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# Submarine topographic control on distribution of supercritical-flow deposits in lobe-and-related environments, Middle Eocene, Jaca Basin, Spanish Pyrenees

CORNARD, Pauline H.[1], PICKERING, Kevin T.[1]

[1] Department of Earth Sciences, University College London (UCL), Gower Street, London, WC1E 6BT, UK

Corresponding author: pauline.cornard.15@ucl.ac.uk

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## ABSTRACT

Submarine lobe-and-related deposits are amongst the largest discrete sandbodies on Earth, and can be significant hydrocarbon reservoirs. In outcrop and core-based studies, tools such as bed-thickness and grain-size distribution analysis have been used to improve the understanding of the composition and architecture of such sandbodies. Analysis of sediment gravity-flow (SGF) processes have also proved to be a useful tool in understanding the evolution of submarine lobes. In this paper, based on outcrop studies of submarine lobe-and-related deposits in the Middle Eocene Jaca Basin, Spanish Pyrenees, a revised interpretation of the depositional environments of the lobe-and-related deposits and a new model for their architectural evolution is presented. This model is based on an analysis of bed-thickness, grain-size distribution and a qualitative and quantitative study of the distribution of supercritical-flow deposits (SFDs) in these environments. The interpretation of lobe-and-related environments is mainly based on sandstone content and the distribution of sedimentary facies. The main supercritical-flow sedimentary structures recognized in the Jaca Basin, are unstable and stable antidunes, upper-plane beds and backset laminated beds.

This study demonstrates that seafloor topography, strongly controlled by both syndepositional tectonics and the accumulation of mass-transport complexes, likely exerted a significant influence on lobe architecture and the distribution of SFDs. Local bed-thickness increases, together with a progressive decrease in grain size and little variation in the proportion of SFDs in proximal-to-distal and axial-to-lateral directions, can be explained by (i) an increase in basin confinement of the distal part of the Jaca Basin due to tectonically-induced narrowing, (ii) enhanced local lateral confinement due, at least in part, to “carbonate

megaturbidites" present in the distal part of the Jaca Basin and creating topography. Thus, basin confinement is introduced as a new parameter playing a role on flow criticality. There is a decreasing proportion of SFDs between the submarine channels and canyons of the Ainsa Basin and the submarine lobes of the Jaca Basin, the last basin being the focus of this paper. This confirms previous studies showing that channel confinement and slope gradient likely played an important role in flow criticality.

## INTRODUCTION

Submarine lobes are a major component of submarine fans, and are amongst the largest depositional sandbodies on Earth. Because of their hydrocarbon potential, they have been the focus of considerable study. Typically, submarine lobe-and-related deposits are defined as broadly radial to elongate sandbodies with a convex-upward shape, and with a decrease in the bed thickness and grain size toward the most distal and lateral areas (Mutti and Ricci Lucchi, 1972, 1975; Mutti, 1977; Normark, 1978; Pickering, 1981, Lowe, 1982; Bouma, 2000). More recent studies have further revealed the geometry and complexity of lobe deposits in modern (Deptuck and Sylvester 2018; Fierens et al. 2019; Fonnesu et al. 2020), and ancient (Prélat et al. 2009; Etienne et al. 2012; Grundvag et al. 2015; Spychala et al. 2015, 2017; Hansen et al. 2019) systems, with varying stacking patterns depending on the basin geometry, degree of confinement and sediment supply. Analyses of bed thickness, grain size and their distribution in such environments have already proved to be a useful tool to improve the understanding of lobe architecture, geometry and stacking pattern (Prélat et al. 2009; Marini et al. 2015; Spychala et al. 2017). Understanding depositional processes, particularly flow processes in submarine lobe-and-related environments, is pivotal to understanding the submarine fan development including evolution of lobe architecture.

In the last decade, supercritical flows and their deposits have become an important topic in the comprehension of flow processes in deep-water settings (Fildani et al., 2006; Ito et al. 2014; Postma and Cartigny, 2014; Postma et al. 2016; Lang et al. 2017; Ono and Plink-Björklund, 2017; West et al. 2019; Cornard and Pickering, 2019; Slootman and Cartigny, 2019). For sediment gravity-flows (SGFs), flow criticality is defined by the densimetric Froude number (Fr):

$$Fr = \frac{U}{\sqrt{\left(1 - \frac{\rho amb}{\rho flow}\right) gh}},$$

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 $s^{-2}$). Flows with Fr exceeding unity (Fr $>1$) are said to be supercritical. Flows where Fr $<1$, are referred to as subcritical. Submarine fans should contain abundant supercritical-flow deposits (SFDs), because it has been postulated that SGFs should be supercritical for a slope > 0.5 ° (Walker, 1967; Komar, 1971; Hand et al. 1972; Hand, 1974; Sequeiros, 2012). Cornard and Pickering (2019) showed that the recognition and statistical analysis of SFDs are a useful tool to better understand and constrain the architecture of submarine fans, particularly deep-marine channel and canyon sites. Recent research has tended to focus on the interpretation of SFDs in canyon/channel and channel-lobe transitions, where several features of erosion and evidence of hydraulic jumps are observed (Ito et al. 2014; Postma et al. 2016; Lang et al. 2017; Ono and Plink-Björklund, 2017; Cornard and Pickering, 2019; West et al. 2019; Postma et al., 2020). As submarine lobe-and-related environments are a major component of submarine fans, they should also be studied for evidence of deposition and erosion under subcritical and supercritical flow. Although, Hamilton et al. (2015, 2017), and Postma and Kleverlaan (2018) showed that supercritical flows and hydraulic jumps play an important role in lobe architecture, particularly on avulsion cycles, relatively little research has considered the hydrodynamic processes in the more distal fan areas, i.e., in submarine lobes-and-related environments.

In this paper, we attempt to show that the facies related to SFDs, including bedforms such as cyclic steps, antidunes or upper-plane beds, defined in the channel-and-related fan environments in the Ainsa Basin (Cornard and Pickering, 2019), are applicable in the more distal lobe-and-related fan environments in the Jaca Basin and, therefore, might be applicable for basin settings other than the Ainsa Basin (with different basin length, width, and water depth). We also evaluate the different parameters likely to have played a significant role in the proportion and distribution of SFDs and, therefore, in the lobe architecture. The distribution of sandstone content and sedimentary facies are also considered in order to complement the mapping of depositional environments. Bed-thickness and grain-size distribution linked with various flow processes, particularly supercritical-flow processes, are analyzed to improve our understanding of the lobe architecture and its evolution in the Jaca Basin.

