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1 **HYBRID EVENT BEDS GENERATED BY LOCAL SUBSTRATE**  
2 **DELAMINATION ON A CONFINED BASIN FLOOR**

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9 Keywords: turbidites, hybrid event beds, substrate delamination, scours, basin plain, entrainment

10 **ABSTRACT**

11 The outer parts of deep-water fans, and the basin plains into which they pass, are often described as  
12 areas where erosion is negligible and turbidite systems have net aggradation. Nevertheless  
13 sedimentological and stratigraphic analysis of outer fan lobe and confined basin plain deposits in  
14 Cretaceous-Paleocene Gottero Sandstone (NW of Italy) has revealed extensive but cryptic bedding-  
15 parallel substrate-delamination features at the base of many sheet-like event beds. These comprise  
16 a variety of shallow but wide scour structures showing evidence of lateral expansion by sand-  
17 injection. The scours commonly occur at the base of beds made up of a basal clean sandstone  
18 overlain by argillaceous sandstone containing abundant mudstone clasts and locally large substrate  
19 rafts (up to 20 meters long). These strata are interpreted as a type of hybrid event bed. Field  
20 observations suggest that mud-clast entrainment occurred by delamination at the base of dense  
21 sandy flows. The large rafts, in some cases only partly detached, were incorporated in the flows  
22 locally and then carried for short distances (100s m to a few km) before partly disaggregating and  
23 undergoing deformation due to internal shearing. The development of such features may be

24 common in flat and/or confined basin settings where high-volume flows interact with a cohesive and  
25 well layered substrate (e.g. muddy outer fans or confined or ponded basins with thick mudstone  
26 caps). Delamination is therefore suggested as an alternative mechanism leading to the formation of  
27 hybrid event beds following local substrate entrainment on the basin floor as opposed to on more  
28 remote slopes and at channel-lobe transition zones.

29

## INTRODUCTION

30 Turbidity currents can both erode and deposit as they pass from slope to basin floor. Erosion occurs  
31 mainly along proximal, higher-gradient and more constricted sectors of the flow pathway where  
32 turbidity currents accelerate, bulk up and exert high bed shear stress (Hall et al., 2008; Fildani et al.,  
33 2013). Over time, net erosion can form canyons, channel systems and scour fields that are often well  
34 imaged on the modern sea floor (Pirmez et al., 2000), in seismic time-slices of ancient systems  
35 (Mayall and Stewart, 2000; Fonnesu, 2003; Kolla et al., 2007) and in outcrop (Mutti and Normark,  
36 1987; Brunt and McCaffrey, 2007; Hubbard et al., 2014). Erosion can also occur at gradient breaks  
37 and flow expansion points due to hydraulic jumps, so scour features are often present in channel  
38 lobe transition zones (Mutti and Normark, 1987; Mutti, 1992; Wynn et al., 2002; Van der Merwe et  
39 al., 2014; Hofstra et al., 2016) and proximal lobe settings (Etienne et al., 2012; Burgreen and  
40 Graham, 2014). Although shallow distributive channels can extend distally to the outer parts of some  
41 lobes (Johnson et al., 2001; Beaubouef et al., 2003; Hodgson et al., 2006), lobe fringes and the basin  
42 plain systems with which they interfinger are generally low relief areas dominated by depositional  
43 flows with negligible erosional capacity (Pilkey, 1987). Successions ascribed to these settings are  
44 often characterized by a tabular bedding geometry consistent with little erosion. However, this  
45 inference may be deceptive. The evaluation of erosion based simply on overall bed geometry can be  
46 misleading as the planar bases of turbidites may hide flat or stepped erosion surfaces (Eggenhuisen  
47 et al., 2011). If present, distal erosion could have important implications for the system architecture  
48 (i.e. sea floor levelling and bed compensation, vertical sandstone amalgamation) and for the

49 dynamics of flows on low gradient basin floors (see Eggenhuisen et al., 2010; Eggenhuisen and  
50 McCaffrey, 2012).

51 The study described here demonstrates significant yet cryptic erosion in outer fan lobe and confined  
52 basin plain sheet deposits of the Cretaceous-Paleocene Gottero Sandstone cropping out on Mount  
53 Ramaceto and Mount Zatta (NW Apennines, Italy). These extensive exposures permit high-resolution  
54 bed correlations that identify where substrate has been removed and incorporated into many of the  
55 thicker event beds. In addition, the M. Ramaceto succession is inverted (Casnedi, 1982) and this  
56 means that unusually extensive exposures of bed bases occur on dip slopes where the platform  
57 geometry of basal features can be documented. Both outcrops show an important association  
58 between scours features and sandstone beds with concentrations of mudstone clasts or central  
59 argillaceous and mudclast-rich sandstone divisions resembling hybrid event beds (HEBs; Haughton et  
60 al., 2009).

61 Most models for hybrid event bed formation stress up-dip incorporation of clays and/or mud clasts  
62 that then modify flow behavior through turbulence damping (e.g. Haughton et al., 2003; Talling et  
63 al., 2004; Baas et al., 2009; Sumner et al., 2009;; Talling, 2013). Thus although typically found down  
64 dip in outer fan and basin floor settings, their origin is often sought in the up-dip erosive sector, or  
65 even in the original slope failures (Haughton et al., 2003; Talling , 2013). Little emphasis has been  
66 placed on erosion and entrainment directly from the basin floor (but see Puigdefàbregas et al. 2004;  
67 Talling et al., 2004; Hodgson, 2009; and Muzzi Magalhaes and Tinterri, 2010). In the examples  
68 discussed here, large quantities of substrate mud were locally entrained, forcing partial flow  
69 transformations. There may thus be a class of hybrid event bed in which down-dip flow evolution is  
70 linked to local basin floor rather than up-dip substrate interactions.

71 The study of the Gottero outcrops described below addresses three main questions: i) how is  
72 erosion achieved in what was the outer part of the system? ii) can the erosion be linked to local

73 hybrid event bed development?; and iii) what factors might promote hybrid flow generation in outer  
74 fan and confined basin plain settings?

## 75 **METHODS AND TERMINOLOGY**

76 The study is based on an extensive dataset from the M. Ramaceto and M. Zatta outcrops of the  
77 Cretaceous-Paleocene Gottero system (Fig. 1A). Over 3800 m of measured logs capturing detail at  
78 cm-scale were collected in the two areas along 10 transects. These are used to frame the overall  
79 stratigraphic architecture, the geometry of individual sandbodies and to document the pattern of  
80 erosion beneath individual event beds. In addition, closely spaced (10s m apart) serial vertical logs  
81 and maps of the erosional features on exposed bed bases were acquired for specific beds. A high-  
82 precision Jacob's staff with rotatable laser pointer (Patacci, 2016) was used in conjunction with a  
83 measuring stick to collect accurate thickness measurements. Paleoflow orientations were  
84 determined using a geological compass and corrected for structural dip. Textures of selected beds  
85 have been analyzed using optical microscopy (11 thin sections). Clay content and the framework  
86 mineralogy were quantified petrographically by point counting (500 points per section).

87 The terminology used in this paper is as follows. We use the term event bed to describe the deposit  
88 left by the passage of a single sediment gravity flow (Kneller and McCaffrey, 2003). The term hybrid  
89 event bed refers to the deposits of a flow varying from poorly cohesive and essentially turbulent  
90 through to increasingly cohesive and turbulence-suppressed flow (Haughton et al., 2009). In an  
91 idealized deposit, this is commonly expressed by an upward transition from a basal clean sandstone  
92 via banded sandstone to argillaceous sandstone with common mudstone clasts. Many hybrid event  
93 beds also have a capping, structured sandstone-mudstone couplet emplaced by a turbulent wake.  
94 Recent studies have highlighted significant variability in hybrid event bed make-up including the  
95 texture of the argillaceous sandstone division. This is thought to reflect variable extent of turbulence  
96 damping, different modes of flow partitioning, and deposits that are frozen at different stages in the  
97 transformation process (Baas et al., 2009; 2011; Kane and Pontén, 2012; Patacci et al. 2014; Fonesu

98 et al., 2015). Hybrid event beds can thus span a range of bed expressions and inferred flow  
99 processes but the common factor is evidence for flow transformation driven by incorporation or  
100 segregation of clay and/or mud clasts. This may involve turbulent fractionation of mud clasts and  
101 other grains (e.g. mica flakes and organic matter) but also includes substrate clasts entrained in the  
102 base of flows that then are carried in a shearing boundary layer. A complete spectrum is recognized  
103 from mud clasts buried by sand rapidly falling out of suspension (mudstone clast-rich turbidites),  
104 through mud clasts that are carried in traction to concentrations of mud clasts and sand that travel  
105 and arrest *en-masse* (e.g. Patacci et al. 2014). Herein mud/mudstone clast refers to equant cm to m-  
106 scale pieces of substrate entrained in the flows; raft refers to large substrate slabs with long axes  
107 much greater than the bed thickness (2-20 m); mud/mudstone chips refer to mm-scale fragments.

108 The study focuses on the outer parts of the Gottero system spanning both outer fan lobe and  
109 confined basin plain settings. Many deep-water settings comprise fan systems characterized by  
110 distributive channels and terminal lobes that pass down slope into lateral equivalent basin plain  
111 sheet systems (Mutti, 1977; Mutti and Johns, 1978; Mutti and Normark, 1987; Piper and Normark,  
112 2001, Remacha et al., 2005; Mutti et al., 2009; Pickering and Hiscott, 2015). The former are  
113 dominated by lobes, tongue-shaped deposits made up of offset compensationally-stacked lobe  
114 elements (Mutti and Sonnino, 1981; Pr elat et al. 2009) producing variable but commonly organized  
115 vertical bed thickness trends including but not restricted to thickening upwards cycles (Pr elat and  
116 Hodgson, 2013). Although they are sheet-like over 100s of m, the lobe elements taper and  
117 compensate at longer length scales. Outer fan lobe refers to the down-dip extension of the lobes  
118 (see Mutti and Normark, 1987) where beds are thinner, finer grained and less commonly  
119 amalgamated compared to more proximal counterparts. Basin plain sheet systems are characterized  
120 by laterally-extensive sheet-like beds that extend many kilometers with minimal change in thickness  
121 and poor vertical organization at m to of 10s m scales. Although basin plains are commonly mud-  
122 prone, those developed in confined and tectonically active settings are generally sandier (Pickering  
123 and Hiscott, 2015), with thick mud (-stone) caps to sand (-stone) beds developed where flows are

124 ponded (Mutti and Johns, 1978; Remacha et al., 2005; Mutti et al., 2009). Fan-attached basin plain  
125 sheet systems commonly have abundant thin-beds emplaced by flows that deposited most of their  
126 load on up-current lobes, but also important coarser and thicker event beds left by exceptionally  
127 large flows that bypassed the up-slope lobe region and deposited mainly on the adjacent basin plain  
128 (Piper and Normark, 2001; Remacha et al., 2005).

