SUPERCRITICAL-FLOW DEPOSITS AND THEIR DISTRIBUTION IN A SUBMARINE CHANNEL SYSTEM, MIDDLE EOCENE, AINSA BASIN, SPANISH PYRENEES

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ABSTRACT: Studies of supercritical-flow deposits (SFDs) and their spatial distribution in ancient deep-water systems should provide an additional tool to improve the understanding of the flow dynamics during deposition and the architecture of sandbodies. Outcrop recognition of SFDs in ancient deep-marine environments remains poorly documented, although their study dates back to the 1970s. This paper focuses on the criteria for recognizing SFDs and their distribution in three selected depositional environments from an ancient mid-lower slope to a proximal-basin floor setting in the middle Eocene Ainsa Basin, Spanish Pyrenees. From field observations, six facies associations interpreted as related to supercritical flow are defined. These facies associations are grouped in two categories. The first group includes facies associations related to erosional coarse-grained supercritical-flow bedforms related to meter and centimeter-scale scour and backfilling structures interpreted as large-scale cyclic steps or small-scale steps, respectively. Erosional coarse-grained supercritical bedforms are observed mainly in relatively high-gradient slopes and relatively confined settings. The second group of facies associations are related to depositional fine-grained supercritical-flow bedforms associated with upflow-dipping sandstone lenses, upflow-stacked wavy bedforms, upflow-stacked sigmoidal bedforms, and plane beds, interpreted as unstable and stable antidunes and upper-flow-regime plane beds. Depositional fine-grained supercritical-flow bedforms are observed mainly in relatively unconfined settings such as lower-slope, break-of-slope and proximal basin-floor environments. Two main SFD trends were observed in the Ainsa Basin in: (i) an axial-lateral direction, showing a decrease in SFDs from channel axis to channel margin, and (ii) a longitudinal proximal–distal direction, showing an increase in SFDs from the Gerbe System (mid-slope environment), to the Banastón System (proximal basin-floor environment), to the Ainsa System (lower-slope environment). From this study, two parameters are recognized as likely playing an important role on whether a flow is under supercritical or subcritical conditions: (i) confinement of the sandbodies, and (ii) slope gradient.

INTRODUCTION

Submarine fans and other deep-water systems can be major oil and gas reservoirs in many sedimentary basins worldwide. In recent years, the increased interest in deep-water reservoirs by the hydrocarbon industry has been a major factor in driving forward a substantial improvement in the understanding of such systems. Sand/mud proportion, grain-size evaluation, bedform architecture, and sedimentary structures all represent criteria used to improve the understanding of deep-water systems. The evaluation of supercritical-flow deposits (SFDs) could provide another useful criterion to understand and constrain the architecture of deep-water systems such as submarine fans.

Flows are considered to be supercritical when the ratio between the flow velocity and thickness exceeds a threshold as defined by the Froude number (Fr). In subaqueous sediment gravity flows (SGFs), the Fr is expressed by the densimetric Frd (Yih and Guda 1955; Komar 1971), considering the density contrast between the underflow and the ambient water:

\[ Fr_d = \frac{U}{\sqrt{g h}} \]  

where \( U \) is the flow velocity (m s\(^{-1}\)), \( \rho_{flow} \) and \( \rho_{amb} \) are the densities of the flow (kg m\(^{-3}\)) and of the ambient water (kg m\(^{-3}\)), \( h \) is the flow depth (m), and \( g \) is the acceleration of gravity (m s\(^{-2}\)). In this paper, we refer to the densimetric Frd as the Fr. Flows where Fr > 1 are said to be supercritical. Flows where Fr < 1 are said to be subcritical. SGFs are more likely to have higher Froude numbers than subaerial flows due to a lower density contrast between flow and ambient medium densities. Therefore, SGFs are more likely to form supercritical bedforms.

Sandy submarine fans likely contain abundant evidence for deposition and/or erosion beneath supercritical flows, because it has been postulated that SGFs should be supercritical for slopes > 0.5\(^{\circ}\) (Walker 1967; Komar 1971; Hand et al. 1972; Hand 1974). Supercritical SGFs are believed to be more common in high-gradient submarine canyons and channels in continental slopes, whereas subcritical SGFs are more common in lower-gradient channels and depositional lobes of the continental slope and basin floor (Komar 1971; Mutti and Normark 1987, 1991; Piper and Normark 2001). Many researchers have focused on the recognition criteria for SFDs, including: using numerical modeling for the different flow parameters that create supercritical-flow bedforms (Kostic and Parker 2006; Cartigny et al. 2011; Vellinga et al. 2017); flume-tank experiments (Garcia and Parker 2001). Many researchers have focused on the recognition criteria for SFDs, including: using numerical modeling for the different flow parameters that create supercritical-flow bedforms (Kostic and Parker 2006; Cartigny et al. 2011; Vellinga et al. 2017); flume-tank experiments (Garcia and Parker 2001).

Experimental, theoretical, and observational research suggests that a large range of sedimentary bedforms are produced under varying densimetric Fr. There remains a significant mismatch between this growing body of work and an understanding of how it might map onto field observations in ancient deep-water systems.

The main aim of this paper is to evaluate the various criteria for the recognition of SFDs in an ancient deep-marine setting, the Middle Eocene Ainsa Basin, Spanish Pyrenees. After describing and interpreting the various SFDs, we present an analysis of their distribution in different channel and related depositional environments in order to better understand and help constrain the link between depositional setting and SFD distribution. We show that the criteria for SFD distribution could be useful in the future to distinguish and interpret depositional environments.

SUPERCRITICAL-FLOW DEPOSITS (SFDs)

It has long been postulated that deep-water sedimentary bedforms formed under supercritical-flow conditions are commonly associated with hydraulic jumps (e.g., Mutti and Normark 1987; Postma and Cartigny 2014; Postma et al. 2016; and references therein). Hydraulic jumps are produced at the transition from supercritical to subcritical flow. In deep-marine systems, it has been suggested that hydraulic jumps form at a break of slope, e.g., the transition from a confined submarine slope canyon into submarine-fan channels, and also onto an unconfined basin floor (Komar 1971; Mutti and Normark 1987). Numerical modeling suggests that hydraulic jumps can develop spontaneously in slope settings and are therefore not necessarily restricted to the slope break (Mutti and Normark 1987; Fildani et al. 2006; Kostic and Parker 2006; Cartigny et al. 2011). Hydraulic jumps are associated with a wide range of processes such as erosion, flow mixing, and changes in sediment distribution and concentration (Wynn et al. 2002; Cartigny et al. 2011, 2014; Sumner et al. 2013; Macdonald et al. 2011; Hofstra et al. 2015; Symons et al. 2016).

In the field, evidence of hydraulic-jump deposits are typically manifest as scours and backfilling structures (Postma et al. 2009, 2016; Ito et al. 2014; Lang et al. 2017a, 2017b).

Under supercritical-flow conditions, a wide variety of bedforms are created (Gilbert 1914; Simons et al. 1965; Allen 1982). Supercritical-flow bedforms formed at low Fr, but still Fr created (Gilbert 1914; Simons et al. 1965; Allen 1982). Supercritical flow comprises a steeply dipping (Fr supercritical) and gently dipping side (Fr subcritical) (Winterwerp et al. 1992; Kostic et al. 2010; Cartigny et al. 2011, 2014). In the rock record, deposits of cyclic steps appear to consist of upflow-dipping backsets, deposited on the stoss side of the bedform and onlap the erosional bed boundary (Kostic and Parker 2006; Cartigny et al. 2011, 2014; Postma and Cartigny 2014; Postma et al. 2014). Scours filled by structureless sand have also been observed and interpreted as cyclic-step deposits in the Monterey Canyon (Fildani et al. 2006; Paull et al. 2010), and in the Squamish Delta, British Columbia (Hage et al. 2018). Due to their long wavelengths, cyclic steps (hundreds of meters to kilometers in downstream length) are amongst the most common supercritical-flow bedforms observed on the modern seafloor, with a large range of grain sizes (Fildani et al. 2006; Lamb et al. 2006; Hughes Clarke et al. 2012; Covault et al. 2014, 2016).

The formation of chutes and pools is characterized by the presence of an irregularly spaced hydraulic jump due to their spontaneous occurrence (Winterwerp et al. 1992; Taki and Parker 2005; Kostic et al. 2010; Cartigny et al. 2014). Lately several authors argued that chutes and pools are unstable transitional features between the antidunes and the cyclic steps and they are not preserved in the rock record (Fedele et al. 2016; Massari 2017). Furthermore, chutes and pools need a high sediment aggradation rate to be preserved in the rock record (Lang and Winsemann 2013). Because the issue of preservation of chute and pool deposits is so controversial, we decided to not undertake the description and interpretation of candidate chute and pool bedforms.

