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RHEOLOGICAL COMPLEXITY IN SEDIMENT GRAVITY FLOWS FORCED TO DECELERATE AGAINST A CONFINING SLOPE, BRAUX, SE FRANCE

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ABSTRACT

Hybrid event beds are now recognized as an important component of many deep-sea fan and sheet systems. They are interpreted to record the passage of rheologically complex sediment gravity currents (hybrid flows) that comprise turbulent, transitional, and/or laminar zones. Hitherto, the development of hybrid flow character has mainly been recognized in system fringes and attributed to distal and lateral flow transformations and/or declining turbulence energy expressed over lateral scales of several kilometers or more. However, new field data show that deposition from hybrid flows can occur relatively proximally, where flows meet confining topography. Turbidity currents primed to transform to hybrid flows by up-dip erosion and incorporation of clay may be forced to do so by rapid, slope-induced decelerations within 1 km of the slope. Local flow transformation and deposition of hybrid event-beds offer an alternative explanation for unusual facies developed at the foot of flow-confining seafloor slopes.

INTRODUCTION

A recurring bed type in many sandy deep-water systems involves an association of clean sand and clay-prone, typically chaotic sand-mud units. An idealized event bed (Haughton et al. 2009) is made up of a basal structureless sandstone (H1), succeeded by a banded sandstone (*sensu* Lowe and Guy 2000; H2), a muddy sandstone with or without mudstone clasts (H3), a laminated very fine sandstone or siltstone (H4), and finally a mudstone cap (H5). Event beds of this general type have been documented for some time (e.g., Wood and Smith 1958, Ricci Lucchi and Valmori 1980), but interest in them has intensified over the last decade as it has become apparent that they occur very widely in deep-marine sequences. They are also an important component of many producing hydrocarbon reservoirs, where they introduce significant bed-level heterogeneity and can impact on production efficiency (Haughton et al. 2003, 2009; Talling et al. 2004; Amy et al. 2009; Hodgson 2009; Muzzi Magalhaes and Tinterri 2010). Examples from various basins have highlighted several variants of the idealized bed; H2 may be poorly expressed in some systems (Talling 2013) although often it is cryptic and requires subtle weathering and/or differential cementation to reveal the characteristic banding. In other cases (e.g., the distal Tyee Formation; Haughton et al. 2010) H4 may be absent, suggesting the lack of a trailing low-density sediment cloud. The H3 division may be mudstone clast-prone, or simply comprise a clay-rich sandy interval. The basal H1 division is generally structureless and/or dewatered sandstone but in some cases may be laminated.

Various emplacement mechanisms have been suggested for such beds (see Sumner et al. 2009, Talling 2013 for reviews), most invoking the development of zones of different rheology within the depositing current (a ‘hybrid flow’). The hybrid event beds that they leave are thus part turbidite (H1, H4), and part debrite (H3) and may include elements of transitional-flow deposition as well (H2). Variable clast and clay content in the H3 division may reflect a range of matrix strengths in the trailing linked debris flow (Talling 2013). In many cases, the change to more cohesive flow behavior distally seems to be promoted by incorporation of significant clay into the flow, often initially in the form of abundant mud clasts that then disintegrate. Near-bed increases in clay content (following local erosion of muddy seafloor, longitudinal fractionation, and/or selective sand deposition; Haughton et al. 2003; Talling et al. 2004) together with declining turbulent energy (Baas and Best 2002; Haughton et al. 2009; Sumner et al. 2009; Baas et al. 2011) and decreases in axial gradient (Talling et al., 2007, Wynn et al., 2012) combine to damp turbulence and promote the onset of cohesive behavior. Hybrid event beds are common in some systems but only locally developed or absent in others; their occurrence may relate to factors such as the availability of clay along the transport path, the likelihood of erosion up-dip, and changes in local gradient. In some basins, hybrid event beds mark periods of tectonic activity that presumably promoted up-dip erosion (Haughton et al. 2003, Muzzi Magalhaes and Tinterri 2010).