## METHODOLOGY

### *Fieldwork techniques*

This study involved 3 months of fieldwork in the Jaca Basin, Spanish Pyrenees. Twenty-five detailed sedimentary logs were made through various lobe-and-related systems from the proximal to the distal parts of the Jaca Basin. For each sedimentary log, the bed thickness, grain size, sedimentary structures and facies were documented (using the facies classification scheme of Pickering et al. (1986), modified in Pickering and Hiscott (2016)). Paleoflow directions were recorded mostly by measuring various sole marks (flute or groove casts) and current ripples.

More than 9,400 beds were measured in the Jaca Basin. For each sedimentary log, the percentage of bed thickness, grain-size classes and SFDs were calculated, in order to analyze their distribution in the different lobe systems of the Jaca Basin. We emphasize that SFD percentages were calculated only for the sandstone beds: mudstones intervals were not taken into account in the calculation, because mudstones are considered deposited under subcritical conditions. The term "proportion" is used to describe the percentage variation. From the recognition criteria for SFDs, such as cyclic steps, antidunes, upper-plane beds, and backset laminated beds, the deposits of each discrete flow event are interpreted as either completely or partially deposited under supercritical-flow or subcritical-flow conditions.

*Facies classification*

In this paper, two different facies classification are used. The first one is based on a descriptive approach of sedimentary structures and is related to the Pickering et al. (1986), modified in Pickering and Hiscott (2016). This facies classification is divided into 7 classes, but only 5 classes are mentioned in our study (more details in Supplementary Material):

- 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 clay.

Whilst, we have used the facies classification scheme of Pickering and Hiscott (2016), here we present a modified version of the facies classification scheme related to SFDs of Cornard and Pickering (2019). The facies classification of Cornard and Pickering (2019) considers the bedform dimensions and shape, as well as the deposit internal architecture, and is based on interpreted flow dynamics rather than a purely descriptive approach. Most of the facies related to SFDs can be considered mostly as part of facies classes B and C of Pickering and Hiscott (2016), related to concentrated density-flow deposits and turbidites, respectively. The term “bedform” is here used to described sedimentary structures in the field.

In this paper, we recognize some inherent contradictions in our definitions of SFDs that were proposed Cornard and Pickering (2019). Specifically, concerning the terminology used to define a facies association. In Cornard and Pickering (2019) the term “facies association” is used to classify the different supercritical-flow sedimentary structures observed throughout the Ainsa Basin. However, here we modify the term “facies association” used to describe the supercritical-flow sedimentary structures in the Ainsa Basin and use the term “facies”. The term “facies” is commonly used to mean a sedimentary rock or body of sedimentary rock, with specific mineral composition, sedimentary structures, and bedding characteristic, that reflect specific depositional processes under which a given bed or group of similar beds was deposited (e.g., p. 19, Reading, 1998). The term “facies” also describes the sedimentary characteristics of a discrete bed deposited during a single depositional event. In some cases, it also can include a group of beds showing the same sedimentary characteristics. The bedforms described in Cornard and Pickering (2019) corresponds to the definition of the term “facies” and not “facies association”.

Two categories of facies related to supercritical-flow sedimentary structures are recognized (Fig. 1) (Cornard and Pickering, 2019): (i) erosional supercritical-flow sedimentary structures: large-scale cyclic steps (F1a), and small-scale cyclic-steps (F1b); and (ii) depositional supercritical-flow sedimentary structures: unstable antidunes (F2a, F2b), stable antidunes (F3) and upper-plane beds (F4). It is also noteworthy that planar-parallel lamination associated to the $T_b$ division of the Bouma sequence is also interpreted as F4 upper-plane beds (Walker, 1965; Skipper, 1971; Stow, 2005; Postma et al. 2009).

From observations in the Jaca Basin, we complement the Cornard and Pickering (2019) facies classification by adding a new facies related to backset laminated beds (F5). Backset laminated beds are thin- to thick-bedded, fine- to coarse-grained sandstones, with sharp bases and contain backset lamination. Low- to high-angle backset lamination is commonly associated with upstream-migrating bedforms, such as antidunes (Middleton, 1965; Normark et al. 1980; Alexander et al., 2001; Spinewine et al., 2009; Cartigny et al., 2014). Although backset lamination is common in the Jaca Basin, discrete beds only composed of backset lamination were not observed. However, backset lamination was commonly observed associated with planar-parallel, sub-planar-parallel, or foreset lamination.

*Interpretation of the detailed depositional environments in the Jaca Basin*

The interpretation of the detailed depositional environments (lobe elements) in the Jaca Basin is based on fieldwork, previous studies (Mutti, 1977, Mutti et al. 1985, Mutti and Normark, 1987, Remacha et al. 2003), and qualified using the work of Prélat et al. (2009), Prélat and Hodgson (2013), Spychala et al. (2015, 2017), where they characterized the lobe elements (lobe axis, lobe off-axis, lobe fringe and lobe distal fringe) based on sedimentary facies and on sandstone percentage (Spychala et al. (2017). Here, we characterize the lobe elements as:

(i) Lobe axis. It consists mainly of thick- to medium-bedded, structureless, amalgamated sandstones of Facies Class B (see Table 2.2 and Fig. 2.4 in Pickering and Hiscott (2016)). Sandstone proportion ranges from 85 to 100%.

(ii) Lobe off-axis (lateral margin). It is dominated by medium- to thin-bedded sandstones of Facies Class C. The proportion of sandstones range from 50-85%.

(iii) Lobe fringe (both laterally and distally). This element is dominated by interbedded thin-bedded sandstones and siltstones of both Facies classes C and D. The proportion of sandstones varies from 20-50%.

(iv) Lobe distal-fringe (basinwards). It is dominated by thin-bedded siltstones of Facies Class D. The proportion of sandstones is <20%.

The boundaries between these lobe elements are obviously transitional.

## GEOLOGICAL SETTING

The Middle Eocene South Pyrenean foreland basin is mainly composed of non-marine to shallow-marine deposits in the Tremp–Graus and Ager basins to the east (e.g., fluvio-deltaic Montanyana Group) and deep-marine deposits in the Ainsa and Jaca basins to the west (Fig. 2A). The accumulation of sediments in the Ainsa and Jaca basins was broadly contemporaneous with maximum rates of tectonic shortening and basin subsidence in the South Pyrenean foreland as the thrust front advanced (Vergés et al. 1998). Sediments of the Ainsa and Jaca basins record the southward migration of the foreland and thrust-top basins, on the flexed boundary of the Iberian plate accreting onto the European plate (e.g., Remacha and Fernández, 2003). The Boltaña Anticline was a growing seafloor high that developed during sediment accumulation in the Ainsa and Jaca basins, although both basins were still connected during the Eocene depositional history of the South Pyrenean foreland basin (Mutti, 1985; Dreyer et al. 1999; Pickering and Corregidor, 2005; Muñoz et al. 2013). Post-depositional uplift of the Boltaña Anticline now precludes any physical correlation between deep-marine deposits in the Ainsa and Jaca basins. The Ainsa Basin is composed of relatively confined and channelized sandy fans, and the deposits of the Jaca Basin are interpreted as relatively unconfined sheet-like lobe-and-related deposits. The Middle Eocene deposits of the

Ainsa and Jaca basins have been defined as the Hecho Group by Mutti et al. (1972), a terminology that we adhere to in this paper.