A problem is the interpretation of small-wavelength ripples and dunes as having formed as antidunes under supercritical-flow conditions. Pickering and Hiscott (1985), using data from Hand et al. (1972), considered this and noted that antidune wavelengths in turbidites should be ~12–14 times the flow depth, so their presence would be imperceptible in most outcrops, i.e., their wavelength under turbidity currents would be in the order of tens to hundreds of meters with bedform amplitudes on the order of tens of centimeters. However, subsequent research suggests that the problem is likely more complex; e.g., Lang et al. (2017a) interpreted aggrading antidunes with wavelengths between 1.2 and 12 m. Postma and Cartigny (2014) argued that bedform wavelength is controlled by the thickness of the dense basal layer for stratified concentrated density flows and by the total flow thickness for turbidity currents (non-stratified flows). From experimental work, Fedele et al. (2016) suggested that ripples can form under subcritical, near-critical, and slightly supercritical flows, with ripples also observed for a range of densimetric Fr of 1.1–1.3 superposed on upstream-migrating antidunes. Caution should be exercised, however, because these experiments involved only saline density currents where the flows were not charged with suspended sediment; i.e., they only reworked the bed and, therefore, may be a special situation in which the morphodynamics might not be the same as for concentrated density flows and turbidity currents. In flume experiments, in a study of the grain-size controls on near-bed density stratification by Tilston et al. (2015), they observed ripple cross-lamination formed under depth-averaged supercritical-flow conditions. Yang et al. (2017, their fig. 1) have described centimeter-scale siltstone to fine-grained sandstone ripples, including climbing ripples, as antidunes and chute-and-pool structures, but this appears to be unsubstantiated by any published theoretical and/or experimental data. In the absence of reliable contrary knowledge for the formation of ripple cross-lamination, in this study we consider ripples...
formed under subcritical-flow conditions during deceleration of a sediment-laden flow.

**METHODOLOGY**

This study involved seven months of fieldwork undertaken in the Ainsa Basin, with 25 detailed sedimentary logs through different submarine-fan and related environments (channel-axis, channel-margin, and levee–overbank settings). In this manuscript, the terminology and definitions we use for the various types of SGFs and their deposits are those of Pickering and Hiscott (2016). For each sedimentary log, the bed thickness, grain size, sedimentary structures, and facies (facies classification scheme of Pickering et al. 1986, modified in Pickering and Hiscott 2016) were recorded. Paleoflow was obtained by measuring the orientation of various sole structures (flute casts, groove casts), current ripples, and clast imbrication. Because outcrops are rarely parallel to paleoflow, we consider sandy bedforms, linked to supercritical flow, with differences between paleoflow and the outcrop photograph generally < 10° but in some cases up to ~ 20°.

More than 7,500 beds were measured and analyzed in order to evaluate the distribution of SFDs in the mid-, lower-slope, and proximal basin-floor environments. From the various criteria used to recognize SFDs, such as supercritical-flow bedforms (cyclic steps and antidunes) and other sedimentary structures (backset, planar-parallel lamination), each discrete flow event or deposit was interpreted as completely or partially deposited under supercritical or subcritical flow conditions. The thickness of each part of a bed, or entire bed, interpreted as deposited under supercritical or subcritical conditions was recorded and tabulated. In this analysis, the percentage of supercritical or subcritical flow deposits was calculated for each sedimentary log. The percentage of SFDs was calculated only on the sandstone beds; mudstone intervals have not been taken into account in the calculation, inasmuch as mudstones are considered deposited under subcritical-flow conditions.

Research in the Ainsa Basin has led to a large database of sedimentology, stratigraphy, architectural elements, and structures of the sandbodies (submarine fans and related deposits). This extensive database makes the Ainsa Basin an ideal natural laboratory in which to analyze SFDs and their distribution. Each detailed sedimentary log was measured in sandbodies already interpreted in terms of their depositional environments (from proximal to distal and lateral directions). These environmental interpretations can be found in Pickering and Bayliss (2009) and Pickering and Cantalejo (2015), and references therein. In this paper, our descriptions and interpretations of SFDs are presented in the context of the channel and related environments previously interpreted (above). We should emphasize here that we do not use the percentage of SFDs to interpret channel environments, but only to characterize (hydrodynamically) such environments that have been recognized on other criteria, i.e., there is no circular reasoning in our environmental interpretations.

Due to the lack of observed sedimentary structures and insufficient criteria to recognize SFDs in mass-transport complexes (MTCs) and cohesive-flow deposits (such as debrises), only relatively more dilute SGFs, such as concentrated density flows, also commonly referred to as high-density turbidity currents, and turbidity currents are considered in this study (terminology in Pickering and Hiscott 2016).

**GEOLOGICAL SETTING**

The middle Eocene Ainsa Basin, south-central Spanish Pyrenees (Fig. 1A), originated as a foreland basin that became a thrust-top (piggyback) basin when it was incorporated into the Gavarnie thrust sheet during the Pyrenean orogeny (e.g., Muñoz 1992; Muñoz et al. 2013). The eastern and western margins of the basin are defined by the Mediano and Boltaña anticlines, which separate the Tremp–Graus Basin (fluvio-deltaic and shallow marine) to the east and the Jaca Basin (submarine lobes and related deposits, including basin floor) to the west. The middle Eocene stratigraphy of the Ainsa Basin comprises submarine fans and related deposits packaged into two groups, the Lower and Upper Hecho Group (Fig. 1B) (Pickering and Cantalejo 2015 and references therein). They accumulated essentially in upper- to mid-bathyal depths of ~ 400–600 m (based on micropaleontological study by Pickering and Corregidor 2005).

This study focuses on selected, representative, parts of various submarine-fan and related deposits in three deep-marine systems in the Ainsa Basin (Fig. 1B): the Gerbe System (mid-slope environment—the youngest system of the Lower Hecho Group), the Banastón System (proximal basin-floor environment—the oldest system of the Upper Hecho Group) and the Ainsa System (lower-slope–base-of-slope environment—middle Upper Hecho Group). The Lower Hecho Group is more structurally deformed than the Upper Hecho Group, and shows locally intense folding, shearing, and thrusting (Pickering and Bayliss 2009). The degree of tectonic deformation in the Hecho Group decreases upwards until the deep-marine Guaso System. This progressive decrease in tectonic deformation upward through the Ainsa Basin demonstrates an important synsedimentary tectonic influence on deposition in the deep-marine basin.

**Gerbe System (899 Beds Logged)**

The Gerbe System is stratigraphically located between the Arro and the Banastón systems in the Lower Hecho Group. It has been interpreted as a submarine canyon-slope-channel system (Clark and Pickering 1996). The Gerbe sandy fans were deposited in mid-slope canyon to lower-slope erosional channel settings (Millington and Clark 1995; Pickering and Bayliss 2009). Millington and Clark (1995) recognized a change in depositional style, which they interpreted as showing an upward change from a sheet system in a base-of-slope canyon during the deposition of the Arro System, to a submarine-canyon channel during the deposition of the Gerbe System. The Gerbe System consists of two sandy fans named the Gerbe I Fan (older) and Gerbe II Fan (younger). Detailed sedimentary logs were produced for the mid-slope environment of the Gerbe System (Fig. 2: Gerbe I Fan: Log 1; Gerbe II Fan: Logs 2 and 3).

**Banastón System (5,450 Beds Logged)**

The Banastón System directly overlies the Gerbe System and is the oldest system deposited in the Upper Hecho Group. The system comprises six sandy fans, designated form oldest to youngest, Banastón I to Banastón VI, respectively. These sandy fans show a transitional depositional style from lower-slope channel infill in the eastern part of the Ainsa Basin, to a more proximal basin-floor and fan lateral-margin and levee–overbank environments in the northwest and northeast of the basin (Bayliss and Pickering 2015). Sedimentary logs were produced in the northwest part of the Ainsa Basin, i.e., in proximal basin-floor fan environments (Fig. 2: Banastón I Fan: Logs 4, 5, and 6; Banastón II Fan: Logs 7, 8, and 9; Banastón III Fan: Logs 10 and 11; Banastón IV Fan: Logs 12 and 13; Banastón V Fan: Logs 14 and 15; Banastón VI Fan: Logs 16, 17, and 18).