## 129 **GOTTERO SYSTEM GEOLOGICAL SETTING**

130 The Gottero Sandstone crops out discontinuously along the eastern Ligurian coast and immediately  
131 inland in the Ligurian Apennines between Genova and Carrara, in north-western Italy (Fig. 1A). It  
132 represents a deep-sea fan and related basin plain sheet system (Nilsen and Abbate, 1984) of  
133 Maastrichtian to Early Paleocene age (Monechi and Treves, 1984) that developed during  
134 convergence between Europe and Adria when sand was supplied to a trench developed in front of  
135 the growing Alpine accretionary prism (Marroni et al., 2004). The sand was sourced from Hercynian  
136 granites and associated metamorphic rocks of the Corsica-Sardinia massif, with sediment transport  
137 from south to the north and northeast (Parea, 1965; Nilsen and Abbate, 1984) consistent with  
138 paleoflow data collected during the present study (Fig. 1A). The Gottero system overlies Jurassic  
139 ophiolitic crust (Bortolotti and Passerini, 1970) and a Valanginian-Santonian basinal sequence  
140 comprising the Diaspri Shale, Calpionella Limestone, Palombini Shale and Lavagna Slates that formed  
141 in the Ligurian-Piedemont Sea (Fig. 1B). It is unconformably overlain by the early Paleocene Giaiette  
142 Shales (Passerini and Pirini, 1964) which constitute a large (>300 m thick) chaotic unit (mass  
143 transport complex; MTC) interpreted as the collapse of the accretionary wedge (Marroni and  
144 Pandolfi, 2001). The Gottero Sandstone and the Ligurian sequence were subsequently extensively  
145 deformed during the Eocene and Oligocene becoming one of several allochthonous units within the  
146 *Internal Liguridi* of the Northern Apennines (Gottero Unit - Abbate and Sagri, 1970).

147 Proximal-to-distal facies associations and lateral grain-size trends are developed in the Gottero  
148 system (Fig. 1A; Nilsen and Abbate, 1984). The lack of continuous exposures precludes precise

149 correlation of individual stratigraphic elements but the Gottero Sandstone itself and the enclosing  
150 stratigraphic units can be consistently mapped across the area (Marini, 1992). The more proximal  
151 system (inner fan) is located in the SW sector of the basin and is characterized by fine-grained slope  
152 deposits and pebbly to coarse sand grade channel fills, interpreted as part of the feeder system. The  
153 intermediate area (mid-fan) crops out mostly along the Ligurian coast and is dominated by thick  
154 coarse to very coarse grained amalgamated sandstone lobes overlain by a sequence of thinner lobe  
155 packages separated by intervening mudstone deposits. The distal part of the system ('outer fan' of  
156 Nilsen and Abbate, 1984) and focus of this study, is located to the north and west and is  
157 characterized by lobe stacks and a thick succession of laterally extensive sheet-like event beds  
158 (Casnedi, 1982; Nilsen and Abbate, 1984).

### 159 *Distal Gottero succession*

160 The north-western and distal sector of the system crops out in the M. Ramaceto and M. Zatta areas  
161 (at least 50 km away from the up-dip feeder channels without taking account of tectonic shortening;  
162 Nilsen and Abbate, 1984). The two distal sections may represent separate depocenters (Marini,  
163 1992; 1995) with a maximum thickness of 1075 m on M. Ramaceto (Fig. 1B). The two successions  
164 reveal that the Gottero system commenced with a rapid progradational or growth trend from thin-  
165 bedded basin plain and fan fringe deposits to proximal amalgamated sandstone lobes. In the M.  
166 Zatta area the succession continued with a stack of outer fan lobes characterized by thick and coarse  
167 grained sandstone beds and mudstone clast-rich hybrid event beds (32% of the beds > 30 cm thick  
168 are of hybrid character; 103 HEBs in total). In the M. Ramaceteo area, the upper Gottero succession  
169 is characterized by a monotonous stack of thick, relatively coarse grained and tabular sandy beds  
170 (i.e. sheets) with a high percentage of mudstone clast-rich hybrid event beds (58 % of the beds > 30  
171 cm thick; 125 HEBs in total) alternating with thin fine-grained and laminated beds. Individual beds  
172 can be traced in the field for up to a kilometer normal to paleoflow and up to 4 km down-dip  
173 without significant thickness changes but with a high degree of internal facies variability in the case



174 of the hybrid event beds (Fig. 2; Fonnesu et al., 2015). In both areas, the non-hybrid thick event beds  
175 are composed of un-structured to weakly laminated coarse to medium grained sandstone grading  
176 into laminated and/or current rippled fine-grained sandstone to siltstone at the top. These are  
177 interpreted as deposits of high-density turbidity currents. Centimeter-size mudstone clasts are often  
178 present and typically clustered in the uppermost unstructured bed portion (see Fonnesu et al.,  
179 2015). Mudstone clast-rich facies are commonly observed in beds that can be correlated downdip or  
180 laterally to hybrid event beds and therefore are considered to be genetically related to them.  
181 Repetition of structured and unstructured sandstone, wavy sinusoidal laminations and silty caps with  
182 pseudonodules in the uppermost part of both hybrid beds and turbidites are common and  
183 interpreted to represent the effect of deflection or ponding of the dilute parts of the flow (Pickering  
184 and Hiscott, 1985; Remacha et al., 2005; Haughton et al., 2001; Patacci et al., 2015). The overall  
185 thickness of individual event beds and their associated mudstone caps tends to increase upwards in  
186 M. Ramaceto section, together with increasingly common structures indicative of flow deflection or  
187 ponding. This is interpreted to record a change to a higher degree of basin confinement (Sinclair and  
188 Tomasso, 2002) due to the on-going Alpine collision and growth of intrabasinal relief that helped to  
189 isolate parts of the trench (i.e. Bracco relief of Elter and Raggi, 1965). A change in the composition of  
190 some sandstone beds towards the top of the succession, with an increase of ophiolite-derived  
191 material (Pandolfi, 1997), is consistent with increasing down-dip confinement by a rising  
192 accretionary complex. Although the relationship between the distal outcrops and the down-dip  
193 basin margin is not preserved, the aggrading sheet-like geometry of the thick and laterally  
194 continuous event beds are consistent with a confined basin plain setting in which the deposits of the  
195 largest volume flows were trapped.

## EROSIONAL AND DELAMINATION FEATURES AT BED BASES

196

197 Many of the beds comprising the distal portion of the Gottero system have extensive but often  
198 cryptic erosional bases that are revealed in inverted exposures of bed soles and by detailed km-  
199 range correlations that identify where substrate is missing beneath event beds.

200

### *Planform and 3D geometry*

201 A number of beds in the distal Gottero succession have bases characterized by multiphase erosional  
202 features expressed at a range of scales, although their recognition is usually difficult in sections  
203 normal to bedding. It is therefore likely that the occurrence of these features is routinely  
204 overlooked. Their geometry is especially evident in plan-view on the inverted base of Bed 14 in the  
205 M. Ramaceto outcrop (Fig. 3). Bed 14 is a 2.3 m thick tripartite bed (or hybrid event bed *sensu*  
206 Haughton et al., 2009 and see earlier) made up of: i) a graded basal, very coarse to medium grade,  
207 generally unstructured and relatively clean sandstone (10% average of dispersed clay) with isolated  
208 floating mudstone clasts that are more abundant at the top of this division. Occasional sheet and  
209 dish dewatering features are observed. ii) A central chaotic mudstone clast-rich (clasts up to 25 cm in  
210 size) muddy sandstone with a dispersed clay volume of about 20% increasing towards the top; and  
211 an upper division iii) of graded fine to very fine sand to silt grade with parallel lamination developed  
212 in the sandstone. The event bed has an overall tabular geometry with minimal thickness changes  
213 when traced along the M. Ramaceto exposure for more than 3 km in the direction of the palaeoflow  
214 and about 1 km across strike. Bed 14 was deposited above a 3.20 m thick mudstone interval  
215 including abundant scattered diagenetic carbonate nodules ("Septarie level" of Andri and Zavatleri,  
216 1990). This is overlain by a 0.05 m thick limestone bed and then by a 0.25 m thick mudstone interval.  
217 The thin limestone bed has been used as a datum in order to quantify the minimum amount of  
218 erosion that took place beneath Bed 14.

219 The bed base is made up of a terraced surface reflecting three levels of substrate erosion (Fig. 4A).

220 These are developed on bedding-parallel surfaces at c. 25, 19 and 12 cm respectively above the

221 limestone datum. The shallowest level (Tier 1) is covered by small-scale grooves, minor flutes and  
222 rare prod marks. Sole structures are densely spaced and uniformly distributed across the entire  
223 surface and aligned along an average 295° N paleoflow orientation with a very small dispersion (Fig.  
224 4B). The sole marks on the first surface are clearly cross-cut by deeper elongated scour features (Fig.  
225 4C, 4D) that coalesced to excavate the sea floor in patches down to a mid-level bedding-parallel  
226 surface (Tier 2). Individual Tier 2 scours are 0.4 to 1.5 m across and 1 to 5 m long and have distinctive  
227 asymmetric edges in flow transverse cross-sections, generally with step-like and wing-like edges (Fig.  
228 4E). Mudstone pieces in the act of being detached from the muddy substrate are often found  
229 beneath the undercut scour margins (Fig. 4F). When the elongated scour features have fallen away  
230 from the outcrop it is possible to observe the internal sandstone fill which includes a surface with a  
231 prominent lineation oriented orthogonal to the axis of elongation of the scour (Fig. 4G). The surface  
232 is present in the sand 4-5 cm above the Tier 1 surface (having rotated the bed back to its original  
233 orientation) but it plunges down into the Tier 2 scours where it is at the level of Tier 1. The main  
234 orientation of Tier 2 scour features is similar to those on Tier 1 (mean orientation 298° N based on  
235 scour edges) but with a slightly higher dispersion. Sparse grooves are present on the Tier 2 surface  
236 but are much less abundant than on the first level. The Tier 2 surface is further incised by the  
237 deepest scours (Tier 3). They are the smallest scour features (10s cm wide), filled with the coarsest  
238 sediment (very coarse sand) and are patchily distributed along the outcrop. Their orientation is  
239 similar to the other features (297° N based on their edges) but the dispersion is again slightly larger  
240 than for the Tier 1 and 2 features.

