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Influence of flow containment and substrate entrainment upon sandy hybrid event beds containing a co-genetic mud-clast-rich division

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ABSTRACT

Individual sandstone beds containing a co-genetic mud-clast-rich (MCR) division are being increasingly described from the distal reaches of many deep-water fan systems. These deposits, termed hybrid event beds, are considered to record a flow whose composition and rheology changed significantly to become increasingly more argillaceous (clay-rich), MCR and turbulence-suppressed during the deposition of a single event bed. Studies of confined systems, in which gravity flows were affected by confining sea-floor topography, have documented similar deposits recording turbulence suppression in proximity to confining sea-floor topography (e.g., basin margins). In new research from a confined, contained system from the Castagnola Basin of NW Italy, lateral transects of individual sandstone beds 5 km in extent show that individual sandstone beds contain a co-genetic MCR division which is often; 1) extensive across the basin rather than localised adjacent to confining topography; 2) exhibits rapid, significant and repeated variation in depositional character over short length scales (tens to hundreds of metres), specifically in terms of the thickness of co-genetic MCR divisions and the size and abundance of clasts contained within them; and 3) exhibits variation in depositional character over larger length scales (>1 km) which is non-systematic in relation to palaeoflow direction or increasing proximity towards the counter slope of the downstream confining northern basin margin. A suite of factors within the Castagnola Basin is thought to have resulted in the deposition of these co-genetic MCR divisions whose thickness and distribution are less predictable in relation to confining sea-floor topography than those described from other confined uncontained settings. Specific factors include; 1) recent and voluminous entrainment of muddy substrate at seemingly random locations across the basin floor and their support and transport within a high sediment concentration gravity flow; and 2) containment (ponding) of gravity flows within a confined basin, which is thought to have established exten\sive and complex three dimensional flow dynamics across the basin following flow interaction with multiple basin margins. This research highlights the role of entrainment of muddy substrate and subsequent transport processes of muddy substrate for developing co-genetic MCR divisions, as well as the importance of understanding the degree of containment depositional systems experienced when considering the spatial distribution of depositional facies, and thus reservoir quality, in topographically complex settings.

1. Introduction

Hybrid event beds (HEB) are now recognised as a significant component of deep-water systems from a variety of settings (e.g., Haughton et al., 2003, 2009; Talling et al., 2004, 2012a; Amy and Talling, 2006; Davis et al., 2009; Hodgson, 2009; Muzzi Magalhaes and Tinterri, 2010; Patacci et al., 2014). Frequently these deposits comprise a mud-clast-rich (MCR) argillaceous (clay-rich) sandstone which directly overlies unstratified to stratified relatively cleaner (clay-poor) sandstones; both facies are co-genetic, having been emplaced during a single gravity-driven current event (Haughton et al., 2003, 2009; Talling et al., 2004; Talling, 2013). HEBs are considered to reflect deposition beneath a passing flow event which evolved significantly in terms of composition and rheology (e.g., becoming increasingly argillaceous, MCR and turbulence-suppressed Haughton et al., 2009). Such flow evolution has been attributed to distal or lateral flow transformations, following significant entrainment of a muddy substrate, and or declining turbulence energy (e.g., Ricci Lucchi and Valmori, 1980; Haughton et al., 2003, 2009; Amy and Talling, 2006; Barker et al., 2008; Hodgson, 2009; Muzzi Magalhaes and Tinterri, 2010; Patacci et al., 2014). HEBs are of great significance as they are characterised by marked heterogeneity in depositional character, and thus reservoir quality, on an intra-bed scale (e.g., Sylvester and Lowe, 2004) and can be an indicator of cleaner, better-quality reservoir sandstone farther upstream (e.g., Haughton et al., 2003; Hodgson, 2009).

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Typically HEBs have been described from the distal parts of unconfined systems with relatively subdued sea-floor topography (e.g., Haughton et al., 2003; Amy and Talling, 2006; Hodgson, 2009); however HEBs and other deposits interpreted to record increasingly argillaceous, MCR and turbulence suppressed deposition during a single flow event have been recognised in more topographically complex settings (e.g., Barker et al., 2008; Patacci et al., 2014). In such settings sea-floor topography can modify gravity current transport direction, velocity and deposition (e.g., Kneller et al., 1991; Kneller and McCaffrey, 1999; Jackson and Johnson, 2009; Athmer and Luthi, 2011; Gamberi and Rovere, 2011); herein termed flow confinement. Additionally, the term flow containment can be applied where sea-floor topography encircles and retains a flow within a depositional low (e.g., a ponded mini-basin), and the size or thickness of the flow is sufficient such that it feels the effects of this containment (Van Andel and Komar, 1969; Pantin and Leeder, 1987). Thus, depositional systems in this study are classified as either unconfined and uncontained (UU), confined and uncontained (CU), or confined and contained (CC; Fig. 1). Contained systems are always associated with flow confinement processes due to the presence of encircling confining sea-floor topography in such settings. From a CU setting Barker et al. (2008) document the increasing thickness of argillaceous sandstone at the expense of underlying co-genetic relatively clean sandstone within the same bed towards a laterally confining basin margin; they interpret such a depositional trend to record increasing turbulence suppression due to flow thinning with distance towards the lateral basin margin. Lateral variation in the depositional character of individual beds towards their point of onlap onto a confining basin margin has also been documented in the outcrop from a CU system (Annot Sandstone, SE France; Patacci et al., 2014). Patacci et al. (2014) describe the systematic development and thickening of a co-genetic MCR division, and the development of a HEB, at the expense of mud-clast-poorer, cleaner sandstone within the same bed locally (<1 km) towards the confining basin margin. They interpreted such a depositional trend to result from the localised confining effects of the basin margin. Observations from such studies suggest that forced flow transformation adjacent to confining topography can result in development of a predictable deposit character and depositional trends towards such topography; such onlapping deposits are of great importance where they form stratigraphic traps in hydrocarbon reservoirs. This study presents examples of HEB depositional character and distribution within a CC setting and demonstrates that their distribution may not be predictable where flow containment occurs in addition to flow confinement. Observations made herein highlight the role of muddy substrate entrainment and the combined effects of flow confinement and containment upon gravity flow dynamics and deposit character, and thus reservoir quality distribution, and how these might vary in topographically complex settings with differing degrees of flow containment.

