Hyperpycnal delivery of sand to the continental shelf: Insights from the Jurassic Lajas Formation, Neuquén Basin, Argentina

ABSTRACT

Hyperpycnal currents are river-derived turbidity currents capable of transporting significant volumes of sediment from the shoreline onto the shelf and potentially further to deep ocean basins. However, their capacity to deposit sand bodies on the continental shelf is poorly understood. Shelf hyperpycnites remain an overlooked depositional element in source to sink systems, primarily due to their limited recognition in the rock record. Recent discoveries of modern shelf hyperpycnites, and previous work describing hyperpycnites deposited in slope or deep-water settings, provide a valuable framework for understanding and recognizing shelf hyperpycnites in the rock record. This article describes well-sorted lobate sand bodies on the continental shelf of the Neuquén Basin, Argentina, interpreted to have been deposited by hyperpycnal currents. These hyperpycnites of the Jurassic Lajas Formation are characterized by well-sorted, medium-grained, parallel-laminated sandstones with hundreds of metre extensive, decimetre thick beds encased by organic-rich, thinly laminated sandstone and siltstone. These deposits represent slightly obliquely-migrating sand lobes fed by small rivers and deposited on the continental shelf. Hyperpycnites of the Lajas Formation highlight several unique characteristics of hyperpycnal deposits, including their distinctively thick horizontal laminae attributed to pulsing of the hyperpycnal currents, the extraction of coarse gravel due to low flow competence, and the extraction of mud due to lofting of light interstitial fluid. Recognition of shelf hyperpycnites in the Lajas Formation of the Neuquén Basin allows for a broader understanding of shelf processes and adds to the developing facies models of hyperpycnites. Recognizing and understanding the geometry and internal architecture of shelf hyperpycnites will improve current understanding of sediment transfer from rivers to deeper water, will improve palaeoenvironmental interpretations of sediment gravity-flow deposits, and has implications for modelling potentially high-quality hydrocarbon reservoirs.

Keywords Continental shelf, hyperpycnal current, hyperpycnite, Lajas Formation, Neuquén Basin, shelf sandstone, turbidite.
INTRODUCTION

Although deep-water deposits dominate the literature regarding sediment gravity flows, gravity-driven processes operating on continental shelves may also play an important role in the transport of sediment from source to sink (e.g. Middleton & Hampton, 1976; Lowe, 1982; Normark & Piper, 1991; Mulder & Alexander, 2001; Mutti et al., 2003). Sand deposition on the continental shelf remains understudied, primarily because few mechanisms explain significant cross-shelf transport of sand, particularly during sea-level highstand. Processes commonly thought to transport sediment on continental shelves include tides, waves and shore-parallel geostrophic currents (Cacchione & Drake, 1990; Myrow & Southard, 1996; Midtgard, 1996). These processes alone may be capable of suspending enough sediment to induce cross-shelf gravity-driven flow, and the addition of flood pulses of river-derived sediment to the continental shelf can generate hyperpycnal currents capable of transporting and depositing large volumes of sand beyond the high energy shoreline (Wright et al., 1988; Mutti et al., 1996, 2003; Warrick et al., 2013; Steel et al., 2016). Recognition of river-derived gravity currents on the continental shelf is critical because it allows for more accurate interpretations of the depositional record, including improved palaeoenvironmental models, and a broader understanding of mechanisms capable of producing shelf sand bodies, which has implications for sediment dispersal into basins and for hydrocarbon reservoir modelling.

Previous work on shelf sand bodies has primarily focused on reworked transgressive features or relict lowstand deposits (e.g. Houbolt, 1968; Bergman & Snedden, 1999, and references therein; Leva López et al., 2016). However, relatively few studies document shelf sand bodies deposited by hyperpycnal currents in the rock record or on modern shelves (Mutti et al., 2003; Lamb et al., 2008; Warrick et al., 2013; Steel et al., 2016). Hyperpycnal currents are gaining recognition as important mechanisms for cross-shelf transport of sediment, and early work on hyperpycnal currents has led to an improved understanding of conditions conducive to the generation of hyperpycnal currents and their deposit characteristics. Mulder & Syvitski (1995) showed the importance of relatively small rivers in the generation of hyperpycnal currents. Studies of modern and ancient hyperpycnites found that deposits commonly contain an abundance of terrestrial organic debris due to the plunging of river outflow as it enters salt water (Plink-Bjorklund & Steel, 2004; Zavala et al., 2006a; Myrow et al., 2008; Zavala et al., 2012a). Furthermore, freshwater within hyperpycnal currents may result in lofting, also known as buoyancy reversal, in which the current becomes lighter than the surrounding ambient water and lifts off from the basin floor (Sparks et al., 1993; Hurzeler et al., 1995; Hogg et al., 1999). Lofting has been shown to affect grain sorting (e.g. Pritchard & Gladstone, 2009; Zavala et al., 2011; Steel et al., 2016) and bed geometry of hyperpycnites (Plink-Bjorklund & Steel, 2004; Gladstone & Pritchard, 2010; Zavala et al., 2011; Steel et al., 2017a). A facies model proposed by Zavala et al. (2011) breaks hyperpycnal deposits into facies formed through bed-load, suspended load and lofting transport processes, and is applicable to many depositional settings. Although hyperpycnites are gaining recognition, wider acceptance and promotion of hyperpycnite facies models necessitates a broader range of studies describing their facies variability and stratigraphic architecture, specifically in continental shelf settings which have largely been overlooked. It should be noted, however, that hyperpycnal, river-derived deposits may be difficult to preserve on open-coast shelves because of storm-wave and possible tidal-current reworking. Preservation potential will be much greater on shelves other than on continental margins, such as rift, back-arc or foreland basins, that are protected from storm-wave activity.

The objectives of this work are to: (i) describe the geometry, internal architecture and facies variability of certain shelfal sandstones deposited on the shallow continental shelf of the Neuquén Basin in south-western Argentina; and (ii) place them in the context of previously described shelf sand bodies in order to understand the processes responsible for their deposition. The hypotheses are: (i) that lobate sand bodies in the La Jardinera region of the Neuquén Basin were deposited by hyperpycnal currents fed by relatively small fluvial systems; and (ii) that these sandstones are well-sorted due to processes inherent to hyperpycnal currents, such as lofting and low flow competence (Sparks et al., 1993; Zavala et al., 2011; Steel et al., 2016). These aims have implications for understanding basin evolution and source to sink sediment transport, particularly in foreland basins characterized by steep basin catchments, narrow margins and high sediment–water ratios, which are
conducive to the generation of hyperpycnal currents (Mulder & Syvitski, 1995). Furthermore, if these sand bodies in the Neuquén Basin were deposited by hyperpycnal currents, describing their facies variability and depositional architecture will help either to confirm or modify recently developed hyperpycnite facies models.