241 Although the full extent of the scour field cannot be determined due to the limited dimension of the  
242 outcrop, the composite erosional feature is at least 150 m wide and 40 m long. When traced down  
243 current, individual (Tier 2) scours coalesce and form a compound erosion surface in the central part  
244 of the outcrop; towards the top of the outcrop and further downstream, the scours become more  
245 isolated again (Fig. 3C), suggesting the full length of the scour feature is unlikely to be much greater  
246 than the 40 meters observed.

247 *Erosional features inferred from detailed bed-to-bed correlations*

248 Several 0.5 to 2 m deep and 100s m wide erosional features can be constrained at bed bases by the  
249 detailed bed-to-bed correlations along the M. Ramaceto outcrop (Fig. 5). The minimum amount of  
250 substrate erosion can be inferred where at least part of the removed stratigraphic succession is  
251 preserved in-situ laterally. It can be more confidently estimated where a thin-bedded sequence is  
252 deposited just beneath the bed (rather than a thick mudstone interval) allowing progressive removal  
253 of stratigraphy to be tracked as the erosion surface steps down through these layers. The surface  
254 between a thin-bedded package and a thick mudstone interval below often acts as the preferred  
255 surface along which deeply-eroded sectors extend flat for several hundred meters before stepping  
256 up again. Sites where the erosion process is arrested in progress are only rarely observed. A  
257 revealing example is seen at the base of an outer fan lobe from the lower part of the M. Zatta  
258 succession (Fig. 6). This shows the lateral juxtaposition of a sandy event bed and a 1.1 m thick  
259 interval of laminated mudstones and thin beds in a section mostly at a high angle to paleoflow  
260 direction. A coarse-grained sandstone sill a few centimeters thick extends from the base of the  
261 sandstone bed along the boundary between the thin-bedded package and the homogenous  
262 mudstone cap to an earlier event bed.

263 The event beds that were deposited above some of the deepest substrate erosion features are  
264 typically very thick (2.5 m to 6 m thick) tripartite hybrid event beds with a chaotic and mud-rich  
265 central division sandwiched between lower structureless or weakly graded, clean coarse-grained  
266 sandstone and upper normally graded fine-grained sandstone to siltstone with parallel lamination  
267 and/or a rippled top. The chaotic divisions can have a variety of complex textures but in many cases  
268 are dominated by large rafts (up to 20 m across in some cases, but commonly of meter scale)  
269 surrounded by injected coarse-grained sandstone coming from the basal sandy division or by a  
270 mudstone clast-rich sand-mud mixture (typically containing ~18-20% dispersed clay). The rafts may  
271 be composed exclusively of mudstone, or they may comprise pieces of thin-bedded stratigraphy,

272 sometimes still in a bedding-parallel orientation but in other cases intensely folded or partly  
273 distended in pinch-and-swell structures (Fig. 7). The presence of intact or deformed thin-bedded  
274 rafts is typical of event beds that have a similar *in-situ* thin-bedded section beneath them  
275 somewhere along the bed correlation (Fig. 5; Fig. 7B-C). Where hybrid event beds directly overlie a  
276 thick mudstone interval without thin beds, the rafts are only made of mudstone (Fig. 7A). When the  
277 larger rafts are present they often plough into the basal sand and extensively modify the previously  
278 just deposited sand (Fonnesu et al., 2015). The area of raft accumulation often corresponds spatially  
279 to the sector with the deepest substrate erosion beneath the bed (Beds 8, 15.4 and 17.3 of Fig. 5).

## 280 **INTERPRETATION OF EROSIONAL AND DEPOSITIONAL FEATURES**

281 The various erosive features (10s to 100s of cm deep) observed in the distal Gottero show similar  
282 geometrical relationships between deposit and substrate, comprising: i) sill-like sandstone  
283 extensions lateral to basal scours; ii) step-like lateral margins of scour features, and iii) flat and bed-  
284 parallel scoured surfaces. Therefore they can be interpreted as the result of the same kind of  
285 substrate interaction processes either frozen at different stages or variably expressed on account of  
286 different flow characteristics or position in relation to the zone of scouring. The absence anywhere  
287 along the bed base of a mud-draped erosion surface (mud-draped scours *sensu* Mutti and Normark,  
288 1987) and the repeated association between scouring and the thicker mudstone clast-charged event  
289 beds suggest the scours were produced by the frontal part of the same gravity flow which deposited  
290 the overlying bed.

### 291 *Mudstone clast and raft-bearing hybrid event beds*

292 The beds overlying the scour features are interpreted to be hybrid event beds, namely complex beds  
293 made of a basal relatively clean sandstone deposited by turbiditic processes (hindered settling, basal  
294 near-bed high concentration layers and locally traction carpets) overlain by a muddy-sandstone with  
295 mudstone clasts and rafts interpreted as a debris flow or shearing low-strength bed layer (i.e. not

296 simply a mudstone clast-rich turbidite). The event beds are completed by a fine-grained graded and  
297 laminated sandstone to mudstone couplet emplaced by the wake of the current which was again  
298 more turbulent (Haughton et al., 2009; Fonesu et al., 2015). As highlighted above, the size of the  
299 entrained mudstone clasts centrally in the bed ranges widely from 5 to 25 cm across (Bed 14), to the  
300 large mudstone rafts (2 meters up to 20 meters long) and pieces of folded thin-bed stratigraphy  
301 contained in beds 5, 8, 15.4 and 17.3 (Fig. 5) which are surrounded by a mixture of sand and mud.

302 The presence in the examples discussed of abundant large mudstone clasts including very large rafts  
303 resembling the immediate substrate preserved beneath less erosional parts of the event bed  
304 suggests that in this case the entrainment happened following very local substrate erosion. As the  
305 large substrate rafts are unlikely to have been carried in suspension, they are interpreted to have  
306 collected near the bed following entrainment (Postma et al., 1988) and been driven for a relatively  
307 short distance down flow within a shearing near-bed layer. Similar beds containing chaotic textures  
308 at their base and interpreted to be related to the impact of dense turbidity currents upon a muddy  
309 seafloor were described by Marschalko (1970) and Mutti and Normark, (1987). During transport, the  
310 clasts were partly deformed and auto-injected by the matrix, in some cases spalling off smaller mud  
311 flakes. The mud clast-rich part of the flow locally had sufficient energy to plough into the underlying  
312 just deposited sand, accounting for the variable preservation of clean sandstone beneath it. These  
313 beds were hence likely deposited by high-volume and catastrophic flows just after rapid substrate  
314 entrainment without long-distance longitudinal flow transformation. The flows probably bypassed  
315 the up-dip lobe region and just deposited on the confined basin plain (e.g. Mutti and Johns, 1978;  
316 Remacha et al., 2005). The resulting hybrid event beds are texturally different (modest clay contents  
317 and more abundant mudstone clasts) compared to the finer grained, usually mudstone clast-poor  
318 (or with smaller mud chips) and better mixed sand-mud textures in hybrid event beds in unconfined  
319 lobe systems elsewhere, such as parts of the Ross Formation (Pyles and Jennette, 2009), the Karoo  
320 Fan in the Tanqua depocenter (Hodgson, 2009) or Paleogene Wilcox Fm. (Kane and Pontén, 2012).

321

### *Delamination features*

322 Understanding the erosional/bypass phase of a flow is challenging as there is often limited  
323 associated deposition and the final erosional features that remain are composite and reveal little of  
324 how they initiated and grew (Stevenson et al., 2015). Different models have been proposed for the  
325 detachment of substrate beneath highly energetic turbulent flow phases by delamination (“hydraulic  
326 jacking” of Pickering and Corregiador, 2005; Puigdefàbregas et al., 2004; Eggenhuisen et al., 2011) or  
327 by shearing of scour edges within a mobile aggrading bed (Butler and Tavernelli, 2006; Clark and  
328 Stanbrook, 2001; Eggenhuisen et al., 2011). In the Gottero examples, the scour features have a  
329 complex asymmetric cross-sectional geometry (across flow) with wings of protruding sand extending  
330 into the substrate, forming detachment zones. Injections are generally coarse to very coarse-grained  
331 with a grain size similar to at the base of the event bed. These are interpreted as syn-depositional  
332 sand-injections. A post-depositional origin is considered unlikely as the top of the bed is never cross-  
333 cut by the injections (cf. Eggenhuisen et al., 2011). Moreover, the absence of deformation features  
334 in the underlying substrate or systematic rotation of mudstone clasts, exclude “shear in a mobile-  
335 aggrading substrate” (cf. Butler et al., 2016) as the active process in substrate delamination. Thus  
336 erosion by hydraulic jacking is the preferred model. The scour and associated injection features are  
337 very similar to those described by Eggenhuisen et al. (2010; 2011) from the Miocene Macigno  
338 Formation (NW Apennines, Italy) and the Champsaur Basin (SE France). Interestingly, the onset of  
339 the scouring and the incision of the grooves found in the Gottero case is the reverse of the  
340 relationship described by Eggenhuisen et al. (2010), with the grooves on Tier 1 in the Gottero Bed 14  
341 pre-dating the scours that then excavated down to Tier 2. In the Champsaur and Macigno cases  
342 deeper scours were interpreted to cut first and then grooves ornamented the erosion surface.

