A stratigraphic example of the architecture and evolution of shallow water mouth bars

Running title: Architecture and evolution of shallow mouth bars

GRANT COLE*, RHODRI JERRETT† and MATTHEW P. WATKINSON*

*School of Geography, Earth and Environmental Sciences, University of Plymouth, Drake Circus, Plymouth, UK
†Department of Earth and Environmental Sciences, University of Manchester, Oxford Road, Manchester, UK (corresponding author: rhodri.jerrett@manchester.ac.uk)

ABSTRACT

Improved understanding of mouth bar morphodynamics, and the resulting stratigraphic architectures, is important for predicting the loci of deposition of different sediment fractions, coastal geomorphic change and heterogeneity in mouth bar reservoirs. Facies and architectural analysis of exceptionally well-exposed shallow water (ca 5 m depth) mouth bars and associated distributaries, from the Xert Formation (Lower Cretaceous), of the Maestrat Basin (east-central Spain), reveal that they grew via a succession of repeated autogenic cycles. An initial mouth bar accretion element forms after avulsion of a distributary into shallow standing water. Turbulent expansion of the fluvial jet and high bed friction results in rapid flow.
deceleration, and deposition of sediment in an aggradational to expansional bar-form. Vertical bar growth causes flattening and acceleration of the jet. The accelerated flow scours channels on the bar top, which focuses further expansion of the mouth bar at individual loci where the channels break through the front of the mouth bar. Here, new mouth bar accretion elements form, downlapping and onlapping against a readily recognizable surface of mouth bar reorganization. Vertical growth of the new mouth bar accretion elements causes flattening and re-acceleration of the jet, leading to channelization, and initiation of the next generation of mouth bar accretion elements. Thus the mouth bar grows, until bed-friction effects cause backwater deceleration and superelevation of flow in the feeding distributary. Within-channel sedimentation, choking and upstream avulsion of the feeding channel, results in mouth bar abandonment. In this study, mouth bars are formed of at least two to three accretion elements, before abandonment happened. The results of this study contrast with the notion that mouth bars form by simple vertical aggradation and radial expansion. However the architecture and facies distributions of shallow water mouth bars are a predictable product of intrinsic processes that operate to deposit them.

Keywords: architecture, Cretaceous, Maestrat Basin, mouth bar, morphodynamics, shallow water

INTRODUCTION

Mouth bars are a fundamental depositional element of deltas. They form at the basinward termination of fluvial distributary channels where fluvial outflow meets the receiving basin, leading to rapid deceleration and deposition of sediment load. They are therefore major sinks of river-derived sediment on marine shelves, represent an important means of land creation and maintenance in coastal areas, and are preserved in the rock record as sandbodies with significant reservoir potential in hydrocarbon and aquifer exploration. Understanding mouth bar morphodynamics, and their resulting internal architecture, then, allows for better prediction of the loci of certain commercial or environmentally sensitive sediment fraction sinks (aggregate sands, terrestrial organic matter or microplastics), coastal geomorphic change, and of porosity and permeability heterogeneity in reservoirs.

Bates (1953) and Wright (1977) applied modified jet flow theory as a model for approximating the principal variables that control mouth bar morphology and evolution. These studies proposed that details of the shape, size and position (relative to the mouth), of the deposited sediment load would be determined by the inter-competing influences of the outflow inertia, its buoyancy relative to the receiving basin waters, and bed friction acting on the outflow. The relative role of these forces, in turn, depend upon the discharge rate and velocity, grain size and proportion of suspended and bedload of the outflow, water depths and...
seabed gradient immediately seaward of the river mouth, and salinity of the receiving basin water (Wright, 1977). This conceptual framework has been difficult to apply to ancient deltaic successions because Bates (1953) and Wright (1977) made few predictions about the expected bedforms or internal architecture of different mouth bar types. The predictions they made about the geometry of the resulting mouth bars have also been difficult to test because of the greater three-dimensional scale and geometry of mouth bars compared with most two-dimensional outcrop data. Mouth bars are also, in many instances, reworked by basinal processes (i.e. waves and tides and associated currents), which can erode primary facies, introduce secondary bedforms, and modify their external geometry and internal architecture (e.g. Nardin & Fagherazzi, 2012; Nardin et al., 2013). Consequently, there has been a tendency to interpret mouth bars from vertical succession as either ‘fluvially-dominated’ (i.e. relatively unmodified), ‘wave’ or ‘tidally’ modified (e.g. Pulhman, 1989; Willis et al., 1999; Willis & Gabel, 2001; Bhattacharya & Giosan, 2003; Gani & Bhattacharya, 2007; Ahmed et al., 2014; Ainsworth et al., 2015; Hampson & Howell, 2017).

In fluvially-dominated deltas, outcrop datasets of preserved mouth bars from the rock record (e.g. Jerrett et al., 2016), time series of aerial photographs of modern mouth bars (e.g. Wellner et al., 2005) and flume tank experiments (e.g. Hoyal et al., 2003; Daniller-Varghese et al., 2020), imply that mouth bars form as lensoid-shaped or lunate-shaped bodies some distance from the river mouth. These mouth bars have been shown to grow via vertical aggradation (e.g. Hoyal & Sheets, 2009; Jerrett et al., 2016), then basinward and lateral expansion (e.g. Gilbert, 1885; Van Heerden & Roberts, 1988; Van Wagoner et al., 2003; Olariu & Bhattacharya, 2006; Jerrett et al., 2016; Shaw et al., 2018; Daniller-Varghese et al., 2020). This is expressed in the rock record as down-basin and laterally accreting clinoforms (e.g. Gilbert, 1885; Barrell, 1912; Rich, 1951; Enge et al., 2010; Schomacker et al., 2010 Jerrett et al., 2016). Mouth bars grow, and levées of the feeding channel prograde, until a critical threshold is reached when the outflow and mouth bar interact, either: (i) forcing bifurcation (Elliott, 1986; Wellner et al., 2005; Olariu & Bhattacharya, 2006; Edmonds & Slingerland, 2007; Fagherazzi et al., 2015; Daniller-Varghese et al., 2020) or deviation (Martini & Sandrelli, 2015; Jerrett et al., 2016) of flow around the mouth bar; or (ii) decelerating flow upstream, leading to sedimentation in, and super-elevation of, the distributary channel above the delta plain, facilitating channel avulsion up-dip of the mouth bar (Hoyal & Sheets, 2009; Ganti et al., 2016). In either case, these processes lead to the abandonment of the initial mouth bar and the formation of a new one. Few outcrop studies, however, document how mouth bars interact with the outgoing flow (jet) prior to its abandonment, and how this influences facies distributions in, and the architecture of mouth bars.

The purpose of this study is to document the architecture and process evolution of mouth bars during their initiation and growth by analysing an exceptionally well-exposed Lower Cretaceous channel-mouth bar succession preserved in the Maestrat (Maestrazgo) Basin, central-eastern Spain. As will be shown, the mouth bar succession was subject to little reworking by tidal and wave processes during and
after deposition, and is therefore, an ideal case study for reconstructing the intrinsic processes operating during initiation, and evolution of the mouth bars, as they increasingly interacted with their feeding outflow before abandonment.

GEOLOGICAL SETTING

The Maestrat Basin in eastern Spain is a north-west/south-east oriented rift basin that formed from the end of the Oxfordian through to the early late Albian (Fig. 1A; Salas & Guimera, 1996; Salas et al., 2001; Salas et al., 2010). Rifting in the basin was related to extension along the Bay of Biscay arm of the North Atlantic (Salas & Casas, 1993; Capote et al. 2002; Salas et al., 2010). During this Late Jurassic to Early Cretaceous rifting cycle, the Maestrat Basin began to divide into a series of sub-basins bounded by major north-west/south-east and west–east oriented normal faults, including the Galve Sub-Basin (Salas et al., 2001), where this study was conducted. Up to 2000 m of terrestrial to marine, siliciclastic and carbonate sediments were deposited during the Late Jurassic to Early Cretaceous rifting cycle in the Galve Sub-Basin (Bover-Arnal et al., 2010, 2012; Embry et al., 2010; Peropadre et al., 2013), including the main focus of this study – the Xert (or Chert) Formation, of Upper Barremian age (Fig. 1C; Garcia et al., 2014; Bover-Arnal et al., 2016; Aurell et al., 2018). The Xert Formation comprises sandstone, marl, silty marl, mixed siliciclastic–carbonates and limestones generally considered of shallow marine origin (Fig. 1C; Bover-Arnal et al., 2016). Peropadre et al. (2012; 2013) named the more sandstone-prone part of the Xert Formation in the north of the sub-basin the Las Parras Formation, but this study considers the sandstones as part of the Xert Formation. The Xert Formation is up to 110 m thick, and overlies open and restricted marine marls, sandstones and limestones of the upper part of the Morella Formation (Fig. 1C; Bover-Arnal et al., 2010). The sandstones attain 70 m thickness in the north of the sub-basin, where they are composed of one or more composite sheet sandstones extending from the north towards the south/south-east (Fig. 1B). The pinch-out of these sandstones towards the south/south-east into coeval marls and carbonates occurs approximately 2 km south of the study site. This, combined with palaeoflow data collected in this study (Fig. 1D), implies one or more clastic entry point(s) to the north/north-west (Fig. 1B). This lithological succession is overlain by marls and limestones of the Forcall Formation representing a deeper and more open marine setting (Fig. 1C; Bover-Arnal et al., 2015; Embry et al., 2010; Moreno-Bedmar et al., 2010). The Galve Sub-Basin and greater Maestrat Basin were inverted during the Palaeogene through the north–south collision of Iberia and Europe, forming the south-eastern part of the present day Iberian Chain (Salas et al., 2001; Capote et al., 2002; Moreno-Bedmar et al., 2010; Salas et al., 2010).

