

Narrow is normal: Exploring the extent and significance of flooded marine shelves in icehouse, transitional, and greenhouse climate settings

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ABSTRACT

Marine shelves are a ubiquitous feature of modern Earth, developed across a wide range of scales in many sedimentary basins and representing the flooded portion of basin-margin clinoform topsets. Analysis of 80 clinoforms from 10 basins spanning Cenozoic and Mesozoic icehouse, transitional, and greenhouse climate settings indicates that normalized mean greenhouse marine shelf width is 33% of normalized mean total measured clinoform topset length. The equivalent value for transitional settings is 43%, and 72% for icehouse marine shelves. These values demonstrate that greenhouse marine shelves were substantially narrower than icehouse equivalents, suggesting that narrower shelves with persistent shelf-edge deltas were a consequence of lower rates of accommodation change in greenhouse climate intervals that lacked the large ice sheets required to drive high-amplitude high-frequency glacio-eustasy. Because greenhouse climates have been the dominant mode through Earth history, narrow shelves have probably been the dominant form, and conceptual models based on modern relatively wide shelves may be poor predictors of paleogeography, sediment routing, and sediment partitioning throughout much of Earth history.

INTRODUCTION

Marine shelves, the flooded portion of basin-margin clinoform topsets, are ubiquitous physiographic features across modern Earth. Marine shelves are important high-productivity ecosystems (Kröger et al., 2018) and also a critical element in source-to-sink sediment transport systems that route sediment, carbon, and pollutants into deep-water-mass sinks beyond the shelf edge (e.g., Burgess and Hovius, 1998; Carvajal and Steel, 2006). Observations of modern shelf topography are central to many conceptual sedimentological and stratigraphic models (Posamentier et al., 1991; Swift and Thorne, 1992; Galloway and Hobday, 1996; Suter, 2006; Catuneanu et al., 2009). These models influence how researchers observe, interpret, and understand ancient strata and how they reconstruct and predict ancient depositional environments, paleogeography, and climate history. The models are founded on a uniformitarian assumption that

ancient marine shelves share similar topography, and especially width, with modern shelves (e.g., Galloway and Hobday, 1996; Suter, 2006). Our study further explores that assumption.

The term “shelf” is most commonly used and understood to refer to the shallow submarine, offshore platform area in front of deltas or other shoreline systems (Swift and Thorne, 1992). In the case of deep-water basins, the shelf is the area that extends to the break of slope (Helland-Hansen et al., 2012), where water depth starts to increase more rapidly down into the basin. However, ancient examples of shelf systems include depositional systems and strata developed in epicontinental seaways (Galloway and Hobday, 1996; Suter, 2006) that were not always on continental margins and may also have lacked deep-water basinal areas. Also, the term “shelf” has sometimes been used in a broader morphological way to include all the shoreline, fluvial, and coastal-plain deposits formed on

the flat-lying topset of a clinoform margin. In these cases, we consider the general term topset depositional systems and strata to be more appropriate.

Most modern conceptual models of accumulation of shallow-marine strata, especially since the advent of modern sequence stratigraphy, assign shelf geomorphic features particular significance in the accumulation of continental-margin (Winker, 1982; Suter and Berryhill, 1985; Posamentier et al., 1991) and epicontinental-seaway (Swift and Thorne, 1992) strata. The assumption, strongly supported by deep-time well-log data (see the Supplemental Material¹), is that repeated cycles of shoreline transgression and regression across the shelf build the thick, progradational sediment wedges observed on continental margins (Burgess et al., 2008; Steel et al., 2020) and in epeiric seaways (Galloway and Hobday, 1996). Modern shelf widths average 57 km, and the average value along passive continental margins is 84 km, more than twice the average width of 31 km along active margins (Harris et al., 2014), showing that rates of tectonic subsidence and sediment supply are key controls on shelf width, as also demonstrated in forward-modeling studies (e.g., Burgess et al., 2008). Shelves are best developed during peak transgression, when high rates of accommodation creation outpace sediment supply, causing previous progradational strata to be drowned. However, shelves and shelf strata also persist during subsequent shoreline normal and forced regression, albeit with gradually decreasing width as the shoreline builds toward the shelf-break area.

