

1 **Running head:** TOPOGRAPHIC CONTROLS ON BASIN-FLOOR DEPOSITIONAL ARCHITECTURE

2 **Title:** TOPOGRAPHIC CONTROLS ON THE DEVELOPMENT OF CONTEMPORANEOUS BUT

3 CONTRASTING BASIN-FLOOR DEPOSITIONAL ARCHITECTURES

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13 **Keywords:** Structurally confined basin, deep-water fan, hybrid event beds, lobe stacking, flow

14 deflection

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16 **ABSTRACT**

17 Sediment-laden gravity-driven flow deposits on the basin-floor are typically considered to form either
18 discrete lobes that stack compensationally, or packages of laterally extensive beds, commonly termed
19 'sheets'. These end-member stacking patterns are documented in several basin-fills. However,
20 whether they can co-exist in a single basin, or there are intermediate or transitional stacking patterns
21 is poorly understood. An analysis of depositional architecture and stacking patterns along a 70 km dip-
22 orientated transect within the Upper Broto Turbidite System (Jaca Basin, south-central Pyrenees,
23 Spain), which displays disparate stacking patterns within contemporaneous strata, is presented.
24 Proximal and medial deposits are characterized by discrete packages of clean sandstones with sharp
25 bed-tops which exhibit predictable lateral and longitudinal facies changes, and are interpreted as
26 lobes. Distal deposits comprise both relatively clean sandstones and hybrid beds that do not stack to
27 form lobes. Instead, localized relatively-thick hybrid beds are inferred to have inhibited the
28 development of lobes. Hybrid beds developed under flows which were deflected and entrained
29 carbonate mud substrate off a carbonate slope that bounded the basin to the south; evidence for this
30 interpretation includes: 1) divergent paleoflow indicators and hummock-like features in individual
31 beds; 2) a decrease in hybrid bed thickness and abundance away from the lateral confining slope; 3) a
32 carbonate-rich upper-division, not seen in more proximal turbidites. The study demonstrates the co-
33 occurrence of different styles of basin-floor stacking patterns within the same stratigraphic interval,
34 and suggests that that characterization of deep-water systems as either lobes or sheets is a false
35 dichotomy.

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INTRODUCTION

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Submarine fans represent some of the largest sedimentary deposits on Earth (e.g. Barnes and Normark, 1985), can contain significant volumes of hydrocarbons (e.g. McKie et al., 2015), and are the ultimate sink for vast quantities of organic carbon (e.g. Cartapanis et al., 2016) and pollutants (e.g. Gwiazda et al., 2015). Despite their economic and environmental importance, the processes and products of submarine fans are relatively poorly-understood, due to limitations associated with remote sensing and monitoring of modern systems, and challenges with imaging and sampling buried ancient systems. Consequently, uplifted ancient fans at outcrop represent an opportunity to study the architecture of these systems at a high resolution (e.g. Walker, 1966; Ricci-Lucchi and Valmori, 1980; Mutti and Sonnino, 1981; Hodgson et al., 2006; Grundvåg et al., 2014).

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Sediment-laden gravity-driven flows develop deposits which are typically considered to stack in one of two end-member patterns on the basin-floor: i) compensational lobes; or ii) individual laterally extensive beds, commonly termed 'sheets' (referred to as tabular stacking herein; e.g. Ricci-Lucchi and Valmori, 1980; Mutti and Sonnino, 1981; Talling et al., 2007; Deptuck et al., 2008; Prélat et al., 2009; Marini et al., 2015; Fonnesu et al., 2018). Basin-floor lobes form discrete composite sand-bodies with subtle convex-upward topography and display predictable bed thickness and facies changes (e.g. Prélat et al., 2009; Grundvåg et al., 2014; Marini et al., 2015; Sychala et al., 2017a). Compensational stacking occurs where depositional relief causes subsequent flows to be routed to and deposited in adjacent topographic lows, as documented from outcrop (Mutti and Sonnino, 1981; Prélat et al., 2009; Prélat and Hodgson, 2013; Grundvåg et al., 2014; Marini et al., 2015); seismic and seabed imaging (Deptuck et al., 2008; Jegou et al., 2008; Saller et al., 2008; Straub et al., 2009; Picot et al., 2016); and experimental studies (Parsons et al., 2002). Tabular stacking has been described in basin settings where flows were fully contained, or laterally confined (e.g. Hesse, 1964; Ricci-Lucchi and Valmori, 1980; Ricci-Lucchi, 1984; Remacha and Fernández, 2003; Tinterri et al., 2003; Amy et al., 2007; Marini et al., 2015). Tabular beds can be traced over tens to hundreds of kilometers and can be

61 basin-wide (e.g. Hirayama and Nakajima, 1977; Ricci-Lucchi and Valmori, 1980; Talling et al., 2007;
62 Stevenson et al., 2014a). Deep-water depositional systems are usually considered to exhibit one style
63 of stacking pattern or the other. However, recent studies recognize that different stacking patterns
64 can develop at different stratigraphic levels within the same basin-fill (Marini et al., 2015; Fonesu et
65 al., 2018). Here, we present a detailed study of two contrasting types of stacking pattern co-occurring
66 within the same well-constrained stratigraphic interval of a confined basin for the first time.

67 Confined basins are characterized by intrabasinal slopes and may include syn-sedimentary
68 structural features, which can influence flow behaviour, and therefore depositional processes and
69 patterns (e.g. Haughton, 1994; Kneller and McCaffrey, 1995; Kneller and McCaffrey, 1999; Hodgson
70 and Haughton, 2004; Remacha et al., 2005; Amy et al., 2007; Pickering and Bayliss, 2009; Kane et al.,
71 2010; Muzzi Magalhaes and Tinterri, 2010; Tinterri et al., 2017). Hybrid beds are a common
72 component of unconfined deep-water systems, and are predominantly identified in fringe locations
73 (e.g. Haughton et al., 2003; Talling et al., 2004; Haughton et al., 2009; Hodgson, 2009; Kane and
74 Pontén, 2012; Grundvåg et al., 2014; Kane et al., 2017; Sychala et al., 2017a; Sychala et al., 2017b;
75 Fonesu et al., 2018). However, recent work suggests hybrid beds also form where flows interact with,
76 and decelerate against, confining slopes (e.g. McCaffrey and Kneller, 2001; Muzzi Magalhaes and
77 Tinterri, 2010; Patacci and Haughton, 2014; Fonesu et al., 2015; Southern et al., 2015; Tinterri and
78 Tagliaferri, 2015). These models generally do not incorporate the effects of slope substrate
79 entrainment during flow deflection and transformation (although see 'sandwich beds' of McCaffrey
80 and Kneller, 2001), the deposits of which are discussed as an important process in generating basin-
81 floor topography in distal settings.

82 This study examines stacking patterns and facies distributions of time-equivalent deep-water
83 stratigraphy deposited within a confined, tectonically-active basin: the Upper Broto Turbidite System
84 of the Jaca Basin, northern Spain. The following research questions are addressed: 1) how are
85 turbidites and other gravity flow deposits distributed spatially within a basin that variably confined

86 the parent flows spatially? 2) What is the spatial distribution of stacking patterns? 3) Where are hybrid
87 beds developed and how do they affect the facies distributions and stacking of basin floor deposits?
88 4) What controlled the development of hybrid beds?

89 **GEOLOGICAL SETTING**

90 The Jaca Basin (Fig. 1), located in the south-central Pyrenees, developed during the Early
91 Eocene as an elongate east-west trending foredeep approximately 175 km long and 40-50 km wide
92 (Puigdefàbregas et al., 1975; Mutti, 1984; Labaume et al., 1985; Mutti, 1985; Mutti, 1992; Teixell and
93 García-Sansegundo, 1995; Remacha and Fernández, 2003; Fernández et al., 2004; Millán-Garrido et
94 al., 2006). The basin was bounded by the Pyrenean orogenic belt to the north, a carbonate-dominated
95 ramp-type margin to the south, and the Boltaña Anticline and the Aínsa Basin to the east (Figs. 1C, 2;
96 Puigdefàbregas et al., 1975; Labaume et al., 1985; Barnolas and Teixell, 1994). Fluvial-to-shallow
97 marine systems of the Tremp-Graus Basin, located to the east, fed clastic sediment into the Aínsa and
98 Jaca Basins through structurally-confined channels and canyons (Fig. 1C; e.g. Nijman and Nio, 1975;
99 Mutti, 1984; Mutti et al., 1988; Mutti, 1992; Payros et al., 1999; Moody et al., 2012; Bayliss and
100 Pickering, 2015). The fill of the Aínsa Basin is interpreted as a submarine slope succession (e.g. Mutti,
101 1977; Millington and Clark, 1995; Clark and Pickering, 1996; Pickering and Corregidor, 2005; Pickering
102 and Bayliss, 2009; Moody et al., 2012), which delivered sediment to the basin-floor environments of
103 the Jaca Basin (Figs. 1C, 2; Mutti, 1977; Mutti 1984; Mutti, 1985; Remacha and Fernández, 2003;
104 Remacha et al., 2005).

105 The Hecho Group in the Jaca Basin comprises submarine-lobe and basin-plain deposits with
106 paleocurrents predominantly to the northwest (Mutti, 1977; Mutti, 1992; Remacha et al., 2005; Clark
107 et al., 2017). The deep-water stratigraphy in the Jaca Basin is constrained through nine carbonate-rich
108 megabeds (named MT-1 to -9 to maintain consistency with nomenclature), which extend 10s – 100s
109 km from southeast to northwest (Fig. 1B; e.g. Rupke, 1976; Seguret et al., 1984; Labaume et al., 1985;

110 Labaume et al., 1987; Rosell and Wiezorek, 1989; Barnolas and Teixell, 1994; Payros et al., 1999).
111 Locally, these deposits can be over 100m thick and contain rafted blocks 10s m thick and 100s m wide.
112 These distinctive beds can be mapped regionally and enable correlation between isolated outcrops
113 (e.g. Remacha and Fernández, 2003).

114 Previous studies in the Jaca Basin have described both tabular stacking patterns (Remacha
115 and Fernández, 2003; Tinterri et al., 2003; Remacha et al., 2005), and compensationally stacked lobes
116 developed due to autogenic avulsion of feeder channels, or through structural controls (Mutti, 1992;
117 Clark et al., 2017). Across-strike architecture is poorly constrained due to a relatively narrow outcrop
118 belt trending approximately along depositional dip (Fig. 1B; e.g. Remacha and Fernández, 2003;
119 Tinterri et al., 2003; Remacha et al., 2005). This study examines the strata of the Upper Broto turbidite
120 system immediately underlying Megabed 4 (Fig. 2; MT-4).

121 DATASET AND METHODS

122 The field area is located along a SE – NW transect between the villages of Fanlo and Ansó (Fig.
123 3). Exposures along road cuts, small gullies and river valleys permit detailed study of stratigraphic
124 sections and the ability to trace bed geometries over 100s meters. Sixteen sedimentary logs were
125 collected over a 70 km depositional dip and 1.5 km depositional strike transect. Sections were logged
126 at centimeter-scale, including individual bed thicknesses and sedimentary textures. Sandstone
127 packages were correlated using three marker beds in order to produce a robust correlation
128 framework. These beds, in stratigraphic order, are: Db-1 (debrite-1), Db-2 and MT-4. MT-4 is mappable
129 across the study area (e.g. Payros et al., 1999), Db-1 and Db-2 are locally present in the study area
130 around Broto (Fig. 3). MT-4 has previously been used as a marker bed by Remacha and Fernández
131 (2003), to constrain the same studied interval in distal localities. Paleocurrent readings (n = 166) were
132 collected from flute and groove casts, and 3D ripple cross-lamination. Lithofacies are described and
133 interpreted in Table 1.

134

FACIES ASSOCIATIONS

135 Correlation of bed packages, both down depositional-dip and across-strike, shows that they
136 thicken and thin over 100s to 1000s m, passing from thick-bedded sandstones into fine-grained, thin-
137 bedded heterolithic intervals. They have lobate geometries similar to those reported from basins
138 where lobes are identified (Prélat et al., 2009; Grundvåg et al., 2014; Marini et al., 2015). Beds within
139 lobes exhibit broadly tabular geometries on a 10s to 100s m scale where observed in outcrop, with
140 localized decimeter- to meter-scale scouring. Between lobes, fine-grained and thin-bedded packages
141 can be traced laterally over 100s to 1000s m between outcrops. These packages are interpreted as
142 either the distal lobe fringes of adjacent lobes, or as interlobe intervals related to reduced sediment
143 supply to the basin (e.g. Prélat et al., 2009).

