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3 1 **Hybrid event bed character and distribution linked to turbidite system**  
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5 2 **sub-environments: the North Apennine Gottero Sandstone (NW Italy)**  
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28  
29  
30 12 **Keywords:** turbidites, hybrid event beds, facies tract, deep-water fan, confined basin, sediment  
31 13 gravity flows, lobes, Apennines.

32  
33  
34 14 ***Abstract***

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37 15 This study documents the character and occurrence of hybrid event beds (HEBs) deposited across a  
38 16 range of deep-water sub-environments in the Cretaceous-Palaeocene Gottero system, NW Italy.  
39 17 Detailed fieldwork (>5200 m of sedimentary logs) has shown that HEBs are most abundant in the  
40 18 distal confined basin plain domain (>31% of total thickness). In more proximal sectors, HEBs  
41 19 occur within outer-fan and mid-fan lobes (up to 15% of total thickness), whereas they are not  
42 20 observed in the inner-fan channelised area. Six HEB types (HEB-1 to 6) were differentiated mainly  
43 21 on basis of the texture of their muddier and chaotic central division (H3). The confined basin plain  
44 22 sector is dominated by thick (max 9.57 m; average 2.15 m) and tabular HEBs (HEB-1 to 4). Their  
45 23 H3 division can include very large substrate slabs, evidence of extensive auto-injection and clast  
46 24 break-up, and abundant mudstone clasts set in a sandy matrix (dispersed clay ~20%). These beds  
47 25 are thought to have been generated by highly energetic flows capable of delaminating the sea-floor  
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3 26 locally, and carrying large rip-up clasts for relatively short distances before arresting. The  
4  
5 27 unconfined lobes of the mid-fan sector are dominated by thinner (average 0.38 m) HEBs (HEB-5  
6  
7 28 and 6). Their H3 divisions are characterised by floating mudstone clasts and clay-enriched matrices  
8  
9 29 (dispersed clay >25%) with hydraulically-fractionated components (mica, organic matter, clay  
10  
11 30 floes). These HEBs are thought to have been deposited by less energetic flows that underwent early  
12  
13 31 turbulence damping following incorporation of mud at proximal locations and by segregation  
14  
15 32 during transport. Although there is a tendency to look to external factors to account for hybrid  
16  
17 33 event bed development, systems like the Gottero imply intrabasinal factors can also be important;  
18  
19 34 specifically the type of substrate available (muddy or sandy) and where and how erosion is  
20  
21 35 achieved across the system producing specific HEB expressions and facies tracts.  
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## 25 36 **(A)INTRODUCTION**

27 37 Bed character and bed stack architecture are two key elements controlling the heterogeneity of  
28  
29 38 deep-water turbidite systems. The former represents the depositional record of sediment gravity  
30  
31 39 flows at a given location with the vertical sequence of grain-size, textures and sedimentary  
32  
33 40 structures recording flow evolution in time and space (Bouma, 1962; Lowe, 1982; Mutti, 1992;  
34  
35 41 Kneller, 1995; Kneller & McCaffrey, 2003). The latter is set by the longer term response of the  
36  
37 42 system to variations in flow volume and concentration over many events modulated by the  
38  
39 43 inherited seafloor topography (Prélat et al., 2010; Brunt et al., 2013b; Marini et al., 2015a). Both  
40  
41 44 define the character and distribution of sedimentary sub-environments in deep-water systems.  
42  
43

44 45 A wide range of sediment gravity flow deposits have been recognised in turbidite systems. They  
45  
46 46 include the well-known Bouma-type graded sandstones and muddier and mostly ungraded debris  
47  
48 47 flow deposits (including all transitional members; see Mutti, 1992; Mulder and Alexander, 2001).  
49  
50 48 However many sandstone beds include co-genetic argillaceous and often mudstone-clast rich  
51  
52 49 divisions in their upper portion. These strata are referred as hybrid event beds (HEBs; Haughton et  
53  
54 50 al., 2009), and are recognised as a key element of deep-water systems across a wide range of scales  
55  
56 51 and tectonic settings (Van Vliet, 1978; Mutti et al., 1978; Haughton et al., 2003; 2009; Talling et  
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3 52 al., 2004; 2012; Amy & Talling, 2006; Hodgson, 2009; Muzzi Magalhaes & Tinterri, 2010; Kane  
4  
5 53 & Pontén, 2012; Southern et al., 2015; Fonnesu et al., 2015; 2016; Kane et al., 2017). If present in  
6  
7 54 subsurface hydrocarbon reservoirs they can severely compromise their performance (Amy et al.,  
8  
9 55 2009; Porten et al., 2016). Many mechanisms have been invoked for their formation involving a  
10  
11 56 range of flow behaviours, but they are generally interpreted as deposits formed by down-dip flow  
12  
13 57 transformation from a turbidity current to an increasingly cohesive flow (Haughton et al., 2009).  
14  
15 58 Nevertheless their bed make-up can be very variable particularly in term of the texture and  
16  
17 59 character of the argillaceous sandstone division. The latter can include large mudstone rafts (m-  
18  
19 60 scale) embedded in a relatively clay-poor sandy matrix (Haughton et al., 2010; Fonnesu et al.,  
20  
21 61 2015; 2016; Southern et al., 2015), mudstone-clast rich debrites (Haughton et al., 2003; Talling et  
22  
23 62 al., 2004; Hodgson, 2009; Patacci et al., 2014; Fonnesu et al., 2015; 2016), clast-poor but clay-rich  
24  
25 63 sandstones (Talling et al., 2004; 2012), or beds with mud-rich 'starry-night' texture (sandy  
26  
27 64 mudstones; Lowe & Guy, 2000; Barker et al, 2008; Haughton et al., 2009). Thick and extensively  
28  
29 65 banded beds (*sensu* Lowe & Guy, 2000) are also sometimes found associated (Barker et al., 2008;  
30  
31 66 Davis et al., 2009) or banded divisions can occur directly beneath argillaceous sandstones in  
32  
33 67 composite hybrid event bed types (Haughton et al., 2009; Kane & Pontén, 2012; Tinterri et al.,  
34  
35 68 2016). Despite their very variable character, the occurrence of each HEB types has rarely been  
36  
37 69 linked to its stratigraphic or palaeogeographical position within deep-water depositional systems.

38  
39  
40 70 HEBs are commonly found as a major bed motif in unconfined distal and lateral fringes of  
41  
42 71 distributive lobe systems (Haughton et al., 2003; Hodgson, 2009; Kane & Pontén, 2012; Kane et  
43  
44 72 al., 2017; Sychala et al., 2017) where they replace beds composed dominantly of clean sandstone  
45  
46 73 either up-dip or axially (Fig. 1A). They are usually concentrated at the base of prograding lobe  
47  
48 74 packages in vertical 1D successions as fringes to lobe bodies deposited further upslope (Hodgson,  
49  
50 75 2009; Kane & Pontén, 2012; Kane et al., 2017; Sychala et al., 2017). Their occurrence is  
51  
52 76 interpreted to reflect the progressive deceleration of clay-enriched flows in which the turbulence  
53  
54 77 was suppressed as flow energy dissipated on flatter and more distal fan sectors. A type of matrix-  
55  
56 78 rich sandstone, resembling hybrid event beds, is also recognised in more proximal locations in the

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2  
3 79 fringes of channel splays (Terlaky & Arnott, 2014). In this case the turbulence suppression is  
4  
5 80 attributed to a combination of fines-entrainment and rapid deceleration of plane-wall jets produced  
6  
7 81 by upslope channel avulsions, as the jets expand into externally unconfined areas. In both cases  
8  
9 82 hybrid event beds are found systematically interbedded with other sandy turbidites in a pattern  
10  
11 83 interpreted to reflect the progradation or lateral switching of depositional sub-environments.

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14 84 HEBs are also an important element in the aggradation of extensive basin plains (Ricci Lucchi &  
15  
16 85 Valmori, 1980; Amy & Talling, 2006; Muzzi Magalhaes & Tinterri, 2010; Tinterri & Muzzi  
17  
18 86 Magalhaes., 2011; Marini et al., 2015a). In these cases they form thick and sheet-like extensive  
19  
20 87 beds (almost basin-wide) in stacks with poor vertical organisation and an overall aggradational  
21  
22 88 trend (Fig. 1B). Long-distance facies tracts extending 10s km to 100s km for individual event beds  
23  
24 89 have been documented in the laterally-confined basin plain of the Miocene Marnoso Arenacea  
25  
26 90 (NW Italy). Here bed correlations show an overall increase of the matrix-rich sandstone at the  
27  
28 91 expense of underlying matrix-poor sandstone moving distally until beds gradually or abruptly  
29  
30 92 pinch out (Ricci Lucchi & Valmori, 1980; Amy & Talling, 2006; Talling et al., 2012). Hybrid  
31  
32 93 event beds in this setting are interpreted to have been deposited by a spectrum of depositional  
33  
34 94 processes ranging from: 1) debris flows released from upslope and partly transforming to a  
35  
36 95 forerunning turbidity current (Haughton et al., 2003) or late stage basal sand settling from a plug  
37  
38 96 flow (Baas et al., 2009; Sumner et al., 2008; Talling, 2013); 2) erosion of mud-rich seafloor  
39  
40 97 resulting in bulking and generation of a subsidiary debris flow (Mutti et al., 1978; Mutti & Nilsen,  
41  
42 98 1981; Talling et al., 2004; Amy & Talling, 2006; Haughton et al., 2009; 2010; Fannesu et al.,  
43  
44 99 2016); 3) generation of a debris flow by rapid deceleration and collapse of a turbidity current  
45  
46 100 (Talling et al., 2004; Haughton et al., 2010).

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48  
49 101 The present study is drawn from the Cretaceous-Paleocene Gottero turbidite system located in the  
50  
51 102 Ligurian Apennines in NW of Italy (Abbate & Sagri, 1970; Nilsen & Abbate, 1984; Marini, 1991).  
52  
53 103 The spectacular exposures and the wide range of deep-water sub-environments recognised, ranging  
54  
55 104 from proximal channels, unconfined proximal and distal lobes and confined basin plain deposits, as  
56  
57 105 well as the abundance and variability in the types of hybrid event beds, make this an instructive  
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3 106 case study to investigate variable HEB character and distribution through the system. The  
4  
5 107 examples provided highlight how different hybrid event bed types occur preferentially in certain  
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7 108 deep-water sub-environments and the possible controls on their deposition. Furthermore the  
8  
9 109 sedimentological analysis of hybrid event beds and their documented lateral transitions gives  
10  
11 110 insight into the mechanisms and the range of flow transformations (and related facies tracts) that  
12  
13 111 occurred in both proximal and distal sectors of the Gottero turbidite system.  
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### 17 **(A) GEOLOGICAL AND STRATIGRAPHIC SETTING**

18  
19 113 The Gottero system is a relatively small deep-water turbidite system of Maastrichtian - Early  
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21 114 Palaeocene age (Passerini & Pirini, 1964; Elter et al., 1997; Marroni & Perilli, 1990; Marroni et al.,  
22  
23 115 2004) developed on oceanic crust in a trench basin (Abbate & Sagri, 1970; Nilsen & Abbate,  
24  
25 116 1984). It was subsequently deformed and thrust north-eastward as an allochthonous sheet in the  
26  
27 117 Eocene and Oligocene during the Alpine-Apennine Orogeny becoming part of the Liguridi  
28  
29 118 structural domain (Marroni et al., 2004). Today the Gottero outcrops extend discontinuously for  
30  
31 119 about 70 km along the eastern Ligurian coast between Genova and Carrara and for about 45 km  
32  
33 120 inland toward the Ligurian Apennines in northwest of Italy (Fig. 2).  
34  
35

36 121 The Gottero system developed in a complex Late Cretaceous palaeogeographic setting on the floor  
37  
38 122 of the Ligure Piemontese Sea during the E-W convergence between Europe and Adria plates (see  
39  
40 123 Marroni & Pandolfi, 2007; Marroni et al., 2010). Calcareous turbidites were fed from the Alps to  
41  
42 124 form the Helminthoid flysch sequences (Sholle, 1971; Sagri, 1974) and a series of siliciclastic  
43  
44 125 flysch units referred to as the Gottero, Elba, Novella, Mt. Venere and Bordighera were sourced  
45  
46 126 from the southwest off the Corsica-Sardinian block (Abbate & Sagri, 1982). Sediment dispersed  
47  
48 127 from the two source areas (clastic and carbonate) only rarely mixed as they filled two basins  
49  
50 128 separated by an inferred topographic ridge (the Bracco high; Elter & Raggi, 1965).  
51  
52

53 129 The Gottero system belongs to the internal basin sector (Internal Liguridi; Fig. 2) which includes  
54  
55 130 oceanic lithosphere and sedimentary deposits formed within the Ligure-Piemontese Sea between  
56  
57 131 the Jurassic and the Paleocene (Fig. 3) first during extension and then convergence. The basement  
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3 132 is composed of oceanic crust including Jurassic lherzolites, gabbros and pillow lavas (Bortolotti &  
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5 133 Passerini, 1970). The overlying sedimentary cover is made up of: Callovian-Santonian basalinal  
6  
7 134 deposits comprising the Diaspri radiolarian cherts, Calpionella limestone and Palombini shales  
8  
9 135 (Elter et al., 1997; Marroni, 1991); a thick (c.1100 m thick) Santonian-Maastrichtian succession  
10  
11 136 comprising siliciclastic basin-plain turbidites forming the Lavagna Group; and the Maastrichtian –  
12  
13 137 Early Paleocene (Monechi et al., 1984, Elter et al., 1997) Gottero sandy deep-water turbidite  
14  
15 138 system. The succession is unconformably overlain by the Early Paleocene Gaiette Shales  
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17 139 (Passerini & Pierini, 1964) a >300 m thick chaotic unit (interpreted as mass transport complex;  
18  
19 140 MTC) containing blocks of Gottero Sandstone and exotic material in the form of siliceous  
20  
21 141 limestones, cherts and ophiolite blocks (Marroni & Pandolfi, 2001). The whole sequence records  
22  
23 142 the trenchward motion of a portion of the Ligure Piemontese oceanic lithosphere until its  
24  
25 143 involvement in the Eo-Alpine accretionary prism (Marroni et al., 2004). The Gottero system is  
26  
27 144 therefore attributed to an evolving trench basin developed above an eastward-directed subduction  
28  
29 145 zone.

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31  
32 146 The Gottero sandstones are feldspathic greywackes containing fragments of metamorphic, volcanic  
33  
34 147 and sedimentary rocks (Malesani, 1966; Pandolfi, 1997) derived from the Sardo-Corso massif  
35  
36 148 where large igneous crystalline masses were exposed (Parea, 1965; Valloni & Zuffa, 1981; Van de  
37  
38 149 Kamp and Leake, 1995). Although upper slope or shallow-water equivalents are not preserved, the  
39  
40 150 southern provenance for the Gottero sandstones is consistent with the regional palaeoflow  
41  
42 151 indicators which are mainly directed towards the north and northeast (Fig. 2; Parea, 1965; Nilsen &  
43  
44 152 Abbate, 1984). Limited changes in petrographic composition are recognised laterally across the  
45  
46 153 Gottero outcrop belt and with stratigraphic position (Pandolfi, 1996; 1997) suggesting a relatively  
47  
48 154 stable source area and confirming that the different components of the Gottero likely belong to a  
49  
50 155 single system. An exception is the presence of several beds with an ophiolitic provenance  
51  
52 156 (Pandolfi, 1997) in the uppermost part of the Gottero succession at the Mt. Ramaceto locality (Fig.  
53  
54 157 3) interpreted to have been sourced from an uplifted accretionary prism which provided sediment  
55  
56 158 to the trench during the last phase of basin filling. The Gottero system crops out in two branches  
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3 159 (the eastern Mt. Ramaceto - Mt. Zatta and the western Mt. Gottero - Mt. Molinatico) separated by  
4  
5 160 the Bracco ophiolite massif (Elter & Raggi, 1965). Sedimentation in the two areas was probably  
6  
7 161 diachronous with siliciclastic sedimentation in the eastern Gottero beginning during the Coniacian-  
8  
9 162 Santonian (Vescovi et al., 2002) whereas in the western part of the system deposition commenced  
10  
11 163 in the Campanian-Maastrichtian (Marroni, 1991).

### 14 **(B) Stratigraphy of the western Gottero system**

15  
16 165 The present study focuses on the portion of the Gottero Sandstone cropping out on the western side  
17  
18 166 of the Bracco massif. Data were collected from six locations (Monterosso, Deiva Marina,  
19  
20 167 Moneglia, Terrarossa, Mt. Ramaceto, Mt. Zatta; Fig. 3), five of which are aligned along a SE-NW  
21  
22 168 transect roughly parallel to the general palaeoflow direction (Fig. 4). The lack of continuous  
23  
24 169 exposure precludes direct correlation of individual stratigraphic elements but the enclosing  
25  
26 170 stratigraphic units and the main internal lithostratigraphic boundaries and trends can be  
27  
28 171 consistently recognised across the area. The earliest of the sandstone bodies comprise four sand-  
29  
30 172 rich units interfingering with fine-grained deposits of the Lavagna Group in the north-western  
31  
32 173 sector of the basin which are defined as the “Lower Gottero” (Casnedi, 1982; Marini, 1991). They  
33  
34 174 are interpreted as channelized bodies and lobes of an early prograding and unconfined fan system.  
35  
36 175 The overlying “Upper Gottero” was deposited above a widespread 20 to 40 m thick mud-rich  
37  
38 176 chaotic deposit (Vallai MTD). The upper Gottero succession begins with a fine-grained slope and  
39  
40 177 basin plain wedge (Gottero 1; GOT1) followed by coarse-grained sand-rich basin floor succession  
41  
42 178 (Gottero 2; GOT2) extending from the proximal Monterosso section to the more distal sections on  
43  
44 179 Mt. Ramaceto and Mt. Zatta without important facies or thickness changes (Fonnesu, 2016). The  
45  
46 180 boundary between the underlying fine-grained units and the Gottero 2 sandstones is sharp and  
47  
48 181 erosive in the Monterosso locality, but it appears transitional at Moneglia, Mt. Ramaceto and Mt.  
49  
50 182 Zatta where the same contact is recorded by an obvious thickening-upward trend. The overlying  
51  
52 183 unit (Gottero 3; GOT3) shows an overall backstepping trend expressed in both proximal and distal  
53  
54 184 locations. An unconfined turbidite fan developed in more proximal areas (Monterosso, Moneglia)  
55  
56 185 but in the distal areas (Mt. Ramaceto and Mt. Zatta) tectonic activity created basin segmentation.

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3 186 The Gottero system thus developed two separate distal depocenters in the Mt. Ramaceto and Mt.  
4  
5 187 Zatta areas where 825 m and 640 m of Gottero 3 succession accumulated, respectively, separated  
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7 188 by a tectonic high (Marini, 1991; 1994). The two areas evolved separately, with the Mt. Zatta  
8  
9 189 succession dominated by stacked outer-fan lobe packages together with an interbedded local MTD,  
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11 190 whereas the Mt. Ramaceto depocentre developed into a confined basin plain (*sensu* Mutti & Johns,  
12  
13 191 1978; Remacha et al., 2005; Mutti et al., 2009; Pickering & Hiscott, 2015; Fonnesu et al., 2015) in  
14  
15 192 which very thick, tabular and laterally-extensive event beds with thick mudstone caps are  
16  
17 193 interbedded with thin-bedded packages (Fonnesu et al., 2016). The down-dip basin margin  
18  
19 194 responsible for late basin confinement is not preserved in the outcrop but it could be represented by  
20  
21 195 the Bracco palaeo-high (Fig. 2).

22  
23  
24 196 The overall stratigraphic trend recorded by the Gottero can be interpreted as comprising a first  
25  
26 197 phase in which the system developed as an unconfined and radial-shaped basin floor fan with the  
27  
28 198 basin boundaries outside of the actual outcrop area. With narrowing of the trench due to syn-  
29  
30 199 sedimentary uplift of the Alpine accretionary prism, local subsidence and progressive confinement  
31  
32 200 of the distal sectors of the basin occurred, but the proximal fan area would still have remained  
33  
34 201 relatively unconfined (Nilsen & Abbate, 1984; Fonnesu, 2016). The presence at Gottero 3 time of  
35  
36 202 separate distal basin depocenters that cannot be easily correlated (Marini, 1991; 1994) might reflect  
37  
38 203 active segmentation of the trench basin during development of the accretionary prism (Fonnesu,  
39  
40 204 2016) until it finally collapsed into the trench causing the regional erosive unconformity at the base  
41  
42 205 of the chaotic deposits of Giaiette MTC unit (Fig. 4).

#### 46 **(A) DATASET AND METHODOLOGY**

47  
48 207 About 5200 metres of sedimentary logs have been collected from the six outcrop localities (Figs 3  
49  
50 208 and 4), 4307 metres of which were measured bed-by-bed at 1 cm resolution mainly using a Jacob's  
51  
52 209 staff (e.g. a 1.5 metre high rod equipped with a clinometer and a flat sighting disc). The remaining  
53  
54 210 ca. 800 metres of logs were drawn by using photomosaics of inaccessible cliff sections. Because  
55  
56 211 most of the coastal sections crop-out on vertical cliffs and the bedding is often vertical or steeply  
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3 212 dipping, the lateral exposure is no more than 50 meters in most cases. An exception is the area  
4  
5 213 around Monterosso, where beds can be traced on vertical cliffs laterally for about 400 metres. The  
6  
7 214 Gottero Sandstone Formation can be mapped from Moneglia to Mt. Ramaceto as a continuous  
8  
9 215 body on the limbs of a regional syncline with the Giaiette Shales at its core (Marini, 1991; Marroni  
10  
11 216 et al., 2004) (Fig. 3). Nevertheless the exposure is very poor between these two localities, with the  
12  
13 217 exception of an abandoned quarry located in Terrarossa where about 140 metres of Gottero  
14  
15 218 Sandstones crop out. The most spectacular exposures of the Gottero system are located on Mt.  
16  
17 219 Ramaceto (Casnedi, 1982; Marini, 1994; Fonnesu et al., 2015; 2016) where the entire succession  
18  
19 220 can be logged over a total thickness of 1075 m (Fig. 5). The uppermost 735 m of the Gottero can  
20  
21 221 be traced for about 4 kilometres in a N-S direction and bed-by-bed correlations were established  
22  
23 222 between eight measured stratigraphic logs. The succession at Mt. Ramaceto is overturned (apart  
24  
25 223 from the southernmost section) being mostly on the inverted limb of a regional syncline (Casnedi,  
26  
27 224 1982; Marroni, 1991; Marroni et al., 2004). The Mt. Zatta Gottero succession is 810 m thick and  
28  
29 225 located slightly off-axis with respect to the cross-section shown in Fig. 4. Samples were collected  
30  
31 226 from specific hybrid event beds and their internal texture has been analysed with optical  
32  
33 227 microscopy (13 thin-sections). Clay content and framework mineralogy has been quantified  
34  
35 228 petrographically by point counting (500 points per section).  
36  
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38

### 39 **(A) BED TYPES AND HYBRID EVENT BED CHARACTER**

40  
41 230 The Gottero system includes a wide range of gravity flow deposits ranging from large mass-  
42  
43 231 transport deposits, debrites, high and low-density turbidites, limestone beds through to a large  
44  
45 232 variety of hybrid event beds. The wide range in grain-size available in the system (Nilsen &  
46  
47 233 Abbate, 1984), ranging from boulders to very fine sand and silt, means that there is a wide variety  
48  
49 234 of facies types in deposits belonging to different sub-environments. Five bed type groups are  
50  
51 235 distinguished: debrites, DEBs; gravelly high-density turbidites, GHDTs; high-density turbidites;  
52  
53 236 HDTs; mudstone-clast rich beds, MRBs; low-density turbidites, LDTs; limestone beds, L; and  
54  
55 237 hybrid event beds, HEBs) (Tab. 1). This paper focuses on the character of the hybrid event beds  
56  
57 238 (HEBs), which are therefore described in more detail. Because the entrainment of mud clasts is  
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3 239 considered an important process in their formation, an additional bed type class termed “mudstone  
4  
5 240 clast rich beds” (MRBs) is also defined to include high-density turbidites carrying abundant  
6  
7 241 mudstone clasts usually clustered in the uppermost structureless bed portion (see Mutti & Nilsen,  
8  
9 242 1981; Postma et al., 1988; Fongnesu et al., 2015). Unlike some types of hybrid event beds,  
10  
11 243 mudstone clasts in MRBs are generally less densely packed and are dispersed in a clean sandstone  
12  
13 244 instead of a clay-enriched sandstone. In the distal confined part of the system, mudstone clast-rich  
14  
15 245 beds show tabular geometries and are found in close spatial association with mudstone clast-rich  
16  
17 246 hybrid event beds (Fongnesu et al., 2015). Therefore they are likely to represent deposits of flows  
18  
19 247 during the early stages of hybrid flow development.  
20  
21

### 22 **(B) Hybrid event beds (HEBs)**

23  
24 249 Hybrid event beds are characterised by a vertical association of a basal clean (interstitial-clay poor)  
25  
26 250 and mostly structureless sandstone (termed H1 by Haughton et al., 2009) and argillaceous  
27  
28 251 sandstone (commonly with a swirled fabric or chaotic appearance) in which there are variable  
29  
30 252 concentrations of mudstone clasts and sheared sand patches (H3). Other divisions can also be  
31  
32 253 found but are not always present (Haughton et al., 2010; Talling, 2013) such as: an interval with  
33  
34 254 scattered mudstone clasts at the transition between the clean and argillaceous sandstone (H1b); an  
35  
36 255 interval comprising alternating paler and darker sandstone bands (H2); a fine/very fine grained  
37  
38 256 parallel to ripple laminated division deposited on top of the argillaceous sandstone (H4); and a silty  
39  
40 257 mudstone cap (H5). These facies are never observed in an inverse or different order. Because the  
41  
42 258 H1 division tends to be thin and pinch out in distal and lateral locations (Haughton et al., 2003;  
43  
44 259 Amy & Talling, 2006) it is possible that some hybrid event beds are expressed just as argillaceous  
45  
46 260 sandstone facies (H3) (Davis et al., 2009) capped by a fine-grained structured sandstone (H4).  
47  
48 261 Hybrid event beds are here classified mainly on the basis of the texture of the H3 division and of  
49  
50 262 the size and shape of the clasts within it. H3 divisions show a range in terms of the intensity of  
51  
52 263 soft-sediment deformation, ranging from intact substrate blocks to a well-mixed argillaceous sand,  
53  
54 264 passing through deformed slump-like and mudstone clast-rich textures from which specific sub-  
55  
56 265 facies are distinguished (Fig. 6). Other characters such as bed thickness, presence of H2 or H4  
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3 266 divisions and type of sole structures are used as complementary criteria (Tab. 2). The H3 facies  
4  
5 267 types form a continuum from which six representative bed types have been identified varying from  
6  
7 268 HEB-1 to HEB-6 (Fig. 6). Bed type classification refers to the aspect of a bed in one location but  
8  
9 269 individual beds can change from one type to another over a relatively short distance (Hodgson,  
10  
11 270 2009; Fonnesu et al., 2015) along lateral or longitudinal facies tracts (see Mutti, 1992; Mutti et al.,  
12  
13 271 2003).

