

Climatic and eustatic signals in a global compilation of shallow marine carbonate accumulation rates

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ABSTRACT

Two of the most important factors that control the accumulation rate of material in carbonate platform environments on geological time scales are climate and eustasy. Accurately assessing the importance of these inter-related factors through the study of both modern and ancient carbonate facies, however, is problematic. These difficulties arise from both the complexities inherent in carbonate depositional systems and the demonstrable incompleteness of the stratigraphic record. Here, a new compilation of more than 19 000 global Phanerozoic shallow marine carbonate accumulation rates derived from nearly 300 individual stratigraphic sections is presented. These data provide the first global holistic view of changes in shallow marine carbonate production in response to climate and eustasy on geological time scales. Notably, a clear latitudinal dependence on carbonate accumulation rates is recognized in the data. Moreover, it can also be demonstrated that rates calculated across the last glacial maximum and Holocene track changes in sea-level. In detail, the data show that globally averaged changes in carbonate accumulation rates lagged changes in sea-level by *ca* 3 kyr, reflecting the commonly observed delay in the response of individual carbonate successions to sea-level rise. Differences between the rates of carbonate accumulation and sea-level change over the past 25 kyr ostensibly reflect changing accumulation mode, with platform drowning (give-up mode) pervasive during peak Early Holocene sea-level rise, followed by a switch to catch-up mode accumulation from *ca* 9 ka to the present. Carbonate accumulation rates older than the Quaternary are typically calculated over time spans much greater than 100 kyr, and at these time spans, rates primarily reflect long-term tectonically mediated accommodation space changes rather than shorter term changes in climate/eustasy. This finding, coupled with issues of stratigraphic incompleteness and data abundance, tempers the utility of this and other compilations for assessing accurately the role of climate and eustasy in mediating carbonate accumulation rates through geological time.

Keywords Accumulation rate, carbonates, climate, eustasy, Holocene.

INTRODUCTION

Tropical biogenic carbonate facies that accumulate at or very near sea-level have long been

used as sensitive gauges of past sea-level change. The utility of these facies is supported by their high growth potential, typically limited compaction, relatively rapid lithification, and

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predictable depositional and diagenetic responses to changes in water depth/elevation (e.g. Bathurst, 1975; Kendall & Schlager, 1981; Cisne, 1986; Goldstein *et al.*, 1991). Moreover, the relatively tight climatic constraints on their formation and preservation underpin their use as important palaeoclimate archives (see, for example, Wilson *et al.*, 1998; Kiessling, 2001). Since the introduction of lightweight drilling equipment (Thorn, 1978), the rate at which individual modern coral species, coral reef communities, and broader carbonate platforms grow and accumulate sediment has been a key topic of study (e.g. Fairbanks, 1989; Opdyke & Wilkinson, 1993; Camoin *et al.*, 2001, 2012; Dullo, 2005). Augmenting these studies are similar analyses of ancient coral reef and peritidal facies from the geological record that have yielded data on the accumulation rate of shallow water carbonates growing under markedly different environmental conditions (Wilkinson *et al.*, 1991; Bosscher & Schlager, 1993; Kiessling *et al.*, 2000, 2012; Kiessling, 2001). Accurately deconvolving eustatic and climatic signals from rate data is problematic. In part, this is due to the complexities inherent in carbonate depositional systems, which are controlled by a multitude of extrinsic physicochemical and intrinsic biological factors (e.g. Kiessling *et al.*, 2000; Schlager, 2003; Dullo, 2005). Moreover, assessing accumulation rate changes in response to climate and eustasy on both modern and geological time scales is hindered by the inherent incompleteness of the stratigraphic record. The presence of hiatuses in the sedimentary record at all temporal scales means that calculated sediment accumulation rates scale negatively with the time span over which the rates are calculated, typically in a linear fashion on log–log plots (e.g. Sadler, 1981; Fig. 1A). Consequently, the first order control on sedimentation rates of shallow water carbonates is neither climate nor eustasy, but the time span over which the rates are calculated (Sadler, 1981; Schlager, 1991, 2005; Wilkinson *et al.*, 1991; Bosscher & Schlager, 1993; Opdyke & Wilkinson, 1993).

The pervasive nature of this scaling is evident in empirical sedimentation rates from all hiatus-prone depositional environments, including shore zone, siliciclastic shelf and fluvial settings (Reineck, 1960; Sadler, 1981, 1994, 1999). Numerical models confirm that this scaling is a universal and inevitable property of unsteady, reversible, depositional processes (Strauss & Sadler, 1989; Sadler & Strauss, 1990; Kemp,

2012). Over progressively longer time spans, a succession encompasses more and longer hiatuses and calculated rates fall (Sadler, 1981). Ostensibly, stratigraphic incompleteness restricts the ability to compare rates of accumulation on both human and geological time scales, and hence also restricts the ability to make sense of ancient rates of carbonate growth/accumulation under fundamentally different climatic and eustatic regimes relative to observed rates in modern depositional settings. Equally, even if the time span dependence on carbonate accumulation rates could be adequately accounted for, the vagarious nature of sedimentation and common importance of local and non-universal growth rate controls requires the assessment of many hundreds of individual rates and/or sections through a given time interval in the hope that pervasive trends and features related to global climate and eustasy stand out.

