INTRODUCTION

The morphological increments of an out-building continental margin or deepwater shelf margin of other basin types, seen most clearly on seismic data (Figure 1), are referred to as “clinoforms”, or “clinothems” when referring to lithological intervals (Rich, 1951, but adapted by Steel & Olsen, 2002). There is general agreement that there are two main categories of clinoform in margin architecture; delta-scale clinoforms that build shelf stratigraphy and occur mainly in water depths from 10 m to 150–200 m, and very large (100 s of m to kms) deepwater (bathyal) clinoforms that occur mainly as margin-building increments. The flat-lying topsets of the large clinothems, when seen only on seismic data, are often little described internally compared...
to the deeper water correlative strata (but there are exceptions, see Ainsworth et al., 2017; Lobo & Ridente, 2014; Pellegrini et al., 2018; Rossi, Paterson, Helland-Hansen, Claussen, & Eide, 2019). However, the complexity of facies and sub-environments of topsets is well known from classical shallow-marine and deltaic literature, for example, from the North Sea Brent Delta (Graue et al., 1987; Helland-Hansen, 1992), Barents Sea deltas (Glorstad-Clark, Birkeland, Nystuen, Faleide, & Midtkandal, 2011; Klausen et al., 2018), Western Interior Seaway (Mellere & Steel, 1995), or modern deltas (Olariu, 2014).

1.1 | Terminology

Patruno and Helland-Hansen (2018) discussed further the complexity of delta scale and deepwater-margin scale clinoforms in their recent review, and they suggested a classification into four clinoform types with extensive and useful datasets that include specified progradation scales and rates. They distinguished subaerial and subaqueous delta clinoforms, as well as “shelf-edge” and “continental-margin” clinoform types. The last two types would rarely occur in the same transect (acknowledged by Patruno & Helland-Hansen, 2018), are easily separated by height, but their lower relief “shelf edge” clinoform is probably more at home in deepwater rift, foreland, cratonic and other noncontinental margin basins where water depth rarely exceeds 1 km, where we refer herein to very large clinoforms at continental margins we qualify with their recommended “continental margin” adjective; however, for smaller scale deepwater-margins, usually in noncontinental margin settings, we prefer to use the well-established term “shelf margin clinoforms” because the term “shelf edge” is in widespread use as a morphologic term, for a variety of purposes other than referring to a type of clinoform.

1.2 | Objectives

Our objectives in this work are to describe and discuss (1) the stratigraphic architecture as well as the details of environmental variability within the topsets of shelf-margin or continental-margin clinothems, (2) how stratigraphic sequences are picked within the topset stratigraphy, (3) how tectonic subsidence and sediment accumulation rates as well as climatic setting impact topset architecture and sequence preservation and (4) discuss the length and duration of regressive shoreline transits vs the duration of the high-frequency sequences that contain such regressive units.

2 | BASIC ARCHITECTURE OF THE TOPSET

In general terms, the topset is built by repeated regression and transgression of shorelines and related environments, across a pre-existing shelf surface; this transiting of the sediment supply system is the normal method for the larger scale topset to systematically aggrade and prograde, except in cases of very high subsidence rate outpacing shelf-transit rate. It is also worth emphasizing that this fundamental back and forth shoreline migration is essentially enacting the shelf-portion of the sequence stratigraphic paradigm, whereby interaction of sediment supply, subsidence and eustatic sea level cycles shapes stratigraphy in a “sequential” manner (Mitchum, Vail, & Thompson, 1977; Lobo & Ridente, 2014; Ridente, 2016). The extent of the seaward and landward migration of shorelines depends mainly on sediment flux and the amplitude of sea level change, as well as on the gradient of the coastal plain and shelf, as discussed further below. The regressive phase of any stratigraphic sequence within the topset is dominated by fluvial, fluvial-to-marine transition (Dalrymple & Choi, 2007) and the coeval marine delta-front, strandplain and shelf...