The study site is a 1.8 km long, 15 m high, NNW–SSE oriented cliff, located to the east of the village of Jorcas, Aragon (40°32’34” N, 0°45’10” W), hereafter termed the ‘Jorcas Section’ (Fig 1D).
cliff provides virtually continuous exposure and an oblique dip section through the whole of a composite sheet sandstone that forms part of the Xert Formation.

**METHODOLOGY AND DATASET**

Fourteen high resolution (1:50), closely spaced (tens of metres) sedimentary logs were collected throughout the Jorcas Section to characterize vertical and lateral facies changes. Their positions are shown in Fig. 1D. Palaeoflow measurements were collected from the foresets of planar cross-beds, axes of trough cross-beds and crests of current ripples. The dip direction of bar-scale accretion surfaces were measured to compare bar accretion direction to palaeoflow measurements. A series of photomosaics of the outcrop were generated using conventional hand-held digital photography, and key surfaces correlated between the logs by physically tracing and walking out individual surfaces and annotating these on to the photomosaics in the field. These data were supplemented by unmanned aerial vehicle (drone) imagery, which were processed into a three-dimensional virtual outcrop model by the Virtual Outcrop Group using the photoscan (Agisoft®) photogrammetric software (Buckley et al., 2019). The virtual outcrop model refined the correlation between logs, and aided observations of internal architecture and interpretation of the panel. Architectural elements were defined using a systematic bounding surface hierarchy based on the ones developed by Miall (1985; 1996) for fluvial deposits and adapted for the delta front depositional environment (Fig. 2). First-order surfaces represent cross-bed foresets and bedding surfaces; second-order surfaces bound individual, inclined cosets or beds and represent bar accretion surfaces in any setting; third-order surfaces cross-cut, or are onlapped, offlapped or downlapped by conformable successions of cosets, and represent a re-orientation of, or change in hydrodynamic conditions during the accretion of a fluvial or mouth bar; fourth-order surfaces represent the basal scour of a channel that is of a smaller scale that the architectural element under consideration; fifth-order surfaces represent the base of a channel or the base of a mouth bar; and sixth-order surfaces partition individual clusters of channels (termed multi-storey channel complexes) or mouth bars (termed mouth bar complexes), in this case flooding surfaces (Fig. 2).

**LITHOFACIES AND ARCHITECTURAL ELEMENTS**

Eleven lithofacies have been identified, based on grain size, sedimentary structures, trace and body fossil occurrence. They are described and interpreted in Table 1, representative photographs are shown in Fig. 3, and their distribution in the Jorcas Section is shown in Fig. 4A. Six architectural elements have been identified. These are: (i) prodelta; (ii) mouth bar accretion; (iii) fluvial downstream accretion; (iv) fluvial lateral accretion; (v) minor channel; and (vi) ravinement elements. Their distribution in the Jorcas section is
shown in Fig. 4B and summarized in Fig. 5. Representative photographs and details of architecture are provided in Figs 6 to 10.

**Prodelta elements**

*Description:* This element consists of cosets of bioturbated silt and very fine sandstone (Fb), massive very fine to fine sandstone (Sm) and bioclastic wackestones, packstones and grainstones (L) interbedded with bioturbated or laminated silty marl (Mfm) containing abundant gastropods, echinoids and large benthic foraminifera (Table 1). Cosets are characterized by coarsening-up packages no more than 1 m in thickness, of either: (i) interbeds of bioturbated and massive sandstone and marl, occasionally capped by well-cemented bioclastic packstones; or (ii) interbeds of wackestone, packstone, grainstone and marl. Multiple ca 1m thick cosets stack to form a coarsening-upward prodelta element that is 5 to 10 m thick. These elements are poorly exposed except in ephemeral stream gullies and trackway excavations. However, distinct beds of sandstone and limestone are continuous over hundreds of metres.

*Interpretation:* This element represents the environment into which mouth bar sands were prograding. The presence of abundant fully marine fauna is indicative of deposition in normal marine salinities. Laminated marl is indicative of a generally low energy environment of *in situ* production, or settling from suspension of carbonate, and silt and clay having settled from suspension. The origin of the silt and clay was likely hypopycnal to hyperpycnal sediment plumes from the mouths of terminal distributary channels, which bypassed the mouth bars. The sandstone beds were likely derived from hyperpycnal flows which bypassed the mouth bars during episodes of increased discharge and suspended sediment load in the distributary channels (i.e. floods; Mulder *et al.*, 2003). The sheet-like nature of these beds is indicative of unconfined deposition on a flat, low gradient surface. The bioclastic beds were possibly derived from the reworking, possibly by waves or organisms, of nearby accumulations of *in situ* bivalves (Donovon *et al.*, 2001).

**Mouth bar accretion elements**

*Description:* The element is dominated by massive sandstone (S), with subordinate massive very fine to fine sandstone (Sm), bioturbated silt to very fine sandstone (Fm), planar (Sp) and trough cross-bedded sandstone (St), current ripple cross-laminated sandstone (Sr) and rare low angle cross-bedded sandstone (Sl) (Table 1). Beds or cosets are bound by bar accretion surfaces (second-order surfaces; Fig. 2), which are organized into two distinctive architectures: (i) bidirectional, sigmoidal closure (a bell shape; Figs 6 and 7); and (ii) a sigmoidal or concave-up geometry (for example, Figs 8 and 9), which dip down or oblique, to down, palaeoflow (Fig. 4B).

Bidirectionally closing bar accretion surfaces stack in an aggradational motif, forming successions 2 to 3 m thick and up to 200 m long, with sequential downlap of foresets and backsets onto an underlying
surface (for example, Figs 6 and 7). Beds comprise massive sandstone, or low angle cross-bedded sandstone on the backset, and massive, trough or planar cross-bedded sandstone on the foreset (Figs 6 and 7).

Down or oblique to down palaeoflow-dipping bar accretion surfaces dip up to 24°, and the cosets define classical clinothems that systematically offlap one another (Figs 8 and 9). Clinothem topsets and bottomsets thin away from foresets, which are up to 1.2 m thick. Some toesets are short, with relatively high angle (oblique) downlap of bar accretion surfaces on to the underlying surface (for example, Fig. 9). These bar accretion surfaces tend to be more highly erosive into the underlying clinothem. Other toesets are long, with low angle (tangential) downlap of bar accretion surfaces onto the underlying depositional surface of the mouth bar (for example, Fig. 8). These bar accretion surfaces display less scouring of the underlying clinothem. In these successions, grain size typically fines down clinothem, with common down-clinothem transformation of massive and cross-bedded sandstone to finer grained massive sandstone, current ripple cross-laminated sandstone, or bioturbated fine sandstone and siltstone. However, some clinothems dominated by massive sandstone display laminae of especially granular material, creating a ‘pinstripe’ appearance (Fig. 3G), which maintain grain size, or even coarsen down clinothem. These tend to be the steeper clinothems with short or absent toesets (Fig. 9). Successions of clinothems form tabular units up to 5 m thick, and generally display a coarsening-up profile of bioturbated siltstone to very fine sandstone, massive very fine to fine sandstone, ripple cross-laminated sandstone and trough cross-bedded sandstone, and medium to coarse, massive sandstone. However, successions dominated by massive sandstone displaying internal granular laminae, show no overall vertical trend.

Erosional surfaces that truncate a series of bar accretion surfaces (for example, Figs 7 and 9), or depositional surfaces that are parallel to underlying bar accretion surfaces that overlying bar accretion surfaces downlap (for example, Fig. 9), represent an episode of mouth bar reorganization during growth (third-order surfaces; Fig. 2). These surfaces can also combine both of these features and are sigmoidal to concave-up geometrically, dip in the direction of palaeoflow, and are generally less steep than the bar accretion surfaces they cross-cut (Figs 7 and 9). These surfaces bound increments of relatively continuous and conformable mouth bar growth and define mouth bar accretion elements (Fig. 2). Both bar accretion surfaces, and those marking a reorganization in mouth bar growth, downlap against a relatively horizontal depositional surface over deeper water deposits, marking the base of the mouth bar (fifth-order; Fig. 2).