14  
15  
16 272 *(C) HEB-1*

17  
18 273 *HEB-1* are very thick tripartite event beds (0.60 - 6.80 m thick; average 3.32 m) characterised by  
19  
20 274 the presence of large and relatively undeformed substrate rafts (bedding-parallel, elongated slabs  
21  
22 275 with long axes much greater than the bed thickness; 0.5 - 2 m thick and up to 20 m long). The rafts  
23  
24 276 are supported by a poorly-sorted, coarse- to fine-grained sandstone matrix including mudstone  
25  
26 277 chips, mud-poor sand patches and sand injections. Substrate rafts can be dark mudstone (RI) or  
27  
28 278 bed-parallel or gently dipping thin-bedded sandstone-mudstone units in some cases with thin  
29  
30 279 limestone beds (SP) (Fig. 6). Lateral bed correlations highlight that the base of these beds is often  
31  
32 280 erosive; producing 1 to 2 m deep and 100s of metres wide scour features. The type of raft  
33  
34 281 contained in the H3 division can often be matched to the substrate encountered directly beneath the  
35  
36 282 event bed when it is traced laterally to less deeply eroded sectors. Thus the presence of rafts  
37  
38 283 comprising mudstones with thin-bedded sandstone is typical of event beds that overlie similar *in-*  
39  
40 284 *situ* thin-bedded sections, whereas mudstone rafts are usually found in HEBs that overlie thick  
41  
42 285 mudstone caps of earlier event beds (Fonnesu et al., 2016). Substrate rafts usually accumulate at  
43  
44 286 the base of the H3 division with their longer axes aligned mostly parallel to bedding. Their upper  
45  
46 287 and lower margins have generally sharp contacts with the surrounding sand-rich matrix or the  
47  
48 288 underlying sandstone but their lateral edges can sometimes be deformed, frayed or preserved  
49  
50 289 breaking into discrete smaller mudstone clasts. The underlying H1 basal division is a very-coarse  
51  
52 290 to medium grained apparently structureless (or very crudely laminated) but generally graded  
53  
54 291 sandstone. The contact between the lower H1 sandstone and H3 is mostly irregular but sharp with  
55  
56 292 the larger rafts often showing evidence of having ploughed into and thinned the basal sandstone or  
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3 293 even occurring fully encased in it suggesting they foundered into what was soft wet sand (Fonnesu  
4  
5 294 et al., 2015). Next to the larger rafts, sand injections extruding from the H1 sandstone division can  
6  
7 295 form large columnar pillars (about 1- 1.5 m in diameter) terminating in *mushroom-like* sill features  
8  
9 296 preferentially developed at the boundary between the H3 and H4 divisions (see Knaust et al.,  
10  
11 297 2014). Slightly deformed, thinner, vertical or inclined sand injections (10-20 cm in diameter) can  
12  
13 298 cross-cut the rafts and the sandy matrix of the H3 division but do not cross the boundary between  
14  
15 299 the H3 and H4 divisions. The effects of dewatering processes are also evident in the texture of the  
16  
17 300 H1 sandstone with sub-vertical but curved dewatering sheets preferentially observed when the top  
18  
19 301 to H1 is dome-shaped or is locally depressed. The H4 division and the H5 mudstone cap are  
20  
21 302 usually well-developed. H4 is present in 94% of HEB-1 beds and is characterised by a fine-grained  
22  
23 303 laminated and/or rippled sandstone division (typically about 35 cm thick) with a very irregular base  
24  
25 304 and flat top. Loading structures with a m-scale wavelength and fine-grained sandstone *ball and*  
26  
27 305 *pillow* structures derived from the H4 unit are commonly observed foundering into the H3 muddier  
28  
29 306 division, especially where the mud content in H3 is higher (Patacci et al., 2014; Fonnesu et al.,  
30  
31 307 2015; Tinterri et al., 2016). The beds cropping out in the upper part of Mt. Ramaceto succession  
32  
33 308 can also contain unusually thick H4 divisions including repetitions of structureless and laminated  
34  
35 309 intervals, H5 intervals composed of a silty homogenous facies and a very thick mudstone cap  
36  
37 310 (sometimes above 3 m thick). The same character is shared by other HEB types (HEB-1 to 4)  
38  
39 311 present in the same stratigraphic interval.

#### 312 (C) HEB-2

313 *HEB-2* beds are very thick, tripartite event beds (0.40 - 9.57 m thick; average 2.37 m) characterised  
314 by a heterogeneous and chaotic H3 division. This is made up of folded pieces of thin-bedded  
315 stratigraphy (SC) or by a complex sand-injection network (MCI) set in a mud-rich matrix (Fig. 6).  
316 Both facies can be interpreted as an advanced deformation stage of heterolithic or mudstone slabs  
317 respectively (Fonnesu et al., 2016). Despite their chaotic appearance, these beds can be  
318 distinguished from gravitational slump deposits because they are consistently associated with a  
319 thick sandy base (H1) and a laminated graded sandy top (H4), and because they pass laterally into

1  
2  
3 320 other hybrid bed types. The H3 divisions in these beds are characterised by abundant well-  
4  
5 321 developed soft-sediment deformation features such as: 1) intense folding of thin-bedded packages  
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7 322 deformed into complex isoclinal and/or recumbent folds; 2) dismembering of sand levels with  
8  
9 323 development of pinch-and-swell structures, attached or detached pseudonodules, ductile shear  
10  
11 324 zones and intense thinning of fold limbs; 3) Deformed sand injections made of coarse-grained and  
12  
13 325 poorly sorted sandstone extruded from the underlying sandy base and bordering or cross-cutting  
14  
15 326 the deformed heterolithic clasts. The deformed strata and the sand-injections are encased in a mud-  
16  
17 327 rich matrix in part produced by squeezed mud-rich blocks. Some of the mudstone appears to be  
18  
19 328 composed of relatively undeformed blocks. However, in other instances the mudstone appears to  
20  
21 329 have behaved in a more plastic way and it seems to be associated with folding having being  
22  
23 330 injected by sand along fold axial planes or sheared out along fold limbs. In other cases, the  
24  
25 331 mudstone can be well mixed with the sand, resulting in a dirty-looking sandstone rich in mm- and  
26  
27 332 cm-sized mudstone clasts. As for HEB-1, the basal H1 sandstone is a structureless, weakly-graded  
28  
29 333 sandstone containing abundant dewatering features and is characterised by an abrupt transition to a  
30  
31 334 muddier H3 division. Also like HEB-1, HEB-2 beds usually (79% of beds) have a well-developed  
32  
33 335 (typically about 35 cm thick) laminated and graded H4 division, loading and sometimes foundering  
34  
35 336 into the underlying mud-rich H3 division.

37  
38 337 *(C) HEB-3*

39  
40 338 *HEB-3* are generally thick (0.30 - 5.30 m thick, 1.77 m average) hybrid event beds in which the H3  
41  
42 339 division is composed of densely packed mudstone clasts (MCB; clasts average above 5 cm across)  
43  
44 340 surrounded by a dirty sandstone rich in mm- and cm-sized mudstone clasts (Figs. 6 and 7), clean  
45  
46 341 sandy patches and sand injections. Individual mudstone clasts are rounded to sub-rounded, and  
47  
48 342 have a generally oblate shape aligned parallel to bedding. Mudstone clasts can be randomly  
49  
50 343 distributed, but more often they display a weak normal grading. Clasts are often in contact or  
51  
52 344 separated only by thin veneers of poorly-sorted dirty sandstone. The inter-clast sandstone has a  
53  
54 345 ratio of interstitial clay vs. clast framework varying from 15 to 21%, showing generally a  
55  
56 346 progressive higher quantity of detrital pore-filling clay and mica flakes towards the upper part of  
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1  
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3 347 the division (Talling et al., 2004; Hodgson, 2009). The value seems to increase in parallel with the  
4  
5 348 concentration and disruption of the mudstone clasts. The H3 division can be laterally continuous or  
6  
7 349 form lenses in which the clasts are more densely packed separated by portions in which clasts are  
8  
9 350 less common and surrounded by cleaner sandstone (Patacci et al., 2014; Fonnesu et al., 2015). The  
10  
11 351 latter facies can also form a transitional unit between the basal H1 sandstone and the H3 division  
12  
13 352 (H1b). The relative proportion of H1 and H3 divisions can be highly variable, with event beds  
14  
15 353 ranging from being H1-dominated to H3-dominated without important changes in the H3 texture  
16  
17 354 over short length scales (10s to 100s m). Bed bases are often extensively grooved and can be  
18  
19 355 characterised by widespread but cryptic composite and multiphase erosional features comprising  
20  
21 356 elongated shallow scours (a few metres long and a few tens of cm deep) associated with lateral  
22  
23 357 sand injections and rip-up clasts from the underlying substrate (Fonnesu et al., 2016). An  
24  
25 358 uppermost H4 division is developed in most cases (87%) and typically is about 25 cm thick; it  
26  
27 359 commonly has tabular boundaries, but local metre-scale wavelength load casts can also occur.  
28  
29 360 HEB-3 represents the most common type of hybrid event bed in the logged Gottero system (Tab.  
30  
31 361 2).

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33  
34 362 *(C) HEB-4*

35  
36 363 *HEB-4* are thick to mid-size beds (0.20 - 3.20 m thick; 0.92 m average) comprising an H3 division  
37  
38 364 with abundant cm-size mudstone clasts (typically about 2-5 cm across) set in a dirty (21 to 23%  
39  
40 365 dispersed clay), medium to fine-grained sandstone matrix (MCD) (Fig. 6). Mudstone clasts, despite  
41  
42 366 being of smaller size than in HEB-3 beds, are still abundant and display many clast-to-clast  
43  
44 367 contacts. As in HEB-3, mudstone clasts are usually disc-shaped, can be randomly orientated or be  
45  
46 368 sub-parallel to bedding and can show a weak normal grading. Similarly, the matrix of the H3  
47  
48 369 division can display a subtle upward increase in the mud content. The contact between the H3  
49  
50 370 division and the basal H1 sandstone is usually sharp but undulose with m-scale wavelength and 10-  
51  
52 371 30 cm amplitude irregularities (Fonnesu et al., 2015). An H4 division is commonly present (82%)  
53  
54 372 but is usually thin (typically about 15 cm), normally graded and planar laminated.  
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3 373 (C) *HEB-5*

4 374 *HEB-5* are event beds ranging from 0.05 to 2.40 m in thickness (average 0.44 m) with the H3  
5  
6 375 division constituted by well-mixed argillaceous sandstone with scattered mudstone clasts (MDC)  
7  
8 376 (Fig. 6). The matrix is enriched in clay (25-27 %) as well as hydraulically 'light' components such  
9  
10 377 as mica flakes, clay flocs and organic matter, which generally tend to concentrate toward the top of  
11  
12 378 the H3 division (Fig. 7). The contact between the H1 and H3 divisions is sharp in the majority of  
13  
14 379 the cases but in a few beds, an intervening banded H2 division is developed in the form of dark  
15  
16 380 clay-prone sandy layers alternating with lighter fine-grained cleaner sandy intervals (Lowe and  
17  
18 381 Guy, 2000; Haughton et al., 2009; Davis et al., 2009). H1 is a poorly to well-sorted and weakly  
19  
20 382 graded, coarse to medium grained sandstone. The bed base is generally sharp, decorated with both  
21  
22 383 grooves and flutes, the latter generally absent in the other hybrid event bed types. In a few cases  
23  
24 384 *HEB-5* beds do not have a basal H1 sandstone and the H3 division dominates the event bed. The  
25  
26 385 H4 division is not systematically developed (occurring in only 48% of beds). Nevertheless,  
27  
28 386 whenever H4 is present, it forms a thin planar or ripple-laminated unit capping the bed that  
29  
30 387 commonly loads and founders into the H3 argillaceous sand below, with an associated  
31  
32 388 development of pseudonodules.

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35  
36 389 (C) *HEB-6*

37 390 *HEB-6* are a relatively uncommon type of hybrid event bed. They have an average thickness of  
38  
39 391 only 0.2 m (0.12 to 0.75 m) and are distinguished from all the other hybrid bed types in that the  
40  
41 392 basal division is a fine-grained parallel or ripple laminated sandstone overlain by a weakly graded  
42  
43 393 fine-sandstone to clay-enriched fine-grained sandstone (MD) (Fig. 6). The bed has an upward  
44  
45 394 transition directly to a dark capping mudstone.

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47  
48  
49 395 (C) *Hybrid event bed morphometrics*

50 396 Although the Gottero hybrid event beds can be assigned to one of six types guided mainly by the  
51  
52 397 character of their H3 divisions, data show a clear correlation between *HEB* type and their average  
53  
54 398 and maximum thickness (Tab. 2; Fig. 8A). It can be observed that beds from *HEB-1* to *HEB-6*  
55  
56 399 follow a thinning trend, with *HEB-5* and *HEB-6* being much thinner than the other types. On the  
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3 400 other hand, a clear relationship between the ratio of H1 to H3 thicknesses and HEB type is not  
4  
5 401 observed (Fig. 8B). HEB-3 seems to have a higher variability of H1/H3 ratio, with a larger number  
6  
7 402 of beds with relative thin H1 divisions. HEB-5 beds more commonly lack an H1 division.  
8  
9

### 10 403 *(C) Interpretation*

11 404 The variability in the hybrid event character observed in the Gottero system and captured by the  
12  
13 405 six-fold classification scheme is comparable with the bed model described by Haughton et al.,  
14  
15 406 (2009). The hybrid event beds described above are interpreted as the deposits left by the passage of  
16  
17 407 individual flows, the rheology of which evolved from being poorly cohesive and essentially  
18  
19 408 turbulent to being more cohesive and turbulence-suppressed (Haughton et al., 2009). As discussed  
20  
21 409 below, the range of bed types is thought to reflect the variable manner of mud entrainment, the way  
22  
23 410 in which the flow was partitioned rheologically, and the mechanism of turbulence damping. (Baas  
24  
25 411 et al., 2009; 2011; Patacci et al., 2014; Fonesu et al., 2015; 2016).  
26  
27

28  
29 412 The basal structureless or weakly stratified H1 sandstone is interpreted as deposited by a sandy  
30  
31 413 high-concentration turbidity current (Haughton et al., 2003; 2009). Deposition was probably  
32  
33 414 characterised by a high-rate of sediment fallout, causing the intense dewatering observed in most  
34  
35 415 H1 divisions and the sand-injections into the overlying H3 division; the sandy basal divisions were  
36  
37 416 prone to liquefaction when dynamically loaded by the H3 divisions. The normal or coarse-tail  
38  
39 417 grading and the occasional presence of traction structures suggest that there were also phases  
40  
41 418 during which layer-by-layer deposition under traction and hindered settling from a non-cohesive  
42  
43 419 flow dominated (Kneller & Branney, 1995). The argillaceous sandstone divisions (H3) with their  
44  
45 420 variety of chaotic or weakly-organised mudstone and heterolithic clasts, show evidence of *en-*  
46  
47 421 *masse* deposition. Deposition of the H3 clay-enriched sandstones is interpreted to be related to  
48  
49 422 three main processes: 1) Rapid entrainment of large quantities of mud-rich substrate material  
50  
51 423 which became partially disaggregated in a shearing near-bed layer (Haughton et al., 2009; Fonesu  
52  
53 424 et al., 2015; 2016). 2) Vertical top-down transformation from turbidity current to debris flow due to  
54  
55 425 rapid flow deceleration (Sumner et al., 2009; Baas et al., 2009; Kane & Pontén, 2012). 3)  
56  
57 426 Longitudinal transformation due to lateral hydrodynamic fractionation of clay and flaky particles  
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3 427 (Haughton et al., 2009; Pyles et al., 2013). The first process is thought to be responsible for  
4  
5 428 formation of HEB-1 to HEB-4 beds. The second and the third processes are interpreted to have  
6  
7 429 operated in the case of HEB-5 and HEB-6 beds.  
8  
9

10 430 A rheology change between the turbulent flow responsible for the deposition of the basal sandstone  
11  
12 431 (H1), and the mostly cohesive laminar flow depositing the H3 division, can be inferred from the  
13  
14 432 presence of progressively more abundant mudstone clasts vertically in the bed (including the  
15  
16 433 development of H1b). The clasts might have been kept in suspension in the upper and rearward  
17  
18 434 part of the dense flow due to their low density and resulting buoyancy (Mutti & Nilsen, 1981;  
19  
20 435 Postma et al., 1988). Alternatively, and less commonly, the flows oscillated between a frictional  
21  
22 436 and a laminar condition, leading to the formation of a banded interval (H2 – Lowe & Guy, 2000;  
23  
24 437 Haughton et al., 2009; Baas et al., 2011). The common presence of an overlying graded and  
25  
26 438 laminated H4 division grading into a mudstone cap (H5) suggests the re-establishment of turbulent  
27  
28 439 flow conditions from a trailing wake followed by sediment fallout from the suspension cloud. The  
29  
30 440 geometry of the H4 division may reflect the rheology of the just-deposited underlying H3 division  
31  
32 441 (Fonnesu et al., 2015; Tinterri et al., 2016). Loaded or foundered H4 divisions might be produced  
33  
34 442 by the wakes to flows decelerating on a very heterogeneous, plastic and mud-rich H3 deposit; a  
35  
36 443 planar boundary suggests a more homogenous and semi-rigid behaviour.  
37  
38  
39

#### 40 **(A) FACIES ASSOCIATIONS AND SUB-ENVIRONMENTS**

41  
42 445 Hybrid event beds and other sediment gravity flow deposits are diversely stacked throughout the  
43  
44 446 Gottero system but can be grouped in specific facies associations. Following the approach of Mutti  
45  
46 447 and Ricci Lucchi (1972) (see also Mutti & Normark, 1987; 1991), each facies association can be  
47  
48 448 considered the stratigraphic expression of a specific sub-environment within a turbidite system,  
49  
50 449 interpretation of which is tied to its characteristic bed stack, general architecture and  
51  
52 450 stratigraphic/palaeogeographic position. Five sandy facies associations and have been identified in  
53  
54 451 the Upper Gottero system (Fig. 9): FA-A) inner fan channels; FA-B) mid-fan lobes; FA-C) outer-  
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56 452 fan lobes; FA-D) weakly amalgamated sheets; and FA-E) isolated basin plain sheets. An additional  
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3 453 facies association (FA-F) includes the remaining dominantly fine-grained facies comprising slope  
4  
5 454 deposits and fine-grained basin plain facies. Facies association terminology has been partially  
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7 455 retained from a previous and prescient sub-environment fan zonation for the Gottero system  
8  
9 456 proposed by Nilsen & Abbate (1984). The proximal Gottero area is dominated by FA-A to FA-C  
10  
11 457 facies associations (Monterosso, Deiva Marina, Moneglia, Terrarossa), representing deposits of a  
12  
13 458 relatively unconfined fan system. The external part of the system (Mt. Ramaceto) is characterised  
14  
15 459 by facies associations FA-D and FA-E and is interpreted as a confined basin-plain environment.  
16  
17 460 The Mt. Zatta succession includes interleaved facies associations of both types in a separate  
18  
19 461 overfilled trough (Marini, 1995). Quantitative log data allow a reliable estimation of characteristic  
20  
21 462 sedimentological parameters such as overall sandstone percentage (St%; includes locally  
22  
23 463 conglomeratic basal divisions of event beds, and clayey sandstone forming H3 divisions in HEBs),  
24  
25 464 component bed types and in particular the abundance and types of hybrid event bed present in each  
26  
27 465 of the facies associations. However, the dimension of large- and medium-scale depositional  
28  
29 466 features such as channels and lobes, and the establishment of their internal hierarchy can only be  
30  
31 467 achieved in a limited number of cases due to the rarity of laterally continuous exposures.

### 32 33 34 468 **(B) FA-A Inner fan**

35  
36 469 The most proximal preserved section of the Gottero system is dominated by conglomeratic and  
37  
38 470 coarse-grained sandy deposits in which the sandstone percentage is extremely high, reaching 99%  
39  
40 471 (Fig. 9A). The only outcrop example of this facies association is located in the Monterosso area  
41  
42 472 (Nilsen & Abbate, 1984; Pandolfi, 1996). The succession includes: an erosive coarse-grained  
43  
44 473 lenticular unit (25 m thick at the axis), interpreted as a channel-body; and a thicker and generally  
45  
46 474 more tabular sandbody, of minimum 250 m thickness (the top cannot be constrained because it has  
47  
48 475 been removed by modern marine erosion). Dominant facies includes mudstone-clast  
49  
50 476 conglomerates, clast-supported lags, and amalgamated coarse-grained turbidites including traction  
51  
52 477 carpets, mudstone clasts and large scale cross-beddings. Shallow erosive “cut-and fill” features  
53  
54 478 (Mutti & Normark, 1987), uneven bed bases (local erosional relief up to 1.5 m), grain-size breaks,  
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56 479 and rapid lateral bed thickness changes, determine important bypass occurring in the area. The  
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3 480 facies association is interpreted to represent a proximal fan environment spanning base-of-slope  
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5 481 channels to channel-mouth (channel-lobe transition) settings. Despite the common presence of  
6  
7 482 substrate erosion and rip-up clasts, hybrid event beds are not present in this facies association in  
8  
9 483 either the channelized or the more tabular units (Fig. 9A).

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11  
12 484 **(B) FA-B Mid-fan lobes**

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14 485 The intermediate part of the Gottero system and most of the Gottero 2 unit (Deiva Marina,  
15  
16 486 Moneglia, Terrarossa, Mt. Ramaceto, Mt. Zatta sections; Fig. 4) are composed of mainly parallel-  
17  
18 487 bedded, amalgamated strata forming 10 to 20 metres-thick sandstone packages organized in  
19  
20 488 thinning- and fining-upward sequences (Fig. 10A-B). These sequences are separated by thinner  
21  
22 489 (metres-thick) mud-prone intervals sometimes containing thin-bedded sandstones. This forms a  
23  
24 490 facies association with an overall St% of 88% (Fig. 9B).

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26  
27 491 The base of individual sandstone packages is alternatively sharp or scoured into the thin-bedded  
28  
29 492 unit underneath (Fig. 10C). Sandstone packages are made up mostly of ungraded and poorly sorted  
30  
31 493 very coarse (occasionally granule grade) to coarse grained sandstone beds (Fig. 10D), rich in  
32  
33 494 dispersed and often angular mudstone clasts some of which are armoured (Fig. 10E). Tractive  
34  
35 495 granule layers and clast-supported conglomeratic lenses directly overlain by horizontally laminated  
36  
37 496 and rippled fine-grained sandstones facies are common (Fig. 10F), showing evidence of flow  
38  
39 497 bypass. These bodies are interpreted as relatively proximal mid-fan lobes (see Mutti & Ricci  
40  
41 498 Lucchi, 1972; Mutti & Normark, 1987). The top of each of the lobes is marked by an abrupt  
42  
43 499 change to a relatively thin (about 1-2 m thick) mud-prone unit constituted by thin-bedded events.  
44  
45 500 These finer-grained intercalations are laterally continuous and are consequently interpreted as  
46  
47 501 inter-lobe deposits and related to phases of reduction in sediment supply to the basin.

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50 502 Hybrid event beds are present as rare thin clast-poor hybrid event beds (generally HEB-5; Fig.  
51  
52 503 10G) interbedded with thin bedded turbidites, siltstone and mudstone in the inter-lobe deposits. In  
53  
54 504 few cases thick and clast-rich or raft-bearing types (HEB-3; more rarely HEB-2 and HEB-1) as the  
55  
56 505 first bed at the base of the lobe packages. These beds systematically overlie a mud-rich inter-lobe  
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3 506 package and in a few cases show evidence of partial detachment of the underlying substrate by  
4  
5 507 lateral injection from the base of the bed. Besides these occasional HEBs, a distinctive hybrid-rich  
6  
7 508 interval is found at the base of Gottero 2 unit marking the stratigraphic initiation of the fan. Hybrid  
8  
9 509 event beds in total represent only 8% by thickness of the facies association (Fig. 9B).

### 11 **(B) FA-C Outer-fan lobes**

12  
13  
14 511 The intermediate part of the system in the Gottero 3 unit (in Moneglia and Terrarossa localities;  
15  
16 512 Fig. 4) is dominated by 5-20 m thick, thickening-upward or symmetric bed sequences (Fig. 11)  
17  
18 513 constituted by coarse-grained and poorly sorted high-density turbidites, mudstone clast-rich beds  
19  
20 514 and hybrid event beds (Fig. 12). These are interbedded with heterolithic sandstone-mudstone  
21  
22 515 packages containing thin-bedded LDTs and HEBs. The overall St% is estimated at 79% (Fig. 9C).

23  
24 516 The basal boundary of the sandy packages with inter-bedded fine-grained units is characterised by  
25  
26 517 a progressive upward coarsening and thickening of the beds. The upper boundary can be sharp and  
27  
28 518 marked by a bypass surface or expressed by a more progressive bed thinning. Beds constituting the  
29  
30 519 sandy packages exhibit lateral continuity (but rapid thickness changes) at 100s m outcrop-scale, but  
31  
32 520 are poorly correlated at km-scale. The high-density turbidites generally have very thin mudstone  
33  
34 521 caps (average sandstone-to-mud cap ratio about 3:1) and in most cases they comprise only a basal  
35  
36 522 sandstone, with no laminated upper division. Many beds have angular to sub-rounded mudstone  
37  
38 523 clasts (sometimes armoured) mostly concentrated at the very top of the bed (MRBs: 36%).  
39  
40 524 Conglomeratic lenses or beds including granule traction carpets are also occasionally present.

41  
42  
43 525 These characteristics define a sub-environment where turbidity flows bypassed their finer grain  
44  
45 526 sizes which are mostly missing and were presumably transported further down-dip. The sandy  
46  
47 527 units are interpreted as relatively distal outer-fan sandstone lobes. The complex changes in the  
48  
49 528 vertical bed thickness stacking are interpreted as an effect of local lobe progradation (Mutti &  
50  
51 529 Ghibaudo, 1972; Mutti & Ricci Lucchi, 1972), compensational stacking (Mutti & Sonnino, 1981)  
52  
53 530 or autocyclic lateral lobe axis switching (Macdonald et al., 2011; Pr elat & Hodgson, 2013). Lateral  
54  
55 531 lobe switching is also suggested by the repeated deviations in the palaeoflow indicators (from  
56  
57 532 WNW to ENE) in the Moneglia locality where this facies association is prevalent (see Fig. 3).

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2  
3 533 Thin-bedded mud-prone packages are interpreted as distal or lateral lobe fringes rather than  
4  
5 534 allocyclic phases of reduced sediment supply, because of their poor correlatability between lateral  
6  
7 535 sections.

8  
9  
10 536 Hybrid event beds represent 15% by thickness of this facies association (Figs. 9C, 12). The most  
11  
12 537 common HEB types include HEB-5 (49% of all HEBs) and HEB-6 (13% of all HEBs). Hybrid  
13  
14 538 event beds with larger mudstone clasts (HEB-3 and HEB-4), substrate slabs (no larger than 2 m)  
15  
16 539 and chaotic textures (HEB-1 and HEB-2) are rare and usually found as outsized event beds directly  
17  
18 540 overlying a mudstone-rich package. HEB-5 and HEB-6 beds are mostly found at the base of  
19  
20 541 thickening-upward lobe cycles together with mudstone-clast rich beds of similar size or as part of  
21  
22 542 thin-bedded inter-lobe packages. They can be vertically organised with beds having relatively  
23  
24 543 thinner H1 divisions located at the base of the thickening-upward cycles and progressively  
25  
26 544 substituted by beds with a thicker H1 division towards the top. Occasionally some thin hybrid beds  
27  
28 545 lack an H1 division, testifying to their very distal position with respect to the axis of the lobe  
29  
30 546 (distal lobe fringe). The HEBs interbedded inside the lobe packages are interpreted as genetically  
31  
32 547 related to the lobe axis cleaner beds and representing the deposits of lateral or frontal lobe fringes  
33  
34 548 (Haughton et al., 2003; Hodgson, 2009; Kane & Pontén, 2012; Kane et al., 2017).