STUDY AREA

Geological setting

The Neuquén Basin lies in west central Argentina between 32°S and 40°S latitude (Fig. 1A). The basin is bounded to the west by the Andean Cordillera, to the north-east by the Sierra Pintada Massif and to the south by the North Patagonian Massif (Fig. 1A). The Neuquén Basin spans an area of over 160 000 km², contains a sedimentary succession up to 7000 m thick, and records a complex basin evolution including multiple phases of extension and tectonic inversion during the Late Triassic to Palaeogene (Yrigoyen, 1991; Vergani et al., 1995; Franzese & Spalletti, 2001; Howell et al., 2005; Mosquera & Ramos, 2006). Late Triassic to Early Jurassic rifting associated with the collapse of the Gondwana orogen created a series of narrow, elongate half-grabens (Uliana et al., 1989; Franzese & Spalletti, 2001; Franzese et al., 2003). In the Early Jurassic, development of a magmatic arc along the western edge of Gondwana led to a transition from mechanical to thermal subsidence and caused integration of the many depocentres into the larger Neuquén back-arc basin (Franzese et al., 2003). The basin experienced several episodes of uplift and erosion associated with tectonic inversion of rift-related fault bocks during the Jurassic (Mosquera & Ramos, 2006). Erosional and angular unconformities provide evidence for partial inversion and segmentation of some depocentres in the Early Jurassic (Mosquera & Ramos, 2006). This was followed by two periods of tectonic inversion in the Callovian and the Late Oxfordian to Early Kimmeridgian, which resulted in partial erosion of Jurassic strata along basin margins and in uplifted regions such as the Dorsal de Huincal, Chacaico, Vaca Muerta, Reyes and Cara Cura ranges (Vergani et al., 1995). During the early Cretaceous, renewed subsidence resulted in widespread marine deposition in all Patagonian back-arc basins and the Neuquén Basin reached its maximum sag phase (Franzese et al., 2003; Howell et al., 2005). Andean compressional tectonics associated with a shallowly dipping subduction zone in the Late Cretaceous initiated a retro-arc foreland basin phase, which

Fig. 1. Study area and stratigraphy. (A) Map of the Neuquén Basin, modified from Franzese et al. (2006). The Neuquén Basin lies in western Argentina, between 32°S and 40°S. The study area near La Jardinera is indicated by the black star. Rift depocentres associated with pre-Andean extension are indicated by grey polygons. The basin is bounded by the Sierra Pintada Massif and the North Patagonian Massif to the north-east and south, respectively. (B) Jurassic and Early Cretaceous stratigraphy of the Neuquén Basin, modified from Paim et al. (2008). The focus of this study is the Lajas Formation, within the Jurassic Cuyo Group.

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resulted in a lost connection to the Proto-Pacific Ocean (Introcaso et al., 1991).

Stratigraphy

A thick and relatively continuous stratigraphic succession records the evolution of the Neuquén Basin during the Late Triassic to Early Cenozoic (Lagarreta & Gulisano, 1989; Lagarreta & Uliana, 1991; Vergani et al., 1995; Howell et al., 2005). The succession contains an excellent record of marine invertebrates, leading to a refined biostratigraphic framework with over 30 Jurassic ammonite biozones (Leanza, 1981; Riccardi, 1983; Howell et al., 2005). During a period of mechanical and thermal subsidence in the Early Jurassic to Early Cretaceous, thick sedimentary successions of the Cuyo, Lotena and Mendoza groups were deposited in the Neuquén Basin, where they record a series of transgressive-regressive cycles due to complex interactions between sediment supply, tectonics and eustatic sea level (Fig. 1B; Howell et al., 2005). One of the second-order transgressive-regressive cycles is recorded within the Middle Jurassic Cuyo Group, which consists of a thick marine shale and turbidite succession of the Los Molles Formation, coeval deltaic and shelfal deposits of the Lajas Formation, and alluvial plain sediments of the Challaco Formation (Fig. 1B; Zavala & Gonzalez, 2001; McIlroy et al., 2005; Paim et al., 2008; Canale et al., 2015; Gugliotta et al., 2015).

The Lajas Formation in the eastern and southeastern reaches of the basin has been interpreted previously in terms of tide-dominated deltas (McIlroy et al., 2005; Morgans-Bell & McIlroy, 2005), mixed-energy deltaic systems (Gugliotta et al., 2015; Rossi & Steel, 2016) and river-dominated deltas affected by hyperpycnal flows (Zavala & Gonzalez, 2001; Canale et al., 2015). The transition between the Lajas Formation and underlying Los Molles Formation is characterized by repeated cycles of shallow marine mid to outer shelf deposits scoured by fluvial channels, and these in turn are overlain by cycles of inner shelf nearshore and deltaic deposits of the upper Lajas Formation (Paim et al., 2008). The focus of this study is within some of the southernmost Lajas Formation outcrops, directly above the transition from the Los Molles Formation. This study area provides insight into processes operating on the mid to outer continental shelf and to the deposition of well-sorted shelf sand bodies.

METHODOLOGY

This study focuses on a locality within the La Jardinera region of the Neuquén Basin cropping out near 39°24′30″S and 70°42′W (Figs 1 and 2). Detailed stratigraphy immediately above the transition from the deep-water slope of the Los Molles Formation to the shelfal Lajas Formation was analyzed by measuring seven, closely spaced sedimentary sections (Figs 3, 4 and S1). These measured sections provide a high resolution analysis of grain-size trends, sedimentary structures and bed characteristics of a ca 40 m thick succession that spans a width of ca 300 m. Grain size of each bed was measured using a Peak pocket microscope (GWJ Company, La Quinta, CA, USA) with 25× magnification and a 0-130° field of view. Grain-size classifications are based on the Wentworth grain-size scale (Wentworth, 1922). Measured sections are supplemented with outcrop photographs, drone photographs and palaeocurrent measurements. Bed orientations and palaeocurrent measurements were made using a Brunton compass (Brunton, Louisville, CO, USA) and reported palaeocurrent measurements have been corrected for structural attitude of the beds. In order to ensure accurate correlations between measured sections, numerous marker beds were walked out between sections and labelled with chalk.