In most of the examples studied to date, hybrid flow conditions are inferred to develop on length scales of several kilometers to tens of kilometers in down-dip lateral and distal fringe settings or on variably confined, distal basin floors. The aim of this study is to re-examine a classic onlap setting in the French Alps where mudstone clast-rich sandstones have previously been related to slope instability induced by the arrival of a turbidity current (McCaffrey and Kneller 2001; Puigdefàbregas et al. 2004). The beds are reinterpreted as either fully developed or incipient hybrid event beds, here developed immediately next to a confining slope. Detailed bed correlations are used to demonstrate coherent facies trends as the paleoslope is approached, suggesting onset of hybrid flow development over very short lengths scales (hundreds of meters) in a relatively proximal part of the overall system. We argue that flow deceleration next to a confining slope can locally force hybrid flow development and deposition, and preserves key stages of the transformation process due to rapid arrest of the flow; these may not be as well expressed (if at all) down-dip where flow energy dissipates more gradually. The emphasis on flow transformation processes at the foot of counter slopes has wider implications for facies prediction next to confining (onlap) slopes and is particularly important for predicting clay distribution and hence likely reservoir quality trends in this setting.

THE BRAUX UNIT, SE FRANCE

The Braux Unit (Annot Sandstone of SE France) records the Upper Priabonian deep-water clastic fill of the lower part of the Annot sub-basin (Callec 2004). The stratigraphy can be divided into a Lower Braux Unit (Crete de la Barre lower member of Callec 2004; La Ray member of Puigdefàbregas et al. 2004) and an Upper Braux Unit (Crete de la Barre upper member of Callec 2004; La Barre member of Puigdefàbregas et al. 2004), separated by a chaotic muddy unit 10-20 meters thick (Sinclair 1994).

The basin is bounded by a marl-cored slope to the west, which in the Crete de la Barre study area (Fig. 1) has a restored dip direction of ENE and a variable dip angle up to 15 degrees (Sinclair 1994, Puigdefàbregas et al. 2004, Salles et al. 2011). Sinclair (2000) provided a basin morphology reconstruction, inferring a slightly NE-SW elongated depression with estimated dimensions of 10 km by 20 km. Whereas the general paleoflow direction for the Annot system is usually consistently towards the north (see summary in Joseph and Lomas 2004), paleoflow within the Braux Unit is more diverse and shows a significant spread, in particular in proximity to the western onlap margin where south-directed paleoflow indicators are locally present (Sinclair 1994); Kneller and McCaffrey (1999) suggested that point-sourced flows entering the basin only a few kilometers from the slope expanded radially across the basin floor, before being deflected either toward the north or the south as they interacted with the slope (their Fig. 6; see also Fig. 1). Additional paleoflow data collected during the present study are consistent with this interpretation of the dispersal pattern (see Appendix Figure 1).

METHODS

The study focusses on the Upper Braux Unit, exposed along the Braux road and on the adjacent hill slopes extending to the southwest and northeast. Some of the sections originally documented by Kneller and McCaffrey (1999) have been remeasured, and additional logs have been collected to better constrain lateral changes in bed character approaching the confining slope. For clarity, the bed nomenclature of Kneller and McCaffrey (1999) has been retained. A total of 400 m of section was logged at a scale of 1:20 in 12 separate logs. A correlation panel 1.5 km long (Appendix 1) has been created by walking out key beds along the outcrop and by matching of beds with distinctive character. The overall sheet architecture of the Upper Braux unit and distinctive vertical bed-thickness patterns allow individual event beds to be traced laterally at kilometer scale with a high degree of confidence. Selected beds have been sampled in vertical profiles for petrographical analysis of sandstone texture.