35  
36  
37 549 **(B) FA-D Basin plain weakly amalgamated sheets**

38  
39 550 This facies association is constituted by distinctive weakly amalgamated sandy packages (7 to 20  
40  
41 551 m thick) made of generally thick event beds (mostly hybrid event beds) interbedded with the  
42  
43 552 otherwise poorly amalgamated succession of the Gottero 3 unit in the Mt. Ramaceto (Figs. 13 and  
44  
45 553 14) and in part of the Mt. Zatta succession. The facies association has an overall St% of about 71%  
46  
47 554 (Fig. 9D). The sandy packages do not display significant lateral thickness variations, at least at  
48  
49 555 scales of up to up to 3 km, but individual beds are poorly correlated due to a high-aspect ratio  
50  
51 556 lenticular shape or display important thickness changes at 100s of m-scale interpreted as  
52  
53 557 compensational patterns (Mutti & Sonnino, 1981) in contrast to the surrounding tabular succession  
54  
55 558 (see FA-E). Beds are coarse to fine grained, well-graded and generally thick, usually preserving a  
56  
57 559 laminated upper division and a thin mudstone cap.

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3 560 The described units are interpreted as basin plain composite sand-bodies developed in the distal  
4  
5 561 part of the Gottero system (Mutti & Ricci Lucchi, 1972; Mutti & Normark, 1987). The  
6  
7 562 relationships with the more proximal mid-fan and outer-fan lobes are unclear, but they presumably  
8  
9 563 represent separate sand-bodies developed in a down-dip depocentre and are not the distal  
10  
11 564 expression of outer-fan lobes. These units are stratigraphically interbedded and probably  
12  
13 565 genetically associated with the distal Gottero basin plain sheets (FA-F) of which they could  
14  
15 566 represent an architectural pattern developed when the basin was not fully ponded and individual  
16  
17 567 flows could not spread across the entire basin floor developing an internal compensational  
18  
19 568 geometry.

20  
21  
22 569 Hybrid event beds are the most common bed type in FA-D units (54% in thickness; Fig. 9D) and  
23  
24 570 include a wide variety of types (HEB-3, 30%; HEB-4 28%, HEB-2, 22%, HEB-1 17%; HEB-5  
25  
26 571 3%) with the majority on the mudstone clast and raft-bearing types.

#### 27 28 29 572 **(B) FA-E Confined basin plain isolated sheets**

30  
31 573 The distal sector of the Gottero 3 unit (Mt. Ramaceto and part of Mt. Zatta) is dominated by  
32  
33 574 laterally-extensive, thick event beds (i.e. sheets; Fig. 13) associated with thick mudstone caps, thin-  
34  
35 575 bedded sandy packages and rare limestone and marly intervals (Figs 9E, 15 and 16). The  
36  
37 576 succession has a St% of about 54% on average, and decreasing from the bottom to the top. Grain  
38  
39 577 size of the sandstones varies from very coarse to very fine-grained and beds are generally well  
40  
41 578 graded, without displaying abrupt internal grain size changes or evidence of amalgamation. Many  
42  
43 579 turbidites and hybrid event beds have complex and thick topmost fine-grained divisions including  
44  
45 580 repetitions of structured and unstructured sandstones, wavy sinusoidal laminations and  
46  
47 581 homogeneous silty graded caps with pseudonodules. Those characteristics, in association with  
48  
49 582 thick mudstone caps (average sandstone-to-mud cap ratio for single bed about 1:3), are interpreted  
50  
51 583 to represent the effect of deflection or ponding of the dilute part of turbidity currents (Pickering &  
52  
53 584 Hiscott, 1985; Remacha et al., 2005; Haughton, 2001; Muzzi Magalhaes & Tinterri, 2010; Tinterri,  
54  
55 585 2011; Patacci et al., 2015). Therefore the present facies association is interpreted as the distal  
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3 586 depositional fill of a confined and relatively sand-rich basin plain (Mutti & Johns, 1982; Remacha  
4  
5 587 et al., 2005; Mutti et al., 2009; Pickering & Hiscott, 2015).

6  
7  
8 588 Hybrid event beds in this setting represent the vast majority of the thicker event beds and comprise  
9  
10 589 31% by thickness of the succession (Fig. 9E). The majority of hybrid event beds are represented by  
11  
12 590 HEB-3 (49%), with the remaining part roughly equally split between HEB-4 (19%), HEB-1 (15%)  
13  
14 591 and HEB-2 (13%). The mixed fine-grained HEBs are very rare with only 5% represented by HEB-  
15  
16 592 5 and no HEB-6. Transitions between different HEBs bed types and between HEBs and MRBs or  
17  
18 593 HDTs are very common along correlative beds. The lateral changes typically involve variations in  
19  
20 594 the proportion of the cleaner basal sandstone and the overlying H3 mudstone-clast rich sandstone  
21  
22 595 divisions and the texture of H3 division. These changes normally occur without substantial  
23  
24 596 variations in the overall bed thickness (Fonnesu et al., 2015).

25  
26  
27 597 Hybrid event beds (or more rarely mudstone-clast rich beds) commonly have a scoured base  
28  
29 598 demonstrating the flows were able to erode the underlying substrate for 10s of cm to a maximum  
30  
31 599 depth of about 2 m. Shallow and elongated scours are preferentially found underneath HEB-3 or  
32  
33 600 MRBs. Deeper scour features can be detected from detailed bed-by-bed correlations mostly  
34  
35 601 underneath HEB-1 or HEB-2 beds eroding into earlier mud caps or thin-bedded heterolithic  
36  
37 602 packages.

### 40 **(B) FA-F Thin-bedded basin plain and slope deposits**

41  
42 604 Fine-grained thin-bedded intervals are commonplace throughout the Gottero system but only rarely  
43  
44 605 constitute thick (10s to 100s of metres) distinctive packages. These fine-grained and mud-rich units  
45  
46 606 have an average St% of 51%. A widespread and wedge-like fine-grained unit is located at the base  
47  
48 607 of Gottero succession (Fig. 4), making up the Gottero 1 unit (see Marini, 1991). This includes  
49  
50 608 slope deposits with common multi-bed slumps in the proximal Monterosso location to a  
51  
52 609 monotonous succession of thin-bedded, graded and ripple-structured low-density turbidites (LDTs)  
53  
54 610 and occasionally limestone beds (L) in intermediate (Riva Trigoso) and distal locations (Mt. Zatta -  
55  
56 611 Mt. Ramaceto) interpreted as basin plain deposits.

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3 612 **(A) HYBRID EVENT BED GROUPS AND FACIES TRACTS**  
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5 613 The sedimentological character of the hybrid event beds, the vertical and lateral bed type changes  
6  
7 614 and transitions, and the facies associations in which they occur, confirm that these beds can have a  
8  
9 615 variable make-up and hence different lateral and longitudinal facies tract expression. The hybrid  
10  
11 616 event bed types described here can be split in two main groups which are thought to have a  
12  
13 617 different origin: 1) beds in which the major component of the H3 division is made up of substrate  
14  
15 618 clasts (ranging from few cm to several metres and 2) beds which include a H3 division with a clay-  
16  
17 619 rich and relative clast-poor texture.  
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20  
21 620 **(B) Mudstone-clast and raft-bearing hybrid event beds (HEBs 1-4)**  
22

23 621 Hybrid event beds attributed to the first class are represented by HEB-1 to HEB-4 types. Beds of  
24  
25 622 these types are mostly found in the confined basin plain areas (FA-D and FA-E) but also (with  
26  
27 623 lower relative abundances) at the base of lobe sequences in more proximal fan areas (FA-B and  
28  
29 624 FA-C), in particularly when the lobe units lie directly on top of inter-lobe fine-grained intervals.  
30

31 625 As demonstrated by the physical correlations of the stratigraphically upper part of the Mt.  
32  
33 626 Ramaceto section (Figs. 13 and 16) hybrid event bed types HEB-1 to HEB-4 can be laterally  
34  
35 627 correlated with one another and therefore represent the expression of the same facies tract. A facies  
36  
37 628 tract represents the lateral or longitudinal bed expression of the same depositional event (Mutti,  
38  
39 629 1992). However, the limited down-dip window in which individual beds can be followed (4 km)  
40  
41 630 cannot capture the complete set of flow transformations in a single correlated bed and multiple  
42  
43 631 beds have to be taken into account in order to reveal the wider t set of lateral transitions. Individual  
44  
45 632 beds show a general down-dip change from thick clean sandstone beds (HDTs) to mudstone-clast  
46  
47 633 enriched hybrid event beds (HEB-1 to 4) (Fig. 17). Field observations suggests that this transition  
48  
49 634 can happen along two distinct facies tract types characterised by different proximal bed types, but  
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51 635 with a similar distal expression.  
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3 636 (C) *FTH-1 Hybrid flow evolution via entrainment of abundant mud clasts*

4 637 In the first facies tract type (FTH-1; Fig. 18A), clean HDTs undergo a down-dip change to hybrid  
5  
6 638 event beds by the acquisition, segregation and breakup of cm- to dm-size mudstone clasts. Clasts  
7  
8 639 are thought to have been collected by delamination of relatively local substrate, as demonstrated by  
9  
10 640 the common formation of composite shallow scours (some 10s of cm deep) on the lower surface of  
11  
12 641 the bed (see Bed 14 - Fonesu et al., 2016). Mud clasts were entrained at the base of the flow, and  
13  
14 642 were presumably suspended by their buoyancy and dispersive pressure in the high-concentration  
15  
16 643 lower part of the flow (Postma et al., 1988). HDTs thus transition down dip into beds with  
17  
18 644 increasing volumes of mudstone clasts (MRBs) which tend to accumulate progressively in higher  
19  
20 645 parts of the bed vertical profile. In both HEBs and MRBs, mudstone clasts and argillaceous  
21  
22 646 sandstones are always contained in the basal relatively coarse grained and mostly structureless part  
23  
24 647 of the bed beneath the Tb division, whereas the finer-grained laminated part is always made of  
25  
26 648 clean sandstone (Tb-e; H4 division). This observation suggests that turbulence suppression and/or  
27  
28 649 an increase in flow cohesion happened in the near-bed, high-concentration part of the flow along  
29  
30 650 the interface with the upper highly turbulent region (see Mutti & Nilsen, 1981 and Postma et al.,  
31  
32 651 1988). The clasts can be rapidly buried by fall out of sand from suspension at the level they were  
33  
34 652 able to reach as they were carried by the dense flow (Mutti & Nilsen, 1981), or accumulated at the  
35  
36 653 top of the aggrading bed, where they started to move as a shearing boundary layer. Evidence of  
37  
38 654 active shear includes the crude stratification of oblate mudstone clasts, occasional imbrication and  
39  
40 655 deformed sand patches in a very heterogeneous sandy-matrix. Clast-to-clast friction and sand-  
41  
42 656 injections extending from the overpressured sandy base of the flow were able to systematically  
43  
44 657 fragment the clasts and release both mud chips and dispersed clay which mixed with the  
45  
46 658 surrounding sandy matrix. Dewatering of the basal sand may have also sustained the transport of  
47  
48 659 what were pseudo-cohesive flows producing a thin overpressure water layer on which the flow  
49  
50 660 decoupled and hydroplaned (Haughton et al., 2009). Clast over-concentration and clay release  
51  
52 661 would have progressively increased the cohesiveness of the flow forcing it to arrest *en-masse*,  
53  
54 662 depositing beds with H3 divisions characterised by poorly-sorted mudstone clasts surrounded by a  
55  
56 663 clay-enriched sandy matrix (HEB-3). Clast attrition would have produced progressively finer clasts  
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3 664 that were deposited in more distal locations resulting in HEB-4. The longitudinal and lateral  
4  
5 665 transition from MRB to HEB-3 and HEB-4 can be irregular and highly variable at short-length  
6  
7 666 scales due to the complex interfingering between the up-dip sandstone-dominated part of the bed  
8  
9 667 and the down-dip muddier section due to pattern of concentration of clasts and clay in the flow  
10  
11 668 (Fonnesu et al., 2015), or by the uneven pattern of substrate entrainment (Fonnesu et al., 2015;  
12  
13 669 2016; Southern et al., 2015). An example of this facies tract is provided by Bed 12, which  
14  
15 670 preserves a 1.6 km down-flow transition from mudstone clast-poor massive turbidite bed (HDT) to  
16  
17 671 a mudstone-clast rich hybrid event bed (HEB-3) via an intermediate MRB bed (Fig. 17A).

18  
19  
20 672 *(C) FTH-2 Hybrid flow evolution via substrate rafts disaggregation*

21 673 A second type of hybrid event bed facies tract (FTH-2; Fig. 18B) involves both lateral and down-  
22  
23 674 dip transitions between raft-bearing and chaotic hybrid event beds (HEB-1 and HEB-2) with  
24  
25 675 mudstone clast-bearing HEBs (HEB-3 and HEB-4). The up-dip equivalent bed type referred to this  
26  
27 676 facies tract is uncertain, but a limited number of beds show transition from proximal coarse-  
28  
29 677 grained high-density turbidites (HDTs) lacking mudstone clasts. This type of facies tract is  
30  
31 678 interpreted to have been generated by flows that were able to deeply erode the underlying substrate  
32  
33 679 and which were capable of detaching and transporting large pieces of remobilized stratigraphy. The  
34  
35 680 mechanism of raft entrainment was probably related to a combination of lateral sand-injection and  
36  
37 681 contemporaneous slab detachment, triggered by flow pressure variations or enhanced turbulence at  
38  
39 682 the front of high-concentration and high-volume flows (Fonnesu et al., 2016). The evidence for  
40  
41 683 erosion cutting down several metres beneath parts of some HEB-1 and HEB-2 beds (Fig. 18B), and  
42  
43 684 matches between the texture and character of the rafts and the underlying substrate, suggest that the  
44  
45 685 blocks were mostly sourced locally. Intact substrate rafts were presumably transported for short  
46  
47 686 distances remaining relatively undeformed (HEB-1), partially ploughing into the unconsolidated  
48  
49 687 basal sand (Fonnesu et al., 2015). Alternatively they may have been entrained in the flow and  
50  
51 688 deformed by shear forming a chaotic texture, or partly invaded and broken up by sand-injections  
52  
53 689 sourced from the basal sand (HEB-2). The basal H1 sand was probably overpressured to be able to  
54  
55 690 support gliding mudstone rafts on top of the just-deposited basal sand with associated hydro-plastic  
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3 691 deformation of the blocks (SC facies; Fig. 6) and their lateral disaggregation as part of a shearing  
4  
5 692 near-bed-layer. Both downcurrent and lateral to the entrained rafts, a mud clast rich flow, partially  
6  
7 693 derived by spalling of fragments from the rafts as they disaggregated, forming HEB-3 and HEB-4  
8  
9 694 beds. A partial example of this down-flow facies transition is provided by Bed 15.4 in which a  
10  
11 695 heterolithic raft-bearing bed erosively cuts through the underlying thin-bedded substrate in the most  
12  
13 696 proximal section, transforming down-dip into HEB types containing smaller mudstone clasts  
14  
15 697 (HEB-3) with occasional pieces of deformed stratigraphy still preserved (Fig. 17B).

16  
17  
18 698 *(C) Distal expression of FTH-1 and 2*

19 699 The normally graded and laminated capping sandstones (H4 divisions) that are developed in both  
20  
21 700 facies tracts are thought to have been deposited just prior to or after the underlying H3 deposit  
22  
23 701 arrested by a slower moving dilute turbulent wake of the flow. The dilute turbulent cloud can  
24  
25 702 potentially have run-out further than the parent high-concentration flow and deposited down-  
26  
27 703 current as a fine-grained normally graded bed (see examples of Amy et al., 2005; Amy & Talling,  
28  
29 704 2006; Muzzi Magalhaes & Tinterri, 2010; Talling et al., 2012; Fonnesu et al., 2015).

30  
31  
32  
33 705 It is reasonable to think that HEB-3 or HEB-4 can transform distally into HEB-5 or HEB-6, if the  
34  
35 706 flow had enough space to evolve and the process of particle disintegration, hydraulic segregation  
36  
37 707 and clay release remained efficient. Examples of similar lateral transitions from very extensive  
38  
39 708 basin plains are provided by Amy & Talling (2006) and Muzzi Magalhaes & Tinterri (2010).  
40  
41 709 However, in the Gottero case study, this evolution is statistically insignificant. The possible  
42  
43 710 reasons could be: 1) the process of clast disaggregation was not efficient enough; 2) the Mt.  
44  
45 711 Ramaceto section is still relatively proximal; 3) the basin was too small and the flows did not have  
46  
47 712 the space to undergo a complete evolution.

48  
49  
50 713 **(B) Clast-poor and clay-rich hybrid event beds (HEBs 5-6)**

51  
52 714 HEB-5 and HEB-6 have a H3 division which is more depleted in mudstone clasts but enriched in  
53  
54 715 pore-filling clay in comparison to the other HEB types. HEB-5 and HEB-6 appear mostly  
55  
56 716 interbedded and systematically arranged in FA-B and FA-C facies associations, located in the  
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3 717 proximal and intermediate Gottero system sectors. Because these HEBs mostly developed in lobe  
4  
5 718 settings controlled by compensational stacking, progradation or lateral switching, it is possible to  
6  
7 719 infer that the systematic vertical distribution of bed thickness and bed types could represent the  
8  
9 720 expression of a longitudinal and lateral bed facies tract, according to the Walther's law. A similar  
10  
11 721 approach has been adopted by Middleton (1973) and Kane & Pontén (2012).

12  
13  
14 722 *(C) FTH-3 Hybrid flow evolution via clay enrichment and fractionation*

15 723 The inferred longitudinal facies tract (FTH-3; Fig. 18C), results in a progressive decrease of the H1  
16  
17 724 thickness and a simultaneous expansion of the H3 division in HEB-5 beds. It distally culminates in  
18  
19 725 the reduction and pinch-out the basal sandstone (and eventually of the overlying H2 banded  
20  
21 726 division), followed by distal pinch out of the H3 division. The dilute turbulent wake responsible for  
22  
23 727 deposition of the graded and laminated H4 division can outrun the deposit of the hybrid flow, and  
24  
25 728 settle in more distal and lateral lobe fringes. In mud-rich lobe fringe sequences, HEB-6 beds  
26  
27 729 containing an argillaceous unsorted interval developed above a graded and well-structured thin  
28  
29 730 bed, are commonly found and interpreted as the most distal and lateral expression of the facies  
30  
31 731 tract.

32  
33  
34 732 The facies tract is interpreted to be the expression of the progressive deceleration and turbulence  
35  
36 733 damping of a mud-enriched flow. The presence of a higher amount of organic matter in the H3  
37  
38 734 division may suggest that most of the cohesive material could be bulked in the flow in a more  
39  
40 735 proximal location than in the other flow types (Hodgson, 2009). A significant amount of fines can  
41  
42 736 be entrained in up-dip fan sectors at channel mouths, proximal lobes or flow expansion points  
43  
44 737 (Haughton et al., 2003; 2009; Talling et al., 2004), maybe on account of hydraulic jump-related  
45  
46 738 erosion (Mutti and Normark, 1987; Mutti, 1992). Alternatively, the facies tract could represent the  
47  
48 739 deceleration and/or fractionation of already clay-laden flows (Haughton et al., 2003). The presence  
49  
50 740 of hydraulically-fractionated flaky materials in HEB-5 beds suggests the onset of efficient  
51  
52 741 longitudinal and transverse segregation of components with lower settling velocities (see Pyles et  
53  
54 742 al., 2013) leading to a transitional to laminar flow conditions (Haughton et al., 2009; Kane and  
55  
56 743 Pontén, 2012; Kane et al., 2017). Alternatively the same bed types could derive from the vertical  
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3 744 segregation of the mud components via top-down turbulence damping in a transitional flow  
4  
5 745 (Sumner et al., 2009; Baas et al., 2009). This model predicts initial onset of near-bed turbulence  
6  
7 746 enhancement before the turbulence is eventually damped. This is consistent with the presence of  
8  
9 747 flute casts at the base of HEB-5 beds, suggesting that the basal flow was more turbulent than in the  
10  
11 748 other HEB types which are dominated by tabular scours and grooves.

12  
13  
14 749 The occasional presence of a banded H2 division in HEB-5 beds, a feature not observed in other  
15  
16 750 bed types, reflects a more gradational change in flow rheology from a turbulent flow to a  
17  
18 751 transitional and then a cohesive and turbulent suppressed flow (Haughton et al., 2009; Davis et al.,  
19  
20 752 2009). The facies tract predicts that the very distal expression of this kind of flow is represented by  
21  
22 753 thin LDTs representing the distal run-out of the trailing turbulent wake which in the more proximal  
23  
24 754 location forms the H4 division. Alternatively the flow can express further transformation recorded  
25  
26 755 by the deposition of HEB-6 beds. In HEB-6, fine-grained mud-enriched sand is deposited on top of  
27  
28 756 a laminated and/or rippled sandstone. The development of a further ungraded sandy, but clay-rich  
29  
30 757 interval, distinctive from a normal mud cap, is interpreted to be related to vertical clay segregation  
31  
32 758 leading to top-down turbulence damping and formation of a mud plug (see Baas et al., 2009;  
33  
34 759 Sumner et al., 2009) in a decelerating flow (Pierce, 2015). The common presence of ripples instead  
35  
36 760 of parallel lamination below the muddy unit in this kind of bed can be related to a slight turbulence  
37  
38 761 enhancement due to the onset of the plug flow (Baas et al., 2009; 2011). Therefore the deposition  
39  
40 762 of the mud-rich interval observed in HEB-6 beds can be interpreted as a mud-enriched flow  
41  
42 763 produced by a secondary turbulence damping episode following the deposition of the trailing  
43  
44 764 turbulent wake, due to the hydraulic separation of clay at the end of current runout (Pierce, 2015).

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48 765 **(A) DISCUSSION**

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51 766 **(B) Hybrid event bed types distribution in Gottero system sub-environments**

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53 767 The two previously highlighted hybrid event bed groups (mudstone-clast rich HEBs and clast-poor  
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55 768 HEBs) are found in different facies associations and hence different Gottero sub-environments.  
56  
57  
58 769 This pattern indicates HEB character and relative abundance is strictly dependent on  
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3 770 palaeogeographic location within the Gottero system. As general rule, the proximal area of the  
4  
5 771 Gottero system is interpreted as a relatively unconfined fan system and mainly includes clast-poor  
6  
7 772 and clay-rich hybrid event beds; the down-dip confined basin plain sectors are in contrast  
8  
9 773 dominated by extensive mudstone-clast rich and raft-bearing HEBs.

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11  
12 774 The most proximal sectors of the Gottero system, including the slope channels fills, sand-prone  
13  
14 775 channel lobe transition zone (FA-A), and slope deposits (FA-F), are completely devoid of hybrid  
15  
16 776 event beds. HEBs have been reported in channelized or proximal fan sectors in a few cases (e.g.  
17  
18 777 East Carpathian Flysch, Romania; Sylvester & Lowe, 2004; Ross Sandstone Formation, Western  
19  
20 778 Ireland; Schiehallion Field, West Atlantic margin; Haughton et al., 2009; Champsaur channel  
21  
22 779 complex, SE France; Vinnels et al., 2010; channelized Permian Brushy Canyon Formation, West  
23  
24 780 Texas U.S.A.; Haughton et al., 2009), but are generally uncommon. This is despite the fact that  
25  
26 781 substrate erosion and clast rip-up are common in these settings; however, erosion products tend to  
27  
28 782 end up deposited in poorly organized mudstone-clast conglomerates rather than hybrid event beds.  
29  
30 783 The clast rip-up is probably mostly linked to local erosion and bypass-lag formation. A possible  
31  
32 784 explanation behind the absence of HEBs in this setting may be that the flow constriction by the  
33  
34 785 channel margins or the onset of hydraulic jumps at the channel-lobe transition, could temporarily  
35  
36 786 increase the flow turbulence (Talling et al., 2007; Kane et al., 2017) preventing the turbulence  
37  
38 787 suppression and hybrid bed deposition until the flows were eventually able to distally expand and  
39  
40 788 decelerate. The loose mud eroded from the substrate could be easily elutriated and transferred to  
41  
42 789 upper turbulent cloud well away from the bed increasing the run-out of the high-density flows  
43  
44 790 (Mohrig & Marr, 2003; Tinterri et al., 2003; Breien et al., 2010), with eventual deposition  
45  
46 791 downslope as mud caps.

47  
48  
49 792 Hybrid event beds are present in the Gottero system in mid- and outer-fan areas (comprising about  
50  
51 793 15% of the event bed inventory by thickness) where they can be found within three stratigraphic  
52  
53 794 contexts. Thin HEBs (HEB-5 and 6, very rarely HEB-4) are interbedded in widespread fine-  
54  
55 795 grained inter-lobe facies that alternate with thick amalgamated lobe sequences (FA-B). The mud  
56  
57 796 necessary to suppress the flow turbulence could be sourced from original slope failures or by  
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3 797 progressive entrainment from poorly compacted substrate, providing clay and small mud chips. A  
4  
5 798 second occurrence comprises clay-enriched HEBs (HEB-5 and HEB-6) that are found interbedded  
6  
7 799 in lobe sequences (FA-C) as a precursor of thickening upward cycles or in thin-bedded bundles  
8  
9 800 interpreted as lobe fringe deposits. These HEBs are thought to have formed from flows that  
10  
11 801 entrained clay up-dip (from channel-lobe transition zones, slope or proximal lobe settings) and  
12  
13 802 underwent progressive turbulence damping and deceleration in distal and lateral lobe fringes. They  
14  
15 803 are thought to be genetically linked with MRBs and HDTs beds observed in the overlying axial  
16  
17 804 lobe deposits. Similar models have been invoked in the Jurassic of North Sea (Haughton et al.,  
18  
19 805 2003), in the Permian Karoo basin (Hodgson, 2009; Kane et al., 2017) and in the Paleogene  
20  
21 806 Wilcox Formation (Kane & Pontén, 2012), in which hybrid event beds are common in the lower  
22  
23 807 prograding base of lobe sequences, being the expression of distal lobe fringes. The presence of  
24  
25 808 armoured mudstone clasts with sand or granules grains in the MRBs vertically associated with the  
26  
27 809 HEBs suggests that at least part of the mud entrained was derived from more proximal fan areas,  
28  
29 810 rather than from the local seabed erosion. A third context in mid-fan and outer-fan sectors in which  
30  
31 811 hybrid event beds can be found is at the base of lobe sequences (FA-B and FA-C) directly  
32  
33 812 overlying mud-rich inter-lobe deposits. In this case they are expressed as thick mudstone clasts or  
34  
35 813 raft-bearing HEBs (HEB-1; HEB-2; HEB-3) which are otherwise rare in the various unconfined  
36  
37 814 fan facies associations. By analogy with the hybrid event beds found in the distal confined basin  
38  
39 815 plain and by the repetitive association with a muddy substrate, these beds are thought to have  
40  
41 816 formed by local delamination and clast entrainment, controlled by the availability of a widespread  
42  
43 817 muddy substrate, combined with the first high magnitude flows to arrive after a lobe avulsion.  
44  
45  
46 818 In the distal areas of the Gottero system where basin topography was flat (e.g. a confining basin  
47  
48 819 plain setting), an aggradational stacking pattern dominated. Here a marked change in the character  
49  
50 820 of the hybrid event beds occurs. HEB-5 and 6 are very uncommon in this setting and are replaced  
51  
52 821 by generally very thick and tabular, laterally-extensive hybrid event beds (HEB-1 to HEB-4).  
53  
54 822 These are found as isolated beds (FA-D), or more rarely in weakly amalgamated packages (FA-C),  
55  
56 823 and usually include thick mudstone caps. Similar stacking patterns have been observed in examples  
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3 824 located in the Castagnola ponded basin (Southern et al., 2015; Marini et al., 2016) or in the  
4  
5 825 extensive foredeep basin plain of the Marnoso Arenacea (Ricci Lucchi & Valmori, 1980; Amy &  
6  
7 826 Talling, 2006; Muzzi Magalhaes & Tinterri, 2010; Tinterri & Muzzi Magalhaes, 2011; Talling et  
8  
9 827 al., 2012; Tinterri & Tagliaferri, 2015).