RESULTS AND INTERPRETATIONS

The lowermost part of the Lajas Formation in this region displays a 40 m thick, crudely coarsening-upward succession in which mudstone and thin sandstone beds are overlain by well-sorted, lobate sandstone bodies with thick, parallel laminations. The well-sorted sandstone bodies are encased by shale and organic-rich siltstone and sandstone, and display compensational stacking as well as slightly oblique migration with respect to the main shelf slope. The succession is capped by thickly bedded conglomeratic sandstones and cross-stratified coarse sandstones. The bedding geometry is described in more detail below.

Sedimentary facies

The following sedimentary facies are present in the lower deposits of the Lajas Formation of the Neuquén Basin near La Jardinera:
Thickly-laminated well-sorted sandstone – facies SL
Facies SL consists of very well-sorted sandstone with grain sizes ranging from medium-lower to coarse-upper sand (Fig. 5A and B). The most distinctive features of facies SL are the continuous planar-laminations that range in thickness from a few millimetres up to centimetre-scale. Bed thicknesses are typically 20 to 40 cm, but range from ca 3 cm up to ca 90 cm. Beds are sharp-based and contain rare tool marks indicating palaeoflow direction. Some beds contain intense bioturbation that disrupts laminations and gives beds a massive appearance (Fig. 6A and B). The tops of some facies SL beds are cross-stratified (Fig. 4). Beds of facies SL are organized into lobate sand bodies with flat bases and convex-upward tops. This facies has a quartz : feldspar : lithic ratio (QFL) of 50 : 40 : 10.
Interpretation of laminated sandstone facies ($S_L$)

Beds of facies $S_L$ are interpreted here to represent deposition by hyperpycnal currents. Packages of facies $S_L$ are distinctive in their well-sorted nature and extensive thick laminae. Many of the laminae are markedly thicker than is common in upper-phase plane beds. Sharp or erosional based, decimetre thick, parallel laminated sandstones are typical for sustained gravity flows and have been commonly interpreted as river-derived hyperpycnites (Mulder et al., 2001, 2003; Mutti et al., 2003; Plink-Bjorklund & Steel, 2004; Petter & Steel, 2006). Modern hyperpycnites with similar characteristics were identified in the Var submarine system (Mulder et al., 2001). Some laminae within beds display a thickening to thinning-upward pattern, over vertical scales of ca 10 to 20 cm, which may record a waxing to waning flood cycle with laminae formed by pulses within a single flood. As discussed in more detail later, laminae within hyperpycnites may also record superposition of oscillatory wave motion on hyperpycnal currents (Myrow & Southard, 1996; Macquaker et al., 2010). The pattern of coarsening-upward and thickening-upward beds within lobes is interpreted as evidence of lobe progradation because thicker and coarser beds suggest more proximal deposition. Palaeocurrent measurements are limited ($n = 13$), but tool marks at the base of facies $S_L$
Sedimentary structures:
- Parallel laminations
- Cross-stratification
- Organic debris
- Shell fragments
- Bioturbation
- Charcoal
- Mud clast
- Convolute bedding

Paleocurrent measurement:
- Unidirectional indicators ($n = 8$; cross-strata)
- Bi-directional indicators ($n = 5$; tool marks; darker shade is preferred orientation)

Sedimentary facies:
- Coarse, pebbly sandstone
- Channelled pebble conglomerate
- Laminaled sandstone
- Massive sandstone
- Fine-grained sandstone
- Shale

Continental shelf hyperpycnites

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beds suggest a palaeoflow to the north-east (with the exception of one south-eastward measurement; Figs 4 and 7), which match the regional palaeoflow directions of nearby slope channels, suggesting offshore-directed flow (Vann, 2013; Tudor, 2014; Steel et al., 2017b). Cross-stratification at the tops of facies SL beds primarily record east/south-eastward palaeoflow directions and one westward palaeoflow direction (Figs 4 and 7). The orientation of these cross-strata probably reflect some post-depositional reworking of hyperpycnites by waves or tidal currents. Another potential interpretation of these palaeocurrent indicators is that the lobes simply underwent frontal accretion towards the east rather than oblique migration. However, the oblique migration interpretation is preferred because: (i) the tool marks, which record primarily north/north-eastward palaeoflow with some eastward-directed palaeoflow, are more likely to record the hyperpycnal flow direction than the cross-strata found at the tops of beds, which may have formed as a result of post-depositional reworking; (ii) the regional

Fig. 5. Sedimentary facies in the study area. (A) Stacked bedsets of facies SL. (B) Closer view of facies SL clearly showing the parallel laminations within these deposits. Pencil for scale is 14 cm long. (C) Hummocky cross-stratification of facies S_{HCS}. (D) Interbedded fine-grained sandstone, siltstone, and shale of facies S_{X}. Dark flecks visible along bedding planes are charcoal and organic debris. Field notebook is 12 cm wide. (E) Coarse-grained sandstone representative of facies S_{C}. (F) Channel fill consisting of conglomerates and coarse-grained sandstone of facies C_{C}. This channel has several fining-upward packages with scoured bases and pinches out laterally. Rock hammer for scale (ca 70 cm long). (G) Clast-supported pebble conglomerate characteristic of facies C_{T}, with some sandy lenses shown. (H) Facies S_{M} is poorly-sorted sandstone with scattered organic debris and shell fragments. (I) Facies S_{F} is fine-grained sandstone that is poorly exposed and easily weathered. This is an example of one of the best exposures of facies S_{F}. (J) Laminated shale, characteristic of facies M.
north-eastward direction of the shelf-slope system (Vann, 2013; Tudor, 2014; Steel et al., 2017b) matches the orientation of measured toolmarks; and (iii) bounding surfaces within the deposits do not indicate simple eastward progradation, with truncated tops and downlap to the east, but instead display a wedge-like geometry in which beds taper and pinch-out to the east and west (Fig. 8). This wedge-shaped geometry suggests that the east–west directed outcrop is not exactly oriented parallel to palaeoflow but is instead at an oblique angle. Palaeocurrent measurements therefore lead to the interpretation that north-east-directed hyperpycnal currents built prograding lobes on the outer continental shelf, followed by an eastward lateral migration and compensational stacking of individual lobes. Subsequent reworking between hyperpycnal events and following lobe abandonment resulted in the development of some cross-strata and hummocky cross-stratification (HCS; see below). Care should be taken, however, when interpreting palaeocurrent measurements in this study because of the limited number of available palaeocurrent indicators, many of which come from similar horizons within the stratigraphy. The authors do not completely rule out the possibility of eastward accretion of these lobes with no oblique migration; however, the distinction between these two possibilities does not change the primary interpretation that these lobate sand bodies were deposited by hyperpycnal currents on the continental shelf.