EVENT BED CHARACTER ADJACENT TO THE BRAUX ONLAP SURFACE

The studied part of the Upper Braux Unit is characterized by a wide range of event-bed types. These include centimeter- to decimeter-thick planar-laminated and ripple cross-laminated, weakly graded beds interpreted as deposits of low-density turbidity currents (LDT *sensu* Bouma 1962), and decimeter- to meter-thick structureless poorly graded sandstones with abundant dewatering structures interpreted as deposits of high-density turbidity currents (HDT *sensu* Lowe 1982). However, many beds (with thicknesses ranging from a few tens of centimetres to 2-3 m) show a tripartite character and sedimentary facies associations involving mudclasts and units of argillaceous sandstone that are less easily reconciled with conventional turbidite models. These are particularly well developed close to the onlap surface (mostly within 1 km) and include beds previously described as sandwich beds containing central units of mudclast-breccia (McCaffrey and Kneller 2001). For the purposes of this study, three intergradational bed types are identified in addition to the familiar LDT and HDT deposits: thick structureless and dewatered sandstones with discontinuous pods and clusters of mudclast breccia (Type A); sandstone beds with a continuous mudclast breccia layer capped by a parallel-laminated or ripple-laminated sandstone interval (Type B), and sandstone beds with a lower medium- to coarse-grained cleaner sandstone overlain by an argillaceous fine-grained sandstone containing floating mudstone clasts and capped by a variably thick division of structured (parallel-laminated and ripple-laminated) fine- to very fine-grained sandstone (Type C). All three bed types are laterally equivalent to HDT deposits when traced away from the onlap over distances approaching a kilometer.

Description

Type A beds are typically 1.5 to 3 m thick and are amongst the thickest of the event beds present (Fig. 2A). They have planar flat or undulose bases and planar flat tops, the former with erosional grooves. They are dominated internally by structureless sandstone with local evidence for dewatering and prominent internal mudstone clast breccias which occur in patches up to 2 m thick and many tens of meters long in which the clasts are densely clustered and surrounded by a clean sandstone matrix. The mudclast patches can have ragged margins with the surrounding sand, but in some cases they have well defined, rounded lateral edges. They occur centrally with thicker sand beds. The mudstone clasts are often elongated and usually up to some tens of centimeters in size (in rare cases up to 1 m) and either chaotically arranged or with a crude bedding-parallel fabric. The matrix is generally of a sand grade similar to that of the surrounding bed.

Type B beds have a well-developed and more continuous chaotic sand-mud division in which variably abundant mudstone clasts are surrounded by fine-grained sandstone (Figs. 2B, 3). Small (millimeter-size) plant fragments can also be present. The breccia division typically varies in thickness due to rugosity on both the lower surface, and irregular contacts with the overlying sandstone. Margins of the breccia layer are generally sharply defined. The underlying sandstones are up to coarse grained and generally graded. They can have abundant groove casts, often deeper and with more diverse orientations than those of Type A beds.

Type C beds (Fig. 2C) range in thickness from 0.5 to 1.5 m and are characterized by a thick central division of structureless argillaceous fine- or medium-grained sandstone with or without millimeter- and centimeter-size mud clasts. This central part of the bed is often rich in plant fragments with dimensions usually of a few millimeters to a few centimeters across, as well as muscovite flakes. The lower interval – typically only a few to a few tens of centimeters thick – consists of cleaner structureless sand, sometimes with rare centimeter-size randomly distributed mud clasts. This interval can be missing, especially in close proximity (a few tens of meters) to the bed pinch-out against the confining slope. Abundant groove casts are common at the bed base. The bed is capped by a fine-grained parallel or ripple-laminated sandstone interval. This division often shows extensive loading and growth due to collapse of the upper sand interval into the underlying argillaceous division, in some cases descending as sheared sandstone balls to coalesce with the basal sandstone (e.g., bed Z3, Fig. 2C). Color banding and the repetition (a few times) of a sequence of laminated sandstone and a supradjacent structureless sandstone that may load into the underlying laminated sandstone can sometimes characterize this upper interval (e.g., bed Z2, Fig 2C).

Compositional analysis of the mudstone clasts in bed types A-C reveals affinities with the siliciclastic turbidite succession rather than the marly confining slope (Patacci 2010; cf. Kneller and McCaffrey 1999; Puigdefàbregas et al. 2004). However, there is no evidence of local erosion beyond the presence of deep (up to 10 cm) groove casts and rarer flute casts on bed bases; inclined erosional contacts or amalgamation surfaces between turbidite beds are very rare within 1 km of the confining slope.