The Banastón I Fan lower-slope channel–canyon infill is mapped as having deposits restricted between the Mediano (in the east) and the Ahsiolo anticlines in the west. The Banastón II and III fans are mapped as showing no significant changes in thickness over the Ahisío anticline; therefore, it is assumed that this structure had temporarily stopped growing or that sediment supply exceeded the rate of growing seafloor relief (see fig. 13 in Bayliss and Pickering 2015), leading to a decrease in confinement of the sandbodies from Banastón I to III fans. However, we
emphasize that the presence of the thickest MTDs (up to ≈ 20 m) at the base of Banastón III probably enhanced local topographic confinement. It appears that during the final stages, or after the deposition of the Banastón III Fan, the Aínscllo Anticline was reactivated as the Banastón IV, V, and VI fans are located to the west of the Aínscllo Anticline (Bayliss and Pickering 2015). From mapping, a progressive decrease in the confinement of the Banastón IV, V, and VI fans is observed, without significant synsedimentary tectonic activity of the Aínscllo Anticline, or the sediment accumulation rate of these three fans exceeded (drowned) any structural growth of the anticline (Bayliss and Pickering 2015).

**Aínsa System (2,391 Beds Logged)**

The Aínsa System stratigraphically overlies the Banastón System. The Aínsa System comprises three sandy fans, interpreted as structurally confined, lower-slope submarine fans with erosional–depositional channels.
and proximal basin-floor environments (Pickering and Corregidor 2005; Pickering et al. 2015). The fans show decreasing confinement from the Ainsa I to III fans, likely due to a period of relative tectonic quiescence in the basin. The Ainsa I Fan shows more lateral confinement compared with the Ainsa II and III fans, due mainly to the presence of type I MTCs (Pickering and Corregidor 2005) which created topography (ponded accommodation).

Apart from the spectacular cliff outcrops around Ainsa, the Ainsa II Fan has less accessible exposures for detailed sedimentological observations than the other Ainsa fans, so only the Ainsa I and III fans were incorporated into this study, with detailed sedimentary logs made in the lower-slope environment of the Ainsa System (Fig. 2: Ainsa I Fan (channel 1): Logs 19 and 20; Ainsa I Fan (channel 2): Logs 21, 22, and 23; Ainsa III Fan: Logs 24 and 25).

**FACIES ASSOCIATION RELATED TO SFDs**

In the Ainsa Basin, a wide range of supercritical-flow bedforms and associated sedimentary structures are observed in the deep-marine deposits. From observations, six different facies associations linked to SFDs are presented. Within the six facies associations, two categories of bedforms are recognized: (i) erosional coarse-grained bedforms of FA1a and FA1b, and (ii) depositional fine-grained bedforms of FAs 2a, 2b, 3, and 4. Bedforms are always described parallel to the main paleoflow.

**Erosional Coarse-Grained Supercritical-Flow Bedforms**

**FA1a: Meter-Scale Scours and Backfilling Structures.**—
**Description.**—Scours are from 2–5 m long and 1–2 m deep and are asymmetric with a high angle (15–20°) in the upstream side and low angle (5–10°) in the downstream side, filled with pebbly sandstones and graded stratified sandstones. The pebbly sandstones at the bases of the scours show considerable thickness variation, between 20 and 70 cm. Representative examples of these scour infills are shown in Figure 3A and 3B. Figure 3A shows an infill dominated by pebbly sandstones (Facies Group A1 of Pickering and Hiscott 2016) and graded stratified sandstones (Facies Group B2 of Pickering and Hiscott 2016). These deposits show convex-upward gently-dipping backset stratification underlain by subrounded to well-rounded pebbles (size range 3–15 cm) and angular mudclasts with some imbrications showing upflow-inclined a-b planes. Graded stratified sandstones, observed at the top of scours, show convex-upward backset lamination that may be underlain by, and incorporate, mudclasts (1–5 cm) with a progressive transition to planar-parallel lamination at the top. Figure 3B shows a scour infill dominated by graded pebbly sandstones observed...
FIG. 3.—A) FA1a meter-scale scours and backfilling structures. Outcrop in the Ainsa Quarry, basal part of Ainsa I Fan (lower-slope channel-axis environments). Spoon-shaped scour filled by discrete SGF deposits. At the base of the scour, concentrated density-flow deposits showing convex-backset lamination underlain by pebbles and mudclasts. Above this, there is an abrupt transition to turbidites, also showing convex-backset lamination. A progressive transition to parallel and foreset lamination occurs at the top of the deposits. B) FA1a meter-scale scours and backfilling structures. Outcrop in the Ainsa Quarry, Ainsa I Fan (lower-slope channel-axis environments). Asymmetric scour filled by a single SGF event. Scour surface outlined by a red thick line to show the erosion surface. At the base of the scour, there are concentrated density-flow deposits with convex-backset lamination. There is an upward change from concentrated density-flow deposits to turbidites with a progressive reduction in sand grain size and a reduction in the proportion of outsize clasts. Convex-backset lamination observed at the base of the turbidites is underlain by pebbles and mudclasts. At the top of the turbidites, there is a progressive transition from convex-backset lamination to parallel and foreset lamination. C) FA1b centimeter-scale scour-and-backfilling structures. Outcrop along Barranco Royo in the Ainsa I Fan (lower-slope channel-axis environments). Centimeter-scale scour filled by medium-bedded, medium-grained sandy turbidites. Backset lamination underlain by centimeter-scale mudclasts is present at the base of the deposit with a progressive transition to parallel lamination at the top. D) FA1b centimeter-scale scour-and-backfilling structures. Outcrop in the Banastón III Fan (proximal basin-floor channel-axis environments) near San-Miguel church, San Vicente village. Centimeter-scale scour is filled by several SGF events. Turbidites showing two sets of backset lamination with varying dips from low-angle long backset lamination (in blue), to higher-angle convex-backset lamination (in red).
at the base of the scour and graded stratified sandstones above (Facies Group A2 and B2 of Pickering and Hiscott 2016). Convex-backset lamination in the pebbly sandstones is underlain by pebbles and angular mudclasts. At the transition between the deposits, there is a reduction in grain size and in the amount of pebbles and mudclasts. Only the convex-upward backset lamination observed at the base of graded stratified sandstones are underlain by pebbles and mudclasts.

Interpretation.—Pebbly sandstones and graded stratified sandstones are interpreted as concentrated density-flow deposits and turbidites, respectively. The asymmetric scour shape associated with convex-upward backset lamination suggests the presence of a hydraulic jump, with the upstream migration of the hydraulic jump eroding the upstream side and depositing on the downstream side (Cartigny et al. 2014; Postma et al. 2016; Lang et al. 2017a; Ono and Pink-Björklund 2017). The convex-upward backset lamination can be interpreted to preserve the migration of hydraulic jumps in an upflow direction (Jopling and Richardson 1966; Macdonald et al. 2009; Ito et al. 2014). In Figure 3A, the scour infill shows an abrupt vertical transition from a concentrated density-flow deposit and an immediately overlying turbidite. Convex-upward backset lamination is consistent with the concentrated density flow and turbidity current having undergone a hydraulic jump. It is difficult to discern how many flow events infill the scour. One hypothesis involves infill of a scour by one discrete flow event undergoing a transition between a concentrated density flow and a turbidity current while going through a hydraulic jump. Due to the initial flow undergoing a hydraulic jump, there was rapid deposition of most of the bedload, in turn leading to a decrease of flow density and concentration, then leading to a flow transformation from a concentrated density flow into a more dilute SGF (turbidity current), all within the zone of a hydraulic jump (Weirich 1988). This transition must have been quite rapid, because the physical transition between the two deposits is abrupt. An alternative hypothesis is that the infill of the scour was from two discrete flow events—first a concentrated density flow undergoing a hydraulic jump and depositing its bedload, followed by a turbidity current that also underwent a hydraulic jump. The absence of a scour at the base of the upper turbidite leads us to prefer the first hypothesis. Pebbles and angular mudclasts underlying the convex-backset lamination suggest the action of erosive concentrated density flows and turbidity currents associated with increased turbulence due to hydraulic jumps (Komar 1971; Garcia and Parker 1989; Garcia 1993; Ito et al. 2014). Furthermore, erosion could have happened before the hydraulic jump, due to increased shear stresses associated with faster and thinner supercritical flow on the lee side of the bedform, also incorporating angular mudclasts into the flow (Vellinga et al. 2017).

Planar-parallel lamination observed in the deposits infilling the uppermost part of the scours can be interpreted as the Td division of the Bouma sequence, covering the hydraulic-jump deposits (convex-upward backset lamination) interpreted here as the Td division of the Bouma sequence (Postma et al. 2009).

In Figure 3B, the transition between a concentrated-density-flow deposit and the overlying turbidite can be explained by a progressive transition between a concentrated density flow into a turbidity current while the flow is undergoing the hydraulic jump (Weirich 1988), as explained in the first hypothesis for the first example of a scour infill (above).