Previous work by Bosscher & Schlager (1993) assessed a compilation of 120 carbonate platform accumulation rates spanning the entire Phanerozoic. These authors corrected for time span dependence by calculating the linear regression between log sedimentation rate and log time span and normalizing the data to a standard time span of 1 Myr. In this compilation, inverse scaling was not restricted to time scales longer than 1 Myr; the chosen threshold was simply of a shorter time span than any of their data. This approach allowed the authors to suggest that marked changes in maximum growth rate and relative abundance of reef facies tracked independently assessed evolutionary patterns in Phanerozoic reef blooms and crises (Bosscher & Schlager, 1993). Although this simple time span correction yielded apparently genuine process-driven changes in accumulation rate and carbonate abundance, it is likely that there are other relevant biases in the data that require further investigation to be adequately appraised and accounted for (e.g. Kiessling, 2006). Notably, the time spans for the rates analysed by Bosscher & Schlager (1993; i.e. >1 Myr) probably exceed the time spans over which climate would be expected to exert the main influence on carbonate production. Indeed, at these relatively long time spans, other processes, such as long-term accommodation space generation controlled by subsidence and tectonism, are expected to influence rates most significantly (see esp. Sadler, 1981, 1994). Moreover, it is questionable whether the data set interrogated by Bosscher & Schlager (1993; 120 rates spanning

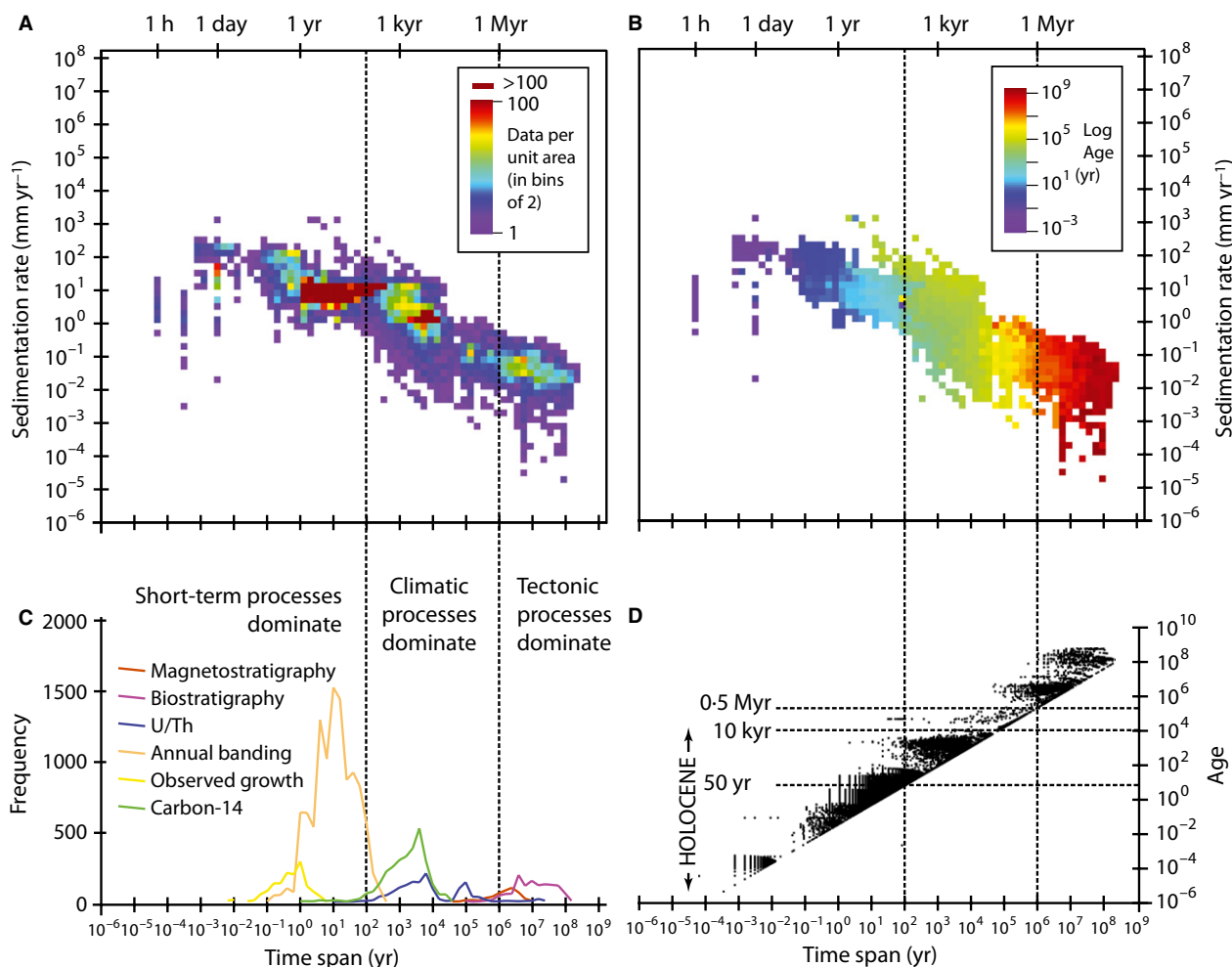


Fig. 1. (A) Accumulation rate versus time span plot of Phanerozoic shallow water carbonates. Data are binned into 0.2×0.2 log bins, with colour reflecting data density within a bin. Note the clear logarithmic scaling trend of rates with increasing time span. (B) Data as in (A) but colour coded according to mean age per bin. This plot emphasizes the clear interdependence between age and time span of the rate data within the compilation. (C) Frequency plot of rate data versus time span according to dating method. This plot highlights the dominance of rates calculated using direct observation and annual band counting over time spans $< 10^2$ years, whereas at longer time spans (and hence ages), rates are calculated via less precise, indirect methods. Time spans most suitable for resolving climatic and eustatic influence on rates lie between *ca* 10^2 and 10^6 years. (D) Age and time span interdependence is illustrated to highlight how time spans between 10^2 and 10^6 years restrict analysis of the compilation data to Quaternary ages, and that there is a paucity of data with ages older than *ca* 10 kyr. See main text for details.

