centennial–millennial timescales.

The Last Glacial Maximum (LGM) and subsequent deglaciation represents a major reorganization of the global climate system, with rapid sea-level rises (for example, meltwater pulses (MWPs) 1A0, 1A, 1B and 1C)[1–4] linked to ice-sheet collapse, changes in global ocean circulation and temperatures[5], and periods of divergent atmospheric CO_2 concentrations and ocean aragonite/calcite saturation states[6]. Although to understand the responses of coral reef systems to these major, abrupt environmental changes is crucial to place possible reef futures into an appropriate time frame within the context of global processes[7,8], few fossil reef records (for example, Barbados, Huon Peninsula, Vanuatu and Tahiti)[1,2,9–11] fully span this ~30–10 thousand years (kyr) period. Thus, questions remain about the critical environmental thresholds that led to reef demise[9,12] in the past and how reefs recover after disturbances on different spatiotemporal scales[13–15].

In this study, we present a synthesis of all the available geomorphic, sedimentological, biological and dating information from fossil reef cores recovered from the Great Barrier Reef (GBR) shelf-edge reefs during Integrated Ocean Drilling Program (IODP) Expedition 325[16]. Radiometric and geochemical investigations of these cores, combined with sediment cores from the adjacent basin, have yielded precise constraints on variations in the relative sea level (RSL) (Y. Yokoyama et al., manuscript in preparation), sea-surface temperature (SST)[17] and sediment flux[18] over this period. We now document how the GBR responded to these major environmental variations, which includes the corresponding changes to reef morphologies, communities and growth rates. We also confirm the existence and location of reef refugia[19,20] during the LGM sea level and establish the critical environmental conditions at which the reef died and re-established on centennial–millennial timescales[8] over the past 30 kyr.

Shelf-edge reef structure, composition and sequences

Transects of reef cores were recovered off Mackay (Hydrographer's Passage at 19.7 °S, HYD-01C, Sites M0030–M0039) and Cairns (Noggin Pass at 17.1 °S, NOG-01B, Sites M0053–M0057), and consisted of 20 holes drilled at 16 different sites (Figs. 1 and 2 and Supplementary Notes 1 and 2), and were used to investigate the evolution of the GBR. U–Th and ^{14}C accelerator mass spectrometry (AMS) dating[16,17,21](Y. Yokoyama et al., manuscript in preparation)

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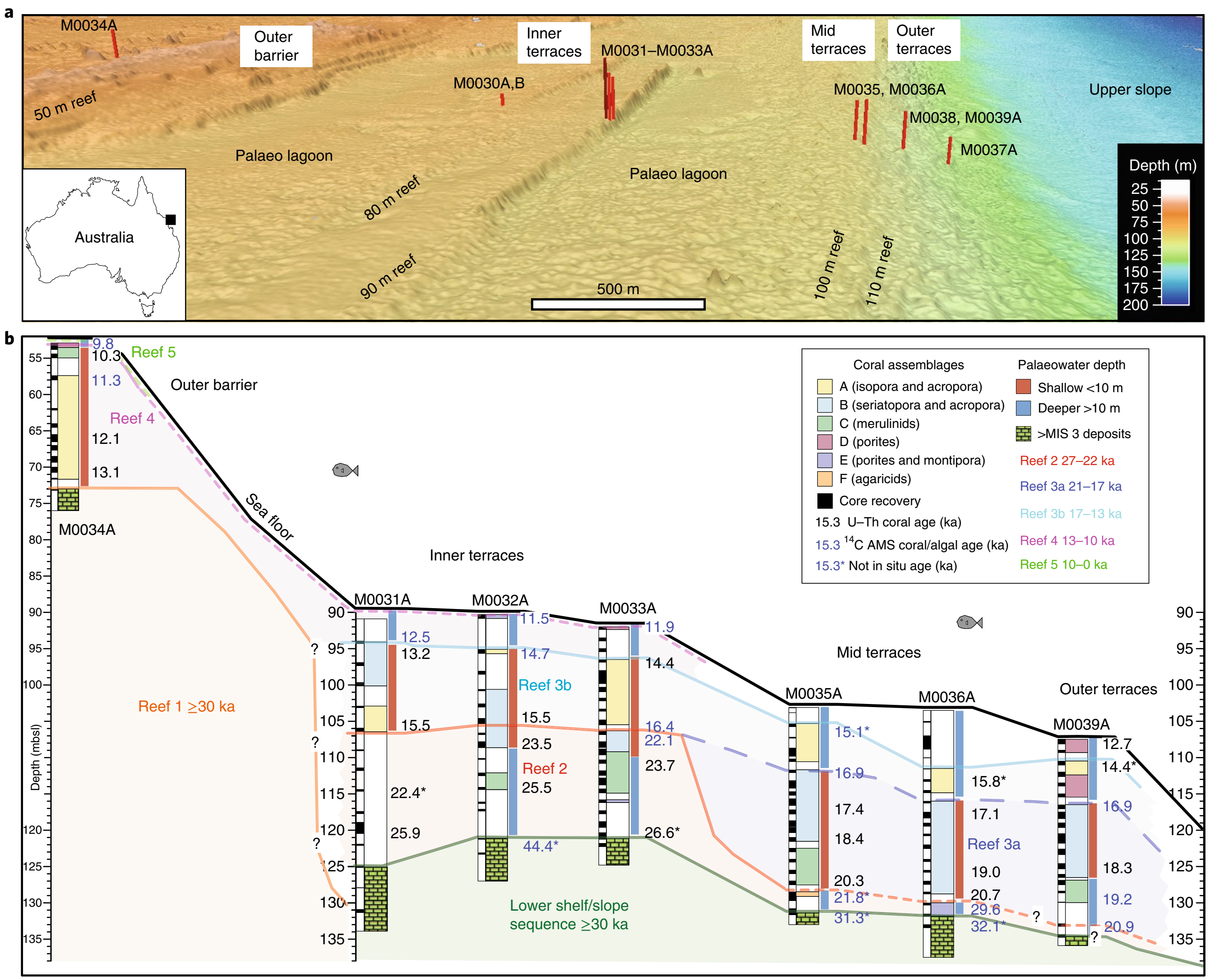


