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Sediment supply: The main driver of shelf-margin growth

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ABSTRACT

Despite the obvious importance of sediment supply to shelf-margin architecture and to the potential of margins to contain and bypass deep-water sands, the role of supply in shelf-margin growth has received limited attention. High cross-shelf sediment flux is critically important for the occurrence of deep-water sands, not least on Greenhouse or rapidly subsiding margins where the impact of eustatic sea-level fall may be insufficient to drive sediment delivery out across the shelf into deep-water areas. To draw greater attention to the supply parameter we review a number of shelf margins that have grown chiefly through supply by shelf-edge deltas and associated sediment-gravity flows. Based on structural style and water depth, we recognize two broad types of shelf-margin. *Moderately deep-water margins* produce clinoforms <1000 m high and show rates of shelf-edge progradation <60 km/My and aggradation <270 m/My, and consequently, infill their basins relatively rapidly, and develop more progradational architectures with morphologically smooth and relatively undeformed slopes. *Very deep-water margins* produce clinoforms >1000 m high and generally show rates of shelf-edge progradation <40 km/My and aggradation <2500 m/My, and therefore infill their basins more slowly and develop more aggradational architectures with much gravity-driven slope deformation, proneness to failure and ponded architectures (salt or shale driven). On both margin types, long-term (>1 My) rates of shelf-edge progradation of several tens of km/My tend to be linked to the delivery of relatively large volumes of sand into the deep-water basin. Delivery of this sand beyond the shelf-edge happens despite Greenhouse conditions and is likely recurrent and periodic (delivery cycles in the order of 100′s ky). Such prominent margin growth is a strong indication that sediment influx was relatively high and we refer to these margins as "supply-dominated" shelf margins. The Gulf of Mexico margin is a well-known and data-rich example of a "supply-dominated" shelf-margin during certain times (e.g., Paleocene). In contrast, on both margin types, low rates of shelf-edge progradation are linked to diminished (or even non-existent) and less frequently recurrent deep-water sediment delivery suggestive of relatively low sediment influx. Occurrence of deep-water sand delivery under low sediment influx probably requires fall of relative sea level. The differences between rapidly and slowly prograding margins indicate that sediment supply (and not sea level) is likely to be the key limiting factor on the growth of shelf margins and that sediment supply, as interpreted through progradation rate, can therefore be used to make a first-order prediction of relative amounts of sand passed to deep-water areas.

Contents

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1. Introduction

There is no doubt that sediment supply is a major external control on shelf-margin growth, architecture and potential to produce deep-water sandstones. Conceptually, the so-called accommodation to supply ratio (*A*/*S*) explicitly acknowledges the importance of sediment supply for shoreline migration (Curtis, 1970; Schlager, 1993). Swift and Thorne (1991) emphasized sediment supply by introducing the concept of "supply-dominated regimes" to refer to those shelves characterized by a large or coarse sediment input with clear progradational patterns. Using data from modern deltaic systems, other researchers (Burgess and Hovius, 1998; Muto and Steel, 2002; Porębski and Steel, 2006) have recently highlighted that given sufficient sediment supply deltas are capable of prograding to the shelf-edge during rising sea level within a characteristic short transit time (<100 ky). Studies of modern river-delta systems have also emphasized the importance of supply by quantifying sediment flux to the ocean based on drainage-basin area, relief, climate, bedrock lithology, etc. (Milliman and Syvitski, 1992; Hovius, 1998; Syvitski et al., 2003; Syvitski and Milliman, 2007). Flume experiments and numerical models (Paola, 2000) explicitly acknowledge supply, as it is an actual variable that needs to be quantified in the experiment or model.

However, in studies of ancient shelf margins, and perhaps in stratigraphic studies in general, the role of sediment supply tends to be overlooked (but see Galloway, 2001; Carvajal and Steel, 2006). Part of this oversight involves the difficulty of quantifying supply in ancient depositional systems as this requires representative data coverage, a good preservation of depositional systems and an adequate methodology to estimate the volume of different lithologies and ultimately sediment supply (e.g., for a discussion see Liu and Galloway, 1997). Furthermore, there has been some continued focus on sea level in efforts to predict the delivery and formation of sandy deep-water deposits (Posamentier et al., 1988; Posamentier and Allen, 1999; Catuneanu et al., 2009a,b; Helland-Hansen, 2009) despite the likelihood that supply 1) can be the key driver for shelf-margin progradation and delivery of deep-water sand even during rising sea level (Kolla and Perlmutter, 1993; Wetzel, 1993; Burgess and Hovius, 1998; Pinous et al., 2001; Muto and Steel, 2002; Carvajal and Steel, 2006) and 2) may also allow the prediction of sediment bypass to deep-water areas, as the data herein suggest.

In this review, we explore the driving role that sediment supply may play in the growth of ancient shelf margins and the potential for reading supply signatures in the strata of margins. We attempt to develop a proxy for interpreting supply, based on the aggradation and progradation rates of ancient shelf margins. In a qualitative way, some recent studies have noted that shelf-margin growth rates are an interesting attribute for shelf-margin differentiation (Hadler-Jacobsen et al., 2005); here we provide estimates of these rates and highlight the importance of sediment supply as a key driver. Results indicate that in progradational margins, progradation rates tend to correlate with sediment supply, and that increasing rates of progradation commonly imply increased volumes of sand being brought to the deep-water basin floor. Furthermore, it seems that over time scales greater than 1–2>My, sediment supply is the *key limiting variable* controlling the volume of sandstone in the slope and basin floor. This is a conclusion in agreement with studies of modern/Quaternary systems that demonstrate fan volumes to be directly related to river discharge (Wetzel, 1993; Sømme et al., 2009b).

2. Selected margins

In this review we focus on rivers and deltas as the main supply agents for shelf-margin growth. They are likely to be most effective both for prograding the margin and for bypassing large sand volumes to deep-water (Mattern, 2005). We have not included margin growth where there has been significant addition of sediment by longshore drifts or tides in relatively narrow shelves (Covault et al., 2007; Boyd et al., 2008), by outer shelf oceanic currents (Lu et al., 2003) or inner shelf supply via cross-shelf incisions (Weber et al., 1997). We have also not included margins with steep, somewhat fixed slopes that, despite having fans, do not exhibit much co-genetic shelf-edge progradation (e.g., Brushy Canyon Fm. of West Texas, see Beaubouef et al. (1999)).

Twelve shelf margins have been selected to evaluate the role of supply on their architecture and on the generation of associated deep-water sand (Fig. 1 and Table 1). The margins represent different basin types and each has enough data available to determine their shelf-edge aggradation and progradation rates with reasonable certainty along the study profiles or from shelf-edge maps. We are not dealing with epeiric or epicontinental seas where the water depth is generally <200 m and where there is no shelf-slope break. Examples are included from foreland (North Slope of Alaska), intermontane (Lewis), rift (Porcupine, Pletmos, Exmouth Plateau, and West Siberia), and piggyback (Spitsbergen) basins, and from passive (New Jersey, Nova Scotia and Gulf of Mexico) and collisional (Orinoco and Borneo) plate boundaries. The examples come from both moderately deep (<1000 m clinoform amplitude) and very deep (>1000 m clinoform amplitude) shelf margins. Even though the New Jersey margin is an Atlantic margin, the clinoforms there that we are considering are less <1000 m high (Fulthorpe and Austin, 1998; Steckler et al., 1999). They developed as a pre-existing carbonate platform subsided at a low rate and provided space for clinoform development and progradation during renewed clastic influx in the late Oligocene and later. On the other hand, the North Slope Alaska margin developed in a foreland basin (McMillen, 1991; Houseknecht et al., 2009), but reached water depths >1000 m as shown by clinoform heights of 1700–2500 m in the foredeep, close to the Brooks Range; naturally as subsidence decreases away from the foredeep in the central basin area, clinoform amplitude becomes <1000 m. By including shelf margins of varying clinoform amplitudes and different tectonic settings we acknowledge Swift and

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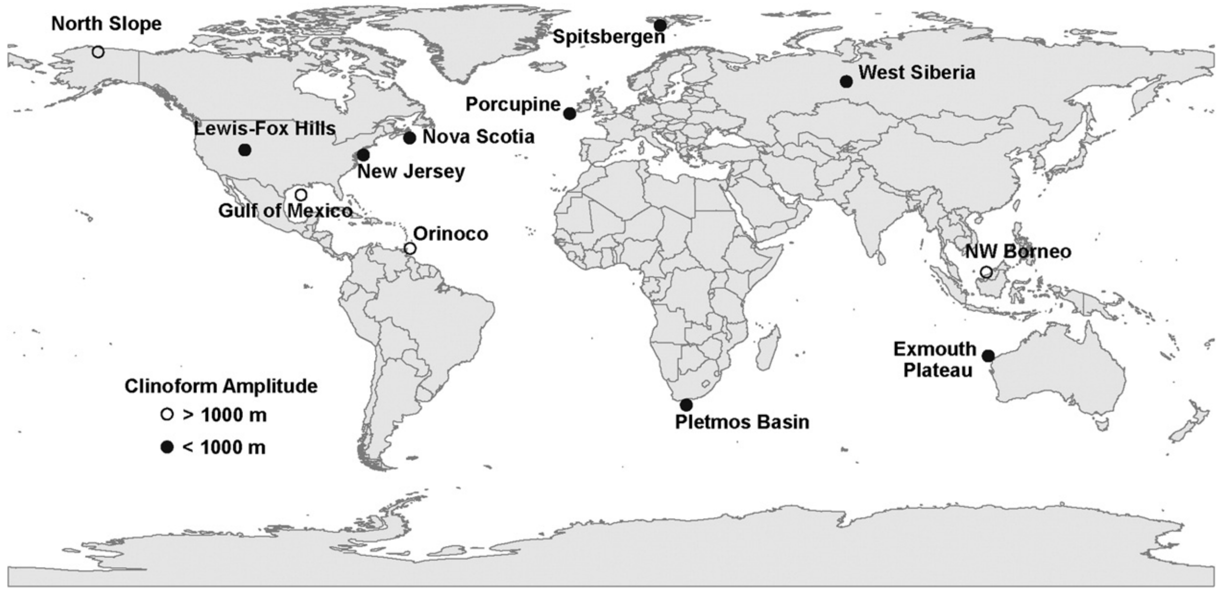

Fig. 1. Location of study margins. New Jersey and Nova Scotia were included in the low-amplitude margins (<1000 m) because clinoforms were of this height during the study periods.

Thorne's (1991) recognition that the shelf-slope-basin floor morphology is a characteristic feature of many basins provided the water is deep enough, not only those on continental margins. Nevertheless, it is quickly apparent there are significant differences between moderately and very deep-water margins and so we analyze them separately.

Direct measurement of shelf-edge progradation and aggradation rates were made on cross-sections and maps between horizons

Table 1
Aggradation and progradation rates for different shelf margins[a].

Shelf margin	Age	*A* (m)	*P* (km)	Time (My)	*A.* rate (m/My)	*P.* rate (km/My)	Reference
New Jersey	M. Miocene	150	60	2.9	43	17	Steckler et al. (1999)
New Jersey	E. Miocene	113	34	7.4	15	5	Steckler et al. (1999)
New Jersey	Oligocene	113	10	9.5	13	1	Steckler et al. (1999)
Spitsbergen	E. Eocene	1150	30	6.0	192	5	Johannessen and Steel (2005)
Porcupine Basin	E. Eocene	400	30	4–5	80–100	7	Johannessen and Steel (2005)
Lewis-Fox Hills	Maastrichtian	>480	>86	1.8	267	48	Carvajal and Steel (2006)
Pletmos Basin	Barremian–Aptian	500	60	4.0	113	15	Brink et al. (1993)
West Siberia	Valanginian–Hauterivian	1000	550	9.0	111	61	Pinous et al. (2001)
Exmouth Plat.	Berrisian–Valanginian	610	>57	6	102	10	Erskine and Vail (1987)
Nova Scotia	Lower Cretaceous				20	5	Pers. Comm. John Gjelberg/Norsk Hydro
North Slope of Alaska	Albian	~1000	152	10.0	100	16	McMillen (1991), Houseknecht et al. (2009)
Orinoco Columbus Basin	Pleistocene–present	4400	29	1.8	2450 (and higher)	16	Sydow et al. (2003), Wood (2000)
Orinoco Plataforma Deltana	Pleistocene	1500	60	1.6	935	38	Di Croce et al. (1999)
Orinoco Plataforma Deltana	Pliocene	2000	60	3.5	550	18	Di Croce et al. (1999)
Orinoco East Venezuela	L. Miocene	1200	200	6	200	33	Di Croce et al. (1999)
Orinoco East Venezuela	M. Miocene	2000	60	5	400	10	Di Croce et al. (1999)
Orinoco East Venezuela	E. Miocene	2000	75	7	280	8	Di Croce et al. (1999)
Gulf of Mexico Louisiana	L. Miocene (UM)	2500–3000	Fig. 7	5.8	460–550	16–20	All from Galloway et al. (2000), Wu and Galloway (2002), Galloway and Williams (1991); and Fig. 7
Gulf of Mexico Louisiana	M. Miocene (MM)	Not avail.	Fig. 7	3.6	Not avail.	16–20	
Gulf of Mexico Texas/Louisiana	E. Miocene (LM2)	Not avail.	Fig. 7	2.6	Not avail.	12–16	
Gulf of Mexico Texas/Louisana	E. Miocene (LM1)	Not avail.	Fig. 7		Not avail.	8–12	
Gulf of Mexico Rio Grande	Oligocene (OF)	Not avail.	Fig. 7	8.6	600–700	16–20	
Gulf of Mexico Rio Grande	L. Eocene (Jackson)	Not avail.	Fig. 7	2	600–800	12–16	
Gulf of Mexico Rio Grande	M.-L. Eocene (Yegua/Cockfield)	Not avail.	Fig. 7	4	600–800	4–8	
Gulf of Mexico Texas	M. Eocene (Sparta)	Not avail.	Fig. 7	3.5	0–200	0	
Gulf of Mexico Rio Grande	M. Eocene (Queen City)	Not avail.	Fig. 7	2.8	1400–1500	8–12	
Gulf of Mexico Rio Grande	E. Eocene (U. Wilcox)	Not avail.	Fig. 7	5.5	150–250	4–8	
Gulf of Mexico S. Marcos Arch	L. Paleocene (M. Wilcox)	Not avail.	Fig. 7	2	200–300	4–8	
Gulf of Mexico Houston Embay.	L. Paleocene (L. Wilcox)	Not avail.	Fig. 7	4.6	500–600	20–30	
Borneo	Pleistocene	2300–1700	~20	1.7	1000–1350	12	Saller and Blake (2003)
Borneo	Pliocene	2000–1700	12–40	3.7	460–540	3–11	Saller and Blake (2003)
Borneo	L. Miocene	Not avail.	20–40	5.7	Not avail.	4–7	Saller and Blake (2003)