### 10 11 828 **(B) Controls on hybrid event bed development in the Gottero system**

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13  
14 829 The importance of external factors on the development of hybrid event beds has been stressed by a  
15  
16 830 number of authors (Haughton et al., 2003; 2009; Talling et al., 2004; Hodgson et al., 2009). Non-  
17  
18 831 equilibrium feeder systems or slopes (e.g. Ross et al., 1994), occurring for both stratigraphic and  
19  
20 832 tectonic reasons, could cause proximal erosion and clay acquisition leading to the development of  
21  
22 833 hybrid flows down-dip (Haughton et al., 2009; Muzzi Magalhaes and Tinterri, 2010; Tinterri and  
23  
24 834 Muzzi Magalhaes, 2011). In tectonically quiescent basins such as the Karoo Basin (Skoorsteenberg  
25  
26 835 Formation) or the Ross Sandstone Formation, western Ireland, it has been suggested that hybrid  
27  
28 836 event beds generation could be related to phases of fan initiation and growth (Hodgson, 2009;  
29  
30 837 Haughton et al., 2009) and controlled by relative sea level falls during early low-stand periods,  
31  
32 838 with consequent increase of sediment supply, flow efficiency and hence capacity for erosion  
33  
34 839 (Hodgson, 2009). A similar process can probably explain the onset of a HEB-prone package at the  
35  
36 840 base of the Gottero 2 unit (Fig. 4), which marks the initiation of the sand-prone Gottero fan.  
37  
38 841 Nevertheless, the Gottero system remains hybrid-prone throughout most of its history, and the  
39  
40 842 variable character and abundance of hybrid event beds appears to be linked to their arrangement in  
41  
42 843 different sub-environments, rather than to external factors. The Gottero hybrid events thus seem to  
43  
44 844 reflect autogenic and intrabasinal factors such as lateral shifting of lobe axes and fringes, flow  
45  
46 845 magnitude and type of substrate. A subsidiary control could be the physiography of the basin, in  
47  
48 846 particular the onset of confined and ponded conditions towards the end of the Gottero basin fill.

### 50 51 847 *(C) Lobe compensational stacking*

52  
53 848 Hybrid event beds have been recognised interbedded with prograding or laterally shifting outer-fan  
54  
55 849 lobes, as part of packages interpreted as lobe fringes. Hodgson (2009) documented that hybrid  
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57 850 event beds can be concentrated in the basal basinward-stepping phases of turbidite lobes, and be  
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3 851 virtually absent during retreat stages. The same pattern has been recognised at multiple scales  
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5 852 (from lobe to fan); including HEBs concentrated in the lower part of overall prograding fan  
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7 853 successions (Haughton et al., 2009). Nevertheless, a similar pattern has not been observed in the  
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9 854 Gottero system, where hybrid beds are present during most of its evolution, and are not more  
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11 855 common at any particular stratigraphic level. In the outer-fan Gottero 3 sections (Moneglia; FA-C),  
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13 856 HEB-5 and HEB-6 beds are found within the thinner bedded portions of thickening- or thinning-  
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15 857 upward cycles, independent of their stratigraphic level, suggesting that their occurrence is linked to  
16  
17 858 the establishment of lobe off-axis or fringe facies preceding or following amalgamated lobe axis  
18  
19 859 facies. Their occurrence in vertical sections is therefore only related to the lateral shifting or  
20  
21 860 progradation of lobes that are constantly hybrid-prone in their fringes. The dynamic of lobe  
22  
23 861 shifting could be controlled by rapid distributary channel avulsions (when there is a rapid vertical  
24  
25 862 transition between coarse-grained amalgamated and thin-bedded intervals), or by lobe progradation  
26  
27 863 or swinging across strike (see Pr elat & Hodgson, 2013).

28  
29  
30 864 *(C) Flow magnitude and entrainment processes*

31  
32 865 Flow volume and concentration control flow run-out distance (Mutti, 1992; Dorrell et al., 2014)  
33  
34 866 and flow interaction with the sea floor (Stevenson et al., 2013), shifting basinward or landward the  
35  
36 867 area of flow bypass and deposition (Mutti et al., 1994), and influencing the mechanism of mud  
37  
38 868 entrainment. The Gottero system contains a wide spectrum of flow types, which deposited their  
39  
40 869 sediment load in different locations (Fig. 19). 1) High-magnitude flows are thought to have  
41  
42 870 generally bypassed the fan area (see Mutti & Johns, 1982; Remacha et al., 2005; Fonnesu et al.,  
43  
44 871 2016), and deposited in the confined distal basin plain (high-efficiency), developing thick clast-rich  
45  
46 872 HEBs (type 1 to 4). 2) Smaller volume flows that deposited the bulk of their sedimentary load in  
47  
48 873 the more proximal fan system (low-efficiency), developing compensating lobes and clast-poor  
49  
50 874 HEBs (type 5 and 6) in the lobe fringes close to the run-out limit. The presence of very different  
51  
52 875 flow types is typical of tectonically-active basins in convergent settings (Mutti et al., 1984; Mutti et  
53  
54 876 al., 2009).

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3 877 High-magnitude flows are thought to be responsible for the deposition of turbidite beds of  
4  
5 878 exceptionally large volume and extent (in comparison with basin size) which presumably filled the  
6  
7 879 entire Gottero basin plain. Most of them deposited thick hybrid event beds attributed to types 1 to  
8  
9 880 4. Uncertainties on the location of basin boundaries do not allow a precise reconstruction of the  
10  
11 881 volumes involved. However, considering the sandy part of the thickest event bed recorded in the  
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13 882 Mt. Ramaceto section (9.5 m) and its minimum areal extension (150 km<sup>2</sup>, but possibly much  
14  
15 883 larger), the total sand volume transported could be greater than 1.3 km<sup>3</sup>. Such high volume event  
16  
17 884 beds may have been generated by catastrophic failures of the Sardo-Corsican margin which were  
18  
19 885 likely triggered by earthquakes during plate convergence (“seismoturbidites” of Mutti et al., 1984).  
20  
21 886 Those events were able to produce flows that mostly bypassed the more proximal fan area and  
22  
23 887 deposited their sediment load in flexural basin plain depocentres producing beds several metre  
24  
25 888 thick. The facies interpretation of their H1 division suggests that they were deposited by high-  
26  
27 889 concentration flows. The local mud entrainment documented by the scours and the H3 character is  
28  
29 890 attributed to substrate delamination rather than turbulent erosion.

31  
32 891 Smaller volume flows formed sandstone lobes in the proximal system area, and deposited HEB-5  
33  
34 892 and HEB-6 in the related lobe fringes or interlobe intervals. Because of their relatively small  
35  
36 893 volume, individual flows did not expand to fill the entire basin area, but they deposited their  
37  
38 894 sediment load on the area in front of the feeder channel mouths, forming composite sandbodies  
39  
40 895 showing lenticular and compensational geometries. These smaller-volume flows probably only  
41  
42 896 occasionally reached the distal basin plain area where they deposited laterally extensive fine-  
43  
44 897 grained low-density turbidites, forming distinctive heterolithic thin-bedded packages, but not  
45  
46 898 hybrid event beds. These events were probably triggered by episodic slope failures caused by  
47  
48 899 sedimentary oversteepening (Kastens, 1984; Mutti et al., 1984; Mutti, 1992), as opposed to large  
50  
51 900 seismic shocks. These flows were likely of low concentration in a distal setting and hence  
52  
53 901 generally did not exercise enough pressure on the substrate to trigger sea floor delamination (e.g.  
54  
55 902 except when the substrate was particularly mud-prone). Instead, the mud entrainment could have  
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57 903 been driven by turbulent erosion at the front of the current in up-dip areas, providing disaggregated

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3 904 mud particles into the flow, which then suppressed the flow turbulence, resulting in deposition of  
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5 905 hybrid event beds in the up-dip lobe region.

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8 906 *(C) Substrate mechanical properties*

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10 907 Evidence of substrate delamination features beneath hybrid event beds deposited on the Gottero  
11  
12 908 basin floor supports the hypothesis that local substrate mechanical properties may have had a  
13  
14 909 significant impact on the development of some types of hybrid event bed (Fonnesu et al., 2016).  
15  
16 910 This appears to be the case for mudstone-clast rich, chaotic and raft-bearing HEBs (HEB-1 to 4) in  
17  
18 911 both confined basin plain and locally in fan settings. The preservation of large and undeformed  
19  
20 912 mudstone or heterolithic rafts in HEB-1 beds confirms that the sea floor from which they were  
21  
22 913 derived was relatively firm and cohesive. A relatively compacted sea floor is also inferred in other  
23  
24 914 confined and ponded basins (Castagnola, Southern et al., 2015; Ventimiglia Flysch, Marini et al.,  
25  
26 915 2015b), An explanation could be that the distal setting with respect to their feeder system meant  
27  
28 916 that only a limited number of events reached the basin plain, resulting in a lower gravity flow  
29  
30 917 frequency and a greater time available for the seafloor mud to dewater and consolidate (Mutti &  
31  
32 918 Johns, 1978; Mutti, 1992; Remacha et al., 2005; Fonnesu et al., 2016). As shown by Remacha et al.  
33  
34 919 (2005), and confirmed by the Gottero case study, such a hypothesis is supported by the fact that the  
35  
36 920 number of individual event beds present in the basin plain areas is lower than in the up-dip lobe  
37  
38 921 settings, despite individual beds being thicker in the former case.

39  
40 922 The presence of a firm sea floor does not hinder its delamination; conversely, it allows flows to  
41  
42 923 detach large pieces of substrate which can be carried intact, instead of being disaggregated  
43  
44 924 immediately. The delamination process could be favoured by the presence of planar mechanical  
45  
46 925 weakness in the substrate formed by thin-bedded intervals, early diagenesis or by subtle fabric  
47  
48 926 changes in mudstone caps (Fonnesu et al., 2016). The same kind of effect could happen also in  
49  
50 927 more proximal setting when flows interact with a mud-prone substrate and produce local  
51  
52 928 delamination and formation of mudstone-clast rich, chaotic or raft bearing HEBs at the base of lobe  
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54 929 sequences.  
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3 930 (C) *Effect of basin confinement and ponding*

4 931 Basin physiography and in particular the presence of topographic highs, basin margins, or  
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6 932 confining slopes is a major control on the development and deposition from hybrid flows (Barker  
7  
8 933 et al., 2008; Davis et al., 2009; Muzzi Magalhaes & Tinterri, 2010; Patacci et al., 2014; Southern et  
9  
10 934 al., 2015; Tinterri & Tagliaferri, 2015; Tinterri et al., 2017). The presence of basin floor highs and  
11  
12 935 counter slopes can favour rapid flow deceleration and hence an increase in fallout rate, flow  
13  
14 936 stratification and associated turbulence damping (Talling et al., 2004; Muzzi Magalhaes & Tinterri,  
15  
16 937 2010; Patacci et al., 2014). In addition, flow impact against counter slopes could focus the flow  
17  
18 938 hydraulic pressure and promote substrate delamination processes by hydraulic jacking  
19  
20 939 (Puigdefàbregas et al., 2004). Examples provided by Patacci et al. (2014) from the Braux Unit of  
21  
22 940 the Annot sandstone of SE France illustrate that flow confinement in a relatively proximal position  
23  
24 941 results in the occurrence of HEBs next to the confining slopes, with transitions from clean  
25  
26 942 turbidites to HEBs occurring over short distances (i.e., few hundreds of metres). In a ponded mini-  
27  
28 943 basin settings (e.g. Castagnola system of NW Italy) flows deposited relatively sandy HEBs (MRBs  
29  
30 944 and HEB-3, rarely HEB-1 and HEB-2) without any systematic variation of their depositional  
31  
32 945 character with respect to distance from a counter slope. Such a trend is thought to be due to  
33  
34 946 complex three-dimensional flow dynamics across the enclosed basin and interaction with multiple  
35  
36 947 basin margins, which inhibited the development of coherent depositional trends (Southern et al.,  
37  
38 948 2015). However, based on their work on the Marnoso-arenacea, Peira Cava and Ranzano case  
39  
40 949 studies, Tinterri et al., (2016; 2017), note that where flows are strongly confined (but not ponded)  
41  
42 950 and the flow efficiency is low, the deposition of clay-rich HEBs is hindered, favouring the  
43  
44 951 deposition of structureless beds with basal impact structures (*sensu* Mutti, 1992) or with traction  
45  
46 952 reworked tops due to enhanced flow bypass

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49  
50 953 The distal and upper part of the Gottero system (Mt. Ramaceto section) was deposited in a  
51  
52 954 confined and presumably ponded basin as demonstrated by the sedimentary facies and thick  
53  
54 955 mudstone caps described in facies association FA-E. High-density turbidites and the basal  
55  
56 956 divisions of HEBs do not record any effect of flow-slope interaction (i.e. rotation of palaeoflow  
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3 957 indicators, systematic trends in H3 development) indicating that the inbound underflows were  
4  
5 958 relatively unaffected by the confinement conditions (Patacci et al., 2015). This suggests that the  
6  
7 959 confining slopes were relatively distant (> 10 km); the counter slope was likely located near the  
8  
9 960 Bracco massif of Elter & Raggi (1965) (Figs 2 and 3) and did not affect the process of substrate  
10  
11 961 entrainment. The presence of HEBs including the variable expression of mudstone-clast rich H3  
12  
13 962 divisions thus cannot be linked to the effect of confining slopes on flow behaviour (c.f. Southern  
14  
15 963 et al., 2015). Furthermore, the persistence of hybrid event beds through the entire Gottero 3 history  
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17 964 indicates they are independent of the changing degree of basin confinement.

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19  
20 965 Evidence for extensive scour features in the basin-plain region suggests that hybrid event bed  
21  
22 966 occurrence in this sector (especially the mudstone-clast and raft-bearing type HEBs) was controlled  
23  
24 967 by the magnitude of the flows and the type of substrate with which they interacted, rather than any  
25  
26 968 up-dip erosion related to phases of tectonic uplift or slope rotation. A tectonic control would have  
27  
28 969 formed a stacking pattern in which HEBs were stratigraphically partitioned, as has been inferred by  
29  
30 970 Muzzi Magalheas and Tinterri (2010) and Tinterri and Muzzi Magalheas (2011) for the Marnoso  
31  
32 971 arenacea. A subtle gradient break between the up-dip fan system and the oversupplied and hence  
33  
34 972 flat basin plain may have played a role in localising erosion and substrate entrainment on account  
35  
36 973 of turbulence enhancement followed by rapid suspension collapse. Local erosion may have formed  
37  
38 974 initial defects which were then expanded by injection-related delamination (Fonnesu et al., 2016).  
39  
40 975 Flow containment seems to have affected only the dilute upper part of the flows, responsible for  
41  
42 976 the deposition of expanded laminated and fine-grained bed tops and the preservation and  
43  
44 977 accumulation of thick mudstone caps. The basin plain area was probably the first location along the  
45  
46 978 flow path where large-volume flows encountered a cohesive and well-layered muddy substrate  
47  
48 979 (including thick ponded mud caps to earlier flows) forming the ideal conditions to promote  
49  
50 980 delamination and mudstone-clast and raft-bearing HEB formation.  
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3 981 **(A) CONCLUSIONS**

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5 982 Hybrid event bed presence and character have been documented across a range of Gottero system  
6  
7 983 sub-environments in both submarine fan and confined basin plain sectors (Fig. 19).

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9  
10 984 1) Hybrid event beds can be differentiated on the basis of the texture of their H3 divisions and of  
11  
12 985 the size and shape of the clasts entrained within them. Six HEB bed types can be distinguished  
13  
14 986 on the following basis: beds with H3 divisions including metre to 10s of metres long substrate  
15  
16 987 rafts (HEB-1); highly deformed chaotic texture or sand-injection rich (HEB-2); mudstone clast  
17  
18 988 to smaller mud-chips rich in a sand-rich matrix (HEB-3 and HEB-4); and H3 division with  
19  
20 989 small mud-chips scattered in a matrix with high dispersed and significant mud content (HEB-5  
21  
22 990 or HEB-6).

23  
24 991 2) The proximal fan area of the Gottero system is virtually devoid of HEBs in channel-fill and  
25  
26 992 amalgamated proximal lobe elements.

27  
28 993 3) Thin and fine-grained HEBs (HEB-5 and 6) are abundant in the lateral and frontal fringes of  
29  
30 994 outer-fan sandstone lobes and less commonly interbedded in mud-prone laterally extensive  
31  
32 995 inter-lobe intervals (Fig. 19). This HEB association is thought to have been produced by flows  
33  
34 996 that underwent turbulence damping following incorporation of mud from proximal lobe  
35  
36 997 locations or at flow expansion points and that longitudinally hydraulically fractionated clay  
37  
38 998 and other low density components. They are thought to produce a facies tract in which H3  
39  
40 999 divisions expand down-dip at expenses of their basal sandstone and may include components  
41  
42 1000 deposited under transitional flow conditions.

43  
44 1001 4) The Gottero confined basin plain is dominated by thick and laterally extensive event beds with  
45  
46 1002 a high proportion of HEBs (31% to 51% in thickness) (Fig. 19). Hybrid event beds in this case  
47  
48 1003 are rich in mudstone clasts and large substrate rafts (HEB-1 to HEB-4) and show evidence of  
49  
50 1004 extensive auto-injection and clast break-up within a sand-rich matrix. These beds are thought  
51  
52 1005 to have been produced by high-magnitude flows capable of delaminating the sea-floor locally  
53  
54 1006 and detaching pieces of substrate. On the basis of this study the process can produce two types  
55  
56 1007 of facies tracts: FTH-1 involving substrate erosion from shallow scours and entrainment of  
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3 1008 abundant mudstone clasts; or FTH-2 driven by delamination of large substrate slabs and their  
4  
5 1009 progressive disaggregation in shearing near-bed layers.  
6  
7 1010 5) The occurrence of fine-grained HEBs (HEB-5 and 6) was controlled by the vertical and lateral  
8  
9 1011 juxtaposition of lobes and lobe fringes which was ultimately related to the pattern of autogenic  
10  
11 1012 lobe stacking.  
12  
13 1013 6) Clast-rich and raft-bearing HEBs relate to less frequent, large-magnitude and high-  
14  
15 1014 concentration flows that interacted with a cohesive substrate either immediately following  
16  
17 1015 deposition of muddy interlobes or beyond the fan on an oversupplied basin plain. Extensive  
18  
19 1016 delamination of the Gottero basin plain may have been promoted by the gradient break  
20  
21 1017 between the fan and the confined basin plain, and the presence of ponded mud caps on  
22  
23 1018 preceding event beds.  
24  
25 1019 7) The Gottero turbidite system was prone to hybrid flow generation through most of its history.  
26  
27 1020 In this case local HEB occurrence and distribution across different sub-environments was  
28  
29 1021 strongly controlled by intrabasinal factors such as the availability of muddy substrate,  
30  
31 1022 mechanical properties of which dictated the mode of substrate entrainment.  
32

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47 1029 improve the final version of the manuscript.  
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### 49 50 1030 **REFERENCES**

51  
52  
53 1031 **Abbate, E. and Sagri, M.** (1982) Le unità torbiditiche cretatiche dell'Appennino settentrionale ed i  
54  
55 1032 margini continentali della Tetide. *Memorie della Società Geologica Italiana*, **23**, 115-126.  
56  
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- 1  
2  
3 1033 **Abbate, E., and Sagri, M.** (1970) The eugeosynclinal sequences: *Sedimentary Geology*, **4**, 251-  
4 1034 340.  
5  
6  
7 1035 **Abbate, E., Bortolotti, V. and Principi, G.** (1980) Apennine ophiolites: a peculiar oceanic crust.  
8 1036 *Ofioliti*, **1**, 59-96.  
9  
10  
11 1037 **Amy, L.A., Talling, P.J., Peakall, J., Wynn, R.B., and Thynne, R.A.** (2005) Bed geometry used  
12 1038 to test recognition criteria of turbidites and (sandy) debrites. *Sedimentary Geology*, **179(1)**, 163-  
13 1039 174.  
14  
15  
16  
17  
18  
19 1040 **Amy, L.A. and Talling, P.J.** (2006) Anatomy of turbidites and linked debrites based on long  
20 1041 distance (120 × 30 km) bed correlation, Marnoso Arenacea Formation, Northern Apennines, Italy.  
21 1042 *Sedimentology*, **53**, 161-212.  
22  
23  
24  
25  
26 1043 **Amy, L.A., Kneller, B.C., and McCaffrey, W.D.** (2007) Facies architecture of the Grès de Peira  
27 1044 Cava, SE France: landward stacking patterns in ponded turbiditic basins. *Journal of the Geological*  
28 1045 *Society*, **164(1)**, 143-162.  
29  
30  
31  
32  
33 1046 **Amy, L.A., Peatchy, S.A., Gardiner, A.A. and Talling, P.J.** (2009) Prediction of hydrocarbon  
34 1047 recovery from turbidite sandstones with linked-debrite facies: Numerical flow-simulation studies.  
35 1048 *Marine and Petroleum Geology*, **26**, 2032-2043.  
36  
37  
38  
39  
40 1049 **Andri, E., and Zavatteri, F.** (1990) Le septarie di Monte Mignano e de il Dente (Complesso di  
41 1050 Monte Ramaceto, Appennino Ligure). *Atti Società Toscana Scienze Naturali*, **96**, 1-48.  
42  
43  
44  
45 1051 **Arfaie, A., Burns, A.D., Dorrell, R.M., Eggenhuisen, J.T., Ingham, D.B., and McCaffrey,**  
46 1052 **W.D.** (2014) Optimised mixing and flow resistance during shear flow over a rib roughened  
47 1053 boundary. *International Communications in Heat and Mass Transfer*, **58**, 54-62.  
48  
49  
50  
51  
52 1054 **Baas, J.H., Best, J.L. and Peakall, J.** (2011) Depositional processes, bedform development and  
53 1055 hybrid bed formation in rapidly decelerated cohesive (mud-sand) sediment flows. *Sedimentology*,  
54 1056 **58**, 1953-1987.  
55  
56  
57  
58  
59  
60

- 1  
2  
3 1057 **Baas, J.H., Best, J.L., Peakall, J. and Wang, M.** (2009) A phase diagram for turbulent,  
4  
5 1058 transitional, and laminar clay suspension flows. *Journal of Sedimentary Research*, **79**, 162-183.  
6  
7  
8 1059 **Barker, S.P, Haughton, P.D.W., McCaffrey, W.D., Archer, S.G. and Hakes, B.** (2008)  
9  
10 1060 Development of rheological heterogeneity in clay-rich high-density turbidity currents: Aptian  
11  
12 1061 Britannia sandstone member, U.K. Continental shelf. *Journal of Sedimentary Research*, **78**, 45-68.  
13  
14 1062 **Bortolotti, V., and Passerini, P.** (1970) Magmatic activity. *Sedimentary Geology*, **4**, 599-624.  
15  
16  
17 1063 **Bouma, A.H.** (1962) Sedimentology of some Flysch deposits; a graphic approach to facies  
18  
19 1064 interpretation. Amsterdam, Elsevier, 168 p.  
20  
21  
22 1065 **Breien, H., De Blasio, F. V., Elverhøi, A., Nystuen, J.P., and Harbitz, C.B.** (2010) Transport  
23  
24 1066 mechanisms of sand in deep-marine environments—insights based on laboratory experiments.  
25  
26 1067 *Journal of Sedimentary Research*, **80(11)**, 975-990.  
27  
28  
29 1068 **Brunt, R. L., Di Celma, C.N., Hodgson, D.M., Flint, S.S., Kavanagh, J.P., and van der Merwe,**  
30  
31 1069 **W.C.** (2013) Driving a channel through a levee when the levee is high: an outcrop example of  
32  
33 1070 submarine down-dip entrenchment. *Marine and Petroleum Geology*, **41**, 134-145.  
34  
35  
36 1071 **Casnedi, R.** (1982) Sedimentazione e tettonica della unità liguri nell'Appennino nord-occidentale  
37  
38 1072 (Valli Lavagna-Sturla Trebbia e Aveto). *Atti Istituto Geologico Università di Pavia*, **30**, 42-66.  
39  
40  
41 1073 **Costa, J.E.** (1984) Physical geomorphology of debris flows. *In* Developments and applications of  
42  
43 1074 geomorphology, pp. 268-317. Springer Berlin Heidelberg  
44  
45  
46 1075 **Davis, C.E., Haughton, P.D.W., McCaffrey, W.D., Scott, E., Hogg, N. and Kitching, D.** (2009)  
47  
48 1076 Character and distribution of hybrid sediment gravity flow deposits from the outer Forties Fan,  
49  
50 1077 Palaeocene Central North Sea, UKCS. *Marine and Petroleum Geology*, **26**, 1919-1939.  
51  
52  
53 1078 **Dorrell, R.M., Darby, S. E., Peakall, J., Sumner, E.J., Parsons, D.R., and Wynn, R.B.** (2014)  
54  
55 1079 The critical role of stratification in submarine channels: Implications for channelization and long  
56  
57 1080 runout of flows. *Journal of Geophysical Research: Oceans*, **119(4)**, 2620-2641.  
58  
59  
60

- 1  
2  
3 1081 **Elter, P., and Raggi, G.** (1965) Contributo alla conoscenza dell'Appennino ligure, 3. Tentativo di  
4  
5 1082 interpretazione delle breccie ofiolitiche cretacee in relazione con movimenti orogenetici  
6  
7 1083 nell'Appennino ligure. *Bollettino della Società Geologica Italiana*, **84**, 1-12.  
8  
9  
10 1084 **Elter, P., Ghiselli, F., Marroni, M. and Ottria, G.** (1997) Note illustrative della Carta geologica  
11  
12 1085 d'Italia alla scala 1: 50.000, Foglio 197-Bobbio. Istituto Poligrafico e Zecca dello Stato, Roma.  
13  
14  
15 1086 **Flemings, P.B., Behrmann, J.H., and Johm, C.M.** (2006) Gulf of Mexico Hydrogeology.  
16  
17 1087 *Proceedings of the International Ocean Drilling Program*, **308**. College Station, Texas, USA.  
18  
19  
20 1088 **Fonnesu, M.** (2016) Hybrid event bed processes, facies trends and distribution in deep-water  
21  
22 1089 turbidite systems. Ph.D thesis, University College Dublin, Ireland.  
23  
24  
25 1090 **Fonnesu, M., Felletti, F., Haughton, P.D.W., McCaffrey, W.D. and Patacci M.** (2013) Bed by  
26  
27 1091 bed correlations and lateral variability in hybrid event beds in the Ramaceto area (Gottero  
28  
29 1092 Sandstone, northern Apennines, Italy), *Journal of Mediterranean Earth Sciences*, **5**, 63.  
30  
31  
32 1093 **Fonnesu, M., Haughton, P., Felletti, F., and McCaffrey, W.D.** (2015) Short length-scale  
33  
34 1094 variability of hybrid event beds and its applied significance. *Marine and Petroleum Geology*, **67**,  
35  
36 1095 583-603.  
37  
38  
39 1096 **Fonnesu, M., Patacci, M., Haughton, P.D.W., Felletti, F., and McCaffrey, W.D.** (2016) Hybrid  
40  
41 1097 Event Beds Generated By Local Substrate Delamination On A Confined-Basin Floor. *Journal of*  
42  
43 1098 *Sedimentary Research*, **86**, 929-943.  
44  
45  
46 1099 **Haughton, P.D.W.** (2001) Contained turbidites used to track sea bed deformation and basin  
47  
48 1100 migration, Sorbas Basin, south-east Spain. *Basin Research*, **13**, 117-139.  
49  
50  
51 1101 **Haughton, P.D.W., Barker, S.P., and McCaffrey, W.D.** (2003) "Linked" debrites in sand-rich  
52  
53 1102 turbidite systems – origin and significance. *Sedimentology*, **50**, 459-482.  
54  
55  
56  
57  
58  
59  
60