343 The absence of bypass features such as abrupt grain-size breaks or large-scale cross-bedding (cf.  
344 Mutti, 1977; 1992; Stevenson et al., 2015) in any of the distal Gottero event beds suggests the multi-  
345 stage scours were produced during a single event (i.e. multiple scouring flows are unlikely to have

346 completely bypassed the area prior to sand deposition). The Gottero flows were strongly  
347 depositional and even the substrate entrainment overlapped with just deposited sand injected  
348 and/or drawn into bedding-parallel fractures beneath detaching clasts or rafts. The presence of  
349 grooves and flutes at bed bases (as in the case of Tier 1, Bed 14 – Fig. 4A) implies initial passage of a  
350 turbulent section of a current that was able to remove a superficial soft muddy layer and fashion  
351 sole structures in the more indurated substrate beneath (Fig. 8). The initial shallow grooves can be  
352 interpreted as produced by vortices in the flow head (Allen, 1982) and/or by the traction of mud  
353 clasts and early diagenetic nodules (*septarie* nodules). Where the grooves were formed as tool  
354 marks, they may have formed beneath an already more dense and stratified basal part of the flow in  
355 which the clasts and nodules were embedded. During the following phase, deeper scours were  
356 incised excavating the substrate and the just formed grooved surface. The lineated surface with a  
357 fabric orthogonal to the paleoflow indicates internal uncoupling and flowage of the just deposited  
358 sand close to the bed to the sites of injection. This suggests that following initial scour formation, the  
359 substrate was not wholly excavated and removed by the by-passing head of the flow. Instead, the  
360 head produced flow-parallel erosive steps that were then expanded by a process of lateral sand  
361 injection and delamination. The substrate was already partly covered by just deposited sand or by a  
362 dense sand-flow with liquefaction, when lateral pressure gradients drove intrusive sand into the  
363 substrate exploiting mechanical heterogeneities in the underlying stratigraphy (see Puigdefàbregas  
364 et al. 2004). Commonly, these injections were emplaced along the contact between stacked thin  
365 beds and an underlying thick mudstone cap to an earlier event bed. The interface along which the  
366 sand injections intruded then acted as a detachment plane. Additional sand may have been drawn  
367 into detachment zones as the substrate rafts were rotated and released up into the flow where they  
368 collected and were carried down flow *en-masse*. Groove casts on the Tier 2 surface indicate that the  
369 flow was still sweeping the bed at this stage.



## DISCUSSION

### *Scour initiation mechanisms*

372 The presence of irregular seafloor topography was probably a prerequisite for injection-related  
373 delamination. Erosive steps would have focused lateral dynamic pressure venting of sand and water.  
374 Injection-related delamination features and related hybrid-like event beds have been observed  
375 onlapping or close to confining slopes in the Gres d'Annot by Puigdefàbregas et al. (2004). These  
376 authors describe sub-horizontal sand injections that delaminated earlier deposits forming chaotic  
377 bed divisions. In this case, delamination was related to the load and tangential stress of dense flows  
378 meeting a steep (c. 10°) counter slope. Although the distal Gottero Sandstone shows evidence of  
379 increasing confinement, an obvious confining slope is not preserved and there are no coherent  
380 spatial trends in terms of the abundance of delamination features with proximity to where the  
381 inferred confinement lay (to the NE). The layer-cake stratigraphy constrained by the bed-to-bed  
382 correlations in the M. Ramaceto section excludes the presence of significant pre-existing  
383 irregularities on the sea floor.

384 Irregularities in the substrate were therefore most likely produced by the flow itself in the form of  
385 the initial erosive scours which were then expanded by lateral injection and clast detachment. In  
386 some cases, the scour depth must have been of the order of the eventual bed itself, as in the case in  
387 example from M. Zatta (Fig. 6). The question then is how such erosion could be present in both outer  
388 fan lobes (M. Zatta) and confined basin plain (M. Ramaceto) settings with likely negligible axial  
389 gradients. Baas et al. (2009; 2011) and Sumner et al. (2009) suggested on the basis of experiments  
390 with clay-sand mixtures in open channels that a combination of high suspended-clay concentrations  
391 and rapid flow deceleration can produce a change from turbulent to transitional flow behavior. This  
392 model predicts that during the early stages of turbulence modification, the near-bed turbulence can  
393 actually increase before being damped as the flow decelerates. Transient turbulence enhancement  
394 might explain the presence of significant distal erosion. Thick mudstone caps on many of the larger

395 event beds imply the flows carried significant clay which is preserved on top of the beds due to the  
396 inferred ponded basin geometry. As the flows decelerated on low gradients having traversed the  
397 higher gradient fan system up dip, turbulence may have been enhanced under transitional flow  
398 conditions (Baas et al., 2009), triggering scouring and then delamination (Fig. 9A). Increasing  
399 stratification and turbulence modulation longitudinally along the flow might explain the tiering  
400 associated with progressively deeper downward excavation of scour surfaces prior to the onset of  
401 deposition.

402 An alternative or contributory explanation for the initial bed topography that seeded the injection  
403 and delamination process could relate to the structure of high-concentration and high-volume flows  
404 and the character of the substrate over which they advanced. Arrival of the flow front would induce  
405 a significant change in ambient pressure (Eggenhuisen and McCaffrey, 2012) that could deform a  
406 cohesive substrate before it was overrun by the body of the flow, causing fractures to open. Once  
407 the body arrived, higher fluid pressures would then force sand downwards into the fracture network  
408 which would expand laterally exploiting planes of weakness in the layered substrate, leading to  
409 delamination and the growth of large erosive patches (Fig. 9B). The presence of a strongly layered  
410 sheet system including extensive thick mudstone caps to beds may have promoted expansion by  
411 delamination. Part of the flow may even have dived below the seabed uplifting entire portions of  
412 compact stratigraphy (cf. *intra-bed turbidites* of Baas et al., 2014 but here exploiting a fractured  
413 instead of a low-density fluid mud substrate). Substrate rafts and smaller mud clasts were then  
414 detached and segregated in the upper and rearward part of the flow where, if not buried by  
415 deposition, they may have been progressively destroyed by internal shearing (Fonnesu et al., 2015).  
416 The clay released could suppress flow turbulence down-dip (Baas et al., 2009; Haughton et al.,  
417 2009). Repeated pressure oscillations in the flow such as those present at the head-body transition  
418 (Best et al., 2005) and inside the body itself (e.g. large Kelvin-Helmholtz instabilities; Kneller and  
419 Buckee, 2000) could promote multistage injection and delamination accounting for the tiered  
420 structure. Across-flow lateral instability can be enhanced by counter-rotating streamwise vortices

421 (Hall et al., 2008) and this may have favored transverse expansion of initial defects at the expense of  
422 those that were at right angles to flow.

423 Whatever the mechanism triggering release of the clasts and rafts, it seems these were likely carried  
424 *en-masse* relatively short distances away from the site of erosion within an underflow in which the  
425 entrained substrate was broken up as it was injected by the sandy matrix which itself became  
426 progressively more contaminated by dispersed clay and clay chips. The dilute turbulent wake of the  
427 flow then deposited the upper fine-grained laminated sandstone which drapes the irregular top of  
428 the mudstone clast-rich central division (Haughton et al., 2009, Fonesu et al., 2015).

#### 429 *Occurrence of hybrid event beds generated by substrate delamination*

430 Mudstone clast-rich and raft bearing hybrid event beds are common in many deep-water systems in  
431 addition to the reported distal Gottero Sandstone examples (e.g. Marnoso Arenacea, Muzzi  
432 Magalhaes and Tinterri, 2010; Tinterri and Muzzi Magalhaes, 2011; Talling et al., 2012; Ventimiglia  
433 flysch, Marini et al., 2015b; Cilento Flysch, basal Ross Fm., Fonesu et al., 2015; Castagnola Fm.  
434 Southern et al., 2015; Annot Sandstone; Patacci et al., 2014; Laga system; Mutti et al., 1978; Marini  
435 et al., 2015a). In some of them basal delamination features are reported (Puigdefàbregas et al.,  
436 2004, and see Fig. 5 of Southern et al., 2015) but in most cases these features have not been  
437 recognized, probably due to widespread and bed-parallel character of the entrainment meaning  
438 they are only revealed in cases where exceptional outcrop is preserved at km scale sufficient to  
439 allow detailed bed-by-bed correlation. Even in modern settings volumetrically important  
440 delamination in basin floor systems is likely to be overlooked because of immediate compensation  
441 by sediment deposited by the event responsible for the erosion. Nevertheless, many hybrid event  
442 beds in confined basin floor settings could form from large-volume and high-concentration flows by  
443 local delamination and mud entrainment. Thus the clasts may not have travelled very far and this  
444 could explain their local aspect, large size and the low degree of sand-mud mixing in the matrix  
445 surrounding them in comparison to other hybrid event bed types where values of mud content

446 percentage can vary between 25% and 80% (e.g. Sylvester and Lowe, 2004 and Talling et al., 2012). A  
447 local mud source in the basin floor area (in contrast to an up-dip source envisaged in other settings  
448 by Haughton et al., 2009) has the important consequence that the high degree of lateral  
449 heterogeneity in terms of the variable proportion of the basal sandstone and upper muddy  
450 sandstone within this type of hybrid event bed could be directly related to the original scour pattern  
451 (Fonnesu et al., 2015). This means that the main parameters controlling the onset of hybrid flow in  
452 this case are the mechanical properties of the substrate, in addition to the volume, velocity and  
453 concentration of the flow. The stratigraphic pattern composed of a thick sandstone bed, overlain by  
454 a thick mudstone cap and followed by a package of thin-bedded turbidites is common in the Gottero  
455 outcrops (see Fig 2). These three components are likely to be deposited with different fabric and  
456 water content and therefore to have different mechanical properties. The interface between a thick  
457 mudstone cap and the thin-bedded sequence above appears to have behaved as a weak layer,  
458 possibly due to the abrupt transition in mechanical properties from an homogenous medium to one  
459 characterized by strong vertical heterogeneity. The presence of clasts and rafts clearly detached  
460 from the substrate and incorporated into the overriding flow, and the propagation of fractures  
461 infilled by sand to form injectites, suggests that the seafloor mud was cohesive and compact. This  
462 type of firm but mechanically heterogeneous and multi-layered substrate including weak planes and  
463 layers can be particularly prone to be delaminated. A stacking pattern of this type where intervals of  
464 thin-bedded turbidites alternate with thick sandstone-mudstone couplets is characteristic of  
465 confined basin plains developed in rapidly subsiding tectonically-active basins dominated by fine-  
466 grained facies but occasionally filled by outsize sheet-like megabeds (Pilkey, 1987; Mutti and Johns,  
467 1978; Remacha et al., 2005, Pickering and Hiscott, 2015). These settings can have rapid  
468 sedimentation rates but an overall lower number of events in comparison to the more proximal fan  
469 areas (Mutti and Johns, 1978; Mutti, 1992; Remacha et al., 2005), resulting in a lower frequency of  
470 the events and a greater time available for the seafloor mud to dewater and be compacted.