Mouth bar accretion elements are characterized by either: (i) aggradational successions with clinothems that bidirectionally downlap a surface of mouth bar reorganization (for example, Fig. 7) or the depositional base of a mouth bar (Fig. 6) conformably offflapped by down-palaeoflow or oblique to down-palaeoflow dipping clinothems (Figs 6 and 7); or (ii) down-palaeoflow or oblique to down-palaeoflow dipping clinothems that sequentially downlap and climb down mouth bar reorganization surfaces, and downlap the depositional base of the mouth bar (for example, Fig. 9).
Interpretation: The non-erosive, relatively flat nature of the surface on to which bar accretion, and mouth bar reorganization surfaces downlap, the long toesets of many clinothems, and the low angle, asymptotic downlapping of many bar accretion surfaces imply that these were bars accreting and expanding into an unconfined setting with limited bathymetric topography. Such settings are characteristic of tidal bars at the broad, open mouths of estuaries and tidal ridges on open shelves (e.g. Berné et al., 2002; Suter, 2007; Olariu et al., 2012), as well as mouth bars forming at river mouths. However, the intimate and consistent geometric relationship of these deposits, occurring down-flow of, and consistency of palaeoflow indicators with fluvial accretion elements (described below), strongly suggests that these are mouth bars.

Aggradational, bidirectionally downlapping bar accretion surfaces (Figs 6 and 7) represent the initiation, vertical growth, lateral and down-stream expansion of an initially small unit bar via rapid deposition of bed and suspended load close to the point of deconfinement of flow. This bidirectionally downlapping portion of the mouth bar accretion element is hereafter referred to as the mouth bar aggradation sub-element.

Downflow of the mouth bar aggradation sub-element, bar accretion surfaces that define down or oblique to down flow dipping clinothems (Figs 7 to 9) represent the subsequent downstream and lateral expansion of the bar. These successions are hereafter referred to as mouth bar expansion sub-elements. In these deposits, the presence of cross-bedded and ripple cross-laminated sandstone attest to bedload deposition in the lower flow regime via downstream migration of dunes and ripples. Down-clinothem fining in these successions are indicative of rapidly waning flows and rapid bedload deposition. By contrast, successions dominated by massive sandstone, displaying coarse laminae which extend down clinothem, and downlap sharply on to the basal mouth bar surface, likely represent grainflow down bar fronts (e.g. Kleinhans, 2005; Orton & Reading, 1993).

Surfaces marking a reorganization in mouth bar growth represent an episode of simple cessation of lateral or downstream growth of the bar if they are parallel to underlying bar accretion surfaces, or represent an episode of erosion if they truncate underlying bar accretion surfaces. Downlap of bar accretion surfaces over surfaces that mark reorganization in mouth bar growth represents re-initiation of mouth bar progradation, either via: (i) the vertical aggradation of bidirectionally downlapping clinothems, followed by downflow and lateral expansion of the bar; or (ii) via simple downflow and lateral expansion.

Therefore, individual mouth bar accretion elements comprise a mouth bar aggradation sub-element and a mouth bar expansion sub-element, or a mouth bar expansion sub-element alone. A mouth bar accretion element is analogous to mid-channel and point-bar accretion elements in fluvial channels (Miall, 1996) and is an architectural component of a mouth bar deposit (Fig. 2).

Fluvial downstream accretion elements
**Description:** This element consists of trough cross-bedded sandstone (St) in sets up to 0.5 m thick, subordinate planar cross-bedded sandstone (Sp), in sets up to 2 m thick, massive granular sandstone (SGh), minor massive sandstone (S), and rare low angle cross-bedded sandstone (Sl) and ripple cross-laminated sandstone (Sr) (Table 1). The dominance of trough cross-bedded sandstone results in a complex architecture of cross-cutting surfaces but, in general, cosets of all lithofacies are bound by inclined, erosional bar accretion (second-order; Fig. 2) surfaces with concave-up geometries, but which dip on average down or oblique to down palaeoflow and downlap on to erosional surfaces (Fig. 4A and B). Successions of bedding and bar accretion surfaces are truncated by sigmoidal to concave-up surfaces that represent reorganization of bar growth (third-order; Fig. 2). The latter also dip down palaeoflow, and in turn downlap against an erosional surface marking the basal scour of a major channel (fifth-order surface; Fig. 2) or are cross-cut by later surfaces marking a reorganization in bar growth. Basal scours of major channels have incisional topography into underlying strata of up to 3 m. Commonly, basal scours of major channels, and occasionally surfaces marking bar reorganization, are lined with a granular lag.

**Interpretation:** The downlap of bar accretion and bar reorganization surfaces on to a basal surface with up to 3 m of erosional topography, imply that the bars migrated within a confined channelized setting. The orientation of bar accretion surfaces, dipping down palaeoflow, is indicative of fields of bedforms migrating down barforms that were themselves migrating in the direction of flow. Bar reorganization surfaces represent a change in the orientation and angle of bar accretion, that has been interpreted as occurring after a change in the flood hydrograph in the channel (a ‘stage change’, *sensu* Miall, 1985; 1996). Hence, the packages between the surfaces representing stage changes in bar growth represent growth increments of down-channel accreting bar macroforms (*sensu* Miall, 1985; 1996; i.e. fluvial downstream accreting elements). Down-channel accreting barforms are indicative of relatively straight channels (Miall, 1996). Straighter channels are common in the most distal, or ‘terminal’ deltaic distributary channels, downstream of the final channel bifurcation, and upstream of flow deconfinement (e.g. Are & Reimnitz, 2000; Schwamborn *et al.*, 2002; Daniller-Varghese *et al.*, 2020), because rollover at the transition from the delta top to the delta front promotes steeper gradients (Wellner *et al.*, 2005; Olariu & Bhattacharya, 2006).

One or more downstream bar accretion elements, contained within a single basal scour of a major channel forms a channel belt, which has the same architectural element hierarchy as a mouth bar deposit (Fig. 2).

**Fluvial lateral accretion element**

*Description:* This element consists of trough cross-bedded sandstone (St), in sets up to 1 m thick, planar cross-bedded sandstone (Sp) in sets that can exceed 2 m in thickness, subordinate massive granular sandstone (SGh) and minor massive sandstone (S) (Table 1). These facies form beds or sets up to 3.5 m thick. Cosets of these lithofacies are bound by erosional bar accretion (second-order; Fig. 2) surfaces with
sigmoidal to concave-up geometries, which dip approximately perpendicular to palaeoflow (Figs 4B and 10). Sets and cosets are truncated by sigmoidal to concave-up (third-order; Fig. 2) surfaces marking a reorganization in bar growth which also dip approximately perpendicular to palaeoflow. Both bar accretion and reorganization surfaces downlap against an erosional surface that has incisional topography into the underlying strata of up to 3 m, and represents a (fifth-order) basal scour of a major channel (Fig. 2). The latter is commonly lined with a granular lag.

**Interpretation:** The downlap of bar accretion and reorganization surfaces on to a basal surface with up to 3 m of erosional topography, imply that the bars migrated within a confined channelized setting. The dominance of cross-bedded sandstone in this element is indicative of sediment deposition from bedload in dunes in the lower flow regime. The orientation of bar accretion surfaces, dipping approximately perpendicular to implied palaeoflow, is indicative of the lateral accretion of barforms. As in the fluvial downstream accreting element, surfaces of bar reorganization are interpreted to represent stage changes in the fluvial hydrograph. They define growth increments of laterally accreting bar macroforms within channels (sensu Miall, 1985; 1996; i.e. fluvial lateral accretion elements). It is not clear whether these represent bank-attached (point) bars, or laterally accreting mid channel bars, but in either case lateral accreting bars are generally indicative of more sinuous channel planforms (Miall, 1996). Therefore, channels in this system had some sinuosity, or the capacity for some amount of lateral migration.

As with downstream accreting elements, one or more laterally accreting elements, contained within a single basal scour of a major channel form a channel belt, which has the same architectural element hierarchy as a mouth bar deposit.

**Minor fluvial channel element**

**Description:** This element comprises trough cross-bedded sandstone (St) in sets up to 0.8 m thick and minor massive granular sandstone (SGh) (Table 1) which are contained within relatively simple symmetrical concave-up (scoop shaped) scours, up to 1.4 m deep and up to 130 m wide (Fig. 4A and B). Beds or cross-sets, bounding surfaces display a concave-up geometry and stack aggradationally within the scour. The basal scour of this element cross-cuts second-order bar accretion surfaces and third-order bar reorganization surfaces of fluvial and mouth bar accretion elements. Therefore it is assigned fourth-order status, and represents the basal scour of a channel that is an architectural element of a smaller scale than those recorded by the lateral and downstream accreting fluvial elements and mouth bar accretion elements (sensu Miall, 1996).