Consideration of how marine shelf geomorphology depends on rates of shoreline

¹Supplemental Material. Tabulated data and calculations for the nine clinoform margin systems included in the study, and further explanation of the method used to determine and measure marine topset widths from well-log and outcrop data. Please visit <https://doi.org/10.1130/GEOL.S.17265488> to access the supplemental material, and contact editing@geosociety.org with any questions.

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transgression and regression raises an interesting question. Accepting that defining discrete states in a complex climate continuum may be simplistic, but following the approach commonly adopted to define icehouse and greenhouse climate-state end members (Summerhayes, 2015), in icehouse-climate settings, large and geologically rapid fluctuations in continental ice volume drive large-amplitude glacio-eustatic sea-level oscillations that are likely to be a key control on marine shelf geomorphology (Galloway and Hobday, 1996). So, are modern shelves (geomorphic features formed by a 120 m rise in glacio-eustatic sea level over the past 20 k.y.) really representative of the shelves on continental margins for most of Earth history, when large ice sheets were not present and rates of global sea-level change were slower? Our study measured the proportion of marine versus terrestrial deposits in a range of ancient clinoform topset strata to explore how common Holocene-scale marine shelf geomorphic features were in ancient depositional systems, and to demonstrate how important this aspect is for our understanding of shallow-marine strata and paleoclimate through geological time.

METHOD

We used well-log, outcrop, and seismic data from 10 different basin margins (Tables S1 and S2 in the Supplemental Material) to measure the maximum width of flooded topset strata. The

examples record vertically repeated regressive-transgressive cycles in strata ranging in age from Cretaceous to Pleistocene, representing greenhouse, transitional, and icehouse climate settings. Basin types range from passive continental margins to margins of deep-water foreland basins. For each regressive-transgressive cycle examined, some combination of data is used to identify the position of the distal shelf-slope break on the clinoform and the more proximal position of maximum marine transgression, and the distance between these two points defines the width of marine topset or shelf. Both points are identified based on identification of marine mud-prone topset strata deposited as relatively thin, relatively flat retrogradational units that backstep from an underlying shelf-slope break (Fig. 1A) (see also the Supplemental Material for a more detailed explanation of the interpretation method for seismic, well-log, and outcrop data).

A key challenge in accurate and reproducible measurement of flooded topset width is distinction of marine from terrestrial topset strata. However, because the position of maximum marine transgression is the same as the proximal end of the subsequent regressive shoreline unit, in outcrop, core, and well-log data, landward pinch-out of basal fine-grained marine strata in upward-coarsening units defines the maximum incursion during topset flooding. In cases where only seismic data are available (e.g., the Rhône

[offshore France] and Bengal [offshore eastern India] margins), high-resolution seismic data image marine topset strata via varying acoustic velocities so that flat-lying, relatively thin interglacial marine strata form easily recognizable “draping” seismic reflections between 40 and 60 m thick overlying thicker regressive subaqueous-delta clinoforms (Fig. 1B). Although there may rarely be more than one marked break of slope on the margin clinoform in some deep-water basins (Patrino and Helland-Hansen, 2018), there is general agreement that topset-to-foreset rollover points in at least 200 m of water depth represent the relevant shelf-slope break (Steel and Olsen, 2002; Hodgson et al., 2018; Pellegrini et al., 2018). In general, we estimate measurement error on the flooded topset widths is <5 km, depending on data resolution; e.g., well-log spacing. A worked example of this method using outcrop and well-log data is presented in the Supplemental Material, with associated discussion of the likely error magnitude.

Clinoforms prograded over lateral distances from a few tens of kilometers to ~100 km, with stratigraphic thicknesses of several hundred meters, making them easy to identify in the available data. Complete transgressive-regressive packages typically do not exceed 100 m in thickness, suggesting progradation across flooded topsets with water depths that did not exceed 150–200 m; so, comparable to Holocene marine shelf systems. Importantly,