- 1  
2  
3 1103 **Haughton, P.D.W., Davis, C.E. and McCaffrey, W.D.** (2010). Reply to Comment by R. Higgs on  
4  
5 1104 "Hybrid sediment gravity flow deposits – classification, origin and significance". *Marine and*  
6  
7 1105 *Petroleum Geology*, **27**, 2066-2069.  
8  
9  
10 1106 **Haughton, P.D.W., Davis, C.E., McCaffrey, W.D. and Barker, S.** (2009) Hybrid sediment  
11  
12 1107 gravity flow deposits – Classification, origin and significance. *Marine and Petroleum Geology*, **26**,  
13  
14 1108 1900-1918.  
15  
16  
17 1109 **Hodgson, D.M.** (2009) Distribution and origin of hybrid beds in sand-rich submarine fans of the  
18  
19 1110 Tanqua depocentre, Karoo Basin, South Africa. *Marine and Petroleum Geology*, **26**, 1940-1956.  
20  
21  
22 1111 **Kane, I.A., and Pontén, A.S.M.** (2012) Submarine transitional flow deposits in the Paleogene  
23  
24 1112 Gulf of Mexico. *Geology*, **40**, 1119-1122.  
25  
26  
27 1113 **Kane, I., Pontén, A., Vangdal, B., Eggenhuisen, J., Hodgson, D. M., and Spychala, Y. T.,** 2017.  
28  
29 1114 The stratigraphic record and processes of turbidity current transformation across deep marine  
30  
31 1115 lobes. *Sedimentology*. DOI: 10.1111/sed.1234.  
32  
33  
34 1116 **Kastens, K.A.** (1984) Earthquakes as a triggering mechanism for debris flows and turbidites on the  
35  
36 1117 Calabrian Ridge. *Marine Geology*, **55(1-2)**, 13-33.  
37  
38  
39 1118 **Knaust, D., Warchol, M., and Kane, I.A.** (2014) Ichnodiversity and ichnoabundance: Revealing  
40  
41 1119 depositional trends in a confined turbidite system. *Sedimentology*, **61(7)**, 2218-2267  
42  
43  
44 1120 **Kneller, B.C** (1995) Beyond the turbidite paradigm: physical models for deposition of turbidites  
45  
46 1121 and their implication for reservoir prediction. In: Hartley, A.J. and Prosser, D.J. (Eds).  
47  
48 1122 Characterization of Deep Marine Clastic Systems. *Geological Society of London Special*  
49  
50 1123 *Publication*, **94**, 31-49.  
51  
52  
53 1124 **Kneller, B.C., and Branney, M.J.** (1995) Sustained high-density turbidity currents and the  
54  
55 1125 deposition of thick massive sands. *Sedimentology*, **42(4)**, 607-616.  
56  
57  
58  
59  
60

- 1  
2  
3 1126 **Kneller, B., and McCaffrey, W.D.** (1999) Depositional effects of flow nonuniformity and  
4  
5 1127 stratification within turbidity currents approaching a bounding slope: deflection, reflection, and  
6  
7 1128 facies variation. *Journal of Sedimentary Research*, **69(5)**, 980-991.  
8  
9  
10 1129 **Kneller, B.C., and McCaffrey, W.D.** (2003) The interpretation of vertical sequences in turbidite  
11  
12 1130 beds: the influence of longitudinal flow structure. *Journal of Sedimentary Research*, **73**, 706-713.  
13  
14  
15 1131 **Lowe, D.R. and Guy, M.** (2000) Slurry-flow deposits in the Britannia Formation (Lower  
16  
17 1132 Cretaceous), North Sea: a new perspective on the turbidity current and debris flow problem.  
18  
19 1133 *Sedimentology*, **47(1)**, 31-70.  
20  
21  
22 1134 **Lowe, D. R.** (1982) Sediment gravity flows: II Depositional models with special reference to the  
23  
24 1135 deposits of high-density turbidity currents. *Journal of Sedimentary Research*, **52(1)**, 272-297.  
25  
26  
27 1136 **Macdonald, H.A., Peakall, J., Wignall, P.B., and Best, J.** (2011) Sedimentation in deep-sea lobe-  
28  
29 1137 elements: implications for the origin of thickening-upward sequences. *Journal of the Geological*  
30  
31 1138 *Society*, **168(2)**, 319-332.  
32  
33  
34 1139 **Malesani, P.** (1966) Ricerche sulle arenarie, XV; L' Arenaria Superiore. *Rendiconti della Società*  
35  
36 1140 *Italiana di Mineralogia e Petrologia*, **22**, 113-175.  
37  
38  
39 1141 **Marini, M., Milli, S., Ravnås, R., and Moscatelli, M.** (2015a) A comparative study of confined  
40  
41 1142 vs. semi-confined turbidite lobes from the Lower Messinian Laga Basin (Central Apennines, Italy):  
42  
43 1143 Implications for assessment of reservoir architecture. *Marine and Petroleum Geology*, **63**, 142-165.  
44  
45  
46 1144 **Marini, M., Patacci, M., Felletti, F., Cerliani, A., Azzarone, M., Decarlis, A., McCaffrey W.D.**  
47  
48 1145 (2015b) The depositional architecture of Mass Transport Deposits from the Ventimiglia Flysch  
49  
50 1146 Fm. (Eocene, NW Italy): implications for seafloor reshaping and turbidite deposition. IAS meeting  
51  
52 1147 Krakov 22-25 June 2015.  
53  
54  
55  
56  
57  
58  
59  
60

- 1  
2  
3 1148 **Marini, M., Patacci, M., Felletti, F. and McCaffrey, W D.** (2016) Fill to spill stratigraphic  
4  
5 1149 evolution of a confined turbidite mini-basin succession, and its likely well bore expression: The  
6  
7 1150 Castagnola Fm, NW Italy. *Marine and Petroleum Geology*, **69**, 94-111.  
8  
9  
10 1151 **Marini, M.** (1991) Considerations on the sandstone bodies of the Mount Gottero Unit west of the  
11  
12 1152 Bracco Massif (Ligurian Apennines, Italy). *Giornale di Geologia*, **53(2)**, 207-218.  
13  
14 1153 **Marini, M.** (1994) Le arenarie del M. Gottero nella sezione del M. Ramaceto (unita del M.  
15  
16 1154 Gottero, Appennino Ligure). *Bollettino della Società Geologica Italiana*, **113(2)**, 283-302.  
17  
18  
19 1155 **Marini, M.** (1995) Le arenarie del Monte Gottero nell'areale del Monte Zatta (Unità del Monte  
20  
21 1156 Gottero, Appennino Ligure). *Bollettino della Società Geologica Italiana*, **114**, 575-598.  
22  
23  
24 1157 **Marroni, M.** (1991) Deformation history of the M. Gottero Unit (Internal Ligurid Units, Northern  
25  
26 1158 Apennines). *Bollettino della Società Geologica Italiana*, **110**, 727-736.  
27  
28  
29 1159 **Marroni, M. and Perilli, N.** (1990) The age of the ophiolite sedimentary cover from the Mt.  
30  
31 1160 Gottero Unit (Internal Ligurid Units, Northern Apennines): new data from calcareous nannofossils.  
32  
33 1161 *Ofioliti*, **15(2)**, 251-267.  
34  
35  
36 1162 **Marroni, M., and Pandolfi, L.** (2001). Debris flow and slide deposits at the top of the Internal  
37  
38 1163 Liguride ophiolitic sequence, Northern Apennines, Italy: A record of frontal tectonic erosion in a  
39  
40 1164 fossil accretionary wedge. *Island Arc*, **10**, 9-21.  
41  
42  
43 1165 **Marroni, M., and Pandolfi, L.** (2007) The architecture of an incipient oceanic basin: a tentative  
44  
45 1166 reconstruction of the Jurassic Liguria-Piemonte basin along the Northern Apennines–Alpine  
46  
47 1167 Corsica transect. *International Journal of Earth Sciences*, **96(6)**, 1059-1078.  
48  
49  
50 1168 **Marroni, M., Meneghini, F. and Pandolfi, L.** (2010) Anatomy of the Ligure-Piemontese  
51  
52 1169 subduction system: evidence from Late Cretaceous–middle Eocene convergent margin deposits in  
53  
54 1170 the Northern Apennines, Italy. *International Geology Review*, **52(10-12)**, 1160-1192.  
55  
56  
57  
58  
59  
60

- 1  
2  
3 1171 **Marroni, M., Meneghini, F., and Pandolfi, L.** (2004) From accretion to exhumation in a fossil  
4  
5 1172 accretionary wedge: a case history from Gottero unit (Northern Apennines, Italy). *Geodinamica*  
6  
7 1173 *Acta*, **17**, 41-53.  
8  
9  
10 1174 **Marroni, M., Molli, G., Ottria, G., and Pandolfi, L.** (2001) Tectono-sedimentary evolution of the  
11  
12 1175 External Liguride units (Northern Apennines, Italy): insights in the pre-collisional history of a  
13  
14 1176 fossil ocean-continent transition zone. *Geodinamica Acta*, **14(5)**, 307-320.  
15  
16  
17 1177 **Marroni, M.** (1994) Deformation path of the Internal Ligurid Units (Northern Apennines, Italy):  
18  
19 1178 record of shallow-level underplating in the Alpine accretionary wedge. *Memorie della Società*  
20  
21 1179 *Geologica Italiana*, **48**, 179-194.  
22  
23  
24 1180 **Middleton, G.V.** (1973) Johannes Walther's law of the correlation of facies. *Geological Society of*  
25  
26 1181 *America Bulletin*, **84(3)**, 979-988.  
27  
28  
29 1182 **Mohrig, D., and Marr, J.G.** (2003) Constraining the efficiency of turbidity current generation  
30  
31 1183 from submarine debris flows and slides using laboratory experiments. *Marine and Petroleum*  
32  
33 1184 *Geology*, **20(6)**, 883-899.  
34  
35  
36 1185 **Monechi, S., Treves, B., and Marri, C.** (1984) Osservazioni sull'età delle arenarie del Gottero;  
37  
38 1186 dati del nannoplancton calcareo. *Ofioliti*, **9(1)**, 93-96.  
39  
40  
41 1187 **Mulder, T. and Alexander, J.** (2001) The physical character of subaqueous sedimentary density  
42  
43 1188 flows and their deposits. *Sedimentology*, **48**, 269-299.  
44  
45  
46 1189 **Mutti, E. and Nilsen, T.H.** (1981) Significance of intraformational rip-up clasts in deep-sea fan  
47  
48 1190 deposits. Int. Assoc. Sedimentol. 2nd Eur. Regional Mtg. Abstr., Bologna, 117-1.  
49  
50  
51 1191 **Mutti, E. and Ricci Lucchi, F.** (1972) Le torbiditi dell'Appennino settentrionale: introduzione  
52  
53 1192 all'analisi di facies. *Memorie della Società Geologica Italiana*, **11(2)**, 161-199.  
54  
55  
56 1193 **Mutti, E.** (1992) Turbidite sandstones. Agip, Istituto di geologia, Università di Parma.  
57  
58  
59  
60

- 1  
2  
3 1194 **Mutti, E., and Ghibaud, G.** (1972) Un esempio di torbiditi di conoide sottomarina esterna: le  
4  
5 1195 Arenarie di San Salvatore (Formazione di Bobbio, Miocene) nell'Appennino di Piacenza.  
6  
7 1196 *Accademia delle scienze Torino*, **4**, 16, 1-40.  
8  
9  
10 1197 **Mutti, E., and Johns, D.R.** (1978) The role of sedimentary bypassing in the genesis of fan fringe  
11  
12 1198 and basin plain turbidites in the Hecho Group System (south-central Pyrenees). *Memorie della*  
13  
14 1199 *Società Geologica Italiana*, **18**, 15-22.  
15  
16  
17 1200 **Mutti, E., and Normark, W.R.** (1987) Comparing examples of modern and ancient turbidite  
18  
19 1201 systems: problems and concepts. *in* Marine clastic sedimentology, pp. 1-38. Springer Netherlands.  
20  
21  
22 1202 **Mutti, E., and Normark, W.R.** (1991) An integrated approach to the study of turbidite systems. *in*  
23  
24 1203 Seismic facies and sedimentary processes of submarine fans and turbidite systems, pp. 75-106.  
25  
26 1204 Springer New York.  
27  
28  
29 1205 **Mutti, E., and Sonnino, M.** (1981) Compensation cycles: a diagnostic feature of turbidite  
30  
31 1206 sandstone lobes. In Int. Ass. Sed. 2nd European Meeting, Bologna, Abstracts, 120-123.  
32  
33  
34 1207 **Mutti, E., Bernoulli, D., Ricci Lucchi, F. and Tinterri, R.** (2009). Turbidites and turbidity  
35  
36 1208 currents from Alpine 'flysch' to the exploration of continental margins. *Sedimentology*, **56**, 267-  
37  
38 1209 318.  
39  
40  
41 1210 **Mutti, E., Nilsen, T.H., and Ricci Lucchi, F.** (1978) Outer fan depositional lobes of the Laga  
42  
43 1211 Formation (upper Miocene and lower Pliocene), East-Central Italy, *in* Stanley, D.J. and Kelling, G.  
44  
45 1212 (Eds.) Sedimentation in submarine canyons, fans, and trenches, pp. 210-222. Stroudsburg, Pa.,  
46  
47 1213 United States, Dowden, Hutchinson & Ross, Inc.  
48  
49  
50 1214 **Mutti, E., Ricci Lucchi, F., Seguret, M., and Zanzucchi, G.** (1984) Seismoturbidites: a new  
51  
52 1215 group of resedimented deposits. *Marine Geology*, **55(1)**, 103-116.  
53  
54  
55 1216 **Mutti, E., Davoli, G., Mora, S. and Papani, L.** (1994) Internal stacking patterns of ancient  
56  
57 1217 turbidite systems from collisional basins. In: Weimer, P., Bouma, A.H. and Perkins, B.F. (Eds).

- 1  
2  
3 1218 GCSSEPM Foundation 15th Annual Research Conference, Submarine Fans and Turbidite  
4  
5 1219 Systems: Sequence Stratigraphy, Reservoir Architecture and Production Characteristics, Gulf of  
6  
7 1220 Mexico and International, 257-268.  
8  
9  
10 1221 **Mutti, E., Tinterri, R., Benevelli, G., di Biase, D., and Cavanna, G.** (2003) Deltaic, mixed and  
11  
12 1222 turbidite sedimentation of ancient foreland basins. *Marine and Petroleum Geology*, **20(6)**, 733-755.  
13  
14  
15 1223 **Muzzi Magalhaes, P. and Tinterri, R.** (2010) Stratigraphy and depositional setting of slurry and  
16  
17 1224 contained (reflected) beds in the Marnoso-arenacea Formation (Langhian-Serravallian) Northern  
18  
19 1225 Apennines, Italy. *Sedimentology*, **57**, 1685-1720.  
20  
21  
22 1226 **Nilsen, T.H. and Abbate, E.** (1984) Submarine-Fan facies associations of the Upper Cretaceous  
23  
24 1227 and Paleocene Gottero Sandstone, Ligurian Apennines, Italy. *Geo-Marine Letters*, **3**, 193-197.  
25  
26  
27 1228 **Pandolfi, L.** (1996) Le arenarie del M. Gottero nella sezione di punta Mesco (Campaniano sup.-  
28  
29 1229 Paleocene inf., Appennino settentrionale): analisi stratigrafica e petrografica della parte prossimale  
30  
31 1230 di un sistema torbiditico. *Atti Società Toscana Scienze Naturali, Memorie, A*, **103**, 197-208.  
32  
33  
34 1231 **Pandolfi, L.** (1997) Stratigrafia ed evoluzione strutturale delle successioni torbiditiche cretacee  
35  
36 1232 della Liguria orientale (Appennino Settentrionale). PhD thesis, Università di Pisa, 175 pp.  
37  
38  
39 1233 **Parea, G.C.** (1965) La provenienza dei clastici dell'arenaria del M. Gottero. *Atti e Memorie*  
40  
41 1234 *Accademia Nazionale di Scienze Lettere e Arti di Modena*, **6**, 7 pp.  
42  
43  
44 1235 **Passerini, P. and Pirini, C.** (1964) Microfaune paleoceniche nella formazione dell'Arenaria del M.  
45  
46 1236 Ramaceto e degli Argilloscisti di Cichero. *Bollettino della Società Geologica Italiana*, **83**, 211-  
47  
48 1237 218.  
49  
50  
51 1238 **Patacci, M., Haughton, P.D.W., and McCaffrey, W.D.** (2014) Rheological complexity in  
52  
53 1239 sediment gravity flows forced to decelerate against a confining slope, Braux, SE France. *Journal of*  
54  
55 1240 *Sedimentary Research*, **84**, 270-277.  
56  
57  
58  
59  
60

- 1  
2  
3 1241 **Patacci, M., Haughton, P.D.W., and McCaffrey, W.D.** (2015) Flow behavior of ponded turbidity  
4  
5 1242 currents. *Journal of Sedimentary Research*, **85**, 885-902.  
6  
7  
8 1243 **Pickering, K.T., and Hiscott, R.N.** (1985) Contained (reflected) turbidity currents from the  
9  
10 1244 Middle Ordovician Cloridorme Formation, Quebec, Canada: an alternative to the antidune  
11  
12 1245 hypothesis. *Sedimentology*, **32(3)**, 373-394.  
13  
14  
15 1246 **Pickering, K.T., and Hiscott, R.N.** (2015) Deep Marine Systems: Processes, Deposits,  
16  
17 1247 Environments, Tectonics and Sedimentation. American Geophysical Union, Wiley, 672 pp.  
18  
19  
20 1248 **Pierce, C.** (2015) Development, distribution and evolution of gravity flows processes in the  
21  
22 1249 Pennsylvanian Ross Formation, Western Ireland. Ph.D thesis. University College Dublin.  
23  
24  
25 1250 **Pierson, T.C.** (1981) Dominant particle support mechanisms in debris flows at Mt Thomas, New  
26  
27 1251 Zealand, and implications for flow mobility. *Sedimentology*, **28(1)**, 49-60.  
28  
29  
30 1252 **Porten, K.W., Kane, I.A., Warchol, M.J., and Southern, S.J.** (2016) A Sedimentological  
31  
32 1253 Process-Based Approach To Depositional Reservoir Quality of Deep-Marine Sandstones: An  
33  
34 1254 Example From the Springar Formation, Northwestern Vøring Basin, Norwegian Sea. *Journal of*  
35  
36 1255 *Sedimentary Research*, **86(11)**, 1269-1286.  
37  
38  
39 1256 **Postma, G., Nemeč, W., and Kleinspehn, K.L.** (1988) Large floating clasts in turbidites; a  
40  
41 1257 mechanism for their emplacement. *Sedimentary Geology*, **58**, 47-61.  
42  
43  
44 1258 **Prélat, A., and Hodgson, D.M.** (2013) The full range of turbidite bed thickness patterns in  
45  
46 1259 submarine lobes: controls and implications. *Journal of the Geological Society*, **170(1)**, 209-214.  
47  
48  
49 1260 **Prélat, A., Covault, J.A., Hodgson, D.M., Fildani, A. and Flint, A.A.** (2010) Intrinsic controls on  
50  
51 1261 the range of volumes, morphologies, and dimension of submarine lobes. *Sedimentary Geology*,  
52  
53 1262 **232**, 66-76.  
54  
55  
56  
57  
58  
59  
60

- 1  
2  
3 1263 **Puigdefàbregas, C., Gjelberg, J., and Vaksdal, M.** (2004) The Grès d'Annot in the Annot  
4  
5 1264 syncline: outer basin-margin onlap and associated soft-sediment deformation. *Geological Society*,  
6  
7 1265 London, Special Publications, 221(1), 367-388.  
8  
9  
10 1266 **Pyles, D.R., Straub, K.M., and Stammer, J.G.** (2013) Spatial variations in the composition of  
11  
12 1267 turbidites due to hydrodynamic fractionation. *Geophysical Research Letters*, **40(15)**, 3919-3923.  
13  
14  
15 1268 **Remacha, E., Fernandez, L.P., and Maestro, E.** (2005) The transition between sheet-like lobe  
16  
17 1269 and basin-plain turbidites in the Hecho Basin (South-Central Pyrenees, Spain). *Journal of*  
18  
19 1270 *Sedimentary Research*, **75**, 798-819.  
20  
21  
22 1271 **Ricci Lucchi, F. and Valmori, E.** (1980) Basin-wide turbidites in a Miocene, over-supplied deep-  
23  
24 1272 sea plain: a geometrical analysis. *Sedimentology*, **27**, 241-270.  
25  
26  
27 1273 **Ross, W.C., Halliwell, B.A., May, J.A., Watts, D.E., and Syvitski, J.P.M.** (1994) Slope  
28  
29 1274 readjustment: a new model for the development of submarine fans and aprons. *Geology*, **22(6)**,  
30  
31 1275 511-514.  
32  
33  
34 1276 **Sagri, M.** (1974) Rhythmic sedimentation in deep-sea carbonate turbidites (Monte Antola  
35  
36 1277 Formation, Northern Apennines). *Bollettino della Societa Geologica Italiana*, **93(4)**, 1013-1027.  
37  
38  
39 1278 **Smith, G.A.** (1986) Coarse-grained nonmarine volcanoclastic sediment: Terminology and  
40  
41 1279 depositional process. *Geological Society of America Bulletin*, **97(1)**, 1-10.  
42  
43  
44 1280 **Southern, S.J., Patacci, M., Felletti, F., and McCaffrey, W.D.** (2015) Influence of flow  
45  
46 1281 containment and substrate entrainment upon sandy hybrid event beds containing a co-genetic mud-  
47  
48 1282 clast-rich division. *Sedimentary Geology*, **321**, 105-122.  
49  
50  
51 1283 **Spychala, Y.T., Hodgson, D.M., Prèlat, A., Kane, I.A., Flint, S.S., and Mountney, N.P.** (2017)  
52  
53 1284 Frontal and lateral submarine lobe fringes: comparing sedimentary facies, architecture and flow  
54  
55 1285 processes. *Journal of Sedimentary Research*, **87**, 75-96.  
56  
57  
58  
59  
60

- 1  
2  
3 1286 **Stevenson, C.J., Talling, P. J., Wynn, R.B., Masson, D.G., Hunt, J.E., Frenz, M., and Cronin,**  
4  
5 1287 **B.T.** (2013) The flows that left no trace: Very large-volume turbidity currents that bypassed  
6  
7 1288 sediment through submarine channels without eroding the sea floor. *Marine and Petroleum*  
8  
9 1289 *Geology*, **41**, 186-205.
- 10  
11 1290 **Sumner, E.J., Talling, P.J., and Amy, L.A.** (2009) Deposits of flows transitional between  
12  
13 1291 turbidity current and debris flow. *Geology*, **37(11)**, 991-994.
- 14  
15  
16 1292 **Sylvester, Z., and Lowe, D.R.** (2004) Textural trends in turbidites and slurry beds from the  
17  
18 1293 Oligocene flysch of the East Carpathians, Romania. *Sedimentology*, **51(5)**, 945-972.
- 19  
20  
21 1294 **Talling, P.J.** (2013) Hybrid submarine flows comprising turbidity current and cohesive debris  
22  
23 1295 flow: Deposits, theoretical and experimental analyses, and generalized models. *Geosphere*, **9**, 460-  
24  
25 1296 488.
- 26  
27  
28 1297 **Talling, P.J., Amy, L.A., Wynn, R.B., Peakall J., and Robinson, M.** (2004) Beds comprising  
29  
30 1298 debrite sandwiched within co-genetic turbidite: origin and widespread occurrence in distal  
31  
32 1299 depositional environments. *Sedimentology*, **51**, 163-194.
- 33  
34  
35 1300 **Talling, P.J., Wynn, R.B., Masson, D.G., Frenz, M., Schiebel, R., Akhmetzhanov, A.,**  
36  
37 1301 **Dallmeier-Tiessen, S., Benetti, S., Weaver, P.P.E., Georgiopoulou, A., Hotz, C., Cronin, B.T.**  
38  
39 1302 **and Amy, L.A.** (2007) Debris flow deposition from giant submarine flow begins far away from  
40  
41 1303 original landslide, *Nature*, **450**, 541-544.
- 42  
43  
44 1304 **Talling, P.J., Malgesini, G., Sumner, E.J., Amy, L.A., Felletti, F., Blackbourn, G., Nutt, C.,**  
45  
46 1305 **Wilcox, C., Harding, I.C., and Akbari, S.** (2012) Planform geometry, stacking pattern, and  
47  
48 1306 extrabasinal origin of low strength and intermediate strength cohesive debris flow deposits in the  
49  
50 1307 Marnoso-arenacea Formation, Italy. *Geosphere*, **8**, 1207-1230.
- 51  
52  
53 1308 **Talling, P.J., Malgesini, G., and Felletti, F.** (2013) Can liquefied debris flows deposit clean sand  
54  
55 1309 over large areas of sea floor? Field evidence from the Marnoso-arenacea Formation, Italian  
56  
57 1310 Apennines. *Sedimentology*, **60**, 720-762.
- 58  
59  
60

- 1  
2  
3 1311 **Talling, P.J., Wynn, R.B., Rixon, R., Schmidt, D., Sumner, E. and Amy, L.A.** (2010) How did  
4  
5 1312 submarine flows transport boulder sized mud clasts to the fringes of the Mississippi Fan? *Journal*  
6  
7 1313 *of Sedimentary Research*, **80**, 829–851.  
8  
9  
10 1314 **Terlaky, V. and Arnott, R.W.C.** (2014) Matrix-rich and associated matrix-poor sandstones:  
11  
12 1315 Avulsion splays in slope and basin-floor strata. *Sedimentology*, **61**. 1175-1197.  
13  
14  
15 1316 **Tinterri, R. and Tagliaferri, A.** (2015) The syntectonic evolution of foredeep turbidites related to  
16  
17 1317 basin segmentation: Facies response to the increase in tectonic confinement (Marnoso-arenacea  
18  
19 1318 Formation, Miocene, Northern Apennines, Italy). *Marine and Petroleum Geology*, **67**, 81-110.  
20  
21  
22 1319 **Tinterri, R., Muzzi Magalhaes, P.M., Tagliaferri, A. and Cunha, R.S.** (2016) Convolute  
23  
24 1320 laminations and load structures in turbidites as indicators of flow reflections and decelerations  
25  
26 1321 against bounding slopes. Examples from the Marnoso-arenacea Formation (northern Italy) and  
27  
28 1322 Annot Sandstones (south eastern France). *Sedimentary Geology*, **344**, 382-407.  
29  
30  
31 1323 **Tinterri, R., Laporta, M., and Ogata, K.** (2017) Cross-currents turbidite facies tract in a  
32  
33 1324 structurally-confined asymmetrical mini-basin (Priabonian-Rupelian, Ranzano Sandstone, northern  
34  
35 1325 Apennines, Italy). *Sedimentary Geology*. Doi: 10.1016/j.sedgeo.2016.12.005.  
36  
37  
38 1326 **Tinterri, R.**, 2011. Combined flow sedimentary structures and the genetic link between sigmoidal-  
39  
40 1327 and hummocky-cross stratification. *GeoActa*, **10(4)**, 1-43.  
41  
42  
43 1328 **Tinterri, R., and Muzzi Magalhaes, P.** (2011) Synsedimentary structural control on foredeep  
44  
45 1329 turbidites: An example from Miocene Marnoso-arenacea Formation, Northern Apennines, Italy.  
46  
47 1330 *Marine and Petroleum Geology*, **28**, 629-657.  
48  
49  
50 1331 **Tinterri, R., Drago, M., Consonni, A., Davoli, G., and Mutti, E.** (2003) Modelling subaqueous  
51  
52 1332 bipartite sediment gravity flows on the basis of outcrop constraints: first results. *Marine and*  
53  
54 1333 *Petroleum Geology*, **20(6)**, 911-933.  
55  
56  
57  
58  
59  
60

- 1  
2  
3 1334 **Valloni, R., and Zuffa, G.G.** (1981) Detrital modes of arenaceous formations of the Northern  
4  
5 1335 Apennines. International Association of Sedimentologists. In 2nd European Regional Meeting,  
6  
7 1336 Bologna, 1981, Abstracts (pp. 198-201).  
8  
9  
10 1337 **Van de Kamp, P.C. and Leake, B.E.** (1995) Petrology and geochemistry of siliciclastic rocks of  
11  
12 1338 mixed feldspatic and ophiolitic provenance in Northern Apennines, Italy. *Chemical Geology*, **122**,  
13  
14 1339 1-20.  
15  
16  
17 1340 **Van Vliet, A.** (1978) Early Tertiary deepwater fans of Guipuzcoa, northern Spain. Sedimentation  
18  
19 1341 in Submarine canyons, fans and trenches, 190-209.  
20  
21  
22 1342 **Vescovi, P., Andreozzi, M., de Nardo, M.T., Lasagna, S., Martelli, L., Rio, D., and Vernia, L.**  
23  
24 1343 (2002) Note Illustrative della Carta Geologica d'Italia alla scala 1: 50,000, Foglio 216 "Borgo Val  
25  
26 1344 di Taro". Presidenza del Consiglio dei Ministri, Servizio Geologico d'Italia, Regione Emilia-  
27  
28 1345 Romagna.  
29  
30  
31 1346 **Vinnels, J.S., Butler, R.W., McCaffrey, W.D., and Lickorish, W.H.** (2010) Sediment  
32  
33 1347 distribution and architecture around a bathymetrically complex basin: an example from the eastern  
34  
35 1348 Champsaur Basin, SE France. *Journal of Sedimentary Research*, **80(3)**, 216-235.