Highlights

- The siliciclastic topset of a continental margin, or of a shelf-margin prism in rift, foreland or cratonic deepwater basins, is the flat-lying upper part of the margin succession, landward of the shelf break.
- Topsets are formed by repeated, cross-shelf regressive and transgressive shoreline migration and therefore consist of a wide range of fluvial, paralic and shallow marine deposits. Thickness of individual regressive–transgressive depositional sequences in any topset is given by shelf accommodation, typically <10 m in embayment or on the inner shelf and up to 200 m on the outer shelf.
- Icehouse cross-shelf transits are slower but extend the marine portion of the topset farther landward than the Greenhouse counterpart. Numerical experiments show that even for the widest shelves and irrespective of Icehouse or Greenhouse conditions, deltas usually take only 10 s of ky to cross their shelf. Despite this, Greenhouse depositional sequences are commonly thought to take three times longer to develop than Icehouse sequences, suggesting that the former may involve multiple sea level cycles.
- Very rapid subsidence increases shelf accommodation, thickens sequences and enhances the preservation of transgressive tracts. Greenhouse conditions or low subsidence rates tends to amalgamate depositional sequences and makes them more difficult to document.
deposits. The regressive unit is most easily picked (in outcrop, well or seismic data) in the outer reaches of the topset where it forms upward coarsening delta-scale (10 s of m) clinoforms that downlap onto a muddy maximum flooding surface (MFS) (cf. Carvajal & Steel, 2006). The transgressive phase of each sequence usually involves fluvial, estuarine, barrier–lagoon and shelf ridge deposits (Boyd, Dalrymple, & Zaitlin, 1992) that have an irregular upward fining and increasingly marine signature until reaching the MFS (Cattaneo & Steel, 2003). Punctuated transgressions can also trigger delta deposits (Pellegrini et al., 2015). A fundamental aspect of the “topset” is that it contains that portion of the total sediment budget retained and stored on the morphological shelf during shoreline transits. The remainder of the sediment budget brought to the margin is partitioned beyond the shelf break onto the deepwater slope and basin-floor fans. In estimates involving only the regressive part of the total budget, this by-passed deepwater sediment volume is, surprisingly, often two thirds of the total regressive budget (Carvajal & Steel, 2012; Petter, Steel, Mohrig, Kim, & Carvajal, 2012).

2.1 | Marine vs nonmarine strata in topset

Orbital cyclicity, as discussed further below, plays a fundamental and dominant role in setting the relatively short timescales for individual shelf transits and fundamental sequences. It is likely that individual transit sequences (sea level highstand to lowstand and back to highstand) in Greenhouse periods develop during ca. 100–300 ky (Miller et al., 2005), whereas Icehouse-margin sequences develop within 100 ky and less (Lobo & Ridente, 2014). This climatic forcing, and in particular the amplitude of eustatic sea level rise and fall, along with shelf gradient and width (Blum, Martin, & Milliken, 2013), largely determine how far back across the topset the marine transgressions and regressions extend from the shelf break during shelf growth, that is, how much of any topset stratigraphic cycle is marine and how much is alluvial or transitional deposits. An important part of the fluvial-to-marine transition zone involves the backwater area of river systems (the distance over which distributary channel scouring is at or below sea level; Paola & Mohrig, 1996). This area, immediately landward of the marine delta front, can be extensive in low-gradient coastal plains and a significant part of the river’s sediment budget can be deposited here (Allison et al., 2012).

2.2 | Marine shorelines dominating the topset and extending far back from shelf edge

Figure 1 illustrates a stack of 5–6 Icehouse sequences (each about 100 ky in duration) that developed across some 120 km of the topset on the Bengal continental shelf and margin, each sequence with a regressive (orange) and capping transgressive (green) interval. Each regressive interval is interpreted as forced regressive (Hübscher & Spieß, 2005; Lobo & Ridente, 2014) where they show flat to slightly downward shoreline trajectories and they are dated to be coeval with falling sea level periods in the Late Quaternary. Each shelf-drowning transgressive interval capping the regressions, reflecting some interglacial warming, is thin and can be irregularly preserved but extends >100 km landwards, sometimes thickening in that direction as the underlying regressive strata thin (Figure 1). The basinward termination of these marine clinothem topsets is the shelf edge, marking an abrupt water depth increase from a neritic environment dominated by river, tide and wave processes, to a deepwater bathyal environment dominated by gravity-driven processes. The topset strata are thus bounded basinward by the shelf break and landwards by an irregular onlap surface onto older strata. This style of topset, with shoreline regression reaching the shelf
break and transgression extending landward for 100 km or more appears to be especially common in Icehouse periods and where the pre-existing shelf gradient is relatively gentle, and has been well illustrated for many other Late Quaternary shelf units including Brazil, South China Sea, Adriatic Sea, Gulf of Lions and Gulf of Cadiz (Hernández-Molina et al., 2000; Lobo & Ridente, 2014).