144 **Thick-bedded sandstones**

145 **Description.**--- Thick-bedded sandstone facies form 1–5 m-thick amalgamated packages comprising
146 thick-bedded (>0.3 m-thick) structureless sandstones (Fig. 4D), and less-common planar-laminated
147 sandstones (Fig. 4B, C). They are fine- to medium-grained and can be normally-graded or ungraded.
148 Mudstone clasts are frequently observed along amalgamation surfaces and near bed-bases (Fig. 4C).
149 Millimeter-scale lamination, and centimeter- to decimeter-scale low-angle cross-lamination is
150 observed at southeastern localities (Fig. 4B).

151 **Interpretation.**--- Structureless turbidite beds, and those with millimeter-scale lamination, are
152 interpreted to represent deposition from high-concentration turbidity currents with relatively high
153 rates of aggradation, preventing the development of tractional sedimentary structures (e.g. Kneller
154 and Branney, 1995; Sumner et al., 2008; Talling et al., 2012). Common amalgamation, and entrainment
155 of mudstone-clasts within thick-bedded sandstones indicates that the parent flows were highly
156 energetic, and capable of eroding and entraining, and bypassing sediment during the passage of the
157 flow (e.g. Lowe, 1982; Mutti, 1992; Kneller and Branney, 1995; Gladstone et al., 2002; Talling et al.,
158 2012; Stevenson et al., 2014b; Stevenson et al., 2015). Thick-bedded sandstone-prone packages are

159 therefore interpreted to represent lobe axis environments (Walker, 1978; Gardner et al., 2003; Prélat
160 et al., 2009; Grundvåg et al., 2014; Marini et al., 2015; Kane et al., 2017).

161 **Medium-bedded sandstones**

162 **Description.**--- Infrequently amalgamated 0.1 – 0.3 m thick fine- to very fine-grained
163 sandstones which typically have sharp to weakly-erosive bed bases. Planar lamination is common,
164 particularly in the upper half of the beds (Fig. 4C), whereas structureless sandstones are infrequently
165 observed. Ripple cross-lamination and wavy-topped beds are common where normal grading at bed
166 tops is present. Bed tops are usually sharp, but locally grade into fine-siltstone.

167 **Interpretation.**--- Structured sandstones represent deposition and reworking by low-
168 concentration turbidity currents, whilst structureless sandstones represent deposition from high-
169 concentration turbidity currents. The mixture and preservation of both high- and low-concentration
170 turbidity current deposits suggests a less-axial location of deposition compared to thick-bedded
171 sandstones. Amalgamated structured sandstones with planar-lamination and ripple cross-lamination
172 have been interpreted to be associated with off-axis lobe environments, deposited by decelerating
173 turbidity currents (Prélat et al., 2009; Marini et al., 2015; Sychala et al., 2017c). Therefore, medium-
174 bedded sandstone-prone packages are interpreted to represent lobe off-axis environments.

175 **Thin-bedded sandstones**

176 **Description.**--- Thin-bedded, fine- to very fine-grained sandstone beds (<10 cm thick) are
177 normally-graded and occur interbedded with fine siltstones. Ripple cross-lamination and wavy-
178 laminated bed tops are dominant, whereas planar lamination is less common (Fig. 4A). Typically, beds
179 have a sharp decrease in grain-size from a lower sandstone to overlying silt-rich mudstone. Packages
180 of thin-bedded sandstones are identified on a centimeter- to decimeter-scale within thicker-bedded
181 packages, but are also identified as meter- to decameter-scale packages between thicker-bedded
182 packages.

183 **Interpretation.**--- Thin-bedded, structured sandstones are interpreted to be deposited from
184 low-concentration turbidity currents (Mutti, 1992; Jobe et al., 2012; Talling et al., 2012). Wavy
185 bedforms are interpreted to form due to later flows filling the topography of previous ripple deposits
186 (e.g. Jobe et al., 2012). The observations are consistent with facies of lobe-fringe settings (e.g. Mutti,
187 1977; Prélat et al., 2009; Marini et al., 2015; Sychala et al., 2017b), and similar to the facies near Linás
188 de Broto and Yésero (Fig. 3B) described and interpreted in the same way (Mutti, 1977).

189 **Hybrid beds**

190 **Description.**--- Hybrid beds (Fig. 5) are 0.1-3.2 m thick and are described within an idealized
191 vertical facies scheme consisting of six divisions. Division 1 (D1) Basal, relatively clean sandstone or
192 coarse-grained siltstone that is typically structureless, with rare planar-laminae; D2) A sharp contact
193 to a rippled and/or wavy sandstone, which is typically clean, but is locally argillaceous; D3) A poorly-
194 sorted, matrix-supported argillaceous sandstone (see Table 1); D4) A poorly-sorted mudstone division
195 (see Table 1). The contact to the underlying argillaceous sandstone can be abrupt or graded (Fig. 5);
196 D5) A gradational or abrupt contact to a silt-rich mudstone division, which can be up to 1.5 m thick;
197 D6) A sharp to gradational contact to a white, normally graded carbonate-rich siltstone to claystone
198 (see Table 1). The above represents an idealized sequence, and in an individual bed one or more of D2
199 – 6 may be absent.

200 **Interpretation.**--- Hybrid beds have been interpreted as the deposits of flows transitional
201 between turbulent and cohesive rheologies (e.g. Haughton et al., 2003; Talling et al., 2004; Haughton
202 et al., 2009; Hodgson, 2009; Baas et al., 2011; Kane and Pontén, 2012; Kane et al., 2017; Southern et
203 al., 2017; Pierce et al., 2018). The vertical assemblage of facies within hybrid beds here indicates
204 temporal flow evolution from 1) high- or low-concentration turbulent; to 2) transitional/laminar; to 3)
205 low-concentration turbulent flow regimes. Structureless and planar-laminated sandstones in D1 are
206 interpreted to have been deposited by high- to low-concentration turbidity currents (Table 1). The
207 ripple cross-laminated D2 indicates a flow with a turbulent component able to tractionally rework the

208 bed. The sharp contact between D1 and D2 suggests there was a hiatus in deposition. D3 and D4 were
209 deposited by cohesive flows, representing the longitudinal transformation of the flow from turbulent
210 to cohesive. D5 and D6 were likely deposited by a dilute turbidity current (e.g. Remacha et al., 2005),
211 or as a result of suspension settling (Mutti, 1977; Remacha et al., 2005). The common grading of D4
212 into D5 suggests the flow became more dilute at a fixed locality through time.

213 Beds with repeated, poorly-sorted, deformed, clast-rich layers have also been attributed to
214 cyclical bores within deflected flows depositing alternate relatively clean and muddier liquefied sand
215 (Pickering and Hiscott, 1985; Remacha and Fernández, 2003; Remacha et al., 2005; Muzzi Magalhaes
216 and Tinterri, 2010; Tinterri and Muzzi Magalhaes, 2011). In these process models, clean sandstones
217 are attributed to weaker bores whereas liquefied sandstones are attributed to stronger bores. Massive
218 divisions which are relatively clast-poor (e.g. D3), or with plastically deformed clasts are interpreted
219 to form through cyclical wave loading and shearing caused by trains of strong internal waves (Remacha
220 et al., 2005; Muzzi Magalhaes and Tinterri, 2010).

221 **Deflected flow facies**

222 **Description.**--- Hummock-type bedforms are identified in distal localities, and exhibit convex-
223 up low-angle laminations. However, thickening and thinning of laminae observed in Hummocky Cross-
224 stratification (Harms et al., 1975) are not clearly observed here (Fig. 6C). Hummock-type bedforms can
225 form a large proportion of an individual bed's thickness (Fig. 6A, 6C), or can occur as a discrete upper
226 division of a bed. Typically, beds with hummock-type bedforms comprise a lower, structureless
227 division overlain by an upper, structured division and exhibit lenticular geometries, with amplitudes
228 of 2 – 15 cm. Hummock-type bedforms have larger wavelengths (decimeter- to meter-scale) and
229 amplitudes (up to 15 cm) than wavy bed tops, typically by up to an order of magnitude (Table 1).

230 Centimeter-scale convolute lamination (Fig. 6B) is rarely observed in proximal and medial
231 localities (e.g. Fanlo 1), but is more common in distal localities where it is associated with hummock-
232 type bedforms (e.g. Hecho N).

233 **Interpretation.**--- Hummock-type bedforms have been identified in confined basins, and are
234 interpreted to form as a result of flow deflection and reflection from a confining margin (Pickering and
235 Hiscott, 1985; Remacha et al., 2005; Tinterri, 2011; Tinterri et al., 2017). Convolute lamination can
236 form as a result of loading (Allen, 1982), or from shear stresses imparted on unconsolidated sediment
237 by a later flow (Allen, 1982; McClelland et al., 2011; Tinterri et al., 2016). Development of both
238 hummock-type bedforms and convolute laminations suggests the bedforms developed through flow
239 reworking of an unconsolidated bed, commonly observed in confined basins (e.g. Pickering and
240 Hiscott, 1985; Tinterri et al., 2016), as opposed to loading.

241 **Draped scour surfaces and coarse-grained lag deposits**

242 **Description.**--- Scour surfaces observed in the field area range from decimeter- to meter-scale
243 in depth and width (Fig. 4F). Scours are recognized in the southeast of the field area around Broto (Fig.
244 3), and decrease in scale and frequency to the northwest. The nature of the scour-fills is variable,
245 including mudstone (Fig. 4F), poorly-sorted mudstone to coarse-grained sandstone, and thin-beds.
246 Commonly, scour surfaces are mantled with coarse-grained lags (Fig. 4E), particularly in thick-bedded
247 packages. Locally, coarse-grained lags are identified as an abrupt grain-size increase near bed-tops.
248 Coarse-grained lag deposits are identified predominantly in the southeast of the field area around
249 Sarvisé and Broto (Figs. 3, 4E).

250 **Interpretation.**--- Coarse-grained lag deposits and draped scour surfaces are interpreted as
251 indicators of sediment bypass (e.g. Mutti and Normark, 1987; Mutti, 1992; Elliott, 2000; Gardner et
252 al., 2003; Beaubouef, 2004; Kane et al., 2010; Stevenson et al., 2015). The presence of numerous lags
253 and draped scour surfaces in the southeast suggests significant amounts of sediment transport and
254 bypass through the proximal field area, to more distal localities in the northwest.

255 *Thick chaotic units*

256 **Debrites**

282 and consists of multiple amalgamated beds that form an overall normal grading from very coarse- to
283 very-fine sandstone. The transition from the calcareous-sandstone into the mudstone division is
284 normally-graded over approximately 0.3–0.8 m.

285 **Interpretation.**--- Thick beds with this character have been termed ‘megabeds’. Megabeds in
286 the Jaca Basin have been interpreted as “megaturbidites”, or “megabreccias” (Puigdefàbregas et al.,
287 1975; Rupke, 1976; Johns et al., 1981; Labaume et al., 1987; Rosell and Wiezorek, 1989; Mutti, 1992;
288 Payros et al., 1999); however the term megaturbidite implies a singular transport process which is
289 misleading (e.g. Bouma, 1987). Therefore, herein the term “megabed” will be used. Megabeds in the
290 Jaca Basin are traditionally thought to be deposited by bi-partite gravity flows consisting of: 1) a basal
291 grain- or debris-flow; 2) an upper, turbulent flow (Rupke, 1976; Labaume et al., 1983; Puigdefàbregas,
292 1986; Rosell and Wiezorek, 1989; Mutti et al., 1999; Payros et al., 1999). Megabeds have been also
293 interpreted to be similar to hybrid beds as they contain divisions deposited by both laminar and
294 turbulent flows (Haughton et al., 2009; Fallgatter et al., 2016). The lateral facies changes observed
295 (see also: Rupke, 1976; Johns et al., 1981; Labaume et al., 1987; Rosell and Wiezorek, 1989; Payros et
296 al., 1999) imply that the relative importance of particular depositional processes varies across the
297 basin, notably an increase in the thickness of the turbidite division with respect to the basal debrite
298 division towards the southeast. This may show the ability of the turbidity current to more easily
299 surmount topography, compared to debris flows, and flow farther up the regional dip-slope into
300 proximal parts of the basin relative to the clastic system (e.g. Muck and Underwood, 1990; Al Ja’aidi,
301 2000; Al Ja’aidi et al., 2004; Bakke et al., 2013). The distinctive facies of MT-4, and the ability to map
302 it reliably over 70 km southeast to northwest, make it a marker bed that is confidently used to
303 correlate turbidite packages between outcrops.

304 **Paleocurrents**

305 Throughout the field area, sole structures indicate paleoflow to the northwest, which is
306 consistent with published data (Figs. 9A, B; Rupke, 1976; Mutti, 1977; Mutti, 1992; Remacha and

307 Fernández, 2003), and defines the approximate direction of depositional dip. Ripple cross-lamination
308 is rare in proximal localities; where present it occurs on bed tops and indicates paleoflow to the
309 northwest. In distal localities, ripple crests occur on the upper surface of D1 of hybrid beds and indicate
310 paleoflow to the north (Figs. 9A and 9B), which is also consistent with previous studies (Remacha and
311 Fernández, 2003; Remacha et al., 2005).