[a] Accretion distance and aggradation measured in shelf-edge maps and cross-sections. All measures un-decompacted except for New Jersey Margin, and Gulf of Mexico in the Paleocene, Eocene and Oligocene whose decompacted aggradation rates are directly provided in Galloway and Williams (1991). Some uncertainties may arise from cross-sections orientations, lack of depth-converted seismic data and limited aerial coverage. Therefore, rates are approximate. Dating is reasonably good for all margins except for the North Slope of Alaska (which may lead to errors in progradation and aggradation rates). In some margins rates were calculated for more than one period to represent variability.

bounding time intervals greater than 1–2 My (Fig. 2). The ages of the study margins range from Early Cretaceous through present. Some margins have a long history spanning several tens of My (e.g., Gulf of Mexico) and so, as far as possible, accretion rates for different periods have been calculated in these cases. Time control is provided through biostratigraphy and is relatively well constrained in most cases except on the North Slope of Alaska margin. We have chosen a minimum of 1–2 My as the time span of interest, because this is the time resolution available in most basins and because we seek to characterize the sediment supply at long enough timescales to produce economic volumes of deep-water sand from an exploration viewpoint. In addition, because our time span is long it includes times when the margin does not prograde much, such as when the deltas are sited on the inner shelf, or when the margin fails and retrogrades. Therefore, our rates are long-term average growth rates and they are probably accurate (i.e. close to the real value) but not necessarily as precise. Shorter time intervals (e.g. <1–2 My) may result in highly focused shelf-margin progradation, because the shelf-edge delta system (not just the individual delta-lobe or set of lobes) may not have had enough time to avulse over wide enough areas in order to prograde significant, along-strike stretches of the shelf-edge (e.g. see the relatively high local rates during the Pliocene and Pleistocene deposodes in the Gulf of Mexico, Fig. 7). On shelf-edge maps (Gulf of Mexico, Borneo, Orinoco, North Slope of Alaska and Lewis shelf margins), data are taken along the axis of the maximum progradation distance of the shelf-edge in the dip direction of the feeding fairway system. In cross-sections (Spitsbergen, Porcupine, Exmouth Plateau, Pletmos Basin and Nova Scotia), transects are aligned as much as possible along the direction of basin infilling, i.e., along the direction of steepest clinoform gradients. The analysis presented indicates that the available cross-sections are adequate to characterize the supply, although they may not necessarily show maximum progradation. In this regard it is important to note that a properly dip-oriented cross-section, i.e. along or close to a sediment feeder pathway, is likely to

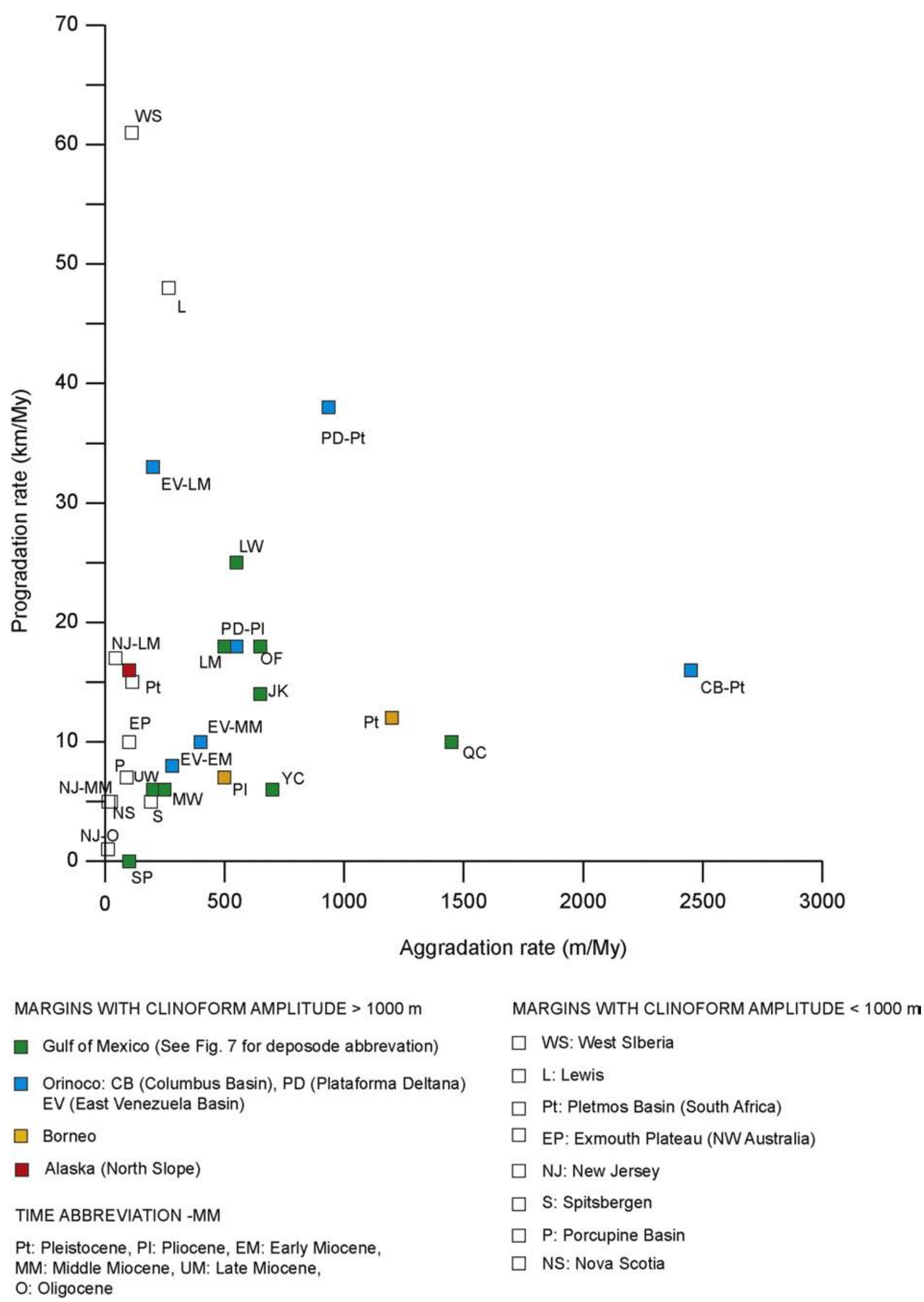

Fig. 2. Progradation and aggradation rates for the study margins.

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offer a reasonable representation of the margin growth style and the supply feeder sediment in the area. This is because shelf-edge maps from the North-West Borneo (Saller and Blake, 2003), Eastern Borneo (Saller et al., 2004), Gulf of Mexico (Galloway et al., 2000; Fig. 7), Orinoco (Sydow et al., 2003), Lewis (Carvajal and Steel, 2006), New Jersey (Fulthorpe and Austin, 1998), North Slope of Alaska (Houseknecht et al., 2009) and New Zealand (Lu et al., 2003) margins indicate that, over time intervals >1–2 My, the shelf-edge seems to prograde and aggrade nearly uniformly for significant distances along the shelf-edge (at least few tens to few hundred kilometers depending on the margin). In general, however, the extent to which a given cross-section may represent the growth style and supply of the margin will depend on how well-placed the line is and on the characteristics of the margin.

3. Shelf-margin aggradation and progradation rates

Accretion rates vary over a wide range on the selected margins (Table 1 and Fig. 2). Rates of progradation range from <1 to 61 km/My; whereas rates of aggradation range from a few m/My to 2500 m/My. On average, margins prograde at 20 km/My and aggrade at 500 m/My approximately, and the average of the progradation to aggradation (*P/A*) ratios is ~100. We note that there are clear and interesting differences between the smaller (<1000 m clinoform height) and larger scale (>1000 m clinoform height) margins, and we refer to these as moderately deep-water and very deep-water margins, respectively.

3.1. Margins with water depths < 1000 m

On these margins (Lewis, Porcupine, Spitsbergen, West Siberia, Exmouth Plateau, South Africa, New Jersey and Nova Scotia), progradation rates vary from <1 km/My (New Jersey, Oligocene) to 61 km/My (West Siberia) and aggradation rates are <270 m/My (Fig. 2 and Table 1). Average progradation and aggradation rates are ca.17 km/My and ca.100 m/My respectively, and the average of the *P/A* ratios is about 210. Aggradation rates in these margins remain relatively low compared to very deep-water margins (Fig. 2). This is likely because the smaller margin mass of these margins induces less regional subsidence due to loading of the crust (typically continental) and less compaction. In addition, these margins are not prone to achieve high local subsidence and so high local aggradation rates, because they do not have significant salt or shale remobilization, and gravity-driven extension at the outer shelf to upper slope, which results in development of large growth faults (Figs. 3–5). The slopes of these margins tend to be less rugose with lower degrees of deformation (Figs. 3–5). It is likely that the overall low deformation of these margins results directly from their smaller scale and resultant smaller mass, which has a decreased potential to induce significant gravity-driven deformation.

Clearly the reduced water depth in front of these margins (compared to the high-amplitude ones) favors shelf-edge progradation, because the clinoform foreset heights are smaller, and therefore require less sediment for accretion. The slope length (horizontal distance from shelf-edge to slope toe, typically <30 km) on these margins is within the potential progradational distance of the clinoform during a 1 My time period, and so the space overlying the slope between the shelf-edge and slope toe can be commonly filled within a few hundred ky in rapidly prograding margins and within 1 My in slowly prograding margins. For instance, the slowly prograding Porcupine and Spitsbergen margins (Figs. 2 and 3) have clinoform amplitudes of 250–400 m (undecompacted) and slope angles of 2–4°, which results in an average slope length of ~6 km (3° slope and 325 m amplitude). This value lies within the range of average progradation rates for these margins (5–7 km/My, Table 1), allowing the clinoform to fill the space below and in front of the shelf-edge within ~1 My. As a consequence, moderately deep-water margins have the potential to build extensive shelf-margin topsets (shelf and coastal plain). The West Siberia margin, for example, built a 550 km wide topset in 9 My (Pinous et al., 2001) (for comparison, the cumulative Gulf of Mexico Cenozoic topset width is ~360 km). So moderately deep-water margins can easily develop obvious patterns of progradation akin to the “progradational” (Hedberg, 1970; Ross et al., 1994) or “constructional” (Galloway, 1998) shelf-margin categories even if the progradational rate is low. The Eocene clinoforms of Spitsbergen are the classic outcrop analog for these margins (e.g. see Johannessen and Steel, 2005; Steel et al., 2008).

3.2. Margins with water depths >1000 m

In this category we have included the Gulf of Mexico, Orinoco, Borneo, and North Slope of Alaska margins (Table 1; Figs. 6 and 7). In these margins, progradation rates tend to be <40 km/My (Table 1, Figs. 2 and 7), whereas aggradation rates are in the scale of hundreds m/My and exceptionally up to 2500 m/My. On average, these margins prograde at 20 km/My and aggrade at 700 m/My approximately, and the average of their *P/A* ratios is about 40. We note that in the Gulf of Mexico progradation rates >30 km/My are reached in the Pliocene and Pleistocene for deposodes that are generally <1 My (Fig. 7). The short duration of these events allowed focusing of the shelf-margin progradation and building of a relatively short stretch of shelf-edge (Galloway, 2005). Previous deposodes are longer and the progradation rates are <30 km/My (Figs. 2 and 7).

The relatively high shelf-edge aggradation rate of these margins is a reflection of their potentially high subsidence rates, especially in large-scale growth fault compartments. The weight of the large margin mass causes flexure of the crust and regional subsidence (Winker, 1982; Rowan et al., 2004) reaching areas even in the coastal plain (e.g., see Gulf of Mexico in Galloway and Williams, 1991; and the Orinoco margin in Sydow et al., 2003). Locally, subsidence can be very high in growth-fault depocenters or areas of salt evacuation and rapid shale compaction. In addition, cooling of oceanic crust in distal areas of passive margins leads to hinged subsidence (Rowan et al., 2004). The growth faults commonly occur in the outer shelf to upper slope forming half-bowl depocenters, several tens of kms wide along the shelf-edge. These depocenters can store large sediment volumes due to high local subsidence, decreasing the sediment available for prograding the rest of the margin. For instance, in the growth-faulted Columbus Basin of the Orinoco margin, the Pleistocene progradation and aggradation rates are ~15 m/My and ~2500 m/My respectively (Wood, 2000; Sydow et al., 2003); whereas just eastwards along the shelf-edge in the Plataforma Deltana of Venezuela, extensive growth faulting is rare and progradation rates increase to ~35 km/My whereas aggradation rates decrease to ~1000 m/My. The high aggradation rates in the Borneo margin (1000 m/My) and others also occur in growth faults.

