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 ten 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, to 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 lack 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 epi-continental seaway (Swift and Thorne, 1992) strata. The assumption, strongly supported by deep-time well-log data (see Supplemental Material), 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 57km, and the average value along passive continental margins is 84km, more than twice the average width of 31km 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 modelling 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 towards the shelf break area.

Consideration of how marine shelf geomorphology depends on rates of shoreline 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 120m 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 ten different basin margins (Tables S1 and S2, 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 was 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 (Figure 1A) (see also supplementary data section for more detailed explanation of 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 pinchout of basal fine-grained marine strata in upward coarsening units defines maximum incursion during topset flooding. In cases where only seismic data are available, (e.g. 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 inter-glacial marine strata form easily recognizable 'draping' seismic reflections between 40-60m thick overlying thicker regressive subaqueous-delta clinoforms (Figure 1B). Although there may occasionally be more than one marked break of slope on the margin clinoform in some deep-water basins (Patruno and Helland-Hansen, 2018), there is general agreement that topset-to-foreset rollover points in at least 200m 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 less than 5km, depending on data resolution, for example well log spacing. A worked example of this method using outcrop and well-log data is presented in the supplementary data, with associated discussion of the likely error magnitude.

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

Results

Widths of flooded topsets from the ten 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 (Figure 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 last 600 My. Interpretations of the prevalence of icehouse climate conditions, with large continental ice sheets that wax and wane over 400ky or 100ky 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 around 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 over-estimate (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 rate of accommodation creation could outpace sediment supply by an order of magnitude or more. This suggests that marine shelves will 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 non-glacial 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 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 with the data of Petter et al. (2013), suggesting that at geological time scales many clinoform margins bypass up to 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 further. 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 ten Cenozoic and Mesozoic icehouse, transitional and greenhouse climate clinoform systems indicates a mean greenhouse marine shelf width 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 less than 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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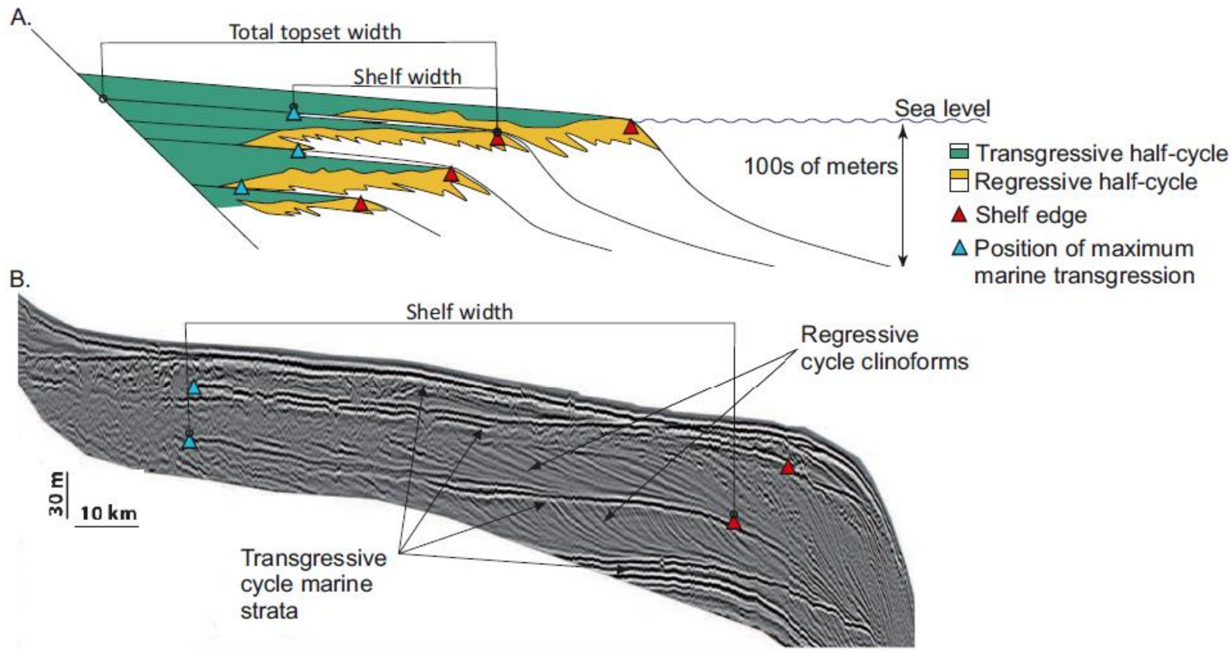