312 **Facies variability and geometry**

313 *Proximal localities*

314 Proximal facies variability and package geometries are documented in a depositional dip-
315 oriented correlation panel (W-W'; Fig. 10) and two strike-oriented correlation panels (X-X' Figs. 3B,
316 12; 1.25 and 2 km-long; minimum distance due to shortening). At least 6 sandstone-prone lobes
317 separated by fine-grained and/or thin-bedded packages are identified in the proximal area of the basin
318 between Fanlo 2 and Yésero; Lobes 1 – 6 (Figs. 10, 12).

319 Lobe 1 immediately overlies Db-1 and is 2.5 – 6 m thick, (Figs. 8, 10, 12). Lobe 1 comprises
320 thick-bedded sandstones in southeastern sections at Fanlo 2 and Fanlo 1 (Fig. 3). Eleven kilometers
321 down-dip to the northwest, Lobe 1 transitions to medium-bedded sandstone facies at Linás de Broto,
322 and to thin-bedded facies 3.5 km further down-dip at Yésero 2 (Fig. 10). Lobe 1 is sandstone-prone
323 and is of broadly consistent thickness at all localities, even with variable underlying topography
324 created by Db-1. Onlap at a decimeter- to meter-scale is locally present and is typically associated with
325 large clasts in the underlying Db-1 (Fig. 8).

326 Lobe 2 is 0.5 – 3 m thick and comprises thick-bedded sandstone facies at Fanlo 2 and Fanlo 1
327 and transitions to thin-bedded facies at Linás de Broto (Fig. 3). Across depositional-strike, Lobe 2
328 scours into Lobe 1 and intervening thin-beds at Fanlo Track (Fig. 12). Further north, Lobe 2 thins and
329 fines northward, and pinches out between A Lecina and El Bano (Fig. 12).

330 Lobe 3 thickens from 2.25 m of thick-bedded sandstone facies at Fanlo 2 to 4.25 m at Fanlo 1,
331 with a concomitant increase in thin- and medium-bedded facies. Lobe 3 then thins northwest to Linás
332 de Broto (Fig. 10). North of Fanlo 1, across depositional-strike, Lobe 3 thins to 3 m of medium-bedded
333 sandstone facies at Fanlo Track before pinching out between A Lecina and El Bano (Fig. 12).

334 Lobe 4 is best exposed at El Bano (Figs. 3, 12) where it comprises 4 m of medium- and thin-
335 bedded sandstone facies. The lobe thins and fines to the south at A Lecina before pinching out south
336 of Fanlo Track (Figs. 3, 12), and as such is not recorded in Figures 8 and 10. The thinning of Lobe 4 to
337 the south, and its distribution of facies associations, suggest that its main depocenter lay to the north
338 of El Bano (Figs. 3, 12).

339 Lobe 5 is subdivided into Lobe 5a and 5b in the El Chate cliff section (Fig. 8), where a thin-
340 bedded package separates them; the two packages are grouped together elsewhere due to challenges
341 in differentiating them at several locations. At Fanlo 2, Lobe 5 is a 9.5 m thick package of thick-bedded
342 sandstones intercalated with medium- and thin-bedded sandstones (Figs. 8, 10). Lobe 5 is 10.25 m
343 thick at Fanlo 1. Lobe 5a is 4 m thick and consists of thick-bedded sandstone facies. Lobe 5b is 6.25 m
344 thick and consists of medium- and thin-bedded sandstone facies. Lobe 5 thins to 3 m down-dip at Linás
345 de Broto (Figs. 3, 10). Across-strike to the north of Fanlo 1, Lobe 5 thins and fines laterally into a thin-
346 bedded interval at Fanlo Track (Figs. 3, 12), and is no longer observed in A Lecina (Fig. 12).

347 Lobe 6 stratigraphically underlies MT-4, and is best exposed in the cliffs of the Barranco El
348 Chate valley (Figs. 3, 8, 12). There, Lobe 6 abruptly thickens from a <1 m-thick thin-bedded package at
349 El Chate Cliffs (Figs. 8D, 12) into a 9 m-thick, thick-bedded sandstone package at Barranco El Chate 1
350 km to the west (Fig. 12). The Lobe 6 package consists of thick- and medium-bedded sandstones at
351 Fanlo Track, A Lecina and El Bano (Fig. 12). Across depositional-strike from Barranco El Chate, Lobe 6
352 thins to ~3 m of thin-bedded sandstone northwards at Buesa (Fig. 12). Physical correlation to Linás de
353 Broto and Yésero (1 and 2) is not possible; however Lobe 6 is represented by one of the thin-bedded
354 intervals immediately below MT-4. The base of Lobe 6 is typically scoured in the El Chate cliffs (Fig. 8),

355 and the Barranco El Chate and Fanlo Track logged sections. Lobe 6 does not crop out at Fanlo 1 (Figs.
356 8, 12).

357 The distinctive scoured base to Lobe 6 is present to the south, north and west of Fanlo 1 (Fig.
358 8), which implies this locality represents a fine-grained sediment bypass-dominated zone (e.g.
359 Stevenson et al., 2015). An alternative explanation is that Lobe 6 shows a lateral facies change to a
360 thin-bedded, fine-grained package at Fanlo 1. However, this is not preferred as the facies would have
361 to transition from relatively thick-bedded to thin-bedded and back to thick-bedded (El Chate Cliffs to
362 Fanlo 1 to Fanlo Track), which is not commonly observed in lobes over short distances. The across-
363 strike geometry of the resultant deposit from the El Chate Cliffs to Fanlo Track implies the updip
364 portion of the lobe has a “finger-like” geometry akin to those described from distal fringe deposits
365 (e.g. Groenenberg et al., 2010).

366 *Medial localities*

367 Medial localities are typified by the Acín locality, approximately 20 km down-dip of the Yésero
368 2 locality (Figs. 3, 10). MT-4 constrains the stratigraphy, and in the absence of evidence of significant
369 erosion, indicates that the deposits here are quasi-contemporaneous with those in proximal localities
370 (Fanlo 2 to Yésero, Fig. 3). Four sharp-based and sharp-topped sandstone-prone packages in the
371 section (Ac1-4; 4-7 m thick), which comprise thick-, medium- and thin-bedded sandstones, separated
372 by 10s cm- to m-scale thin-bedded or mudstone-prone intervals (Fig. 10), are interpreted as lobes.
373 Bed types are dominated by high- and low-concentration turbidity current deposits; hybrid beds
374 make-up only 2% of beds (Fig. 11A). The Ac1-4 sandstone lobes are generally thicker, thicker-bedded
375 and coarser-grained than the sandstone lobes observed up-dip at the Linás de Broto and Yésero 2
376 localities.

377 *Distal localities*

378 Four sections were logged in a down-dip transect between the villages of Aragüés del Puerto
379 and Ansó, and two in across-strike positions at Ansó and Hecho (Figs. 3, 10, 13). The studied
380 stratigraphy, previously described in Remacha and Fernández, (2003), is correlated using the MT-4
381 megabed. The proportion and cumulative thickness of hybrid beds increases abruptly from Acín to
382 Aragüés del Puerto (Figs. 10, 11A; see also: Remacha and Fernández, 2003), but decreases northwards
383 from Hecho South to Hecho North over 1 km (Figs. 3, 11B, 13). Sandstone bed thicknesses and
384 grainsize do not change significantly from proximal areas (see also Remacha et al., 2005). However,
385 total bed thicknesses do increase as D3 and D4 are developed in distal localities, and mudstone caps
386 are also thicker (see also Remacha et al., 2005). Hummock-type bedforms and convolute ripple cross-
387 laminations are identified in distal localities, in both turbidites and hybrid beds (Fig. 6).

388 Typically, beds and packages of beds (of similar thicknesses and facies) show significant
389 changes in bed thickness, grain-size and sedimentary textures on a km-scale between localities and
390 are challenging to correlate (Figs. 10, 13). Hybrid beds can be highly variable in character over 100s-m
391 (e.g. Fonesu et al., 2015); therefore caution is needed when correlating beds based on facies alone.
392 Only Beds 1 (3.2 m thick), 2 (3 m thick) and 3 (1.2 m thick) are tentatively correlated between localities
393 in a down-dip direction (Fig. 10). There is ~3 m of relatively thin-bedded stratigraphy between beds 1
394 and 2, which is consistent between localities in a down-dip orientation. However, Beds 1 and 2 are
395 less correlatable across strike on a 100s- to 1000's-m scale (Fig. 13). There is a general northward bed-
396 thinning over 400 m at Ansó, whereas from Hecho South to Hecho North (~1 km) Beds 1-3 appear less
397 distinctive (Figs. 3, 13). The proportion of hybrid beds also decreases and D6 is less common, indicating
398 major bed-scale variability over relatively short distances (although potentially tectonically shortened
399 by ~30%; Teixell and García-Sansegundo, 1995).

400

Discussion

401

Process transformations and products of flow deflection

402 **Evidence and origin of flow deflection.**--- Documented paleocurrent trends suggest variability in flow
403 direction during single events (Fig. 9A, B). The consistent west/northwest orientation of sole
404 structures indicates the primary direction of the lower/earlier flow-components. By contrast, the
405 ripple cross-lamination suggests that the upper/later flow-components (deflected flow) flowed
406 northwards. This suggests that the primary and deflected parts of the flows were divergent (see also:
407 Remacha et al., 2003; Remacha et al., 2005). Paleogeographic reconstructions of the Jaca Basin
408 suggest a narrowing of the basin westward of Jaca, which is attributed to the development of axial
409 thrust sheets and the influence of the Pamplona Fault that separated the Jaca Basin from the Basque
410 Basin to the northwest (e.g. Mutti, 1985; Puigdefàbregas and Souquet, 1986; Puigdefàbregas et al.,
411 1992; Payros et al., 1999; Remacha and Fernández, 2003). Distal narrowing of the basin likely caused
412 an increase in flow interactions with basin margin slopes. Higher concentration parts of flows were
413 strongly confined and “steered” by basinal topography (e.g. Muck and Underwood, 1990; Al Ja’aidi,
414 2000; McCaffrey and Kneller, 2001; Sinclair and Tomasso, 2002; Amy et al., 2004; Bakke et al., 2013;
415 Stevenson et al., 2014a; Sychala et al., 2017c). In contrast, the upper, more dilute, parts of the flow
416 were able to run up confining slopes and deflect back into the basin to produce paleocurrent indicators
417 divergent to those formed by the basal flow components (e.g. Pickering and Hiscott, 1985; Kneller et
418 al., 1991; Kneller and McCaffrey, 1999; McCaffrey and Kneller, 2001; Hodgson and Haughton 2004;
419 Remacha et al., 2005; Tinterri et al., 2017).

420

421 **Generation of hybrid beds through flow deflection.**--- Hybrid beds have been recognized in
422 a wide range of deep-water sub-environments, and attributed to a variety of depositional processes
423 (e.g. Talling et al., 2004; Baas et al., 2009; Haughton et al., 2009; Hodgson, 2009; Patacci and
424 Haughton, 2014; Hovikoski et al., 2016; Tinterri et al., 2016; Kane et al., 2017). Here, poorly-sorted
425 divisions (D3 and D4) are interpreted to be deposited from predominantly cohesive flows. Common
426 sharp boundaries between different divisions (Fig. 5) imply rheological contrasts within the parent
427 flows (Kane and Pontén, 2012). Instabilities within the flow, which imparted changes in velocity,

428 sediment concentration and fall-out rate, may have been caused by internal waves within the
429 deflected flow (Patacci et al., 2015). Variations in flow concentration and velocity of deflected flows
430 (e.g. Kneller et al., 1991) are likely to promote transitional flow behaviour (e.g. Baas et al., 2009).
431 Disaggregated and folded layers of clasts within D3 and D4 (Fig. 5) are interpreted to be deposited
432 from a flow transitional between turbulent and laminar flow regimes (Fig. 14B; *sensu* Baas et al., 2011).
433 Clasts of similar lithology to underlying divisions are interpreted to have been eroded or entrained
434 into an overriding laminar flow (Fig. 14B; see also: Baas et al., (2011)). Turbulent flow conditions are
435 interpreted to have promoted deposition of relatively clean silts and sands, which were then entrained
436 and carried in laminar flows (Fig. 14B).