The growth faults are a consequence of the large-scale gravity-driven deformation that affects the margin, which is a consequence of the great margin mass and the presence of weak basal layers (e.g. salt). Gravity-driven deformation results in proximal extension (growth faults) compensated by distal shortening and development of fold and thrust belts in the slope and beyond (Fig. 6). Deformation typically involves gravity gliding (Rowan et al., 2004) or translation of the margin on basal detachments along salt and other evaporites, or shales typically overpressured and undercompacted due to rapid burial (Billoti and Shaw, 2005) (Fig. 6). Deformation can also involve gravity spreading in which the margin collapses and spreads laterally due to its weight and superficial slope (Winker, 1982; Rowan et al., 2004). Coexistence of extension and shortening result in significant margin instability due to local uplift and subsidence, squeezing of diapirs, salt-nappe extrusions, tilting, salt/mud remobilization, etc. (Winker, 1982; Rowan et al., 2004). Therefore, the margin is very prone to failure. For instance, Galloway (2002) interpreted shelf-edge

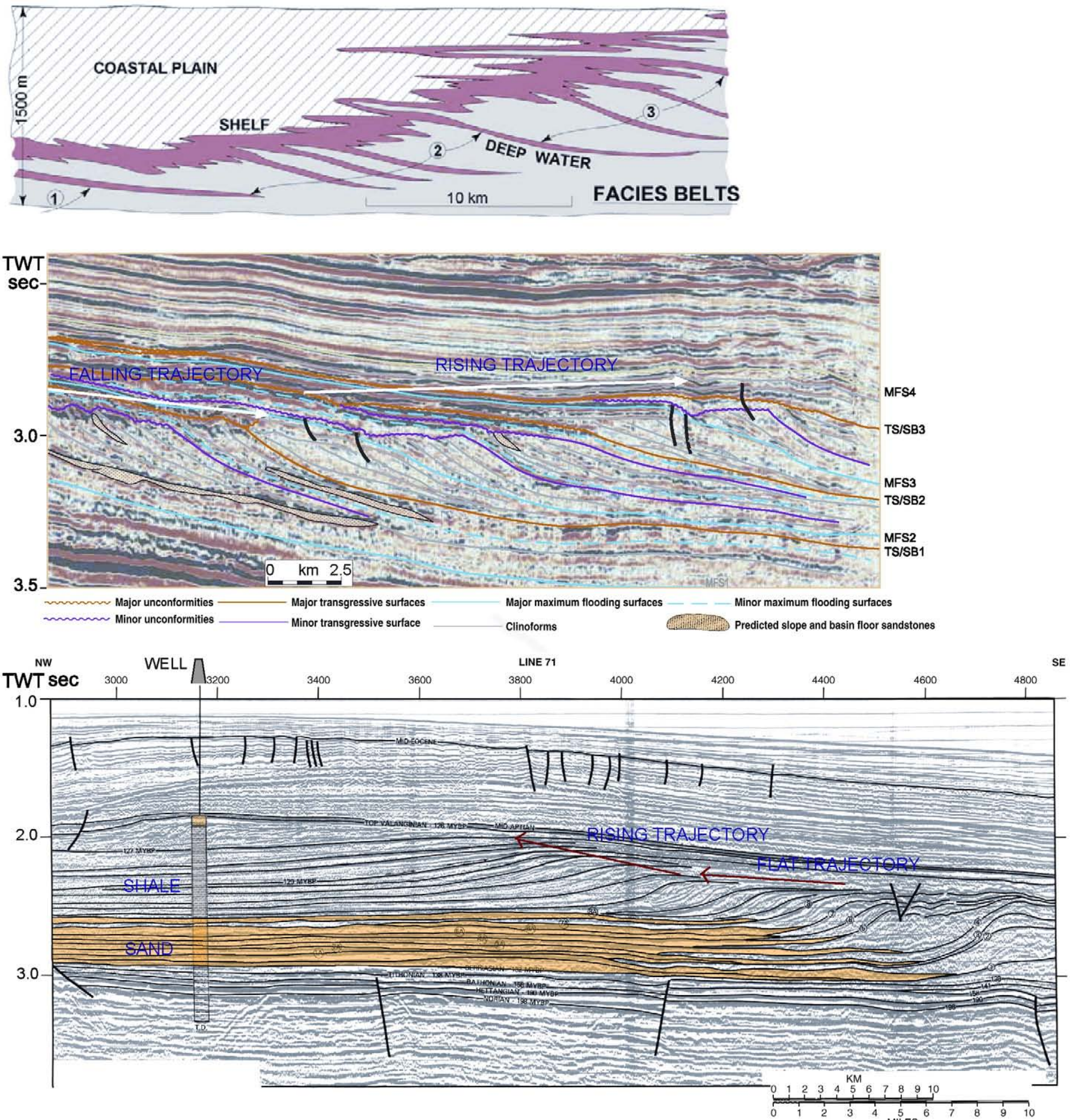

Fig. 3. Three examples of moderately deep-water shelf margins of relatively low to moderate shelf-edge progradation rate: Spitsbergen (above), Porcupine (middle) and Exmouth Plateau (bottom). From Johannessen and Steel (2005) and Erskine and Vail (1987).

retreat of as much as 24 km over an along-shelf-edge distance of 460 km in the north-east Gulf of Mexico (early Pliocene), an area underlain at shallow depths by an extensive and mobile salt canopy. Bypass of the failed sediment to deep-water caused the formation of sand-rich deep-water deposits.

3.3. Accretion rates and shelf-margin architecture

The above-described variability in rates of progradation and aggradation, slope geometry and tendency to failure show that shelf-margin clinoforms fill their basin in very different ways in moderately versus very deep-water margins (Fig. 8). The moderately deep-water margin tends to develop simple, straighter slopes and more progradational architectures with higher *P*/*A* ratios. In the very deep-water margins, maximum water depth is thousands of meters. Therefore, the large space in front of the margin between the shelf-edge and slope toe requires several millions years (in cases > 10 My) to fill, which together with the high aggradation rate results in a lower *P*/*A* ratio and a more aggradational style of clinoform growth across the margin including the slope. In addition, slopes tend to be more

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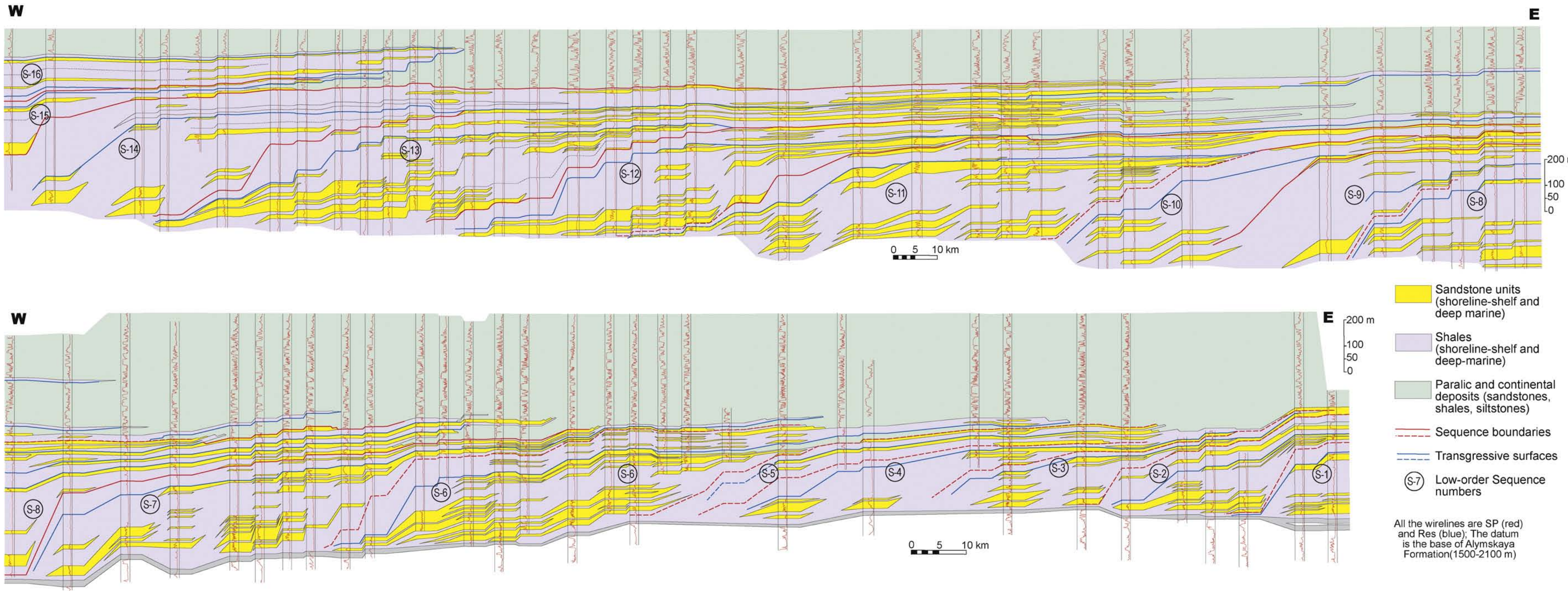

Fig. 4. West Siberia shelf-margin (from Pinous et al., 2001). Contrast the prominent progradation and deep-water fan dimensions with those in Fig. 3.

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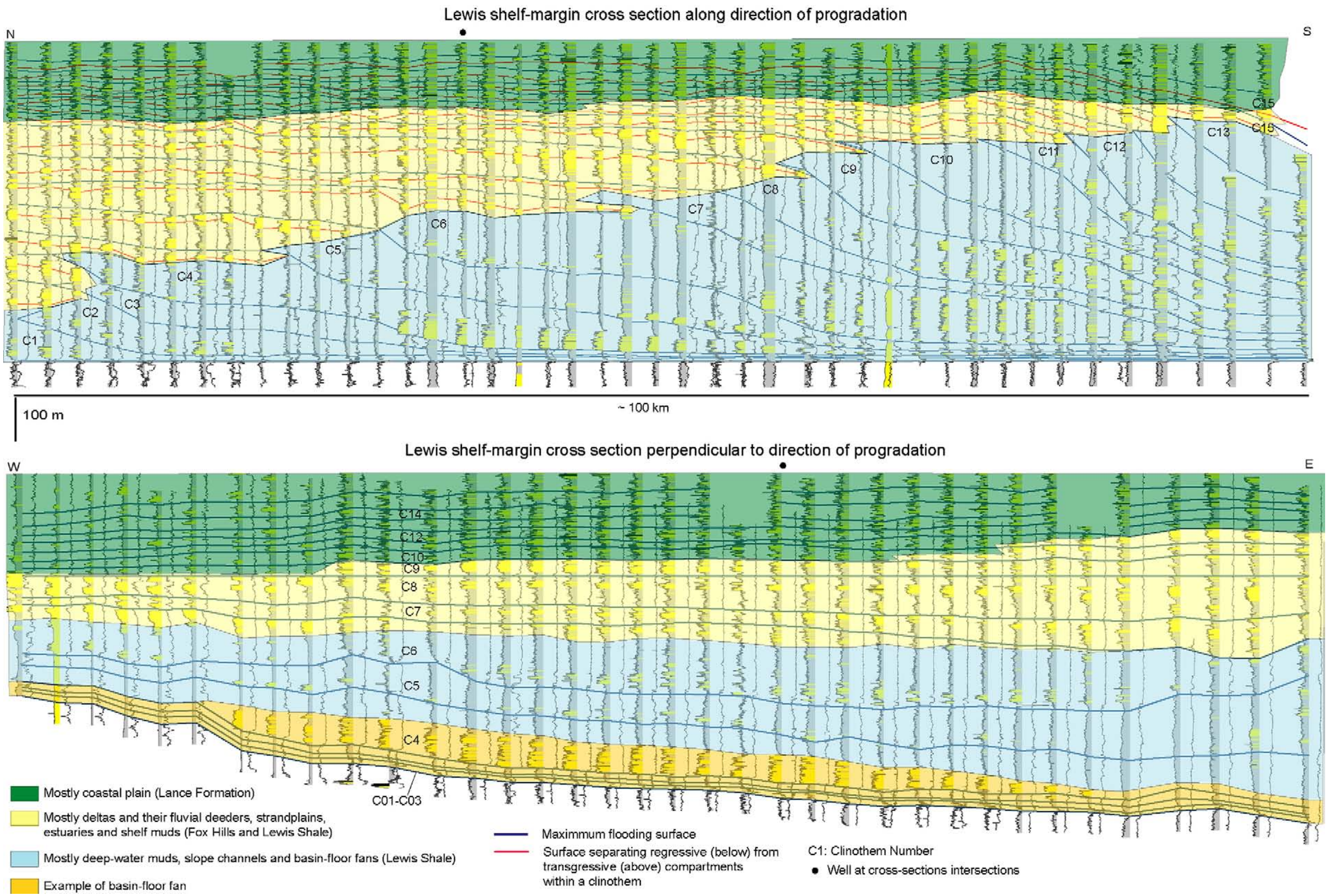

Fig. 5. The Lewis shelf-margin. Time span for progradation is about 1.8 My and undecompacted water depth was some 400–500 m. Contrast the frequency of delivery and dimensions of deep-water sandstones here with the shelf margins in Fig. 3. Style of delivery and progradation of the margin are similar to the West Siberia (Fig. 4). In the bottom diagram increasing thickness to the East is due to increase subsidence rate in this direction.