2. Geological setting

The Tertiary Piedmont Basin of NW Italy was an episutural basin formed during late Cretaceous to late Eocene Meso-Alpine collision of the European plate and Adria micro-plate (Ricci Lucchi, 1986; Biella et al., 1992; Maino et al., 2013) (Fig. 2A–C). The eastern Tertiary Piedmont Basin contains a late Eocene to early Miocene deep-water turbiditic succession (c. 3000 m thick, Fig. 2A) with several major unconformities, most present in the lower part of the succession, recording regional tectonic events that caused important changes in basin physiography (Cavanna et al., 1989; Di Giulio and Galbiati, 1993). Transpressive motion along the E–W trending Villalvernia–Varzi line in the easternmost Tertiary Piedmont Basin during the Chattian–Aquitanian, folded Oligocene strata to form the asymmetric, ENE–WSE trending Castagnola sub-basin (Ibbeken, 1978; Andreoni et al., 1981; Cavanna et al., 1989; Di Giulio and Galbiati, 1993) (Fig. 2B, C).

Sediment gravity currents entered the Castagnola Basin from the SW (Stocchi et al., 1992) and emplaced the c. 800 m thick Castagnola Formation which onlapped the underlying Rigoroso Formation (Cavanna et al., 1989; Andreoni et al., 1981; Di Giulio and Galbiati, 1993) (Fig. 2A–C). During emplacement of the Costa Grande Member, termination of activity on the Villalvernia–Varzi line around the Chattian–Aquitanian boundary forced a change from deposition of laterally offset, stacked sand bodies, to simple sheet-like deposits (e.g., sub-units A–H and sub-unit I, respectively, of Felletti, 2002, 2004b); the latter style of deposition persisted throughout the remainder of the Costa Grande Member (Stocchi et al., 1992; Baruffini et al., 1994). Outcrop upstream (south) of the basin is sparse, and thus little is known of the shelf and feeder system to the Castagnola Basin. Estimates of the basin width (c. 11 km) and basin length downstream (c. 5 km) are constrained by the extent of Costa Grande Member deposits. However, this basin area would have necessarily increased during progressive infill of a basin with inclined (i.e., non-vertical) basin margin slopes. Gravity currents emplacing the Costa Grande member were contained (ponded) within the basin, resulting in the development of thick mud caps between beds and a lack of comparable correlative strata beyond the basin (Stocchi et al., 1992; Baruffini et al., 1994). Palaeocurrent indicators record flow reflection and deflection at the downstream counter slope of the northern basin margin (Stocchi et al., 1992; Felletti, 2002) (Fig. 2C). Dips on the northern basin margin at the time of deposition are estimated to be on the order of 10° (Baruffini et al., 1994; Felletti, 2002, 2004a).

3. Methods

A well exposed interval (c. 250 m stratigraphic thickness) within the turbiditic Costa Grande Member was logged using a Jacob staff at eight

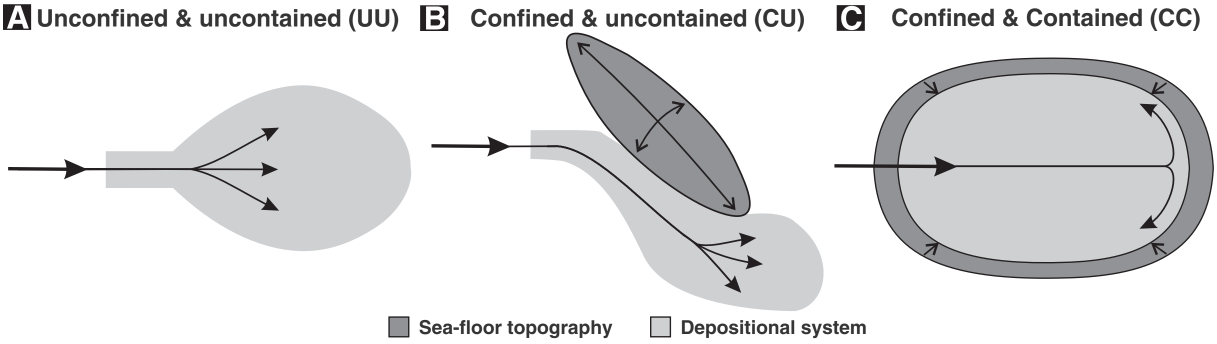

Fig. 1. Schematic plan view depicting the difference between unconfined and uncontained (A), confined and uncontained (B) and confined and contained (C) deep-water systems. (A) Sediment gravity flows and the depositional systems they emplace are free to expand in unconfined uncontained settings due to the absence of confining sea-floor topography. (B, C) In the presence of confining sea-floor topography flows and depositional systems are modified (confined) and may be additionally contained in the presence of suitable encircling confining sea-floor topography (C only).