437 Bores within a deflected flow are attributed to the formation of hummock-type bedforms
438 (Pickering and Hiscott, 1985; Remacha et al., 2005; Tinterri et al., 2017), and convolute lamination
439 (Tinterri et al., 2016). The lateral juxtaposition of convolute lamination, hummock-type bedforms,
440 crudely laminated liquefied divisions, and hybrid beds has been interpreted as a continuum of facies
441 formed due to flow deflection (Muzzi Magalhaes and Tinterri, 2010; Tinterri and Tagliaferri, 2015;
442 Tinterri et al., 2016). Hybrid beds deposited from this process response are tripartite, including an
443 overlying laminated division, and are interpreted to form due to flow deceleration against a slope (e.g.
444 Tinterri et al., 2016). Here, the absence of crudely laminated liquefied divisions, and laminated
445 divisions that overlie the poorly sorted divisions (i.e. D3 and D4) suggest hybrid beds formed from the
446 collapse and deflection of an individual flow, which transformed from turbulent to cohesive.

447 Beds in confined basins with poorly-sorted divisions featuring thin layers of siltstone or
448 sandstone, and/or clasts, which may be present as folded or disaggregated layers, or dispersed
449 through the bed, have also been interpreted to form through liquefaction of beds caused by flow
450 deflection (Pickering and Hiscott, 1985; Remacha and Fernández, 2003; Remacha et al., 2005; Muzzi
451 Magalhaes and Tinterri, 2010). Post-depositional reworking of the clean sandstone divisions (e.g. D1
452 and D2) by successive internal waves or 'bores' have been interpreted to develop fining-upwards

453 divisions of sandstone-mudstone couplets from a progressively waning flow (Pickering and Hiscott,
454 1985; Remacha et al., 2005; Muzzi Magalhaes and Tinterri, 2010). Liquefaction of beds is attributed to
455 shearing caused by internal waves within the flow (Pickering and Hiscott, 1985; Remacha and
456 Fernández, 2003; Remacha et al., 2005; Muzzi Magalhaes and Tinterri, 2010). This mechanism fails to
457 explain the entrainment of lower divisions into upper divisions observed here (Figs. 5E, F), as
458 liquefaction would promote loading into underlying sediment. Furthermore, the common sharp
459 contacts between divisions (Figs. 5A, B, C, E) imply that no significant liquefaction took place. Trains
460 of bores have also been invoked to explain beds with abrupt contacts between poorly-sorted divisions
461 and mudstone forming through obliteration of primary fabrics (Remacha et al., 2005; Muzzi Magalhaes
462 and Tinterri, 2010). However, we consider this mechanism unlikely as: 1) the most dilute part of the
463 flow would be associated with the strongest bores; 2) no further bores depositing sandstone-
464 mudstone couplets could occur; and 3) thin hybrid beds (e.g. Fig. 5A), deposited from smaller
465 magnitude flows or the dilute lateral fringes of flows, would require strong bores to form in small or
466 dilute flows. The observations are more adequately explained by deposition from cohesive flows.

467 **Role of slope substrate entrainment.**--- The increase in the proportion of hybrid beds from
468 proximal to distal localities (Fig. 11), and evidence of flow deflection (Figs. 9A, B), indicate changes in
469 flow behaviour and basin physiography. Slope substrate clasts have been observed in hybrid beds of
470 the Gres d'Annot system (McCaffrey and Kneller, 2001), however, these have not been linked to flow
471 transformation. Here, we suggest that hybrid beds were generated distally within the Jaca Basin by
472 flows interacting with the southern carbonate slope (Fig. 14). This interpretation is underpinned by 3
473 lines of evidence:

474 1) Frontal and lateral lobe fringes in proximal and medial locations (Fig. 3) lack hybrid beds, whereas
475 they become significantly more abundant to the northwest of Acín (Figs. 10, 11). This suggests the
476 location of flow transformation lay northwest (basinward) of Acín. In distal locations, the northward

477 decrease in hybrid bed prevalence and thickness, for example from Hecho South to Hecho North (Figs.
478 11B, 13), suggests a local control on the development of hybrid beds.

479 2) Here, a ripple or wavy laminated division (D2) is identified above D1 (Fig. 5), which is normally
480 occupied by banded or muddy sandstone in conventional hybrid bed models (e.g. Haughton et al.,
481 2009). Ripple and hummock-type bedforms are indicative of flows that tractionally reworked the bed
482 (e.g. Walker, 1967; Allen, 1982; Southard, 1991; Remacha et al., 2005; Sumner et al., 2008; Baas et al.,
483 2009; Tinterri et al., 2016), suggesting D2 is a product of a separate or later flow-component (Fig. 14).
484 The deposition of D2 prior to the deposition of D3 and D4 suggests the deflected flows were
485 longitudinally segregated (Fig. 14), with a forerunning turbulent flow-component that reworked the
486 D1 deposits. This was followed by deposition of laminar or transitional flow-components that
487 deposited D3 and D4.

488 3) The presence of D6 (Fig. 5) is interpreted to reflect substrate entrainment from the carbonate-rich
489 southern slope, which shares mineralogical and biogenic content with carbonate observed in D6
490 (Mutti et al., 1972; Cámara and Klimowitz, 1985; Remacha et al., 2005). An alternative explanation is
491 that the carbonate enrichment of flows occurred across the basin, or that D6 represents a hemipelagic
492 drape (Mutti et al., 1972; Rupke, 1976; Mutti, 1977). A local origin of D6 is inferred as the absence of
493 D6 in proximal and medial localities (Fig. 10) would require either: 1) D6 to be eroded by every
494 subsequent flow; or 2) the flow responsible bypassed in these localities in every case, which we
495 consider implausible. The more-common occurrence of D6 in hybrid beds compared to turbidites,
496 suggests that deflected flows entrained carbonate mud substrate, whereas a hemipelagic drape
497 should be present in both hybrid beds and turbidites (see also: Remacha et al., 2005). Furthermore,
498 the common normal-grading of D5 into D6 suggests a turbiditic origin where terrigenous and
499 carbonate clay was hydraulically fractionated within the dilute parts of flows (Remacha et al., 2005).

500 In most basins featuring hybrid beds, the source of clay driving flow transformation can only
501 be inferred (see also: Fonnesu et al., 2016), as the type of intrabasinal clay is similar to that in the flow,

502 making it challenging or impossible to distinguish in outcrop or core. Here, D6 acts as a distinctive
503 'tracer' near the location of flow transformation. This demonstrates that flow transformation can
504 occur as a result of flows entraining substrate as they deflect off intrabasinal slopes in confined
505 settings.

506 *Contemporaneous systems with different stacking patterns*

507 **Spatially Distinct Stacking Patterns.**--- Stacking patterns within the Upper Broto System have
508 been described as tabular, where proximal and medial sheet-like lobes transition to the individual bed-
509 scale stacking of the basin-plain environment (Mutti et al., 1999; Remacha and Fernández, 2003;
510 Tinterri et al., 2003). However, the evidence outlined in this work suggests that individual bed
511 correlation in both proximal and distal localities is, at best, challenging (see also Mutti, 1992).
512 Stratigraphic changes in bed stacking patterns are attributed to changing confinement as a basin fills
513 (e.g. Hodgson and Haughton, 2004; Marini et al., 2015; Fonnesu et al., 2018; Liu et al., 2018). Here,
514 different lobe stacking styles are described within the same stratigraphic interval, and interpreted to
515 reflect different flow processes and depositional architectures from proximal to distal localities (see
516 also: Fonnesu et al., 2018).

517 Lobes are identified in proximal localities based on their geometries, facies, and facies
518 transitions (Figs. 10; 12). The lateral and longitudinal offset of thick-bedded sandstone facies indicates
519 the depocentre of successive lobes moved away from the depositional relief of previous lobes, and
520 stacked in a compensational manner (Figs. 12, 15B; e.g. Mutti and Sonnino, 1981; Parsons et al., 2002;
521 Deptuck et al., 2008; Prélat et al., 2009; Marini et al., 2015; Picot et al., 2016). The identification of
522 lobes medially within the basin, and bypass-dominated facies proximally, indicates some lobes are the
523 products of flows that bypassed proximal localities (Fig. 15). These interpretations are supported by
524 longitudinal and lateral facies and thickness changes within the lobes identified (Figs. 10, 12).

525 In distal localities, beds do not form clear packages with lobate geometries as they do in
526 proximal and medial locations (Fig. 13). Similarly, they do not exhibit persistent lateral and longitudinal

527 trends in thickness and facies (e.g. lobe axis to lobe fringe) observed in proximal localities, and in other
528 basins (e.g. Mutti and Sonnino, 1981; Pr lat et al., 2009; Grundv g et al., 2014; Marini et al., 2015;
529 Spychala et al., 2017a). Some anomalously thick beds can be tentatively correlated (Fig. 10). However,
530 it is not possible to confidently correlate most beds across these areas, particularly across
531 depositional-strike (Fig. 13B; *c.f.* Remacha and Fern ndez, 2003), suggesting beds may not be as
532 tabular as previously suggested.

533 The outcrop belt is slightly oblique to the primary paleocurrent direction, and therefore some
534 changes in architecture could be attributed to across depositional-strike facies variations. However,
535 irrespective of individual bed correlations and outcrop belt orientation, this study recognizes
536 differences in facies and stacking patterns between proximal, medial, and distal localities. The marked
537 distribution of facies, bed types, and stacking patterns indicates a basinal control. The implications of
538 these differences are that fundamentally different stacking styles can occur within the same
539 stratigraphic interval of deep-water systems in confined basins.

540 A similar distribution of facies is observed in the Gottero Sandstone, Italy. Proximal localities
541 are characterized by lobes, whereas distal localities comprise thick, basin-wide, tabular turbidites and
542 hybrid beds in these basins (Fonnesu et al., 2018). It is interpreted that regular-sized flows were
543 relatively unconfined and formed proximal lobes, whereas large flows bypassed proximal localities
544 (see also: Wynn et al., 2002; Remacha et al., 2005), entrained large rafts of substrate, and deposited
545 thick basin-wide turbidites and hybrid beds (Fonnesu et al., 2018). The distal deposits of the Upper
546 Broto do not exhibit evidence of significant basin-floor erosion and entrainment, suggesting highly
547 energetic flows were not present. Some anomalously thick beds (1–3.2 m) in the Upper Broto could
548 be associated with larger volume flows into the basin (e.g. Remacha et al., 2005); however, the vast
549 majority of beds are thinner than 1 m (Figs. 10, 13). Bed thickness increases in the Upper Broto are
550 predominantly facilitated by the development of hybrid beds, the thickness of which are shown to be
551 highly variable and strongly controlled by local topography (e.g. Sumner et al., 2012; Fonnesu et al.,

552 2015). Therefore, it is suggested that facies distribution and hybrid bed emplacement are
553 predominantly controlled by flows interacting with a confining slope (Fig. 15), which does not
554 necessitate, but does not preclude, larger flows.

555 **The Effect Of Deflected-Flows On Stacking Patterns.**--- Hybrid beds, up to 3.2 m-thick (post-
556 compaction; Fig. 10), which thin and decrease in abundance away from the slope (Figs. 11B, 13; in this
557 case, from south to north; see also Amy et al., (2004)), are present in distal localities. These beds could
558 have created, and/or healed, significant 3D topography on the contemporaneous seabed, influencing
559 the routing of subsequent events (e.g. Remacha et al., 2005; Figs. 15C, 16). Beds with relatively thick
560 mudstone caps are often associated with flow ponding (e.g. Pickering and Hiscott, 1985; Haughton,
561 1994; Remacha et al., 2005; Muzzi Magalhaes and Tinterri, 2010), suggesting some flows deposited in
562 bathymetric lows. Flows were deflected near perpendicular to the main paleocurrent of the primary
563 flows, causing deflected-flow deposits to develop geometries and facies tracts perpendicular to those
564 of the primary deposits (Figs. 15C, 16). This may have resulted in complicated 3D bed geometries,
565 which can overlap the stacking pattern of the primary flow deposits (Figs. 15C, 16). This subtle
566 topography was likely felt by the flows and drove deposition in the inherited topographic lows,
567 developing complex bed-scale compensation patterns (Fig. 16).

568 **Conclusions**

569 Well-constrained outcrops along a 70 km dip-orientated transect of an exhumed deep-water
570 depositional system permit proximal to distal analysis of facies and stacking patterns.
571 Contemporaneous but contrasting stacking pattern within the same stratigraphic interval is described
572 in detail for the first time. Proximal localities are characterized by sandstone-rich lobes interpreted to
573 stack compensationally. Distal localities are characterized by interbedded comparatively tabular clean
574 sandstones and hybrid beds which neither stack to form lobes, nor form well-defined tabular sheets.