In this study, we focus on the lobe-and-related deposits of the Jaca Basin (Fig. 2B). The Jaca Basin is delimited to the north by the Lakora and Eaux-Chaudes thrust sheets (Labaume et al. 1985; Teixell, 1992), and to the south by the Guara carbonate platform (Puigdefabregas and Souquet, 1986; Barnolas et al. 1991; Barnolas and Teixell, 1994). The eastern boundary of the Jaca Basin is defined by the Boltaña Anticline, with the westernmost edges exposed in the Pamplona area (Payros et al. 1999), corresponding to the distal basin floor of the system (not included in this study). West of Jaca, the narrowing of the Jaca Basin was caused by the southward advance of the axial thrust sheets that separated the Jaca Basin from the Basque Basin father west (e.g., Mutti, 1985; Puigdefabregas et al. 1992; Bell et al. 2018). A further causal process leading to narrowing (lateral constriction) of the Jaca Basin was the uplift of the foreland-basin forebulge, together with seafloor uplift at the western end of the basin due to displacement of the Pamplona Fault and associated structures (Mutti, 1985; Payros et al. 1999).

A distinctive feature in the Jaca Basin is the presence of several very thick carbonate “megaturbidites” from a few meters to > 200 m thick, interpreted to be a consequence of the periodic, seismically-generated, large-scale collapse of the northern and southern carbonate platforms (Johns et al. 1981; Labaume et al. 1983, 1985, 1987; Seguret et al. 1984; Barnolas and Teixell 1994; Payros et al. 1999). These megaturbidites provide useful marker beds for stratigraphic correlation. The Hecho Group in the Jaca Basin is represented by five principal sandy deep-marine systems composed of various types of SGF deposits: they are, from oldest to youngest: the Figols, Torla-Broto, Cotefablo, Banastón and Jaca systems. Cumulatively, these systems reach a maximum (aggregate) thickness of ~4,500 m (Mutti et al. 1985, 1988;

Remacha et al. 2003) (Fig. 3). As the Figols System has poor and very limited outcrop exposure, and is difficult to access, it is not considered further in this study.

*Broto System*

The Broto System (lobe-and-related deposits), also including the Torla System (although not clearly differentiated in the literature), forms an elongate and ~1,000 m thick sandbody that can be traced downcurrent for a distance of ~80 km, from the area of Broto village to the area around Roncal village. This system is dated as mid-Cuisian stage and lies immediately above the MT-3 and below the MT-4 megaturbidites (Remacha et al. 2003) (Figs 2B, 3). During deposition of the Broto System, the basin was narrow, elongate and relatively small (Barnes and Normark, 1985). For this study, seven detailed sedimentary logs were made in the Broto System (Table 1, Fig. 4A). The distance between the most proximal measured log (Log 1) and most distal measured log (Log 7) is ~55 km.

*Cotefablo System*

The Cotefablo System is stratigraphically immediately above the Broto System and consists of a succession of sheet-like lobe-and-related deposits (Remacha et al. 2003) (Figs 2B, 3). Seven detailed sedimentary logs were measured in the Cotefablo System (Table 1, Fig. 5A). The distance between the most proximal measured log (Log 8) and most distal measured log (Log 14) is ~65 km.

*Banastón System*

The Banastón System is amongst the most studied systems in the Jaca Basin. Remacha and Fernández (2003), using long distance bed-by-bed correlations (>30 km) following the main paleocurrent direction down-basin, and focused on the sheet-like lobes and basin-plain elements, mainly to investigate the detailed architecture and sedimentary features of the Banastón System (Figs 2B, 3). In this study, eight detailed sedimentary logs were made in the Banastón System (Table 1, Fig. 6A). The distance between the most proximal measured log (Log 15) and most distal measured log (Log 22) is ~38 km.

*Jaca System*

The Jaca System is located in the southern part of the Jaca Basin. The northern part of the Jaca System is delimited by the MT-8 megaturbidite (boundary between the Banastón and Jaca systems) (Figs 2B, 3). The southern boundary is defined by the Sabiñanigo fluvio-deltaic and carbonate-ramp deposits (Remacha and Fernández, 2003). Three detailed sedimentary logs were made in the Jaca System (Table 1, Fig. 7A). The distance between the most proximal measured log (Log 23) and most distal measured log (Log 25) is ~15 km.

## DEPOSITIONAL ENVIRONMENTS, BED-THICKNESS AND GRAIN-SIZE VARIATION IN THE JACA BASIN

Due to relatively poor exposure and locally severe tectonic deformation, the depositional systems in the Jaca Basin have been less studied compared with those of the Ainsa Basin. From previous studies in the Jaca Basin, it has been established that the most proximal lobe environments are located in the eastern part of the basin near Fiscal, and the most distal environments occur in the western parts of the Jaca Basin, near Pamplona, with paleoflow from east to west (Fig. 2A) (Labaume et al. 1985; Mutti et al. 1985, 1988; Remacha and Fernández, 2003; Remacha et al. 2005; Bell et al. 2018). The detailed depositional environments (lobe elements) for each system in the Jaca Basin were determined based on fieldwork to ascertain bedding characteristics and sandstone content, and distribution of sedimentary facies, and by using the results of previous studies in the Jaca Basin (Mutti, 1977; Mutti and Normark, 1987), and other recent studies in lobe-and-related deposits from the Karoo Basin, South Africa, particularly of Prélat et al. (2009), Prélat and Hodgson (2013), and Spychala et al. (2015, 2017).

For the four depositional systems in the Jaca Basin, a decrease in sandstone content is observed from lobe-axis to lobe-fringe environments. Moreover, there is a general decrease in grain size and bed thickness, leading to a decrease in the proportion of Facies classes B and C, from proximal to distal environments for all four systems. Variation of these parameters are reported in figures 4, 5, 6 and 7, and in Table 1.

*Broto System*

Depending on the proportion of sandstones in conjunction other sedimentary features such as bedding characteristics (see above), three depositional environments (lobe elements) are recognized in the Broto System (Figs 4A, 4B). For example, detailed sedimentary logs 1 and 5, with >85% sandstones (Table 1), are interpreted as lobe axis. The deposits observed in sedimentary logs 2, 3, 4 and 6 are interpreted as lobe lateral off-axis, because they are located south of the lobe axis sites, and contain sandstone proportions ranging from 50–85%. Log 7 is interpreted as representing a lobe frontal-fringe environment with 34% of sandstones. To provide support for the interpretation of detailed depositional environment in the Broto System, the facies classes and associated depositional processes are placed within these environments. Lobe-axis environments (logs 1 and 5) show the highest percentages of beds associated to Facies Class B with 21% (Log 1) and 42% (Log 5) related to concentrated density-flow deposits. However, proportion of Facies Class B in the lobe off-axis environment ranges from 13% to 18% and drops down to 2% in the lobe-fringe environment. Proportion of turbidites, represented by Facies Class C, is relatively stable from lobe axis

(47% to 56%) to lobe off-axis (41% to 52%) environments, however, there is a decrease in their proportion in the lobe-fringe (27%) environment.