**Interpretation:** The erosional concave-up base and dominance of St facies in this element is indicative of bedload deposition via migrating dunes within a channel (Miall, 1985; 1996). The simple geometries of the element, representing scour and then fill, and its truncation of larger scale lateral and downstream accreting elements, suggest that these represent transient chute channels formed over
otherwise exposed bar crests (e.g. Brierley, 1991a, b), during periods of excess discharge in the main distributary.

**Ravinement element**

*Description:* This element comprises bioturbated fine to granular sandstone (Sb), and rare discontinuous decimetre-scale trough cross-bedded (St) and ripple cross-laminated sandstone (Sr) (Table 1). Beds are highly tabular, become increasingly bioturbated upwards and form sets or cosets up to 1.4 m thick that extend throughout the exposure (ca. 1.8 km; Fig. 4B), bounded at the base by a sub-horizontal erosional surface which truncates all other underlying strata. The basal surface generally marks an abrupt vertical increase in grain size.

*Interpretation:* This element represents wave erosion and re-working of underlying shallower water facies during transgression. The lateral persistence of the deposits indicates the existence of unconfined conditions, the presence of discontinuous cross-bedded and cross-laminated sandstone suggests that energy conditions enabled bedload deposition. The coarse nature of the sediment relative to other elements may be indicative of winnowing of the sediment, probably as a result of wave agitation. The ferruginous cement and the presence of occasional intact oysters suggest that early diagenesis of this element took place following deposition – possibly as the result of drowning and subsequent sediment starvation. Consequently, these successions are interpreted as a ravinement element, deposited following abandonment and drowning of the underlying succession. Comparable facies have been similarly interpreted in the Lower Cretaceous Star Point Formation of the Panther Tongue in the Western Interior Basin of the USA (Hwang & Heller, 2002).

**ARCHITECTURE OF THE JORCAS SECTION**

Mean palaeoflow data (Fig. 1D) for the entire Jorcas section indicates that the NNW–SSE oriented cliff exposure which provides the basis of Figs 4 and 5, is an oblique dip-oriented view through the architecture. The fluvio-deltaic succession of the Jorcas section contains three throughgoing, relatively horizontal surfaces, which partition the stratigraphy into three units, each comprising a succession of channel belts that coalesce to form a multi-storey channel complex to the NNW, and a single mouth bar deposit to the SSE (Figs 4 and 5). Each of these surfaces cross-cut multiple fifth-order surfaces marking the base of a major channel fill, and are therefore assigned sixth-order status (Figs 4 and 5). In each case the surface is overlain by ravinement elements, representing deeper water than the underlying mouth bar and channels, and it therefore represents a flooding surface. The three units demarked by the flooding surfaces represent a sixth-order depositional unit termed the lower, middle and upper channel-mouth bar complex, respectively (Fig. 4). They have strikingly similar architectures, and similarly-oriented palaeoflow measurements in the

This article is protected by copyright. All rights reserved
fluvial and mouth bar elements, strongly indicating a genetic relationship between the fluvial and mouth bar elements within the same complex. Each is 3 to 5 m thick, and the generic aspects of their architecture are summarized below.

Each channel-mouth bar complex is characterized by the deposition of mouth bar elements onto elements that represent deeper water. In the case of the lower channel-mouth bar complex, these are a succession at least 9.0 m thick of prodelta elements, whereas mouth bar elements of the middle and upper channel-mouth bar complexes are deposited on to Ravinement Elements 1 and 2 (RE1 and RE2), up to 1.5 m thick (Figs 4 and 5). The basal surface of the mouth bar in the lower channel-mouth bar complex is poorly exposed, but the mouth bar appears to be made up to at least two mouth bar accretion elements – Mouth Bar Accretion Elements 1A and 1B (MB1A and MB1B), up to 5.0 m thick. In the better exposed middle and upper channel-mouth bar complexes, the oldest mouth bar accretion elements – Mouth Bar Accretion Elements 2A (MB2A) and 3A (MB3A), respectively – are represented by 2.0 to 2.5 m thick mouth bar aggradation sub-elements deposited in the middle of the section, between sedimentary logs J8 and J9 (Figs 4 and 5). These mouth bar aggradation sub-elements are offlapped to the south-east by cliniforms of mouth bar expansion sub-elements that form part of the same mouth bar accretion element (i.e. MB2A and MB3A; Figs 4 and 5).

In the middle channel-mouth bar complex, at sedimentary logs J11 to J13, MB2A is truncated to the south-east by a surface of mouth bar reorganization. The latter is downlapped by Mouth Bar Accretion Element 2B (MB2B) which is up to 3.0 m thick. MB2B comprises an aggradational bidirectionally downlapping sub-element, which is offlapped to the south-east by down-palaeoflow accreting cliniforms of a mouth bar expansion sub-element (Figs 4, 5 and 7). Mouth Bar Accretion Element 2C (MB2C), up to 4.0 m thick, is characterized by bar accretion surfaces in a bar expansion sub-element, that downlap and climb down a largely depositional surface, that is parallel to bar accretion surfaces in the older MB2B. A similar architecture is observed in the upper channel-mouth bar complex, where between sedimentary logs J9 and J11, MB3A is offlapped to the south-east by Mouth Bar Accretion Element 3B (MB3B). In this element, up to 3.0 m thick, mouth bar expansion cliniforms downlap and climb down a non-erosive, depositional surface of mouth bar reorganization. Between Logs J12 and J13, low angle cliniforms of MB3B are truncated by another, steeper mouth bar reorganization surface, which in turn is offlapped to the south-east by a 3.0 m thick mouth bar expansion sub-element that makes up Mouth Bar Accretion Element 3C (MB3C).

Each channel–mouth bar complex is therefore composed of one mouth bar, made up of at least two to three mouth bar accretion elements. The middle and upper mouth bars were initiated, and grew vertically in what is now the middle of the Jorcas Section, and then expanded towards the south-east, via repeated phases of mouth bar growth, as evidenced by mouth bar accretion elements, and episodes of hiatus or
erosion and re-progradation, as evidenced by the reorganization surfaces that bound the mouth bar accretion elements.

Each mouth bar is juxtaposed with a younger multi-storey fluvial channel complex, which occurs up palaeoflow, to the north-west. The multi-storey channel complexes are up to 5 m thick, and comprise three to four channel belts; Channel Belts 1A to 1C (CB1A to CB1C) in the lower multi-storey channel complex, Channel Belts 2A to 2C (BC2A to CB2C) in the middle, and Channel Belts 3A to 3D in the upper multi-storey channel complex (Figs 4 and 5). Individual channel belts are up to 3.5 m thick and over 1.0 km long, and comprise either downstream-accreting or laterally accreting elements, but each multi-storey channel fill comprises channel belts of downstream and laterally accreting channel belts. There is no systematic vertical order in the organization of downstream and laterally accreting channel belts. There is, however, a systematic de-amalgamation of each multi-storey channel complex towards the south-east, but analysis of cross-cutting relationships reveals the most progradational channel belt to be the oldest in the lower channel-mouth bar complex (i.e. CB1A), the second to oldest in the middle channel-mouth bar complex (i.e. CB2B) and the second to youngest in the upper channel-mouth bar complex (i.e. CB3C). The most progradational channel belt, in each case, is characterized by a very gradual thinning to pinch-out towards the south-east, and the basal scour of the channel truncates multiple mouth bar accretion elements (Figs 4 and 5). Two minor channel elements, Minor Channel Element 2A and 3A (MC2A and MC3A), truncate bar accretion surfaces of the youngest channel belts of the middle and upper channel-mouth bar complexes, respectively (i.e. CB2C and CB3D).

DISCUSSION

Process regime in mouth bars of the Jorcas Section

Maximum channel belt thickness in all three of the channel–mouth bar complexes is approximately 3.5 m, and maximum clinoform heights vary from 5.0 m in the lower mouth bar to 3.0 m in the upper mouth bar (Figs 4 and 5). Taking into account decompaction of sandstone, and truncation of clinoform topsets in the mouth bars, these data imply consistent bank-full channel depth of at least 3.5 to 4.0 m at the channel outlets, and bathymetries of 3.0 to 5.0 m into which the mouth bars were prograding.

The absence of wave-generated or tidally-generated sedimentary structures, bidirectional flow indicators and the preservation of foresets indicate the mouth bars were not noticeably affected by tidal or wave re-working at the time of deposition (e.g. Fondini & Ghinassi, 2016). The preservation of some clinoform topsets (for example, Fig. 9) suggest that the ravinement elements that sit above each of the channel mouth bar pairs likely represent post-depositional re-working of the upper 1 m or less of the mouth bars. This implies either that wave action during ravinement was minimal, or that the mouth bars were rapidly drowned below wave base following their abandonment. In either case, this wave activity appears
to have had negligible influence during the phases of initiation and growth of the mouth bars. The fully marine fauna of prodelta deposits demonstrate that the mouth bars prograded into water of normal marine salinities, but the general paucity of evidence for wave and tide action argues for a depositional site protected from the open waters of the Tethys, possibly landward of carbonate build-ups which are characteristic of the Xert Formation towards the south-east (Embry et al., 2010). Overall, they can be classified as fully river-dominated (sensu Galloway, 1975), shallow water mouth bars, and are therefore ideal candidates to reconstruct the inherent mouth bar processes operating to deposit them.

