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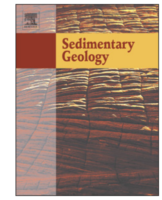

The classical turbidite outcrop at San Clemente, California revisited: An example of sandy submarine channels with asymmetric facies architecture

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ABSTRACT

A 1.1–1.2 km long, 3–15 m thick exposure of the late Miocene to Pliocene Capistrano Formation crops out at San Clemente, California, providing a superb example of submarine channel elements with an asymmetric cross-sectional facies distribution. Coarser-grained, thicker bedded and more amalgamated channel axial deposits are partitioned towards one side of channel elements (200–400 m wide), whilst finer-grained and thinner bedded channel margin deposits are partitioned towards the other side. Two end-member types of silty channel-base and intra-channel drapes are recognized, namely, bypass drapes and deposition drapes. There are both draping silty turbidites that show either strong (bypass drapes) or insignificant (deposition drapes) evidence of erosion and/or sediment bypass during deposition. Bypass drapes and deposition drapes are interpreted to result from flow bypass and flow stratification, respectively, and have significantly different implications for reservoir connectivity and down-dip sediment transport. Channel elements are nested to form two channel complexes. Channel complex 1 comprises four channel elements and shows a vertical aggradation dominated stacking pattern, whilst channel complex 2 comprises five channel elements and shows a mixed lateral migration/vertical aggradation stacking pattern. This study also suggests that these exposures represent only a fragment of a larger channel complex set that might bear varying degrees of resemblance to its formative geomorphic channel(s) on the paleo-seafloor. The reinterpretation of this classic outcrop provides valuable insight into other turbidite channel systems at outcrop and in the subsurface, both in a sedimentological and applied context.

1. Introduction

Submarine channels are long-lived conduits for the transport of clastic sediments and organic material from fluvial and shallow marine environments to the deeper parts of basins. Their role in the transport of sediment, organic carbon and, increasingly, pollutants are important to understand. In addition, channels focus flows that pose a hazard to seafloor infrastructure, and their deposits may constitute important hydrocarbon reservoirs. Studies of modern and subsurface deep-water systems have provided significant insights into turbidite channels in terms of their morphologies, initiation, large- and small-scale stratigraphic architecture and evolution (e.g., Abreu et al., 2003; Deptuck et al., 2003, 2007; Babonneau et al., 2004; Cross et al., 2009; Mayall et al., 2010; Paull et al., 2011, 2013; Kolla et al., 2012; Maier et al., 2012; Gamberi et al., 2013; Janocko et al., 2013). However, bed-scale cross-sectional variability, such as changes in facies architecture from channel axis to channel margin, and their causal depositional processes, are in general poorly-constrained by these datasets due to limitations of scale or data resolution. In these respects, well-exposed outcrops can provide more detailed insights (e.g., Hickson and Lowe, 2002; Gardner et al., 2003; Grecula et al., 2003; Arnott, 2007; Kane et al., 2009; Jobe et al., 2010; Pyles et al., 2010; Hodgson et al., 2011; Hubbard et al., 2014). Nonetheless, to our knowledge, outcrop studies on submarine channels (especially sandy submarine channels) with asymmetric facies architecture and well-developed intra-channel tabular deposits are rarely reported and investigated in detail (Walker, 1975; Hein and Walker, 1982; Sullivan et al., 2000; Pyles et al., 2010; McHargue et al., 2011; Hodgson et al., 2011; Fildani et al., 2013). In this study, we document such channels in outcrops of the late Miocene-Pliocene Capistrano Formation exposed at San Clemente, California, USA. Specifically, we document channel fill geometries, sedimentary facies and facies distributions, bed to bedset scale correlations, with the aim of answering the following specific questions: (1) How does submarine channel architecture vary from the channel axis to the channel margin at channel element scale? (2) What are the associated depositional processes for emplacing various types of drapes? (3) What are the stacking

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patterns of those channel elements? (4) Do the channel-fills at outcrop represent most of the system or just a small slice thereof? If it is the latter, then what are the likely cross-sectional dimensions of the entire depositional system? And (5) what are the new implications of this reinterpretation of the classical outcrop for hydrocarbon exploration and production?

2. Geological setting

2.1. Regional setting

During deposition of the late Miocene-Pliocene Capistrano Formation (~10–4 Myr), the study area in San Clemente lay within a N-S trending marine embayment (the Capistrano Embayment) (Fig. 1a). The embayment is characterized by a physiographic and structural trough bounded by the San Joaquin Hills to the west and the Cristianitos Fault to the east (Ingle, 1971; Ehlig, 1979; Bouroullec and Pyles, 2010). Along the present day coastline, the embayment extends from Dana Point eastward to the Cristianitos Fault (c. 15 km wide) and narrows northwards until it terminates at the Santa Ana Mountains. The embayment extends southward from the coastline and merges with a deeper open ocean basin offshore (Ehlig, 1979).