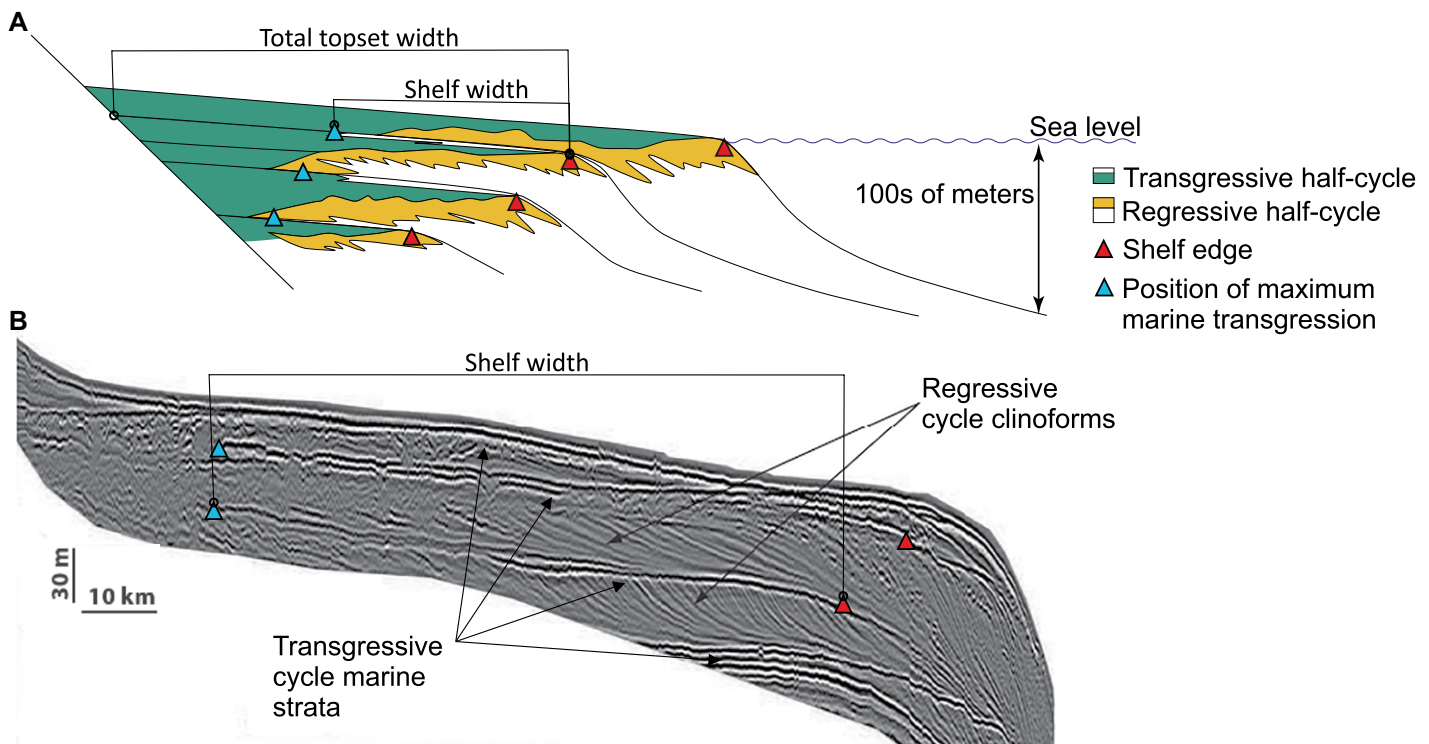


Figure 1. (A) Schematic diagram of typical basin-margin clinoform strata showing their constituent regressive-transgressive alternation and the distinction between total width of the topset and width of the flooded marine part of the topset typically referred to as the shelf (modified from Zhang et al., 2016). (B) Identification of the marine topset width on the Bengal (offshore eastern India) Pleistocene margin using seismic image data from Hübscher and Spieß (2005). Transgressive marine strata in each glacial-interglacial sequence are identified by interpretation of high-amplitude, low-angle reflections that extend from the shelf break to the landward pinch-out of overlying prograding clinoform strata.

because of different sediment supply and basin geometries, the clinoform systems differ significantly in scale, ranging from a total measured topset length of 4 km to 250 km in these data. To allow meaningful comparison between systems with such different total transport lengths, we calculated the lengths of the marine topset as a proportion of the total topset length. This normalized marine topset length allows comparison of different clinoform systems between climate settings irrespective of their different scales, but may also introduce additional error through an underestimate of the total length due to erosion (see the Supplemental Material for additional discussion of measurement uncertainty).