The lower mouth bar is not well-exposed, but in the middle and upper mouth bars, the oldest mouth bar deposits occur immediately basinward of amalgamated distributary channel deposits (Figs 4 and 5). Here, they are represented by the bar aggradation sub-element (Figs 4 to 7). They are indicative of rapidly decelerating flow, high rates of sedimentation, that lead to bar initiation, and the vertical ascension of the bar crest close to the channel outlet. Rapid flow deceleration and unloading of bedload, and possibly suspended sediment, would be expected in settings with high bed friction (Wright, 1977). This agrees with the small difference between reconstructed channel depths (ca 4 m), and bathymetries of the receiving basin at the channel mouth (ca 5 m) (Wright, 1977; Orton & Reading, 1993; c.f. the ‘topset-dominated’ delta of Edmonds et al., 2011).

Deposits in the lower, middle and upper mouth bars include, to a greater or lesser degree, cross-bedding and current ripple cross-lamination that extend down the full length of the mouth bar foreset to the toesets. These are most notably developed in the middle mouth bar (Fig. 8), and demonstrate that the incoming jet was able, at least at times, to expand vertically to occupy the majority of the water column in the receiving basin and drive the migration of ripples and dunes down the length of the mouth bar front to the foresets (Fig. 11A). However, the majority of the lower and upper mouth bar deposits are dominated by massive sandstone facies displaying down-clinothem fining (Fig. 4). It is unclear what process created these clinothsms but down-clinothem fining is more supportive of waning tractional flow. The absence of sedimentary structures in these mouth bar deposits could be due to a lack of preservation through either diagenesis, bioturbation or a lack of grain size variation. It is significant that clinoforms containing cross-bedding display markedly less well-developed breaks-of-slope between the topsets, foresets and toesets, as well as low angle, tangential downlaps (Fig. 11A). This architecture is in keeping with Wright’s (1977) conceptual prediction and Edmonds & Singerland’s (2007) numerical model of the frontal morphology of mouth bars deposited in relatively shallow bathymetries.

A minority of the massive sandstone facies, is characterized by a distinctive ‘pinstriping’ of coarse laminae which extend down clinothem foresets to the toesets. These occur especially in MB2B and MB2C (Figs 4 and 9). This implies that at the time of deposition of the coarse laminae, grainflow was the predominant process on the mouth bar lee. Sediment was delivered to the topset–foreset bathymetric break through either: (i) rapid suspended load deposition from a jet detached from the mouth bar top (i.e. there
was no traction at the bed across the crest of the mouth bar); or (ii) bedload transport along the mouth bar top via an attached jet (i.e. the tractive jet was in contact with the bed at crest of the mouth bar), but which detached from the bed at the topset–foreset bathymetric break (Fig. 11B). The general absence of sedimentary structures in the topset beds (for example, MB2B; Fig. 9) may reflect rapid deposition of suspended load and could argue for a jet that was detached from the mouth bar top. However, cross-bedding and current ripple cross-lamination is also observed on topsets (for example, MB2C; Fig. 9), passing down clinothem to grainflow deposits. The latter case suggests that, at certain times, the jet was attached to the mouth bar top, but detached from the foreset. In general, clinoforms dominated by grainflow deposits have well-developed breaks-in-slope at the transition from the topset to foreset and the foreset to bottomset (for example, MB2C, Fig. 9; Fig. 11B). They display a classical ‘Gilbert’ type profile – the product of deposition in relatively deep water predicted by conceptual and numerical models (e.g. Wright, 1977; Orton & Reading, 1993; Jiménez Robles & Ortega-Sánchez, 2018).

In the middle mouth bar, there is a trend of a decreasing proportion of tractive bedforms in early mouth bar deposits (MB2A; Figs 4 and 8), towards the ‘pinstripe’ facies indicative of grainflow processes in later clinothems (MB2B and MB2C; Figs 4 and 9). This change is accompanied by a concomitant increase in clinoform height and gradient, and a change towards more clearly defined breaks-of-slope at the topset–foreset and foreset–bottomset transition (Fig. 4A). This change can be interpreted in terms of a general detachment of the jet from the bed with time (Fig. 11A and B). The predominance of tractive sedimentary structures in the early deposits of the middle mouth bar suggests that frictional deceleration of the jet, in relatively shallow waters, led to deposition. The increasing heights of the clinoforms show that the mouth bar was prograding into increasingly deeper water during its progradation. The likely reason for this increase in water depth was that the seafloor was gently dipping away from the input point of the mouth bar (Fig. 11). It is also possible that relative sea-level was rising as the mouth bar was prograding, either through compaction of the substrate or eustatic sea-level rise. For a jet with a fixed outlet, and a fixed discharge, vertical growth and lateral expansion of the mouth bar increases the distance of the mouth bar front from the input point of the jet. When combined with the fact that the mouth bar is obliged to build into deeper and deeper water, this will reduce the capability of the jet to move sediment all the way down the mouth bar foreset (Fig. 11B). Consequently, with growth of the mouth bar, bedload sediment will be deposited further and further up the foreset, leading to over-steepening, and grainflow down the mouth bar front into quiescent waters at the bottomset (Fig. 11B). This trend is not observed in the lower and upper mouth bars, but trends from the middle mouth bar suggest that this process regime change might commonly be expected if shallow-water mouth bars prograde into increasingly deeper.

Architecture and evolution of shallow water mouth bar successions

This article is protected by copyright. All rights reserved
An architectural element identified in this study is the ‘mouth bar accretion element’, a succession of conformable second-order clinoforms, that are separated from one another by an erosional or depositional third-order surface, against which younger clinoforms downlap. The downlapping (rather than onlapping) of clinoforms against these surfaces is a key observation, because it implies that the surfaces represent back-stepping of the locus of sedimentation up the clinoform foreset, before re-progradation. Hence they represent growth of the same mouth bar with the third-order surface representing an intra-mouth bar surface of reorganization. In terms of architectural elements, the mouth bar accretion element occupies a hierarchical position between a bed/coset and a mouth bar, and is equivalent to a point or mid channel bar accretion element in fluvial systems (Miall, 1988; Doyle & Sweet, 1995; Durkin et al., 2017; Fig. 2) and lobe elements in submarine fan systems (Prelat et al., 2009).

Flume tank experiments reported by Van Wagoner et al. (2003) and Shaw et al. (2018) provide an autogenic mechanism for the formation of mouth bar accretion elements (Fig. 12). Following avulsion of a distributary into some standing body of water with an assumed depth greater than the potential of the associated jet to scour its base, jet deceleration via turbulent mixing results in deposition of suspended load to form a bar with a markedly long axis extending towards the basin. Vertical growth of the initial bar into the pathway of the jet leads to interaction between the jet and its own deposit, resulting in the jet flow shallowing and expanding laterally over the new obstacle. This introduces bed friction which supplements turbulent friction in the jet. Vertical growth of the mouth bar ceases at some threshold where the jet is too powerful to allow deposition, and further growth of the mouth bar occurs via basinward and lateral expansion. With time, flow shallowing over the mouth bar crest will also result in (Eulerian) flow acceleration and re-entrainment of sediment on the mouth bar top. Flow instabilities and topographic irregularities lead to the formation of one or more sub-channels at the top of the mouth bar, which stabilize and become the conduits for delivery of sediment to the margin of the mouth bar. This channelization extends the terminal distributary channel through the back of the mouth bar and begins to focus deposition where these channels meet open water at the topset–foreset break-in-slope. Thus, beyond some threshold (Phase V of Shaw et al., 2018), smooth, symmetrical expansion of the mouth bar ends, and further expansion is focused at one or more ‘sub-bars’. The experiments of Van Wagoner et al. (2003) show the formation of multiple ‘sub-bars’, either simultaneously or in close succession, with highly variable individual primary accretion direction vectors, that leads to the formation of a dendritic or leaf-like plan view morphology for the composite sandbody (Fig. 12).

These ‘sub-bars’ are represented in the stratigraphic record by the mouth bar accretion element described in this study (Fig. 2). The mouth bar aggradation sub-elements in MB2A and MB3A (Figs 4 and 5) record the initiation and vertical accretion of the middle and upper mouth bars immediately following channel avulsion into the standing body of water. The occurrence of bedforms in MB2A that extend to the toesets of clinothems, suggest that, unlike the experiments of Shaw et al. (2018), the distributary avulsed...
into a standing body of water that was initially shallow enough for the jet to interact with the bed (Fig. 11A). Down-flow and oblique to flow offlapping bar accretion clinoforms (the mouth bar expansion sub-element) record the basinward and lateral expansion of the mouth bar as the feature became an obstacle to the jet, resulting in flow expansion. Flattening of the jet results in flow acceleration which begins to channelize the top of the mouth bar (Fig. 11B). Rapid flow acceleration can lead to extensive truncation of the mouth bar topset and foreset, and flow can burst through the mouth bar front initiating a new aggradational bidirectionally downlapping barform over the erosional surface (the third-order mouth bar reorganization surface; for example, Figs 7 and 11B). The downlap of clinoforms onto these third-order surfaces inside the mouth bars (for example, Fig. 9) imply that later mouth bar elements initiate as smaller scale features than the earlier mouth bar accretion element. The likely explanation for this is that erosion on the mouth bar top initially forms small channels, which gradually become excavated, focusing increasing volumes of water and sediment at the element, before choking and abandonment of the element (Fig. 11C and D).