Prior to deposition of the Capistrano Formation, the area subsequently occupied by the Capistrano Embayment was part of a larger closed basin below sea level that was characterized by laminated and diatomaceous mudstone of the Monterey Formation, which was deposited under oxygen-deficient conditions at middle to lower bathyal water depths (Ingle, 1971; Ehlig, 1979) (Fig. 2). During the late Miocene, the Capistrano Embayment, with a submarine scarp on its eastern side, began to develop as a result of movement along the Cristianitos Fault. The sediments of the Capistrano Formation were subsequently deposited in the Capistrano Embayment until the early Pliocene when movement on the Cristianitos Fault ceased. During this period, sediment gravity flows transported sediment westward down the submarine scarp along the Cristianitos Fault. These flows formed muddy slope deposits and coarser-grained slope channel-fills on the east side of the embayment, part of which crops out in the study area (Ehlig, 1979; Malone and Alba, 1979; Camacho et al., 2002; Campion et al., 2005). Foraminiferal assemblages and radiolarian tests from the Capistrano Formation around Dana Point indicate middle or lower bathyal paleo-water depths of approximately 900 m to 2000 m during deposition (White, 1956, 1971; Ingle, 1971). The prevailing deep-water conditions were followed by at least 1000 m of uplift during the Pliocene to Pleistocene, resulting in widespread erosion and development of the unconformable contact of the Capistrano Formation with the overlying Pleistocene marine terrace deposits (Campion et al., 2005).

2.2. Study area

The Capistrano Formation is well exposed on the 1.1–1.2 km long and 3–15 m high, NNW–SSE to NW-SE orientated sea cliffs at San Clemente State Beach in the city of San Clemente, California, USA (Fig. 1b). It consists of three primary sections, corresponding to sections A, B, and C in this study, which are dissected by three gullies and a parking lot that provide a partial 3D view of the outcrop (Fig. 1b). These sections show that the exhumed Capistrano Formation in the study area is largely a sand-dominated turbidite channel system that features a wide range of channel fills, ranging in grain size from strongly bioturbated mudstone to boulder-sized conglomerates (Walker, 1975; Busby et al., 1998; Camacho et al., 2002; Campion et al., 2005, 2007) (Figs. 3, 4; Table 1). Bedding dips within channel fills and the enclosing Monterey Formation mudstones are largely sub-horizontal except close to the channel edges, where beds within the channel fills may dip away from the channel edges towards channel axes at up to 15° to 20°. The channel fills are overlain at the top of the cliffs by sandy or gravely deposits of Pleistocene marine terrace origin (Walker, 1975) (Fig. 2). A 300–400 m gap separates section C from the outcrops to the northwest. These outcrops were first described by Camacho et al. (2002) and recently by Jester (2013), but are not included in this study due to the uncertainty in correlation across the exposure gap.

Numerous studies have been undertaken on the well-exposed channel fills within sections A, B and C since 1971 (Weser, 1971; Walker, 1975; Hess, 1979; Clark and Pickering, 1996; Busby et al.,

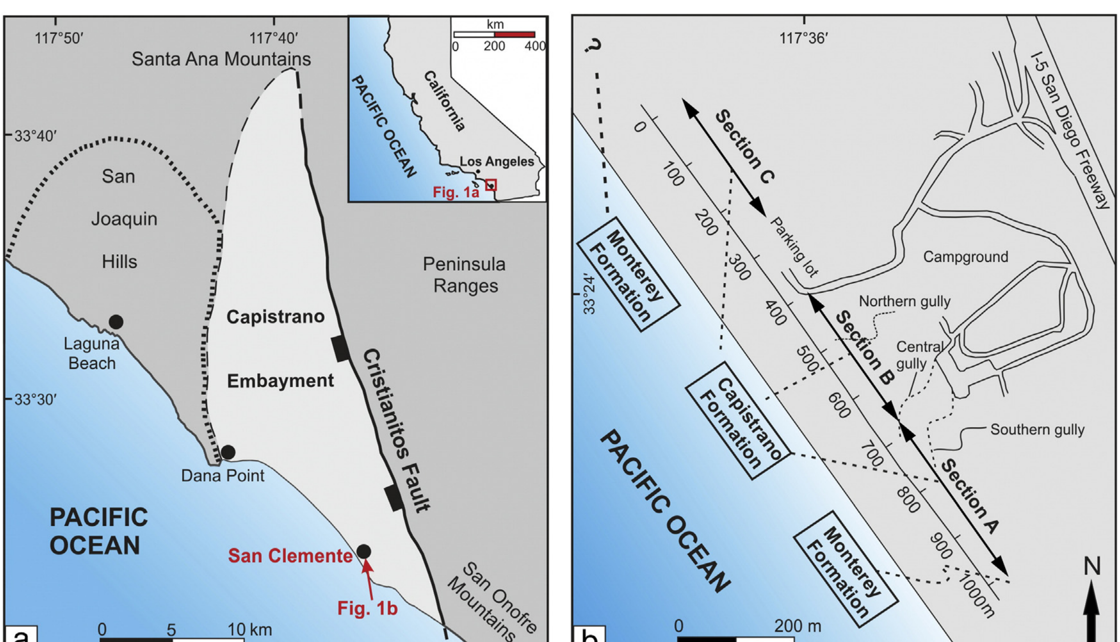

Fig. 1. (a) Map showing the location and paleogeography of the study area with the Capistrano Embayment highlighted (modified from Ehlig, 1979). (b) Map of the study area showing the three primary sections of this study (sections A–C).