Hummocky cross-stratified sandstone – facies SHCS
Facies S_{HCS} is found near the base of the section as well as at the top of some packages of facies S_{L} (Fig. 4). This facies consists of well-sorted fine to medium-grained sandstone containing HCS with metre-scale wavelengths (Fig. 5C; Harms et al., 1975; Hamblin & Walker, 1979; Dott & Bourgeois, 1982). Over distances of tens of metres, many beds with HCS transition laterally to beds of the same thickness that contain millimetre-scale wavy laminations.

Interpretation of hummocky cross-stratified facies (S_{HCS})
The presence of hummocky cross-stratified facies S_{HCS} above and below the sand lobes suggests shelfal water depths (Harms et al., 1975; Hamblin & Walker, 1979; Dott & Bourgeois, 1982; Morsilli & Pomar, 2012). Hummocky cross-stratification is most commonly attributed

Fig. 6. Photographs of sedimentary structures and outcrop features. (A) and (B) Examples of bioturbation within facies S_{L}. Field notebook is 12 cm wide. (B) Bi-directional cross-stratification at the top of a hyperpycnal lobe. Cross-stratification directions indicated by white arrows. (D) Scoured surface filled with coarse-grained sandstone at the top of a bedset of facies S_{L}. Scour and fill structures such as these may be formed by reworking of sediment by storms or tides, or may reflect pulses in flood strength. (E) Aligned organic material and charcoal at the base of a bed of facies S_{L}. (F) Large charcoal fragment aligned with a bedding plane of facies S_{L}. Hand lens is 44 cm long.
Internal waves may also form HCS, which expands the depth range that may be associated with these sedimentary features, but no clear evidence allows for the distinction between HCS formed by wind waves or internal waves. Although HCS formed by internal waves may deposit in a wide range of water depths associated with the depth of the pycnocline, internal waves most commonly interact with the sea bed in the mid-shelf region (Morsilli & Pomar, 2012). Hummocky cross-stratification is found only at the top of lobes, which suggests that reworking by storm waves most probably occurred after the locus of deposition migrated to the east, during the development and progradation of a new lobe. Alternatively, the formation of HCS within lobes could have occurred during flood events and been removed by successive hyperpycnal currents. Moderate bioturbation also suggests quiescent periods between deposition of bedsets and following lobe abandonment.

**Heterolithic sandstone, siltstone and shale – facies $S_{H}$**
Facies $S_{H}$ is commonly found below, lateral to, and above most beds of facies $S_{L}$ (Fig. 4). This facies is heterolithic, with alternating millimetre-scale laminations of fine-grained sandstone, siltstone and shale (Fig. 5D). The most predominant lithology in this facies is fine-grained sandstone with millimetre-scale parallel laminations. Charcoal, plant fragments and organic debris are abundant and are typically aligned along laminations and bedding planes (Figs 5D and 6E). The QFL ratio for this facies is 40 : 50 : 10.

**Interpretation of heterolithic sandstone facies ($S_{H}$)**
In La Jardinera, the thinly laminated, organic-rich facies $S_{H}$ are interpreted as deposits from
lofted plumes. Freshwater within hyperpycnal currents has the potential to loft from the flow and rise vertically, or to induce buoyancy reversal of the entire current (Sparks et al., 1993). The lofting plume can carry with it light constituents, such as fine-grained sediment and organic matter, which eventually settle out over a broader region (Zavala et al., 2011; Pritchard & Gladstone, 2009). These beds are analogous to lofting rhythmites of Zavala et al. (2006b).

Tabular pebble conglomerate – facies $C_T$

Facies $C_T$ predominantly comprises clast-supported pebble conglomerates, although beds range from very coarse-grained sandstone to cobble conglomerates (Fig. 5G). Pebbles and coarse grains typically form faint laminations or coarse lenses within beds. Many beds contain mud clasts ranging from 1 mm up to 30 cm in diameter, and some beds contain internal scours filled with gravel. The average pebble conglomerate bed thickness is ca 1 m, but beds can reach up to 2.5 m thick.

Interpretation of tabular conglomerate facies ($C_T$)

Conglomerates and very coarse-grained sandstone beds of facies $C_T$ were deposited above the hyperpycnites and are interpreted to represent the shallow-water fall-out of coarse material in the early stages of hyperpycnal flow development. The hyperpycnal flows are likely to have had low competency compared to surge-type turbidity currents due to their fresh rather than saline interstitial water, which would limit their ability to carry very coarse sand and gravel far beyond the shoreline. These conglomerates contain scour and fill structures, faint parallel laminations and rare mud clasts at their bases. They
are likely to be affected by shallow-water processes, such as wave reworking, which would explain the faint laminations, scouring, and discontinuous coarse-grained lenses. Deposits of facies C_F are interpreted to mark a shallow-water gravel front landward of the sandy hyperpycnites. The fairly distinct break in grain size between facies C_F and the underlying fine-grained sandstones (Figs 4 and 7) suggests an abrupt deposition of gravelly beds, probably due to low hyperpycnal flow competence. Furthermore, ca 10 m of poorly exposed mudstone and fine-grained sandstone between facies C_F and the underlying hyperpycnites suggests some bypass of hyperpycnal currents on the inner continental shelf before the deposition of thick hyperpycnite lobes (facies S_L; Figs 4 and 7).

Coarse-grained cross-stratified sandstone – facies S_C
Facies S_C is characterized by very coarse-grained sandstone with floating granules and pebbles (Fig. 5E). Beds of facies S_C are typically trough cross-stratified, contain scour and fill structures, and rarely contain bi-directional cross-stratification. Mud rip-up clasts are common at the base of facies S_C. Granules and coarse sand grains form laminations in some beds. Facies S_C is found at the top of the section and in association with conglomerates of facies C_C (Fig. 4).

Channelized conglomerate – facies C_C
Facies C_C is characterized by pebble conglomerates with scoured bases and abundant internal scours (Fig. 5F). Large (decimetre-scale) pieces of petrified wood are common and a 1.5 m diameter tree trunk was found within this facies ca 50 m to the east of measured section ‘A’ (Fig. 4). Conglomerates form sedimentary bodies that are tens of metres wide and ca 1 m thick with concave-up basal contacts and are interpreted as channel fills. Multiple sets of truncated surfaces within channel bodies suggest that they were built by several episodes of scour and fill. Beds are clast-supported, poorly sorted, and display coarse-tail fining-upward patterns, typically from cobble-size to coarse sand.