555 Myr) was of sufficient size and resolution to provide statistically robust mean rates and trends across several orders of averaging time. To investigate these concerns and extend the analysis to shorter time scales, a new compilation of over 19 000 rates of globally distributed Phanerozoic tropical shallow water carbonate accumulation is presented and analysed. This compilation is used to deconvolve major climatic and eustatically mediated variations in carbonate accumulation rates through time and, in particular, through the latter part of the last

glacial cycle. The fundamental biases present in the data that limit the utility of this and other compilations are also explored in detail.

THE COMPILATION

The new compilation comprises 19 624 individual rates of accumulation from coral, coral reef and peritidal facies. Rates have been assessed from across the Phanerozoic (0 to 554 Ma), and over time spans spanning *ca* 13 orders of

magnitude (<1 h to >100 Myr; Fig. 1). The data have been mined from 252 citations and from 289 geographically distinct localities (see Data S1). The compilation builds on an earlier version (Sadler, 1994; 15 533 rates) that also includes carbonate facies types not typically restricted to very shallow water depths (for example, mud mounds and peri-platform and slope deposits). The rates in the new compilation are restricted to those derived from near sea-level biogenic carbonate accumulations where production was predominantly *in situ* and controlled by frame building photoautotrophs. Both the older data set and the new compilation derive from a wider ranging effort to compile globally distributed Phanerozoic sediment accumulation rate data from multiple depositional environments (>450 000 rates as of 2013).

BIASES IN THE COMPILATION

A clear, but detailed complex scaling of decreasing sedimentation rates with increasing time span is apparent in the raw data (Fig. 1A). This scaling trend matches closely with that in the smaller compilation (see fig. 1 in Sadler, 1994), suggesting that database size is sufficient for this generalization. The bias this imparts within the compilation for assessing changes in accumulation rate over different time spans can reach more than four orders of magnitude. Of key importance to the present study is the fact that additional biases are also apparent in the data. Notably, analysis of the compilation highlights how the time span of measurement is characterized not only by duration, but also by age (Fig. 1B). The interdependence between time span and age is unavoidable: the median age of the measurement interval cannot be less than half the time span. The outcome is that age increases approximately linearly with time span (Fig. 1D). Differences in age require different methods of rate calculation (Fig. 1C). At very short averaging times (<10¹ years), rates can be assessed via direct physical observations of sediment surface elevation change and growth rates of reef-building organisms (Fig. 1C). At longer time spans, rates are calculated via indirect measures of accumulated sediment thickness divided by elapsed time, which is determined by methods such as radiometric dating or typically less numerically precise biostratigraphy (Fig. 1C). The differences are marked: at short human time spans, the ability exists to measure

precisely the sedimentation process, regardless of long-term preservation potential. At longer time spans, it is only possible to measure the surviving products of sedimentation and indeed only those sections that actually leave a long-term record. Over these long-term time scales, the data measure only net sediment aggradation. True carbonate production is likely to be underestimated in successions with a significant progradational component (e.g. Dullo, 2005); i.e. where production exceeds accommodation. Allied to this temporal bias is the fact that processes that impact deposition and accommodation may have characteristic time spans (e.g. Milankovitch cycles; Kemp, 2011, 2012) or characteristic return times (for example, tides, floods, hurricanes and earthquakes). Long averaging times yield rates that integrate many short-term processes in representative proportions. Short averaging times are more likely to capture single events (for example, storm beach deposits and single tidal laminae), but in potentially unrepresentative proportions. Short-term sedimentation rates of <10² years probably predominantly reflect localized depositional processes, whilst at longer geological time spans (i.e. >10⁶ years), global factors such as subsidence and tectonics prevail (Sadler, 1981). At these long time spans, sediment accumulation rates will converge with the rate at which accommodation space is being created, and hence subsidence will be the primary control on sedimentation rates. Evidence for this comes from the observation that, regardless of environment of deposition, shallow-marine sediment accumulation rates converge at these long time spans (Sadler, 1981, 1994, 1999). The critical time span range through which rates are likely to be most influenced by climatic and eustatic processes is 10² to 10⁶ years (Sadler, 1994); i.e. shorter than the scales analysed by Bosscher & Schlager (1993). The mean ages of accumulation rates within this time span range predominantly span the Quaternary (0 to 2.558 Ma), with the bulk of the data drawn from Holocene sections (i.e. the last *ca* 11.7 kyr; Fig. 1D). The heavily skewed nature of the rate data to younger ages prevents the application of the compilation to the study of more ancient (i.e. pre-Quaternary) changes in sedimentation rates. No rates older than the Quaternary exist that are calculated over time spans shorter than 45 kyr (Fig. 1D). Although some rates calculated at time spans <10⁶ years do exist that are much older than the Quaternary, some depend upon assumptions

about bundling of tidal laminae and the rest are insufficient to be representative of global geological phenomena. Nevertheless, the density of suitable rate data from recent Earth history makes it possible to investigate fully the precise climatic and geographical controls on carbonate production independent of major palaeogeographical changes. Moreover, because the Holocene is a time of well-documented sea-level rise, it is also possible to examine expected balances between carbonate production and accommodation since the last glacial maximum (LGM).