Data from this study suggest that multiple mouth bar elements form a larger, composite, mouth bar sandbody before its combined volume ahead of the feeding distributary leads to deceleration of the flow through intense bed friction, resulting in upstream channel avulsion via backwater effects. Within each channel-mouth bar complex there is one mouth bar, but up to four channel belts (Figs 4 and 5). A single mouth bar (and its deposit) should be the product of a single channel (and its deposit – a channel belt), so there is an apparent inconsistency in the number of architectural elements of equivalent hierarchy (c.f. Fig. 2). The explanation for this discrepancy is that mouth bar abandonment was accompanied by within-channel sedimentation of the feeding distributary, and avulsion occurred upstream (i.e. to the north-west) of the analysed section (Fig. 11D). Newly avulsed channels can cross-cut the older channel belts (forming a multi-storey channel sandbody), whereas their mouth bars are deposited compensationally, in or out of the approximately dip-oriented plane of cross-section provided by the cliffs at Jorcas (Fig. 11D). The hierarchical equivalent deposit to the multi-storey sand body is therefore a lithosome called mouth a bar complex (Fig. 2), which likely has a more strongly compensational stacking architecture than multi storey channel sandbodies when viewed in strike section.

Erosion surfaces at the base of ravinement elements in the Jorcas Section truncate multi-storey channel sand bodies, and by implication mouth bar complexes (Figs 4 and 5). Therefore, the ravinement at the top of each channel-mouth bar complex occurred after abandonment of the entire mouth bar complex, rather than after abandonment of individual mouth bars. Abandonment and ravinement may have been caused by wholesale abandonment of the mouth bar complex by upstream avulsion of a major distributary to a new location many kilometres away. In the context of slow basin subsidence and/or gradual but sustained eustatic sea-level rise and/or compaction of the mouth bar complex and its substrate, the mouth bar complex, and its associated multi-storey channel belt would have been drowned and its upper surfaces

This article is protected by copyright. All rights reserved
reworked. Deposition of the next channel-mouth bar complex did not resume again until the major feeding distributary re-avulsed to the site of the Jorcas Section.

SUMMARY AND CONCLUSIONS

Detailed architectural element and facies analysis of an exceptionally well-exposed shallow water mouth bar succession reveals that individual mouth bars are made up of lower order mouth bar accretion elements. Mouth bar accretion elements themselves can be made up of one or both of two sub-elements: (i) mouth bar aggradation sub-elements, characterized by beds or cosets that downlap bidirectionally on to a basal substrate, and are stacked in an aggradational motif; and (ii) mouth bar expansion sub-elements, characterized by beds or cosets that sequentially offlap mouth bar aggradation sub-elements, forming classical progradational clinothems with topsets, foresets and bottomsets that dip down or oblique to palaeoflow. Multiple mouth bar accretion elements are bound by higher (third) order erosional or depositional surfaces of mouth bar reorganization, against which younger clinoforms downlap and offlap. The mouth bar accretion element occupies the same hierarchical position as, for example, point or mid channel bar accretion elements and lobe elements, that have been previously described in fluvial and submarine fan systems, respectively.

These elements and sub-elements can readily be explained by intrinsic shallow water mouth bar processes that are supported by flume tank experiments of mouth bar growth and evolution. Following avulsion of a distributary into a standing body of water, the bathymetry of which is not much greater than the depth of the channel, turbulent expansion of the jet in combination with high bed friction results in rapid flow deceleration, and deposition of sediment in an aggradational bar-form – the mouth bar aggradation sub-element. Bar aggradation increases its interaction with the jet; the new obstacle causing flattening and lateral expansion of the jet and concomitant lateral expansion of the bar – the mouth bar expansion sub-element. Further flattening of the flow leads to its acceleration. The flow begins to form discrete channels on the bar top, which focuses further expansion of the mouth bar at individual loci where the channels break through to the front of the mouth bar. Here new mouth bar accretion elements form, downlapping and onlapping against third-order surfaces of mouth bar reorganization. New mouth bar accretion elements can form via the vertical growth of a new mouth bar aggradation sub-element, followed by evolution into a mouth bar expansion sub-element, or simply via the addition of mouth bar expansion sub-elements which offlap the older mouth bar accretion element. This mouth bar grows via the addition of multiple generations of mouth bar accretion elements in this manner, until the size of the composite mouth bar becomes too great an obstacle for the jet to sustain growth. In this case study, up to three mouth bar accretion elements are observed in each mouth bar, setting a minimum threshold of mouth bar growth by
addition of mouth bar accretion elements, before abandonment. The mouth bar is abandoned via upstream avulsion of the feeding distributary.

A general evolution in the style and facies of clinothems in the shallow water mouth bars is observed in one of the mouth bars analysed. Earlier clinothems are dominated by cross-bedded sandstone, and are characterized by low angle, tangential downlap of clinothems against the basal substrate. Later clinothems are dominated by ‘pinstripe’ and massive sandstone, and characterized by steep, oblique downlap of clinothems against the basal substrate. This facies and morphological change reflects the evolution from a scenario where the incoming jet is attached to the bed, and capable of driving ripples and dunes down the bar front, to one where the jet detaches from the bed at the mouth bar foreset, unloading its bedload at the mouth bar crest. Sand avalanches down the foreset until angle of repose is attained. This change is likely a function of the growth of the mouth bar as an obstacle to the jet, diminishing its ability to expand enough to remain attached to the seafloor at the mouth bar front. It is also likely a function of the progradation of the mouth bar into ever deeper waters because the seafloor was gently dipping basinward.

ACKNOWLEDGEMENTS

This work forms part of a University of Plymouth PhD studentship awarded to Grant Cole. Fieldwork costs were supported by grants received from the Cambridge Arctic Shelf Programme (CASP), the AAPG Foundation and the Geologists Association. Additional financial support was provided by PDS Group. The authors thank Matthew Mayer and Roderick Van Der Kroef (PDS Group) and Benjamin Dolva (University of Bergen) for assistance and discussion in the field and after. Figure 12A to D are modified from Shaw et al. (2018) with the kind permission of the authors. The manuscript enormously benefited from constructive comments and suggestions provided by Christian Haug Eide, Cornel Olariu, John Shaw and an anonymous reviewer, as well as Associate Editor Anna Pontén.
REFERENCES


This article is protected by copyright. All rights reserved


Peropadre, C., Liesa, C.L. and Meléndez, N. (2013) High-frequency, moderate to high-amplitude sea-
level oscillations during the late Early Aptian: Insights into the Mid-Aptian event (Galve sub-basin, Spain). Sed. Geol., 294, 233-250.


FIGURE CAPTIONS

Fig. 1. (A) Location of the study area on the Iberian Peninsula. (B) Geological map of the Aliaga–Allepuz area of the Galve Sub-Basin, based on the maps of Canerot et al. (1976), Gautier (1977) and aerial photographic interpretation undertaken for this study. Superimposed is an isopach map of net sandstone in the Xert Formation. Sedimentary logs from which the isopach map was constructed and their locations are provided in Supporting Information Appendix A and B. The location of the study area in (D), is shown. (C) Stratigraphic context and age of the fluvio-deltaic sandstones of the Xert Formation which are the subject of this study. Chronostratigraphy based on Garcia et al. (2014), Bover-Arnal et al. (2016) and Aurell et al. (2018). (D) Detailed geological map of the study area east and north of Jorcas, based on aerial photographic interpretation and field mapping undertaken for the purpose of this study. Mean dip direction of bar accretion surfaces (i.e. clinoforms) and azimuth of all palaeoflow measurements are also shown.

Fig. 2. Hierarchy of bounding surfaces and architectural elements developed in this study. Modified from Miall (1985; 1996) and adopted for a fluvio-deltaic setting. Surfaces are shown in bold and elements are shown in italic text. Scale and geometry are schematic and are not implied. See Figs 4 to 10 and text for specific details of scale and geometry of architectural elements and their bounding surfaces in the Jorcas case study.