Fig. 1 | Geomorphic, chronostratigraphic and biological development of the Hydrographer's Passage drill transect (HYD-01C) off Mackay. a, A high-resolution multibeam image shows the surface geomorphic context[16,38] of HYD-01C and the drill-hole locations (red lines represent the penetration depths). **b**, A simplified stratigraphic section that shows the distribution of recovered core intervals, coral assemblages and their interpreted palaeowater depths, and selected U–Th and ^{14}C AMS ages. Chronostratigraphic boundaries of the four main shallow reef sequences (Reefs 1–4) are represented by solid coloured lines and long dashes; short dashes show their corresponding deep-water fore-reef slope deposits (Methods, Supplementary Notes 1–3 and Supplementary Fig. 1). Reef 5 represents the modern Holocene reef and is characterized by deep-water fore-reef slope deposits on the shelf edge. The *x* axis represents the distance across the shelf and is schematic (**a** gives the actual core locations).

of >580 corals and coralline algae, combined with sedimentological and biological analyses (Methods), provided a robust chronostratigraphic framework to assess the impacts of abrupt sea-level and associated environmental changes (Supplementary Notes 2–5 and Supplementary Figs. 1 and 2). First, we show that the GBR had a complex and dynamic history of reef growth and demise over the past 30 kyr, characterized by five distinct reef sequences (Reefs 1–5) that recorded episodic seaward (offlapping) then landward (onlapping) reef growth across the shelf (Figs. 1 and 2). Each reef sequence consists of coherent, coeval shallow and deep reef habitats that can be traced in time and space. Second, we establish the nature and timing of the reef initiation and demise events, and document the corresponding changes in coral–algal assemblages, vertical accretion (VA) rates (that is, upward growth of the reef) and palaeoenvironmental conditions at each stage of the GBR's development.

The development of the five reef sequences over the past ~30 kyr reflects the GBR's responses to major changes in global climate (Fig. 3a). As temperatures cooled into the LGM, high-latitude ice sheets reached their maximum extent and reduced global mean sea levels (GMSL ~125–130 metres below sea level (mbsl)). In the GBR, the RSL was lowest (~118 m) by ~20.7–20.5 thousand years ago (ka) (Y. Yokoyama et al., manuscript in preparation) (Fig. 3b,d). Western Pacific SSTs were also lowest at 18–20 ka (refs [17,22]) (Fig. 3a), with a corresponding much larger north–south SST gradient that points to a northward expansion of cooler subtropical waters and changes to GBR ocean currents[17]. As the deglaciation progressed from the LGM to 10 ka, SSTs warmed and sea level rose, albeit rapidly and non-linearly, as a result of global ice-sheet melting (Fig. 3a). Sea-level change over the LGM to deglacial period was the primary, although not the sole, driver of spatiotemporal variations in reef development, coral–algal assemblages and VA rates, as recorded