CLIMATE SIGNALS

Latitudinal controls on accumulation rates

Modern accumulations of shallow water carbonates have a clear latitudinal control on their distribution, which reflects a distinct water temperature control on biogenic carbonate production and prosperity, probably augmented by constraints on annual light availability for photosynthesis (Frakes *et al.*, 1992; Kiessling, 2001; Dullo, 2005; Schlager, 2005). In the modern ocean, shallow water biogenic accumulation is bounded in the northern and southern hemispheres to a limit of *ca* 30° latitude, where cold month mean temperatures are almost always above 20°C. The spatial distribution of Holocene rates in the compilation reflects this (Fig. 2). Previous work has shown that accumulation rates generally increase with decreasing latitude, although equatorial latitudes (<10°) are typically marked by a reduction in average growth rates (Schlanger & Konishi, 1975; Opdyke & Wilkinson, 1993; Wilson *et al.*, 1998). In part, these latitudinal controls on accumulation rates can be attributed to clear changes in framework building organisms/communities, which have different latitudinal affinities and physiological rates of carbonate production (Schlanger & Konishi, 1975; Opdyke & Wilkinson, 1993). Nevertheless, in the two main carbonate provinces of the modern ocean (the Caribbean and Indo-Pacific regions; Fig. 2), carbonate production is dominated by different organisms; yet overall rates of accumulation in the two regions are similar (Dullo, 2005).

Following the approach adopted by both Boscher & Schlager (1993) and Opdyke & Wilkinson (1993), linear regression of the log rate versus log time span data between time spans of 10² and 10⁶ years in the compilation was used to normalize rates to a constant time span duration of

5 kyr. Five kyr represents the typical duration of Holocene and Pleistocene sections lacking major exposure surfaces (Opdyke & Wilkinson, 1993; Eberli, 2013). Plotting the normalized rate data against latitude emphasizes the very broad range of rates that exist within the compilation, but also reveals clear trends (Fig. 3). Rates reach maximum values (typically *ca* 10 mm yr⁻¹, although up to *ca* 60 mm yr⁻¹) at latitudes of *ca* 10° to 20° in both hemispheres, with a decrease in maximum growth rate to *ca* 3 mm yr⁻¹ at equatorial latitudes (Fig. 3). Records of carbonate accumulation are absent from the compilation at latitudes below 33°S and above 33°N, and rates fall as these boundaries are reached (Figs 2 and 3). These results match well with work by Opdyke & Wilkinson (1993), who used a smaller database of 220 rates and recognized a similar pattern. Contrary to the findings of Opdyke & Wilkinson (1993), however, analyses here show that it is minimum accumulation rates that are most sensitive to latitude, and that minimum rates are actually attained at the same latitudes as maximum rates in the tropics (Fig. 3). This is likely to be in part a consequence of the observational biases inherent in the data set: a larger number of studied successions for a given latitude will probably result in a greater range of observed rates. Kiessling (2006) documented a number of similar statistical biases in a global database of geological reef abundance, including observational biases related to the research intensity of the Caribbean and Great Barrier Reef areas, and even the gross domestic product of the researching nations. Figure 2 clearly emphasizes the dominance of research in and around the Caribbean Sea and Great Barrier Reef areas (and for older Phanerozoic carbonates, Europe). Nevertheless, the fact that the compilation is so large and dominated by modern day species supports the reasoning that both carbonate occurrence and accumulation rates reflect genuine differences related to physical and biological processes. Hence, the trends recognized in Fig. 3 probably reflect the taxonomic diversity and population differences of the tropics relative to equatorial latitudes and locations close to the northern and southern latitudinal limits of shallow water coral growth (see for example Kiessling *et al.*, 2012; Wilson, 2012).

Greenhouse versus icehouse controls on accumulation rates

The ambient temperature of sea water exerts a major effect on the physiological growth rate of