There is an overall decrease in the bed thickness and grain size in a proximal-to-distal direction, and lateral off-axis, i.e., from lobe-axis to lobe frontal-fringe (Fig. 4C), and from lobe axis to lateral lobe off-axis sites (Figs 4D, 4E).

*Cotefablo System*

Based on the bedding characteristics and sandstone proportion, two depositional environments are recognized in the Cotefablo System. Two sedimentary logs were measured in the lobe off-axis environment, sedimentary Log 8 at the Cotefablo tunnel and sedimentary Log 9 near the Rio Sia, with a sandstone content >60% (Figs 5A, 5B) (Table 1). Five sedimentary logs characterize the lobe frontal-fringe environments with the proportion of sandstones ranging from 22–31%.

Regarding sedimentary facies distribution, Facies Class C (turbidites) forms a relatively high proportion in the lobe off-axis environment with >47%, whereas Facies Class B ranges from 12% to 15%. As in the Broto System, an abrupt decrease in the proportion of Facies Class C is observed from lobe off-axis to lobe-fringe (14% to 17%) environments.

The highest proportion of thick- and medium-bedded sandstones are observed in lobe frontal-fringe environments (logs 11, 12 and 13; Table 1). In a proximal-to-distal direction, there is an increase in bed thickness from the most proximal measured log, Log 8, to Log 12 (Fig. 5C), then, a decrease in bed thickness from Log 12 to the most distal measured log, Log 13. A lateral (lobe axis to off-axis) cross-section in lobe-fringe environments shows that there is an increase in bed thickness from west to east, e.g., from Log 14 to Log 12 (Fig. 5D).

Regarding the distribution of grain size, the coarsest grain sizes occur in the most proximal measured logs in the Cotefablo System, e.g., logs 8 and 9 (Table 1). There is a progressive decrease in grain size from proximal to distal (Fig. 5C). No change in grain size is observed in a lateral cross-section of the lobe fringe (Fig. 5D).

*Banastón System*

Based on the bedding characteristics and sandstone proportion, two depositional environments are recognized in the Banastón System. Log 15, measured at the South entrance of Castiello de Jaca village contains 65% of sandstones, and is interpreted as typical of lobe off-axis environments (Figs 6A, 6B; Table 1). All the other sedimentary logs were measured from Tiesas Bajas (Log 16) to Burgui (Log 22), and are interpreted as lobe frontal-fringe environments as their sandstone content ranges from 46% in Log 16 to 26% in Log 22. This transition from lobe off-axis to lobe-fringe sites is in agreement with the interpretation of Remacha and Fernández (2003), where they observed a progressive transition from sheet-like lobes in the Jaca area to basin-plain deposits in the Anso area.

The lobe off-axis environment contains a relatively high proportion of Facies Class C, constituting 47% of the total log, with Facies Class B as 17%. As in the Broto and Cotefablo systems, an abrupt decrease is observed in the proportion of Facies Class C (turbidites) from lobe off-axis to lobe-fringe environments (15% to 36%). Facies Class D is absent in the lobe off-axis environment, whereas an increase in its proportion is noted from the proximal to the distal lobe-fringe environment (from 3% to 13% and 8%).

Regarding bed-thickness distribution, the highest proportion of medium- and thick-bedded sandstones is observed in lobe frontal-fringe environments (logs 19 and 20; Table 1). In a proximal-to-distal direction, there is a general increase in bed thickness from lobe off-axis (Log 15) to proximal lobe frontal-fringe environments (Log 17) (Fig. 6C). The proportion of medium- and thick-bedded sandstones does not vary significantly in the most proximal logs. The general basinward increase in bed thickness reflects a decrease in the proportion of very-thin bedded sandstones, and an increase in the proportion of thin-bedded sandstones (Fig. 6C). From Log 17 to the most distal log measured in the lobe frontal-fringe environments of the Banastón System (Log 22), there is a general decrease in bed thickness (Fig. 6C). In a lateral cross-section (Fig. 6D), an increase in bed thickness is observed from the SSE (Log 17) toward NNW (Log 20).

In a proximal-to-distal direction, a progressive decrease in grain size is observed from lobe off-axis to frontal-fringe environments (Fig. 6C). There is no grain-size variation in the lateral cross-section of the lobe frontal-fringe environment (Fig. 6D).

*Jaca System*

Based on the sandstone content, two depositional environments are recognized in the Jaca System. Sedimentary Log 23 shows >50% of sandstones, and is interpreted as a lobe off-axis environment (Figs 7A, 7B; Table 1). Logs 24 and 25 show <50% of sandstone content, and are interpreted as lobe-fringe deposits. Sedimentary Log 24 is interpreted as the lateral fringe of the Jaca System, because it is located in the northern part of the lobe off-axis and not in the most distal part of the system. Log 25, located in a proximal-to-distal direction compared to Log 23, is interpreted as a lobe frontal-fringe environment.

The interpretations of the detailed depositional environments in the Jaca System are supported by the analysis of the distribution of sedimentary facies. Lobe off-axis environments show a relatively comparable proportion of concentrated density-flow deposits (Facies Class B, >25%) and turbidites (Facies Class C, >28%). No change in the proportion of Facies Class C is observed from lobe off-axis to lobe-fringe environments. However, an abrupt decrease in the proportion of Facies Class B is noted from the lobe off-axis to lobe-fringe environments, e.g., proportion of Facies Class B in the lobe-fringe environment ranges from 11% to 13%.

In terms of bed-thickness distribution, the lobe off-axis environments in the Jaca System show the highest proportion of medium-and thick-bedded sandstones occurring in the Jaca Basin (Log 23; Table 1), with >27% of medium-bedded sandstones and >7% of thick-bedded sandstones (Table 1). In a proximal-to-distal direction, there is a decrease in bed thickness from Log 23 to Log 25 (Fig. 7C). In lateral cross-section, across the lobe off-axis and lobe fringe, there is a progressive decrease in the bed thickness from Log 23 to Log 24.

There is a progressive decrease in grain size in both proximal-to-distal (Fig. 7C) and axial-to-lateral direction (Fig. 7D).

## SFDs IN THE JACA BASIN

In the Jaca Basin, depositional supercritical-flow sedimentary structures are documented and erosional supercritical-flow sedimentary structures were not recognized.