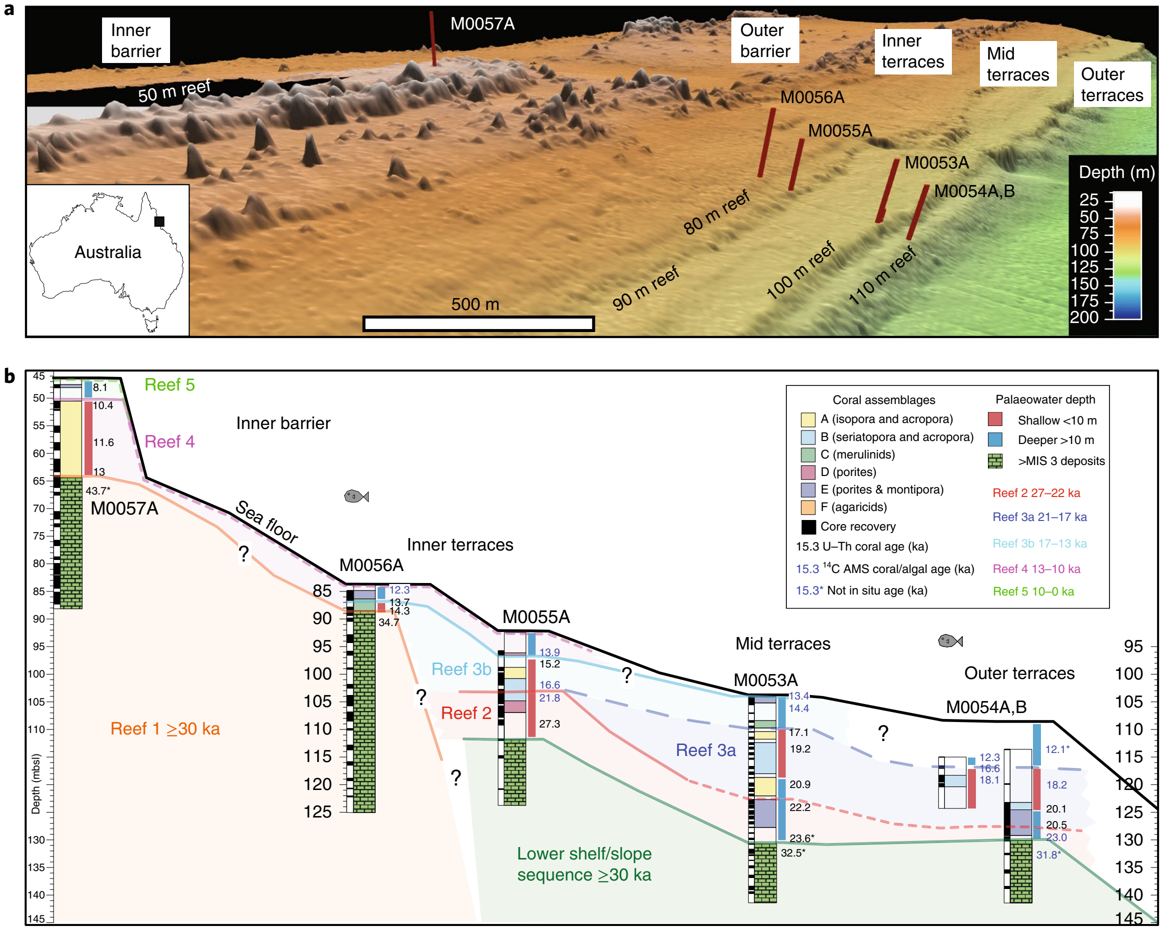


Fig. 2 | Geomorphic, chronostratigraphic and biological development of the Noggin Pass drill transect (NOG-01B) off Cairns. a, The high-resolution multibeam image shows the surface geomorphic context[16,38] of NOG-01B and the drill-hole locations (red lines represent penetration depths). **b**, A simplified stratigraphic section that shows the distribution of recovered core intervals, coral assemblages and their interpreted palaeowater depths, and selected U–Th and ^{14}C AMS ages. Chronostratigraphic boundaries of the four main shallow reef sequences (Reefs 1–4) are represented by solid coloured lines and long dashes; short dashes show their corresponding deep-water fore-reef slope deposits (Methods and Supplementary Notes 1–3 and Supplementary Fig. 1). Reef 5 represents the modern Holocene reef and is characterized by deep-water fore-reef slope deposits on the shelf edge. The *x* axis represents the distance across the shelf and is schematic (**a** gives the actual core locations).

in the five reef sequences (Figs. 3 and 4). Below we explore the interplay between the major environmental drivers (sea level, SST and sediments) at each stage of the GBR's development and demonstrate that its growth and demise was more complex than previously thought[19,20].