471 Hodgson (2009) documented the common occurrence of mudstone clast-rich hybrid event beds at  
472 the top of interlobe sequences as the first events in overall thickening-upward more proximal lobe  
473 sequences in an unconfined setting (Karoo Basin). The occurrence of these HEBs could also be  
474 interpreted as related to the type of substrate (thick mudstone interlobe intervals) rather than to a  
475 change in gradient related to lobe avulsion. Conditions promoting distal delamination are likely to  
476 include large-volume early lowstand failures that trigger flows which carry sand across previous  
477 highstand mud drapes, and tectonically-triggered failures associated with particularly mobile flows  
478 that penetrate into otherwise fine-grained sectors of the basin floor.

479 Despite the presence of erosion in outer fan and confined basin plain areas, this is unlikely to  
480 contribute to increased sand-on-sand amalgamation and better vertical connectivity. Where  
481 documented so far, delamination develops within the intervening thick mudstones, expanding  
482 laterally rather than excavating vertically, therefore reducing the likelihood of sandstone layers  
483 becoming connected.

484

## CONCLUSIONS

- 485 • Large scour features may be commonplace beneath mudstone clast-rich hybrid event beds  
486 in distal (confined basal plain and outer fan lobe) settings, but can be easily overlooked  
487 without exceptional laterally continuous exposures, and likely are similarly hard to detect in  
488 modern settings, due to associated sediment infill and compensation of erosional  
489 topography.
- 490 • Scours are inferred to start as small erosional features and develop through injection,  
491 hydraulic jacking and delamination processes during later stages of flow evolution under  
492 depositional and highly stratified conditions.
- 493 • Considerable erosion can occur with limited sediment bypass in sheet-like confined basin  
494 plains and outer fan lobes traversed by high-volume flows, in contrast with canyons,

495 channels and channel-lobe-transition environments where flows tend to bypass and  
496 erosional products are carried further down dip.

- 497 • Substrate delamination results in large mud clasts and substrate rafts that are incorporated  
498 into the flow and deposited as part of locally-generated hybrid event beds. It is inferred that  
499 clasts do not travel very far (they are sourced through delamination and do not become  
500 significantly disaggregated) and therefore the pattern of scours might control the  
501 heterogeneity within the intermediate muddy-sandstone division of the bed.
- 502 • Favorable conditions for substrate delamination are low-gradient and mud-rich cohesive  
503 substrates characteristic of outer fan lobe or confined basin plain settings, or other scenarios  
504 where large-volume flows traverse muddy and cohesive basin floors.

505

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511

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729

## FIGURE CAPTIONS

730 **Figure 1.** Geological map of the Gottero turbidite system and summary stratigraphy. A) Simplified  
731 geological and location map of the Gottero system with approximate distribution of main facies  
732 associations and the paleocurrent pattern (modified from Nilsen and Abbate, 1984); the rectangle  
733 outlines the area considered in this study. The black line indicated as “Bracco High” represents the  
734 inferred location of an intra-basinal high and potential external basin boundary (Elter and Raggi,  
735 1965). B) Internal Liguridi basin stratigraphy (modified from Marroni, 1991) with an expanded  
736 section for the Gottero succession in the M. Ramaceto section. The main interpreted sub-  
737 environments and the stratigraphic position of the beds referred to in the text are indicated.



738 **Figure 2.** Architecture of the upper Gottero stratigraphy in the M. Ramaceto section. A) Correlation  
739 panel of the M. Ramaceto succession between beds 11 and 16 (between 188 and 285 m below the  
740 top of the formation), highlighting the tabular geometry and correlativity of individual beds at km-  
741 scale albeit with local erosion into the substrate. Datum plane is the base of a mudstone interval rich  
742 in carbonate nodules (“Septarie level”). B) Panoramic photo of the northern side of the M. Ramaceto  
743 succession, showing measured log locations, the main faults (red lines) and the base of the Giaiette  
744 chaotic unit (Giaiette MTC). The stratigraphic interval between the two white dashed lines  
745 corresponds to the interval shown in the overlying correlation panel; trace of Bed 14 (see Figs. 3 and  
746 4) is highlighted in yellow. Note the succession is overturned. C) Close-up of the highlighted interval  
747 in Fig. 2B showing the sheet-like geometry of the succession in which individual beds can be traced  
748 (note bed amalgamation is very rare).

749 **Figure 3.** Depositional and erosional features of Bed 14 at M. Ramaceto (Outcrop location – Latitude:  
750 44°25'10.80"N; Longitude: 9°18'15.35"E). A) Bed 14 facies stack and outcrop photograph (note the  
751 succession is upside-down due to tectonic folding) at Log C, and relative grain to dispersed clay  
752 (G/M) abundance calculated from thin-section point counting. B) Lateral variability of the mudstone  
753 clast-rich intermediate division of Bed 14 on a 10s to 100s of meters scale. Scours are observed at  
754 most locations. However, the planform geometry can only be characterized where the inverted bed  
755 base forms an extensive dip-slope (3C). Numbers refer to levels of substrate erosion observed (T1,  
756 T2, T3). C) Basal scours planform and close-up of the main outcrop areas showing geometries of the  
757 scour margins.

758 **Figure 4** Basal surface of Bed 14. A) Schematic illustration of the terraced geometry of the scour  
759 surface, the underlying limestone bed is used as a datum; B) Rose diagrams representing the  
760 direction of the overall paleoflow indicators collected on the base of Bed 14 base and subdivided by  
761 tier; C) cross-cutting relationship between Tier 1 grooves and Tier 2 scours on the southern side of  
762 the outcrop; D) three levels of substrate erosion captured in the northern side of the outcrop; E)

763 step-like and wing-like edges of scour features that tend to coalesce and form a compound erosional  
764 surface (2 m laser Jacob's staff for scale); F) Undercut margin associated with mud clast detachment;  
765 G) Lineation fabric oriented perpendicular to the paleoflow in sandstone just above Tier 2 broken  
766 scours. Circled numbers in all parts of the figure refers to the tier level of the surface.

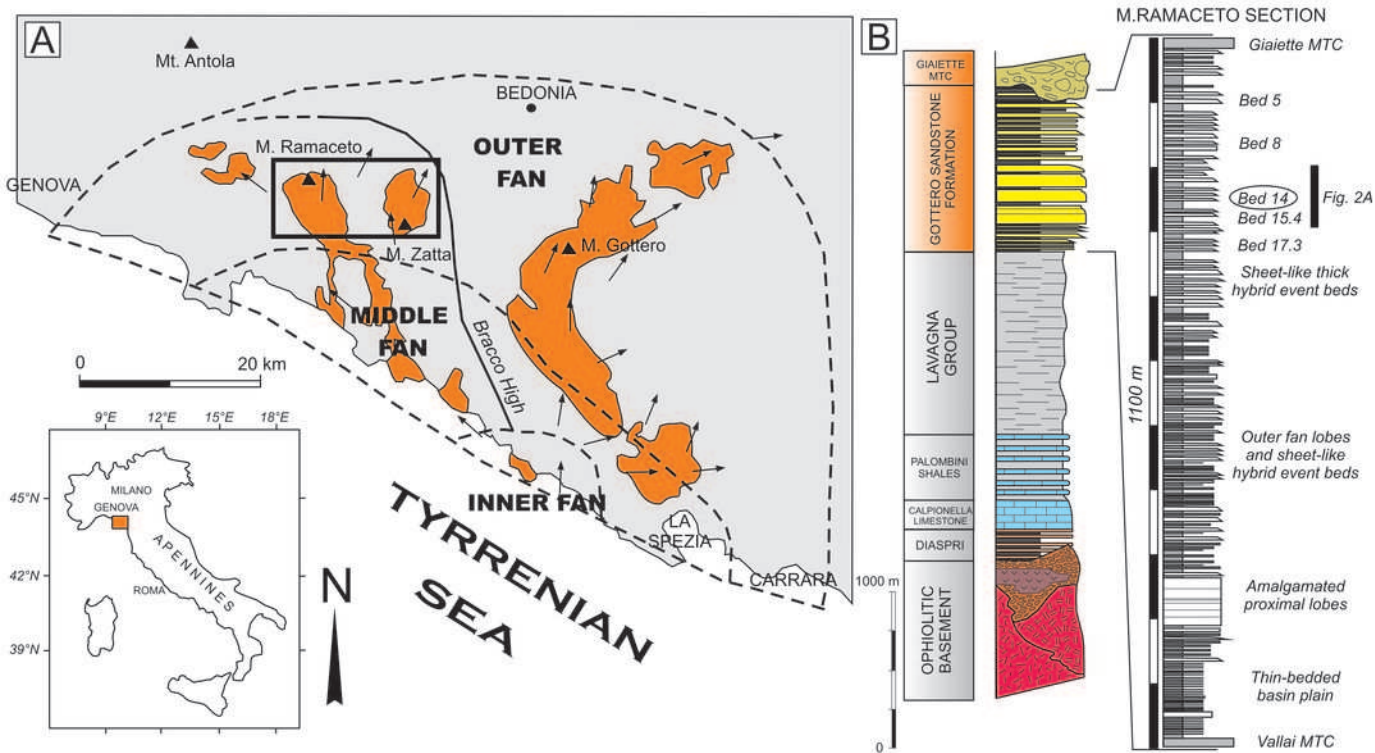
767 **Figure 5.** Event bed correlations in M. Ramaceto area showing differential substrate delamination  
768 using correlated beds beneath as datum planes; the examples are conservative estimates of the  
769 amount of erosion as it cannot be determined whether the erosion surfaces continue to cut up and  
770 down section outside of the correlation panel.