RESULTS

Widths of flooded topsets from the 10 basin margin systems range from a 2 km minimum to a 150 km maximum, and when normalized against total clinoform topset length, from 0.09 to 0.94 (Fig. 2). Most significantly, flooded topset examples grouped according to depositional climatic setting and related amplitude of eustatic oscillations (greenhouse, transitional, and icehouse; Fig. 2) show a clear distinction in mean width, with a normalized difference of just less than 0.4 of the mean total topset widths between icehouse and greenhouse systems. Comparison of raw numbers is more difficult because the systems analyzed span a broad range of scales, but mean greenhouse marine topset width is 18.8 km versus 93.8 km for the equivalent mean of icehouse systems. In summary, these data

demonstrate that greenhouse marine shelves are significantly narrower, on average, than transitional and icehouse marine shelves.

DISCUSSION

Our analysis demonstrates that mean marine clinoform topset width during greenhouse climate intervals is significantly lower than during icehouse climate intervals. This difference suggests that assertions of normally narrow shelves, all-stand shelf-edge deltas, and common sediment bypass onto the deep-water basin floor (e.g., Burgess et al., 2008; Blum et al., 2013) are likely correct given that warm greenhouse-type climates are most typical, at least over the past 600 m.y. Interpretations of the prevalence of icehouse climate conditions, with large continental ice sheets that wax and wane over 400 k.y. or 100 k.y. cycles, vary considerably (Markwick and Rowley, 1998; Royer et al., 2004; Summerhayes, 2015). Even the highest estimates of the duration of cool climates do not exceed 50% of Phanerozoic time (Summerhayes, 2015) and, using the best available evidence from multiple sources, suggest icehouse intervals represent only ~19%–23% of Phanerozoic time (Royer et al., 2004, their figure 2B; Scotese et al., 2021, their figure 13), though even this may be an overestimate (Markwick and Rowley, 1998). Based on a 19%–23% icehouse proportion, all-stand shelf-edge deltas and much narrower marine shelves may have been the norm for most of Earth history. In contrast, wide marine shelves and river estuaries, formed by flooding during

high-amplitude, high-frequency sea-level rise, were likely restricted to only relatively short intervals making up less than a quarter of Phanerozoic time.

Tectonic subsidence, isostasy, sediment compaction, and delta-lobe abandonment due to avulsion also contributed to the effectiveness of transgression to create marine shelves (Steel et al., 2020), but only where subsidence rates were high so that the rate of accommodation creation could outpace sediment supply by an order of magnitude or more. This suggests that marine shelves would typically be narrow in slowly subsiding, greenhouse settings without high-amplitude, high-frequency sea-level oscillations. Lower-amplitude, lower-frequency eustatic sea-level changes forced by nonglacial mechanisms would generate only minimal transgression distances in these cases. Also, data indicate (Burgess and Hovius, 1998; Porebski and Steel, 2006) that sediment supply rate commonly exceeds the rate of eustatic accommodation creation on many, or even most, potential shelf areas. In these cases, sediment supply from rivers would typically pass directly from shelf-edge deltas to the deep-water slope and basin-floor areas of the basin (Burgess et al., 2008). Also, once a topset depositional system is established, the delta system may simply “lock-in” or “dock” at the shelf break, remaining in this position for a prolonged interval of geological time and producing a thick, aggradational package of shelf-edge deltaic strata (Burgess et al., 2008; Blum et al., 2013). These conclusions are consistent