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37 1349 **CAPTIONS**

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40 1350 **Fig. 1.** Different styles of hybrid event bed distribution in turbidite systems, based on published  
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42 1351 examples. (A) Hybrid event beds in distributive lobe systems (modified from Hodgson, 2009) and  
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44 1352 their vertical arrangement in 1D logs at the base of prograding lobes (Kane & Pontén, 2012). (B)  
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46 1353 Hybrid event beds in confined basin plains (based on stratigraphic cross-section of Unit 3 of  
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48 1354 Miocene Marnoso-arenacea Formation, *sensu* Tinterri and Muzzi Magalhes, 2011, from Talling et  
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50 1355 al., 2012 in the interval below the Contessa key bed ); the synthetic vertical log shows the lack of  
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52 1356 vertical organization of hybrid event beds and conventional turbidites at c. 20 m scale.

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55 1357 **Fig. 2.** - Location map of the Gottero system (modified from Nilsen & Abbate, 1984) and sketch  
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57 1358 map showing the tectonic units of the Northern Apennines (modified from Elter et al., 1992). The

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3 1359 arrows in the location map indicate the main palaeocurrent pattern deduced by Nilsen & Abbate  
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5 1360 (1984).  
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8 1361 **Fig. 3.** (A) Simplified geological map of the Western Gottero study area (modified from Marroni,  
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10 1362 1994) showing the location of measured sections (1 to 6) and palaeocurrent roses obtained during  
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12 1363 this study; the numbers in brackets indicate the number of palaeocurrent measurements. The  
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14 1364 palaeoflow pattern broadly corresponds to that established by Nilsen & Abbate (1984) (see Fig. 2).  
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16 1365 (B) Internal Liguridi stratigraphy of the Gottero tectonic unit (modified from Marroni et al., 2001).  
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18 1366 The colours on the map correspond to those displayed in the stratigraphic log.  
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21 1367 **Fig. 4.** General NW-SE cross-section of the Gottero system aligned in a direction approximately  
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23 1368 parallel to the sediment transport. Colour shading according to the major grain-size and lithofacies  
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25 1369 (red colours: conglomerate and coarse grained sandstones, green: hybrid event beds, grey: mostly  
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27 1370 siltstone and mudstones or fine-grained sandstones, pink: mass transport complexes). The area  
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29 1371 interpreted as confined basin plain is coloured in light grey on the correlation panel. Note the  
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31 1372 distances between sections have not been palinspastically restored and could potentially be longer  
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33 1373 than indicated.  
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36 1374 **Fig. 5.** Exposure of the upper stratigraphic part of the Gottero Sandstone in the Mt. Ramaceto area.  
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38 1375 Note the succession is tectonically inverted (arrow indicates succession way-up). Numbers refer to  
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40 1376 photohorizons highlighted in the correlation panel of Fig. 13. Orange colour represents the outcrop  
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42 1377 of the stratigraphically overlying Giaiette mass transport complex unit (MTC). The picture capture  
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44 1378 about 2.2 km lateral exposure and 740 m of stratigraphic thickness.  
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47 1379 **Fig. 6.** Hybrid event bed classification scheme. Typical bed profiles (with average bed thicknesses)  
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49 1380 and photo examples. Arrows indicate the way-up when bedding is inverted (b, base of the bed; t,  
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51 1381 top of the bed).. Typical H3 sub-facies are indicated in the boxes. HEB-1 and HEB-2 can contain  
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53 1382 H3 divisions of two types: RI and MCI sub-facies can be made of undeformed or deformed  
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55 1383 mudstone rafts; SP and SC sub-facies can include undeformed pieces of thin-bedded stratigraphy  
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57 1384 or their deformed equivalents respectively. MCB: densely packed mudstone clasts (average over 5  
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3 1385 cm) surrounded by dirty sandstone; MCD: small (2-5 cm) mudstone clasts in a dirty sandstone  
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5 1386 matrix; MDC: argillaceous sandstone with scatter mudstone clasts; MD: argillaceous sandstone  
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7 1387 without mud-chips.  
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10 1388 **Fig. 7.** Petrographic and textural characteristics of the H3 division in the Gottero hybrid event  
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12 1389 beds. Samples are from HEB-3 and HEB-5 event beds located in Mt. Ramaceto and Moneglia  
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14 1390 sections respectively. The dispersed clay content (counted 500 points per section) reaches 20% in  
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16 1391 the first sample and 27% in the latter. In the HEB-3 sample mud chips are captured in the act of  
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18 1392 being partially disaggregated and contributing mud to the matrix.  
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21 1393 **Fig. 8.** Thickness characteristics of hybrid event beds. (A) Box-plot showing the direct correlation  
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23 1394 between average, maximum and minimum thickness of the sandy portion (H1 to H4) of the bed,  
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25 1395 and the type of hybrid event bed. (B) Box-plot displaying the lack of correlation between the  
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27 1396 hybrid event bed type and the H1/H3 ratio, HEB-3s have the higher variability.  
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30 1397 **Fig. 9.** Sandy facies associations and related interpreted depositional environments identified in the  
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32 1398 Gottero Sandstone and event bed percentages. Sedimentological logs represent examples of  
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34 1399 stacking patterns for each facies association. Pie charts show the relative abundance of bed types  
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36 1400 (for number of events and in thickness) and hybrid event bed types for each facies association (in  
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38 1401 thickness). St%: sandstone percentage of the facies association. Debrites (DEBs) and gravelly  
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40 1402 high-density turbidites (GHDTs), and low-density turbidites (LDTs) and limestones (L) categories  
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42 1403 are merged together in the statistics.  
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45 1404 **Fig. 10.** Mid-fan amalgamated lobe facies and stacking patterns. (A) Representative log and typical  
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47 1405 bed types of Gottero mid-fan amalgamated lobe deposits (from the Moneglia locality, see location  
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49 1406 in Fig. 3). (B) Gottero 2 mid-fan lobes in the Mt. Ramaceto section: despite being grouped in the  
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51 1407 same facies association, the beds are slightly less amalgamated and finer grained than in the  
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53 1408 Moneglia or Deiva Marina examples. (C) Amalgamated coarse-grained sandstone beds in  
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55 1409 Moneglia showing slightly erosive bases on the underlying deposits. (D) Poorly sorted coarse-  
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57 1410 grained bed in Moneglia. (E) Granule-armoured mudstone clast. (F) Conglomeratic lenticular bed  
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3 1411 draped by fine-grained and rippled bed (Moneglia). (G) Thin and fine-grained HEB-5 bed in mud-  
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5 1412 prone inter-lobe deposits. Way-up is indicated by arrows and by b (base) and t (top) labels.  
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8 1413 **Fig. 11.** Outer-fan lobe architecture in Moneglia (Punta Baffe locality). (A) Cliff exposure of  
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10 1414 Gottero 3 sandstone; numbers represent surfaces across which changes in stacking pattern occur.  
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12 1415 (B) Close-up of the logged section displaying a 20 m thick thickening and thinning cycle. (C)  
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14 1416 Three smaller-scale thickening upward cycles in the intermediate part of the section in which thin  
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16 1417 HEBs are concentrated at the bases. Way-up to the right in B and C. Bed thickness trends are  
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18 1418 indicated by triangles.  
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21 1419 **Fig. 12.** Outer-fan lobes facies and related stacking pattern. (A) Representative log and bed types  
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23 1420 of the Gottero outer-fan lobes (from Moneglia locality, see location in Fig. 3). (B) Example of  
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25 1421 HEB-5 interbedded with thin-bedded lobe fringe deposit at the base of a lobe cycle. (C) HEB-5  
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27 1422 including a well-developed H2 banded division. (D) Poorly sorted mudstone-clast rich bed (MRB)  
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29 1423 in Moneglia lobe deposits. (E) Poorly sorted coarse-sandstone texture with small scattered angular  
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31 1424 mudstone clasts (Terrarossa section; location in Fig. 3). (F) Thin HEB-5 bed interbedded in lobe  
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33 1425 fringe deposits including a thin H2 banded interval and a rippled H4 division. All beds examples  
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35 1426 are right way-up (b: base; t: top).  
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38 1427 **Fig. 13.** Architecture and stacking pattern of the Gottero 3 succession in the Mt. Ramaceto area  
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40 1428 including FA-D and FA-E facies associations (modified from Fonnesu et al., 2013). (A)  
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42 1429 Correlation panel of the upper Gottero succession from eight logs spaced over 4 km laterally. The  
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44 1430 turbiditic succession is overlain by a >300 m thick chaotic level (Gaiette shales) emplaced by  
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46 1431 mass transport processes. The base of the mass transport complex records the erosion of more than  
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48 1432 250 m of turbiditic succession over less than 2.5 km laterally. The numbers refer to the  
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50 1433 photohorizons shown in Fig. 5, and to other labelled beds. The datum is taken at a distinctive mud-  
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52 1434 prone level rich in diagenetic carbonate nodules (“Septarie level” of Andri and Zavatteri, 1990).  
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54 1435 Three units bounded by mud-prone intervals (Gottero 3a, 3b, 3c; GOT3a-3b-3c) are distinguished  
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56 1436 on the basis of a progressive upward increase of sedimentological characteristics indicating an  
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3 1437 increase in the degree of flow ponding (see text for details). Red boxes represent areas covered by  
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5 1438 the detailed correlation panels of Fig. 16. (B) Simplified outcrop map showing the position of the  
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7 1439 measured sections, the bed strikes and dips and the boundaries of the stratigraphic units.  
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10 1440 **Fig. 14.** Vertical and lateral stacking pattern displayed by weakly amalgamated sheets in an  
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12 1441 increasingly confined basin plain setting. (A) Representative log and bed types of weakly  
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14 1442 amalgamated sheets (from Mt. Ramaceto F section; see Fig. 13). (B) Correlation panels (about 1.5  
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16 1443 km wide) of weakly amalgamated sheets in the Mt. Ramaceto area showing consistency in bed  
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18 1444 package thickness but the poor correlatability of individual beds. The upward reduction in the  
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20 1445 lenticularity of individual beds is interpreted to reflect the increased confinement of the system.  
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23 1446 **Fig. 15.** "Confined basin plain isolated sheet" facies and bed stacking pattern. (A) Representative  
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25 1447 log and bed types of Gottero confined basin plain deposits (from Mt. Ramaceto C section; see Fig.  
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27 1448 13). (B) Landscape view of event beds in the Gottero 3 Mt. Ramaceto succession (note inversion of  
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29 1449 beds) including a mudstone clast rich (HEB-3) and chaotic HEBs (HEB-2) with thick mudstone  
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31 1450 caps and interbedded with hybrid-devoid, thin-bedded packages. (C) HEB-1 bed including  
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33 1451 heterolithic thin-bedded substrate rafts enclosed in the H3 division. (D) HEB-3 bed including  
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35 1452 relatively thin H1 sandy base with irregular top, a relatively abrupt transition into a mudstone-clast  
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37 1453 rich H3 division, and a thin draping laminated H4. Way-up is indicated by arrows and by b (base)  
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39 1454 and t (top) labels.  
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42 1455 **Fig. 16.** Detailed cross-sections of selected intervals of the Gottero Sandstone succession in the Mt.  
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44 1456 Ramaceto area confirming the generally tabular geometry and correlativity of individual beds at  
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46 1457 km-scale albeit with local erosion of hybrid event beds into the substrate. The distances between  
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48 1458 the different logs are indicative only, because of the variable angle between them. (A) Panel A  
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50 1459 representing the succession between 120 m and 177 m from the stratigraphic top of the Gottero  
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52 1460 formation in Mt. Ramaceto area (see Fig. 13); (B) Panel B shows the succession between 260 m  
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54 1461 and 354 m from the stratigraphic top. The two panels capture a large-scale stratigraphic trend in  
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56 1462 which single event beds are increasingly separated by mudstone intervals towards the uppermost  
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3 1463 part of the succession interpreted as effect of progressive increase in the degree of confinement of  
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5 1464 the distal Gottero depocentre.

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8 1465 **Fig. 17.** Examples of observed facies tracts of mudstone-clast and raft-bearing HEBs from the Mt.  
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10 1466 Ramaceto succession. The letters refers to the section measured (see their location and context on  
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12 1467 Fig. 13). (A) Example of Type 1 facies tract (FTH-1) showing a longitudinal/lateral transition from  
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14 1468 a clean massive turbidite sandstone (section C) by enrichment and concentration of mudstone  
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16 1469 clasts (MRB – section E) and development of an HEB-3 (section G). The lateral transition is  
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18 1470 recorded also in the vertical bed profile of section G by the presence of a mudstone-clast rich H1b  
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20 1471 interval beneath the H3 division of the bed. Shallow scours (about 30 cm deep) are detected in  
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22 1472 section C, providing a possible source of mudstone clasts from the underlying substrate. (B)  
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24 1473 Examples of Type 2 facies tract (FTH-2) showing that in section A, where the degree of substrate  
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26 1474 removal is at a maximum, the event bed includes large substrate rafts within the H3 division,  
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28 1475 characterised by preserved thin-bedded stratigraphy (HEB-1). Proceeding through the more distal  
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30 1476 sections the substrate rafts are progressively destroyed and the texture of the H3 division became a  
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32 1477 mudstone clast-rich debrite (MCB - HEB-3) but with some pieces of chaotic material still  
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34 1478 preserved (HEB-2). In both cases the thickness of the H4 division is similar throughout the entire  
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36 1479 facies tract.

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39 1480 **Fig. 18.** Hybrid event bed facies tracts detected in the Gottero system. All of them show a  
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41 1481 downcurrent and lateral transition from relatively clean high-density turbidite (HDT) to a hybrid  
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43 1482 event bed (HEB) due to abundant mud clast incorporation. (A) FTH-1 is characterised by a very  
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45 1483 strong lateral relationship between mudstone clast-rich but relatively clean sandstone beds (MRBs)  
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47 1484 and hybrid event beds with mud clast-rich H3 divisions (HEB-3). This lateral facies association is  
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49 1485 linked to elongated shallow scours. (B) FTH-2 shows a downcurrent and lateral passages between  
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51 1486 a large raft-bearing HEB (HEB-1) and a different kind of strongly injected/chaotic (HEB-2) or  
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53 1487 mudstone clast-rich HEB (HEB-3). In this case the beds are associated with large deep scours  
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55 1488 where substrate blocks were locally detached from the sea-floor and incorporated into the flow. (C)  
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57 1489 FTH-3 predicts a downflow/lateral transformation from clean high-density turbidites to thin hybrid  
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3 1490 event beds that may include a banded division (H2). The down-dip transition occurs from beds  
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5 1491 with thin H3 divisions to beds with an expanded H3. The mud entrainment can be provided in form  
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7 1492 of loose clay and small mud chips, by turbulent erosion in up-dip locations.  
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10 1493 **Fig. 19.** Sketch summarising the stratigraphic distribution, character and typical stacking pattern  
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12 1494 of hybrid event beds in fan and basin plain settings, based on the Gottero example. (1) Unconfined  
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14 1495 fan systems are generally devoid of hybrid event beds in their proximal area, developing HEBs  
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16 1496 preferentially in the fan fringe and at the base of thickening upward lobe sequences. HEBs are  
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18 1497 characteristically thin and belong to types 5 and 6. HEBs 1 to 4 can be occasionally found directly  
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20 1498 above mud-prone inter-lobe deposits. (2) In confined basin plain successions developed in  
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22 1499 tectonically active basins characterised by flat basin floor topography, the sedimentation is  
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24 1500 dominated by high-volume flows able to delaminate the substrate and develop thick mudstone clast  
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26 1501 or raft-bearing HEBs (HEB-1 to 4).  
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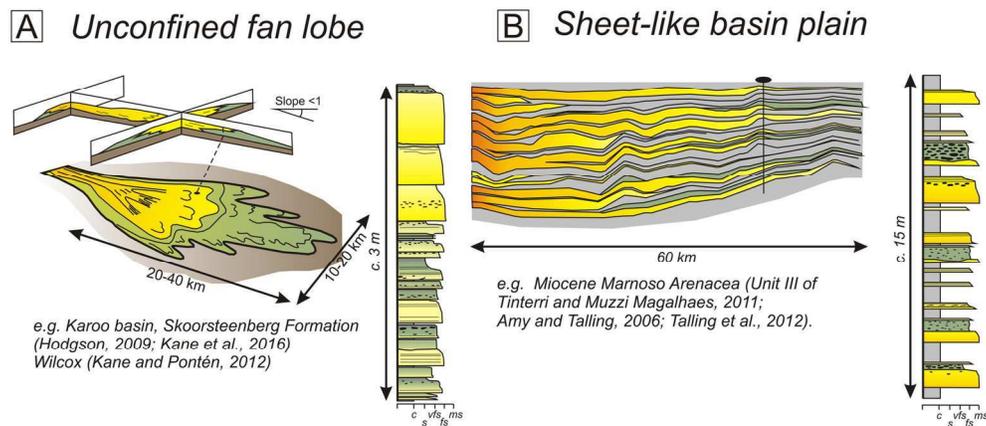
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29 1502 **Tab. 1.** Description and interpretation of bed type classes distinguished in the present study.  
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32 1503 **Tab. 2.** Hybrid event bed character statistical summary.  
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| Bed type class                           | Description   | Interpretation  |
|--|---|---|
| Debrites (DEBs)                          | Matrix-supported poorly sorted conglomerates and muddy sandstones   | Deposited by cohesive debris flows whose larger clasts are supported by a cohesive clay-rich matrix (Pierson, 1981; Mulder and Alexander, 2001; Mohrig & Marr, 2003)  |
| Gravelly high-density turbidites (GHDTs) | Clast-supported conglomerates and pebbly sandstones found as either isolated deposits or at the base of thick graded beds. They can be distinguished as: i) mudstone-clast conglomerates; ii) conglomeratic-lag lenses and iii) pebbles and granules in planar to cross-laminated sandstones.   | Deposited by hyperconcentrated flow – i.e. non-Newtonian but non-plastic flows with high shear strength and intermediate rheology between cohesive and fluidal flows; sediment was supported by a combination of turbulence, dispersive pressure and buoyancy (Costa, 1984; Smith, 1986; Mutti, 1992; Mulder & Alexander, 2001). When hyperconcentrated flows undergo flow transformation to a high-density turbidity current, they deposit lenticular conglomeratic lags because of the progressive loss of flow strength (Mutti, 1992) and can be reworked by the overlying flow forming dunes. |
| High-density turbidites (HDTs)           | Beds including coarse (occasionally granule grade) to medium sand grade bases, eventually grading into or being overlain by finer facies. Bed bases can be characterised by structureless normally graded or ungraded sandstone, inverse graded intervals characterised by granules or coarse sand alignments. More rarely coarse-grained medium scale cross-laminations both as single sets and as a component facies are present.   | Beds related to the rapid or progressive (e.g. layer-by-layer) deposition of high-concentration turbidity currents and by the reworking or suspension fall-out of the low-concentration turbulent flow tail (Lowe, 1982; Mutti, 1992; Kneller and Branney, 1995; Mulder & Alexander, 2001).   |
| Mudstone-clast rich beds (MRBs)          | Beds composed by a basal structureless sandstone and an uppermost structured and finer-grained division, sandwiching an interval enriched in mudstone clasts. Mudstone clasts are preferentially accumulated at the interface between the basal structureless and coarser-grain sandstone and the overlying finer-grained structured division. Occasionally larger mudstone clasts can be armoured by granules and pebbles in distinctive coarse-grained poorly sorted and massive beds. In the distal confined part of the system they are often found in close spatial relationship in the same event with mudstone clast-rich hybrid event beds. | Beds deposited by high-concentration turbidity currents and eventually capped by their associated low-concentration turbulent flow tails. The presence of abundant intra-formational mudstone clasts suggests that the flows were highly erosive at some stage during their runout and were able to detach and incorporate substrate pieces of variable size. The lateral transitions between MRBs and HEBs suggests the former can be interpreted as deposits of flows during the early stages of hybrid flow development (Fonnesu et al., 2015; Southern et al., 2015).                         |
| Hybrid event beds (HEBs)                 | Bipartite or tripartite beds constituted by a basal massive to crude laminated sandstone overlain by an argillaceous generally poorly sorted but texturally very variable sandstone, often rich in mudstone clasts and sheared sand patches. A fine/very fine-grained parallel to ripple laminated division graded into a silty to mudstone cap is eventually present at the top of the sequence.   | Deposition from high-density turbidity currents enriched in mud by erosion of substrate or being already mud enriched, and underwent different degree of flow partitioning (Haughton et al., 2009; Kane & Pontén, 2012; Talling, 2013; Fonnesu et al., 2015; 2016). (See text).   |
| Low-density turbidites (LDTs)            | Generally thin, rippled, wavy to horizontally parallel laminated, fine-grained graded beds.   | Product of low-concentration turbidity currents. They can be the deposit of smaller-volume flows or the distal expression of high-density (or hybrid; see Amy and Talling, 2006; Muzzi Magalhaes & Tinterri, 2010; Fonnesu et al., 2015) sediment flows that have already deposited the majority of their sediment load in more proximal or adjacent regions.   |
| Limestone beds (L)                       | Calcareous to micritic, structureless to planar or wavy laminated beds grading into marls found as continuous or in nodular layers.   | Limestone beds record deposition from rare calcareous turbidity currents (Marini, 1994). Some nodule layers could be of early diagenetic origin.  |

|                            | HEB-1      | HEB-2    | HEB-3     | HEB-4      | HEB-5      | HEB-6    |
|----------------------------|------------|----------|-----------|------------|------------|----------|
| N° of beds (%)             | 32 (10.7%) | 33 (11%) | 129 (43%) | 55 (18.3%) | 46 (15.3%) | 5 (1.7%) |
| Tot thickn. (%)            | 86.6 m     | 78.3 m   | 228 m     | 50.3 m     | 20.4 m     | 1.02 m   |
|                            | (18.6%)    | (16.9%)  | (49.1%)   | (10.8%)    | (4.4%)     | (0.2%)   |
| Max sandst. thickness      | 6.80 m     | 9.57 m   | 5.30 m    | 3.20 m     | 2.40 m     | 0.75 m   |
| Min sandst. thickness      | 0.40 m     | 0.40 m   | 0.30 m    | 0.20 m     | 0.05 m     | 0.12 m   |
| Aver. sandst. thickness    | 3.32 m     | 2.37 m   | 1.77 m    | 0.92 m     | 0.44 m     | 0.20 m   |
| Aver. thickn. of<br>H1+H1b | 0.96 m     | 0.77 m   | 0.81 m    | 0.38 m     | 0.17 m     |          |
| Aver. thickn. of H3        | 1.37 m     | 1.27 m   | 0.72 m    | 0.39 m     | 0.23 m     | 0.10 m   |
| Presence of H4 (%)         | 30 (94%)   | 26 (79%) | 112 (87%) | 45 (82%)   | 22 (48%)   |          |
| Aver. thickn. of H4        | 0.32 m     | 0.35 m   | 0.24 m    | 0.15 m     | 0.09 m     | 0.10 m   |

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22 Fig. 1. Different styles of hybrid event bed distribution in turbidite systems, based on published examples.  
23 (A) Hybrid event beds in distributive lobe systems (modified from Hodgson, 2009) and their vertical  
24 arrangement in 1D logs at the base of prograding lobes (Kane & Pontén, 2012). (B) Hybrid event beds in  
25 confined basin plains (based on stratigraphic cross-section of Unit 3 of Miocene Marnoso-arenacea  
26 Formation, sensu Tinterri and Muzzi Magalhaes, 2011, from Talling et al., 2012 in the interval below the  
27 Contessa key bed ); the synthetic vertical log shows the lack of vertical organization of hybrid event beds  
28 and conventional turbidites at c. 20 m scale.

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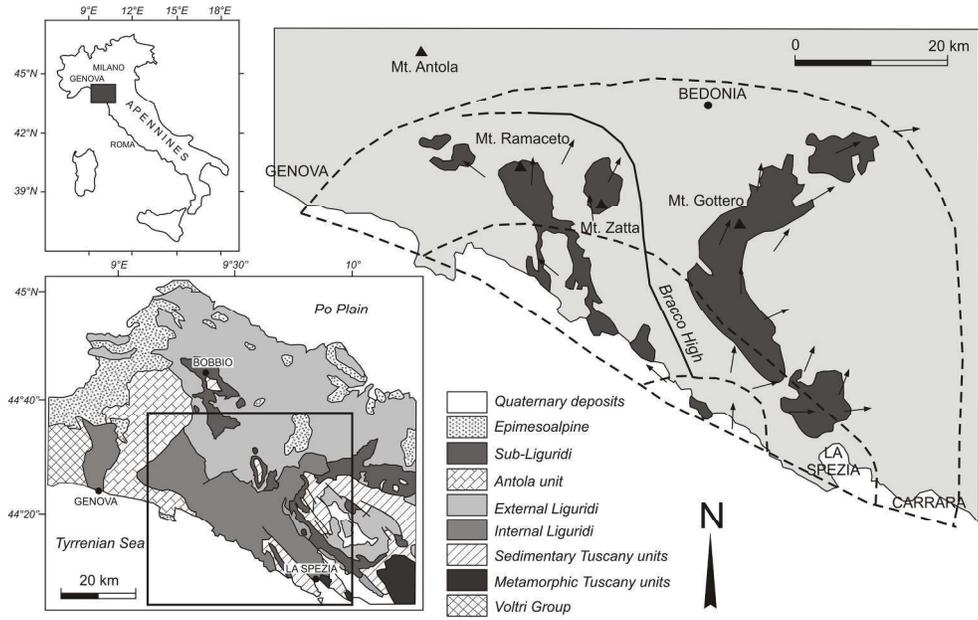


Fig. 2. - Location map of the Gottero system (modified from Nilsen & Abbate, 1984) and sketch map showing the tectonic units of the Northern Apennines (modified from Elter et al., 1992). The arrows in the location map indicate the main palaeocurrent pattern deduced by Nilsen & Abbate (1984).