Interpretation of coarse-grained sandstone facies (S_C) and coarse-grained conglomerate facies (C_C)
The stratigraphic section is capped by trough cross-stratified sandstone and channelized conglomerates of facies S_C and C_C. Based on the abundant petrified wood, clast-supported framework, fining-upward patterns and erosional bases, these facies are interpreted as deposits from the streams that fed the hyperpycnal currents. The absence of lateral accretion in these deposits supports the interpretation of a small, braided system rather than a larger, meandering river (Miall, 1977).

Massive, organic-rich sandstone – facies S_M
Facies S_M is characterized by massive, organic-rich, fine to medium-grained sandstone (Fig. 5H). These sandstone beds contain scattered organic fragments and shell fragments up to 1 cm in diameter and are more poorly sorted than other sandstone facies, with grains ranging from coarse silt to medium-grained sand. Beds of this facies are most common at the base of the section, but can also be found between S_L beds and the overlying conglomeratic beds of facies S_C and C_C (Fig. 4). This facies has a QFL ratio of 50 : 30 : 20.

Interpretation of massive sandstone facies (S_M)
Beds of facies S_M make up a small proportion of the section, but are observed both below and above hyperpycnal lobes (facies S_L). These beds are structureless and contain scattered shells and organic fragments. The origin of this facies is unclear, but potential interpretations include debris-flow deposition or tidally reworked shelf sands.

Fine-grained sandstone facies (S_F)
Facies S_F is characterized by very fine to fine-grained sandstone that typically contains millimetre-scale laminations (Fig. 5I). Facies S_F contains moderate amounts of organic debris and shell fragments. This facies weathers easily and typically has very poor exposures. This facies has more lithic grains than facies S_L and is moderately sorted, with a QFL of 35 : 30 : 35.

Interpretation of fine-grained sandstone facies (S_F)
The origin of facies S_F is difficult to interpret, primarily because these deposits are heavily weathered and poorly exposed. These sandstones are thinly laminated and very fine-grained, and contain organic debris and few shell fragments. Plunging of river effluent and the subsequent generation of hyperpycnal currents requires very high suspended sediment concentrations, and rivers more commonly generate hypopycnal plumes in which freshwater
and suspended sediment override the ambient salt water and eventually settle from suspension (Bates, 1953). A tentative interpretation is that beds of facies $S_T$ were deposited by hypopycnal plumes from local rivers and were possibly reworked or re-distributed by background shelf processes (for example, tides and waves).

**Shale facies M**
Facies M is found at the base of all measured sections (Fig. 4) and consists of laminated shale, with rare siltstone and sandstone interbeds (Fig. 5J). Siltstone and sandstone interbeds are commonly ca 1 cm thick, but can be up to 5 cm in thickness. Facies M becomes less abundant higher in the succession.

**Interpretation of shale facies (M)**
Facies M is interpreted as muds deposited in a distal shelf environment. Thin sand interbeds within facies M are interpreted as distal turbidites deposited either on the axial margins or basinward reaches of hyperpycnite deposition.

**Sandstone lobe stratigraphy**
The apparent geometry of the deposits is lobate (flat base and convex-up, with a thick centre thinning laterally) rather than channelized (convex-down and flat top; Fig. 7). Sandstone beds in this succession are organized into four discrete lobate packages, each of which are on the order of 10 m thick and ca 150 m wide (Figs 4 and 7). Beds coarsen and thicken upward within lobes. A hierarchy exists in which 1 to 10 cm thick beds amalgamate to form bedsets of facies $S_L$ (interpreted as hyperpycnites) and bedsets stack together, in some instances separated by heterolithic facies $S_H$, to create lobes (Fig. 8). Organic-rich, heterolithic beds of facies $S_H$, which are interpreted as deposits from lofted plumes, typically lie below, in between, and lateral to individual lobes (Figs 4, 7 and 8).

Lobes contain many amalgamation surfaces and internal scour and fill structures (Figs 4 and 7). Few bedsets display a thickening to thinning-upward sequence, with centimetre or millimetre-scale beds at their bases and tops, and up to ca 10 cm thick beds in the centre (Fig. 4). Sandstone beds commonly contain moderate amounts of charcoal and organic debris and some beds are bioturbated. Hummocky cross-stratification and scour and fill can be found at the top of lobes (Figs 4 and 5C). Lobes thin and pinch out over a few hundred metres to the west and east (Fig. 7).

**Large-scale stacking patterns**
Lobes migrate and stack compensationally to the east through the succession (Fig. 7) with the surfaces between the lobes dipping at ca 8° relative to flat-lying strata. In addition to bed coarsening and thickening-upward within individual lobes, the lobes themselves display an overall coarsening and thickening-upward trend (Fig. 4). The outcrop stratigraphy records a transition from mudstone deposition with a few thin sandstone and siltstone beds (facies M) and hummocky cross-stratified beds (facies $S_{HCS}$), to lobate sand bodies prograding to the north-east and stacking laterally, back to deposition of finer-grained facies M and $S_H$, and finally capped by the deposition of very coarse sandstones and conglomerates (facies $G_T$, $G_C$ and $S_C$; Fig. 4). The uppermost deposits within this study area are interpreted as streams feeding shelfal deposits. Above the succession described in this study, the Lajas Formation comprises several hundred metres of regressive–transgressive cycles that form alternating mudstone–sandstone units which are tens of metres thick (Paim et al., 2011). The regressive package of these cycles is typically capped by a coarse deposit, previously interpreted as fluvial (fig. 12 of Paim et al., 2011), which is analogous to patterns described in the present study.

**Deposition of hyperpycnal lobes**
Further evidence for a hyperpycnal origin of these shelf sands is the abundance of charcoal along bedding planes (Fig. 5E and F), which has been linked to river floods in ancient deposits (Petter & Steel, 2006; Zavala et al., 2012a). The occurrence of wildfires in drainage basins is known to ‘prime’ rivers for significant suspended sediment loads during subsequent floods (e.g. Florsheim et al., 1991; Silins et al., 2009; DiBiase & Lamb, 2013), making rivers more likely to produce hyperpycnal effluent. The presence of charcoal, which can be up to 1 cm in diameter in Lajas sandstones, may reflect this process in which wildfire leads to excessive sediment discharge. Finally, internal scouring and amalgamation of beds as well as tool marks at the base of bedsets suggests that these sandstones were deposited by turbulent currents capable of scouring into the substrate. Currents with light interstitial fluid are likely to have a slower-moving head than surge-type turbidity currents, and are therefore less likely to
be as erosive: a contrast that is reflected by the relatively small number of sole marks at the base of beds in this study area compared to ‘classic’ turbidite systems. A ‘gravel front’ marked by the break in grain size between proximal conglomeratic beds (Facies C_T and C_C) and more distal well-sorted hyperpycnal sandstones may also reflect a distinction between surge-type turbidity currents and those with light interstitial fluid, which are likely to have a lower flow competence.