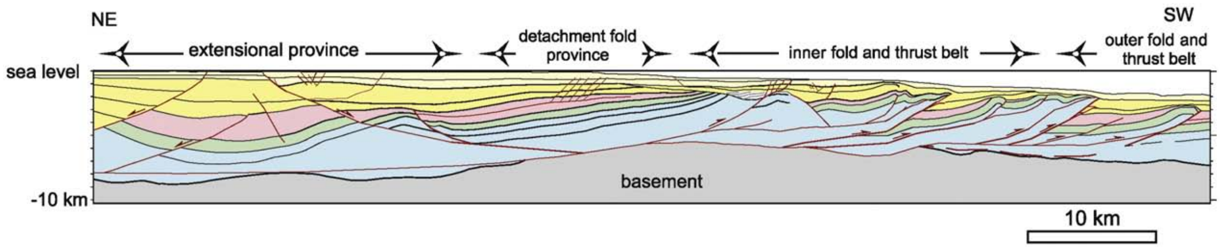

Fig. 6. Example of a very deep-water margin from offshore Nigeria (from Billoti and Shaw, 2005). Gravity-driven deformation induces the development of extensional domains in proximal areas of the margin, and this is compensated by compression in fold and thrust belts that are formed in more distal margin segments. Compare the morphology of this margin with those in Figs. 3–5.

complex and prone-to-failure on very deep-water margins. Therefore, the moderately and very deep-water margins are not scaled versions of each other; they are architecturally different, infill the basin at a different pace and show some significant differences in accretion processes (Fig. 8). To a large degree the observed differences between each margin type arise from the different sediment masses, water depths and the relative importance of shale and salt mobilization. Thus, as water depth and margin mass increase there should be transitional architectures between the two margin types, and therefore we see them as end members of a continuum of morphologies and processes.

4. Do aggradation and progradation rates reflect high/low sediment supply?

The rate at which a shelf-margin progrades and aggrades is a direct result of the volume of sediment supplied, relative sea level changes, and basin dimensions, particularly clinoform amplitude. Therefore, for margins of similar clinoform amplitude and sea-level regime, accretion rates should show some degree of correlation with sediment supply; increasing accretion rates should be linked to increasing supply at least along the segment of the margin under consideration and provided waves, tides and outer shelf currents do not spread sediment along-strike to the extent that progradation rate is severely decreased and supply is underestimated. Redistribution of sediment by waves, as well as high-frequency delta-lobe and sub-lobe shifting (while the larger scale delta complexes cross the shelf) causes the along-strike morphology of the shelf-edge area to be relatively smooth compared to the morphology of the component shorelines. As a result of this, the shelf-edge moves basinwards in a surprisingly even way, at least over strike distances of 100–200 km (Steel et al., 2008; see also shelf-edge maps cited in previous sections).

4.1. Margins with water depths <1000 m

In these margins, high progradation rates correlate reasonably with sediment volume as interpreted simply from infill dimensions. On the West Siberia margin (Fig. 4), the rapidly prograding clinoforms ($P=61$ km/My) filled a basin area (proxy for volume) of some 100,000′s km^2 (total basin area is ~2×10^6 km^2) and built an extensive topset at least ~550 km wide during about 9 My (Pinous et al., 2001). In the Lewis–Fox Hills margin ($P>48$ km/My; Fig. 5), the clinoforms infilled a basin area on the order of 10,000′s km^2 (Hettinger and Roberts, 2005) and built a topset wider than 100 km. In contrast, the slowly accreting margins in the Central Basin of Spitsbergen, Pletmos Basin (South Africa), Porcupine Basin (offshore Ireland) filled basinal areas of only some 100′s km^2 and built platforms typically <60 km wide (Fig. 3). These slowly accreting margins remained active for a time interval shorter than the West Siberia margin, but even if their life had been longer they would not have reached the infill dimensions of West Siberia (other variables remaining the same); the supplied sediment volumes in West Siberia were simply very large. Notice also that the duration of the Lewis–Fox Hills margin building was <2 My, i.e., a shorter life span than all the other margins, but its infill dimensions are still greater than in the slowly accreting margins. On the Lewis margin the high sediment flux was due to uplift in the Wind River Range, Granite Mountains, and Rawlins Uplift area (Reynolds, 1976; Steidtmann and Middleton, 1991; Connor, 1992; Carvajal, 2007; Pyles and Slatt, 2007), whereas in West Siberia the large supply was likely due to a very large drainage area sourced in the East Siberian Highlands and the Urals (Pinous et al., 2001), although it is not clear how much uplift was involved. In the next sections, we describe the associated deep-water fans which provide further evidence supporting the relatively high volumes of sediment in the Lewis and West Siberia margins. Thus, in the study cases high rates of progradation correlate with high volumes of supplied sediment and vice versa.

This correlation seems to apply when different sequences are compared within the same basin. For example, increasing rates of progradation and aggradation on the New Jersey margin correlate with increased rates of sediment supply (Fig. 9). Steckler et al. (1999) calculated rates of sediment supply from the cross-sectional areas of Eocene through middle Miocene sequences using a well-placed, representative cross-section, and determined that supply increased from a few m^2/y in the Eocene to about 40 m^2/y in the Middle Miocene. During the Oligocene, supply was 1.5 m^2/y and the shelf-margin prograded at a rate of ~1 km/My and aggraded at a rate ~12 m/My. In the Early Miocene, supply rose to ca. 5 m^2/y, and the shelf-margin progradation and aggradation rates increased to ~5 km/My and 15 m/My, respectively. During the Middle Miocene (16.6–13.1 My), supply increased to rates between 10 and 40 m^2/y and progradation rates increased to ~17 km/My and aggradation rates to 43 m/My. Thus, it is clear that increases in supply correlate with increases in accretion rate on this margin. Although the analysis does not take into account the volume of sediment, if any, that may have bypassed the clinoform entirely, the New Jersey margin data, at least along the profile under consideration, suggest that increased accretion rates reflect an increase in the volume of supplied sediment with time.

4.2. Margins with water depths >1000 m

The Gulf of Mexico is an appropriate example of this margin type and some data from this margin suggest that maximum progradation rate may correlate with sediment supply (Fig. 9). For instance, Galloway (2001) showed that for deltaic and shorezone systems on the shelf, volumetric-accumulation rates: 1) were relatively large (~5–7$\times10^4$ km^3/My) during the growth of the Upper Paleocene (Lower Wilcox) and the Oligocene (Frio-Vicksburg) which show maximum progradation rates of 16–20 to 20–30 km/My respectively (Figs. 2, 7 and 9); 2) were moderate (3–5$\times10^4$ km^3/My) during the growth of Miocene shelf margins (LM1, LM2, MM, and UM deposodes), which show maximum progradation rates of 8–12 to 16–20 km/My (Figs. 2, 7 and 9); and 3) were relatively low (<3$\times10^4$ km^3/My) during the development of uppermost Paleocene

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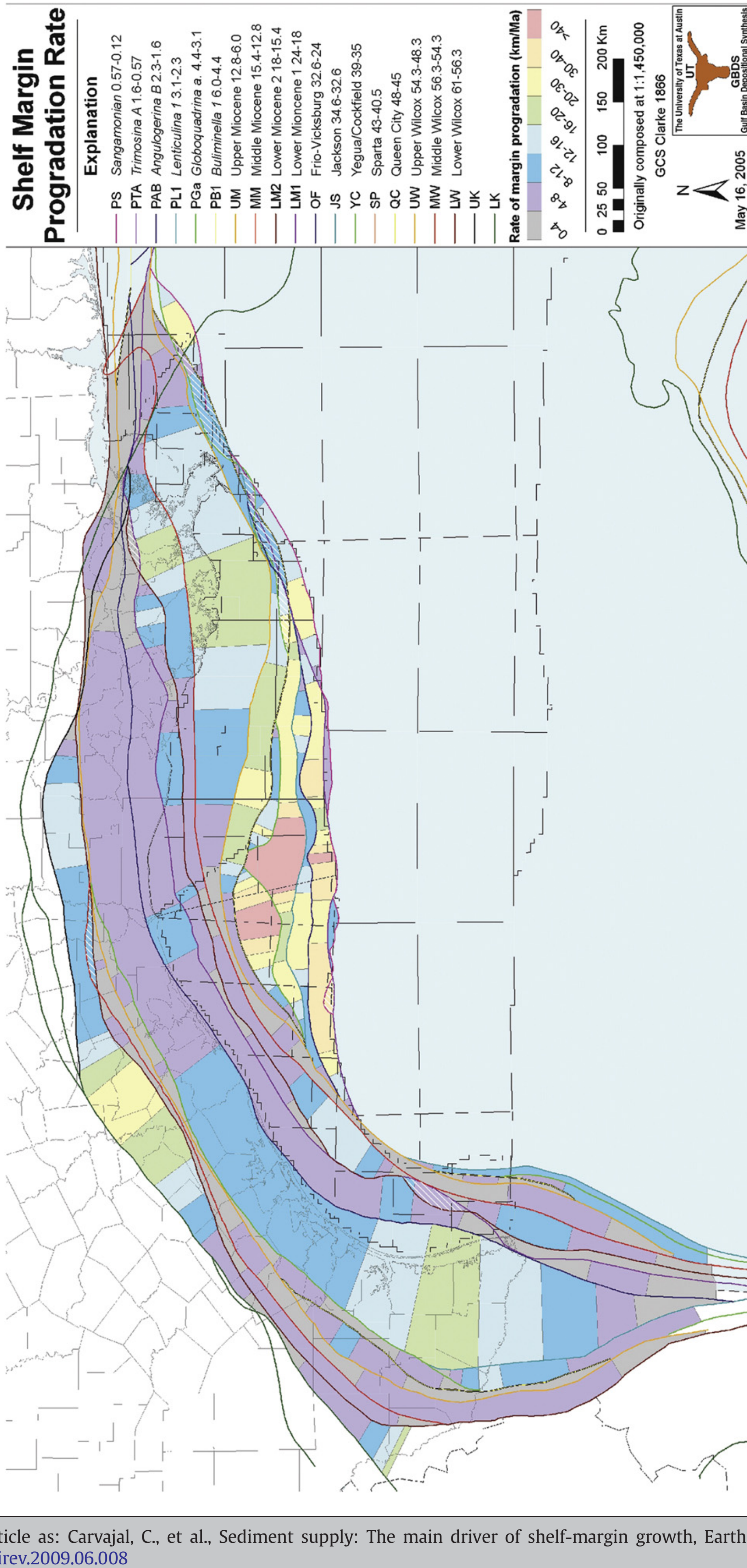

Fig. 7. Map showing variability of progradation rate of the shelf-edge for the Gulf of Mexico margin during different deposodes (figure courtesy of William Galloway from The University of Texas at Austin).

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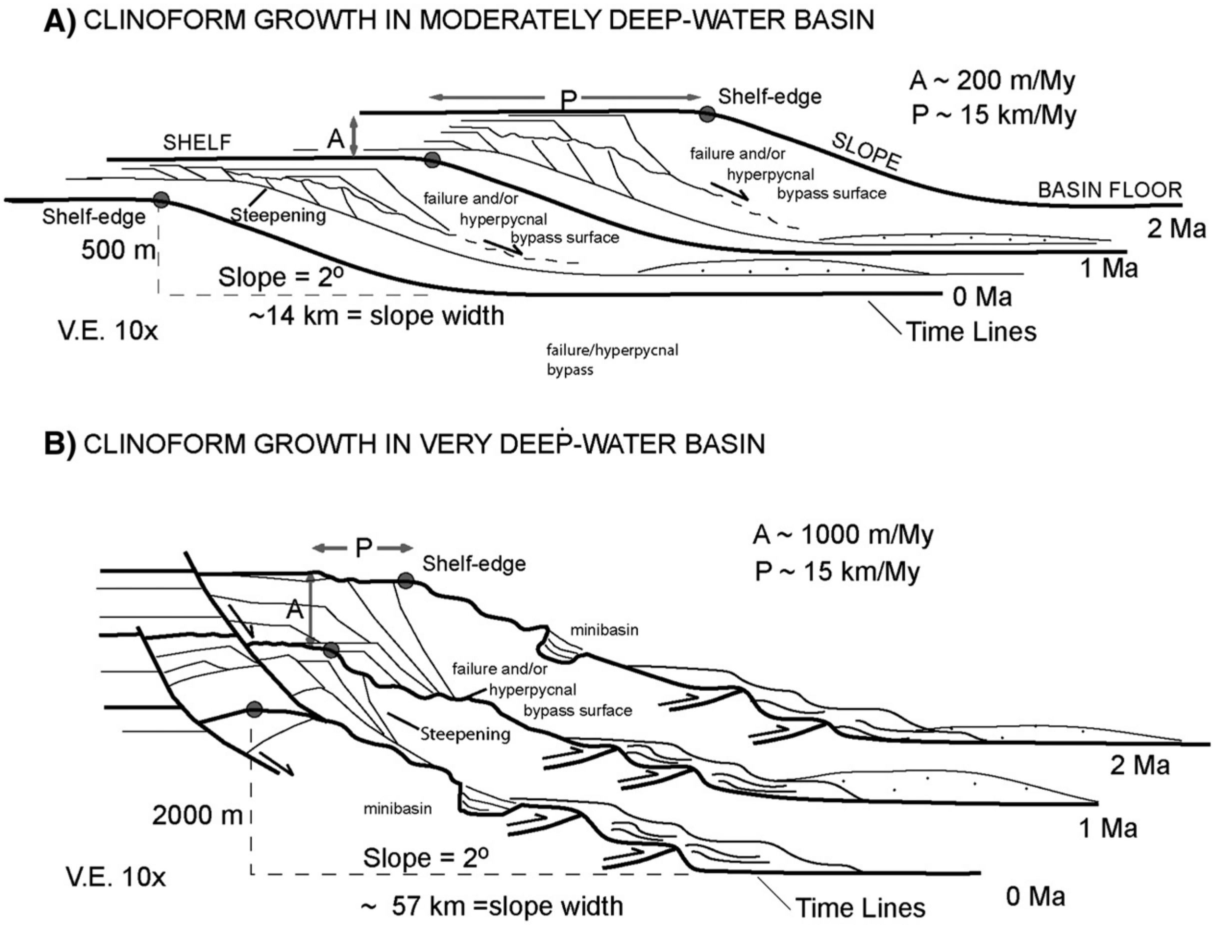

Fig. 8. Styles of clinoform growth in moderately and very deep-water margins. To illustrate architecture rather than dimensions, diagrams are at different scales, but the vertical exaggeration is similar. Both architectures are likely end members of a continuum of margin morphologies that develop as water depth and margin mass increase and there are basal weak layers (e.g. salt).