Reef growth and demise during global glaciation

The GBR-initiated growth on the shelf edge at 28–27 ka following the GMSL fall[23] from Marine Isotope Stage (MIS) 3 to MIS 2. At Noggin Pass, an age of 35.6 ± 0.30 to 34.3 ± 0.30 ka[21] (core M0056A-2R) constrains the timing of the exposure and death of Reef 1 (Supplementary Note 2) as GMSL fell ~40 m (ref. [23]) at the inception of the LGM. The oldest ages from the inner terraces (holes M0031–M0033A and M0055A) indicate that Reef 2 started to grow on MIS 3 or older slope deposits between 27.35 ± 0.14 to 27.34 ± 0.07 ka, synchronously across the two regions as shallow-water reef growth migrated seaward. At this time the GBR formed a very narrow and ephemeral fringing reef system[24] that was capable only of a slow vertical growth (0.3–2.5 mm yr^{-1}) compared with the adjacent modern Holocene counterparts (Reef 5) (Fig. 3b,d and Supplementary Figs. 3 and 4). These apparently poor reef-growth conditions are consistent with globally synchronous slow VA rates (a meta-analysis is given Supplementary Figs. 5 and 6), but the reasons remain unclear (for example, restricted accommodation space or higher local sedimentation during the sea-level fall)[25].

Although the timing and maximum extent of the LGM remain controversial[23], RSL in the GBR fell to ~118 m below the present by 20.70 ± 0.20 to 20.51 ± 0.02 ka (Y. Yokoyama et al., manuscript in preparation). Major growth hiatuses at ~105 mbsl, at both transects (holes M0055A and M0031–M0033A), represent the turn-off of Reef 2 at 22.11 ± 0.23 to 21.87 ± 0.24 ka. Coral–algal assemblages indicate that palaeowater depths were shallow (<10 m) before Reef 2 death, and lithological, diagenetic and seismic evidence[16,21,24] confirm that the top of the reef is a subaerial exposure surface, consistent with a major RSL fall (Methods and Supplementary Note 2). However, shallow-reef development migrated from ~0.25 to 1 km seaward in <2 kyr, which indicates a robust GBR ecosystem during the LGM capable of average reef habitat migration rates of ~0.5 and 0.2 m yr^{-1} at Hydrographer's Passage and Noggin Pass, respectively.

Surviving and thriving during the LGM

These are the first direct data to show that reefs were established on the GBR shelf edge during the LGM sea level, and demonstrate that the recruitment by propagules from external reef refugia (for example, the Queensland Plateau)[20] was not necessary for the GBR to survive harsh LGM conditions. At both locations, Reef 3a