Figure 1. A. A schematic diagram of typical basin-margin clinoform strata showing their constituent regressive-transgressive alternation and the distinction between the total width of the topset, and the width of the flooded marine part of the topset typically referred to as a shelf (Modified from Zhang et al., 2016). B. Identification of marine topset width on the Bengal (offshore eastern India) Pleistocene margin using seismic image data. 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 the overlying prograding clinoform strata.

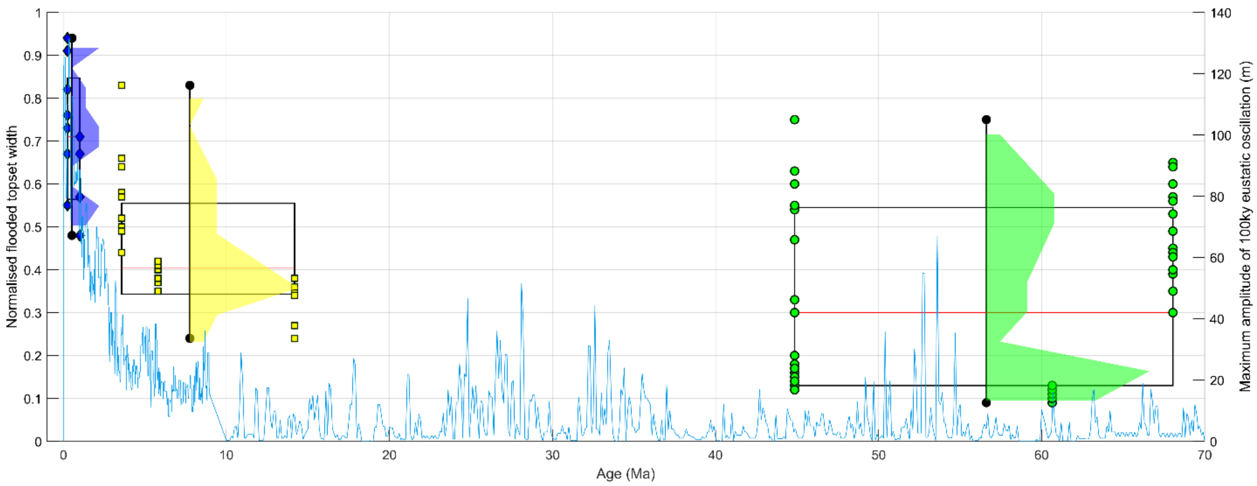

Figure 2. Normalized flooded topset width, as a proportion of the total topset width for each clinoform, plotted against age, and grouped according to icehouse (blue), transitional (yellow) or greenhouse (green) climatic setting. For each group a box plot shows the range of ages and topset widths, with minimum and maximum widths marked by solid circles, and the quantiles and mean values shown by black and red lines, respectively, in the box plot. In each case the 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 the greenhouse and transitional examples, highest frequency is skewed to the narrower widths. Frequencies are scaled such that the maximum count in the greenhouse data plots at 10My wide on the time x-scale. See Table 1 for summary of the data, including sample size in each group. Also plotted (blue line) is the maximum eustatic change per 100 ky interval, as calculated from the Miller et al. (2005) global sea-level model. The plot shows a clear distinction, despite some overlap in the 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.

[1]Supplemental 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 348 https://doi.org/10.1130/XXXXX to access the supplemental material, and contact 349 editing@geosociety.org with any questions.