These meter-scale scour-and-fill structures are interpreted as candidate large-scale cyclo-step deposits (Postma et al. 2014, 2016; Lang et al. 2017a; Ono and Pink-Björklund 2017). The presence of angular mudclasts underlying and within the convex-backset lamination suggests erosional hydraulic-jump zones, where intense turbulence with upward flow migration triggers liquefaction and possibly rip-up of the unconsolidated substratum (Komar 1971; Lennon and Hill 2006; Postma et al. 2009, 2014; Ito et al. 2014; Lang et al. 2017a). Their presence might argue for a train of scours where the mudclasts are incorporated into a highly erosive flow to be rapidly deposited in successive (down-flow) scours, i.e., the mudclasts have not come from the scour in which they sit but rather upflow scours and erosion such as might be expected in cyclic steps. Only isolated scour and backfilling structures have been observed in the Ainsa Basin. Limited exposure is likely the best explanation for this observation. We suspect that with larger outcrops in a downflow direction trains of scours might well have been observed. In other outcrop studies, where scour-and-fill are interpreted as cyclic-step deposits, only isolated scour-and-backfilling structures have been observed (Postma et al. 2016; Lang et al. 2017a; Ono and Björklund 2017) due to the poor preservation of these bedforms, which depend on both the magnitude of the SGFs and net sediment aggradation rates (Hage et al. 2018).

FA1a is the first type of erosional coarse-grained bedform and was observed in the channel axis of the Gerbe (I and II), Banastón I, and Ainsa I fans, suggesting that large-scale cyclic steps are present mainly in relatively high slope gradients (mid-slope environment) and in confined settings in lower-slope and proximal basin-floor environments.

FA1b: Centimeter-Scale Scours and Backfilling Structures,—

Description.—The main difference between the FA1a and FA1b is the scale of the scours. Scours of FA1b are characteristically 30–80 cm long and 20–50 cm deep and show an asymmetric shape. These spoon-shaped scours are filled by thick- to thin-bedded, fine- to coarse-grained sandstones. As in FA1a, two types of scour infills are observed. In the first case, sandstone beds show a progressive transition from convex-backset lamination to longer and less inclined backsets, to planar-parallel lamination at the top of the deposits (Fig. 3C). In the second case, different angles are observed in a succession of stacked deposits showing convex-backset lamination (Fig. 3D). A break in the angle of convex-backset lamination is seen from long inclined backset lamination to high-angle convex-backset lamination. Each set of backsets is normally graded with an abrupt transition from fine- to coarse-grained sandstone between the set of backset lamination. No planar lamination was observed between two sets of convex-backset lamination, but planar-parallel lamination is observed at the top of the bedforms. In some cases, the convex-backset lamination is underlain by angular mudclasts.

Interpretation.—As in FA1a, the asymmetric shape associated with convex-backset lamination of the scour implies the occurrence of a hydraulic jump (Cartigny et al. 2014; Postma et al. 2016; Lang et al. 2017a; Ono and Pink-Björklund 2017). The presence of convex-upward lamination suggests an upstream migration of a hydraulic jump in the flow where the backset lamination is formed downstream of the upstream-migrating hydraulic jump (Jopling and Richardson 1966; Macdonald et al. 2009; Ito et al. 2014; Postma et al. 2014). Both types of scour infill show a progressive decrease in grain size, and these deposits are interpreted as turbidites. In the first type, the scour is infilled by one discrete turbidity current, and the progressive transition from convex-backset lamination to long-backset and planar-parallel lamination is probably explained by the reduction of average grain size, flow velocity, and bedload discharge (Massari and Parea 1990; Massari 1996). In the second case, the scour is filled by different turbidity-current deposits created during several hydraulic jumps. When the flow undergoes a hydraulic jump, it erodes the convex-backset lamination of the underlying deposits, thereby explaining the backset lamination with varying internal angles. The lack of planar-parallel lamination at the top of the initial deposit can be explained by a reworking of planar-parallel lamination by a subsequent flow event into convex-backset lamination while the flow undergoes a hydraulic jump.

These centimeter-scale scour-and-fill structures are interpreted as candidate small-scale cyclic steps. The dimension of cyclic steps depends on the flow discharge, flow depth, slope, grain size, and thickness of the dense basal layer (Postma and Cartigny 2014), therefore, the wavelength of cyclic steps can form at any length from tens of meters to several kilometers (Kostic and Parker 2006; Lamb et al. 2008; Spinewine et al.)
2009; Hughes Clarke 2016). In the case of FA1b, infills are mainly turbidites, whereas infills of FA1a are both concentrated density-flow deposits and turbidites; therefore, the type of SGF might have had an influence on the scale of the scour. Structures of FA1b appear very similar to the high-angle cross-stratified sandstone infilling a small-scale scour, forming a downstream-lengthening set, as described by Arnott and Al-Muffi (2017). However, the paleoflow direction is 180° to that inferred in the Ainsa Basin, therefore leading us to a very different interpretation for bedform formation.

FA1b is part of the erosional coarse-grained bedform category and is observed in all three studied systems (Gerbe, Banastón, and Ainsa fans), but is dominant in coarse-grained sand and confined environments such as the channel axis of the Gerbe, Banastón I, and Ainsa I fans.

**Depositional Fine-Grained Supercritical-Flow Bedforms**

**FA2a: Upflow Dipping Sandstone Lenses.**—**Description.**—FA2a is characterized by upflow-dipping lenticular sandstone beds. Lenses are thin-to-medium-bedded, medium- to fine-grained sandstone. Lenses vary from 50 cm to 4 m long. Lenses can occur as a train of solitary lenticular bedforms (Fig. 4A), or as vertically stacked lenses in an upflow direction (Fig. 4B, C). Within an individual lens, the inclination of the lamination varies widely, from convex upward in the upstream side to forested dipping in the downstream parts. Generally, a structureless mudstone layer is observed at the top of the train of the solitary lenses. In stacked lenses, truncation and scour surfaces are observed at a decimeter scale. Most of the lamination is observed at the top of the lenses, whereas strata in the lower part are structureless. At outcrop, lenses can have a concave (Fig. 4B) or convex-up (Fig. 4A, C) shape.

**Interpretation.**—Upflow-dipping lenticular bedforms with variable internal architecture (backset to foreset) are interpreted as antidune deposits (e.g., Cheł 1990; Alexander et al. 2001; Cartigny et al. 2014; Ono and Plink-Björklund 2017). Based on bedform descriptions in flume experiments by Cartigny et al. (2014), FA2a is interpreted as candidate unstable antidune deposits. The multiple truncations observed are interpreted as having been produced by the upstream migration of a scour, eroding and forming the lenticular shape. Depending on how far the surge migrates, sediments are deposited on the stoss side of the lens, forming backset lamination. Then, due to a pulse in the flow, the scour is flushed downstream, reworking the top of the lens into forested lamination (Cartigny et al. 2014). Depending on the amount of sand supplied to the depositional surface, this facies association occurs either as solitary lenses or upflow-stacked centimeter-scale lenses. The structureless mud cap observed at the top of the train of solitary lenses is likely explained by the high mud content. One hypothesis could be that the solitary lenses are mainly formed within the basal layer of the SGF. The main body of the SGF could have had a high concentration of suspended mud, creating a mud drape at the top of the solitary lenses, also suggesting that the flow may have been stratified. Upflow-dipping sandstone lenses are commonly observed in the channel axis of the Banastón and Ainsa sandbodies and are part of the fine-grained depositional bedform category. One good example of trains of solitary lenses is observed in the channel axis of the Gerbe II Fan.

**FA2b: Upflow-Stacked Wavy Bedforms.**—**Description.**—FA2b is characterized by medium- to thick-bedded, medium- to coarse-grained sandstone showing wavy bedforms. Their wavelength is irregular and varies from 70 to 380 cm. Depending on the outcrops, wavy bedforms show varying amplitudes, from high-amplitude waveforms (10–20 cm) from the bottom of the scour to the top of the bedform crest) (Fig. 5A, B) to low-amplitude waveforms (5–10 cm), thereby making them hard to observe in many outcrops. Troughs at the top of the bedform have an asymmetric shape with a steep lee side and a gently inclined stoss side and are filled by structureless mudstones or sandstones. The internal architecture exhibits a large variation in the dip of laminae from convex-backset, subhorizontal to foreset lamination. These types of laminae are developed at the tops of the bedforms. The bottom part of the bedform is characterized by a structureless deposit or backset lamination.