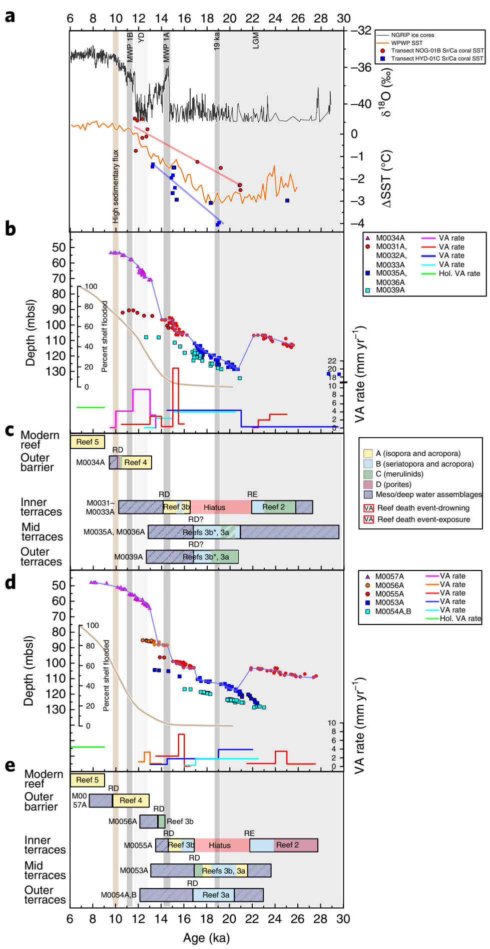


Fig. 3 | Evolution of the GBR over the past 30 kyr in relation to major sea-level and environmental changes. a, North Greenland Ice Core Project (NGRIP ice-core $\delta^{18}O$ record, with timing and duration of MWPs 1A0 (19 ka), MWP 1A and MWP 1B and other global climate events (LGM and YD) as vertical grey shaded bars[1,2,29,30]. The brown bar shows a massive flux of fine sediment to the slope at ~10 ka (ref. [18]) when >60–75% of the GBR shelf area was flooded (Supplementary Note 4). The orange line shows the western Pacific warm pool (WPWP) SST anomalies (reconstructed from planktonic foraminifera Mg/Ca (ref. [22])). Points and regression lines are regional SST anomalies (Expedition 325 coral Sr/Ca (ref. [17])) from Noggin Pass (red) and Hydrographer's Passage (blue). **b**, VA history for HYD-01C with the GBR maximum RSL curves (Y. Yokoyama et al., manuscript in preparation) (blue line) and percentage of shelf flooded (brown lines, not scaled to depth). Stepped plots are calculated VA rates, binned at 0.5 kyr intervals. **c**, Summary of spatial and temporal patterns of reef evolution (Reefs 1–5) at HYD-01C that encompass the outer-, mid- and inner-reef terraces, the inner- and outer-reef barriers and the modern Holocene reef. Periods of major reef turn-on, reef turn-off or reef death events caused by RD, RE and hiatus events are shown along with the distribution of coral assemblages (same colours as in Figs. 1, 2 and 4). The grey dashed boxes represent the timing and duration of the deep-water (>10 m) fore-reef slope deposits, which are sometimes coeval with shallow-water (<10 m) reef deposits upslope. **d**, VA history for NOG-01B (colours and plots as for **b**). **e**, Summary of spatial and temporal patterns of reef evolution (Reefs 1–5) at NOG-01B that encompass the outer-, mid- and inner-reef terraces, the inner- and outer-reef barriers and the modern Holocene reef. Periods of major reef turn-on, reef turn-off or reef death events caused by RD, RE and hiatus events are shown along with the distribution of coral assemblages (same colours as in Figs. 1, 2 and 4). The grey dashed boxes represent the timing and duration of the deep-water (>10 m) fore-reef slope deposits, which are sometimes coeval with shallow-water (<10 m) reef deposits upslope.

initiated growth at 20.70 ± 0.20 to 20.51 ± 0.02 ka on top of deeper fore-reef slope deposits of Reef 2 (Figs. 1 and 2) at the base of the mid-terraces (holes M0036A, M0035A, M0039A and M0053A), which indicates a pattern of shallowing, offlapping sequences related to seaward migration of the GBR. Shallow coral–algal assemblages (<10 m) dominate the LGM and the subsequent sea-level rise until 17 ka, which leads to a continuous vertical aggradation of Reef 3a at accretion rates of 3.9–4.4 mm yr^{-1}, similar to Holocene rates. Although Reef 3a has no discernible reef-drowning event or distinct changes in coral–algal assemblages associated with the 19 ka MWP 1A0, hole M0053A has a clear inflection point, which indicates a major slowing of accretion (3.9 to 1.8 mm yr^{-1}) after 19.22 ± 0.01 ka.

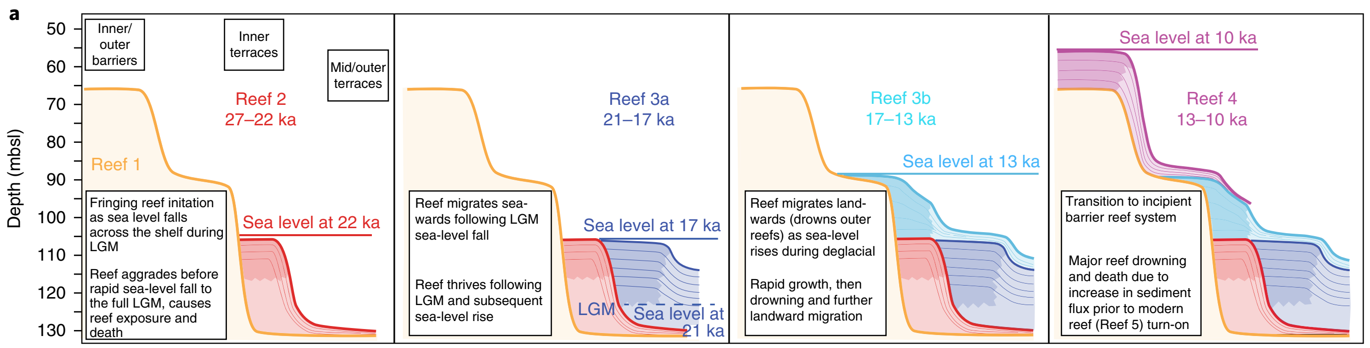
Rapid sea-level rise, shelf flooding, reef growth and demise