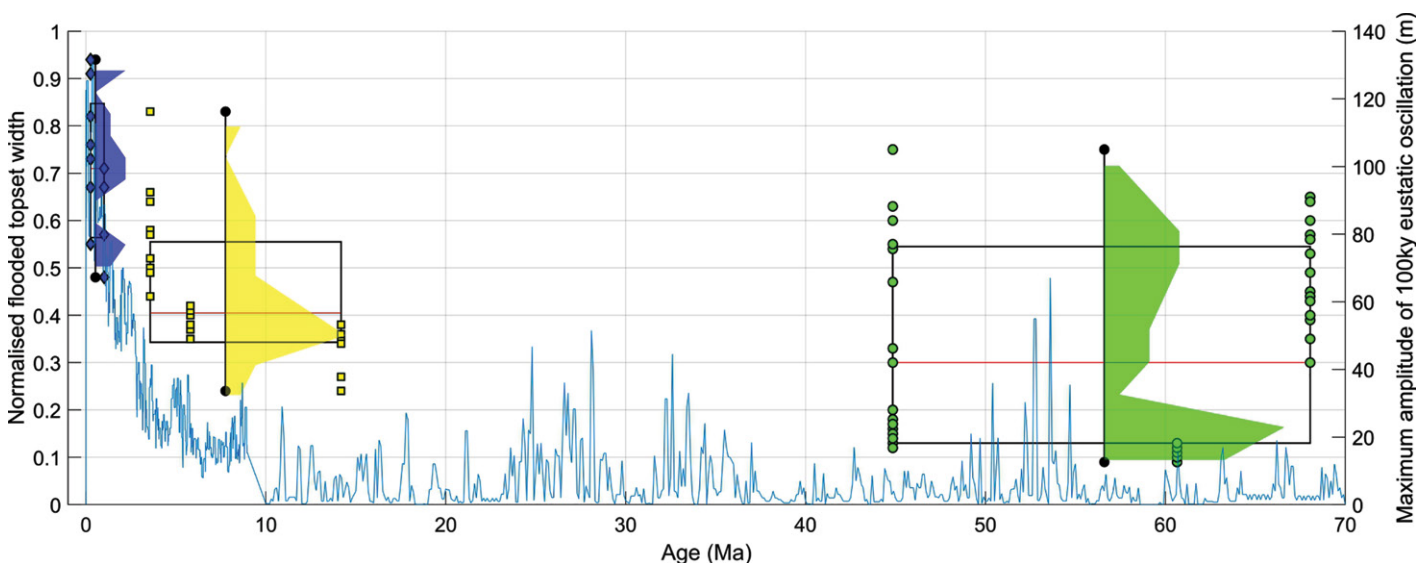


Figure 2. Normalized flooded topset width, as a proportion of total topset width for each clinoform, plotted against age and grouped according to icehouse, transitional, or greenhouse climatic setting. For each group, the box plot shows the range of ages and topset widths, with minimum and maximum widths marks by solid circles, and quantiles and mean values shown by black and red lines, respectively, in the box plot. In each case, width data for each topset are also summarized as a probability density function ($n = 45$ for greenhouse systems, $n = 24$ for transitional systems, and $n = 11$ for icehouse systems), showing that for greenhouse and transitional examples, the highest frequency is skewed to narrower widths; frequencies are scaled such that the maximum count, occurring in the greenhouse data, plots at 10 m.y. wide relative to age x-axis. See Table S1 for a summary of the data, including sample size in each group. Also plotted (blue line) is the maximum eustatic change per 100 k.y. interval, as calculated from Miller et al.'s (2005) global sea-level model. Plot shows a clear distinction, despite some overlap in tails, between the mean normalized width for each climate setting. This is robust evidence that greenhouse flooded shelves were narrower than transitional and icehouse shelves.

with the data of Petter et al. (2013), suggesting that at geological time scales, many clinoform margins bypass as much as two-thirds of their sediment budget across the shelf break.

The analysis of marine shelf widths presented here is the simplest appropriate method to test for differences in mean marine shelf width between icehouse and greenhouse intervals. Aside from climate setting and magnitude of glacio-eustatic oscillations, other variables could also impact on marine shelf width, most notably the rate of tectonic subsidence and sediment supply (Carvajal et al., 2009). More detailed and more sophisticated analyses are required to test and further explore these controls and their consequences. For example, it may be the case that in many greenhouse clinoform systems, a large fraction of time is represented by near-vertically stacked clinoforms representing aggradation of persistent shelf-edge deltas. If this is the case, the estimates of mean greenhouse marine shelf width here are likely to be overestimates because they ignore potential long periods of shelf-edge deltas with marine shelf widths close to zero.

CONCLUSIONS

Analysis of 10 Cenozoic and Mesozoic icehouse, transitional, and greenhouse climate clinoform systems indicates a mean greenhouse marine shelf width of 33% of the mean total estimated clinoform topset length, 43% for transitional strata, and 72% for icehouse strata. The results demonstrate that greenhouse marine shelves were substantially narrower than icehouse equivalents, most likely because of lower rates of accommodation change in greenhouse climate intervals due to absence of the large terrestrial ice sheets required to drive high-amplitude, high-frequency glacio-eustasy. Given that greenhouse climates dominated through Phanerozoic history, with icehouse climates representing <25% of Phanerozoic time, conceptual models based on modern icehouse analogues may be a poor predictor for key aspects of paleogeography, sediment routing, and sediment-volume partitioning across margins throughout much of Earth history. Instead, typical clinoform topsets were likely dominated by wide coastal plains and deltas perched near the clinoform break of slope, with significant all-stand sediment bypass into deep water.

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