(Middle Wilcox) and Eocene margins (Upper Wilcox, Queen City, Sparta, Yegua/Cockfield, and Jackson deposodes) which show, in general, maximum progradation rates of 0–4 to 4–8 km/My (Figs. 2, 7 and 9). In the last case, the exception to the trend is the Jackson deposode which shows an anomalously high maximum progradation rate of 12–16 km/My, but we note that this rate was achieved in a relatively narrow stretch of the shelf-edge (<25 km), and also that the shelf-edge during Jackson time did not prograde over a wide area (Fig. 7). To account for this problem, Galloway (2005) compared the growth rate of the platform generated by shelf-edge progradation (i.e. not just maximum progradation) with the volume accumulation rate of sediment in shorezone and deltaic sediments, and the comparison validated the described trend. Therefore, there seems to be a trend in the Gulf of Mexico in which maximum progradation rates tend to be linked to higher volumes supplied to deltaic and shorezone systems. These higher volumes most likely point to higher total sediment volumes because the main source-land uplift events influencing the sediment flux to the Gulf of Mexico (Crabaugh and Elsik, 2000) date to Upper Paleocene, Oligocene and Miocene, when the shorezone and deltaic volumes, and maximum progradation rates are high to moderate. In the Late Paleocene, major segments of the Rocky Mountains were actively uplifted during the Laramide Orogeny (Dickinson et al., 1988; DeCelles, 2004), while the Eocene records the gradual decline of this mountain building event. Beginning in the Late Eocene but escalating markedly in the Oligocene, intense volcanism and uplift in Mexico (Dickinson, 2004; Jicha et al., 2009) and the southern United States (Lipman, 2007) drove a sharp increase in sediment supply relative to the Eocene. The Late Eocene and Oligocene Yegua/Cockfield and Frio sandstones show an increased content of volcanic clastics (Galloway et al., 2000), and the Frio deposode (Oligocene) records vigorous growth of the Gulf Mexico margin over a wide area (Fig. 7). During the Miocene, uplift of the Edwards, S. Appalachian and Cumberland Plateaus provided a continued but declining supply of sediment to accrete the margin (Galloway et al., 2000; Galloway, 2005).

5. Accretion rates and deep-water sedimentation

5.1. Margins with water depths <1000 m

In margins with water depths <1000 m, there are sharp differences between rapidly prograding margins (Figs. 4 and 5); and slowly prograding margins (Fig. 3) as regards their ability to bypass sand to deep-water (Fig. 10). A common theme on the West Siberia and Fox Hills margins (Figs. 4 and 5) is the recurrent and abundant delivery of sand to deep-water fans. In West Siberia, Pinous et al. (2001) have interpreted 16 clinoformed sequences during a 9 My time span, averaging ~0.6 My per sequence (Fig. 4). Almost all of these sequences contain abundant sandstones on the slope and basin floor. Common intervening shales separating deep-water sandstones suggested to Pinous et al. (2001) that delivery may have occurred even during shorter sea-level cycles (though no evidence is presented for such high-frequency cycles during Greenhouse times). The deep-water sandbodies frequently reach thicknesses greater than 100 m within

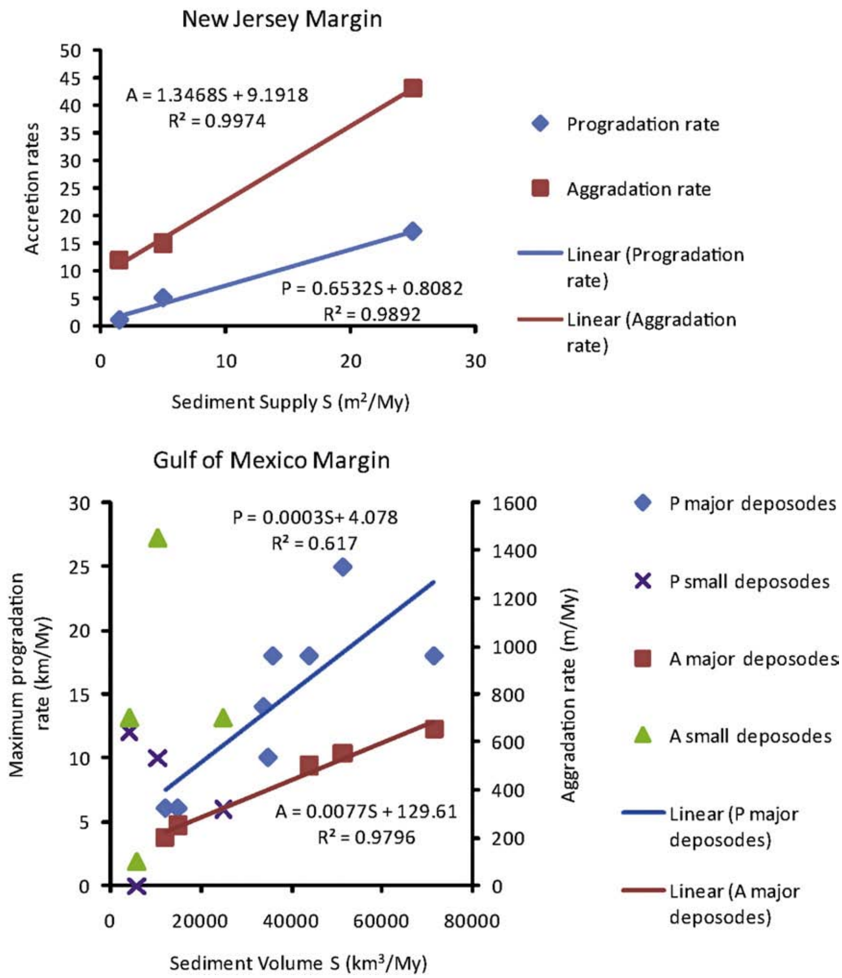

Fig. 9. Plots of progradation and aggradation rates versus sediment supply. Data in the charts are from Table 1 and Fig. 7. In the Gulf of Mexico, the median value of the maximum progradation range was used (Fig. 7). Major deposodes are the Wilcox (LW, MW, and UW), Frio (OF) and Miocene (LM1, LM2, MM, and UM) margins, and small deposodes are the Eocene margins (QC, SP, YC, and JS). Both plots show increasing supply with increasing accretion rates, albeit small deposodes in the Gulf of Mexico deviate from the trendlines.

individual sequences. In the lowstand systems tract (excluding the prograding wedge) of one of these sequences (~0.6–0.7 My), basin-floor and slope sand deposits cover map areas of a few thousands of km^2 (Pinous et al., 1999) (Fig. 10). Notably, in West Siberia, there are significant amounts of deep-water sand on both the slope and basin floor that are linked to shelf-edge deltas interpreted as lowstand prograding wedges; i.e., sands that were bypassed to the basin floor when sea level was not falling, but was at stillstand or rising slowly (Pinous et al., 1999). It is also notable that sand was bypassed to deep-water areas during transgression, albeit in apparently very small volumes. Similarly, Carvajal and Steel (2006, 2009) have interpreted 15 cycles of basin infill in the Lewis shelf-margin sedimentary prism, during a 1.8 My period, averaging ~120 ky per cycle (Fig. 5). During each of these cycles there was bypass of relatively large volumes of sand to the deep-water slope and basin floor. Maximum thickness of sandbodies in the cycles of the Lewis–Fox Hills margin range from 50 to 120 m with areal extents of 1400–2600 km^2 (Figs. 5 and 10). Slope sandstones in the Lewis form channel belts that can reach tens of kilometers of width (Fig. 4). Furthermore, some cycles in the Lewis–Fox Hills margin show flat shelf-edge trajectories, indicating that delivery of sand happened during falling or lowstand of relative sea level. Other cycles exhibit steeply rising shelf-edge trajectories, indicating that sand delivery occurred during highstand (Carvajal and Steel, 2006). Therefore, both the Lewis and West Siberia margins provide clear examples of high-volume, recurrent (i.e., in successive cycles of duration <hundreds ky) delivery of deep-water sand during both falling and rising relative sea level. These trends, along with the high progradation rates of the margins (Fig. 10), further support a relatively larger sediment influx to the basin.

These characteristics contrast with what is observed in slowly prograding margins (Figs. 3 and 10) as documented at present mainly through public literature. For instance, the Spitsbergen fans are less than 50–60 m thick (Crabaugh and Steel, 2004; Fig. 3). Fan area in the Porcupine margin is <200 km^2, though maximum thickness can reach 240-280 m (Johannessen and Steel, 2005; Ryan et al., 2009; Fig. 10) and in Spitsbergen maximum fan length (along the exposed cross-section) is <10–12 km (Crabaugh and Steel, 2004; Fig. 4). The deep-water setting on the very slowly accreting Nova Scotia margin (Cretaceous) is relatively muddy and exploration for large sandy fans has been so far disappointing (J. Gjelberg, Norsk Hydro, pers. comm. 2006). Fan area in the Pletmos Basin is ca.150 km^2 and if the "slope fan" is included it may reach ~300 km^2 (Brink et al., 1993). It should be noted that in the Pletmos margin (moderate progradation rate of ~14 km/My), sand bypass to deep-water areas was recurrent (i.e. fans occur successively in cycles with a duration of ca. few hundred ky). Similarly on the New Jersey margin, reported fan thickness is 15–75 m in sequences that generally span 1–3 My (Greenlee et al., 1992). The area of these fans is not provided, but isochron maps of strata packages that are ~0.35 to 1.2 My in duration (Poulsen et al., 1998) suggest that areally they are probably smaller than several hundreds of km^2. For comparison, cycles of ~120 ky duration in the Lewis margin contain sand-rich fans that are nearly 120 m thick and 2500 km^2; if longer time periods are considered on the Lewis margin, the fan complexes' combined thickness and area

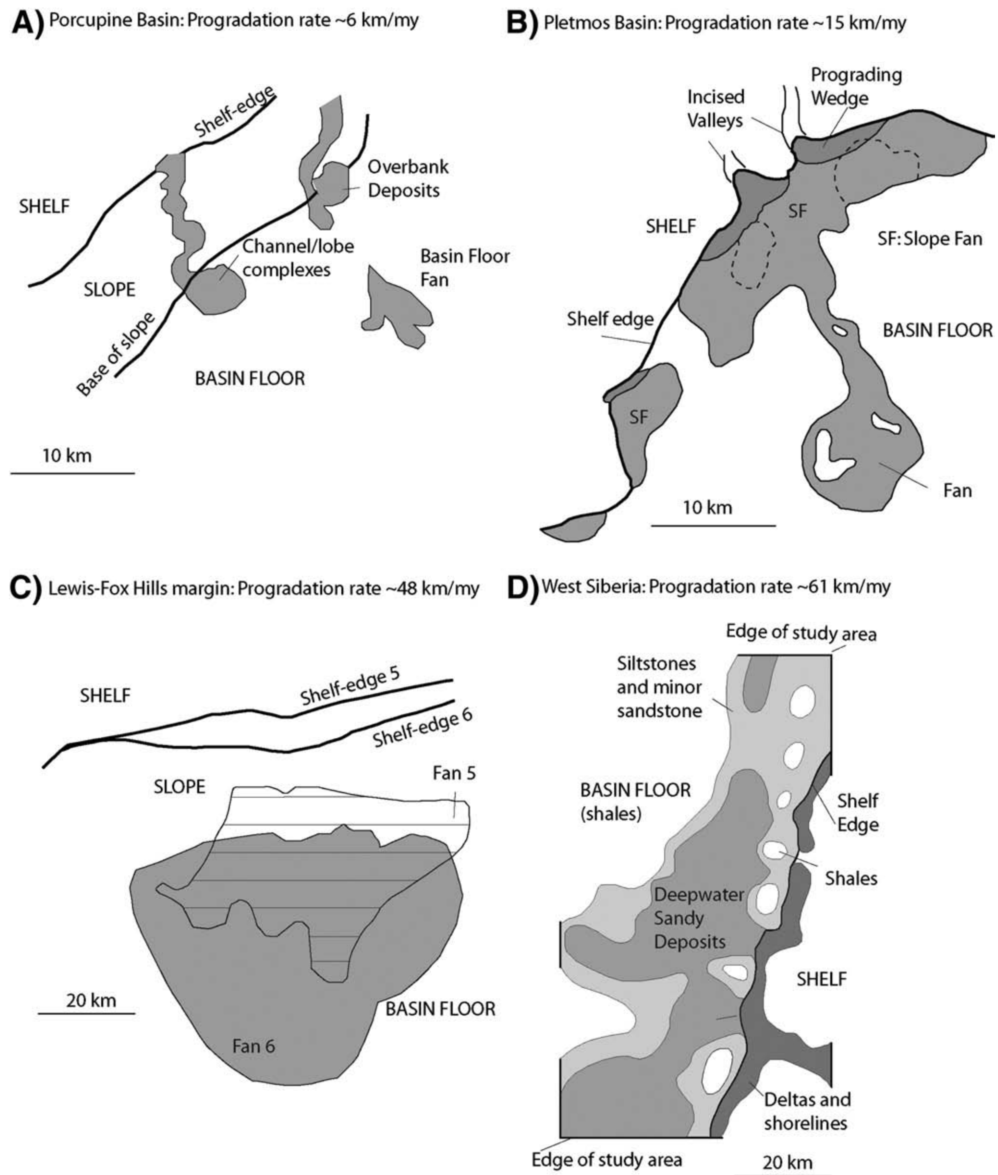

Fig. 10. Deep-water fan areas versus shelf-edge progradation rate for different moderately deep-water shelf margins. The very rapidly prograding West Siberia and Lewis margins have greater fan areas and also thicker fans indicating larger deep-water volumes (notice different scales in the maps) (compiled from Johannessen and Steel (2005; Porcupine), Brink et al. (1993; Pletmos), Carvajal and Steel (2006; Lewis), and Pinous et al. (1999; West Siberia)).

would reach hundreds of m and at least a few thousands km^2 respectively (i.e. an order of magnitude larger than the fan dimensions in the Pletmos and New Jersey margins). Therefore, the relatively small volumes of deep-water sand support an interpretation of low supply in the margins with low progradation rates.