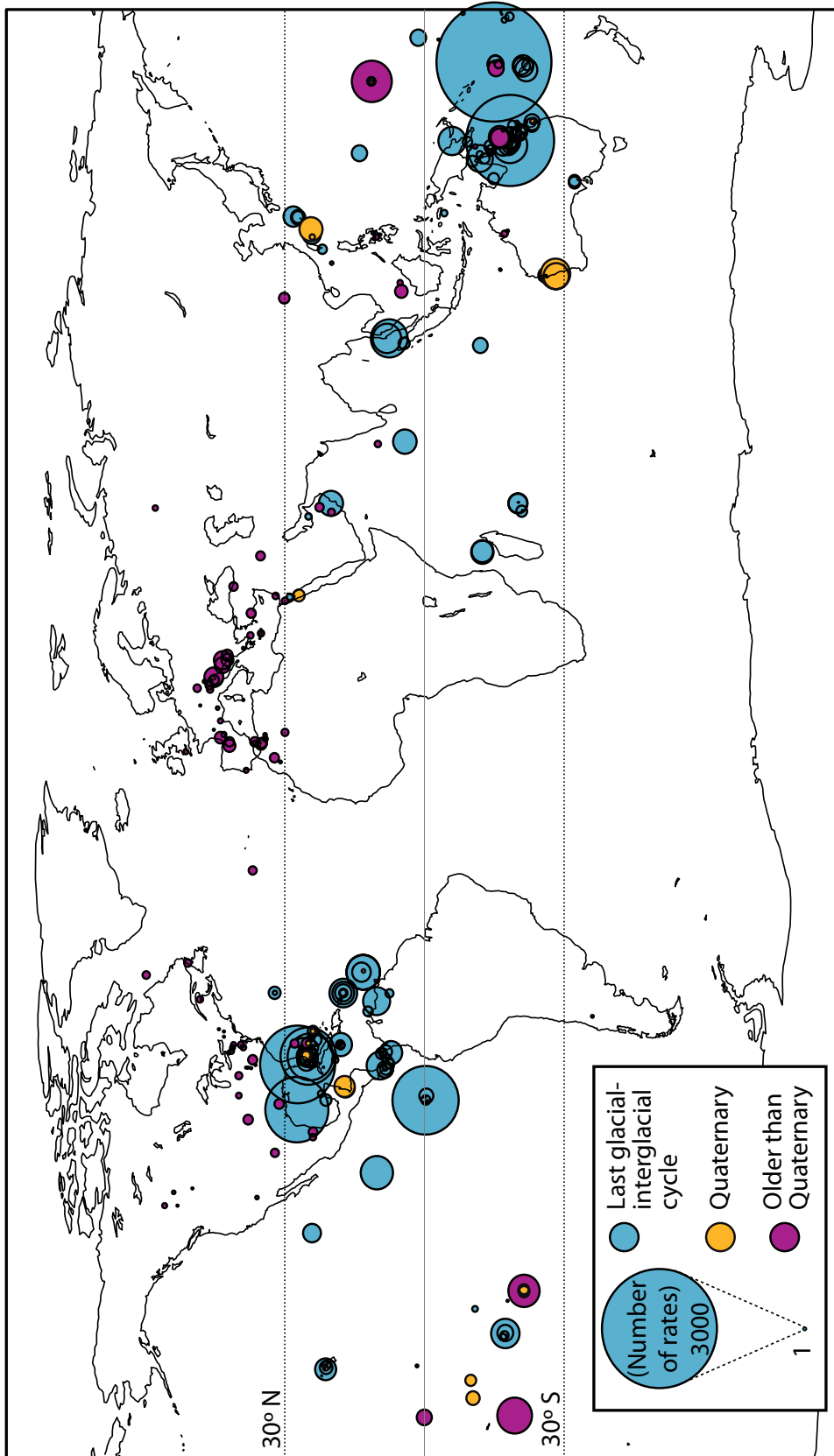
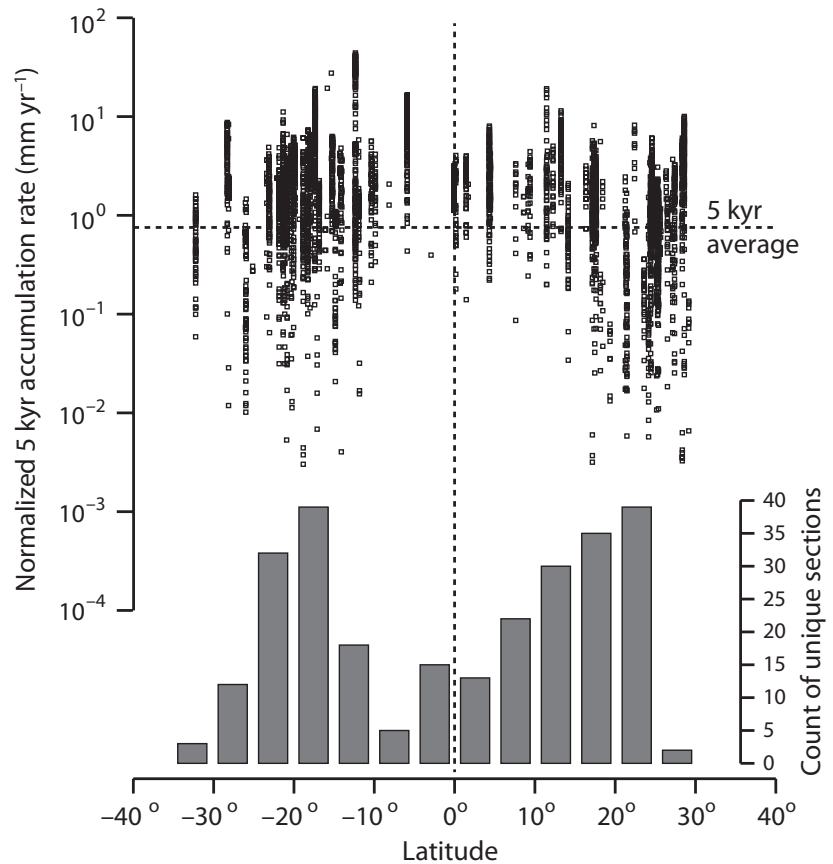


Fig. 2. Bubble plot showing the distribution and quantity of all data used within the compilation. Bubble size reflects number of rates per locality. Rates from the last glacial cycle (100 ka or younger but predominantly Holocene) dominate the compilation, and these rates are predominantly from the two most well-studied areas of modern carbonate accumulation: the Great Barrier Reef and the Caribbean Sea.

Fig. 3. Accumulation rates plotted against latitude. The upper plot shows normalized accumulation rates calculated between time spans of 10^2 and 10^5 years versus latitude. Data were normalized via removal of the time span-dependent trend of rates versus time span over this interval and normalized to a constant time span of 5 kyr. The lower plot illustrates the frequency and distribution of unique sections in the compilation by latitude (in 5° bins). A reduction in the occurrence of rates at equatorial latitudes is associated with lower rates of accumulation relative to the tropics and reduced variance of rates. See main text for explanation.



coral species, and the latitudinal trends recognized in the compilation probably reflect this control at least in part. Ostensibly, the marked differences in global climate, oceanography and palaeogeography between icehouse and greenhouse climate modes should manifest themselves as differences in the growth potential of shallow water carbonate environments. These differences might also be amplified by differences in coral reef communities and taxonomic diversity associated with both the climate modes and the geological ages over which they occurred. Equally, because accommodation space is the overriding factor limiting the maximum growth potential of shallow water carbonates, it could be argued that reduced or absent glacioeustatic mediation of sea-levels during greenhouse intervals actually restricts growth potential relative to the high amplitude sea-level changes known from icehouse intervals (see, for example, Wright, 1992). This point emphasizes clearly how climate and eustasy are interrelated phenomena on geological time scales. Nevertheless, rates of reef and platform aggradation during the major sea-level rises of the Early Holocene were generally lower than the rate of eustatically driven accommodation

space creation (e.g. Kendall & Schlager, 1981; Schlager, 1981). This observation hints at the existence of physiological factors that play an important role in limiting reef and platform growth potential, regardless of accommodation space constraints (Schlager, 1981, 1991).