2.3 | Marine shorelines reach the shelf break but remain restricted to the outermost part of the topset during stacking of subsequent sequences

Topset cases of this type are discussed below for the Eocene West Spitsbergen foreland basin (Steel & Olsen, 2002) where shorelines rarely extend landward from the shelf break more than 7 km, for the Maastrichtian Washakie Basin (Carvajal & Steel, 2006) where marine deposits penetrate some 40 km landwards from the shelf break, for the Paleocene Wilcox, Gulf of Mexico passive margin (Zhang, Steel, & Ambrose, 2016) where marine deltas are restricted to the outermost 50 km of the topset and for the Early Jurassic Neuquen Basin margin where marine deltas extend less than 10 km from the shelf break (Brinkworth et al., 2017). Common to all these cases is a Greenhouse climate with very modest amplitudes of eustatic change ensuring that shorelines remained relatively near the shelf break (cf. Blum et al., 2013; Sømme, Helland-Hansen, & Granjeon, 2009). The reason for the variability in extent of landward penetration of marine deposits in these Greenhouse cases is that shelf width and gradient, in addition to eustatic amplitude, are also important controls.

2.4 | Other cases where shorelines do not reach the shelf break, but terminate far back on the shelf as platform-edge deltas

On some shelves the topset geometry is more complex because the deltas simply do not reach the shelf edge. The far-travelled Triassic deltas that migrated across the very broad, epicontinental Barents Sea shelf from the Ural mountains appear to have simply been abandoned and transgressed before they crossed the entire shelf, creating intra-shelf topography that became platforms on the shelf (few 10 s of m high), causing the next younger deltas to become platform edge deltas (Klausen et al., 2018, but see also Rossi et al., 2019 for alternative interpretation) (Figure 2).

Intra-shelf clinoforms, coarser grained than the example above, of several hundred metres height have also been described from some other shelves, particularly from Early–Mid-Miocene segments of the New Jersey shelf (Hodgson et al., 2018).

3 | ENVIRONMENTS AND VARIABILITY WITHIN TOPSETS

The regressive strata of the Gulf of Mexico Lower Wilcox topset sequences (each ca. 300 ky duration) (Figure 3a) were dominated by forward-accreting, delta-scale clinoforms that were river, tide and storm wave influenced. They repeatedly crossed some 50 km of the Gulf of Mexico mid- to outer-margin topset (Zhang et al., 2016). The regressive half cycles thicken basinward, and are increasingly truncated landward by deep fluvial and fluvio-tidal channel belts. During transgression and sea level rise, the channelized erosion surfaces with basal fluvial deposits were further backfilled by tide influenced estuaries. Despite the forward growth of the delta, there is significant lateral spreading and shifting during the shelf transit. In addition to what is shown in Figure 3a, there is also growth faulting and significant associated process regime changes in the delta front (Olariu & Ambrose, 2016) as well as significant areas with muddy shelf-break progradation (Olariu & Zeng, 2018).

The St. Bernard delta lobe within the topset of the Holocene Mississippi Delta Complex, in Figure 3b (from Ainsworth et al., 2017, data from Frazier, 1967) has prograded irregularly, with sub-lobes, across at least 100 km of the Gulf of Mexico northern shelf. The complex architecture at 1 ky scale shows
multiple delta-front sub-lobes (yellow within Figure 3b) with capping delta plain deposits (green) and deeply downcutting distributary channels (red). The youngest transgressive deposits reach landward for ca. 40 km, probably deposited during compactional subsidence because the submergence has happened relatively quickly in the past thousand years.

The last Pleistocene sequence generated during falling stage and subsequent transgression (glacial–interglacial) on the Gulf of Lions margin, is summarized in Figure 3c (Bassetti et al., 2008). The regressive half cycle has an easily recognized erosional base and is composed by up to 60-m-thick delta-scale clinothems that built across the shelf with a slightly falling trajectory (during sea level fall from 55 ky to 18 ky). Each of the regressive delta lobes (parasequences in up to 20-m-thick off-lapping units) appear to have formed within 1 ky and prograded 1–2 km during sea level drops of 10–30 m (Bassetti et al., 2008). The reflectors in the topset above D70 have been eroded. D70 is a transgressive ravinement surface, a transgressive lag deposit and capping tidal shelf ridges at sea bottom. Broken clinoform lines indicate reconstruction of what has been removed in places by the post-LGM ravinement surface (from Bassetti et al., 2008)
and any other deposits developed during landward translation of the ravinement surface, possibly tidal shelf ridges (Bassetti et al., 2008). The topset represented here on this part of the Rhone shelf is merely the distal and youngest portion of the transgressive tract.