A representative example of unstable antidunes (F2b) is shown in Figure 8A. This medium-bedded sandstone has a sharp base and an undulating top with an irregular wavelength varying from 60 cm to 1.5 m. The top part of the bed is structureless, although low-angle backset lamination is observed at the base of the bed.

Few examples of stable antidunes (F3) were recognized in the Jaca Basin. An example of stable antidunes is shown in Figure 8B. This example is composed of two stable antidunes (F3), both dipping in the upflow direction. Both examples show variability in lamination dip from low-angle backset, to horizontal lamination. Because there is a mudstone drape between both beds, they were formed by two different flows, both undergoing an upstream-migrating surge during deposition.

The dominant supercritical-flow sedimentary structures observed in the Jaca Basin are upper-plane beds (F4) (Fig. 8C and 8D). Upper-plane beds are typically very-thin- to thick-bedded sandstones with a sharp base and pervasive planar-parallel lamination observed throughout most of the bed. Ripple-cross lamination is commonly observed on top of the upper-plane beds, indicating a waning flow. Upper-plane beds F4 observed in the Jaca Basin displays grain-size or mineral composition segregation between the lamination and grain imbrication, suggesting a shear fabric (*cf.* Allen, 1984; Paola et al. 1989; Sumner et al. 2008).

Planar-parallel lamination related to the $T_b$ division of the Bouma sequence, also interpreted as upper-plane beds, is very common in the Jaca Basin and was observed from the lobe-axis to the lobe-fringe environment (Fig. 9A). Turbidites that display the Bouma sequence, are commonly normally-graded, very-thin to medium-bedded, very-fine to medium-grained sandstones. In most cases, the association of the $T_a$, $T_b$ and $T_c$ division was observed in the Jaca Basin, generally with the $T_d$ and $T_e$ division lacking. However, Figure 9A shows an example of a complete Bouma sequence with the $T_a$, $T_b$, $T_c$, $T_d$ and $T_e$ divisions, interpreted as reflecting a decrease of energy in the flow and in the Fr.

Backset laminated beds are also very common in the Jaca Basin, and occur from the lobe-axis to lobe-fringe environments. A wide range of lamination was associated with backset lamination, including foreset, planar-parallel and sub-planar-parallel lamination (slightly wavy). Figures 9B and 9C show examples of the different types of lamination association observed in Facies F5. Variation in the type of lamination, such as shown in figures 9B and 9C, is interpreted to reflect flow velocity fluctuation, and therefore Fr variations, and may be the result of surges and associated breaking waves observed under supercritical-flow conditions (Alexander et al., 2001; Cartigny et al., 2014). Progressive waning flows result in the formation of ripple-cross lamination as observed in figure 9C.

## DISTRIBUTION OF SFDs IN THE JACA BASIN

*Qualitative analysis*

Four types of SFDs are recognized in the Jaca Basin (Figs 8 and 9): (i) F2b, upflow-stacked, wavy bedforms: unstable antidunes; (ii) F3, upflow-stacked sigmoidal bedforms: stable antidunes, (iii) F4, plane beds: upper-plane beds and, (iv) F5, backset laminated beds. Unstable antidunes (F2b) and stable antidunes (F3) were mainly observed in the most proximal part of the Jaca Basin in the lobe-axis and off-axis environments (Fig. 10). However, the absence of antidunes (F2b and F3) is conspicuous in the distal part of the basin, e.g., the lobe frontal- and lateral-fringe environments. Upper-plane beds (F4) and backset laminated beds (F5) were observed throughout the entire Jaca Basin, from lobe-axis to lobe frontal- and lateral-fringe environments (Fig. 10).

*Quantitative analysis*

All the measured logs from lobe-axis to lobe-fringe environments show >20% of SFDs. Lobe-axis and lobe off-axis sites show no significant differences in the proportion of SFDs: SFD percentages range from 30–45%. The proportion of SFDs in lobe-fringe environments ranges from 23–39% (Table 1). For the four studied systems in the Jaca Basin, a small decrease in the proportion of SFDs is noted in a proximal-to-distal direction (see Figs 4C, 5C, 6C and 7C). With a progressive decrease in flow velocity toward the distal basin areas observed in typical submarine-fan lobes (Mutti and Norwark, 1987), a significant decrease in the proportion of SFDs was expected from the lobe-axis to the lobe frontal-fringe sites in the Jaca Basin. However, the difference in the proportion of SFDs from proximal to distal basin environments is only 8–15%, making it difficult to interpret these as significant. Especially as Cornard and Pickering (2019) suggested that any significant variation of SFDs should be >9%. Also, in a lateral direction (axis-to-off-axis lobe environments), there is no significant variation in the proportion of SFDs (Figs 4D, 5D, 6D and 7D).

## DISTRIBUTION OF SFDs IN THE AINSA AND JACA BASINS

Correlation between the channel-dominated submarine fans of the Ainsa Basin and the submarine lobe-and-related deposits of the Jaca Basin is controversial with little consensus on the most likely correlations (e.g., Mutti et al. 1985; Remacha et al. 2003; Das Gupta and Pickering, 2008; Scotchman et al. 2015). Therefore, in this study, the proportion of SFDs is not compared between individual submarine fans in the Ainsa Basin and their interpreted correlated lobe-and-related deposits in the Jaca Basin. Instead, we seek to establish general comparisons between the fan environments in the proximal Ainsa Basin, and the distal Jaca Basin. An important observation is that there is a higher proportion of SFDs in the submarine channels of the Ainsa Basin than in the lobe-and-related deposits of the Jaca Basin. Cornard and Pickering (2019) postulated that the proportion of SFDs is mainly controlled by the slope gradient and confinement of the sandbodies (fans). It was also suggested that the percentage of SFDs is biased by the degree of sediment bypass in the Ainsa Basin and, therefore, affecting the preservation potential.

Figure 11 depicts the substantial decrease in the proportion of SFDs in a proximal-to-distal transect from the Ainsa to the Jaca basins, i.e., from proximal basin-floor to lobe-and-related environments. This decrease can be explained by the inferred occurrence of hydraulic jumps at the break-of-slope in the Ainsa Basin, e.g., at the channel-lobe transition zone (CLTZ) (Wynn et al. 2002; Cartigny et al. 2011, 2014; Sumner et al. 2013; Hofstra et al. 2015; Dorell et al. 2016; Postma et al., 2020). Hydraulic jump develop at two scales, i.e., at the basin scale and at the bedform scale. At the basin scale, several researchers have proposed that hydraulic jumps can develop at the CLTZ (but see Pohl et al. 2019 for situations where there appears not to have been a hydraulic jump), e.g., at the transition between relatively confined (submarine canyons and channels) and relatively unconfined settings, such as in submarine lobes (Komar, 1971, and references therein). After a hydraulic jump, the increase in flow thickness and decrease in flow velocity together induce a decrease in Fr, leading to bedforms forming under subcritical-flow conditions basinward of the break-of-slope.