575 Here, we present a system that generated hybrid bed through interaction with an intrabasinal
576 confining slope. In most basins featuring hybrid beds, the source of clay responsible for flow
577 transformation can only be inferred as the clay in the flow is compositionally similar to the clay present
578 on the basin-floor. Here, a locally derived and distinct carbonate mud lithofacies demonstrates that
579 entrainment of substrate from an adjacent slope is capable of causing flow transformation. The
580 localized development of hybrid beds through entrainment of slope mud could create depositional
581 relief that influenced flow behavior and deposit geometries, resulting in depositional architectures
582 that diverge from traditional models of either lobe or tabular-sandstone stacking patterns. The co-
583 development of different stacking patterns in the same stratigraphic interval suggests that a false
584 dichotomy of lobes *versus* sheets to characterize basin-floor architectures could exist, and that the
585 stratigraphic and process record of their transitions merit future investigations to better our
586 understanding of submarine fan architecture.

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996

997 Figure 1: A) Location of the field area in Spain; B) Simplified geological map of the Hecho Group
998 (adapted from Remacha et al., 2003); C) Paleogeographic map of the Pyrenean Foreland Basin during
999 the Early Lutetian (modified from Dreyer et al., 1999).

1000 Figure 2: Stratigraphic column of the Pyrenean foreland basin fill. Nomenclature is given for the
1001 stratigraphy of the Jaca Basin (adapted from: Remacha et al., 2003; Caja et al., 2010). Several
1002 correlation schemes for the Jaca turbidite systems with those of the Aínsa Basin have been proposed
1003 (e.g. Mutti, 1985; Das Gupta and Pickering, 2008; Caja et al., 2010; Clark et al., 2017).

1004 Figure 3: Satellite imagery of the field area showing proximal (B), distal (C) and medial (Acín; see A)
1005 localities. Transects W, X, Y and Z are illustrated in Figs. 9, 12, and 13.

1006 Figure 4: Bed-scale facies deposited from turbidity currents, typically, but not exclusively identified in
1007 proximal and medial localities (Fig. 3). A) Thin-bedded sandstone with planar lamination at the base
1008 and ripple-cross lamination towards the top. Identified basin-wide; B) Stepped planar-laminations
1009 observed at the most proximal location, Fanlo 2; C) Planar-laminated fine-grained sandstone; D)
1010 Structureless medium-grained sandstone with mudstone-clasts; E) Coarse-grained lag on the upper-
1011 surface of a scour. There is a grain-size break from relatively clean upper-fine sandstone to coarse
1012 and very-coarse sandstone with abundant mm- and cm-scale mudstone clasts; F) Mudstone-draped
1013 scour observed at Fanlo 2.

1014 Figure 5: Selected hybrid bed facies demonstrating the range of bed-types observed. A) Thin hybrid
1015 bed with a thin siltstone basal division, overlain by a sharp break to D3 which has a sharp upper
1016 surface to D6; B) Hybrid bed with lower structureless sandstone with a ripple cross-lamination top.
1017 Overlain by a poorly sorted D3 and D4 which normally-grade upwards into D5 and D6; C) Lower
1018 structureless sandstone with a sharp upper contact with argillaceous sandstone D3. There is a sharp,
1019 sheared boundary between D3 and D4. D4 is gradational into D5 and D6; D) Outsized hybrid bed
1020 (Bed 2; Fig. 10). The basal 5cm consists of a lag of very coarse-grained sandstone clasts, armoured
1021 mudstone-chips and Foraminifera. Overlying is a poorly-sorted division which fines gradationally

1022 upwards into D5 and D6; E) Inset of (C) illustrating the sharp, sheared boundary between D3 and D4
1023 with entrainment of clasts from D3; F) Example of D3 containing clasts of underlying D1.

1024 Figure 6: A) Lenticular, hummock-type bedform observed at Hecho N (Fig. 3C). B) Convolute
1025 laminations observed at Acín (Fig. 3A). C) Hummock-type bedform observed at Hecho N.

1026 Figure 7: Contact of Db-1 with substrate near the Yésero locality (Fig. 3). Local entrainment of
1027 substrate appears to occur through a stepped delamination process similar to that described in
1028 turbidites and hybrid beds (Butler and Tavarnelli, 2006; Eggenhuisen et al., 2011; Fonesu et al.,
1029 2016).

1030 Figure 8: A, B) Overview of the proximal stratigraphy in cliffs adjacent to the Fanlo 1 locality
1031 (Barranco El Chate Cliffs; Fig. 3). Several of the described sandstone lobes are observed (numbered),
1032 along with 3 marker beds (Db 1, Db 2 and MT-4); C) The transition of Lobe 6 from bypass-dominated
1033 features to deposition-dominated features is observed in the cliffs, potentially forming a sand-
1034 detached lobe (at least in two-dimensions); D) Line drawing of (C).

1035 Figure 9: A) Paleocurrent data collected within the field area. Proximal data are collected from flutes,
1036 grooves and ripple crests which are consistent in trend and are grouped together (n=57). Medial and
1037 distal localities are segregated by paleocurrent indicator. Data show that flute and groove marks
1038 (n=103) diverge from ripple cross-laminations (n=6) directions in medial and distal locations. Flutes
1039 and grooves formed at the bed bases, whereas ripple cross-lamination formed on bed tops,
1040 suggesting the initial and later stages of the flows had divergent paleoflow directions. Refer to Figure
1041 1 for key to stratigraphy, map modified from Remacha et al., (2003); B) Example of a single bed with
1042 divergent paleocurrent indicators at the bed base and bed top. This suggests that the initial flow was
1043 to the northwest, while a later, deflected flow-component was to the north.

1044 Figure 10: Down depositional-dip oriented correlation panel from proximal to distal (right to left),
1045 note changes in horizontal scale. Log locations are shown in Fig. 3. Logs are tied to the basin-wide
1046 MT-4 marker bed. There is an overall fining, and thinning at both bed- and lobe-scale between Fanlo
1047 2 and Yésero 2. Lobes Ac1-4 at Acín are thicker bedded and coarser than at Yésero and Linás de

1048 Broto, suggesting the flows which deposited these lobes bypassed the proximal area of the system.
1049 Beds in distal localities (west of Acín) do not form well-developed lobes. Lobe 4 is not observed in
1050 the panel as it pinches out to the north of Fanlo 1.

1051 Figure 11: Graphs illustrating the spatial variability of hybrid bed abundance and proportional
1052 thickness: A) Down-dip from proximal localities to distal localities; B) across strike in distal localities.

1053 Figure 12: Stratigraphic interpretations of proximal lobes and geometry of Lobe 6. Lobes exhibit
1054 lateral facies changes on a kilometer-scale. Lobe 6 is not observed at Fanlo 1, whereas it is observed
1055 to the north and south at Fanlo Track and El Chate Cliffs (Fig. 8) respectively. The stratigraphy can be
1056 walked 1.5 km to the west to Barranco El Chate where Lobe 6 is 9 m-thick.

1057 Figure 13: Across strike architectural panels at the distal locations of Ansó (A) and Hecho (B; Fig. 3):
1058 A) The Ansó strike panel is tied to the mudstone cap of MT-4. Tentative individual bed correlations
1059 are indicated by dotted lines. B) The Hecho panel is tied to the base of MT-4 as the top of the unit is
1060 difficult to access. Individual bed correlations are challenging to make due to the disparity in facies
1061 between the two outcrops over relatively short distances.

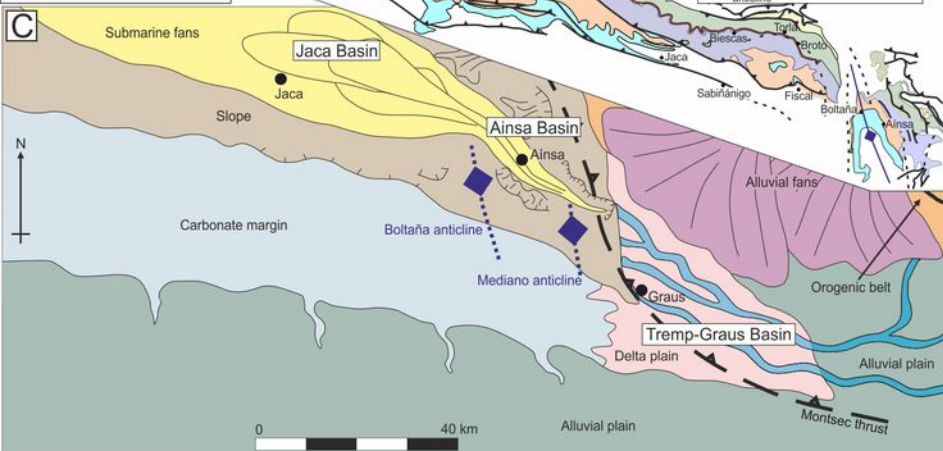
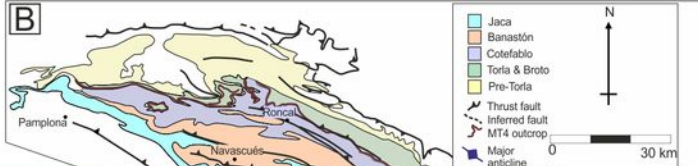
1062 Figure 14: Model to explain the facies, structures and paleocurrents observed: A) Deflected flows
1063 with differing rheological properties rework and/or shear previous deposits. The initial deflected,
1064 turbulent, flow reworks the bed-top (2) of the non-deflected flow deposit (1) and is followed by
1065 deflected flows which entrained slope substrate, becoming cohesive (3). Later parts of the flow are
1066 more dilute and carbonate-rich (4); B) Schematic reconstruction of the deposition of a characteristic
1067 bed by a flow transitional between turbulent (TF) and laminar (LF) flow regimes.

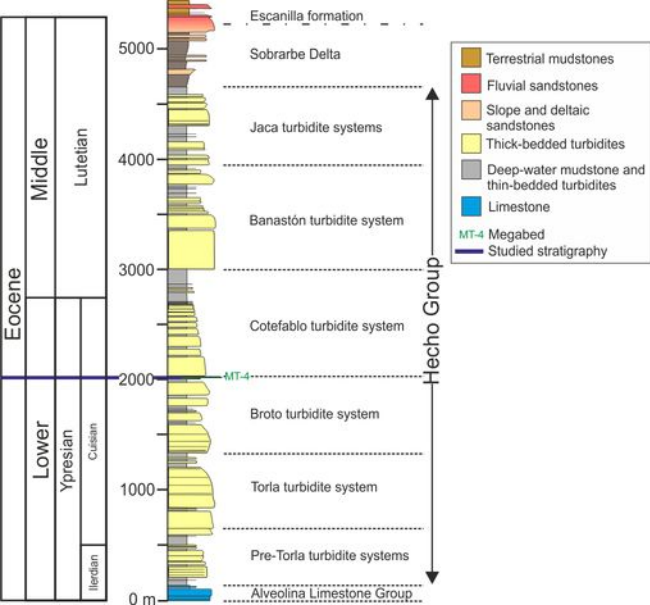
1068 Figure 15: A) Schematic interpretation of the Jaca Basin paleogeography during deposition of the
1069 Upper Broto turbidite system; B) Proximally, lobes stacked compensationally, and did not develop
1070 hybrid beds. The solid colour box is based on data presented in Fig. 12; C) Distally, flows were able to
1071 interact with the southern carbonate margin, which deflected flow-components to the north. These
1072 deflected flows entrained carbonate-rich muddy slope material, increasing flow cohesion; these

1073 flows then deposited the hybrid bed D3 and D4 overlying the primary deposits not affected by the
1074 slope.

1075 Figure 16: Schematic illustration of how deflected cohesive flows can influence depositional
1076 topography. The relative across-strike orientation of the primary (orange) and deflected (purple)
1077 flows develop perpendicular to each other, creating subtle topography which could influence the
1078 architecture of subsequent flows.