Figure 4 shows the scaling trends of separated greenhouse and icehouse accumulation rates with time span. No greenhouse rates exist within the compilation that have been calculated at a time span of <300 kyr. Within the 300 kyr to 100 Myr range of time spans, where rates from both climate modes exist, there is no statistically significant difference in rates. It is therefore not possible to prove unambiguously any differences between the rate of accumulation of shallow water carbonates during icehouse and greenhouse intervals using the compilation. It cannot, of course, be ruled out that this lack of difference in rates is real. Equally, however, these findings also support the reasoning that the dominance of longer term processes in controlling accumulation rates at time spans >1 Myr precludes an accurate assessment of geological changes in carbonate accumulation in response to climate/climatically driven eustasy.

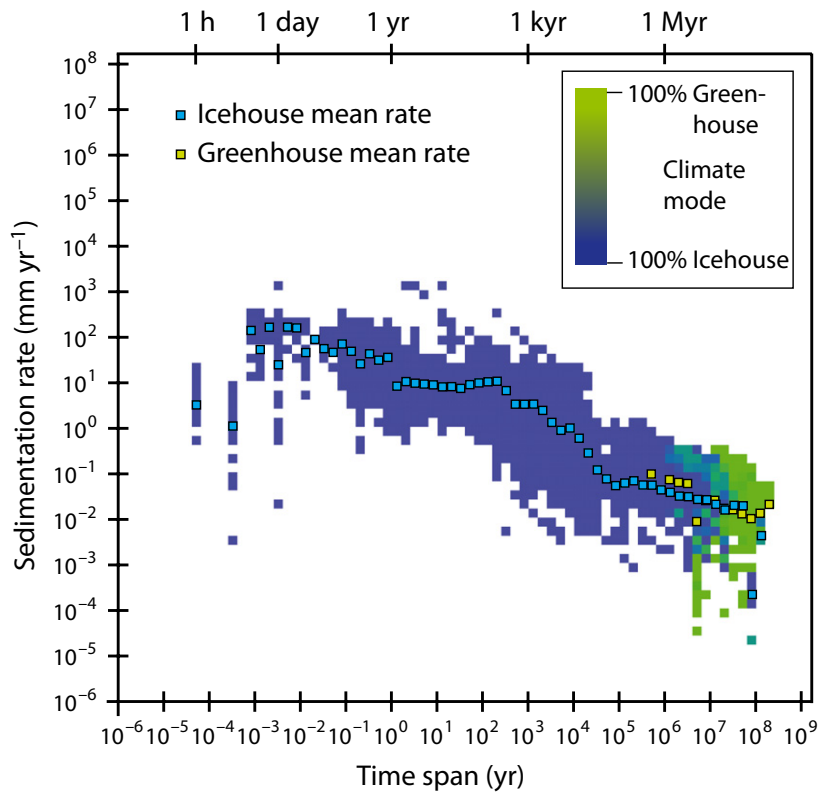


Fig. 4. Comparison of scaling trends and rates from icehouse and greenhouse climate intervals of the Phanerozoic. Because Quaternary and younger rates dominate the compilation, there is a paucity of representative greenhouse rates, and these are not easily compared with icehouse rates owing to the fact they have been calculated over time spans generally >1 Myr and, hence, are influenced predominantly by long-term accommodation space creation by subsidence, and not climate. Mean rates (coloured squares) from both climate modes are not statistically distinct from each other at the time spans where they co-occur.