Hydraulic jumps also occur at the bedform scale, during the formation and evolution of supercritical-flow bedforms such as cyclic-steps or chute-and-pool (Simons et al. 1965; Parker, 1996; Cartigny et al. 2014).

The abrupt decrease in the proportion of SFDs from submarine canyons and channels (typical in the Ainsa Basin) to submarine lobe-and-related deposits (typical in the Jaca Basin) can be interpreted as linked with a large-scale hydraulic jump from flows that were most likely under supercritical-flow conditions in the Ainsa Basin, to flows that were most likely under subcritical-flow conditions in the Jaca Basin. Furthermore, proximal basin-floor environments in the Ainsa Basin (Banastón System) are characterized by several features that support erosion, such as meter- and centimeter-scale scours and backfilling structures (F1a or F1b; Cornard and Pickering, 2019), whereas scour-and-backfilling structures were not observed in the lobe-axis environments of the Jaca Basin.

## DISCUSSION

### *General bed-thickness, grain-size and SFD distribution in a proximal-to-distal direction*

In the four Jaca Basin systems considered in this paper (Broto, Cotefablo, Banastón and Jaca systems), there is a general decrease in bed thickness toward the most distal parts of the basin (Figs. 4C, 5C, 6C, 7C). In a proximal-to-distal direction the very-thin bedded sandstones show an increasing proportion of current-ripple lamination ($T_c$ division of the Bouma sequence), and a decrease in grain size, all indicating a decrease in flow velocity, flow competence and capacity basinward (Sadler, 1982).

There is also a change in the type of SFDs observed from proximal-to-distal sites. Unstable (F2b) and stable (F3) antidunes are most commonly observed in the most proximal parts of the Jaca Basin. More distally in the Jaca Basin, there appear to be no clear antidunes (F2b and F3), where only upper-plane beds (F4) and backset laminated beds (F5) occur, likely developed under a lower Fr (but still >1) (Fig. 10).  The proportion of SFDs shows a slight decrease in a proximal-to-distal direction. The greatest decrease in SFDs is seen in the Cotefablo System (from 35% to 25%), and in the Banastón System (from 39% to 24%). This decrease in the proportion of SFDs is likely linked with an overall decrease in flow velocity (Lang et al. 2017; Cornard and Pickering, 2019), including a greater proportion of low-density turbidity currents reaching the lobe-fringe environments in the basin (Normark et al. 1980; Spychala et al. 2017).

*General bed-thickness, grain-size and SFD distribution in axial-to-lateral direction*

In the Broto, Cotefablo and Jaca systems, there is a decrease in bed thickness in an axial-to-lateral direction, toward the lobe off-axis or fan fringe. A similar trend in the Banastón System would be expected, but there is a stratigraphic log missing towards the most extreme lobe off-axis and/or fan-fringe environments (erosion due to tectonic uplift) and, therefore, we could not test this prediction.

A decrease in grain size in a lobe axial-to-lateral direction were only recorded in the most proximal environments of the Broto and Jaca systems, where there are changes in depositional environments, i.e., from lobe-axis to lobe off-axis sites in the Broto System, or from the lobe off-axis to the lobe-fringe sites in the Jaca System. In the Banastón and Cotefablo systems, no significant variations in grain size and SFD proportion were observed within the fan-fringe environments (Fig. 5D, 6D).

*Irregularity in bed-thickness distribution*

The Cotefablo and Banastón systems show intriguing bed-thickness variation. Both in a down-paleoflow and across-paleoflow direction, there is an increase in the proportion of thicker beds from the lobe-axis towards the lobe-fringe environments, then a decrease in bed thickness toward the most distal parts of the Jaca Basin (Figs 5C and 6C). These trends in bed thickness could have two explanations.

The first is that during deposition of the Cotefablo and Banastón systems, there was substantial sediment bypass in the most proximal parts of the Jaca Basin, leading to a high proportion of very thin-bedded and coarse-grained sandstones in proximal lobe-axis and lobe off-axis environments, and an increase in thick-bedded and fine-grained sandstones in the distal parts of the basin.

The second possibility involves both basin-scale and local confinement of SGFs transiting through the basin. Relative confinement of SGFs had a direct effect on the geometry and sedimentary structures of the deposits, due to processes such as flow deflection (e.g., Pickering and Hiscott, 1985; Kneller et al. 1991; Alexander and Morris, 1994; Kneller and McCaffrey, 1999; Al Ja'aidi et al. 2004). Basin confinement in the Jaca Basin was caused by southward thrust propagation in the rising orogen, and structural steepening of the southern carbonate platform due to forebulge uplift (Fig. 12) (Labaume et al. 1983, 1985, 1987; Seguret et al. 1984; Payros et al. 1999). In the Jaca Basin, the episodic large-scale collapse of the northern and southern carbonate platforms to generate the megaturbidites/mass-transport deposits (MTDs)/mass-transport complexes (MTCs), such as the Roncal megabed, would have created significant local confinement in what was a narrow elongate basin (Fig. 12) (Payros et al. 1999, their figs 13A, 13B). The Roncal megabed has been traced down the axis of the Jaca Basin for ~75 km and commonly reaches >100 m thickness (Johns et al. 1981; Rosell and Wieczorek 1989). The MTDs/MTCs, resulting from the collapse of the northern and southern carbonate platforms, tended to preferentially accumulate and be preserved on the southern basin margin (carbonate breccia – slope talus), probably because of the southward migration of the foreland basin. The cumulative effects of these basin-narrowing and, therefore SGF-confining processes, would have caused greater bed thickness due to flow deflection. Bell et al. (2018) also noted the increased bed thicknesses, but ascribed the lobe confinement only to tectonic narrowing and only for the Broto System (their fig. 15A).

In summary, in the Jaca Basin both (i) substantial sediment bypass in the most proximal parts of the basin and (ii) basin-scale and local confinement were contributory factors in controlling the distribution of bed thickness for the Cotefablo and Banastón systems in the lobe-fringe environments of the Jaca Basin (Fig. 12). Here, we propose that the MTDs/MTCs (including carbonate megaturbidites) were important topographic features in creating local accommodation for bed thickening, and at times for overall basin narrowing during the emplacement of the Jaca Basin systems. Such bed-thickness trends have not been observed in the Broto and Jaca systems.

*Impact of flow criticality on lobe architecture*

Cornard and Pickering (2019) argued that seafloor gradient and confinement likely played a key role on the flow criticality, i.e., whether a flow was under subcritical- or supercritical-flow conditions. Seafloor gradient and confinement are supported by the results from this study, because a higher proportion of SFDs was observed in the relatively confined-channel and canyon environments with greater slope gradients in the Ainsa Basin, when compared with the relatively unconfined lobe-and-related environments in the Jaca Basin.