**Interpretation.**—As observed in FA2a, the presence of convex-backset and forest lamination suggests that deposition was under supercritical-flow conditions (Alexander et al. 2001; Spinewine et al. 2009; Cartigny et al. 2014). The scale, wavelength, and internal structures are consistent with the interpretation as unstable-antidune deposits (Cartigny et al. 2014). Unstable-antidune deposits of FA2a and FA2b have different shape and thickness. These differences can be explained by the strength of the upstream-migrating surge. The surge in FA2a has to be strong enough to erode and scour the sediment located upstream to create a lenticular shape to the bed. In FA2b, the upstream-migrating surge is weaker than for the unstable antidunes of FA2a, and produces troughs only at the tops of the bedforms. Structureless mudstone or sandstone infilling a trough is interpreted to represent deposition of the remaining part of the flow or a later flow.

Upflow-stacked wavy bedforms are observed mainly in the channel axis of Banastón and Ainsa fans.

**FA3: Upflow-Stacked Sigmoidal Bedforms.**—**Description.**—FA3 is characterized by meter-scale sigmoidal bedforms. The term sigmoidal is used to define the shape of a bedform that has an “S” form. Upflow-stacked sigmoidal beds are medium- to thick-bedded, medium- to coarse-grained sandstone 2–6 m long (Fig. 6A, B, C). Sigmoidal bedforms show characteristic variation from structureless sandstone in the lower part of a bed to normally graded low-angle convex-backset lamination at the top of a bed on the upstream sides of bedforms. The downstream side of the bedform shows subhorizontal lamination and foreset low-angle lamination.

**Interpretation.**—As in FA2a and FA2b, the presence of backset lamination and convex-upward lamination suggests deposition under supercritical-flow conditions (Alexander et al. 2001; Spinewine et al. 2009; Cartigny et al. 2014). Upflow-stacked beds suggest an upflow bedform migration. Upflow-stacked bedforms together with convex-backset, forest, and subhorizontal lamination are interpreted as deposition from upstream-migrating stable antidunes (Lang et al. 2017a). Upflow-stacked sigmoidal bedforms are seen mainly in channel-axis and off-axis sites in the Banastón and Ainsa sandy fans and are part of the fine-grained depositional bedforms category.

**FA4: Plane Bed.**—**Description.**—Plane bed occurs as very thin- to thick-bedded, very fine- to medium-grained sandstone that shows planar-parallel lamination (Fig. 6D, E). Beds show a sharp base with paleoflow indicators as flutes or grooves. Planar-parallel lamination may occur at the bottom and/or top of a bed. Where they occur in the lower part of a bed, they are typically underlain by mudclasts and pebbles (< 1 cm). In most cases, ripple cross-lamination overlies the plane beds. Due to poor exposure, it is difficult to follow plane beds for lateral distances greater than approximately 10 m.

Banded layers in sandstone are observed in the middle of a bed and are commonly associated with structureless beds. This structure is characterized by centimeter-scale normally graded (and in some cases inverse-graded) parallel (planar) layers of coarse-grained sediment.

Observations of planar-parallel lamination in the Ainsa System in Well L2 core from the Ainsa Basin were undertaken (see well location in Pickering et al. 2015). No mineral segregation was observed. However, lamination is visible because of grain-size segregation, with the coarsest grains forming the laminae. In some cases, it is possible to observe grain imbrication in these laminae (upflow-dipping a–b planes). Each lamina is separated by the structureless finest grain size.
Interpretation.—We interpret the plane-bed deposits described above as having formed under upper-flow-regime (UFR) conditions (supercritical flow). There is considerable disagreement amongst researchers over UFR plane-bed formation, i.e., if UFR plane beds are formed under supercritical or subcritical conditions. UFR plane beds can be found in three supercritical-flow bedforms: the very low-amplitude bedforms (in-phase bed), in plane bed under slow aggradation rates (Allen 1984; Paola et al. 1989; Cheel 1990) and on the stoss sides of cyclic-step bedforms (Postma and Cartigny 2014). In most cases, the parallel lamination can be interpreted as the Bouma Tb division in turbidites (cf. traction carpet of Hiscott 1994 and Postma et al. 2009). Skipper (1971) and Walker (1965) proposed that UFR plane beds observed in the Tb division of the Bouma sequence formed under supercritical-flow conditions. Fielding (2006) asserted that plane beds with a grain size from very fine- to medium-grained sandstone formed under supercritical-flow conditions (UFR). Tilston et al. (2015) suggest that formation of plane beds may be related to how sediment is distributed in the flow. Throughout the Ainsa Basin, the widespread presence of spaced parallel (banded layers) stratification in sandy deposits is used as evidence for traction under supercritical turbulent currents (cf. Hiscott and Middleton 1979; Hiscott 1994; Postma et al. 2009).

Fig. 4.—A) FA2a, showing individual lenticular bedforms. Outcrop in the Gerbe II Fan (mid-slope channel-axis environments) near Gerbe village. Trains of symmetric lenticular bedforms with a structureless mud cap are observed. Each bedform is 1–6 m long and 30–50 cm thick. Some lenses are stacked, which can be interpreted as successive discrete SGF deposits. The lens observed at the right of the picture is interpreted as FA1a representing a part of a large-scale cyclic step. B) FA2a related to upflow-dipping centimeter-scale lenticular beds. Outcrop in the Ainsa III Fan (lower-slope channel-axis environments) along Rio Buchosa. In this case, lenses with a concave-up shape can reach 1 m long. They show a large variability in the dip of lamination from backset, sub-planar parallel to foreset lamination. Many truncation surfaces are also observed. C) FA2a related to upflow-dipping centimeter-scale lenticular beds. Outcrop in the Ainsa III Fan (lower-slope channel-axis environments) along the Rio Buchosa. Stacked lenses with a convex-up shape, varies between 10 and 30 cm thick, normally graded, medium- to fine-grained sandstones. Most of the lenses are structureless at the base and show backset lamination at the top; some lenses show foreset lamination at the top with truncation surfaces.
Ripple cross-lamination is observed at the tops of upper-plane beds, showing flow deceleration to produce bedforms interpreted as the $T_c$ division of the Bouma sequence formed by tractional reworking of fine-grained sediment (Sumner et al. 2008). As in many previous studies, we note the absence of dunes between the upper-plane beds and the ripple cross-lamination (for a discussion of this issue and possible explanations, see section 1.5.7 in Pickering and Hiscott 2016).

The interpretation of upper-plane bed in terms of facies association requires some discussion, because they could be observed in many of the facies associations described above (FA1a, FA1b, FA2a, FA2b, or FA3). Plane beds observed over lateral distances $\sim 10 \text{ m}$ can be interpreted as UFR plane beds. Where the lateral exposure is more limited ($\sim 10 \text{ m}$, it is difficult, if not impossible, to interpret plane beds as FA4 because they could be part of another supercritical-flow bedform described above (e.g., long-wavelength antidunes, FA2a, FA2b, and FA3, or on the stoss sides of cyclic steps, FA1a).

FA4 was observed in many types of depositional environments, from channel axis to channel levee-overbank in all three studied systems (the Gerbe, Banastón, and Ainsa sandy fans).

**DISTRIBUTION OF SUPERCRITICAL-FLOW DEPOSITS**

**Gerbe System (Mid-Slope Environment)**

Interpretations of depositional environments of the Gerbe System and constituent fans are based on the following papers: Millington and Clark (1995), Clark and Pickering (1996), and Pickering and Bayliss (2009).

**Gerbe I Fan.**—In the Gerbe I Fan, a detailed sedimentary log was compiled in channel-axis deposits. The lower part of the Gerbe I Fan consists mainly of medium- to thick-bedded, structureless, concentrated density-flow deposits with pebble to coarse-grade sandstones. Supercrit-
supercritical-flow bedforms were observed only in the upper and finer-grained parts of the sedimentary log in the sandy fan deposits. 35% of the Gerbe I Fan total sandstone thickness (Table 1, Log 1) can be interpreted to have been deposited under supercritical-flow conditions.

**Gerbe II Fan.**—In the Gerbe II Fan, four detailed sedimentary logs were measured (three logs in channel-axis and one log in channel levee–overbank deposits). The three sedimentary logs in channel-axis deposits are along an upflow–downflow transect (Log A is the more proximal and log C more distal—summarized in Table 1, Log 2A, B, and C). Most of the candidate supercritical-flow bedforms recognized in the channel axis are candidate unstable antitides (FA2a) and cyclic steps (FA1a and FA1b). Log B shows good examples of scour-and-backfilling structures and individual (solitary) lenticular bedforms, interpreted as candidate cyclic steps (FA1a and FA1b) and unstable antitides (FA2a), respectively (Fig. 7). Outcrop limitations mean that the sedimentary logs were made with horizontal separations of 20–50 m. These three closely spaced logs provide an opportunity to check the degree of accuracy of the method used. Because the sedimentary logs are spaced equal to the bed form length, very similar percentages of SDFs were expected in these logs. The three logs show a similar proportion of sediments deposited under supercritical-flow conditions (Log A, 40%; Log B, 42%; Log C, 33%). Therefore, the error bar is estimated to be on the order of 9% (from 42% to 33%). Supercritical-flow bedforms recognized in the channel levee–overbank are mainly stable-antitide deposits or upper-plane beds. The channel levee–overbank deposits show a proportion of SDFs similar to that of the channel axis, with 32% (Table 1, Log 3).