**DISCUSSION**

**Conditions for hyperpycnal flow**

Hyperpycnites in the Lajas Formation have a median grain size of ca 0-4 mm, but contain grains up to ca 1 mm in diameter. The critical shear stress for entrainment of grains with diameters of 0-4 to 1-0 mm ranges between 2-5 dynes cm\(^{-2}\) and 5-0 dynes cm\(^{-2}\) (from fig. 7 of Miller et al., 1977). Estimates for minimum flow velocities required to produce shear stresses between 2-5 dynes cm\(^{-2}\) and 5-0 dynes cm\(^{-2}\) can be obtained by rearranging the drag force equation,

\[
\tau = \rho C_d U^2
\]

in which \(\tau\) is shear stress, \(\rho\) is the fluid density (\(\rho = 0.998 \text{ g cm}^{-3}\) for freshwater at 20°C), \(C_d\) is the drag coefficient and \(U\) is flow velocity. Using a typical range for the drag coefficient of 0-003 to 0-01 (Scully et al., 2003; Wright et al., 2002), minimum flow velocities range from 32 to 58 cm sec\(^{-1}\) for 1-0 mm grains and 22 to 40 cm sec\(^{-1}\) for 0-4 mm grains. These values appear reasonable and of similar order of magnitude to those measured in modern systems (Wright et al., 2002; Best et al., 2005). Field measurements from hyperpycnal flows in Lillooet Lake, British Columbia, record velocities reaching 58 cm sec\(^{-1}\) at 25 m water depth (Best et al., 2005), and estimates for wave-enhanced cross-shelf flows from the Mid Atlantic Bight off Duck, North Carolina, reach values up to 36 cm sec\(^{-1}\) (Wright et al., 2002). Although measurements from modern shelves are similar to those estimated here, calculated velocities are minimum values associated with entrainment of sediment. Based on bedform stability diagrams, the abundance of medium-grained parallel laminations within the hyperpycnites suggests that flow velocities were likely to be higher than minimum estimated velocities, and were perhaps closer to 1 m sec\(^{-1}\) (Southard & Boguchwal, 1990). It is difficult to provide further estimates on the parent flow properties, such as run-out distances, without better constraints on sea-floor gradient and three-dimensional deposit geometry (for example, streamwise length of deposits). However, sandy hyperpycnites have been documented in a variety of continental shelf, slope and deep basin settings (e.g. Mulder et al., 2001; Mutti et al., 2003; Plink-Bjorklund & Steel, 2004; Zavala et al., 2012b; Warrick et al., 2013; Deville et al., 2015; Steel et al., 2016), which supports the ability of hyperpycnal currents to transport sand beyond the shoreline.

**Palaeogeography of the Lajas shelf in the study area**

Progradation is recorded by the succession of outermost shelf (possibly upper-slope) mudstone and thin sandstone beds overlain by shelfal hyperpycnites (facies S_L), which are capped by hypopycnal deposits (facies S_F) and coarser shallow-water gravel beds and channelized fluvial deposits (facies C_T, C_C and S_C). The shelf edge indicated in Figs 2 and 3 is estimated by previous workers based on a marked down-stratigraphy shift to mudstones, which contain distal turbidites more characteristic of typical surge-type turbidity currents (for example, partial Bouma sequences and some evidence of chaotic bedding and soft-sediment deformation associated with rapid sediment deposition; Vann 2013; Tudor, 2014). Within ca 10 km along depositional strike of this study area, portions of the Lajas to Los Molles system contained large, well-developed fluvial to submarine canyon systems interpreted to indicate significant bypass of the continental shelf and transport of coarse-grained conglomeratic material across the slope break into deep water (Paim et al., 2008; Vann, 2013; Steel et al., 2017b). In these other locales, thick fluvial successions within the Challaco Formation are seen up-dip from the conglomeratic slope channels (Veiga, 1998; Paim et al., 2008). The present study area is interpreted to represent a segment of the continental shelf where relatively small rivers fed hyperpycnal sand lobes onto the outer shelf (Fig. 9A). These hyperpycnal shelf sand bodies are likely to be found adjacent to or between systems in which larger rivers connect with canyons and channels on the continental slope to feed deep-water fans.
The fluvial systems feeding the Lajas shelf in the present study area are interpreted as relatively small based on the size of the channels seen at the top of the study succession, which have widths of ca 15 m and depths of ca 1 m. Furthermore, large rivers are less likely to induce hyperpycnal currents than small mountainous rivers due to the storage of sediment within their extensive floodplains and deltas preventing the high sediment concentrations necessary to induce plunging of river effluent (Mulder & Syvitski, 1995).

A hypothesized palaeogeography of the study area is shown in Fig. 9. It is worth noting that in the hyperpycnal shelf systems the coarse-grained material is likely to be trapped within the fluvial environment or in a shallow water gravel ‘front’, and clay-sized particles may be stripped from the flow through lofting of fresh interstitial water, resulting in well-sorted shelf sands (Steel et al., 2016). This scenario is in contrast to larger systems that connect with slope conduits and which may be capable of bypassing the shelf and sending coarse-grained material onto the slope or continental rise.