Four depositional sequences of Fox Hills topset (Figure 4; each ca. 100 ky duration) (Carvajal, Steel, & Petter, 2009) thicken basinward and were built by river- and tide-dominated deltas (Olariu, Carvajal, Olariu, & Steel, 2012) developing against growing Laramide relief along the eastern reaches of the Washakie Basin, and by storm wave dominated deltas along the lower accommodation western half of the basin. The distance of repeated cross-shelf delta transits, from shelf edge back to initiation point of new regression, varies up through the succession from 20 to 50 km (Carvajal et al., 2009). Landward of what is shown in Figure 4, in each sequence there is a muddy zone with relatively deep but narrow distributary channels within what is likely to be the backwater zone. The sandy delta lobes initiate just seaward of this zone.

4 | WHY SUBDIVIDE THE TOPSET INTO SEQUENCES?

4.1 | Recognition of the regressive and transgressive parts of the topset sequences

It is important to recognize that thick topset successions consist of stacked stratigraphic sequences, and that these need to be identified. The regressive part of any sequence is easily recognized by its upward coarsening (few metres thick proximally in the topset, 10 s to 100 m thick on the outer shelf) from a muddy and heterolithic lower part to a sandier upper part (Figure 4). Its MFS is picked in the muddiest level (top green in Figure 4), and the maximum regressive surface (MRS) is usually picked at the top or coarsest grained level (top yellow in Figure 4). If the upper part of the regressive unit is channelized, the MRS is placed at the base of these upper channels. The channel infills may have been initially fluvial and deposited in a lowstand period, but are likely to have become estuarine as they were backfilled and transgression proceeded. Some confirmation that the channels at the turnaround level are estuarine usually comes with strong tidal signals within the fill, and the fact that the sediments become marine and finer grained upwards. The transgressive part of the sequence above the MRS often contains a wave-ravinement surface, separating brackish paralic deposits below (not always preserved) from an overlying marine transgressive lag, and culminates in the next muddy MFS (see Cattaneo & Steel, 2003 for multiple examples). The transgressive interval is generally much thinner than the underlying regressive unit (Figure 4), except when incised valleys have formed. The fundamental stratigraphic sequence within a topset succession is therefore determined from the identification of regressive-to-transgressive units bounded by extensive muddy MFSs. The thickness of each half cycle should be consistent with the depth of a transgressive estuary/barrier–lagoon system, and with the height of a regressive strandplain or delta. Where sequences in the topset are vertically or offset stacked, it may be tempting to refer to them as “parasequences”, but the thickness of the sandy units (thicker than normal deltas), the upward-finising transgressive intervals (albeit relatively thin) and the identification of muddy or sandy estuarine deposits with strong tidal signals suggests that the landward flooding is more than local abandonment and shifting of individual delta lobes. The above-described regressive-transgressive (or transgressive-regressive of some authors) package is considered a fourth-order stratigraphic sequence if it tracks across most or all of the pre-existing shelf and has a duration of 10 s of ky to several 100 ky. When tracked beyond the shelf break and onto the deepwater slope it is commonly seen to be a composite sequence or sequence set of...
more “fundamental” (Lopez-Blanco, Marzo, & Pina, 2000; Marzo & Steel, 2000) or “elemental” (Pellegrini et al., 2017) clinothems.

4.2 | Compound clinothems in the topset

There are further complications within the regressive part of many topset sequences, as has become clear from the study of many modern deltas (Swenson, Paola, Pratson, Voller, & Murray, 2005). The regressive part often consists of a basinward-migrating delta that has a double or compound clinothem. An upper, shoreline part (10–30 m thick), commonly shoreface or mouth bar deposits, is separated from a lower, subaqueous delta clinothem (20–130 m high) that can be muddier and more tidally influenced. Between the two there is commonly an intervening zone with evidence of strong tidal current or wave scouring referred to as the subaqueous platform (Figure 5) (Peng, Steel, Olariu, & Rossi, 2018). These genetically related, paired shoreline and subaqueous clinoforms are well known from modern deltas, especially the muddy ones (Cattaneo, Correggiari, Langone, & Trincardi, 2003; Kuehl, Levy, Moore, & Allison, 1997; Nittrouer et al., 1996; see also review of modern and ancient compound clinoforms by Patruno, Hampson, & Jackson, 2015). In the case of the modern Orinoco Delta, this double clinoform can be seen in the bathymetry, and the preservation of the “double clinothem bump” in the deltaic stratigraphy can be interpreted in a well log that is drilled on the outer shelf of the Pliocene Orinoco Delta.

The reason to highlight this double clinothem is that it is, as yet, quite rarely recognized in ancient examples, and this has consequences for correct recognition of the shoreline in log data or in vertical measured sections, as well as for estimating water depth. The top of the subaqueous clinothem can easily be misinterpreted as the shoreline. The relatively small scale of the parasitic upper clinothem within the topset of the larger margin clinothem, is often poorly resolved in seismic data. However, with high-quality 3D seismic data, application of seismic geomorphology may help to reduce uncertainty in interpreting shoreline location (e.g. identification of shallow marine depositional elements) even if shoreline clinoforms are not resolved on a 2D cross section.