**Banastón System (Proximal-Basin-Floor Environment)**

Interpretations of depositional environments for the Banastón System and constituent fans are based on Bayliss and Pickering (2015).

**Banastón I Fan.**—Three detailed sedimentary logs in the Banastón I Fan (Table 1, Logs 4, 5, and 6) were measured. The channel axis shows a high content of structureless conglomerates and coarse-grained sandstones. At the base of the fan, candidate cyclic steps (FA1a) are observed. The channel axis of the Banastón I Fan contains one of the lowest proportions of SDFs in the Banastón System, with 37% of the logged section. The channel margin is composed mainly of many very fine- to fine-grained sandstones comprising supercritical-flow bedforms such as dunes and ripples, explaining the low proportion of SDFs.

**Banastón II Fan.**—From the three detailed sedimentary logs in the Banastón II Fan (Table 1, Logs 7, 8, and 9), a decrease is observed in the proportion of SDFs from the channel axis to the channel margin. More supercritical-flow structures such as stable (FA3) and unstable antitides (FA2a and FA2b) have been observed in the Banastón II Fan than in the Banastón I Fan, explaining the increase of the percentage of SDFs between these two fans.

**Banastón III Fan.**—From the two detailed sedimentary logs in the Banastón III Fan (Table 1, Logs 10 and 11), no significant changes in the proportion of SDFs are observed between the channel axis (45%) and channel off-axis (38%). Changes in the proportion of SDFs are expected between various depositional environments, e.g., channel-axis and off-axis sites will be associated with SDFs with differences in hydrodynamics (flow density, velocity, and height). Where no significant changes (> 9%) are observed between the channel-axis and channel off-axis environments, we suspect that the detailed sedimentary logs were too close to each other and made in essentially similar sedimentary environments. Channel widths are typically up to several hundred meters, making it difficult to precisely define channel-axis, off-axis, and channel-margin environments.

**Banastón IV Fan.**—The two sedimentary logs in the Banastón IV Fan are spaced ~ 1,000 m apart (Table 1, Logs 12 and 13). An insignificant decrease in the proportion of SDF is observed from the channel-axis sites (44%) to channel off-axis (36%) sites (Fig. 8). Even if the percentages of SDFs is somewhat similar between channel-axis and channel off-axis sites, making it difficult to characterize different channel environments, it is still possible to observe a variation in the type of supercritical-flow bedforms (high or low Fr) between channel environments. Several erosive supercritical-flow structures (high Fr) were observed in the channel axis, e.g., small-scale cyclic-step deposits (FA1b). In contrast, supercritical-flow bedforms with a lower Froude number (but Fr > 1) are more common in channel off-axis sites than in channel-axis sites (e.g., FA3 and FA4).

**Banastón V Fan.**—As in the Banastón III Fan, the Banastón V Fan shows no significant change in the percentage of SDFs from channel-axis sites (39%) to channel off-axis sites (34%) (Table 1, Logs 14 and 15) (Fig. 8). The channel-axis environment contains erosional supercritical-flow bedforms, e.g., candidate cyclic steps (FA1a and FA1b). Many candidate unstable and stable antitides (FA2a, FA2b, and FA3) and upper-plane bed (FA4) deposits containing a high proportion of medium- and coarse-grained sandstone were recorded in channel off-axis environments. The high proportion of erosional structures in channel-axis environments can be explained by the presence of several hydraulic jumps creating the scours with a rapid reduction in flow turbulence immediately following a hydraulic jump, leading to deposition of most of the bedload (high proportion of Facies Class A of Pickering and Hiscott 2016).

**Banastón VI Fan.**—From the three detailed sedimentary logs in the Banastón VI Fan (Table 1, Logs 16, 17, and 18), a decrease in the proportion of SDFs is observed from the channel-axis to the channel off-axis and channel-margin sites (Fig. 8). The channel axis in the Banastón VI Fan is characterized by many supercritical-flow bedforms, such as candidate stable (FA3) and unstable antitides (FA2a and FA2b) and upper-plane beds (FA4), dominated by medium- to fine-grained sandstones. The Banastón VI Fan shows the highest percentage of SDFs of all the Banastón fans. The Banastón VI Fan is considered to be more depositional rather than erosional (and with less sediment bypass), compared with the other
Table 1.—Percentage of the total thickness calculated for each sedimentary log of the sandstone and mudstone (silt is included in sandstone percentages), bed thickness (very thin beds, 1–3 cm; thin beds, 3–10 cm; medium beds, 10–30 cm; thick beds, 30–100 cm; very thick beds, > 100 cm; Pickering and Hiscott 2016), Facies Classes (Facies Class A, gravels, muddy gravels, gravelly muds and pebbly sand; Facies Class B, sands; Facies Class C, sand–mud couplets and muddy sands; Facies Class D, silts, silty muds and silt–mud couplets; Facies Class E, muds and clays; facies classification scheme of Pickering and Hiscott 2016), grain size and proportion of SFDs (the percentage of mudstone is not taken into account in the calculation of proportion of SFDs). The sedimentary logs are in different fan environments in an across-fan (lateral) direction (channel axis to the channel margin and levee–overbank) and in a proximal-to-distal direction, from a mid-slope environment (Gerbe System), proximal-basin floor environment (Banastón System), and lower-slope environment (Ainsa System).

<table>
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<th>Depositional environments</th>
<th>GERBE SYSTEM (MID-SLOPE)</th>
<th>BANASTÓN SYSTEM (PROXIMAL BASIN-FLOOR)</th>
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<td>Gerbe II Channel axis (698 beds)</td>
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<td>Sandstone deposited under supercritical conditions</td>
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Notes: SFDs = Simple Fluid Deposits.
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<th>Facies C</th>
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<td>22%</td>
<td>20%</td>
<td>45%</td>
<td>29%</td>
<td>12%</td>
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<td>43%</td>
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<tr>
<td>Banastón VI Channel margin</td>
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<td>20%</td>
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<td>29%</td>
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<th>Facies B</th>
<th>Facies C</th>
<th>Facies D</th>
<th>Facies E</th>
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<td>82%</td>
<td>18%</td>
<td>26%</td>
<td>32%</td>
<td>8%</td>
<td>30%</td>
<td>4%</td>
<td>11%</td>
<td>44%</td>
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<td>2%</td>
<td>18%</td>
<td>4%</td>
<td>1%</td>
<td>7%</td>
<td>6%</td>
<td>0%</td>
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Fig. 7.—Panorama of the Gerbe II cliff where Log B was measured in channel-axis deposits (42% interpreted as SFDs). The outcrop of the channel off-axis was inaccessible, but it is possible to observe a decrease in the sandstone content and in supercritical-flow structures such as scour and backfilling structures and/or lenticular bedforms. The base of the Log 2 shows a good example of candidate large-scale cyclic steps and unstable antidune deposits.
systems: the overall Fr still being supercritical, but generally lower than in
the other Banastón fans.

Ainsa System (Lower-Slope Environment)

Interpretations of depositional environments of the Ainsa System and
constituent fans are based on Pickering and Corregidor (2005) and
Pickering et al. (2015).

Ainsa I Fan.—The closely spaced detailed sedimentary logs made in
channel 1 of the Ainsa I Fan (< 400 m) militated against the clear
recognition of any subtly different channel environment. Both logs (Table
1, Logs 19 and 20; Fig. 9) were measured in channel-axis environments in
the Ainsa I Fan, and show a range in SFD distribution between 52 and
59%. However, the increase of mudstone percentage from Log 19 (18%) to
Log 20 (33%), is consistent with the latter being a slightly more off-axis
channel environment, albeit still within the main channel(s). Furthermore,
the observation of the different types of supercritical-flow bedforms might
aid in the discrimination of depositional environments. Log 19 contains
several structures that can be interpreted as candidate cyclic steps, whereas
Log 20 is characterized by deposits showing typical partial Bouma
sequences (Tbc) where only the Tb division is interpreted as deposited
under supercritical-flow conditions.

The study of another channel (channel 2) in the Ainsa I Fan was
undertaken, where three detailed sedimentary logs were measured. In this
case the sedimentary log in the channel axis is spaced ~ 2 km from the
channel off-axis and channel-margin logs, thereby providing a clear
distinction between the channel-axis and off-axis sites. The channel axis
contains several thick- to medium-bedded, erosionally based structures,
interpreted as candidate cyclic steps, most of which are associated with
Facies Class B of Pickering and Hiscott (2016). The channel-margin
environment contains more structures interpreted as deposited under
subcritical-flow conditions.