**Recognition of hyperpycnites**

Distinguishing hyperpycnites from ‘classic’ turbidites (extrabasinal versus intrabasinal turbidites, sensu Zavala & Arcuri, 2016) is critical for accurate palaeoenvironmental interpretations; however, the distinction can be challenging to make, because both are deposited by turbulent sediment gravity flows. Despite this challenge, hyperpycnal currents have several unique characteristics that can alter both their dynamics and deposit characteristics with respect to ‘classic’ turbidites. A diagnostic criterion for the recognition of hyperpycnites is the abundance of terrestrial organic matter (Plink-Bjorklund & Steel, 2004; Petter & Steel, 2006; Myrow et al., 2008; Zavala et al., 2012a). Additionally, hyperpycnal currents are distinct from other turbidity currents in that they are river-derived, and therefore contain fresh interstitial...
water. This freshwater can alter the dynamics of hyperpycnal currents through a process called lofting, in which part or all of the current becomes buoyant and rises from the sea bed after deposition of a critical amount of suspended sediment (Sparks et al., 1993; Hurzeler et al., 1995; Hogg et al., 1999). Lofting can result in narrower deposits than expected from ‘classic’ turbidity currents that remain ground-hugging (Steel et al., 2017a), and it can enhance sorting because light constituents such as plant fragments, very fine sand, silt and clay are stripped from the bed-attached portion of the current by the rising freshwater plume (Pritchard & Gladstone, 2009; Zavala & Arcuri, 2016).

The Lajas hyperpycnites share many similarities with existing hyperpycnite models, including the abundance of terrestrial organic matter, the well-sorted nature of the deposits, the thick planar laminae (Petter & Steel, 2006, fig. 4), and their overall morphology and architecture (e.g. Mulder et al., 2003; Zavala et al., 2006a, 2011; Steel et al., 2016). Hyperpycnal currents in the Var submarine system deposited well-sorted sands containing thick laminations, suggested to represent individual floods of the Var River (Mulder et al., 2001). These Mediterranean hyperpycnites are 3 to 12 cm thick and do not exceed fine-grained sand. Individual laminations are difficult to distinguish visually in the Var submarine system, and were only recognized through detailed grain-size analysis (Mulder et al., 2001). Similarly, Holocene hyperpycnites on the continental shelf of the Santa Barbara Channel, Southern California (Warrick et al., 2013; Steel et al., 2016), contain well-sorted fine-grained sand with individual beds that could only be distinguished through detailed grain-size analysis (Steel et al., 2016). Although the Lajas sand bodies are medium-grained rather than fine-grained, their well-sorted nature is analogous to observations from the Mediterranean and the Santa Barbara Channel hyperpycnites. The grain-size difference among these systems may simply be attributed to differences in the velocity of the currents or in the size distribution of the material in the parent fluvial system.

Lajas hyperpycnites form lobate sand bodies that are ca 150 m wide and have maximum thicknesses of ca 2 to 8 m. This limited lateral extent is analogous to shelf hyperpycnites of Southern California (Steel et al., 2016) and to flume experiments on lofting turbidity currents (Steel et al., 2017a). The lobes consist largely of well-sorted parallel laminated sandstones (facies $S_T$), surrounded by thinly laminated fine-grained sandstone and siltstone with abundant plant debris (facies $S_R$). These facies correspond to previously described hyperpycnite facies of Zavala et al. (2011), in which the bed-attached portion of the current produces parallel laminated sandstone ($S_2$), and the lofting plume produces laminated sandstone and silt with plant debris ($L$), termed lofting rhythmites. The presence of light interstitial fluid within hyperpycnal currents is likely to reduce flow competency, resulting in rapid fall-out of coarse grain-size fractions near the shoreline (facies $B$ of Zavala et al., 2011). The distinct lack of coarse-grained material in the Lajas hyperpycnal lobes within this study area, shelf hyperpycnites of the Santa Barbara Channel (Steel et al., 2016) and Var River hyperpycnites in the Mediterranean (Mulder et al., 2001) reflects this low flow competency. Pebble sandstones and conglomerates of facies $C_T$ deposited above the Lajas hyperpycnal lobes are interpreted to represent the fall-out of coarse material near the shoreline due to the low competency of hyperpycnal currents.

One of the most distinctive characteristics of the sandstone beds in the study area is their thick laminations and thin beds, which amalgamate to form bedsets. Lobes are composed of several bedsets separated by thinly-laminated, organic-rich beds of facies $S_R$ (Fig. 8). Several mechanisms may be operating to produce the thick laminations and thin beds observed within these sandstones. The combination of storm wave oscillations and hyperpycnal currents could produce pulses within the current and cause the sustained deposition of laminae (Myrow & Southard, 1996). Laminae may also be the result of pulses in flood strength or possibly of migration of the flow axis during floods (Best et al., 2005). Storm waves or flood pulses can also explain internal scour and fill structures observed within some of the hyperpycnites. Alternatively, thicker laminations may represent individual hyperpycnal events. The observed architecture is probably developed due to a combination of many hyperpycnal events, modified by flood pulses and oscillatory wave motion.

Previously described shelf sand bodies

An assortment of explanations has been proposed for the origin of shelf sand bodies, many of which are large-scale transgressive features.
typically oriented at an oblique angle to the strongest tidal current (e.g. Houbolt, 1968; Bergman & Snedden, 1999; Reynaud & Dalrymple, 2012; Olariu et al., 2012). The various models include tidal sand ridges, which grow from irregularities in the sea bed (Fig. 10A; e.g. Houbolt, 1968; Tillman & Martinsen, 1984; Rine et al., 1991), recycled lowstand shoreface deposits (Fig. 10B; Posamentier et al., 1992; Berné et al., 1998), reworked ebb-tidal deltas (Fig. 10C; Snedden et al., 1999) and overstepped barrier islands (Fig. 10D; Rodriguez et al., 1999; Cooper et al., 2016). Despite some similarities, such as sharp-based, prograding, well-sorted sandstones, existing shelf sand models do not easily explain those on the Lajas shelf. The Lajas deposits studied do not exhibit the deep incisions or high-angle clinoforms observed in sandstone ridges composed of recycled lowstand shorefaces (Berné et al., 1998). Furthermore, based on limited palaeocurrent data from this study, as well as regional palaeocurrent directions (Tudor, 2014), the Lajas sandstone bodies are smaller and appear to be less laterally extensive (hundreds of metres to kilometres) than would be expected if they originated from a lowstand shoreface. Even considering the possibility that the sandstones in this study are features from a minor transgression within an overall regression, the existing sand ridge models cannot explain the extensive thick parallel laminations characteristic of the Lajas sandstones (Figs 4 and 5). Tidal currents play a strong role in shaping and reworking sediment in tidal sand ridges, and the extensive compound cross-bedding typically associated with these processes (Dalrymple, 2010; Olariu et al., 2012; Leva López et al., 2016) is not observed in the study area. Furthermore, sand ridge models proposed by Snedden et al. (1999) and Rodriguez et al. (1999) would imply that a filled tidal inlet or incised valley should be represented in the stratigraphy, but these features are not observed in the section or within tens of kilometres along-strike from the study area. Overall, the lack of tidal mud drapes, the low abundance of cross-stratification, and the abundant parallel laminations deposited within a regressive sequence suggests that these sandstones are distinct from previously described shelf sandstone ridges (Fig. 10; Leva López et al., 2016).