The deglaciation (~17–16.5 ka) saw a major reorganization of GBR shelf-edge reefs from aggrading to onlapping shallow sequences. Continued and rapid sea-level rise and associated environmental changes (for example, sediment flux) had two main impacts: (1) reflooding and re-initiation of reef growth on the inner terraces (holes M0033–M0031A and M0055A) and (2) major changes in lithologies, assemblages, accretion rates and ultimately reef drowning (RD) on the most distal part of the shelf edge (mid and outer terraces) (holes M0035A, M0036A, M0039A, M0053A and M0054A,B). Inner-terrace ages tightly constrain reflooding of the dead Reef 2 and the turn-on of Reef 3b at 16.85 ± 0.24 to 16.24 ± 0.24 ka. This represents a landward migration of shallow-water coral–algal assemblages from outer and mid terraces to the inner terraces that coincided with a major environmental perturbation that caused the drowning of Reef 3a. Down-hole gamma-ray logs[16] from the inner and mid terraces at Hydrographer's Passage (holes M0031A and M0036A) (Supplementary Figs. 1 and 2) indicate an increased flux of fine terrigenous sediments ~16 ka on the now-deeper fore-reef slope that may have reduced light availability and water quality to cause Reef 3a drowning. This is consistent with shelf-flooding reconstructions that show a peak in the area of flooded shelf at Hydrographer's Passage at ~16 ka (Supplementary Note 5).

Meanwhile, on the inner terrace (holes M0031–M0033A and M0055A), active fringing-reef growth continued, even flourishing at Hydrographer's Passage, with VA rates up to 20 mm yr^{-1} at 15.5–15.0 ka. These rates, the highest recorded from the GBR (Fig. 3) for the past 30 ka, coincided with a shift to shallow, high-energy, reef habitats characterized by a mix of coral assemblages (dominated by *Isopora, Acropora* or *Seriatopora*). At this location, in spite of the high sediment flux indicated by the gamma-ray data, Reef 3b kept pace with the rapid rises in sea level and SST[17,22] prior to MWP 1A. Studies of Holocene near-shore reefs in the GBR indicate that even the most turbid fringing reefs are capable of VA rates that match or exceed those of clear water outer-shelf reefs[26,27]. Unlike the mid and outer terraces, the near-shore Reef 3b was less sensitive to sediment flux, and grew rapidly as accommodation increased with rapidly rising sea levels.

Although the exact timing differs, our meta-analysis of Barbados and Tahiti data (Supplementary Figs. 5 and 6) shows the highest accretion rates in both records clustering around the disputed[1,2] timing of MWP 1A. Results from Tahiti provide firm constraints on the timing (14.65–14.31 ka) and magnitude (14–18 m) of MWP 1A (ref. [2]) and confirm that the Tahiti reef did not drown then[9]. The GBR record also shows no distinct drowning event directly correlated with MWP 1A, and the continuous shallow-water assemblages (<10 m) throughout some cores (M0031–M0033A) and the lack of recovery in others (M0055A) make it impossible to improve the Tahiti MWP 1A constraints. Ultimately, however, the sustained rapid sea-level rise during MWP 1A (ref. [2]) and prior to the Younger Dryas (YD), combined with

a



b

	Turn-on (ka)	Turn-off (ka)	RSL (mm yr^{-1})	ΔSST (°C)	Sediment flux	Reef-death cause
Reef 1	–	≥30	↓	–	–	Sea-level fall → exposure and death
Reef 2	27	22	↓ 16–11	▬ −4 to −2.5	↑	Rapid sea-level fall → exposure and death
Last Glacial Maximum (lowest global sea level)						
Reef 3a	21	17	↑ 7–25	↑ −3 to −1.5	↑	Rapid sea-level rise and high local sediment flux → drowning and death
Reef 3b	17	14–13	↑ 27–30	↑ −2 to −0.5	↑	Rapid sea-level rise and increasing regional sediment flux → drowning and death
Reef 4	13	10	↑ 4	▬ 0	↑	Massive regional sediment flux (3× LGM–Holocene level) and sea-level rise → drowning and death

Fig. 4 | Simplified model that shows the evolution of the GBR over the past 30 kyr. a, Basic chronostratigraphy, facies relationships and key stages during the development of the shelf-edge reefs. Darker shading indicates the distribution of shallower (<10 m) reef facies and paler shading that of deeper (>10 m) reef facies. The basement substrate (orange line) is composed of MIS 3 or older deposits that range from shallow reef (Reef 1) to deep lower shelf/slope settings. **b**, Key reef events (turn-on and reef death) and associated palaeoenvironmental changes, which include the rate of RSL change (Y. Yokoyama et al., manuscript in preparation), mean SST relative to the modern SST[17,22] and sediment flux[18,24,25,31] (Supplementary Table 6).

declining oceanographic conditions[25], contributed to the final demise of Reef 3b at 13.72 ± 0.07 ka.