5 | EFFECTS OF TECTONIC SUBSIDENCE AND CLIMATE ON TOPSET ARCHITECTURE

Here, we present three cases with varying states of accommodation development caused by tectonic subsidence/sediment accumulation rate, as well as eustatic sea level amplitude (Icehouse vs. Greenhouse) to highlight the role of accommodation in preservation of topset stratigraphy.

5.1 | Case 1—Rapid Subsidence: The Orinoco Icehouse margin

The Orinoco margin accumulated ca. 8–10 km of topset sediment during a 5 my Icehouse period from late Miocene to early Pleistocene (Chen, Steel, Olariu, & Li, 2018; Dixon, 2005). The characteristic flat-lying topset reflectors seen in the seismic data (Figure 6a) arise from the repeated,
cross-shelf transits of Orinoco delta system. The Pliocene interval seen in Figure 6a (TP25–TP95) represents about 3 my.

5.1.1 | Proof for widespread, cross-shelf delta transits, from well data

The seismic resolution is not sufficient to show delta-scale clinoform progradation across the topset and so the proportion of marine vs nonmarine deposits across the topset is unclear from just the seismic data. However, proof that the Orinoco Delta did repeatedly cross back and forth on the shelf over distances of 100 km is clear from outcrop data in south-westernmost Trinidad (Chen et al., 2018) and from the data of a well-log positioned on the Pliocene outer shelf (Figure 6b; see location of SEG area well in Figure 6a). The well data images about 19 stratigraphic sequences, each characterized by an irregular, upward-coarsening (regressive) to rapid upward-finishing (transgressive) grain size trend. The sequences vary from 200 m thick at the base of the well succession, near to the shelf break and 100 m thick in younger sequences (Figure 6b). The seismic data show flat-lying, “tramline-like” seismic reflections across the topset due to the repeated deltaic transits causing lithologic contrast between transgressive and prodelta mud and overlying regressive delta-front sandstone, sometimes with coals. Proof that the repeated marine transgressions seen on the well log extend more than 100 km farther landward comes from outcrop sequences in the same Upper Morne L’Enfer Formation on westernmost Trinidad and described as having similar aged but thinner regressive-transgressive sequences (Chen et al., 2018).

5.1.2 | Lateral spreading of sediment across the Orinoco margin topset

During shelf building by the Orinoco delta, there was also great lateral spreading of sediment across the topset area, as delta lobes shifted by longshore drift or moved laterally and abandoned, while irregularly and slowly transiting towards the shelf break. This irregular autogenic lobe shifting and lateral spreading of sediment can also be read from the well log in Figures 5 and 6b. The 100–200 m thick, upward-coarsening regressive units can be seen to have many sandy and muddy sub-units, representing significant autogenic “noise” within the overall upward-coarsening, regressive half-cycle. In wave-dominated deltaic and strandplain settings this lateral spreading can be extreme, as sediment is brought to the mouth of the river distributary.
and then transported alongshore into sets of beach ridges. This longshore sediment transport is evidence to suggest that wave-dominated deltas are much less efficient than other delta types in partitioning sand from the shelf edge to adjacent deepwater areas (Dixon, Steel, & Olariu, 2012), emphasizing that shelf and shelf-edge processes as well as sea level behaviour, sediment supply and shelf width are controls on partitioning of the topset sediment budget into deepwater areas.

One architectural aspect of the Orinoco margin topsets, likely caused by a combination of high subsidence rate, high-amplitude Pliocene Icehouse sea level changes (70–90 m) and re-routing of the sediment supply distributaries is the accumulation and preservation of extensive transgressive mudstone intervals, far back across the topset area on Trinidad. The three main transgressive intervals (dark blue in Figure 6a, including one below TP25 not shown) reach up to >100 km westwards across Trinidad, and deposit 10 s to 100 m of mud. In addition, there are more frequent thinner (up to 10 m on outer shelf, see Figures 5 and 6b) muddy transgressive estuarine intervals capping the sandy part of clinothems at shorter time scale (50–100 ky; Chen et al., 2018; Sydow et al., 2003).