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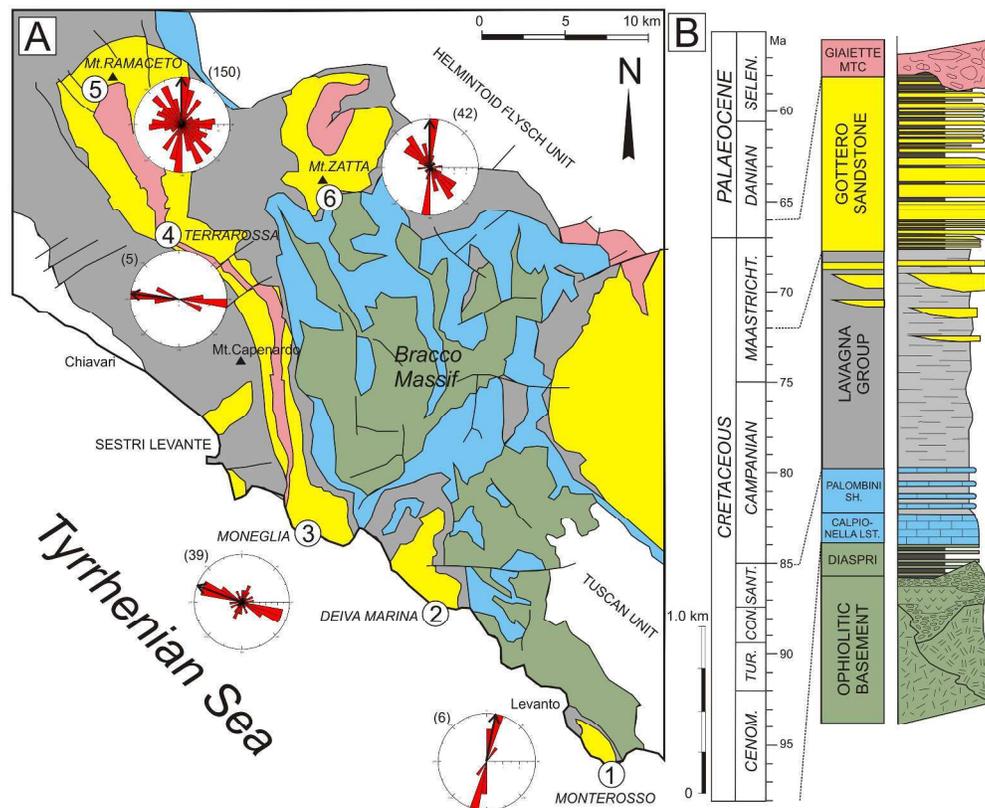


Fig. 3. (A) Simplified geological map of the Western Gottero study area (modified from Marroni, 1994) showing the location of measured sections (1 to 6) and palaeocurrent roses obtained during this study; the numbers in brackets indicate the number of palaeocurrent measurements. The palaeoflow pattern broadly corresponds to that established by Nilsen & Abbate (1984) (see Fig. 2). (B) Internal Liguridi stratigraphy of the Gottero tectonic unit (modified from Marroni et al., 2001). The colours on the map correspond to those displayed in the stratigraphic log.

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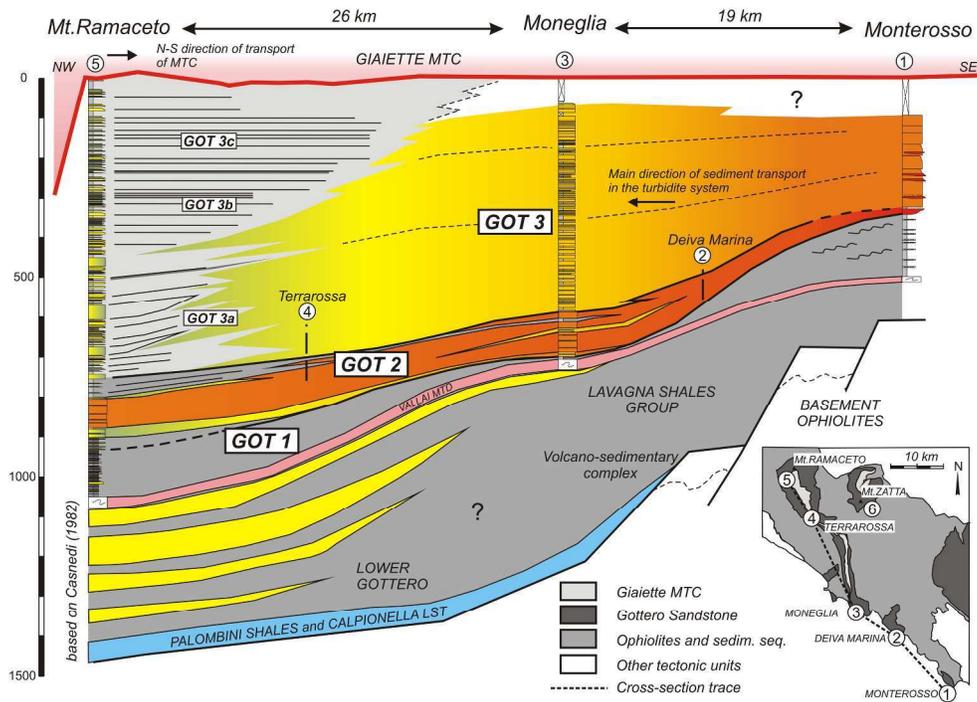


Fig. 4. General NW-SE cross-section of the Gottero system aligned in a direction approximately parallel to the sediment transport. Colour shading according to the major grain-size and lithofacies (red colours: conglomerate and coarse grained sandstones, green: hybrid event beds, grey: mostly siltstone and mudstones or fine-grained sandstones, pink: mass transport complexes). The area interpreted as confined basin plain is coloured in light grey on the correlation panel. Note the distances between sections have not been palinspastically restored and could potentially be longer than indicated.

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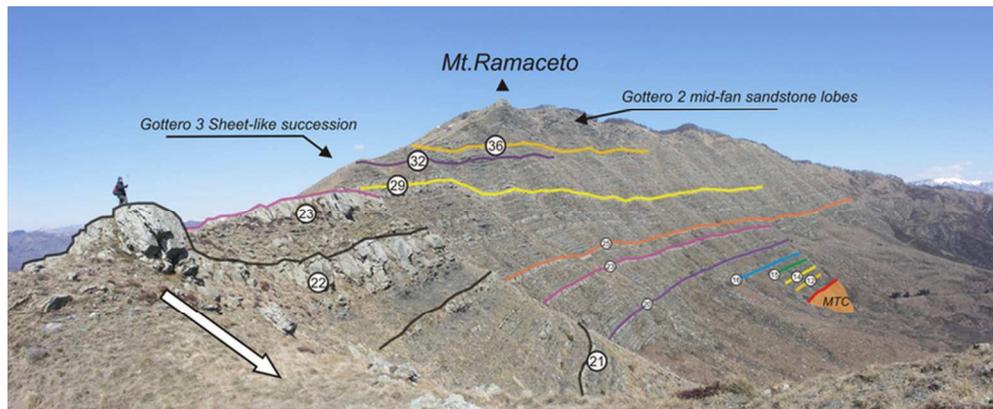


Fig. 5. Exposure of the upper stratigraphic part of the Gottero Sandstone in the Mt. Ramaceto area. Note the succession is tectonically inverted (arrow indicates succession way-up). Numbers refer to photohorizons highlighted in the correlation panel of Fig. 13. Orange colour represents the outcrop of the stratigraphically overlying Gaiette mass transport complex unit (MTC). The picture capture about 2.2 km lateral exposure and 740 m of stratigraphic thickness.

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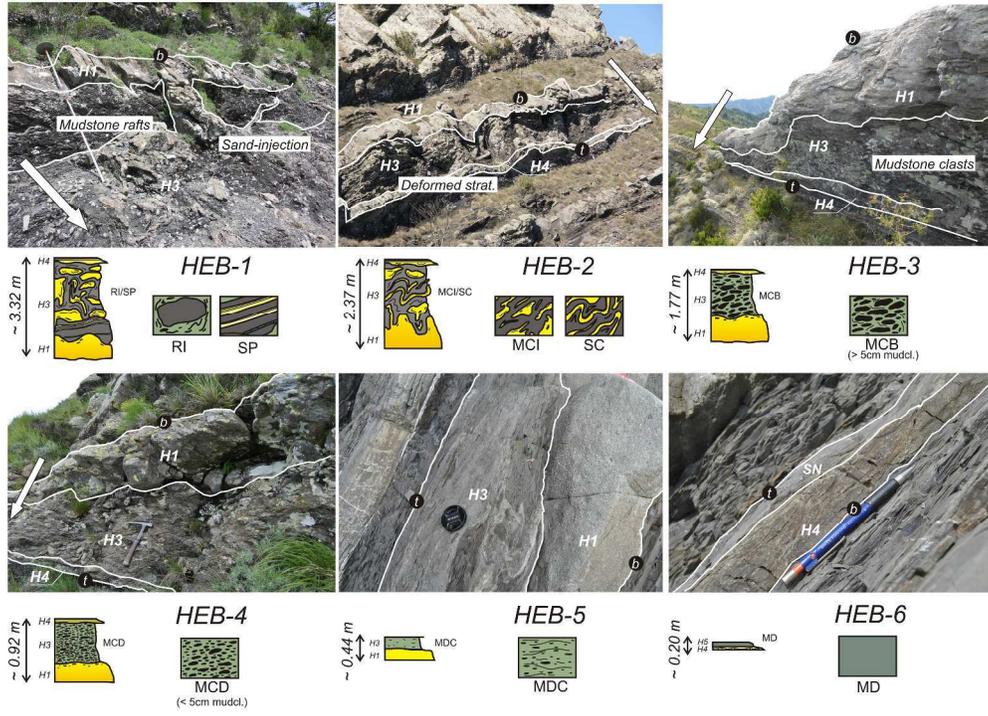


Fig. 6. Hybrid event bed classification scheme. Typical bed profiles (with average bed thicknesses) and photo examples. Arrows indicate the way-up when bedding is inverted (b, base of the bed; t, top of the bed).. Typical H3 sub-facies are indicated in the boxes. HEB-1 and HEB-2 can contain H3 divisions of two types: RI and MCI sub-facies can be made of undeformed or deformed mudstone rafts; SP and SC sub-facies can include undeformed pieces of thin-bedded stratigraphy or their deformed equivalents respectively. MCB: densely packed mudstone clasts (average over 5 cm) surrounded by dirty sandstone; MCD: small (2-5 cm) mudstone clasts in a dirty sandstone matrix; MDC: argillaceous sandstone with scatter mudstone clasts; MD: argillaceous sandstone without mud-chips.

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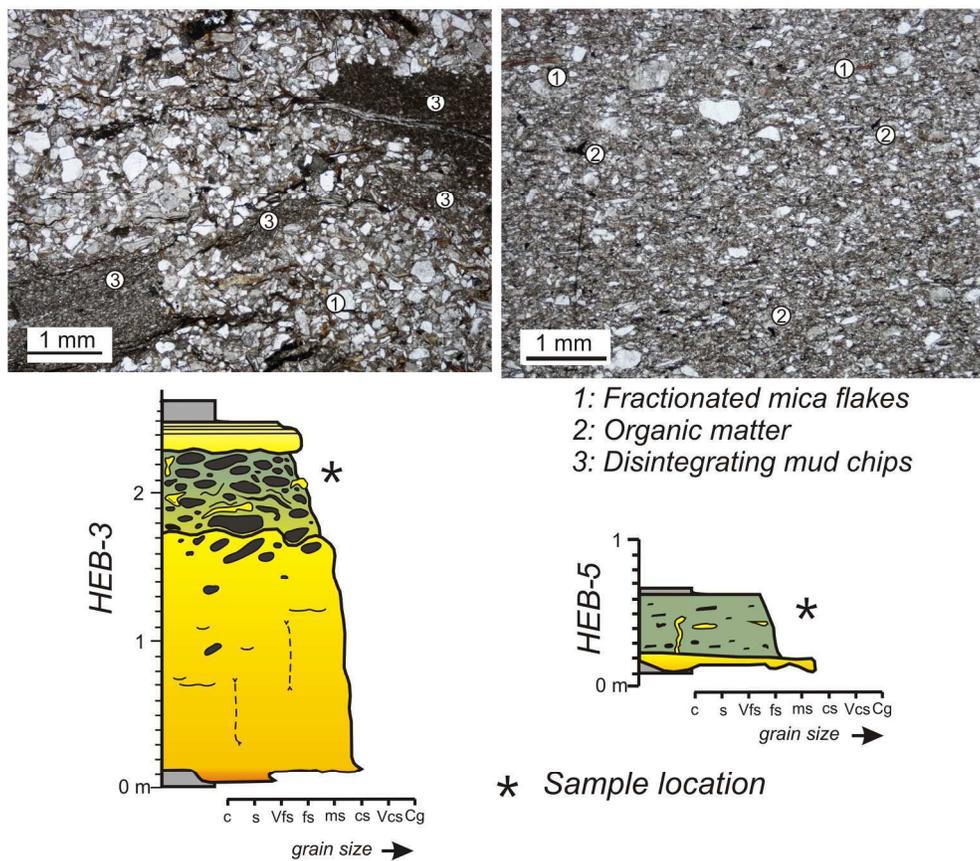


Fig. 7. Petrographic and textural characteristics of the H3 division in the Gottero hybrid event beds. Samples are from HEB-3 and HEB-5 event beds located in Mt. Ramaceto and Moneglia sections respectively. The dispersed clay content (counted 500 points per section) reaches 20% in the first sample and 27% in the latter. In the HEB-3 sample mud chips are captured in the act of being partially disaggregated and contributing mud to the matrix.

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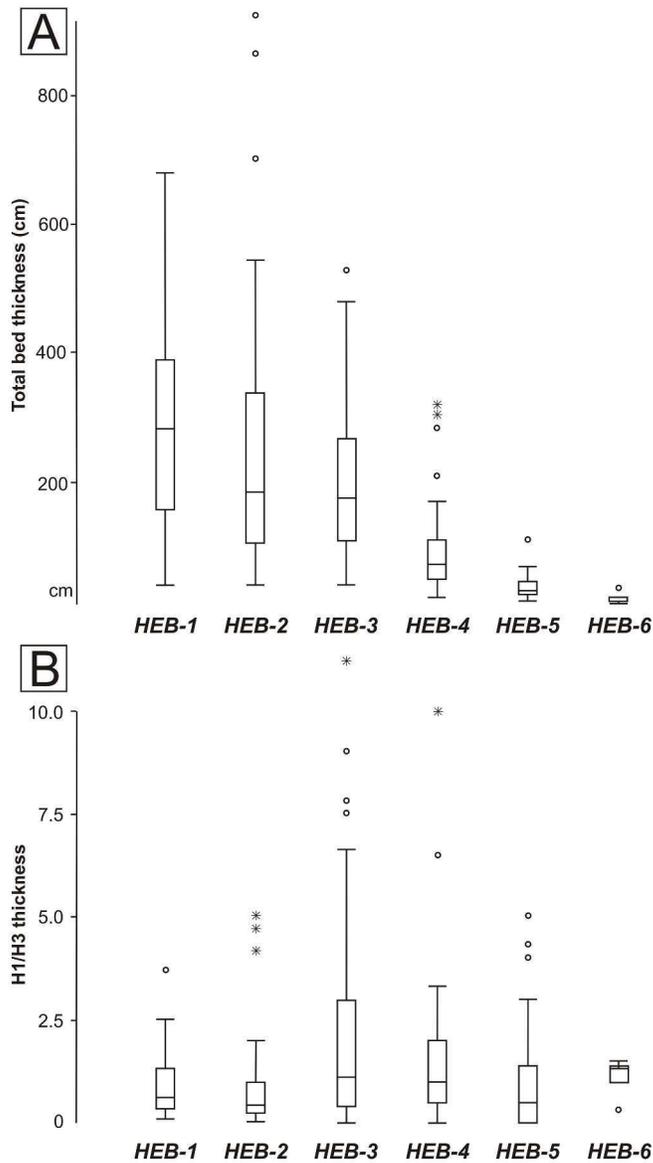


Fig. 8. Thickness characteristics of hybrid event beds. (A) Box-plot showing the direct correlation between average, maximum and minimum thickness of the sandy portion (H1 to H4) of the bed, and the type of hybrid event bed. (B) Box-plot displaying the lack of correlation between the hybrid event bed type and the H1/H3 ratio, HEB-3s have the higher variability.

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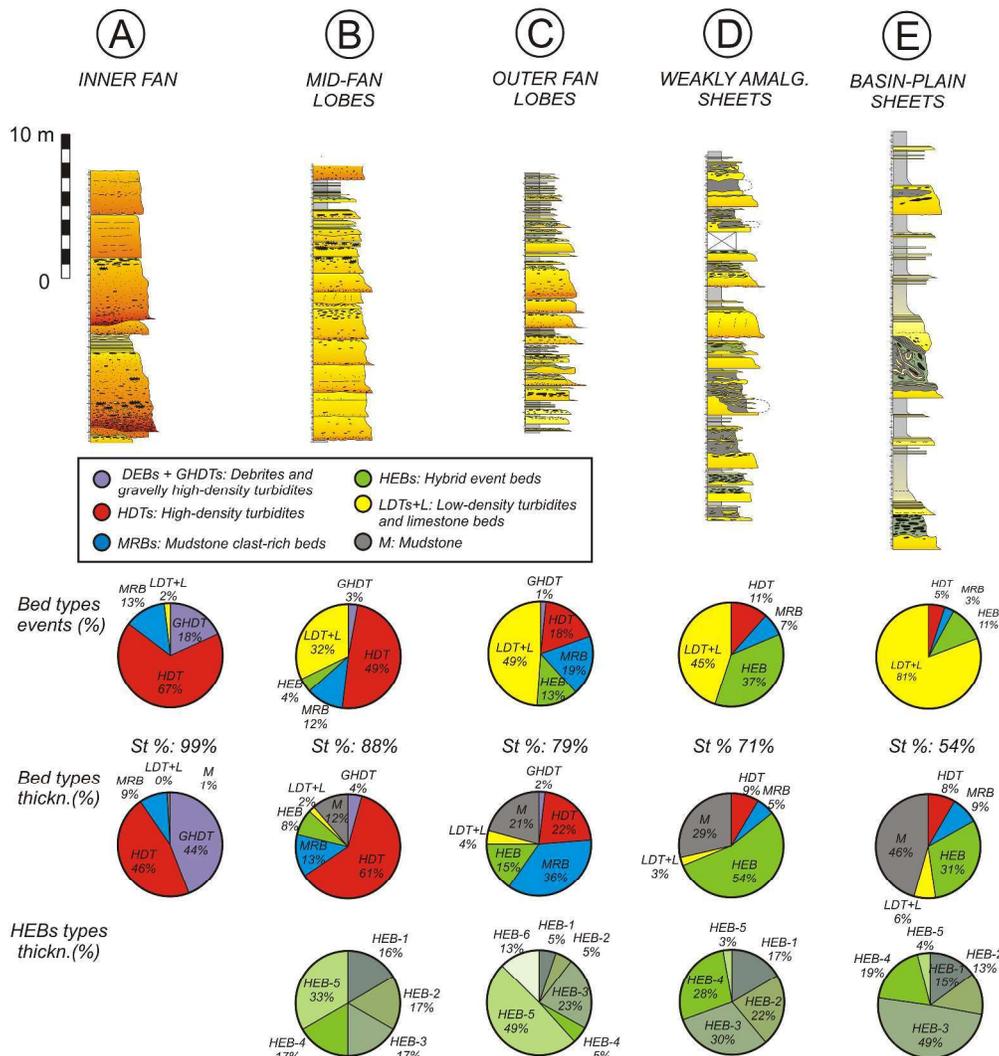


Fig. 9. Sandy facies associations and related interpreted depositional environments identified in the Gottero Sandstone and event bed percentages. Sedimentological logs represent examples of stacking patterns for each facies association. Pie charts show the relative abundance of bed types (for number of events and in thickness) and hybrid event bed types for each facies association (in thickness). St%: sandstone percentage of the facies association. Debrisites (DEBs) and gravelly high-density turbidites (GHDTs), and low-density turbidites (LDTs) and limestones (L) categories are merged together in the statistics.

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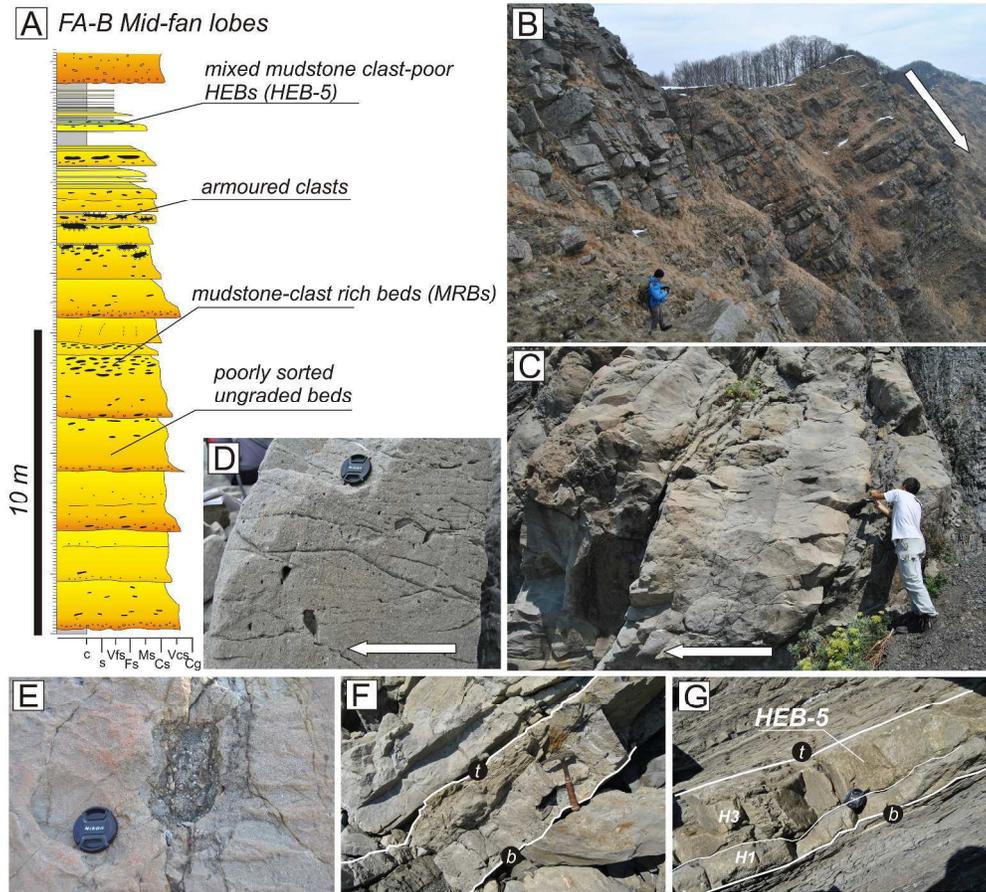


Fig. 10. Mid-fan amalgamated lobe facies and stacking patterns. (A) Representative log and typical bed types of Gottero mid-fan amalgamated lobe deposits (from the Moneglia locality, see location in Fig. 3). (B) Gottero 2 mid-fan lobes in the Mt. Ramaceto section: despite being grouped in the same facies association, the beds are slightly less amalgamated and finer grained than in the Moneglia or Deiva Marina examples.

(C) Amalgamated coarse-grained sandstone beds in Moneglia showing slightly erosive bases on the underlying deposits. (D) Poorly sorted coarse-grained bed in Moneglia. (E) Granule-armoured mudstone clast. (F) Conglomeratic lenticular bed draped by fine-grained and rippled bed (Moneglia). (G) Thin and fine-grained HEB-5 bed in mud-prone inter-lobe deposits. Way-up is indicated by arrows and by b (base) and t (top) labels.

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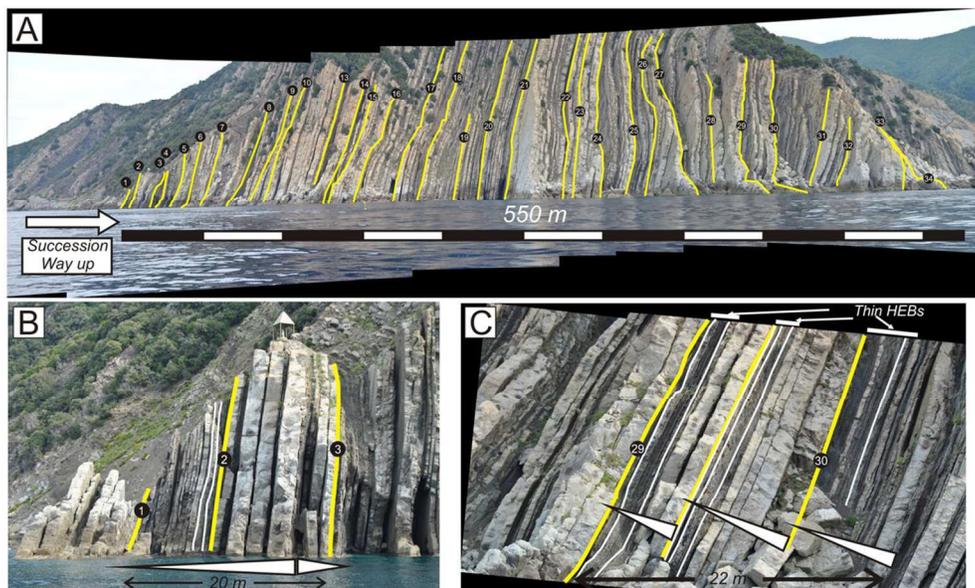


Fig. 11. Outer-fan lobe architecture in Moneglia (Punta Baffe locality). (A) Cliff exposure of Gottero 3 sandstone; numbers represent surfaces across which changes in stacking pattern occur. (B) Close-up of the logged section displaying a 20 m thick thickening and thinning cycle. (C) Three smaller-scale thickening upward cycles in the intermediate part of the section in which thin HEBs are concentrated at the bases. Way-up to the right in B and C. Bed thickness trends are indicated by triangles.