The complex irregular boundaries between internal divisions are in contrast to the overall event-bed geometries, which are characterized by sharp planar and parallel bases and tops (Fig. 4; see also full correlation panel, Appendix 1). Remote from the slope, Types A-C beds are rare and the stratigraphy comprises mostly HDTs with subsidiary LDTs. The LDTs tend to maintain their character along the studied transect. However, when traced toward their onlap, over half of the HDTs pass laterally into a type A-C bed within 500-1000 m of the paleoslope (Fig. 1). Approaching the slope, Types A-C beds themselves vary their character greatly and can pass one into another (Fig. 4). They usually show an increase in thickness of the central mudclast-rich and chaotic divisions which occur progressively lower in the bed. Observed transitions approaching the slope are between Type A and B and between Type B and C, but never in the opposite direction. Type C beds in particular show an increase in the thickness of the central argillaceous interval and the thinning (and sometimes the disappearance) of the basal cleaner sandstone when traced toward the onlap slope. The argillaceous interval does not climb the confining slope, whereas thin (up to 25 cm thick) LDT event beds that can be directly correlated to the upper division of a related tripartite bed adjacent to the slope can be followed for at least a few tens of meters upslope (e.g., beds P and Z2, Fig. 4).

Interpretation

Several models have previously been suggested for the tripartite beds of the Upper Braux Unit (here distinguished as types A, B, and C). These have generally focussing on individual examples and therefore not on the full variety of beds developed. Stanley (1980) suggested that tripartite beds were the result of syndepositional and postdepositional dewatering-related liquefaction processes. McCaffrey and Kneller (2001) invoked slope instability triggered by the arrival of a turbidity current, with the chaotic division being emplaced by a debris flow originating from the confining slope. Puigdefàbregas et al. (2004) interpreted such beds as a product of local substrate deformation and delamination induced by the arrival of a sandy turbidity current. Whereas there is evidence for local instability in the form of muddy slumps and debris flows shed from the slope (Sinclair 1994), and evacuated scars and multi-bed remobilisation higher on the onlap surface (Puigdefàbregas et al. 2004), field observations highlight several problems with the existing models: (1) the mud clasts are clastic in composition (so cannot be sourced from higher on the marly confining slope); additionally, they do not appear to be locally sourced on or adjacent to the confining slope inasmuch as there is no direct evidence for slope failure or delamination there; (2) while it might be expected that higher-energy flows (i.e., those depositing thicker beds with coarser grain size) would trigger more extensive local failure, beds of Types A-C show various thicknesses and maximum grain sizes; (3) the chaotic middle division of bed Types B and C often contains carbonaceous material likely sourced from along the gravity-flow pathway and not the local lateral slope; (4) the variability of the chaotic and deformed central division (ranging from mudclast breccias to well-mixed argillaceous sandstone) cannot easily be explained by local failure or deformation, because the proximity of the source of the material should have resulted in deposits with a similar degree of disaggregation and mixing.

An alternative interpretation is that the facies trends result from the rheological complexity of the primary flows. The argillaceous sandstone division in Type C beds is thus interpreted as an expression of rheological transformations that occurred as consequence of flow interaction with the slope, resulting in the development of zones of turbulence-suppressed and/or fully cohesive behavior and their associated deposits. These beds are interpreted to be hybrid event beds *sensu* Haughton et al (2009). Types A and B beds (clean sandy turbidites with mudstone clasts in clusters or in a continuous layer) can be thought of as the deposit of flows approaching some transformation point, such that they were arrested by the confining slope at different stages before full transformation could occur; here the mud clasts have been hydraulically segregated and then buried under high suspension-fallout rates of sand (see Postma et al. 1988 and Kneller and Branney 1995).