Fig. 3. Representative photographs of the lithofacies identified in this study (A) Soft-weathering silty marl (Mfm), interbedded with more resistant beds of massive very fine to fine sandstone (Sm). (B) Bioturbated sandstone (Fb). (C) Soft-weathering silty marl (Mfm) interbedded with more resistant beds of bioturbated siltstone to very fine sandstone (Fb). (D) Bioclastic packstone bed (L). (E) Current ripple cross-laminated sandstone (Sr). (F) Massive, structureless sandstone (S). (G) An interval of coarse granular laminae within S. (H) Trough cross-bedded sandstone (St). (I) Planar cross-bedded sandstone (Sp). (J) Low-angle cross-bedded sandstone (Sl). (K) Intensely bioturbated granular sandstone (Sb). (L) Massive granular sandstone (Sgh). Barred increments on logging pole in (A), (I) and (J) are 10 cm long. Lens cap in (B), (D), (E), (K) and (L) is 5.5 cm across.

Fig. 4. (A) Lithofacies architecture of the Jorcas Section. The positions of Sedimentary Logs J1 to J14 are shown, and the positions of Figs 6 to 10 are highlighted. (B) Architectural elements of the Jorcas Section. The positions of Sedimentary Logs J1 to J14 are shown. So too are palaeoflow and direction of dip bar accretion (clinoform) surfaces, with blue and black rose diagrams, respectively. Bedding, and bar accretion surfaces have been removed for clarity. Abbreviations: CB = channel belt; MB = mouth bar accretion element; MC = minor channel element; RE = ravinement element. Note that CB, channel belts, are a higher
order of architectural element that MB, mouth bar accretion element and MC, minor channel. A summary cartoon of (B) is shown in Fig. 4. Sedimentary logs J1 to J14 are also provided in Supplementary Material Appendix C. (C) and (D) Parts of the virtual outcrop model used to make architectural sketches shown in (A) and (B).

**Fig 5.** Summary cartoon of the architectural elements of the Jorcas Section.

**Fig 6.** (A) Segment of the virtual outcrop model showing a mouth bar aggradation sub-element. (B) The same part of the virtual outcrop model with annotations. (A) and (B) show perspective. (C) Architectural sketch based on the virtual outcrop model, showing bed and coset boundaries (second-order bar accretion surfaces) bidirectionally downlapping a relatively flat depositional surface, and defining a bell-shape architecture. The underlying surface represents the (fifth-order) base of the mouth bar. (C) is corrected for perspective. See Fig. 4 for a key. The position of this architecture shown in this figure is shown on Fig. 4.

**Fig 7.** (A) Segment of the virtual outcrop model showing mouth bar aggradation, and mouth bar expansion sub-elements within a single mouth bar accretion element. (B) The same part of the virtual outcrop model with annotations. (A) and (B) show perspective. (C) Sketch based on the virtual outcrop model showing facies distribution and architecture of mouth bar aggradation and expansion sub-elements within a single mouth bar accretion element. Bed and coset boundaries (second-order bar accretion surfaces) in the middle upper part of the sketch downlap bidirectionally on to an erosional surface which truncates underlying beds and cosets. This is a mouth bar aggradation sub-element. To the right of the mouth bar aggradation sub-element, beds and cosets systematically offlap one another towards the right, defining classic clinothems, and represent a mouth expansion sub-element. This erosive, underlying (third-order) surface marks an intra-mouth bar episode of hydrodynamic reorganization. (C) is corrected for perspective. See Fig. 4 for a key. The position of this architecture shown in this figure is shown on Fig. 4.

**Fig 8.** (A) Segment of the virtual outcrop model showing a mouth bar expansion sub-element. (B) The same part of the virtual outcrop model with annotations. (A) and (B) show perspective. (C) Sketch based on the virtual outcrop model showing facies distribution and architecture of mouth bar expansion sub-elements. Bed and coset boundaries (second-order bar accretion surfaces) downlap sequentially on to a relatively flat, depositional surface. Clinothems topsets are absent, foresets are short, and toesets are long and inclined at low angles. Cross-beds, extend all the way down the bottomsets, and therefore so did dune migration. The underlying surface represents the (fifth-order) base of the mouth bar: (C) is corrected for perspective. See Fig. 4 for a key. The position of this architecture shown in this figure is shown on Fig. 4.

This article is protected by copyright. All rights reserved
**Fig 9.** (A) Segment of the virtual outcrop model showing mouth bar expansion sub-elements. (B) The same part of the virtual outcrop model with annotations. (A) and (B) show perspective. (C) Sketch based on the virtual outcrop model showing facies distribution and architecture of mouth bar expansion sub-elements. Clinothems and have short topsets and bottomsets, and relatively long, steeply dipping foresets. Clinothems are dominated by massive sandstone containing abundant granular laminae that represent grainflow avalanches down the mouth bar foresets. Three mouth bar accretion elements (MB2A to MB2C), from the same mouth bar, are shown. In the oldest, MB2A (second-order) bar accretion surfaces downlap on to a relatively flat, depositional surface that represents the base of the mouth bar. Topsets and foresets of MB2A bar accretion surfaces are truncated by a (third-order) mouth bar reorganization surface. The latter is downlapped by bar accretion surfaces of the later mouth bar accretion element, MB2B. Bar accretion surfaces of the youngest mouth bar accretion element, MB2C downlap, and climb down a mouth bar reorganization surface, that is largely parallel bar accretion surfaces in MB2B. Note the increase in inclination of mouth bar accretion foresets from MB2A to MB2C: (C) is corrected for perspective. See Fig. 4 for a key. The position of this architecture shown in this figure is shown on Fig. 4.

**Fig 10.** (A) Segment of the virtual outcrop model showing fluvial laterally accreting bar elements. (B) The same part of the virtual outcrop model with annotations. (A) and (B) show perspective. (C) Architectural sketch based on the virtual outcrop model, showing complex internal structure of cross-cutting bed and coset contacts (second-order bar accretion surfaces), but systematic downlap of (third-order) surfaces representing reorganization of the bar on to the basal (fifth-order) erosion surface that marks the basal scour of a major channel: (C) is corrected for perspective. See Fig. 4 for a key. The position of this architecture shown in this figure is shown on Fig. 4.

**Fig. 11.** Dip-oriented plan view and cross-sectional evolution of shallow water mouth bars, based on the architecture and facies of the middle mouth bar in Fig. 4. Implicit to the model is a bathymetric gradient of deepening away from the mouth of the channel. (A) Avulsion of a channel into the standing body of water. The jet expands vertically and laterally into the unconfined space and decelerates, leading to deposition of bed and suspended load. The mouth bar is initiated, aggrades vertically and expands laterally. The shallow bathymetries, and a relatively small size of the present mouth bar mean that the jet expands to occupy the full volume of the water column and is capable of driving bedload and bedforms down the length of the mouth bar. The first mouth bar accretion element is initiated. (B) Continued growth of the mouth bar as an obstacle in front of the distributary leads to horizontal expansion and flattening of the jet. This causes flow acceleration over the mouth bar, erosion of the back of the mouth bar and the formation of one or more subsidiary channels over the mouth bar top. These feed new mouth bar accretion elements with different scales, and accretion vectors which build out into progressively deeper water. The increasingly flattened jet,
combined with increasing bathymetries, results in the gradual detachment of the jet from the basin floor. Sediment is deposited on the crest of the mouth bar, attains angle of repose, and avalanches down the mouth bar front as grainflow deposits. (C) Mouth bar growth is sustained via the repetitive addition of mouth bar accretion elements, leading to a dendritic plan view morphology. (D) A critical threshold of mouth bar growth is attained where frictional deceleration of the jet by the mouth bar obstacle leads to choking of the feeding distributary. Within-channel sedimentation results in upstream avulsion, and abandonment of the mouth bar. Multiple mouth bars coalesce to form a Mouth bar Complex.

**Fig 12.** Flume tank experiment from Shaw *et al.* (2018) (A) to (D) and a modern day example (E) showing mouth bar growth via mouth bar elements. (A) Initiation of the mouth bar via vertical aggradation and basinward extension. (B) Horizontal expansion of the mouth bar. (C) First instance of channelization of flow on the mouth bar top and focusing of sedimentation at a single locus – the formation of a new mouth bar accretion element. (D) A mature mouth bar, composed of multiple mouth bar accretion elements, and a dendritic plan view. Run times and phases of the experiment of Shaw *et al.* (2018) are shown. (E) A similar morphology to (D) is expressed at the mouth of the Rio Garumo River, Panama (9°00’21” N, 82°10’46” W). This river is depositing a mouth bar into the Laguna de Chiriqui, which is protected from open ocean processes by a reef system, and is no deeper than 4 m (Hederndorf, 1982).

**SUPPLEMENTARY MATERIAL**

**Appendix A.** Geological map of the Aliaga–Allepuz area of the Galve Sub-basin, based on the maps of Canerot *et al.*, (1976), Gautier (1977) and aerial photographic interpretation undertaken for this study. Total sandstone isopach for the Xert Formation is overlain, and was constructed from sedimentary logs collected at Locations 1 to 28. The sedimentary logs are provided in Appendix B.

**Appendix B.** Sedimentary logs used to create total sandstone isopach map shown in Appendix A and Fig. 1B. Their locations are shown on Appendix A.