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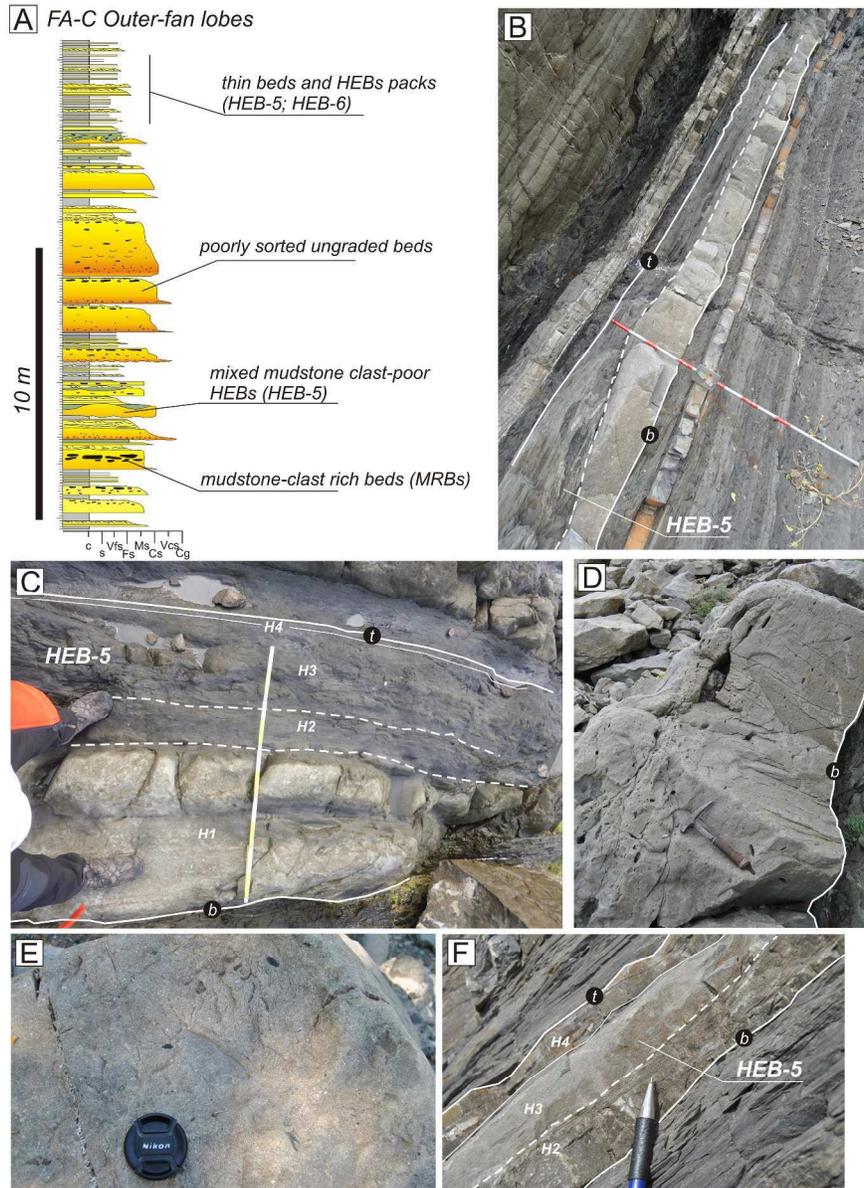


Fig. 12. Outer-fan lobes facies and related stacking pattern. (A) Representative log and bed types of the Gottero outer-fan lobes (from Moneglia locality, see location in Fig. 3). (B) Example of HEB-5 interbedded with thin-bedded lobe fringe deposit at the base of a lobe cycle. (C) HEB-5 including a well-developed H2 banded division. (D) Poorly sorted mudstone-clast rich bed (MRB) in Moneglia lobe deposits. (E) Poorly sorted coarse-sandstone texture with small scattered angular mudstone clasts (Terrarossa section; location in Fig. 3). (F) Thin HEB-5 bed interbedded in lobe fringe deposits including a thin H2 banded interval and a rippled H4 division. All beds examples are right way-up (b: base; t: top).

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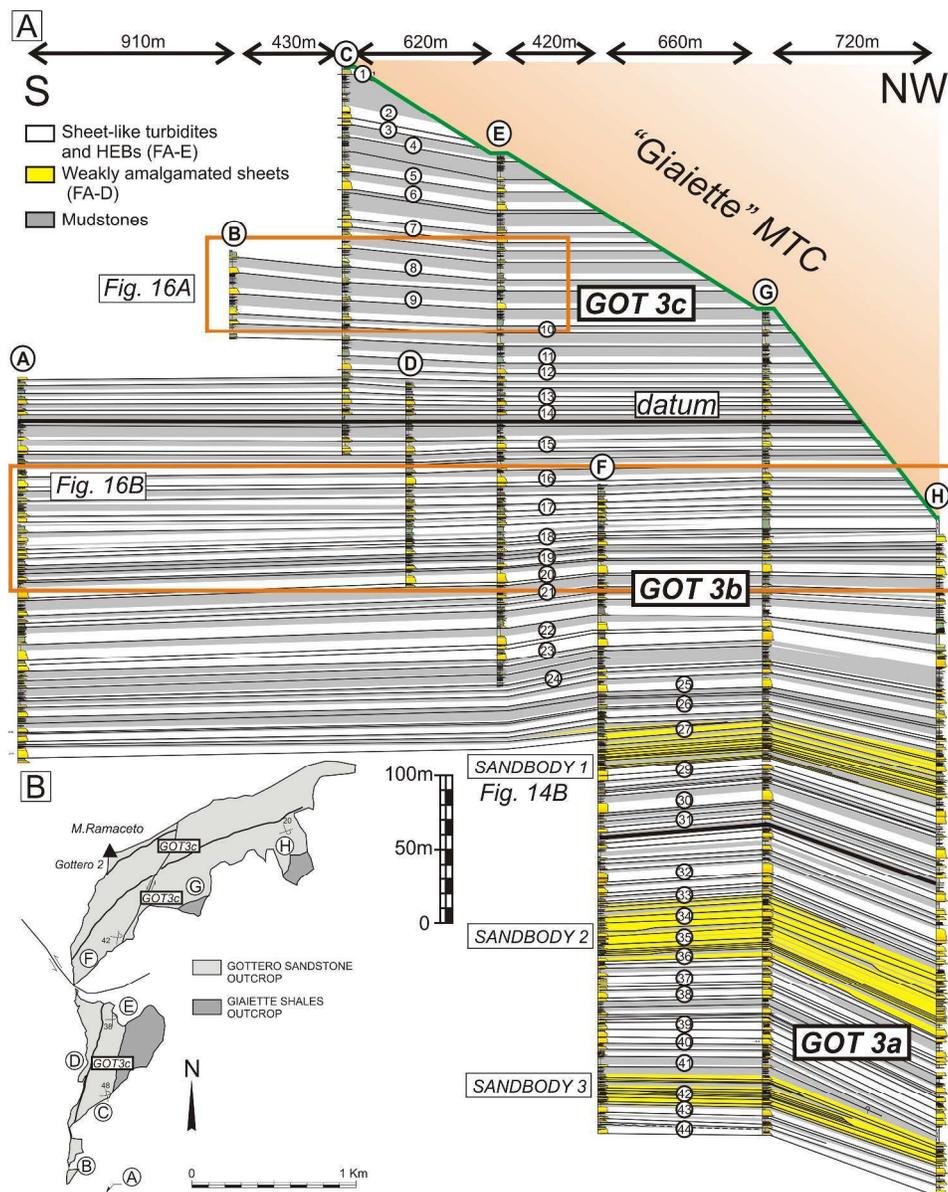


Fig. 13. Architecture and stacking pattern of the Gottero 3 succession in the Mt. Ramaceto area including FA-D and FA-E facies associations (modified from Fonesu et al., 2013). (A) Correlation panel of the upper Gottero succession from eight logs spaced over 4 km laterally. The turbiditic succession is overlain by a >300 m thick chaotic level (Giaiette shales) emplaced by mass transport processes. The base of the mass transport complex records the erosion of more than 250 m of turbiditic succession over less than 2.5 km laterally. The numbers refer to the photohorizons shown in Fig. 5, and to other labelled beds. The datum is taken at a distinctive mud-prone level rich in diagenetic carbonate nodules ("Septarie lavel" of Andri and Zavatteri, 1990). Three units bounded by mud-prone intervals (Gottero 3a, 3b, 3c; GOT3a-3b-3c) are distinguished on the basis of a progressive upward increase of sedimentological characteristics indicating an increase in the degree of flow ponding (see text for details). Red boxes represent areas covered by the detailed correlation panels of Fig. 16. (B) Simplified outcrop map showing the position of the measured sections, the bed strikes and dips and the boundaries of the stratigraphic units.

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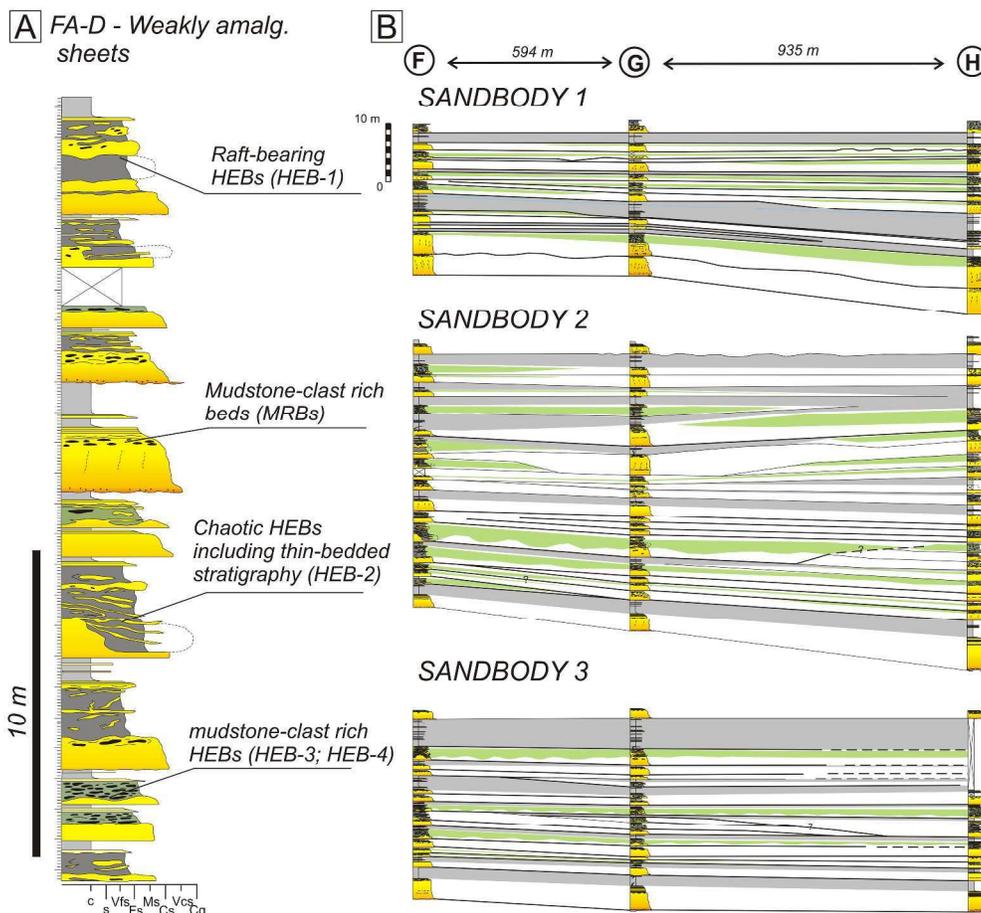


Fig. 14. Vertical and lateral stacking pattern displayed by weakly amalgamated sheets in an increasingly confined basin plain setting. (A) Representative log and bed types of weakly amalgamated sheets (from Mt. Ramaceto F section; see Fig. 13). (B) Correlation panels (about 1.5 km wide) of weakly amalgamated sheets in the Mt. Ramaceto area showing consistency in bed package thickness but the poor correlatability of individual beds. The upward reduction in the lenticularity of individual beds is interpreted to reflect the increased confinement of the system.

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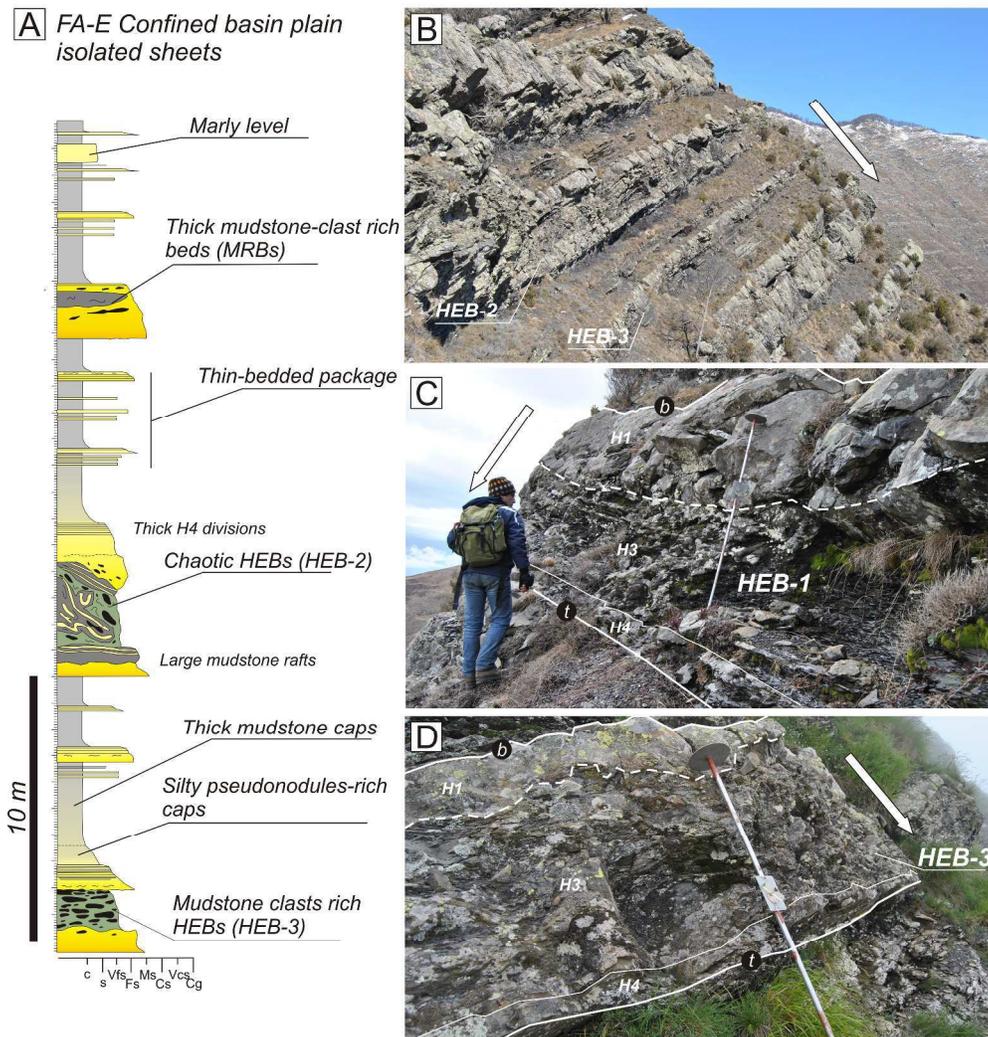


Fig. 15. "Confined basin plain isolated sheet" facies and bed stacking pattern. (A) Representative log and bed types of Gottero confined basin plain deposits (from Mt. Ramaceto C section; see Fig. 13). (B) Landscape view of event beds in the Gottero 3 Mt. Ramaceto succession (note inversion of beds) including a mudstone clast rich (HEB-3) and chaotic HEBs (HEB-2) with thick mudstone caps and interbedded with hybrid-devoid, thin-bedded packages. (C) HEB-1 bed including heterolithic thin-bedded substrate rafts enclosed in the H3 division. (D) HEB-3 bed including relatively thin H1 sandy base with irregular top, a relatively abrupt transition into a mudstone-clast rich H3 division, and a thin draping laminated H4. Way-up is indicated by arrows and by b (base) and t (top) labels.

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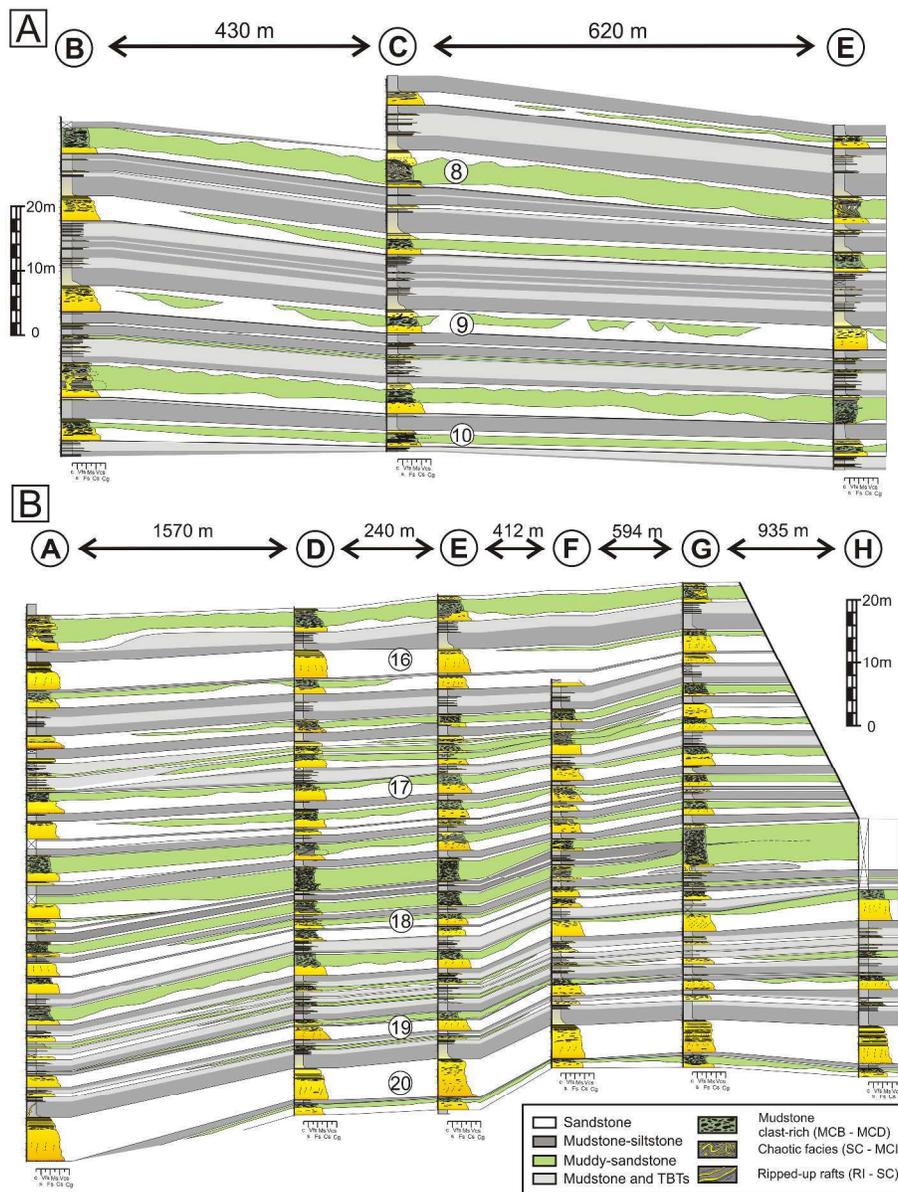


Fig. 16. Detailed cross-sections of selected intervals of the Gottero Sandstone succession in the Mt. Ramaceto area confirming the generally tabular geometry and correlativity of individual beds at km-scale albeit with local erosion of hybrid event beds into the substrate. The distances between the different logs are indicative only, because of the variable angle between them. (A) Panel A representing the succession between 120 m and 177 m from the stratigraphic top of the Gottero formation in Mt. Ramaceto area (see Fig. 13); (B) Panel B shows the succession between 260 m and 354 m from the stratigraphic top. The two panels capture a large-scale stratigraphic trend in which single event beds are increasingly separated by mudstone intervals towards the uppermost part of the succession interpreted as effect of progressive increase in the degree of confinement of the distal Gottero depocentre.

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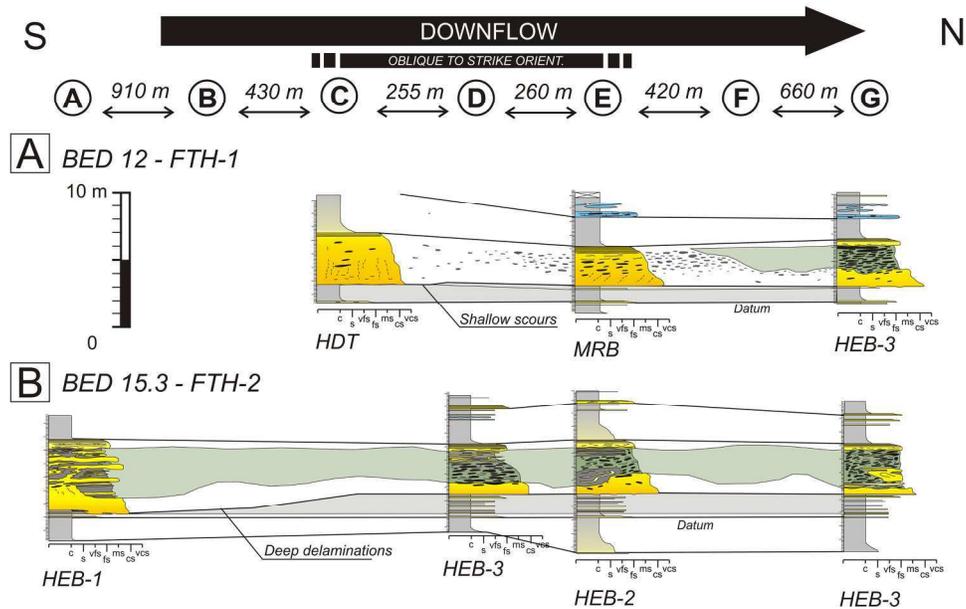


Fig. 17. Examples of observed facies tracts of mudstone-clast and raft-bearing HEBs from the Mt. Ramaceto succession. The letters refers to the section measured (see their location and context on Fig. 13). (A) Example of Type 1 facies tract (FTH-1) showing a longitudinal/lateral transition from a clean massive turbidite sandstone (section C) by enrichment and concentration of mudstone clasts (MRB – section E) and development of an HEB-3 (section G). The lateral transition is recorded also in the vertical bed profile of section G by the presence of a mudstone-clast rich H1b interval beneath the H3 division of the bed. Shallow scours (about 30 cm deep) are detected in section C, providing a possible source of mudstone clasts from the underlying substrate. (B) Examples of Type 2 facies tract (FTH-2) showing that in section A, where the degree of substrate removal is at a maximum, the event bed includes large substrate rafts within the H3 division, characterised by preserved thin-bedded stratigraphy (HEB-1). Proceeding through the more distal sections the substrate rafts are progressively destroyed and the texture of the H3 division became a mudstone clast-rich debrite (MCB - HEB-3) but with some pieces of chaotic material still preserved (HEB-2). In both cases the thickness of the H4 division is similar throughout the entire facies tract.

102x62mm (600 x 600 DPI)

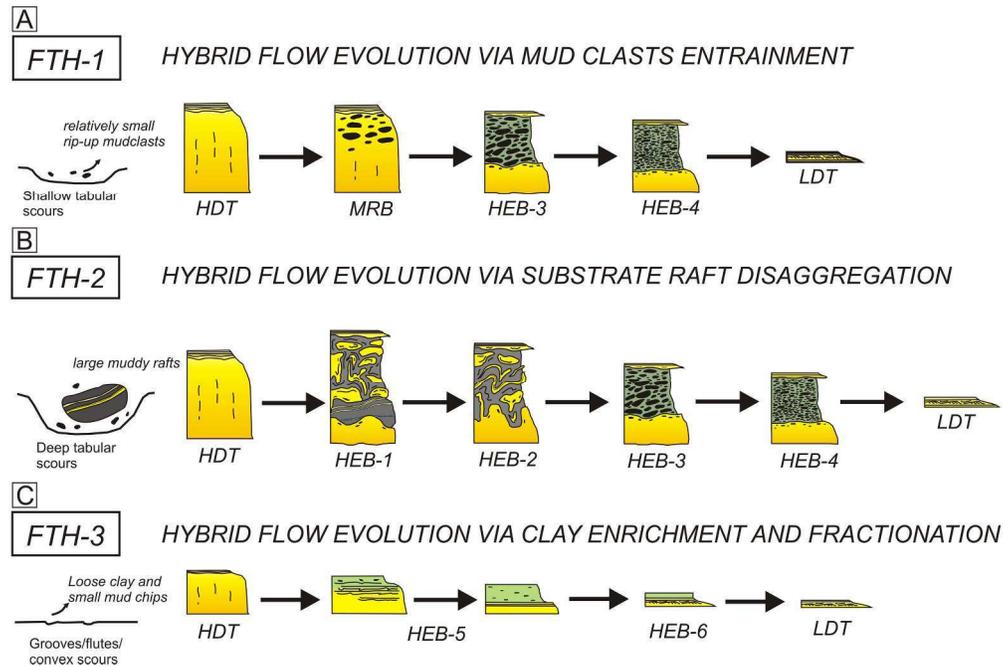


Fig. 18. Hybrid event bed facies tracts detected in the Gottero system. All of them show a downcurrent and lateral transition from relatively clean high-density turbidite (HDT) to a hybrid event bed (HEB) due to abundant mud clast incorporation. (A) FTH-1 is characterised by a very strong lateral relationship between mudstone clast-rich but relatively clean sandstone beds (MRBs) and hybrid event beds with mud clast-rich H3 divisions (HEB-3). This lateral facies association is linked to elongated shallow scours. (B) FTH-2 shows a downcurrent and lateral passages between a large raft-bearing HEB (HEB-1) and a different kind of strongly injected/chaotic (HEB-2) or mudstone clast-rich HEB (HEB-3). In this case the beds are associated with large deep scours where substrate blocks were locally detached from the sea-floor and incorporated into the flow. (C) FTH-3 predicts a downflow/lateral transformation from clean high-density turbidites to thin hybrid event beds that may include a banded division (H2). The down-dip transition occurs from beds with thin H3 divisions to beds with an expanded H3. The mud entrainment can be provided in form of loose clay and small mud chips, by turbulent erosion in up-dip locations.

112x74mm (600 x 600 DPI)

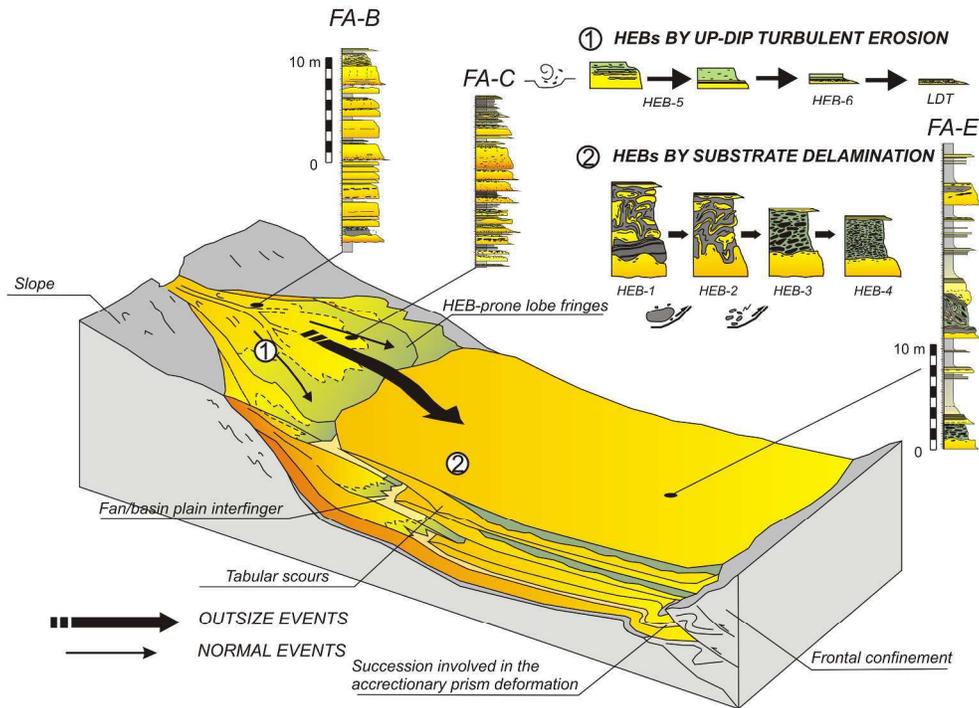


Fig. 19. Sketch summarising the stratigraphic distribution, character and typical stacking pattern of hybrid event beds in fan and basin plain settings, based on the Gottero example. (1) Unconfined fan systems are generally devoid of hybrid event beds in their proximal area, developing HEBs preferentially in the fan fringe and at the base of thickening upward lobe sequences. HEBs are characteristically thin and belong to types 5 and 6. HEBs 1 to 4 can be occasionally found directly above mud-prone inter-lobe deposits. (2) In confined basin plain successions developed in tectonically active basins characterised by flat basin floor topography, the sedimentation is dominated by high-volume flows able to delaminate the substrate and develop thick mudstone clast or raft-bearing HEBs (HEB-1 to 4).

123x90mm (600 x 600 DPI)