In addition, most of the sand bypass to deep-water areas in these slowly prograding margins is interpreted to have taken place at sea-level lowstand. This is confirmed by the case of Clinoform 17 in Spitsbergen which shows highstand shelf-edge deltas but no associated deep-water sands (Uroza and Steel, 2008) whereas Clinoform 14 shows lowstand shelf-edge deltas with an associated sand-rich basin-floor fan. The low supply rates would have been unable to compete with rising sea-level at highstand to both position the deltas at the shelf-edge and deliver deep-water sands. Consequently, falling sea level seems to be required to drive the delivery of sand to deep-water areas in these slowly accreting margins. Porębski and Steel (2006) referred to the delivery deltas in such cases as accommodation-driven deltas, in contrast to the supply-driven ones that are able to deliver at sea-level highstands. In summary, in the selected moderately deep margins, increasing progradation rates are linked to 1) increasing sediment supply, 2) larger volumes of sand on deep-water areas, and 3) higher potential of deep-water sand bypass during sea-level highstand.

5.2. Margins with water depths >1000 m

The Gulf of Mexico (GOM) is the most researched of the very deep-water margins and provides the best case study. In the Gulf of Mexico, the largest deep-water accumulations occurred during the Late Paleocene to earliest Eocene (Wilcox deposodes), during the Oligocene (Frio Formation) and during the Miocene (and especially in the lower Miocene), when the GOM margin shows moderate to high maximum progradation rates (Galloway et al., 2000; Table 1, Figs. 2, 7, and 12). The presence of abundant deep-water deposits at these times further supports a linked large sediment supply at the same times, which is also consistent with coeval active uplift and/or volcanism in the continent during such periods (Dickinson et al., 1988; Galloway et al., 2000; Dickinson, 2004; Lipman, 2007; Jicha et al., 2009). Therefore, for very deep-water margins, increased progradation rates also tend to be linked to increased sediment influx and

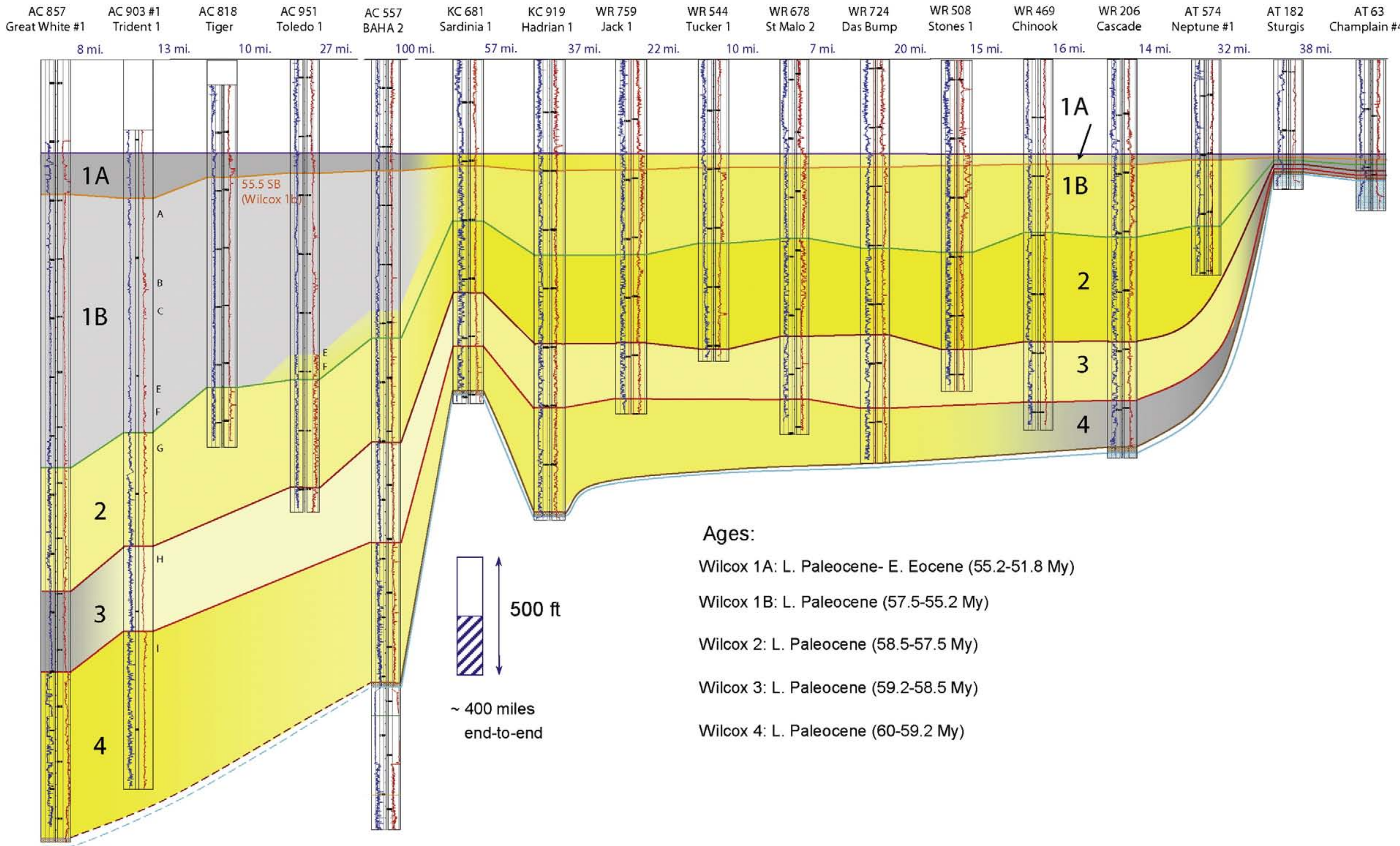

Fig. 11. Cross-section through the Wilcox deep-water systems on the Gulf of Mexico slope and basin floor (see Fig. 12 for location) (from Zarra, 2007). Most of the section is on the basin floor but the thickening of shale strata to the west (gray color of Wilcox 1A and 1B) suggest this part of the section reaches the slope. The stratigraphic datum on top of Wilcox interval causes the artificial dip to the west, which does not represent the progradation direction of the margin that was mainly south to south-east (see Fig. 7).

increasing volumes of sediment being supplied to deep-water. Unfortunately, there is not enough data in the literature to evaluate with confidence the relative volumes of the deep-water accumulations. The basin-floor systems of the Wilcox deposodes are a serious candidate for some of the very largest, to judge from the abundant turbidites in deep-water well-log cross-sections that extend for hundreds of kilometers across the basin floor (Zarra, 2007; Fig. 11). Although the Frio deposode may not contain as much basin-floor sand as the Wilcox, it records margin progradation over a stretch >1500 km (Fig. 7) along the Gulf Coast. Margin accretion across such a distance requires the storage of large volumes in the slope. The Miocene (and especially the Lower Miocene) seems to have abundant sand in both slope and basin-floor systems. More data is needed to evaluate which deposodes contain the largest deep-water sandstones; despite this uncertainty, the data do suggest that the largest deep-water volumes occur when the supply and the progradation rates are moderate (8–12 to 12–16 My) to high (16–20 to 20–30 My).

The Wilcox deposodes provide additional data on deep-water sandstone distribution and its relationship to progradation of the approximately contemporaneous margin (Figs. 11 and 12). The deep-water Wilcox has been divided into 4 informal units, Wilcox 1–4 (younger to older) (Zarra, 2007). As presently correlated and dated (Zarra, 2007), the Wilcox 2–4 strata have a combined thickness of <670 m (Hadrian Well, basin floor, Fig. 11) and were deposited between

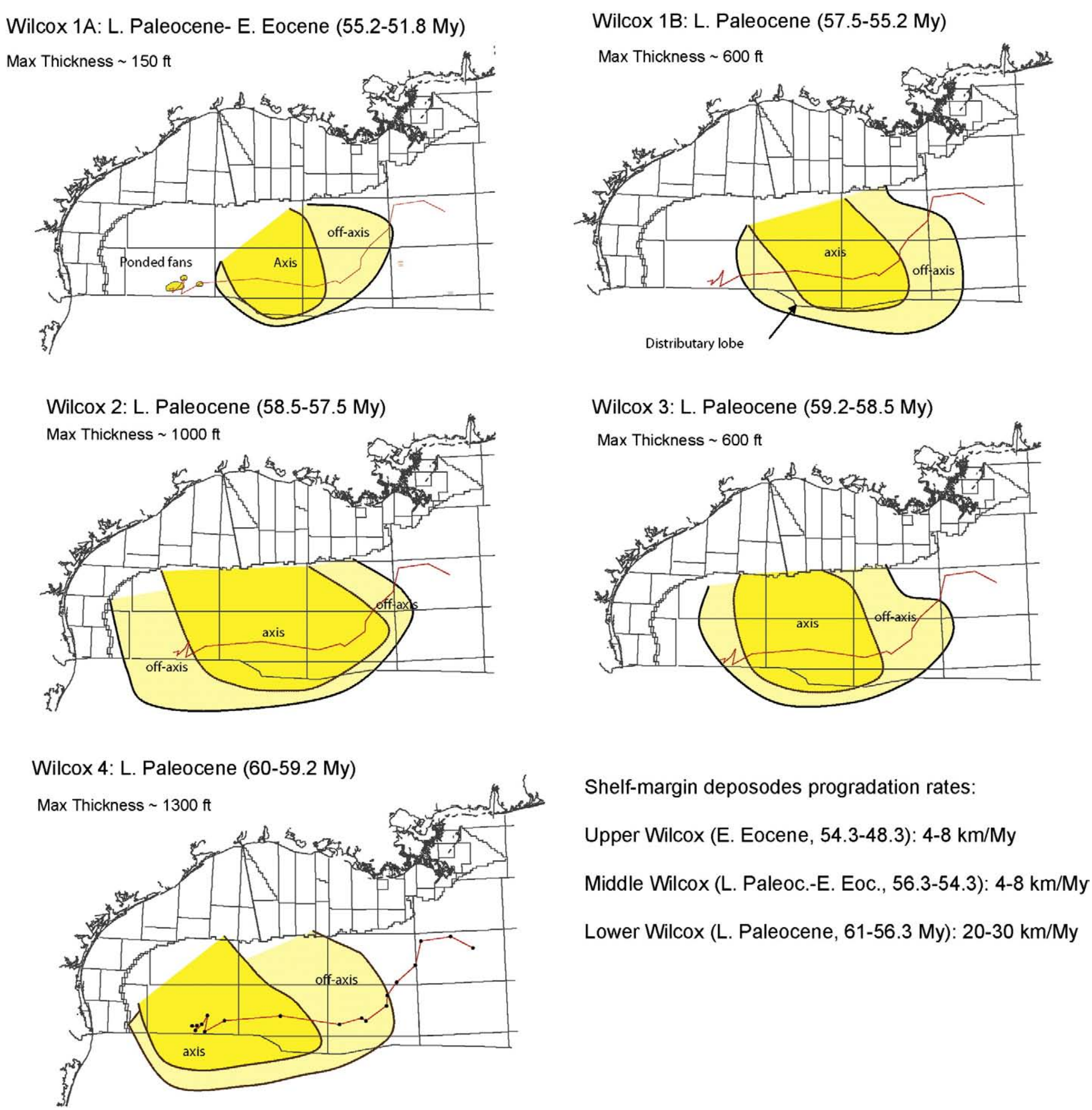

Fig. 12. Inferred deep-water sandstone distribution for the Wilcox fans (modified from Zarra, 2007). The decreasing areas and thickness (Fig. 11) from Wilcox 2 to 1B and 1A point to decreasing fan volumes, which correlates with decreasing rates of shelf-margin growth and suggest diminishing sediment supply (maximum thicknesses are from deep-water fan systems, not from slope shales; see Fig. 11). However, lack of enough well control adds uncertainty to fan area and geometry interpretation, which should be considered preliminary.

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60 and 57.5 My, roughly equivalent to the Lower Wilcox deposode (61–56.3 My) when the shelf-edge prograded at a maximum rate of 20–30 km/My (Figs. 7 and 11). The combined thickness of the Wilcox 1A–1B units is <260 m (Hadrian Well, basin floor) and their age is 57.5–51.8 My (Fig. 11). This time span is approximately contained within the Middle and Upper Wilcox deposodes (56.3–48.3 My) when the margin prograded at maximum rates <4–8 km/My (Fig. 7). Therefore, total fan thickness decreases in conjunction with maximum progradation rates from Wilcox 2–4 to Wilcox 1. The interpreted planform of the fans exhibits a similar pattern (Fig. 12) of decreasing areal extent from the Wilcox 2–4 to Wilcox 1 suggesting that fan volume decreased over this time span. However, limited well control increases the uncertainty of fan extent interpretation, which should be considered preliminary. The decreases in progradation rate and inferred fan volumes through the Wilcox deposodes clearly suggest a decreasing sediment supply. This most likely reflects decreased rates of Laramide uplift (from the early Eocene, Dickinson et al., 1988) in the Rocky mountain region, the main sediment catchment area for the Wilcox systems.