DISCUSSION – A WINDOW INTO FLOW TRANSFORMATION STAGES

The range of bed types in the Upper Braux Unit is likely the result of a combination of both parent-flow character and local topographic influence. Because the variety of bed types does not appear associated to any change in slope morphology, a wide spectrum of parent flows of various magnitude and mud content is inferred to have reached the study area. Flows which deposited Type C beds (where the matrix of the chaotic division contains dispersed clay and lacks large clasts) must have been longitudinally well fractionated, with segregation of mud clasts and/or carbonaceous matter and/or clay to the rearward part of the flow, before encountering the slope. Immediately prior to rapid deceleration, collapse, and deposition of the central argillaceous division, such flows may already have developed zones with turbulence-suppressed or fully laminar rheology, or may have been on the threshold of doing so. Types B and A beds seem to represent stages of less evolved flows, where continuous or clustered collections of mud clasts were buried by sand before they could be incorporated into a linked debris flow; they may have acquired the muddy material relatively locally, perhaps due to erosion of the local feeder conduit. In general, the argillaceous sandstone intervals in Type C beds (H3 division *sensu* Haughton et al., 2009) have relatively little matrix clay (10-15%). None achieves the "starry night" textures of linked debrites seen in the distal parts of other systems where sand grains are suspended in dark clay (e.g., Haughton et al. 2003).

This may be a function of the relatively proximal setting, which limited both longitudinal fractionation prior to transformation and the potential for mudclast abrasion and clay release. Low-density turbidity currents depositing thin turbidites (LTD) may not have been erosional at all along their transport pathway.

The effect of the topographic setting on the flow non-uniformity is discussed in detail by Kneller and McCaffrey (1999), who suggested that flows successively experienced depletive, accumulative, and uniform conditions (*sensu* Kneller 1995) away from the slope, on impact and after flow reorientation parallel to the slope, respectively. However, basin-floor topography may have had a contrasting effect on different parts of the hybrid or incipiently hybrid flow, as inferred by the relative proportions of the different divisions within the tripartite beds as they are traced away from the slope (Figs. 4 and 5). Where topography captures and deflects the fully turbulent and relatively thick flow front, turbulence intensity may be enhanced next to the slope, as inferred by Kneller and McCaffrey (1999) and depositional fallout rates subdued, causing the clean-sandstone basal division to thin toward the slope, as observed. However, the geometry of the chaotic mud-rich divisions is different, in that they usually thicken toward the confinement, pinching out at the base of the slope, but without climbing up it. This suggests that in the turbulence-suppressed parts of the flow which deposited this division, the run-up-induced deceleration adjacent to the slope might have dominated, resulting in a rapid loss of momentum next to the confining topography, with consequent rapid deposition. Deposition from a trailing low-density and relatively thick turbulent cloud completed depositional events, emplacing thin, structured sandstones that pinch out higher up the onlap surface, succeeded by thin mudstones pinching out yet higher.

The combined effect of radial expansion onto a flat basin floor together with flow deflection and run-up onto a counter slope close to the point of entry into the basin (Figs. 1 and 5) is thought to have forced the flows to experience an overall deceleration, inducing deposition from parts of the flow that might ordinarily have bypassed, thus providing evidence of flow transformation stages generally not captured in the deposit at one location. In the absence of local flow non-uniformity effects, such flows may have run out for many further kilometers, either dropping out the clasts en route or perhaps eventually depositing as fully developed hybrid event beds (HEBs).

CONCLUSIONS

We document the occurrence and character of different types of tripartite event bed, including fully developed hybrid event beds, immediately adjacent to a proximal lateral basin margin, in a narrow band within a few hundreds of meters from a counter slope. Flow deceleration and arrest induced by flow interaction with the slope is thought to have overprinted the depositional patterns of larger-scale flow evolution by forcing the deposition (and transformation) of flows at different stages of development that otherwise might have left no depositional record at this location. A variety of flow transformation stages are recorded by the tripartite beds, ranging from incipient (producing sandy intervals with mudstone clast clusters) to fully evolved (resulting in a homogeneous argillaceous sandstone division with small or no mudstone clasts – hybrid event beds). The presence of a confining slope can thus be a key element controlling facies variability and geometry in hybrid-prone deep marine clastic systems in areas remote from the ultimate down-dip pinch-out.