Fringing to barrier–reef transition and the proto-GBR

Rapid deglacial sea-level rise forced a major landward migration of shallow-reef habitats 1.3–1.8 km to the inner (Noggin Pass, hole M0057A) and outer barrier (Hydrographer's Passage, hole M0034A) in <2 kyr. Reef 4 initiated growth soon after the reflooding of Reef 1 between 73 and 64 mbsl at 13.09 ± 0.08 and 12.97 ± 0.07 ka for Hydrographer's Passage and Noggin Pass, respectively. Reef 4 exhibits mainly continuous, shallow-water (<5–10 m) *Isopora*-dominated assemblages with very rapid initial accretion rates up to 9.6 mm yr^{-1} (Fig. 3). The Tahiti, Vanuatu and Huon Peninsula records have similarly rapid accretion rates (8–12 mm yr^{-1}) during the YD (Supplementary Figs. 5 and 6). This rapid growth probably reflects the dominance of *Acropora*–*Isopora* reef frameworks and coincides with the West Pacific SST reaching modern values[17,22]. For the GBR, this also represents a major reorganization from fringing to barrier–reef-dominated morphologies (Figs. 1 and 2) that can be traced almost continuously over 2,000 km (ref. [24]), and represents the true 'proto-GBR' that preceded the modern Holocene barrier reef. Basement substrate highs beneath the barriers[24] may have influenced this morphological change, and similar fringing to barrier–reef transitions are observed in Tahiti as the developing barrier acted initially to trap sediments and promote rapid reef growth[28].

Demise of the proto-GBR caused by massive sediment flux

The top of Reef 4 is marked by a slower accretion (4.2 and 1.4 mm yr^{-1} at Hydrographer's Passage and Noggin Pass, respectively) as the sequence transitioned to deeper assemblages at 10.32 ± 0.04 to 10.14 ± 0.16 ka, well after the 11.45 ka MWP 1B at Barbados[1,3,29]. The GBR data are consistent with Papeete[30] and Expedition 310 data[9] and show no evidence for an abrupt drowning event directly associated with the 14 ± 2 m sea-level pulse at ~11.45 ka. The question remains as to what caused this period of slower accretion and suboptimal conditions that prevented keep-up growth, and led to the final drowning of the proto-GBR at 10.31–10.14 ka. Sediment cores along a 2,700 km north–south GBR transect show a massive increase in the flux of fine siliciclastic and carbonate sediments to the slope between 11 and 8 ka, peaking at ~10 ka, and almost three times above the LGM to Holocene background levels[18,31]. This is consistent with shelf-flooding models showing >60–75% of the shelf area inundated around this time (Fig. 3b,d and Supplementary Note 5). Although the impact of a higher p_{CO_2} (>260 ppm) and reduced reef calcification[32] cannot be ruled out, we propose that Reef 4 drowned as a direct consequence of this elevated sediment flux and reduced water quality reaching a threshold level against a backdrop of continued sea-level rise. This interpretation is consistent with declining VA rates prior to the final drowning as the barrier building, but highly sediment intolerant[33], *Isopora*-dominated community became stressed and eventually gave up[28,34]. However, this remains to be tested against other indicators of sediment stress (for example, increased bioerosion). The final landward reef migration and GBR-wide turn-on of the modern Holocene GBR (Reef 5) at ~9 ka (ref. [19]) occurred as sea levels rose above the Last Interglacial (125 ka)[20,21] reef substrate at ~10–20 mbsl.

Implications for understanding GBR demise and resilience

IODP Expedition 325 provides the first continuous record of the GBR's evolution over the past 30 kyr (Fig. 4). Patterns of growth and demise of the five reefs are consistent between the two locations, although some differences in reef architecture and composition reflect local variations in shelf geometry, substrate, sediment flux and SST gradients. Sea-level change was the fundamental control on reef development and position as the GBR closely tracked falling and rising sea levels across the shelf edge. At times, the reef was able to track rising sea level, accreting vertically at up to 20 m kyr^{-1} and migrating laterally at 1.5 m yr^{-1}. Reef death occurred in two ways: subaerial exposure caused by sea-level fall or RD due to rapid sea-level rise and associated environmental changes (Supplementary Table 6). Unlike previous studies[1,12,34], our findings highlight the importance of a high sediment flux and poor water quality, rather than of an abrupt sea-level rise alone (that is, MWPs), in ultimately determining reef demise. We also show that reef morphology (fringing versus barrier), reef location (shelf distal versus proximal) and coral assemblage composition (for example, *Isopora* dominated) also influenced the sensitivity of the GBR to past sediment fluxes.