Other cases also indicate that the deep-water sand volumes decreased during times of lower shelf-margin progradation rates, sometimes also coupled with high aggradation. In offshore eastern Borneo (East Kalimantan), the shelf-edge did not prograde during the latest two Pleistocene glacioeustatic lowstands (~18 and ~130 ky) and no sand is found in the deep-water areas through these two cycles (~100 m) (Saller et al., 2004). Low supply and high subsidence likely kept deltas on the outer shelf so that they did not reach the shelf-edge. Similarly deltas did not reach the shelf-edge during the Sparta deposode in the Gulf of Mexico. Shelf-edge progradation did not occur, and the cycle is sediment-starved in the deep-water. Other Eocene Gulf of Mexico deposodes (Queen City, Yegua/Cockfield, and Jackson) are quite aggradational (>500 m/My, Fig. 2) and have moderate to low maximum progradation rates (8–12 km/My) (Feng, 1995; Galloway et al., 2000). All three deposodes seem to have small deep-water volumes compared to those in the Late Paleocene, Oligocene and Miocene. The Queen City deposode experienced much deep-water sediment starvation and the shelf-edge prograded only by addition of prodelta muds. As pointed out above, the Jackson deposode is an exception to this trend in that it progrades at 12–16 km/My, but developed small deep-water sediment accumulations. However, margin accretion occurs over a short shelf-edge distance and the topset did not grow much at all. The north-western Borneo margin also shows low progradation rates (about 5–12 km/My; Table 1) and relatively high aggradation rates (500–1350 m/My) during the Pliocene and Pleistocene and the margin is built significantly by prodelta muds and contains much storage of sediment in growth fault compartments. However, turbidites have been found in the outer neritic to bathyal reaches of the system and it is postulated that sand may have bypassed to deep-water areas at sea-level lowstand (Koopman and Schreurs, 1996; Saller and Blake, 2003), though the quantity of sand is unknown. In the Columbus Basin of the Orinoco margin, the Pleistocene stacking is extremely aggradational (~2500 m/My), and shelf-edge/upper slope failure has led to some bypass of sediment to deep-water areas (Moscardelli et al., 2006). At least one modern fan presently exists on the Orinoco basin floor (the “Orinoco Fan”, Belderson et al., 1984), but the volume of this fan and its complete relationship to the margin is unknown. The Gulf of Mexico and Borneo data suggest that high aggradation and low progradation rates may reflect increased storage of sediment on the shelf and reduced sediment bypass to deep-water (Fig. 13).

5.3. Rationale for the use of progradation rates: importance of shelf-edge deltas, margin growth processes, and sediment budget partitioning

The reviewed cases demonstrate that shelf-edge deltas and associated strandplains are very good (and perhaps the main) drivers of shelf-margin accretion (Suter and Berryhill, 1985; Galloway, 2001; Porębski and Steel, 2003; Steel et al., 2008). Shelf-edge deltas have been documented in outcrop (e.g. in Spitsbergen and Fox Hills margins) with typical upward-coarsening and -thickening clinoformed rock successions fed by fluvial channels. Outer shelf and shelf-edge deltas and strandplains can be identified on well logs (e.g. Orinoco, West Siberia, Fox Hills, Gulf of Mexico margins) through their well-developed funnel-shaped motifs that indicate progradation over condensed sections. High resolution seismic data (e.g. shallow seismic data sets) commonly image clinoform reflection sets dipping toward the shelf-edge which are interpreted as shelf-edge deltas (Deptuck et al., 2008). Although there are cases where longshore drift takes marine sediment far from the original deltaic supply fairway, in most cases where waves, tides and ocean currents rework marine sediments they are still retained on the same margin and contribute to build it, albeit laterally from their original supply fairway. In addition, besides deltaic accretion, other processes may prograde the shelf-margin but they are rare and less effective, and produce significantly lower rates of accretion. For instance, contour currents in the Miocene Canterbury Basin, offshore New Zealand, caused shelf-margin accretion but with modest progradation rates <2–3 km/My (Lu et al., 2003).

The importance of shelf-edge progradation driven by shelf-edge deltas is that in the long-term it results in coeval growth of both the slope and basin floor with concurrent deep-water sand deposition. All the cross-sections used in this review show that in the longer term (>1–2 My), the shelf-edge, slope, and basin floor accrete as a linked depositional unit. The “failure-bypass-healing” shelf-margin growth style (Hedberg, 1970; Ross et al., 1994), implicit in sequence stratigraphic models (Posamentier and Vail, 1988; Kolla, 1993; Weimer and Slatt, 2004, p. 7–23) and interpreted to be common in the Gulf of Mexico (Kolla and Perlmutter, 1993; Galloway, 1998; Edwards, 2000) as well as Indonesia, Nigeria, Trinidad, and other margins (see Posamentier and Kolla, 2003; Moscardelli and Wood, 2008; Wild et al., 2009), postulates that bypass of sediment to deep-water, and thus growth of the slope and basin floor, is preceded and driven by failure of sediments accumulated at the shelf-edge in fluvio-deltaic systems. Failure-triggering mechanisms include shelf-edge to upper slope over-steepening, rapid sedimentation, salt or shale evacuation, methane-hydrate dissolution etc. The removal of failed sediment may lead to subsequent rebound of the shelf-edge area (Edwards, 2000; Blum et al., 2008). The failure-space created at the shelf-edge is infilled or “healed” sometime after bypass and so the complete margin is built. More recently, several researchers have proposed that hyperpycnal flows can also build the slope and basin floor (Piper et al., 1999; Piper and Normark, 2001; Plink-Björklund et al., 2001; Mellere et al., 2002; Mulder et al., 2003; Posamentier and Kolla, 2003; Plink-Björklund and Steel, 2004; Petter and Steel, 2006; Gerber et al., 2008; Soyinka and Slatt, 2008; Steel et al., 2008). In this case, there is no major failure of the shelf-edge (though pre-existing mouth-bars are likely to be washed out during flood) and river-sediment discharge directly bypasses the shelf-edge and ignites turbidity currents that feed sediment to the deep-water areas beyond. The flows may accrete the entire slope without basin-floor deposition (more likely in moderately deep-water margins, see clinothem type 2 in Plink-Björklund et al., 2001; Mellere et al., 2002), or they may trigger sediment bypass to the basin floor too. A final phase of shelf-edge delta progradation typically follows bypass (Plink-Björklund et al., 2001; Mellere et al., 2002; Posamentier and Kolla, 2003; Petter and Steel, 2006; Steel et al., 2008). During forced regression the shelf-edge can also accrete. Despite their differences in processes, timing and resulting architecture, the “failure” and “hyperpycnal” mechanisms (that may alternate or be contemporaneous during shelf-margin evolution) emphasize that over the long-term (>1 My) the shelf-edge does not prograde in isolation. Rather the lower slope and basin floor, the foundation of the shelf-margin, has to be built in conjunction with the shelf-edge. This coupled growth explains our observations that increasing shelf progradation tends to be linked to larger volumes of sediment in deep-water.

Furthermore, it seems that most of the marine-sediment volume is stored in deep-water compartments. In the Lewis shelf-margin, the

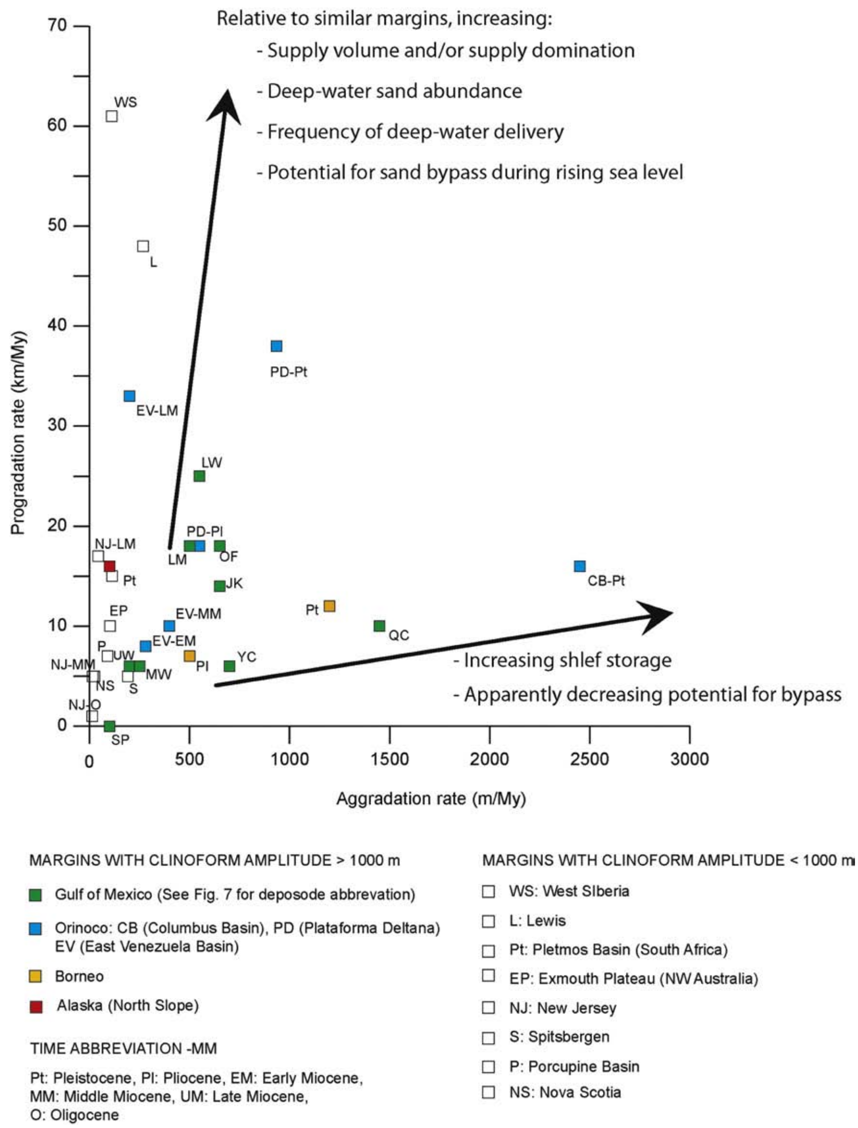

Fig. 13. Progradation rates and inferred trends for sediment supply and deep-water sandstone volumes.

sediment volume proportion in the slope and basin floor is >70% of the marine budget (at times close to 80%) (Carvajal, 2007) whereas in the Gulf of Mexico this fraction averages about two thirds of total volume (Galloway et al., 2009). Our own measures of cross-sectional area in the Spitsbergen and West Siberia margins also seem to indicate greater storage of marine sediment in deep-water compartments over the long term (Fig. 3). This proportionally higher partitioning into deep-water compartments makes sense in the light of our accretion rates (Table 1, Fig. 2), which show that the shelf and shelf-edge aggrade on the order of tens to hundreds m/My (locally few km/My in growth faults); whereas the shelf-edge progrades one to three orders of magnitude faster (a few to several tens of km/My) (Table 1 and Fig. 2). Such a relationship necessitates a greater fraction of sediment storage basinward of the shelf-edge. In principle, therefore, sediment budget partitioning provides a reasonable explanation as to why increased margin progradation rates should reflect increasing sediment supply, when comparing margin of similar dimensions.

5.4. Supply-dominated shelf margins

The review data indicate that there are margins or times in a margin's history marked by relatively high sediment supply, as seen by relatively large accretion rates and inferred volumes of deep-water sediments. "High" is a relative measure, however. In terms of actual volume of sediment, "high" has quite a different meaning in the Lewis margin compared to the Gulf of Mexico margin. Similarly, even though both the West Siberia and the Lewis margins have comparable clinoform amplitudes and progradation rates, the total marine-sediment volumes in the former are much higher than in the latter, because the marine Siberian Neocomian basin is extensive (e.g., ~160,000 km^3 and more including coastal plain, see Ulmishek, 2003), whereas the Lewis margin infilled only a local Laramide depocenter in which Carvajal (2007) calculated a total marine-grain volume of less than 10,000 km^3.

We suggest that rapidly prograding margins are "supply-dominated shelf margins", an expansion of the "supply-dominated shelf regime" concept of Swift and Thorne (1991). Regime variables include sediment supply and caliber, rate of relative sea-level change and dispersal system (e.g. frequency and power of waves, tides, river currents and sediment-gravity flows). In supply-dominated shelf regimes, such variables harmonize so that sediment supply outpaces accommodation over time intervals >1 My and the dispersal of sediment produces a clear pattern of deltaic or shoreline progradation. Two shelves may have quite different sediment budgets but both can be supply-dominated depending on relative sea-level characteristics, and basin processes and dimensions. Similarly, a supply-dominated

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shelf-margin reflects the prevalence of variables that drive construction of the margin for long time periods, most notably sediment supply. Criteria for supply-dominated shelf margins are therefore (Fig. 13): 1) a relatively high progradation rate (several tens km/My) maintained over long time scales (>1 My) and over significant areas, 2) the formation of large basin-floor fans relative to margins of similar dimensions, and 3) recurrent delivery of sediment which may occur under conditions of rising relative sea level (rising shelf-edge trajectory).