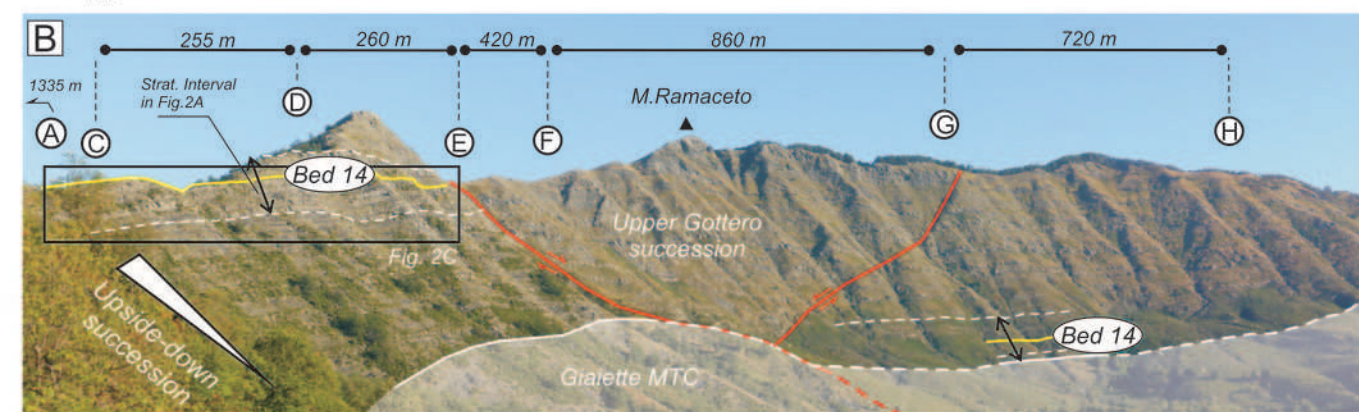
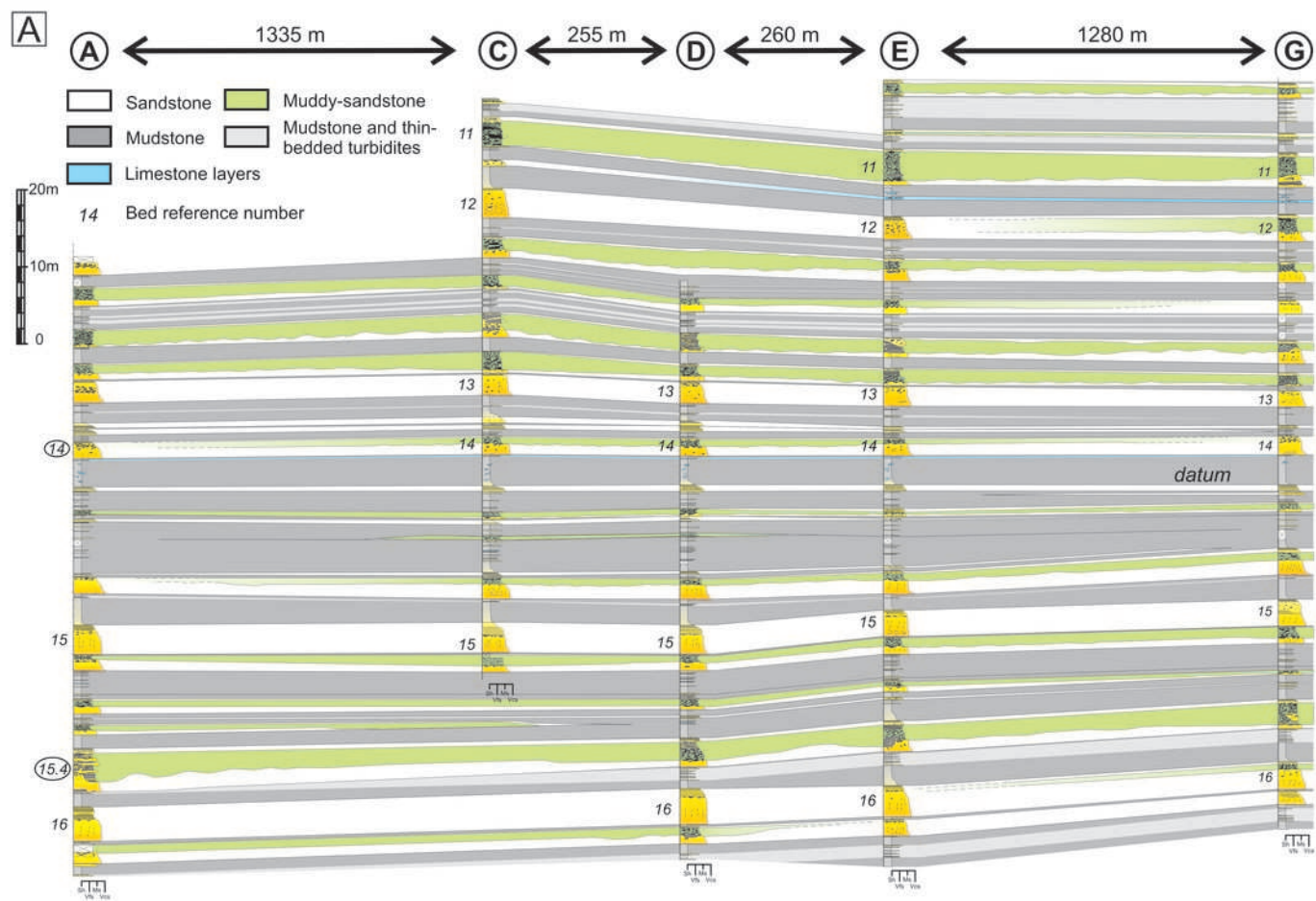
771 **Figure 6.** Delamination process of substrate rafts at the base of an hybrid event bed in M. Zatta area.  
772 A) Detail correlation of a bed sequence in M. Zatta area capturing delamination of 1.1 meters of  
773 thin-bedded stratigraphy (log 8). B) Outcrop view in log 8 location capturing a 20 m length substrate  
774 slab containing thin-bedded interval (a) and lateral extension of an underlying sand injection (b). C)  
775 Close-up of the source of the sand injection and lateral deformation of the substrate in the act of  
776 being detached. D) Detail from log 3, showing texture of mudstone clast-rich dirty sandstone (c) and  
777 shape of substrate clast containing thin-bedded stratigraphy (d) torn from the underlying seafloor  
778 and buried in the bed (40 cm ruler for scale).

779 **Figure 7.** Raft-bearing hybrid event beds and relationship with their substrate. A) Raft-bearing bed  
780 from M. Zatta succession with a 3 m long muddy raft (highlighted by dashed line) containing  
781 scattered limestone nodules, encapsulated in a mudstone clast-rich dirty sandstone and capped by  
782 fine-grained and laminated clean sandstone (arrowed). B) Bed from M. Zatta succession including a  
783 deformed thin-bedded raft resembling the underlying substrate. C) Bed 5 from M. Ramaceto  
784 succession in log E (see Fig. 5) containing a 8 m long substrate raft in which there are thin beds. (*b*:  
785 base of the bed; *t*: top of the bed).

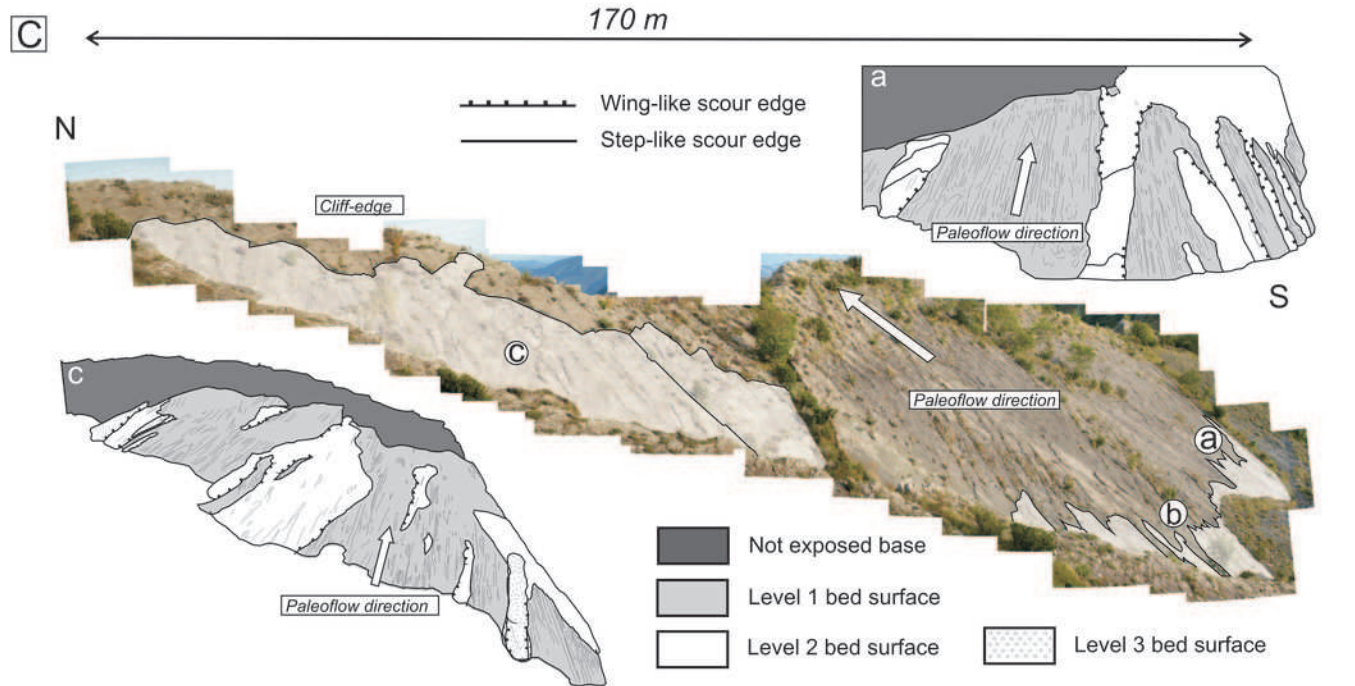
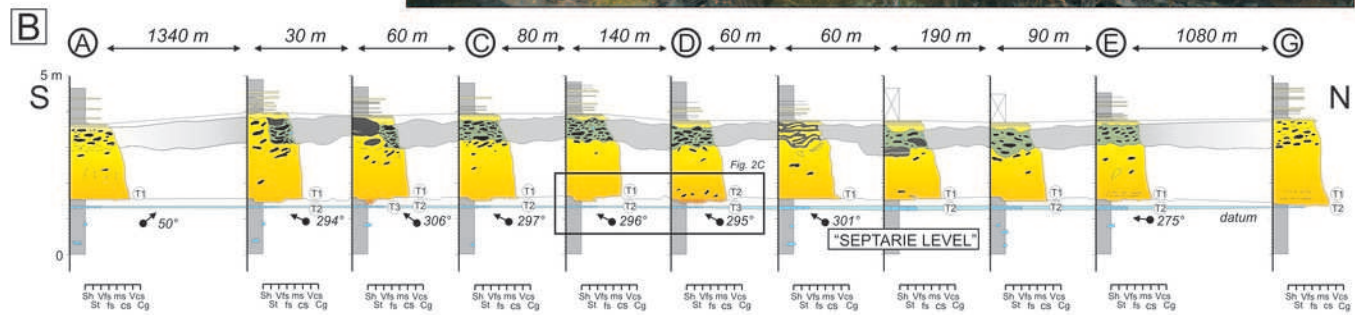
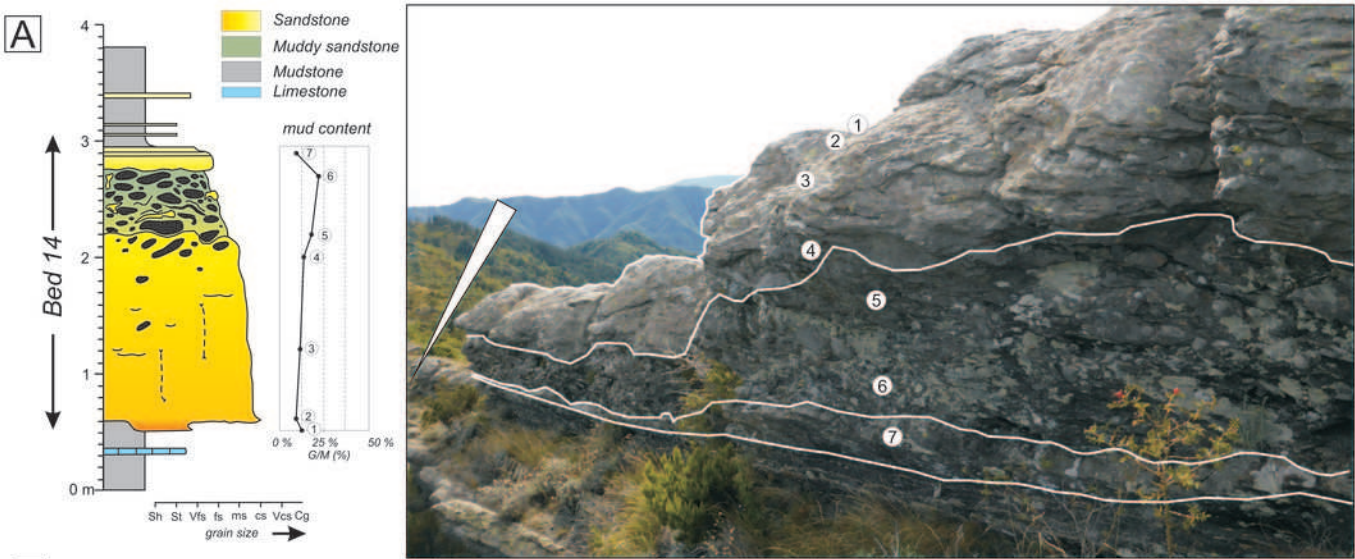
786 **Figure 8.** Phases of flow evolution and interactions with substrate in a strike-view. T1) Flow mostly  
787 bypassing and incising shallow sole structures (grooves and flutes) on sea floor; T2) Incision of  
788 elongated scours; T3) Intrusion of basal sand layer into underlying substrate exploiting weak  
789 interfaces in the thin-bedded package and expanding laterally in a direction perpendicular to  
790 paleoflow, with associated uplift of substrate rafts and mud clasts; T4) Bed aggradation and  
791 deposition of muddy rafts and mud clasts collected via a similar mechanism immediately upstream,  
792 which are in the process of disaggregation following internal shearing and upward sand injections  
793 from the overpressured basal sand. Red curves represent idealized flow concentration profiles.