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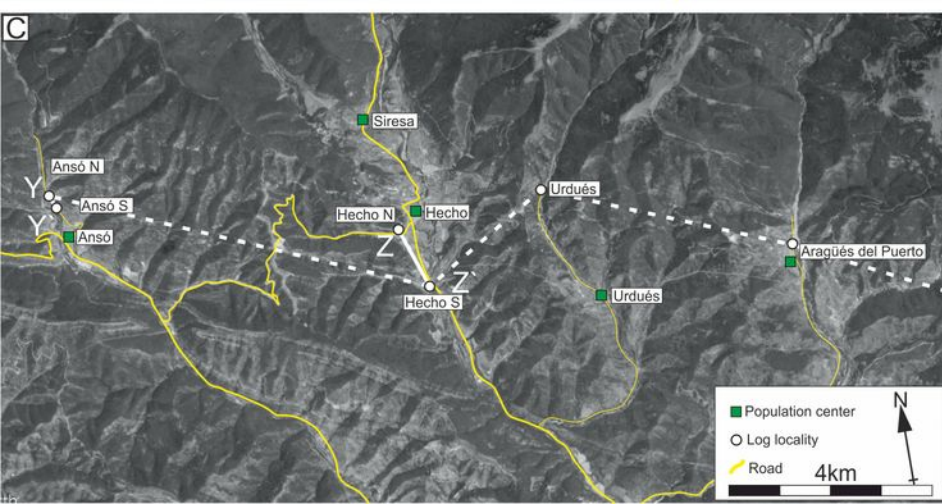
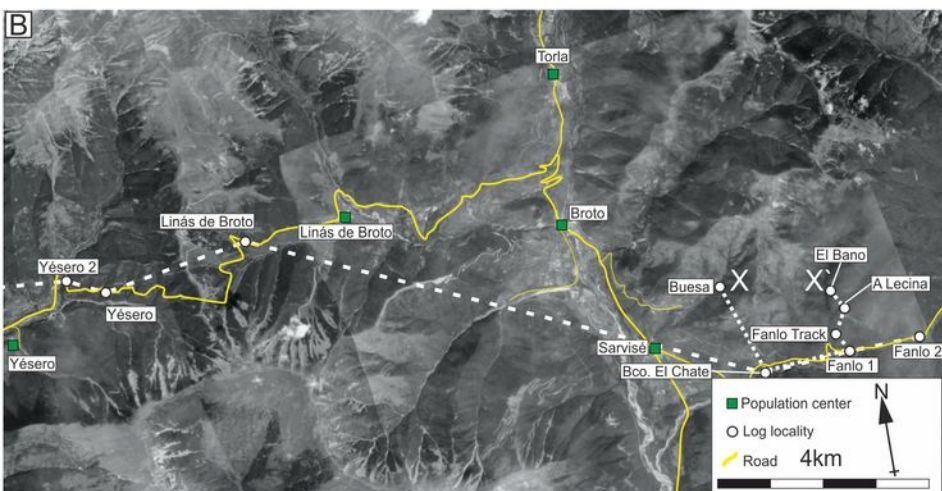


Table 1: Summary of lithofacies observed in the study area.

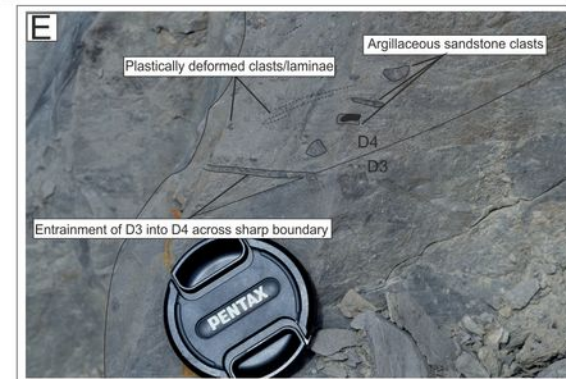
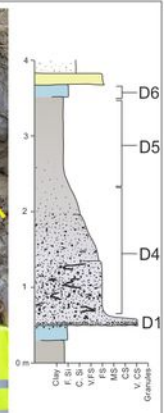
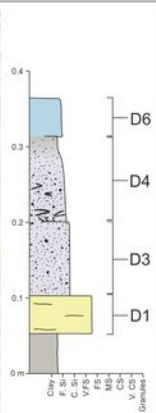
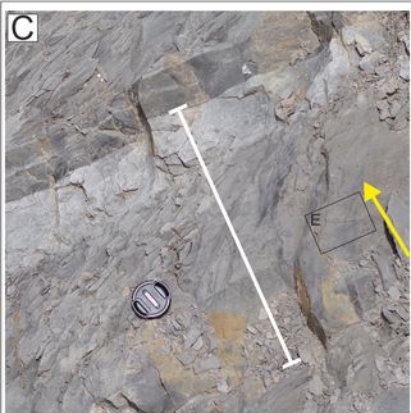
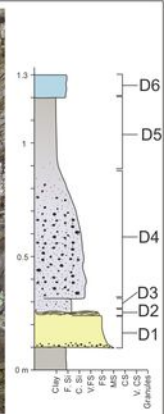
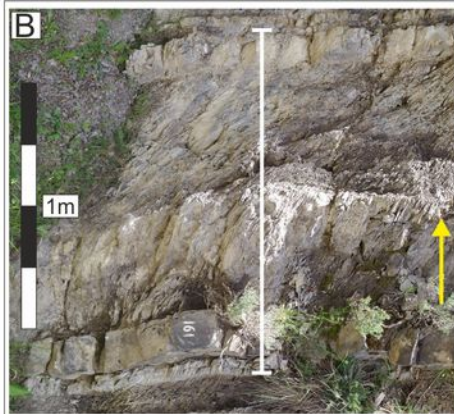
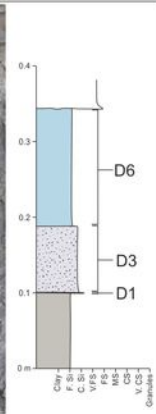
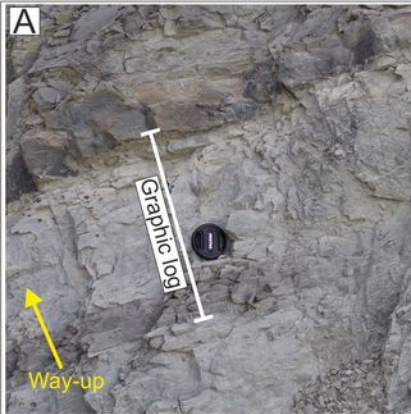
Facies	Lithology	Sedimentology	Thickness (m)	Interpretation
Structureless sandstone	Very fine- to medium-grained sandstone, rare coarse-grained sandstone. Siltstone caps are infrequently present in distal localities but are not present in proximal localities.	Typically structureless and frequently normally-graded or coarse-tail graded. Occasional mudstone chips occur, typically in fine- to coarse-grained sandstone beds. <i>Nummulites</i> are infrequently observed.	0.05 – 0.5	Rapid aggradation from a high-concentration flow (Lowe, 1982; Mutti, 1992; Kneller and Branney, 1995).
Stepped-planar-laminated sandstone	Medium- to coarse-grained sandstone.	Laminated sandstone, laminae are 5 – 15 mm thick, parallel to sub-parallel and typically coarser grained than surrounding sandstone. Coarser laminae are typically inversely graded.	0.1 – 0.5	Repeated collapse of traction carpets below a high-concentration turbidity current (Talling et al., 2012; Cartigny et al., 2013).
Planar-laminated sandstone	Very fine- to medium-grained sandstone.	Laminated sandstone with μm – mm scale alternating coarser – finer laminae. Laminae are typically parallel, rarely sub-parallel. Common coarse-tail grading. Infrequent occurrence of plant fragments and mudstone chips aligned with laminae.	0.04 – 0.5	Layer-by-layer deposition from repeated development and collapse of near-bed traction carpets (Sumner et al., 2008) and migration of low-amplitude bed-waves (Best and Bridge, 1992; Sumner et al., 2008).
Ripple-laminated sandstone	Very fine- to fine-grained sandstone, rarely medium-grained sandstone and coarse siltstone.	Ripple-cross laminations, typically located in the upper parts of the bed. Climbing ripples locally observed. Commonly produces wavy bed tops.	0.02 – 0.1	Tractional reworking beneath a dilute, slow-moving flow (Allen, 1982; Southard, 1991).
Convolute ripple cross laminations	Very fine- to fine-grained sandstone.	Deformed, folded and overturned ripple cross lamination.	0.02 – 0.1	Liquefaction due to loading of overlying sediment (Allen, 1982), or shear stresses caused by subsequent flow (Allen, 1982; McClelland et al., 2011; Tinterri et al., 2016).
Hummock-type bedforms	Very fine- to fine-grained sandstone.	Decimeter- to meter-wavelength undulating bedforms. Typically consist of smaller-scale wavy, convolute or ripple cross-laminations.	0.02 – 0.15	Reworking of initial deposit of a bipartite flow by a bypassing flow-component (Mutti, 1992; Tinterri et

al., 2017), or reworking of initial flow deposits by internal bores within a deflected flow (Pickering and Hiscott, 1985; Remacha et al., 2005).

Argillaceous sandstone	Poorly-sorted, claystone- and siltstone-rich sandstone.	Beds have higher mud contents in the matrix compared to relatively clean sandstone beds. Infrequently contain spheroidal or folded sandstone and mm-scale mudstone blebs. Where two argillaceous sandstones overlie each other, delamination and shearing structures are sometimes observed.	0.05 – 0.3	Transitional flow deposit (Sylvester and Lowe, 2004; Baas et al., 2009; Sumner et al., 2009; Kane and Pontén, 2012).
Poorly-sorted mudstone	Siltstone- and sandstone-rich claystone	Commonly graded into mudstone; however, infrequent non-graded, sharp-topped examples occur. Mudstone- and siltstone-clasts, and mudstone-armoured <i>Nummulites</i> are frequently present. Clasts are commonly present as sub-rounded balls or as plastically deformed layers. Infrequent disaggregated and sheared layers are observed. Where overlying argillaceous sandstone, delamination and shearing structures are sometimes observed.	0.05 – 3.2	Clast-rich, poorly-sorted, matrix supported beds are suggestive of <i>en-masse</i> deposition from laminar flows (e.g. Nardin et al., 1979; Iverson, 1997; Sohn, 2000). Beds which exhibit grading are likely to have retained some level of turbulence within the flow; and are therefore interpreted to have deposited from a transitional-flow regime (Baas et al., 2009; Sumner et al., 2012; Baas et al., 2013).
Carbonate-rich siltstone	Carbonate-rich siltstone. Rare carbonate-rich mudstone.	Distinctive off-white colour. Exhibits a gradational base where overlying graded mudstones, but is often sharp where overlying argillaceous sandstone. Generally homogenous texture.	0.02 – 0.3	Fine-grained carbonate hydraulically fractionated from siliciclastics, deposited from dilute remnants of the flow (Remacha and Fernández, 2003).
Matrix-supported chaotic deposits	Poorly-sorted, clast-rich matrix consisting of sandstone, siltstone and mudstone.	Clasts include: cm – m scale sandstone balls, m – 10s m scale sandstone rafts, dm – m scale mudstone rafts. Sandstone rafts are frequently found at the top of the beds.	0.2 – 25	“Freezing” of a flow with yield strength, i.e. a debris flow (e.g. Iverson et al., 2010).
Mudstone	Silt-rich mudstone	Massive- to weakly-laminated.	0.01 – 2.5	Background sedimentation or

deposition from a dilute flow.