5.1.3 Sequence structure of the Orinoco Pliocene margin

In summary, Figure 6a shows that the Orinoco Delta system spectacularly prograded its margin by more than 60 km in a time period of about 3 my, accumulating some 6 km of topset in the process. The cumulative topset consists of four units (<1 my each) separated by major intervals of muddy transgression. The four units can be considered third-order stratigraphic sequences, each showing a broad, irregular progradational to aggradational stacking pattern, followed by the capping muddy transgression. Each third-order sequence contains a series of higher frequency, fourth-order sequences, as betrayed by the elementary R-T sequences shown in the well log (Figure 6b). As such, the Pliocene margin exhibits composite sequences of several time scales (cf. Mitchum & Van Wagoner, 1991). We speculate further that the progradational to aggradational stacking character of the third-order sequences could have been forced by feedback relationships between sediment flux and subsidence (cf. Reynolds, Steckler, & Coakley, 1991).

What then are the main signatures of rapid subsidence on the paleo-Orinoco margin? We suggest:

- Extremely high subsidence rates (ca. 2,000 m/my) allowing for the accumulation of 8–10 km thickness of margin strata in a 5-my time span.
- Development of very thick, extensive open-marine mudstone (>100 m on outer shelf, thinning to 10 s of m on inner shelf) intervals, 3 times within a 2-my Pliocene period (Figure 6a); interpreted in terms of major delta distributary avulsion/re-routing and widespread, lengthy transgression. Particularly, the long duration of the mudstone blankets is consistent with a high subsidence rate.
- On a shorter time scale (50–100 ky), development of accommodation and the well-preserved, upward-fining tops of individual clinothems regularly preserved 10 m+ estuarine transgressive tracts underneath the MFS. These thin but laterally continuous transgressive intervals can be seen clearly in the well log of Figure 5b. We consider these a product of interaction between subsidence rate and eustatic sea level rises, both of which acted at these short time scales in the Orinoco case.

5.2 Case 2: Moderate subsidence & supply, Greenhouse climate, normal regression: Spitsbergen margin

The Spitsbergen margin is at least partly earliest Eocene, close to the Paleocene–Eocene climate optimum and so classed as a Greenhouse margin, though cooling was beginning to create an icesheet in Antarctica already in the Oligocene. The Spitsbergen case was one of the first seismic-scale outcrop examples illustrating many of the connected systems-tract details of the early Exxon sequence model (Steel & Olsen, 2002). The Van Mijenfjorden Group clinoforms, like the Orinoco case, and have well-developed nonmarine to marine topsets highlighted by a distinct series of about 20 shorelines linked to a long-term, rising shelf-edge trajectory (Figure 7). However, there are also significant differences, including a much shorter, total topset length of clinothems. The open marine portion of any clinothem (shelf width) in the topset is narrow, so that each sequence is dominated by fluvial and fluvial-to-marine transition deposits. The marine shoreline regressive component is river-dominated delta and often wave reworked (Helland-Hansen, 2010), and is mostly normal regressive except possibly near the shelf break of some clinothems where there is likely forced regression (Mellere, Breda, & Steel, 2003). The transgressive component is frequently sandy and more tidally dominated (Mellere et al., 2003). So, the marked feature in contrast to the Orinoco case is that marine deposits in any topset are restricted to a belt less than 7 km wide behind the shelf break.

There are also other important contrasts between the Orinoco and Spitsbergen cases. The Eocene, Greenhouse succession on Spitsbergen reaches about 1,000 m thick in the cross section shown (Figure 7), in contrast to the 8–10km-thick Orinoco succession in Figure 6. The Spitsbergen sediments were probably deposited mainly in the early Eocene (Manum & Throndsen, 1986), though there is much uncertainty about the age of the upper boundary. Stratal back-stripping by Dörre, Clift, Lisker, and Spiegel (2013) suggested basin subsidence of <50 m/my, and even if their time interval
estimate is reduced to the earliest 5 my of the Ypresian (rather than the entire Eocene), the topset accumulation rate increases to about 200 m/my., that is, sediment accumulation rate was moderate, but an order of magnitude slower than discussed above for the Orinoco margin, and this is consistent with the estimate of slow (<5 km/my) clinoform progradation rate on Spitsbergen (Carvajal et al., 2009). The relatively small size of the basin-floor fans (Figure 7) is also consistent with a low to moderate sediment supply. The catchment area within the West Spitsbergen fold and thrust belt likely provided significant relief but the relatively modest channel sizes in the delta plain and estuaries (Helland-Hansen, 2010; Plink-Bjorklund, 2005) suggest that these were relatively small rivers. Using the above assumptions for timing of deposition, individual clinoform duration was possibly 2–300 ky. The Spitsbergen margin topsets, compared to the Orinoco case, were impacted by moderate to low subsidence rates as follows:

- Sediment accumulation rates, likely between 50 and 200 m/my for 1 km of strata shown in Figure 7, are an order of magnitude lower than in the Orinoco case
- Although there are transgressive tracts capping most sequences (Figure 7), and there is a marked marine penetration extending up to 10 km landwards in the middle of Storvola Mountain (Figure 7), the transgressions rarely extend more than 5–6 km landwards. This indicates that the marine shelf portion of the topset was always relatively narrow, and accommodation for both shoreline regression and transgression was limited. The total width of the topset, including the nonmarine deposits was also low, and probably exceeded 50 km only for the youngest clinoforms
- However, the limited extent of shelf transgressions might also be explained by slow background subsidence superimposed by low-amplitude eustatic sea level rises in the Greenhouse climate setting (Table 1).