Ainsa II Fan.—Two sedimentary logs were measured in the Ainsa II
Fan. Several bedforms in the channel axis can be interpreted as unstable-
antidune deposits (FA2a and FA2b), associated with a greater proportion
of Facies Class B deposits (Pickering and Hiscott 2016) in the channel
axis. The predominant deposits are fine- and medium-grained sandstones,
both in channel-axis and channel off-axis sites, even where channel off-
axis deposits contain more coarse-grained sandstones and conglomerates
than do channel-axis sites. The Ainsa III Fan appears to have been dominated by depositional processes under supercritical-flow
conditions. With the presence of conglomeratic and coarse-grained
sandstones in channel off-axis environments, they can be interpreted as
the vestiges of bedload bypass processes through the channel axis to
depositional sites basinwards in the more distal parts of channels and
lobes (Jaca Basin).

DISCUSSION

Our description and analysis of the distribution of SFDs in ancient
submarine-fan channels and related environments has contributed to an
improved understanding of the likely flow dynamics and depositional
processes in deep-marine siliciclastic systems. Erosional coarse-grained
supercritical-flow bedforms (FA1a and FA1b) are observed mainly in
channel-axis sites, in relatively high-gradient, and in confined, basin
settings (Gerbe System and at the base of the Banastón I and Ainsa I)
(Fig. 10). The location of these bedforms towards the base of the sandy
fans suggests that they could have been precursors to the development of
channels in the Banastón I and Ainsa I fans. At a significantly larger
scale, similar processes of active cyclic steps eroding a submarine
canyon have been observed in the Monterey channel (Fildani et al.
2006) and in Eel Canyon, California (Lamb et al. 2008). Depositional
fine-grained supercritical-flow bedforms (FA2a, FA2b, FA3, and FA4)
are more common in low-gradient slopes and relatively unconfined
settings, such as the Banastón II, III, IV, V, and VI and in the Ainsa III
fans (Fig. 10). These facies associations are also present in channel-axis
and off-axis sites. Upper-plane beds are observed from the channel-axis
sites to the channel–levee–overbank sites. We acknowledge that a flow
can be thicker than seabed topography, in which case a relatively
unconfined flow could leave a confined deposit (e.g., in a large scour or
large-aspect-ratio channel). We, therefore, use the terms “confined” and
“unconfined” to indicate relative confinement based on mapping
criteria.
SFD Distribution from Channel-Axis to Channel-Margin Sites

In the three studied systems in the Ainsa Basin (Gerbe, Banastón, and Ainsa), for most of the fans there is a decrease in the proportion of SFDs from channel-axis to channel-margin sites (Fig. 11). From channel-axis to channel-margin and levee–overbank sites, there is a systematic decrease in sandstone bed thickness and an increase in mudstone proportion, suggesting a lateral (axial-to-lateral) decrease in the strength of SGFs away from the channel axis. Similar SFD distributions and comparable interpretations were made by Lang et al. (2017a) for the upper Eocene Brito Formation (Nicaragua Basin), i.e., with an inferred decrease in flow strength (decrease in flow density and velocity) away from channel axes. Several researchers (e.g., Normark et al. 1980; Migeon et al. 2001; Fildani et al. 2006) observed supercritical-flow bedforms along channel margins or channel levees constructed by turbidity currents overspilling the confines of channels and creating crevasse splays or sediment slides. Very few candidate crevasse-splay structures were observed in the channel levee–overbank systems in the Ainsa Basin, which could explain why very few supercritical-flow bedforms were observed in channel-margin or levee–overbank environments.

SFD Distribution from Proximal to Distal Sites

When the percentage of SFDs is binned into different depositional environments, the data reveal an overall increase in the proportion of SFDs from the Gerbe (mid-lower slope), to Banastón (proximal-basin floor), and Ainsa (lower slope) systems (Fig. 11). Comparison between systems is linked with the SFD percentage in channel-axis sites where most of supercritical-flow bedforms are observed.

In the Gerbe System, a low percentage of SFDs is observed with 35% and 38% in the Gerbe I and Gerbe II fans, respectively (Fig. 11). Because these are mid-lower slope environments, with likely slope gradients $\approx 0.5^\circ$, a higher percentage of SFDs was expected. Concentrated density flows and turbidity currents can have substantial erosional potential to create scour structures at least partially infilled with conglomerate and coarse-grained sandstones that otherwise might have bypassed these sites (cf. Wynn et al. 2002; Macdonald et al. 2011; Ito et al. 2014). In such cases, one would not expect the formation of supercritical-flow bedforms in the conglomerate-dominated Gerbe I Fan, i.e., resulting in the observed low percentage of SFDs. Furthermore, lens-shaped conglomeratic layers, pebbly sandstones, and truncated sandstone beds are a common feature in the Gerbe System.
and can be considered as characteristic of sediment bypass. The increased proportion of SFDs in the Gerbe II Fan (compared with that in the Gerbe I Fan) can be explained by decreased confinement of the fan, all consistent with mapping (Pickering and Bayliss 2009). A decrease in confinement will lead to a flow that spreads more laterally, therefore the flow will be thinner. The Fr is directly linked with the flow height. For the same sediment concentration and flow discharge, if the flow height decreases, the Fr increases in the density flow; thereby, the flow is more likely to produce supercritical bedforms. There is also an increase in the proportion of fine-grained sediment (medium- to fine-grained sandstones) from the Gerbe I to the Gerbe II Fan, an observation that we believe is coincidental rather than resulting from any genetic association, i.e., this represents local preservation from a time when there was more sediment bypass in the Gerbe I compared with the Gerbe II Fan. The Gerbe System was deposited during the terminal stage of a period of intense tectonic shortening and deformation associated with folding, thrusting, and local overturning of the underlying Arro System (Millington and Clark 1995; Pickering and Cantalejo 2015). The generally low percentage of SFDs in the Gerbe System can be explained by deposition during the development of a new system of canyon and submarine channel following basin reorganization, with sandy SGFs generally having been strongly erosional rather than depositional, thereby generating more erosional structures rather than supercritical-flow depositional structures. Mapping by Pickering and Bayliss (2009) has suggested that, unlike in many continental margins, sandy fans in the Ainsa Basin were separated by tens to hundreds of meters of basin-wide fine-grained sediment accumulation that infilled and healed any point sources that provided coarse siliciclastics to older fans.

In the Banástón System, the transition from middle to lower slope to proximal basin-floor environments resulted in an overall decrease of confinement (Pickering and Bayliss 2009; Bayliss and Pickering 2015). During deposition of the Banástón I, II, and III fans (compared with the later Banástón IV, V, and VI fans), the growth of the Añisclo Anticline likely ceased or the sediment accumulation rate exceeded the growth of the Añisclo Anticline, resulting in a progressive decrease in lateral confinement. The Banástón I Fan has the highest proportion of coarse-grained sediment (including conglomerates) in the Banástón System, and with one of the lowest proportions of SFDs (37%). In contrast, the Banástón II Fan shows a greater percentage of SFDs (58%) which can be linked to decreased confinement compared with that for the Banástón I Fan. The decrease in the proportion of conglomerates and coarse-grained sandstones from the Banástón I to the Banástón II Fan can be explained by more sediment bypass in the Banástón I Fan, with a lower preservation of SFDs in the latter. The Banástón III Fan has ~ 45% SFDs, a value significantly lower than the underlying Banástón II Fan but greater than the Banástón I Fan. Whilst mapping of the Banástón III Fan shows that it is the least confined sandy fan of the Banástón I, II, and III fans, it has the

Fig. 10.—Schematic depositional model for the Ainsa Basin sandy fans to show the environmental distribution of the six facies associations with SFDs. The SFDs occur across a wide range of environments but are shown where they are most abundant. Erosional coarse-grained supercritical-flow bedforms (red) are dominant in channel-axis environments in relatively confined settings, and also high slope gradients such as in the mid-slope and transition between middle- to lower-slope environments. Depositional fine-grained supercritical-flow bedforms (blue) are the dominant facies association in channel-axis and off-axis sites in relatively unconfined settings, and in relatively low-gradient slope sites.
thickest MTDs (up to ~20 m), as well as abundant MTDs and, therefore, is likely to have been associated with substantial lateral confinement of sands due to reduced accommodation space created by depositional topography. Thus, in any discussion of the proportion of SFDs, it is important to distinguish between both system-wide confinement (between the basin-bounding growth anticlines) and more local confinement caused by the deposition of MTDs.