Within the Jaca Basin, a small variation in the proportion of SFDs was observed, whereas a significant decrease in SFD percentages was anticipated from the proximal lobe-axis to the more distal lobe-fringe due to decrease in flow velocity. This small variation in inferred flow criticality in the Jaca Basin could be explained by the geometry of the basin. Interpretation of bed-thickness and grain-size distribution for the Cotefablo and Banastón systems shows that there was an increase in basin-scale and local confinement in the lobe-fringe environments of the Jaca Basin. An increase in relative confinement will initially increase flow velocity. Any decrease in the flow velocity of SGFs with increasing distance from the sediment source was likely offset by increasing flow confinement and, therefore, resulted in increased flow criticality in the area of the lobe fringe environments in the Jaca Basin. Therefore, there appears to have been a trade-off between the increase in basin confinement that would favor an increase in flow velocity and the general decrease in flow velocity, as SGFs traveled basinwards. In the latter case, basin confinement probably exerted an important role in the distribution of SFDs in the Jaca Basin. Basin geometry is another criterion to be taken into account as likely playing a role in the flow criticality.

A relatively high proportion of SFDs was observed in lobe-fringe environments in the Banastón System (>50% in Log 19). This value is exceptionally high and unrepresentative of most lobe-fringe environments in the Jaca Basin. Log 19 is relatively short (~28 m), and with a high proportion of Facies Class B deposits as defined by Pickering and Hiscott (2016), with several beds showing backset and planar-parallel lamination. This log also has a high proportion of upper-plane beds. Log 18 (~1 km east of Log 19) shows 34% of SFDs. This abrupt increase in the proportion of SFDs, from 34% to >50%, might be due to local changes in seafloor topography, such as a local increase in seafloor gradient, a local increase in flow confinement, or the presence of meter-to-kilometer-scale obstacles on the seafloor such as redeposited carbonate breccias / megaturbidites (Alexander and Morris, 1994) (Fig. 12).

In this study, we emphasize the role of flow confinement in explaining the distribution of SFDs. Enhanced relative confinement will initially increase flow velocity and, therefore, Fr, but the increase of flow thickness in time and space due to expansion of the flow, tends to lower Fr. In the context of the Jaca Basin, the sediment record of the submarine lobe environments shows an insignificant decrease in the proportion of SFDs from lobe axis to lobe fringe environments, an observation that can be explained by the increase in confinement in the lobe-fringe environments. Although no sedimentary log was measured in the most distal environments in the basin plain of the Pamplona area, we predict a significant decrease in the proportion of SFDs from lobe-fringe environments in the Jaca Basin to the basin plain in the Pamplona Basin, due to the progressive decrease in flow velocity decreasing the Fr.

*SFDs or reflected-flow deposits?*

In confined settings, as in the Jaca Basin, one might argue that the SFDs described in this paper might have resulted from flow due to reflection. However, the beds described in this paper are different in character from those described in the literature for reflected flows (Pickering and Hiscott, 1985; Haughton, 1994; Kneller and McCaffrey, 1999; Patacci et al. 2015). Deposits of reflected flows are characterized by grain-size breaks and thick structureless silty mudstone caps (cf. Pickering and Hiscott, 1985). For flow reflection, SGFs need to be sufficiently thick to maintain momentum and be blocked in a down-flow direction, otherwise they would simply be deflected and continue basinwards (Pickering and Hiscott, 1985; Alexander and Morris, 1994). The beds described in this paper, have neither thick silty mudstone caps, nor do they contain sedimentary structures that can be readily identified as as formed by reversing flows. We do, however, recognize the presence of flow deflection against the lateral basin slopes as previously reported (Remacha et al. 2005; Bell et al. 2018).

We also recognize the presence of thick siliciclastic megaturbidites (>5 m) showing typical features of reflected flows, e.g., grain-size breaks and thick structureless silty mudstone caps: SFDs have not been described as part of these beds. These siliciclastic megaturbidites have not previously been described in the literature. The sedimentary structures that are described in this paper in the context of experimental and theoretical work, lead us to reject flow containment, and therefore flow reflection, in favor of supercritical-flow conditions.

## CONCLUSIONS

Based on the sedimentary facies distribution and proportion of sandstones, we propose a revised interpretation of the local depositional environments (lobe axis, off-axis and fringe) in the Jaca Basin. From the observations of SFDs in the Jaca Basin, a new facies was added to complete the facies classification related to SFDs (Cornard and Pickering, 2019): backset laminated beds. Four types of depositional SFDs are recognized in this study: unstable antidunes (F2b) and stable antidunes (F3), mainly observed in the most proximal environment of the basin, and upper-plane beds (F4) and backset laminated beds (F5) seen distributed over the entire Jaca Basin.

Variations in the spatial distribution of SFDs from the Ainsa Basin to the Jaca Basin support the hypothesis that channel confinement and slope gradient likely played an important role on the flow criticality (parameters defined in Cornard and Pickering, 2019). Basin geometry likely also exerted an important influence on the flow criticality. The increased basin confinement in the distal part of the Jaca Basin, caused both by basin-scale (tectonic) and local MTD-induced confinement, would have offset any decrease in flow velocity, leading to little or no variation in SFD distribution from the proximal-to-distal environments in the Jaca Basin.

This integrated study, using bed-thickness, grain-size and SFD distribution provides an improved understanding of the lobe architecture in the Jaca Basin, and of the impact of seafloor topography (e.g., confinement, seafloor gradient, obstacles on the seafloor such as the presence of MTDs) and basin geometry on the evolution of lobe architecture. Facies related to SFDs, as defined by Cornard and Pickering (2019), and further developed in this paper for the Jaca Basin, should be applicable to deep-water settings other than these basins, where basin length, width, shape and water depth vary.

**Supplementary materials**

Table summarizing the facies classification of Pickering and Hiscott (2016), twenty-five detailed sedimentary logs and their hydrodynamic interpretations are available as Supplementary Materials.

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## FIGURE CAPTIONS

**Figure 1**: Facies classification related to SFDs defined by Cornard and Pickering (2019). **(A)** Red frame of F1a and F1b indicates deposits related to erosional supercritical-flow sedimentary structures (both examples of erosional supercritical-flow sedimentary structures were observed in the Ainsa Basin) **(B)** Blue frames (F2a, F2b, F3, F4, F5) designate deposits associated with depositional supercritical-flow sedimentary structures (examples of F2a, F2b, F3, and F4 presented in this figure were observed in the Ainsa Basin whereas example of F5 was observed in the Jaca Basin).