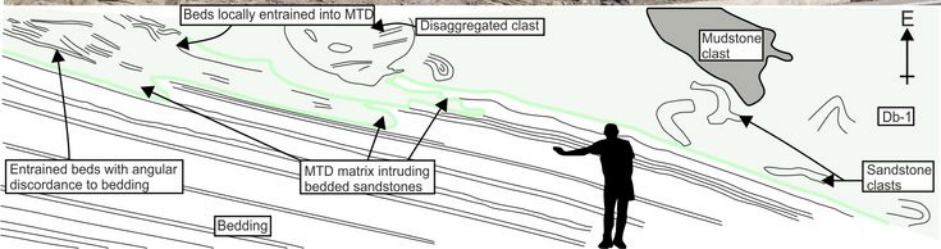
Clean sandstone

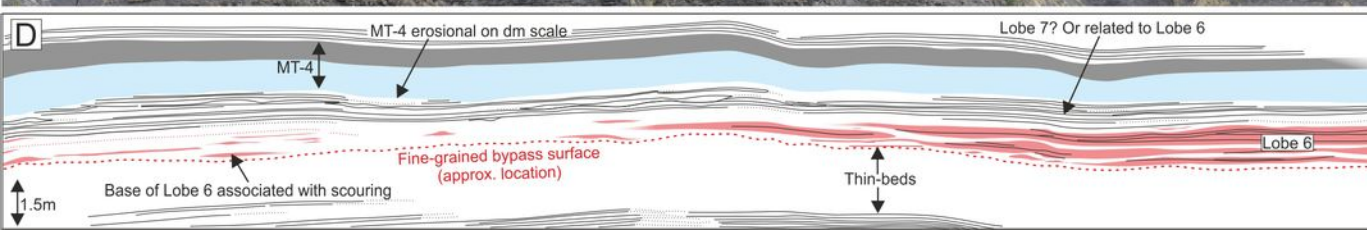
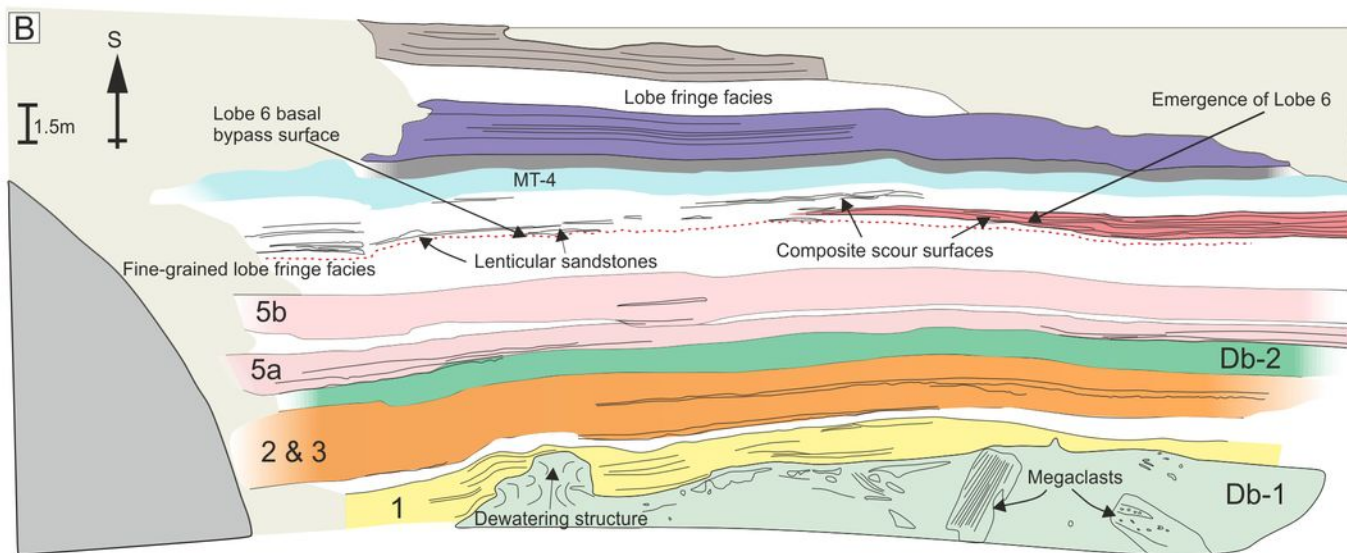
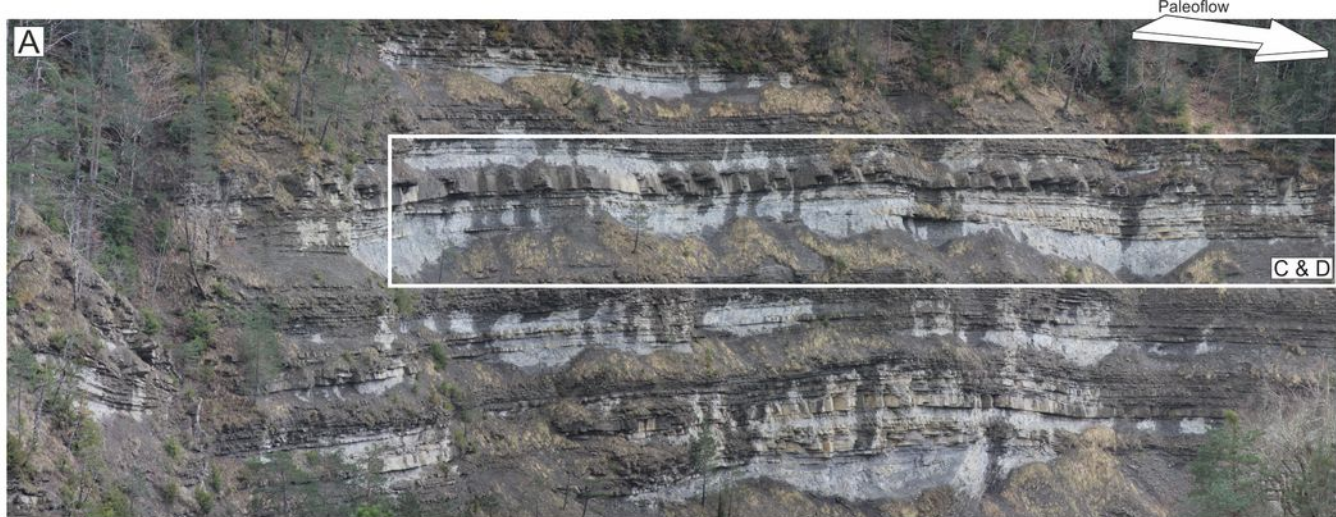
Argillaceous sandstone

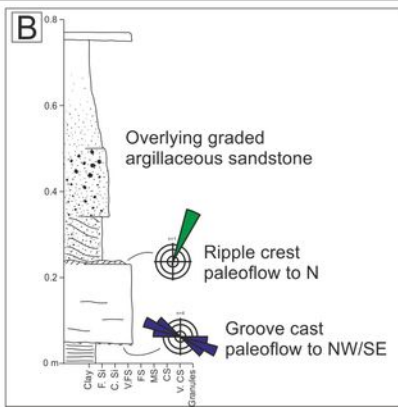
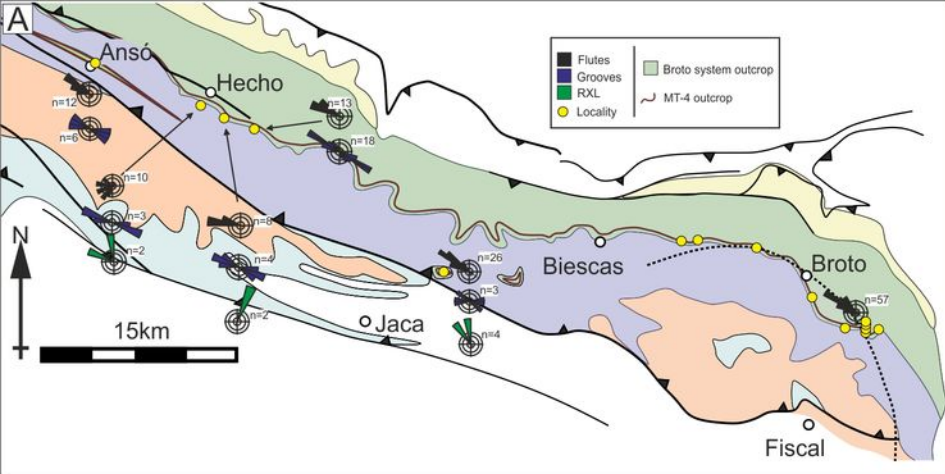
Carbonate-rich division

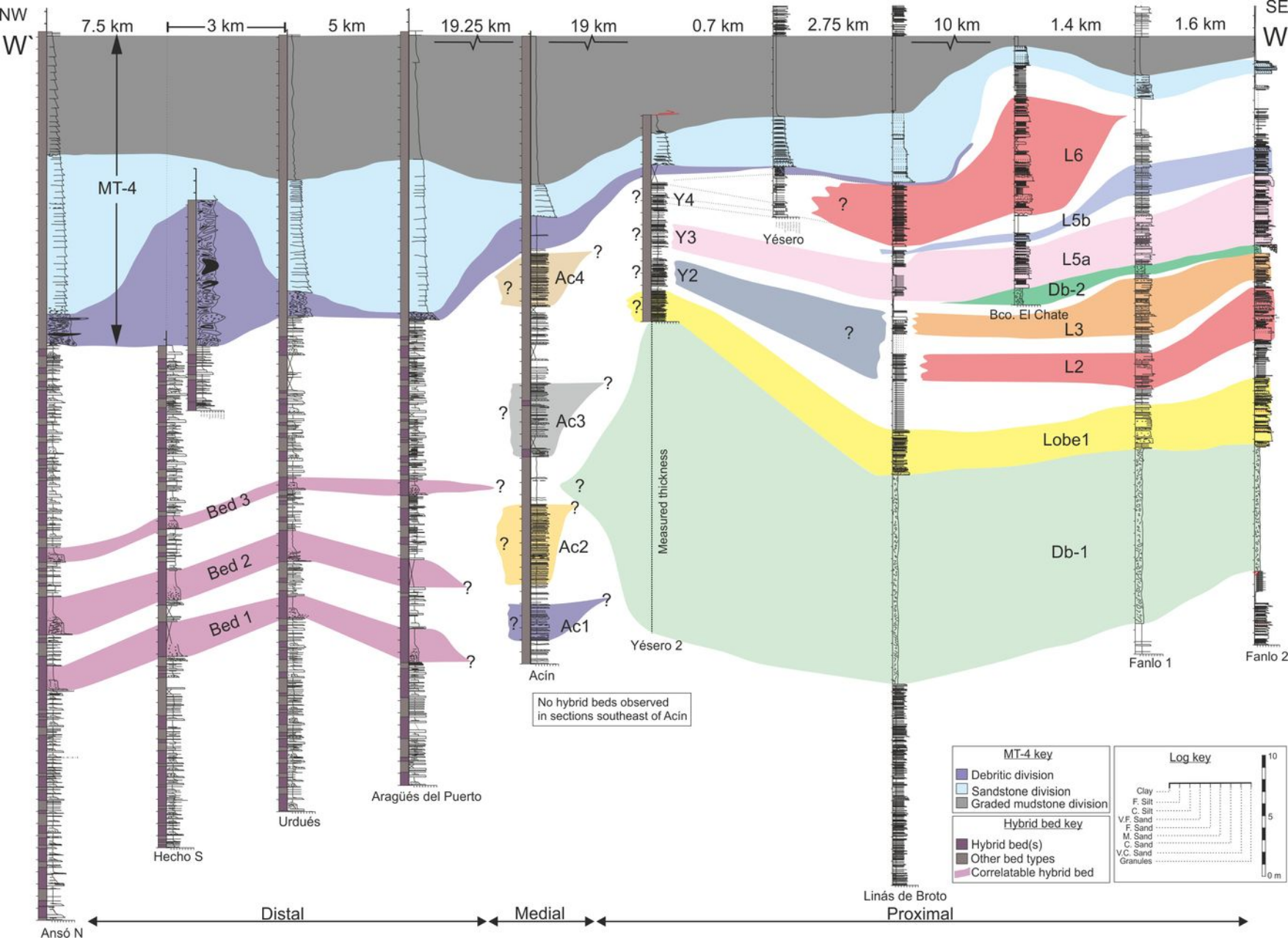
Mudstone



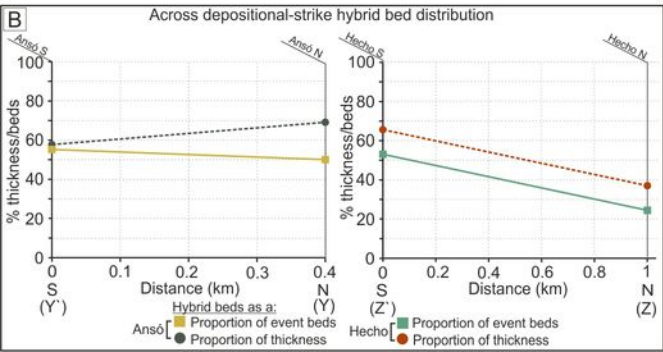
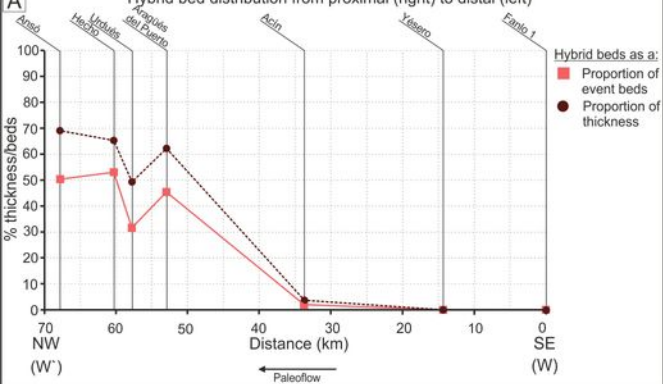