In the Banastón IV, V, and VI fans, there is no change in the thickness of sandbodies across the Añisclo Anticline, interpreted as due to essentially no growth of this seafloor high during sandy-fan deposition (Bayliss and Pickering 2015). This lack of significant syndepositional tectonic activity resulted in a progressive decrease of confinement from the Banastón IV to Banastón VI fans. The decreased lateral confinement of these fans resulted in a progressive increase in the proportion of SFDs from the Banastón IV Fan (44%) to the Banastón VI Fan (53%) (Fig. 11). Symons et al. (2016) and Covault et al. (2016) show that large-scale fine-grained sediment waves are most likely to develop in unconfined settings.

In the Ainsa System, the high proportion of SFDs is attributed to it being a lower-slope environment (in the SE of the Ainsa Basin, where the data for this study was collected) with relatively steep gradients compared with the Banastón System. The Ainsa System also has a higher percentage of fine- to medium-grained sandstones compared with the Gerbe System, suggesting less sediment bypass than in the Gerbe System. Additionally, the Ainsa System shows a transition from lower-slope to proximal basin-floor environments (Pickering and Corregidor 2005; Pickering et al. 2015). In such a setting, transiting SGFs are very likely to have experienced hydraulic jumps at the break of slope associated with a rapid decrease of lateral confinement, all conductive to the generation of supercritical-flow bedforms. The Ainsa I Fan shows greater lateral confinement compared with the Ainsa II and III fans, most likely due to the presence of both underlying and laterally deposited Type I MTCs, which created substantial irregular topography and locally ponded accommodation (Pickering et al. 2015). Fan lateral confinement can explain the relatively low percentage of SFD of the Ainsa I Fan compared to Ainsa II and III fans (Fig. 11). Throughout deposition of the Ainsa System, relatively little significant intrabasinal tectonic activity favored a progressive decrease in lateral confinement from the Ainsa I to Ainsa III fans. The Ainsa III Fan contains the highest proportion of fine-grained sediments and, based on mapping (Pickering et al. 2015), was the least confined fan, showing the highest proportion of SFDs, with 66% of the total channel-axis deposits (Fig. 11).

**Fig. 11.—** Variation in proportion of SFDs in an axial-to-lateral direction. Note the decrease in the proportion of SFDs from channel-axis to channel-margin sites, and between the different systems, with an increase in SFDs from the Gerbe System (mid-slope environments), to the Banastón System (proximal basin-floor environments), and to the Ainsa System (lower-slope environments). This increase is seen in the channel-axis environments of each system, where most of the supercritical-flow bedforms were recorded.
Parameters Influencing SGF Criticality

In this study, two main parameters are recognized as having played an important role on the hydrodynamics of SGFs (i.e., if the flow was under supercritical or subcritical conditions): (i) lateral confinement of the sandy fans, and (ii) seafloor gradient. In the Ainsa Basin, these parameters vary both within and between depositional environments. At present, it is difficult to assess which of these parameters (above) might have exerted the greatest influence in determining the criticality of any SGF. However, in ancient systems such as in the Ainsa Basin, mapping makes confinement easier to recognize than subtle differences in seafloor gradient.

Concerning confinement, a greater proportion of fine-grained SFDs were observed in relatively unconfined (compared with more confined) settings. However, this observation does not preclude SGFs being under supercritical-flow conditions in confined settings. Most of the SFDs observed in relatively confined settings are coarse-grained erosional bedforms with a strong erosional component, and bedforms likely formed under the highest Fr. In relatively unconfined settings, fine-grained depositional supercritical-flow bedforms are the dominant SFDs and form at lower Fr (but Fr erosional component, and bedforms likely formed under the highest Fr). We suspect that the preservation potential of SFDs is greatest in relatively unconfined systems, due to deceleration of SGFs at the transition from a relatively confined system (mid-slope environment—Gerbe System) to a relatively unconfined system (break-of-slope, lower-slope, and proximal basin-floor environments—Banástón and Ainsa Systems). We suspect that there is a trade-off between confinement of sandbodies and slope gradient, with both playing a role in the criticality of a flow and in the preservation of any supercritical-flow bedforms, e.g., we observe the highest percentage of SFDs in the Ainsa System (lower-slope environment) which shows moderate confinement and intermediate slope gradient.

SFDs or Tidal Deposits?

A curious aspect of the Ainsa Basin is that many of the deposits we describe and interpret here appear to be poorly documented from other ancient deep-marine systems. This might simply be that such bedforms have been overlooked in the past, because they have not fitted expected depositional models, including the Bosma sequence. Alternatively, one might argue that they could represent a deep-water tidal influence in the Ainsa Basin, which was certainly a narrow and elongate seaway connected to the global ocean, perhaps with similarities to submarine canyons, where tidal processes are recognized in deep water (e.g., Beaulieu and Baldwin 1998). The absence of candidate tidal bundling (e.g., neap-spring depositional cycles), a lack of convincing flaser, wavy, and lenticular ripples, and the ubiquitous presence of deep-water foraminifera, leads us to reject this interpretation in favor of processes linked to supercritical versus subcritical flow in SGFs.

CONCLUSIONS

In this paper, we describe a large range of sedimentary structures, bedforms, and deposits from the middle Eocene deep-marine Ainsa Basin that were likely deposited under supercritical-flow conditions. From field observations, we propose six facies associations related to supercritical SGFs. These facies associations are binned in two categories:

(i) Erosional coarse-grained supercritical-flow bedforms, commonly observed in relatively confined settings such as mid- to lower-slope environments. These bedforms are associated with meter and centimeter scale scour and backfilling structures, interpreted as candidate large-scale cyclical steps and small-scale cyclical steps.

(ii) Depositional fine-grained supercritical-flow bedforms, commonly observed in intrachannel sites in relatively unconfined settings, such as base-of-slope, break-of-slope, and proximal basin-floor environments. These bedforms are related to upflow-dipping sandstone lenses, upflow-stacked wavy bedforms, upflow-stacked sigmoidal bedforms, and plane beds interpreted as unstable and stable antitridunes and UFR plane beds.

We demonstrate the importance of determining the relative proportion of SFDs in different submarine-fan and related environments as a tool for improving the understanding of likely flow dynamics in deep-water siliciclastic systems. We have produced an erosional–depositional model for this distribution of structures, bedforms, and deposits, something that should prove useful for comparison with other deep-water systems. In this study, we have determined the distribution of supercritical-flow bedforms in the Ainsa Basin, showing that it varies with:

(i) Axial-lateral changes: a decrease in the proportion of SFDs from channel-axis to the channel-margin environments, interpreted as due to decreased flow strength from channel axis to channel margin.

(ii) Proximal-to-distal changes: an increase in the proportion of SFDs from the older Gerbe (mid-lower-slope, coarsest-grained fans), to Banástón System (proximal-basin-floor environment), and to the younger Ainsa System (lower-slope environments with the relatively finest-grained fans of all three systems).

The parameters that appear to have the most impact on the criticality of a flow are the relative confinement and seafloor gradient, and not grain size. We would argue that any apparent genetic association between the proportion of SFDs and grain size is coincidental and related to preservation potential. Tectonic activity, such as the growth of the Mediano, Boltaña, and Añisclo anteciles, will have played an important role in the confinement of the fans (and also in slope gradient), thereby impacting the criticality of any flows.

Until further studies similar to ours are conducted in other ancient deep-water depositional systems, we do not know how typical our values for SFDs (channel axis, from 35% to 66%; channel off-axis, from 30% to 59%; channel margin, from 26% to 30%) might be to characterize channel and related environments. This study is a first step in the recognition and evaluation of SFDs in deep-marine environments. More work is required to understand the mechanisms of sediment gravity flows. From this paper, several questions arise, such as: how common are these SFDs in others deep-water systems with basin settings different from that of the Ainsa Basin (basin width and length, slope gradient, or water depth). How do we evaluate the difference in scale between structures observed in ancient and modern deep-water systems but also structures obtained in flume-tank experiments? What are the typical values for Fr, flow density, ambient fluid, flow depth? Based on field observations only, these questions are difficult to answer. There is, therefore, a need to be combine field observations and measurements with results from flume experiments and numerical modeling, and with observation of sediment gravity flows and their deposits in modern systems.

ACKNOWLEDGEMENTS

We thank Hess Corporation (in particular Richard Beaubouef and Scott Pham) and University College London (UCL) for funding this research. We thank Rick Hiscott (Memorial University, Newfoundland) for his constructive criticism, which has led to a much-improved paper. We would also like to thank Matthieu Cartigny, Andrea Fildani, Bill Arnott, Marco Patacci, and John Southard for their helpful comments.

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WILLENBACH, P.H., CORNARD AND K.T. PICKERING
Received 28 March 2018; accepted 19 February 2019.
Queries for sedp-89-06-02

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