**Figure 2:** (**A**) Paleogeography reconstructions of the Ainsa–Jaca basins and the surrounding areas during the Middle Eocene. Note that MT-5 Roncal megabed extends below the younger lobe-and-related deposits and contacts the basin margin, as shown in figure 5 of Rosell and Wieczoreck (1989). Redrawn and modified from Dreyer et al. (1999). The white background with vegetation symbols indicates terrestrial environments in the Ebro Basin, including coastal and delta plain. (**B**) Geological map of the Jaca Basin (modified from Remacha et al. 2003).

**Figure 3**: Stratigraphic column of the Eocene infill of the Jaca Basin, modified from Caja et al. (2010) and Bell et al. (2018).

**Figure 4**: (**A**) Map with the location of the sedimentary logs (black dots) associated with their depositional environment in the Broto System. (**B**) Graphic showing the percentage of sandstones for each log. Dashed lines show the limit as defined by Spychala et al. (2017) between the lobe axis, off-axis and fringe environments. (**C**) Longitudinal cross-section A from lobe axis to lobe fringe environment in the Broto System (logs 1, 5 and 7) associated with the bed-thickness, grain-size and SFD distribution. (**D**) Lateral cross-section B in the proximal area of the Broto System, crossing logs 1, 2, and 3. (**E**) Lateral cross-section C in the more distal area of the Broto System, crossing logs 5 and 6. Detailed sedimentary Log 1 (right) located in lobe axis environments and sedimentary Log 7 (left) measured in lobe fringe environments of the Broto System. These sedimentary logs give an indication of the sandstone content and distribution of SFDs in each log (red = SFDs; blue = subcritical-flow deposits). See supplementary material for high-resolution sedimentary logs measured in the Broto System.

**Figure 5**: (**A**) Map with the location of the sedimentary logs associated with their depositional environment in the Cotefablo System. (**B**) Graphic showing the percentage of sandstones for each log (see fig. 3B for details). (**C**) Longitudinal cross-section A of the Cotefablo System (**D**) Lateral cross-section B in the lobe fringe environment of the Cotefablo System. Detailed sedimentary Log 8 (right) was measured in lobe off-axis environments and sedimentary Log 14 (left) measured in lobe fringe environments of the Cotefablo System. These sedimentary logs give an indication of the sandstone content and distribution of SFDs

in each log (red = SFDs; blue = subcritical-flow deposits). See supplementary material for high-resolution sedimentary logs measured in the Cotefablo System.

**Figure 6**: (**A**) Map with the location of the sedimentary logs associated with their depositional environment in the Banastón System. (**B**) Graphic showing the percentage of sandstones for each log (see fig. 3B for details). (**C**) Longitudinal cross-section A from lobe off-axis to lobe fringe environment in the Banastón System (**D**) Lateral cross-section B in the lobe fringe environments of the Banastón System. Detailed sedimentary Log 15 (right) was measured in lobe off-axis environments and sedimentary Log 22 (left) measured in lobe fringe environments of the Banastón System. These sedimentary logs give an indication of the sandstone content and distribution of SFDs in each log (red = SFDs; blue = subcritical-flow deposits). See supplementary materials for high-resolution sedimentary logs measured in the Banastón System.

**Figure 7: (A)** Map with the location of the sedimentary logs associated with their depositional environment in the Jaca System. **(B)** Graphic showing the percentage of sandstones for each log (see fig. 4B for details). **(C)** Longitudinal cross-section A from lobe off-axis to lobe fringe environments in the Jaca Basin . **(D)** Lateral cross-section B from lobe off-axis to lobe fringe environments in the Jaca Basin. Detailed sedimentary Log 23 (right) was measured in lobe off-axis environments and sedimentary Log 25 (left) measured in the lobe fringe environments of the Jaca System. These sedimentary logs give an indication of the sandstone content and distribution of SFDs in each log (red = SFDs; blue = subcritical-flow deposits). See supplementary materials for high-resolution sedimentary logs measured in the Jaca System.

**Figure 8:** Example of supercritical-flow sedimentary structures observed in the Jaca Basin **(A)** Upflow-stacked wavy bedforms associated with backset lamination observed in package of medium- to thick-bedded sandstones. Theses bedforms are interpreted as unstable antidunes (F2b), observed in the Broto System – Fanlo Pass. Note that the outcrop is oblique to paleoflow. **(B)** Upflow-stacked sigmoidal bedforms interpreted as stable antidunes (F3), observed in Jaca System – road N-330 section at the northern entrance of Jaca. **(C)** Upper-plane beds F4, road section A176 between villages of Berdun and Javierregay, Jaca System. **(D)** Upper-plane beds F4, Rio El Chate section, Broto System. Note that paleoflow is ~ 10°–15° oblique (into) the photographs of A, B, C and D.

**Figure 9:** Example of supercritical-flow sedimentary structures observed in the Jaca Basin **(A)** Thin-bedded turbidite showing $T_{abcde}$ divisions of the Bouma sequence, with the $T_b$ division interpreted as deposited under supercritical-flow conditions, Hecho-Siresa road section, Cotefablo System **(B)** Backset laminated beds F5, thin-bedded sandstones showing a progressive transition from low-angle backset lamination to high-angle backset lamination. Backset lamination is capped by a new set of sub-planar-parallel lamination. Burgui village road section, Banastón System **(C)** Backset laminated beds F5, medium-bedded, fine-grained sandstones showing a vertical transition from foreset to backset lamination in the basal part of the bed. Cross-lamination is followed by a set a sub-planar-parallel ripple-cross lamination toward the top. Road section, west of Garde village, Cotefablo System.

**Figure 10:** Qualitative distribution of the different SFDs observed in the Jaca Basin.

**Figure 11:** Conceptual depositional model of the Ainsa and Jaca basins with the different depositional environments and their proportion of SFDs indicated. Percentages of SFDs in

the Ainsa Basin are from the study of Cornard and Pickering (2019). BR: Broto System; C: Cotefablo System; B: Banastón System (both in the Ainsa and Jaca basins); J: Jaca System; A: Ainsa System; G: Gerbe System; CLTZ: channel-lobe transition zone; SD: Standard deviation; N: number of measured sandstone beds for each depositional environment.

**Figure 12**: Conceptual depositional model of the Jaca Basin paleogeography. Red arrows show the directions of the flow deflected due to the narrowing of the basin (progress of thrust faulting toward the south and "forebulge" uplift of the Southern Carbonate platform) and the collapse of the carbonate "megaturbidite" from the northern and southern carbonate platforms, accumulated in the south of the basin. Green arrows indicate the direction in which bed thicknesses increase. Mauve arrow indicates the direction of the (small) variation in the proportion of SFDs.

**Table 1:** Percentage of the total thickness for each detailed sedimentary log of: sandstones and mudstones, 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), grain size and SFDs (calculated only on the sandstones as mudstones are considered deposited under subcritical conditions).