**Appendix C.** Sedimentary logs J1 to J14 used to create Fig. 4.

**TABLES AND CAPTIONS**

**Table 1.** Lithofacies of the Jorcas section. Carbonate facies are classified based after Dunham (1962). Facies codes are adapted from Miall (1996). Bioturbation index based on Taylor & Goldring (1993).
<table>
<thead>
<tr>
<th>Facies code</th>
<th>Facies</th>
<th>Colour and sedimentary features</th>
<th>Body and trace fossils</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mfm</td>
<td>Marl (silty)</td>
<td>Blue-grey to green-grey massive or fissile (laminated) marls and massive silty marls (Fig. 3A and C). These form successions up to 9 m thick</td>
<td>Abundant echinoids, gastropods and bivalves, rare brachiopods and occasional foraminifera (<em>Orbitolina</em>). BI = 0 to 6 with vertical and horizontal burrows</td>
<td>Suspension settling of clay and silt under low current velocities, combined with <em>in situ</em> micritic carbonate production. Occurrence of open marine fauna is indicative of normal marine salinities. Variation in BI suggests fluctuating depositional rates</td>
</tr>
<tr>
<td>Fb</td>
<td>Bioturbated siltstone to very fine sandstone</td>
<td>Massive, blue-grey siltstone to very fine, buff, yellow or orange, massive sandstone (Fig. 3B and C), occasionally containing convolute dish and pillar structures. These form successions up to 80 cm thick</td>
<td>Occasionally contains disarticulated, fragmented shelly material (mostly oyster) and coal flakes. BI = 5 to 6</td>
<td>Suspension settling from hypopycnal sediment plumes. The high BI indicates low depositional rates</td>
</tr>
<tr>
<td>Sm</td>
<td>Massive very fine to fine sandstone</td>
<td>Buff to ochre, sharp to occasional gradational based, massive, very fine to fine-grained sandstone (Fig. 3A). Slight normal grading occurs</td>
<td>Occasional occurrences of disarticulated, fragmented oyster shells. BI = 0 to 2</td>
<td>Deposition of sand under low-energy or waning flow conditions, possibly from hyperpycnal</td>
</tr>
</tbody>
</table>
at the top of a bed. Rarely contain convolute and dish and pillar structures. Beds are up to 40 cm thick but are commonly 10 to 20 cm thick.

<table>
<thead>
<tr>
<th>L</th>
<th>Limestone</th>
<th>Bioclastic wackestones, packstones (Fig. 3D) or grainstones with common nodular wackestones to packstones. The matrix of the wackestones and packstones is predominantly marl. Beds up to 30 cm thick</th>
<th>Allochems are predominantly fragmented, disarticulated bivalve shells. BI = 4 to 6 with vertical and horizontal burrows.</th>
<th>Re-working of bioclastic shelly material under moderate to high energy flow conditions to allow the allochems to be washed in and rapidly deposited. The high BI indicates prolonged non-deposition between events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sr</td>
<td>Current ripple cross-laminated sandstone</td>
<td>Buff, pink to orange, sharp to gradationally based, fine to medium-grained current ripple cross-laminated sandstone (Fig. 3E). Ripple cross-laminae commonly have a trough scour base. Beds are no more than 20 cm thick</td>
<td>No evidence of trace or body fossils. BI = 0</td>
<td>Migration of 2D and 3D ripples under unidirectional flow conditions in the lower flow regime</td>
</tr>
<tr>
<td>S</td>
<td>Massive sandstone</td>
<td>Buff to ochre, pink to orange, quartz-rich, very fine to granular, massive, and sharp based sandstone beds (Fig. 3F). Internally, a sandstone bed shows varying grain-size profile trends of normal, inverse or no grading. Within the coarser grained sandstones, granular laminae are common creating centimetre to decimetre vertical normal grading within beds, creating a pinstriped appearance (Fig. 3G). Finer beds rarely contain convolute and dish and pillar structures. Beds range from 0.4 to 1.0 m thick</td>
<td>BI = 0 to 1, less commonly 2 to 4 with horizontal and vertical burrows. Rare fragments of wood</td>
<td>Deposition of sand under conditions of waxing and waning flows. The presence of bioturbation indicates periods of non-deposition between events allowing faunal re-working of the sediment. The granular laminae are interpreted to be the result of grainflow.</td>
</tr>
<tr>
<td>St</td>
<td>Trough cross-bedded sandstone</td>
<td>Buff, pink to orange, quartz-rich, upper fine to upper granular, moderately sorted trough cross-bedded sandstones (Fig. 3H). Large granules to small pebbles are often encountered at the base of the sandstone beds. Beds range from 0.1 m to 1.3 m, but generally 0.3 to 0.5 m thick. Toesets of the trough cross-beds are often granular creating normally graded bedsets</td>
<td>No evidence of trace or body fossils</td>
<td>Migration of 3D dunes under unidirectional flow conditions in the lower flow regime. The granular foresets likely represent grain avalanching</td>
</tr>
<tr>
<td>Sp</td>
<td>Planar cross-bedded sandstone</td>
<td>Buff, pink to orange, quartz-rich, upper fine to upper granular, moderately sorted sandstones (Fig. 3I). Large granules to small pebbles are often encountered at the base of beds. Sandstone beds contain small (10 to 30 cm) and medium to large scale (ca 0.5 m) planar to sometimes slightly concave-up</td>
<td>No evidence of trace or body fossils</td>
<td>Migration of 2D dunes (transverse) under unidirectional flow conditions in the lower flow regime. The granular foresets likely represent grainflow</td>
</tr>
</tbody>
</table>
cross-stratification. Internally, the sandstone beds are normally graded. The foresets of the planar cross-bedding are often granular, creating small-scale (cm) normal grading. Beds range from 0.2 to 1.5 m thick

<table>
<thead>
<tr>
<th>SI</th>
<th>Low-angle cross-bedded sandstone</th>
<th>Buff, pink, orange, sharp based, fine to medium-grained sandstones (Fig. 3J) that contain low-angle (&lt;15°) cross-bedding (up to 0.7 m in thickness). Sandstone beds show normal grading with rare inverse grading at their tops and erosional bases. Beds range from 0.2 to 0.7 m thick</th>
<th>No evidence of trace or body fossils</th>
<th>The high energy erosional cut and waning energy back-filling of sediment to produce scour-fill bedforms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sb</td>
<td>Bioturbated fine to granular sandstone</td>
<td>Buff, cream, grey, purple, pink, orange and ferruginous, fine to (predominantly) granular, massive sandstone (Fig. 3K). Beds range</td>
<td>Bioturbation index of 5 to 6. Rare articulated oyster shells at the top of beds</td>
<td>Erosive re-working of material through wave action resulting in a lag deposit. The high BI indicates prolonged non-deposition. The presence of articulated</td>
</tr>
</tbody>
</table>
from 0.2 to 1.0 m thick

| SGh        | Massive granular sandstone | Buff to ochre, pink to orange massive granular sandstone (Fig. 3L). Decimetre beds ranging from 10 to 30 cm thick | No evidence of trace or body fossils | Erosive, re-working of material through the cut of a new channel | oyster shells at the top of beds likely represents the formation of a firm or hardground |

This article is protected by copyright. All rights reserved
Truncation of (2nd order) bar accretion surfaces by (3rd order) intra mouth bar reorganization surface

(2nd order) bar accretion surfaces downlap (3rd order) intra mouth bar reorganization surface
Cross-beds extend down length of clinotherm

Low angle downlap of (bar accretion) clinoforms on to base of mouth bar

sed_12825_f8.tif
Erosional base of channel belt

Downlap of bar reorganization surfaces on to the erosional base

sed_12825_f10.tif
A) Initiation, vertical growth and lateral expansion of a shallow-water mouth bar accretion element.

B) Jet flow flattening and acceleration leads to the formation and addition of a new mouth bar accretion element.

Vertical mouth bar growth flattens and accelerates the jet over the mouth bar crest. The flow erodes the mouth bar crest, bursts through and begins to deposit a new mouth bar accretion element which overtops or offlaps the older accretion element. Growth of a composite mouth bar body and expansion of the mouth bar into deeper water reduces the capacity of the jet to remain attached to the bed beyond the mouth bar crest.

C) Repeated phases of (B) lead to the formation and addition of multiple mouth bar accretion elements

The composite mouth bar grows, via the repeated addition of mouth bar accretion elements. Expansion into ever deeper water results in a change in mouth bar morphology and processes, from one with relatively low angle foresets, dominated by traction at the bed, to a mouth bar characterized by a steep front dominated by grainflow deposition.

D) Channel avulsion abandons the composite mouth bar.

Critical threshold of mouth bar growth where frictional deceleration of the jet leads to backwater choking and sedimentation in the feeding channel. The channel avulses and the mouth bar is abandoned.

Upstream avulsion results in the deposition of a new mouth bar out of the plane of observation.