794 **Figure 9.** Alternative initiation mechanisms for substrate delamination in a section along the  
795 depositional dip. A) Substrate scouring due to enhanced turbulence (see Baas et al., 2009; 2011)  
796 followed by dense flow substrate delamination; B) Substrate weakening and deformation by  
797 oscillating pressure followed by dense flow substrate delamination. Note most of the delamination  
798 occurs in the across flow direction where wing-like scour margins are preferentially preserved (see  
799 Fig. 8). HDF: high-density flow; LDF: low-density flow.

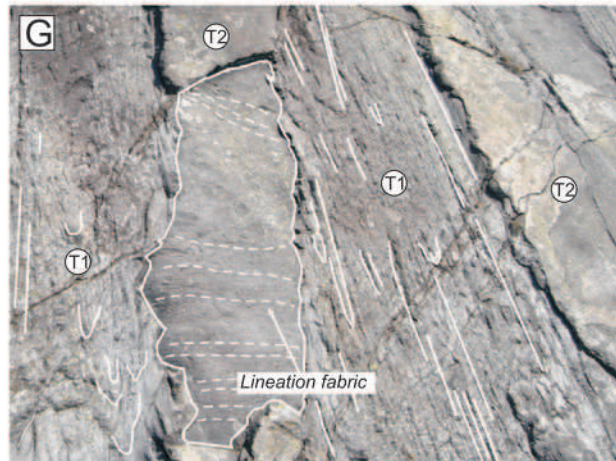
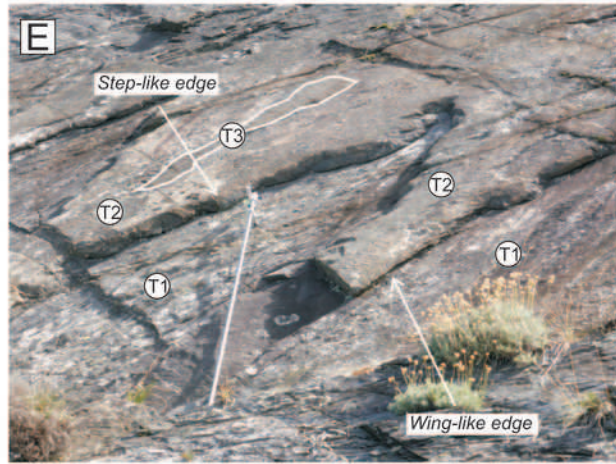
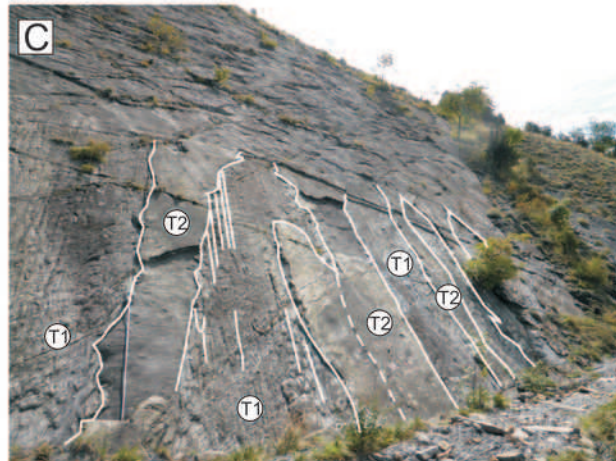
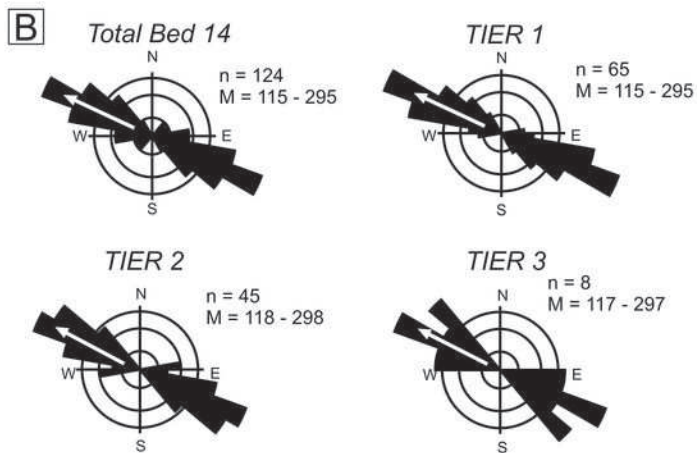
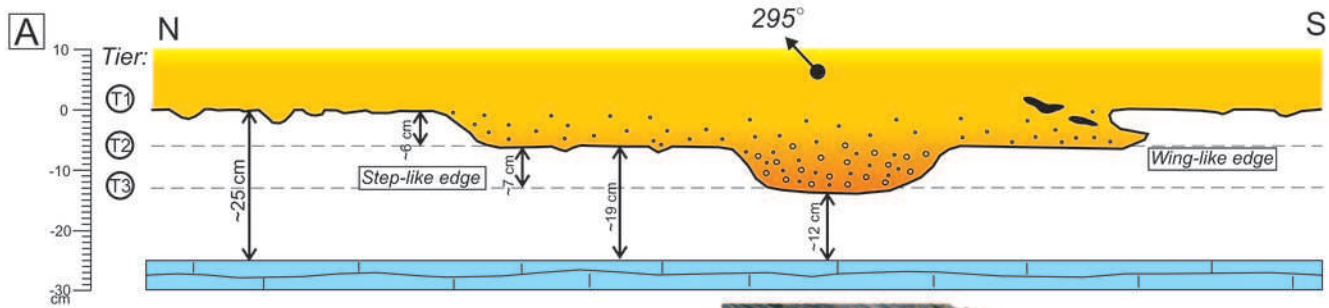












S

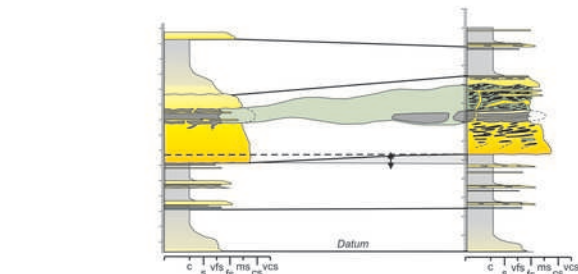
DOWNFLOW

N

**Bed 5**

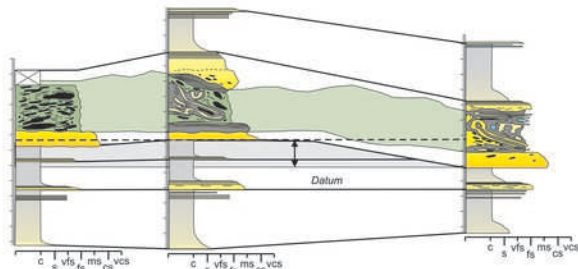
Observed max.  
substrate removed:  
50 cm