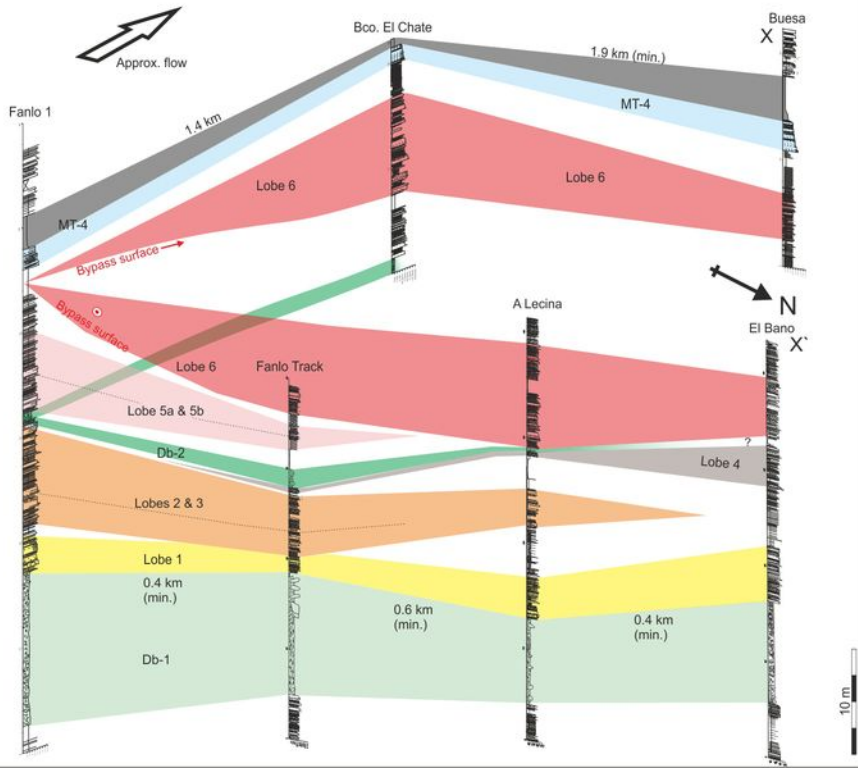


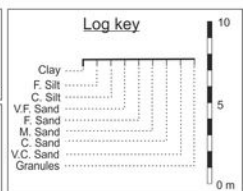
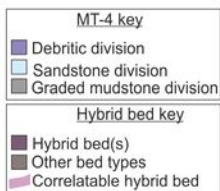
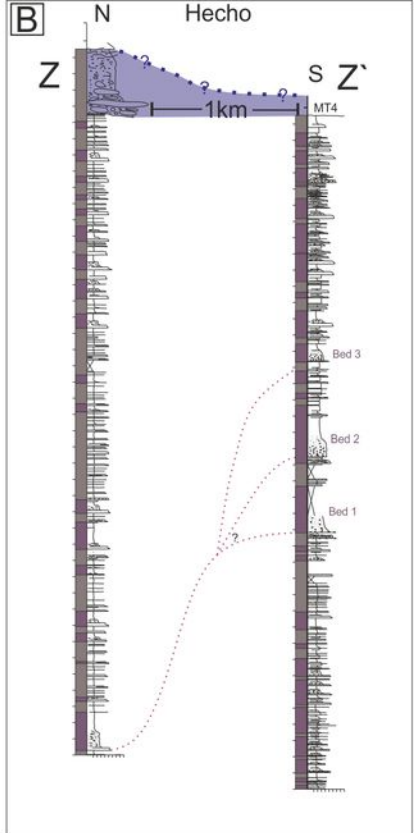
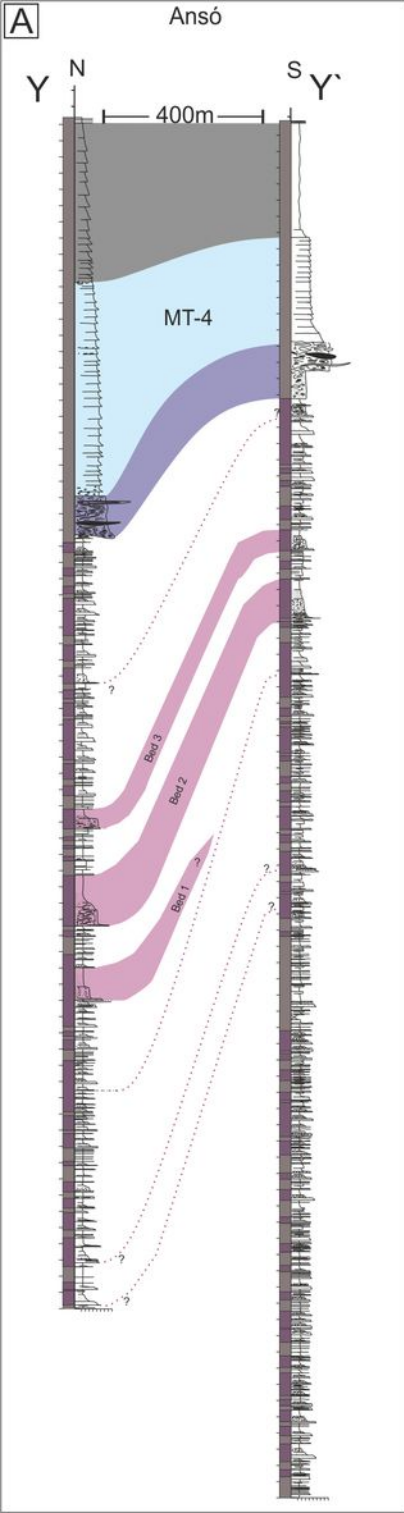


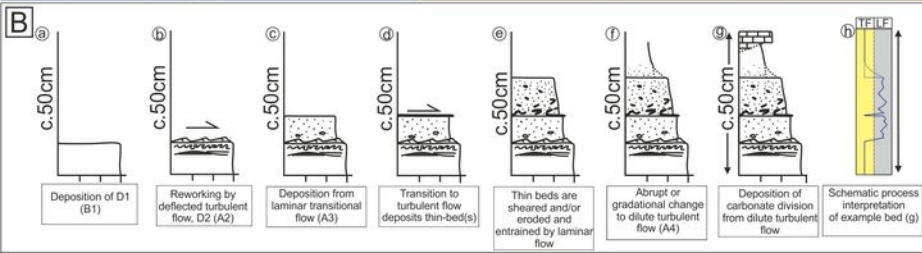
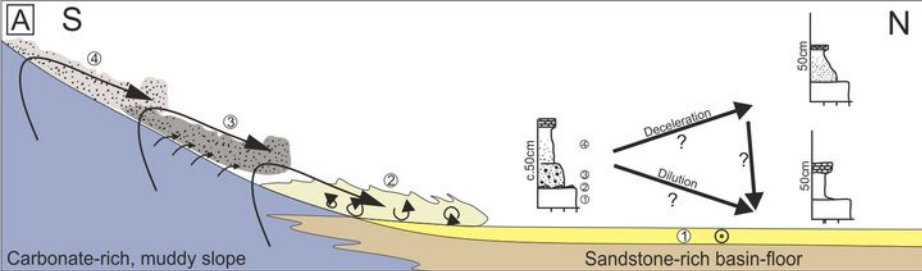


Hybrid bed distribution from proximal (right) to distal (left)

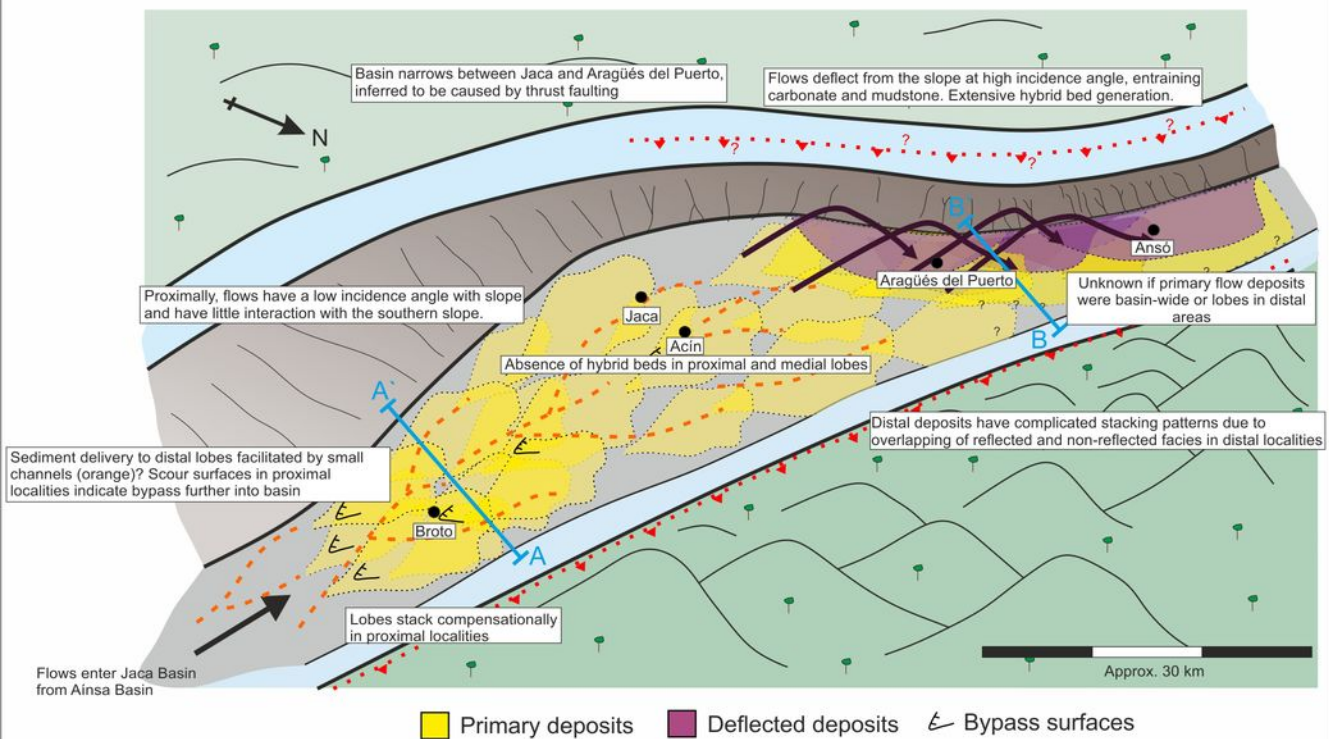




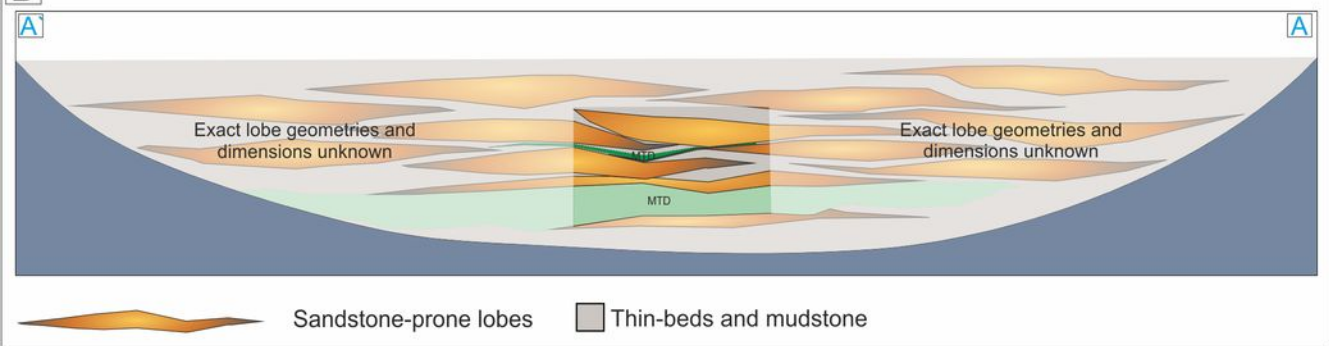




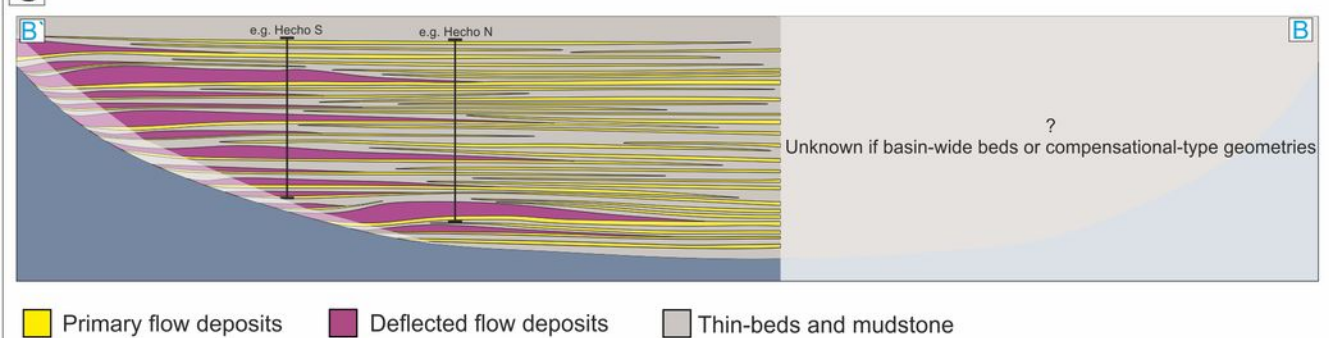
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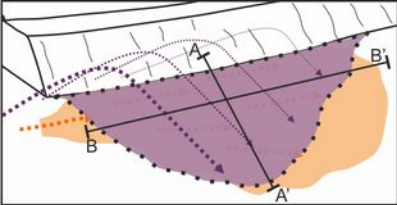


B



C





- Primary flow deposit
- Deflected flow deposit
- Primary paleocurrent
- Deflected paleocurrent