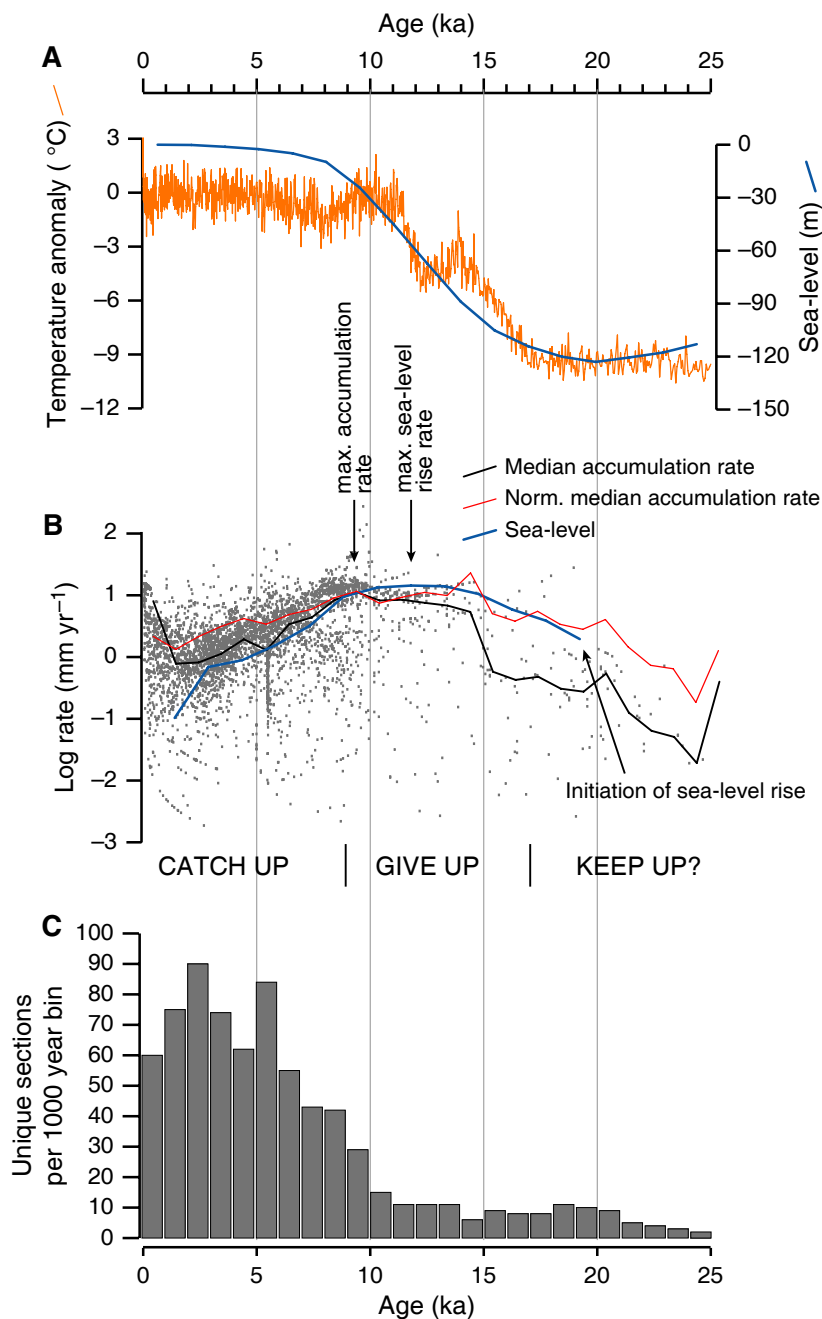
EUSTATIC SIGNALS

The compilation provides the most complete, holistic picture yet presented of global tropical carbonate accumulation over the last 25 kyr of Earth history. It is possible therefore to assess the ability of the compilation to provide meaningful information on carbonate responses to sea-level change through the last glacial cycle. Importantly, the pervasive correlation between time span and age (Fig. 1D) means that normalization of the rate data to account for time span effects risks also normalizing, and hence subduing, genuine age-dependent trends. Without normalization, and considering only those rates measured at time spans between 100 years and 50 kyr, clear trends in accumulation rates over the last 25 kyr are recognized, with rates rising from a median value of *ca* 0.04 mm yr⁻¹ to *ca* 9 mm yr⁻¹ between 25 ka and 9 ka (Fig. 1). Rates then fall to *ca* 1 mm yr⁻¹ at *ca* 2 ka before rising again to *ca* 10 mm yr⁻¹ at the present day (Fig. 5). With normalization of the rate data to a time span of 1500 years, the differences in rates through time are less marked, with the amplitude of rate changes reduced by approximately one order of magnitude (Fig. 5B). Notably, the sharp rise in accumulation rates over the last

2000 years recognized in the raw data is absent from the normalized data set, because this increase results from the strong time span dependence on rates between 100 and 1000 years (Fig. 5; see also Fig. 1A). Peak median accumulation rates remain close to *ca* 10 mm yr⁻¹ with or without normalization and, importantly, the timing of this peak at *ca* 9 ka is also consistent. The anomalously high median rate in the normalized data at *ca* 14 ka is due to the influence of a single study (Fairbanks, 1989) and a relatively low number of studied sections for this age interval (just five unique sections). The data density at *ca* 9 ka is much higher (29 unique sections; Fig. 5C), and this peak in rates represents a more statistically stable result. The normalized rate data suggest that modern median rates of accumulation are *ca* 1 mm yr⁻¹, and are broadly similar to the median average rate of accumulation at 25 ka during the LGM.

Both normalized and raw accumulation rates show trends through time that are broadly similar to the trends in the rate of sea-level change over the same period (Fig. 5A and B). This observation supports the reasoning that the compilation reflects global trends in accumulation in response to sea-level change. The sea-level curve used here is that of Waelbroeck *et al.*

Fig. 5. Assessment of eustatic signals in the compilation over the last 25 kyr. (A) Climate and sea-level change over this period. Climate data are the EPICA Dome C Antarctic record (Jouzel *et al.*, 2007) that shows the temperature difference from the average mean global temperature over the last 1000 years. Sea-level curve is from Waelbroeck *et al.* (2002). (B) Raw rate data determined between time spans of 100 years and 50 kyr plotted against time (grey squares). The median rate determined in 1000 year bins (black line) is also shown. Red line shows median rates of normalized data, where normalization was achieved by removing the trend of rate versus time span between 100 years and 50 kyr and normalizing to a constant time span of 1500 years. The blue line shows the rate of change in sea-level from the Waelbroeck *et al.* (2002) data. Note the close tracking of carbonate accumulation rates to these sea-level changes. Differences in the accumulation rates from the rate of sea-level change reflect changing modes of accumulation, with a switch from give-up mode (i.e. drowning, where rates are predominantly lower than sea-level change rates) to catch-up mode (where rates are predominantly greater than sea-level change rates) at *ca* 9 ka. (C) Count of unique sections through time in 1000 year bins. Note the sudden acceleration in number of unique sections close to when peak sea-level rise and maximum rates occur. See main text for details.