5.3 | Case 3: Topset shaped by Icehouse sea level fall: Po-Adriatic shelf margin

In contrast to the two previous cases, the Po margin in Figure 8 is represented by a lowstand wedge of the last Glacial cycle, containing topsets (20–50 m thick) developed during a remarkably short time span (ca. 17 ky), though with a high rate of sediment supply onto the margin (Pellegrini et al., 2018). In the Po-Adriatic margin (Figure 8), nearly 350 m of strata developed during a well-dated period of the late falling stage and lowstand of sea level (31.8–14.4 ky BP) during the last glacial-interglacial period (Pellegrini et al., 2017). The succession shows at least five “elemental” clinothem pairs (repeated B+A in Figure 8), each of duration up to several thousand years, and each with a strongly regressive lower portion and an aggradational upper portion, separated by a marked surface. The regressive portion of the clinotherms tends to be erosively capped by a forced regressive surface, thus creating, by definition, an “oblique” clinoform type (Mitchum et al., 1977), whereas the aggradational portions are of “sigmoidal” type with continuity between topsset and slope. It is predictable that the topset is thin because of falling eustatic sea level during the glacial half cycle (Pellegrini et al., 2018).

The important feature to be highlighted here is the thinness of the topset and flat to slightly falling trajectory of the Po Delta front that migrated forward by >40 km during approximately 17 ky of eustatic sea level fall. However, it is noteworthy that most aggradation on the margin occurred with
the most recent clinothems (C-clinothems in Figure 8) that follow the maximum lowstand of sea level during the early stages of post-glacial sea level rise. The repeated irregularity along the outer edge of the topset and the flat-to-rise cycles, suggest that slow sea level fall was being forced periodically into “rise” (brief warming) with little or no transgression.

Table 1 summarizes some of the above observations on how topset geometry is affected by tectonic subsidence/sediment accumulation rates in the basin and by a climate setting that dictates amplitude of sea level change. Not unexpectedly, high cumulative accommodation from tectonic subsidence and Icehouse eustasy preserves best the cycles and enhances...
transgressions, whereas Greenhouse climate and lower subsidence produce shorter landward penetration of the marine shorelines and also tend to cause greater amalgamation of fourth-order depositional sequences, so that they are more difficult to distinguish. Additionally, however, we note that there are also other end-member Greenhouse scenarios with high supply and high subsidence that promoted very thick topset aggradation and high margin progradation rates (e.g. Barrow Group, NW Australia during an active phase of Cretaceous rift extension; Paumard et al., 2018).

Finally, it should be noted that with epicontinental margins, such as the Po-Adriatic case shown above, there is a more complex arrangement of margin paleogeography between times of lowstand and highstand of sea level than a simple moving back and forth of the sediment entry point across the pericontinental margin (cf. Amorosi, Maselli, & Trincardi, 2016).
6 | SHELF TRANSIT TIME AND SEQUENCE GENERATION

6.1 | Icehouse stratigraphic sequences

There is ample evidence that Pleistocene Icehouse depositional sequences, that is, their combined regressive, deepwater and transgressive parts, have a duration of ca. 10–100 ky (Miller et al., 2005; Somme et al., 2009; Ridente, 2016). However, these sedimentary sequences are not likely to correspond exactly with orbitally-driven, glacial to interglacial, eustatic sea level changes because the rock stratigraphy will necessarily be modulated by intermediate “on the ground” factors, especially shelf width and gradient, but also climate/sediment supply changes. For example, the latter was especially important on the Armorican margin during the last glacial cycle when rising sea level and climate warming produced increased sediment flux and margin progradation during the early transgressive limb of the cycle (Toucanne et al., 2012).