Another potential interpretation worth exploring is the possibility that the sand bodies

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**Fig. 10.** Models for formation of isolated shelf sand bodies, modified from Snedden et al. (1999). (A) In-place ridge growth from shelf currents. (B) Lowstand shoreface deposits from rapid forced regression. (C) Reworking of ebb tidal delta sand during transgression. (D) Reworking of overstepped barrier island sediment during transgression. (E) Deposition by hyperpycnal currents (this study).
described in this study are simply beach deposits. The foreshore, which lies between mean low and high water levels, is exposed to the daily swash of waves and is characterized by gently-dipping parallel laminations similar to those described in the Lajas Formation (Reading & Collinson, 1996). Studies from modern beaches in California and Oregon and from the rock record suggest that prograding beaches typically deposit a succession of ripple laminated sandstone and siltstone transitioning vertically into cross-bedded sandstone and capped by planar-laminated sandstone (Clifton et al., 1971; Harms et al., 1975; Howard & Reineck, 1981; Clifton, 2006). Although the Lajas Formation contains the planar-laminated sandstone that would be expected in a beach succession, there is no clear evidence for ripple-laminated and cross-bedded sandstones expected in the shoreface environment. Cross-bedding may be absent in low-energy beach environments; however these environments tend to be much more extensively bioturbated than is observed in the study area (Reineck & Singh, 1973; Howard & Reineck, 1981). Most importantly, the organic-rich layers of facies S1f surrounding the parallel-laminated sand bodies contain abundant plant debris, suggesting a fluvial sediment source rather than the combined fluvial–marine sediment source for beach deposits (Reading & Collinson, 1996). It is therefore difficult to explain the origin of the heterolithic facies S1f if the Lajas Formation sand lobes were deposited in a beach environment rather than a shelfal environment.

Storm-induced deposition of sediment on the continental shelf is shaped by a combination of waves, tides, geostrophic currents and gravity-driven flow (Myrow & Southard, 1996). A model of tempestite deposition presented by Myrow & Southard (1996) suggests that, although storm-driven suspension of sediment on continental shelves may be capable of inducing turbidity currents (i.e. through an ‘excess weight force’), cross-shelf transport and deposition of sediment solely through storm waves and geostrophic currents is likely to be negligible. However, with the introduction of large sediment pulses from river floods or sediment failure triggered by earthquakes it may be possible to deposit significant thicknesses of sand via sediment gravity flows (Myrow & Southard, 1996; Mutti et al., 2003; Steel et al., 2016). Storm waves can promote the continuation of hyperpycnal currents across the shelf by enhancing turbulence, and laminations may reflect pulsation of the currents from the addition of wave oscillations (Myrow & Southard, 1996; Wright & Friedrichs, 2006; Macquaker et al., 2010). Hummocky cross-stratification is commonly associated with tempestites (Harms et al., 1975; Hamblin & Walker, 1979) and is found below, on top of, and within Lajas hyperpycnite lobes (Fig. 4), suggesting that hyperpycnal currents of the Lajas system were generated either in conjunction with storm conditions or that the hyperpycnites were later reworked by storm waves.

CONCLUSIONS

Criteria used to recognize hyperpycnites within the Jurassic Lajas Formation that could be applied to identify hyperpycnites in other localities include:

1. Presence of terrestrial organic debris and charcoal along bedding planes (Plink-Bjorklund & Steel, 2004; Petter & Steel, 2006; Myrow et al., 2008; Zavala et al., 2012a,b).
2. Well-sorted sandstones with limited lateral extent, suggesting that currents underwent lofting (Steel et al., 2016, 2017a; Pritchard & Gladstone, 2009; Gladstone & Pritchard, 2010).
3. Extensive thick parallel laminations, suggesting pulsing flows associated with plunge-point dynamics or effects of oscillatory wave motion during flows (Myrow & Southard, 1996; Mulder et al., 2001; Best et al., 2005).
4. Lobate geometry similar to Holocene deposits identified in the Santa Barbara Channel, California, USA (Warrick et al., 2013; Steel et al., 2016).
6. Connection to small fluvial systems, identified by coarse-grained, clast-supported, channelized deposits containing petrified wood (Mulder & Syvitski, 1995).

Deposits of the Lajas Formation near La Jardinera, Argentina record the deposition of ca 2 to 8 m thick sandstone bodies on the continental shelf. These sandstones were deposited by hyperpycnal currents fed by small rivers, and are predominantly characterized by well-sorted, medium-grained sandstones with centimetre to decimetre-thick laminations. Deposits in this study area are part of a relatively short system, implied by the deposition of hyperpycnites on.
Continental shelf hyperpycnites

the shelf rather than on the slope or in deeper water, in which significant grain-size fractionation occurred, with gravel deposition near the shoreline, sand deposition by hyperpycnal currents on the shelf, and finer-grained sediment and organic debris stripped from the flow by lofting. Lofted material settled nearby on the shelf in this setting; however, in ocean basins with cross-currents, the lofted plume and its constituents may be dispersed over a broad region on the shelf and therefore may not always be present in outcrop.

Hyperpycnal currents are beginning to gain recognition as important mechanisms for the deposition of large volumes of sand on the continental shelf (e.g. Mutti et al., 2003; Wright & Friedrichs, 2006; Pattison, 2005; Lamb et al., 2008; Steel et al., 2016). This study adds to a small but growing body of work focused on shelf and shallow-water fans (e.g. Okay et al., 2011; Normandeau et al., 2013; Steel et al., 2016; Wang et al., 2017) which suggests the need for facies models beyond those developed for conventional deep-water fan systems. Facies models for hyperpycnites have been proposed (Mulder et al., 2001; Zavala et al., 2011), but the development of robust models necessitates a broad range of examples in a variety of settings. Understanding the ways in which hyperpycnites can be deposited in deep-water settings is significant. However, recognizing their ability to build shelf sand bodies is equally important and will reduce the potential for these features to be misinterpreted as deep-water deposits. Finally, the well-sorted nature of these deposits makes them potentially high-quality hydrocarbon reservoirs. Accurate predictions of their reservoir quality, however, will require a deep understanding of their morphology, grain-size distributions and internal architecture.

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### Supporting Information

Additional Supporting Information may be found in the online version of this article:

**Figure S1.** Additional measured sections