(2002), and is constructed from a record of benthic foraminifera oxygen-isotopes (Fig. 5A). It is thus independent of sea-level histories from the Holocene that are directly calculated from the modern depths of carbonates themselves (e.g. Fairbanks, 1989; Camoin *et al.*, 2001, 2012). The sea-level history of the past 25 kyr is dominated by a rapid rise in sea-level associated with the last deglaciation between *ca* 17 ka and 9 ka (Fig. 5A and B). The sea-level rates are calculated across a 1500-year time span, i.e. the same time span of the normalized data presented in

Fig. 5B. Peak median accumulation rates (*ca* 10 mm yr⁻¹) in both the normalized and raw data are similar to the maximum rates of change in sea-level (Fig. 5B; up to 14.8 mm yr⁻¹ in the Waelbroeck *et al.* 2002 data). One difference that exists, however, is the timing of these peak rates, with peak accumulation rates lagging peak sea-level by *ca* 3000 years (Fig. 5B). This lag is likely to represent the commonly observed delay of individual carbonate successions to respond fully to sea-level rises (e.g. Schlager, 1981, 2005). The magnitude of the lag (*ca* 3 kyr) is

within the range assessed from direct measurement of individual platforms and regions, i.e. 2 to 5 kyr (e.g. Montaggioni, 2005; Schlager, 2005). Recent evidence has suggested that this lag phenomenon reflects patchy colonization of new reefs following exposure and re-flooding (Tipper, 1997; Blanchon & Blakeway, 2003). In one-dimensional successions (i.e. cores), this patchy colonization motif will commonly lead to under-represented occurrences of immediate reef growth following sea-level rise, and suggests the presence of a lag that is not reflected by the platform as a whole (Blanchon & Blakeway, 2003). The available data do not allow this lag genesis issue to be addressed unequivocally, although it is noted here that an increase in the number of studied sections in the compilation occurs close to both maximum rates of accumulation and maximum rates of sea-level rise (*ca* 10 ka; Fig. 5C). If the number of studied sections reflected genuine differences in the abundance of shallow water carbonates through time, then this would argue that accelerated rates of colonization occurred broadly concomitantly with peak sea-level rise, but still *ca* 8 kyr after initiation of sea-level rise at *ca* 19 ka (Fig. 5A and C). This observation is in line with previous work, suggesting that the key period of reef inception and growth in the Great Barrier Reef area was between 8500 and 6000 years ago (Montaggioni, 2005). Nevertheless, this ostensible lag between sea-level rise and reef initiation could be attributed to the fact that many reef sites in the compilation would have been well above sea-level during the LGM, and would have remained emergent for a significant period of time after initiation of sea-level rise. Equally, the apparent increase in reef abundance at *ca* 10 ka could be an observational bias resulting from a lack of study of reefs older than 10 kyr, perhaps because of the prohibitive present day depth of LGM and Early Holocene reef material (e.g. Kiesling *et al.*, 2012).

These issues notwithstanding, the carbonate accumulation rate data show global trends in the mode of carbonate accumulation through the past 25 kyr (Fig. 5B). Rates between *ca* 19 ka and leading up to peak sea-level rates at *ca* 11.7 ka in both the normalized and raw data rarely exceed sea-level rates, and suggest common carbonate drowning (i.e. give-up mode) during deglaciation (Schlager, 1981). At ages less than *ca* 10 ka, close to the timing of peak carbonate accumulation rates and the onset of decelerating sea-level rise, both raw and normal-

ized rates typically exceed the rate of sea-level rise. The data distribution of these rates relative to the rate of sea-level rise thus indicates the predominance of catch-up style accumulation through the Holocene. The implication is that the mode of carbonate accumulation is dictated by the apparent lagged response globally of carbonates to rapid sea-level rise. Whether this observation is reflected by carbonate platforms as a whole or not, this fundamental change in the relation between sea-level and carbonate accumulation suggests that defining entire cycles in terms of their overall accumulation style (i.e. catch-up, give-up, etc.) may be overly simplistic.

CONCLUSIONS

The largest compilation of global Phanerozoic shallow water carbonate accumulation rates yet constructed is presented. Analysis of this compilation yields key insights into the global response of shallow water carbonate communities to latitude and sea-level changes over the latter part of the last glacial cycle. In particular, controls on the geographical distribution of rates and the response of rates to Early Holocene sea-level rise emerge from the compilation, and hence represent broadly universal features of carbonates globally. Peak rates of accumulation appear to post-date maximum sea-level changes by *ca* 3 kyr. The consequential differences between the rates of carbonate accumulation and sea-level change over the past 25 kyr ostensibly reflect changing accumulation mode, from restricted growth and drowning operating prior to *ca* 9 ka, to growth that outstripped sea-level rise and hence catch-up style accumulation operating from *ca* 9 ka to the present day. Although carbonate accumulation rates during sustained sea-level rise may be the best measures of growth potential, data biases and limitations hinder a fuller understanding of the true responses of pre-Holocene carbonates to climate and eustasy. Notably, a lack of data precludes the accurate assessment of meaningful trends in accumulation rates in the pre-Quaternary at the short time scales of climate and eustatic change. Moreover, potential differences between shallow water carbonate accumulation rates during greenhouse and icehouse intervals of Earth history cannot be unambiguously determined from the compilation. This is because of a lack of pre-Eocene

greenhouse interval rates that are calculated over time spans <100 kyr. At time spans >100 kyr, it is likely that the primary control on calculated rates is long-term accommodation space generation driven by tectonics, rather than shorter-term changes in climate and/or eustasy. These issues emphasize the care that must be taken when attempting to ascribe changes in temporal geological processes such as accumulation rates to global causes such as climate and sea-level change.

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Supporting Information

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

Data S1. Full reference list: Kemp and Sadler, Climatic and eustatic signals in a global compilation of shallow marine carbonate accumulation rates.