Average bed thick.:  
513 cm

**Bed 8**

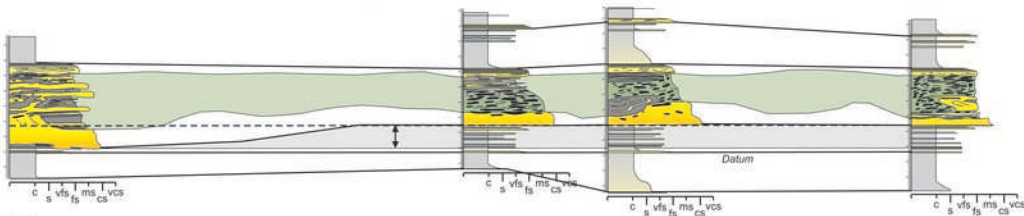
Observed max.  
substrate removed:  
180 cm

Average bed thick.:  
488 cm

**Bed 15.4**

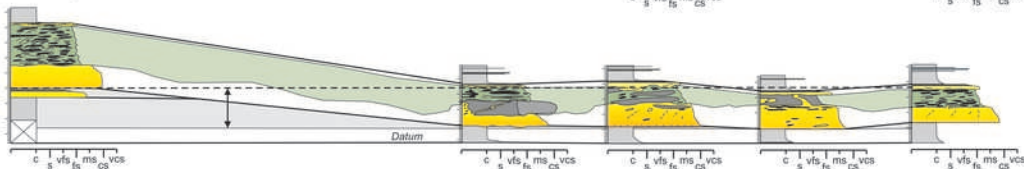
Observed max.  
substrate removed:  
145 cm

Average bed thick.:  
425 cm

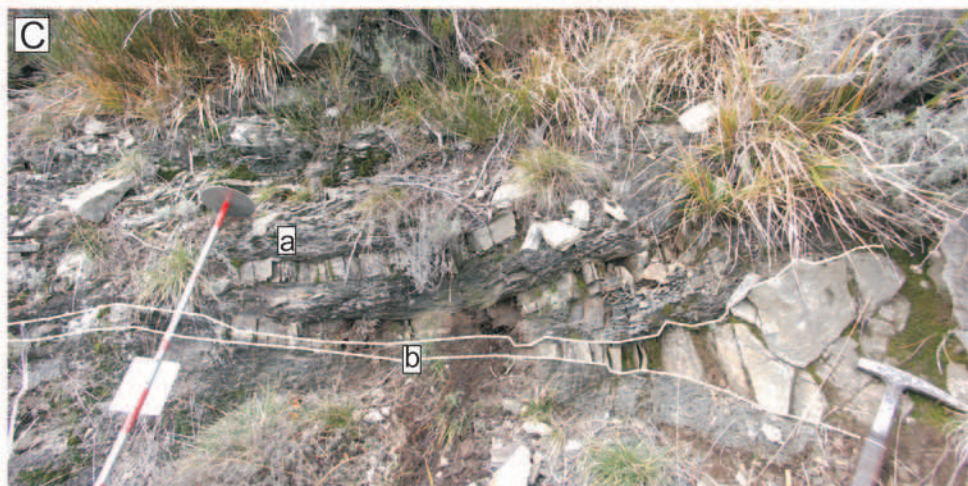
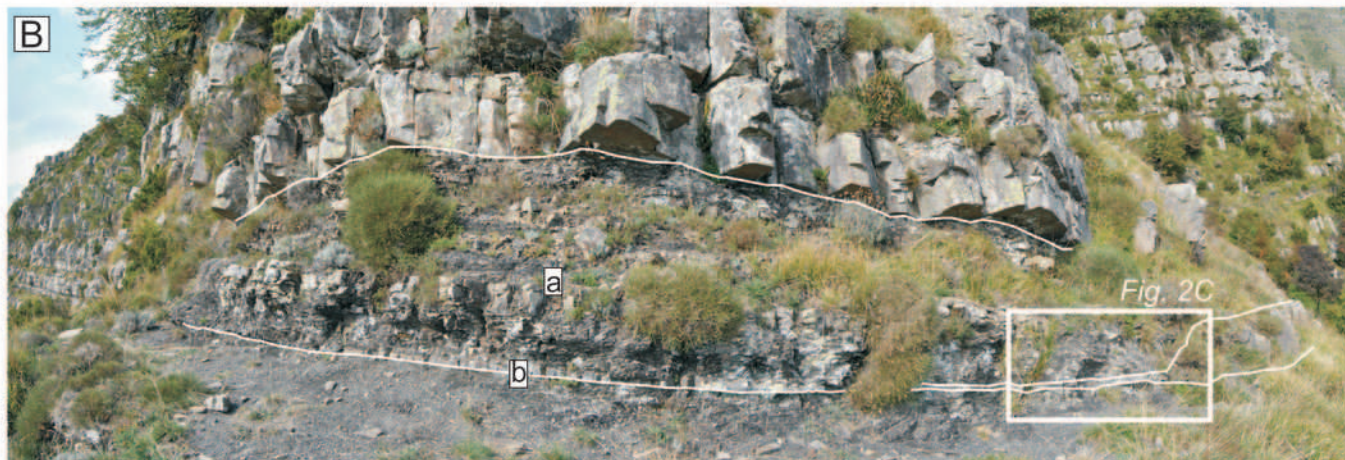
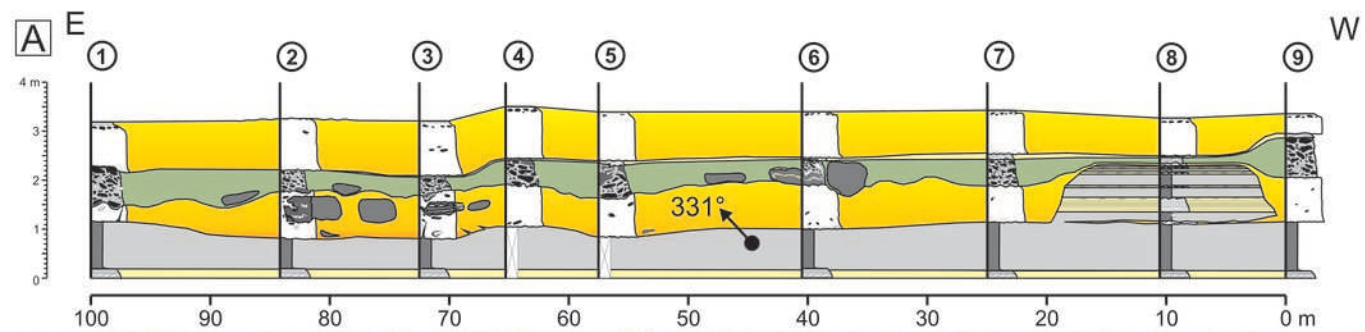
**Bed 17.3**

Observed max.  
substrate removed:  
265 cm

Average bed thick.:  
301 cm



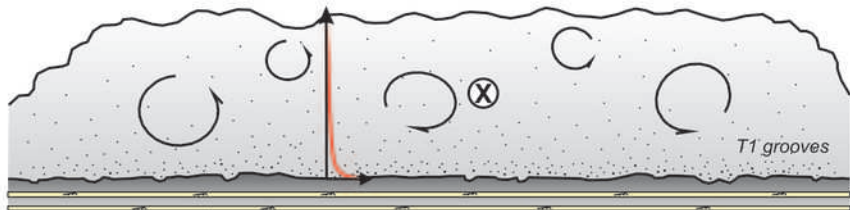




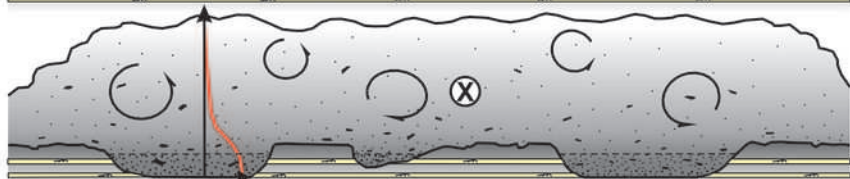


**A****B****C**

T1



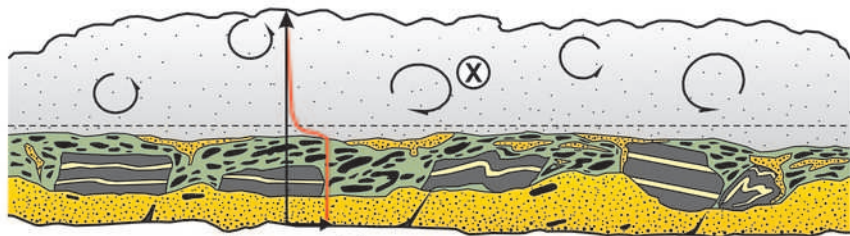
T2



T3

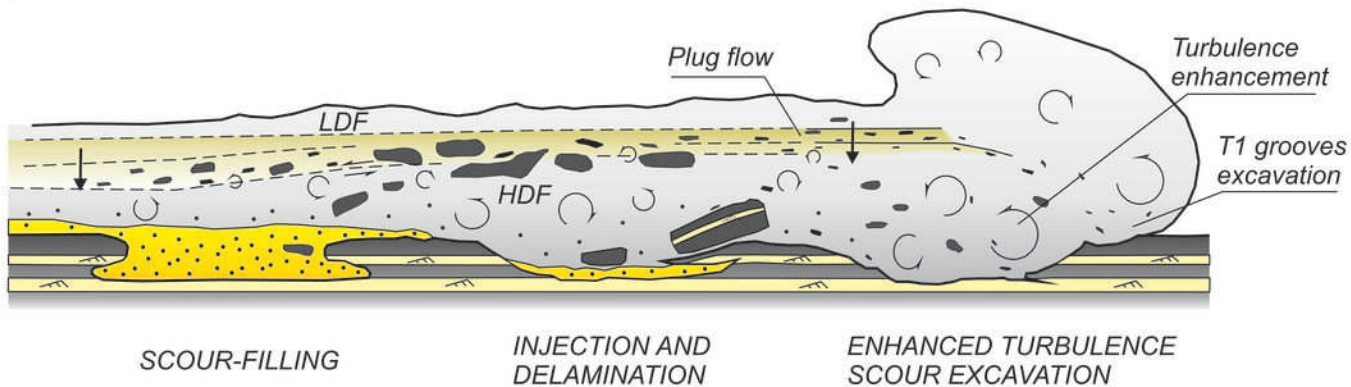


T4





## A ENHANCED TURBULENCE SCOURING AND DELAMINATION



## B HIGH-PRESSURE FLOW DELAMINATION