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FIGURE CAPTIONS

Figure 1. Geological and location map of the Crête de la Barre area. Positions of logged sections (logs 0-2, log 3.5, and log 5) are shown. The onlap traces (dot-dashed line) represent the base of the Upper and Lower Braux Units. Inferred paleoflow (arrows) was drawn using data after Kneller and McCaffrey (1999) and inferred onlap surface contours (thick dashed lines) are after Puigdefàbregas et al. (2004). N.L., Nummulitic Limestone; U.C., Upper Cretaceous. Pie charts show bed types at each location (% by thickness). HDT, deposits of high-density turbidity currents; LDT, deposits of low-density turbidity currents; Type A, sandstones with discontinuous pods and clusters of mudclast breccia; Type B, sandstone beds with a continuous mudclast breccia layer; Type C, sandstone beds with a middle argillaceous sandstone interval with floating mudstone clasts. Tripartite beds (Types A-

B-C) are common 0-400 m from the confining slope (logs 0-2), but are rare farther away from it. The plots consider only beds and intervening mudstones that crop out at all three log locations (26 event beds).

Figure 2. A) Type A tripartite bed on the Braux road section (Bed D, log 2) showing discrete pods of a thick mudstone-clast breccia enclosed in clean sandstone. B) Type B tripartite bed (Bed M, log 2) characterized by a laterally continuous central unit made up of densely packed mud clasts surrounded by fine sandstone (hammer for scale). C) Beds Z2 and Z3 (both Type C tripartite beds) at log 2 location showing central clay-rich sandstone divisions with scattered mudstone clasts sandwiched between cleaner sandstone divisions. Bed Z3 is characterized by a thin upper clean sandstone which shows prominent loading and growth into the underlying mixed mud-sand chaotic division (hammer for scale). D) Thin section in plane polarized light from argillaceous sandstone in Bed Z3 (from location labelled “d” on Part C) showing abundance of pore-filling clay and small clay chips in the central division of this Type C bed.

Figure 3. Bed P at log 0.8 location (Type B tripartite bed). A) Photograph, B) sedimentary log, and C) thin-section images are shown. Bed P is characterized here by three distinct divisions: 1) a relatively thick fining-upward clean sandstone basal division with scattered mudstone clasts up to 20 cm in size; 2) a chaotic middle division with a mixed mud-sand matrix and usually smaller centimeter-size mud clasts and 3) an upper cleaner sandstone with laminations. Boundaries between divisions are rugose, showing loading and growth geometries in basal parts of the upper cleaner sandstone. Thin-section photographs (c) indicate the overall fining-upward trend and an enrichment in clay in the chaotic middle division.

Figure 4. Sedimentary logs showing representative examples of development of different types of "tripartite character" toward the confining slope. An overall increase in thickness of the middle mudclast-rich and chaotic divisions and their shift toward the base of the bed can be observed in most beds approaching the slope. Bed transitions approaching the slope are shown. Bed names are

after Kneller and McCaffrey (1999). Numbers in square brackets are estimated pinch-out distances in meters (measured normal to inferred paleoslope). Correlation confidence is very high as bed correlations are based on full bed-to-bed detailed matching and walking of individual key beds (however, dashed correlations are only inferred), which confirm the correlations established by earlier workers (Kneller and McCaffrey 1999, Puigdefabregas et al. 2004, Callec 2004). See Fig. 1 for logs location and Appendix 1 for full correlation panel. Note: given outcrop constraints, it is not possible to specify what the relative likelihoods of transition are.

Figure 5. A) Cartoon illustrating the forced deceleration and consequent partial transformation of a flow encountering the Braux confining slope. X-X' shows the approximate location of the studied outcrop section. B-D) Summary of bed lateral changes observed in the outcrop. Large-magnitude flows may either pass untransformed down the basin (in which case the bed comprises structureless sandstone extending to the pitchout) or as shown in Part B, they may preserve evidence in the form of mudclast clusters for incipient transformation frozen in the deposit. Intermediate-magnitude flows that had sufficient energy to entrain mud clasts and clay up-dip are forced to transform, creating hybrid event beds (Type C beds) at the base of slope. Less energetic flows that were less erosional up-dip decelerated without flow transformation.

Appendix 1. Correlation panel showing the Upper Braux Unit onlapping toward the SW along the Crête de la Barre ridge. Bed names (A-Z) are after Kneller and McCaffrey (1999). Distance between log 0 and log 2 is to scale. Log 2 is drawn "inclined" to highlight its spatial relationship with logs to the SW.