The GBR persisted on the shelf edge throughout the LGM and, where suitable substrates were available, shallow-water reef habitats were capable of migrating seawards and then landwards in response to sea-level and other environmental changes. This temporal continuity of reef habitats within the GBR also provided a potential source of coral–algal recruits to re-establish reefs locally, without requiring external or regional refugia[20]. We attribute the GBR's robustness on centennial–millennial scales, despite such major environmental perturbations as rising sea levels (~120 m at up to 30 mm yr^{-1}) (Y. Yokoyama et al., manuscript in preparation) and temperatures (~3–4 °C over the deglacial, up to 0.04 °C per 100 years)[17], to the presence of adjacent coeval shallow and deep reef habitats that provided the recruits (particularly broadcast spawners) that enabled a rapid migration across the shelf and persistence of the ecosystem connectivity similar to modern reef systems[35]. This hypothesis may explain (in part) how the GBR has reconstituted again and again on 100 kyr timescales over its longer-term history[15]. Finally, our findings that demonstrate the GBR's sensitivity to such environmental factors as sediment flux and water quality over centuries to millennia are consistent with the declines on some inshore GBR reefs over the past two centuries since European settlement[13]. However, given the current rate of SST increase (0.7 °C per 100 years), sharp declines in coral coverage[36] and the potential for year-on-year mass coral bleaching[37], our new findings provide little evidence for resilience of the GBR over the next few decades.

Methods

Methods, including statements of data availability and any associated accession codes and references, are available at https://doi.org/10.1038/s41561-018-0127-3.

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Author contributions

J.M.W. and Y.Y. were co-chief scientists of Expedition 325. J.M.W. wrote the manuscript in collaboration with J.C.B., M.H., D.C.P., Y.I., R.B., T.E., Y.Y. and H.M., and the paper was refined by contributions from the rest of the co-authors.

Competing interests

The authors declare no competing interests.

Additional information

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Methods

Lithological and chronostratigraphic analysis. The cores were logged and the stratigraphic distribution of the main reef framework (boundstones) and detrital (packstones–rudstones and unconsolidated sediments) facies defined. We used a database of >580 published U–Th coral and ^{14}C AMS coral and coralline ages[16,17,21] (Y. Yokoyama et al., manuscript in preparation) combined with all the available geomorphic, lithological, coral–algal assemblage, petrophysical and seismic information (Supplementary Notes 1 and 2 and Supplementary Fig. 7) to establish a robust, new chronostratigraphic framework for the evolution of the GBR shelf-edge reef system. Four distinct reef sequences, distinguished by depth and proximity to the shelf edge, are bounded at the base by unconformities that are either subaerial exposure or maximum flooding surfaces. The top of each reef sequence records the reef-death event and is bounded by either (1) the last stratigraphic appearance of shallow (<10 m palaeowater depths) coral reef facies in Reefs 3a, 3b and 4 (that is, RD) or (2) a subaerial exposure surface in Reefs 1 and 2 (that is, reef exposure (RE)). Wherever possible, the closest in situ U–Th coral age to these boundaries was used to constrain the timing of the turn-on and turn-off of each reef sequence (Supplementary Table 6). Due to recovery issues and dating gaps, the record and cause of reef demise at ~16–17 ka and the boundary between Reefs 3a and 3b are more tentative (long dashed lines in Figs. 1 and 2 and Supplementary Figs. 1 and 2).

Coral–algal assemblage and palaeoenvironmental analysis. The lowest taxonomic level possible of all corals, and their growth positions and context, were assessed in cores. Coral assemblages were identified by examining the succession of in situ coral taxa in each hole and by using a suite of statistical analyses (cluster analysis and multidimensional-scaling ordination of Bray–Curtis similarities, analysis of similarities and similarity percentage analysis) on coral taxa and growth forms (Supplementary Note 3 and Supplementary Figs. 7 and 8). The coral data were then combined with coralline algal assemblage data (based on the analysis of 400 thin sections) and other key indicators (percentage of coral–algal components, coralline algal crust thickness and presence or absence of vermetid gastropods measured every 10 cm) to form a coherent, internally consistent coral–algal assemblage scheme (Supplementary Table 1). We then reconstructed the likely depositional environment (including palaeowater depths) of each assemblage by comparison with their modern GBR and other Indo-Pacific counterparts (Supplementary Note 3).

VA analysis. VA rates within each reef sequence were estimated using only in situ corals and coralline algae that yielded robust U–Th and calibrated ^{14}C AMS ages. The sample context was assessed using a range of established criteria[16,28], and samples from highly drill-disturbed intervals were excluded. A total of 435 samples that satisfied these criteria were used to construct a robust age model and reconstruct the VA pathway for each site. To quantify the uncertainties in the age model, we used two approaches: (1) a traditional linear visual fit and regression analysis widely used to study reef cores[2,9,30] and (2) a Monte Carlo simulation[39]. The visual fits and regression analysis, including the rates and major inflection points, were in agreement with the Monte Carlo analysis, which indicates this traditional approach accurately reflects the VA histories of the GBR (Supplementary Note 4, Supplementary Figs. 3 and 9 and Supplementary Tables 3–5).

Data availability. The data supporting the findings of this study are available from the corresponding author upon request.

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