5.4.1. Low margin-progradation rate and low supply

The reviewed cases suggest that low progradation rates are symptomatic of a low sediment supply. It may be argued, however, that a low observed progradation rate may also result from one or from a combination of the following variables: 1) high fraction of sediment storage on the clinoform topset (due to high shelf subsidence and aggradation, and/or strong lateral sediment dispersal by waves and tides); 2) high fraction of sediment bypassing the shelf-edge to deep-water areas without accreting the margin (e.g. margins that repeatedly collapse and/or that are cut by shelf-slope incisions that transfer sediment to deep-water without accreting the margin); and 3) greater than normal lateral variability along the shelf-margin, combined with limited data transects which severely underestimate the supply. Scenarios such as these may erroneously lead one to interpret a low progradation rate as a sign of low supply. Even in these cases, however, indications of high supply should be found in aggradational topsets or in large fans in the basin-floor compartment.

5.5. Implications for exploration

This analysis suggests that a rapidly prograding margin with its linked high supply will tend to reduce the basin-floor fan occurrence risk. In addition, when the supply is high, the greater area of such reservoirs will make them easier to target. In contrast, low supply shelf margins are likely to generate smaller fan reservoirs which are more difficult to target. Though these trends are clear for the study margins, more testing of these results are needed.

6. Discussion: sediment supply as the key driver of shelf-margin growth

6.1. Margin-topset width and supply

Our review suggests that sediment supply is the primary variable driving the growth and deep-water sand content of the selected margins. Increased sediment supply leads to increased rates of margin progradation and larger volumes of deep-water sediment. In the moderately deep-water margins, the larger supply also caused increased frequency of sand delivery to deep-water areas and an enhanced potential to generate both highstand and lowstand fans. Using fan volumes (calculated from fan area and maximum thickness) and present-day river discharges to the ocean, Wetzel (1993) developed a compelling case that the size of modern river-fed deep-sea fans is controlled in the long-term by sediment flux rather than sea level. In the Gulf of Corinth and New Jersey shelf margins increase in topset width is related to increases in supply (Fulthorpe and Austin, 1998; Deptuck et al., 2008). Forward models (Burgess and Steel, in press) suggest that for a given clinoform amplitude, topset width increases linearly with sediment supply rate, whereas it shows minor variations (for the same supply) for relative sea-level cycles resulting from eustatic variations (25, 50 and 100 m) superimposed on average subsidence trends. In these models, relative sea level had a greater influence on topset width when marine sediment-transport efficiency increased, but sediment supply still remained the primary control.

6.2. High subsidence rates hinder sea-level fall

The importance of sediment supply is highlighted if we consider the high aggradation rates observed on many of the very deep-water margins. The stratal-thickness observations signal high rates of subsidence, especially in outer shelf to shelf-edge growth fault depocenters. High subsidence rate makes it more difficult for eustatic fall to drop sea level below the shelf-edge and trigger deep-water sand bypass. Obviously, the large (several tens of m) and frequent (reaching 100 ky cycles) Icehouse eustatic sea level oscillations (Abreu and Anderson, 1998) are likely to be more effective in creating relative sea level falls, but even this eustatic regime may not always be able to outpace subsidence. In the eastern Borneo margin, for instance, the last two Pleistocene eustatic falls (about 18 and 130 ky ago) were apparently not able to generate relative sea level falls below the shelf-edge in spite of their large amplitude (~100 m). No shelf-edge progradation and no delivery of sand to deep-water occurred because deltas remained on the outer shelf due to a decreased supply and great subsidence both locally (in growth faults) and regionally (Saller et al., 2004). On the other hand, both the Orinoco (Belderson et al., 1984; Sydow et al., 2003) and Mississippi (Suter and Berryhill, 1985; Weimer, 1990) Icehouse fans developed well despite occurring within high subsidence settings.

6.3. Eustasy versus supply: Wilcox example in the Gulf of Mexico and the Greenhouse world

The contrast between different Paleogene shelf margins in the Gulf of Mexico is instructive to illustrate the driving role of sediment supply for shelf-margin growth. During Wilcox 4 and 3 informal units (60–58.5 My) there was continuous rise of eustatic sea level according to the oxygen-isotope curve of Abreu and Anderson (1998) and the sequence stratigraphy of Hardenbol et al. (1998). However Wilcox 4 and 3 units contain abundant deep-water deposits and the margin was built significantly (Figs. 7 and 11) indicating that high supply was critical for the margin growth during the long-term eustatic rise. During Wilcox 2 times (58.5–57.5 My), there could have been eustatic fall beginning at 58.53 My (Abreu and Anderson, 1998; Hardenbol et al., 1998), which along with the high supply may explain apparently greater deep-water sediment volumes in Wilcox 2 versus Wilcox 4 and 3 (Figs. 11 and 12). From Wilcox 1 (57.5–51.8 My; including Wilcox 1A and 1B) and up through the Eocene there would have been several eustatic falls (Hardenbol et al., 1998; Abreu and Anderson, 1998), and yet both the margin-progradation and the deep-water sediment volumes show a severe decline to the point that during the Sparta deposode (43–40.5) there was deep-water sediment starvation and no shelf-margin progradation (Figs. 2 and 7, see also Galloway et al., 2000). The reduced supply would have prevented much margin growth and deep-water sand bypass despite the eustatic falls. During the Oligocene, the margin was vigorously re-built due to renewed sediment influx from uplift and volcanism in Mexico and southern U.S. (Galloway et al., 2000; Dickinson, 2004; Lipman, 2007; Jicha et al., 2009). The presence of large deep-water sediment volumes and significant margin growth during periods of long-term eustatic sea-level rise as well as the reduced margin growth and absence or diminished volumes of deep-water sediment despite eustatic sea-level fall suggest that the Gulf of Mexico Paleogene margins primarily accreted in response to sediment supply (Fig. 14).

It is also interesting to highlight that the Wilcox margins as well as the Lewis–Fox Hills and West Siberia supply-dominated margins developed during Greenhouse times. At these times (e.g. Late Cretaceous to early Eocene, Zachos et al., 1994), glacioeustatic sea-level oscillations are thought to have been smaller (20–30 m) and of low frequency (<1 My) (Miller et al., 2005), and so they would have had a decreased potential to produce relative sea-level fall. Therefore, the possibility of having much margin growth and sand bypass to deep-water driven by sediment supply at highstand of relative sea level

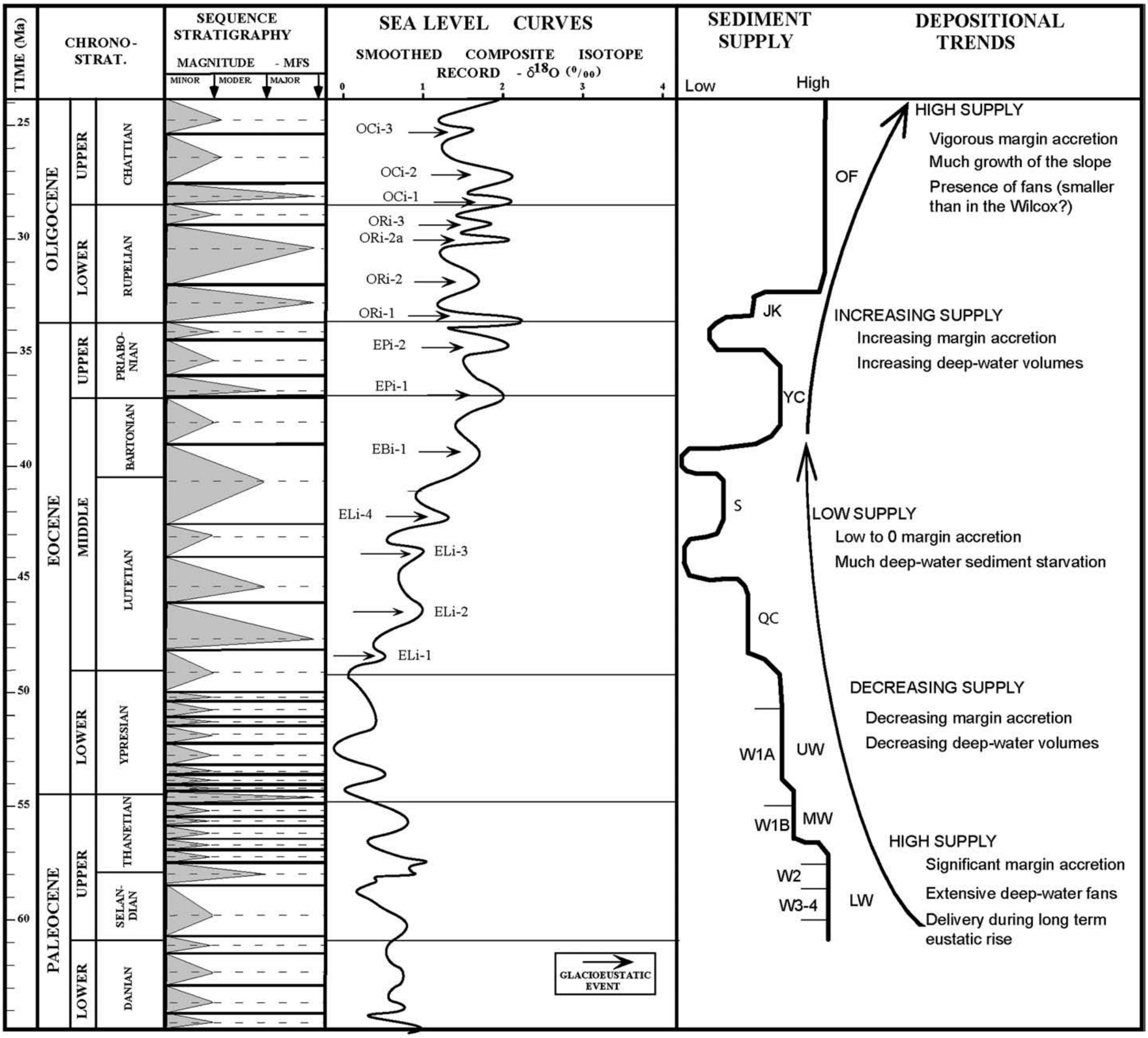

Fig. 14. Evolution of inferred sediment supply in the Gulf of Mexico during the Paleogene compared to the isotope oxygen curve (proxy for eustasy) of Abreu and Anderson (1998) and the sequence stratigraphy of European basins of Hardenbol et al. (1998). The Paleogene data for the Gulf of Mexico suggest that accretion and deep-water sandstone volumes are related primarily to sediment supply rather than to eustasy (modified from Abreu and Anderson, 1998; supply column is our interpretation; see text and Figs. 7 and 11 for explanation of the abbreviations).

deserves consideration. In this regard, both the storage of two thirds of the shelf-margin sediment budget in deep-water compartments (Carvajal, 2007; Galloway et al., 2009) and numerical models for delta progradation during rising sea level (Burgess and Hovius, 1998; Muto and Steel, 2002; Sømme et al., 2009a) suggest that sediment supply is commonly more than enough to drive deltas to the shelf-edge during highstand of sea level. Of further interest in this respect is the suggestion that Greenhouse deltas, once established at the shelf-edge, may tend to remain there for prolonged periods because of a lack of extensive cross-shelf flooding and the strength of their supply drive (Blum and Steel, 2007). However, regardless of whether much highstand shelf-margin growth can take place, our analysis strongly suggests that the pattern of progradation and deep-water sand abundance in the Gulf of Mexico and in the reviewed moderately deep-water margins is first and foremost a story of sediment supply.

7. Conclusions

Moderately deep-water margins produce clinoforms <1000 m high and show rates of shelf-edge progradation <61 km/My and aggradation <270 m/My. Due to their smaller relief and aggradation rate, these margins infill their basins more rapidly and develop more progradational architectures with morphologically less rugose and relatively undeformed slopes.

Very deep-water margins produce clinoforms >1000 m and tend to show rates of shelf-edge progradation <40 km/My and aggradation up to 2500 m/My. Due to their greater fronting water depth, higher aggradation rate, large sediment mass and weak basal layers (salt or shale), these margins infill their depocenters more slowly, and develop more aggradational architectures with much gravity-driven slope deformation, instability, and failure.

In both margin types, high progradation rates over long periods of time are symptomatic of supply domination on the shelf-margin. Signatures of supply-dominated shelf margins are: 1) a high progradation rate (several tens km/My) during long time scales (>1 My) and over widespread areas, 2) the formation of large fans relative to other margins of similar dimensions, and 3) recurrent bypass of sediment to deep-water despite rising shelf-edge trajectory (high shelf aggradation rates) or rising relative sea level.

The rationale behind using progradation rates to evaluate sediment supply in ancient shelf-margin successions stands on the following observations: 1) on long time scales (>1–2 My), significant progradation of the shelf-edge is typically achieved through the discharge from shelf-edge deltas and is intimately linked to building of the slope and basin floor either by margin failure and/or sustained turbidity-current (hyperpycnal) flows; 2) although there are cases where longshore drift takes marine sediment far from the original supply fairway, in most cases where waves, tides and ocean currents rework marine sediments they are still retained on the same margin and contribute to build it, albeit laterally from their original supply fairway; and 3) it seems that on average, two thirds (more at times) of the marine-sediment volume is ultimately stored in the slope and basin-floor segments of a margin (despite high shelf subsidence), strongly suggesting that most of the marine sediment is stored in deep-water compartments. It is therefore suggested that shelf-edge progradation rates are a reasonable proxy for the total volume of marine sediment supplied to the margin.

The review cases strongly indicate that sediment supply is really the primary driver behind significant and sustained shelf-margin growth and accumulation of large volumes of deep-water sand. A strong supply can grow the margin despite high subsidence rates and insignificant sea-level falls, e.g., during Greenhouse times. A low supply causes reduced margin growth, even with significant sea-level falls.

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