6.2 | Greenhouse stratigraphic sequences

Perhaps some of the best-researched Greenhouse stratigraphic sequences are of Cretaceous and Paleogene time intervals. These successions also show regressive-transgressive stratal repetitions on their topsets, but appear to be generally of 200–400 ky duration (Zhang et al., 2016). However, the cyclicity can be harder to detect in Greenhouse cases because of amalgamation where aggradation rate is low, and also cross-shelf shoreline transit duration may sometimes be shorter (e.g. the Washakie Basin case in Figure 4 shows well-developed 100 ky sequences; Carvajal & Steel, 2006). It is much less clear what drives these Greenhouse sequences, though changes in sediment supply may play a greater role in Greenhouse compared to what it does in Icehouse, because Greenhouse sea level change is usually considered as low amplitude and low frequency. These longer time scale Greenhouse changes have been documented and advocated by Miller et al. (2005). Additional evidence on sequence duration can also be gleaned from another source; shelf transit time, that is, the time needed for deltas to cross their shelves entirely, allowing them to potentially shed sediment into deepwater areas. Numerical experiments on shelf-transit time (Burgess & Hovius, 1998) have suggested that complete regressive transit needs only 10 s of ky. We use a recently published shelf database in Zhang, Steel, and Olariu (2017) to calculate the shelf transit time for both Greenhouse (SL amplitude 30 m) and Icehouse (SL amplitude 130 m) systems (Table 1). Our results again demonstrate that on most margins, the shelf transit time is only 10 s of ky with only several cases of >100 ky transit time. In addition, Icehouse conditions consistently require longer transit times than Greenhouse conditions because of higher amplitude (up to 100 m instead of a few 10 s of m) of sea level change and more extensive transits. However, the shelf transit time calculated here is a minimal estimate because (1) longshore drift is able to rework 10%–50% sediments along strike (Liu et al., 2009); and (2) in some cases, the period of sea level change is less than the shelf transit time, and some sediments are delivered into deep water during sea level lowstand.

7 | CONCLUSIONS

Shelf-margin topsets, the flat-lying uppermost portion of shelf-margin prisms, prograde and aggrade by repeated regressive-transgressive, cross-shelf shoreline transits. In this manner, and by the addition of a deeperwater segment, they form fundamental fourth-order stratigraphic sequences containing shallow-to-deepwater systems tracts. The topset regressive portion consists of fluvial, fluvial-to-marine transition, then delta-front and shelf deposits, with a capping of distributary channels. The topset transgressive part of any sequence is dominated by estuarine, barrier–lagoon and back-stepping delta deposits, and a wave-ravinement surface capped by overlying shelf deposits including tide/storm ridge sandstones and mudstones. The topsets are most easily correlated by using MFSs for each fourth-order sequence, but the thinner lithosomes inside systems tracts (e.g. distributary channels, inter-distributary mudstones, delta lobes), created usually as autogenic stratigraphic responses (e.g. channel avulsions, lobe shifts) are difficult to correlate.

Individual fourth-order sequences within the topsets commonly thicken from 10 to 15 m in their proximal reaches up to 150–200 m at the shelf break. The regressive part of the sequence generally takes only 10 s of ky to attain a shelf-edge position, with Icehouse transits taking slightly longer, because of a more extensive landward transgression. The latter climate setting also causes a higher proportion of marine to nonmarine deposits in the topset. Tectonic subsidence rate can be seen to play an increasing role as sequences within the topset stack on each other; sequences amalgamate with each other when rates are low, but become well defined at high rates. At very high rates of subsidence, transgressive tracts are better preserved and become thicker.

ACKNOWLEDGEMENTS

We thank the RioMar industry consortium (ExxonMobil, Shell, Chevron, Anadarko, Equinor, CNPC) for continued support and discussion about margins, as well as the University of Texas at Austin, Jackson School of Geosciences. Reviewers Elisabeth Steel, Claudio Pellegrini, Fabio Trincardi and Victorien Paumard are thanked for insightful comments that improved the paper.
DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Si Chen https://orcid.org/0000-0002-0305-8641

REFERENCES


Amorosi, A., Maselli, V., & Trincardi, F. (2016). Onshore to offshore anatomy of a late Quaternary source-to-sink system (Po Plain-Adriatic Sea, Italy). Earth-Science Reviews, 153, 212–237.


Mitchum, R. M., Vail, P. R., & Thompson, S. (1977) Seismic stratigraphy and global changes in sea level, part 2: The depositional sequence as the basic unit for stratigraphic analysis. In C. E. Payton (Ed.), *Seismic stratigraphy: Applications to hydrocarbon exploration* (pp. 53–62). AAPG Memoir 26.


---

**How to cite this article:** Steel RJ, Olariu C, Zhang J, Chen S. What is the topset of a shelf-margin prism? *Basin Res.* 2019;00:1–16. https://doi.org/10.1111/bre.12394